



Doctoral Thesis

Search for Supersymmetry with Multiple Charged Leptons at $\sqrt{s} = 13$ TeV with CMS and Radiation Tolerance of the Readout Chip for the Phase I Upgrade of the Pixel Detector

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Search for Supersymmetry with Multiple
Charged Leptons at $\sqrt{s} = 13$ TeV with CMS
and
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Phase I Upgrade of the Pixel Detector

A thesis submitted to attain the degree of
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presented by

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Abstract

The present dissertation documents contributions to two complementary aspects of high-energy particle physics research with the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). The work includes an analysis of proton-proton collisions to search for physics beyond the standard model (SM) and radiation tolerance assurance studies conducted in the context of the development of a new pixel detector.

The first part of the thesis describes a search for so-far undiscovered physics processes, which are predicted for example by supersymmetric extensions of the SM. To this end, events with at least three charged leptons as well as hadronic jets and missing transverse momentum are analyzed at the unprecedented center-of-mass energy of 13 TeV. The study is based on a data set corresponding to an integrated luminosity of 12.9 fb^{-1} of proton-proton collisions that has been recorded with the CMS detector in 2016. The examined final state features very low SM background contributions. The resulting high sensitivity for different beyond the SM processes can be further enhanced by categorizing events of interest into 32 exclusive signal regions. Reducible and irreducible SM background contributions to these signal regions are estimated with data and Monte Carlo simulations, respectively. The observed data are found to agree with the SM predictions within the assigned uncertainties. The results are therefore interpreted in terms of exclusion limits on masses of supersymmetric particles in the context of simplified model topologies that feature gluino pair production and a neutralino as the lightest supersymmetric particle (LSP). In a model producing four top quarks and two LSPs, gluino masses up to 1 200 GeV could be excluded, extending the exclusion limit set by a similar search at $\sqrt{s} = 8 \text{ TeV}$ by about 200 GeV. Gluino masses up to 1 000 GeV could be excluded in a model with light-flavor jets, vector bosons, and two LSPs in the final state.

The second part of the thesis is dedicated to irradiation studies with the new readout chip (ROC) for the Phase I Upgrade of the CMS pixel detector. The replacement of the pixel detector with an improved version has been completed in February 2017 and aims at maintaining and improving the performance of the detector at increased instantaneous luminosities of up to $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. One of the key components of the new detector is a revised ROC, which is used in the forward part and in layers 2–4 of the central detector, designed for hit detection efficiencies above 99% at pixel hit rates up to 120 MHz/cm^2 . Because of the close proximity to the collision point, the new ROC is faced with stringent demands in terms of tolerance against ionizing radiation damage. Studies conducted in the context of this dissertation significantly contributed to improving the radiation tolerance of the chip during its development phase. Moreover, it could be confirmed that the performance of the final version of the chip meets the design specifications even after accumulating the expected lifetime doses for layers 2 and 1 of 0.5 MGy and 1 MGy, respectively. Several important performance figures of the ROC have been shown to comply with the specifications even after heavy irradiation of up to 4.2 MGy. The thesis not only describes comprehensive functionality tests after irradiation, but also provides recommendations for dose dependent adjustments of operation parameters that will be necessary to optimize the performance of the chip in the experiment.

Zusammenfassung

Die vorliegende Dissertation beschreibt Forschungsergebnisse zu zwei unterschiedlichen Teilaspekten der Untersuchung hochenergetischer Teilchenkollisionen mit dem Compact Muon Solenoid (CMS) Experiment am Large Hadron Collider (LHC). Die Arbeit beinhaltet eine Analyse von Proton-Proton Kollisionen, mit deren Hilfe nach Hinweisen für Physik jenseits des Standard Modells (SM) der Teilchenphysik gesucht wird, und Bestrahlungsstudien die im Rahmen der Entwicklung eines neuen Pixeldetektors durchgeführt wurden.

Der erste Teil der Arbeit beschreibt eine Suche nach bisher unentdeckten physikalischen Prozessen, welche zum Beispiel durch supersymmetrische Erweiterungen des SMs vorhergesagt werden. Dazu werden Ereignisse mit mindestens drei geladenen Leptonen sowie Jets und fehlendem Transversalimpuls bei einer zuvor unerreichten Schwerpunktsenergie von 13 TeV untersucht. Der zugrundeliegende Datensatz aus dem Jahr 2016 entspricht einer integrierten Luminosität von 12.9 fb^{-1} . Die aus der geringe Untergrundrate des betrachteten Endzustandes resultierende hohe Sensitivität für Prozesse jenseits des SMs kann durch Kategorisierung der Ereignisse in 32 nicht überlappende Signalregionen weiter erhöht werden. Detektor- und rekonstruktionsbedingte Untergrundbeiträge werden durch datengestützte Abschätzungen vorhergesagt, wohingegen die Vorhersagen für irreduzible SM Prozesse auf Monte Carlo Simulationen beruhen. Die Messdaten stimmen mit diesen Vorhersagen innerhalb der betrachteten Unsicherheiten überein, weshalb die Resultate zur Berechnung von Ausschlussgrenzen bezüglich der Massen von supersymmetrischen Teilchen in vereinfachten Modellprozessen herangezogen werden. Für ein Modell mit Gluino-Paarerzeugung, bei dem zwei Neutralinos sowie vier Topquarks produziert werden, konnten Gluino-Massen bis zu 1 200 GeV ausgeschlossen werden. Das entsprechende Ausschlusslimit einer ähnlichen Studie bei 8 TeV konnte damit um etwa 200 GeV erweitert werden. Gluino-Massen von bis zu 1 000 GeV konnten in einem Modell mit Neutralinos, Jets und Vektorbosonen ausgeschlossen werden.

Der zweite Teil der Arbeit beschreibt Bestrahlungsstudien mit dem neuen Auslesechip (ROC) für das Phase I Upgrade des CMS Pixeldetektors. Der zuvor eingebaute Pixeldetektor wurde im Februar 2017 durch eine verbesserte Version ersetzt, um die Leistungsfähigkeit des Systems bei einer erhöhten instantanen Luminosität von bis zu $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ zu garantieren und zu verbessern. Der neue ROC für den Vorwärtsbereich und für die Lagen 2–4 im zentralen Segment des Detektors stellt eine der wichtigsten Neuerungen dar und soll eine Effizienz von mehr als 99% bei Signalaraten bis zu 120 MHz/cm^2 garantieren. Auf Grund der Nähe zum zentralen Kollisionspunkt muss der ROC strengen Anforderungen hinsichtlich der Toleranz gegenüber ionisierender Strahlung genügen. Während der Entwicklungsphase des ROCs konnte diese Eigenschaft durch die im Rahmen dieser Arbeit durchgeführten Studien verbessert werden. Außerdem konnte gezeigt werden, dass die Leistungsfähigkeit des finalen Chipdesigns auch nach Absorption der maximalen für die Lagen 2 und 1 erwarteten Energiedosen von 0.5 MGy und 1 MGy den Anforderungen genügt. Viele wichtige Leistungsmerkmale erfüllen die Anforderungen selbst nach sehr hoher Bestrahlung von bis zu 4.2 MGy. Neben umfangreichen Funktionstests beinhaltet die vorliegende Arbeit Empfehlungen für dosisabhängige Anpassungen von Betriebsparametern, die für den optimalen Betrieb des ROCs im Experiment notwendig sein werden.

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Introduction

Earth, water, air, and fire — the idea of four fundamental constituents that make up all matter, proposed by ancient Greek philosopher Empedocles in the fifth century B.C. and later referred to as the *classical elements*, can be considered the first historical attempt to classify and structure the complexity of our material world [1]. The fact that similar concepts have been developed in many different pre-scientific cultures from Egypt over Babylonia to India, China, and Japan, shows an apparent yearning of humanity for order, simplicity, and categorization when explaining nature. And — on an even more fundamental level — there seems to be a common desire throughout human history and across different cultures, to ‘explain’ nature in the first place instead of just accepting it and coping with the consequences.

Today we know that the four classical elements are in fact not elemental and our understanding of the fundamental constituents of nature has grown from philosophical considerations to a mature and both theoretically and experimentally well tested and largely consistent picture, the standard model of particle physics. However, the goals of modern elementary particle physics are still the same — to deepen our understanding and to improve the description of matter and its interactions at the most fundamental level possible. While the aforementioned desire for simplicity and structure might be considered a rather anthropocentric demand — why should nature favor a few elementary constituents over a complex structure? — it has proven to be a very fruitful guiding principle in the history of natural sciences, although this by far did not mean that progress in the understanding of nature translated into a monotonous reduction of the number of known fundamental constituents. Rather, this number was subject to considerable oscillations.

The clearly arranged ancient Greek picture with four elements — later the aether was added as a fifth element — had to be given up at latest after first alchemy, then modern chemistry revealed the existence of a plethora of different chemical elements and compounds. However, simplicity and structure was re-established by the discovery of the periodic table by D. Mendeleev in 1869 [2]. A huge number of compounds could be reduced to a smaller number of chemical elements and those in turn could later be interpreted as bound objects made up from integer multiples from only three different fundamental particles: electron, proton, and neutron. Only shortly after the discoveries of these stable constituents of matter, the development of particle accelerators allowed to study heavier, short-lived particles, and yet again the number of known ‘elementary’ particles grew considerably as more and more hadronic resonances were discovered. With the formulation of the *Eightfold Way* by M. Gell-Mann in 1961 [3], this utterly complex particle zoo could be interpreted within a more fundamental structure, eventually leading to the development of a model which describes

all hadronic particles as bound states of six different fundamental particles, today known as *quarks*. Together with another six fundamental particles called *leptons* and twelve particles mediating the interactions between quarks and leptons, plus the Higgs boson, they form the particle content of the standard model and represent the latest state of the art in the hunt for the fundamental constituents of the universe. Given the historic examples of change of paradigms that followed phases with an increasing number of ‘elementary’ particles, the relative complexity of the particle content of the standard model begs the question whether it can be interpreted in the context of an even deeper underlying mechanism.

This and other fundamental questions are addressed by modern high-energy particle physics, both theoretically and experimentally. Research progress is made based on a close interplay between the two disciplines and the knowledge frontier has been pushed in the past both by theoretical predictions, which could eventually be confirmed by experiment, as well as by unexpected experimental observations, which only later could be understood theoretically. Especially experimental particle physics has become an interdisciplinary and complex effort, requiring expert knowledge in many fields of science: from civil engineering for the construction of huge underground accelerator and experiment caverns, to sophisticated particle detector and large-scale computing infrastructure development and statistics based data analysis to list just a few of them.

This thesis documents contributions to two important aspects of experimental particle physics: analysis of data obtained from particle collisions and the development of particle detectors conducted with and for the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC), the most powerful particle accelerator built to date. In order to put the achievements presented in this thesis into context, Chapter 1 briefly reviews the methods of accelerator based particle physics. Accelerator concepts and important performance parameters are introduced and the principal structure of modern high-energy physics experiments is introduced. Chapter 2 summarizes the standard model as the best description of particles and their interactions at the fundamental level available to date. Subsequently, its shortcomings and limitations are reviewed in order to motivate the interest in theories beyond the standard model and the search for experimental evidence for them. General concepts and ideas of one of the most popular of these extended theories, known as supersymmetry, are introduced and the associated phenomenological aspects are reviewed. These theoretical considerations pave ground for Part I of the thesis, dedicated to a search for supersymmetry in events with multiple charged leptons in the final state. The experimental setup used for this search, namely the LHC and the CMS experiment, are briefly described in Chapter 3. In addition, phenomenological aspects of proton-proton collision are summarized.

Chapters 4 to 11 describe the aforementioned search for supersymmetry in proton-proton collisions with an unprecedented center-of-mass energy of 13 TeV. The new energy frontier, which is accessible since the consolidation of the LHC in 2015, makes the search for new particles as predicted by supersymmetric theories especially exciting and the analysis presented in this thesis does its stint to shed light on uncharted territory. A motivation for investigating the final state with multiple charged leptons is outlined in Chapter 4, along with an overview of relevant standard model background processes and simplified signal models which can produce the examined final state. Chapter 5 describes how final-state physics objects, such as leptons or hadronic jets, are reconstructed from the detector response. The search strategy, including criteria for the event selection and the signal region categorization, is detailed in Chapter 6, followed by Chapter 7 presenting methods for estimating standard model background contributions which are later on compared to the observed data. As any search or measurement, the analysis is subject to different sources of systematic uncertainties. Chapter 8 describes how these uncertainties affect the result of the search. Finally, proton-proton collision data recorded at $\sqrt{s} = 13$ TeV with the CMS experiment between March and July 2016 are compared with the standard model background predictions in

Chapter 9 and the results are interpreted in the context of simplified supersymmetric signal models in Chapter 10. The first part of the thesis concludes with an intermediate summary in Chapter 11.

The second part of the thesis presents studies that have been conducted in the context of an upgrade of the CMS pixel detector — a subdetector which measures the trajectories of charged particles at the center of the experiment. The new pixel detector, which has been installed in February 2017, employs new front-end electronics for signal readout. During the development phase, this new digital readout chip required thorough characterization to detect design flaws early in the development process and to provide rapid feedback to the chip designers. Especially challenging for the operation of electrical circuitry at the center of a high-energy particle physics experiment like CMS is the total ionizing dose absorbed by the detector, arising from the passage of huge quantities of charged particles. This harsh environment poses stringent demands on the resilience of all detector components against radiation induced damage and Part II of the present work is dedicated to proton irradiation studies that have been conducted to validate the radiation tolerance of the new readout chip. As an introduction to the topic, Chapter 12 briefly sketches state and prospects of high-energy physics at the LHC at the time of writing this thesis to motivate the roadmap for advancements of the accelerator and for planned upgrades of the CMS experiment. Chapter 13 reviews the basic principles employed by position sensitive semiconductor tracking detectors. In addition, goals and implications of the so-called Phase I Upgrade of the CMS pixel detector are summarized to introduce the project the presented irradiation studies relate to. The readout chip as the central device of interest of the study is described in Chapter 14 and emphasis is given to the advancements with respect to its predecessor chip. Chapter 15 provides an overview of the total ionizing dose and particle fluence expected in the experiment and the associated radiation damage mechanisms that influence the performance of the readout chip. Moreover, the laboratory setups used to irradiate and examine prototypes and the final version of the readout chip are described. Finally, the results of the study are presented in Chapter 16. Besides comprehensive functionality and performance tests, radiation induced changes of optimal operation parameters are described to provide recommendations how to optimize the performance of the readout chip after irradiation in the experiment.

A summary of the findings and a brief outlook on the future of high-energy particle physics at the LHC is given in the Summary and Outlook chapter.

1. Methodology of High-Energy Physics at Particle Colliders

The three constituents of stable matter – electron, proton, and neutron — had been discovered before 1932 by studying different macroscopic materials like heated wires and radioactive elements. Already in this classical era of particle physics, the scattering experiment was employed as a powerful tool to infer the inner structure of matter, and soon after, the first particle accelerators had been used to increase the energy of the projectiles in these experiments. With increasing collision energies, heavier and unstable particles could be discovered — an endeavor that is still ongoing as the discoveries of the top quark in 1995 [4, 5] and of the Higgs boson in 2012 [6, 7] show.

Section 1.1 of this chapter introduces the scattering experiment, which has proven to be one of the most important workhorses of elementary particle physics since E. Rutherford’s famous experiments revealed the inner structure of the atom. In Section 1.2, the concepts of particle accelerators are reviewed, as these machines are indispensable tools to achieve higher and higher collision energies, needed to explore even smaller structures and to create new, unknown particles. Basic principles of particle detection are summarized in Section 1.3 in order to give an overview of how modern high-energy particle physics experiments work. The chapter closes with Section 1.4 outlining how these experimental setups are used to measure properties of fundamental particles and how evidence for unknown physics processes is searched for.

1.1 Scattering experiments

Exploring properties of fundamental particles requires to find a way to deduce microscopic properties and the mechanisms of processes that act on subatomic length scales from macroscopically measurable observables. A particular class of experiments where one particle is used as a projectile and shot onto a target has proven to be one of the most viable approaches to this challenge. In these so-called *scattering experiments* a detector is placed in the vicinity of the target in order to observe the outgoing particles after the interaction with the target. Figure 1.1 depicts the situation schematically: An incoming state $|\psi_i\rangle$ undergoes some unknown interaction $\mathcal{I}$ with the target, resulting in an outgoing state $|\psi_f\rangle$, also called *final state*, which is measured with a detector. Formally this process can be described as an operator that acts on the initial state

$$|\psi_f\rangle = \mathcal{I}|\psi_i\rangle. \tag{1.1}$$

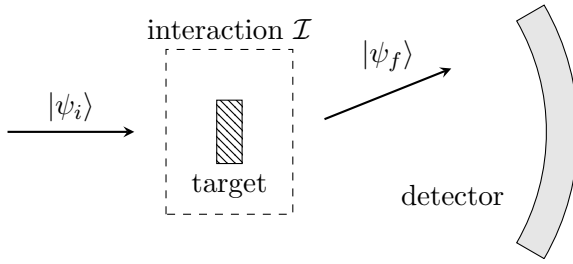


Figure 1.1: Schematics of the scattering experiment. An incoming state $|\psi_i\rangle$ undergoes an interaction with the target. The resulting state $|\psi_f\rangle$ is measured with a detector.

Such an experiment poses two major challenges: Most obviously it requires to construct and operate suitable detectors to quantify $|\psi_f\rangle$. Furthermore, and nonetheless complex, the unknown interaction process has to be inferred from the properties of $|\psi_i\rangle$, the target, and $|\psi_f\rangle$.

One of the first very successful scattering experiment was conducted by E. Rutherford and collaborators who studied the deflection angles of α -particles passing through a thin gold foil. It was observed that the majority of the incident particles passed through the lattice of atoms without significant deflection, while a small number of them were scattered by very large angles. The result suggested that the positive electric charge of the atom is concentrated in a small and heavy nucleus and rejected a model with homogeneous positive charge distribution [8]. This historic example shows how a microscopic structure — here the distribution of the electric charge within the atom — could be deduced from macroscopic observables like the deflection angle of the α -particles. Similar principles have been employed to resolve the inner structure of the nucleons themselves, the particles that build up the atomic nucleus, and they still form the basis of almost all high-energy particle physics experiments to date.

1.1.1 Cross section

One of the most important figures of merit in such scattering experiments is the ‘reactivity’ of the incoming particle with the target, a quantity that can be defined as follows: A particle incident in the area $d\sigma$ is deflected by the angle θ and scattered into the corresponding solid angle $d\Omega$, as shown in Figure 1.2. The scattering angle θ depends on the impact parameter b , defined as the shortest distance by which the incoming particle would miss the scattering center if it was not deflected. With $d\sigma = |b db d\phi|$ and $d\Omega = |\sin \theta d\theta d\phi|$, the so-called differential cross section is then given by [9]

$$\frac{d\sigma}{d\Omega} = \left| \frac{b}{\sin \theta} \left(\frac{db}{d\theta} \right) \right|, \quad (1.2)$$

where the functional relation between θ and b depends on the type of the interaction, in particular on the interaction potential. The differential cross section is proportional to the expectation value of the so-called *scattering amplitude* $\mathcal{M}_{if}$, which is related to the interaction via $\mathcal{M}_{if} = \langle \psi_f | \mathcal{I} | \psi_i \rangle$:

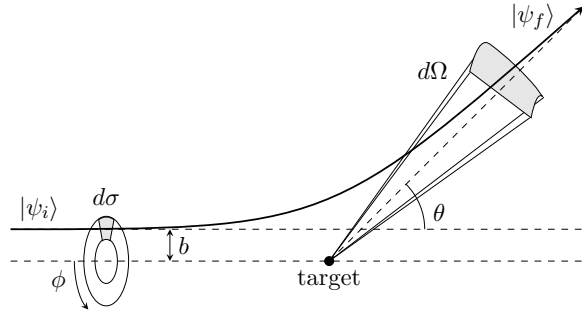
$$\frac{d\sigma}{d\Omega} \propto |\mathcal{M}_{if}|^2. \quad (1.3)$$

Integrating over the full solid angle yields the total cross section σ . In particle physics this quantity is a generalization of the geometrical cross section of the hard sphere scattering target and has the dimensions of area. It is usually expressed in units of *barn*, defined as

$$1 \text{ b} = 1 \times 10^{-24} \text{ cm}^2. \quad (1.4)$$

Cross sections of particle physics processes cover several orders of magnitude and depend on the type of interaction, on the energy of the incident particle, and on the target.

Figure 1.2: Parameters of the scattering experiment. The initial state $|\psi_i\rangle$ is incident in the area $d\sigma$ and is scattered into the solid angle $d\Omega$. The associated scattering angle is denoted as θ , while b indicates the impact parameter and ϕ the angular coordinate of the incident particle.



1.1.2 Inelastic scattering and center-of-mass energy

Unlike the Rutherford experiment, contemporary high-energy physics experiments mostly investigate *inelastic scattering* processes in which the initial and final state particles are not necessarily identical. According to Einstein's energy-mass relation, such processes can lead to a transformation of the kinetic energy of the incoming particle into rest-energy (and kinetic energy) of other particles that are produced in the collision. This mechanism allows to produce new, potentially undiscovered particles if the energy available in the collision is high enough. Many of the particles that are produced in inelastic collisions are unstable and decay into a lighter set of particles with a characteristic time constant τ . The lifetimes of unstable particles vary greatly between different types of particles and depend on the dynamically and kinematically allowed decay paths, also called channels. If multiple decay channels are viable, a branching ratio β_i can be defined for each channel, characterizing the probability that the particle decays according to this specific channel. Unitarity requires the sum of all branching ratios to be one.

The *center-of-mass energy* $\sqrt{s}$ quantifies the amount of energy available in the collision of an elementary particle with a target. Because of its relevance for the production of heavy, unstable particles it is one of the most important figures of merit in a scattering experiment. In order to maximize it, modern particle physics experiments at the energy frontier are usually implemented as so-called *colliding beam experiments*, where two particles are accelerated in opposite directions and brought into collision with each other. Although technologically more challenging, colliding beam experiments are often favored over experiments with fixed, macroscopic targets since the center-of-mass energy rises linearly with increasing particle energy E , while it rises as $\sqrt{E}$ for the fixed target experiments.

In high-energy physics, energies are usually expressed in units of *giga-electronvolts* (GeV) or *tera-electronvolts* (TeV), where $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$. Using natural units with $c = \hbar = 1$, as done throughout this thesis, allows to also express particle masses and momenta in these units.

1.2 Particle accelerators

The working principle of all particle accelerators is to manipulate a certain type of particle with electromagnetic fields to prepare the initial state of the collision. On top of the obvious requirement that the candidate particle has to be stable on time scales needed for accelerating and transferring it to the experiment, this requires that the particle carries electric charge. Such particles can be accelerated with high-frequency radio cavities, which switch the polarity of the accelerating electric field synchronously to the passage of the particle. The particles are guided through the accelerator and to the experiment by strong magnetic fields, which are provided by dipole magnets. Higher-order magnets with more complex field geometries are used to focus the accelerated particles onto the target.

1.2.1 Accelerator layouts

Two conceptually different geometrical layouts exist for constructing particle accelerators: linear acceleration lines and circular ones. Both options have their own advantages and downsides and the choice mainly depends on the physics processes to be studied in experiments at the accelerator and hence on the envisaged center-of-mass energy.

Circular accelerators offer the advantage that the particle can be accelerated for an arbitrary amount of time as the particles pass the acceleration cavity on every turn, provided that bending and focusing magnets keep them on track long enough. Additionally, particles can be ‘stored’ in such a configuration, until the experimenter decides to bring them into collision with the target. Therefore, circular accelerators are also referred to as storage rings. For colliding beam experiments, two particles are accelerated in opposite directions using two individual beam pipes. In practice, many particles are accelerated together forming a beam, which is often organized in spatially separated bunches, a necessity enforced by the acceleration mechanism of the radio frequency cavity. The two oppositely circulating beams of particles can then be intersected in the experimental setup. The advantages of circular accelerators, however, come at the expense of an inevitable energy loss of the charged particles via synchrotron radiation. This emission of electromagnetic radiation in the tangential direction of the beam arises from the centripetal acceleration of the charged particles on their circular track. In the relativistic regime, the energy loss per turn in a circular ring with radius r is given by

$$\Delta E = \frac{q^2 E}{\epsilon_0 3r (m_0 c^2)^4}. \quad (1.5)$$

Here, q is the charge of the circulating particle in units of the electron charge e , E is its energy, ϵ_0 the vacuum permittivity, and c the speed of light. Most notably the energy loss depends on the fourth power of the inverse rest mass m_0 of the circulating particle. Synchrotron radiation is therefore a severe energy loss for light particles such as electrons, whereas it is less of a problem in storage rings accelerating protons, which are heavier by a factor of ≈ 2000 . Another means of reducing the energy loss by synchrotron radiation is to increase the radius r of the storage ring. This led to increasingly larger accelerators over the past decades. The final choice of this parameter is usually driven by economic boundary conditions rather than scientific arguments. At a given radius, the center-of-mass energy of proton accelerators is limited by the achievable field strength of the dipole magnets rather than by synchrotron radiation. The most powerful particle accelerator build to date, the LHC hosted at the European Organization for Nuclear Research (CERN) near Geneva, is a circular collider with a circumference of 27 km and a design center-of-mass energy of 14 TeV.

Linear accelerators are the natural choice to avoid the aforementioned synchrotron radiation in the first place and are therefore often used to accelerate light particles such as electrons or positrons. Instead, the main challenges arise from the fact that the particles can pass the acceleration cavities only once before they are brought into collision. This entails that their maximum energy strongly depends on the length of the acceleration line. Moreover, particles that do not take part in the collision cannot be reused for subsequent collision as in circular colliders, unless dedicated beam recycling techniques are employed [10]. For colliding beam experiments, another difference is that linear colliders only have one beam intersection point, while the beams can be brought into collision in several different points at circular accelerators. Thus, only one experiment can be conducted at the time at a linear collider.

1.2.2 Luminosity

One of the key performance parameters of a particle accelerator is its center-of-mass energy, denoted as $\sqrt{s}$, since this energy determines the energy available for the production of new particles. Additionally, high energies are needed to resolve small structure sizes in deep inelastic scattering experiments, as the de Broglie wavelength λ_B of the accelerated particle is proportional to the inverse of the particle's momentum p according to $\lambda_B = h/p$, where h is the Planck constant.

Nonetheless important is the ‘intensity’ of the beam, i.e., the number of particles delivered by the accelerator per unit time and area. This quantity is referred to as *instantaneous luminosity* $\mathcal{L}$. For a storage ring it is proportional to the number of particles per bunch in each beam N_1 and N_2 , the number of bunches n , the revolution frequency f , and to the inverse of the beam cross section area A and it can be written as

$$\mathcal{L} = \frac{N_1 N_2 n f}{A}. \quad (1.6)$$

High instantaneous luminosities therefore require excellent focusing of the beams in the intersection point to minimize A . Integrating the instantaneous luminosity over time yields the *integrated luminosity*

$$\mathcal{L}_{\text{int}} = \int_0^t \mathcal{L} dt. \quad (1.7)$$

The integrated luminosity has units of inverse area and is commonly expressed in inverse barn, or as in the context of this thesis in *inverse femto barn* (fb^{-1}). The definition of luminosity easily allows to calculate event rates dN/dt and total number of events N_{tot} for a given process with cross section σ :

$$\frac{dN}{dt} = \mathcal{L} \sigma \quad (1.8)$$

$$N_{\text{tot}} = \mathcal{L}_{\text{int}} \sigma. \quad (1.9)$$

For a given physical process, the total number of observed events in the detector is then given by

$$N_{\text{obs}} = N_{\text{tot}} \mathcal{A} \epsilon \quad (1.10)$$

$$= \mathcal{L}_{\text{int}} \sigma \mathcal{A} \epsilon, \quad (1.11)$$

where $\mathcal{A}$ is the detector acceptance, i.e., the fraction of the solid angle covered by the detector, and ϵ the detection efficiency.

1.3 Basic detector concepts for high-energy physics experiments

To conduct an experiment at a storage ring, the two particle beams circulating in opposite directions can be brought into collision at a certain intersection point, also called interaction point (IP), which conventionally serves as the origin of the experiment's coordinate system. The z axis of this system is typically defined in the direction of one of the incident beams and the azimuthal angle ϕ and the polar angle θ are defined as depicted in Figure 1.2. The latter can be used to define the so-called *pseudorapidity* η

$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right). \quad (1.12)$$

The pseudorapidity is favored over the scattering angle θ in collider experiments since differences in pseudorapidity $d\eta$ are Lorentz invariant in the limit of relativistic particles. They therefore do not depend on the frame of reference in which the collision is described.

In order to quantify the collision products, the IP is surrounded by several layers of detectors, each of which is dedicated to measure a particular property of the particles emerging from the collision. Combining the measurements of all subdetectors allows to identify the collision products and to infer the underlying interaction process. Two main classes of subdetectors can be distinguished: Systems for measuring the trajectories of charged particles and systems for measuring the particle's energy. Their fundamental working principles are briefly summarized below.

1.3.1 Tracking detectors

Reconstructing the tracks of charged particles emerging from the IP is a crucial objective in most experiments as it allows to derive several particle properties. Tracking detector used for these measurements come in various implementations but all of them rely on the fact that charged particles ionize a suitable medium along their trajectory.

The most cost effective tracking detectors are ionization chambers filled with gas. Gas ions created by traversing charged particles are accelerated by an electric field established between electrodes, often wires, there they induce a measurable signal. Gaseous detectors are typically used to cover large areas where a moderate spatial resolution is acceptable. If high spacial resolution must be achieved, a different class of tracking detectors, based on semiconductor materials is used. These detectors offer the possibility to implement a finer segmentation of the electrodes. Moreover, the energy required to generate a pair of charge carriers is of the order of a few eV and thus about one order of magnitude smaller than in gaseous detectors. This advantage entails signals with larger amplitudes, which in turn improves the *signal-to-noise ratio*, i.e., the ability to discriminate signals induced by traversing particles against electronic noise in the readout system. The basic working principle is very similar to the one of gaseous detectors but instead of ionizing gas, the traversing particles create electron hole pairs in a semiconductor material, usually silicon. The working principles of semiconductor tracking detectors and an example of a concrete implementation are detailed in Chapter 13, where the CMS pixel detector is presented. Semiconductor tracking detectors offer better spacial resolution compared to gaseous detectors but are technologically more challenging and require more sophisticated readout and cooling infrastructure. A competing requirement is the necessity of building such solid state detectors as lightweight as possible to reduce multiple scattering of traversing particles in the detector material. Such deflections significantly complicate the track reconstruction and degrade the resolution of the detector as will be described below.

Depending on the geometrical implementation of the electrodes, individual layers of such detectors offer one or two-dimensional spatial resolution. In order to obtain a three dimensional reconstruction of the track, several detector layers are arranged at increasing radii from the IP.

Tracking detectors are used to identify the point of interaction, called *vertex*, by reconstructing and intersecting the tracks of charged particles produced in the collision. In a similar way, so-called secondary vertices can be identified. These secondary vertices are the result of unstable particles that are created at the primary vertex and decay after traveling a distance that is long enough to be resolved by the detector. The spatial resolution of a tracking detector depends on the spatial separation of the electrodes, also denoted as *pitch* d , and on the mode of operation. In the simplest case where the electrodes provide only binary information — signal or no signal — and where the signal is not shared between adjacent electrodes, the resolution is given by the second central moment of a normalized flat probability density function of the width d

$$\sigma_x^2 = \int_{-d/2}^{d/2} x^2 \frac{1}{d} dx \quad (1.13)$$

$$\sigma_x = \frac{d}{\sqrt{12}}, \quad (1.14)$$

where σ denotes the standard deviation. However, this resolution can be considerably improved by exploiting charge sharing between adjacent electrodes. Charge sharing arises from lateral diffusion of the cloud of charge carriers while drifting along the electric field and can be enhanced by superimposing a magnetic field perpendicular to the drift direction, causing the charge carriers to be deflected by Lorentz force. If the charge carriers are shared between two or more adjacent electrodes, the intersection point of the incident particle can be estimated with a better resolution. This is particularly powerful if a signal proportional to the created charge is read out. Using this so-called *pulse height (PH) information* additionally improves the spatial resolution of the detector, e.g., by finding the center-of-gravity of the resulting charge distribution.

Operating a tracking detector in a homogeneous magnetic field additionally allows to measure the *transverse momentum* p_T of a particle with charge q , where the subscript denotes the momentum component orthogonal to the magnetic field B . This is achieved by measuring the radius R of the particle's trajectory, which is bent by Lorentz force. For B and R measured in units of tesla and meters, respectively, the particle's momentum in units of GeV is given by [11]

$$p_T = 0.3 B q R. \quad (1.15)$$

The momentum resolution depends on the uncertainty on the measurement of the curvature $k = 1/R$, which is determined by two contributions: firstly, the uncertainty arising from the finite measurement resolution in each detector plane δk_{res} , and secondly, the uncertainty arising from multiple scattering of the traversing particle in the detector material δk_{ms} . For a sufficiently large number of track measurement points N , the effect of the former contribution on the momentum resolution can be approximated by [12]

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_x}{a B L^2} \sqrt{\frac{720}{N+4}} p_T, \quad (1.16)$$

where L denotes the length of the trajectory projected on the plane perpendicular to the magnetic field, and $a = 0.3 \text{ T}^{-1} \text{ m}^{-1} \text{ GeV}$ a constant. In addition, the direction of the bend of the track allows to determine the sign of the particle's charge.

1.3.2 Calorimetry

A second class of subdetectors, known as *calorimeters*, is devoted to energy measurements. While one of the crucial requirements for tracking detectors is their lightweight construction in order to reduce multiple scattering of the traversing particles, calorimeters aim at stopping the particles within their volume and therefore require a heavy absorber material. The energy deposited in the calorimeter by the particle is measured with an active material that produces a signal proportional to the deposited energy. The active material can be, e.g., a scintillator, an ionizing noble liquid, or a semiconductor. It can either also serve as absorber material in a so-called *homogeneous calorimeter*, or active material and absorber are arranged in alternating layers. The latter implementation is referred to as *sampling calorimeter*. The key figure of merit of any calorimeter is the energy resolution σ_E/E . It can be factorized into three components, which are to be added in quadrature

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}. \quad (1.17)$$

Here, a denotes a stochastic term arising from statistical fluctuations in the absorption process, b a constant term representing detector nonuniformity and calibration uncertainties, and c a contribution from electronic noise from the signal readout.

Electromagnetic calorimeters are used to measure the energy of electrons, positrons, and photons. Within the absorbing material, these particles lose their energy in cascade reactions of electron-positron pair production and bremsstrahlung, so-called *electromagnetic showers*. In order to measure the full energy of the incident particle, the calorimeter dimensions need to be large enough to contain the full shower, whose longitudinal and lateral dimensions are characterized by the radiation length X_0 and the Molière radius of the absorber material, respectively. Typical electromagnetic calorimeters feature $15 - 30 X_0$ of absorbing material [11]. Spatial resolution can be obtained with an electromagnetic calorimeter by segmenting the active material in the lateral direction. In combination with a tracking detector, energy deposits in the calorimeter can be related to tracks of charged particles, which allows to discriminate photons against electrons and positrons.

Hadronic calorimeters serve to measure the energy of hadrons, i.e., particles that are subject to the strong nuclear interaction. Such particles are capable of penetrating multiple electromagnetic radiation lengths and therefore reach the hadronic calorimeter, which is typically located adjacent to the electromagnetic calorimeter at larger radii from the IP. Showers initiated by hadrons in the hadronic calorimeter are far more complex than their electromagnetic counterparts, owing to a rich spectrum of hadronic shower constituents. Similarly to X_0 , there is an absorber dependent *nuclear interaction length* λ_i , which determines the longitudinal dimension of the hadronic shower. The energy resolution of hadronic calorimeters is largely limited by the fact that $20 - 40\%$ of the deposited energy is used to overcome nuclear binding energies in the absorber and hence is not contributing to the signal [11].

1.4 Searches and measurements

With the collision products being identified and their properties determined, there is an almost infinite amount of possibilities for analyzing the underlying interaction. As in the case of the Rutherford experiment, detailed measurements of particle properties such as the deflection angle can be used to infer the structure of the scattering center and inelastic

collisions can be used to create short-lived particles whose properties can be determined by studying their decay products. In general, analyses can be grouped into two subcategories: precision measurements and searches.

Precision measurements aim at determining a specific property of a known particle or interaction with high accuracy. Typical examples are mass measurements for elementary particles or cross section measurements for a certain interaction process. Such analyses are characterized by a thorough assessment of the systematic uncertainties and require premium detector calibrations in order to minimize the uncertainty on the final result. Especially measurements targeting processes with small cross sections are therefore usually performed after an experiment has been run for a longer period of time such that accelerator and detector performances could be studied in detail and large amounts of data have been collected.

Searches for new particles or interactions that have not been observed so far on the other hand are usually among the first analyses performed with new experiments and in particular when an increase of the beam energy offers to study a new, uncharted phase space. Record beam energies can lead to the discovery of unknown particles whose rest mass is too large for them to be produced in previous experiments. In contrast to precision measurements, searches have in general more conservative uncertainty estimations in order to prevent false positive results. While precision measurements are specifically tailored for one observable, searches often require a more generalized approach, as the target is unknown or at least diffuse by definition. A search for unknown physics processes or particles can be performed in two ways. The first approach is to search for unknown features such as bumps, ledges, or tails in otherwise smooth distributions of a certain observable. Often the observable is the *invariant mass* m of a system of collision products, a Lorentz invariant quantity that describes the total energy and momentum of an object or system. For two massless or relativistic particles it can be defined as a function of the transverse momentum p_T , the pseudorapidity η , and the azimuthal angle ϕ of the two particles

$$m^2 = 2 p_{T,1} p_{T,2} (\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2)). \quad (1.18)$$

If the invariant mass spectrum of the collision products exhibits a local maximum, this can indicate resonant production of an unknown particle at this specific mass, which decays into the observed decay products.

The other possibility is to define some region of interest by defining boundaries in one or more observables. Subsequently, the number of observed events falling in this so-called *signal region* (SR) are compared with the number of events expected from known physics processes, also referred to as *background*. As is the case for the previously described class of searches, such *cut-and-count analyses* requires a statistical interpretation to determine whether or not the observed result is compatible with the background expectation or if a significant excess has been observed. Such an excess would indicate some unknown physics process that produces the final state studied by the analysis. An example for such a search for new particles is presented in Part I of this thesis.

2. Theoretical Framework

As is the case for most mature sciences that have left behind their purely empiric beginnings, elementary particle physics is founded on a solid theoretical understanding of the observed experimental results. Fundamental particles and their interactions are described by a set of relativistic quantum field theories, collectively known as the standard model (SM) of particle physics, which is introduced in Section 2.1. The particles and their properties as well as the interactions between them are briefly reviewed with emphasis on introducing phenomenological aspects relevant in the context of this thesis. Subsequently, a brief summary of electroweak symmetry-breaking and the Higgs mechanism is presented since its experimental confirmation in 2012 not only marks the latest great success of elementary particle physics, but is also considered the final keystone of the SM. Finally, a short review introduces Feynman diagrams and summarizes how important observables in particle physics such as cross sections can be approximated using perturbative calculations.

Despite its great success in describing experimental data with stunning precision, the SM has some shortcomings and conceptual limitations. Examples of open questions and experimental observations that are not addressed by the SM are summarized in Section 2.2 to motivate why one of the key aspects of contemporary particle physics experiments is to search for evidence for theories beyond the SM.

One of the both theoretically and phenomenologically most compelling extensions of the SM is supersymmetry (SUSY), a postulated symmetry between fermions and bosons. The concept of SUSY is introduced in Section 2.3, along with a description of the so far undiscovered particles that are postulated by the theory. Emphasis is also put on how SUSY can solve some of the questions that are not answered by the SM and on phenomenological aspects and their implications for experimental searches.

2.1 The standard model of particle physics

The formulation of the SM in its present structure has been a collective effort that started in the 1960's and was crowned in 2012 by the discovery of the Higgs boson, a particle that is thought of as its final missing piece [6, 7]. The SM categorizes all known elementary particles and describes three fundamental interactions between them — the electromagnetic, the weak, and the strong nuclear interaction. The SM is exhaustively described in literature and the summary given here largely follows Ref. [9]. A concise summary can be found in Ref. [13].

The principles of nonrelativistic quantum mechanics, which govern the behavior of subatomic particles at low velocities, can be extended to account for relativistic effects by describing

particles and interactions as quantized fields pervading space-time, hence the name quantum field theory (QFT). Different QFTs, characterized by distinct internal symmetries, have been formulated for different fundamental interactions of particles, namely quantum electrodynamics (QED) to describe the electromagnetic interaction and quantum chromodynamics (QCD) to describe the strong nuclear interaction. Electromagnetic and weak interaction have eventually been merged into a common electroweak theory.

The common principle of these QFTs is to construct a *Lagrangian density* $\mathcal{L}$ that depends on the fields Φ_i corresponding to a set of i regarded particles and on their space-time derivatives

$$\partial_\mu \psi_i = \frac{\partial \psi_i}{\partial x^\mu}, \quad (2.1)$$

where $\mu = 0, 1, 2, 3$ is the Lorentz index. Much like the Lagrange function in classical mechanics, $\mathcal{L}$ can be used to determine the dynamics of the fields by applying the principle of least action $\delta \mathcal{S} = 0$, where the action $\mathcal{S}$ is defined as $\mathcal{S} = \int \mathcal{L} dt$. This leads to a generalized form of the Euler-Lagrange equations:

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial (\partial_\mu \psi_i)} \right) = \frac{\partial \mathcal{L}}{\partial \psi_i}. \quad (2.2)$$

In contrast to the Lagrange function in classical mechanics, the Lagrangian density itself cannot be derived from first principles in QFT. Instead it is taken as axiomatic and has to be postulated in such a way that the resulting field equations are compatible with experimental observations. There is, however, one important boundary condition that $\mathcal{L}$ has to respect. As known from quantum mechanics, global phase transformations of the form

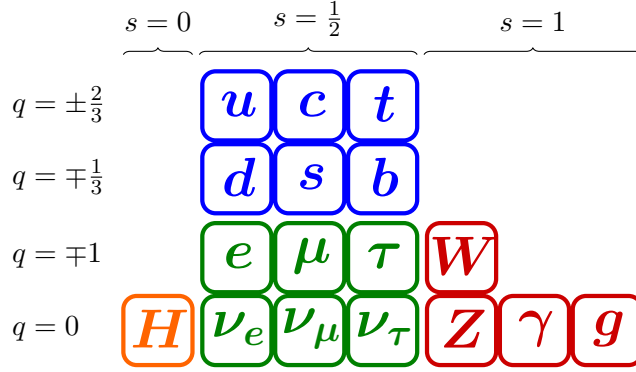
$$\psi \rightarrow e^{i\theta} \psi \quad (2.3)$$

leave the system's observables unchanged since only the square of the wave function ψ has physical relevance and the same is true in QFTs. One of the corner stones of QFTs is the extension of this invariance by demanding that also *local* phase transformations of the fields, i.e., transformations where the real number θ is a function of the space-time coordinate x_μ , leave $\mathcal{L}$ invariant. This ad hoc requirement, referred to as *local gauge invariance*, appears to be a fundamental principle of physics and it enforces modifications of the 'free' Lagrangian density, which describe the interactions between elementary particles. Another important implication of local gauge invariance is the conservation of physical quantities. According to Noether's theorem a conserved current exists for each local symmetry that leaves the action invariant [14].

2.1.1 Particles

The SM's particle content can be classified into different subgroups based on mutual properties of the particles, called *quantum numbers*. A schematic visualization of this categorization is shown in Figure 2.1. The horizontal arrangement in the figure is based on the particle's spin, which can be considered an internal angular momentum. Its quantum number s takes positive half integer and integer values and is related to the measurable spin of the particle S^2 by the relation $S^2 = s(s+1)\hbar^2$, with the reduced Planck constant $\hbar = h/(2\pi)$.

Figure 2.1: SM particles grouped by spin s and electrical charge q . Each three generations of quarks and leptons constitute the fermionic sector and are supplemented by the spin-1 bosons, which mediate the interactions between the fermions. The SM particle content is completed by the Higgs boson, the only particle in the SM with spin 0.



Fermions

Particles sharing the quantum number $s = 1/2$ are called *fermions*. This property implies that fermions have antisymmetric wave functions, which forces them to comply with the Pauli exclusion principle that states that no two identical fermions in one system can agree in all their quantum numbers [15].

Elementary fermions can be further subdivided into *leptons* and *quarks*. These two groups are distinguished by the fact that quarks are subject to the strong interaction whereas leptons are not. In terms of quantum numbers, the quarks carry a property called *color*, which can take values of blue, green, and red as well as the corresponding anti-colors anti-blue, anti-green, and anti-red. In addition to the strong force, all quarks and the electrically charged leptons interact electromagnetically and all fermions couple to the weak interaction. There are six different species for both leptons and quarks, which are organized in each three *generations*.

For **quarks** the different species, also referred to as *flavors*, and their corresponding antiparticles are organized as follows. The first generation quarks are the *up* and the *down quark*, the former carrying $q = +2/3 e$ of charge, where e is the electron charge, and the latter $q = -1/3 e$. These quarks build up the atomic nuclei of ordinary matter. Second (*charm* and *strange*) and third (*bottom* and *top*) generation quarks do not occur in stable matter but can be produced in collider experiments. As for the first generation there is one up-type and one down-type quark in each generation, denoting that the quark carries the same electrical change as the up and the down quark, respectively. The different quark flavors usually refer to the mass eigenstates of the quarks. Those are, however, not eigenstates of the weak interaction and hence a heavy quark can decay into a lighter quark via the exchange of a $W^\pm$ boson. This process can be described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [16, 17]

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (2.4)$$

Here, the left column vector denotes the weak eigenstates of the down-type quarks and the right one their mass eigenstates. The entries V_{ij} describe the probability that a quark of flavor i decays into the flavor j and have been measured experimentally. It has been found that the diagonal entries are large, i.e., decays within one generation are favored while cross-generation decays are suppressed. The exchange of a Z boson between quarks, also referred to as flavor-changing neutral current, is not observed experimentally.

Similarly to the quarks, also the **leptons** are organized in three different generations with a certain mass hierarchy. The lightest one of the charged lepton is the electron e^- . The

unstable, heavier charged leptons are the muon μ^- and the tau τ^- , all of which carry the same electrical charge. The corresponding particles with positive charge are their antiparticles. Moreover, there is an electrically neutral and, in the SM, massless neutrino ν associated with each of the three flavors. In the absence of color and electric charge, neutrinos only interact weakly with other particles. Fermions come in two different chirality states denoted as left- and right-handed and a special peculiarity of the weak force is that it only couples to left-handed fermions, a feature called *maximum parity violation* [18]. Besides violating parity, weak processes can also violate the combined symmetry of charge conjugation and parity, known as *CP violation* [17]. As for the other interactions there is a ‘charge’ related to the weak interaction, called *weak charge*, which is only carried by left-handed fermions. Since neutrinos only interact weakly and the weak interaction does not couple to right-handed fermions, it is not possible to observe right-handed neutrinos, as — if they were to exist — they would not interact with any of the SM particles.

The masses of the elementary particles are free parameters in the SM and have to be determined experimentally. Both in the quark and in the lepton sector, they have been found to differ substantially between the respective flavors. For the quarks, the masses span a range from a few MeV for the up and down quarks to approximately 174 GeV for the top quark. Even larger discrepancies are observed in the lepton sector, where the nearly massless neutrinos* contrast the heavier charged leptons, which span a mass range of 511 ke for the electron to about 1.78 GeV for the tau lepton. The origin of these large mass differences as well as the reason for having exactly three generations both in the quark and in the lepton sector are not yet understood.

Bosons

The second class of SM particles comprises particles where s takes integer values. As a consequence, these particles, called *bosons*, are not subject to the Pauli exclusion principle and can be described by symmetric wave functions. Bosons with $s = 1$ act as mediators of the interactions between the particles in the SM.

The electromagnetic force is mediated by exchange of photons between electrically charged particles. Similarly, the strong force is mediated by gluon exchange between colored particles. Both photon and gluons are massless, but while photons are electrically neutral, gluons carry color charge themselves — one unit of color and anti-color each. This leads to gluon self-interaction and renders processes involving the strong interactions more complicated than electromagnetic processes. While photons and gluons are massless, the mediators of the weak interaction, the electrically neutral Z^0 and the charged $W^\pm$ bosons are massive. Theoretically, the mass of these so-called *vector bosons* has been challenging to accommodate in the SM and has led to the prediction of a further boson, namely the Higgs boson H , which has been discovered in 2012. The underlying Higgs mechanism will be briefly summarized in Section 2.1.3. Differently than all other known elementary bosons, the Higgs boson is a spin-0 particle.

2.1.2 Interactions

The three fundamental interactions described by the SM lead to the exchange of energy, momentum, and quantum numbers between particles involved in the interaction, the latter giving rise to transitions between different particles. Formally, these interactions are described by Lagrangian densities $\mathcal{L}$, which are invariant under local gauge transformations.

*While the SM considers massless neutrinos, the observation of neutrino oscillations implies that at least two mass eigenstates have non-vanishing mass (c.f. Section 2.2).

Electroweak interaction

Within QFT, the fermion fields are described by *spinors* ψ , four component objects that differ from vectors by their transformation properties under rotations. These spinors and their derivatives can be used to construct a Lagrangian density $\mathcal{L}$ for a free spinor field. By imposing the requirement of local gauge invariance, $\mathcal{L}$ needs to be extended by additional terms including a vector field A_μ . In particular, a term representing an interaction between ψ and A_μ and a term for the ‘free’ vector field need to be added. Local gauge invariance forces the new vector field, also called gauge field, to be massless.

The invariance under the global phase transformation in Equation 2.3 can be written in terms of a unitary matrix U and is a manifestation of an internal symmetry under transformations of all unitary matrices, summarized as the $U(1)$ group. Requiring that this global invariance holds locally gives rise to the Lagrangian density of QED

$$\mathcal{L}_{QED} = [i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi] - \left[\frac{1}{4}F^{\mu\nu}F_{\mu\nu}\right] - (q\bar{\psi}\gamma^\mu\psi)A_\mu, \quad (2.5)$$

where γ^μ are the gamma matrices and $F^{\mu\nu} = (\partial^\mu A^\nu - \partial^\nu A^\mu)$. The vector field A_μ is the electromagnetic potential and the Lagrangian density describes the interaction between fermions with electrical charge q via coupling to the massless photon. The underlying symmetry requires the conservation of electrical charge.

As shown by S. L. Glashow, A. Salam, and S. Weinberg, the electromagnetic and the weak force can be regarded as two low energy manifestations of the more fundamental electroweak force [19–21]. Formally, this is represented by a $SU(2)_L \otimes U(1)_Y$ symmetry, where the subscript L denotes the fact that the weak interaction only couples to left-handed fermions. The symmetry gives rise to the conservation of electric charge q and of the weak hypercharge Y . Both are related via the third component of the weak isospin I^3 as

$$q = I^3 + \frac{1}{2}Y. \quad (2.6)$$

Requiring invariance under local gauge transformations requires to introduce four gauge fields, one represented by the isosinglet B , which couples to the weak hypercharge current, and three fields represented by the isotriplet W , which couples to the three weak isospin currents. These four fields, however, cannot be identified with the four mediators of the electroweak force, the photon, the Z , and the $W^\pm$ bosons, because it has been observed experimentally that the Z boson couples to right-handed fermions, which do not carry weak isospin. The problem can be resolved by introducing the electroweak mixing angle θ_W , which rotates the electroweak eigenstates of the fields to the experimentally observed neutral mass eigenstates

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B \\ W^3 \end{pmatrix}. \quad (2.7)$$

Furthermore, the fields corresponding to the charged $W^\pm$ bosons are mixings of the first and second W component, given by

$$W^\pm = \frac{1}{\sqrt{2}} (W^1 \mp iW^2). \quad (2.8)$$

However, this approach has the blemish that the gauge fields need to be massless in order not to impair the local gauge invariance. Though, experiments show that the Z and the $W^\pm$ bosons are massive ($m_Z = 91.2 \text{ GeV}$, $m_{W^\pm} = 80.4 \text{ GeV}$ [11]) and the way how these masses can be accommodated in a local gauge theory is to employ spontaneous symmetry breaking. This phenomenon and the related Higgs mechanism are summarized in Section 2.1.3.

Strong interaction

In a similar way as in the case of QED, also the Lagrangian of QCD can be constructed based on the Lagrangian for free fermions. Here, the underlying symmetry concerns the three color states of the quarks and the fermion field ψ is a shorthand for a three-component column vector, whose entries are spinors for the blue, the red, and the green state of the quark. The free Lagrangian is invariant under global $SU(3)$ transformations and similarly than in QED, additional terms have to be added in order to guarantee that the invariance also holds for local gauge transformations. The resulting Lagrangian describing the interactions of quarks via the strong force then reads as

$$\mathcal{L}_{QCD} = [i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi] - \left[\frac{1}{4}F^{\mu\nu}F_{\mu\nu}\right] - (g_s\bar{\psi}\gamma^\mu\lambda^a\psi)A_\mu^a, \quad (2.9)$$

with λ denoting the Gell-Mann matrices. The vector field A_μ introduced here has eight components, which correspond to eight massless gluons and the conserved quantity is the color charge g_s . The second term of the above Lagrangian stems from the non-Abelian character of the $SU(3)$ symmetry. It implies that the gluons as mediators of the strong nuclear interaction carry color charge themselves leading to the aforementioned gluon self-interaction.

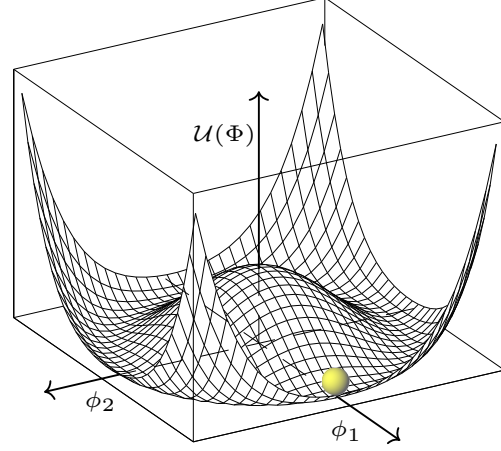
A characterizing feature of the strong interaction is related to the dependence of the coupling $\alpha_s = g_s^2/4\pi$ on the transferred four-momentum squared, denoted Q^2 . Contrasting the behavior of the electromagnetic force, the coupling becomes weaker for larger Q^2 , which can be exploited to calculate QCD processes using perturbation theory when α_s is sufficiently small as will be discussed below. Ultimately, the decreasing coupling strength leads to so-called *asymptotic freedom* [22] for very large Q^2 , corresponding to small distances between colored particles. This means that quarks and gluons inside a bound object, such as the proton, can be treated as quasi-free particles.

Experimentally it has been found that it is not possible to produce and observe isolated quarks. This is due to a second implication of the Q^2 dependence of α_s , referred to as *confinement* [23], which describes that the strong force diverges with the distance between two colored objects. It would therefore require an infinite amount of energy to isolate a quark, with the consequence that only color neutral objects, i.e., composite objects with equal shares of all colors or combinations of color and corresponding anti-color can be observed experimentally. Such compound objects based on three quarks are called *baryons* while two quark compound objects are called *mesons*. The formation of these color-neutral objects is referred to as *hadronization* and is based on the transformation of the binding energy of two increasingly separated quarks into rest-energy of a new quark antiquark pair, which then forms new compound objects and re-establish the color neutrality. As a consequence, a bundle of color-neutral particles, also referred to as *hadronic jet*, will be observed in an experiment instead of individual quarks or gluons.

2.1.3 Electroweak symmetry breaking and the Higgs boson

The SM not only describes elementary particles and their interactions on the fundamental level, but also has predictive power. This is particularly exemplified by the postulation of a

Figure 2.2: Potential $\mathcal{U}(\Phi)$ as a function of a complex scalar singlet $\Phi = \phi_1 + i\phi_2$. The ground state consists of an infinite number of degenerated minima, located on a circle with radius m_H/λ around $\phi_1 = \phi_2 = 0$. Selecting an arbitrary ground state, e.g., $\phi_1 = m_H/\lambda$ and $\phi_2 = 0$ as illustrated by the sphere, breaks the symmetry of the Lagrangian.



scalar field that pervades space-time by P. Higgs [24] and F. Englert and R. Brout [25] in 1964 and its experimental proof by discovering the Higgs boson in 2012 by the ATLAS and the CMS Collaborations [6, 7]. The scalar Higgs field had been postulated in order to address the problem of the massive Z and $W^\pm$ bosons, which requires a mass term in the Lagrangian density of the electroweak theory, which in turn breaks the local gauge invariance.

The solution to this problem is the so-called *Higgs mechanism* [24–26], which is summarized, e.g., in Ref. [27]. It is based on a phenomenon called *spontaneous symmetry-breaking*, which describes that an internal symmetry of the field Φ in the Lagrangian density is not manifest in the physical system or *broken*, owing to a nonzero ground state. This means that $\Phi \neq 0$ in the configuration that minimizes the system’s energy. In order to visualize the symmetry-breaking one can consider the case where a single complex field $\Phi = \phi_1 + i\phi_2$ with $\phi^*\phi = \phi_1^2 + \phi_2^2$ is added to the Lagrangian density of the electroweak theory. The resulting potential takes the form

$$\mathcal{U} = -\frac{1}{2}m_H^2(\phi_1^2 + \phi_2^2) + \frac{1}{4}\lambda^2(\phi_1^2 + \phi_2^2)^2, \quad (2.10)$$

where $\lambda > 0$ and the so-called *Higgs mass parameter* $m_H^2 < 0$. As depicted in Figure 2.2, the potential has an infinite number of degenerated minima, which are located on a circle of radius m_H/λ around $\phi_1 = \phi_2 = 0$. This gives the freedom to choose for instance $\phi_1 = m_H/\lambda$ and $\phi_2 = 0$ as one possible ground state. Subsequently, the fields ϕ_1 and ϕ_2 can be expressed in terms of fluctuations around this specific ground state. It is this arbitrary choice of one particular ground state that breaks the internal symmetry of the Lagrangian density.

For a phenomenologically viable theory that accommodates the masses of all three heavy vector boson, it is necessary to extend this concept by adding a doublet of complex scalar fields instead of a singlet. The doublet has the form

$$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix} = \exp\left(\frac{i\vec{\sigma}}{v}\vec{\varphi}(x)\right) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}, \quad (2.11)$$

where $\vec{\sigma}$ are the Pauli matrices. The parameter v is called *vacuum expectation value* and can be expressed with the parameters introduced in Equation 2.10

$$v = \sqrt{-\frac{m_H^2}{\lambda}}. \quad (2.12)$$

Similar to the case of the singlet, this entails a nontrivial potential of the form

$$\mathcal{U} = m_H^2 |\Phi|^2 + \lambda |\Phi|^4. \quad (2.13)$$

The fields $H(x)$ and $\vec{\varphi}(x)$ introduce four degrees of freedom to the Lagrangian and describe the potential as fluctuation around a specific ground state — $\vec{\varphi}(x)$ in the direction corresponding to the circle of minima in Figure 2.2 and $H(x)$ in the direction orthogonal to the circle. Setting $H(x) = \vec{\varphi}(x) = 0$ in Equation 2.11 shows that the ground state has an energy of $v/\sqrt{2}$. As soon as a specific ground state has been chosen, the $SU(2)_L \otimes U(1)_Y$ symmetry of the electroweak interaction is spontaneously broken into the electromagnetic symmetry $U(1)$, which remains a valid symmetry of the vacuum.

The spontaneous symmetry breaking gives rise to three massless states according to Goldstone's theorem [28–30]. These states correspond to excitation of the $\vec{\varphi}(x)$ field in the direction along the minima. Requiring that the aforementioned $U(1)$ symmetry holds for local gauge transformations and choosing the unity gauge with $\vec{\varphi}(x) = 0$ results in a Lagrangian in which the massless states are absorbed by the gauge fields of the electroweak interaction. The corresponding three degrees of freedom are thereby used to accommodate the masses of the vector bosons — a procedure that is justified because the three massless scalars have not been observed experimentally. Additionally, the Lagrangian includes an interaction term between the scalar Higgs field and the gauge bosons plus a mass term for the Higgs field itself. The latter originates from the remaining degree of freedom after the gauge bosons acquired mass.

The parameters λ and m_H^2 of the Higgs potential have been unknown prior to the discovery of the Higgs boson and only their relation (c.f. Equation 2.12) was known from measurements of the vacuum expectation value. The latter is related to the coupling constant of the weak interaction G_F and can therefore be measured by studying the decay rate of muons to electrons and neutrinos $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ [31–33], which yields $v = 246 \text{ GeV}$. All experimental evidence available to date suggests that the new boson that has been observed by the ATLAS and CMS Collaborations in 2012 is compatible with the Higgs boson predicted by the SM. Under this assumption, the remaining free parameter in the SM can be derived from the measured mass of the boson of $M_H = 125.09 \pm 0.24 \text{ GeV}$ [11].

2.1.4 Perturbation theory and Feynman diagrams

The structure of the Lagrangian densities allows to derive prescriptions for calculating experimental observables such as cross sections of particle interactions. Such theoretical calculations can be used to probe the SM when they are compared to experimental measurements. Moreover, they allow to simulate particle physics processes as will be discussed in Section 3.4.

The field equations that follow from $\mathcal{L}$ by applying Equation 2.2 are in general not analytically solvable. However, their solutions can be approximated by expanding the interaction process as a power series in the parameter g . Extending Equation 1.1, this reads as

$$|\psi_f\rangle = \mathcal{I} |\psi_i\rangle = \left(\sum_{n=0}^{\infty} c_n g^n \right) |\psi_i\rangle, \quad (2.14)$$

with $g \propto \sqrt{\alpha}$ is the coupling constant of the interaction $\mathcal{I}$. In the case of QCD the expansion variable is $g_s = \sqrt{4\pi\alpha_s}$, where α_s represents the strength of the strong coupling.

This perturbative approach is justified if g is sufficiently small for the series to converge, i.e., the contributions from higher orders of g are increasingly small. For the coupling constants of

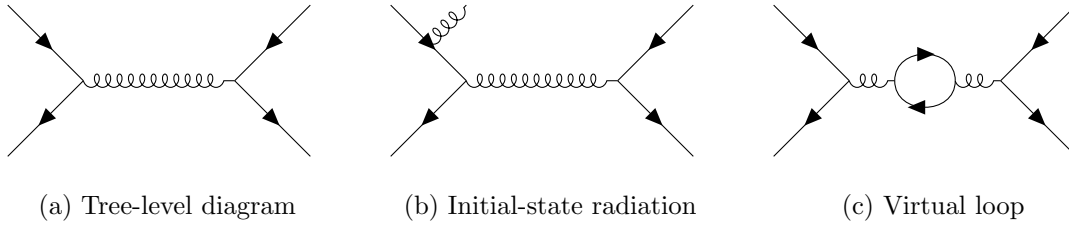


Figure 2.3: Feynman diagrams showing the interaction of two quark-antiquark pairs. A leading order diagram shows the exchange of a virtual gluon (a). Next-to-leading order contributions arise, e.g., from the emission of a gluon by one of the initial state quarks (b) or from loop corrections leading to the production of a virtual quark-antiquark pair (c).

the electromagnetic and the weak interaction this is the case for all energy regimes. For the strong interaction, however, the pronounced Q^2 dependence of the coupling implies that α_s is only small enough for energies larger than some factorization scale $\mu_F = \mathcal{O}(100 \text{ MeV})$. This has implications for the description of QCD processes at lower energies as will be discussed in Section 3.2.1.

The first non-zero coefficient in Equation 2.14 is c_2 , rendering terms proportional to g^2 the leading contribution to the interaction. Calculations of physical observables that only consider this term are hence referred to as leading order (LO) calculations. If a better precision is required, the term for $n = 3$ is included in the calculation, which is then referred to as next-to-leading order (NLO) calculation. The complexity of the calculation strongly increases as higher-order terms are included and calculations beyond NLO accuracy are only available for a few processes so far.

The different terms in Equation 2.14 correspond to different fundamental interaction processes between the particles of a given initial and final state. So-called *Feynman diagrams* [34] both serve as pictorial representations of these processes and allow to determine the coefficients c_n of the power series following a prescription known as *Feynman rules* [35], which are derived from the structure of the respective Lagrangian density. Knowing the coefficients c_n up to a given order allows to calculate the scattering amplitude, also called *matrix element* $\mathcal{M}_{if}$ from Equation 1.3 and therewith physical observables such as the production cross section of a given process. Feynman diagrams such as the examples shown in Figure 2.3 represent the initial and the final state of the interaction on the left- and on the right-hand side of the pictogram, respectively. The topology of the intermediate particles, so-called *virtual particles*, whose lines start and end within the pictogram, characterize the underlying interaction process. In the simplest case this is the exchange of one virtual particle leading to two vertices in the diagram as shown in Figure 2.3 (a). Such so-called *tree-level diagrams* contribute to the LO term in Equation 2.14. NLO terms are represented by diagrams that are extended by the emission of an additional particle by one of the incoming (Figure 2.3 (b)) or outgoing particles, referred to as initial-state radiation (ISR) or final-state radiation (FSR), respectively, or by an additional loop as shown in Figure 2.3 (c). As dictated by the Feynman rules, the additional vertices included in higher-order diagrams introduce additional powers of g to the calculation, rendering contributions of such processes progressively smaller if the series converges.

Loops of virtual particles such as the one shown in Figure 2.3 (c) have far-reaching consequences for the calculability of the perturbation expansion. Because of Heisenberg's uncertainty relation of time and energy, virtual particles can have arbitrary momenta. This leads to logarithmic divergences when integrating over their momenta as required for calculating the scattering amplitude, which renders the result unphysical. The remedy for this problem is known as *renormalization* [36]. The procedure requires to introduce an unphysical cutoff scale, also referred to as *renormalization scale* μ_R , which regularizes the term that causes

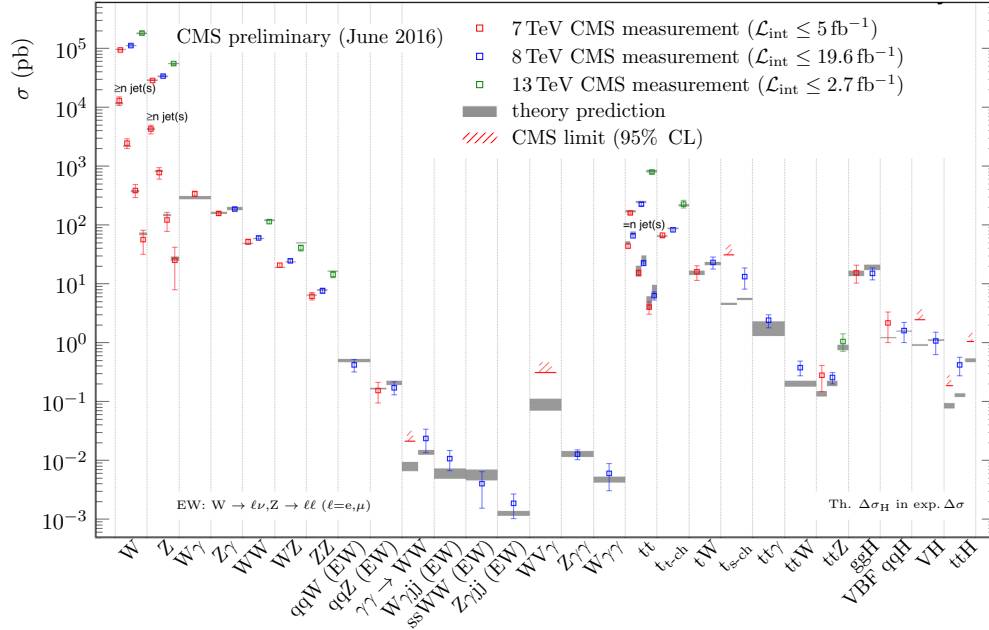


Figure 2.4: Theory prediction and corresponding experimental measurement by the CMS experiment of cross sections for various signal processes. The SM describes the observed results with a high level of agreement for cross section spanning eight orders of magnitude. Modified from [40].

the divergence. Subsequently, the perturbation expansion is reparameterized such that the coefficients are finite and finally the limit $\mu_R \rightarrow \infty$ is taken while the parameters are kept constant. If the theory is renormalizable, this recovers the original expression of the expansion. The underlying idea is to absorb the divergences in the modified coupling constant for which a reference value has to be determined experimentally. As μ_R is unphysical, theoretical predictions are subject to a systematic uncertainty that can be assessed, e.g., by testing the effect of variations of the scale on the predicted observable.

It has been shown by G. 't Hooft and others that all gauge theories are renormalizable [37–39] and hence both electroweak theory and QCD allow to predict physical observables using perturbative calculations. These predictions are in very good agreement with experimental measurements, as exemplified in Figure 2.4 for cross section predictions and the corresponding measurements by the CMS experiment at center-of-mass energies of 7 TeV, 8 TeV, and 13 TeV.

2.2 Limitations of the standard model and open questions

The SM is hugely successful in predicting and describing phenomena observed in high-energy physics experiments. It has successfully survived countless attempts of falsification at yet it is known to be incomplete and to represent only a low-energy limit of a more fundamental theory. This knowledge is based on several experimental observations that the SM fails to explain as well as on conceptual limitations that beg fundamental questions. This sections presents an overview of these shortcomings, starting with brief remarks on neutrino oscillations before focusing on open questions that can be addressed by supersymmetry (SUSY), an extension of the SM that evidence is searched for in Part I of this thesis. Other open questions that are not directly linked to SUSY are briefly mentioned at the end of the section.

2.2.1 Neutrino oscillations

The experimental observation of neutrino oscillations by the Super-Kamiokande [41] and Sudbury Neutrino Observatory [42] Collaborations has been awarded with the 2015 Nobel

prize in physics and provides an example of an experimental observation that is not described by the SM. It has been found that the flavor eigenstates by which neutrinos interact according to the weak force sinusoidally convert into each other in-flight. This shows that flavor and the mass eigenstates of neutrinos are not identical and implies that at least two of the mass eigenstates to have non-zero mass. Although this is in tension with the SM, where neutrinos are assumed to be massless, it can be argued that this is not a conclusive evidence for beyond the standard model (BSM) physics, as flavor mixing is known in the quark sector and because neutrino masses are not conceptually forbidden in the SM as opposed to, e.g., massive photons [9].

2.2.2 Dark matter

A more compelling sign for BSM physics that unveils the incompleteness of the SM is of astrophysical nature. It has been observed, that the tangential velocities of stars moving around a galactic center are substantially faster than expected from gravitational calculations based on estimates of the visible mass within the galaxy. While the latter predicts a drop of the velocities for large distances r from the galactic center as $1/\sqrt{r}$, increasing velocities have been found, e.g., in the NGC 1560 galaxy [43]. Left aside a modification of the laws of gravitation, this can only be explained by the presence of a cluster of invisible mass, called *dark matter*. Similar behavior has been observed for many other galaxies and also for the rotational speed of galaxies within galaxy clusters. It is estimated that the amount of this unknown type of matter exceeds the amount of ordinary baryonic matter by a factor of five. The absence of any observed type of radiation from dark matter clusters indicates that dark matter particles neither carry color nor electric charge and their ability to cluster around galactic centers indicates that they are nonrelativistic. None of the particles described by the SM meets all these characteristics, which suggests that there are huge quantities of an unknown type of particle present in the universe.

If this particle interacts with baryonic matter by any of the forces described by the SM at all, then only by means of the weak interaction. Direct or indirect detection of so-called weakly interacting massive particles (WIMPs) is therefore amongst the primary goals of modern particle and astroparticle physics. Direct-detection experiments [44] aim at observing the recoil of a baryonic matter particle after weak interaction with a dark matter particle, while indirect searches [45] aim at identifying annihilation or decay products of WIMPs. If their mass is of the order of 1 TeV or below, WIMPs could also be produced in proton-proton collisions at the LHC, where they would traverse the detectors without interaction. Such signatures would lead to a significant imbalance of the summed transverse momentum of the remaining collision products that are accessible to direct measurements.

2.2.3 Higher energy scales

A further undeniable shortcoming of the SM is its inability to describe gravitation. While gravitational interactions are extremely weak in energy regimes probed at modern particle accelerators and can safely be neglected, this approach no longer holds at energies around 10^{19} GeV. At this energy, called the *Planck scale* M_P , the coupling constant of gravity has a strength comparable to the couplings of the interactions described by the SM, requiring a new theory to describe quantum gravitation. However, all attempts to formulate a renormalizable theory for point masses have failed so far. The most viable candidate for such a *theory of everything* is *string theory*, which describes fundamental particles as excited states of one-dimensional objects, called *strings* in nine or ten space dimensions [46]. One of the main problems of string theory, however, is to make predictions that are accessible to experimental examination in any foreseeable future collider experiment.

New phenomena could also occur at energies smaller than the Planck scale as an extrapolation of the energy dependence of the three coupling constants in the SM suggests. At an energy

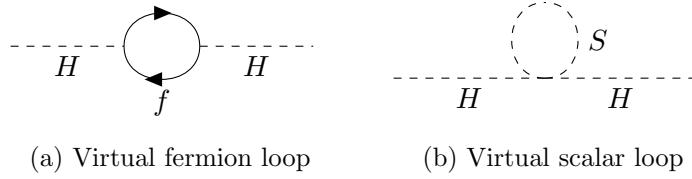


Figure 2.5: Quantum corrections to the squared Higgs mass parameter from virtual loops via interaction with a fermion f (a) and a scalar S (b).

of about 10^{16} GeV, all three of them become of similar strength, which inspires hopes to unify electroweak and strong interaction at this energy scale, similar to the unification of electromagnetic and weak interaction at the electroweak scale M_W . Such a theory is referred to as *grand unified theory (GUT)* and would, in its simplest implementation, postulate a $SU(5)$ symmetry between the fundamental quarks and leptons [47]. While such theories have attractive features, such as to explain the relation of the electrical charge of quarks and leptons, all GUTs proposed so far predict proton decay rates that are in tension with the experimental limit of the proton lifetime of $\tau_{\text{proton}} > 10^{33}$ years. Moreover, they predict magnetic monopoles that have not been observed so far [48, 49].

2.2.4 Hierarchy problem

As motivated above, the existence of BSM physics, also referred to as *new physics*, is evident for energies above the Planck scale M_P . This insight raises the fundamental question why the observed mass of the Higgs boson of 125 GeV is so much smaller than M_P — a question that is referred to as *hierarchy problem* [50]. The link between the Higgs mass parameter m_H (c.f. Section 2.1.3) and the Planck scale arises from quantum corrections from virtual loops in the calculation of m_H . In contrast to the masses of fermions and gauge bosons, the Higgs boson mass is not protected against such corrections by chiral or local gauge symmetries. For every fermion f that couples to the Higgs boson with a strength λ_f , virtual loops as depicted in Figure 2.5 (a) alter the fundamental Higgs boson mass by

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{\text{NP}}^2 + \dots, \quad (2.15)$$

where terms with higher orders of λ_f that grow at most logarithmically in energy are omitted. These corrections are proportional to the square of the energy scale Λ_{NP} where new physics sets in. As the coupling of the SM fermions to the Higgs boson scale with the fermion mass, the largest correction arises from the top quark, for which λ_f is close to unity. If new physics sets in at the $\Lambda_{\text{NP}} = M_P$ this means that the loop corrections from virtual top quark pairs are about 30 orders of magnitude larger than the experimentally observed Higgs mass. Models that attempt to achieve smaller corrections by assuming small values for Λ_{NP} usually exhibit unphysical behavior in terms of causality or unitarity [51].

Additional corrections arise from any so far unknown heavy particle that couples to the Higgs boson, be it directly or indirectly via gauge interactions. Also these corrections can be large if the particle is very heavy. Both cases, the corrections proportional to Λ_{NP}^2 and the corrections arising from unknown heavy particles beg the question why the fundamental Higgs boson mass seems to be *fine-tuned* against these huge corrections such that its effective mass is of the order of 100 GeV. In summary, the hierarchy problem is not a limitation of the SM itself, since the Higgs mass is not calculable but a free parameter in the theory. It rather is a discomforting sensitivity of the Higgs mass to almost any possible extension of the SM.

2.2.5 Further open questions

Other questions that the SM leaves unanswered are, e.g., related to the observed accelerated expansion of the universe. This phenomenon requires to introduce a cosmological constant into the laws of general relativity, which implies a homogeneous and constant energy density related to the vacuum expectation value of some unknown quantum field that pervades the universe [52]. This energy density is referred to as *dark energy* and the SM does not attempt to explain it.

Moreover, the SM cannot answer the observed asymmetry between matter and antimatter in the visible universe [53]. Pair production of fermions in the early universe should have led to equal shares for both types of matter and the CP violation of the weak interaction as described by the SM is too small to account for the observed difference. Thus other, unknown mechanisms must have been at work in the early universe, making searches for new sources of CP violation an important aspect of contemporary particle physics.

The SM also does not answer why fermions are organized in three generations. Finally, the large number of free parameters, which determine the masses of the elementary particles, the coupling constants, the quark mixing angles, and the CP violating phase, is unsatisfying for a fundamental theory from a reductionist's point of view.

2.3 Supersymmetry

Large theoretical efforts have been made to propose extensions of the SM in order to address some of the open questions discussed above. Such extensions must comply with all known experimental constraints and should make predictions that are verifiable at energy scales accessible with modern particle accelerators, i.e., at the TeV scale. Two main classes of BSM theories that meet both requirements have gained the most attention by experimental physicists in the past decades. Theories belonging to the first category postulate additional space-time dimensions, so-called *extra dimensions* [54, 55] and often imply that the Higgs boson constitutes a composite object [56]. A second class of theories addresses open questions of the SM by postulating a symmetry between fermions and boson, referred to as *supersymmetry* (*SUSY*). While both approaches have interesting theoretical and phenomenological implications, the following discussion is dedicated to the concept of SUSY, largely following the review in [57] in order to introduce the theoretical background relevant for the work presented in Part I of this thesis.

Supersymmetric theories of increasing complexity have been developed since the 1970's [58–65]. The central idea is to postulate an invariance of the Lagrangian density under transformations that translate fermionic states into bosonic ones and vice versa,

$$|\text{Boson}\rangle = Q |\text{Fermion}\rangle \quad (2.16)$$

$$|\text{Fermion}\rangle = Q |\text{Boson}\rangle, \quad (2.17)$$

where Q is an anti-commuting spinor operator. For a theory that ought to incorporate the SM and hence has to describe parity-violating interactions, the Haag-Lopuszanski-Sohnius extension [66] of the Coleman-Mandula theorem [67] restricts Q to respect the following set of (anti-)commutator relations

$$\{Q, Q^\dagger\} = P^\mu, \quad (2.18)$$

$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0, \quad (2.19)$$

$$[P^\mu, Q] = [P^\mu, Q^\dagger] = 0, \quad (2.20)$$

where P^μ is the four-momentum generator of space-time. Fermions and bosons that can be transformed into each other by a combination of Q and $Q^\dagger$ are called *superpartners* and constitute a so-called *supermultiplet*, the irreducible representation of the SUSY algebra with equal numbers of bosonic and fermionic degrees of freedom. From the commutation of Q with the squared-mass operator $-P^2$ it follows that superpartners have equal masses for an unbroken supersymmetry. Moreover, superpartners also have identical quantum numbers for color charge, weak isospin, and electric charge as follows from similar commutator relations with the generators of the SM gauge interactions.

2.3.1 Minimal supersymmetric standard model

The simplest implementation of a supersymmetric model with the smallest number of additional particles and interactions that is consistent with phenomenological constraints is the so-called minimal supersymmetric standard model (MSSM). In this model, each of the two chirality states of the SM fermions, i.e., left- and right-handed quarks and leptons, get assigned a spin-0 superpartner whose name is derived from the fermion name by prepending an ‘s’. Superpartners of the two chirality states can mix to form two mass eigenstates, however, it is theoretically well motivated to assume that mixing is only relevant for the superpartners of the third generation fermions. The superpartners of the quarks and leptons are called *squarks* and *sleptons*, respectively. Their gauge interactions are identical to those of the SM particles as a consequence of the identical charge quantum numbers. This also includes the maximum parity violation of the weak interaction, i.e., only the superpartners of the left-handed fermions participate in the weak interaction. The superpartners of the SM particles, or *sparticles* for short, are denoted with the same symbol as the SM particle, complemented with a tilde on top. SM fermions and their superpartners form so-called *chiral supermultiplets*.

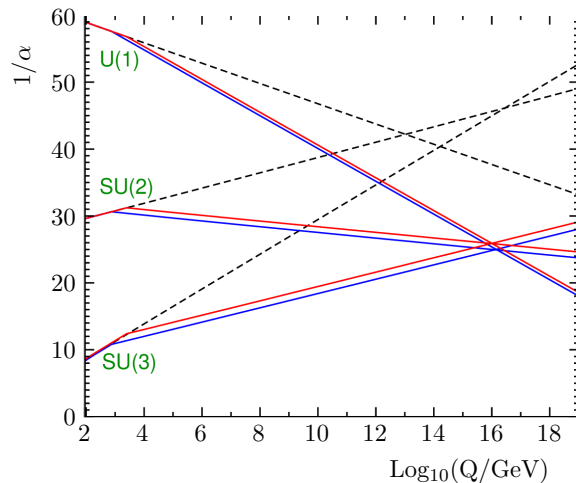
Additional chiral supermultiplets are needed to accommodate the Higgs boson. Differently than in the case of fermions, not one but two chiral supermultiplets with different weak hypercharge $Y = \pm 1/2$ are necessary for the Higgs boson. The first reason for that is to avoid gauge anomalies in the electroweak sector and the second is to enable Yukawa couplings to both up- and down-type quarks, as required to describe the quark masses. Since these two complex $SU(2)_L$ -doublets constitute eight degrees of freedom, five of them remain after electroweak symmetry breaking giving rise to five Higgs bosons, two of which are electrically charged. Their corresponding superpartners are called *higgsinos*.

Similarly as for the fermions, each spin-1 boson in the SM is associated with a superpartner called *gaugino*. Together they build a *gauge supermultiplet*. The names of the gauginos are constructed from the SM particles names by attaching the suffix ‘ino’, for instance the superpartner of the gluon is called *gluino*. In the electroweak sector, the superpartners of the isosinglet B and the third component of the isotriplet W are the *bino* and the *winos*. The neutral gauginos and the neutral higgsinos mix with each other after electroweak symmetry-breaking and give rise to four distinct mass eigenstates, called *neutralinos*. They are denoted as $\tilde{\chi}_i^0$, where i ranges from one to four to order the neutralinos by ascending mass. In similar vein, the charged higgsinos mix with the charged winos to two mass eigenstates called *charginos*, which are denoted as $\tilde{\chi}_i^\pm$ with $i = 1$ for the lighter and $i = 2$ for the heavier one.

With this particle content, the MSSM provides a natural solution to the hierarchy problem described in Section 2.2.4. Loop corrections from the coupling of the scalar superpartners of the SM fermions to the Higgs boson as depicted in Figure 2.5 (b) contribute corrections of the form

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} [\Lambda_{\text{NP}}^2 - 2m_S^2 \ln(\Lambda_{\text{NP}}/m_S) + \dots]. \quad (2.21)$$

Figure 2.6: Energy dependence of the inverse gauge couplings of the electromagnetic, the weak, and the strong nuclear interaction in the SM (dashed lines) and in the MSSM (solid lines). For the MSSM, the two lines indicate the interval of the coupling strength if the sparticle masses are varied between 750 GeV and 2.5 TeV and $\alpha_s(m_Z)$ is varied between 0.117 and 0.120. Modified from [57].



Comparing with the correction arising from fermionic loop corrections in Equation 2.15 reveals that the term proportional to Λ_{NP}^2 is canceled by the corrections from the two complex scalar fields introduced as superpartners. This is true if the superpartners have the same mass and if the couplings are related according to

$$\lambda_S = |\lambda_f|^2. \quad (2.22)$$

It can be shown that this cancellation holds for all orders of perturbation theory and thus the quadratic sensitivity of the squared Higgs mass parameter to Λ_{NP} is removed in the MSSM.

The Lagrangian density of the MSSM can in principle contain terms that violate baryon or lepton numbers without impairing SUSY. Since such processes are not observed experimentally and heavily constrained by the limits on the proton lifetime, such terms are undesirable in a phenomenologically viable theory. Instead of postulating conservation of baryon number B and lepton number L , which would contradict known nonperturbative effects in electroweak processes [68], the MSSM is defined to conserve *R-parity* [69], which is defined for each particle with spin s as

$$P_R = (-1)^{3(B-L)+2s}. \quad (2.23)$$

Hence, all SM particles have even R-parity with $P_R = +1$, while their superpartners have odd R-parity with $P_R = -1$. Assuming R-parity conservation has important implications for searches for supersymmetric particles at colliders. It requires that sparticles are produced in even numbers and that the lightest supersymmetric particle (LSP) is absolutely stable as it cannot decay into SM particles. If the LSP is electrically neutral and only interacts weakly with SM particles it is a viable dark matter candidate. While R-parity conservation is not an intrinsic necessity of supersymmetric models, it is well motivated both phenomenologically and theoretically [70, 71] and most models assume it. Nevertheless, R-parity violating supersymmetric models also exist [72], however, they are not relevant in the context of this thesis.

Another intriguing feature of the MSSM is that the additional particles slightly modify the energy dependence of the coupling constants of the three SM gauge interactions. As a result, the aforementioned unification of the couplings at the GUT scale is much more precise in the MSSM than in the SM [73–77] where only roughly the same values are reached as depicted in Figure 2.6. While this might be pure coincidence it could also suggest a unification of the SM forces at a GUT scale of $\Lambda_{\text{GUT}} \approx 1.5 \times 10^{16} \text{ GeV}$.

2.3.2 Supersymmetry breaking

Assuming an unbroken SUSY in the MSSM is theoretically compelling, as it entails perfect cancellation of the quadric terms in Equations 2.15 and 2.21. However, it would also imply that particles and their superpartners have equal masses, which is not the case as the absence of any experimental evidence for sparticles at low energies shows. If broken SUSY should still solve the hierarchy problem, Equation 2.22 must hold also after symmetry-breaking, otherwise quadratically divergent terms reappear in the squared Higgs mass parameter corrections. This boundary condition can be respected when considering so-called *soft SUSY-breaking*, which means that the effective Lagrangian density of the MSSM can be written as

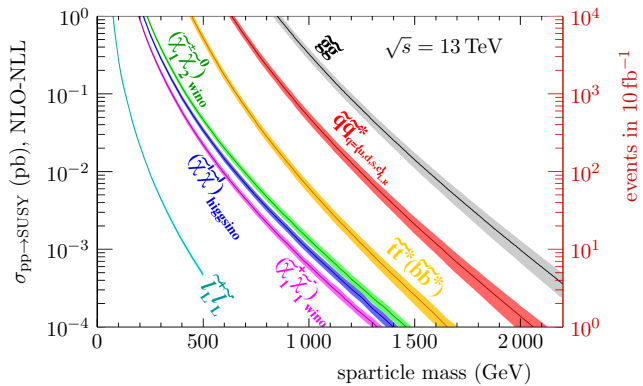
$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}}. \quad (2.24)$$

In this representation $\mathcal{L}_{\text{SUSY}}$ remains supersymmetric and contains all gauge and Yukawa couplings while $\mathcal{L}_{\text{soft}}$ contains the SUSY-breaking interactions, where the largest mass scale is denoted as m_{soft} . After symmetry breaking, corrections to the squared Higgs mass parameter appear, which are proportional to $m_{\text{soft}}^2 \ln(\Lambda_{\text{NP}}/m_{\text{soft}})$. These corrections vanish in the absence of symmetry-breaking for $m_{\text{soft}} \rightarrow 0$ and it can be shown that the cancellation of quadratic divergences from quantum corrections to scalar masses remains intact for soft SUSY-breaking to all orders of perturbation theory [78]. Hence, even softly broken SUSY can solve the hierarchy problem if m_{soft} is not too large. As m_{soft} determines the mass splitting of particles and their superpartners, this translates into the requirement that the masses of the superpartners should not be too large. While this introduces a notion of subjectiveness, it is generally accepted that the masses of the lightest particles should be $\mathcal{O}(1 \text{ TeV})$ in order to avoid a level of fine-tuning that is considered *unnatural*.

It is expected that SUSY is spontaneously broken by a nonzero vacuum expectation value, similar to the electroweak symmetry-breaking. However, there is no consensus concerning the exact mechanism of the symmetry-breaking and many different models have been proposed. All of them extend the MSSM by introducing new particles and interactions at high mass scales that mediate the symmetry-breaking to the MSSM particles. Depending on the nature of this mediating interaction one distinguishes gravity-mediated, or Planck-scale-mediated supersymmetry breaking (PMSB) [79–85] and gauge-mediated supersymmetry breaking (GMSB) [86–91] scenarios. The splitting of the Lagrangian density as shown in Equation 2.24 is a way of parameterizing the lack of knowledge concerning the mechanism behind the SUSY-breaking and allows to derive general properties of $\mathcal{L}_{\text{soft}}$. For the MSSM, the most general form of the SUSY-breaking term in Equation 2.24 contains new masses, phases, and mixing angles that introduce 105 additional free parameters to the theory [92]. Without knowing the exact mechanism for SUSY-breaking they cannot be explained from first principles, however, some of them are severely constrained by SM precision measurements.

A drastic reduction of the number of free parameters is needed in order to systematically investigate the parameter space in experimental searches and to exclude or verify a signal with a given set of parameters. Making experimentally and theoretically well-motivated assumptions, including the absence of additional sources of CP violation, the absence of flavor changing neutral currents, and the mass degeneracy of the first and second generation particles allows to reduce the number of free parameters to 19 in a model known as phenomenological minimal supersymmetric standard model (pMSSM) [93]. Together with additional, partly controversial theoretical assumptions, a further reduction to only five free parameters can be achieved in a model known as minimal supergravity (MSUGRA) or constraint minimal supersymmetric standard model (cMSSM). Its relatively small phase space has made this PMSB scenario an important benchmark model for experimental searches in the past [94].

Figure 2.7: Pair production cross sections for sparticles in proton-proton collisions at $\sqrt{s} = 13$ TeV. The cross section strongly depends on the sparticle masses and on the gauge interaction they participate in. For a given mass, the largest cross sections are expected for gluino and squark production. Modified from [95].



2.3.3 Production and decay of supersymmetric particles

Possible production mechanisms and decay channels of particles in the MSSM are extremely difficult to predict, owing to the large number of free parameters in the Lagrangian term responsible for the soft symmetry-breaking. The absolute masses of the sparticles determine which of them are light enough to be produced at a given center-of-mass energy and the mass hierarchy including relative mass splittings determines which decay modes are kinematically allowed. Both of these unknowns are strongly model dependent and even for heavily constrained scenarios such as the cMSSM a plethora of different final states have to be considered in experimental searches in order to scan the parameter space. Nevertheless, some general assumptions can be made, following, e.g., from the coupling strengths of the SM gauge interactions. Other assumptions are popular because they are reoccurring in many different models.

For the production of sparticles one distinguishes between production of colored sparticles such as squarks or gluinos and electroweak production of neutralinos and charginos. The former mechanism is expected to have significantly larger cross sections at the LHC compared to electroweak sparticle production, since it is governed by the strong coupling constant α_s . Assuming R-parity conservation, gluinos and squarks can only be produced in even numbers, two in most cases. Expected cross sections for pair production of different sparticles at $\sqrt{s} = 13$ TeV at the LHC are shown in Figure 2.7.

Concerning the mass hierarchy, many models imply that the gluino is much heavier than the lighter charginos and neutralinos. Moreover, the lighter of the two mass eigenstates of the stop and sbottom quarks are expected to be the lightest of all squarks. This is in part due to the larger mixing of the scalar superpartners of the left- and right-handed fermions in the third generation, which tends to decrease the mass of the lighter mass eigenstate. In PMSB models, the lightest neutralino is the LSP and hence all decay cascades starting with pair-produced gluinos or squarks result in final states containing two neutralinos that escape detection. The inability to detect such an LSP with a high-energy physics particle detector leads to a significant imbalance in the transverse momenta of the reconstructed particles. A large amount of *missing transverse momentum*, carried away by the LSP therefore constitutes a unique experimental signature and makes this quantity an important observable in searches for R-parity conserving SUSY models.

Another experimental implications concerns the mass difference between the sparticle initially produced in a collision and the LSP. Depending on whether this mass difference is small or large, one distinguishes so-called *compressed* and *uncompressed* SUSY scenarios. Experimentally, uncompressed models produce more energetic secondary particles arising from the decay cascade. Contrariwise, compressed models are characterized by low- p_T final state particles in the detector, which typically degrades the sensitivity for such models.

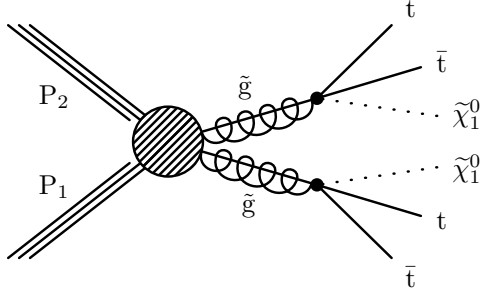


Figure 2.8: Example diagram for a simplified model topology investigated in the context of this thesis. Gluino-gluino production leads to two top-antitop quark pairs and two neutralinos as LSPs in the final state.

2.3.4 Simplified model spectra

The huge parameter space of the MSSM and more elaborate models like the next-to-minimal supersymmetric standard model (nMSSM) make it impossible to experimentally study all possible signal scenarios in a systematic manner. A way of reducing the number of free parameters even more drastically than in constraint models such as MSUGRA, is to examine so-called simplified model spectra (SMSs) [96, 97]. These topologies consider only a very small number of sparticles and assume that all other sparticles are too heavy to be produced at the LHC. Additionally, a certain mass hierarchy and fixed branching ratios are considered for the sparticles in order to define a specific decay chain. This approach allows to study different production mechanisms and decay channels independently from each other, by calculating associated production cross sections and the total branching ratios into a specific final state. These numbers then allow to unambiguously confirm or reject the signal hypothesis for a given SMS topology in experimental searches.

It is, however, important to note that SMS topologies are not meant to be realistic descriptions of a viable supersymmetric theory. Rather, they represent a tool to confront experimental data with BSM predictions in a model independent way [98] with the possibility to reinterpret the results in the context of more realistic SUSY scenarios. An example for a SMS topology examined in this thesis is shown in Figure 2.8. The model features gluino-gluino production where the effective proton-proton interaction is depicted as the hatched circle. Each of the gluinos subsequently decays into a top quark and a virtual stop quark. The virtual stop quark decays into another top quark and the lightest neutralino as the LSP. In Figure 2.8 the virtual stop quark is suppressed and an effective three-body decay is shown instead. This model is referred to as T1tttt. The nomenclature of SMS follows the following conventions. Model names start with a generic ‘T’ for *topology*, followed by an integer number between 1 and 6. A combination of letters indicates the SM particles produced in the interaction. The number encodes the production mechanism and the number of intermediate charginos or neutralinos in the decay chain. Even numbers are used to label models with squark pair production, while odd numbers indicate gluino pair production. The integers 1 and 2 indicate that no intermediate charginos and neutralinos are involved in the decay chain, while the numbers 5 and 6 are used for models with such intermediate gauginos in both decay chains. Models labeled with the numbers 3 or 4 feature an intermediate gaugino in one of the two decay chains.

3. The Large Hadron Collider and the CMS Experiment

Ideas for reusing the Large Electron-Positron Collider (LEP) [99] tunnel for the construction of a hadron accelerator have been gathered already back in 1984, even before LEP became operational. Ten years later, after the construction of the Superconducting Super Collider, a high-energy particle accelerator in Texas, USA, had been canceled by Congress in 1993 [100], the plans for building the Large Hadron Collider (LHC) were approved. The interest in complementing the research at electron-positron colliders with studies of hadronic interactions was motivated by the fact that a large circumference hadron collider was required in order to push the energy frontier into the TeV range, an energy range where signs for BSM physics were — and still are — expected. Additionally, collisions of composite hadrons offer the possibility to scan large energy ranges for resonant production of new particles without modifying the beam energy, a feature that was of particular interest for the hunt for the, at the time, elusive Higgs boson.

This chapter introduces the experimental setups to which the studies described in this thesis relate to, namely the LHC and the Compact Muon Solenoid (CMS) experiment. In Section 3.1, the LHC is introduced and a summary of its design and performance parameters is given along with a brief overview of the different operation periods of the LHC since its start-up in 2010. Phenomenological aspects of proton-proton collisions as the main mode of operation at the LHC are reviewed in Section 3.2. Section 3.3 describes the CMS experiment, a high-energy particle detector that is used to analyze the proton-proton collisions provided by the LHC to search for new, known phenomena and to measure properties of fundamental particles and their interaction with high precision. Besides studying real proton-proton collisions, it is also important to simulate collisions and the expected detector response in order to optimize the performance of the detector or to probe a certain theory by comparing data with simulation. Section 3.4 summarizes the underlying principles and the software tools used for such simulations employed for the analysis presented in this thesis.

3.1 The Large Hadron Collider

With a design center-of-mass energy of 14 TeV the LHC is the most powerful particle accelerator to date and one of the largest and most complex machines ever built. It is hosted at the European Organization for Nuclear Research (CERN) in a circular tunnel with a circumference of 27 km that had been excavated for the LEP collider. The LHC is the latest

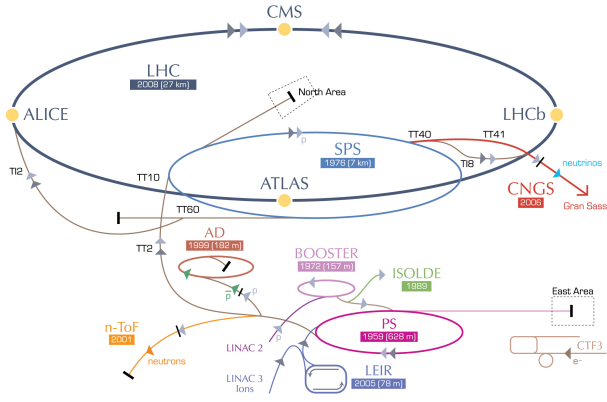


Figure 3.1: The CERN accelerator complex. Before being injected into the LHC with an energy of 450 GeV, protons are preaccelerated by the linear accelerator LINAC 2 and three circular accelerators: the booster, the Proton Synchrotron (PS), and the Super Proton Synchrotron (SPS). Alongside, other particle extraction facilities and experiments are shown [105].

one of a series of linear and circular particle accelerators built at CERN and its predecessors now serve to preaccelerate particles before being injected into the LHC.

3.1.1 Accelerator design and performance

As indicated by its name, the LHC is designed to accelerate and collide hadrons, composite objects that are bound by the strong nuclear interaction. A part of the collider's schedule is dedicated to the collision of lead ions, heavy objects whose collision are studied to investigate a special state of matter, the *quark-gluon plasma* [101]. The following considerations, however, focus on its main mode of operation, the acceleration and collision of protons. Extensive reviews of the LHC can be found in Refs. [102, 103].

One of the main purposes of the LHC and its experiments is to probe the SM at the TeV energy scale, since several BSM theories, including SUSY, predict new particles at this scale. Moreover, the LHC was built to prove or disprove that elementary particles acquire mass via electroweak symmetry breaking and the Higgs mechanism as outlined in Section 2.1.3. As the LEP experiments had excluded the Higgs boson for masses up to 114 GeV [104], the LHC was designed to probe even higher masses. Studying proton-proton collisions is suited for addressing both questions because of two characterizing properties of the proton. First, its relatively large rest mass and the resulting small energy loss by synchrotron radiation (c.f. Equation 1.5) allow to achieve considerably larger collision energies compared to using electrons or positrons in an accelerator of the same circumference. Secondly, the proton is a composite projectile. This implies that not the protons themselves collide, but rather two or more of their constituents, i.e., quarks or gluons. By this means, each collision differs in collision energy, which allows to scan a broad energy range for resonant production of the Higgs boson or other new particles without continuously adjusting the beam energy. Important aspects of proton-proton collisions, also including some disadvantages, are summarized in Section 3.2.

Protons for collisions are gained by stripping off electrons from hydrogen atoms. The electrically charged particles can then be accelerated and guided through a sequence of preaccelerators and transfer lines using electromagnetic fields. Before being injected into the LHC, protons need to acquire a minimum energy of 450 GeV. This is achieved through acceleration with the linear accelerator LINAC 2 and subsequent further acceleration using the so-called booster, the Proton Synchrotron (PS), and the Super Proton Synchrotron (SPS) accelerators as depicted in Figure 3.1.

Subsequently, protons are injected into the two separated beam pipes of the LHC in which they circulate in opposite directions. The LHC beams are organized in bunches, i.e., packets with a nominal number of 1.15×10^{11} protons, which are kept on their track around the

Table 3.1: Key performance figures of the LHC. The nominal values and the actual values during the data taking period relevant for this thesis from May to July 2016 are presented [102, 108, 111]. For the actual value of the number of pileup collisions, the mean and the root-mean-square (RMS) of the distribution are given.

Quantity	Nominal value	Actual value 2016
center-of-mass energy (TeV)	14	13
max. instantaneous luminosity ($\text{cm}^{-2} \text{s}^{-1}$)	1×10^{34}	1.1×10^{34}
bunches per beam	2808	2040
protons per bunch	1.15×10^{11}	1.25×10^{11}
bunch spacing (ns)	25	25
pileup collisions, mean $\pm$ RMS	20	18.5 ± 4.6

storage ring by the Lorentz force provided by the magnetic fields of 1 232 superconducting niobium-titanium dipole magnets with a field strength of 8.3 T. Rather than synchrotron radiation, it is the field strength of these dipole magnets that limits the center-of-mass energy of the LHC. Higher-order magnets keep the beams focused and counteract the repelling force between the like-charged protons in the bunch. The bunch structure of the beams is enforced by the acceleration mechanism based on eight radio frequency cavities per beam. Each of these resonators provides a voltage of up to 2 MV to accelerate the protons until they reach the target energy. Additionally, the cavities maintain the spacing between the bunches by automatically decelerating and accelerating protons that are ahead or behind the nominal timing. Up to 2 808 bunches can be filled into the LHC. Once accelerated to the final energy, the beams are intersected at four different IPs around the storage ring where four experiments, named ALICE [106], ATLAS [107], CMS [108], and LHCb [109] are located. In order to maximize the instantaneous luminosity provided to the general purpose experiments ATLAS and CMS, quadrupole magnets focus the beams to a diameter of about $16 \mu\text{m}$ (c.f. Equation 1.6). Depending on the focusing of the beams and the number of protons per bunch, a certain number of protons will interact with protons from the other beam during the crossing of two bunches. This number is referred to as *pileup* and is usually larger than one to increase the probability for rare processes to happen. The rest of the bunch is kept in orbit and can be brought into collisions again at the next IP. If no disruption causes a loss of the beams, they can be kept circulating for more than a day, continuously providing luminosity to the experiments. In summer 2016, the longest of these so-called *fills* lasted about 37 hours and provided more than 700 pb^{-1} of integrated luminosity to the CMS experiment [110]. Table 3.1 summarizes key performance parameters of the LHC, comparing the nominal values to the actual values during the data taking period relevant for this thesis.

3.1.2 LHC operation periods

The LHC runtime can be subdivided into different periods, mainly characterized by different center-of-mass energies. Because of faulty solder joints in the dipole magnets that led to a magnet quench incident in 2008 [112], the LHC has been operated at a reduced center-of-mass energy of initially 7 TeV and later 8 TeV during the first run period between March 2010 and February 2013. During this so-called *Run 1*, a total of 5 fb^{-1} and 20 fb^{-1} of proton-proton collisions has been delivered to the experiments at 7 TeV and 8 TeV, respectively. During this period of operation, the spacing between the proton bunches had been increased by a factor of two with respect to the nominal value of 25 ns. The maximum instantaneous luminosity achieved by the end of the run in 2012 was $0.77 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ [111].

After the first run, which led to the discovery of the Higgs boson, the LHC temporarily suspended operation between 2013 and 2015. During this so-called long shutdown (LS) 1,

maintenance and consolidation work has been carried out for both the accelerator and the experiments. Most prominently this included the dipole magnet solder joints that limited the center-of-mass energy during Run 1. As a result of the consolidation, the LHC is now operating at a center-of-mass energy of 13 TeV since June 2015, almost reaching its design energy. Additionally, the bunch spacing had been reduced to the nominal value of 25 ns after LS 1. In summer 2016, the LHC reached its design luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This milestone could be achieved by compensating a restriction to 2040 bunches per beam, enforced by different limitations in the accelerator chain, by squeezing the beam in the IP of the ATLAS and the CMS experiments to below its nominal value.

During this second operation period, colloquially referred to as *Run 2*, the LHC delivered 4.2 fb^{-1} of proton-proton collisions in 2015 and another 14 fb^{-1} until July 2016, out of which 2.3 fb^{-1} and 12.9 fb^{-1} have been collected and certified for analysis by the CMS experiment, respectively. The data set of 12.9 fb^{-1} of proton-proton collisions is analyzed in Part I of this thesis.

3.2 Proton-proton collisions

Using protons in a scattering experiment at a storage ring is beneficial for minimizing energy loss by synchrotron radiation but also comes with several challenges. Deep inelastic scattering experiments have revealed that the proton is a complex composite system, consisting of three valence quarks — two up and one down quark — plus a mixture of virtual gluons and quark-antiquark pairs, so-called sea quarks, which continuously convert into each other via QCD processes [113]. These constituents are referred to as *partons*. Colliding protons therefore implies to collide individual partons, which in turn means that the initial state of the scattering experiment is not precisely defined. Additional challenges are the description of the formation of final state objects accessible to measurement and the overwhelming presence of QCD multijet background that a certain signal process of interest has to be discriminated against.

3.2.1 Hadron interaction modeling

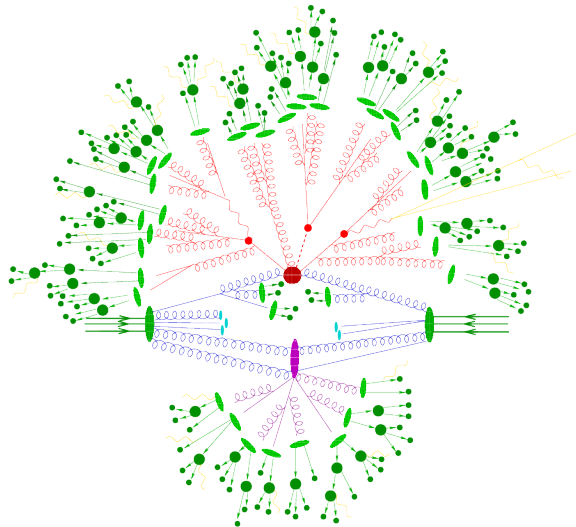
The energy dependence of the coupling constant of the strong interaction α_s , which on the one hand leads to asymptotic freedom for the partons within the proton, and to confinement resulting in hadronization of quarks and gluons on the other hand, makes the modeling of hadron interactions and the calculation of the corresponding cross sections a challenge. Neither the initial state of the collision, nor the hadronization can be described using perturbation theory, owing to low-energy contributions that entail nonconverging power series.

The quantitative description of proton-proton collisions therefore needs to be factorized into separate steps, which are governed by different energy scales [114] — the description of the partons inside the proton, the hard interaction process between two partons, the subsequent parton showering and hadronization to form color neutral final state objects, and the description of additional particles that do not originate from the hard interaction. Each of these steps requires a dedicated approach for its modeling in event simulations. Experimentally it has been found that the factorization approach is justified above an energy of $\mathcal{O}(100 \text{ MeV})$. The different stages of the collision are visualized in Figure 3.2 and are briefly summarized below.

Parton distribution functions

The fraction x of the proton’s longitudinal momentum carried by a colliding parton, depends on the energy scale Q^2 of the proton, i.e., on the center-of-mass energy provided by the accelerator. It is described by the so-called *parton distribution function (PDF)*. Two examples are

Figure 3.2: Schematic representation of a simulated proton-proton collision [115]. Two partons of the incoming protons undergo a hard interaction (big red dot) and produce particles, some of which decay before hadronization, e.g., top quarks (small red dots). Subsequently, parton showers induce hard QCD radiation (red) and hadronization forms color neutral particles (light green), which decay if they are unstable (dark green). Additional final-state particles originate from the underlying event (purple) and from photon radiation (yellow).



shown in Figure 3.3 and it can be seen that the relative share of energy carried by sea quarks and gluons increases with the energy of the proton, rendering interactions involving gluons dominant at energies provided by the LHC. Proton PDFs are derived phenomenologically by fitting data from deep inelastic scattering and collider experiments. Their evolution as a function of the energy scale Q^2 is described by the DGLAP formalism [116–118], which allows to extrapolate PDFs determined at a certain energy scale to a different energy.

Hard interaction

In contrast to the description of the PDFs, the so-called *hard interaction* between two colliding partons can be calculated in QCD perturbation theory, if the energy is high enough for α_s to be small, a prerequisite that is fulfilled for hard interactions at the LHC. According to the methodology presented in Section 2.1.4, the cross section $\sigma_{ij \rightarrow f}$ for an interaction between the initial partons i and j into a final state f is proportional to the square of the transition matrix element $\mathcal{M}$

$$\sigma_{ij \rightarrow f} \propto |\mathcal{M}|^2. \quad (3.1)$$

The total cross section for the interaction of two protons is then derived from the partonic cross sections by summing over all partons and integrating over the parton momenta x_i and x_j as given by the proton PDFs.

Parton showering and hadronization

The parton-parton interaction is followed by the emission of hard QCD radiation in a so-called *parton shower*, where the initial partons can split and radiate other partons. Once the energy of the partons becomes too low, the perturbative description of the process breaks down and the evolution of the final state partons is governed by *hadronization*, a process that transforms partons into color neutral hadrons, followed by subsequent decay of unstable hadrons. Final state hadrons and their decay products that originate from the hadronization of a single parton produced in the hard interaction manifest themselves as collimated bundles of particles and are referred to as *hadronic jets*. The different regimes of parton shower and hadronization are separated by the factorization scale μ_F . Similarly, as the renormalization scale μ_R (c.f. Section 2.1.4), its value is introduced artificially when simulating proton-proton collisions and the results are subject to a systematic uncertainty that is usually assessed by varying the scale. Due to the importance of low-energy contributions, both the parton shower and the hadronization require phenomenological models for their description.

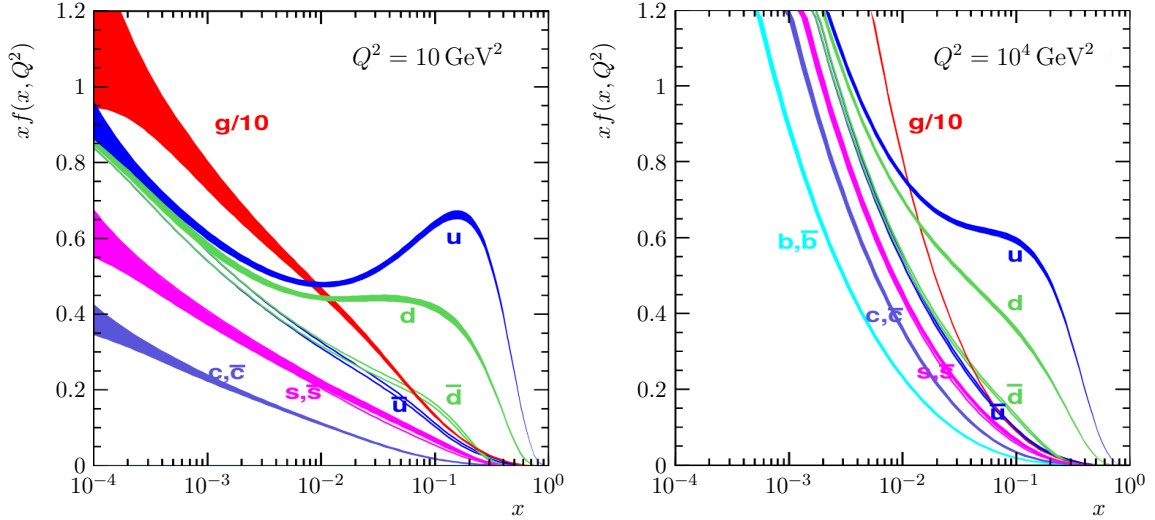


Figure 3.3: MSTW 2008 parton distribution functions, calculated at next-to-leading order accuracy including their $\pm 1\sigma$ uncertainty band for two different energy scales Q^2 . Modified from [119].

Underlying event

In addition to the particles produced in the hard interaction and in the subsequent hadronization, the final state comprises further particles that are summarized as underlying event (UE). It consists of hadronized fragments of beam-beam remnants, i.e., the partons that did not take part in the hard interaction, and of hadronized fragments of potential multiple parton scattering and their associated initial and final state radiation. The UE is described using phenomenological models [120] whose free parameters are tuned using proton-proton collision data. The UE must not be confused with particles emerging from pileup collisions, i.e., additional proton-proton collisions within the same bunch crossing.

3.2.2 Transverse observables

Colliding composite objects such as protons implies that the sum of the momenta of the collision products is not necessarily zero. This is because the two colliding partons in general do not carry the same fraction x of the protons' longitudinal momenta. However, the conservation of momentum can be applied to the sum of momenta transverse to the beam direction p_T . Apart from small deviations arising from the beam crossing angle, the transverse momenta of all collision products must be zero. This, and the orthogonality to the magnetic field whose field lines are usually parallel to the beam axis, render the transverse momentum and other derived transverse quantities important observables.

3.2.3 QCD multijet background

An additional challenge at hadron colliders is related to the dominance of the strong interaction over the electromagnetic and the weak interactions, which leads to overwhelming background of QCD multijet events that a given signal process of interest needs to be discriminated against. At $\sqrt{s} = 13$ TeV, the total inelastic proton-proton cross section is of the order of 71–79 mb [121, 122], while cross sections of typical signal processes are often orders of magnitude lower, e.g., in the range of pb (c.f. Figure 2.4). This large discrepancy makes QCD background rejection a key challenge in most analyses. One possibility that largely suppresses QCD background is to require multiple, locally isolated charged leptons in the final state, an approach that is employed in analysis presented in Part I of this thesis.

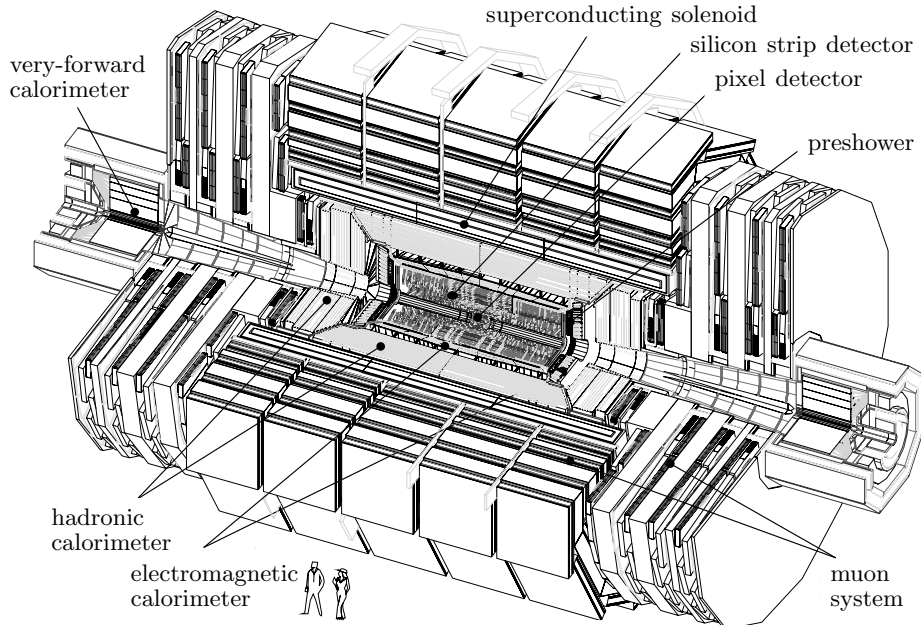


Figure 3.4: Perspective view of the CMS detector with a cut through the central barrel part of the detector and the two endcaps on either side. From inside out, the inner tracking system consisting of the pixel and the silicon strip detector, the electromagnetic and the hadronic calorimeter, the solenoid magnet, and the muon systems embedded in the iron return yoke can be seen. Modified from [124].

3.3 The Compact Muon Solenoid Experiment

The Compact Muon Solenoid (CMS) experiment is a multi-purpose, high-energy physics particle detector located at one of the four beam intersection points of the LHC. It serves to measure the properties of particles produced in proton-proton collisions at its center with high accuracy in order to study the underlying interactions at the unprecedented energy scale provided by the LHC. After the discovery of the Higgs boson in Run 1 of the LHC, the experiment’s main goals are now to study the properties of this particle in greater detail, to probe the predictions of the SM at the TeV scale, and to search for new particles predicted by BSM theories in order to answer some of the fundamental questions discussed in Section 2.2. The name of the experiment pays tribute to central features of the detector, namely a superconducting 3.8 T solenoid magnet used to bend the trajectories of charged particles emerging from the collisions, and a powerful system for reconstructing muons.

As most collider physics experiments, the CMS detector consists of several subsystems, arranged in layers around the IP. Each of them is dedicated to determining different properties of the particles emerging from the IP, following the basic principles outlined in Section 1.3. In order to unambiguously relate measurements from all subdetectors with a particular bunch crossing, also referred to as *event*, all subdetectors are operated synchronously at 40 MHz. The following section briefly reviews the layouts and performances of the subdetectors and associated systems that CMS is composed of. This provides the necessary background knowledge for subsequent descriptions of the reconstruction and identification of the collision products as employed in the analysis that is presented in Part I of this thesis. More detailed descriptions of the detector and its performance can be found in Refs. [108, 123].

The coordinate system employed by CMS has its origin in the nominal IP with the y axis pointing vertically upwards, the x axis pointing to the center of the LHC ring, and the z axis along the counter clockwise circulating beam. The polar coordinates follow the definition

introduced in Figure 1.2. In order to achieve the best possible geometrical coverage of the full solid angle around the IP, the detector and its subsystems are divided into a cylindrical central part, referred to as *barrel*, and two disc-like forward parts, or *endcaps*, on either side of the barrel, as shown in Figure 3.4.

3.3.1 Magnet

Important aspects of the design of the CMS detector are governed by its central feature, a 13 m long superconducting solenoid magnet with an inner bore of 6 m. A strong magnetic field is crucial to achieve p_T measurements with high resolution by providing a sufficiently large bending power for charged particles with large transverse momenta (c.f. Equation 1.16). The inner field strength of the solenoid of 3.8 T is large enough to achieve a momentum resolution of below 5% and unambiguous charge identification for muons with transverse momenta up to 1 TeV. The large inner diameter allows to accommodate the inner tracking system and both the electromagnetic and hadronic calorimeter within the solenoid. This feature allows to measure the energy of particles unobstructed by energy loss in the material of the solenoid and minimizes the uncertainties on the calorimetry.

An iron return yoke, accounting for the lion's share of the weight of the experiment of about 14 000 tons, guides the flux of the magnetic field outside of the solenoid volume. By this means, an outer field strength is retained that is large enough to bend the trajectories of muons, the only particles that pass through the magnet and its outer field.

3.3.2 Inner tracking system

The inner tracking system of CMS is composed of two all-silicon subdetectors, which aim at reconstructing the trajectories of charged particles for p_T measurements and to identify primary and secondary vertices of the interactions. A flux of $\mathcal{O}(1000)$ charged particles traverses the detector per bunch crossing, requiring fine granularity and fast readout of the detector. As multiple scattering of the particles in the detector material degrades the spacial resolution, the tracking detectors have to be as lightweight as possible, while maintaining a sufficient mechanical stability. This so-called *material budget* is quantified with the number of electromagnetic radiation lengths imposed by its material. Depending on the η region, the tracking detectors constitute about 0.4–1.8 X_0 . Close to the IP where the particle flux is the highest, a pixel detector provides three trajectory measurements with high spacial resolution. A silicon strip detector provides nine additional measurement points, extending the lever arm for p_T measurements to a radius of 1.1 m. Both tracking detectors cover solid angles up to $|\eta| < 2.5$ and achieve a transverse momentum resolution of 1–2% up to $|\eta| \approx 1.6$ for particles above 100 GeV. The vertex resolution for high- p_T tracks is about 10 μm , limited by the resolution of the innermost pixel layer.

Pixel Detector

The main goal of the pixel detector is to provide excellent spatial resolution of the trajectories of charged particles close to the IP in order to achieve a good resolution of primary and secondary vertices, the latter being crucial characteristics for the identification of short-lived b quarks and τ leptons. The close proximity to the IP and the associated large particle flux, together with the requirement to keep the occupancy of the detector below 1% in order to minimize data loss and dead times, determine the pixel size of 100 μm in the r - ϕ direction and 150 μm in the z direction. Reading out analog pulse-height information associated with each pixel hit and exploiting charge sharing between adjacent pixels, the pixel detector achieves a spatial resolutions up to 10 μm in the plane perpendicular to the beams and of about 24 μm in z direction.

The detector is divided into a barrel pixel detector (BPix) consisting of three layers at radii between 4.4 cm and 10.2 cm, and a forward pixel detector (FPix) consisting of two endcaps on either side of the barrel at distances of 34.5 cm and 46.5 cm from the nominal interaction point. The two subsystems total about 66 million readout channels, making zero-suppressed readout a necessity. Each layer of the detector is built up from subunits, which measure about $2 \times 8 \text{ cm}^2$ and are referred to as *detector modules*. These modules consist of a silicon sensor as active material for signal generation and associated electronics for signal readout. Sensor and front-end electronics are arranged on top of each other and are joined by bump-bonding, i.e., through small solder balls that connect each sensor segment with its associated readout electronics. The operation temperature of the detector is stabilized with a liquid mono-phase C_6F_{14} cooling system. A detailed description of the successor of the pixel detector is given in Chapters 13 to introduce Part II of this thesis. This new pixel detector has been installed in February 2017 to improve the performance of the original system and to cope with even more challenging conditions arising from the increasing instantaneous luminosity of the LHC.

Silicon strip detector

While the pixel detector uses sensors that are segmented in two dimensions, the sensors of the tracking detector at larger radii are implemented as strips and provide one-dimensional spacial resolution. This makes the connection of individual channels to their front-end electronics easier as they can be wire-bonded at the end of each of the strips, which avoids the need for the cost intensive bump-bonding. Two-dimensional spacial resolution can be achieved by arranging sensors with rotated strip orientation in different layers on top of each other.

The CMS strip detector consists of three subsystems, the tracker inner barrel and inner disks, the tracker outer barrel, and the tracker endcaps, the sensors of which differ slightly in geometry and granularity. The strip pitch decreases from smaller to larger radii, ranging from 80 μm in the first layer of the tracker inner barrel to 184 μm in the tracker endcaps. Spatial resolutions of 23–53 μm can be achieved in the different parts of the detector. Measurements of the respective second coordinate with a resolution between 230 μm and 530 μm are provided by strip modules that are mounted back-to-back with a stereo angle of 100 mrad for selected layers in the detector, ensuring that at least four out of the nine strip detector measurements are two-dimensional. The different subsystems total 9.3 million readout channels and cover almost 200 m^2 of active area, making the system the largest silicon tracking detector built to date.

3.3.3 Calorimetry

Both the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL) are installed within the solenoid magnet, to minimize the particles' energy loss prior to calorimetry. An electromagnetic calorimeter based on lead tungstate (PbWO_4) crystals as sensing and absorbing material is used to absorb electrons, positrons, and photons to determine their energy. Between the ECAL and the inner bore of the solenoid, a hadronic sampling calorimeter is installed to measure the energy deposited by hadron induced showers. It is composed of layers of brass absorber, interleaved with plastic scintillator tiles as active material. A hadronic very-forward calorimeter complements the system at large pseudorapidities and makes CMS an almost hermetic detector, an essential requirement for reconstructing missing transverse momentum arising from particles that escape the detection.

Electromagnetic calorimeter

The most important goal for the design of the ECAL has been to achieve the best possible energy resolution, in particular because diphoton production has been predicted (and proven)

to be one of the discovery channels of the Higgs boson. The choice of lead tungstate crystals for the ECAL has been motivated by the material's large density, resulting in a short radiation length of 0.89 cm and a small Molière radius of 2.2 cm. This allows for the construction of a compact calorimeter that fits inside the solenoid. Additional requirements met by PbWO_4 are a sufficient radiation tolerance for the particle fluence expected in 10 years of operation and a short scintillation decay time of the order of the LHC bunch spacing of 25 ns. Similar to the tracking system, the ECAL is separated into a central barrel part and two forward calorimeters. Altogether they consist of more than 68 000 individual crystals, each with a surface of $22 \times 22 \text{ mm}^2$ on the side facing the IP and a length corresponding to $25.8 X_0$. The scintillation light induced by electromagnetic showers in the crystals amounts to 4.5 photoelectrons per MeV and is converted into electrical signals by photo detectors — avalanche photo diodes in the barrel part and vacuum photo triodes in the forward detector to account for different radiation levels and magnetic field configurations.

Since both the light yield in the crystal and the amplification in the photo detector are temperature dependent, the ECAL is stabilized at its nominal operating temperature of 18°C by a water cooling system. A key challenge for obtaining a premium energy resolution are frequent detector calibrations, both concerning the absolute energy scale and the calibration between different crystals to achieve a homogeneous signal response. Inter-channel differences can be introduced, e.g., by variations in the light yields of the crystals, different amplifications of the photo detectors, and radiation and annealing dependent variations of crystal transparency [108]. The evolution of the crystal transparency with increasing irradiation is monitored with a laser system and the inter-channel calibration parameters are updated accordingly.

For energies below 500 GeV, the energy resolution of the ECAL can be described by Equation 1.17, as shown in test beam measurements, where the energy has been reconstructed by summing 3×3 crystals around a central impact point. The parameters have been determined as $a = 2.8\%$ for the stochastic term, which falls as $1/\sqrt{E}$, $b = 0.30\%$ for the constant term, and $c = 0.12$ for the noise term, which falls as $1/E$ [125]. For energies above 500 GeV the energy resolution is degraded because of shower leakage at the rear end of the crystals out of the calorimeter.

The ECAL is complemented by a two-layer sampling calorimeter, consisting of lead absorbers and silicon strip sensors. This so-called preshower detector is 20 cm thick and installed at $1.653 < |\eta| < 2.6$ to identify neutral pions.

Hadronic calorimeter

Since the ECAL only corresponds to about 1.1 nuclear interaction lengths λ_i , hadrons largely reach the HCAL where they deposit the bulk for their energy by inducing hadronic showers in the brass absorbers. The absorbed energy is measured with plastic scintillators, which are interleaved with the absorber plates and read out via wavelength shifting fibers and photo detectors. The HCAL is composed of four different subdetectors. The central component is the HCAL barrel at $|\eta| < 1.3$ contributing between 5.82 and 10.6 nuclear interaction lengths, depending on the pseudorapidity. It is complemented with two endcaps, extending the coverage to $1.3 < |\eta| < 3.0$. The endcaps of the HCAL have to be especially radiation tolerant as about a third of all produced hadrons are incident in this part of the solid angle.

Because of the importance to reliably reconstruct the missing transverse momentum of a collision in order to detect particles that do not interact with the detector, e.g., neutrinos or the LSP in SUSY processes (c.f. Section 2.3), a very forward calorimeter is installed at $z = \pm 11.2 \text{ m}$ from the IP to extend the pseudorapidity coverage up to $|\eta| < 5.2$. Because of the extremely high fluence of charged hadrons in the very forward direction of up to $1 \times 10^{11} \text{ cm}^{-2}$ projected for ten years of LHC operation, radiation tolerant quartz fibers

have been chosen as active medium for this part of the detector. The very forward calorimeter is also used for real-time monitoring of the instantaneous luminosity delivered to CMS [126].

The fourth component of the HCAL is installed outside of the solenoid and hence called outer calorimeter. It serves to measure the remainder of high-energy hadronic showers that leak through the inner barrel and the solenoid. This blemish arises from geometrical constraints of the HCAL barrel's position between outer extend of the ECAL and inner extend of the solenoid, which does not allow to place sufficiently thick absorbers in the central position. With the outer calorimeter, also called tail-catcher, the minimum calorimeter depth is increased to 11.8 nuclear interaction lengths.

The performance of the HCAL is limited by the intrinsic challenges of hadronic calorimetry mentioned in Section 3.3.3 and its implementation as sampling calorimeter with significant amounts of inactive absorber material. The parameter a in the stochastic term of Equation 1.17 has been determined in pion test beam measurements to be 115% and the constant b amounts to 5.5% [127]. Noise has a negligible effect to the resolution but induces a trigger rate of about 100 Hz. For typical jet energy thresholds of the order of 40 GeV, the energy resolution is of the order of 10–20% and decreasing for higher energies. However, the resolution can be improved by combining the HCAL measurements with data from other subdetectors using a so-called *particle-flow* (PF), which will be summarized in Section 5.1.

3.3.4 Muon system

The muon system is of paramount importance to the CMS experiment. Their straight forward identification and efficient reconstruction make muons a valuable handle to suppress QCD multijet background in many physics analyses and provide indispensable information for selecting events of interest out of the vast amount of collisions provided by the LHC. Their relatively long lifetime of $\tau = 2.2 \mu\text{s}$, which is additionally prolonged by time dilatation in the experiment's frame of reference, allows them to travel distances much longer than the dimensions of the detector and their large mass and the absence of color charge cause them to penetrate HCAL, solenoid, and flux return yoke. Since all other electromagnetically interacting particles are absorbed by the subdetectors described above, muons can be easily identified as the only particles reaching the muon system. The challenges for the muon detectors are to cover a huge area of about $25\,000 \text{ m}^2$, requiring a cost-effective design. In addition, the detectors have to provide precise momentum measurements of muons with transverse momenta up to 1 TeV and fast information for real-time reconstruction to contribute to the level-1 (L1) trigger decision as will be discussed in Section 3.3.5. Because of different requirements, depending on the location of the detector and the corresponding variations of the magnetic field, three different types of muon detectors are used in CMS.

In the barrel part, i.e., for $|\eta| < 1.2$, four layers of drift tubes are embedded in the rings of the flux return yoke. These detectors provide robust and precise measurements in the central region, where both the muon flux and the neutron induced background are low and where the magnetic field strength is comparatively low and homogeneous. The chambers feature different orientations of the sensing wires to allow for measurements of both the r - ϕ and the z coordinate. In the endcap regions ($0.9 < |\eta| < 2.4$), cathode strip chambers are used, allowing for a finer electrode segmentation and better radiation tolerance, two essential features to account for the higher particle flux in these regions. The muon system is complemented with double-gap resistive plate chambers, operated in avalanche mode, which are installed in the barrel and endcap regions. While drift tubes and cathode strip chambers provide good spacial resolution for muon p_T measurements, resistive plate chambers constitute an independent muon system with excellent timing resolution, mainly exploited for fast trigger decisions.

The resolution and reconstruction efficiency of the muon system has been measured in 7 TeV proton-proton collisions [128]. A spacial resolution of 80–120 μm and 40–150 μm could be achieved with the drift tubes and the cathode strip chambers, respectively. Both systems reached a muon detection efficiency of 95% per chamber. The timing resolution of the resistive plate chambers has been determined to be better than 3 ns and is hence considerably smaller than the LHC bunch spacing of 25 ns. The standalone p_T resolution of the muon system of about 9% for energies up to 200 GeV and up to 40% for 1 TeV muons at high η , is mainly limited by multiple scattering in the detector material. It can be improved by approximately one order of magnitude by combining measurements of the muon system with information from the inner tracking detectors in a global fit using the PF algorithm [129].

3.3.5 Trigger and computing

The combined raw data recorded by all subdetectors have a size of about 1.5 MB/event. Given the LHC bunch crossing frequency of 40 MHz this would correspond to a data rate of 60 TB/s, a rate that is not only too large to be read out continuously from the detector but also to be written on tape in its entirety. One of the crucial challenges of the experiment is therefore data reduction. This is achieved with a two stage trigger system, designed to filter out potentially interesting events, while discarding those associated with well-known physics processes.

The first stage is the L1 trigger, which uses coarse information from the calorimeters and the muon system in order to select events of interest within a latency of 3.2 μs [108]. The maximum allowed latency is limited by the buffering capabilities of the front-end electronics of the subdetectors, where the full data are kept while the trigger decision is pending. The L1 trigger is implemented in custom hardware to guarantee fast decisions, based on energy deposits in so-called *trigger towers* of the calorimeters and the number and the p_T of muons. The event rate read out from the detector is thereby reduced to about 100 kHz, depending on the instantaneous luminosity provided.

Further event reduction is based on the full data that are read out from the detector and involves more sophisticated calculations and the reconstruction of final-state physics objects. These steps are carried out by the software based high-level trigger (HLT), running on a dedicated computer farm. A global logical OR of different so-called *trigger paths* finally accepts or discards a given event. Each trigger path probes the event for a range of properties that can make it interesting for further examination by different analyses, e.g., large jet or lepton multiplicities, large energy deposits, or large missing transverse momentum. In order to reserve a certain fraction of the maximum HLT output rate for rare event topologies, trigger paths can be *prescaled* by a certain factor x to reduce the acceptance rate for frequently occurring signatures. This means that only one in x events is accepted by the trigger and written to tape. Changing the prescale scheme during runtime allows to maintain an approximately constant HLT output rate of about 1 kHz, independent of the instantaneous luminosity provided by the LHC.

Data validated by the HLT have to be stored, processed to reconstruct final state physics objects, and distributed for further analysis to institutes around the globe. This is achieved by a multi-tiered computing infrastructure with the tier-0 computing center at CERN as its central node. The tier-0 computing center provides mass storage with high availability and short latencies and carries out a first reconstruction to guarantee fast data quality feedback to the experiments. Additionally, it exports both raw and reconstructed data to tier-1 computing centers, where copies are stored as backup. Tier-1 computing centers are hosted at several large national research centers around the world. Their main tasks are to run full reconstruction of the raw data and to ensure high data availability for tier-2 computing centers. Besides detector data, also simulated data are stored at tier-1 computing

centers. Final-stage analysis of the data is then carried out at tier-2, or in case of analyses investigating smaller data sets at tier-3 computing centers hosted at CMS member institutes. The Worldwide LHC Computing Grid integrates these resources into a coherent system, allowing for distributed execution of computing task and making data recorded by CMS available to institutes around the world [130].

3.4 Event simulation with the Monte Carlo method

The solid theoretical understanding of elementary particles and their interactions allows to simulate particle collisions with so-called *event generators* [131]. Such simulations are of paramount importance for any particle physics experiment and also widely used by theoreticians to test implications of new physics models. The simulation of particle collisions in high-energy physics employs a statistical approach referred to as Monte Carlo (MC) method [132]. It is based on generating pseudo-random numbers that are used to approximate the result of analytically not solvable integrals or to sample probability density functions that arise from the probabilistic nature of elementary particles.

For the search for SUSY presented in Part I of this thesis, MC simulations have been used for several purposes. Firstly, simulated events have been used to optimize and validate the analysis framework, and secondly MC simulations are used to predict various SM processes that enter the search as background events. Moreover, the statistical interpretation of the result relies on the simulation of different SUSY signal processes as will be discussed Chapter 10.

As outlined in Section 3.2, the simulation of proton-proton collisions proceeds in several factorized steps, each of which requires dedicated software tools. For the simulations used in the context of this thesis, the following inputs and tools have been used. The colliding protons are described by PDFs provided by the NNPDF Collaboration [133]. They define the parton momenta needed to calculate proton-proton cross sections for the hard interaction. The latter is calculated at LO accuracy with the MADGRAPH5 [134] event generator or at NLO accuracy with the MADGRAPH5_aMC@NLO 2.2.2 [134, 135] or the POWHEG v2 [136–139] event generators. SUSY signal processes for optimizing the analysis and interpreting the results are simulated at LO accuracy using the MADGRAPH5_aMC@NLO event generator with up to two additional partons at the matrix-element level. The event generators are interfaced with PYTHIA 8.2x [140] to model the subsequent parton shower and the hadronization of colored particles. As described in Section 3.2, the final state contains additional particles from the UE. This contribution is modeled using the CUETP8M1 [141] event tune in conjunction with PYTHIA 8.2x. Free parameters of this event tune have been adjusted based on UE data extracted from proton-proton collisions recorded at $\sqrt{s} = 0.9 \text{ TeV}$, 1.96 TeV , and 7 TeV . Finally, particles produced at generator level after hadronization and decay are fed into a GEANT4-based model [142] of the CMS detector to simulate the response of the different subdetectors. For simulated signal processes, the detector response is modeled with a fast-simulation package [143] that is validated against the GEANT4-based model. The fast-simulation package is required to simulate the large amount of signal models needed for scans of the sparticle mass parameter space with the available computing resources.

Part I

Search for Supersymmetry in Events with Multiple Charged Leptons, Jets, and Missing Transverse Momentum

4. Motivation

Supersymmetry is one of the theoretically most compelling extensions of the SM, not only because it addresses the hierarchy problem, predicts an energy scale where the three coupling constants have the same value, and — given R-parity conservation — provides a dark matter candidate particle, but also because the approach of postulating and exploiting a new internal symmetry of the Lagrangian density has been a successful concept in the past. As outlined in Section 2.3, there is strong theoretical motivation to expect the gluino and the lighter mass eigenstates of the third generation squarks to have masses below or around an energy of 1 TeV and consequently large hopes have been pinned on exploring this energy range with the LHC. As no evidence for SUSY has been found in Run 1 at $\sqrt{s} = 7$ TeV and 8 TeV [144], searches for new physics and SUSY in particular have gained even more interest after the successful consolidation and the restart of the accelerator in summer 2015 and the associated increase in center-of-mass energy to 13 TeV.

Because of the unknown mass hierarchy of the potential SUSY particles and the uncertainty concerning the type and the decay mode of sparticles that might be produced at the LHC, there exists no ‘golden discovery channel’, in which SUSY would definitely manifest itself, if it were to exist. Consequently, the ATLAS and CMS Collaborations have set up a comprehensive program of SUSY searches to investigate a multitude of different final states and energy ranges. All of these searches need to employ dedicated techniques to discriminate potential SUSY signal events against SM background to achieve sensitivity for extremely rare processes with cross sections of the order of 1 pb and below. Background rejection can be achieved, e.g., by employing advanced kinematic variables such as M_{T2} , α_T , or the ‘razor variable’, which are utilized by different all-hadronic SUSY searches [145–147]. An alternative method is to require charged leptons in the final state, since the amount of SM background decreases significantly for increasing lepton multiplicities. However, this comes at the expense of decreasing signal efficiencies because of the leptonic branching fractions of $\approx 11\%$ and $\approx 3.4\%$ per lepton flavor for $W^\pm$ and Z bosons, respectively. Examples for leptonic SUSY searches at CMS with decreasing SM background are various single lepton searches [148, 149], a dilepton search, requiring opposite-sign, same-flavor leptons in the final state [150], and a search for two leptons of the same charge [151].

The analysis presented in this thesis requires at least three charged leptons in the final state and therefore marks the leptonic SUSY search with the lowest SM background conducted with the CMS experiment. This brief introductory chapter is structured as follows. Simplified SUSY signal models that can produce multiple charged leptons are introduced in Section 4.1. Section 4.2 provides a motivation to search for such signatures with the final state examined in

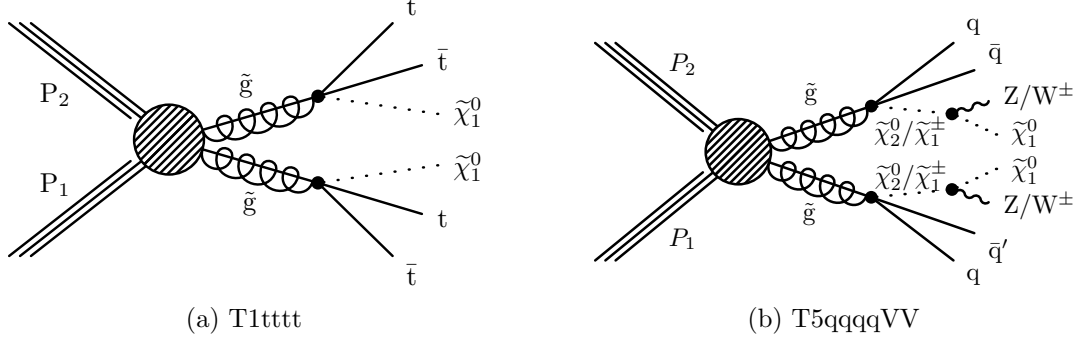


Figure 4.1: Simplified SUSY models with gluino pair production that can produce multiple leptons in the final state. Missing transverse momentum arises from the production two neutral LSPs ($\tilde{\chi}_1^0$). Depending on the model, leptons that produced in the decay of vector bosons are accompanied by jets originating from b quarks (a) or light-flavor jets (b).

this thesis, followed by a brief review of the relevant SM background processes in Section 4.3. Finally, an overview of prior analyses that targeted the same final state is given in Section 4.4 and the analyzed data set is specified.

4.1 Supersymmetric signals models

The analysis strategy, which will be discussed in detail in Chapter 6, follows a model independent approach, rendering the search sensitive to any BSM physics process that yields three or more final state leptons, jets, and missing transverse momentum. Nevertheless, certain simplified SUSY models are used as benchmark processes in order to optimize the event selection and to interpret the result in terms of exclusion limits on the masses of the SUSY particles of a given model.

Two simplified SUSY models that can yield multiple leptons in the final state are shown in Figure 4.1. In both models, the LSP is the lightest neutralino ($\tilde{\chi}_1^0$), which escapes detection and gives rise to missing transverse momentum in the final state. Figure 4.1 (a) shows a model featuring gluino-gluino production, where each gluino ($\tilde{g}$) subsequently decays via an intermediate virtual stop quark into a top-antitop pair ($t\bar{t}$) and a neutralino. As the top quark decays almost exclusively into a b quark and a $W^\pm$ boson ($t \rightarrow b W$), the final state can comprise multiple charged leptons if the $W^\pm$ bosons decay leptonically. In addition, this model is characterized by producing up to four b quarks leading to jets with displaced secondary vertices. The model is denoted as T1tttt, following the nomenclature introduced in Section 2.3.4. Figure 4.1 (b) shows another simplified model with gluino-gluino production, referred to as T5qqqqVV. Here, the gluinos decay into light flavor quarks and either the lightest chargino ($\tilde{\chi}_1^\pm$) or the second lightest neutralino ($\tilde{\chi}_2^0$). Subsequently, the chargino (neutralino) decays into a $W^\pm$ (Z) boson and the LSP. Unlike T1tttt, this model does not produce b jets in the final state. Instead, a pair of opposite-sign, same-flavor (OSSF) leptons is produced if the Z boson decays leptonically. The invariant mass of this OSSF dilepton pair is compatible with the Z boson mass of $m_Z = 91.2$ GeV, if the Z boson is produced on-shell. This is the case if the mass difference between the intermediate neutralino and the LSP is not too small. Different combinations of vector bosons give rise to three distinct signal topologies. Assuming equal probabilities for the three decay channels $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0$ and $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^\pm$, the relative production probabilities are 4/9 and 1/9 for the topology featuring WZ and ZZ, respectively. While these two topologies can produce up to three and four leptons respectively, the WW topology, produced with a probability of 5/9 yields at most two leptons if both $W^\pm$ bosons decay leptonically.

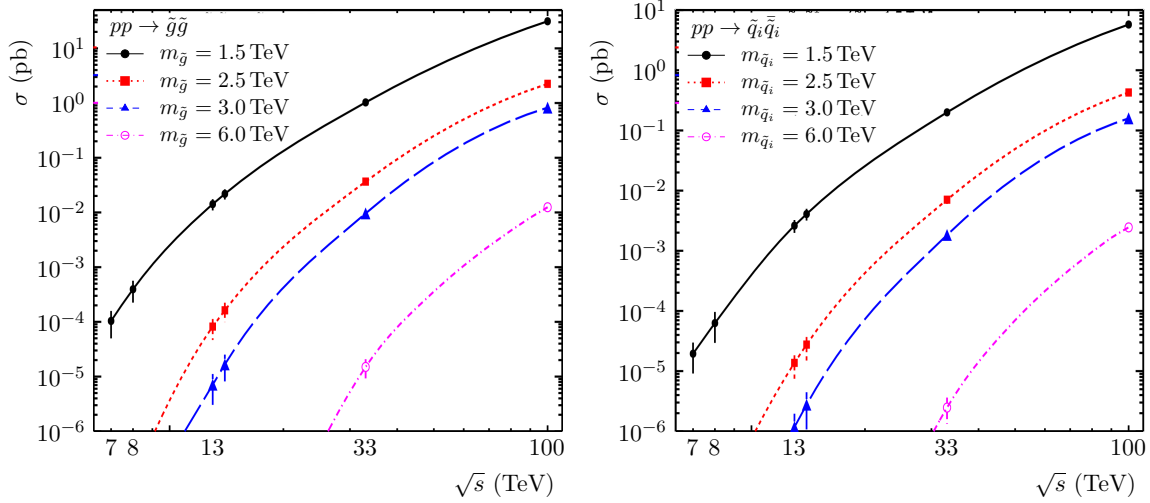


Figure 4.2: NLO+NLL cross section of gluino (left) and squark pair production (right) as a function of the center-of-mass energy $\sqrt{s}$ for different sparticle masses. Data from [95, 152].

4.2 The multilepton final state

The signal models introduced above can produce multiple leptons arising from leptonic decays of vector bosons. This allows to discriminate signal events against SM background by requiring three or more charged leptons (electrons or muons) in the final state, a signature that is hereafter referred to as *multilepton* final state. The large lepton multiplicity drastically reduces the background of the search, since only very few SM processes produce three or more leptons. Processes producing final state signatures that genuinely resemble those of the signal models include, e.g., diboson production or the production of $t\bar{t}$ in association with a vector boson. The fact that these processes involve the production of $W^\pm$ and Z bosons, make them theoretically well understood. Experimentally, the reconstruction of muons and electrons is robust and efficient, thanks to the excellent performance of the CMS inner tracking detectors, the high energy resolution of the ECAL, and the efficient muon system in conjunction with the large magnetic field.

In addition to the lepton multiplicity, events that are selected for this analysis have to meet two additional requirements that are motivated by the details of the targeted SUSY processes. The search presented here focuses on SUSY particle production mediated by the strong nuclear interaction, resulting in gluino-gluino or squark-squark pair production. This choice is motivated by the larger cross sections of these processes compared to electroweak production of SUSY particles at the LHC and the goal to achieve sensitivity already with relatively small data sets recorded early after the increase of the center-of-mass energy to 13 TeV. Experimentally, this is taken into account by requiring a minimum number of jets in the final state that arise from quarks that are produced in the decay chains of the colored SUSY particles. Figure 4.2 shows the production cross sections for gluino-gluino and squark-squark production as a function of the center-of-mass energy for different sparticle masses. It can be seen that the cross sections increase steeply with the center-of-mass energy. This allows to greatly improve the sensitivity to these production modes at 13 TeV compared to a data set of a comparable size recorded at $\sqrt{s} = 8$ TeV.

The second additional requirement for the final state targeted by this search is motivated by considering R-parity conserving SUSY models. In such models, the LSPs escape detection, which allows to increase the signal-to-background ratio by requiring a minimum amount of missing transverse momentum. More details on the event selection are given in Chapter 6.

4.3 Standard model background

SM background processes relevant for this analysis can be categorized as *irreducible* and *reducible* background sources. While processes belonging to the former category produce signatures that genuinely resemble those of the targeted signal models, reducible background processes enter the event selection because of detector or reconstruction related limitations.

Irreducible SM background arises from processes producing three or more final state leptons that originate from the decay of $W^\pm$ or Z bosons. Such leptons are referred to as *prompt* leptons because of their origin from the primary vertex. Examples for irreducible background processes are diboson production, mainly WZ +jets, and the production of a $t\bar{t}$ pair in association with a vector boson or the Higgs boson ($t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$). Very small contributions arise from so-called *internal conversions*, i.e., processes involving a virtual photon that decays into leptons. Such processes are denoted as $X+\gamma$, where X is a placeholder for other particles produced along with the virtual photon. ZZ diboson production and other irreducible background contributions that are characterized by having very small cross sections of below 1 pb are summarized in a category denoted as *rare backgrounds*. More detailed information on different background sources are given in Chapter 7. Contributions arising from irreducible backgrounds are estimated with MC simulations including scale factors to account for small differences in the reconstruction of data and simulated events. In case of the WZ background the normalization of the simulation is validated in a control region with data.

Reducible background arises from SM processes that produce two or less prompt leptons. Events from such processes can pass the event selection if at least one other object is incorrectly identified as prompt lepton. For this search the main source of these *nonprompt* leptons is the production of $t\bar{t}$ in association with jets, where decay products of the b quarks can be misidentified as prompt leptons. Other sources of nonprompt leptons are misidentified hadrons, electrons from unidentified photon conversions, or muons from light-meson decays in flight. Since this background arises from detector and reconstruction effects, simulation is less reliable than for the modeling of irreducible backgrounds. This is taken into account by predicting the reducible background with a data-driven strategy that does not rely on MC simulations. Detailed information on the background estimation techniques used in this search and their validation are given in Chapter 7.

4.4 Data set and prior analyses

Similar searches as the one presented in this thesis have been carried out by the ATLAS [153] and the CMS [154, 155] Collaborations at $\sqrt{s} = 8$ TeV based on data sets corresponding to 20.3 fb^{-1} and 19.5 fb^{-1} of proton-proton collisions, respectively. All of these searches did not show significant deviations of the observed data from the SM background expectation, which allowed to exclude gluino masses of up to 1 TeV for the $T1tttt$ model.

A first version of the search presented in this thesis has been conducted with the first data set of proton-proton collision collected by CMS at $\sqrt{s} = 13$ TeV in 2015, totaling an integrated luminosity of 2.3 fb^{-1} [156]. Subsequently, the search has been optimized for a larger data set and has been repeated with 12.9 fb^{-1} of data collected between May and July 2016. Results and figures in this thesis are based on this second iteration of the analysis. Parts of these results have been made public in a physics analysis summary [157].

5. Trigger and Object Reconstruction

In order to reduce the vast amount of data read out from the CMS detector, the high-level trigger (HLT) filters out events of interest that are stored on tape for further analysis. The decision whether to keep or to discard an event is based on a combination of data from all subdetectors, which allows to reconstruct collision products at the particle level. This is accomplished with the so-called particle-flow (PF) algorithm, which is briefly described in Section 5.1. Selection criteria and efficiencies of HLT triggers, used for preselecting events for the presented analysis are discussed in Section 5.2.

For events passing the HLT requirements, a second, more refined reconstruction is performed that is not limited by the stringent constraints on the processing time at HLT level. Following this reconstruction, analysis specific quality requirements can be applied to define the physics objects. The selection criteria for leptons used in the presented analysis are detailed in Section 5.3. Additionally, the lepton isolation is introduced, a quantity that serves as the most important discriminant between signal-like leptons and leptons originating from reducible background sources. Finally, Section 5.4 summarizes quality requirements for jets and defines the hadronic activity and the missing transverse momentum.

5.1 Particle flow

The PF algorithm [158–160] is utilized by CMS to identify each individual particle emerging from the IP. Two slightly different versions of the algorithm are used at HLT level and for the final reconstruction of the events that have been stored on tape, where the former version is simplified to allow for a shorter processing time. This is mainly achieved by omitting the time intensive reconstruction of low- p_T tracks. The common working principle is to combine information from all subdetectors, with emphasis on improving the limited energy resolution of the HCAL by exploiting the superb performances of the inner tracking system and the ECAL. Rather than just measuring clustered energy deposits in the calorimeters, the PF algorithm aims at decomposing the jet constituents down to the particle level. This allows to determine the energy of charged hadrons with much better resolution compared to calorimeter-only based measurements, by relating tracks of charged particles to energy deposits in the calorimeter. Since the energy fraction carried by photons can be determined with good resolution with the ECAL, only the remainder of about 10% of the energy of a typical jet that is carried by neutral hadrons is solely measured by the HCAL with its rather coarse energy resolution, which is governed by the stochastic term of $115\%/\sqrt{E}$ (c.f. Section 3.3.3).

The working principle of the PF algorithm can be summarized as follows [161]. The procedure starts with independent clustering steps in the calorimeters and with charged particle tracking with the inner tracking system. For the latter, an iterative approach guarantees high efficiencies and small probabilities to reconstruct unphysical tracks by first reconstructing tracks with high quality requirements. Subsequently, hits associated with these tracks are removed and the quality requirements are gradually relaxed. The clustering in the calorimeters is seeded by local maxima of the deposited energy. Deposits in between these seeds are then distributed among the clusters, based on the distances between the seed and the crystal or cell of the respective energy deposit. The clustering and tracking procedure provides a list of so-called unassociated objects which the PF algorithm works through sequentially. First, tracks and clusters that are compatible with tracks in the muons systems are associated to muon candidates and removed from the list. In the next step, electron candidates are identified and related tracks and clusters, including such from bremsstrahlung photons are removed from the collection. Subsequently, the energy of clusters in the HCAL that are matched to tracks is compared to the track p_T measurement. If both measurements are compatible, a charged hadron is added to the list of identified particles and its energy is calculated as the weighted average of the two measurements. Otherwise the excess energy of the cluster is attributed to a neutral hadron that is not visible in the tracking detector. A similar approach is followed if an additional ECAL cluster can be related to a track and an HCAL cluster. If the excess of the calorimeter measurement over the p_T measurement is smaller than or equal to the energy of the ECAL cluster, it is attributed to a photon candidate. If the excess is larger, the energy in the ECAL cluster is still attributed to a photon candidate and the remainder of the excess is attributed to a neutral hadron candidate [160]. Finally, after all tracks have been associated with objects and removed, remaining ECAL and HCAL clusters are interpreted as photon and neutral hadron candidates, respectively.

The hereby generated list of particles serves as input for the subsequent clustering of particles into jets. Together with analysis specific quality requirements on the relevant physics objects, this list of identified particles forms the basis for identifying the final state under study. Compared to solely calorimeter based measurements, the PF algorithm significantly improves the angular resolution of jets and the resolution of the jet energy, especially for jets with small momenta. Additionally, PF improves the quantification of the lepton isolation, as will be discussed below.

5.2 Triggers

The presented analysis targets events with at least three well-identified muons or electrons in any combination. In order to examine this final state, a selection is applied to all events that have been validated by the HLT trigger and stored on tape. This selection is referred to as *offline selection* to distinguish it from the *online selection* at trigger level. For the presented analysis, the first step of the offline selection is to filter out events that have been validated by at least one out of several *dilepton triggers*, which are described below.

5.2.1 Trigger paths

A first set of triggers, referred to as *isolated dilepton triggers*, selects events with at least two loosely isolated leptons. As will be discussed in detail in Section 5.3.3, the isolation of a lepton is an important discriminant between nonprompt and prompt leptons since the former ones are predominantly contained within jets, whereas prompt leptons tend to be locally isolated. The isolation is calculated as the ratio of the sum of transverse momenta of all objects within a cone around the lepton candidate and the p_T of the lepton candidate itself. At trigger level, the cone size is defined by $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$. The isolated dilepton triggers employed in this analysis impose p_T thresholds of 17 GeV and 8 GeV on the leading

and the subleading muon. The corresponding thresholds for electrons are higher — 23 GeV and 12 GeV for the leading and the subleading electron, respectively, to account for the higher misidentification rate for electrons compared to muons.

A second set of so-called *nonisolated dilepton + H_T triggers* poses no requirement on the lepton isolation. Instead, these triggers require a minimum amount of hadronic activity H_T^{HLT} in the event, defined as

$$H_T^{\text{HLT}} = \sum_{\text{PF-jets}} p_T^{\text{HLT}}, \quad (5.1)$$

where the superscript denotes that the respective observable is evaluated at HLT level and not after the final reconstruction. During the data taking period relevant for the presented analysis, the computation of H_T at HLT level was based on all jets with $p_T > 30$ GeV that are reconstructed with the PF algorithm and the subsequent jet clustering. The nonisolated dilepton + H_T triggers used in this analysis require $H_T^{\text{HLT}} > 300$ GeV and feature transverse momentum thresholds of $p_T > 8$ GeV for both leptons, independently of the lepton flavor.

In addition to these signal triggers, a set of single lepton triggers that impose no isolation requirement on the lepton are employed in the analysis. Events selected by these auxiliary triggers are used to measure the lepton misidentification rate that is used for the data-driven estimation of the nonprompt lepton background, as will be discussed in Chapter 7. Owing to the large amount of events that can pass these triggers, their rates have been decreased by applying different prescale factors, resulting in lower effective integrated luminosities $\mathcal{L}_{\text{eff}}$, compared to the signal triggers. Overview tables showing all signal and auxiliary triggers used in the presented analysis can be found in Appendix A.

5.2.2 Trigger efficiency

The trigger efficiency is the probability for at least one of the considered triggers to validate a signal event, given that at least three leptons fall into the detector acceptance. For the dilepton triggers considered here, the trigger efficiency can be factorized as a product of the individual efficiencies for the trigger to correctly recognize the leading lepton, the subleading lepton and, in case of the nonisolated triggers, the hadronic activity H_T separately. These efficiencies are measured in data using the so-called *tag-and-probe* technique [129, 162]. Events entering the denominator of the efficiency are selected by a single lepton trigger that imposes more stringent requirements on the so-called *tag* lepton than the dilepton trigger requirement under study. Additionally, the tag lepton has to pass the analysis specific lepton selection that will be described in Section 5.3. A second lepton in the event, which also has to pass the lepton selection with the p_T requirement omitted, serves as the *probe* lepton. This allows to measure the factorized efficiency for triggering the event as a function of p_T and η of the probe lepton.

Isolated dilepton triggers

The p_T dependence of the trigger efficiency is described by a step function at the trigger threshold, whose turn-on is smeared to a certain width corresponding to the p_T resolution at HLT level. Following the prescription outlined above allows to obtain separate trigger efficiency curves for the leading and the subleading lepton. Two important figures are derived from these curves. Firstly, the p_T value at which the efficiency reaches its plateau value. This figure determines the minimum p_T a lepton has to have in order to be accepted for this analysis to avoid lepton p_T dependent trigger efficiencies that would require dedicated corrections. The p_T thresholds at trigger level, together with measured turn-on widths of 2–3 GeV, lead to the offline lepton p_T requirements that are summarized in the upper row

Table 5.1: Flavor and H_T dependent lepton p_T requirements for muons (electrons). The thresholds are chosen to be as small as possible while ensuring p_T independence of the trigger efficiencies. H_T values refer to the hadronic activity after full reconstruction (c.f. Section 5.4.3).

H_T (GeV)	$p_T^{\text{leading lepton}}$ (GeV)	$p_T^{\text{subleading lepton}}$ (GeV)	$p_T^{\text{3rd lepton}}$ (GeV)
< 400	> 25 (25)	> 10 (15)	> 10 (10)
> 400	> 10 (15)		

of Table 5.1. The leading lepton is required to satisfy $p_T > 25$ GeV for both flavors, while the subleading lepton needs to exceed a threshold of 10 GeV in the case of muons and 15 GeV in the case of electrons. For the third lepton, a flavor independent p_T requirement of 10 GeV is imposed.

The second figure of merit of the trigger efficiency curve is the plateau efficiency itself. The factorized plateau efficiencies for triggering the leading and the subleading lepton determine the total trigger efficiency for signal-like events, a quantity that is important to obtain the correct normalization when comparing data with simulation. The factorized plateau efficiencies have been measured to be 90% or better for leading and subleading leptons of both flavors and all trigger paths considered in this analysis. With this minimum plateau efficiency of $\epsilon_p = 0.9$, the total efficiency for triggering events with at least three leptons using a dilepton trigger can be expressed as

$$\epsilon > 1 - (1 - \epsilon_p) - 3 \cdot (\epsilon_p (1 - \epsilon_p)^2) = 0.972 \quad (5.2)$$

The second term in the above equation is the probability for not triggering on any of the three leptons in the event and the third term represents the probability for triggering on exactly one of them. The redundancy of triggering events with at least three leptons with dilepton triggers thus entails trigger efficiencies above 97% if the leptons have sufficiently large transverse momenta. If this is the case, a trigger efficiency of 100% with a lower uncertainty of 3% is considered.

If the leptons do not have sufficiently large transverse momenta, correction factors are derived on an event-to-event base to model the decreased HLT efficiency for such events. These correction factors are applied by assigning a weight smaller than 1 to the respective event, which scales down the number of simulated events in the final selection. Table 5.2 illustrates the cases in which corrections are applied. The first case are events in which only one of the leptons surpasses the minimum p_T required for the leading lepton. Such events are weighted with the single lepton efficiency for the leading lepton. This efficiency is measured in data and parametrized as a function of lepton p_T and $|\eta|$. The second case are events in which only two leptons surpass the p_T threshold required for the subleading lepton. These events are weighted with the product of the efficiencies measured for leading and subleading lepton. The effect of these corrections on the simulations used for estimating irreducible SM processes will be shown in Chapter 8.

Nonisolated dilepton + H_T triggers

Events exceeding a certain amount of hadronic activity can additionally be triggered by the nonisolated dilepton plus H_T triggers. For a minimum offline H_T^* of 400 GeV, all three nonisolated dilepton triggers used for this search have reached their plateau efficiency. The lower lepton p_T threshold of these triggers allows to decrease the offline p_T requirement

*The offline H_T will be defined in Section 5.4.3.

Table 5.2: Lepton p_T criteria for applying HLT efficiency corrections. The number of checkmarks represents the number of leptons falling into one of the three different p_T regions defined by the offline lepton p_T thresholds. The weight applied to events is shown in the last column, where ϵ_1 and ϵ_2 are the measured trigger efficiencies for the leading and the subleading lepton.

$p_T > 10 \text{ GeV}$	$p_T > p_T^{\min}$ subleading lepton	$p_T > p_T^{\min}$ leading lepton	weight
		✓ ✓ ✓	1
	✓	✓ ✓	1
	✓ ✓	✓	ϵ_1
✓		✓ ✓	$\epsilon_1 \cdot \epsilon_2$
✓	✓	✓	$\epsilon_1 \cdot \epsilon_2$

for leptons in such events as shown in the lower row of Table 5.1. Lepton p_T independent trigger efficiencies are achieved for offline thresholds of 10 GeV and 15 GeV for muons and electrons respectively, both for the leading and the subleading lepton. As for events with $H_T < 400 \text{ GeV}$, the third lepton has to fulfill $p_T > 10 \text{ GeV}$. Because of the identical p_T requirements for leading and subleading lepton, the aforementioned redundancy criterion is always fulfilled and a trigger efficiency correction is not needed for simulated events if they satisfy $H_T > 400 \text{ GeV}$.

5.3 Lepton identification

A robust and efficient identification of muons and electrons is of paramount importance to achieve a high selection efficiency for events with at least three such lepton. Additionally, prompt muons and electrons need to be discriminated against their nonprompt counterparts in order to minimize the contribution from reducible SM background processes. Different sets of quality requirements are employed to form two main categories for each of the lepton flavors, differing in the purity of contained prompt leptons. A so-called *tight selection* with stringent quality requirements aims at reducing the contamination with nonprompt leptons as far as possible while maintaining a high selection efficiency for prompt leptons. Leptons satisfying this selection form the basis for identifying multilepton events for examination in this analysis. A second selection with relaxed quality requirements is referred to as *loose selection*. Events with leptons passing this selection are employed for the data-driven estimation of the nonprompt lepton background. A *very loose selection* with even more relaxed requirements is defined for muons and used to avoid double counting of electrons and muons. The three selections are inclusive, i.e., the more stringent selection contains a subset of leptons that pass the respective looser selection.

5.3.1 Muons

Muons are reconstructed within the acceptance of the muon system with $|\eta| < 2.4$ by combining information from the inner tracking system with measurements in the muon system in a global fit [129]. The identification relevant for this analysis distinguishes two working points, a relaxed one and a more stringent one, called *medium muon identification*. The relaxed working point requires the muon to be identified by the PF algorithm and to be reconstructed from hits in the inner tracking system or as a so-called *global muon* by matching tracks measured with the pixel and the strip detector with tracks obtained from the standalone muon system using a Kalman filter [163]. This quality requirement mainly rejects hits in the muons system from hadrons that leak through the calorimeter and the magnet.

The medium muon identification aims at rejecting muons from hadron decays in flight by imposing requirements on the number of hits in the pixel detector and the silicon strip detector, the maximum kink angles of the track in the detector planes, the χ^2 of the global fit, and the compatibility between measurements in different muon system segments. It does not aim at rejecting nonprompt muons originating from b quark decays. Their rejection is more analysis specific and will be addressed in Section 5.3.3. All muons considered in this analysis have to pass the medium muon identification, except those that only satisfy the very loose selection.

Impact parameter requirements are applied to ensure that the muon candidate originates from the primary vertex, which is defined as the vertex with the largest sum of squared transverse momenta of all reconstructed particles. In the transverse plane, the impact parameter must respect $d_{xy} < 0.05$ cm and in direction of the beam axis $d_z < 0.1$ cm. In order to reject nonprompt muons from b quark decays with displaced secondary vertices, an additional requirement on the impact parameter significance $\text{SIP}_{3\text{D}}$ is applied, requiring $\text{SIP}_{3\text{D}} < 4$. The impact parameter significance is defined as the ratio between the impact parameter in three dimensions and its uncertainty from the track fit.

5.3.2 Electrons

Electron candidates are reconstructed by associating trajectories measured with the inner tracking system with energy deposits in the ECAL [162]. The geometrical acceptance is restricted by the tracking detector to $|\eta| < 2.5$. Two complementary approaches for seeding electron candidates are employed. The first one uses clustered energy deposits in the ECAL as a starting point to predict the position of hits in the tracking detector, the second one matches charged particle tracks with clusters in the ECAL. The clustering algorithms take into account that electrons can radiate large fractions of their energy as bremsstrahlung when interacting with the detector material. This causes their energy to be spread over an array of ECAL crystals. For the track reconstruction, this energy loss implies the complication that the curvature of the trajectory increases along the track, which requires to employ a dedicated Gaussian sum filter [164].

The identification of electrons utilizes a multi-variate discriminant (MVA), which is based on input variables describing the shape of the electromagnetic shower in the ECAL, the track-cluster matching, and the standalone track quality. The training is performed in three distinct regions of η , namely in the inner barrel ($|\eta| < 0.8$), in the outer barrel ($0.8 < |\eta| < 1.479$), and in the endcaps ($1.479 < |\eta| < 2.5$). Two different working points of the MVA are defined for electrons passing the tight and the loose selection, respectively. The more stringent working point is tuned to select prompt electrons with an efficiency of about 90% and has an acceptance of electrons contained in jets of 10% (20%) in the barrel (endcap) region. The working point used for the loose electron selection has been optimized with regard to the performance of the nonprompt background estimation (c.f. Section 7.1).

All selected electrons need to be incompatible with a secondary vertex which solely one other electron originates from. Additionally, the track of any selected electron needs to comprise hits in all pixel detector layers. Both requirements aim at rejecting electrons produced by photons interacting with the material of the inner tracking system via pair production. In order to reject electrons that do not originate from the primary vertex, the same impact parameter requirements as for the muons are applied.

Additional requirements are applied for all selected electrons in order to guarantee that the offline selection is more stringent than the selection at trigger level. To this end, requirements are imposed on variables describing the shower shape ($\sigma_{i\eta i\eta}$, $\Delta\eta_{i\eta}$, $\Delta\phi_{i\eta}$), the ratio of energy deposits in the ECAL and HCAL (H/E), and the relation of energy E and momentum p of an electron ($|1/E - 1/p|$).

Finally, double counting of electrons and muons is avoided by rejecting electrons if they are geometrically matched to a muon that passes the very loose selection within an isolation cone of the size $\Delta R = 0.05$.

5.3.3 Lepton isolation

The most important discriminant between prompt and nonprompt leptons is their local isolation. While the direction of prompt leptons originating from the decay of $W^\pm$ and Z bosons is not correlated with the direction of any other final state particles, nonprompt leptons are mainly contained within jets and hence not locally isolated. To quantify the isolation, a cone with a size ΔR is defined around the lepton candidate in the η - ϕ space, and the isolation is defined as the ratio of the sum of the transverse momenta of all particles identified by the PF algorithm within the cone and the p_T of the lepton candidate itself

$$I = \frac{\sum_{\Delta R} p_T(h^\pm) - \max \left[0, \sum_{\Delta R} \left(p_T(h^0) + p_T(\gamma) - \rho A \left(\frac{R}{0.3} \right)^2 \right) \right]}{p_T(\ell)}. \quad (5.3)$$

In the order of appearance in the above equation, the sigma signs denote the total transverse momenta of charged hadrons, neutral hadrons, and photons within the cone with ΔR . The last term in the numerator quantifies the contribution from pileup collisions that has to be subtracted. It is expressed as the product of the average pileup energy density ρ and an effective area of the clustered jet A . The latter has been measured in five discrete bins of η for both lepton flavors separately [165].

Comparable analyses during Run 1 of the LHC [154, 155] employed a fixed cone size for evaluating the lepton isolation. However, the increase in center-of-mass energy to 13 TeV leads to more energetic collision products, which causes the decay products of such boosted particles to be increasingly collimated. This in turn can cause hadronic decay products to overlap with the cones around prompt leptons, which degrades their local isolation when employing fixed cone sizes. This motivates to introduce a lepton p_T dependent cone size ΔR [166], parametrized as

$$\Delta R = \frac{10}{\min[\max(p_T(\ell), 50), 200]} \quad (5.4)$$

which helps to maintain the local isolation of prompt leptons in boosted topologies. A visualization of the p_T dependence of the cone size is given in Figure 5.1 (a). The isolation criterion based on the variable cone size is referred to as *mini-isolation* I_{mini} .

A downside of this approach is that certain nonprompt leptons can pass the isolation requirement, especially if their p_T is large enough to decrease the cone size. This can be the case for nonprompt leptons that originate from the decay of low- p_T b quarks. For such decays, the angle between the trajectory of the lepton and the jet that arises from the hadronization of the light quark can exceed the opening angle of the isolation cone ΔR_{mini} , which causes them to pass the isolation requirement. The rejection of such nonprompt leptons can be achieved by employing a second isolation variable, named p_T^{ratio} , and defined as

$$p_T^{\text{ratio}} = \frac{p_T(\ell)}{p_T(\text{jet}_{\text{PF}})}, \quad (5.5)$$

where the numerator is the transverse momentum of the lepton candidate and the denominator the p_T of the closest jet within a cone of radius $\Delta R = 0.4^\dagger$. For the case of nonprompt

[†]The subscript ‘PF’ denotes that PF jets are considered, as opposed to jets that pass additional analysis specific quality requirements (c.f. Section 5.4.1).

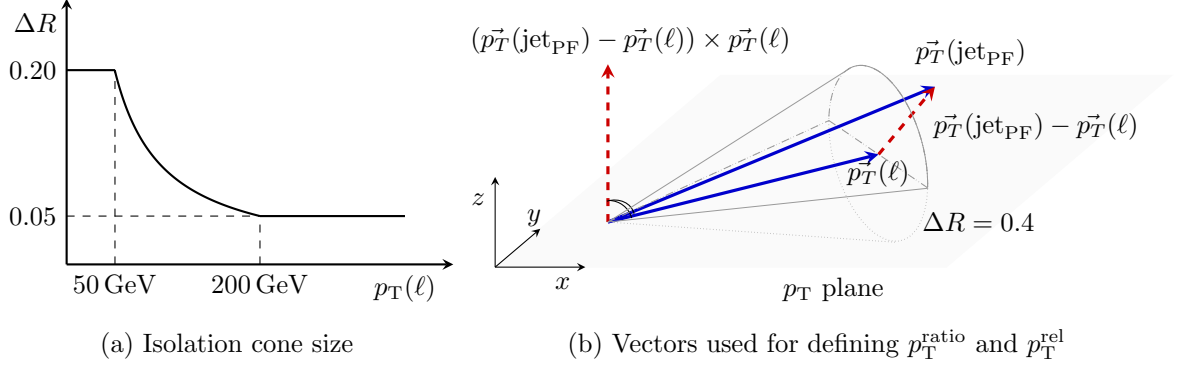


Figure 5.1: Cone size ΔR as a function of the transverse lepton momentum $p_T(\ell)$ (a) and representation of the vectors used for constructing the p_T^{ratio} and p_T^{rel} variables (b). The variables p_T^{ratio} and p_T^{rel} are calculated as ratios of the norms of the vectors shown in blue and those shown as red dashed arrows, respectively.

Table 5.3: Flavor dependent requirements on the isolation variables I_{mini} , p_T^{ratio} , and p_T^{rel} , employed in the tight lepton selection.

	Muons	Electrons
$I_{\text{mini}}^{\text{cut}}$	0.16	0.12
$p_T^{\text{ratio, cut}}$	0.69	0.76
$p_T^{\text{rel, cut}}$	6.0	7.2

leptons from the decay of low- p_T b quark, the jet typically contains the lepton. This causes p_T^{ratio} to be small, whereas values close to 1 are associated with prompt leptons, where the PF jet only contains the lepton candidate itself.

A third variable, the lepton's transverse momentum relative to the momentum of the closest jet after subtraction of the p_T of the lepton candidate, denoted as p_T^{rel}

$$p_T^{\text{rel}} = \frac{|(\vec{p}_T(\text{jet}_{\text{PF}}) - \vec{p}_T(\ell)) \times \vec{p}_T(\ell)|}{|\vec{p}_T(\text{jet}_{\text{PF}}) - \vec{p}_T(\ell)|}, \quad (5.6)$$

is utilized to recover nonsystematical, accidental overlaps between prompt leptons and adjacent jets in boosted topologies [167]. Similar as for p_T^{ratio} , prompt leptons yield large values of this variable whereas nonprompt are characterized by having small p_T^{rel} . The vectors used to define p_T^{ratio} and p_T^{rel} are shown schematically in Figure 5.1 (b).

A powerful discrimination between nonprompt and prompt leptons can be achieved by requiring that a lepton candidate is locally isolated (small I_{mini}) and either carries the major part of the momentum of the associated jet (large p_T^{ratio}) or is considered to overlap with the jet only accidentally (large p_T^{rel}). Mathematically, this requirement can be formulated as

$$[I_{\text{mini}} < I_{\text{mini}}^{\text{cut}}] \wedge \left[(p_T^{\text{ratio}} > p_T^{\text{ratio, cut}}) \vee (p_T^{\text{rel}} > p_T^{\text{rel, cut}}) \right], \quad (5.7)$$

where $I_{\text{mini}}^{\text{cut}}$, $p_T^{\text{ratio, cut}}$, and $p_T^{\text{rel, cut}}$ are criteria tuned to define working points with different prompt lepton efficiencies and nonprompt lepton rejection powers. While leptons entering the very loose and the loose selection only need to meet the requirement $I_{\text{mini}} < 0.4$, leptons passing the tight selection need to satisfy more stringent isolation criteria and additional requirements on p_T^{ratio} and p_T^{rel} as shown in Table 5.3. These criteria are flavor dependent

Table 5.4: List of all quality criteria for muons and electrons for passing the loose and the tight selection. An additional very loose selection is only defined for muons.

Muons				Electrons		
Criterion	Very loose	Loose	Tight	Criterion	Loose	Tight
$ \eta < 2.4$	✓	✓	✓	$ \eta < 2.5$	✓	✓
$p_T > 10 \text{ GeV}$	✓	✓	✓	$p_T > 10 \text{ GeV}$	✓	✓
$I_{\text{mini}} < 0.4$	✓	✓	✓	$I_{\text{mini}} < 0.4$	✓	✓
$ d_{xy} < 0.05 \text{ cm}$	✓	✓	✓	$ d_{xy} < 0.05 \text{ cm}$	✓	✓
$ d_z < 0.10 \text{ cm}$	✓	✓	✓	$ d_z < 0.10 \text{ cm}$	✓	✓
loose muon ID	✓	✓	✓	conversion rejection	✓	✓
medium muon ID	-	✓	✓	no missing pixel hits	✓	✓
SIP _{3D} < 4	-	✓	✓	trigger emulation	✓	✓
tight isolation	-	-	✓	SIP _{3D} < 4	✓	✓
				electron MVA loose	✓	✓
				electron MVA tight	-	✓
				tight isolation	-	✓

and optimized to achieve comparable selection efficiencies for prompt electrons and muons. Owing to the larger probability to misidentify electrons compared to muons, this results in more stringent requirements for electrons. The prompt lepton efficiency obtained with these requirements is better than 97% for leptons with $p_T > 25 \text{ GeV}$ and the probability for non-prompt leptons to pass the selection is less than 20% for both flavors. For muons (electrons) with $10 \text{ GeV} < p_T < 25 \text{ GeV}$, the signal efficiency drops to 80% (72%) and the background acceptance amounts to 15% (10%). Plots showing the selection efficiency for prompt leptons as a function of the nonprompt lepton acceptance can be found in Appendix B. With respect to a search for two leptons with the same charge [151], which utilizes the same isolation variables, the working points are chosen to be looser in order to compensate for the smaller signal efficiency of the multilepton final state arising from the additional leptonic branching factor. The slightly increased background acceptance is tolerable because of the inherently low SM background of the multilepton final state.

A summary of all lepton identification criteria for the different selections is given in Table 5.4 for muons and electrons. The difference between the loose and the tight selection is the more stringent isolation requirement described above and, in the case of electrons, stricter demands on the identification MVA. The motivation for the latter difference will be discussed in Section 7.1.1.

5.3.4 Lepton efficiency and efficiency scale factors

All variables employed in the lepton identification and isolation have been carefully validated in terms of agreement between data and simulation. Nevertheless, small reconstruction differences remain, which lead to disagreements when comparing data with simulation. In order to mitigate this effect, correction factors ξ are used to reweight simulated events. These scale factors are derived for each lepton flavor by measuring the reconstruction efficiencies separately in data and simulation, using the *tag-and-probe* technique in $Z \rightarrow \ell^+ \ell^-$ events [129, 162]. The scale factor is computed as the ratio of the two efficiencies

$$\xi(p_T, \eta) = \frac{\epsilon_{\text{data}(p_T, \eta)}}{\epsilon_{\text{sim}(p_T, \eta)}}. \quad (5.8)$$

An example showing the efficiency differences in data and simulation for the medium working point of the muon identification and the corresponding scale factors in the p_T - η plane is shown

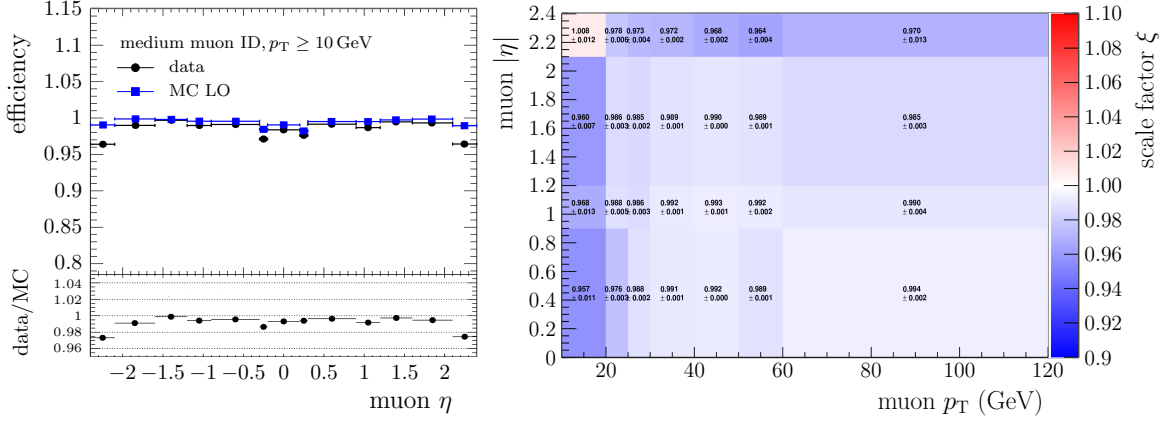


Figure 5.2: Lepton efficiency scale factors for the medium working point of the muon identification. A small correction factor compensates for differences between the selection efficiencies in data and simulation (a). This correction is parametrized as a function of p_T and η of the lepton (b).

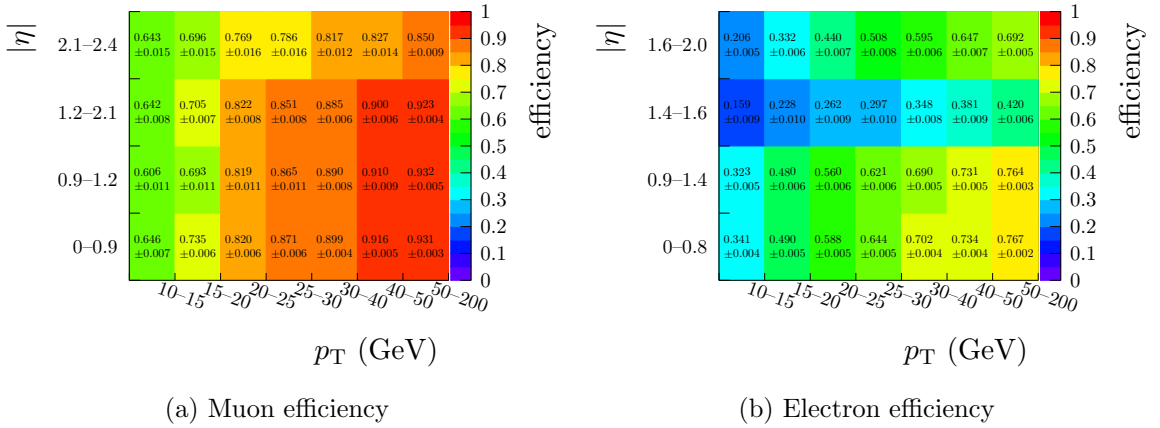


Figure 5.3: Total lepton selection efficiency as a function of lepton p_T and $|\eta|$, including all reconstruction, identification, and isolation requirements. The efficiency is measured for leptons from $W^\pm$ decays in simulated $t\bar{t}$ events and includes the efficiency scale factors [168].

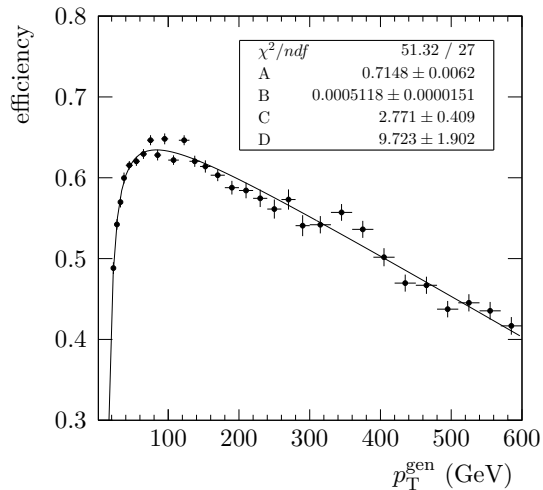
in Figure 5.2. The total scale factor is a product of the factorized scale factors for the lepton identification, the vertex requirements, and the isolation criteria. Its deviation from unity typically ranges from 2–10%, depending on p_T and η of the lepton.

Absolute lepton selection efficiencies have been measured for leptons from $W^\pm$ decays in simulated $t\bar{t}$ events as a function of lepton p_T and $|\eta|$. The efficiencies include all reconstruction, identification, and isolation requirements and have been corrected with the aforementioned scale factors to match the efficiency measured in data. Figure 5.3 shows the muon and electron efficiencies, which range from 64% to 93% and from 16% to 77%, respectively. The electron efficiency for $1.442 < |\eta| < 1.556$ is reduced, owing to a small gap between the barrel part and the endcap of the ECAL. The total selection efficiencies are not used as a input to the analysis itself but are an important quantity for re-interpretations of the results of this search in the context of additional BSM scenarios by other researchers.

5.4 Jets and missing transverse momentum

Events examined in the presented analysis need to contain jets arising from the hadronization of quarks or gluons produced in the proton-proton collisions or in subsequent decays. In order to be considered for the analysis, reconstructed jets need to fulfill a set of quality requirements

Figure 5.4: Tagging efficiency for b jets with the medium working point of the combined secondary vertex tagger as measured in simulated $t\bar{t}$ events. The efficiency has been corrected to match the efficiency observed in data and ranges from 40% to 65%, depending on the jet p_T at generator level. The line shows a fit function of the form $f(x) = A - Bx - (C/(x - D))$ [168].



that are described below. Jets that meet certain additional characteristics can be tagged as originating from the decay of b quarks and the analysis makes use of this distinction in order to optimize the sensitivity for SUSY models that produce b jets and such that are not expected to produce this signature (c.f. Section 4.1). Additionally, the hadronic activity H_T and the missing transverse momentum p_T^{miss} are defined in this section.

5.4.1 Jets

Individual particles identified by the PF algorithm are clustered into jets if they are likely to originate from hadronization of the same parton in the hard interaction or in subsequent decays. The clustering is performed with the anti- k_t algorithm [169] using a distance parameter of $R = 0.4$. The algorithm yields circular jets around high- p_T particles, whose shapes are resilient to nearby low- p_T particles originating, e.g., from pileup. The shapes of adjacent low- p_T jets, however, can have noncircular shapes if they overlap with the hard jet.

To reject noise and to avoid mismeasurements, PF jets considered for this analysis have to meet additional requirements. The amount of energy carried by neutral hadrons has to be smaller than 99% of the total energy of the jet. The same requirement also applies to the energy fraction deposited in the ECAL. Furthermore, selected jets are required to consist of more than one constituent, have to satisfy $p_T > 30 \text{ GeV}$, and must reside within $|\eta| < 2.4$. Double counting with leptons is avoided by discarding the jet closest to a muon or electron passing the loose selection if the distance between the jet and the lepton is smaller than $\Delta R = 0.4$. The number of jets in the event that pass this selection is denoted as N_{jets} .

In order to account for the contribution of pileup to the measured jet energy and to compensate for nonlinear detector responses, jet energy correction (JEC) [170, 171] are applied to relate the measured energy to the true energy deposit at particle level.

5.4.2 Jets originating from b quarks

The suppression of b quark decays by the CKM matrix (c.f. Section 2.1.1) leads to comparatively long lifetimes of $\mathcal{O}(10^{-12} \text{ s})$ for particles containing a b quark. This entails that the distance between the primary vertex and the point where such particles decay is usually long enough to be resolved with the CMS pixel detector. The resulting so-called *b jets* can therefore be discriminated against jets originating from light flavor quarks or gluons by detecting displaced secondary vertices. This allows to enhance the sensitivity of the search for signal models that are expected to produce this signature by categorizing events according to the number of identified b jets.

The identification of b jets is performed with the combined secondary vertex algorithm [172, 173], which evaluates reconstructed secondary vertices and particle lifetime information based on track measurements in an MVA. As shown in Figure 5.4, the working point of the algorithm chosen for this analysis has an efficiency between 40% and 65% to correctly tag a jet as b jet, while the mis-tag rate is less than 1%. Small differences between data and simulation concerning the reconstruction efficiency and the mis-tag rate are accounted for by reweighting simulated events with dedicated b-tagging scale factors.

The quality requirements listed in the previous section for jets also apply to b jets. The only difference is the additional criterion on the b-tagging discriminant and a relaxed p_T threshold of 25 GeV. The latter aspect further enhances the discrimination between topologies with or without b jets. The number of b jets that pass all quality requirements is denoted as N_b .

5.4.3 Hadronic activity

The so-called *hadronic activity* H_T is defined as the scalar sum of the transverse momenta of all jets and b jets that pass the quality requirements described above and satisfy $p_T > 30$ GeV

$$H_T = \sum_{(b) \text{ jets}} p_T. \quad (5.9)$$

This variable serves as an estimate of the amount of energy that is released in a decay cascade between the particles that are initially produced in the collision and the final state objects for a given event. As discussed in Section 2.3.3, such a variable can be used to discriminate compressed and uncompressed SUSY topologies. The presented analysis therefore utilizes H_T for event categorization to enhance the sensitivity of the search for signal scenarios with different mass splittings as described in Chapter 6.

5.4.4 Missing transverse momentum

Finally, the *missing transverse momentum* $\vec{p}_T^{\text{miss}}$ is defined as the negative vectorial sum of the momenta of all particles reconstructed with the PF algorithm

$$\vec{p}_T^{\text{miss}} = - \sum_{\text{PF particles}} \vec{p}_T. \quad (5.10)$$

This variable provides a measure of the imbalance of the transverse momentum in an event, which can arise either from jet mismeasurements and detector artifacts or from particles that escape the detector without interacting with its material. Genuine $\vec{p}_T^{\text{miss}}$ arises from SM processes involving neutrinos, but even larger contributions are expected for SUSY processes with a stable, neutral LSP. This renders $\vec{p}_T^{\text{miss}}$ the most important observable in searches for R-parity conserving SUSY models and motivates the need for nearly hermetic calorimeters. The first class of JECs that is used to subtract the pileup energy, is also propagated to the calculation of $\vec{p}_T^{\text{miss}}$ [174]. In the following, the absolute value of the missing transverse momentum will be denoted as p_T^{miss} .

6. Event Selection and Search Strategy

Any search for supersymmetric signatures faces the challenge that the mass hierarchy of the predicted sparticles and their experimental signature are inherently unknown. Different simplified SUSY models have been introduced in Section 4.1 and it has been shown that their topologies can widely differ, leading, e.g., to the presence or absence of b jets or on-shell Z bosons in the final state. Moreover, even for a given mass hierarchy and decay chain, additional unknown parameters describe the relative mass splitting between the sparticles involved in the decay cascade. This mass difference determines the amount of hadronic activity and missing transverse momentum to be expected in signal events. Rather than focusing on one specific signal model, the presented analysis follows an inclusive approach to achieve sensitivity for a wide range of BSM physics processes that produce three or more prompt leptons. To this end, a selection is applied to filter out events of interest from the huge amount of proton-proton collisions recorded by the CMS experiment. The expected number of background events as well as the expected signal yields for different signal topologies after applying the event selection are presented in Section 6.1. In order to further enhance the signal-to-background ratio for different models, selected events are categorized into different signal regions (SRs). The definition of the SRs is described in Section 6.2 and is based on four different event observables: the invariant mass of the opposite-sign, same-flavor (OSSF) dilepton system closest to the Z boson mass, the b jet multiplicity, the hadronic activity, and the missing transverse momentum. In these SRs, BSM physics processes, such as the SUSY signals presented in Chapter 4, would manifest themselves as notable excess of data over the SM background prediction.

All key features of the analysis, including the object selections, the SR definition, and the background estimation techniques have been defined prior to analyzing the data set of 12.9 fb^{-1} in order to avoid potential biases.

6.1 Baseline selection

The characterizing feature of this analysis is the requirement for three or more well-identified and isolated leptons that pass all quality requirements of the tight selection. As outlined in Chapter 4, this selection drastically reduces the background, restricting it to contributions from just a few irreducible SM processes and reducible background from nonprompt leptons. However, even better background rejection has to be achieved to probe potential SUSY processes that are typically characterized by very small cross sections — gluino pair production for example would have a cross section of 0.3 pb for a gluino mass of 1 TeV (c.f. Figure 2.7).

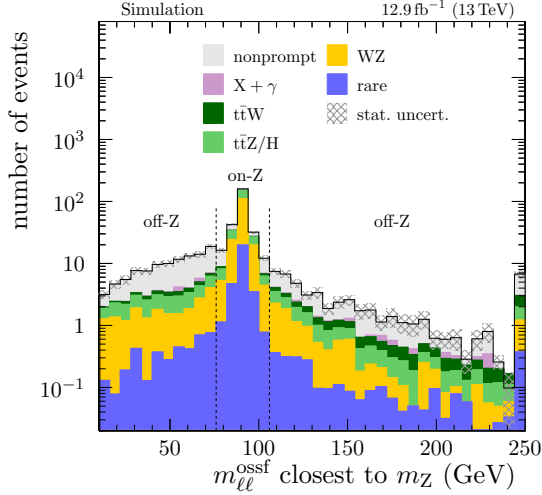


Figure 6.1: Invariant mass spectrum of two opposite-sign, same-flavor leptons in events that pass the baseline selection. If several pairs are found in the event, the mass closest to the mass of the Z boson is shown. Larger background contributions and the change of the relative importance of different background sources around the Z mass pole motivate the splitting of the baseline region into two exclusive regions, denoted as *on-Z* and *off-Z*.

Additionally, the number of signal events relevant for this search is reduced by the leptonic branching fractions of the vector bosons involved in the decay chain.

Events considered in the presented analysis therefore have to meet additional requirements, which are collectively referred to as *baseline selection*. The criteria aim at further rejecting SM background while maintaining a high signal efficiency. Besides the requirement on the lepton multiplicity ($N_{\text{lep}} \geq 3$) and the lepton p_T selection summarized in Table 5.1, the baseline selection comprises the following requirements. Any event containing an OSSF lepton pair with an invariant mass below 12 GeV is rejected to suppress background from quarkonium and low-mass Drell-Yan (DY) processes. Additional rejection of DY events with higher invariant mass is achieved by selecting only events with $p_T^{\text{miss}} > 50$ GeV, as such events do not involve genuine p_T^{miss} . The goal of the analysis to search for the production of colored SUSY particles is reflected by the requirement of having at least two jets in any selected event ($N_{\text{jets}} \geq 2$). Given the definition of H_T , this requirement is equivalent to $H_T > 60$ GeV. Selecting events with at least two jets also rejects a large portion of the WZ background, since no jets are produced in this process at leading order (LO).

Figure 6.1 shows the background composition as a function of the invariant mass $m_{\ell\ell}^{\text{ossf}}$ of two OSSF leptons after applying the baseline selection. If several such pairs are found in the event, the one whose invariant mass is closest to the mass of the Z boson $m_Z = 91.2$ GeV is considered. As can be seen, both the total amount of SM background and the relative importance of different background sources changes drastically around Z mass peak. While processes with on-shell Z bosons, like $t\bar{t}Z$ and WZ dominate around the Z mass peak, background from nonprompt leptons is the most important contribution elsewhere. In conjunction with the goal to maximize the sensitivity for signal processes without or with on-shell Z bosons, this motivates to split events passing the baseline selection into two exclusive regions according to $m_{\ell\ell}^{\text{ossf}}$. As depicted by the dashed lines in Figure 6.1, events with $|m_{\ell\ell}^{\text{ossf}} - m_Z| < 15$ GeV are categorized as *on-Z* events. All others, including those without any OSSF dilepton pair, are called *off-Z* events.

The effect of the separation in *on-Z* and *off-Z* events and the rejection power of the requirements of the baseline selection are shown in Tables 6.1 and 6.2 for different background processes. It can be seen that background from DY is efficiently suppressed by the requirements for $N_{\text{jets}} \geq 2$ and $p_T^{\text{miss}} > 50$ GeV. Additional rejection of DY events is achieved by increasing the minimum requirement for p_T^{miss} from 50 GeV to 70 GeV for *on-Z* events with small b jet multiplicities, low H_T , and low p_T^{miss} . This rejects about 90% of the remaining DY events that pass the nominal p_T^{miss} requirement and renders the contribution of this background source very small for both selections. The dominant background sources in the

Table 6.1: Evolution of the number of expected events for important background processes when subsequently applying requirements for the off-Z baseline selection. The number of events corresponds to an integrated luminosity of 12.9 fb^{-1} . The shown uncertainty reflects the statistical uncertainty arising from the finite number of simulated events.

Process	DY	$t\bar{t}$	WZ	$t\bar{t}Z/H$	$t\bar{t}W$
$N_{\text{lep}} \geq 3, p_T > 10 \text{ GeV}$	1121.3 ± 51.1	397.9 ± 8.7	1046.5 ± 5.7	154.8 ± 0.3	29.7 ± 0.1
$m_{\ell\ell} \geq 12 \text{ GeV}$	1121.3 ± 51.1	397.9 ± 8.7	1046.5 ± 5.7	154.8 ± 0.3	29.7 ± 0.1
lepton p_T selection	1109.4 ± 50.9	392.6 ± 8.7	1039.7 ± 5.7	154.5 ± 0.3	29.6 ± 0.1
Z / γ^* veto	96.4 ± 14.7	300.8 ± 7.6	136.4 ± 2.0	40.6 ± 0.2	24.3 ± 0.1
$N_{\text{jets}} \geq 2$	6.8 ± 3.9	171.0 ± 5.8	43.7 ± 1.2	36.8 ± 0.2	18.8 ± 0.1
$p_T^{\text{miss}} \geq 50 \text{ GeV}$	-	124.4 ± 4.9	26.6 ± 0.9	27.4 ± 0.2	15.2 ± 0.1

Table 6.2: Evolution of the number of expected events for important background processes when subsequently applying requirements for the on-Z baseline selection. The number of events corresponds to an integrated luminosity of 12.9 fb^{-1} . The shown uncertainty reflects the statistical uncertainty arising from the finite number of simulated events.

Process	DY	$t\bar{t}$	WZ	$t\bar{t}Z/H$	$t\bar{t}W$
$N_{\text{lep}} \geq 3, p_T > 10 \text{ GeV}$	1121.3 ± 51.1	397.9 ± 8.7	1046.5 ± 5.7	154.8 ± 0.3	29.7 ± 0.1
$m_{\ell\ell} \geq 12 \text{ GeV}$	1121.3 ± 51.1	397.9 ± 8.7	1046.5 ± 5.7	154.8 ± 0.3	29.7 ± 0.1
lepton p_T selection	1109.4 ± 50.9	392.6 ± 8.7	1039.7 ± 5.7	154.5 ± 0.3	29.6 ± 0.1
Z / γ^* selection	1013.1 ± 48.7	91.8 ± 4.2	903.3 ± 5.3	113.9 ± 0.3	5.3 ± 0.1
$N_{\text{jets}} \geq 2$	79.3 ± 13.5	53.8 ± 3.3	312.1 ± 3.1	105.5 ± 0.2	4.1 ± 0.1
$p_T^{\text{miss}} \geq 50 \text{ GeV}$	18.6 ± 6.1	37.9 ± 2.8	188.5 ± 2.4	72.5 ± 0.2	3.3 ± 0.0
$p_T^{\text{miss}} \geq 70 \text{ GeV SR1/5}$	3.0 ± 2.1	29.7 ± 2.5	135.2 ± 2.1	61.2 ± 0.2	2.9 ± 0.0

Table 6.3: Evolution of the number of expected signal events for two mass scenarios of the T1tttt (T5qqqqWZ) model when subsequently applying requirements for the off-Z (on-Z) baseline selection. The number of events corresponds to an integrated luminosity of 12.9 fb^{-1} . The shown uncertainty reflects the statistical uncertainty arising from the finite number of simulated events.

Signal model $m_{\tilde{g}}/m_{\tilde{\chi}_1^0} \text{ (GeV)}$	Off-Z		On-Z	
	T1tttt 1200/100	T1tttt 1200/700	T5qqqqWZ 1000/100	T5qqqqWZ 800/500
$N_{\text{lep}} \geq 3, p_T > 10 \text{ GeV}$	18.6 ± 0.6	17.9 ± 0.6	16.8 ± 0.8	58.1 ± 3.0
$m_{\ell\ell} \geq 12 \text{ GeV}$	18.6 ± 0.6	17.9 ± 0.6	16.8 ± 0.8	58.1 ± 3.0
lepton p_T selection	18.6 ± 0.6	17.9 ± 0.6	16.8 ± 0.8	58.1 ± 3.0
Z / γ^* veto (selection)	15.6 ± 0.5	14.4 ± 0.5	15.0 ± 0.7	54.3 ± 2.9
$N_{\text{jets}} \geq 2$	15.6 ± 0.5	14.3 ± 0.5	15.0 ± 0.7	53.0 ± 2.9
$p_T^{\text{miss}} \geq 50 \text{ GeV}$	15.3 ± 0.5	13.8 ± 0.5	14.7 ± 0.7	51.5 ± 2.8
$p_T^{\text{miss}} \geq 70 \text{ GeV SR1/5}$			14.7 ± 0.7	50.5 ± 2.8

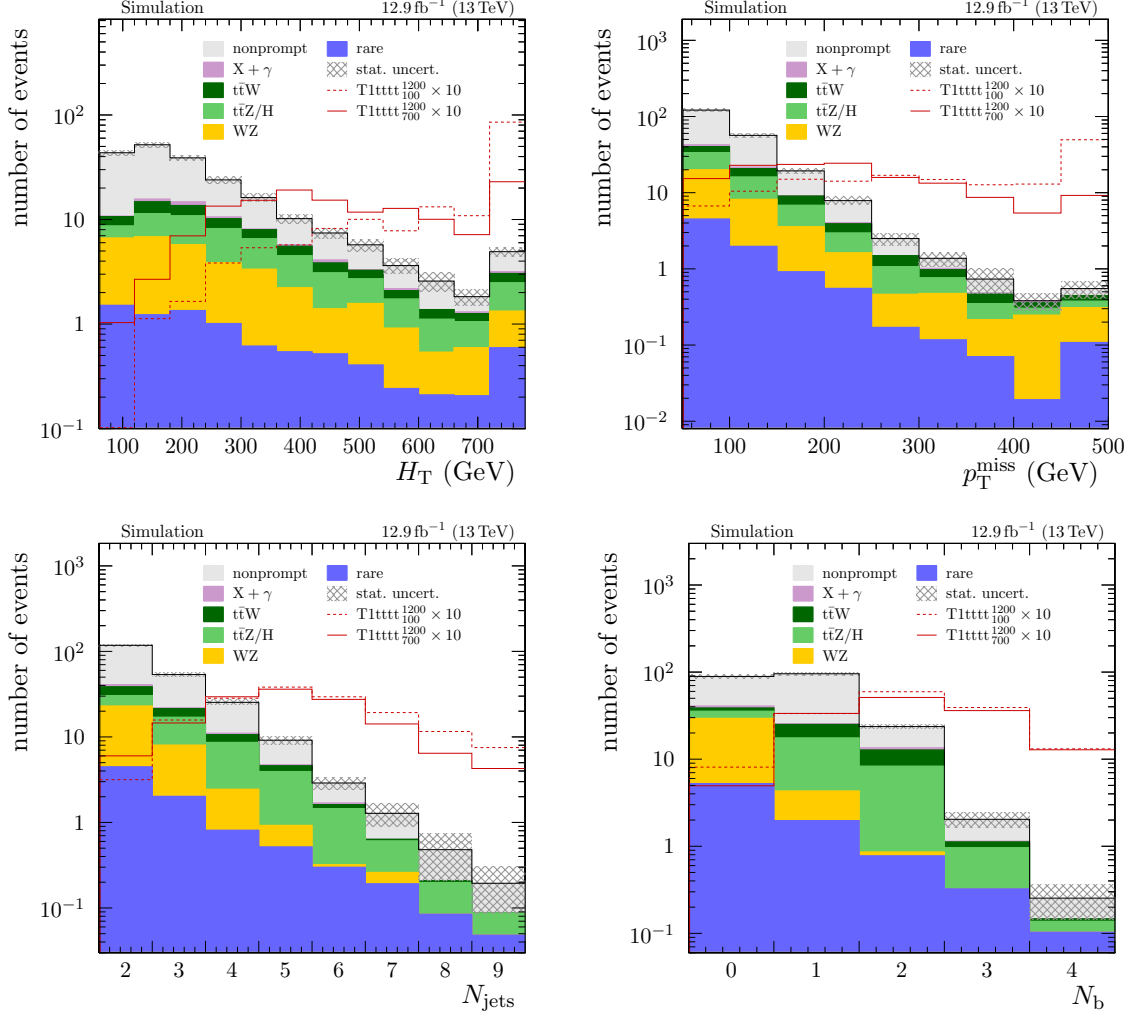


Figure 6.2: Hadronic activity (top left), missing transverse momentum (top right), jet multiplicity (bottom left), and b jet multiplicity (bottom right) for simulated events passing the off-Z baseline selection, corresponding to an integrated luminosity of 12.9 fb^{-1} . The dominant background contribution for this selection arises from nonprompt leptons. Two mass scenarios of the T1tttt simplified model are overlaid for comparison with their cross section scaled up by a factor of ten for better visibility. Super and subscript after the model name in the legend indicate the gluino and the LSP mass in GeV, respectively.

off-Z and on-Z region are reducible background from $t\bar{t}$ and irreducible background from WZ, respectively. About 60% of the nonprompt lepton background is rejected by the combined p_T^{miss} and N_{jets} requirements. The background contribution from WZ events is even reduced by 85%. On the other hand, less than 50% of the $t\bar{t}V$ background is suppressed, owing to the presence of harder jets and larger amounts of genuine p_T^{miss} in these processes.

In order to estimate the signal selection efficiency and to assess the sensitivity of the analysis, different mass splitting scenarios of the T1tttt and the T5qqqqWZ topologies have been simulated as benchmark models. For each model, one uncompressed and one more compressed spectrum is considered. In the case of T1tttt, both scenarios feature a gluino mass of 1 200 GeV, while the LSP mass is set to 100 GeV and 700 GeV, respectively. For the T5qqqqWZ model, the uncompressed spectrum features $m_{\tilde{g}} = 1\,000$ GeV and $m_{\tilde{\chi}_1^0} = 100$ GeV, while a slightly lighter gluino mass of 800 GeV is probed with the compressed spectrum, assuming an LSP mass of 500 GeV. The mass of the intermediate chargino and neutralino is set to the average of the two other masses $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} = 0.5 \cdot (m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$. Table 6.3 shows that a large fraction of the simulated signal events pass the baseline selection. The selection efficiency for events with at least three leptons is larger than 80% for the two different mass scenarios of the T1tttt model and larger than 85% for the two scenarios of the T5qqqqWZ model. It can also be seen that the exacerbated p_T^{miss} requirement for on-Z events with small b jet multiplicities, low H_T , and low p_T^{miss} does not impair the signal efficiency notably.

Figures 6.2 and 6.3 show the distribution of important event observables — hadronic activity, missing transverse momentum, and the jet and b jet multiplicities — for simulated background processes for the off-Z and on-Z regions after applying the baseline selection. The number of events are normalized to $\mathcal{L}_{\text{int}} = 12.9 \text{ fb}^{-1}$ and the hatched bands show the statistical uncertainty arising from the finite number of simulated events. The benchmark signal models introduced above are overlaid for comparison, with their cross sections scaled by a factor of ten for better visibility. For the off-Z selection, Figure 6.2 shows that the dominant background arises from nonprompt leptons and that the shapes of the distributions are distinctively different for the SM background processes compared to the T1tttt signal model. The latter exhibits significantly larger jet and b jet multiplicities as well as larger p_T^{miss} and H_T values. Additionally, it can be observed that the uncompressed spectrum produces events with larger values of p_T^{miss} and H_T owing to the larger amount of energy available in the decay chain. A similar behavior can be observed in Figure 6.3, where the SM background is compared to the two benchmark scenarios of the T5qqqqWZ model in the on-Z baseline region. Depending on the mass splitting between gluino and LSP, different shapes of H_T and p_T^{miss} are expected, which would lead to different levels of excess of data over the background prediction in the tails of these distributions. Owing to the production of light quarks in the T5qqqqWZ model, the distribution of the b jet multiplicity does not show a distinctively different shape for signal and background for this model.

6.2 Signal regions

The different shapes in the distributions of the aforementioned event observables for background and signal processes can be exploited to improve the sensitivity of the search. This can be achieved by categorizing events that pass the baseline selection into different exclusive SRs to enhance the signal-to-background ratio for specific signal topologies. The SRs are defined for off-Z and on-Z events separately by a set of boundary conditions on the event observables H_T , p_T^{miss} , and N_b . The categorization in N_b maximizes the sensitivity for signal models that yield multiple top quarks such as the T1tttt model. Such models populate SRs with large b jet multiplicities while important background processes, e.g., WZ and nonprompt lepton background are mainly contained in SRs requiring no or only one b jet. Nevertheless, also background dominated SRs with low b jet multiplicities are considered. Firstly, they are

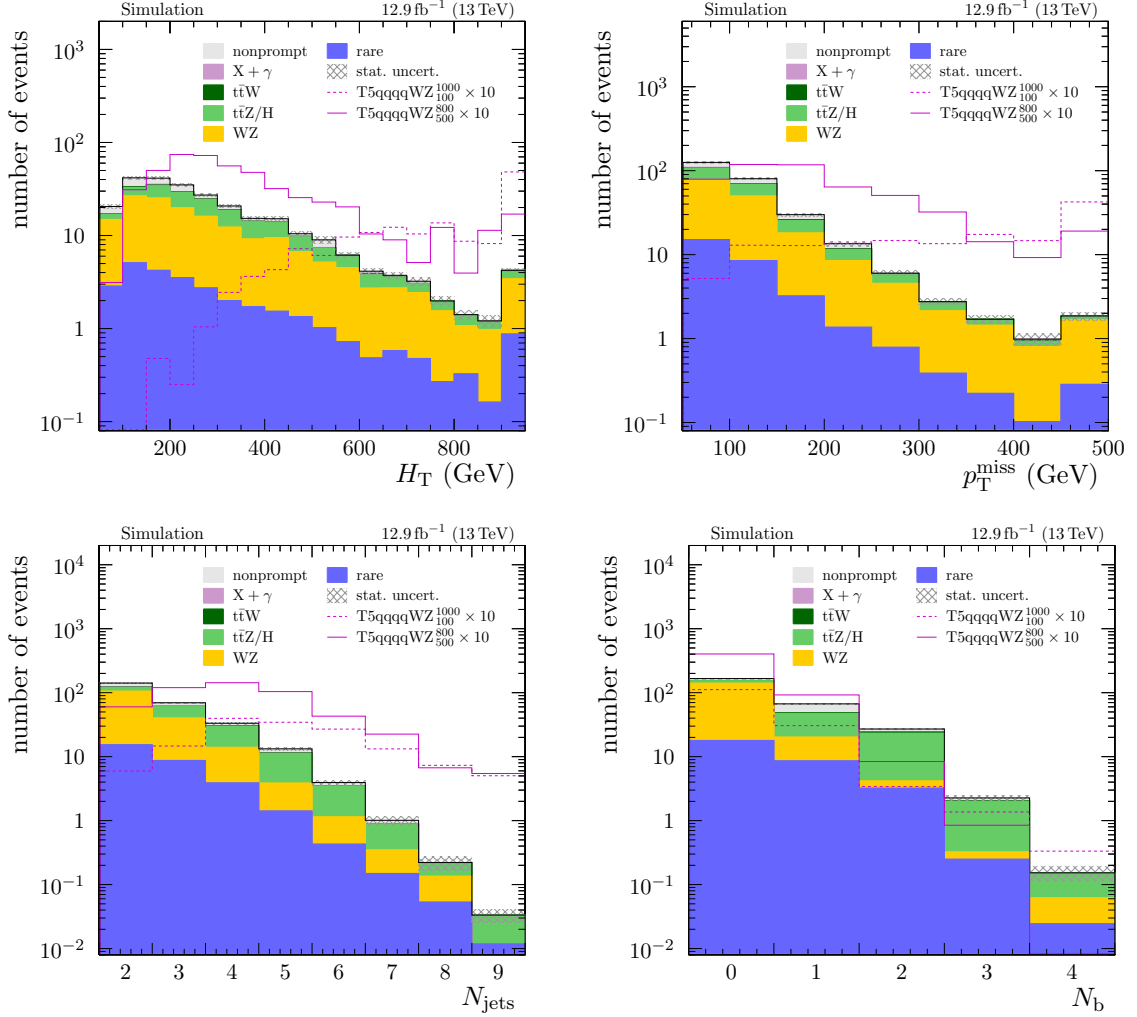


Figure 6.3: Hadronic activity (top left), missing transverse momentum (top right), jet multiplicity (bottom left), and b jet multiplicity (bottom right) for simulated events passing the on-Z baseline selection, corresponding to an integrated luminosity of 12.9fb^{-1} . The dominant background for this selection arises from WZ+jets, while the contribution from nonprompt leptons is small. Two mass scenarios of the T5qqqqWZ simplified model are overlaid for comparison with their cross section scaled up by a factor of ten for better visibility. Super and subscript after the model name in the legend indicate the gluino and the LSP mass in GeV, respectively. The chargino mass is fixed to the average of these masses.

Table 6.4: Definition of the 15 off-Z and the 17 on-Z SRs. The categorization is based on hadronic activity H_T , missing transverse momentum p_T^{miss} , and the number of b jets N_b in the event. The splitting of SRs 14 and 15, indicated by the dashed lines applies to the on-Z selection only. SR 14a requires $50 \text{ GeV} < p_T^{\text{miss}} < 150 \text{ GeV}$ and SR 14b $150 \text{ GeV} < p_T^{\text{miss}} < 300 \text{ GeV}$. The asterisk marks the increased p_T^{miss} requirements in on-Z SRs 1 and 5.

N_{jets}	N_{b}	$p_{\text{T}}^{\text{miss}}$ (GeV)	$60 \text{ GeV} \leq H_{\text{T}} < 400 \text{ GeV}$	$400 \text{ GeV} \leq H_{\text{T}} < 600 \text{ GeV}$	$H_{\text{T}} \geq 600 \text{ GeV}$	
≥ 2	0	$50(70^*) - 150$	SR 1	SR 3	SR 14a	SR 14b
		$150 - 300$	SR 2	SR 4		
	1	$50(70^*) - 150$	SR 5	SR 7		
		$150 - 300$	SR 6	SR 8		
	2	$50 - 150$	SR 9	SR 11		
		$150 - 300$	SR 10	SR 12		
	≥ 3	$50 - 300$	SR 13			
	inclusive	≥ 300	SR 15a			

used to constrain the background prediction in the statistical interpretation of the results as will be discussed in Chapter 10. Secondly, such SRs allow to probe signal models that do not produce top quarks like the T5qqqqWZ model. The sensitivity for this topology, which predominantly populates on-Z SRs, profits from the fact that the contribution from nonprompt lepton background is mainly contained in the off-Z regions.

Additional event categorization according to the observed missing transverse momentum and the hadronic activity allows to further enhance the signal-to-background ratio as more stringent requirements on these variables increasingly suppress SM background, especially contributions from processes with nonprompt leptons. Moreover, such a categorization separates compressed and uncompressed signal models as outlined above.

Events passing the off-Z baseline selection are grouped into 15 exclusive SRs. Each four regions are defined for events with zero, one, and two b jets, depending on the amount of H_T and p_T^{miss} as summarized in Table 6.4. For events with three or more b jets, an inclusive SR has been defined to account for the lower expected background contribution in this category. Additionally, a high- H_T region with $H_T > 600 \text{ GeV}$ and $50 \text{ GeV} < p_T^{\text{miss}} \leq 300 \text{ GeV}$, which is inclusive in N_b , features very low SM background contributions and targets uncompressed signal models. Any event with $p_T^{\text{miss}} > 300 \text{ GeV}$ is categorized in SR 15, another SR with very low SM background that provides good sensitivity for signal models with high- p_T LSPs. The SR boundaries have been optimized to separate different background sources and to maximize to sensitivity for the T1tttt and T5qqqqWZ benchmark models. The latter aspect has been addressed by calculating expected exclusion limits (c.f. Section 10.1) for various SR configurations. Additional SR categorization in N_{jets} has been omitted to reduce the overall number of SRs and because the impact on the expected limits was found to be small, owing to the strong correlation between this observable and H_T . An additional benefit of this choice is that the analysis is not sensitive to the inability of certain event generators to simulate a sufficiently large number of partons to correctly model very large jet multiplicities.

For the on-Z selection, the SRs are defined similarly, however with two distinct differences. The first difference with respect to the off-Z regions is the raised minimum p_T^{miss} requirement in SRs 1 and 5, while the second one affects the high- H_T and high- p_T^{miss} SRs. Because of the larger number of expected background events in these regions compared to their counter-

parts in the off-Z search, they can be split in each two subcategories to further enhance the sensitivity, while still respecting the requirement of having $\mathcal{O}(1)$ expected background event per SR for $\mathcal{L}_{\text{int}} \approx 10 \text{ fb}^{-1}$. The latter requirement reduces the susceptibility of the analysis to statistical fluctuations. The two subcategories of the high- H_T region are denoted as SRs 14a and 14b and separate events with $p_T^{\text{miss}} < 150 \text{ GeV}$ from events with $p_T^{\text{miss}} \geq 150 \text{ GeV}$. Similarly, SRs 15a and 15b contain high- p_T^{miss} events with $H_T < 600 \text{ GeV}$ and $H_T \geq 600 \text{ GeV}$, respectively. The separation improves the sensitivity of the search for the T5qqqqWZ model with respect to a SR definition without the splitting in terms of expected exclusion limits by up to 14%, depending on the mass splitting.

Figure 6.4 shows the expected number of SM background events in the 15 off-Z and in the 17 on-Z SRs for an integrated luminosity of 12.9 fb^{-1} , based on MC simulations. Additionally, the expected number of signal events are shown for the benchmark models, with their cross sections scaled by a factor of ten for better visibility. The signal-to-background ratios in the individual bins suggests that the largest sensitivity for the T1tttt model can be expected from the off-Z SR 13 with large b jet multiplicities and from the high- p_T^{miss} region (SR 15). For the uncompressed scenario of the T5qqqqWZ model, the best discrimination between signal and background is provided by SRs 14b and 15b, containing events with large H_T and large p_T^{miss} , whereas the compressed signal also shows a significant contribution in on-Z SR 2 ($N_b = 0$, small H_T , medium p_T^{miss}).

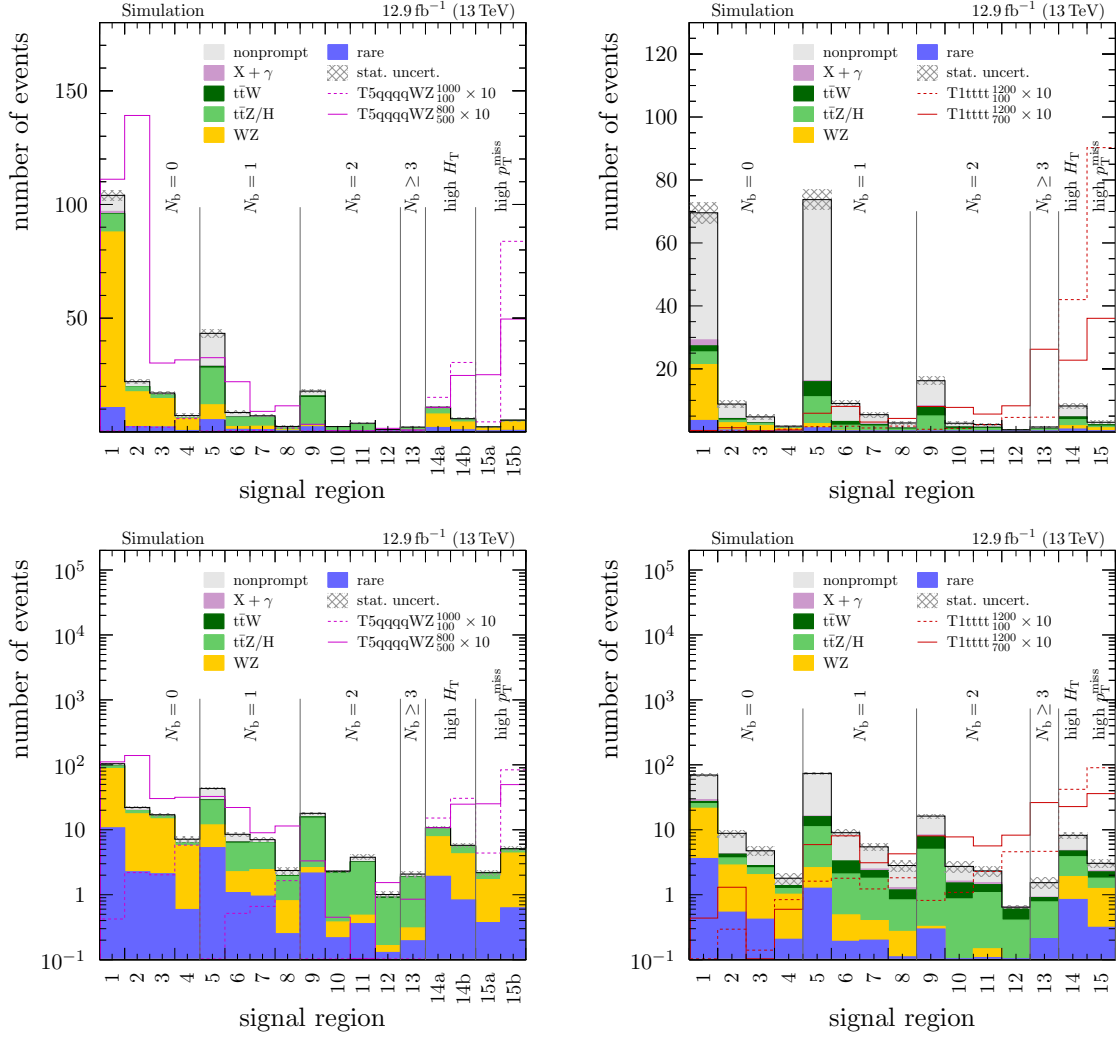


Figure 6.4: Simulated background contribution in the on-Z (left) and off-Z (right) signal regions. The number of expected SM background events are shown for an integrated luminosity of 12.9 fb^{-1} using a linear (top) and a logarithmic y axis scale (bottom). Each two mass scenarios for T1tttt and the T5qqqqWZ simplified model topologies are overlaid with their cross sections scaled by a factor of ten for better visibility. Superscript and subscript after the model name in the legend indicate the gluino and the LSP mass in GeV respectively. For T5qqqqWZ, the chargino mass is fixed to the average of these masses.

7. Background Estimation

The analysis strategy outlined in the previous chapter relies on comparing data with known SM processes that enter the baseline selection as background. This allows to identify potential BSM physics processes as a significant excess of the data over the background prediction in some of the SRs. Therefore, a robust and precise estimation of the different background sources is essential to obtain a reliable and unbiased result. This Chapter describes the methods used for estimating SM background contributions and their validation in data and simulation.

Section 7.1 describes SM processes that produce less than three prompt leptons that can enter the selection if at least one nonprompt lepton passes all identification and isolation requirements. Subsequently, a data-driven technique is presented that is used to estimate this background contribution, based on the number of events in which at least one of the leptons satisfies a looser selection but fails the full set of requirements. The method is validated in simulation and in a control region in data for a selection of events that is not overlapping with the SRs.

Background from WZ diboson production is the dominant background contribution in various on-Z SRs, especially in those with low b jet multiplicities. Section 7.2 presents how this background source is estimated using MC simulation and a WZ enriched control region in data in which the overall normalization of the simulation is validated.

Finally, Section 7.3 summarizes other irreducible SM background sources, which are estimated using simulation. The most important contribution amongst these background sources arises from $t\bar{t}W$ and $t\bar{t}Z/H$ production. For these processes, simulations based on LO and NLO theory predictions are compared with each other and the statistical precision of the available simulations is presented.

7.1 Nonprompt lepton background

The term *nonprompt lepton background* collectively describes all SM processes that do not produce three or more prompt leptons, which, however, can enter the baseline selection if at least one of the nonprompt or misidentified leptons passes all identification and isolation requirements of the tight selection (c.f. Section 5.3). In the context of this analysis, the main source of this background is the production of $t\bar{t}$ in association with jets. In such events, two prompt leptons can originate from leptonic decays of the $W^\pm$ bosons that are produced in the top quark decays while p_T^{miss} arises from the escaping neutrinos. Such events can enter

the baseline selection if a nonprompt lepton, usually a muon contained in one of the b jets, passes the lepton isolation requirements. Even though these isolation requirements suppress the vast majority of the $t\bar{t}$ background, the remainder is large enough to constitute the main source of background in several off-Z SRs. Especially SRs with low or medium H_T and p_T^{miss} and small b jet multiplicities receive significant contributions. In a similar way, DY events with two prompt leptons can enter the selection. Though, the absence of genuine p_T^{miss} in this process allows for an efficient rejection by the baseline requirement $p_T^{\text{miss}} > 50$ GeV. The stricter requirement of 70 GeV for on-Z SRs 1 and 5 additionally improves the rejection of DY events. As a result, the contribution from this background source are extremely small in both selections as shown in Tables 6.1 and 6.2. Other sources of nonprompt lepton background are various single top quark production channels and the production of $W^\pm + \text{jets}$. However, the presence of only one prompt lepton in these processes renders their contribution to a multilepton selection negligible, owing to the small probability that two nonprompt leptons pass the isolation requirements.

7.1.1 Tight-to-loose method

The amount of nonprompt lepton background depends on the probability for a nonprompt lepton to pass the tight selection, a parameter that in turn depends on the performance of the detector and the reconstruction algorithms. Simulating this source of background is therefore complex and less reliable than the simulation of processes involving theoretically well-understood vector bosons. Consequently, an estimation technique that is independent of MC simulations is employed to predict the contribution from nonprompt lepton background. This technique is referred to as *tight-to-loose method* and described in detail below.

Since a discrimination of prompt and nonprompt leptons that pass the tight selection is inherently impossible, the method predicts the contribution of nonprompt lepton background in a given SR by weighting the number of events measured in an orthogonal sideband region with a transfer factor x_{TF} . This region is called *application region*. It is populated by events for which the sum of all leptons that pass the tight selection ($N_{\text{lep}}^{\text{tight}}$) plus the number of leptons that pass the loose selection but fail the tight selection, so-called *loose-not-tight (LNT) leptons* ($N_{\text{lep}}^{\text{LNT}}$), is three or greater. Orthogonality to the corresponding SR is guaranteed by requiring that the number of leptons that pass the tight selection is smaller than three

$$\left(N_{\text{lep}}^{\text{tight}} + N_{\text{lep}}^{\text{LNT}} \geq 3\right) \quad \wedge \quad \left(N_{\text{lep}}^{\text{tight}} < 3\right). \quad (7.1)$$

All other criteria, such as the lepton p_T thresholds and the bounds on p_T^{miss} , H_T , or N_b are identical in the SR and the corresponding application region.

The transfer factor x_{TF} , which is used to weight the number of events in the application region, is a function of the *misidentification rate* f . The latter quantity is defined as the probability of a nonprompt lepton that passes the loose selection to also pass the tight selection. It is measured in a data control region that does not overlap with neither the signal regions nor the application regions of the analysis and that is enriched with processes yielding nonprompt leptons.

As will be demonstrated in the following, the logic behind this method can be regarded as a rotation of the physical prompt–nonprompt lepton space into the space of leptons that pass the tight or the loose selection respectively, the latter of which is accessible to measurement.

Transfer factors

The transfer factors x_{TF} used to weight the number of event measured in the application regions can be derived for the three lepton final state as follows*. Let the subscripts ‘t’ and ‘l’ denote leptons that pass the tight selection and LNT leptons, respectively. Furthermore, subscripts ‘p’ and ‘n’ denote prompt and nonprompt leptons. The goal of the method is to predict the number of events with three leptons passing the tight selection N_{ttt} (signal region), based on the number of events where one, two, or all three of them pass the loose but fail the tight selection N_{ttl} , N_{tll} , and N_{lll} (application region). Given the probability $f_i > 0$ that nonprompt lepton i passes the tight selection and given the efficiency $\epsilon_i < 1$ for prompt lepton i to pass the tight selection, both the signal region and the application region receive contributions from events containing $i = 0, \dots, 3$ prompt leptons denoted as N_i . Using the efficiency ϵ and the misidentification rate f , the number of events that contain i leptons that pass the tight selection and $3 - i$ LNT leptons can be expressed as a function of N_i

$$\begin{pmatrix} N_{\text{ttt}} \\ N_{\text{ttl}} \\ N_{\text{tll}} \\ N_{\text{lll}} \end{pmatrix} = \begin{pmatrix} \epsilon\epsilon\epsilon & \epsilon\epsilon f & \epsilon f f & f f f \\ 0 & \epsilon\epsilon(1-f) & \epsilon f(1-f) & f f(1-f) \\ 0 & 0 & \epsilon(1-f)(1-f) & f(1-f)(1-f) \\ 0 & 0 & 0 & (1-f)(1-f)(1-f) \end{pmatrix} \begin{pmatrix} N_3 \\ N_2 \\ N_1 \\ N_0 \end{pmatrix}. \quad (7.2)$$

The notation employs shorthands for the different permutations of prompt and nonprompt leptons, e.g., $\epsilon f f N_1$ stands for $\epsilon_1 f_2 f_3 N_{\text{pnn}} + f_1 \epsilon_2 f_3 N_{\text{npn}} + f_1 f_2 \epsilon_3 N_{\text{nnp}}$. The matrix elements below the diagonal are approximated as zero, as their full expression contains different powers of the factor $(1 - \epsilon)$, which is small because of the high probability for a prompt lepton to pass the tight selection. By solving the resulting set of linear equations, the unknown variables N_i in the expression of N_{ttt} can be expressed with the observables N_{ttl} , N_{tll} , and N_{lll} , which are experimentally accessible in the application region. By introducing $F_i = f_i/(1 - f_i)$, the number of events with three leptons passing the tight selection N_{ttt} can be written as

$$N_{\text{ttt}} = F_1 N_{\text{ltt}} + F_2 N_{\text{tlt}} + F_3 N_{\text{ttl}} - F_1 F_2 N_{\text{llt}} - F_1 F_3 N_{\text{ltl}} - F_2 F_3 N_{\text{tll}} + F_1 F_2 F_3 N_{\text{lll}}, \quad (7.3)$$

which means that every event in the application region with two leptons that pass the tight selection is weighted with a factor $f_i/(1 - f_i)$, where f_i is the misidentification rate of the lepton that fails the tight selection. Similarly, events with only one lepton that passes the tight selection are weighted with the negative factor $-(f_i f_j)/[(1 - f_i)(1 - f_j)]$ calculated with the misidentification rates of the leptons that fail the tight selection. Finally, events without any lepton that passes the tight selection enter the prediction with a weight of $F_i F_j F_k$. Figure 7.1 illustrates the relative importance of these three cases by showing the number of events in the application region corresponding to the baseline selection as a function of the number of LNT leptons in the event. It can be seen that the relative abundance of such events drops by about an order of magnitude for each additional LNT lepton, rendering contributions from events with less than two leptons that pass the tight selection small.

Events entering the application region may contain three or more leptons. In the case of three leptons the transfer factor is directly given by the above expressions and depends on the number of leptons passing the tight selection in the event. For events with more than three leptons, all possible three-lepton combinations are considered. Transfer factors are calculated for all combinations of leptons satisfying the p_{T} selection requirements (c.f. Table 5.1) and are summed to obtain the event weight w

*The generalization to the four lepton final state has been omitted as SRs are not binned in lepton multiplicity and because the fraction of events with four lepton among all selected events is below 2%.

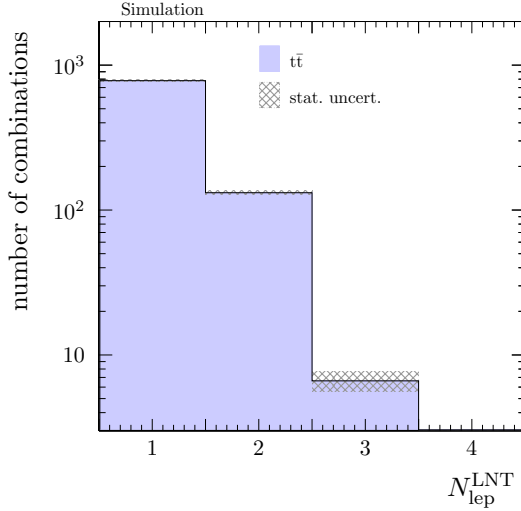


Figure 7.1: Multiplicity of leptons in the application region that pass the loose selection criteria but fail the tight selection. Shown are all combinations that satisfy the p_T selection criteria for simulated $t\bar{t}$ events. The main contribution to the nonprompt lepton background estimation arises from events with only one LNT lepton and two leptons that pass the tight selection.

$$w = w_{\text{before}} \cdot \sum_{\text{comb.}} x_{\text{TF}}. \quad (7.4)$$

While the lepton p_T selection is evaluated for each individual combination of three leptons, the invariant mass veto $m_{\ell\ell}^{\text{ossf}} > 12 \text{ GeV}$ and the on-Z or off-Z categorization is evaluated at event level, taking into account all leptons.

Measurement of the misidentification rate

The misidentification rate f is a key ingredient of the tight-to-loose method. As it strongly depends on the flavor and on the kinematic properties of the lepton, it has to be determined as a function of the lepton p_T and $|\eta|$ for both regarded lepton flavors individually. The measurement of the misidentification rate is performed in the so-called *measurement region*, defined by a selection that targets QCD multijet events to obtain a sample that is enriched with nonprompt leptons. Suitable events are preselected by a set of auxiliary single lepton triggers that are listed in Appendix A. The offline selection of events entering the denominator of the misidentification rate calculation requires exactly one lepton that passes the loose selection. Electroweak processes involving $W^\pm$ and Z bosons are suppressed by additionally requiring one recoiling jet with $\Delta R(\ell, \text{jet}) > 1.0$, $p_T^{\text{jet}} > 30 \text{ GeV}$, and $p_T^{\text{miss}} < 20 \text{ GeV}$. Furthermore, the transverse mass M_T , defined as

$$M_T = \sqrt{2 p_T(\ell) p_T^{\text{miss}} (1 - \cos \Delta\phi)}, \quad (7.5)$$

with $\Delta\phi$ being the difference in azimuth of the lepton and $\vec{p}_T^{\text{miss}}$, is required to be smaller than 20 GeV . Remaining contamination from electroweak processes is subtracted using estimates from simulation. The normalization of the simulation used for this subtraction is corrected by applying electroweak scale factors, which are derived from a data-MC comparison in a further control region that is orthogonal to the measurement region and enriched with electroweak processes. The control region is defined by $p_T^{\text{miss}} > 30 \text{ GeV}$ and $70 \text{ GeV} < M_T < 120 \text{ GeV}$, while the other criteria of the measurement region remain unchanged. Scale factors of 0.96 ± 0.04 for muons and 1.36 ± 0.36 for electrons have been obtained with 12.9 fb^{-1} of data in this region and are used to correct the simulated electroweak processes in the measurement region. While the statistical uncertainty on the scale factors is found to be negligible, the systematic uncertainty is conservatively estimated as their deviation from unity.

The tight-to-loose method relies on the universality of the misidentification rate, i.e., it assumes that the nonprompt leptons in the measurement region exhibit the same misidentification rates as the those in the application regions. Two main obstacles impair this universality and have led to an uncertainty of 50% on the prediction of nonprompt lepton background in past analyses that employed this method [154, 155]. The first restriction arises from the dependence of the misidentification rate on the p_T of the nonprompt lepton's parent parton and the fact that the p_T distributions of the parent partons are not necessarily identical in the measurement region and in the application region. A second difficulty stems from the dependence of the misidentification rate on the flavor of the jet the nonprompt lepton originates from. New methods have been developed during LS 1 of the LHC to address these problems and are employed in this analysis [175]. The dependence of the misidentification rate on the parent parton p_T is mitigated by modifying the lepton p_T for LNT leptons depending on the energy in their isolation cone. For leptons that pass the requirement $p_T^{\text{rel}} > p_T^{\text{rel, cut}}$ the transformation is given by

$$p_T \rightarrow p_T \cdot \left(1 + \max\left(0, I_{\text{mini}} - I_{\text{mini}}^{\text{cut}}\right)\right), \quad (7.6)$$

while the p_T of leptons for which the above requirement does not hold is transformed as

$$p_T \rightarrow \max\left(p_T, p_T^{\text{jet}} \cdot p_T^{\text{ratio, cut}}\right), \quad (7.7)$$

with the lepton isolation criteria as defined in Table 5.3. The transformed p_T , also referred to as *cone-corrected* p_T , serves to approximate the parent parton p_T . Parameterizing the misidentification rate as a function of this quantity instead of the regular lepton p_T , considerably improves the uniformity of the misidentification rate in the measurement region and the application region. Note that the transformation only modifies the p_T of LNT leptons and does not affect leptons in events that enter the SRs.

The cone-corrected p_T is also used to calculate the invariant mass of OSSF lepton pairs that enter the application region in order to decide whether they enter the off-Z or the on-Z selection. Moreover, the cone-corrected p_T is also employed for calculating the transverse mass M_T , used to define the application region corresponding to the WZ control region (c.f. Section 7.2) and for the definition of the measurement region and the electroweak control region described above. Contrariwise, the regular lepton p_T is employed to calculate the invariant mass used to veto events in the application region with $m_{\ell\ell}^{\text{osf}} < 12 \text{ GeV}$. This difference is motivated as follows. The low invariant mass veto aims at rejecting narrow low mass resonances, which need to be reconstructed using the best estimate of the physical lepton p_T . At larger invariant masses, as relevant for the on-Z and off-Z discrimination, the larger contribution from $t\bar{t}$ background and the necessity to correctly predict this background with the tight-to-loose method requires to use the cone-corrected p_T to improve the precision of the prediction.

The second advancement of the tight-to-loose method aims at reducing the nonuniformity of the electron misidentification rate that arises from different jet flavor compositions in the application region and the measurement region. This difference can be accounted for by matching the electron misidentification rates for jets originating from b quarks and jets that stem from the hadronization of lighter quarks and gluons. This can be achieved by relaxing the working point of the MVA discriminant used for electron identification in the loose selection (c.f. electron selection in Table 5.4). A similar matching of the misidentification rates is not needed in the case of muons since nonprompt leptons of this flavor almost exclusively originate from b jets.

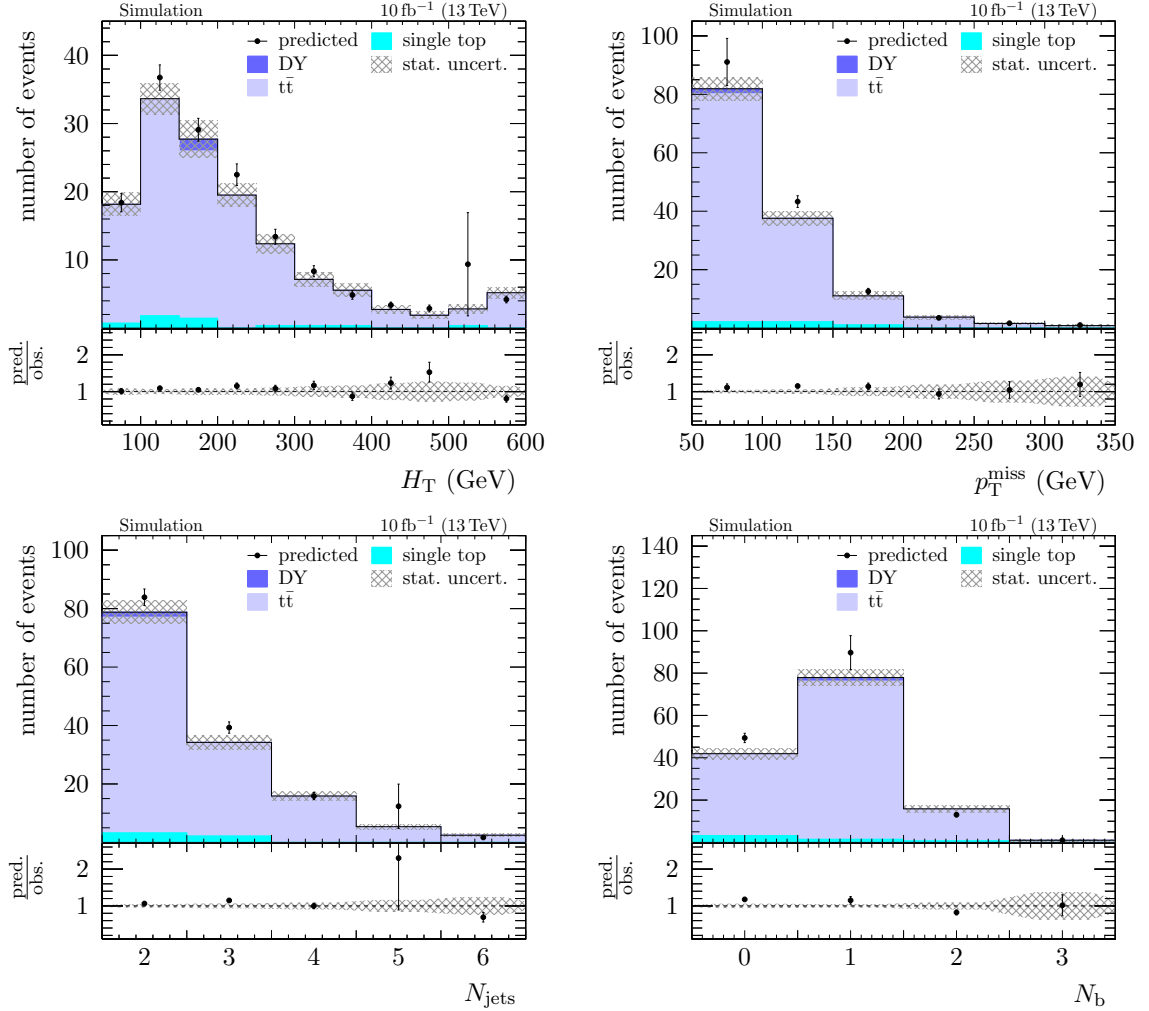


Figure 7.2: MC closure test of the nonprompt lepton background estimation method in the off-Z baseline selection. The number of events measured in the SR (solid histogram) is compared to the predicted number of events (point markers). Shown is the closure with a mixture of simulated $t\bar{t}$, DY, and single top production processes for the main event observables H_T , p_T^{miss} , N_{jets} , and N_b (top left to bottom right). The hatched bands indicate the statistical uncertainty.

Misidentification rates used for the prediction of nonprompt lepton background in this analysis have been measured with the full data set of 12.9fb^{-1} of proton-proton collisions, parameterized as a function of the cone-corrected lepton p_T , η , and the lepton flavor. For muons with $p_T > 15\text{ GeV}$, misidentification rates in the range of 4–15% have been measured for the loose and tight selections defined in Section 5.3. For low- p_T muons with $10\text{ GeV} < p_T < 15\text{ GeV}$ the misidentification rate increases significantly to about 55%. For electrons, the misidentification rates for $p_T > 15\text{ GeV}$ are similar to those measured for muons, ranging from 6% to 20%. Low- p_T electrons, however, exhibit a smaller misidentification rate compared to low- p_T muons of only up to 25%.

7.1.2 Validation with simulation

The nonprompt lepton background estimation method is validated using simulated events in a so-called *closure test*. The closure test assesses the capability of the tight-to-loose method to correctly predict the nonprompt lepton background. This is done by comparing the number of events directly observed in the baseline region or a certain SR with the number of events predicted in these regions, where the prediction is based on the number of events measured

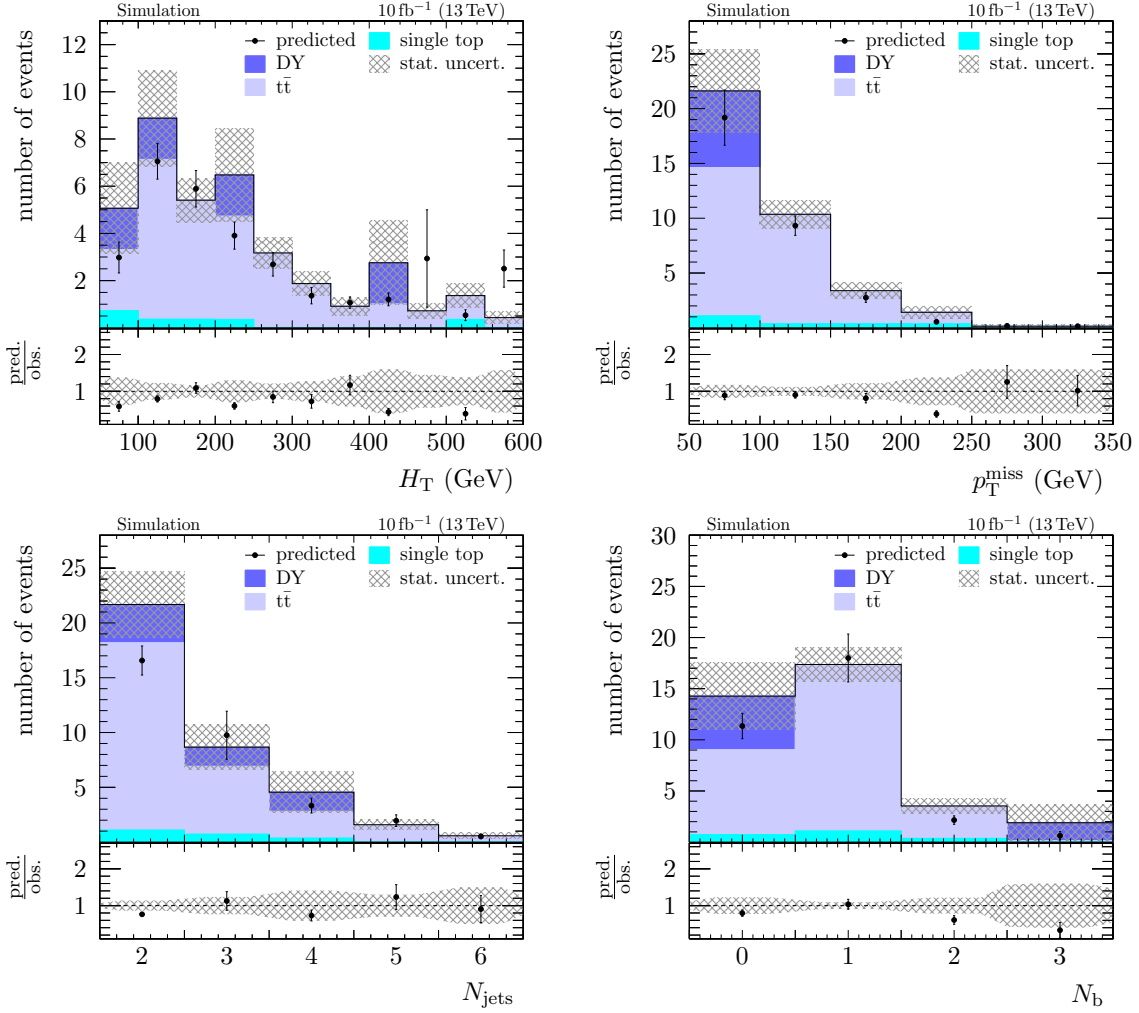


Figure 7.3: MC closure test of the nonprompt lepton background estimation method in the on-Z baseline selection. The number of events observed in the SR (solid histogram) is compared to the predicted number of events (point markers). Shown is the closure with a mixture of simulated $t\bar{t}$, DY, and single top production processes for the main event observables H_T , p_T^{miss} , N_{jets} , and N_b (top left to bottom right). The hatched bands indicate the statistical uncertainty.

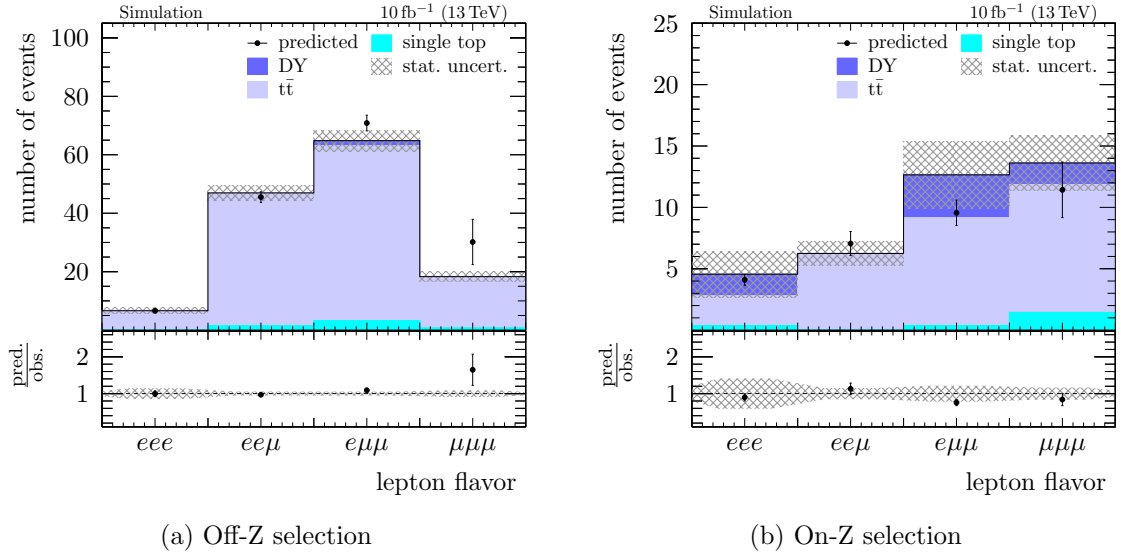


Figure 7.4: Result of the closure test for the off-Z (a) and on-Z (b) baseline selection for simulated events with different lepton flavor compositions. The number of events observed in the SR (solid histogram) is compared to the prediction (point markers). Shown is the result of the closure test with a mixture of simulated $t\bar{t}$, DY, and single top production processes. The hatched bands indicate the statistical uncertainty.

in the corresponding application region. A mixture of different background processes that yield nonprompt leptons, consisting of simulated $t\bar{t}$, DY, and single top quark production processes has been used for this test. Contributions from simulated $W^\pm + \text{jets}$ events have been found to be negligible. As this test is fully based on simulation, misidentification rates used for the prediction have been measured in simulated QCD multijet events using the same prescription as for the measurement of the misidentification rate in data.

Figure 7.2 shows the result of the closure test for main event observables of the off-Z baseline selection. Both the normalization and the shape of the H_T , p_T^{miss} , N_{jets} , and N_b distributions are very well predicted by the method. As already pointed out in Chapter 6, the dominant source of nonprompt lepton background in the off-Z selection is $t\bar{t}$ (95%), with only minor contributions from DY (1%) and single top processes (4%). The corresponding result for the on-Z baseline selection is presented in Figure 7.3. It can be seen that the statistical uncertainties, depicted as the hatched bands, are larger compared to the closure in the off-Z region, owing to the significantly smaller contribution of nonprompt lepton processes in the on-Z region and the limited number of simulated events. Within these statistical uncertainties, a fair agreement of observation and prediction can be observed. Similarly than for the off-Z selection, $t\bar{t}$ is the dominant source of nonprompt lepton background (75%), but the share arising from DY (19%) is higher. The contribution from single top production (6%) is similar to the off-Z selection.

In order to maximize the statistical precision, both muons and electrons have been selected for the closure test. However, it is important to verify that the closure works for both flavors independently to exclude a potential compensation of an under- and an overprediction for the two flavors. This is achieved by categorizing events within the baseline region and the corresponding prediction according to the flavor composition of the leptons in the event. The result is shown in Figure 7.4 and confirms that a good agreement between the observed and the predicted number of events is achieved independently for both flavors. The different shapes of the two distributions originate from the bias introduced by selecting only events with OSSF dilepton pairs in the on-Z region. The asymmetry within both distributions arises from the higher efficiency for reconstructing muons compared to electrons.

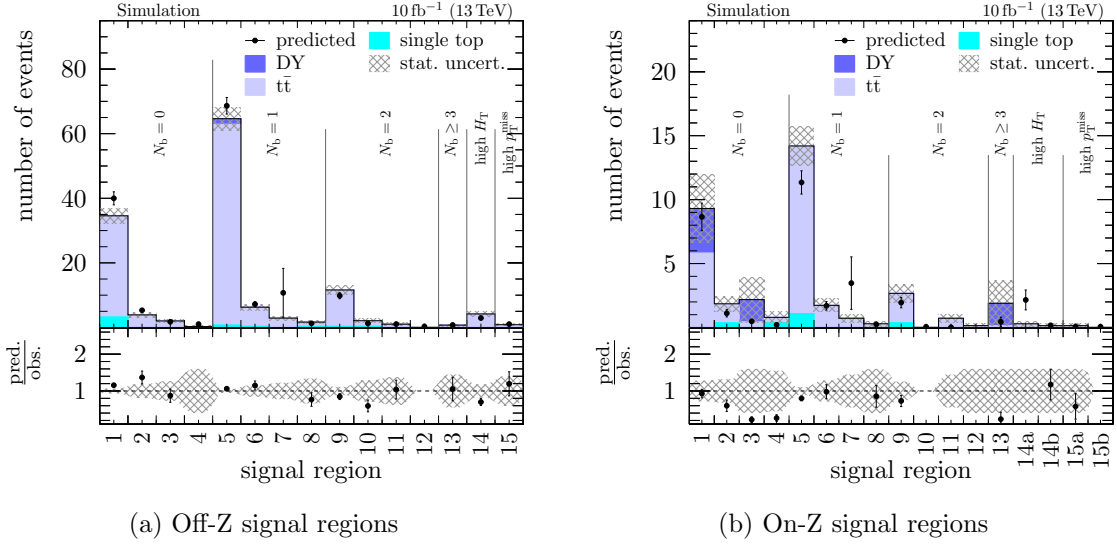


Figure 7.5: Closure test in the 15 SRs of the off-Z (a) and in the 17 SRs of the on-Z (b) selection. The number of events observed in the different SRs (solid histogram) is compared to the prediction (point markers). Shown is the result of the closure test with a mixture of simulated $t\bar{t}$, DY, and single top quark production processes. The hatched bands indicate the statistical uncertainty.

The ability of the method to model the distribution of the observables H_T , p_T^{miss} , and N_b in the baseline region is crucial to correctly predict the nonprompt lepton background in the individual SRs. The result of the closure test comparing observed and predicted event numbers in the 15 SRs of the off-Z selection and in the 17 SRs of the on-Z selection is shown in Figure 7.5 (a) and (b), respectively. A very good level of agreement is found for the off-Z SRs, where the background from nonprompt leptons is particularly important. In the on-Z regions, larger fluctuations related to the larger statistical uncertainties are observed and a fair level of agreement is found. In this regard it is worthwhile noticing that processes producing nonprompt leptons are not the dominant background source in the on-Z SRs. The deviation of the predicted number of events from the observed number can be estimated from the ratio plots in Figures 7.2 to 7.5 to be of the order of 30%.

Figure 7.6 presents additional plots that allow to quantify the level of agreement between the observed and the predicted number of events for simulated $t\bar{t}$ events in the off-Z (left) and the on-Z (right) SRs. The plots in the upper row show the pull distributions, where the pulls are defined as the difference of the prediction and the observation over the uncertainty of the prediction. The latter is calculated by summing the statistical uncertainty of the prediction and the systematic uncertainty of 30%, derived from the level of closure observed in Figures 7.2–7.5, in quadrature. The resulting histograms are fitted with Gaussian distributions whose mean and standard deviation are found to be zero and one respectively within the uncertainties of the fit parameters. This indicates the absence of any bias in the prediction and shows that a systematic uncertainty of 30% of the prediction is an appropriate estimate. The plots in the lower row of Figure 7.6 show the ratio of the prediction and the observation as a function of the observed number of events in the SRs and in the baseline region. For sufficiently populated regions, the data points are contained within the dashed lines that indicate 1 ± 0.3 , providing additional motivation to assign a systematic uncertainty of 30% on the prediction of the nonprompt lepton background.

7.1.3 Validation with data

The estimation of the nonprompt lepton background is additionally verified in a dedicated control region with data. The control region requires three leptons that pass all nominal iden-

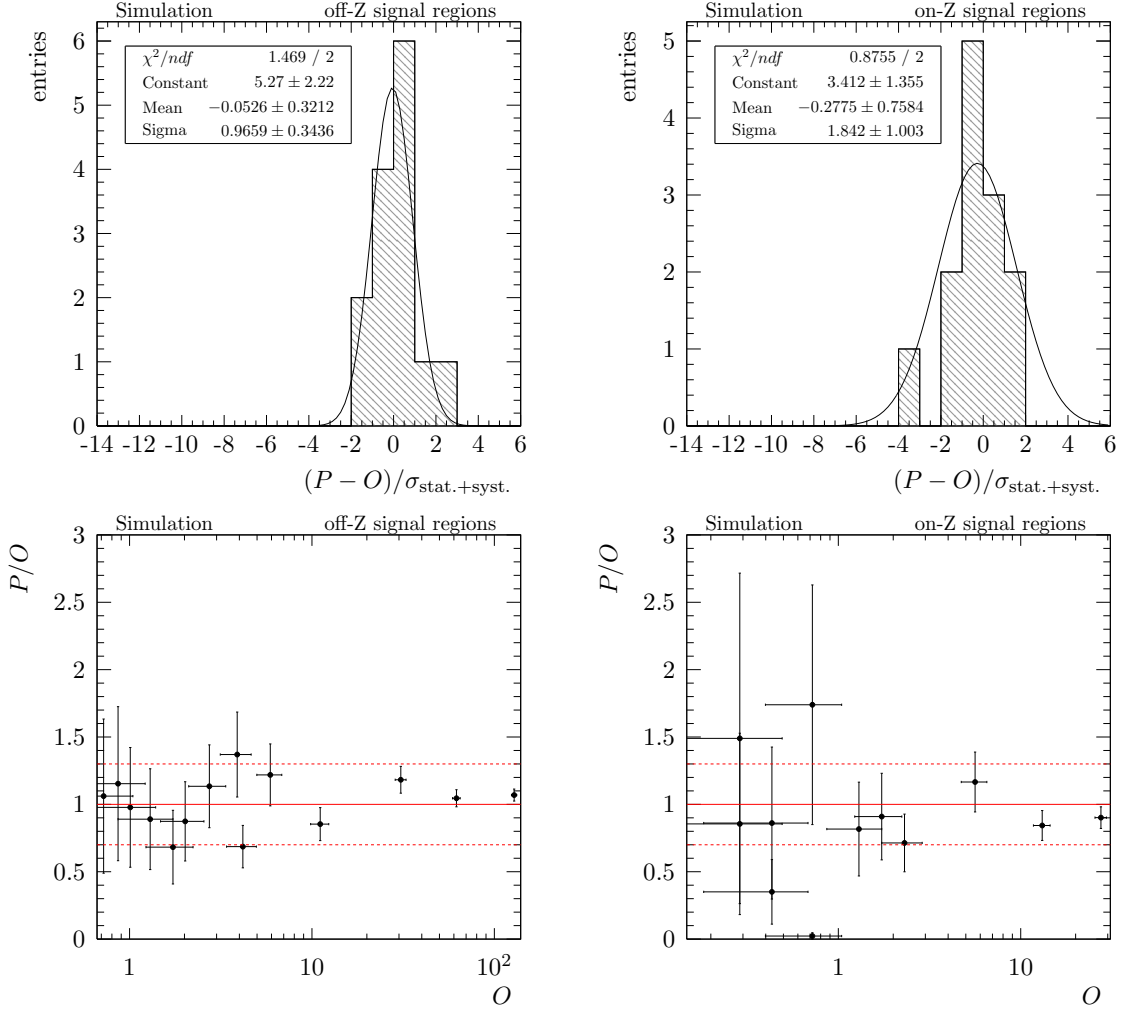


Figure 7.6: Statistical quantification of the level of agreement between the observed (O) and the predicted (P) number of simulated $t\bar{t}$ events in the off-Z (left) and the on-Z (right) SRs. The pulls (top) are calculated with the statistical uncertainty of the prediction and a systematic uncertainty of 30% summed in quadrature. The ratio P/O (bottom) is shown for all SRs and for the baseline selection (rightmost point in each plot). The dashed lines indicate a deviation of $\pm 30\%$ from unity.

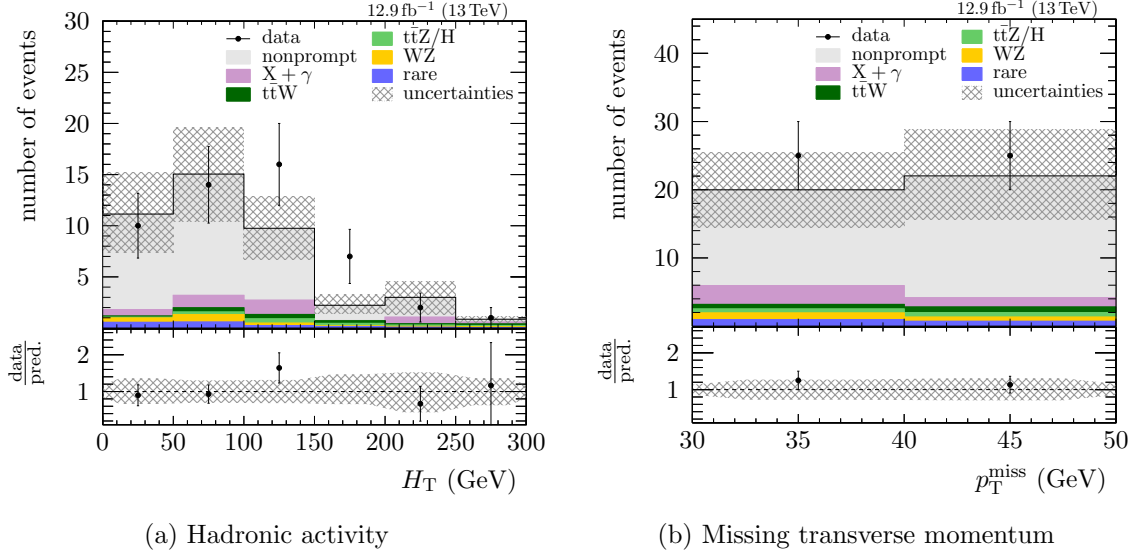


Figure 7.7: H_T (a) and p_T^{miss} (b) distributions in the nonprompt lepton background control region. For a integrated luminosity of 12.9fb^{-1} , an agreement on the level of about 20% is found between data and the background prediction. The hatched bands represent the uncertainty of the prediction, including statistical and systematic uncertainties.

tification, isolation, and p_T requirements in order to obtain a region similar to the SRs of this analysis. Selecting events with $30\text{ GeV} < p_T^{\text{miss}} < 50\text{ GeV}$ ensures orthogonality to the baseline selection. The control region is enriched with nonprompt lepton background by applying an off-Z selection for the three leptons and by requiring $N_{\text{jets}} = 1$ or 2 and $N_b \geq 1$. With this selection, a purity of 76% in nonprompt lepton background is achieved. A comparison of the observed data and the nonprompt lepton background as predicted by the tight-to-loose method is shown in Figure 7.7 for the full data set of 12.9fb^{-1} of proton-proton collisions. The small contributions from irreducible background sources are taken from MC simulations and the uncertainty band includes both the statistical and systematic uncertainties, the latter of which will be discussed in detail in Chapter 8. The agreement between data and the prediction is found to be on the level of 20% in the control region. The signal contamination in the control region was found to be negligible for the benchmark signals introduced in Section 4.1.

7.2 WZ background

Irreducible background from WZ diboson production constitutes the dominant source of background in on-Z SRs without b jets and in the high- p_T^{miss} and high- H_T regions. The estimation of this background is based on a POWHEG MC simulation whose normalization is validated in a dedicated control region enriched with WZ events. The requirement of $N_{\text{jets}} = 0$ or 1 ensures orthogonality of the control region to the baseline selection. An enrichment with WZ background is achieved by requiring three leptons that pass all nominal identification, isolation, and p_T requirements, out of which two have to be an OSSF pair with an invariant mass within a window of $\pm 15\text{ GeV}$ around the Z mass (on-Z selection). Additionally, a veto on b-tagged jets is applied and events need to have a moderate amount of missing transverse momentum ($30\text{ GeV} < p_T^{\text{miss}} < 100\text{ GeV}$). Remaining contamination of DY events is minimized by requiring $M_T > 50\text{ GeV}$, where M_T is calculated with the lepton that is not part of the OSSF pair. With this selection, about 80% of the events that enter the control region arise from WZ diboson production.

A comparison between data and the background prediction in the control region is shown in Figure 7.8 for 12.9fb^{-1} of data. The nonprompt lepton background is estimated with the

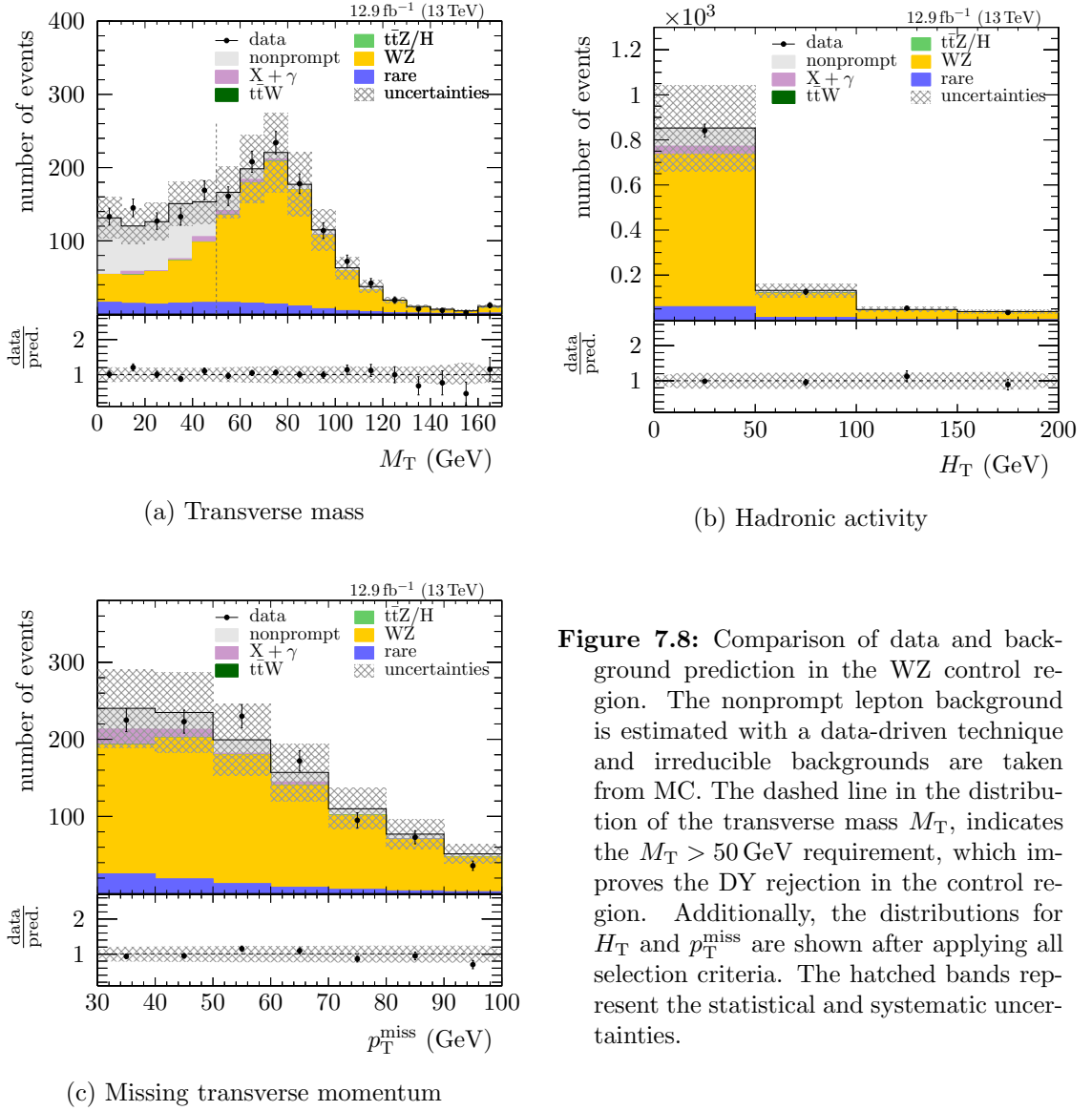


Figure 7.8: Comparison of data and background prediction in the WZ control region. The nonprompt lepton background is estimated with a data-driven technique and irreducible backgrounds are taken from MC. The dashed line in the distribution of the transverse mass M_T , indicates the $M_T > 50$ GeV requirement, which improves the DY rejection in the control region. Additionally, the distributions for H_T and p_T^{miss} are shown after applying all selection criteria. The hatched bands represent the statistical and systematic uncertainties.

tight-to-loose method described above and the prediction of irreducible backgrounds is based on MC simulations. With the MC estimates scaled to the luminosity available in data and all efficiency corrections applied, a very good agreement between data and the prediction is found. The scale factor S_{WZ} is derived by comparing the number of events from WZ background (N_{WZ}) and for non-WZ background sources ($N_{\overline{WZ}}$) with the number of events obtained in data (N_{data})

$$S_{WZ} = \frac{N_{\text{data}} - N_{\overline{WZ}}}{N_{WZ}}. \quad (7.8)$$

Including the statistical uncertainties and a flat uncertainty of 50% on the contribution from non-WZ backgrounds, a scale factor of 0.98 ± 0.13 is found. As it is compatible with unity within its uncertainty, the WZ simulation is not scaled in the SRs. However, a systematic uncertainty of 15% on the normalization is considered, derived from the uncertainty of the scale factor. The scale factor is also in agreement with a dedicated measurement of the WZ cross section at $\sqrt{s} = 13$ TeV performed by CMS, in which the measured cross section agrees with the theoretical prediction [176].

7.3 Other background processes

Several other SM processes can produce events that enter the SRs as irreducible background. Even though all of them are characterized by having very small cross sections, some of these processes constitute the dominant source of background in SRs with high b jet multiplicities. Specifically, this is the case for processes leading to the production of $t\bar{t}$ in association with a vector boson or Higgs boson. Their contributions are estimated using MC simulations, scaled to the luminosity available in data. Additionally, scale factors for matching the reconstruction efficiencies in data and simulation for leptons (c.f. Section 5.3.4) and for b-tagged jets are applied.

Background processes are grouped into different subcategories to visualize their contribution in the different SRs. A list of all MC simulations used for this analysis, including their equivalent luminosity and the associated cross sections can be found in Appendix C.

$t\bar{t}W$

Background arising from the $t\bar{t}W$ process is shown in a dedicated category, owing to its importance in SRs with high b jet multiplicities in the off-Z selection. This process is simulated at LO accuracy with the MADGRAPH5 event generator. As will be motivated in Section 7.3.1, a LO simulation has been chosen in order to minimize the total uncertainty on the prediction, which is driven by statistical uncertainties in case of the available NLO simulation. Differences between the LO and NLO simulation from higher-order terms in perturbation theory are accounted for by considering a dedicated systematic uncertainty as described below.

$t\bar{t}Z/H$

A background category denoted as $t\bar{t}Z/H$ summarizes the contributions from the $t\bar{t}Z$ and the $t\bar{t}H$ processes, which represent the dominant background sources in on-Z SRs with large b jet multiplicities. The $t\bar{t}Z$ background is simulated using two collections of events simulated at LO with the MADGRAPH5 event generator, one to account for the small contribution arising from the production of virtual Z bosons with masses between 1 GeV and 10 GeV and the other one for higher Z/γ^* masses. Similarly as in the case of $t\bar{t}W$, the LO simulation has been favored over the NLO one to minimize the total uncertainty on the prediction. The contribution from $t\bar{t}H$ is simulated with the POWHEG event generator.

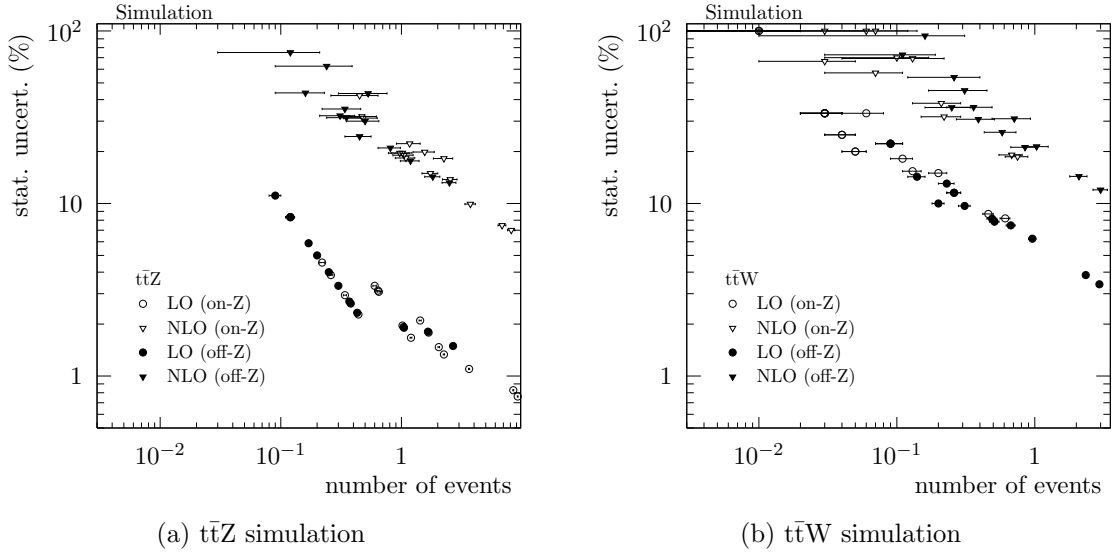


Figure 7.9: Statistical uncertainty as a function of the number of events per SR for the available LO and NLO simulations of the $t\bar{t}Z$ (a) and $t\bar{t}W$ (b) processes. The significantly larger number of events simulated at LO accuracy reduces the statistical uncertainty on the prediction by about an order of magnitude.

$X+\gamma$

Processes that contain a virtual photon decaying into leptons, referred to as *internal conversions*, are summarized in a category denoted as $X+\gamma$. The X is a placeholder for different topologies, with the main contribution arising from $t\bar{t}+\gamma$ and $Z+\gamma$. Processes where X is a single top quark or a $W^\pm$ boson have very small contributions. The latter process is simulated at LO accuracy with MADGRAPH5, while all others are simulated at NLO accuracy with the MADGRAPH5_aMC@NLO event generator. This source of background must not be confused with *external conversions* where a real photon converts into leptons upon interaction with the detector material. This background is largely suppressed by the requirement for tracks to have hits in all pixel detector layers and its estimate is included in the nonprompt lepton background.

Rare backgrounds

All other background processes relevant for this search are collected in the category denoted as *rare backgrounds*. The background with the largest cross section in this group is ZZ diboson production, which can yield up to four prompt leptons and predominantly populates on-Z SRs with small b jet multiplicities. It is simulated with the POWHEG event generator. The same generator is used to model the contribution from Higgs boson production through gluon fusion with subsequent leptonic decay via two Z bosons ($gg \rightarrow H \rightarrow ZZ$). The remaining processes in this category are simulated with MADGRAPH5_aMC@NLO and include tri-boson production (VVV, with V standing for Z or $W^\pm$) and the production of a Higgs boson in association with a vector boson (VH). Small contributions also arise from the production of two top-antitop pairs ($t\bar{t}t\bar{t}$) and from the production of a top quark in association with a Z boson and a light quark (tZq).

7.3.1 Leading order/next-to-leading order comparison for $t\bar{t}V$ simulations

The equivalent luminosity of the $t\bar{t}Z$ and $t\bar{t}W$ processes simulated at LO accuracy is about a factor of 20 larger than the equivalent luminosity of the corresponding NLO simulation. This results in a reduction of the statistical uncertainties of about one order of magnitude when using the LO simulation instead of the NLO one, as demonstrated in Figure 7.9. The

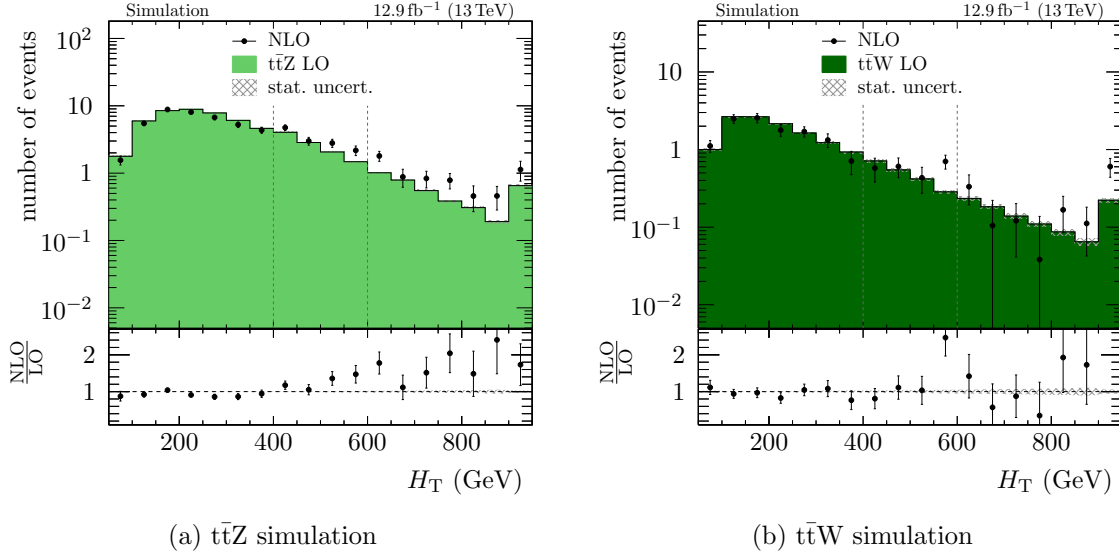


Figure 7.10: Distribution of the hadronic activity for the $t\bar{t}Z$ (a) and the $t\bar{t}W$ (b) background. The distributions obtained from the LO (solid histogram) and the NLO simulation (point markers) are compared to derive H_T dependent uncertainties for the LO simulation.

Table 7.1: NLO/LO uncertainties considered for the estimation of the $t\bar{t}Z$ and $t\bar{t}W$ background. The three different H_T bins correspond to the boundaries employed for the SR categorization.

Process	$60 \text{ GeV} < H_T < 400 \text{ GeV}$	$400 \text{ GeV} < H_T < 600 \text{ GeV}$	$H_T > 600 \text{ GeV}$
$t\bar{t}W$	1%	13%	30%
$t\bar{t}Z$	13%	13%	70%

statistical uncertainty is shown as a function of the number of events per SR for the $t\bar{t}Z$ (a) and the $t\bar{t}W$ (b) processes. Potential mis-modeling of the LO simulation arising from higher-order terms in perturbation theory is estimated by comparing the shapes of the distributions obtained from the LO and the NLO simulation. While a good agreement has been found in the distributions for p_T^{miss} and the b jet multiplicity, differences have been found in the shape of the H_T distribution as shown in Figure 7.10. The solid histogram shows the distribution obtained from the LO simulation and the point markers show the corresponding distribution obtained from the NLO simulation. As can be seen, some underestimation of the number of events in the LO simulation is observed at high H_T for the $t\bar{t}Z$ process in the on-Z selection as well as for the $t\bar{t}W$ process in the off-Z selection. An intrinsic problem of this comparison is that it is subject to the statistical uncertainty of the NLO simulation. Considering this limitation, the effect of higher-order terms in perturbation theory is accounted for by assigning the H_T dependent uncertainties on the $t\bar{t}V$ prediction presented in Table 7.1. Additional uncertainties relevant for the estimation of the $t\bar{t}V$ background are discussed in Chapter 8.

8. Systematic uncertainties

Both the background contributions and the number of simulated signal events entering the SRs, are subject to different sources of uncertainties. A thorough assessment of these uncertainties is required as their under- or overestimation can lead to false positive or false negative results, respectively. This chapter details which sources of uncertainties are relevant for the analysis and how the associated effects on the predicted number of events are estimated. Section 8.1 describes experimental uncertainties that affect background and signal processes that are estimated with MC simulations. Subsequently, Section 8.2 details the uncertainties associated with the data-driven background estimation of the nonprompt lepton background and those relevant for the estimation of the WZ background and its normalization in the control region. A different set of uncertainties concerns the limited theoretical knowledge of, e.g., cross sections or proton PDFs, quantities that are important to correctly model a certain process with MC simulations. These uncertainties are described in Section 8.3, with emphasis on the $t\bar{t}V$ processes as the dominant background sources in some of the most sensitive SRs. Uncertainties related to the limited number of simulated events affect all simulated backgrounds and are summarized in Section 8.4. Finally, dedicated uncertainties considered for simulated signal processes are described in Section 8.5.

An overview of all systematic uncertainties relevant for the search is given at the end of the chapter in Table 8.2. It shows the source and the magnitude of the uncertainty and its effect on the expected number of background and signal events.

8.1 Experimental uncertainties

Experimental uncertainties arise, e.g., from the limited precision of detector calibrations or from uncertainties on the measurement of scale factors that are used to match the reconstruction efficiencies in data and simulation. These uncertainties therefore affect all background and signal processes that are estimated with MC simulations. Additionally, uncertainties related to the overall normalization of the simulation, e.g., uncertainties on the luminosity measurement and on the trigger efficiency affect the estimation of these processes. An exception is the WZ background, as the overall normalization of the simulation of this background is validated in the control region.

8.1.1 Jet energy corrections

As mentioned in Section 5.4.1, so-called JECs are used to match the jet energies and momenta measured in data and simulation, in order to account for differences arising from pileup

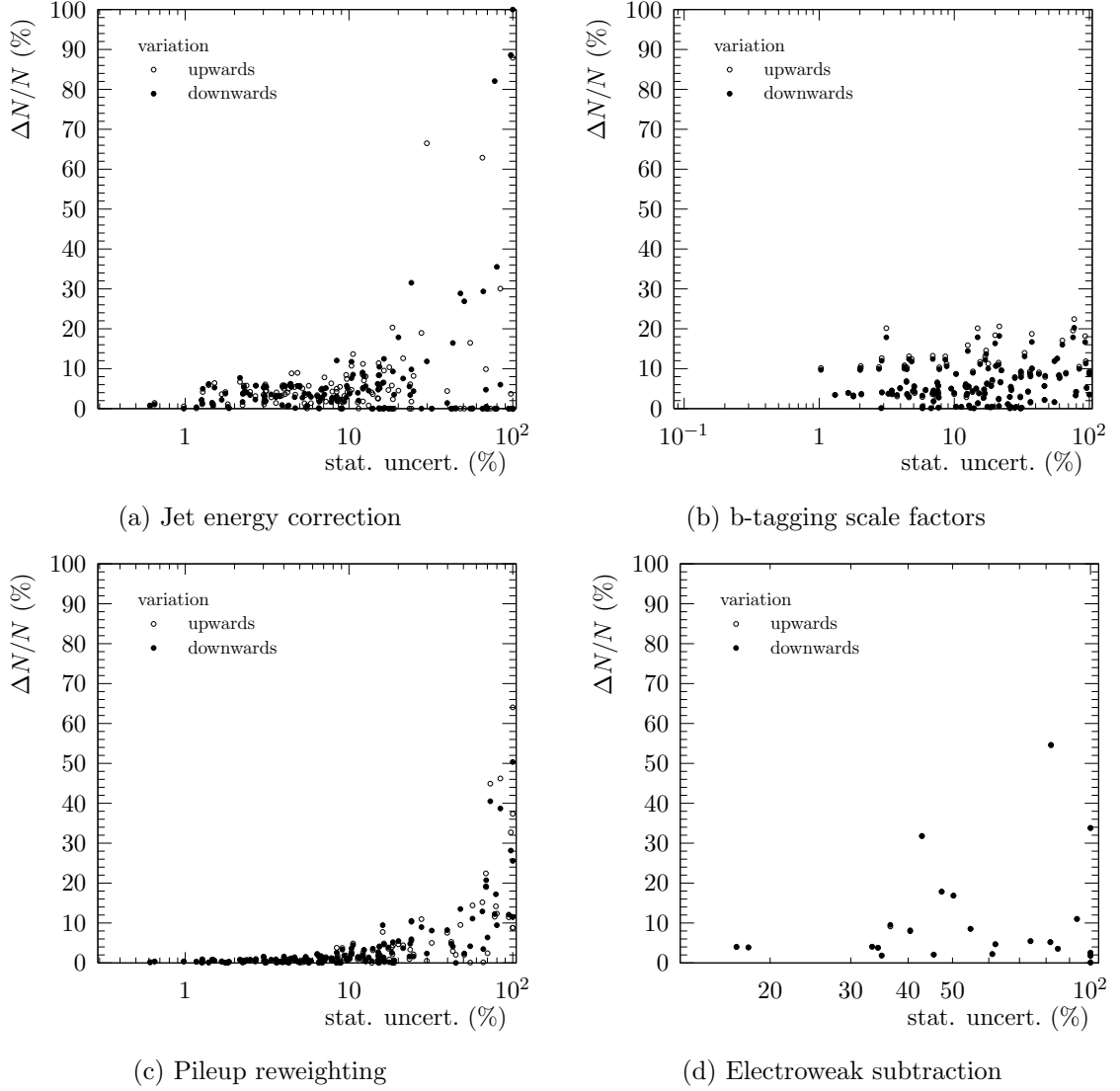


Figure 8.1: Relative variation of the number of expected background events N associated with several systematic uncertainties. The variation of the background prediction related to the uncertainty of the jet energy correction (a), the b-tagging efficiency scale factors (b), and the pileup reweighting (c) is shown for the five categories of irreducible background sources in all SRs. Additionally, the variation of the nonprompt lepton background prediction, associated to the uncertainty of the electroweak subtraction employed in the derivation of the misidentification rate is shown (d). Each data point corresponds to the variation of the prediction of one of the relevant background categories in one of the SRs.

and to compensate for the nonlinear detector response. Depending on the p_T and η of the jet, an uncertainty with a standard deviation between 1% and 8% is assigned to the correction [177]. The effect of varying the JEC by ± 1 standard deviation is propagated to all jet related observables relevant for this analysis, i.e., to the calculation of H_T , N_{jets} , and N_b . Furthermore, the variation is also considered for the calculation of p_T^{miss} . These upward and downward variations are propagated through the full event selection and thereby change the number of expected background and signal events in individual SRs, i.a., through migration of events between different regions. The relative variation of the number of expected background events associated to the upward and downward variations of the JEC, denoted as $\Delta N/N$, is shown in Figure 8.1 (a) as a function of the statistical precision on the number of simulated events. Each data point corresponds to the variation of the number of background events for each of the five categories of irreducible backgrounds in each SR. This representation allows to evaluate the effect of the uncertainty on the prediction decoupled from statistical limitations in SRs with small background contributions. A variation of the background prediction of about 1–10% can be observed in SRs with statistical uncertainties below 10%.

8.1.2 Tagging efficiency for b jets

An additional experimental uncertainty is considered for the scale factors employed to match the different b tagging efficiencies in data and simulation (c.f. Section 5.4.2). These scale factors are provided for bottom, charm, and light-flavor jets and are binned in p_T and η . The uncertainty on the scale factor is at maximum 10% per jet and is propagated to the background prediction by reweighting the events with respect to their nominal weight. Figure 8.1 (b) shows the effect of the variation on the expected number of events for all simulated background processes in the 32 SRs as a function of the statistical uncertainty on the background prediction. The expected number of background events varies between 1% and 20% when varying the b tagging efficiency scale factors within their uncertainties, rendering this effect the most important experimental source of uncertainty.

8.1.3 Pileup and luminosity

Another experimental uncertainty considered in the analysis is related to the pileup reweighting of simulated events. The pileup distribution in data depends on the LHC performance, in particular on the number of protons per bunch and on the beam cross section at the IP. Since the pileup distribution influences the detector and reconstruction performance, it has to be reproduced in simulation in order to obtain comparable results for data and MC simulations. However, the pileup distribution in data is not known a priori when starting the time intensive simulation process. Therefore, the two distributions have to be matched by reweighting simulated events based on the number of primary vertices once the distribution in data is known. For this purpose, a visible inelastic proton-proton cross section of 63 mb is assumed with an uncertainty of $\pm 5\%$ [178]. This uncertainty is propagated to the reweighting and through the full selection and categorization of the analysis and leads to a variations of 1–5% in the number of expected background events as shown in Figure 8.1 (c).

An additional uncertainty is taken into account to model the precision of the luminosity measurement of CMS. Except of the WZ diboson production, all background and signal processes that are estimated with MC simulations and scaled to the luminosity available in data, are affected by this uncertainty. For the data set of 12.9fb^{-1} analyzed in this thesis, an uncertainty of 6.2% is quoted on the luminosity measurement [178].

8.1.4 Lepton selection and trigger efficiency

A further systematic uncertainty is considered for the lepton efficiency scale factors used to match the selection efficiencies in data and simulation. The uncertainty has been found to

Table 8.1: HLT efficiency correction. Events in which the leptons do not fulfill certain p_T requirements (c.f. Table 5.2), are reweighted based on the trigger efficiencies measured for leptons in data. The table shows the resulting reduction of the expected number of events for all background processes and SRs with respect to the number of events without HLT efficiency correction.

On-Z						Off-Z					
SR	Rare	WZ	X+ γ	$t\bar{t}Z/H$	$t\bar{t}W$	SR	Rare	WZ	X+ γ	$t\bar{t}Z/H$	$t\bar{t}W$
1	0.994	0.994	1	0.996	1	1	0.984	0.989	0.995	0.993	0.995
2	1	0.992	1	0.996	1	2	1	0.980	1	0.989	1
3	1	1	1	1	1	3	1	1	1	1	1
4	1	1	1	1	1	4	1	1	1	1	1
5	0.993	0.994	1	0.996	1	5	0.985	0.979	0.976	0.991	0.992
6	0.991	0.992	1	0.998	1	6	0.952	1	1	0.994	0.992
7	1	1	1	1	1	7	1	1	1	1	1
8	1	1	1	1	1	8	1	1	1	1	1
9	0.996	0.980	1	0.996	1	9	1	1	1	0.992	0.993
10	0.957	1	1	1	1	10	1	1	1	0.988	1
11	1	1	1	1	1	11	1	1	1	1	1
12	1	1	1	1	1	12	1	1	1	1	1
13	1	1	1	0.994	1	13	1	1	1	1	1
14a	1	1	1	1	1	14	1	1	1	1	1
14b	1	1	1	1	1	15	1	1	1	1	1
15a	1	0.993	1	1	1						
15b	1	1	1	1	1						
Total	0.996	0.995	1	0.997	1	Total	0.990	0.990	0.994	0.994	0.995

be of the order of 3% muons, while a p_T and η dependent uncertainty of a similar magnitude is considered for electrons. For the latter, an additional uncertainty of 1% is taken into account to cover a potential pileup dependence of the scale factor. Another 3% are added for low- p_T electrons with $p_T < 20$ GeV. The uncertainties for different leptons are conservatively assumed to be correlated, leading to about 9% uncertainty for events with three leptons. In contrast to the uncertainty of the b tagging efficiency scale factors, this uncertainty can be propagated linearly to the number of predicted background events.

Comparability between the number of events observed in data and in simulation requires to take the trigger efficiency into account and to consider an associated systematic uncertainty. As outlined in Section 5.2.2, a trigger efficiency of 100% is assumed for all events that satisfy the lepton p_T requirements listed in the two upper rows of Table 5.2. For such events a lower uncertainty of 3% is considered.

All other events are reweighed with the lepton efficiencies measured in data. The resulting average event weight for the five categories of irreducible background sources are shown in Table 8.1 for all SRs. The average event weights are above 0.95 and most of them are very close to unity, owing to the small abundance of events that require reweighting. As for events that are not reweighted, an uncertainty of 3% is considered. Note that corrections are not applied in SRs with $H_T > 400$ GeV since the logical OR with the nonisolated dilepton plus H_T triggers ensures trigger efficiencies close to 100% in these regions.

8.2 Uncertainties related to data-driven background estimations

Another class of uncertainties is related to the data-driven background estimation of the nonprompt lepton background. Additional uncertainties are also considered for the normalization of the WZ simulation in the control region and the associated extrapolation to the SRs.

8.2.1 Nonprompt lepton background

Three different uncorrelated uncertainties are considered for the estimation of the nonprompt lepton background. The first is a SR independent uncertainty of 30% on the prediction, where the magnitude is motivated by the level of agreement between the observed and the predicted number of simulated events in the closure test presented in Section 7.1.2.

A second contribution accounts for the uncertainty associated to the simulation based subtraction of electroweak processes in the measurement region. The electroweak scale factors found in the control region with $p_T^{\text{miss}} > 30 \text{ GeV}$ and $70 \text{ GeV} < M_T < 120 \text{ GeV}$ are varied within their systematic uncertainty, which is estimated as their deviation from unity (c.f. Section 7.1.1). This results in two alternative misidentification rates for each flavor, which are parametrized in the nominal cone-corrected p_T and $|\eta|$ binning. Propagating the alternative misidentification rates through the full background estimation procedure allows to derive SR dependent upward and downward variations of the estimated number of background events with respect to the nominal value. Figure 8.1 (d) shows that these variations are of the order of 5% for well-populated SRs.

Finally, the nonprompt lepton background estimate is subject to the statistical uncertainty on the number of events in the application region. For SRs with large nonprompt lepton background contribution, this uncertainty is of the order of 15%, while it can increase to 100% in regions with very small contributions. A special case are application regions in which no event is observed for the data set under study. This is the case in the application regions associated to three on-Z SRs, namely SR 12, 15a, and 15b. The statistical uncertainty on the prediction of zero nonprompt lepton events in these regions is derived as follows. A transfer factor corresponding to the most likely misidentification rate is multiplied with 1.8 events, which corresponds to the upper uncertainty of a zero event expectation from a Poisson distribution [179]. Hereby, the most likely misidentification rate is defined as the misidentification rate measured in the bin corresponding to the most probable cone-corrected p_T and η of leptons in events that enter the application region. For both considered lepton flavors, this is the bin with $15 \text{ GeV} < p_T^{\text{cone}} < 25 \text{ GeV}$ and small $|\eta|$. The muon misidentification rate in this bin is 14% and slightly higher than the corresponding misidentification for electrons. With this misidentification rate, a transfer factor of 0.16 is derived, which in turn gives an upper statistical uncertainty of 0.29 events on the nonprompt lepton background prediction in SRs with empty application regions.

8.2.2 WZ background

In addition to the experimental uncertainties described above, the estimation of the WZ background is affected by a systematic uncertainty on the normalization of the simulation. This uncertainty is estimated to be 15%, corresponding to the uncertainty of the scale factor measured in the WZ enriched control region (c.f. Section 7.2). This uncertainty includes the statistical uncertainty on the number of events observed in the control region as well as the systematic uncertainties on the contribution of non-WZ backgrounds.

The control region differs from the SR in which the WZ background is estimated by requiring small jet multiplicities (one or zero jets) and by applying a b jet veto. In order to account

for potential mis-modeling of larger b jet and jet multiplicities and the resulting bias in H_T , a dedicated, uncorrelated uncertainty is considered for the extrapolation from the control region to the SRs. Based on a study with DY events that have a similar event topology, different uncertainties depending on the requirement on H_T and on the b jet multiplicity in a given SR are considered. An uncertainty of 10% is assigned for SRs with $H_T < 400$ GeV, while 20% are assumed for events with $H_T > 400$ GeV. Due to the large b jet multiplicity of $N_b \geq 3$ in on-Z and off-Z SR 13, the uncertainty is increased to 30% in these regions.

8.3 Theoretical uncertainties

Theoretical uncertainties on the QCD renormalization and factorization scales (c.f. Section 3.2.1) and on the proton PDFs affect the theoretical prediction of the cross section that is assumed in the simulation. Additionally, the relative acceptance of events in the different SRs is affected by these theoretical uncertainties.

8.3.1 Uncertainties related to the estimation of $t\bar{t}V$ background

The effect of the theoretical uncertainties on the cross section and on the acceptance have been studied separately for $t\bar{t}W$ and $t\bar{t}Z$. In order to assess the effect of the uncertainty of the renormalization and factorization scales, all eight possible permutations of independent upward and downward variations of the scales have been considered. For the upward variation the nominal value of the scales has been doubled, while it has been decreased by 50% for the downward variation. The largest effect has been found when both scales are varied in the same direction and the associated effect on the cross section was found to be about 13% and 11% for $t\bar{t}W$ and $t\bar{t}Z$ background, respectively. The effect of this variation on the acceptance has been studied by comparing the resulting differences in the number of background events in the different SR with respect to the nominal prediction. The effect is taken into account by considering an additional uncorrelated uncertainty of 3–18%, depending on the SR and on the regarded process.

A further uncorrelated uncertainty is considered to account for theoretical uncertainties related to the proton PDF. The number of events from $t\bar{t}V$ processes in each SR has been computed for a set of 100 variations of the NNPDF 3.0 PDFs [133]. The uncertainty on the cross section and the acceptance effect is considered together [180] and estimated as the root-mean-square of the deviations with respect to the nominal number of background events. Differences between the SRs have been found to be small and flat uncertainties of 3% and 2% independent of the SR are considered for the $t\bar{t}W$ and $t\bar{t}Z$ background, respectively. Motivated by the similar topologies of the $t\bar{t}Z$ and the $t\bar{t}H$ processes, the QCD scale and PDF related uncertainties derived for $t\bar{t}V$ are also considered for the background contribution from $t\bar{t}H$.

Additional uncertainties are considered for the $t\bar{t}W$ and the $t\bar{t}Z$ background to account for contributions from terms beyond LO in perturbation theory. The magnitude of this uncorrelated uncertainty ranges from 1% to 70%, depending on the H_T requirement of the respective SR as summarized in Table 7.1.

8.3.2 Other rare background processes

The same theoretical uncertainties also affect the $X+\gamma$ and the remaining rare background processes. An uncertainty of 50% is considered for the contribution from these processes to take into account all of the effects described above. Due to the very small number of expected events from these processes, this uncertainty has only a small impact on the sensitivity of the search.

8.4 Uncertainties arising from limited Monte Carlo statistics

Uncertainties arising from the finite number of simulated events affect all irreducible background processes that are estimated with MC simulations. A large equivalent luminosity of all simulations (c.f. Appendix C) ensures a sufficient statistical precision of the background prediction. However, in certain SRs in which a given simulated process contributes only with a very small number of events, the associated uncertainty can be as high as 100%. In the off-Z and the on-Z baseline selection, the statistical uncertainties for $t\bar{t}W$, $t\bar{t}Z/H$, WZ , and rare processes are below 4% while uncertainties between 32% and 60% are found for $X+\gamma$, owing to the extremely small contribution from this type of background. As high statistical uncertainties only occur in conjunction with very small background contributions, they do not dominate the total uncertainty in any case.

8.5 Additional uncertainties on simulated signal processes

Additional uncertainties are considered for simulated signal processes that are used to interpret the results of the search. One class of such additional uncertainties aims at covering potential differences in the number of signal events that arise from the usage of the fast-simulation package [143] instead of the full GEANT4-based model of the CMS detector (c.f. Section 3.4). Scale factors for the b-tagging efficiency and lepton selection efficiency, as well as a dedicated set of JECs are derived to match the responses in the full simulation and in the fast-simulation package. These scale factors are applied on top of the corrections that are used to match the efficiencies in data and in the full simulation. The associated uncertainties are propagated to the number of simulated signal events following the same prescription as for the background processes outlined above.

Theoretical uncertainties related to the QCD scales are evaluated using so-called *Les Houches Event (LHE) weights*, corresponding to simultaneous upward and downward variations of the renormalization and factorization scales, while PDF related uncertainties are neglected. Moreover, dedicated uncertainties related to the calculation of p_T^{miss} in the fast-simulation package and to the uncertainty on the ISR modeling for signal processes are considered [178]. To evaluate the former, the analysis is performed twice, once using p_T^{miss} calculated as the negative vectorial sum of the momenta of all PF objects and once with p_T^{miss} as calculated with generator truth information. The mean of the signal contribution in the two cases is taken as central value and half of the difference of the two values is assigned as systematic uncertainty, correlated among all SRs. Potential ISR mis-modeling is taken into account by reweighting the events according to the number of ISR jets. ISR jets are thereby defined as jets that are not matched to a generator particle originating from a top quark, $W^\pm$, Z , H , or sparticle decay, using a cone with $\Delta R = 0.3$. The weights are derived in simulated $t\bar{t}$ events that decay leptonically and half of the correction is assigned as systematic uncertainty. The normalization of the simulation is kept constant in all cases. Finally, simulated signal events are cleaned from spurious jets by vetoing certain events. The veto applies for events that contain a jet with $|\eta| < 2.5$, $p_T > 20$ GeV, and a hadronic energy fraction $H/E < 0.1$ if the jet is not matched ($\Delta R < 0.3$) to a jet at generator level. Uncertainties on the production cross section of the signal models are taken into account separately as uncertainty bands in the exclusion limit plots as will be discussed in Chapter 10.

Table 8.2: Overview of systematic uncertainties that affect the prediction of SM backgrounds and the expected number of signal events. The second column indicates the magnitude of a given uncertainty and the third column shows the effect on the number of expected background and signal events when varying the uncertainty by ± 1 standard deviation. The last four columns indicate which processes are affected by the respective uncertainty, where ‘MC bkg.’ stands for $t\bar{t}V$, $X+\gamma$, and rare backgrounds. Migration of events between different SRs arises from variations of the jet energy correction.

Source	Magnitude	Effect on bkg. pred.	Nonprompt	WZ	MC bkg.	Signal
luminosity	6.2%	6.2%			✓	✓
jet energy scale	1 – 8%	1 – 10%		✓	✓	✓
b tagging efficiency	5 – 10%	1 – 20%		✓	✓	✓
pileup	5%	1 – 5%		✓	✓	✓
lepton efficiencies	$\approx 3\%$ per leg	$\approx 9\%$			✓	✓
HLT efficiencies	3%	3%			✓	✓
lepton eff. FastSim	2% per leg	6%				✓
appl. region stat.	15 – 100%	15 – 100%	✓			
nonprompt norm.	30%	30%	✓			
EWK scale factors	$4\%(\mu)/36\%(e)$	5%	✓			
WZ CR norm.	15%	15%		✓		
WZ CR extrapol.	10 – 30%	10 – 30%		✓		
MC stat.	1 – 100%	1 – 100%		✓	✓	✓
QCD scales	$\times 0.5 / \times 2$	11 – 13% (σ) 3 – 18% ($\mathcal{A}$)			$t\bar{t}V$ $t\bar{t}V$	
PDFs	–	2 – 3%			$t\bar{t}V$	
NLO/LO	–	6 – 70%			$t\bar{t}W$, $t\bar{t}Z$	
other rare bkg.	50%	50%			$X+\gamma$, rare	

9. Results

This chapter presents the results of the search for SUSY in events with three or more charged leptons, jets, and missing transverse momentum in the final state. As pointed out earlier, all object definitions, event selections, and background estimation methods have been defined prior to analyzing the data set corresponding to 12.9 fb^{-1} of proton-proton collisions recorded with the CMS detector between March and July 2016. The number of observed events is compared to the SM background prediction, first for the on-Z baseline selection in Section 9.1 and subsequently for the off-Z baseline selection in Section 9.2. Section 9.3 presents the comparison of the observed and the predicted number of events in all 32 exclusive SRs, where potential BSM physics processes could lead to significant excesses of data over the SM prediction. The background prediction is based on the methods outlined in Chapter 7 and the hatched bands in the distributions indicate the total statistical and systematic uncertainties on the prediction, arising from the sources detailed in Chapter 8. The last bin in all distributions contains all events beyond the range of the histogram. An interpretation of the results in the context of simplified supersymmetric signal models will be given in Chapter 10.

9.1 On-Z baseline selection

A comparison of the observed data with the SM background prediction in distributions of the event observables used for SR categorization H_T , p_T^{miss} , and N_b is presented in Figure 9.1 for the on-Z baseline selection. Additionally, distributions showing the lepton flavor composition as well as the jet and lepton multiplicities in events entering the on-Z regions are shown. For an integrated luminosity of 12.9 fb^{-1} of proton-proton collisions, 283 events pass the on-Z baseline selection, which is in fair agreement with the total number of events expected from SM background processes of 270.0 ± 5.0 . A good agreement between data and the prediction is observed in all distributions, with the exception of one larger deviation in the last bin in the p_T^{miss} distribution. For events with $p_T^{\text{miss}} > 450 \text{ GeV}$, six events are observed in data while only 1.86 ± 0.48 events are predicted. These six events have been inspected thoroughly to exclude detector related noise artifacts and their location in the other distributions has been investigated. If a new physics process was responsible for this surplus of events, one would expect some common features in the events, e.g., in the invariant mass of the leptons. Since no such common features could be identified and no accumulation of the events in any other distribution has been observed, they are considered a statistical fluctuation. Event displays and further details concerning these six events can be found in Appendix D.

The distribution of the lepton multiplicity in Figure 9.1 shows that 2.8% of the selected events contain four leptons that pass all identification and isolation requirements, in accordance

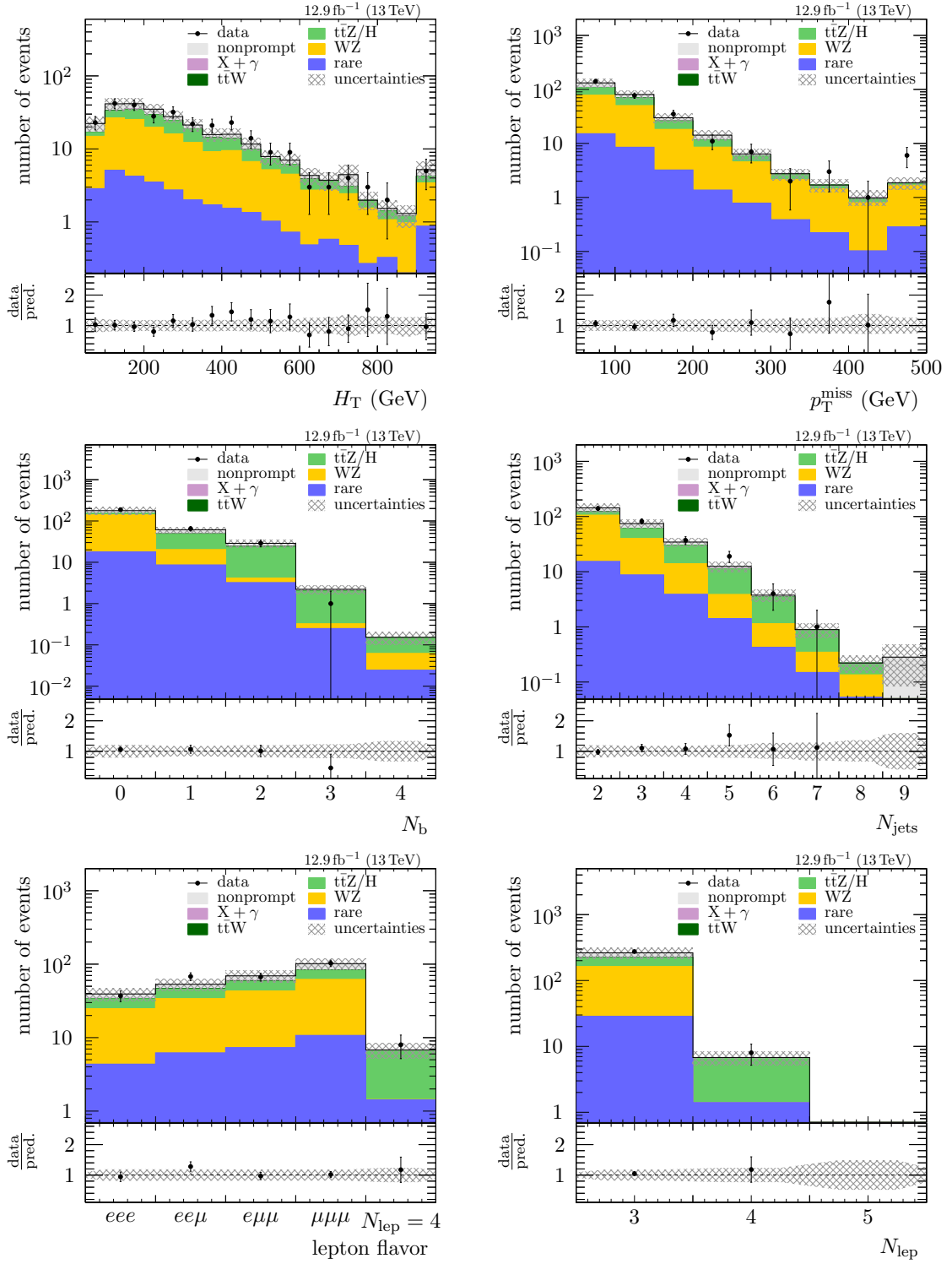


Figure 9.1: Comparison of the observed and the predicted number of events in observables of the on-Z baseline selection. Shown are the distributions for the hadronic activity (top left), the missing transverse momentum (top right), the b jet multiplicity (middle left), and the jet multiplicity (middle right). Additionally, the lepton flavor composition (bottom left) and the lepton multiplicity (bottom right) in the events are shown. The panel below the distribution shows the ratio between the observed and the predicted number of events and the hatched bands represent the total uncertainty on the prediction.

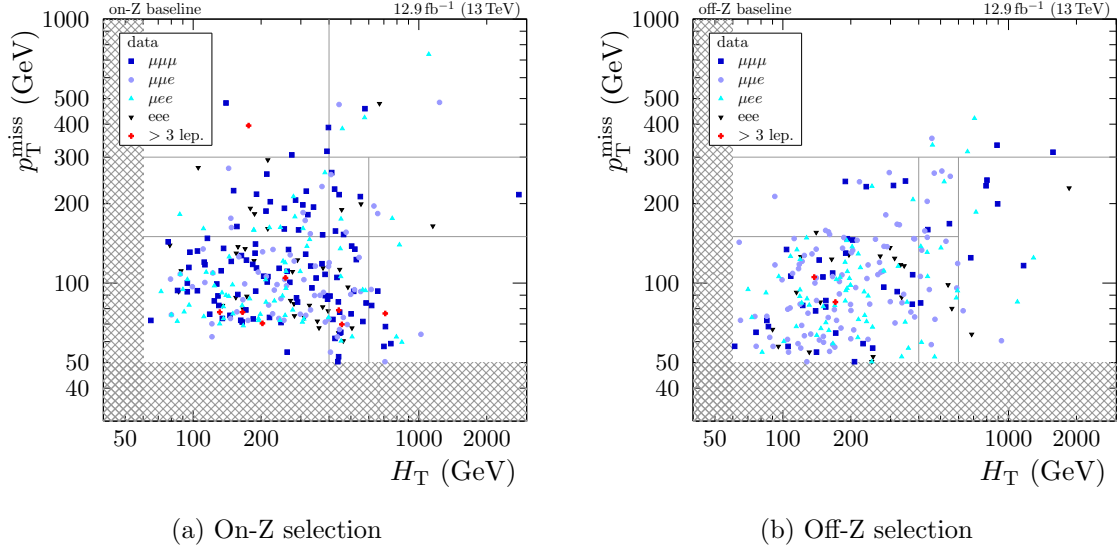


Figure 9.2: Distribution of observed events passing the on-Z (a) and the off-Z (b) baseline selection in the H_T - p_T^{miss} plane. The hatched band represents regions of phase space rejected by the baseline selection. Vertical and horizontal lines indicate SR boundaries.

with the prediction. Higher lepton multiplicities have neither been observed nor predicted. Figure 9.2 (a) shows the distribution of the observed on-Z events in the H_T - p_T^{miss} plane, broken down by different lepton flavor channels. The hatched band represents regions of phase space that are rejected by the baseline selection and SR boundaries are indicated by the horizontal and vertical lines. The apparent shortage of events at low p_T^{miss} and low H_T in Figure 9.2 (a) arises from the increased lower bound on p_T^{miss} of 70 GeV in the on-Z SRs 1 and 5.

9.2 Off-Z baseline selection

Figure 9.3 presents the comparison of the observed data and the SM prediction for 12.9 fb^{-1} of data for events satisfying the off-Z baseline selection. A total of 232 events enter this selection, while 210.6 ± 8.5 are predicted by SM background sources. A good agreement between data and the prediction is observed in the distributions of the event observables that are used for SR categorization, namely H_T , p_T^{miss} , and the b jet multiplicity. Unlike in the on-Z selection, no surplus of events with large p_T^{miss} values is found. The observed data also agree with the SM prediction in the distributions of the lepton flavor composition and of the lepton multiplicity. The share of events with four leptons is below 1% in the off-Z selection both in data and for the background prediction. Events with more than four leptons are neither observed nor predicted.

A striking feature, however, is found in the N_{jets} distribution, where a considerable under-prediction is observed for events with $N_{\text{jets}} \geq 6$. In the bin with $N_{\text{jets}} = 6$, seven events have been observed in data while 2.25 ± 0.50 are predicted. For $N_{\text{jets}} = 7$, five observed events contrast a prediction of 0.74 ± 0.21 . Detailed studies have been performed to understand this disagreement. Besides a thorough investigation of the events to exclude detector noise artifacts and a contribution from pileup collisions, emphasis has been put on understanding the sudden drop of the predicted nonprompt lepton background in these bins, which contrasts the smoothly falling number of observed events. It is worthwhile mentioning that the MC closure test used to validate the estimation of the nonprompt lepton background correctly predicts the number of events with six or more jets in the off-Z selection within the statistical uncertainties (c.f. Figure 7.2). However, the observed behavior could be the

result of a downward fluctuation of data in the application region used to predict the non-prompt lepton background in these bins. A comparison of data and simulated $t\bar{t}$ events in the application that corresponds to the off-Z baseline selection supports this hypothesis, as shown in the supplementary material in Appendix E. While the simulation models the SM background in the application region very well in all distributions, the bins with $N_{\text{jets}} \geq 6$ contain considerably fewer events in data than predicted by the simulation.

Another possible cause for the underprediction could be mis-modeling of the $t\bar{t}V$ background in these bins. Predicting the $t\bar{t}V$ background with NLO simulations produced with the MADGRAPH5_aMC@NLO event generator instead of the LO MADGRAPH5 simulations, yields comparable predictions within the uncertainties and does not remove the disagreement. Instead, the disagreement might be explained by limitations for both generators concerning the number of partons generated at the matrix-element level, when preselecting events with three or more leptons. Simulated $t\bar{t}W$ events entering the selection feature only two jets that originate from the b quark decays, This is because all $W^\pm$ bosons involved in the process must decay leptonically in order to produce enough leptons for the event to be selected for this analysis. In addition to these two jets only up to one or two extra jets can arise from partons generated at the matrix-element level for the MADGRAPH5_aMC@NLO and MADGRAPH5 generators, respectively. This yields a maximum of only four jets for the LO simulation used in this analysis, which evidently can cause underprediction at higher jet multiplicities. In the case of the $t\bar{t}Z$ simulation, on the other hand, up to four jets can arise from the $t\bar{t}$ decay for multilepton events. With one, respectively two additional jets arising from partons produced at the matrix-element level, this yields a total of five to six jets and explains the better agreement of the data and the prediction at high jet multiplicities for the on-Z selection where $t\bar{t}Z$ dominates over $t\bar{t}W$.

In summary, a potential downwards fluctuation of data in the application region used to predict the nonprompt lepton background at high jet multiplicities and limitations of the event generator used to model the $t\bar{t}W$ background are the most likely causes for the observed discrepancy between data and the background prediction at high jet multiplicities in the off-Z selection. Together with the observation that the twelve excess events do not share any other common feature that could characterize a BSM physics process, this suggests that the disagreement is not caused by a signal process.

The distribution of the observed off-Z events in the H_T - p_T^{miss} plane is shown in Figure 9.2 (b).

9.3 Signal regions

Events satisfying the on-Z or the off-Z baseline selection are categorized into 17 and 15 exclusive SRs, respectively. Figure 9.4 shows the comparison of the number of events expected from SM background sources with the number of observed events for 12.9 fb^{-1} of data in all SRs. The results are presented using a linear (top) and a logarithmic y axis scale (bottom). The observed data are compatible with the predicted SM background in all SRs within the uncertainties. The surplus of on-Z events with high p_T^{miss} leads to a mild excess in on-Z SR 15a, which contains events with $p_T^{\text{miss}} > 300\text{ GeV}$ and $60\text{ GeV} < H_T < 600\text{ GeV}$. In this SR, five events are observed while $2.2 \pm 0.2 \pm 0.5$ are predicted.

A similar level of agreement between data and prediction is also found for the off-Z SRs, owing to the fact that the SRs are not binned in N_{jets} and that the twelve events in the tail of the jet multiplicity distribution are not localized in any other observable used for SR categorization. Rather, the events are spread out over eight different SRs as shown in the supplementary material in Appendix E. The largest difference between data and the background prediction in the off-Z search is found in SR 14 ($50\text{ GeV} < p_T^{\text{miss}} < 300\text{ GeV}$, $H_T > 600\text{ GeV}$), where 12 events are observed while $7.2 \pm 1.1^{+1.0}_{-1.1}$ are predicted.

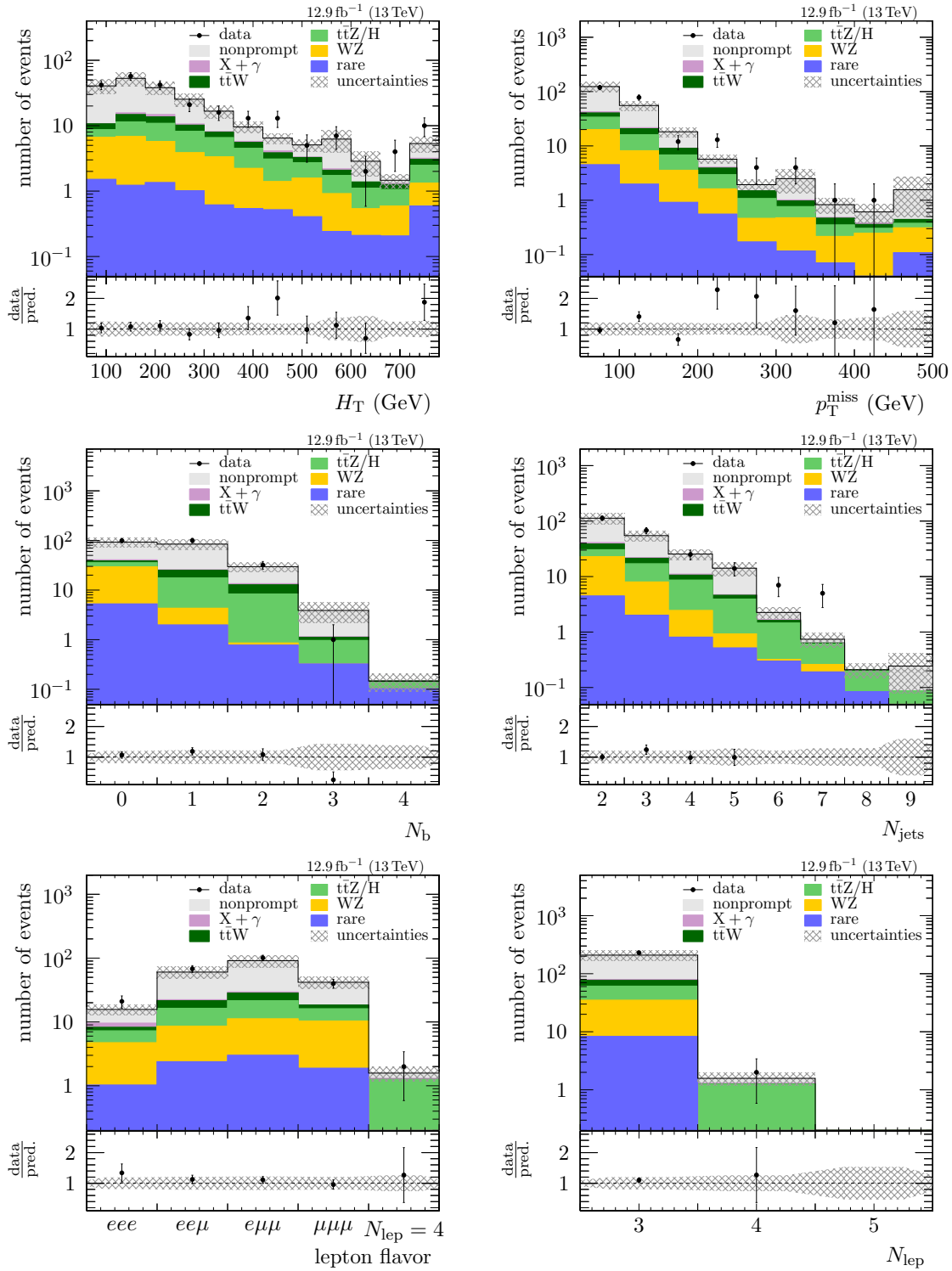


Figure 9.3: Comparison of the observed and the predicted number of events in observables of the off-Z baseline selection. Shown are the distributions for the hadronic activity (top left), the missing transverse momentum (top right), the b jet multiplicity (middle left), and the jet multiplicity (middle right). Additionally, the lepton flavor composition (bottom left) and the lepton multiplicity (bottom right) in the events are shown. The panel below the distribution shows the ratio between the observed and the predicted number of events and the hatched bands represent the total uncertainty on the prediction.

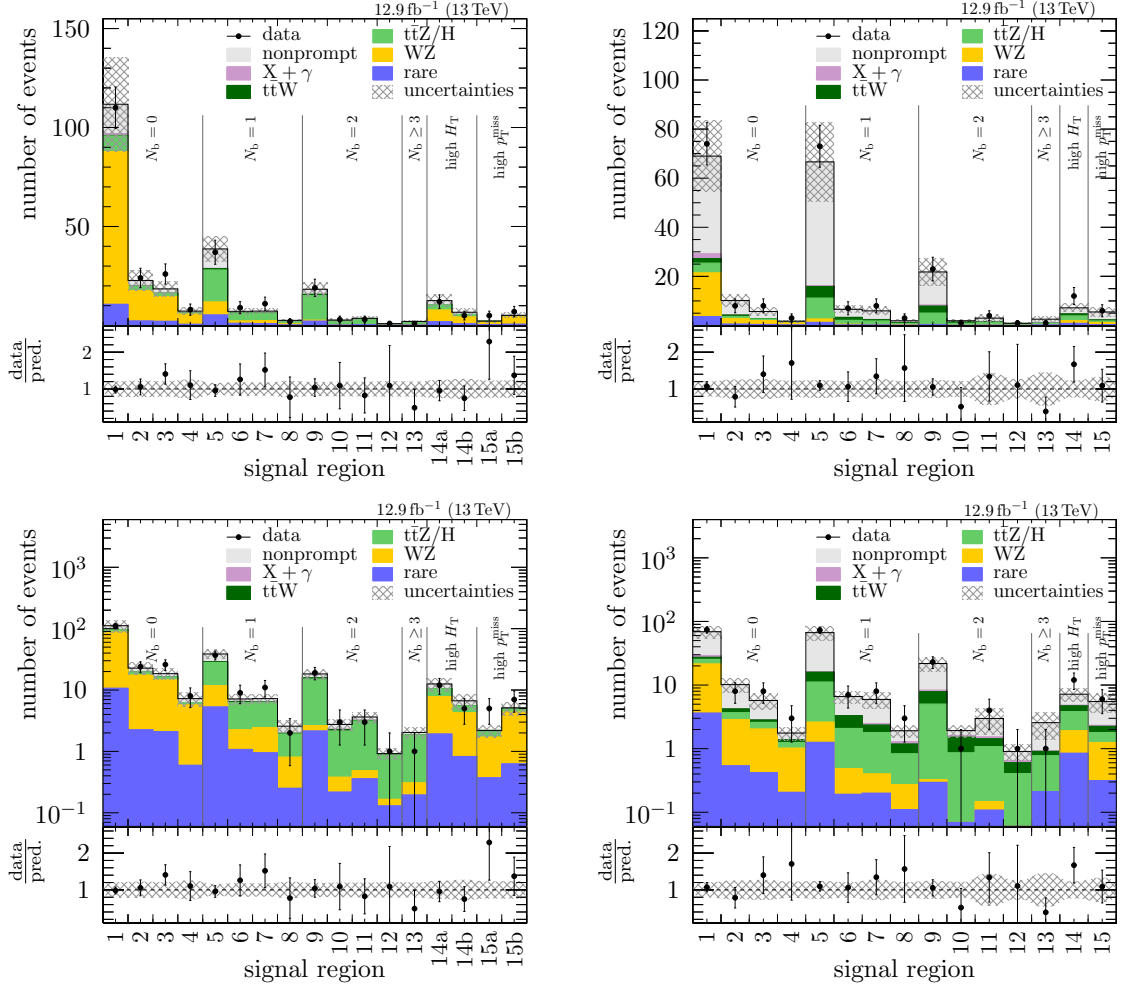


Figure 9.4: Observed number of events and predicted SM background contributions for 12.9 fb^{-1} of data in the on-Z (left) and the off-Z (right) SRs, shown with a linear (top) and with a logarithmic y axis scale (bottom). The panel below the distribution shows the ratio between the observed and the predicted number of events and the hatched bands represent the total uncertainty on the prediction.

The number of the observed and the predicted events presented in Figure 9.4 are also show in Tables 9.1 and 9.2 for the on-Z and off-Z selection, respectively. Additional information is provided by separately showing the statistical and the systematic contribution to the total uncertainty on the background prediction. A breakdown of the total background prediction by different background tt sources can by found in Appendix F.

Table 9.1: Observed number of events and predicted SM background contributions in the 17 SRs of the on-Z selection for 12.9 fb^{-1} of data. Uncertainties on the background prediction are given as $\pm \text{stat.} \pm \text{syst.}$

Signal region	N_b	H_T (GeV)	p_T^{miss} (GeV)	Expected	Observed
SR 1	0	60 – 400	70 – 150	$111.8 \pm 3.4^{+23.4}_{-23.8}$	110
SR 2			150 – 300	$22.7 \pm 1.7^{+4.8}_{-4.7}$	24
SR 3		400 – 600	50 – 150	$18.5 \pm 0.9^{+3.8}_{-3.8}$	26
SR 4			150 – 300	$7.3 \pm 1.1^{+1.5}_{-1.5}$	8
SR 5	1	60 – 400	70 – 150	$38.7 \pm 1.7^{+6.2}_{-6.2}$	37
SR 6			150 – 300	$7.2 \pm 0.4^{+1.3}_{-1.3}$	9
SR 7		400 – 600	50 – 150	$7.3 \pm 0.5^{+1.2}_{-1.2}$	11
SR 8			150 – 300	$2.6 \pm 0.4^{+0.4}_{-0.4}$	2
SR 9	2	60 – 400	50 – 150	$18.4 \pm 1.2^{+3.3}_{-3.3}$	19
SR 10			150 – 300	$2.8 \pm 0.3^{+0.5}_{-0.5}$	3
SR 11		400 – 600	50 – 150	$3.6 \pm 0.2^{+0.7}_{-0.7}$	3
SR 12			150 – 300	$0.9 \pm 0.0^{+0.2}_{-0.2}$	1
SR 13	≥ 3	60 – 600	50 – 300	$2.0 \pm 0.1^{+0.4}_{-0.4}$	1
SR 14a	inclusive	> 600	50 – 150	$12.6 \pm 1.4^{+2.8}_{-2.8}$	12
SR 14b	inclusive	> 600	150 – 300	$6.7 \pm 1.1^{+1.5}_{-1.5}$	5
SR 15a	inclusive	60 – 400	≥ 300	$2.2 \pm 0.2^{+0.5}_{-0.5}$	5
SR 15b	inclusive	> 400	≥ 300	$5.1 \pm 0.4^{+1.2}_{-1.2}$	7

Table 9.2: Observed number of events and predicted SM background contributions in the 15 SRs of the off-Z selection for 12.9 fb^{-1} of data. Uncertainties on the background prediction are given as $\pm \text{stat.} \pm \text{syst.}$

Signal region	N_b	H_T (GeV)	p_T^{miss} (GeV)	Expected	Observed
SR 1	0	60 – 400	50 – 150	$69.0 \pm 4.9^{+13.5}_{-13.4}$	74
SR 2			150 – 300	$10.2 \pm 1.7^{+2.0}_{-2.0}$	8
SR 3		400 – 600	50 – 150	$5.8 \pm 1.1^{+1.1}_{-1.1}$	8
SR 4			150 – 300	$1.8 \pm 0.3^{+0.3}_{-0.3}$	3
SR 5	1	60 – 400	50 – 150	$66.7 \pm 5.0^{+15.4}_{-15.4}$	73
SR 6			150 – 300	$6.6 \pm 0.8^{+1.2}_{-1.2}$	7
SR 7		400 – 600	50 – 150	$6.0 \pm 1.2^{+1.1}_{-1.1}$	8
SR 8			150 – 300	$1.9 \pm 0.3^{+0.3}_{-0.3}$	3
SR 9	2	60 – 400	50 – 150	$21.8 \pm 3.2^{+4.3}_{-4.3}$	23
SR 10			150 – 300	$2.0 \pm 0.3^{+0.3}_{-0.3}$	1
SR 11		400 – 600	50 – 150	$3.0 \pm 1.2^{+0.5}_{-0.5}$	4
SR 12			150 – 300	$0.9 \pm 0.2^{+0.1}_{-0.1}$	1
SR 13	≥ 3	60 – 600	50 – 300	$2.6 \pm 1.0^{+0.5}_{-0.5}$	1
SR 14	inclusive	> 600	50 – 300	$7.2 \pm 1.1^{+1.3}_{-1.2}$	12
SR 15	inclusive	inclusive	≥ 300	$5.5 \pm 1.5^{+1.0}_{-1.1}$	6

10. Interpretation

The results presented in the previous chapter can be interpreted in terms of upper limits on the production cross sections of simplified supersymmetric signal topologies. This allows to set exclusion limits on sparticle masses within a given signal model by comparing the excluded cross section to the theoretically expected cross section of the regarded model. In the absence of significant deviations between the observed data and the SM background expectation, such exclusion limits allow to compare the sensitivity of the search with previous or similar competing searches that are sensitive to the same signal topologies. Additionally, exclusion limits are important measures to reject theoretically viable SUSY models that are disfavored by observed data. Limits on sparticles masses in simplified models, however, do not rule out the existence of such sparticles if they are part of more complex signal topologies or if the perturbatively calculated cross section overestimates the true value. Nevertheless, the combination of exclusion limits on different sparticle masses set by a multitude of different SUSY searches can be used for a re-interpretation of the results in the context of more complex BSM physics processes [98], a task that is, however, beyond the scope of this thesis.

In order to pave the way for interpreting the results of this search in terms of exclusion limits and observed significances, Section 10.1 introduces important terminology and reviews the statistical methods that the following sections are based on. The calculation of upper limits on the production cross sections of new physics processes using the so-called *CL_s method* is reviewed and the significance of an observation is defined. Subsequently, exclusion limits for two different simplified model topologies are presented in Section 10.2. Additionally, significance scans that quantify the level of agreement between the observation and the background prediction in SRs sensitive to a given signal process are presented. While these results are based on the statistical combination of all 32 SRs of the search, Section 10.3 presents exclusion limits calculated using only the two most sensitive SRs for each model. This approach provides easy-to-implement search regions for re-interpretation of the results while maintaining almost the same sensitivity compared to the combination of all SRs. Finally, the achieved exclusion limits are compared with other searches for this and similar final states performed by the ATLAS and CMS Collaborations at 8 TeV and 13 TeV in Section 10.4.

10.1 Statistical analysis

The result of this search for SUSY processes featuring squark or gluino pair production is interpreted in terms of exclusion limits on the masses of the sparticles involved in the decay cascades of SMS topologies. The underlying statistical procedure, known as *modified frequentist CL_s method* is summarized in this section, closely following the prescription for limit setting defined by the ATLAS and CMS Collaborations in the context of the search for the Higgs boson [181].

10.1.1 Observed exclusion limit

The procedure is based on comparing the observed number of events in each SR or *bin* i , with the predicted number of SM background events b_i and the expected number of signal events s_i for a given signal model and fixed sparticle masses. Additionally, the nominal signal cross section can be scaled using a real, positive number μ , the so-called *signal strength modifier*. The total number of expected events can therefore be written as $\lambda_i = \mu s_i + b_i$.

As the event selection in this analysis represents a simple pass/fail criterion, the probability of observing n events in a certain SR with the expected number of events λ is described by the binomial distribution, which — in the limit of large number of trials — can be approximated with a Poisson distribution

$$\text{Poisson}(n|\lambda) = \frac{\lambda^n}{n!} e^{-\lambda}. \quad (10.1)$$

Here and in the following, parenthesized expressions as on the left of Equation 10.1 have to be read as conditional probability to observe n events given the expectation of λ events.

For a search with discrete, statistically independent bins, the likelihood for observing the data for some fixed signal strength modifier μ is given by the product of the Poisson distributions for all SRs

$$\mathcal{L}(\text{data}|\mu) = \prod_i \frac{(\mu s_i + b_i)^{n_i}}{n_i!} e^{-\mu s_i + b_i}. \quad (10.2)$$

However, this likelihood needs to be extended as the predicted numbers of signal and background events s_i and b_i are subject to systematic uncertainties as detailed in Chapter 8. Each uncertainty is described by a so-called *nuisance parameter* θ , which itself is modeled by some probability density function. For the presented analysis, log-normal distributions [182] are used to model so-called *flat uncertainties* that affect a given background or signal contribution in all SRs by a constant percentage. *Shape uncertainties*, whose magnitude vary between the SRs, are modeled with Gaussian distributions. In the following, the symbol θ represents a vector including the full set of all nuisance parameters. The function $p(\theta|\tilde{\theta})$ describes the probability density of the true nuisance parameter θ , given its estimate $\tilde{\theta}$. In Chapter 8 it has been shown how estimates $\tilde{\theta}$ for the nuisance parameters are obtained, based on the variation of parameters that are subject to systematic uncertainties, such as efficiencies or cross sections. Using Bayes' theorem with a flat prior $\pi_\theta(\theta)$ the probability density function of the nuisance parameter $p(\theta|\tilde{\theta})$ can be described as posterior of the probability density function $p(\tilde{\theta}|\theta)$ that describes the probability for obtaining the estimate $\tilde{\theta}$

$$p(\theta|\tilde{\theta}) \propto p(\tilde{\theta}|\theta) \cdot \pi_\theta(\theta). \quad (10.3)$$

This approach allows to describe the nuisance parameters in a fully frequentist context and the posterior of the probability density function of the nuisance parameter $p(\theta|\tilde{\theta})$ can be used to extend Equation 10.2 in order to include systematic uncertainties

$$\mathcal{L}(\text{data}|\mu, \theta) = \prod_i \frac{(\mu s_i(\theta) + b_i(\theta))^{n_i}}{n_i!} e^{-\mu s_i(\theta) + b_i(\theta)} \cdot p(\theta|\tilde{\theta}). \quad (10.4)$$

For a given observation, this likelihood function can now be maximized in two different ways. Firstly by finding nuisance parameters $\hat{\theta}_\mu$ that maximize $\mathcal{L}$ for a fixed signal strength modifier $\mu \geq 0$, and secondly by letting both the nuisance parameters and the signal strength modifier float to find values $\hat{\theta}$ and $\hat{\mu}$ that correspond to the global maximum of $\mathcal{L}$. Here, $\hat{\mu}$ is restricted to $0 \leq \hat{\mu} \leq \mu$, where the lower bound is motivated by the assumption that BSM physics process cannot reduce the SM background and the upper bound ensures that upward fluctuations of data are not interpreted as evidence against the presence of a signal. The upper bound μ is a fixed parameter in the calculation and is incremented until a certain condition is met as discussed below.

A test statistics q_μ is constructed based on the ratio of theses two maximized likelihoods, which is referred to as the *profile likelihood ratio*

$$q_\mu = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}, \quad \text{where } 0 \leq \hat{\mu} \leq \mu. \quad (10.5)$$

This test statistics forms the basis for comparing the compatibility of the observation with the *background-only hypothesis* H_0 on the one hand and the *signal-plus-background hypothesis* H_1 on the other hand. First, the value of the test statistics q_μ^{obs} corresponding to the observed data is evaluated for a fixed μ . Then, nuisance parameters $\hat{\theta}_0^{\text{obs}}$ and $\hat{\theta}_\mu^{\text{obs}}$ are derived that maximize the likelihood function (Equation 10.4) for the background-only hypothesis ($\mu = 0$) and for the signal-plus-background hypothesis ($\mu \neq 0$), respectively. These sets of nuisance parameters are then used to construct probability density functions $f(q_\mu|\mu, \hat{\theta}_\mu^{\text{obs}})$ and $f(q_\mu|0, \hat{\theta}_0^{\text{obs}})$, which describe the test statistic q_μ for the two hypotheses. Since the integrals of these functions are usually not analytically calculable, they are determined using MC methods by drawing so-called *pseudo-data* from the respective probability density function. Based on these distributions, p-values p_μ and p_b are defined for the signal-plus-background and the background-only hypothesis, which give the probability for an observation with the same or greater incompatibility with the respective hypothesis

$$p_\mu = P(q_\mu > q_\mu^{\text{obs}}|H_1) \quad (10.6)$$

$$1 - p_b = P(q_\mu > q_\mu^{\text{obs}}|H_0). \quad (10.7)$$

Finally, the quantity CL_s is calculated as the ratio of the two probabilities p_μ and $1 - p_b$

$$\text{CL}_s(\mu) = \frac{p_\mu}{1 - p_b}. \quad (10.8)$$

Figure 10.1 schematically shows two probability density functions of the test statistics for H_0 and H_1 . The p-values p_μ and $1 - p_b$ correspond to the integrals $\int_{q_\mu^{\text{obs}}}^\infty f(q_\mu) dq_\mu$ over the normalized probability density functions f , where q_μ^{obs} is the value of the test statistics found for the observed data.

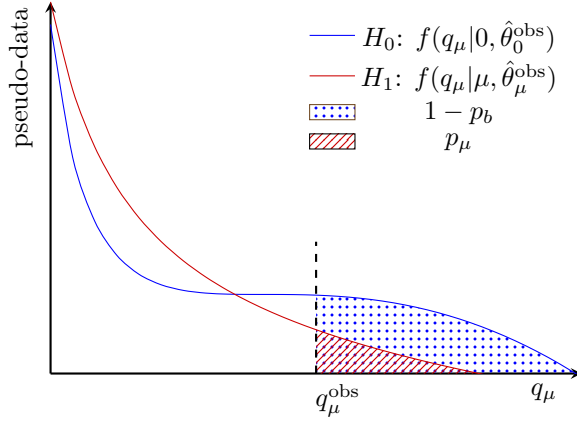


Figure 10.1: Schematic representation of the probability density functions $f(q_\mu|\mu, \hat{\theta}_\mu^{\text{obs}})$ for the signal hypothesis H_1 and $f(q_\mu|0, \hat{\theta}_0^{\text{obs}})$ for the background-only hypothesis H_0 . The p-values p_μ and $1 - p_b$ used for the calculation of CL_s correspond to the integrals $\int_{q_\mu^{\text{obs}}}^{\infty} f(q_\mu) dq_\mu$ over the normalized probability density functions f , where q_μ^{obs} is the value of the test statistics found for the observed data.

For claiming the exclusion of a signal model, it has become customary to require $\text{CL}_s < 0.05$ for $\mu = 1$, which means that the respective signal is excluded at the 95% confidence level, considering its nominal cross section $\sigma_s \propto s_i$.

The exclusion limits presented for this analysis are calculated using approximate formulae to calculate CL_s values [183, 184] in order to allow for the evaluation of a large number of sparticle mass configurations. This so-called *asymptotic limit* converges against the limit obtained with the full set of pseudo-experiments if the number of expected events is sufficiently large. Results obtained for the asymptotic limits have been validated against the results without approximation for several mass scenarios close to the exclusion limit and good agreement has been found for the two methods.

10.1.2 Upper limit on production cross section

In addition to separating signal scenarios that can be excluded and such that cannot, an upper limit at 95% confidence level on the production cross section $\mu^{95\% \text{CL}} \sigma_s$ can be calculated for each signal, where σ_s is the nominal production cross section. The value of $\mu^{95\% \text{CL}}$ is determined by varying μ until $\text{CL}_s < 0.05$ is fulfilled.

10.1.3 Expected exclusion limit

Expected exclusion limits for the background-only hypothesis can be calculated by generating pseudo-data drawn from the probability density function $f(q_\mu|0, \hat{\theta}_0^{\text{obs}})$. This pseudo-data can then be treated as if it were real data in order to calculate CL_s and thereby to separate signal models that are expected to be excluded ($\mu^{95\% \text{CL}} < 1$) and such that are not ($\mu^{95\% \text{CL}} > 1$). For the optimization of the SR definition, expected limits have been calculated for various signal models in order to assess the sensitivity of the search for different SR configurations (c.f. Section 6.2). For the final interpretation, the relative positions of the expected and the observed exclusion limits indicate the level of agreement between data and the background prediction in sensitive SRs. Fluctuations of data over the background prediction in such SRs result in weaker observed exclusion limits with respect to the expected limit and vice versa for the fluctuation of data below the background prediction.

10.1.4 Observed significance

The results of the search are also interpreted in terms of the observed significance as a function of the sparticle mass for a given signal model. These scans are intended to quantify the probability that, given a certain signal model, the background-only hypothesis leads to the observed or more extreme deviations from the SM background expectation. Similarly to Equation 10.5, a test statistics q_0 is constructed, this time only for the background-only hypothesis, i.e., for $\mu = 0$

$$q_0 = -2 \ln \frac{\mathcal{L}(\text{data}|0, \hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}. \quad (10.9)$$

Differently than in the case of the limit setting procedure, $\hat{\mu}$ is neither restricted to be smaller than μ since the background-only hypothesis is evaluated in this case, nor is it restricted to nonnegative values. The latter aspect is not a standard for the calculation of observed significances, where normally fluctuations of data below the background expectation are not considered as evidence against the background-only hypothesis. Removing the restriction to positive values, however, allows to quantify also downward fluctuations of data below the background prediction in sensitive SRs. Note that the signal model dependence of the observed significance enters via $\hat{\mu}$ in the denominator of Equation 10.9. Similarly as for the calculation of CL_s, the test statistics corresponding to the observation q_0^{obs} is calculated and pseudo-data are created based on the probability density function of the test statistics for the background-only hypothesis $f(q_0|\hat{\theta}_0^{\text{obs}})$. Subsequently, the p-value p_0 , defined as

$$p_0 = P(q_0 \geq q_0^{\text{obs}}) \quad (10.10)$$

can be converted into a significance Z in terms of a one-sided tail of a Gaussian distribution, as given by

$$p_0 = \int_Z^\infty \frac{1}{\sqrt{2\pi}} \exp(-x^2/2) dx. \quad (10.11)$$

By convention, a significance of 5σ ($Z = 5$, corresponding to $p_0 = 2.8 \times 10^{-7}$) is required for claiming discovery of a new physics phenomenon. Excesses above 3σ are referred to as *evidence* for a new process.

10.2 Simplified model interpretation

Observing good agreement of the observed number of events with the SM background prediction in all SRs, the results presented in Chapter 9 are interpreted in terms of exclusion limits on masses of SUSY particles in the context of SMS topologies. As mentioned in Section 2.3.4, these models comprise only a small number of sparticles by assuming that the masses of all remaining particles are too heavy to be produced at the LHC. The decay chain is defined by considering fixed branching ratios of a parent particle to a given daughter particle. The unknown masses of the sparticles influence the expected number of signal events, firstly by determining the production cross section of the process, and secondly by influencing the kinematic properties of the final state particles and therefore the reconstruction efficiency of signal events. The ability of the search to discriminate a given signal model against SM background is probed by scanning the two-dimensional phase space of mass configurations of two of the sparticles involved in the decay chain. Masses of potential additional sparticles are either set to a fixed value or calculated as a function of the two variable masses. For each mass configuration, a signal cross section $\mu^{95\% \text{CL}} \sigma_s$ that can be excluded at 95% confidence level using the LHC-type CL_s method is extracted as described above. Hereby, the nominal signal cross section σ_s is calculated at NLO accuracy with next-to-leading-log gluon re-summation [95, 185–189].

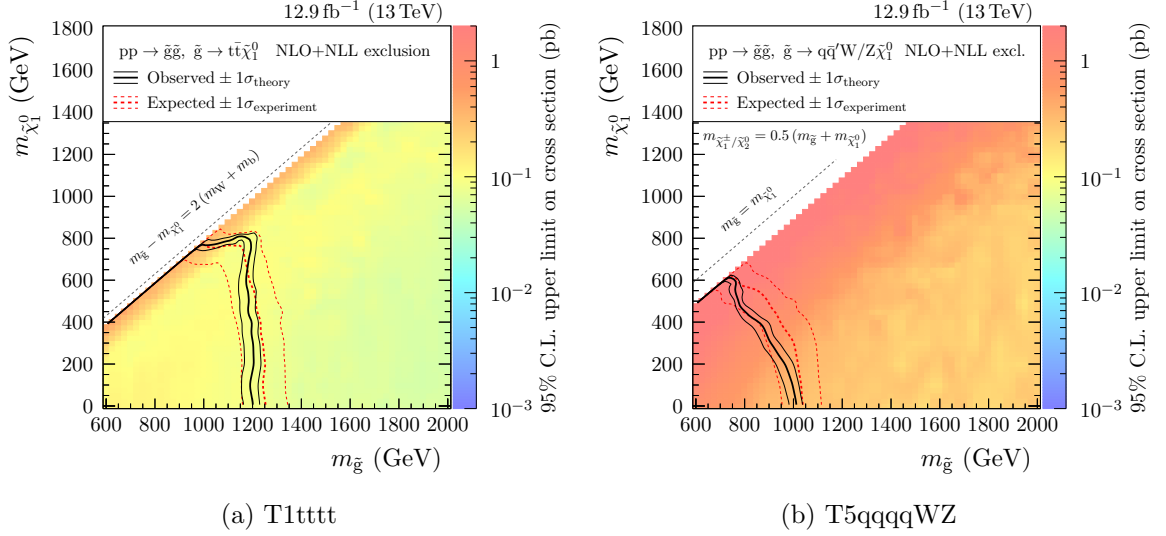


Figure 10.2: Exclusion limits in the gluino–LSP mass plane for the T1tttt (a) and the T5qqqqWZ simplified model (b), using the statistical combination of all 32 SRs of the search. The color scale indicates the signal cross section that is excluded at 95% confidence level. Mass scenarios below and to the left of the thick black line are excluded by the observed data for 12.9fb^{-1} of proton-proton collisions, where the uncertainty band is given by the theoretical uncertainty on the signal cross section. The thick red dashed line shows the expected exclusion limit whose uncertainty band is determined by the experimental uncertainties.

10.2.1 Exclusion limits for the T1tttt model

Figure 10.2 (a) shows the result of the limit setting procedure for the T1tttt simplified model using the statistical combination of all 32 SRs of the search for 12.9fb^{-1} of data. The observed exclusion limit is visualized as a solid, black line and separates mass scenarios that are excluded ($\mu^{95\text{CL}} < 1$) and such that are not excluded ($\mu^{95\text{CL}} > 1$). The excluded scenarios are below and to the left of the exclusion limit. The $\pm 1\sigma$ uncertainty band of the observed exclusion limit is obtained by varying the nominal signal cross section within its theoretical uncertainty. The expected exclusion limit is shown as red, dashed line and its uncertainty band includes the systematic uncertainties detailed in Chapter 8. Finally, the upper limit on the signal cross section at 95% confidence level is shown on the z axis of the plot.

As a result of the agreement between the observed and the expected number of events in all SRs, the expected exclusion limit is compatible with the observed limit within their $\pm 1\sigma$ uncertainty bands. Gluino masses up to 1200 GeV can be excluded in this model for LSP masses up to 775 GeV. For very small mass differences between the gluino and the LSP, the decay products have only low transverse momenta. This causes the signal selection efficiency to drop and leads to a lower exclusion limit. The excluded signal cross section is of the order of 0.1 pb and increases to 0.3–0.4 pb for compressed spectra close to the diagonal. The diagonal marks the kinematic limit, where the total rest mass of the decay products equals the gluino mass.

The relative positions of the observed and the expected exclusion limit can be understood by identifying the most sensitive SRs in different parts of the mass plane. For this purpose, exclusion limits have been calculated for each SR individually for one uncompressed spectrum with a gluino mass of 1200 GeV and an LSP mass of 100 GeV and one more compressed spectrum with the same gluino mass but heavier LSP with $m_{\tilde{\chi}_1^0} = 700$ GeV. The SRs are then ranked by ascending signal strength modifier $\mu^{95\text{CL}}$ of the expected exclusion limit. Table 10.1 shows the observed number of events and the expected contributions from

Table 10.1: Observed number of events and expected contribution from background and signal processes for an uncompressed ($m_{\tilde{g}} = 1200$ GeV, $m_{\tilde{\chi}_1^0} = 100$ GeV) and a compressed ($m_{\tilde{g}} = 1200$ GeV, $m_{\tilde{\chi}_1^0} = 700$ GeV) spectrum of the T1tttt simplified model for the three most sensitive SRs. The SRs are ranked by ascending signal strength modifier of the expected exclusion limit. Additionally, the signal strength modifier for the observed limit is listed.

$m_{\tilde{g}} / m_{\tilde{\chi}_1^0}$ (GeV)	SR	$N_{\text{bkg}}^{\text{exp}}$	N_{sig}	N_{obs}	μ_{exp}	μ_{obs}
1200 / 100	15 off-Z	$5.5 \pm 1.5^{+1.0}_{-1.1}$	$9.0 \pm 0.4^{+3.4}_{-2.8}$	6	0.9	1.0
	14 off-Z	$7.2 \pm 1.1^{+1.3}_{-1.2}$	$4.2 \pm 0.3^{+1.5}_{-1.3}$	12	2.2	3.8
	15b on-Z	$5.1 \pm 0.4^{+1.2}_{-1.2}$	$1.6 \pm 0.2^{+0.6}_{-0.5}$	7	4.7	6.2
1200 / 700	13 off-Z	$2.6 \pm 1.0^{+0.5}_{-0.5}$	$2.6 \pm 0.2^{+1.0}_{-0.8}$	1	1.5	2.0
	15 off-Z	$5.5 \pm 1.5^{+1.0}_{-1.1}$	$3.6 \pm 0.2^{+1.4}_{-1.1}$	6	2.5	2.3
	14 off-Z	$7.2 \pm 1.1^{+1.3}_{-1.2}$	$2.3 \pm 0.2^{+0.9}_{-0.7}$	12	4.0	7.0

background and signal processes for the three most sensitive SRs for the two signal scenarios. Additionally, the signal strength modifiers required to exclude the respective mass point at 95% confidence level are shown for the expected and the observed exclusion limits.

For the uncompressed spectrum, the high- $p_{\text{T}}^{\text{miss}}$ off-Z SR 15 provides the best sensitivity and the slight upward fluctuation of data over the prediction (c.f. Table 9.2) in this SR makes the observed limit slightly weaker than the expected limit. Close to the diagonal, the decreased mass splitting between the gluino and the LSP leads to smaller amounts of $p_{\text{T}}^{\text{miss}}$ in the final state, which degrades the sensitivity of SR 15. Instead, off-Z SR 13, which requires three and more b-tagged jets, provides the best sensitivity. The small downwards fluctuation of data below the expectation in this regions makes the observed limit stronger than the expected limit for compressed T1tttt scenarios.

The areas in the mass plane, where off-Z SRs 15 and 13 drive the sensitivity of the search can be visualized by plotting the observed significance as defined in Section 10.1.4. Figure 10.3 (a) shows the observed significance in the gluino–LSP mass plane in units of σ for the T1tttt model. Significances of about $+0.6\sigma$ are observed in regions where off-Z SR 15 drives the sensitivity, while significances of up to -1.1σ are found in regions where the sensitivity is dominated by SR 13. This result shows that all significances are small and compatible with statistical fluctuations.

10.2.2 Exclusion limits for the T5qqqqWZ model

In order to set a limit on the gluino and the LSP masses in the T5qqqqWZ model, events with the ZZ and the WW final state of the T5qqqqVV model have been filtered out, and the gluino-gluino pair production cross section has been scaled down by a factor of 4/9, assuming equal probabilities to produce each of the vector bosons. The exclusion limit in the gluino–LSP mass plane as derived from the statistical combination of all SRs is shown in Figure 10.2 (b). The mass of the intermediate chargino and neutralino has been fixed to the average of the gluino and the LSP mass, $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$. For this model, the limit on the gluino mass reaches 1000 GeV for a light LSP and drops to about 750 GeV for a compressed spectrum with an LSP mass of 600 GeV.

Table 10.2 shows the three most sensitive SRs for an uncompressed spectrum with a gluino mass of 1000 GeV and an LSP mass of 100 GeV and for one more compressed scenario with a gluino mass of 800 GeV and an LSP mass of 500 GeV. The best sensitivity for the

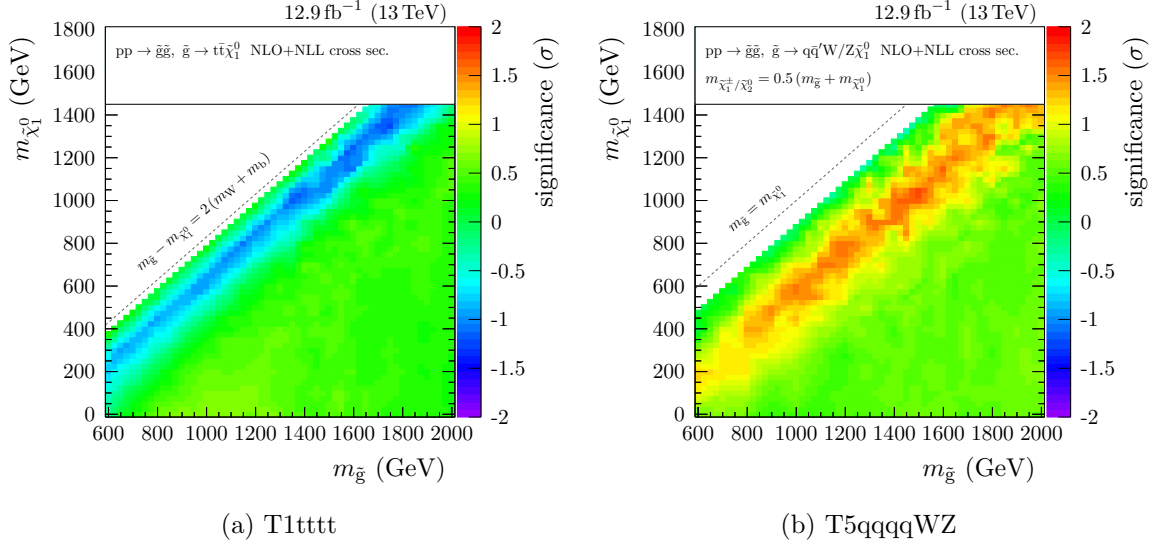


Figure 10.3: Significance scans for the T1tttt (a) and the T5qqqqWZ simplified model (b), visualizing the observed significance in different regions of the gluino–LSP mass plane. For both signal models the observed significances are below 2σ , indicating that the observed data are compatible with the background-only hypothesis.

uncompressed scenario is provided by the high- p_T^{miss} , high- H_T on-Z SR 15b, while on-Z SR 2, which imposes a b tag veto and requires small amounts of p_T^{miss} and H_T , drives the sensitivity for the signal model with smaller mass splitting. Owing to slight upwards fluctuations of data over the background prediction in both of these SRs, the observed limit is slightly weaker than the expected limit. Though, both limits are compatible with each other within their 1σ uncertainty bands. In this model, the excluded cross sections range from about 2 pb for compressed spectra to 0.3–0.5 pb for uncompressed scenarios.

Figure 10.2 (b) shows that significances of about $+0.5\sigma$ are observed for uncompressed spectra corresponding to regions in the mass plane where on-Z SR 15b provides the largest sensitivity and very close to the diagonal. Larger significances of up to $+1.8\sigma$ are observed for a moderate mass degeneracy between the gluino and the LSP. For such models the sensitivity is shared among several SRs, with on-Z SR 2 being the most sensitive one. As for the T1tttt model, all significances are below 2σ , which indicates that the observed data are compatible with the background-only hypothesis.

10.2.3 Post-fit nuisance parameters

As outlined in Section 10.1, the nuisance parameters used to model the uncertainties on the number of expected background and signal events are floating parameters while maximizing the likelihood function (Equation 10.4) for the background-only and the signal-plus-background hypotheses. Their so-called *pre-fit values* $\tilde{\theta}$ as given in Chapter 8 can therefore be modified during the maximization of the likelihood function. After the maximization they are referred to as *post-fit* nuisance parameters and denoted as $\hat{\theta}$. The associated parameter uncertainty changes from the pre-fit value $\sigma(\tilde{\theta})$ to the post-fit width denoted as $\sigma(\hat{\theta})$. Figure 10.4 presents the changes in both of these quantities for all 285 nuisance parameters used in the analysis. The shift of the central value is presented as pull parameter, defined as $(\hat{\theta} - \tilde{\theta})/\sigma(\tilde{\theta})$ (black point), while the change of the parameter uncertainty is shown as variance ratio $\sigma(\hat{\theta})/\sigma(\tilde{\theta})$ (blue error bar). Pull parameters that deviate significantly from zero can indicate wrong assumptions concerning the related systematic uncertainty and a wrong choice of the pre-fit nuisance parameter. Additionally, variance ratios significantly smaller than one indicate that the respective nuisance parameter is over-constrained by the

Table 10.2: Observed number of events and expected contributions from background and signal processes for an uncompressed ($m_{\tilde{g}} = 1000$ GeV, $m_{\tilde{\chi}_1^\pm} = 550$ GeV, $m_{\tilde{\chi}_1^0} = 100$ GeV) and a compressed ($m_{\tilde{g}} = 800$ GeV, $m_{\tilde{\chi}_1^\pm} = 650$ GeV, $m_{\tilde{\chi}_1^0} = 500$ GeV) spectrum of the T5qqqqWZ simplified model for the three most sensitive SRs. The SRs are ranked by ascending signal strength modifier of the expected exclusion limit. Additionally the signal strength modifier for the observed limit is listed.

$m_{\tilde{g}} / m_{\tilde{\chi}_1^0}$ (GeV)	SR	$N_{\text{bkg}}^{\text{exp}}$	N_{sig}	N_{obs}	μ_{exp}	μ_{obs}
1000 / 100	15b on-Z	$5.1 \pm 0.4^{+1.2}_{-1.2}$	$8.4 \pm 0.5^{+3.1}_{-2.5}$	7	0.9	1.2
	14b on-Z	$6.7 \pm 1.1^{+1.5}_{-1.5}$	$3.1 \pm 0.3^{+1.1}_{-0.9}$	5	2.8	2.4
	14a on-Z	$12.6 \pm 1.4^{+2.8}_{-2.8}$	$1.5 \pm 0.2^{+0.6}_{-0.5}$	12	8.6	8.2
800 / 500	2 on-Z	$22.7 \pm 1.7^{+4.8}_{-4.7}$	$13.9 \pm 1.5^{+5.2}_{-4.3}$	24	1.3	1.4
	15b on-Z	$5.1 \pm 0.4^{+1.2}_{-1.2}$	$5.0 \pm 0.8^{+2.5}_{-2.1}$	7	1.8	2.5
	15a on-Z	$2.2 \pm 0.2^{+0.5}_{-0.5}$	$2.5 \pm 0.6^{+1.0}_{-0.8}$	5	2.3	4.3

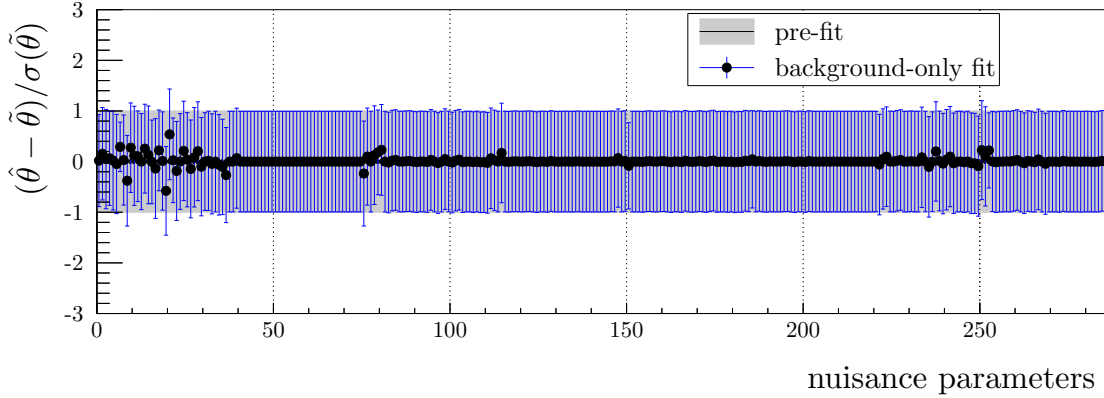


Figure 10.4: Post-fit versus pre-fit nuisance parameters for background-only hypothesis. The relative change of the central value of the nuisance parameter (black point) and the variance ratio (blue error bar) are shown with respect to their pre-fit values, normalized to a Gaussian function with mean zero and width one (grey band).

fit. The minor fluctuations of the pulls on the left-hand side of Figure 10.4 correspond to nuisance parameters that describe the statistical uncertainties on the number of events in the application regions used to estimate the nonprompt lepton background in some of the off-Z SRs. Slightly increased post-fit nuisance parameters are observed for the 15% uncertainty of the WZ normalization (pull +0.18, variance ratio 0.84), for the 50% uncertainty of the rare background normalization (pull +0.23, variance ratio 0.90), and for the uncertainty on the WZ extrapolation from the control region to the SRs (pull +0.22, variance ratio 0.74). Nevertheless, all variations are small compared to the parameter uncertainty with maximum deviations around $\pm 0.5 \sigma(\hat{\theta})$, indicating that the considered pre-fit values are appropriate estimates that are not modified drastically in the likelihood maximization procedure. Similar behavior has also been found for the signal-plus-background hypothesis for several tested signal scenarios.

10.3 Interpretation with most sensitive signal regions

In addition to the exclusion limits presented above, a simplified interpretation is provided using only the most sensitive SRs found for the compressed and the uncompressed benchmark

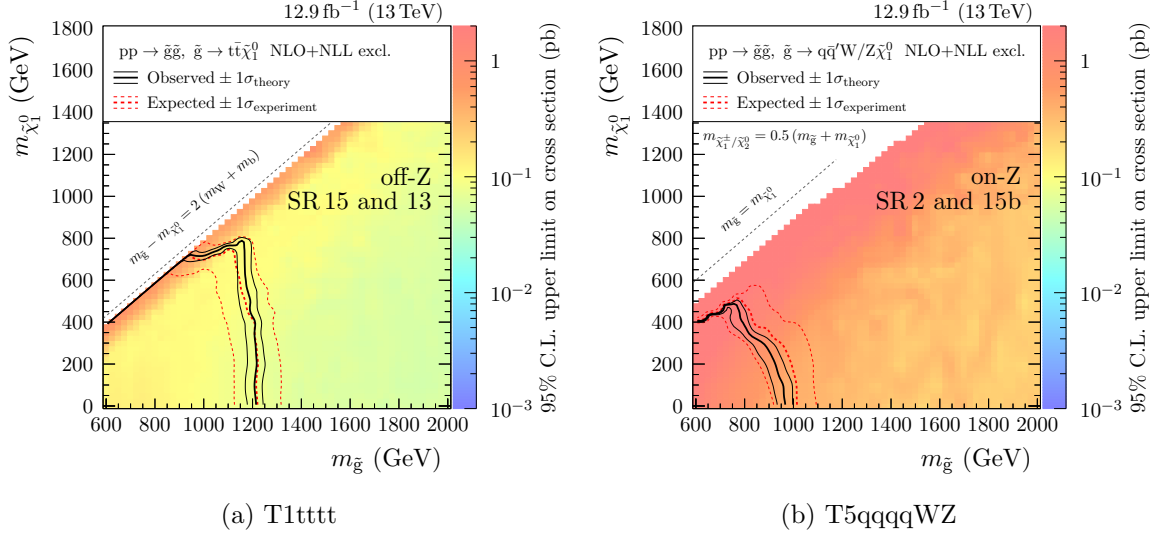


Figure 10.5: Exclusion limits in the gluino–LSP mass plane for the T1tttt (a) and the T5qqqqWZ simplified model (b), based on the combination of the most sensitive SRs for the compressed and the uncompressed benchmark models. The color scale indicates the signal production cross section that is excluded at 95% confidence level. Mass scenarios below and to the left of the thick black line are excluded by the observed data for 12.9 fb^{-1} of proton-proton collisions. The thick red dashed line marks the expected exclusion limit. Additionally, the $\pm 1 \sigma$ uncertainty bands are shown for both limits.

signals described above (c.f. Tables 10.1 and 10.2). This approach aims at largely reproducing the sensitivity achieved with the combination of all SRs while simplifying the selection criteria to allow for easier re-interpretation of the results by external researchers.

Exclusion limits based on a combination of the two most sensitive SRs are shown in Figures 10.5 (a) and (b) for the T1tttt and the T5qqqqWZ signal topologies, respectively. For the former, off-Z SR 15 ($p_T^{\text{miss}} > 300 \text{ GeV}$) and SR 13 ($N_b \geq 3, p_T^{\text{miss}} < 300 \text{ GeV}$) have been combined to maintain the sensitivity for uncompressed and compressed spectra. As can be seen from the comparison with Figure 10.2 (a), almost the same sensitivity can be achieved for the T1tttt model using only these two SRs.

Figure 10.5 (b) shows the exclusion limit for the T5qqqqWZ model using only on-Z SR 15b ($p_T^{\text{miss}} > 300 \text{ GeV}$, $H_T > 600 \text{ GeV}$) and SR 2 ($p_T^{\text{miss}} < 150 \text{ GeV}$, $H_T < 400 \text{ GeV}$, b jet veto). For a light LSP, almost the same sensitivity as with the combination of all SRs can be achieved, however, the maximum exclusion limit on the LSP mass drops from about 600 GeV to just below 500 GeV. Moreover, models with very small mass differences between the gluino and the LSP can no longer be excluded, owing to the distribution of signal events for compressed scenarios of the T5qqqqWZ model over several SRs with b tag veto (c.f. Figure 6.4). Overall, the simplified interpretation offers similar sensitivity for the T5qqqqWZ model as the combination of all SRs with some limitations for compressed scenarios.

10.4 Comparison with other results

Despite the smaller data set available at 13 TeV, the exclusion limits placed on gluino and LSP masses by this search extend the limits set by previous searches by CMS that examined the multilepton final state at $\sqrt{s} = 8 \text{ TeV}$ [154, 155]. With an integrated luminosity of 19.5 fb^{-1} of proton-proton collisions, these searches excluded gluino masses up to 1000 GeV in the T1tttt simplified model. The limit set by the presented analysis therefore constitutes an improvement of about 200 GeV in the gluino mass. The maximum exclusion limit on the LSP mass has been extended by a similar margin. This improvement is mainly due to the increase

of the gluino pair production cross section with the increased collision energy (c.f. Figure 4.2). Additionally, the systematic uncertainty on the nonprompt lepton background estimation could be reduced from 50% to 30% by employing the advancements in the tight-to-loose method outlined in Section 7.1.1. Limits set in the T5qqqqWZ model have been added as new interpretation for this search and have no comparable counterpart in the searches at $\sqrt{s} = 8$ TeV by CMS.

An analysis targeting events with same-signed dilepton pairs plus jets and p_T^{miss} in the final state [190], carried out by CMS at $\sqrt{s} = 13$ TeV with the same data set as the analysis presented in this thesis places even stronger limits of around 1 400 GeV on gluino masses in the T1tttt simplified model. This is due to the fact that the final state examined by the two analyses partly overlap as no veto on events with a third lepton has been employed in the same-sign dilepton analysis. The additional sensitivity for the T1tttt model arises from events with two same-signed leptons, where the third lepton is not reconstructed and which thus do not enter the event selection of the multilepton analysis. The limits placed on this model by the analysis presented in this thesis therefore have to be seen as complementary result. A genuine advantage of the multilepton search over the same-sign dilepton analysis, is the sensitivity to signal models with final state Z bosons, such as the T5qqqqWZ topology. This advantage arises from the necessity for a veto on events that contain an OSSF lepton pair whose invariant mass is compatible with the Z mass in the same-sign dilepton analysis. This veto is needed in order to reduce the large amount of SM background around the Z mass peak, a drawback that can be avoided by requiring a third lepton as in the multilepton analysis.

Finally, the results can be compared with the findings of a search targeting events with a same-signed dilepton pair or three leptons, performed by ATLAS at $\sqrt{s} = 13$ TeV, based on 13.2 fb^{-1} of proton-proton collisions [191]. Basic techniques for the discrimination of signal leptons against nonprompt leptons as well as the nonprompt lepton background estimation resemble the methods employed in analysis presented in this thesis. A conceptual difference is that each one dedicated SR is defined in the ATLAS search to target one specific signal model, whereas the search by CMS follows a more inclusive, model independent approach. A one-to-one comparison of the results is difficult because the ATLAS search analyzes events with less than three leptons if they contain a same-signed dilepton pair, whereas the search presented in this thesis is dedicated to events with three or more leptons only. In the ATLAS search, gluino masses up to about 1 450 GeV are excluded in the T1tttt model based on a SR that requires $N_b \geq 3$, $N_{\text{jets}} \geq 4$, $p_T^{\text{miss}} > 150$ GeV and $m_{\text{eff}} > 600$ GeV, where m_{eff} is a quantity similar to H_T in this analysis plus the scalar sum of the transverse lepton momenta. Note that the observables N_b , N_{jets} , and p_T^{miss} are defined similarly but not identically as in the context of this thesis. As outlined for the same-signed dilepton search performed by CMS, the sensitivity for this model is increased with respect to the multilepton analysis by including events with only two leptons if they have the same charge. Two SRs that impose a veto on b-tagged jets and that require $N_{\text{jets}} \geq 6$, $p_T^{\text{miss}} > 150$ GeV and $m_{\text{eff}} > 500$ (900) GeV are interpreted in a model featuring gluino pair production with light quarks and vector bosons in the final state ($\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_1^\pm \rightarrow q\bar{q}'W^\pm\tilde{\chi}_2^0 \rightarrow q\bar{q}'W^\pm Z\tilde{\chi}_1^0$). In contrast to T5qqqqWZ, each gluino decay chain produces one Z and one $W^\pm$ boson, mediated by each one intermediate chargino and neutralino, thus giving rise to a total of four vector bosons yielding up to six leptons. For this model, gluino masses up to 1 550 GeV are excluded, representing a stronger limit on the gluino mass compared to the T5qqqqWZ model because the larger lepton multiplicities result in larger signal selection efficiencies.

11. Intermediate Summary

The results of a search for supersymmetry in events with three or more charged leptons, jets, and missing transverse momentum have been presented. The analyzed data set corresponds to 12.9 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV that has been recorded with the CMS detector in 2016. The large lepton multiplicity and the resulting low background contributions make the regarded final state well suited to probe the standard model and to search for deviations from its predictions that could arise from the decay of pair produced supersymmetric particles. Specifically, the presented analysis targets signal models that involve the production of colored supersymmetric particles — squarks or gluinos — and that conserve R-parity.

In order to maximize the sensitivity of the search for various signal topologies, 32 exclusive signal regions are examined. Events are categorized according to the invariant mass of opposite-sign, same-flavor dilepton pairs in the event, the amount of hadronic activity and missing transverse momentum, and the number of b jets. Irreducible standard model background contributions are predicted with Monte Carlo simulations, while reducible backgrounds are estimated with a data-driven method. The latter predicts the contribution of the nonprompt lepton background within an uncertainty of about 30%.

The observed data are found to agree with the standard model prediction within the uncertainties in all 32 signal regions. The results are therefore interpreted in terms of exclusion limits on gluino and LSP masses in the context of two different simplified model topologies featuring gluino pair production. In a model that produces four top quarks and two stable neutralinos, gluino masses up to 1 200 GeV and LSP masses up to 775 GeV have been excluded. Compared to a similar search conducted by CMS at $\sqrt{s} = 8\text{ TeV}$ [154], this represents an extension of the exclusion limit of about 200 GeV in both masses. In another model that yields four light quarks, a $W^\pm$ and a Z boson, and two stable neutralinos, gluino masses up to 1 000 GeV and LSP masses up to 600 GeV have been excluded. The observed significances are found to be below 2σ for both signal models across the examined phase space with gluino masses between 600 GeV and 2 000 GeV, indicating that the observed data are compatible with the standard model-only hypothesis.

Part II

Radiation Tolerance of the Digital Readout Chip for the Phase I Upgrade of the CMS Pixel Detector

12. Status and Prospects of High-Energy Physics at the LHC

At the time of submitting this thesis, the LHC had been delivering proton-proton collisions at $\sqrt{s} = 13$ TeV for about one and a half years and a host of publications have been released by the experiments studying this uncharted territory. Many important results have confirmed SM predictions and the properties of the Higgs boson could be determined more accurately than at the time of its discovery. However, hopes to find compelling evidence for new physics phenomena early after the increase of the center-of-mass energy have been dashed. Although a few incompatibilities between data and SM predictions with local significances up to 2.5σ (e.g., Refs. [192, 193]) have been observed, they should be interpreted reservedly as none of them is found in both the ATLAS and the CMS experiment in the same channel or in consistency with previous results. Furthermore, some incompatibilities of this order of magnitude are expected from statistical fluctuations, given the large number of final states and search regions examined by the experiments. The SM therefore seems to correctly predict observations at $\sqrt{s} = 13$ TeV, at least at a level of precision that is accessible with the amount of data available so far and the agreement between data and SM predictions found in the analysis presented in Part I of this thesis can be seen as exemplary for the current situation of BSM searches at the LHC.

However, the theoretical and phenomenological indications for BSM physics discussed in Chapter 2 remain nonetheless intriguing and the first few years of LHC operation only mark the start of a long endeavor that will last long into the 2030's. Two complementary approaches for the search for new physics will be followed during that era. Direct searches for new particles will be continued, to compare SM predictions and data with smaller statistical uncertainties. This is especially important for searches with relatively small signal efficiencies such as the presented search in the multilepton final state. In addition, analyses will have to be refined in order to reduce systematic uncertainties to resolve potentially small deviations from the SM expectation. Additional effort is needed to cover gaps in the investigated phase space, e.g., close to kinematic boundaries in compressed SUSY scenarios, where the final state particles have very small transverse momenta and are thus harder to detect. The second strategic thrust on the quest for evidence for BSM physics are precision measurements, e.g., of properties of the Higgs boson and the top quark. The underlying idea is that the existence of undiscovered particles can alter properties of SM particles through virtual loop corrections as outlined in Section 2.2.4. Detecting such deviations from the SM predictions would therefore provide indirect evidence for new physics.

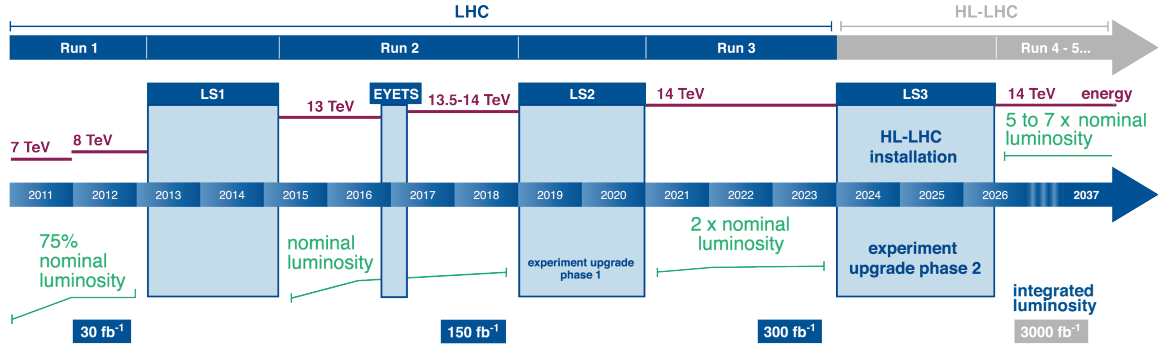


Figure 12.1: Schedule for different LHC expansion stages and anticipated temporal evolution of the center-of-mass energy as well as the instantaneous and the integrated luminosity. The instantaneous luminosity is given with respect to the nominal LHC luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The Phase I Upgrade of the CMS pixel detector has been completed during the extended year end technical stop (EYETS) of the accelerator in the beginning of 2017. Modified from [194].

Both approaches, direct BSM searches and precision measurements, require significantly larger amounts of data compared to the integrated luminosity available so far in order to answer if the SM is an accurate description of physics at the TeV scale. To this end, it is planned to increase the instantaneous luminosity of the LHC in the forthcoming years to twice its current design specification, i.e., to $\mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. It is foreseen to operate the accelerator at this instantaneous luminosity until the end of the year 2023 and by then it is expected to have delivered a total of about $300\text{--}500 \text{ fb}^{-1}$ of data to the ATLAS and CMS experiments [194, 195]. This so-called *Run 3* of the LHC is followed by the two and a half year long lasting LS3 to prepare a second major expansion stage of the accelerator, referred to as High-Luminosity Large Hadron Collider (HL-LHC), where the luminosity will be increased to $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ or more. The HL-LHC is planned to be operated for more than ten years to increase the integrated luminosity by another order of magnitude to about 3000 fb^{-1} . An overview of the LHC schedule and the anticipated temporal evolution of the instantaneous and the integrated luminosity is shown in in Figure 12.1.

The large increase in instantaneous and integrated luminosity poses several challenges to the experiments and requires major hardware upgrades of the detectors. The increased instantaneous luminosity needs to be accounted for by increasing the readout speed of the subdetectors, as a significantly increased number of particle interactions is to be expected per bunch crossing. Especially in view of the instantaneous luminosity expected for the HL-LHC, the larger number of pileup collisions requires finer segmentation of the tracking detectors. A finer segmentation keeps the occupancy of individual channels low and allows to maintain a high hit detection efficiency. The main challenge arising from the long operation time and the large integrated luminosity is to develop radiation tolerant detectors, which withstand an enormous flux of particles and the associated radiation damage in the sensors and the readout electronics. Both the ATLAS and the CMS Collaborations plan to replace most of the subdetectors and large parts of the service infrastructure in the so-called *Phase II Upgrade* of the experiments, foreseen to be installed during LS3 before the HL-LHC becomes operational [196, 197]. Selected subsystems that are especially affected by the tightened conditions are upgraded even earlier in the so-called *Phase I Upgrade*. Most of these advancements are planned to be installed during LS2 (c.f. Figure 12.1). In case of the CMS experiment, however, the Phase I Upgrade of the pixel detector has been brought forward to the extended year end technical stop of the LHC in winter 2016/2017. This exception is motivated by two aspects. Firstly, the pixel detector as the innermost subsystem of the experiment is especially affected by radiation damage and the original design specification

of $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ has already been exceeded by the LHC in summer 2016. Secondly, the technical layout of the CMS detector allows for a relatively fast replacement of the pixel detector. This makes it possible to install the new detector without waiting for the next long shutdown of the LHC and therefore provides the possibility to profit from the improved performance of the new system as early as possible.

The second part of this thesis is dedicated to studies conducted in the context of this Phase I Upgrade of this CMS pixel detector. More stringent requirements in terms of radiation tolerance and readout speed required the design of a new readout chip (ROC), used to amplify, buffer, and read out signals from the silicon sensors of the detector. The goal of the presented study is to verify the design of this new front-end chip after proton irradiation, used to induce comparable radiation damage as expected during the lifetime of the detector and beyond. A concise summary of the results presented in Part II of this thesis has been published in Ref. [198].

13. The CMS Pixel Detector and the Phase I Upgrade

Silicon pixel detectors are indispensable devices for almost all modern high-energy particle physics experiments that operate in high-occupancy environments. They are used whenever trajectories of charged particles need to be determined with the best possible spatial resolution in environments with very high track densities close to the interaction region of the colliding particles. Charged particles emerging from the collisions create electron-hole pairs in the semiconductor sensors of the tracking detector and thereby induce electrical signals that allow to detect the particles' passage. As opposed to strip detectors, which have a one-dimensional segmentation of the sensors, pixel detectors employ a checkered segmentation of the electrode to achieve two-dimensional spatial resolution and to decrease the occupancy of individual readout channels. Key aspects for the construction and operation of pixel detectors are the technologically challenging connection of the individual sensor segments to the associated front-end electronics, the requirement to read out at large data rates, and the stringent demands concerning the tolerance of all detector components against radiation damage arising from the passage of large quantities of particles.

In order to put the studies presented in the second part of this thesis into context, Section 13.1 summarizes basic concepts of semiconductor physics and how they are exploited to build tracking detectors. A review of important aspects of silicon as sensor material and of radiation induced damage mechanisms is complemented with a concise summary of the hybrid pixel detector layout and basic functionalities of the associated front-end electronics.

Section 13.2 then expands on this general information to introduce the Phase I Upgrade of the CMS pixel detector. The motivation for developing a new detector is outlined and specifications and the projected performance of the new system are presented. Furthermore, the different detector components are introduced with emphasis on advancements with respect to the former CMS pixel detector, which had been used prior to the upgrade.

13.1 Semiconductor tracking detectors

Trajectories of charged particles provide crucial information for the reconstruction of particle collisions in high-energy physics experiments. Intersecting the trajectories allows to locate primary and secondary vertices and combining tracking information with measurements of other subdetectors is essential for particle identification as described in Section 5.1. Additionally, the curvature of a charged particle's trajectory in a magnetic field allows to determine

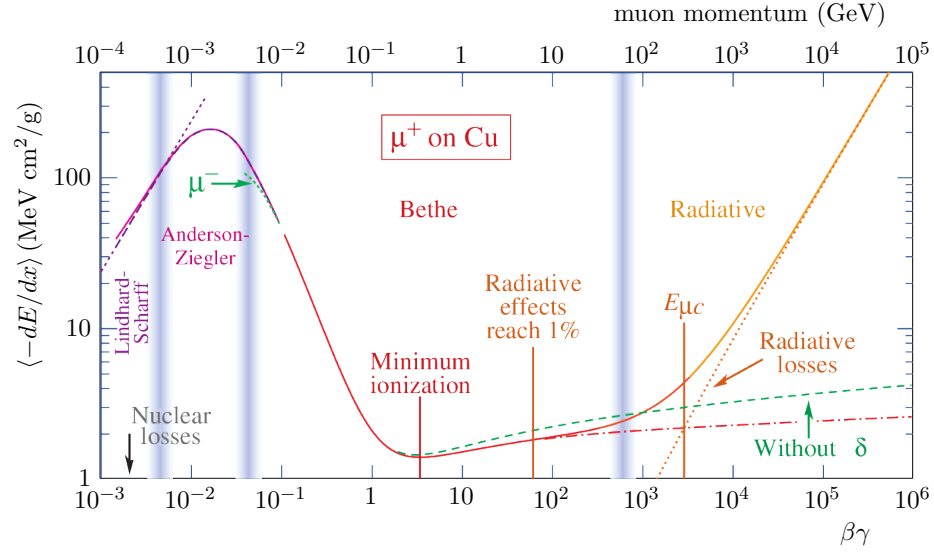


Figure 13.1: Mean energy loss of muons traversing copper. The Bethe equation describes the mean energy loss of moderately relativistic heavy charged particles in absorbers with intermediate atomic numbers Z . For $\beta\gamma \approx 2-3$ the mean energy loss exhibits a global minimum. Modified from [11].

the polarity of the charge and the particle's transverse momentum. In order to acquire this information, the particle needs to interact with a suitable detector material, where the deposited energy is transformed into an electrical signal. This signal is amplified, read out, and stored, followed by the reconstruction of the particle's trajectory based on signals induced in several successively arranged detector layers. In order to unambiguously identify signals induced by traversing particles, the detector needs to have a high *signal-to-noise ratio*, i.e., particle induced signals need to be large compared to the noise in the readout electronics.

13.1.1 Interaction of charged particles with matter

The working principle of semiconductor tracking detectors in high-energy physics experiments is based on electromagnetic interactions between a traversing charged particle and the sensing material of the detector. Two different energy loss mechanisms of particles in matter can be distinguished: ionizing and non-ionizing energy loss. For charged particles ionizing energy loss is the dominant contribution and leads to the ionization of the absorber material, or, in the case of semiconductor materials, to the creation of electron-hole pairs as will be discussed in Section 13.1.2. Non-ionizing energy loss arises from electromagnetic, and in the case of traversing hadrons, from nuclear interactions between the traversing particle and the atomic nuclei of the absorber material. The latter form of energy deposition cannot be exploited for signal generation in tracking detectors but plays an important role for radiation induced damage of the sensor material as will be described in Section 13.1.5.

The energy loss of charged particles passing through matter can be regarded as a sequence of collisions with very small energy transfers and hence as quasi-continuous deceleration. For moderately relativistic particles with rest-masses significantly above the electron mass, the mean energy loss rate or *stopping power* is well described by the Bethe formula [11]

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right], \quad (13.1)$$

where z denotes the charge number of the incident particle, Z and A the atomic number and the mass of the absorber material, and $K \approx 0.307 \text{ MeV mol}^{-1} \text{ cm}^2$ a constant. Additional absorber dependent parameters are the maximum energy transfer in a single collision $W_{\max}$ (in

units of MeV) and the mean excitation energy I (in units of eV). The last term $\delta(\beta\gamma)$ describes a correction arising from relativistic distortions of the electric field of the traversing particle and the associated polarization of the absorber. The mean energy loss of heavy charged particles shows a distinct momentum dependence, which enters Equation 13.1 through the relativistic factors $\beta = v/c$ and $\gamma = (1 - \beta^2)^{-1/2}$. As can be seen in Figure 13.1 at the example of muons traversing copper, the Bethe equation is valid in the range $0.1 \lesssim \beta\gamma \lesssim 1000$ and exhibits a global minimum at around $\beta\gamma \approx 2-3$. For absorbers with moderate atomic numbers Z , the location of the minimum is, in good approximation, independent of the material. Particles in this energy range are therefore called minimum ionizing particles (MIPs). At low energies, where the velocity of the traversing particle becomes comparable to the velocity of the shell electrons of the absorber material, Equation 13.1 breaks down and other models have to be used to describe the energy loss. On the other side of the spectrum, radiative energy losses that rise linearly with $\beta\gamma$ dominate the stopping power for particles with high momenta.

13.1.2 Silicon as sensor material

The part of the deposited energy that is transferred to the absorber's shell electrons can cause ionization of the atoms along the trajectory of the traversing charged particle. In order to collect the thereby freed charge carriers within a short latency, an electric field has to be applied between two or more electrodes at the surface or within the absorber. Viable sensor materials have to meet two important requirements. First and foremost, the mean free path of the charge carriers drifting through the absorber has to be large compared to the drift distance. This is required to obtain a high charge collection efficiency (CCE), defined as the fraction of the charge that is collected at the electrodes over the total amount of initially freed charge. Secondly, the absorber needs to have a high electrical resistance in order to minimize the current flowing between the electrodes in the absence of incident particles. This so-called *leakage current* needs to be small as it constitutes a background that the small signals induced by traversing particles have to be discriminated against. Absorbers that are widely used in tracking detectors for high-energy physics experiments are gases and semiconductor materials. While the former allow for the construction of cost-effective and robust large-scale detectors, semiconductor detectors are used to achieve the best possible spatial resolution in environments with large track densities as they allow for finer electrode segmentation and offer larger signal amplitudes. Silicon is the most widely used sensor material in contemporary position sensitive semiconductor detectors, both because of suitable properties of the material and because of economical and practical reasons related to the availability of mature and reliable production processes for silicon-based technologies in industry. Extensive reviews of electric properties of silicon are available in literature and the following summary largely follows Ref. [199].

Band gap energy

When binding individual atoms of an element into a crystal lattice, the identical and discrete energy levels of the shell electrons degenerate and the large density of states forms quasi-continuous energy bands. Individual bands can be separated by 'forbidden' energy ranges or *band gaps*. The highest energy band in which all states are occupied by electrons at absolute zero and in the absence of external excitations is called *valence band*. The next higher band is referred to as *conduction band*, since electrons populating this band engender the electrical conductivity of the material.

Semiconductor materials are characterized by having a small energy gap of only a few eV between the valence and the conduction band and an empty conduction band at $T = 0\text{ K}$. For $T > 0\text{ K}$, however, electrons from the valence band can be thermally excited and promoted to the conduction band, where they increase the material's conductivity. In the case

of silicon, the band gap amounts to $E_g = 1.12 \text{ eV}$. Constraints from momentum conservation with quantized phonons in the lattice of the silicon crystal increase the energy needed for an electron to be excited into the conduction band to $E_i = 3.6 \text{ eV}$. The band gap of silicon is therefore referred to as an *indirect band gap*. The fundamental working principle of semiconductor detectors builds on the fact that electrons can not only be excited thermally, but also by energy deposited by a traversing charged particle. Once excited, electrons leave a vacant state in the valence band. Such states act as positive quasi-particles, referred to as *holes*, which also contribute to the conductivity of the semiconductor. The number of electron-hole pairs N_e created along the trajectory of the particle is proportional to the deposited energy E

$$N_e = \frac{E}{E_i}. \quad (13.2)$$

The corresponding signal charge of $Q_s = eN_e$ is larger compared to gaseous detectors where an ionization energy of $\mathcal{O}(10 \text{ eV})$ is required per charge carrier. Once excited, electrons and holes drift through the silicon sensor with a velocity of

$$\vec{v}(x) = \mu \vec{E}(x), \quad (13.3)$$

proportional to the applied electric field and are collected at the electrodes. The mobility μ of electrons in silicon is $1350 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, limited by scattering processes of the electrons with crystal defects, impurities, and phonons, i.e., quantized excitations of the lattice atoms. For field strengths above 10^3 V/cm , the mobility decreases and the drift velocity saturates at about 10^7 cm/s . For holes, the mobility is about three times smaller compared to electrons [199].

Charge carrier density and *pn*-junction

For any technically feasible operation temperature of a detector, thermal excitation in silicon leads to charge carrier densities that are orders of magnitude larger than signals induced by traversing particles. As this would render the detector insensitive, a drastic reduction of the intrinsic charge carrier density is required in order to make silicon a viable sensor material.

This is achieved by exploiting the strong dependence of the conductivity of silicon on the concentration of impurities in the crystal lattice. In a process called *doping*, very low concentrations of impurities are introduced into the silicon lattice deliberately. Doping silicon with group-V elements such as phosphorous, which feature one more valence electron than silicon, increases the concentration of free electrons in the material. This is because the dopant introduces a donor state slightly below the conduction band, allowing loosely bound electrons to be easily excited into the conduction band. Contrariwise, doping with group-III elements, which have one valence electron less than silicon, introduces an acceptor state slightly above the valence band and hence increases the concentration of holes in the valence band. Semiconductors with increased free electron densities are referred to as *n*-doped and such with increased free positive charge carriers as *p*-doped semiconductors.

When joining *n*- and *p*-doped silicon in a so-called *pn*-junction, it is energetically favorable for electrons to diffuse from the *n*-doped into the *p*-doped silicon, while holes move across the junction in the opposite direction. A stable equilibrium is established once the electric field built up by the positive and negative space charges is strong enough to stop the diffusion. As a result, a region depleted of free charge carriers is formed at the junction, whose penetration depth into the two silicon layers depends on the respective doping concentrations and can be asymmetric. The potential difference arising from the migration of charge carriers across the *pn*-junction is referred to as *build-in voltage* U_{bi} and amounts to about 0.5 V in silicon.

Depletion voltage

The desired reduction of the charge carrier concentration in the sensor material can be achieved by extending the build-in depletion zone at the pn -junction. This is achieved by applying a reverse bias voltage U_b with the positive polarity at the n -side of the junction. For a typical implementation, where a thin layer of heavily p -doped silicon, denoted as p^+ , is joined with a thicker moderately doped n -substrate or *bulk material*, the width of the depletion zone in the bulk is given by

$$w_{\text{depl}} = \sqrt{\frac{2\epsilon(U_b + U_{\text{bi}})}{Ne}}. \quad (13.4)$$

Here, N denotes the dopant concentration in the bulk material and $\epsilon = 11.9\epsilon_0$ the dielectric constant of silicon, which can be expressed as a multiple of the vacuum permittivity ϵ_0 . The *depletion voltage* U_{depl} is defined as the minimum bias voltage needed to deplete the full sensor volume. For smaller bias voltages, the sensor is only partially depleted and the collected signal charge decreases linearly with the width of the depletion zone $Q_s \propto w_{\text{depl}}$. In practice, detectors are often operated in *overbias mode* with $U_b > U_{\text{depl}}$ to minimize the charge collection time.

13.1.3 Capacity and leakage current

The pn -junction forms a plate capacitor with capacity $C \propto A/\sqrt{U_b}$ for $U_{\text{bi}} \ll U_b < U_{\text{depl}}$, where A is the area of the regarded junction. Once the depletion voltage is reached, the capacity becomes independent of the bias voltage and is proportional to the inverse of the sensor thickness d . For fine segmented pixel detectors, additional contributions to the total capacity of one pixel arise from the fringing capacitance to adjacent pixels. The sensor capacitance has to be kept small, as a large capacitance, among other things, degrades the signal-to-noise ratio of the detector [199].

While the reverse bias mode depletes the sensor volume of free charge carriers to first approximation, a small residual leakage current flows between the electrodes even in the absence of external traversing particles. Its origin in the thermal excitation of electrons into the conduction band is reflected by the exponential dependence on the temperature T [199]

$$I_{\text{leak}} \propto T^2 \exp\left(-\frac{E_g}{2kT}\right), \quad (13.5)$$

where k is the Boltzmann constant and E_g band gap energy. The exponential dependence on the temperature allows to significantly reduce leakage currents by moderate cooling of the silicon sensors, a feature that is usually used to minimize the power consumption of the detector. Additionally, lower leakage currents improve the signal-to-noise ratio [199]. The leakage current strongly depends on the presence of impurities in the lattice crystal, since they introduce additional energy levels between the valence and the conduction band. Such additional energy levels facilitate the stepwise promotion of electrons into the conduction band and hence increase the leakage current at a given temperature. This effect is particularly important after irradiation of the silicon sensor as will be discussed in Section 13.1.5.

13.1.4 Signal formation and collection

Charge carriers created by a traversing particle drift to the electrodes under the influence of the applied electric field. The drift time required to traverse the full sensor width is referred to as charge collection time t_c . Approximating the average electrical field as $\bar{E} = U/d$ with $U = U_{\text{bi}} + U_b$ and using Equation 13.3 yields

$$t_c \approx \frac{d}{v} = \frac{d}{\mu U}. \quad (13.6)$$

The above equation is only valid in the low-field regime, where the electron mobility is independent of the electric field. For a typical sensor thickness of $d = 300 \mu\text{m}$, the maximum drift velocity of about 10^7 cm/s results in charge collection times of a few ns, which allows to collect the charge within one LHC bunch spacing interval. Because of induction effects, a signal current can be measured at the electrodes during the full charge collection time and not only after the first charge carriers have reached the respective electrode [200, 201].

While drifting, the cloud of charge carriers experiences thermal diffusion. Using the average field approximation and the diffusion constant $D = kT\mu/e$, the width of the cloud increases to

$$\sigma_y = \sqrt{2Dt} \approx \sqrt{2 \frac{kT}{e} \frac{d^2}{U}}, \quad (13.7)$$

after drifting through a sensor of the width d . This spread is independent of the mobility of the charge carriers. As indicated in Section 3.3.2, charge sharing between adjacent pixels can be exploited to improve the spacial resolution of the detector. However, the width of the charge carrier cloud arising from thermal diffusion in the lateral direction is typically significantly smaller than the pixel pitch and only amounts to a few μm . Therefore, the lateral deflection of the charge carriers is often enhanced by taking advantage of the magnetic field that is superimposed to the tracking volume to bend the trajectories of charged particles for p_T measurements. Orientating the sensors in such a way that the magnetic field is orthogonal to the drift of the charge carriers to the electrodes, causes a Lorentz force induced deflection in the lateral direction under the Lorentz angle θ_L

$$\tan \theta_L = B\mu. \quad (13.8)$$

Depending on the magnetic field strength, the sensor thickness, and the pixel pitch, this results in a spread of the charge carrier cloud over several adjacent pixels. The Lorentz angle is smaller for holes than for electrons because of its dependence on the mobility.

The proportionality between the deposited energy and the generated charge makes energy measurements with silicon detectors basically possible. However, tracking detectors aim at minimizing multiple scattering and therefore feature sensors with thicknesses of only 50–300 μm . Such thin sensors entail that the energy deposited by a charged particle is subject to large statistical variations, which renders energy measurements relatively imprecise. The fluctuations are caused by rare collisions in which the incident particle undergoes a head-on collision with one of the absorber's shell electrons. If a sufficiently large amount of energy is transferred in such a collision, the freed electron itself can produce electron-hole pairs along its path through the sensor. In order to account for the large energy deposits from these so-called *delta rays* [202], the resulting spectrum can be approximated using a Landau-Vavilov distribution [203, 204]. The distribution resembles a Gaussian distribution at low energies but features a distinct asymmetric tail towards high energies, causing its mean value to be considerably larger than its most probable value.

13.1.5 Radiation damage in silicon sensors

Silicon tracking detectors are usually operated in close proximity to the IP and hence in an highly radiative environment. The passage of $\mathcal{O}(10^{14} - 10^{15})$ particles/ cm^2 through the

detector during a typical lifetime entails stringent demands in terms of radiation tolerance. Ionizing and non-ionizing energy loss of these particles in the detector lead to two distinct radiation induced damage mechanisms: space charge accumulations in non-conductive parts of the detector and displacement damage in the lattice structure of the silicon sensor. Both of these cumulative damage mechanisms affect different properties of the detector. Ionizing radiation damage arises from permanent or semi-permanent space charge accumulations in insulator layers, often implemented as silicon dioxide (SiO_2). In such layers, the creation of electron-hole pairs yields a positive net space charge if the electrons can migrate out of the insulation layer while the holes remain within the layer owing to their significantly lower mobility. Additionally, space charge accumulation occurs at interfaces between these oxide layers and the crystalline silicon. This damage mechanism depends on the total ionizing dose (TID) absorbed by the detector. In the sensors, the effect can change the inter-pixel or inter-strip resistances. In addition, ionizing radiation damage affects the readout electronics of the detector by modifying the properties of transistors and integrated circuits (ICs). As this aspect of ionizing radiation damage is of central importance for the radiation tolerance assurance tests presented in this thesis, it is described in greater detail in Chapter 15.

Displacement damage on the other hand is the dominant mechanism affecting characteristics of the silicon sensor and arises from non-ionizing energy loss of traversing particles. The damage depends on the total kinetic energy transferred to a silicon lattice atom in a collision and hence on the type and on the energy of the incident particle. Energy transfers larger than 25 eV dislocate silicon atoms in the sensor bulk, forming interstitials and vacancies in the lattice. Since typical collision of incident particles in the MeV range yield energy transfers much higher than 25 eV, the recoiling silicon atom usually displaces of the order of 1 000 additional lattice atoms along its path, creating damage clusters with a size of about 0.1 μm [205]. Displacement damage is commonly normalized to the damage caused by neutrons with an energy of 1 MeV, expressed in units of $n_{\text{eq}}/\text{cm}^2$. The multiplicative factor relating the damage of an incident particle with a given energy to the damage caused by 1 MeV neutrons is referred to as *hardness factor* α and needs to be determined experimentally. As described in the following paragraphs, displacement damage alters three main characteristics of silicon sensors: leakage current, effective doping concentration, and the CCE. Detailed information on radiation effects in silicon sensors can be found, e.g., in Ref [206].

Increasing **leakage currents** after irradiation are related to the formation of energy states in between the valence and the conduction band. These mid-gap states facilitate the thermal excitation of electrons into the conduction band. Experimental data show that the leakage current increases linearly with the particle fluence Φ , which suggests a uniform distribution of defects in the sensor volume $A \cdot d$

$$I_{\text{irrad.}} = I_0 + \alpha \Phi A d, \quad (13.9)$$

where I_0 denotes the current before irradiation and α the aforementioned hardness factor. Because of the steep increase of the leakage current, cooling of the detector becomes of paramount importance after irradiation to minimize the power consumption of the detector. Fitting the observed temperature dependence of the leakage current after irradiation with a fluence of $2.3 \times 10^{13} \text{ cm}^{-2}$ with Equation 13.5 indicates an increased activation energy of 1.2 eV compared to the band gap energy of $E_g = 1.12 \text{ eV}$ in the nonirradiated case [207].

A second effect of the displacement damage affects the **effective doping concentration** in the bulk material. For n -type silicon it has been observed that the effective doping concentration initially decreases with fluence until the material appears to be undoped. Further irradiation leads to an effective doping concentration with opposite polarity, giving the sensor characteristics comparable to p -doped silicon [208]. This process is referred to as *type*

inversion and occurs after a fluence of the order of 10^{13} cm^{-2} , with the exact value depending on the initial doping concentration. The effect can be explained with the creation of additional acceptor states. Additionally, indications for a concurrent process of donor removal exist [209]. The acceptor states are populated by electrons from the bulk and constitute a growing negative space charge that gradually compensates the positive space charge in the depleted *n*-type silicon and finally inverts it. As a consequence, the effective doping concentration of the bulk material N_{eff} changes with increasing particle fluence. This requires an adjustment of the bias voltage proportional to the absolute value of N_{eff} in order to deplete the full sensor volume (c.f. Equation 13.4)

$$U_b = \frac{e}{2\epsilon} |N_{\text{eff}}| d^2. \quad (13.10)$$

When using *n*-bulk sensors, the bias voltage required for full depletion therefore initially decreases before it increases significantly after type inversion.

The charge carrier density shows a distinct time dependence, known as *annealing*, which is strongly influenced by the temperature of the sensor. At room temperature, so-called *beneficial annealing* reduces the charge carrier concentration by ‘healing’ lattice defects through thermal migration of interstitials. This effect has a time constant of the order of days. For longer periods, *reverse annealing* dominates and leads to increasing charge carrier concentrations. The effect acts on time scales of months to years and enhances aging effects even in the absence of incident irradiation. Annealing effects can be mitigated by cooling the sensors to temperatures below 0°C , which is why semiconductor detectors are usually kept cold after irradiation.

Finally, displacement damage creates energy states close to the band edges, where they can cause **trapping** of charge carriers. This reduces the mean free path and the lifetime τ of the charge carriers. After the sensor received a small initial fluence, the latter can be approximated as

$$\tau \approx \frac{K}{\Phi}, \quad (13.11)$$

where K is a damage constant. While the charge carriers are released from the trap after some time by thermal excitation, they cannot contribute to the signal formation if the trapping time is too long. As a result, the CCE of the sensor degrades. This effect severely limits the lifetime of silicon tracking detectors and to mitigate it, front-end electronics need to have a low signal detection threshold.

13.1.6 Hybrid pixel detector layout

The sensor electrodes of pixel detectors have a checkered segmentation in order to achieve two-dimensional spatial resolution and to minimize the occupancy of individual readout channels. Each readout channel, also referred to as *pixel*, consists of a rectangular highly doped implant in the bulk material with edge lengths of $\mathcal{O}(100 \mu\text{m})$. The upper surface of the implant is metalized and usually acts as positive electrode where electrons freed by traversing charged particles are collected. The metalization allows to connect the pixel implant to its associated readout electronics, the so-called pixel unit cell (PUC) which constitutes the smallest subunit of the ROC. Sensor and ROC are joined in a process called *bump-bonding*, in which the connection between the pixel implants and the PUCs is established under high pressure and high temperatures through small solder balls with diameters of approximately $20 \mu\text{m}$. A sketch of this so-called *hybrid pixel detector layout* is shown in Figure 13.2.

Figure 13.2: Sketch of the geometry of a hybrid pixel detector. Each of the pixel implants in the silicon sensor is bump-bonded to individual pixel unit cells of the ROC using small solder balls. Auxiliary components for reading out the pixel array and for buffering the data are located outside the active region and are shown on the lower right edge of the figure [210].

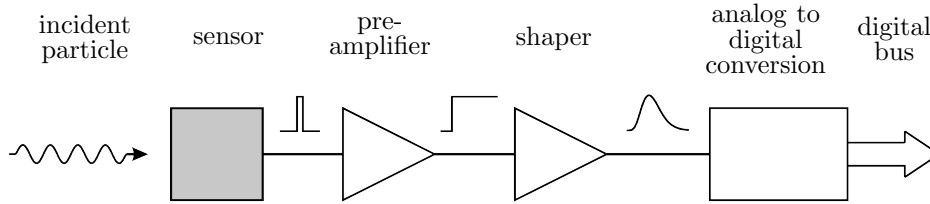
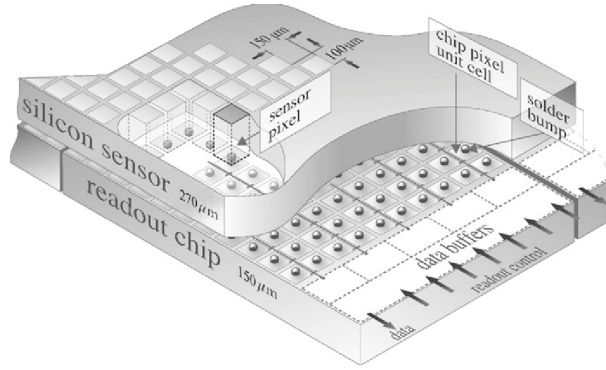


Figure 13.3: Basic signal processing of a particle detector. An incident particle creates a signal in the sensor. The resulting signal pulse is preamplified and shaped in the pixel unit cell in order to increase the signal-to-noise ratio, before it is digitized for further processing. Modified from [199].

Figure 13.3 schematically illustrates the basic signal processing steps of such a detector. The signal charge created in the sensor by an incident particle is preamplified in the PUC of the ROC. Subsequently, it is processed by a pulse shaper to further increase the signal-to-noise ratio and to form a pulse with a smooth cusp, which allows to sample the pulse in a broad maximum. At this stage, the signal can optionally be compared to a defined threshold using a comparator. This is crucial when a limited bandwidth requires zero-suppressed readout. Finally, the analog signal is digitized for further processing. More details on front-end electronics and data readout are given in Chapter 14, where the ROC for the CMS pixel detector is described in detail.

13.2 The Phase I Upgrade of the pixel detector

The former pixel detector of the CMS experiment had been successfully operated since its installation in 2008 until the end of the year 2016. It had been designed for instantaneous luminosities of up to $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to 25 pileup interactions at the nominal bunch spacing of 25 ns. This luminosity has been surpassed by the LHC in summer 2016 and a further increase to up to twice the nominal luminosity and up to 50 pileup collisions is foreseen for the coming years as outlined in the previous chapter.

One of the most important performance figures of a pixel detector is the efficiency to detect the passage of a charged particle in individual detector planes, a quantity that is referred to as *single hit efficiency*. While single hit efficiencies above 99% have been achieved throughout the operation of the former detector, the increase of the instantaneous luminosity to twice the original design specification would degrade this efficiency beyond a tolerable level. The main reasons are the limited size of the on-chip buffers where the data is stored during the L1 trigger latency and increasing readout related dead times. At the nominal LHC luminosity, these dynamic inefficiencies amount to 4% in the innermost detector layer of the former system and they would increase to 15% when the instantaneous luminosity is increased by a

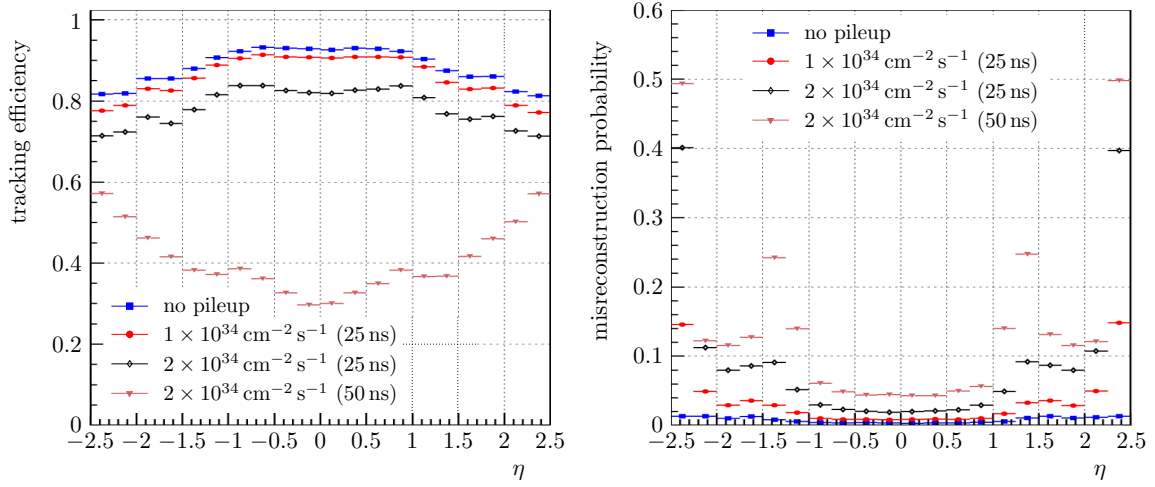


Figure 13.4: Performance of the former pixel detector for different luminosity and bunch spacing scenarios. Shown are the track reconstruction efficiency (left) and the probability for misreconstructing tracks (right) as a function of the pseudorapidity for simulated $t\bar{t}$ events. Modified from [195].

factor of two [195]. Additional data loss is caused by single event upset (SEU), where particle interactions in the readout electronics cause bit flips that can lead to a temporary disabling of detector channels. The effect of different LHC bunch spacing and luminosity scenarios on the track reconstruction efficiency and on the probability for misreconstructing tracks is shown in Figure 13.4, based on a simulation of $t\bar{t}$ events.

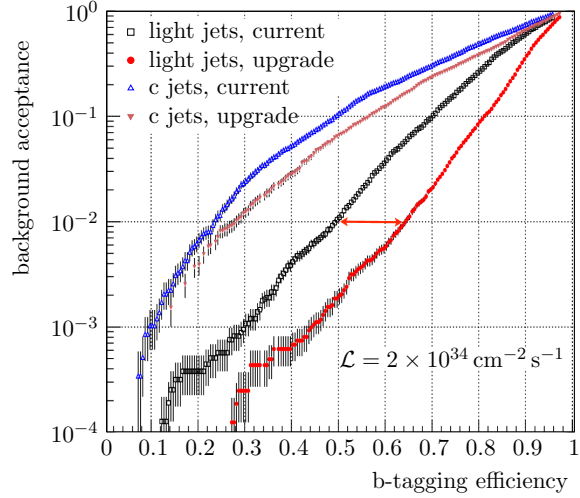
As this degradation of the detector performance would impair almost all physics analyses conducted with the experiment, the CMS Collaboration has decided to replace the pixel detector with an improved system that takes the exacerbated conditions into account. This new, so-called *Phase I pixel detector* has been installed during the extended year end technical stop of the LHC in the beginning of 2017.

13.2.1 Specifications and performance of the upgraded detector

The main goal of the new pixel detector is to maintain and improve the performance of the former system at an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with up to 50 pileup collisions. This requires several improvements of the detector, the most important of which being the design of a new ROC to overcome the aforementioned dynamic data loss at the increased instantaneous luminosity. Two different ROC versions have been developed to guarantee high detection efficiencies at the expected single pixel hit rates* of up to 120 MHz/cm^2 and up to 600 MHz/cm^2 in layers 2–4 and layer 1 of the barrel detector, respectively. In addition, the new detector is faced with more stringent demands concerning radiation tolerance. The maximum integrated luminosity foreseen to be collected during the envisaged lifetime of the detector of 500 fb^{-1} corresponds to a normalized hadron fluence of $\Phi \approx 3 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ in the innermost layer of the barrel detector. Such high particle fluences require radiation tolerant sensors and front-end electronics. The latter aspect will be discussed in detail in Chapters 15 and 16. Furthermore, the new detector features an improved geometrical layout, including a forth layer in the barrel part of the detector and each one additional layer in the forward/backward direction in the FPix system. This ensures four pixel hits for tracks within the detector acceptance of $|\eta| < 2.5$, providing additional redundancy for the track reconstruction and a compensation for a potential degradation of the innermost layers of the silicon strip detector due to radiation damage. In order to cope with large pileup scenarios

*The single pixel hit rate has to be distinguished from the particle hit rate, as each particle creates clusters with two or more pixel hits.

Figure 13.5: Discrimination of b jets against jets arising from the hadronization of light flavor quarks and c quarks with the former and the upgraded pixel detector geometry for an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. For a fixed background acceptance of 1% for light flavor jets, the b-tagging efficiency can be improved by about 15% as indicated by the arrow. Modified from [195].



and to improve the resolution of secondary vertices for the identification of b jets and tau leptons, the innermost layer of the barrel detector is installed closer to the nominal IP with respect to the former system. This decreases the extrapolation distance from the first measurement point to the interaction region from 4.4 cm to 3 cm, an improvement that has been made possible by the installation of a new beam pipe with smaller diameter during LS 1.

The additional detector layers increase the number of readout channels by approximately a factor of two with respect to the former detector. The number of readout links for connecting the detector to the periphery, however, is subject to mechanical constraints and could not be increased during the short installation time of the new detector. Reusing the pre-existing links entails the necessity for the new ROC to provide a larger bandwidth for data transmission. This is achieved by replacing the 40 MHz multi-level analog readout of the former detector with a digital protocol. More detailed information on the new digital ROC and changes with respect to its predecessor are presented in Chapter 14.

Further requirements for the upgraded detector arise from the necessity to reuse other pre-existing service infrastructure, in particular for powering the detector. Furthermore, the amount of passive material in the tracking volume should not be increased despite adding additional detector layers, in order to minimize multiple scattering. Resulting requirements and advancements of different detector components will be discussed below.

With these improvements, the upgraded detector is expected to feature high efficiencies and low misreconstruction probabilities as well as small dead times and data losses at instantaneous luminosities up to $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The envisaged performance significantly improves the reconstruction of b jets and tau leptons, enhances the identification of muons and electrons, and even allows to achieve more precise measurements of the missing transverse momentum by improving the particle reconstruction with the PF algorithm [195]. The performance is demonstrated by comparing the ability of the former detector and the new system to discriminate b jets against jets originating from the hadronization of light flavor quarks or c quarks. In Figure 13.5, the b-tagging efficiency is compared for the former and the new pixel detector and shown as a function of the light flavor and c jet acceptance. The results are obtained from simulated $t\bar{t}$ events and assume an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. It can be seen that the efficiency for discriminating light-flavor and b jets is improved by about 15% for a fixed misidentification rate of 1%. This significantly enhances the signal-to-background ratio for analyses targeting signal models with b jets such as the simplified T1tttt SUSY model in Part I of this thesis.

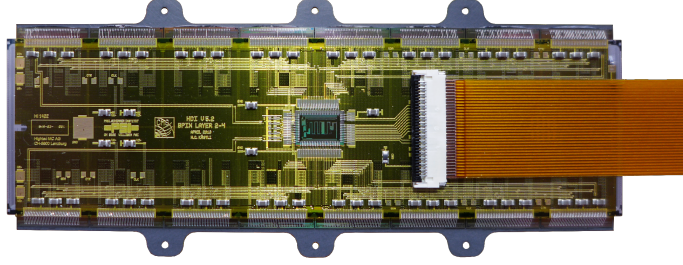


Figure 13.6: Top view photograph of a pixel detector module for barrel layers 2–4. The largest part of the picture shows the high-density interconnect, which is glued onto the silicon sensor. It connects the token bit manager, situated in the middle of the module, to the ROCs through the wirebonds visible at the long edges of the module. Additionally, the base strips and a power and signal cable can be seen. The cable is replaced by a micro-twisted pair cable in the final deployment situation in the detector.

13.2.2 Pixel detector modules

The four barrel layers and three disks in the forward/backward direction of the upgraded pixel detector will be assembled from 1856 so-called *pixel modules*, which constitute the smallest subunits of active area of the detector. Differently than in the former system, only two types of modules will be used for barrel layers 2–4 and in the endcaps, a feature that simplifies the production and the installation of the detector. A photograph of a module for barrel layers 2–4 is shown in Figure 13.6. Modules used for barrel layer 1 differ from this layout to account for higher particle rates and to allow for an even more lightweight construction. The different module components and differences between the two types of modules are described below.

The **silicon sensor** is the central component of the detector module in which charged particles induce signals as outlined in Section 13.1. The sensors for the upgraded detector are identical to the ones that have been used in the former detector and are implemented in n^+ -in- n technology. As shown in Figure 13.7, this means that the bulk of the sensor material consists of n -doped silicon, while the pixel implants feature significantly higher doping concentrations, denoted as n^+ . The pn -junction of the sensor is formed at the interface between the bulk and the positively doped backplane of the sensor. Before irradiation alters the effective doping concentration in the sensor, a reverse bias voltage of about 150 V is applied between the backplane and the pixel implants, extending the intrinsic depletion zone from the backplane towards the pixel implants and ensuring sufficiently large overbias. With this configuration electrons are collected at the pixel implant. Collecting electrons instead of holes is preferred because of the larger mobility of electrons, which entails faster signal collection and a lower trapping probability after irradiation of the sensor. Using n^+ -in- n technology for the sensor layout is motivated by yet another radiation induced effect. As outlined in Section 13.1.5, n -doped bulk material undergoes type inversion after a fluence of about 10^{13} cm^{-2} , which moves the pn -junction from the backplane to the interface between the bulk and the pixel implants. This ensures that the sensor is depleted in the vicinity of the pixel implants, even after irradiation has increased the effective doping concentration so much that the sensor can no longer be fully depleted with the power supplies available. Because of the decrease of the effective doping concentration before type-inversion, a n -bulk material exhibits a smaller effective doping concentration compared to a p -doped bulk and hence allows to operate the detector at lower bias voltages for intermediate fluences.

The silicon sensor measures $16.2 \times 64.8 \text{ mm}^2$ and is segmented into 66 560 pixels with a pitch of $100 \mu\text{m}$ in the r - ϕ direction and $150 \mu\text{m}$ in the z direction. Pixels that are connected to PUCs on three out of the four edges of the ROC have doubled dimensions in the respective direction to avoid insensitive gaps between adjacent ROCs. The pitch in r - ϕ direction is

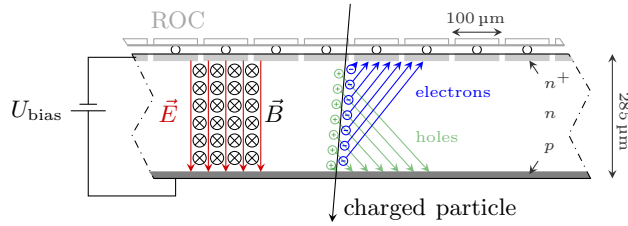
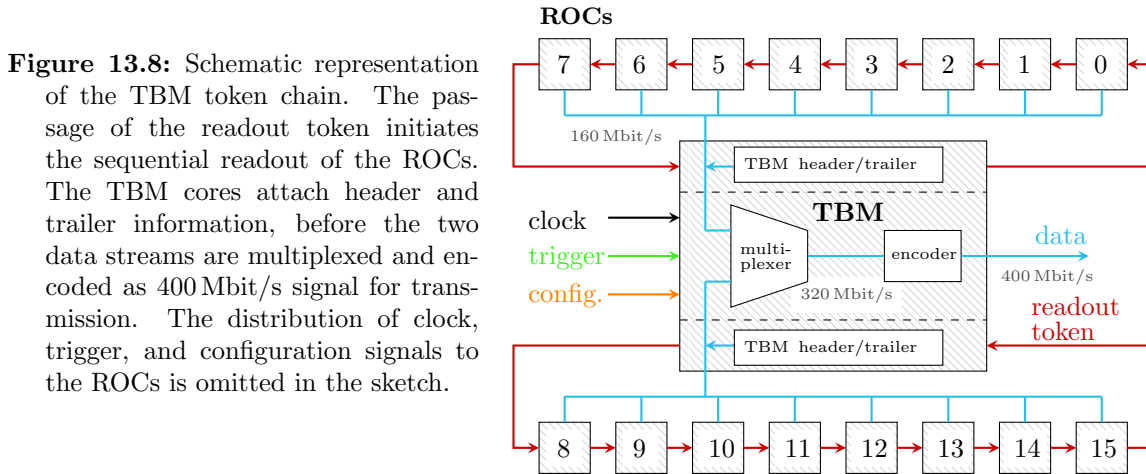


Figure 13.7: Schematic cross-sectional view of the silicon sensor of the CMS pixel detector. Traversing charged particles create electron-hole pairs in the bulk material. These charge carriers drift to the electrodes under the influence of an electric field, which is applied between p -doped backplane of the sensor and n^+ implants. Charge sharing between adjacent pixels is enhanced by Lorentz drift of the charge carriers in the magnetic field of the CMS solenoid.



optimized for charge sharing between two adjacent pixels, given the sensor thickness of $285\ \mu\text{m}$ and the Lorentz drift angle of the charge carriers of about 25° , resulting from the $3.8\ \text{T}$ magnetic field of the CMS solenoid [211]. As a result of charge sharing, traversing charged particles create clusters of about two pixels, depending on the η region. In conjunction with reading out PH information, which is proportional to the charge collected by each pixel, the spatial resolution can be improved by weighting the signals from individual pixels to better estimate the particle's intersection point with the sensor [212]. The radiation tolerance of the silicon sensors has been confirmed using tests with radioactive sources [213] and test beam measurements [210].

Signals induced by traversing charged particles are processed by **readout chips (ROCs)** that are bump-bonded to the silicon sensor. Each ROC comprises 52×80 PUCs, in which the signal collected at the associated implant is amplified, shaped, and compared to a tunable threshold to suppress signals arising from noise, which would unnecessarily occupy readout bandwidth. Pixel hits exceeding the charge threshold are stored in buffers on the periphery of the ROC during the L1 trigger latency, along with a corresponding time stamp information that allows to relate them to the correct bunch crossing. If an event is validated by the trigger, the corresponding data are read out from the ROC, otherwise the data are discarded. The most important improvements with respect to the ROC employed in the former detector are a faster readout scheme, larger buffering capabilities, and a lower charge threshold. The latter aspect improves the identification of pixel hits after radiation damage has degraded the CCE of the silicon sensor. More detailed information about the new ROC and the advancements with respect to its analog predecessor chip are presented in Chapter 14.

Each 16 ROCs, arranged in two rows of eight chips each, are bump-bonded to one silicon sensor. Their readout is coordinated by the so-called **token bit manager (TBM)** chip,

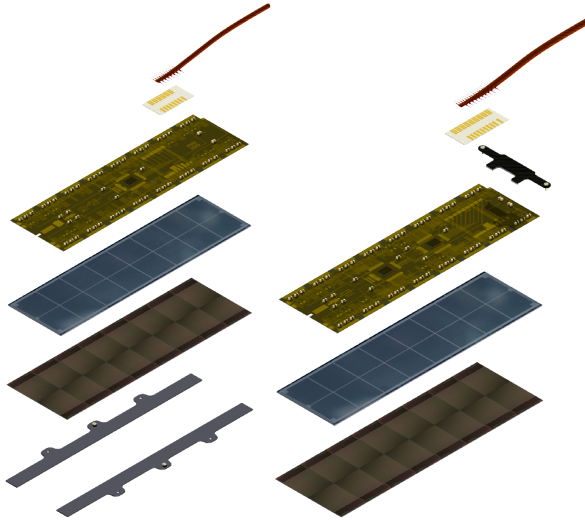


Figure 13.9: Exploded view of the pixel detector modules for layers 2–4 and the endcaps (left) and for layer 1 of the barrel detector (right). From top to bottom the following components can be seen: a cable for power and signal transmission, the HDI with a TBM chip, the silicon sensor, 16 ROCs, and two base strips for mounting the module on the support structure. Layer-1 modules differ from layer 2–4 modules by employing different ROCs and two TBMs per module. Furthermore, the base strips are omitted to reduce the amount of passive material [195].

which also serves as central node for communication between the module and the detector periphery. It receives clock, trigger, and module configuration signals that are brought to the module through a cable consisting of micro-twisted copper-clad aluminum wires. The same cable is also used to provide power and sensor bias to the module and to transmit data from the module to the data acquisition (DAQ) system. The TBM distributes the incoming signals to the ROCs through an ultra-thin printed circuit board (PCB), referred to as **high-density interconnect (HDI)**, which is glued onto the backplane of the silicon sensor. The connection to the ROCs is established through wire-bonds at the long edge of the module. Each TBM comprises two independent *TBM cores*, which orchestrate the readout of the module. For each event that has been validated by the L1 trigger, the TBM marks the start of the readout sequence with a defined bit pattern, called *TBM header*, plus additional status information. The readout from the ROCs is then initiated by sending out a readout token, which sequentially passes through the ROCs belonging to the respective token chain. Upon receipt of the readout token, each ROC sends an identification pattern, known as *ROC header*, followed by a sequence encoding the pixel hits and the PH information. Once the readout token is returned to the TBM, the end of the readout is marked with a *TBM trailer* bit pattern. The two 160 MBit/s data streams from the two TBM cores are multiplexed and converted into a 400 MBit/s differential signal using a custom 4-to-5 bit encoding and transmitted via the micro-twisted pair cable. A schematic representation of the TBM token chain and the module readout as employed in layer 3 and 4 modules is shown in Figure 13.8.

In order to account for occupancy differences at different distances from the IP, three distinct TBM versions are used in the detector. Modules that are installed in BPix layers 3 and 4 and in the FPix system are equipped with each one TBM08c [214], featuring two token chains with eight ROCs each as depicted in Figure 13.8. In order to increase the bandwidth for modules closer to the IP, a version denoted TBM09c [215] with four token chains of four ROCs each will be used for layer-2 modules. For such modules, the data are transmitted through two 400 MBit/s links. Four such readout links are used for modules that are installed in the innermost detector layer, where each module is equipped with two TBMs of the version TBM10c [215]. Each TBM10c features two ROCs per token chain.

Layer 2–4 modules will be glued onto 250 μm thick silicon-nitrate base strips to mount them on the carbon fiber support structure of the detector. For layer-1 modules, the base strips are omitted to further reduce the passive material close to the IP and to comply with geometrical constraints. These modules will be attached to the support structure using carbon fiber clamps. An exploded view of the components of the two module types is shown in Figure 13.9.

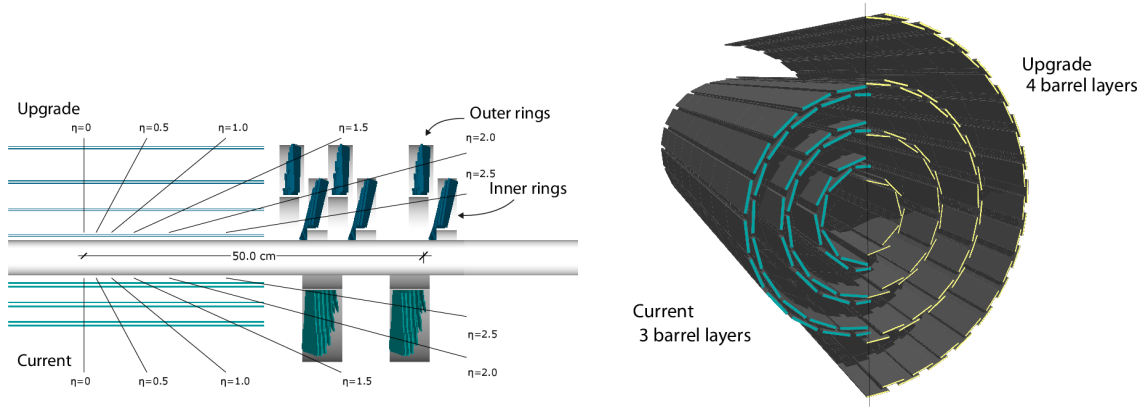


Figure 13.10: Side view (left) and perspective view (right) comparing the geometries of the former and the new pixel detector [195].

13.2.3 Detector geometry and cooling

Detector modules are mounted onto a lightweight 200 μm thick carbon support structure to assemble half-shells and half-disks for the BPix and FPix detector systems, respectively. This structure allows to insert the upgraded pixel detector into the CMS experiment while silicon strip detector and beam pipe are readily installed. Figure 13.10 shows the geometrical layout of the upgraded detector in comparisons to the former system. As can be seen in the side view, the additional detector layers in the barrel and the endcap regions ensure four-hit coverage for pseudorapidities up to $|\eta| < 2.5$. Additionally, the radius of the innermost barrel layer is reduced from 4.4 cm to 3 cm to improving the b-tagging performance as outlined above.

A further improvement in the new detector is the replacement of the liquid monophase C_6F_{14} cooling with a two-phase CO_2 system with an evaporation temperature of $T = -20^\circ\text{C}$. The new cooling system allows to reduce the operation temperature of the detector, which minimizes leakage currents in the silicon sensor. This is especially important in view of the higher fluences the new detector will be exposed to compared to its predecessor and the associated larger radiation induced increase of the leakage current. The new system has a cooling power of 15 kW to account for the increased number of readout channels and to compensate for the larger temperature difference between pixel detector and strip detector arising from the lower pixel detector operation temperature. Another advantage of the CO_2 cooling system is a significant reduction of absorbing material in the tracking volume. This is achieved by using the more lightweight coolant and by the fact that vaporized CO_2 allows to use much thinner cooling pipes.

13.2.4 Powering and data readout

Outside of the active tracking volume, the upgraded pixel detector is complemented with a range of services and connectors. They are installed on cylinder-like structures, which extend the length of the system in z direction to about 5 m as shown in Figure 13.11. Independent systems called *service cylinder* and *supply tube* connect the FPix and the BPix detector to a patch panel from where cables and cooling pipes are routed to the outside of the experiment. The following considerations apply to the supply tube but the implementation of the service cylinders is very similar.

Reusing the patch panels and power cables of the former detector was required to comply with mechanical constraints and allowed for a short installation time of the new detector. In order to account for the increased power consumption of the four-layer system, higher voltages need to be applied to the legacy power cables, which limit the maximum current. The supply

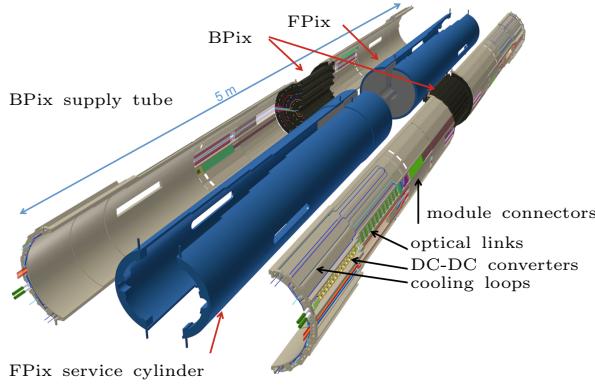


Figure 13.11: Perspective view of the upgraded pixel detector with service cylinder and supply tube. The two systems connect to the FPix and BPix detector, respectively, and host DC-DC converters, cooling loops, and pixel optical hybrids for transforming the electrical signals sent by the modules into optical signals. Modified from [195].

voltages for the front-end electronics are generated by stepping down the increased voltage in close proximity to the detector. This is achieved by using DC-DC power converters, which are installed at the outer end of the supply tube. Besides ensuring sufficient voltage stability and resilience against radiation and magnetic fields, it was important to correctly estimate the required output voltages prior to the fabrication of the converters, as they do not allow to change this parameter after their installation in the experiment.

The supply tube also hosts so-called *pixel optical hybrids*. They are used to transform electrical signals sent by the TBMs into optical signals for transmission to the front-end drivers (FEDs), which are located in a service cavern some 50 m away from the experiment. The FEDs are responsible for decoding the data for HLT event reconstruction and offline storage. The service cavern also hosts the front-end controller (FEC) units, which send configuration, clock, trigger, and reset commands to the pixel detector. In the course of the Phase I Upgrade, the original VME based FED and FEC systems have been replaced with μ TCA technology.

Another improvement with respect to the former system is that several connector boards on the supply tube have been relocated to remove them from the tracking volume. In conjunction with the material reduction achieved with the new cooling system, this results in a smaller number of electromagnetic and nuclear interaction lengths with $X_0 < 0.4$ and $\lambda_i < 0.15$ in the entire tracking volume of the upgraded detector. With respect to the former system, a reduction of up to 50% in X_0 and λ_i could be achieved in the forward region [195].

14. The Digital Readout Chip

Signals generated in the silicon sensor of the pixel detector are read out with custom-made front-end electronics, referred to as readout chips (ROCs), which are bump-bonded to the sensor. In order to avoid inefficiencies associated to the increasing instantaneous luminosity of the LHC, a new ROC with digital readout [216–218] has been designed for the Phase I Upgrade of the pixel detector. The new chip is an advancement of its predecessor *PSI46V2*, a ROC with analog readout that has been operated in the former pixel detector since 2008 [219]. If not otherwise noted, the following information refers to the ROC that will be used for barrel layers 2–4 and in the endcaps of the detector, which is named *PSI46digV2.1respin*. A dedicated ROC, called *PROC600*, that will be used in the innermost layer of the BPix system is not investigated in the context of this thesis, however, cross references will be made where appropriate.

The new digital ROC measures $10.3 \times 7.9 \text{ cm}^2$ and it is manufactured in the same commercially available 250 nm complementary metal-oxide semiconductor (CMOS) process as its predecessor. While large aspects of the legacy architecture remained unchanged, the performance of the ROC could be significantly improved by changing the readout protocol, by eliminating leading data loss mechanisms, and by improving the analog performance. The chip can be divided into three main building blocks: pixel array, double column interface (DCI), and ROC controller and interface block (RCI). Electronics for the individual readout channels are hosted in 4160 identical pixel unit cells (PUCs), each of which can be divided into an analog and a digital domain as detailed in Section 14.1. The PUCs are arranged in an array of 52×80 pixels, with each 2×80 of them being organized in a so-called double column (DCol). The readout mechanism for DCols, as well as their communication with the DCI are reviewed in Section 14.2, complemented with remarks on the DCol buffers used to store pixel hits and timing information. Section 14.3 presents components that are hosted in the RCI, with emphasis on those that have been added to improve the performance of the ROC with respect to its analog predecessor. Section 14.4 details the data format transmitted by the ROC and Section 14.5 gives an overview of different versions of the ROC, along with a brief summary of advancements implemented in the layer 1 ROC. The chapter concludes with Section 14.6, presenting a review of essential test and calibration routines, used to assess the chip functionality, to tune operation parameters, and to calibrate its output signals.

While the PUCs of the chip are self-triggering, the DCol readout and the RCI run synchronously to the 40 MHz LHC master clock, allowing to unambiguously relate individual measurements to the correct LHC bunch crossing. As further input, the ROC requires two supply voltages, which are regulated on-chip to power different circuits. The analog

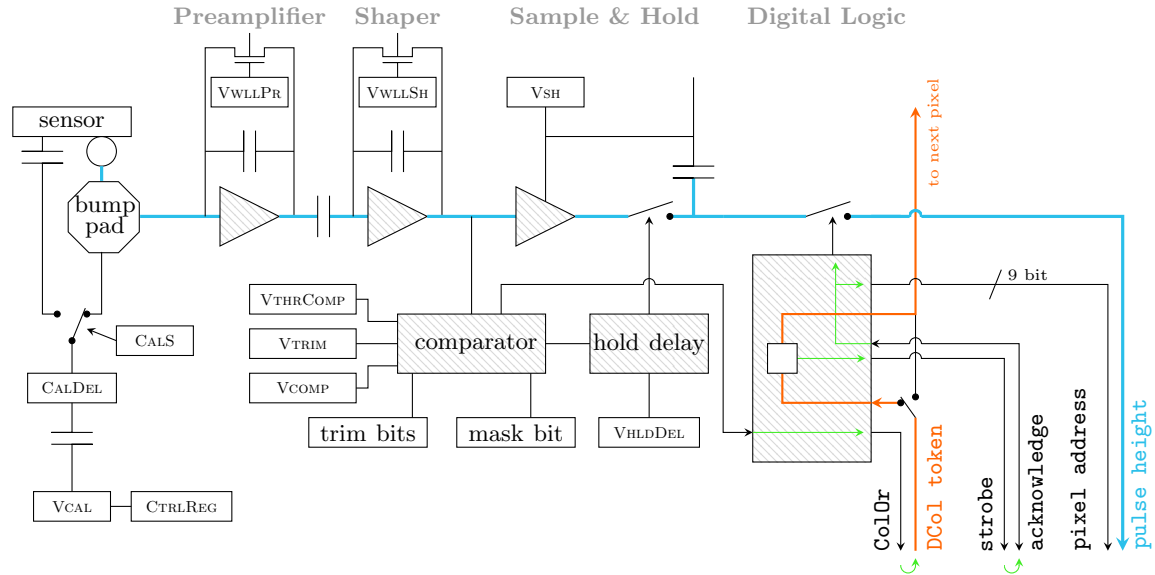


Figure 14.1: Simplified block diagram of the pixel unit cell. A signal charge generated in the sensor enters the cell via the bump pad to the left and is processed by the preamplifier and the shaper to increase the signal-to-noise ratio. If the amplified charge exceeds a certain threshold at the comparator, it is transferred to the sample-and-hold circuit, where it is temporarily stored before it is sent to the periphery. Green arrows indicate that a certain logic signal initiates another signal.

parts of the PUCs are supplied with a nominal voltage of $V_A = 1.6\text{ V}$ and the digital logic with $V_D = 2.4\text{ V}$. This separation decouples the sensitive analog circuitry from noise induced by transistor switching in the digital logic of the chip. The global operation parameters of the ROC can be controlled by 16 programmable digital-to-analog converters (DACs) and several registers, which are hosted on the RCI. Dedicated low-power settings of the DACs are used at start-up by default. They allow to bring the detector into a well-defined state with a low current consumption. Only afterwards, the DACs are programmed to their nominal settings for operation.

14.1 The pixel unit cell

The pixel unit cell (PUC) is the smallest, independently working entity on the ROC. It can be divided into an analog domain where the signal is amplified, shaped, and compared to a threshold, and a digital part, responsible for the communication with the DCI.

14.1.1 Analog domain of the pixel unit cell

Figure 14.1 shows a simplified block diagram of the PUC. The most probable signal charge for MIPs traversing the fully depleted sensor is of the order of 24 ke [195]. Charge sharing causes the cloud of charge carriers to be distributed over about two adjacent pixels, creating signals of a few fC, which enter the PUC via the bump pad, shown on the left-hand side of the figure. The signal is amplified with a charge sensitive preamplifier, whose feedback resistor is implemented as metal-oxide-semiconductor field-effect transistor (MOSFET). This allows to adjust the ohmic resistance of the feedback loop with the $VWLLPR$ DAC by regulating the gate voltage of the transistor. Further increase of the signal-to-noise ratio is achieved with a pulse shaper, which is coupled capacitively to the output of the preamplifier. Its frequency response favors the signal and attenuates the noise. Additionally, it forms a signal pulse with a smooth cusp to allow for a robust sampling of the pulse at its maximum. As a competing requirement, the pulse duration must be short enough to prevent a pileup of

successive pulses. The resistance of the pulse shaper feedback loop can be adjusted with the VWLLSH DAC. The absolute electronic noise of the preamplifier/shaper system for a fully depleted, nonirradiated sensor is well below 150e as will be shown in Section 16.2.2.

The large number of readout channels of the pixel detector makes zero-suppression mandatory in order to limit the transmitted data rate. This is achieved using a comparator to discriminate signals against noise by comparing the output charge of the shaper to an adjustable threshold. Only pulses exceeding the threshold are passed to the sample-and-hold (S&H) circuit and are counted as *pixel hits*. The global VTHRCOMP DAC can be used to modify the thresholds of all PUCs of one ROC. Note that VTHRCOMP is an inverse DAC, i.e., low DAC values correspond to high pixel thresholds. In order to compensate for production process related inhomogeneities of individual transistor thresholds, each PUC is equipped with four so-called *trim bits*, which allow to tune the threshold of individual pixels to achieve a homogeneous threshold distribution across the ROC. This is required for an effective suppression of noise hits and to avoid having pixels with unnecessary high thresholds, which would degrade the signal efficiency and hence the spatial resolution of the detector. Moreover a homogeneous threshold distribution improves the comparability between measurement and simulation where a uniform threshold is assumed. Two additional global DACs are related to the comparator. The first one serves as a voltage regulator for the comparator (VCOMP) and the second one scales the effect of the trim bits on the pixel threshold (VTRIM). Pixels can be disabled by switching off the comparator output using a *mask bit*. This feature is used to prevent defective pixels from flooding the readout with noise hits.

Once a signal exceeds the threshold, the comparator issues a signal that causes the S&H circuit to sample the signal pulse after a certain delay. The latter can be adjusted with the inverse VHLDEL DAC. As shown in Figure 14.2, the delay needs to be correctly adjusted to ensure that the pulse is sampled at its maximum. In practice, the peaking time of the shaper is so fast that the delay does not allow to sample the pulse at the rising edge and consequently the VHLDEL DAC is set to its maximum value for the digital ROC, corresponding to the shortest delay possible. The signal charge is passed through S&H amplifier with a gain factor of one to decouple the S&H circuit from the shaper output and the PH is temporarily stored on the S&H capacitor before it is sent to the periphery.

Analog current

The analog performance of the PUC, i.e., the behavior of the preamplifier/shaper system and the pixel threshold, strongly depends on the analog supply current I_{ana} , which can be adjusted with the current regulating VANA DAC. The nominal working point of the chip is $I_{\text{ana}} = 24\text{ mA}$, with deviations of a few mA being acceptable if the chip parameters, in particular the threshold, are readjusted after changing the current.

Pixel threshold and timewalk

One of the major improvements of the new digital ROC with respect to the analog predecessor chip is a lower pixel threshold, which improves the lifetime of the detector, as it maintains the sensitivity after radiation damage has degraded the CCE in the sensor. For the evaluation of the threshold one needs to distinguish the absolute threshold of the comparator from the effective, so-called *in-time threshold*. As depicted in Figure 14.2, a small signal exceeds the charge threshold at a point of time that is delayed by T_{walk} with respect to a larger signal. This phenomenon is referred to as *timewalk*. If $T_{\text{walk}} > 25\text{ ns}$, the small signal gets assigned to the succeeding bunch crossing and is therefore lost since the succeeding event is not necessarily validated by the L1 trigger. If that is the case, the threshold needs to be increased such that the largest possible timewalk does not exceed the bunch crossing time. For this reason, the threshold of the analog ROC had to be increased from the lowest

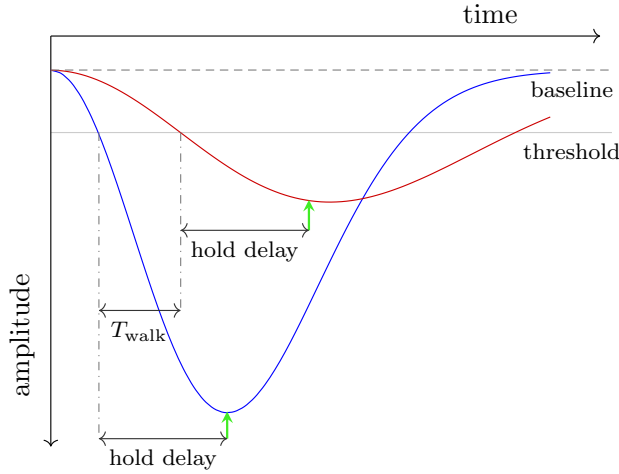


Figure 14.2: Schematic visualization of a large and a small pulse at the shaper output. After exceeding the comparator threshold, the pulses are sampled after a fixed delay, which is programmable with the VHLDEL DAC. The pulse with the smaller amplitude has a longer rise time, causing it to exceed the threshold at a later point of time compared to the large pulse. This delay is denoted as time-walk T_{walk} .

possible absolute threshold of about 2.5 ke to 3.2 ke. With the new digital ROC an absolute thresholds of about 1.8 ke can be achieved, with T_{walk} sufficiently below 25 ns as will be shown in Section 16.2.4.

Test pulse injection

For test and calibration purposes, a test charge can be injected into the preamplifier by discharging a 4.8 nF capacitor in the RCI. The voltage applied to the capacitor and hence the test charge can be regulated with the VCAL DAC. In order to extend the available range of test charges, the CTRLREG register can be used to increase the test charge associated to a certain DAC value by about a factor of seven. The register takes values of zero for the low range and four for the high VCAL range. The injection of the test charge can be delayed using the CALDEL DAC, to ensure that the test pulse is injected within the triggered bunch crossing. Approximately 60 DAC units correspond to one bunch spacing of 25 ns.

Test pulses are only injected into those PUCs that have been configured accordingly. This allows to selectively route the test pulse to one or several pixels under test. Additionally, each PUC features a register, denoted as CALS, that can be programmed to capacitively couple the test charge into the silicon sensor instead of injecting it directly to the preamplifier. This functionality can be used, e.g., to test the bump bonding quality by measuring the signal strength through the solder ball connection.

14.1.2 Digital domain of the pixel unit cell

A second part of the PUC hosts the digital circuitry, responsible for orchestrating the readout of the pixel and for exchanging logic signals with the DCI. Once a signal exceeds the threshold, the comparator not only initiates the sampling of the pulse, but also causes the pixel to go into a state in which it cannot receive further hits before the readout of the previous one is completed. Additionally, a fast column OR signal is sent out to notify the DCol periphery about the pixel hit. In order to minimize deadtimes, two such buses, denoted as Col0r A and Col0r B are available and a DCI controlled signal ensures that they are used alternately. Upon receipt of the Col0r signal, a time stamp is generated in the DCI in order to unambiguously relate the pixel hit to the correct LHC bunch crossing. The readout of the pixel hit is initiated by the passage of a DCol readout token, which is sent out by the DCI after it received the Col0r signal. As the arrival of this token at the hit pixel is not synchronized to the 40 MHz clock, PUC and DCI exchange a **strobe** and an **acknowledge** signal after the token has arrived at the PUC. Upon receipt of the **strobe** signal, the DCI releases the **acknowledge** signal with the next falling edge of the 40 MHz clock, to synchronize the pixel readout with the master clock. After receiving the **acknowledge** signal, the PUC

transfers the pixel address and the analog PH information to the DCI. Simultaneously, the readout token is passed to the next pixel in the DCol and the pixel resumes data taking.

The digital part of the PUC, as well as all other digital logic on the ROC, is supplied with a regulated digital voltage V_{dd} , which can be adjusted with the VD_{IG} DAC. The input to this voltage regulator is the unregulated digital voltage V_D , mentioned above. In digital CMOS devices, current only flows while the field effect transistors switch between the two logic states. Therefore, the digital current I_{dig} strongly depends on the rate of incident particles and the resulting workload of the readout logic, as will be shown in Section 16.3.2.

14.2 Double column and double column interface

The pixel array is subdivided into 26 DCols, each consisting of 2×80 pixels plus associated buffers and readout logic in the DCI. DCols work independently of each other and transfer hits from the PUCs to the on-chip buffer cells in the periphery, where the pixel addresses, the associated time stamps, and the PH information are temporally stored before being transferred to the RCI.

14.2.1 Double column drain mechanism

The 160 pixels belonging to one DCol are daisy-chained and successively read out in one *column drain* sequence. To this end, the DCol internal readout token is passed from pixel to pixel along the left column from the DCI upwards and returned to the DCI through the right-hand column. It is released once at least one of the DCol's pixels has sent a **Co10r** signal after receiving a hit. The passage of the token is paused during the communication between a PUC and the DCI. Pixels without hits are bypassed by the token as depicted in Figure 14.1. Two DACs are related to the column drain: the VIBIASBUS DAC sets the threshold of a comparator in the DCI, which detects incoming **Co10r** signals and the VICOLOR DAC limits the current in the **Co10r** buses. While the exchange of all other logic signals between PUC and DCI happens practically instantly, the propagation velocity of the DCol readout token is limited to $\mathcal{O}(100 \text{ pixels/bunch crossing})$. This is necessary to allow the token to be stopped during the readout of a pixel that has received a hit. Only after the readout of the pixel is completed the token is released and passed on to the next pixel. Two clock cycles per pixel hit plus an offset of one clock cycle for synchronizing the data transmission with the 40 MHz clock are needed in order to complete the column drain. The propagation velocity of the DCol token depends on the temperature and on the regulated digital voltage as will be shown in Section 16.5.1.

The DCol structure is enforced by the geometrical size of the associated buffer cells, which are too wide to accommodate 52 of them in the DCI. Additionally, it allows for an efficient read out of two-pixel clusters that are spread along the column direction by the Lorentz drift.

The column drain mechanism and the DCol structure remained unchanged with respect to the analog ROC. However, the routing of signal buses and power rails within the DCol has been improved to minimize the coupling of the noisy digital logic to the analog signals and to reduce parasitic inter-channel couplings, referred to as *crosstalk*. These advancements are important to fully benefit from the improved analog performance of the ROC, in particular from the lower charge threshold.

14.2.2 Data and time stamp buffers

The lion's share of the DCI is occupied by buffers in which pixel hit and time stamp information are temporarily stored after the column drain.

Time stamp buffers store a list of time stamps that are used to associate pixel hits to the correct bunch crossing. To this end, the buffer stores the value of the 8-bit *write bunch crossing (WBC)* counter once one of the `Co10r` buses signals a new pixel hit. With a fixed L1 trigger latency of 3.2 μs , this allows to unambiguously identify the pixel hits associated to the bunch crossing validated by the trigger. The oldest time stamp in the buffer is continuously compared with the value of the *select bunch crossing (SBC)* counter, which runs with a fixed programmable delay with respect to the WBC counter, where the delay corresponds to the trigger latency. In case the L1 trigger validated the event, the DCol enters readout mode and stops data taking to prevent validated hits from being overwritten. If no trigger arrives within the latency, the time stamp and the corresponding pixel hit information are discarded. When the number of time stamps created within the trigger latency exceeds the buffer size, further `Co10r` signals are held back and the associated data are lost. New hits are only accepted once time stamps have been cleared from the buffer after the trigger latency has passed. This mechanism leads to a hit rate dependent inefficiency as will be shown in Section 16.3.1. For occupancies expected in the experiment this inefficiency is found to be below 1%.

Data buffers store the analog PH information as a charge on dedicated capacitors, while the corresponding pixel address is stored digitally. A flag bit marks the start of the data belonging to one event, followed by the address and the PH of all pixel hits that are read out in one DCol drain. Pixel hit data and time stamps are associated with each other by correspondence of the entry number in the respective buffer. If a time stamp is validated by the trigger, the corresponding data are read out from the buffer and both time stamp and data buffers are cleared. Otherwise, if the event matching the SBC counter value has not been validated by the trigger, the corresponding entry in the data buffer is deleted along with the respective time stamp. Data buffer overflow occurs when additional pixel hits arrive while the associated data buffer is already fully occupied. This causes the DCol to be reset, which deletes all time stamp and data buffer entries, as well as pixel hits presently stored on S&H capacitors of the associated PUCs.

Data buffer overflow and filled time stamp buffers would lead to severe data loss if the analog ROC was to be operated at an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [195]. In the digital ROC, the buffer capacities have therefore been increased. Instead of twelve time stamps, 24 can be stored in the digital ROC, and the data buffers have been enlarged from 32 to 80 cells. The associated increase of the geometrical footprint of the buffers could be kept small by minimizing the cell sizes.

14.3 ROC controller and interface block

The RCI hosts several services and supply circuits that are shared among all PUCs and DCol. The following summary focuses on components that have been added to improve the performance of the chip, while components that are similar in the analog predecessor chip are briefly summarized at the end of the section.

14.3.1 Pulse height sampling ADC

One of the most significant improvements in the design of the new ROC is the 160 Mbit/s digital readout protocol, which replaces the 40 MHz multi-level analog readout of its predecessor. As outlined in Chapter 13, this change is required to achieve the increased bandwidth needed to transmit larger amounts of data through the existing readout links. The analog PH information is therefore digitized on-chip using an 8-bit successive approximation current analog-to-digital converter (ADC), whose comparator voltage can be set with the `VCOMPADC` DAC. The ADC output can be shifted using the `PHOFFSET` DAC and the gain is set with the `PHSCALE` DAC. The ADC runs at a frequency of 80 MHz and requires eight clock cycles to digitize each pixel hit plus four clock cycles for each event with hits.

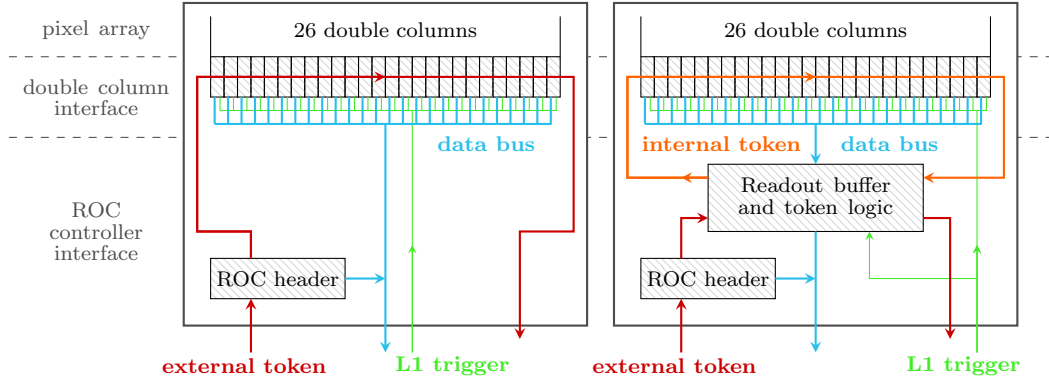


Figure 14.3: Schematic visualization of the token passage for initializing the readout of the double column buffers for the analog (left) and the digital ROC (right). An additional readout buffer decouples the readout of the double column buffers from the passage of the external readout token and allows to reduce readout related deadtimes from 3–4% to below 1% for hit rates expected for the upgraded detector. Modified from [216].

14.3.2 Phase-locked loop and data serializer

Another new component in the RCI is a phase-locked loop (PLL), which generates an 80 MHz and a 160 MHz clock from the 40 MHz master clock to supply the PH sampling ADC and the 4-bit data serializer, respectively. The latter component generates the 160 Mbit/s data stream for transmitting pixel hits and auxiliary information.

14.3.3 Readout buffer

The readout of the DCol buffers is initiated by the passage of a readout token, which is passed through all 26 DCols. This approach ensures that only one DCol sends data at the time. As depicted on the left-hand side of Figure 14.3, this token is an external signal in the analog ROC. It is issued by the TBM upon receipt of a L1 trigger signal as outlined in Section 13.2.2 and passed through all ROCs that belong to the respective token chain. Since DCols do not take data between the trigger validation and the readout of the triggered event, this causes deadtimes of up to 4% for an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [216].

In order to mitigate this inefficiency, an additional, global readout buffer has been added to the RCI for the digital ROC. As shown on the right-hand side of Figure 14.3, the revised readout logic utilizes an internal token to initiate the readout of the DCol buffers once the L1 trigger signal arrives at the RCI. After receiving the internal token, the DCol sends its data to the readout buffer. Before being stored in the readout buffer, the analog PH is digitized with the ADC described above. Data stored in the readout buffer is transmitted by the ROC once the external readout token, which is sent by the TBM as in the analog ROC, arrives. This new readout scheme significantly reduces the length of the token chain responsible for initiating the DCol buffer readout and hence reduces DCol deadtimes to below 1% at hit rates expected for the upgraded detector [216].

14.3.4 Readback mechanism

A second, slow ADC in the RCI can be used to read back information from the ROC for debugging and monitoring purposes. The digitized information is transmitted through a dedicated *readback bit* encapsulated in the ROC data stream. As only one bit per event is reserved for this purpose, a full readback word is transmitted in 16 successive events and the start of a new word is indicated using a dedicated marker bit. The READBACK register is used to define what kind of data are read back. Digital information such as the latest modified DAC value or the latest transmitted pixel address can be chosen. Alternatively, analog

signals such as the unregulated digital and analog voltages, the regulated analog voltage and the analog current can be read back. In order to translate the readback output into physical units, the ADC has to be calibrated using external voltage and current measurements for reference. The associated calibration parameters are subject to radiation induced drifts as will be shown in Section 16.5.2.

14.3.5 Other services and supply circuits

In addition to the new components included in the digital ROC, several other services are hosted in the RCI that are similar to those in the analog ROC [211].

For programming DACs and registers, as well as trim and mask bits via an I²C-like protocol, the ROC is equipped with a serial programming interface. The configuration commands are sent by the FEC or equivalent units in laboratory or test-beam measurements.

A fast signal decoder interprets a low-voltage differential control, trigger, reset (CTR) signal. As the name suggests, the signal is used to transfer commands for test pulse injection (calibrate), L1 trigger signals, and a command for resetting the ROC to its initial state. The commands are encoded as pulses with a width of one, two, and three clock cycles, respectively.

Furthermore, voltage regulators, DACs, and registers are hosted in the RCI. A necessary reference voltage is provided by a dedicated circuit that generates an input voltage and temperature independent voltage of 1.12 V, derived from the band-gap energy of silicon [220]. A stable reference voltage is extremely important for reliable measurements, since the output voltages and currents of all DACs and ADCs depend on it. The outputs therefore scale with a potential radiation induced drift of the band gap reference voltage that will be investigated in Section 16.1.1. The absolute value of the band gap reference voltage can be measured with a probe needle on a dedicated pad on the RCI, or alternatively, with the readback mechanism.

A range of other pads, situated at the edge of the RCI are used to connect the ROC to the HDI via wire bonds to establish the connections for in- and output signals.

14.4 Readout format

The serializer unit in the RCI generates a 160 Mbit/s data stream to transmit pixel addresses, PH, and auxiliary information to the TBM once the *token in* signal is raised upon arrival of the external readout token. As depicted in Figure 14.4, every event sent by a ROC is preceded by a 12-bit *ROC header*, consisting of a zero, followed by eight consecutive ones and another zero. The last two bits of the header are the start marker bit for the readback word, followed by the one-bit readback information itself (c.f. Section 14.3.4). Counting ROC headers in the data stream allows to associate pixel hits to a certain ROC on a module. The header is followed by 24 bits per pixel hit, where sequences of six and nine bits encode the pixel row and DCol address using Gray code [221]. The following eight bits are reserved for transmitting the PH, including an intermediate zero bit to prevent ambiguities with the ROC header format. The sequence encoding the address and PH information is repeated for every pixel hit in the event. Two clock cycles before the readout is finished, the *token out* signal is raised to pass on the external token to the next ROC in the chain or back to the TBM, depending on the ROC's position in the readout chain.

14.5 Digital ROC versions

In the course of the development process of the digital ROC, several versions of the chip have been produced and tested to iteratively remove remaining design flaws and to optimize its performance. In addition to different versions of the layer 2–4 ROC, a dedicated layer 1 ROC has been developed in order to account for the considerably larger hit rates in the innermost layer of the BPix system.

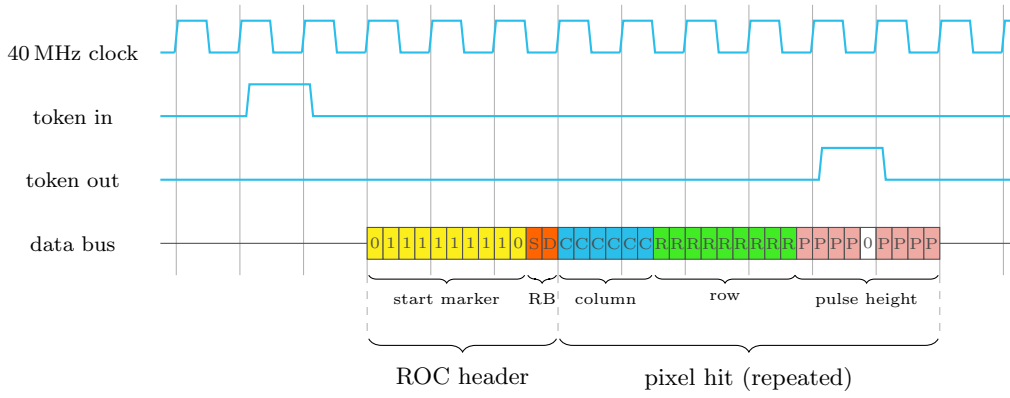


Figure 14.4: ROC data format. The readout of the chip is initiated by the *token in* signal. The transmission on the data bus is preceded by the ROC header, consisting of a distinct 10-bit pattern, followed by the readback (RB) start marker and payload bit. Subsequently, all addresses and pulse heights of all pixel hits are transmitted. The *token out* signal passes the external readout token on to the next ROC or back to the TBM in case the ROC is the last one in the token chain. Modified from [222].

14.5.1 Layer 2–4 ROC

Four different versions of the layer 2–4 ROC have been produced. The first version, denoted as *PSI46dig* had been followed by two further prototype versions of the chip, named *PSI46digV2* and *PSI46digV2.1*. Results reported in this thesis, mostly refer to the final production version of the ROC, named *PSI46digV2.1respin*, which is used in the upgraded detector. Comparisons with intermediate versions will be shown where appropriate along with remarks on relevant differences in the design. The different versions mark successive advancements in the chip design, with flaws being removed and design parameters tweaked. Additionally, several DACs, whose settings were never changed in practice have been replaced with constant voltage regulators. In particular the adjustment of the PH sampling ADC has been simplified considerably by disentangling different parameters and by replacing three DACs with fixed voltages in the final design.

14.5.2 Layer 1 ROC

The development of the layer 1 ROC, named *PROC600*, where ‘600’ refers to its specification of having a high hit detection efficiency for hit rates up to 600 MHz/cm^2 , had been finalized only after the studies presented in this thesis have been conducted. Although measurements presented here are exclusively obtained with the layer 2–4 ROC, some results have been used to project the behavior of the layer 1 ROC and thereby improved its design even before to its first submission. This is the case for results that are related to components that are used in both layouts, in particular the PUC and the PH ADC.

In order to achieve high hit detection efficiencies of above 98% for hit rates up to 600 MHz/cm^2 , central aspects of the DCol drain mechanism and the associated signal logic have been re-designed for *PROC600* with respect to the layer 2–4 ROC. Three main aspects improve the efficiency at high occupancies. Instead of waiting for the *Co10r* signal to notify the DCI about a pixel hit, the *PROC600* chip employs a continuous column drain, which does not require buffer resets after a DCol buffer has been read out. In addition, an enhanced communication logic between PUCs and DCI allows for up to seven pending column drains instead of one running and two pending ones in the layer 2–4 ROC. Finally, a new *dynamic cluster column drain (DCCD)* mechanism allows to drain an array of 2×2 pixels at a time instead of reading out all pixel hits sequentially as done in the layer 2–4 ROC. The new mechanism is tailored for two-pixel clusters in column direction, as they are typically created in the 3.8 T

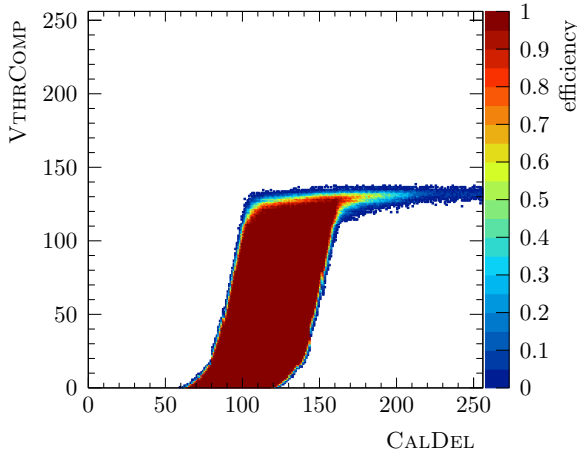


Figure 14.5: Working point in the pixel threshold ($V_{THRCOMP}$) – test pulse delay ($CALDEL$) phase space for an arbitrary pixel of the ROC. Full efficiency is achieved if the test pulses arrive within the triggered bunch crossing, and if the threshold is set to a value above the noise level.

magnetic field of the CMS solenoid. For reading out n such clusters, the DCCD requires $n+2$ clock cycles as opposed to $2 \times n + 3$ clock cycles needed by the mechanism employed in the layer 2–4 ROC. This represents a reduction of the DCcol drain duration by roughly a factor of two. The envisaged hit detection efficiency and radiation tolerance has been demonstrated in proton test beams and irradiation campaigns, respectively [223].

14.6 Chip commissioning and calibrations

Prior to operating a ROC in a laboratory setup, a sequence of commissioning and calibration steps has to be performed. Different routines are used to configure the chip via the I²C-like serial interface, to find suitable settings for several DACs and the trim bits, which have to be optimized for each ROCs, and to obtain calibration parameters that are used to translate the output of the PH sampling ADC into units of the internal test pulse injection. A supplementary calibration allows to translate these arbitrary units into charge, using external reference energies provided by characteristic X-ray emission lines of different materials. The latter calibration requires the ROC to be bump-bonded to a silicon sensor.

In order to obtain these settings and calibration parameters for ROCs that will be operated in the detector, the commissioning and calibration steps described below have been part of a comprehensive module characterization procedure, which has been performed for all modules that are installed in the upgraded detector. In the context of this thesis, however, individual samples of the ROC that have not been integrated into the upgraded detector have been tested for research and development purposes.

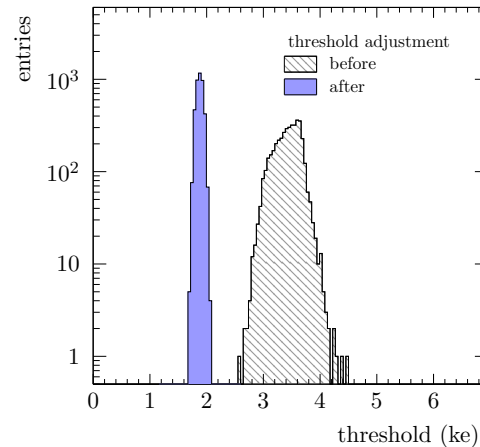
14.6.1 Pretest

Initializing the ROC programs all DACs and registers, as well as trim and mask bits according to the values stored in dedicated configuration files. A first test routine is typically executed to verify that the communication to the ROC can be established and that the sample is programmable. To this end, the VANA DAC is programmed to different values and the corresponding change of the analog current is measured externally. Variations of the current depending on the VANA setting indicate proper programmability.

Subsequently, VANA is adjusted until the nominal analog current of 24 mA is reached. This ensures that preamplifier, pulse shaper, and comparator are correctly powered.

The succeeding step aims at setting a global threshold that is low enough to make the pixels sensitive to injected test pulses, but high enough suppress noise hits. This is achieved by programming the $V_{THRCOMP}$ DAC to a fixed value, usually $V_{THRCOMP} = 50$. At this

Figure 14.6: Pixel threshold distribution for all 4160 pixels of one ROC before and after threshold adjustment. By optimizing the settings for the global VTHRCOMP and VTRIM DACs and adjusting the trim bits for each pixel, a threshold of about 1.8 ke with a spread of 60 electrons can be achieved.



stage, the threshold distribution of all pixels of the ROC is rather broad with a typical width of 200–250 electrons.

Finally, the CALDEL DAC is adjusted. The setting of this DAC is irrelevant for reading out signals generated by external particles in the silicon sensor. However, a correct setting is required to adjust the delay of the internal test pulses in such a way that they arrive within the triggered bunch crossing. In laboratory experiments the bunch crossing to be triggered is defined by the fixed latency between the `calibrate` and the `trigger` signal sent on the CTR line to the chip and the corresponding setting of the WBC register. The viable phase-space of VTHRCOMP and CALDEL settings can be scanned by sending a certain number of test pulses to a pixel for all possible settings. As shown in Figure 14.5, this allows to discriminate a region where all hits are readout, from regions in which the test pulses are not registered because the comparator threshold is below the noise level (top) or because the test pulse arrives in a bunch crossing that is not triggered (left and right). The curved edges of the viable phase-space arise from timewalk effects associated to the variation of the threshold. The CALDEL setting is usually chosen in the center of the efficiency plateau for VTHRCOMP = 50. Approximately 60 CALDEL units correspond to one bunch crossing interval of 25 ns.

14.6.2 Pixel threshold adjustment

In order to achieve a homogeneous sensitivity amongst all pixels of the ROC, pixel-to-pixel variations in the threshold must be compensated by tuning the trim bits for each individual pixel. The target value for the threshold is typically chosen as low as possible but sufficiently high to avoid large numbers of noisy pixels. With the new digital ROC, a sufficient suppression of noise hits is usually achieved by setting a threshold of about 1.8 ke as demonstrated in Chapter 16.

The procedure used to adjust the threshold utilizes several so-called *threshold scans*. Such a scan aims at determining the threshold of an individual pixel in VCAL units by injecting test pulses of increasing amplitude. The resulting efficiency curve, which shows the number of successfully read out test pulses as a function of the amplitude, allows to determine the threshold of the pixel as the VCAL value for which at least 50% of the injected test pulses can be read out. Similar efficiency curves can also be obtained for other DACs. A two-dimensional example has been shown in Figure 14.5, where the edges of the valid phase-space mark the turn-on curves when fixing one DAC and varying the other one.

The pixel threshold adjustment algorithm is separated into three steps. First, VTHRCOMP is chosen low enough (i.e., the threshold is chosen high enough) for the pixel with the lowest

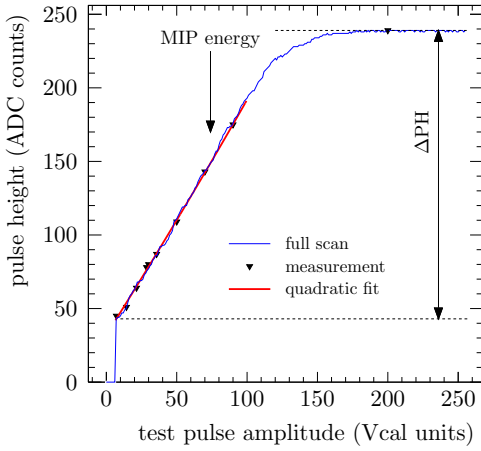


Figure 14.7: ADC response as a function of the test pulse amplitude in Vcal units of the high Vcal range (CTRLREG = 4). For amplitudes up to a charge corresponding to signals created by MIPs in the silicon sensor of the detector, the pulse height can be modeled with a quadratic fit, which takes into account potential small non-linearities of the ADC response at low amplitudes.

Vcal threshold to be above the target value. This is required since enabling of trim bits can only decrease the pixel threshold. Second, the VTRIM DAC is optimized to scale the effect of the trim bits on the threshold. The value for VTRIM is chosen large enough for the pixel with the highest Vcal threshold to be decreased to the target value when all of its trim bits are enabled. Higher values of VTRIM would unnecessarily degrade the resolution of the 16 available states the trim bits can take. After the two global DAC settings are adjusted, the third step optimizes the trim bit configuration for each individual pixel such that its threshold is as close to the target threshold as possible. This is achieved using a four-step binary search to iteratively find the optimal configuration. Details of the algorithm can be found, e.g., in Ref. [224].

Optimizing the trim bits for each individual pixel allows to reduce the width of the threshold distribution from 200–250 electrons to about 60 electrons, as shown in Figure 14.6 for a typical ROC sample. The conversion of internal Vcal DAC units to charge is based on a calibration with external reference charges that will be described in Section 14.6.4.

14.6.3 Pulse height optimization and calibration

Gain and offset of the PH sampling ADC have to be adjusted with the global PHSCALE and PHOFFSET DACs in order to fully exploit the available output range of 8-bits and to ensure that the response scales linearly with the signal charge. Pulses can yield zero output at the ADC, independently of their amplitude, e.g., if the offset is chosen too small. As shown in Figure 14.7 for optimized DAC settings, the PH rises approximately linearly with the test pulse amplitude and saturates at high Vcal values due to a saturation of the preamplifier. As the saturation occurs for signal amplitudes that are considerably higher than those expected for MIPs, this is not relevant for operating the ROC in the experiment. The range of covered ADC values is denoted as ΔPH as depicted in Figure 14.7.

In order to relate the output of the ADC to Vcal units (and later on to charge), a PH calibration is performed. Test pulses with increasing amplitude are sent to a pixel and the response of the ADC is measured and saved to a calibration file. In order to mitigate the influence of statistical fluctuations, a series of test pulses with the same amplitude is usually used to average the response of the ADC. As the response shows non-negligible pixel-to-pixel variations, the calibration is performed for each pixel individually. The acquired data can be fitted for each pixel with a second-order polynomial to interpolate between the measurements below the amplifier saturation. As shown in Figure 14.7, the quadratic fit provides a good description of the PH in the energy range relevant for signals induced by external particles and takes potential small non-linearities of the ADC response for small signals into account.

14.6.4 Charge calibration

A calibration with external reference charges is required to express important chip properties, such as the charge threshold and the electronic noise of the preamplifier/shaper system in physical units. Especially the charge threshold needs to be known precisely, since this parameter is an important input for any simulation of the pixel detector response. Such simulations are utilized by many particle collision analyses, e.g., for comparing data to MC based background estimations (c.f. Part I).

The method requires the ROC to be bump-bonded to a sensor, where reference signal charges are generated by absorption of X-ray photons of a precisely defined and known energy. The narrow, characteristic K_α emission lines of zinc, copper, molybdenum, silver, tin, and barium have proven to provide suitable reference signals and can easily be provided by illuminating the target material with a continuous X-ray retardation spectrum of a 60 kV electron tube. X-ray photons are absorbed in the sensor via photoeffect and deposit a target material dependent, characteristic energy in the sensor. According to Equation 13.2, this generates a known amount of electron-hole pairs, which serve as a reference charge. The response of the ADC to this reference charge is measured and converted into VCAL equivalent units using the PH calibration data. The resulting energy spectrum in VCAL units can be fitted with a Gaussian distribution to extract the mean of the peak corresponding to the K_α emission line. Plotting this value against the known reference charge for a set of fluorescence materials allows to obtain a calibration constant in units of electrons/VCAL as the slope of a linear fit to the data. Details of the method are discussed, e.g., in Refs. [225, 226].

15. Readout Chip Irradiation and Testing

As the innermost component of the CMS experiment, the pixel detector is amongst the subsystems that are exposed to the largest particle rates and fluences. During its envisaged lifetime until LS3 of the LHC in 2024, huge quantities of particles produced in proton-proton collisions at its center will pass through the detector and will affect its performance by means of ionizing and non-ionizing damage mechanisms. These harsh conditions make a thorough assessment of the radiation tolerance of all of its components mandatory to ensure the required performance throughout the detector's lifetime. The newly designed digital ROC as one of the central improvements of the upgraded detector requires especially profound design verifications. Laboratory [225] and test beam measurements [227, 228] have therefore been complemented with comprehensive irradiation studies, both with prototypes and with the final production version of the ROC. These studies provided important insights, which allowed to remove flaws in the layout and to tweak design parameters during the development phase of the chip. In addition, they allow to forecast the evolution of important performance figures and optimal operation parameters with increasing radiation induced damage in the experiment.

Radiation effects in ICs and their components can be divided into single-event phenomena and total ionizing dose (TID) effects. An example for the former category are single event upset (SEU), where the absorption of a single, heavily ionizing particle can cause bit-flips in digital logic blocks. As its predecessor, the digital ROC employs dedicated capacitors aided by Miller effect to increase the critical charge required to induce a change of the logic state of the trim and the mask bits [219]. This reduces the SEU rate by two orders of magnitude compared to a version without protected storage cells. The remainder of the SEU induced errors can be resolved by detecting the error state and reprogramming the affected module. The study presented in this thesis, however, focuses on TID related radiation effects. In order to provide a minimal background knowledge for interpreting the test results presented in Chapter 16, Section 15.1 reviews the effects of ionizing radiation on metal-oxide-semiconductor field-effect transistor (MOSFETs). Subsequently, the radiation environment at CMS is described in Section 15.2 in order to motivate the design specifications of the ROC in terms of TID. Section 15.3 describes the irradiation facility and the setup used to expose samples of the ROC to a 23 MeV proton beam to accumulate the TID expected during the operation of the detector and beyond. Moreover, details concerning the number of tested samples and tested dose levels are presented. Finally, the experimental setup used to examine the samples before and after irradiation is described in Section 15.4.

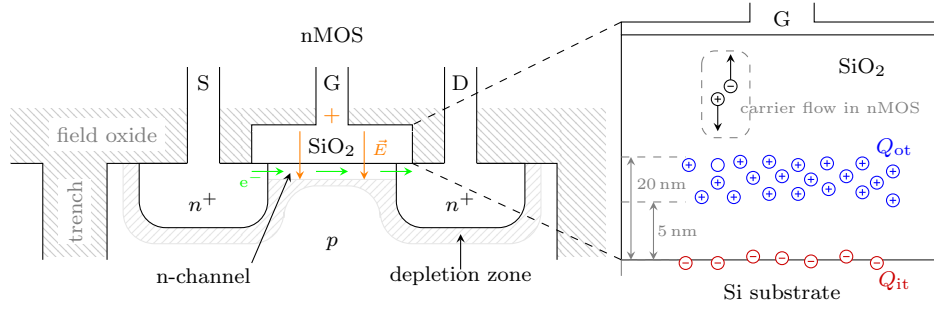


Figure 15.1: Schematic cross-sectional view of an n-channel MOSFET device (left). Source (S) and drain (D) are implemented as n^+ -doped implants in a p -doped substrate. The gate (G) is electrically isolated by a layer of silicon dioxide (SiO_2). Applying a positive potential to the gate creates a conducting channel between source and drain. Ionizing radiation creates a positive, semipermanent space charge Q_{ot} in the oxide, caused by trapped holes (right). An additional space charge Q_{it} , whose polarity depends on the device type is accumulated at the interface between the amorphous oxide and the crystalline substrate.

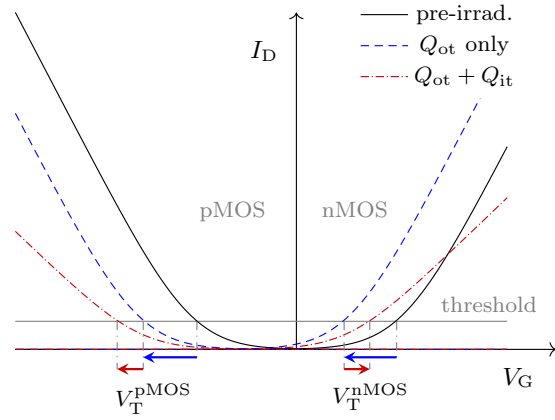
15.1 Radiation damage in MOSFETs and integrated circuits

The ROC consists of about 1.6 million MOSFETs [229], whose performance is subject to radiation induced changes. While non-ionizing displacement damage plays the leading role in the degradation of silicon sensors as described in Section 13.1.5, the performance of MOSFETs and ICs composed thereof, is predominantly affected by ionizing energy loss of traversing charged particles and absorbed photons. Rather than the particle fluence, the absorbed TID is therefore the quantity of interest when characterizing radiation damage in ICs. An extensive review of radiation induced effects in electronics that forms the basis of the following summary can be found in Ref [230].

Figure 15.1 shows a schematic cross-sectional view through a MOSFET. The device consists of n^+ -doped drain (D) and source (S) terminals, implanted into a p -doped bulk substrate. The intrinsic built-in voltage of the pn -junction causes the terminals to be electrically isolated from the bulk by a thin depletion zone. The metalized gate (G) of the transistor is electrically isolated from drain and source by a thin layer of silicon dioxide (SiO_2). Applying a positive potential to the gate creates an electric field, which penetrates the dielectric and deforms energy bands in the substrate such that free minority charge carriers — electrons in the case of an n-channel MOSFET — are attracted and accumulate underneath the oxide. This establishes a conductive channel, allowing electrons to flow from the source to the drain terminal. Because of the negative polarity of the charge carriers, such devices are referred to as nMOS transistors, while implementations with oppositely doped terminals and positive charge carriers are called pMOS transistors. The strong dependence of the source-drain current I_D on the gate voltage V_G allows to use such devices both as amplifiers in analog circuits and as switching devices in digital logic.

Ionizing radiation influences the performance of MOSFETs through the generation of semi-permanent space charges in the gate oxides and at the interface between oxide layers and silicon. As in the sensors, ionizing radiation creates electron-hole pairs in the oxide, where the ionization energy amounts to 18 eV per pair. Charge carriers that do not instantly recombine drift through the oxide under the influence of the applied electric field. While electrons largely reach the gate or the silicon substrate in nMOS and pMOS devices respectively, the significantly lower mobility of holes causes a large fraction of them to be trapped within the oxide layer. The majority of them is accumulated in an area with a large concentration of deep hole traps, which extends from the oxide-substrate interface into the oxide for roughly 20 nm. Electron tunneling from the substrate leads to recombination of charge carriers in close proximity to the interface, restricting the positive oxide-trapped space charge Q_{ot} to a region

Figure 15.2: Drain current I_D as a function of gate voltage V_G for pMOS (left) and nMOS devices (right). After irradiation, the oxide-trapped space charge Q_{ot} causes the threshold voltage V_T to shift to more negative values (blue). Accumulation of a space charge Q_{it} at the oxide-substrate interface distorts the IV characteristic and leads to smaller slopes of the curve (red). Modified from [230].



of 5–20 nm in front of the interface, as depicted on the right-hand side of Figure 15.1. If the oxide layer is substantially thicker than 30 nm, the effective volume for creating holes that are eventually trapped in the oxide is smaller in pMOS transistors compared to an equivalent nMOS device, however, the accumulated space charge has positive polarity in both cases.

These microscopic effects alter macroscopic properties of the transistor, in particular its threshold voltage. Figure 15.2 schematically represents the relation between the gate voltage V_G and the drain current I_D for pMOS and nMOS devices on left- and right-hand side of the figure, respectively. The threshold voltage V_T of the transistor is depicted as gate voltage needed to achieve a certain drain current I_D . As illustrated in the figure, the generation of the positive space charge in the oxide shifts the threshold voltage to lower values compared to its pre-irradiation value. As a consequence, the working points of both types of transistors get shifted. Further irradiation leads to a sharp increase in the quiescence current for nMOS devices once $V_T < 0$ V and can eventually cause fatal device failure when a change of the logic state becomes impossible. In pMOS transistors, increasing absolute values of the threshold voltage cause the conducting channel to become progressively high-ohmic if the available gate voltage is kept constant. Additional degradation of the channel conductivity can also arise from displacement damage [230].

An additional effect arises from the generation of space charges at the Si-SiO₂ interface [231]. At the transition from the amorphous SiO₂ to the crystalline substrate, open atomic bonds of the silicon atoms introduce energy levels within the band gap, which act as trapping centers. Before irradiation, these so-called *dangling bonds* are usually occupied with hydrogen atoms, which are deliberately introduced during the production process to deactivate the trapping centers. During and after irradiation, however, these bindings can be broken and the trapping centers become re-activated. Depending on the Fermi level, this entails an accumulation of a positive or negative space charge for pMOS and nMOS devices, respectively. This interface space charge, denoted as Q_{it} , tends to decrease the slope of the IV -curve as schematically depicted by the dotdashed lines in Figure 15.2. While this worsens the threshold voltage shift for pMOS devices, it can be beneficial for nMOS transistors where a negative space charge is accumulated at the interface, which counteracts the positive oxide-trapped space charge. If Q_{ot} saturates because all traps in the oxide are filled, while the interface charge keeps building up, this can increase the threshold voltage even beyond its pre-irradiation value. For digital circuitry, the decreased slope of the IV -curve translates into slower switching times.

Similar as for displacement damage, ionization effects in the oxide and at the oxide-silicon interface show a temperature dependent temporal evolution, even after the irradiation has stopped. The oxide-trapped space charge can be decreased by annealing and eventually vanishes if the temperature and the annealing time are sufficiently large [230]. Charges

trapped at the interface, however, exhibit this behavior only at very large temperature and hence the interface space charge does not decrease at typical operation temperatures. On the contrary, the development of new interface states can even increase Q_{it} after the irradiation has stopped. Such temporal evolutions of the space charge densities can introduce dose-rate dependencies when studying the radiation tolerance of a device under test (DUT). Especially at high temperatures, where annealing effects are significant, this can affect the comparability of the long-term irradiation of a device in the final deployment situation on the one hand, and the accelerated testing with high dose-rates on the other hand. This discrepancy can be minimized by cooling the device to temperatures to below 0 °C both in operation and for accelerated irradiation and testing.

Sub-micron processes mitigate the problem of oxide-trapped space charges since the gate oxides are usually thin enough for Q_{ot} to be small. In case of the new ROC for the upgraded pixel detector, the gate oxide layers have an effective thicknesses of the order of 6 nm [229], which entails that trapped oxide charges are very likely to recombine with tunneling electrons from the substrate (c.f. Figure 15.1). However, charge carriers trapped in interface states still lead to thresholds shifts and additional problems can arise from space charges that develop at the interfaces and within field oxides and trenches that are used to electrically isolate different layers and domains of the chip. For the new CMS pixel ROC, these field oxide layers have a thickness of 0.36 μm [229] and are hence thick enough to accumulate oxide-trapped space charges.

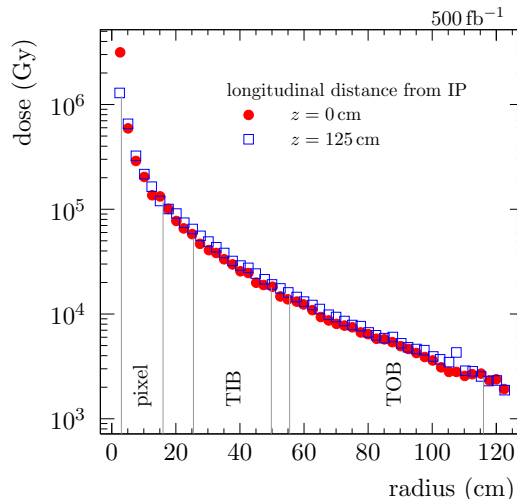
Once a specific process technology has been chosen, little can be done to prevent the described microscopic TID effects from developing. However, following specific design rules [232] and using enclosed transistor layouts that avoid trench isolations between the terminals allows to design systems that can tolerate radiation induced damages to a certain extent. The goal of radiation tolerance assurance tests, such as the one presented in this thesis, is therefore to verify that the DUT does not experience fatal failures and that its performance is not degraded beyond a tolerable level after accumulating the expected lifetime dose.

15.2 Radiation environment of the upgraded pixel detector

The radiation environment at CMS is a complex composition of multiple types of elementary and composite particles, with the largest fluences arising from neutrons, charged hadrons, and photons. Owing to considerable variations in energy transfer between the colliding partons (c.f. Section 3.2), the collision products can vary starkly in energy from collision to collision. However, the vast majority of the events consist of MIPs with energies of a few hundred MeV. It is worthwhile noting that the geometrical $1/r^2$ attenuation of the particle fluence is significantly altered by low energy particles, which loop in the magnetic field of the solenoid and thereby cause increased particle rates and ionizing doses. Accurately predicting particle fluences and TIDs is crucial for defining design specifications of detectors and to assess questions of radioprotection. At CMS, such studies are performed using the FLUKA simulation package [233], which is capable of simulating hadron-hadron interactions and the subsequent transport of the collision products through a model of the CMS detector, including particle interactions with the detector material.

During the operation of the Phase I pixel detector between 2017 and the beginning of LS 3 in 2024, the CMS experiment is expected to collect a total of 300–500 fb^{-1} of proton-proton collisions, depending on the performance of the LHC. In order to assess the worst case scenario in terms of radiation damage, the FLUKA simulations used to define the design specifications of the upgraded pixel detector are based on the upper estimate of 500 fb^{-1} . The corresponding particle fluences and the TID absorbed by the detector have been simulated for proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$, assuming an inelastic collision cross section of 80 mb [234]. The tracking detector geometry has been modeled using 500 μm thick layers of silicon, surrounded

Figure 15.3: Expected total ionizing dose for 500 fb^{-1} of proton-proton collisions. The absorbed dose is shown for radii covering the pixel detector, the tracker inner barrel (TIB), and the tracker outer barrel (TOB). The innermost layer of the pixel detector is expected to receive more than 1 MGy of ionizing radiation during the foreseen lifetime of the detector. Modified from [195].



by material with a density of 0.047 g/cm^3 . The surrounding material was assumed to be composed of 31% carbon, 30% iron, 23.5% aluminum, 8% oxygen, 2% nitrogen, and 5.5% hydrogen. For 500 fb^{-1} of proton-proton collisions, the simulation predicts a normalized charged hadron fluence of approximately $3 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ in the innermost barrel layer of the pixel detector [195]. The TID expected for the same integrated luminosity is shown in Figure 15.3 as a function of radial distance from the IP. The expected TID is shown at two longitudinal distances from the IP, namely for the central position and for $z = 125 \text{ cm}$. It is estimated that the innermost barrel layer of the pixel detector, located at a distance of 3.0 cm from the IP, will absorb a dose of just above 1 MGy. With increasing radius, the expected dose quickly drops, falling by a factor of two for barrel layer 2 (6.8 cm) and by almost an order of magnitude for the layers 3 (10.9 cm) and 4 (16.0 cm). The radial coverage of the endcaps ranges from $4.5\text{--}16.1 \text{ cm}$ [195], implying that the innermost part of the disks will be exposed to doses in between the values expected for barrel layers 1 and 2.

15.3 Proton irradiation of readout chip samples

In order to assess the radiation tolerance of the new ROC, various samples of prototypes and the final production version of the chip have been exposed to ionizing radiation for accelerated testing.

15.3.1 Target doses and samples

The dose levels investigated in the presented study aim at testing the high-dose capability of the new ROC and are motivated by the maximum lifetime doses expected for barrel layers 1 and 2, assuming an integrated luminosity of 500 fb^{-1} of proton-proton collisions. Motivated by data presented in Figure 15.3, a target dose of 0.6 MGy has been chosen as upper estimate of the maximum dose the layer 2–4 ROC will be exposed to in the experiment. Furthermore, a dose of 1.2 MGy has been targeted in order to assess the ROC's radiation tolerance for maximum dose expected for the innermost layer of the detector. While the ROC examined in this study will not be used in layer 1, results obtained at this dose allowed to project and improve the radiation tolerance of the layer 1 ROC prior to its first submission as outlined in Section 14.5.2. In addition, samples irradiated to doses of 2.4 and 4.8 MGy — far beyond what is expected in the Phase I detector — have been investigated in order to explore the limits of the ROC in terms of TID.

Instead of irradiating and testing full modules, individual samples of the ROC have been used for this purpose. This greatly facilitates logistics by reducing the beam time required

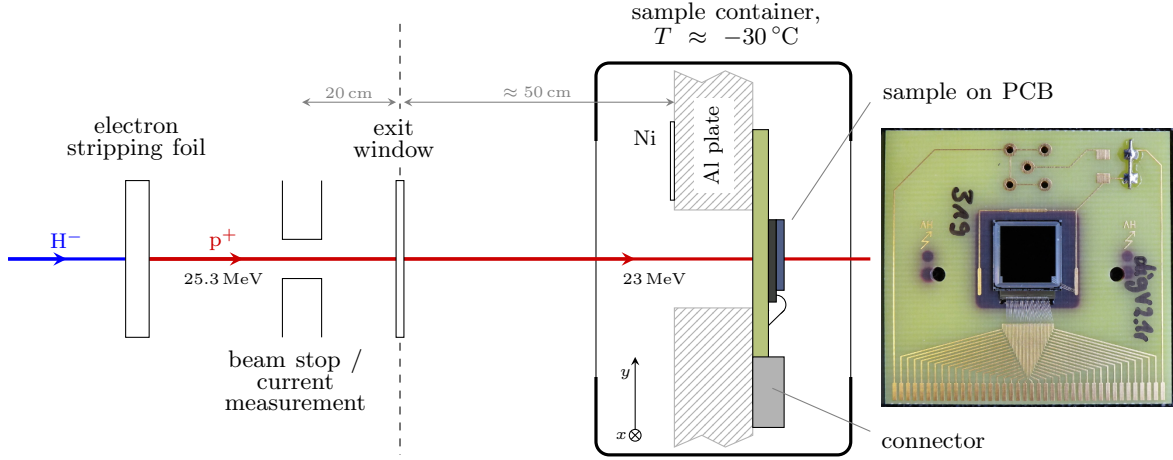


Figure 15.4: Schematic representation of the beam extraction and irradiation setup. Electrons are stripped from H^- ions to gain protons, which are shot onto the samples with an energy of 23 MeV. Samples are placed inside a thermally and electrically isolated box, where they are mounted onto the far side of an aluminum plate with cutouts for the beam. The sample holding box can be moved through the beam to scan the sample along the x and y direction. A top view photograph of a sample after irradiation to 4.2 MGy is shown on the right-hand side. The dark area shows the radiation induced discoloration of the PCB in the beam.

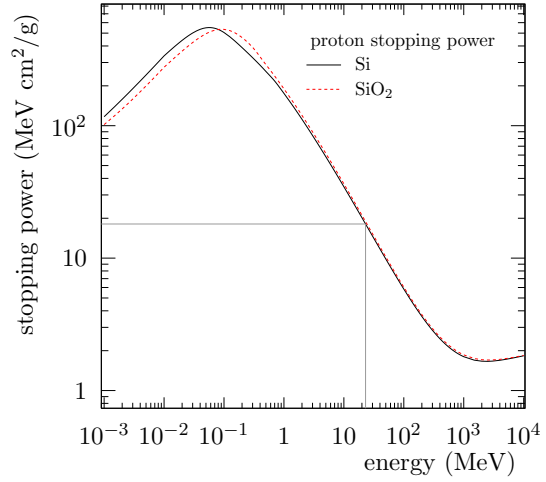
for the irradiation and the activation of the samples. In addition, the approach allows to study irradiation effects in the ROC without interference from effects in other components of the module, e.g., in the TBM. For irradiation and testing, ROC samples have been glued and wire-bonded onto a PCB, which allows to connect the sample to the DAQ system. A second type of sample consists of a single ROC bump bonded to a silicon sensor with 52×80 pixels. Such a sample is referred to as single-chip module (SCM). It offers the possibility to not only test the sample with internal test pulses, but also with signals generated by external particles in the sensor allowing, e.g., to evaluate the performance of the ROC in a high occupancy environment after irradiation. Comparing samples with and without sensor also allows to investigate the influence of the input capacitance imposed by the sensor on certain chip properties.

15.3.2 Irradiation facility and setup

Samples have been irradiated with a 23 MeV proton beam at the Compact Cyclotron, operated by ZAG Zyklotron AG [235] in Karlsruhe, Germany. Figure 15.4 illustrates the beam extraction and irradiation setup. Protons for irradiation are gained by accelerating H^- ions and stripping off the two electrons at a foil [236]. The released electrons provide a measurement of the beam current I_{beam} . A second beam current measurement can be obtained at the beam stop that is located at a distance of 20 cm from the exit window, the latter of which is made from a $7 \mu\text{m}$ thick cobalt alloy foil. At extraction, the protons have an energy of 25.3 MeV. This energy drops to 23 MeV at the samples, which are hosted in a thermally and electrically isolated box, located at a distance of about 50 cm from the exit window. To prevent overheating and annealing effects during irradiation, the sample holding box is flushed with nitrogen to cool the samples to -30°C . At the beam spot the temperature rises but stays below 0°C . Since the beam diameter ($\approx 4 \text{ mm}$) is smaller than the sample size, an evenly distributed accumulation of energy is achieved by moving the sample through the beam using an x - y motor stage.

Within the irradiation box, up to 15 samples can be mounted onto an aluminum plate with cutouts for the beam of a size of approximately $1 \times 1 \text{ cm}^2$. As shown in Figure 15.4, the samples are attached to the far side, such that the plate shields the largest part of the PCB

Figure 15.5: Stopping power of protons in silicon and silicon dioxide for a wide range of energies. For 23 MeV protons, as available in the chosen irradiation facility, the stopping power in silicon amounts to $18.1 \text{ MeV cm}^2 \text{g}^{-1}$. The corresponding value in silicon dioxide is only marginally larger (4%) [237].



to minimize radioactivation. The mounting plate also provides connectors for applying the nominal ROC supply voltages of $V_A = 1.6 \text{ V}$ and $V_D = 2.4 \text{ V}$ for ten out of the 15 samples. Powering the samples during irradiation is important to obtain a similar electric field and charge carrier drift in the gate oxides and hence comparable space charge accumulation as during the operation in the experiment. Samples without irradiation bias have been tested as a control group.

As shown in Figure 15.5, 23 MeV protons have a stopping power of $18.1 \text{ MeV cm}^2 \text{g}^{-1}$ in silicon. The corresponding value in SiO_2 is only marginally larger ($S = 18.9 \text{ MeV cm}^2 \text{g}^{-1}$). This material specific parameter allows to express the dose D , defined as the total absorbed energy E_{tot} per mass m , as a function of the proton fluence F_p

$$D = \frac{E_{\text{tot}}}{m} = \frac{(S d \rho) \cdot (F_p A)}{\rho A d} = S F_p. \quad (15.1)$$

The sample properties, namely thickness d , density ρ , and surface area A cancel, making the TID absorbed in the oxide layers independent of the thickness. Irradiation to a dose of 1.2 MGy requires a fluence of $F_p = 0.4 \times 10^{15} \text{ protons/cm}^2$. The proton fluence in turn can be calculated with parameters of the irradiation setup as [238]

$$F_p \approx \frac{n I_{\text{beam}}}{e v_x \Delta y}, \quad (15.2)$$

where n denotes the number of scans, $I_{\text{beam}} = 2 \mu\text{A}$ the beam current, $v_x = 115 \text{ mm/s}$ the horizontal scan velocity, and $\Delta y = 1 \text{ mm}$ the vertical step width [236]. In order to avoid inhomogeneous irradiation at the turning points of the horizontal scans, an area with margins of about 1 cm around the sample is scanned. The values for beam current and scan velocity specified above yield a dose rate of about 130 kGy/min .

15.3.3 Dosimetry and tested samples

Post-irradiation dosimetry is performed by measuring the fluence dependent activation of ^{57}Ni in nickel foils that are affixed to the front of the aluminum plate and irradiated with the same proton fluence as the sample (c.f. Figure 15.4). The activity measurement itself is performed with a germanium detector and an uncertainty of 20% on the measured dose is quoted by the operators of the cyclotron.

Tables 15.1 and 15.2 summarize the target doses and proton fluences of the irradiated SCM and ROC samples. While SCMs have been irradiated up to doses of 4.8 MGy , bare ROC

Table 15.1: Nominal target dose D^{nom} and corresponding proton fluence F_p^{nom} for single chip module (SCM) samples investigated in the presented study. The fluence is also given in units of 1 MeV neutron equivalents, assuming a hardness factor of 2. Furthermore, the actual dose as measured by dosimetry D_{measured} and the number of tested samples is specified.

D^{nom} (MGy)	F_p^{nom} (p/cm ²)	F_p^{nom} (n _{eq} /cm ²)	D_{measured} (MGy)	# of SCMs
0.6	0.2×10^{15}	0.4×10^{15}	0.52 ± 0.10	3
1.2	0.4×10^{15}	0.8×10^{15}	1.1 ± 0.22	4
2.4	0.8×10^{15}	1.6×10^{15}	2.2 ± 0.45	3
4.8	1.6×10^{15}	3.2×10^{15}	4.2 ± 0.84	3

Table 15.2: Nominal target dose D^{nom} and corresponding proton fluence F_p^{nom} for readout chip samples without sensor investigated in the presented study. The fluence is also given in units of 1 MeV neutron equivalents, assuming a hardness factor of 2. Furthermore, the actual dose as measured by dosimetry D_{measured} and the number of tested samples is specified.

D^{nom} (MGy)	F_p^{nom} (p/cm ²)	F_p^{nom} (n _{eq} /cm ²)	D_{measured} (MGy)	# of ROCs
0.6	0.2×10^{15}	0.4×10^{15}	0.57 ± 0.11	6
1.2	0.4×10^{15}	0.8×10^{15}	1.5 ± 0.29	6

samples are only tested up to the expected lifetime dose of layer 1 of the detector of 1.2 MGy. Even though less important for assessing the radiation tolerance of the ROC itself, the fluence is also expressed in units of 1 MeV neutron equivalents, which allows to estimate the non-ionizing radiation damage associated to the irradiation. For normalizing the proton fluence, a hardness factor of 2 has been suggested [236]. Finally, the actual dose as determined by dosimetry and the number of samples investigated in the presented study are shown. The measured doses tend to be slightly lower than the envisaged target dose, with the exception of the ROC samples with a target dose of 1.2 MGy, which accumulated about 1.5 MGy. However, all deviations are smaller than the uncertainty of the dosimetry measurement. Photographs of the irradiated samples can be found in Appendix G.

15.4 Test setups

All samples are characterized before and after irradiation in order to detect radiation induced changes in performance and optimal operation parameters. The DAQ system and the test stands used for this purpose are described below.

15.4.1 Data acquisition

In order to read out a DUT the sample holding PCB, shown on the right-hand side of Figure 15.4, is inserted into an adapter and connected via a 33-pin ribbon cable to a custom-made readout board, the so-called *digital test board* (DTB). The DTB has been designed and produced within the Pixel Phase I Upgrade Collaboration and is used in laboratory and test beam measurements to emulate the functionality of the FED and FEC units in the CMS experiment. To this end, the DTB provides the sample with configuration commands via the I²C-like interface, with the 40 MHz master clock, and with high voltage for sensor biasing. For reading out ROCs that are not integrated into a full module, the DTB emulates the TBM by sending and receiving the external token, which initiates the readout of a the DUT. Furthermore, the DTB issues CTR signals for initiating test pulses injections and for triggering and resetting the DUT. To allow for a rapid succession of these commands with

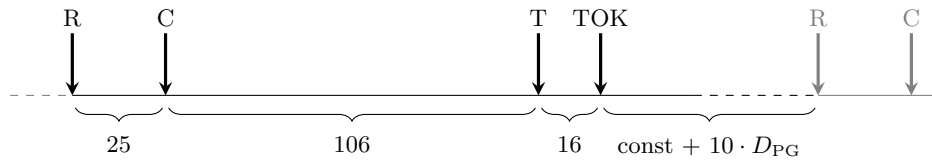


Figure 15.6: Default pattern generator signal sequence consisting of a **reset** (R), a **calibrate** (C), a **trigger** (T), and a **token** (TOK) signal. The delays between the signals are given in units of 25 ns clock cycles. The delay between consecutive sequences can be adjusted with the D_{PG} setting.

precisely defined delays in between them, a pattern generator can be programmed before starting a test [239]. The defined signal sequence can then be issued either once or as a repetitive loop. The pattern generator is integrated into the test board firmware, which runs on an Altera FPGA. The firmware also includes an emulated NIOS II CPU, which is used to execute frequently reoccurring tests such as sequentially sending test pulses to each pixel of the DUT or probing the response of a certain pixel under test while scanning through a range of DAC settings. Such tests require frequent reconfigurations of the DUT, which would lead to a large communication overhead if each of the commands was sent by an external PC via USB to the DTB. Executing them on the emulated CPU instead allows to significantly speed up the test procedures. Additional firmware modules are responsible for deserializing the data sent by the DUT to the DTB. Differential input data at 160 Mbit/s, as sent by ROC and SCM samples, can be received as well as the 400 Mbit/s stream sent by a full module. Further features of the DTB, such as handling external triggers and reading out analog CMS pixel ROCs are not relevant in the context of this thesis.

The DTB connects to a standard PC via USB, where a readout software runs to execute the following tasks. Firstly, the software is responsible for transmitting the DUT configuration as defined in dedicated configuration files. Secondly, the software is used to program the pattern generator and to invoke test procedures in the NIOS core. Finally, the it decodes deserialized data sent by the DTB and visualizes the test results. The central part of the software used for measurements presented in this thesis is referred to as *pxarCore* [239] and has been developed for module and chip testing for the Phase I Upgrade project. It is used for a wide range of applications, including quality assurance tests for modules that are installed in the detector as well as test beam and laboratory measurements for research and development purposes. The *pxarCore* software provides a library for communication to the NIOS core on the DTB via an application programming interface and a hardware abstraction layer. In the context of this thesis, high-level tests are defined in a python interface (*pyXar*), which calls *pxarCore* functions for invoking test sequences. Several test implemented in *pyXar* resemble the standard test used for module qualification (e.g. pretest and threshold adjustment, c.f. Section 14.6), which are described elsewhere [224, 225]. Others are specifically tailored for investigating radiation induced effects and have been implemented as part of the presented study. Such non-standard tests will be described along with the presentation of their results in Chapter 16.

Pattern generator signal sequence

The default signal sequence issued by the pattern generator for tests presented in this thesis is shown in Figure 15.6. It commences with a **reset** command to bring the sample into a well-defined state. After a delay of 25 clock cycles, a **calibrate** command is issued for test pulse injection, followed by the **trigger** signal with a fixed latency of 106 clock cycles. The WBC register of the ROC is programmed correspondingly to ensure that the correct bunch crossing with the test pulse is triggered. With these settings, the trigger latency has a similar order of magnitude as expected in the experiment. For testing ROC samples that are not

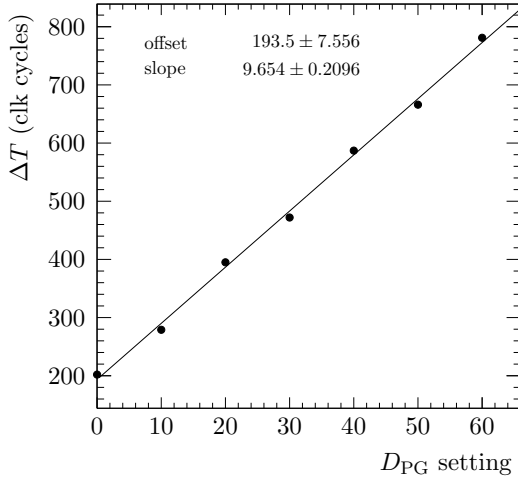


Figure 15.7: Periodicity of the test pulse injection for different settings of the pattern generator delay D_{PG} as measured with an oscilloscope. For the default setting $D_{PG} = 0$, the test loop sequence has a period length of about 200 clock cycles. The line shows a linear fit to the data.

integrated into a module with a TBM, the readout **token** is sent by the DTB 16 clock cycles after the trigger signal to initiate the readout of the sample. For tests employing a different signal sequence, the pattern generator setup will be described explicitly in Chapter 16.

The time interval between the **token** and the **reset** of the following signal sequence determines the test pulse injection frequency in a repetitive pattern generator loop. For the nominal loop, the additional delay D_{PG} at the end of the sequence is set to zero. In this case, the test pulse injection frequency reaches its maximum of 200 kHz, limited by the clock of the FPGA and firmware setup. The maximum injection frequency corresponds to a period length of about 200 clock cycles between consecutive test pulses. This interval can be increased by setting D_{PG} to a number between 1 and 255, which adds an additional waiting time after each pattern generator sequence in units of 10 clock cycles. The resulting linear increase of the test pulse periodicity, as measured with an oscilloscope, is shown in Figure 15.7. For all measurements presented in Chapter 16, D_{PG} is set to zero if not otherwise noted.

15.4.2 Climate chamber setup

In order to obtain reproducible results, the samples have been tested at controlled and well-defined environmental conditions. For electrical tests that probe the response of the samples to internal test pulse injections, a climate chamber test stand has been used, which allows to perform tests at temperatures down to -20°C . The samples are placed on an anodized aluminum plate whose temperature is stabilized by thermoelectric cooling and hosted in a sealed volume. Thermal contact between the cooling plate and the far side of the sample holding PCB is established through a thin metal base with grooves for protruding parts of the connector. Condensation at low temperatures is avoided by flushing the sealed volume with dry air. Cooling plate and dedicated contacts at the sample adapter are connected to ground potential to avoid crosstalk from the pulse-width modulated current in the thermoelectric elements. Photographs of the climate chamber setup can be found in Appendix H.

15.4.3 X-ray test stand

A second test stand is equipped with an 1.8 kW X-ray tube. It is used to investigate the performance of SCM samples in high-occupancy environments and for charge calibrations with monochromatic X-radiation. Within the tube, electrons are accelerated with up to 60 kV and absorbed by a water-cooled chromium anode. The resulting white retardation spectrum, also referred to as *primary beam*, can be directed onto the DUT, which is placed vertically below the tube at a distance of about 60 cm. The sample itself is hosted in a sealed volume with a cooling system similar to the one described above to allow testing at the same temperature

of -20°C as in the climate chamber. X-rays enter the sealed volume through a window covered with a thin aluminum foil, which isolates the testing volume from the humidity of the ambient air. The intensity of the primary X-ray beam linearly depends on the tube current, which can be adjusted between 2 mA and 30 mA. The intensity of the primary beam of the X-ray tube is large enough to induce hit rates of several hundred MHz/cm² in the silicon sensor of a SCM sample. This allows to test the performance of the ROC in a high occupancy environment with a readout load that is similar to the one expected during the operation in CMS.

For performing charge calibration measurements, the electron retardation spectrum can be used to illuminate several X-ray fluorescence targets instead of being directed onto the DUT directly. The energy of the material's characteristic K_{α} -emission line is used as a reference energy for calibrating the internal test pulse amplitude as outlined in Section 14.6.4. With $\mathcal{O}(100\text{ kHz/cm}^2)$, the hit rates induced by the monochromatic X-radiation are significantly lower compared to the ones induced by the primary beam.

The compact climate chamber used in the X-ray test stand has been designed, installed, and commissioned as part of the present work. It was not only used for measurements presented in this thesis, but also allowed to characterize detector modules at well-defined environmental conditions prior to their installation in the new detector. Photographs of the setup can be found in Appendix I.

16. Results

In order to assess the radiation tolerance of the digital readout chip (ROC) for the Phase I Upgrade of the CMS pixel detector, several samples of the chip have been irradiated in a 23 MeV proton beam to accumulate a total ionizing doses (TIDs) as expected for the envisaged lifetime of the detector and beyond. All samples, including several ROCs that have been bump-bonded to small silicon sensors, so-called SCMs, have been thoroughly characterized before and after irradiation using the same set of test routines under identical environmental conditions. This approach allows to identify both statistical variations among the samples and systematic radiation induced changes of performance figures and operation parameters. In order to minimize annealing, all samples have been maintained at temperatures below -20°C during and after irradiation, interrupted only by short warm-up periods to perform dosimetry measurements and to avoid condensation while inserting the samples into the test setups. The qualification itself has been performed at $T = -20^{\circ}\text{C}$ to reduce the sensor leakage current of the SCM samples and to operate the samples under similar conditions as in the experiment. If not otherwise noted, all samples have been powered with the nominal supply voltages of $V_A = 1.6\text{ V}$ and $V_D = 2.4\text{ V}$. A reverse bias voltage of 150 V and 400 V has been applied to the sensors of the SCM samples before and after irradiation, respectively.

The presentation of the test results is structured as follows. Section 16.1 describes the radiation induced drift of the band gap reference voltage and shows the power consumption of the ROC in different modes of operation. Furthermore, adjustments of operation parameters that are required to prepare the irradiated samples for test pulse readout are detailed. Test results characterizing the analog performance of the ROC are presented in Section 16.2. The preamplifier/shaper noise, the comparator threshold, and the timewalk behavior are examined. Subsequently, measurements of the response efficiency to test pulse injections and the power consumption of the ROC in a high occupancy environment are presented in Section 16.3. Additionally, the minimum digital supply voltage required to operate the ROC under load is discussed. A radiation induced performance reduction of the pulse height (PH) sampling ADC is described in Section 16.4, along with a prescription that allows to mitigate the effect for TIDs relevant for the layer 2–4 ROC. Supplementary measurements concerning the propagation velocity of the DCol token as well as a radiation induced drift of the readback calibration parameters are presented in Section 16.5. Finally, Section 16.6 summarizes the observed radiation effects and their implications for operating irradiated ROCs in the experiment. An overview table with all operation parameters employed before and after irradiation can be found in Appendix J.

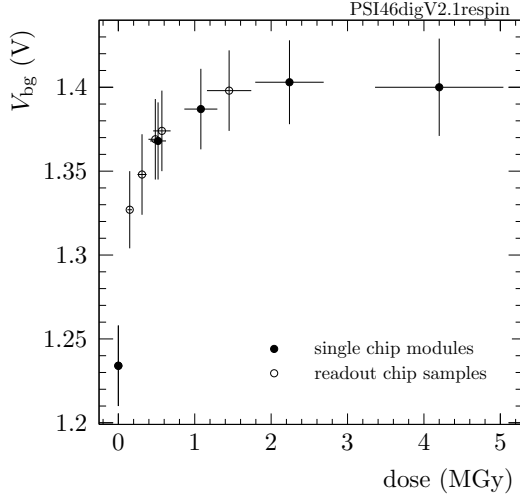


Figure 16.1: Absolute drift of the band gap reference voltage with increasing TID.

Table 16.1: Relative drift of the pre-irradiation band gap reference voltage V_{bg}^0 with increasing TID.

Dose (MGy)	$\Delta V_{bg}/V_{bg}^0$ (%)
0.15	8.3 ± 0.4
0.31	10.0 ± 0.5
0.48	11.8 ± 0.6
0.52	11.1 ± 0.9
0.57	11.3 ± 1.0
1.08	12.2 ± 0.8
1.45	13.3 ± 1.0
2.24	13.4 ± 0.8
4.20	13.9 ± 0.9

16.1 Chip commissioning and working points

Before testing high-level performance figures, the ROC needs to be prepared for basic test pulse readout. This includes an adjustment of the analog supply current and the identification of a viable setting in the phase space of the test pulse delay and the pixel threshold as outlined in Section 14.6.1. Potential radiation induced changes of these working points are investigated as well as effects on basic chip parameters such as the band gap reference voltage and the power consumption.

16.1.1 Band gap reference voltage

The band gap reference circuit of the ROC exploits canceling temperature dependencies of voltage drops across an ohmic resistor and across a pn -junction in forward bias mode [220]. This cancellation allows to generate a temperature and supply voltage independent output voltage V_{bg} , which serves as reference potential of the DACs and ADCs on the ROC. The voltage drop across the pn -junction, however, can be altered by radiation induced changes of the effective doping concentration in the pn -junction. This causes a dose dependent drift of the reference voltage, which in turn requires readjustments of the DAC settings in order to keep their output voltages and currents stable. Similarly, the response of the ADCs on the chip may be subject to radiation induced drifts.

The band gap voltage has been measured for each sample before and after irradiation with a probe needle on a dedicated pad on the RCI. This measurement has been performed at room temperature, as physical access to the sample is needed. A complementary measurement has been performed by measuring V_{bg} with the readback mechanism described in Section 14.3.4. The readback ADC output has been converted into a voltage using a linear calibration based on reference voltages provided by the DTB and a new calibration has been performed after irradiation in order not to bias the measurement by potential radiation induced change of the calibration parameters. A systematic uncertainty of 1.7% is considered for the voltage measurement based on the agreement between the values obtained with the two methods. Figure 16.1 shows the mean band gap reference voltage for all tested samples as a function of TID. The indicated uncertainties represent the standard deviation of all samples at a given dose point from the mean value and the systematic uncertainty of 1.7% added in quadrature. A steep increase of V_{bg} can be observed at low irradiation doses, followed by a saturation for doses above about 2 MGy. Additional data points obtained with ROCs irradiated to doses

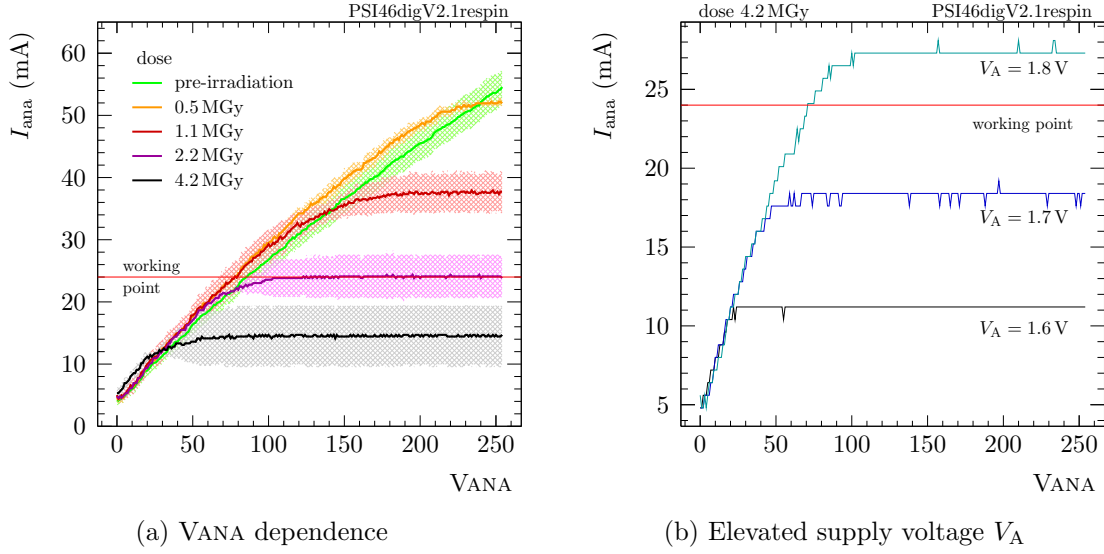
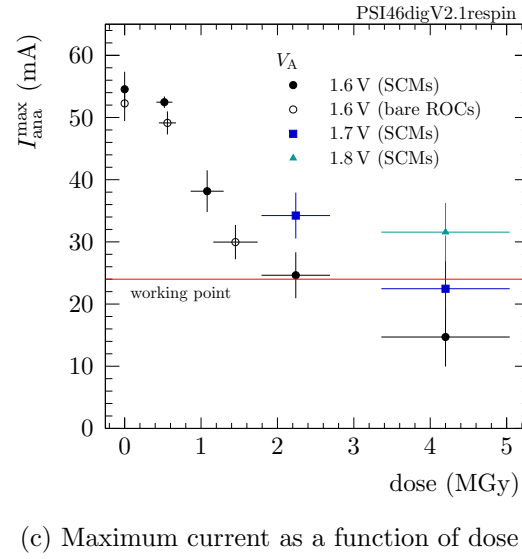


Figure 16.2: Dependence of the analog current I_{ana} on the regulator setting VANA for SCM samples irradiated up to 4.2 MGy (a). The dose dependent saturation level of the current can be increased by elevating the analog supply voltage V_A with respect to the nominal value of 1.6 V (b). The maximum analog current $I_{\text{ana}}^{\text{max}}$ therefore depends on the TID and on V_A (c).



of 0.15 MGy, 0.31 MGy, and 0.48 MGy have been added to better resolve the steep rise at low doses [240]. As expected, SCM and ROC samples exhibit a consistent behavior as the band gap reference voltage is not influenced by the sensor. Table 16.1 shows the relative drift of V_{bg} with respect to its pre-irradiation value V_{bg}^0 . A maximum drift of $(13.9 \pm 0.9)\%$ is observed with samples irradiated to 4.2 MGy. A similar saturation for doses above 2 MGy has been observed with other conventional band gap reference circuits [241].

16.1.2 Supply currents

The analog supply current I_{ana} and the digital voltage V_{dd} are regulated with the VANA and VDIG DACs, respectively. The functioning of the regulators after irradiation is verified and the current consumption of the idling ROC is investigated, both in the nominal mode of operation with all DACs programmed and the 40 MHz clock running and in a dedicated low-power start-up mode.

Nominal mode of operation

Figure 16.2 (a) shows the **analog current** I_{ana} as measured with the DTB as a function of VANA for samples before and after irradiation up to doses of 4.2 MGy. For each DAC setting,

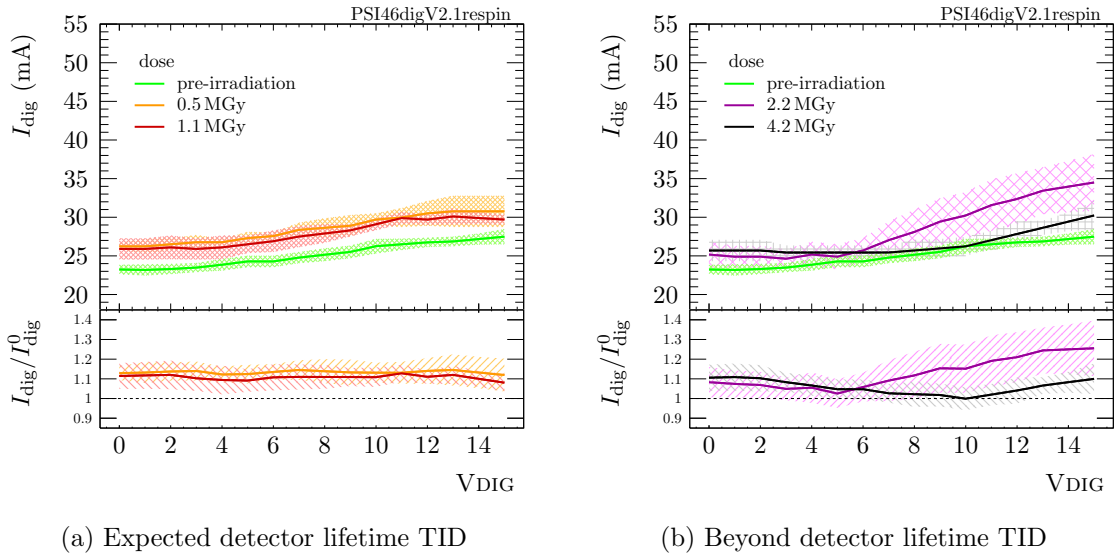


Figure 16.3: Digital current consumption for idling ROCs after irradiation to 0.5 MGy and 1.1 MGy (a) and up to 4.2 MGy (b). For doses of 0.5 MGy and 1.1 MGy, I_{dig} increases by about 10% with respect to the pre-irradiation current I_{dig}^0 , compatible with the drift of the band gap reference voltage. Samples irradiated to 2.2 MGy exhibit a larger increase of I_{dig} at large regulator settings.

the mean value (solid line) and the standard deviation (hatched band) of the current measurement for all tested samples are shown. The nominal working point of 24 mA is indicated by the red horizontal line. Before irradiation, a monotonous increase of I_{ana} between 4 mA and 55 mA can be observed for increasing regulator settings. Two modifications to this dependency are observed after irradiation. Firstly, the slope of the curve becomes steeper at low regulator settings, resulting in lower VANA values when adjusting the current to 24 mA. After irradiation to 0.5 MGy, the mean value of the adjusted VANA settings is 77.0 ± 5.2 and hence 10% lower than the corresponding pre-irradiation setting of 85.5 ± 8.5 . The effect is compatible with the drift of the band gap reference voltage, which leads to an increased regulator output.

The second radiation induced effect observed in Figure 16.2 (a) is a dose dependent saturation of the current, where the maximum current provided by the regulator drops with increasing TID. This observation indicates a dose dependent increase of the regulator drop-out voltage, defined as the difference between input and maximum output voltage, which in turn limits the current. This hypothesis is supported by the measurement displayed in Figure 16.2 (b). For a sample irradiated to 4.2 MGy, the analog current is shown as a function of VANA for different supply voltages V_A . It can be observed that the saturation level increases for elevated input voltages and that I_{ana} is independent of V_A in the regime where the regulator operates correctly. Figure 16.2 (c) summarizes the findings by showing the maximum analog current as a function of dose. For the nominal supply voltage of $V_A = 1.6$ V, the maximum current drops below 24 mA for doses beyond 2 MGy. Samples irradiated to a dose of 2.2 MGy (4.2 MGy) are therefore operated at an elevated analog supply voltage of 1.7 V (1.8 V) to allow for a proper adjustment of VANA to obtain $I_{\text{ana}} = 24$ mA. For doses below 2 MGy, the saturation level of the current is sufficiently above the working point of 24 mA for the nominal supply voltage of $V_A = 1.6$ V. The observed effect is therefore not expected to affect the operation of the ROC in the detector.

The dependence of the **digital current** I_{dig} on the voltage regulator setting is shown in Figure 16.3. The digital current consumption exhibits only a small dependence on V_{DIG} , ranging from 23 mA to 28 mA before irradiation. Figure 16.3 (a) shows that the digital cur-

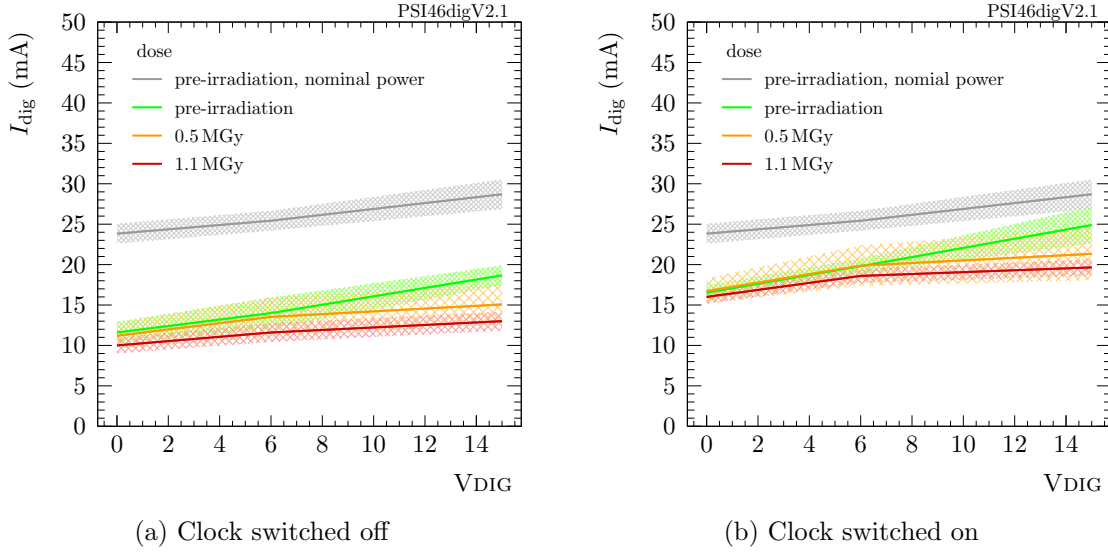


Figure 16.4: Digital current consumption in the low-power start-up mode before programming the DACs with the 40 MHz clock switched off (a) and on (b). The upper most line in each plot shows the current consumption in the nominal mode of operation for comparison.

rent increases by about 10% with respect to its pre-irradiation value I_{dig}^0 for doses of 0.5 MGy and 1.1 MGy. This increase is a direct consequence of the drift of the band gap reference voltage, leading to a larger regulated digital voltage after irradiation and hence to larger currents. Deviating behavior has been observed for samples irradiated to 2.2 MGy. While the increase of I_{dig} is 10% at low VDIG settings, a larger increase of up to 25% is observed at the maximum VDIG setting as shown in Figure 16.3 (b). The maximum digital current of samples irradiated to 4.2 MGy is again compatible with the drift of the band gap reference voltage.

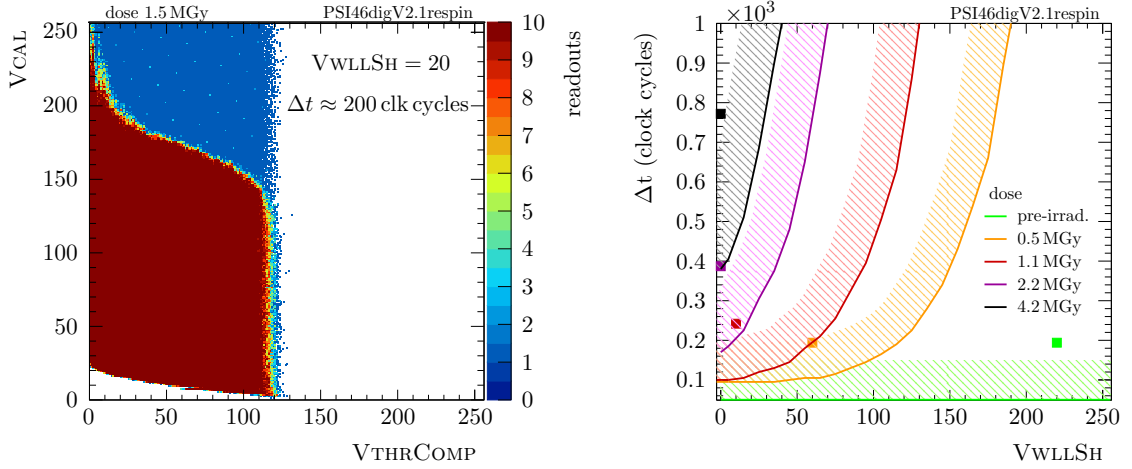
It is worthwhile noticing that the digital current substantially increases when pixel hits are processed by the ROC. The current consumption under load will be discussed in Section 16.3.2.

Low-power start-up mode

The ROC features a dedicated start-up mode, which is entered when switching on the system to bring the detector into a well-defined state with a low power consumption. In this configuration, the DACs are not yet programmed, which corresponds to setting all of them to zero, except $V_{\text{WLLPR}} = V_{\text{WLLSH}} = 255$. The measurement aims at verifying that the current consumption in the low-power mode is not significantly increased after irradiation, e.g., by the development of parasitic conducting channels along oxide-silicon interfaces. This study has been performed with the prototype version *PSI46digV2.1* at a temperature of -10°C and the results have been verified with irradiated samples of the final production version of the ROC.

Figure 16.4 shows the digital current consumption as a function of VDIG in the low-power mode with stopped (a) and running (b) 40 MHz clock. Without running clock, the digital current is about 10 mA lower compared to the nominal mode of operation when the ROC is idling. No increase of the current is observed after irradiation up to 1.1 MGy, on the contrary, a decrease of about 5 mA is observed for $\text{VDIG} = 15$ after irradiation. Switching on the 40 MHz clock increases the digital current consumption by 5–6 mA, independent of the dose and the regulator setting.

As expected, the analog current does not depend on VDIG or on the state of the clock. I_{ana} has been found to increase from the pre-irradiation value of (4.8 ± 0.8) mA to (5.4 ± 0.8) mA



(a) Response efficiency after irradiation for $V_{WLLSH} = 20$ and a test pulse periodicity of about 200 clock cycles (b) Working points in V_{WLLSH} -test pulse periodicity space for $V_{CAL} = 200$ and a pixel threshold of 1.85 ke

Figure 16.5: Pixel response efficiency in the phase space of the test pulse amplitude (V_{CAL}) and the pixel threshold ($V_{THRCOMP}$) after irradiation to 1.5 MGy (a). Only the first out of a series of 10 test pulses can be read out for large test pulse amplitudes and low thresholds. Working points with fully efficiency test pulse readout can be chosen above and to the left of the solid lines in the phase space of V_{WLLSH} setting and test pulse periodicity Δt (b). The dose dependent working points chosen for measurements presented in this work are indicated by the squares.

after the samples have accumulated a TID of 1.1 MGy, constituting an increase of 13%. The uncertainty on the measurement is dominated by the resolution of the current measurement of the DTB of 0.8 mA.

16.1.3 Basic test pulse readout

Efficient readout of pixel hits is a mandatory prerequisite for successfully operating the detector and thus constitutes a crucial functionality test after irradiation. In the simplest implementation such a test probes the response efficiency of the ROC to test pulse injections with only one pixel under study at the time. The response efficiency is tested by sequentially sending N test pulses with the default pattern generator sequence (c.f. Figure 15.6) and calculating the efficiency ϵ as the ratio of the number of read out hits over N . This test is performed after adjusting V_{ANA} such that $I_{ana} = 24$ mA and in the absence of any other readout traffic as all PUCs except the one under investigation are masked and thus insensitive to test pulses and noise induced hits.

Shaper feedback adjustment

As elucidated in Section 14.6, successful readout of test pulses requires to select a valid working point in the phase space of the pixel threshold and the test pulse delay. For irradiated samples, including those exposed to the lowest dose of 0.5 MGy, no viable setting with 100% response efficiency could be found by performing the standard pretest described in Section 14.6.1.

Figure 16.5 (a) shows the response efficiency for one pixel of a ROC irradiated to 1.5 MGy as a function of pixel threshold ($V_{THRCOMP}$) and test pulse amplitude (V_{CAL}). For thresholds above the noise level (left-hand side of the plot) the phase space is clearly separated into a region where all $N = 10$ pixels hits are found (dark red area) and another region where only one out of N hits is found in the readout (blue region). This inefficiency is observed for large

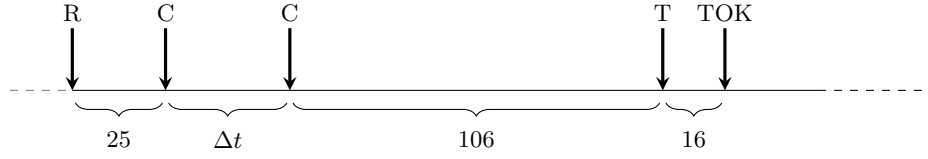


Figure 16.6: Pattern generator configuration for testing the minimum required delay Δt between consecutive test pulses. The delays between the signals are given in units of 25 ns clock cycles.

test pulse amplitudes and low pixel thresholds. The size of the region in phase space where the inefficiency occurs strongly depends on the VWLLSH DAC setting. It can be reduced and eventually removed by decreasing the VWLLSH setting, i.e., by lowering the resistance of the shaper's feedback loop.

The working hypothesis to explain this behavior assumes that the ohmic resistance of the shaper feedback loop increases with irradiation due to a threshold drift in the MOSFET that is used to adjust the resistance (c.f. Figure 14.1). The increased resistance in turn causes a longer recovery time of the shaper during which the potential at the shaper input drifts back to its baseline after processing a signal pulse. Only after the input potential has reached the baseline, the working point of the shaper is restored and the succeeding pulse can be processed. This recovery time can be decreased by reducing the feedback resistance, i.e., by a dose dependent readjustment of VWLLSH. In this picture, the dependence on the test pulse amplitude observed in Figure 16.5 (a) can be explained by the larger deviation of the potential at the shaper input from the baseline when shaping a pulse with a large amplitude compared to the deviation occurring for pulses with small amplitudes.

This hypothesis predicts that the ability to read out consecutive test pulse with a fixed amplitude depends on the time lag Δt between the pulses and on the VWLLSH DAC setting. Experimentally, this dependence can be quantified with a dedicated test that employs the pattern generator sequence shown in Figure 16.6. The default sequence is amended by an additional `calibrate` signal, which follows the first `calibrate` signal with an adjustable delay Δt . The timing of the `trigger` signal and the WBC register is configured in such a way that the bunch crossing with the second test pulse injection is triggered. The working hypothesis predicts that the second test pulse cannot be read out if either Δt is too short or if the VWLLSH setting is too large. Figure 16.5 (b) shows the result of a scan through test pulse delays between 50 and 1000 clock cycles and for all VWLLSH settings in steps of 10 DAC units. Fixed test pulse amplitudes with $V_{CAL} = 200$ have been used for this test. For each irradiation dose, the solid line separates the region of phase space where the second test pulse cannot be read out, from the region where the test pulse is found in the readout (above and to the left of the line). It was found that full response efficiency can be achieved in the whole phase space before irradiation. After irradiation, however, the phase space in which the second test pulse is found in the readout shrinks towards the upper left corner of the plots, i.e., lower VWLLSH settings or longer test pulse delays are required. The colored squares mark the dose dependent working points that have been chosen for tests presented in this thesis. These working points are also listed in Table 16.2.

For doses up to 1.1 MGy, lowering VWLLSH is sufficient to achieve full efficiency for signals with a periodicity of about 100 clock cycles, corresponding to 2.5 μ s, which is below the L1 trigger latency. Limitations related to the shaper feedback resistance are therefore not expected for the expected lifetime doses of the detector and the envisaged instantaneous luminosity if the VWLLSH setting is lowered appropriately. For higher doses, however, increased delays are required as the adjustable range of the VWLLSH setting reaches its lower limit.

Table 16.2: Chosen working points for the VWLLSH DAC and the delay Δt between consecutive test pulses. For doses beyond 2 MGy, Δt needs to be increased as VWLLSH hits the lower limit of the adjustable range.

Dose (MGy)	VWLLSH	Δt (clk cycles)	(μ s)
0	220	194	4.9
0.5	60	194	4.9
1.1	10	242	6.1
1.5	10	242	6.1
2.2	0	387	9.7
4.2	0	772	19.3

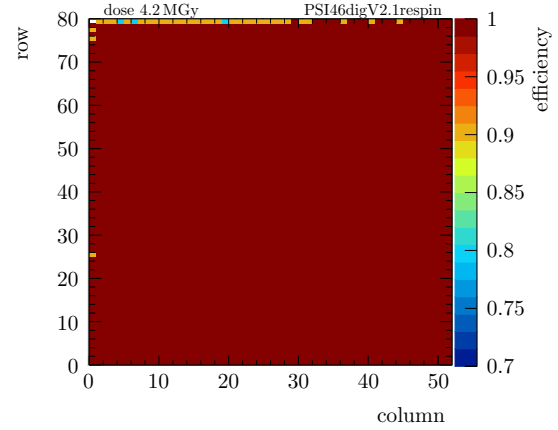


Figure 16.7: Response efficiency map of a ROC sample irradiated to 4.2 MGy after optimizing VANA and VWLLSH and performing a standard pretest.

Pixel response efficiency

After readjusting VANA to obtain an analog supply current of 24 mA, choosing the dose dependent VWLLSH settings, and introducing additional delays between consecutive test pulses for highly irradiated samples, the standard pretest as described in Section 14.6.1 allows to find an efficient working point in the VTHRCOMP–CALDEL phase space. As expected from the drift of the band gap reference voltage, the width of the efficiency window (c.f. Figure 14.5) in CALDEL DAC units decreases by about 10% from the pre-irradiation value of 60 DAC units. Optimized CALDEL settings after irradiation have been found to be increased by up to 10% with respect to the pre-irradiation settings.

Preparing the samples with the adjustments outlined above allows to achieve full response efficiency to test pulse injections for well above 99% of all pixels of all irradiated samples. An example for an efficiency map for all pixels of a sample irradiated to the highest dose of 4.2 MGy is shown in Figure 16.7. Minor inefficiencies are only observed in some of the edge pixels, while the vast majority of the pixels is fully efficient.

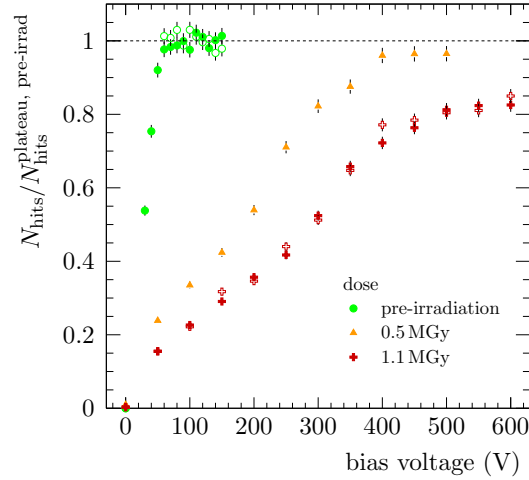
16.2 Analog performance

The performance of the analog section of the ROC is mainly characterized by the electronic noise of the preamplifier/shaper system, the charge threshold of the comparator, and the timewalk behavior of signals with different amplitudes. With the samples being commissioned for test pulse readout, these parameters can be examined and compared to pre-irradiation measurements. These studies are supplemented with auxiliary measurements with SCM samples to determine the sensor depletion voltage and the charge calibration of the internal test pulse amplitude.

16.2.1 Charge calibration and depletion voltage

In order to translate the results of the noise and threshold measurements from units of the internal test pulse amplitude (VCAL DAC units) into physical units, a charge calibration with monochromatic X-radiation as reference energies has been performed with all SCM samples before irradiation as described in Section 14.6.4. A mean calibration constant of $(46.4 \pm 2.5) \text{ e/VCAL}$ has been obtained, where the uncertainty indicates the standard

Figure 16.8: Number of pixel hits as a function of the sensor bias voltage for a fixed number of events and constant X-ray intensity. The number of observed pixel hits is normalized to the number of hits observed for a fully depleted sensor before irradiation. The beginning of the plateau indicates full depletion of the sensor.



deviation of the calibration constant of all tested samples. After irradiation, the calibration constant is corrected for the increased output voltage of the VCAL DAC arising from the drift of the band gap reference voltage. The correction consist of a multiplication of the pre-irradiation calibration parameter with the dose dependent relative increase of V_{bg} (c.f. Table 16.1). A direct measurement of the calibration constant after irradiation could not be performed, as the reduced charge collection efficiency (CCE) in the irradiated sensors distorts the measured spectrum and therefore biases the result.

The inevitable irradiation of the silicon sensor along with the ROCs of the SCM samples also changes the bias voltage required to fully deplete the sensor after irradiation. In order to estimate the depletion voltage, SCM samples have been exposed to monochromatic X-radiation with an energy well above the pixel threshold. All pixels of the DUT have been unmasked to achieve sensitivity to signals generated by X-ray photon absorption in the sensor and the sample has been read out with a periodic random trigger. For a fixed amount of events and constant X-ray intensity, the number of observed pixel hits has been measured as a function of the applied bias voltage. Since only the charge generated by photon absorption within the depleted volume is collected fast enough to form a sufficiently large signal within one bunch crossing, the number of observed hits depends on the width of the depletion zone and hence on the bias voltage (c.f. Equation 13.4). Once the depletion voltage is reached, the number of observed pixel hits saturates as shown in Figure 16.8 for various samples before and after irradiation up to 1.1 MGy. The number of hits is normalized to the maximum number of hits observed with the fully depleted non-irradiated samples. It can be seen that full depletion is reached for $V_{bias} \approx 60$ V before irradiation. For the sample irradiated to a dose of 0.5 MGy, the number of observed pixel hits saturates for voltages above 400 V at almost the same plateau level, while a 20% lower saturation level is observed with two different samples irradiated to 1.1 MGy. The latter observation can be explained with a decreased CCE in the sensor, which causes the collected charge for some pixel hits to drop below the threshold. The small increase of the number of pixel hits beyond 400 V can be attributed to the faster charge collection time in overbias mode, which slightly reduces the trapping probability. This test could not be performed with samples irradiated to even higher doses as no stable operation could be achieved when unmasking all pixels. Even in the absence of incident X-radiation, thousands of pixel hits were registered within a few events, mainly concentrating in large connected areas of the pixel array, often observed around the corners of the ROC. Because of the inhomogeneous distribution over the pixel array and the occurrence even at high pixel thresholds of about 4 ke, it is unlikely that noise in the ROC causes this phenomenon. Instead, it is assumed that the charge injection arises from the high leakage current in the highly irradiated sensors.

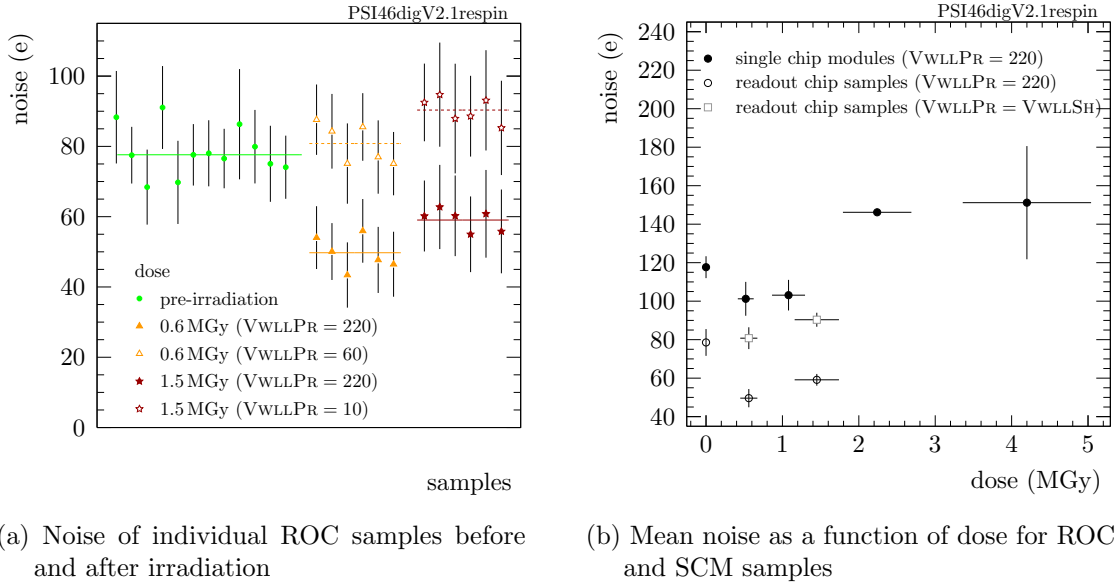


Figure 16.9: Preamplifier/shaper noise of individual ROC samples before and after irradiation (a). The decreased VWLLSH setting reduces the noise by about 35% with respect to the pre-irradiation value when VWLLPR is kept at the pre-irradiation value of 220. For $VWLLSH = VWLLPR$, the noise stays approximately constant. The noise measured with SCM samples is slightly higher compared to the noise measured with ROC samples and slightly increases for doses beyond 2 MGy (b).

Based on the results presented in Figure 16.8, a reverse bias voltage of 400 V has been chosen to test SCM samples after irradiation. While full depletion is reached for samples irradiated up to 1.1 MGy, the sensors of SCM irradiated to even higher doses are potentially under-depleted at this voltage.

16.2.2 Noise

Low electronic noise of the preamplifier/shaper system in the PUCs is a mandatory prerequisite to minimize random pixel hits, which would degrade the tracking performance of the detector. Moreover, such noise hits would unnecessarily increase the data rate sent by the detector. The noise in the PUC is therefore measured by scanning the response efficiency for each individual pixel to test pulses injections with increasing amplitudes. As the test pulse amplitude exceeds the pixel threshold, the response efficiency exhibits a turn-on from zero to one. This turn-on curve is smeared in the presence of electronic noise, which can be estimated by fitting the response efficiency with an error function [242] and extracting the parameter describing the width of the turn-on. Measuring this quantity for all pixels of a ROC yields a distribution with a certain mean value and a root-mean-square. The two figures are multiplied with the charge calibration constant to translate the measurement from VCAL units into charge. As outlined above, the drift of the band gap reference voltage is used to correct the calibration constant after irradiation.

Figure 16.9 (a) shows the mean value (data point) and the root-mean-square (indicated uncertainty) of the noise distribution for several ROC samples irradiated up to 1.5 MGy. Fitting the set of samples at one dose point with a constant shows that the pre-irradiation noise of 78.6 ± 7.0 electrons drops by 37% (25%) after irradiation to 0.5 MGy (1.5 MGy), when keeping the DAC setting that controls the resistance of the preamplifier feedback loop at its pre-irradiation value of $VWLLPR = 220$. This rather unexpected result is related to the changed ratio of the feedback resistors in preamplifier and shaper, introduced by the necessary lowering of $VWLLSH$ (c.f. Section 16.1.3). This is confirmed by the measurement

shown by the open markers in Figure 16.9 (a), which indicates that the noise level stays approximately constant after irradiation when keeping $V_{WLLSH} = V_{WLLPR}$ as before irradiation by lowering V_{WLLPR} along with V_{WLLSH} . Lowering V_{WLLSH} after irradiation is hence not only required to achieve full efficiency for signal pulses in rapid succession, but also has the beneficial side effect of reducing the noise.

The evolution of the mean noise of all ROC and SCM samples as a function of dose is shown in Figure 16.9 (b), where the indicated uncertainty represents the standard deviation of all tested samples from the mean value. The decrease of the noise level for TIDs of 0.5 MGy and 1.1 MGy with $V_{WLLPR} = 220$ is also observed with the SCM samples. Both before and after irradiation, the noise of the SCM samples is 40–50 electrons higher than the noise measured with the ROCs without sensor. This can be attributed to the increased preamplifier input capacitance of the SCM samples, imposed by the silicon sensor. For irradiation doses beyond 2 MGy, the noise of the SCM samples increases by about 30% with respect to the pre-irradiation value. Whether this increase is a genuine radiation effect in the ROC itself or if it originates from the larger input capacitance caused by possibly under-depleted sensors of the highly irradiated SCM samples could not be disentangled as ROC samples without sensor have not been irradiated to such high doses. In any case, the noise stays well below 200 e even after irradiation up to 4.2 MGy and hence an order of magnitude below the typical pixel threshold of about 2 ke.

16.2.3 Pixel threshold

A lower charge threshold is one of the key improvements of the new ROC with respect to its predecessor. Maintaining this feature after irradiation is crucial to achieve a high signal efficiency after non-ionizing radiation damage has degraded the CCE of the silicon sensors. Two important questions therefore need to be addressed: whether or not a low and homogeneous pixel threshold can be set after irradiation and how the threshold evolves with increasing TID if the responsible DAC parameters and trim bits are not re-optimized after irradiation.

Threshold re-optimization after irradiation

Figure 16.10 (a) shows the mean value (data points) and the standard deviation (indicated uncertainty) of a Gaussian function fitted to the threshold distribution of individual SCM samples featuring a prototype (bottom) and the final version of the ROC (top) after optimizing the threshold before and after irradiation as described in Section 14.6.2. This optimization includes a readjustment of the global $V_{THRCOMP}$ and V_{TRIM} DACs, as well as a re-optimization of the trim bits for each pixel. For the final version of the ROC, the chosen target threshold of 1.85 ke can be configured for all samples up to a dose of 4.2 MGy. This value has been chosen to test a threshold of a similar magnitude as envisaged in the experiment. Values found for $V_{THRCOMP}$ during the optimization are approximately 30% lower after irradiation to 0.5 MGy and 1.1 MGy with respect to the values obtained from the pre-irradiation optimization. Additionally, the mean value of the re-optimized trim bit distribution was found to be about 1 trim bit unit larger than before irradiation.

For the prototype version *PSI46digV2* of the ROC, the same measurement showed that the adjustable range of the $V_{THRCOMP}$ DAC is insufficient to adjust the threshold to the target value after irradiation. This resulted in lower and wider threshold distributions as shown in the lower panel of Figure 16.10 (a). For the succeeding prototype version and the final production layout, the adjustable range of the $V_{THRCOMP}$ DAC has been enlarged, which successfully removed the limitation as demonstrated in the upper panel of Figure 16.10 (a).

Figure 16.10 (b) shows that the width of the optimized threshold distribution stays below 80 electrons for the final version of the ROC up to the highest tested dose of 4.2 MGy. It

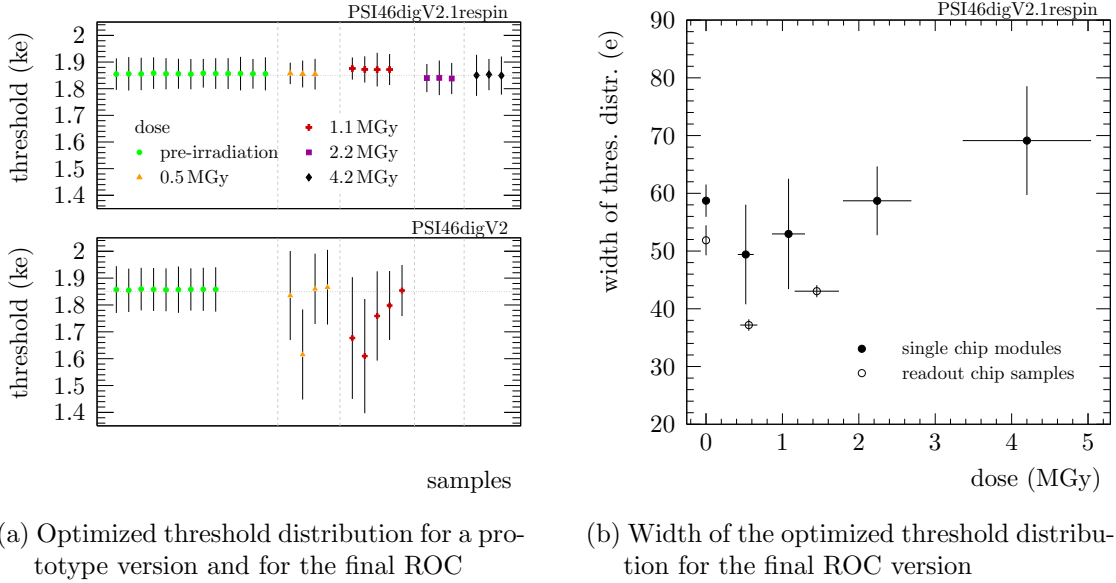


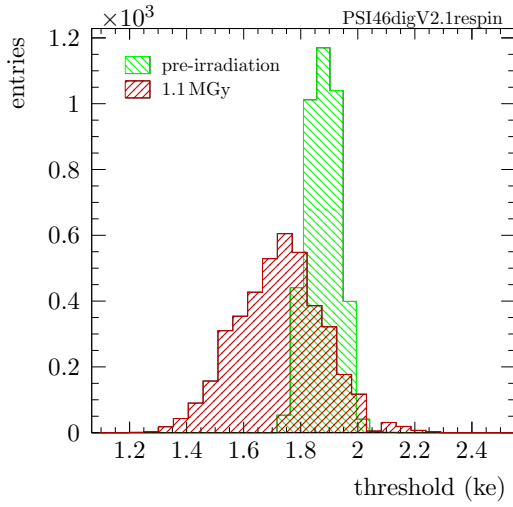
Figure 16.10: Mean and width of the optimized threshold distribution of the final (top) and a prototype (bottom) version of the ROC before and after irradiation (a). For the final version of the ROC, the width of the threshold distribution stays below 80 electrons when the threshold is re-optimized after irradiation (b).

also can be seen that narrower threshold distributions can be achieved for samples without sensor as a result of the lower noise of these samples (c.f. Figure 16.9 (b)). Furthermore, the lower VWLSH setting and the resulting drop of the noise level allows to achieve narrower threshold distributions for the samples irradiated to 0.5 MGy and 1.1 MGy compared to the width before irradiation.

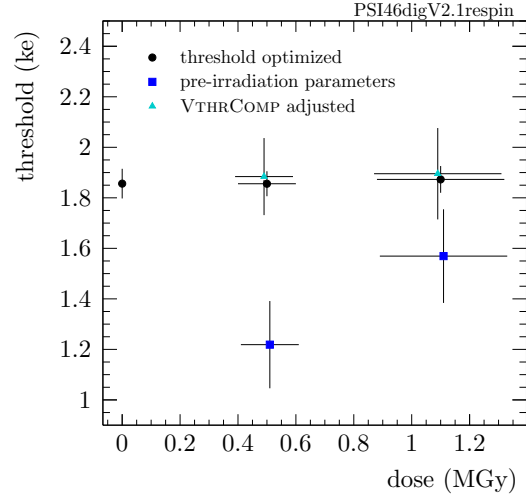
Dose dependent evolution of the threshold without re-optimization

Presently, a re-optimization of the trim bits is not foreseen after the installation of the detector in the experiment because of the time intensity of the re-optimization procedure for $\mathcal{O}(100 \text{ million})$ pixels. Moreover, an interactive optimization as performed in the laboratory setup is not possible in the experiment because of a lack of communication between the FED and FEC systems.

Radiation induced effects on the threshold distribution without re-optimization after irradiation have therefore been studied in the context of a semester project [243]. Figure 16.11 (a) shows a threshold distribution of a SCM sample before and after irradiation to 1.1 MGy. Without re-optimization of the VTHRCOMP and VTRIM DACs and the trim bits, the distribution gets shifted to lower values and becomes significantly broader. The shift of the mean value is quantified in Figure 16.11 (b), where the average mean value (data point) and the standard deviation of all tested samples (indicated uncertainty) is shown for three scenarios: The round markers show the mean value after re-optimizing the threshold as in Figure 16.10 to illustrate the best case scenario. Not re-optimizing the threshold parameters after irradiation results in lower thresholds, shown by the square markers. The triangles show that the mean value can be shifted back to the target value by readjusting VTHRCOMP. The latter optimization was achieved by iteratively increasing VTHRCOMP until the same mean threshold as before irradiation was reached. This required to increase VTHRCOMP by 17 ± 2 (10 ± 3) DAC units for the samples irradiated to 0.5 MGy (1.1 MGy). Figure 16.11 (c) quantifies the broadening of the threshold distribution with increasing TID for the three scenarios described above. Without re-optimization, the width of the threshold distribution doubles (triples) after irradiation to 0.5 MGy (1.1 MGy). Additional broadening

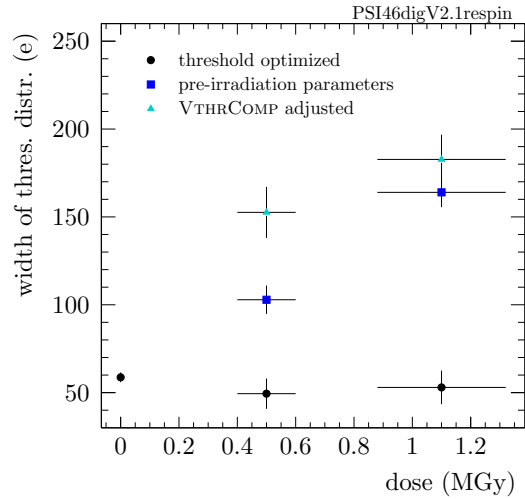


(a) Threshold distribution



(b) Mean of threshold distribution

Figure 16.11: Evolution of the mean value and the width of the threshold distribution without re-optimization after irradiation. Not re-optimizing the threshold DACs and trim bits after irradiation results in a shifted and broader threshold distribution (a). The mean value of the distribution can be shifted back to the target value by adjusting VTHRCOMP (b), but the distribution becomes broader with increasing irradiation (c). In Figures (b) and (c) the indicated uncertainties represent the standard deviation of all tested samples from the mean value. Data from [243].



(c) Width of threshold distribution

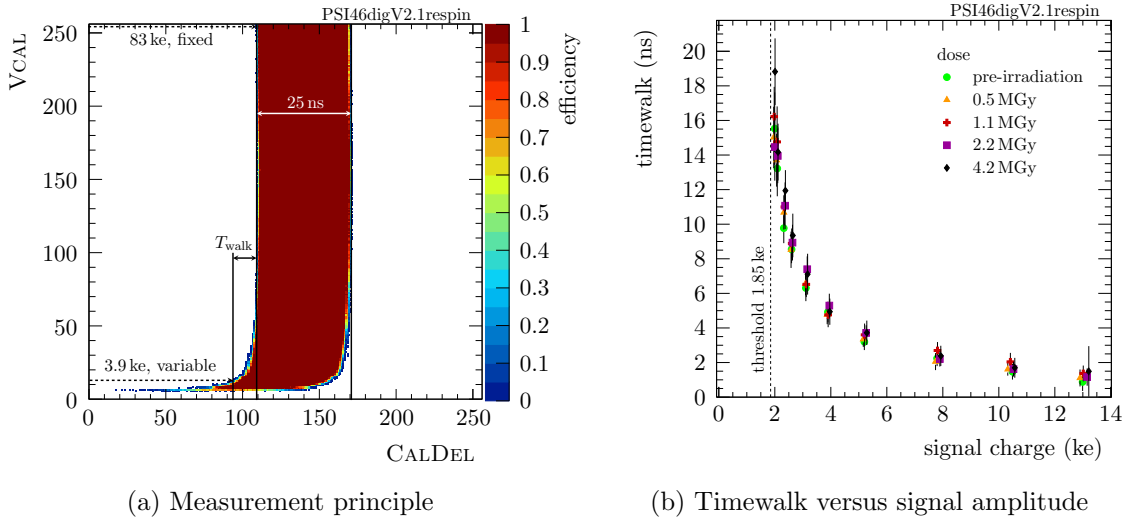


Figure 16.12: Evolution of timewalk with increasing irradiation dose. The timewalk is measured as timing difference between a large signal of about 83 ke, corresponding to $V_{CAL} = 255$, $CTRLREG = 4$, and a smaller test pulse with variable amplitude (a). Even for signal just above the pixel threshold, the timewalk stays well below 25 ns and only marginally increases with TID (b).

is introduced by the readjustment of $V_{THRCOMP}$ to shift the mean value of the distribution. Including this correction, the pre-irradiation width of 59 ± 3 electrons increases to 183 ± 14 electrons after irradiation to 1.1 MGy.

16.2.4 Timewalk

In order to fully profit from the low charge threshold, the timewalk as defined in Section 14.1.1 needs to stay below 25 ns after irradiation. Figure 16.12 (a) illustrates the methodology of the test that is used to measure the timewalk of the ROC before and after irradiation. The efficiency window in the $CALDEL$ space is shown as a function of the test pulse amplitude V_{CAL} (shown in the high range with $CTRLREG = 4$). The efficiency window is shifted towards lower $CALDEL$ values for small pulses, corresponding to a delayed surpassing of the comparator threshold. The timing difference between a fixed large signal ($V_{CAL} = 255$, $CTRLREG = 4$, corresponding to about 83 ke) and a variable smaller signal (exemplified in Figure 16.12 (a) with a signal of 3.9 ke) is measured by determining the 50% points in the turn-on of the response efficiencies for the two signals. This measure in $CALDEL$ units is converted into time by determining a calibration parameter, based on the width of the efficiency window for the large signal that corresponds to one bunch crossing of 25 ns. This approach allows to take the radiation induced change of this calibration parameter arising from the drift of the band gap reference voltage into account. The observed drift of the reference voltage is also used to correct V_{CAL} settings after irradiation to obtain the same test pulse amplitudes as before irradiation. The pixel threshold has been adjusted to 1.85 ke for all tested samples before and after irradiation to measure the timewalk under realistic conditions. Figure 16.12 (b) shows the calibrated timing difference of a small signal with respect to the large signal of 83 ke as a function of the amplitude of the small signal. By construction, the timewalk increases as the signal amplitude approaches the comparator threshold indicated by the dashed vertical line. It can be seen that the timewalk stays well below 25 ns even for small signals of about 2 ke just above the threshold for all tested doses. Only a marginal increase of the timewalk of below 3 ns is observed for doses up to 4.2 MGy. This renders an increase of the pixel threshold to prevent hit migration into adjacent bunch crossings unnecessary even after heavy irradiation.

16.3 High-rate performance

Electrical tests, such as the ones presented in the previous section, create only a very small load for the ROC, as only one pixel is tested at the time while all others are masked and thus insensitive to hits. Moreover, the test pulse periodicity of $\mathcal{O}(100 \text{ clock cycles})$ (c.f. Table 16.2) implies that the chip is idling during more than 99% of the testing time. In order to emulate more realistic operation conditions, SCM samples have been tested under X-radiation with all pixels unmasked. Absorption of X-ray photons in the sensor via photoeffect allows to create hit rates of several hundreds of MHz/cm², adjustable with the current setting of the X-ray tube.

An important difference between signals created by charged particles in the experiment on the one hand and photons in the laboratory setup on the other hand concerns the cluster size created by individual hits. The point-like interaction of photons via photoeffect and the absence of a magnetic field in the laboratory setup cause hits induced by X-radiation to predominantly create one-pixel clusters. In the final deployment situation in the experiment, however, charge carriers are created along the trajectory of a charged particle through the sensor and the deflection of the charge carriers by the Lorentz angle creates clusters of two or more adjacent pixels. This difference implies that the ratio of occupied time stamp to data buffer cells is close to unity under X-radiation, while it is designed for a ratio of about 1/2, since two-pixel clusters occupy two data buffers and only one time stamp buffer cell. Because of this difference, tests presented in this section do not replace dedicated test beam measurements with charged particles [227]. Nevertheless, the X-ray setup provides an indispensable tool to test the ROC in a high occupancy environment.

16.3.1 Test pulse response efficiency in high occupancy environment

The functionality of the full readout chain of the ROC can be verified by measuring the response efficiency to test pulse injections while the DUT is exposed to a well-defined rate of incident X-radiation to create a load comparable to operating the ROC in the CMS experiment. The test procedure is similar to the measurement of the response efficiency introduced in Section 16.1.3. The fundamental difference is that all pixels of the DUT are unmasked and that the `calibrate` signals in the pattern generator test loop are not preceded by a `reset` command (c.f. Figure 15.6) as this would discard previously accumulated hits in the chip buffers. A series of $N_{\text{tot}} = 100$ test pulses is sent to each of the 4160 pixels of the ROC sequentially. Each of these 100×4160 events is triggered to read out the whole DUT. If a pixel hit with the address of the pixel under study is found in the event, the hit is attributed to the test pulse injection. Hits in any other pixel in the same event are considered to originate from absorbed X-ray photons. The response efficiency ϵ is then calculated for each pixel as

$$\epsilon = \frac{N_{\text{vcal}}}{N_{\text{tot}}}, \quad (16.1)$$

where N_{vcal} is the number of read out test pulse hits for the regarded pixel. The probability of coincidentally having a hit induced by X-radiation in the pixel under study is negligible as the expected layer 2 single pixel hit rate of 120 MHz/cm² only corresponds to about two hits in the full pixel array per bunch crossing. The mean response efficiency of all pixels is calculated for pixels within a fiducial volume, excluding the left and right-most DCols and the upper row of the pixel array. Selecting the fiducial volume is motivated by the larger size of the pixels at the ROC edges and the resulting larger occupancy of these pixels, which degrades their efficiency compared to the pixels within the fiducial volume.

The background hit rate R is calculated based on the total number of observed hits in the fiducial volume that are attributed to photon interaction in the sensor in all triggered events

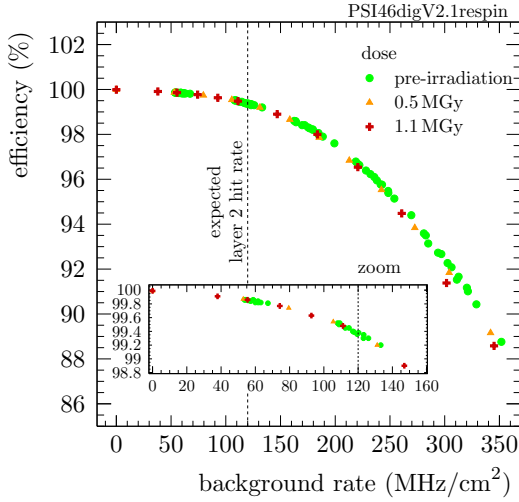


Figure 16.13: Pixel response efficiency to test pulse injections in a high occupancy environment. X-ray photon interaction with the silicon sensor of the tested SCM samples creates a readout load that reduces the response efficiency with increasing background rate. No radiation induced degradation of the response efficiency is observed for relevant rates up to 120 MHz/cm² and doses up to 1.1 MGy.

N_{trig} , denoted as N_{xray} . Assuming that such hits are subject to the same inefficiencies as hits induced by test pulse injections, this number is corrected with the efficiency ϵ from Equation 16.1. The background pixel hit rate is then calculated as

$$R = \frac{N_{\text{xray}}}{\epsilon A N_{\text{trig}} \Delta t_{\text{bx}}}, \quad (16.2)$$

with $\Delta t_{\text{bx}} = 25 \text{ ns}$ and $A = 0.569 \text{ cm}^2$ as the active sensor area in the fiducial volume. In order to eliminate the small dependency of the response efficiency to the CALDEL setting, the latter has been optimized for each sample before and after irradiation to achieve the maximum efficiency [225].

Figure 16.13 shows the measured response efficiency to test pulse injections as a function of the X-radiation induced background rate. The pixel hit rate expected for layer 2 of the detector of 120 MHz/cm² is indicated by the vertical dashed line. It can be seen that the efficiency is well above 99% for this rate and that no degradation of the efficiency is observed after irradiation up to 1.1 MGy. Uncertainties on the efficiency and the estimated rate arising from the statistical uncertainties on the number of test pulse and X-ray induced hits are small and covered by the markers in Figure 16.13.

The pixel threshold of samples used to determine the response efficiency before and after irradiation to 0.5 MGy has been set to 1.85 ke and has been re-optimized after irradiation. After irradiation to 1.1 MGy, the threshold had to be elevated to about 2.3 ke in order to reduce the number of noisy pixels, i.e., pixels that receive hits in the absence of incident X-radiation. At this threshold 32 out of 4160 pixels remained noisy and had to be disabled using the mask bit. Additionally, VDIG has been increased from the nominal setting of 6 to 15 for the 1.1 MGy sample in order to speed up the column drain mechanism, which slightly improves the efficiency. Because of the aforementioned difference concerning the cluster size of hits induced by absorption of X-ray photons and charged particles in the experiment, the inefficiency probed in this test is dominated by the limited size of the time stamp buffers, as described in Section 14.2.2. A detailed description of the mechanisms contributing to the hit rate dependent inefficiency relevant for detecting charged particles with the associated larger cluster sizes can be found in Ref. [225].

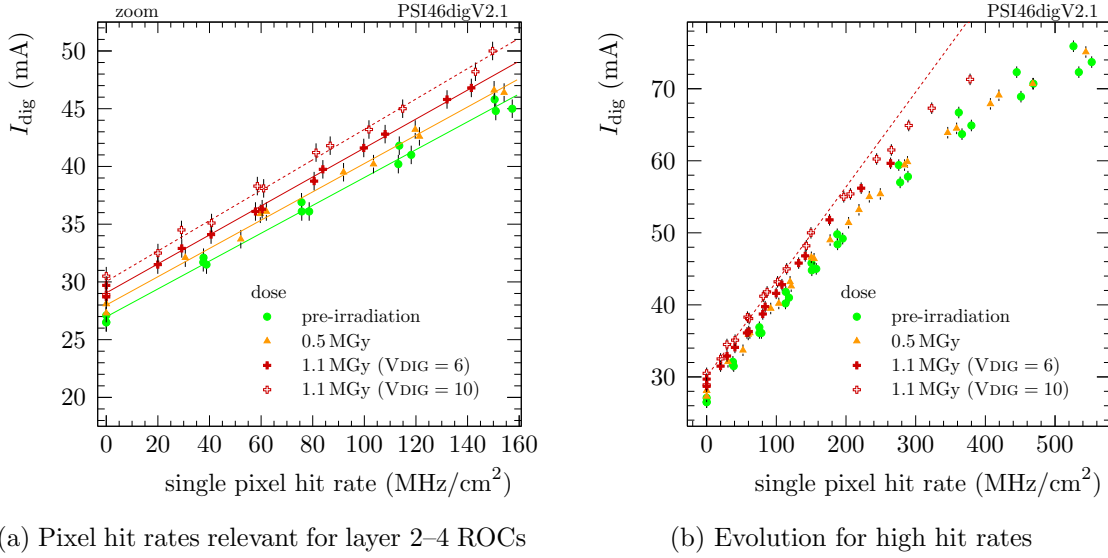


Figure 16.14: Hit rate dependence of the digital current I_{dig} for different irradiation doses up to 1.1 MGy. For hit rates relevant for the operation of the ROC in the detector, the dependence of the current on the hit rate is linear in good approximation (a). A deviation from the linear dependence is observed for hit rates beyond ≈ 200 MHz/cm² (b). The dashed line shows a fit to the current measurement of the sample irradiated to 1.1 MGy in the range of zero to 160 MHz/cm².

16.3.2 Hit rate dependence of the current consumption

Projecting the power consumption of the ROC in the experiment is important to define specifications for the power supplies of the detector. These specifications also have to take into account a potentially increased power consumption after irradiation. The digital supply current I_{dig} depends on the work load of ROC and is therefore examined as a function of the single pixel hit rate before and after irradiation. This study has been conducted with the prototype version *PSI46digV2.1* of the ROC at $T = -10^\circ\text{C}$. In order to obtain a conservative estimate of the power consumption, the nominal supply voltages have been raised by 100 mV with respect to their nominal value to $V_A = 1.7$ V and $V_D = 2.5$ V. Readout load has been created by exposing SCM to X-radiation as described in the previous paragraph but no test pulses are injected. The rate is measured according to Equation 16.2, but without the efficiency correction. This is motivated by the fact that the efficiency at a given rate is not necessarily identical in the absence of the additional load arising from test pulse injections. Not correcting for the efficiency slightly underestimates the rate and thus provides an upper limit of the current consumption. Currents have been measured with the DTB and its intrinsic measurement resolution of 0.8 mA is considered as uncertainty.

Figure 16.14 (a) shows the dependence of the digital current on the hit rate, focusing on hit rates in the range relevant for the operation of the layers 2–4 ROC. Current measurements are shown for non-irradiated samples and for samples irradiated to doses of 0.5 MGy and 1.1 MGy for the nominal setting $\text{VDIG} = 6$. For the 1.1 MGy sample, the current is also measured for an increased regulator setting of $\text{VDIG} = 10$ to evaluate the effect of increased VDIG regulator settings as employed to maximize the response efficiency in high occupancy environments and to mitigate a radiation induced limitation that will be discussed in Section 16.4.

A parametrization of the digital current as a function of the single pixel hit rate, based on the linear fits to the data shown in Figure 16.14 (a), is presented in Table 16.3. The slope of $(0.123 \pm 0.004) \text{ mA cm}^2 \text{ MHz}^{-1}$ is independent of the accumulated TID within the uncertainties and the increase of the offset of the current is compatible with the results for the idling ROC presented in Section 16.1.2.

Table 16.3: Linear parametrization of the digital current as a function of single pixel hit rate at irradiation doses up to 1.1 MGy. For the sample irradiated to 1.1 MGy, the parametrization is also reported for an increased VDIG setting. The parametrization is valid up to a rate of about 160 MHz/cm². For higher rates, the linear parameterization over-estimates I_{dig} .

Dose (MGy)	VDIG	Offset (mA)	Slope (mA cm ² MHz ⁻¹)
0	6	27.0 ± 0.4	0.121 ± 0.004
0.5	6	28.0 ± 0.4	0.123 ± 0.004
1.1	6	29.1 ± 0.4	0.125 ± 0.005
1.1	10	30.0 ± 0.4	0.132 ± 0.005

Figure 16.14 (b) shows the evolution of the digital current for single pixel hit rates beyond the rates relevant for operating the layer 2–4 ROC in the experiment. The linear fit to the data up to 160 MHz/cm² obtained with the sample irradiated to 1.1 MGy and VDIG = 10 is shown as a reference. It can be seen that the linear parametrization over-estimates I_{dig} at rates above 200 MHz/cm². Qualitatively this can be understood by considering a model for the digital current consumption that takes into account a contribution for the current of the idling ROC c_0 , a contribution c_1 proportional to the number of read out hits H , and a contribution c_2 proportional to the number of column drains D needed to read out all hits. Within this model, I_{dig} can be written as

$$I_{\text{dig}} = c_0 + c_1 H + c_2 D \quad (16.3)$$

$$= c_0 + H \left(c_1 + c_2 \frac{D}{H} \right). \quad (16.4)$$

For low single pixel hit rates with one-pixel clusters, the ratio D/H , i.e., the number of column drains per hit is close to unity because of the low probability of having multiple hits in the same DCol of the ROC. As a consequence I_{dig} is proportional to H and thus to the hit rate. For increasing hit rates, the probability of having multiple hits within the same DCol rises and hence D/H decreases, leading to a smaller slope at higher rates. In the final deployment situation with a large abundance of two-pixel clusters created by traversing charged particles, the ratio D/H is smaller than one since the clusters predominantly develop in column direction and hence multiple pixel hits require only one column drain. The linear parametrization of the current obtained from current measurements under X-radiation therefore provides an upper limit of the current consumption at a given hit rate.

The analog current was found to be independent of the hit rate as expected. The results reported for the idling chip in Section 16.1.2 therefore also hold in a high occupancy environment.

16.3.3 Minimum digital supply voltage

In the detector, low voltage supply for the ROCs is provided by DC-DC converters as outlined in Section 13.2.4. Since an adjustment of their output voltage is not possible once they are installed in the experiment, the minimum supply voltage required to successfully operate the ROC after irradiation had to be investigated prior to fabricating the power converters for the upgraded detector. As the final version of the ROC had not been available at the time, this study has been conducted with the prototype version *PSI46digV2.1* at a testing temperature -10°C . In order to examine the functionality of the ROC at the maximum

Figure 16.15: Response efficiency to test pulse injections as a function of the digital supply voltage V_D without and with a background rate of 110 MHz/cm². The data are fitted with error functions to guide the eye.

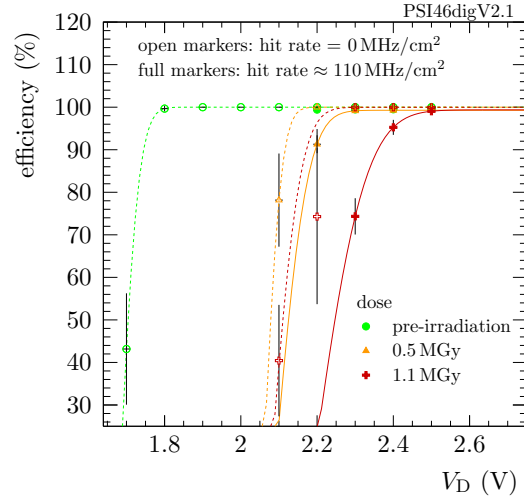


Table 16.4: Minimum digital supply voltage required to achieve an efficiency above 99% with and without a background hit rate of 110 MHz/cm² after irradiation up to 1.1 MGy.

Dose (MGy)	$V_D^{\min}$ (V)	$V_D^{\min}$ (V)
	0 MHz/cm ²	110 MHz/cm ²
0	1.8	≤ 2.2
0.5	2.2	2.3
1.1	2.3	2.5

regulated voltage V_{dd} possible at a given supply voltage V_D , the regulator setting has been maximized to $VDIG = 15$.

In order to assess the functionality of the ROC at a given value of V_D , the response efficiency to test pulse injections has been measured as explained in Section 16.3.1 with all pixels unmasked. The efficiency has been measured once without any background rate from X-radiation and once at a background rate of approximately 110 MHz/cm² to emulate realistic readout load as expected in layer 2 of the detector. Figure 16.15 shows the mean response efficiency (data point) and the standard deviation from the mean value (indicated uncertainty) of each three tested samples before irradiation and after accumulating a TID of 0.5 MGy and 1.1 MGy. The turn-on of the efficiency is fitted with error functions to guide the eye. Open markers and dashed lines indicate the evolution of the efficiency with increasing V_D without background rate. Full markers and solid lines show the corresponding measurement with a background rate of 110 MHz/cm². Without load from hits induced by X-radiation, the minimum supply voltage required for full efficiency increases from the pre-irradiation value of 1.8 V to 2.2 V (2.3 V) after irradiation to 0.5 MGy (1.1 MGy). With a background rate of 110 MHz/cm², $V_D = 2.2$ V is sufficient to reach an efficiency above 99% before irradiation. After irradiation, V_D needs to be raised to 2.3 V (2.5 V) to maintain the same response efficiency for samples irradiated to a dose of 0.5 MGy (1.1 MGy). The minimum required supply voltages are also summarized in Table 16.4.

Lowering V_D below the specified values results in a steep increase in data encoding errors, leading to events with invalid pixel addresses or invalid PH values. While the exact mechanism responsible for the increase of the encoding errors could not be resolved, it is assumed that they are related to a degradation of the signal quality arising from a drop of the regulated digital voltage V_{dd} . In this picture, the increase of the minimum supply voltage under load is caused by larger chip-internal voltage drops resulting from the increased current consumption. The increase of $V_D^{\min}$ observed for fixed hit rate and increasing irradiation dose

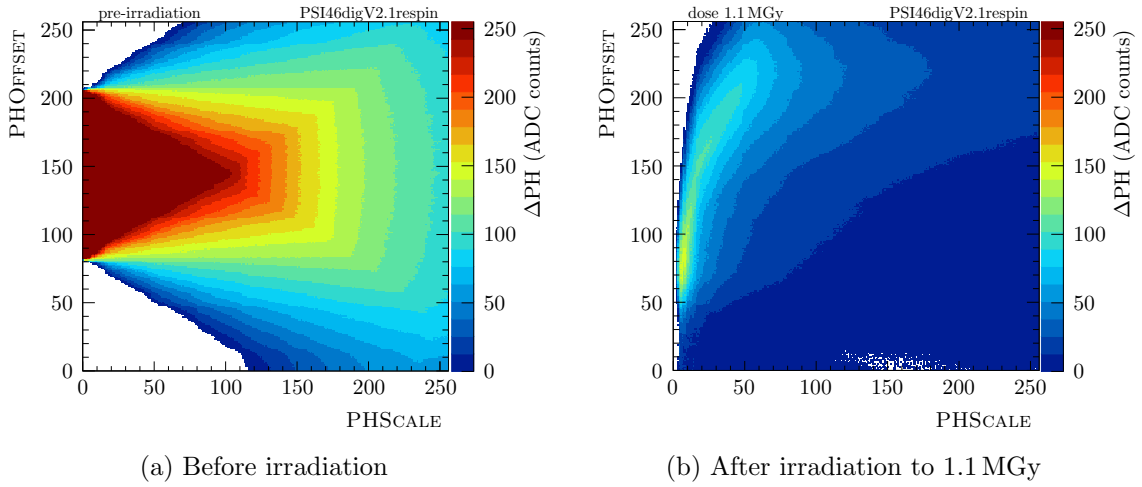


Figure 16.16: ΔPH as a function of the gain (PHSCALE) and the offset (PHOFFSET) of the pulse height sampling ADC before (a) and after irradiation to 1.1 MGy (b).

suggests a dose dependent increase of the drop-out voltage of the VDIG regulator, similar to the one observed for the regulator of the analog current (c.f. Section 16.1.2). An additional indication for a dose dependent increase of the drop-out voltage of the VDIG regulator is provided by measurements that will be discussed in Section 16.5.1.

16.4 Pulse height sampling ADC

The ROC features an 8-bit ADC to digitize the analog PH information that is proportional to the collected charge of each pixel hit. The PH information is used to weight the pixel hits belonging to individual clusters to improve the spacial resolution of the detector. Because of its relevance for this important figure of merit of the detector, maintaining a good PH resolution after irradiation is desirable.

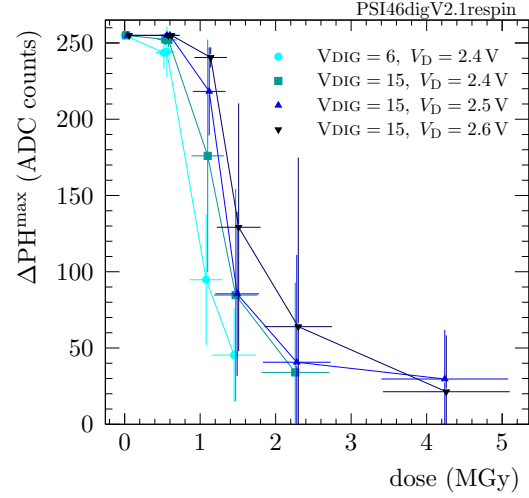
16.4.1 Radiation induced degradation of the pulse height information

As outlined in Section 14.6.3, the response of the 8-bit PH sampling ADC to test pulses of different amplitudes can be adjusted by optimizing its gain and offset with the PHSCALE and PHOFFSET DACs, respectively. Optimizing these settings such that ΔPH (c.f. Figure 14.7) is close to 255 maximizes the resolution of the PH information. Figure 16.16 (a) shows ΔPH as a function of PHSCALE and PHOFFSET for a non-irradiated sample. A sizable part of the phase space can be identified where $\Delta\text{PH} = 255$. Note that not all DAC settings in the phase space with $\Delta\text{PH} = 255$ are optimal settings, since small pulses might yield $\text{PH} = 0$, independent of the amplitude of the pulse if the gain of the ADC is too large or the offset too low. Optimizing the PH DACs is, however, not the scope of this test. Rather, it provides a measure of the maximum achievable ΔPH for any combination of PHSCALE and PHOFFSET.

After irradiation it has been observed that the maximum ΔPH achievable for any combination of PHSCALE and PHOFFSET is severely limited. This is exemplified in Figure 16.16 (b) for a sample irradiated to 1.1 MGy. It can be seen that $\Delta\text{PH} < 150$ for any combination of PHSCALE and PHOFFSET and that the working point that maximizes ΔPH is shifted with respect to the pre-irradiation result.

Figure 16.17 shows the maximized pulse height difference $\Delta\text{PH}^{\text{max}}$ as a function of irradiation dose. The markers indicate the mean $\Delta\text{PH}^{\text{max}}$ of all tested samples at a given dose and the uncertainty represents the standard deviation of the samples from the mean value. For the default settings of $\text{VDIG} = 6$ and $V_D = 2.4\text{ V}$, $\Delta\text{PH}^{\text{max}}$ steeply falls off for doses

Figure 16.17: Maximized ΔPH as a function of the TID. For doses beyond 1 MGy, $\Delta\text{PH}^{\text{max}}$ decreases substantially, eventually resulting in binary readout for samples irradiated to 4.2 MGy. The effect can be mitigated by increasing the regulated digital voltage V_{dd} by increasing the supply voltage V_{D} and the regulator setting VDIG . Lines connecting the data points have been added to guide the eye.



beyond 0.5 MGy and approaches zero for doses beyond 2 MGy. This leads to binary readout of the detector, i.e., no PH information is measured and the detector only registers ‘hit’ or ‘no hit’, which significantly degrades the spacial resolution. Figure 16.17 also shows that $\Delta\text{PH}^{\text{max}}$ can be increased at a give dose when the regulated digital voltage V_{dd} is raised by increasing VDIG and the supply voltage V_{D} . Choosing $V_{\text{D}} = 2.6\text{ V}$ and $\text{VDIG} = 15$ allows to largely recover the PH information after irradiation to the expected lifetime dose of layer 1 of the detector of 1.1 MGy. At larger doses, however, $\Delta\text{PH}^{\text{max}}$ is significantly reduced even at this elevated voltage.

16.4.2 Explanation and mitigation

The observed vulnerability of the PH sampling ADC to TID effects could be identified and traced back to a limitation in the current mirrors in the input stage of the differential current ADC. Each one current mirror is utilized for the **gain-** and the **gain+** part of the differential PH signal to disentangle the sampling of the current from the input line. A simplified circuit diagram of the **gain-** current mirror is shown in Figure 16.18. Its **gain+** counterpart is identical. Once the raised **hold** signal makes the sampling pMOS transistor T_{s} conducting, the input current in the left vertical branch (between **gain-** and V_{dd}) is copied to the branch on the right-hand side of the figure. Simultaneously, the **hold** signal initiates the copying of the **gain+** part of the differential signal and the two currents are sampled by the ADC. It is important to note that the **hold** signal opens the conducting channel of T_{s} only for 25 ns. During that time, the potential at the hold capacitance C_{eff} rises exponentially and its maximum value determines the magnitude of the copied current. As illustrated in Figure 16.19, the sampling potential rises quickly enough to reach the actual value within the sampling time of 25 ns after the first test pulse (green line). This reproduces a mirrored current of the same magnitude as the input current, resulting in a correct sampling of the PH. When sampling a succeeding signal pulse with a different amplitude (not shown in the figure), the potential would rise or drop to the new actual value, depending whether the amplitude of the succeeding pulse is larger or smaller compared to the first pulse.

As detailed in Section 15.1, space charge accumulation in Si-SiO₂ interfaces and in field oxides leads to transistor threshold drifts towards more negative values (c.f. Figure 15.2). For pMOS transistors, this implies that a higher absolute gate voltage needs to be applied after irradiation in order to make the channel conducting. The vulnerability of the PH ADC to TID effects arises from the fact that the channel of the sampling transistor T_{s} in Figure 16.18 becomes increasingly high-ohmic with irradiation for a constant gate voltage V_{dd} . Together with the hold capacitance its ohmic resistance R acts as a RC -circuit whose charging time $\tau = RC$ increases with irradiation as indicated by the red dashed line in Figure 16.19. If

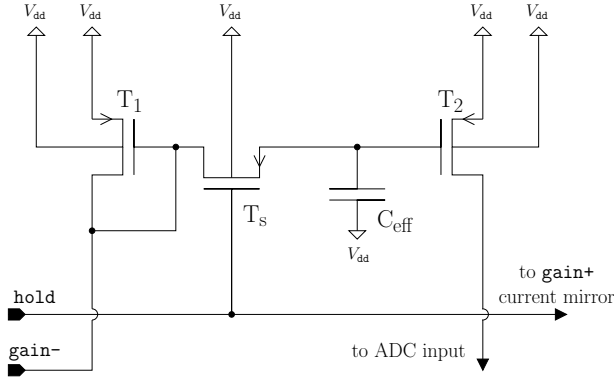


Figure 16.18: Simplified circuit diagram of the current mirror in one of the two differential input stages of the pulse height sampling ADC [244]. The pMOS transistor T_s opens the current mirror for 25 ns to sample the current. After irradiation its channel becomes high-ohmic and builds an RC-circuit with the hold capacitance C_{eff} .

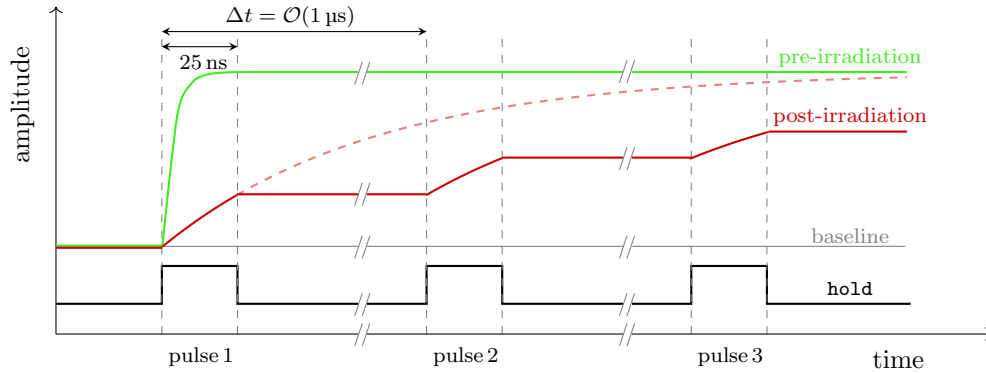


Figure 16.19: Potential at the hold capacitor C_{eff} in the current mirror of the ADC input stage. The rising hold signal causes the channel of the sampling pMOS transistor T_s to become conductive. The potential at the hold capacitance rises from the baseline and saturates at the nominal value. After irradiation, the increased rise time leads to an incorrect pulse height after the first test pulse. For several consecutive test pulses with a periodicity of a few μs and constant amplitudes, the sampling potential successively approaches its actual value.

the rise time is too large for the actual potential to be reached within the sampling time of 25 ns after the first test pulse, this leads to a wrong sampling potential (red solid line). As a consequence, the copied current is too small and a wrong PH is measured.

This hypothesis suggests that the correct sampling potential and hence the correct PH information can be obtained by issuing multiple consecutive test pulses of the same amplitude. This would allow the sampling potential to successively approximate the actual potential as depicted in Figure 16.19 for test pulses two and three, if the potential stays constant in between the pulses. This behavior has been confirmed experimentally as shown in Figure 16.20 (a) for a sample irradiated to 0.5 MGy. A series of 10 consecutive test pulses with fixed amplitude is sent to a pixel and all events with test pulse injections are read out. No **reset** command has been sent between the test pulses in order not to force the sampling potential back to its baseline between the test pulses. As shown in Figure 16.20 (a), increasing (decreasing) PH values are measured for the first five test pulses for $\text{VCAL} > 50$ ($\text{VCAL} < 50$) in the high VCAL range with $\text{CTRLREG} = 4$. A stable saturated PH is observed after the fifth test pulse, indicating that the sampling potential has reached the nominal value. The different behavior observed for test pulses with small and large amplitudes arises from the working principle of the differential PH ADC, where a sampling of the baseline in both current mirrors yields intermediate ADC values (≈ 100 as for $\text{VCAL} = 50$ in Figure 16.20). The sampling potential rises and falls from the baseline to the nominal value for large and small pulses, respectively. The open markers in Figure 16.20 show that constant PH values are measured for all test pulses with a non-irradiated sample.

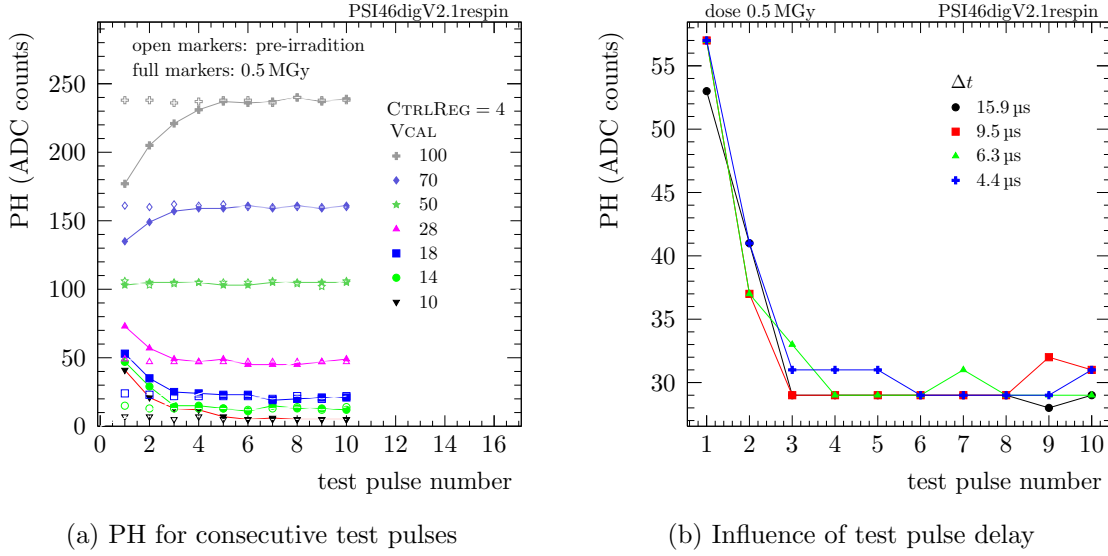


Figure 16.20: PH measurement for a series of test pulse injections with constant amplitude (a). The increased rise time of the sampling potential in the PH ADC causes the PH to saturate at the actual value only after about five test pulses for the irradiated sample. This convergence against the actual PH is independent of the time lag between the consecutive test pulses (b).

Figure 16.20 (b) shows the successive approximation of the actual PH value for different delays between the consecutive test pulses. The measurement shows that the sampled PH values are independent of the delay, which confirms that the sampling potential stays constant between the sampling of the test pulses on time scales of $\mathcal{O}(1 \mu\text{s})$. For significantly longer delays, constant PH values corresponding to a sampling of the baseline potential have been observed. This indicates that leakage currents through the gates of transistors T_1 and T_2 in Figure 16.18 cause the sampling potential to crawl back to its baseline on a time scale of $\mathcal{O}(500 \text{ ms})$.

The empirically observed dependence of the maximum achievable ΔPH on the digital voltage (c.f. Figure 16.17) is consistent with the proposed explanatory model. The radiation induced drift of the threshold of the sampling transistor can be compensated by increasing the gate voltage V_{dd} . For a fixed supply voltage V_{D} this can be achieved by increasing the regulator setting V_{DIG} . If this is not enough, an elevation of the digital supply voltage is required to mitigate the effect. The dependence of the charging time of the RC -circuit in the current mirrors on the regulated digital voltage V_{dd} is shown in Figure 16.21 (a). The PH is measured for 20 consecutive test pulses with identical amplitudes for different values of V_{dd} . The voltage has been measured with a probe needle on a dedicated pad on the RCI. It can be seen that the evolution of the PH with increasing test pulse number can be well modeled with a limited exponential growth function as expected for charging a capacitor in an RC -circuit. The time constant of the falling potential strongly depends on V_{dd} . A voltage difference of less than 500 mV separates a measurement where only the baseline is sampled, indicating that the channel of the sampling transistor does not become conductive at all, from a measurement where the potential rises quickly enough for the first pulse to be correctly sampled.

Such a measurement can be used to extract a dose dependent minimum voltage $V_{\text{dd}}^{\text{min}}$ required to counteract the radiation induced threshold drift of the sampling transistor. In the example shown in Figure 16.21 (a) this is $V_{\text{dd}}^{\text{min}} = 2.7 \text{ V}$ as this is the smallest voltage for which the PH of the first test pulse is correctly sampled. Besides proton irradiated ROC samples with doses of 0.6 MGy and 1.5 MGy, additional samples have been investigated in order to resolve the increase of $V_{\text{dd}}^{\text{min}}$ for doses below 0.6 MGy. For this purpose the same test has been conducted with ROCs that are integrated into two different full detector modules. One of these modules

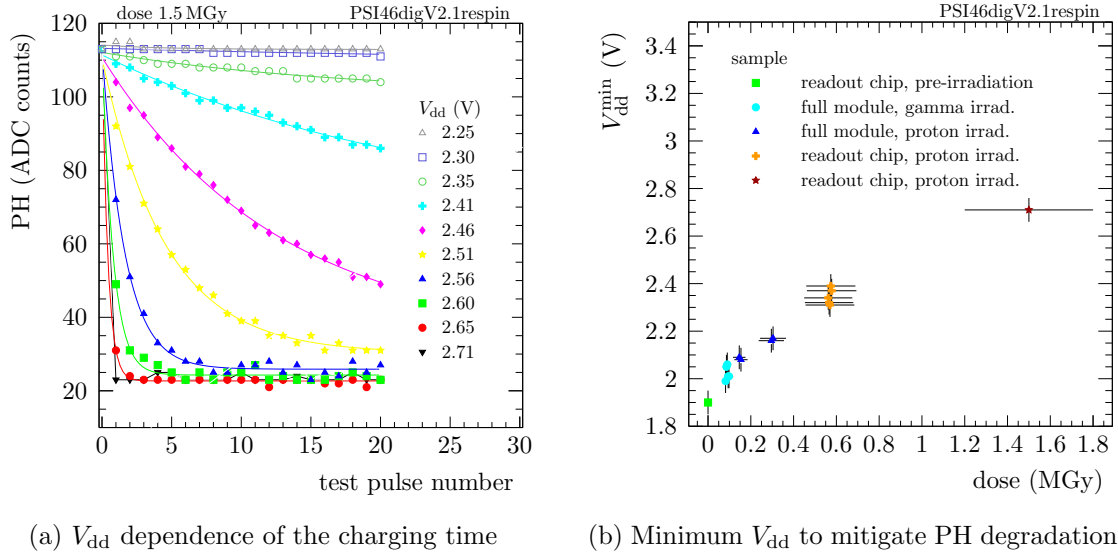


Figure 16.21: The charging time of the RC -circuit in the current mirrors of the PH ADC and hence the measured PH for consecutive test pulses strongly depends on the regulated digital voltage V_{dd} (a). Applying a dose dependent minimum voltage $V_{dd}^{\min}$ to the gate of the sampling transistor T_s allows to mitigate the effect by decreasing the rise time to below 25 ns (b).

had been irradiated to a dose of 150 kGy in the same 23 MeV proton irradiation facility as the SCM and ROC samples investigated in other tests described in this thesis. After determining $V_{dd}^{\min}$, the module had been further irradiated to a dose of 300 kGy to provide an additional measurement point. Another module had been irradiated with a ^{60}Co source, which produces gamma rays with energies of 1.17 MeV and 1.33 MeV [245]. ROCs integrated into this module provide measurements for a TID of 90 kGy.

Figure 16.21 (b) shows $V_{dd}^{\min}$ as a function of TID, measured with the different samples. A monotonous increase of $V_{dd}^{\min}$ is observed for increasing dose. The consistent behavior of samples irradiated with protons and gamma rays confirms that the degradation of the channel conductivity of the sampling transistor in the ADC current mirror only depends on TID and not on the type of ionizing radiation. It has also been observed that the sampling potential exhibits a rise time larger than 25 ns if V_{dd} is decreased to below 1.9 V for non-irradiated ROCs. This yields the pre-irradiation measurement point in Figure 16.21 (b). The measurement shows that the nominal digital supply voltage of $V_D = 2.4$ V is just above the critical voltage $V_{dd}^{\min}$ for the expected lifetime dose of layer 2 of the detector of about 0.6 MGy. Probe needle measurements of V_{dd} as a function of VD_{DIG} show that a drop-out voltage of about 50 mV needs to be taken into account, bringing the maximum V_{dd} achievable at the nominal supply voltage even closer to the critical minimum. As a result of this finding, the output voltage of the DC-DC converters for layer 2 modules has been increased by 100 mV to guarantee a larger safety margin to the critical voltage. With this modification, the observed vulnerability of the PH sampling ADC can be compensated by a sufficiently high digital voltage.

The details of the radiation induced degradation of the PH information were understood only after submitting the final design of the layer 2–4 ROC. For the layer 1 ROC, for which the effect would have been more pronounced because of the higher TID close to the IP, however, the findings could be used to eliminate the problem at chip level. This was achieved by replacing the responsible pMOS transistor with a transmission gate whose conductivity is not degraded by radiation effects [244]. Studies with proton irradiated layer 1 ROCs showed that the problem could be successfully removed by this measure and that no radiation induced degradation of the PH information is observed up to 1.2 MGy [240].

16.5 Supplementary tests

Additional tests have been conducted to assess possible radiation induced variations of the propagation velocity of the DCol readout token and of the readback calibration parameters.

16.5.1 Propagation velocity of the double column token

As described in Section 14.2.1, a token signal is passed through a DCol to initiate the readout of pixels that have received hits. Compared to other signals that are exchanged between the PUCs and the DCI, the token's propagation velocity is significantly reduced to allow it to be stopped during the PUC's communication with the DCI and the transmission of the data. While the token is passed upwards through the left-hand and downwards through the right-hand column of the DCol in the layer 2–4 ROC, the revised DCCD mechanism of the layer 1 ROC only requires the token to be passed once from the lower to the upper end of the DCol. However, in order to prevent a wrong assignment of timing information to hits at the upper end of the DCol, the token must be passed through the whole DCol within one clock cycle, i.e., a propagation velocity $v_{\text{TOK}} > 80 \text{ pixels}/25 \text{ ns}$ is required. In order to verify this prerequisite already before the first submission of the layer 1 ROC, v_{TOK} has been measured with the layer 2–4 ROC as it features the same device parameters that determine v_{TOK} .

The measurement principle used to determine v_{TOK} is based on a scan of the PH as a function of the setting of the VHLDDDEL DAC. An example of such a scan is shown in Figure 16.22 (a). As outlined in Section 14.1.1, VHLDDDEL is an inverse 8-bit DAC, which controls the delay between firing of the comparator in the PUC and sampling of the pulse with the S&H circuit. Figure 16.22 (a) therefore shows a scan of the falling edge of the signal pulse at the shaper output. The strong non-linearity of the VHLDDDEL DAC causes the shape of the pulse to appear distorted in the scan*.

Because of the inverse behavior of the DAC, the region marked with ‘max’ in Figure 16.22 (a) corresponds to a sampling of the pulse at or close to its maximum (c.f. Figure 14.2), while intermediate DAC settings correspond to a sampling of the falling edge of the pulse. As described in Section 14.1.2, firing of the comparator not only initiates the sampling of the pulse, but also initiates the `Co10r` signal, which notifies the DCI about the hit. This notification releases the DCol token. Upon arrival of the token at the PUC with the hit, the `strobe` and the `acknowledge` signals are exchanged between PUC and DCI to synchronize the readout with the 40 MHz clock. Afterwards, the data are transferred with the next rising edge of the clock. If the hold delay is very long (small VHLDDDEL settings), the described mechanism causes the pixel to be read out even before the S&H circuit goes into the *hold modus*, i.e., before the pulse is sampled. Consequently, the baseline of the S&H circuit is sampled, resulting in the flat line labeled with ‘BL’ for baseline in Figure 16.22 (a). For the measurement of v_{TOK} , the key feature of the scan is the small dip of the PH between the regimes where the falling edge of the pulse and the baseline are sampled, respectively. It arises from charge injection at the switch when the S&H circuit goes into hold modus (c.f. Figure 14.1). Because the dip marks the transition between activating the hold modus before and after reading out the pixel, it can be used as a marker indicating the point of time when the pixel is read out. Since the readout is synchronized to the 40 MHz clock, this point of time and hence the dip in the VHLDDDEL scan jumps in discrete steps of 25 ns, depending on the time of arrival of the DCol token at the pixel under study. This allows to determine the number of pixels along the token path that lie in between these jumps by measuring the position of the dip for all pixels within a DCol. The result of such a scan is shown in Figure 16.22 (b) for all 26 DCols of a sample. The position of the dip is plotted on the z axis in units of the VHLDDDEL DAC. Three distinct areas with constant positions of

*Note that the hold delay cannot be made short enough to extend the scan into the rising edge of the pulse.

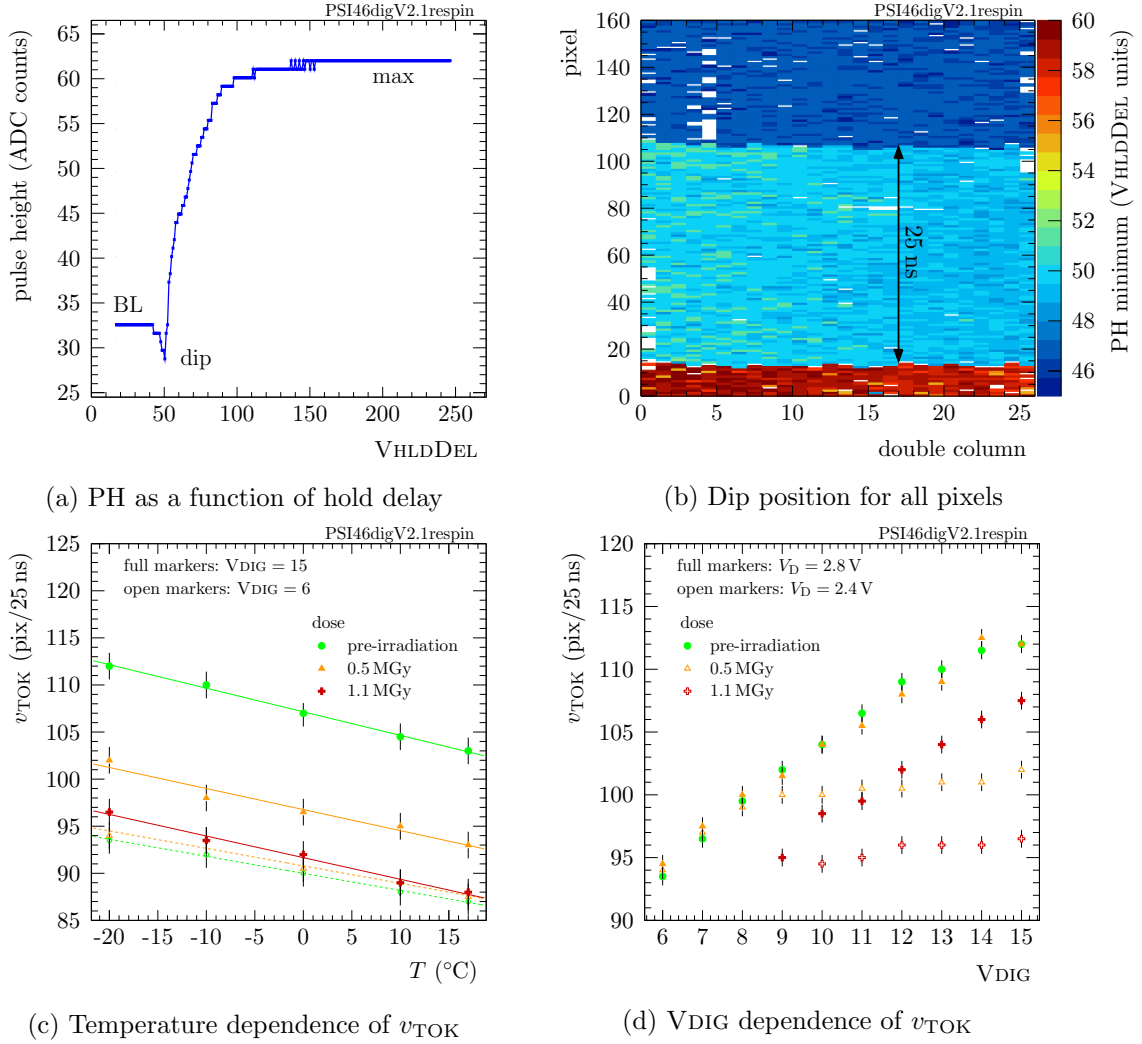


Figure 16.22: Propagation velocity of the double column token. The measurement exploits the dip in the PH versus VHLDEL scan as a marker indicating the point of time when the pixel is read out (a). Determining the position of the PH minimum for all pixels within a DCol provides a measure for the number of pixels the token passes within 25 ns (b). This allows to measure v_{TOK} as a function of temperature (c) and as a function of the regulator setting VDIG (d).

the PH minimum can be identified. They allow to identify pixels whose readout is started with the first, second, and third rising edge of the clock after the pixel hit is registered, respectively. The vertical separation of the transitions therefore provides a measure for the number of pixels the DCol token passes within 25 ns. The uncertainty on the measurement is estimated by assuming that both jumps of the PH minimum observed in Figure 16.22 (b) can be determined with an accuracy of one pixel each.

Figure 16.22 (c) shows that v_{TOK} exhibits a linear temperature dependence with a dose independent slope of $(-0.23 \pm 0.05) \text{ pix}/(25 \text{ ns K})$ for $\text{VDIG} = 15$. For $\text{VDIG} = 6$, the slope is slightly reduced to $(-0.18 \pm 0.05) \text{ pix}/(25 \text{ ns K})$. Distinct differences are observed concerning the absolute values of v_{TOK} for the two regulator settings at a certain fixed temperature. A constant velocity of about $94 \text{ pix}/25 \text{ ns}$ is measured at $T = -20^\circ\text{C}$ and $\text{VDIG} = 6$ before and after irradiation to 0.5 MGy. This observation is contrasted by a distinct dose dependence of v_{TOK} observed with $\text{VDIG} = 15$. In the latter case, v_{TOK} is about 20% higher for the non-irradiated sample while it is of a similar magnitude after irradiation to 1.1 MGy as the pre-irradiation measurement with $\text{VDIG} = 6$.

This behavior can be understood by investigating the influence of the VDIG regulator setting on v_{TOK} at a fixed temperature of $T = -20^\circ\text{C}$ as shown in Figure 16.22 (d). A monotonous increase of v_{TOK} with increasing regulator settings is observed before irradiation. The same velocities are found for different digital supply voltages of $V_{\text{D}} = 2.4\text{ V}$ and 2.8 V . This behavior is expected as v_{TOK} depends on the regulated digital voltage V_{dd} , which is independent of the supply voltage as long as the drop-out voltage of the regulator is smaller than the difference between supply voltage and largest possible output voltage of the regulator.

After irradiation to 0.5 MGy , v_{TOK} is found to be unchanged with respect to the pre-irradiation measurement up to $\text{VDIG} = 8$. For higher regulator settings, v_{TOK} saturates at about $100\text{ pix}/25\text{ ns}$ for the nominal supply voltage $V_{\text{D}} = 2.4\text{ V}$. This indicates that V_{dd} becomes independent of VDIG , which in turn can be interpreted as a radiation induced increase of the regulator drop-out voltage similar to the one observed for the regulator of the analog current (c.f. Section 16.1.2). This hypothesis can be substantiated by increasing the supply voltage to 2.8 V . This provides the regulator with a sufficiently large input voltage to correctly adjust V_{dd} over the whole range of VDIG settings. As a result, v_{TOK} follows the pre-irradiation measurement up to $\text{VDIG} = 15$. For a sample irradiated to 1.1 MGy , the same behavior is observed with the only difference that the absolute values measured for v_{TOK} are $5\text{--}6\text{ pix}/25\text{ ns}$ smaller compared to the measurements obtained with the samples before and after irradiation to a dose of $0.5\text{ MGy}^\dagger$.

The observation that v_{TOK} does not change after irradiation to 0.5 MGy but then drops by $5\text{--}6\text{ pix}/25\text{ ns}$ after further irradiation to 1.1 MGy is likely related to the radiation induced drift of the band gap reference voltage. A potential radiation induced decrease of v_{TOK} between the measurements at zero and 0.5 MGy might be compensated by an increase of V_{dd} for fixed VDIG arising from the increase of V_{bg} by about 11% . After further irradiation to 1.1 MGy the band gap voltage and hence V_{dd} only rise by 1% and the radiation induced reduction of v_{TOK} is no longer compensated for by an increase of V_{dd} .

In summary, the measurement shows that v_{TOK} is sufficiently high above the critical value of $80\text{ pix}/25\text{ ns}$ before and after irradiation and for all relevant temperatures. This validates the device parameters that determine the DCOL token propagation for use in the layer 1 ROC. In addition, the measurement provides evidence for a radiation induced increase of the drop-out voltage of the digital voltage regulator, similar to the observation made for the regulator of the analog current. This underpins the explanatory model used in Section 16.3.3, where it has been assumed that increasing drop-out voltages are the reason for the necessary increase of the digital supply voltage to achieve high response efficiencies to test pulses after irradiation.

16.5.2 Readback calibration

In addition to the PH ADC, a second ADC is hosted on the RCI, which allows to read back digital and analog information from the ROC. For interpreting readback values corresponding to current or voltage measurements, a calibration of the ADC response is required as described in Section 14.3.4. Once installed in the detector, new readback calibrations cannot be performed as there is no possibility for external reference measurements. It is therefore important to investigate potential radiation induced drifts of the calibration parameters, which would bias readback measurements after irradiation when using the pre-irradiation calibration parameters.

The **voltage calibration** employs a linear fit of the readback response to known external reference voltages. Performing a new calibration before and after irradiation and inverting

[†]For $\text{VDIG} < 10$ the measurement could not be performed because of the radiation induced limitation of the PH ADC described in Section 16.4, which renders the scan of PH versus VHLDDEL flat.

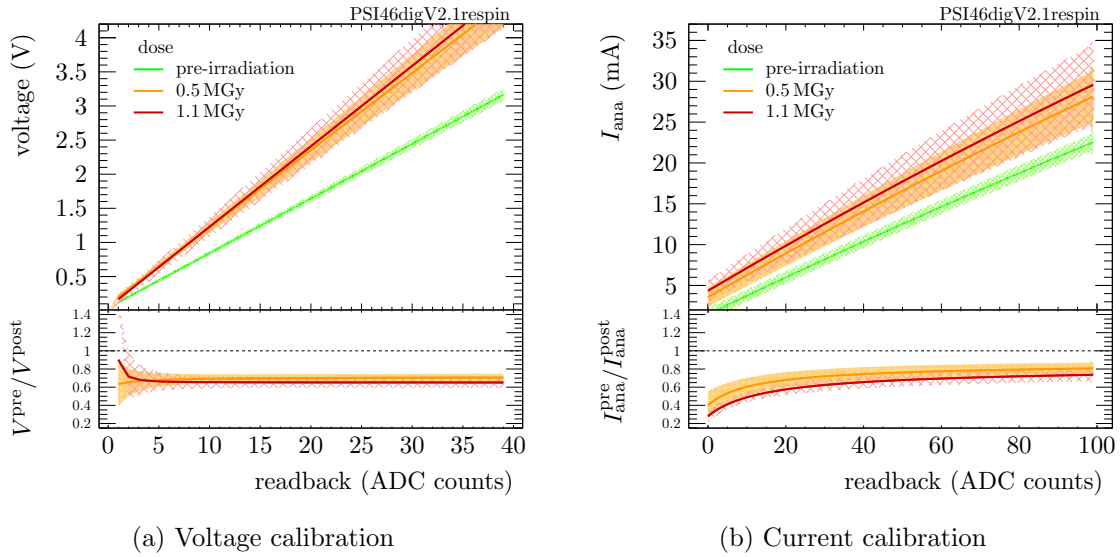


Figure 16.23: Radiation induced drift of the readback calibration parameters for voltage (a) and current measurements (b). The absolute calibration before and after irradiation is shown (upper panel) as well as the ratio between the readback based post-irradiation measured using the pre-irradiation calibration over the actual value based on a new calibration after irradiation (lower panel). The ratio plot of the current calibration includes the post-irradiation calibration of the VANA versus readback relation.

the calibration curve allows to read the actual voltage corresponding to a given value when reading back, e.g., the band gap reference of the ROC at a given dose. This inverted calibration curve is shown in the upper panel of Figure 16.23 (a). The solid lines show the mean value of the respective calibration of all tested samples while the hatched band represents the standard deviation of the samples from the mean value. It can be seen that the slope of the calibration exhibits a sizable drift after irradiation up to 0.5 MGy. Further irradiation to 1.1 MGy does not cause a significant additional drift as indicated by the overlapping uncertainty bands of the two post-irradiation calibration curves. The radiation induced drift of the calibration parameter causes voltage measurements after irradiation to underestimate the true value when converting a given readback value with the pre-irradiation calibration parameters. This is quantified by calculating the ratio of the voltage measured after irradiation over the actual voltage based on a post-irradiation calibration. The mean value and the standard deviation of this ratio for all tested samples is shown as a function of the readback value in the lower panel of Figure 16.23 (a). For a voltage of the order of the post-irradiation band gap reference voltage of about 1.4 V, this yields an underestimation of $(31 \pm 5)\%$ [$(35 \pm 6)\%$] after the ROC has absorbed a dose of 0.5 MGy [1.1 MGy].

The **current calibration**, employed for reading back the analog current I_{ana} consist of two steps. Firstly, a second order polynomial

$$I_{\text{ana}}(V_{\text{ana}}) = p_0 + p_1 \cdot V_{\text{ana}} + p_2 \cdot V_{\text{ana}}^2 \quad (16.5)$$

is used to describe the non-linear relation of I_{ana} as a function of the VANA DAC setting V_{ana} , where I_{ana} is measured with the DTB (c.f. Figure 16.2 (a)). Because of the observed dose dependent saturation of the analog current, the post-irradiation current calibration is only valid up to the VANA setting where the saturation sets in and the fit range of the polynomial is restricted accordingly. Secondly, a linear function

$$R(V_{\text{ana}}) = q_0 + q_1 \cdot V_{\text{ana}} \quad (16.6)$$

is used to model the readback response R as a function of the VANA DAC setting. Combining both equations to substitute V_{ana} and solving for $I_{\text{ana}}(R)$ yields

$$I_{\text{ana}}(R) = p_0 + p_1 \left(\frac{R - q_0}{q_1} \right) + p_2 \left(\frac{R - q_0}{q_1} \right)^2. \quad (16.7)$$

Similar as for the voltage calibration, the radiation induced drift of the calibration parameters causes underestimation of the true current after irradiation when employing the pre-irradiation calibration parameters. An actual post-irradiation current corresponding to the nominal working point of the ROC of $I_{\text{ana}} = 24$ mA is underestimated by $(37 \pm 4)\%$ [$(37 \pm 6)\%$] after irradiation to a dose of 0.5 MGy [1.1 MGy]. In other words, a measured current of about 15 mA corresponds to an actual current of 24 mA after irradiation.

This underestimation can be reduced by performing a post-irradiation calibration of the readback response as a function of V_{ana} , i.e., by remeasuring the calibration parameters q_0 and q_1 . In contrast to the calibration of the parameters p_i with $i = 0, 1, 2$, this calibration can be performed also after the installation of the detector. Figure 16.23 (b) shows the current calibration before and after irradiation after re-calibrating q_0 and q_1 . The remaining underestimation of the current, which results from the drift of the calibration parameters p_i is shown in the lower panel of the figure. A post-irradiation current of 24 mA is underestimated by $(21 \pm 7)\%$ [$(29 \pm 7)\%$] after irradiation to a dose of 0.5 MGy [1.1 MGy], which shows that the post-irradiation calibration of q_0 and q_1 significantly reduces the underestimation compared to relying entirely on pre-irradiation calibration parameters.

16.6 Summary of observed radiation effects and implications for operating the ROC in the CMS pixel detector

Radiation effects observed with the final version of the digital ROC for the Phase I Upgrade of the CMS pixel detector comprise changes of chip characteristics that influence the performance of the detector and dose dependent adjustments of its optimal operation parameters. In the following, the observed radiation effects relevant for the expected lifetime dose of the detector are summarized. Additionally, recommendations for dose dependent adjustments of operation parameters, necessary for successfully operating the ROCs in the experiment after irradiation, are given.

Expected lifetime dose for BPix layer 2

The maximum TID expected for the layer 2–4 ROC of the upgraded pixel detector is 0.6 MGy for an integrated luminosity of 500 fb^{-1} of proton-proton collisions. After accumulating a dose of (0.5 ± 0.1) MGy in a 23 MeV proton beam, the band gap reference voltage of the ROC increases by $(11.3 \pm 1.0)\%$, causing the output voltages and currents of the chip's regulators to rise accordingly. The major part of the voltage drift occurs while the detector accumulates the first quarter of its expected lifetime dose, reaching $(8.3 \pm 0.4)\%$ after a dose of 150 kGy. In order to keep the analog current consumption of the detector stable, this increase can be counteracted by decreasing the VANA setting of the ROCs proportionally to the increase of the reference voltage. The observed dose dependent increase of the drop-out voltage of the VANA regulator does not reach critical values for the expected lifetime dose. The ROC can therefore be supplied with the analog supply voltage of $V_A = 1.6 \text{ V}$ throughout its lifetime. The increase of the digital current consumption by about 10% on the other hand cannot be compensated and needs to be taken into account for dimensioning the power supplies of the detector. The power consumption in the low-power start-up mode of the ROC increases by about 13% for the analog domain while the digital current dose not increase with TID.

The radiation induced increase of the resistance of the pulse shaper feedback loop in the PUC needs to be compensated by a dose dependent decrease of the VWLLSH DAC setting. After irradiation to 0.5 MGy, the pre-irradiation default setting of $VWLLSH = 220$ has to be lowered to $VWLLSH = 60$ in order to allow for a sufficiently fast recovery time of the shaper working point after processing a signal pulse. Too large settings of VWLLSH cause a loss of signals in rapid successions of pixel hits. Readjusting VWLLSH after irradiation allows to achieve 100% response efficiency to test pulse injections with time lags below the L1 trigger latency. A significant increase of radiation induced pixel defects is not observed.

The electronic noise of the preamplifier/shaper system in the PUC does not increase with respect to the pre-irradiation value of 120 ± 6 electrons for samples with fully depleted sensor. This allows to operate the ROC at thresholds below 2 ke also after irradiation. Decreasing the setting of the VWLLSH DAC as described above even decreases the noise to 100 ± 9 electrons after irradiation to 0.5 MGy. While a seamless adjustment of the pixel threshold to 1.85 ke can be achieved in the laboratory setup after irradiation, a drift of the thresholds towards lower values accompanied by a broadening of the threshold distribution of all pixels of a ROC has to be expected in the experiment, where re-optimization of the trim bits is not foreseen. After accumulating 0.5 MGy, the average pixel threshold drops from the pre-irradiation value of (1.85 ± 0.05) ke to (1.22 ± 0.17) ke when keeping the trim parameters and the VTHRCOMP and VTRIM DAC settings unchanged. In order to counteract the threshold drift, which would substantially increase the number of noise hits, the threshold can be shifted back to the pre-irradiation value by increasing VTHRCOMP by 17 ± 2 DAC units. In the experiment, such a correction can be performed during periods without collisions by iteratively adjusting VTHRCOMP such that the amount of noise induced hits complies with a certain tolerable maximum. Such threshold optimizations have already been a standard procedure to set the lowest possible threshold with the former CMS pixel detector. The impracticability of re-optimizing the trim bits of irradiated ROCs in the experiment results in a broadening of the threshold distribution of the pixels of a ROC. The presented study indicates that the root-mean-square of the threshold distribution increases from 59 ± 3 electrons to 153 ± 15 electrons in layer 2 of the detector towards the end of its lifetime. An additional increase of the pixel threshold to prevent migration of hits with small amplitudes into adjacent bunch crossings as has been necessary with the predecessor detector is not required since the timewalk stays well below 25 ns even after irradiation.

SCM samples irradiated to 0.5 MGy could be successfully operated in a high occupancy environment under X-radiation with all pixels active and at a threshold of 1.85 ke, indicating that the upgraded detector can be operated at a low threshold throughout its foreseen lifetime. Neither an increased sensitivity to noise hits nor a degradation of the hit detection efficiency of the ROC is to be expected for relevant pixel hit rates up to 120 MHz/cm^2 . As a result of the drift of the band gap reference voltage, the digital current consumption of the idling ROC increases by about 10%. Under load, the digital current increases with a dose independent slope of $(0.123 \pm 0.004) \text{ mA cm}^2 \text{ MHz}^{-1}$. The minimum digital voltage required for efficient readout of the ROC after irradiation of $V_D = 2.3 \text{ V}$ complies with the specifications of the nominal supply voltage provided by the DC-DC converters.

For the expected lifetime dose of BPix layer 2, the degradation of the PH information related to the observed vulnerability of the PH sampling ADC to TID effects can be mitigated by providing a regulated digital voltage $V_D > 2.4 \text{ V}$. In order to increase the safety margin to this critical voltage, the nominal digital supply voltage for layer 2 modules has been increased by 100 mV. With this adaption, the effect is not expected to affect the operation of the detector up to its expected lifetime dose.

Radiation effects observed in the second ADC, used to read back analog and digital information from the ROC, lead to an underestimation of current and voltage measurements when

relying on pre-irradiation calibration parameters. Towards the end of the lifetime of the detector, this underestimation reaches 30–40% for ROCs operated in layer 2 of the detector. For current measurements, which are used to monitor the analog current of the ROCs in the experiment, it is recommended to regularly re-calibrate the ADC response as a function of the VANA DAC setting to reduce the underestimation to $(21 \pm 7)\%$. Further studies with ROCs irradiated to lower doses are required to investigate the evolution of the readback calibration parameters during the operation of the detector and to assess the effect for doses expected in the outer layers.

Expected lifetime dose for BPix layer 1

Irradiation studies with samples of the layer 1 ROC are underway to verify the radiation tolerance of those parts of its architecture that are new with respect to the layer 2–4 ROC. Nevertheless, findings of the present study allow to project the behavior of chip components that are identical in the two designs. To this end, samples of the layer 2–4 ROC have been irradiated to the TID expected for layer 1 of the detector of about 1 MGy. Components that are shared between the two designs include, e.g., the band gap reference voltage circuit, the PUC, and the two ADCs.

For samples irradiated to (1.1 ± 0.2) MGy, an increase of the band gap reference voltage of $(12.2 \pm 0.8)\%$ with respect to the pre-irradiation value is observed. With respect to the maximum drift observed for the expected lifetime dose of layer 2, this is a difference of only about 1% and hence band gap drift related effects are expected to exhibit a similar behavior in both detector layers. The observed radiation induced increase of the drop-out voltage of the VANA regulator does not affect the operation of the innermost layer of the detector after irradiation to 1.1 MGy, as the saturation level of I_{ana} is sufficiently above the nominal working point for the nominal supply voltage of $V_A = 1.6$ V. The identical layout of the PUC in the layer 1 ROC and the layer 2–4 ROC suggests that the observed dose dependent adjustment of the VWLLSH setting will also be necessary for the layer 1 ROC and that a lowering of VWLLSH to its minimum is required towards the end of the lifetime. The radiation induced drift of the pixel threshold distribution has to be compensated by regularly adjusting VTHRCOMP as described above and the broadening of the distribution is expected to reach 183 ± 14 electrons for the expected lifetime dose of the innermost detector layer. Other analog performance figures such as noise and timewalk stay well within their specifications and no problems are expected.

The observed sensitivity of the PH sampling ADC of the layer 2–4 ROC to TID effects would have led to a severe impairment of PH measurements in the innermost detector layer. However, the limitation could be removed for the layer 1 ROC and hence no degradation of the PH information is expected for layer 1 modules, even for doses beyond 1 MGy. The drift of the readback calibration parameters saturates after 0.5 MGy and hence the projections made in the previous paragraph are expected to hold also for higher TIDs as expected for the innermost detector layer. Measurements of the propagation velocity of the DCol token confirm that the token is passed through the DCol within one clock cycle as required by the revised column drain mechanism of the layer 1 ROC.

Radiation effects on the hit detection efficiency in high occupancy environments and the digital power consumption of the layer 1 ROC cannot be projected from the findings of this study because of significant differences in the digital logic of the two ROC versions. Dedicated studies with irradiated samples of the layer 1 ROC are therefore ongoing at the time of submitting this thesis.

Summary and Outlook

The increase of the center-of-mass energy of the Large Hadron Collider (LHC) to 13 TeV in summer 2015 allows to probe predictions of the standard model of particle physics at an unprecedented energy scale and has opened new possibilities for the production of undiscovered particles in proton-proton collisions. Such particles are predicted for instance by theories that postulate a symmetry between fermions and bosons, known as supersymmetry, to address fundamental questions that the standard model leaves unanswered. In parallel to analyzing proton-proton collisions, comprehensive detector upgrade projects are underway to guarantee efficient data taking by the experiments at the increasingly challenging conditions imposed by a rising instantaneous luminosity of the LHC.

The present thesis documents contributions to both of these efforts. In Part I, the first analysis of the final state with at least three charged leptons as well as hadronic jets and missing transverse momentum conducted at 13 TeV with the Compact Muon Solenoid (CMS) experiment is presented. Part II of the thesis is dedicated to proton irradiation studies that have been an essential part of the design verification of the new readout chip for the Phase I Upgrade of the CMS pixel detector.

Search for supersymmetry in events with multiple charged leptons

The final state with at least three electrons or muons in any combination, jets, and missing transverse momentum examined in the presented analysis of proton-proton collisions features very low standard model background contributions. This allows to achieve a high sensitivity for various predicted signal topologies, e.g., processes involving supersymmetric particles. Such processes could lead to an excess of events with multiple charged leptons with respect to the background-only hypothesis. The presented search features a robust reconstruction of leptons that originate from the decay of $W^\pm$ and Z bosons, so-called prompt leptons, with selection efficiencies of up to 93% and 77% for central, high- p_T muons and electrons, respectively. With respect to earlier analyses of this final state at $\sqrt{s} = 7$ TeV and 8 TeV, the lepton reconstruction criteria include novel techniques for defining the lepton isolation to achieve a better suppression of nonprompt leptons in events with boosted collision products. The new criteria employ a p_T dependent size of the lepton isolation cone [166] as well as additional variables to improve the rejection of nonprompt leptons arising from low- p_T b quark decays and to recover accidental overlaps of decay products in boosted environments [167].

In order to improve the signal-to-background ratio for different signal topologies, events of interest are categorized into 32 exclusive signal regions. The categorization is based on the

number of b jets, the amount of missing transverse momentum, the hadronic activity, and the invariant mass of opposite-sign, same-flavor dilepton pairs in the event. Contributions from irreducible standard model background processes, such as diboson production and the production of $t\bar{t}$ in association with a vector boson or Higgs boson are estimated with Monte Carlo simulations. For WZ diboson production, which constitutes the irreducible background source with the largest cross section, the overall yield of the simulation is validated in a control region with data. Reducible standard model background arises mainly from the production of $t\bar{t}$ plus jets. Such events can enter the signal regions if one or more nonprompt leptons pass the lepton selection criteria. This type of background is estimated with data, based on the number of events observed in dedicated sideband regions populated with events that contain leptons that pass a set of relaxed selection criteria but do not pass the full set of requirements for signal leptons. Employing advancements of this method, which have been developed during the consolidation of the LHC [175], allows to reduce the systematic uncertainty related to the nonprompt lepton background estimation with respect to a comparable analysis at $\sqrt{s} = 8 \text{ TeV}$ [154] from 50% to 30%.

For the analyzed data set with an integrated luminosity of 12.9 fb^{-1} of proton-proton collisions, the observed data are found to agree with the standard model predictions within the uncertainties in all 32 signal regions. In the absence of any significant excess, the results are interpreted in terms of exclusion limits on the masses of supersymmetric particles in the context of two simplified signal model topologies. The first model considers gluino pair production, where each gluino decays via an intermediate virtual stop quark into two top quarks and a neutralino as the lightest supersymmetric particle (LSP). In this model, gluino masses up to 1 200 GeV have been excluded for a light LSP, while LSP masses up to 775 GeV have been excluded for a gluino mass between 1 000 GeV and 1 150 GeV. For both masses, this represents an extension of the exclusion limit set by a similar analysis at 8 TeV [154] by about 200 GeV. In the second model, gluino-gluino production yields multiple light-flavor jets, a $W^\pm$ and a Z boson, and two neutralinos as LSPs. For this topology, gluino masses up to 1 000 GeV have been excluded for a light LSP, as well as LSP masses up to 600 GeV for a gluino mass of 775 GeV. With local significances well below 2σ across the examined phase space of supersymmetric particle masses, the presented analysis favors the standard model-only hypothesis.

Radiation tolerance of the digital readout chip for the Phase I Upgrade of the CMS pixel detector

In order to avoid performance losses at instantaneous luminosities that exceed the original design specifications of the pixel detector by a factor of two, the CMS Collaboration has decided to replace the whole subdetector with a new, improved system. This so-called Phase I pixel detector has been installed in February 2017 to maintain and improve the excellent performance of its predecessor in an even more challenging pileup and radiation environment. A key aspect of the upgraded pixel detector is a new front-end chip, which is used in the forward part and in layers 2–4 of the central detector. Extended on-chip buffer capabilities, a revised readout logic, and a new digital data transmission protocol allow to maintain hit detection efficiencies above 99% at hit rates up to 120 MHz/cm^2 . Additionally, a lower charge threshold of below 2 ke extends the lifetime of the detector by improving the sensitivity to small signal pulses after non-ionizing radiation damage has degraded the charge collection efficiency of the silicon sensors.

In order to guarantee the expected performance of the readout chip (ROC) throughout the envisaged lifetime of the detector until 2024, the new chip design has to fulfill stringent requirements in terms of tolerance against ionizing radiation damage. The proton irradiation studies presented in this thesis have therefore been a key aspect of the design verification during the development of the ROC and additionally provide valuable insights concerning the

expected evolution of the optimal operation parameters of the chip in the experiment. The present work demonstrates that the new ROC remains fully functional after accumulating the expected lifetime dose of layer 2 of the detector of about 0.5 MGy. Moreover, the findings qualify chip components that are identical in a dedicated readout chip for layer 1, in particular the analog domain of the architecture, for use after irradiation to about 1 MGy corresponding to the expected lifetime dose of the innermost detector layer. Important characteristics of the ROC, e.g., low electronic noise, a low charge threshold, small timewalk, and a high efficiency for reading out test pulses, meet the design specifications even after irradiation up to 4.2 MGy.

The most important effects observed after irradiation up to the expected lifetime dose include an increase of the resistance of the feedback loop of the pulse shaper in the pixel unit cell. This requires a dose dependent adjustment of the responsible digital-to-analog converter (DAC) setting (VWLLSH) in order to counteract the increased recovery time of the shaper after processing a pulse. Additionally, the radiation induced reduction of the pixel threshold has to be counteracted by readjusting the DAC settings that defines the global charge threshold of the ROC (VTHRCOMP). The impracticability to optimize the charge threshold on a pixel-to-pixel level in the experiment entails a broadening of the threshold distribution of all pixels within one ROC by up to a factor of three towards the end of the detector's lifetime. Further radiation effects have been identified in the analog-to-digital converters (ADCs) used to digitize the pulse height and the analog readback information. Radiation induced drifts of the readback calibration parameters lead to a systematic underestimation of voltage and current measurements of up to 40% when relying on pre-irradiation calibration parameters. The radiation induced degradation of the pulse height sampling ADC on the other hand can be mitigated by providing a sufficiently large digital voltage, which counteracts the observed threshold drift of the responsible pMOS transistor. This is ensured by an adaption of the output voltage of the respective DC-DC power converters for layer 2 modules, which has been implemented as a result of this study. For the dedicated ROC for layer 1 modules, the results of the present work allowed to remove the limitation of the pulse height ADC at chip level and dedicated mitigation strategies are not needed.

Outlook

The physics program of the LHC has only just begun and the four main experiments at the accelerator have accumulated just a small fraction of the total data foreseen to be collected within the next 20 years. At the time of writing this thesis, evidence for physics beyond the standard model remains elusive and the search presented in Part I is no exception to this. However, the theoretical and phenomenological hints for new physics at the TeV scale remain compelling and high expectations are placed on analyzing the significantly larger data sets to be collected in the coming years.

For future implementations of the presented multilepton analysis, larger data sets offer new possibilities to validate the simulation of rare background contributions such as ZZ or $t\bar{t}Z$ in dedicated control regions in data. Additionally, the determination of the lepton misidentification rate in the measurement region could be complemented with a measurement in the baseline region itself. This could be achieved by inverting the lepton selection requirement on the impact parameter significance ($SIP_{3D} > 4$) for one of the leptons, similar to the strategy employed in Ref. [246]. Finally, multilepton searches that target signal models with pair production of electroweak sparticles will gain growing attention, as the increasing data sets will allow to also probe neutralino and chargino masses beyond 1 TeV.

With the Phase I Upgrade of the pixel detector, the CMS experiment is well-equipped for this endeavor and the work presented in this thesis significantly contributed to achieving a radiation tolerant design of the ROC, which will allow to profit from the excellent performance of the detector throughout its lifetime.

Appendix – Part I

A High-level trigger paths

Table A.1 lists the high-level trigger paths that are used to select signal events for the presented analysis. All of these dilepton triggers have not been prescaled during the relevant data taking period. Auxiliary single lepton triggers, which are listed in Table A.2, are used to select QCD multijet events for measuring the lepton misidentification rate, which is used for the estimation of the nonprompt lepton background. The auxiliary triggers have been prescaled to reduce their rate, resulting in a smaller effective luminosity $\mathcal{L}_{\text{eff}}$ compared to the full data set of 12.9fb^{-1} .

Table A.1: Isolated dilepton triggers and nonisolated dilepton plus H_T triggers used to select signal events at HLT level. No prescales have been used for these paths during the relevant data taking period.

Lepton isolation	Channel	Trigger name
required	$\mu\mu$	HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL
	ee	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL
	$e\mu$	HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL
		HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL
not required	$\mu\mu$	HLT_DoubleMu8_Mass8_PFHT300
	ee	HLT_DoubleEle8_CaloIdM_TrackIdM_Mass8_PFHT300
	$e\mu$	HLT_Mu8_Ele8_CaloIdM_TrackIdM_Mass8_PFHT300

Table A.2: Auxiliary triggers used to select QCD multijet events for measuring the lepton misidentification rate. Different trigger prescale factors have been used during the data taking period, leading to reduced effective luminosities $\mathcal{L}_{\text{eff}}$ with respect to the full data set of 12.9fb^{-1} .

Channel	Trigger name	$\mathcal{L}_{\text{eff}}$ (pb^{-1})
μ	HLT_FR_Mu8	3.0
	HLT_FR_Mu17	230.1
e	HLT_Ele8_CaloIdM_TrackIdM_PFJet30	3.0
	HLT_Ele17_CaloIdM_TrackIdM_PFJet30	42.4

B Lepton isolation efficiency curves

The lepton isolation requirement, defined in Equation 5.7, allows to tune the selection efficiency for prompt leptons and the corresponding background acceptance for nonprompt leptons by defining different working points of the isolation variables I_{mini} , $p_{\text{T}}^{\text{rel}}$, and $p_{\text{T}}^{\text{ratio}}$. Table B.3 lists the cutoff values of these variables for different working points. They are tuned separately for muons and electrons to achieve similar selection efficiencies for the two lepton flavors.

Table B.3: Cutoff values for the lepton isolation variables corresponding to different working points. In the presented analysis, the ‘loose’ and the ‘medium’ working points are employed in the muon and electron selection, respectively.

Internal name	$I_{\text{mini}}^{\text{cut}}$	$p_{\text{T}}^{\text{ratio, cut}}$	$p_{\text{T}}^{\text{rel, cut}}$
loose	0.20	0.69	6.0
medium	0.16	0.76	7.2
tight	0.12	0.80	7.2
very tight	0.09	0.84	7.2

The corresponding selection efficiency for prompt leptons versus the background acceptance as obtained with simulated $t\bar{t}$ events is shown in Figure B.1. The efficiencies are shown separately for muons and electrons as well as for high- p_{T} leptons with $p_{\text{T}} \geq 25$ GeV and low- p_{T} leptons with $10 \text{ GeV} \leq p_{\text{T}} < 25 \text{ GeV}$. For a fixed selection efficiency of prompt leptons, the isolation requirement based on I_{mini} , $p_{\text{T}}^{\text{rel}}$, and $p_{\text{T}}^{\text{ratio}}$ (c.f. Equation 5.7) allows to reduce the background acceptance with respect to an isolation requirement that only imposes an upper bound on I_{mini} (gray line), especially for low- p_{T} leptons.

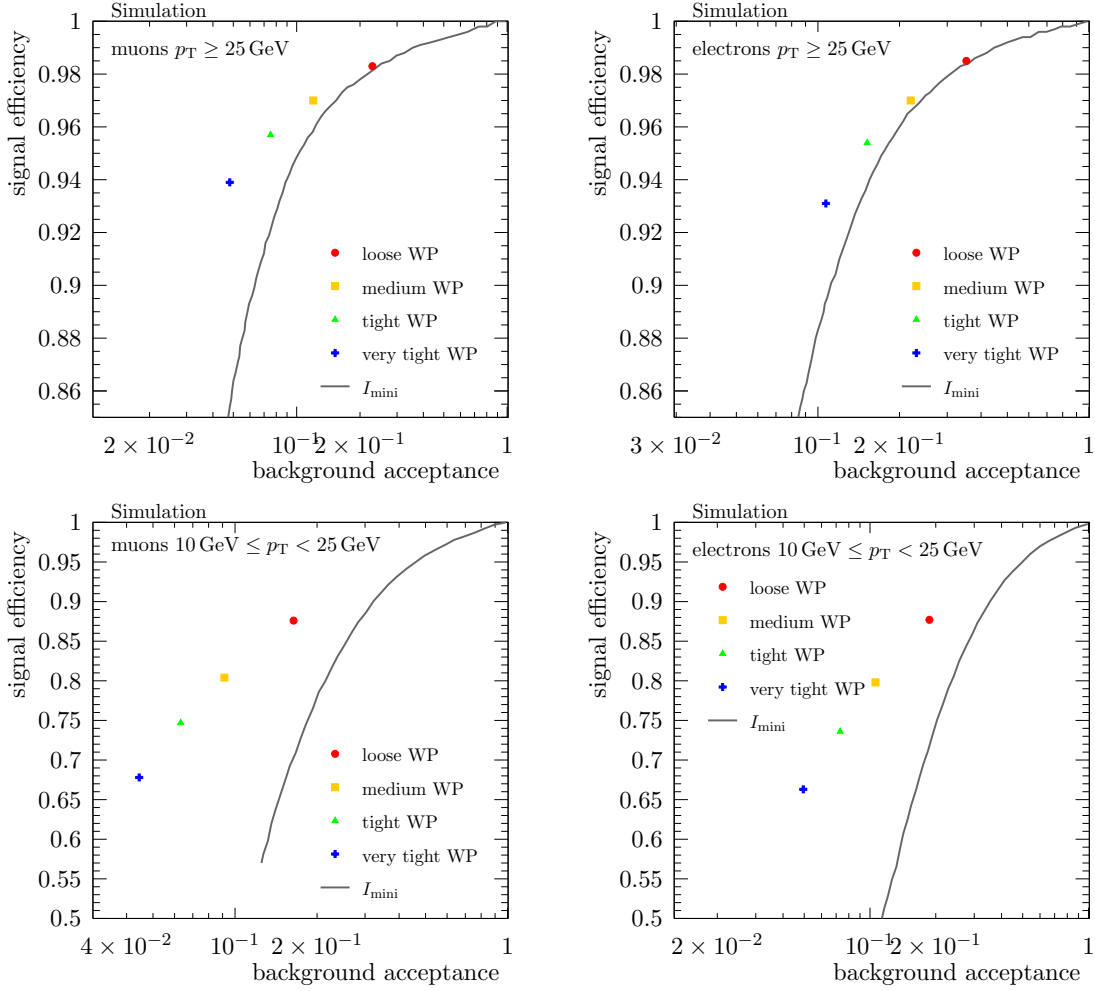


Figure B.1: Lepton selection efficiency for prompt leptons versus acceptance of nonprompt leptons as obtained with simulated $t\bar{t}$ events. The efficiency curves are shown separately for muons (left) and electrons (right) and for high- p_T leptons with $p_T \geq 25$ GeV (top) and low- p_T leptons with $10 \text{ GeV} \leq p_T < 25$ GeV (bottom). Different working points of the isolation criterion that employs the variables I_{mini} , p_T^{rel} , and p_T^{ratio} corresponding to the cutoff values listed in Table B.3 are shown by the various markers. For a fixed selection efficiency for prompt leptons, the three-variable isolation requirement allows to improve the background rejection with respect to an isolation requirement based on I_{mini} only (gray line). For the presented analysis, the loose (medium) working point has been chosen for muons (electrons). Modified from [247].

C List of standard model background simulations

Table C.4 lists all Monte Carlo (MC) simulations for standard model (SM) background processes used in the presented analysis. Besides the name of the corresponding background category and the internal name of the simulation, also the number of simulated events, the cross section times a so-called k -factor, and the equivalent integrated luminosity are given. The k -factor is used to scale cross section calculated at leading-order accuracy to the corresponding next-to-leading order prediction. The background simulations listed in the ‘nonprompt’ category are not used for the final result of the analysis where this type of background is estimated with a data-driven technique. Instead, these simulations are used for closure tests to validate the nonprompt lepton background estimation and for the plots in Chapter 6, which are based on simulation only.

Table C.4: List of Monte Carlo simulations of standard model background processes used for the presented analysis. Background category, collection name, number of simulated events, processes cross section times k -factor, and the equivalent luminosity of the simulation are presented.

Category	Internal name	N_{events}	$\sigma \times k$ (pb)	$\mathcal{L}_{\text{equ}}$ (fb $^{-1}$)
ttW	ttWJets_13TeV_madgraphMLM	1.29×10^7	0.6105	21130
	TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	2.53×10^5	0.2043	1238
ttZ/H	ttZJets_13TeV_madgraphMLM	2.19×10^7	0.8393	26093
	TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8	3.99×10^5	0.2529	1578
	TTLL_m1to10_LO_NoMS_for76X	4.38×10^4	0.0283	1548
	tHToNonbb_M125_13TeV-powheg-pythia8	3.84×10^6	0.2151	17852
X+ γ	TGJets_TuneCUETP8M1_13TeV-amcatnlo-madspin-pythia8	2.93×10^5	2.967	99
	TTGJets_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	4.87×10^6	3.697	1317
	ZGTo2LG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	4.39×10^6	131.3	33
	WGToLNuG_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	5.92×10^6	585.8	10
rare	ZZTo4L_13TeV-powheg-pythia8	6.64×10^6	1.256	5287
	GluGluHToZZTo4L_M125_13TeV-powheg2_JHUGenV6-pythia8	1.00×10^6	0.0121	82645
	VHToNonbb_M125_13TeV-amcatnloFXFX-madspin-pythia8	1.00×10^6	0.9561	1046
	WWW_4F_TuneCUETP8M1_13TeV-amcatnlo-pythia8	2.40×10^5	0.2086	1151
	WWZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	2.49×10^5	0.1651	1508
	WZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	2.50×10^5	0.0557	4488
	ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	2.50×10^5	0.0140	17857
	TTTT_TuneCUETP8M1_13TeV-amcatnlo-pythia8	9.89×10^5	0.0091	108681
	tZq_ll4f_13TeV-amcatnlo-pythia8_TuneCUETP8M1	2.97×10^6	0.0758	39182
WZ	WZTo3LNu_TuneCUETP8M1_13TeV-powheg-pythia8	2.00×10^6	4.4297	451
nonprompt	TTJets_DiLept_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	6.06×10^6	87.315	69
	TTJets_SingleLeptFromTbar_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	1.19×10^7	182.18	65
	TTJets_SingleLeptFromT_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	9.47×10^6	182.18	52
	DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	3.51×10^7	18610	2
	DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	4.24×10^7	6024.0	7
	ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	9.85×10^5	35.6	28
	ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	9.98×10^5	35.6	28
	ST_t-channel_antitop_4f_leptonDecays_13TeV-powheg-pythia8_TuneCUETP8M1	1.68×10^6	26.2	64
	ST_t-channel_top_4f_leptonDecays_13TeV-powheg-pythia8_TuneCUETP8M1	3.28×10^6	44.1	74
	WJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	9.91×10^6	61526.7	0.2

D On-Z events with high p_T^{miss}

Table D.5 lists the run number, the luminosity section, and the event number of the six observed on-Z events with $p_T^{\text{miss}} > 450$ GeV. Additionally, the number of selected muons, electrons, jets, and b jets as well as the measured values of p_T^{miss} and H_T are given. Details on the kinematic variables of the selected jets and leptons are listed in Table D.6. For the leptons, also the impact parameter significance $\text{SIP}_{3\text{D}}$ and the isolation variables I_{mini} , p_T^{rel} , and p_T^{ratio} are presented. Figure D.2 shows the event displays for these events. For each event, reconstructed physics object candidates are shown in the $r\phi$ plane perpendicular to the beam pipe (left) and in the rz plane (middle right). Additionally, a perspective view of the event (bottom right) and a projection on the $\eta\phi$ plane (top right) are shown. Visual inspection of the events reveals no indication that the events can be attributed to noise or other detector or reconstruction related artifacts. Candidate objects are displayed as follows:

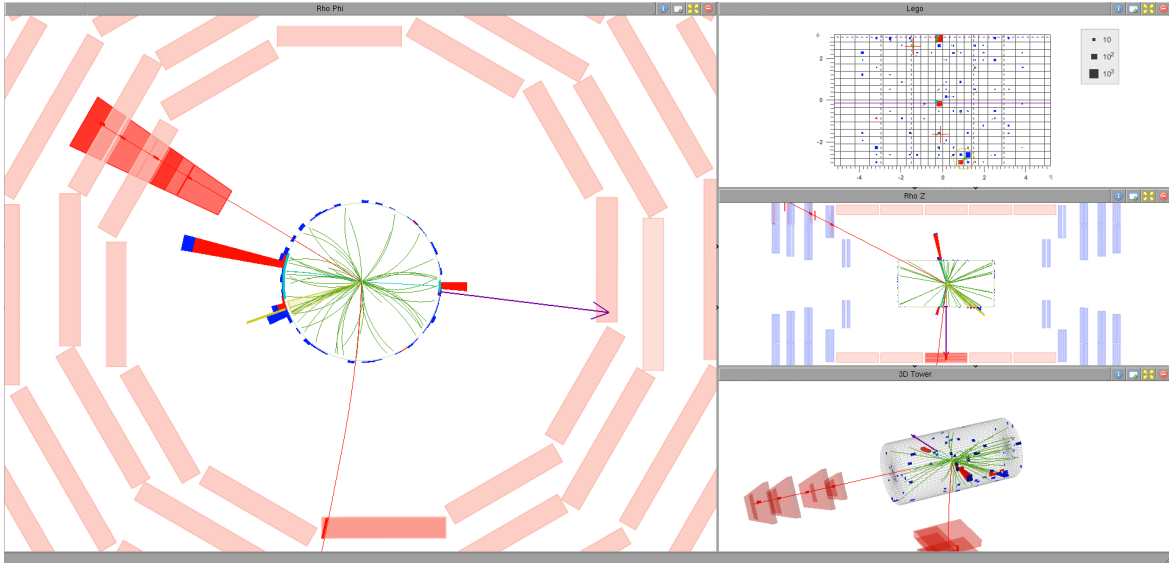
- Muon candidates are shown as red lines, which reach the muon system represented by the light red rectangles. The detector segments that are hit by the muon candidate are highlighted in darker red.
- The red (blue) shapes emanating from the circle or rectangle indicating the tracking detectors, represent energy deposits in the electromagnetic (hadronic) calorimeter.
- Green lines within the tracking volume indicate tracks from charged particles.
- Jet candidates are represented by yellow cones.
- Electron candidates are represented by cyan lines within the tracking volume.
- The magnitude and direction of the imbalance of the momenta of all reconstructed particle flow candidates ($\vec{p}_T^{\text{miss}}$) is shown by the length and the orientation of the violet arrow.

Table D.5: Run number, luminosity section, and event number of the six on-Z events with $p_T^{\text{miss}} > 450$ GeV. For each event, the number of selected muons, electrons, jets, and b jets, as well as the measured values for p_T^{miss} and H_T are listed.

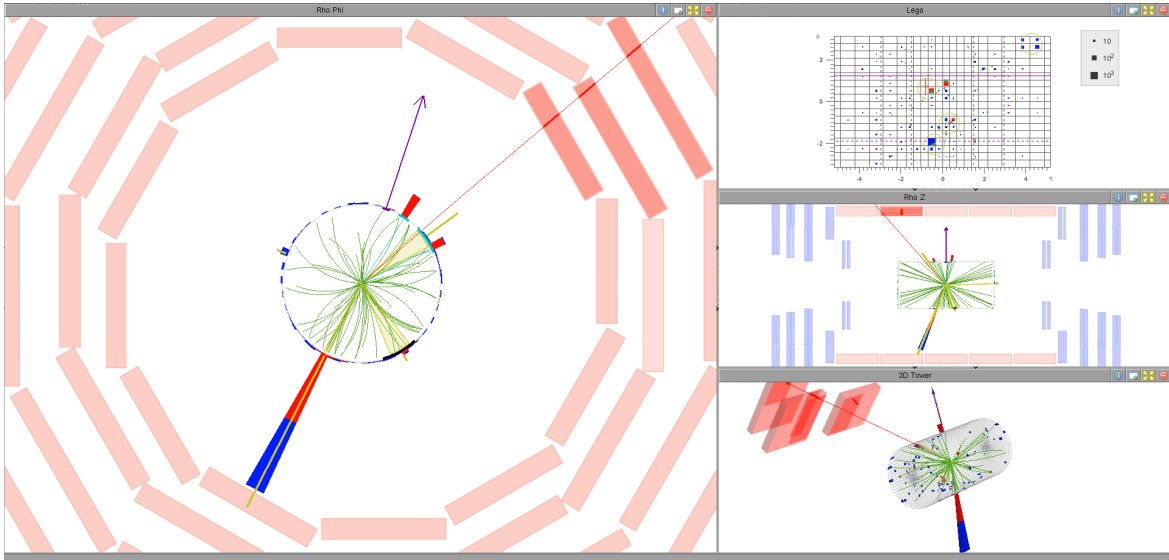
Run	Lumi. sec.	Event	N_μ	N_e	N_{jets}	N_b	p_T^{miss} (GeV)	H_T (GeV)
276437	1107	2012142827	0	3	5	1	478	666
274161	15	26362629	2	1	2	0	471	443
274422	1220	2097023176	1	2	2	0	738	1106
275890	1277	2394839465	3	0	3	0	458	576
276283	607	1123841210	2	1	5	0	482	1240
276808	10	18593098	3	0	3	0	484	137

Table D.6: Kinematic variables for selected jets and leptons for on-Z events with $p_T^{\text{miss}} > 450$ GeV. For the selected leptons, also the isolation variables I_{mini} , p_T^{rel} , and p_T^{ratio} and the impact parameter significance $\text{SIP}_{3\text{D}}$ are listed.

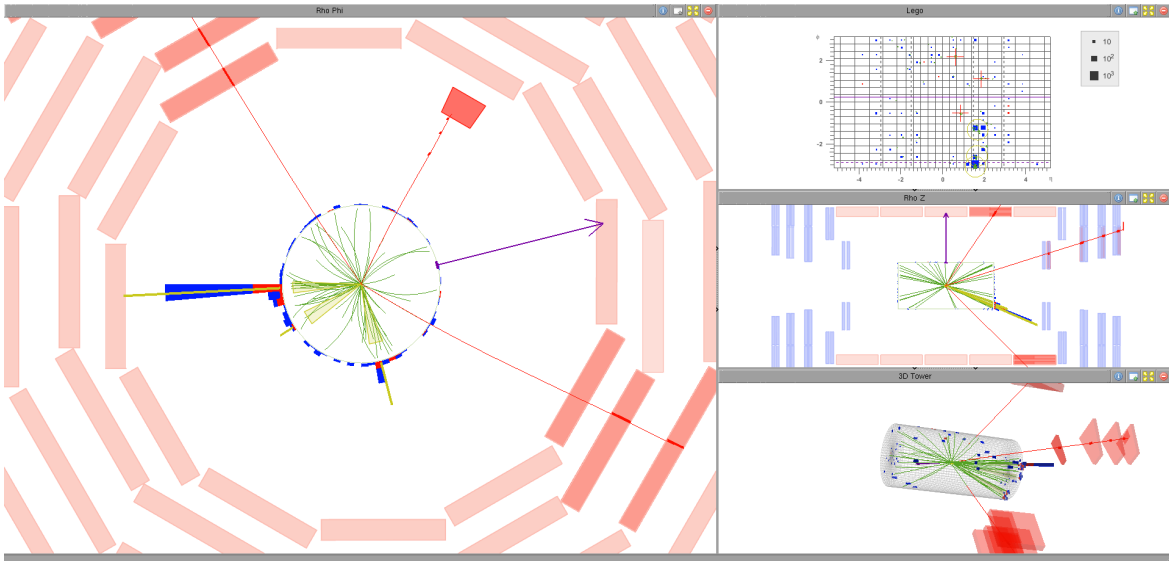
Event	Object	p_T (GeV)	η	ϕ	$\text{SIP}_{3\text{D}}$	I_{mini}	p_T^{rel}	p_T^{ratio}
2012142827	jet	182.9	0.79	5.45				
	jet	171.8	-0.46	5.94				
	jet	106.8	0.45	4.43				
	jet	106.2	-2.33	6.03				
	jet	98.2	1.42	3.96				
	e^-	99.3	0.98	2.05	1.58	0.007	22.21	0.948
	e^+	56.2	0.26	0.50	1.80	0	52.75	0.998
	e^-	36.1	0.31	3.93	2.96	0.065	9.36	0.777
26362629	jet	328.4	-0.23	2.89				
	jet	115.0	1.03	3.48				
	μ^+	76.2	-1.42	2.57	1.04	0	156.96	1.001
	e^-	72.3	-0.28	6.24	1.40	0	26.57	0.969
	μ^-	22.4	-0.12	4.68	0.82	0.145	2.53	0.881
2097023176	jet	1051	-0.40	4.24				
	jet	55.3	0.34	5.24				
	e^+	144.3	0.18	0.99	1.00	0	43.64	0.929
	μ^-	131.8	-0.79	0.73	1.41	0	51.28	0.594
	e^-	78.5	-0.52	0.47	2.74	0.044	26.14	0.346
2394839465	jet	421.5	1.58	3.19				
	jet	115.6	1.69	4.96				
	jet	39.2	1.65	3.71				
	μ^-	69.9	0.64	2.17	1.36	0.009	17.06	0.97
	μ^+	33.5	0.89	5.73	2.66	0.013	12.15	0.910
	μ^-	22.5	1.87	1.14	1.07	0	0	1
1123841210	jet	434.4	0.11	0.76				
	jet	333.1	0.66	4.10				
	jet	271.1	-0.41	1.24				
	jet	109.3	-1.42	5.76				
	jet	91.6	-0.98	5.54				
	μ^-	152.2	-0.07	5.54	0.75	0	36.70	0.981
	μ^+	55.4	0.79	5.95	0.31	0	62.63	0.992
	e^+	10.1	-0.43	4.70	1.20	0	8.82	0.971
18593098	jet	49.8	-0.36	6.20				
	jet	45.5	-1.13	1.39				
	jet	41.5	0.57	1.11				
	μ^-	512.9	0.26	2.25	1.02	0	263.06	1.001
	μ^+	114.4	0.09	4.71	0.81	0	3.89	1.040
	μ^+	71.1	0.69	2.08	1.62	0	60.78	0.996



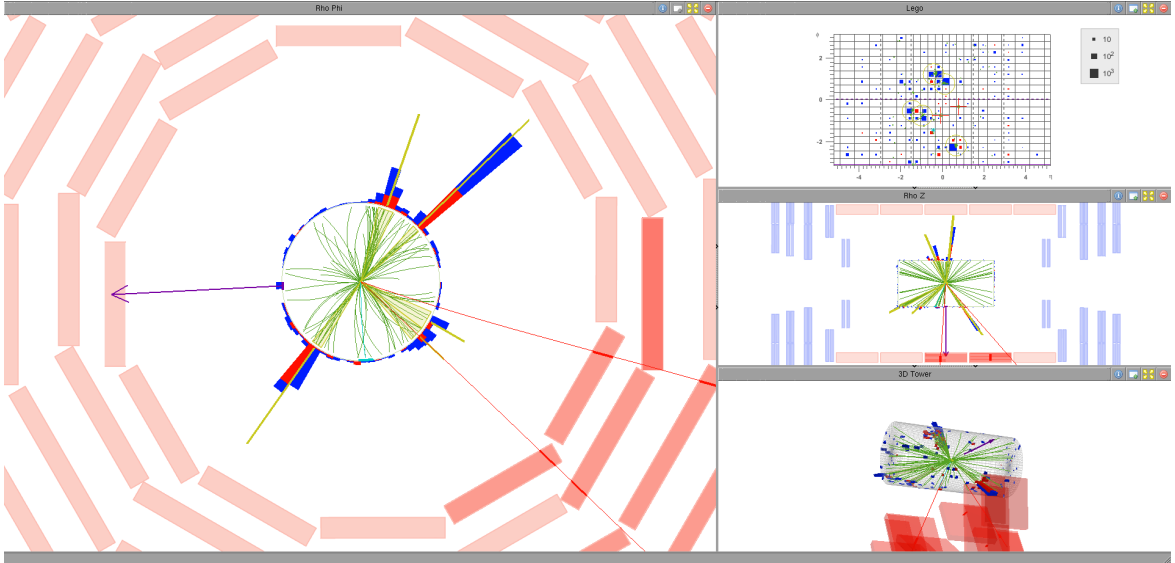
(a) Event 274161



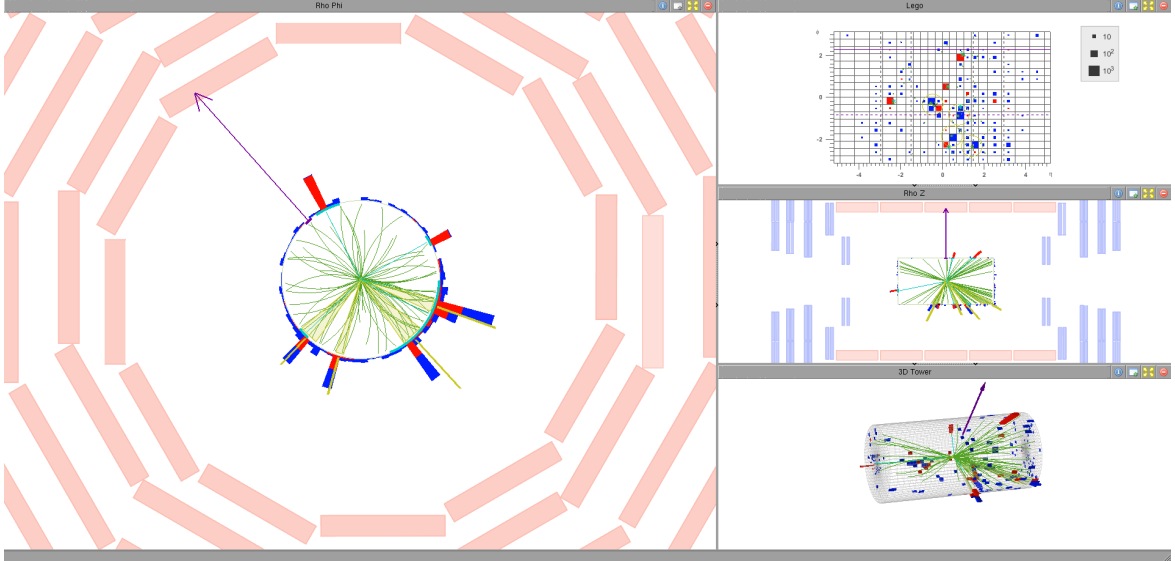
(b) Event 274422



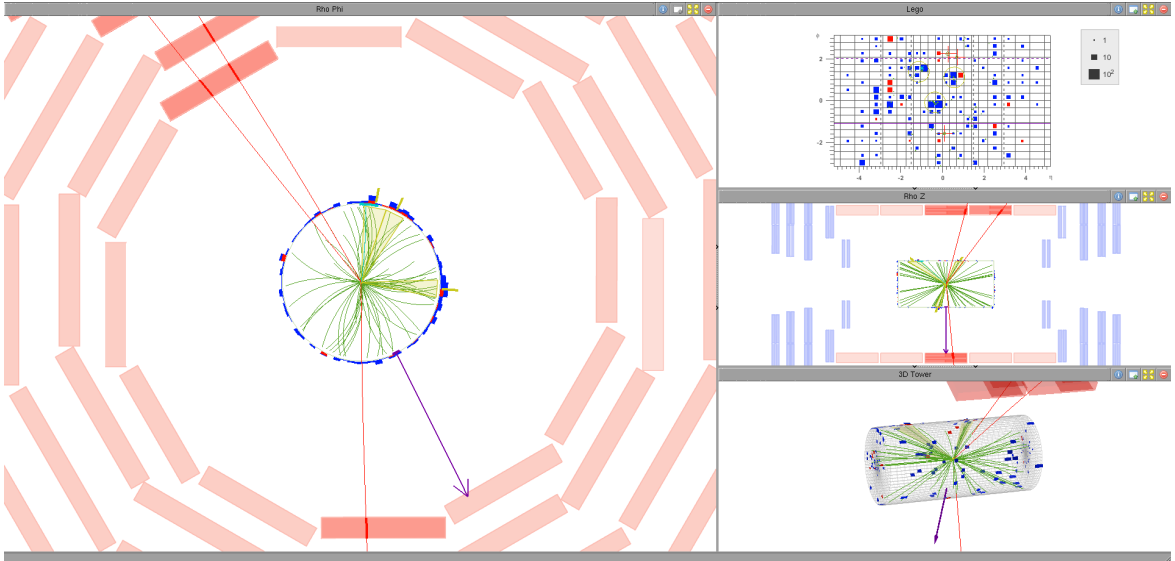
(c) Event 275890



(c) Event 276283



(d) Event 276437



(e) Event 276808

Figure D.2: Event displays for on-Z events with $p_T^{\text{miss}} > 450$ GeV.

E Off-Z events with high jet multiplicities

Table E.7 lists the run number, the luminosity section, and the event number of the twelve observed off-Z events with $N_{\text{jets}} \geq 6$. Additionally, the number of selected muons, electrons, jets, and b jets as well as the measured values of $p_{\text{T}}^{\text{miss}}$ and H_{T} are presented. Details on the kinematic variables of the selected jets and leptons are listed in Table E.8. For the selected leptons, also the impact parameter significance $\text{SIP}_{3\text{D}}$ and the isolation variables I_{mini} , $p_{\text{T}}^{\text{rel}}$, and $p_{\text{T}}^{\text{ratio}}$ are presented. Figure E.3 shows the distribution of the twelve events with $N_{\text{jets}} \geq 6$ in other event observables and their categorization into the 15 off-Z signal regions (SRs). No exceptional accumulation of the events is observed in any other distribution apart from the jet multiplicity. The twelve events are categorized into eight different SRs.

The sharp drop of the nonprompt lepton background prediction for $N_{\text{jets}} \geq 6$ in Figure 9.3 suggests that an underprediction of the nonprompt lepton background may be responsible for the observed discrepancy between data and the background prediction for off-Z events with high jet multiplicities. Such an underprediction could arise from an underfluctuation of events in the corresponding application region. A comparison of data and MC simulations of the SM background contributions in the application region of the off-Z baseline selection is shown in Figure E.4. The contribution from nonprompt leptons is estimated with a sample of $t\bar{t}$ events, simulated with MADGRAPH5. A good agreement between data and the simulation can be observed for the H_{T} , $p_{\text{T}}^{\text{miss}}$, and N_{b} distributions. Good agreement between data and simulation is also observed in the N_{jets} distribution, however, only for $N_{\text{jets}} \leq 5$. For higher jet multiplicities, i.e., for the bins that correspond to the discrepancy in the off-Z baseline selection, considerably fewer events are observed than predicted by the simulation. This observation provides additional motivation for the assumption that the observed discrepancy between data and the background prediction for off-Z events with $N_{\text{jets}} \geq 6$ is at least partly caused by an underfluctuation of data in the corresponding application region.

Table E.7: Run number, luminosity section, and event number of the twelve off-Z events with $N_{\text{jets}} \geq 6$. For each event, the number of selected muons, electrons, jets, and b jets, as well as the measured values for $p_{\text{T}}^{\text{miss}}$ and H_{T} are listed.

Run	Lumi. sec.	Event	N_{μ}	N_e	N_{jets}	N_{b}	$p_{\text{T}}^{\text{miss}}$ (GeV)	H_{T} (GeV)
275311	601	744848963	1	2	7	1	90	585
275890	1156	2190755104	0	3	6	1	83	562
276808	669	1286804872	1	2	7	1	245	516
274344	532	820990721	3	0	6	1	92	322
274422	1014	1760535058	2	1	6	0	98	588
275073	444	790355068	3	0	7	3	156	439
275375	1270	2185582671	1	2	7	2	122	1292
275890	398	759065657	2	1	6	1	264	468
276437	920	1644425191	2	1	7	1	144	527
276501	1539	2580593845	2	1	6	2	110	406
276542	375	585686292	3	0	6	2	117	1168
276586	771	1295612941	3	0	6	0	311	1572

Table E.8: Kinematic variables for selected jets and leptons for off-Z events with $N_{\text{jets}} \geq 6$. For the selected leptons, also the isolation variables I_{mini} , $p_{\text{T}}^{\text{rel}}$, and $p_{\text{T}}^{\text{ratio}}$ and the impact parameter significance $\text{SIP}_{3\text{D}}$ are listed.

Event	Object	p_{T} (GeV)	η	ϕ	$\text{SIP}_{3\text{D}}$	I_{mini}	$p_{\text{T}}^{\text{rel}}$	$p_{\text{T}}^{\text{ratio}}$
744848963	jet	251.6	0.53	3.83				
	jet	89.8	-1.95	0.53				
	jet	72.9	-0.15	5.92				
	jet	50.8	-1.28	3.34				
	jet	45.8	-1.64	0.02				
	jet	42.3	-1.09	6.25				
	jet	31.9	1.53	5.52				
	μ^-	72.7	-0.27	0.73	0.51	0.01	12.48	0.98
	e^+	37.9	-2.16	1.57	0.29	0.09	4.00	0.76
	e^+	22.4	-0.66	2.23	3.49	0.08	4.55	0.93
2190755104	jet	226.6	-0.14	6.22				
	jet	93.6	1.14	1.52				
	jet	73.6	2.07	2.25				
	jet	69.8	-0.77	3.29				
	jet	63.9	-1.24	5.43				
	jet	34.9	-2.31	5.31				
	e^-	81.2	-0.76	5.89	2.01	0	30.56	0.96
	e^+	68.7	-1.10	2.91	0.75	0	29.68	1.00
	e^+	39.2	-1.17	2.03	1.22	0	19.55	0.97
1286804872	jet	90.3	-1.07	0.91				
	jet	88.2	-1.62	5.95				
	jet	87.7	1.13	4.00				
	jet	79.6	-1.56	4.55				
	jet	58.1	-2.00	0.46				
	jet	57.5	1.15	5.98				
	jet	54.5	-0.14	5.79				
	μ^-	166.4	-0.38	2.25	1.39	0	29.03	0.93
	e^-	131.0	-1.57	0.23	0.96	0.12	8.73	0.80
	e^+	47.8	-1.22	3.72	1.02	0.02	11.19	0.97
820990721	jet	94.3	-0.85	3.83				
	jet	53.0	0.00	0.61				
	jet	46.7	-0.01	1.68				
	jet	46.1	0.75	0.43				
	jet	41.4	0.62	5.76				
	jet	40.5	0.28	5.46				
	μ^+	134.4	-0.16	3.73	2.07	0	16.74	0.91
	μ^-	96.6	0.39	1.42	3.11	0	77.13	1.00
	μ^+	29.0	1.21	1.99	2.15	0	16.79	0.97
1760535058	jet	200.7	-0.26	4.51				
	jet	131.3	0.23	0.18				
	jet	76.0	1.32	2.13				
	jet	75.8	0.66	0.58				
	jet	71.3	-0.66	4.19				
	jet	32.9	-0.71	3.38				
	μ^+	105.0	-0.51	2.96	0.26	0.10	22.11	0.82
	e^+	46.6	0.16	1.24	1.78	0	0.53	0.91
	μ^-	23.2	0.57	3.84	0.88	0	7.76	0.79
790355068	jet	125.4	-2.10	1.83				
	jet	81.1	1.13	2.12				
	jet	56.0	0.92	6.10				
	jet	54.6	-2.03	5.24				
	jet	48.1	-2.05	3.00				
	jet	42.6	-0.07	5.17				
	jet	31.1	1.61	3.11				
	μ^-	109.0	0.43	5.22	0.50	0.00	25.27	0.91
	μ^+	53.8	0.57	0.89	0.55	0	10.57	0.97
	μ^-	22.0	0.81	1.40	0.43	0.14	5.10	0.81

Event	Object	p_T (GeV)	η	ϕ	SIP _{3D}	I_{mini}	p_T^{rel}	p_T^{ratio}
2185582671	jet	451.7	-1.69	1.00				
	jet	432.3	-0.14	3.82				
	jet	140.5	-2.02	0.37				
	jet	89.2	-1.20	3.39				
	jet	71.0	1.96	4.17				
	jet	54.5	-1.44	0.56				
	jet	52.5	0.57	0.42				
	e^-	169.5	-1.31	5.80	0.70	0	15.30	0.73
	e^-	117.6	1.76	3.18	0.35	0	4.20	0.94
	μ^+	25.0	-0.09	3.35	0.48	0	17.66	0.98
759065657	jet	193.6	1.83	2.17				
	jet	115.0	0.29	0.40				
	jet	49.3	0.81	0.04				
	jet	46.6	-0.29	1.10				
	jet	31.7	-0.48	5.58				
	jet	31.6	-0.95	3.43				
	e^+	227.4	-0.51	3.15	3.09	0	28.65	0.75
	μ^-	117.3	1.33	5.69	1.15	0	174.66	1.00
	μ^+	51.9	1.26	2.17	0.72	0	5.13	0.92
1644425191	jet	152.7	1.53	5.27				
	jet	108.8	2.23	5.03				
	jet	77.4	-1.74	2.25				
	jet	76.4	-1.25	4.30				
	jet	38.5	-1.42	1.65				
	jet	38.0	-1.67	3.88				
	jet	35.1	-0.92	1.09				
	μ^+	60.2	-0.55	1.39	1.08	0	14.88	0.85
	e^-	30.2	-0.88	0.52	0.90	0.06	7.58	0.91
	μ^-	15.5	0.43	2.55	1.09	0	9.02	1.05
2580593845	jet	155.8	-0.71	5.08				
	jet	75.4	0.67	0.07				
	jet	64.2	-0.88	4.45				
	jet	37.7	0.63	5.70				
	jet	36.8	-1.64	1.35				
	jet	36.1	0.45	1.69				
	μ^+	67.2	1.90	2.27	0.94	0	20.22	0.95
	μ^-	31.7	0.56	2.33	0.55	0.06	2.12	0.84
	e^+	19.7	-0.11	4.18	1.98	0	3.47	0.86
585686292	jet	528.4	-0.01	3.63				
	jet	449.5	1.33	0.75				
	jet	71.2	0.32	6.02				
	jet	48.3	-0.42	5.38				
	jet	39.6	1.57	3.50				
	jet	31.3	-1.31	1.87				
	μ^+	331.2	0.91	0.14	0.81	0	108.07	0.98
	μ^-	112.8	-0.38	3.28	0.71	0	26.87	0.98
	μ^+	22.0	-1.45	5.67	1.56	0	3.90	0.81
1295612941	jet	1255.5	-0.13	3.08				
	jet	128.1	0.30	6.00				
	jet	69.6	1.01	5.70				
	jet	46.8	-1.41	3.22				
	jet	38.4	0.34	3.61				
	jet	33.2	1.60	4.27				
	μ^+	488.8	0.62	0.09	0.14	0	123.56	0.60
	μ^+	132.5	0.28	4.97	1.22	0	20.61	0.95
	μ^-	18.8	0.72	4.84	0.90	0.05	6.66	0.85

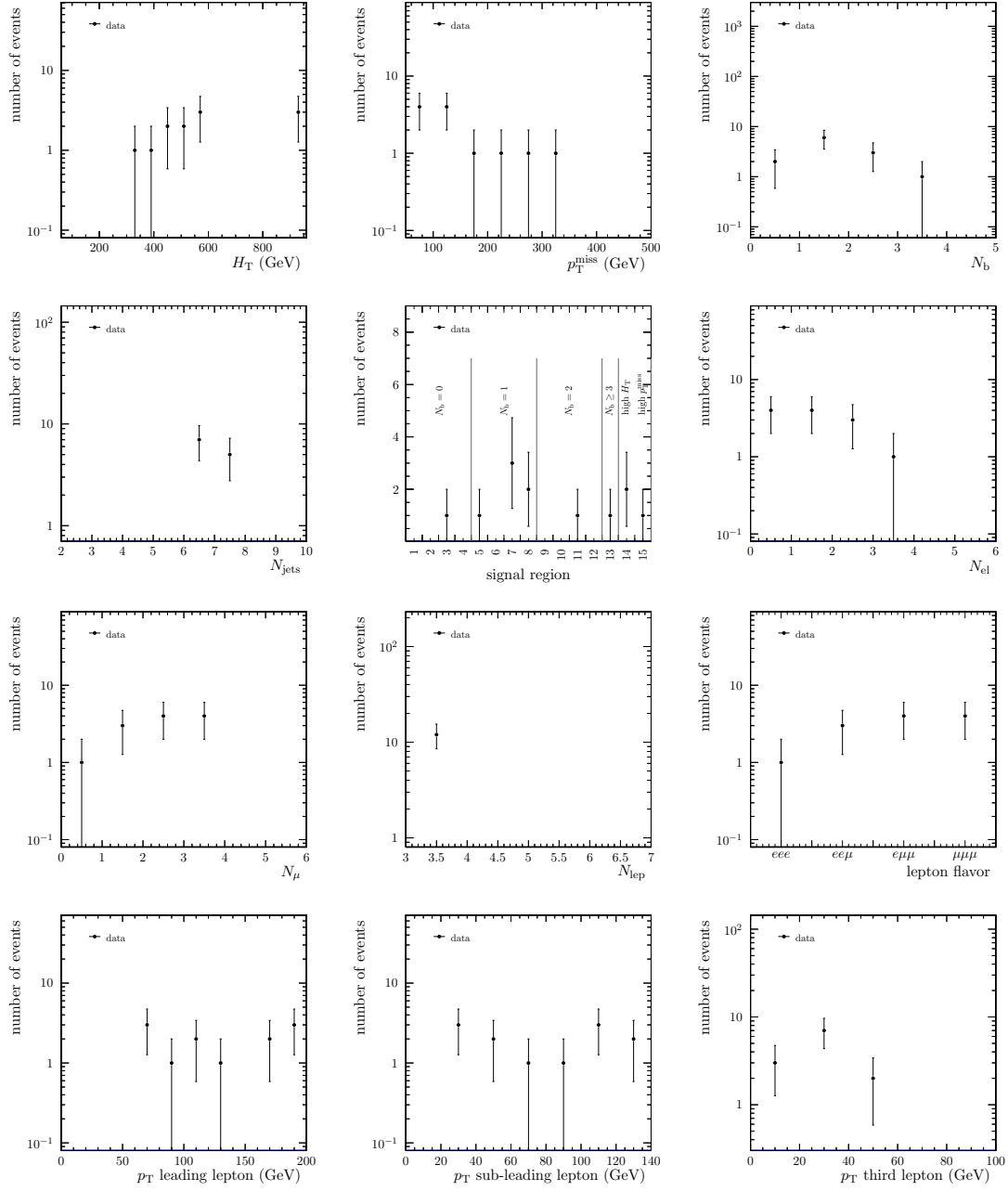


Figure E.3: Distribution of the twelve off-Z events with $N_{\text{jets}} \geq 6$ in other event observables and in the 15 off-Z signal regions.

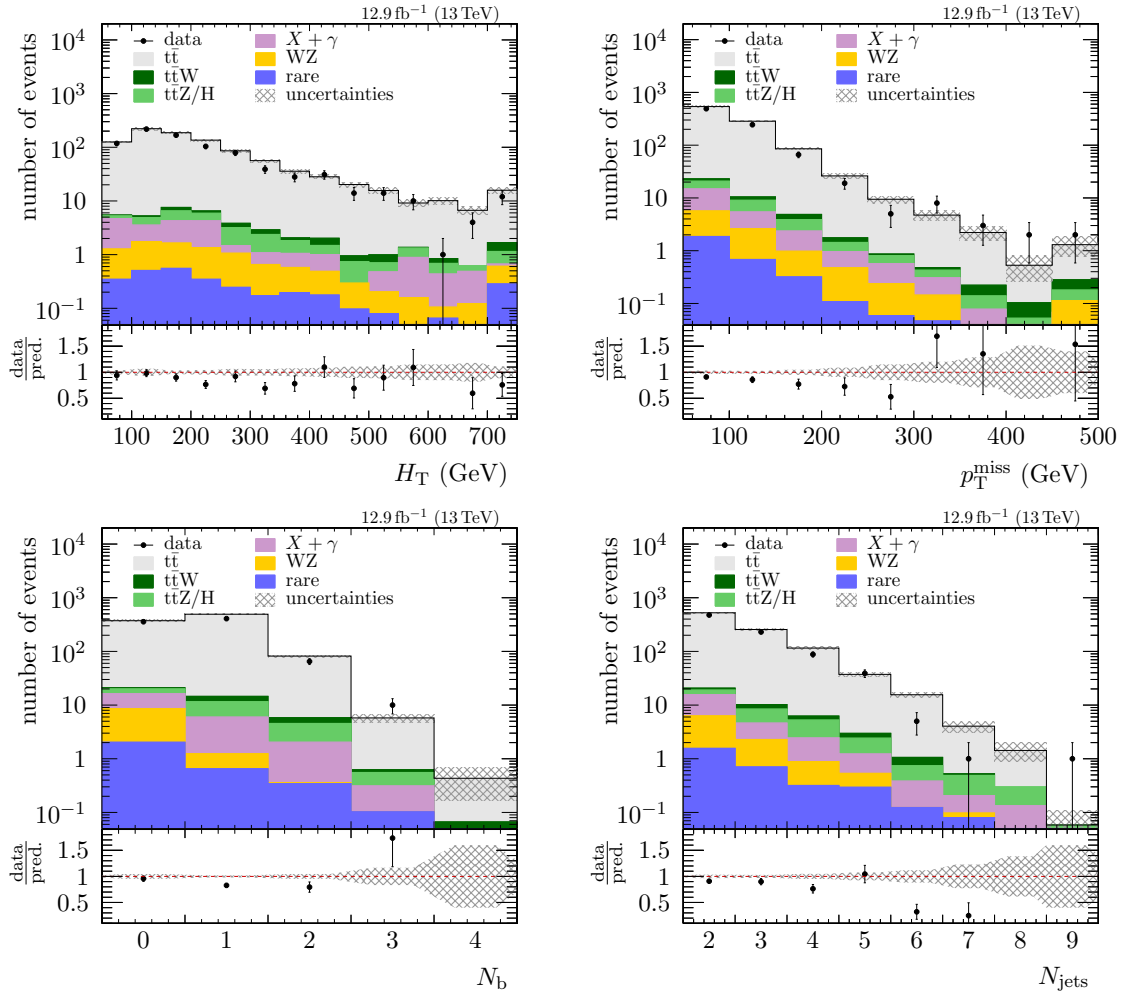


Figure E.4: Data–Monte Carlo comparison in the application region of the off-Z baseline selection. The contribution from nonprompt leptons to the application region is estimated with a MADGRAPH5 simulation of $t\bar{t}$ events. A good agreement between data and the simulation is observed for the event observables H_T , p_T^{miss} , and N_b , which are used for signal region categorization. The N_{jets} distribution, however, shows a pronounced discrepancy between data and simulation for $N_{\text{jets}} \geq 6$ and suggests an underfluctuation of events with high jet multiplicities in the application region. Such an underfluctuation could explain the observed discrepancy between data and the background prediction in the corresponding bins of the off-Z baseline region (c.f. Figure 9.3).

F Result table split by background sources

Table F.9 shows a breakdown of the total background prediction presented in Tables 9.1 and 9.2 by different SM background sources for all 32 signal regions considered in the presented analysis. The statistical and systematic uncertainties are represented as $\pm\text{stat} \pm\text{syst}$. The second-last column of the table shows the total background prediction, which can be compared to the number of events observed in data shown in the last column.

Table F.9: Observed number of events and standard model background prediction split by different background categories in all 32 signal regions for 12.9 fb^{-1} of data. Uncertainties on the prediction are given as $\pm\text{stat} \pm\text{syst}$.

Selection	SR	Rare	WZ	X+ γ	t $\bar{t}$ Z/H	t $\bar{t}$ W	Nonprompt	Exp.	Obs.
off-Z	SR 1	$3.6 \pm 0.3^{+1.9}_{-1.9}$	$17.8 \pm 0.7^{+5.1}_{-4.9}$	$1.9 \pm 1.0^{+1.1}_{-1.0}$	$4.0 \pm 0.1^{+0.8}_{-0.8}$	$1.9 \pm 0.0^{+0.5}_{-0.5}$	$39.8 \pm 4.7^{+12.0}_{-12.0}$	$69.0 \pm 4.9^{+13.5}_{-13.4}$	74
	SR 2	$0.5 \pm 0.1^{+0.3}_{-0.3}$	$2.3 \pm 0.3^{+0.7}_{-0.6}$	$0.1 \pm 0.1^{+0.0}_{-0.1}$	$0.8 \pm 0.0^{+0.2}_{-0.2}$	$0.5 \pm 0.0^{+0.1}_{-0.1}$	$5.9 \pm 1.7^{+1.8}_{-1.8}$	$10.2 \pm 1.7^{+2.0}_{-2.0}$	8
	SR 3	$0.4 \pm 0.1^{+0.2}_{-0.2}$	$1.6 \pm 0.2^{+0.5}_{-0.5}$	-	$0.6 \pm 0.0^{+0.1}_{-0.1}$	$0.2 \pm 0.0^{+0.1}_{-0.1}$	$3.0 \pm 1.1^{+0.9}_{-0.9}$	$5.8 \pm 1.1^{+1.1}_{-1.1}$	8
	SR 4	$0.2 \pm 0.0^{+0.1}_{-0.1}$	$0.8 \pm 0.2^{+0.2}_{-0.2}$	-	$0.2 \pm 0.0^{+0.0}_{-0.0}$	$0.1 \pm 0.0^{+0.0}_{-0.0}$	$0.4 \pm 0.2^{+0.1}_{-0.1}$	$1.8 \pm 0.3^{+0.3}_{-0.3}$	3
	SR 5	$1.3 \pm 0.1^{+0.7}_{-0.6}$	$1.3 \pm 0.2^{+0.4}_{-0.4}$	$0.3 \pm 0.2^{+0.2}_{-0.2}$	$8.5 \pm 0.1^{+1.7}_{-1.7}$	$4.8 \pm 0.1^{+1.2}_{-1.2}$	$50.4 \pm 5.0^{+15.2}_{-15.2}$	$66.7 \pm 5.0^{+15.4}_{-15.4}$	73
	SR 6	$0.2 \pm 0.0^{+0.1}_{-0.1}$	$0.3 \pm 0.1^{+0.1}_{-0.1}$	-	$1.6 \pm 0.0^{+0.3}_{-0.3}$	$1.2 \pm 0.0^{+0.3}_{-0.3}$	$3.3 \pm 0.8^{+1.0}_{-1.0}$	$6.6 \pm 0.8^{+1.2}_{-1.2}$	7
	SR 7	$0.2 \pm 0.0^{+0.1}_{-0.1}$	$0.2 \pm 0.1^{+0.1}_{-0.1}$	$0.1 \pm 0.1^{+0.1}_{-0.1}$	$1.4 \pm 0.0^{+0.3}_{-0.3}$	$0.6 \pm 0.0^{+0.2}_{-0.2}$	$3.5 \pm 1.2^{+1.0}_{-1.0}$	$6.0 \pm 1.2^{+1.1}_{-1.1}$	8
	SR 8	$0.1 \pm 0.0^{+0.1}_{-0.1}$	$0.2 \pm 0.1^{+0.0}_{-0.0}$	$0.1 \pm 0.1^{+0.1}_{-0.1}$	$0.6 \pm 0.0^{+0.1}_{-0.1}$	$0.4 \pm 0.0^{+0.1}_{-0.1}$	$0.6 \pm 0.3^{+0.2}_{-0.2}$	$1.9 \pm 0.3^{+0.3}_{-0.3}$	3
	SR 9	$0.3 \pm 0.0^{+0.2}_{-0.2}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.4 \pm 0.2^{+0.2}_{-0.2}$	$4.7 \pm 0.1^{+1.0}_{-1.0}$	$2.9 \pm 0.0^{+0.7}_{-0.7}$	$13.5 \pm 3.2^{+4.1}_{-4.1}$	$21.8 \pm 3.2^{+4.3}_{-4.3}$	23
	SR 10	$0.1 \pm 0.0^{+0.0}_{-0.0}$	-	$0.1 \pm 0.1^{+0.1}_{-0.1}$	$0.8 \pm 0.0^{+0.2}_{-0.2}$	$0.7 \pm 0.0^{+0.2}_{-0.2}$	$0.4 \pm 0.2^{+0.1}_{-0.1}$	$2.0 \pm 0.3^{+0.3}_{-0.3}$	1
	SR 11	$0.1 \pm 0.0^{+0.1}_{-0.1}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.1 \pm 0.1^{+0.1}_{-0.1}$	$0.9 \pm 0.0^{+0.2}_{-0.2}$	$0.3 \pm 0.0^{+0.1}_{-0.1}$	$1.5 \pm 1.2^{+0.4}_{-0.4}$	$3.0 \pm 1.2^{+0.5}_{-0.5}$	4
	SR 12	$0.1 \pm 0.0^{+0.0}_{-0.0}$	-	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.4 \pm 0.0^{+0.1}_{-0.1}$	$0.2 \pm 0.0^{+0.1}_{-0.1}$	$0.3 \pm 0.2^{+0.1}_{-0.1}$	$0.9 \pm 0.2^{+0.1}_{-0.1}$	1
	SR 13	$0.2 \pm 0.0^{+0.1}_{-0.1}$	-	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.6 \pm 0.0^{+0.1}_{-0.1}$	$0.1 \pm 0.0^{+0.0}_{-0.0}$	$1.6 \pm 1.0^{+0.5}_{-0.5}$	$2.6 \pm 1.0^{+0.5}_{-0.5}$	1
	SR 14	$0.9 \pm 0.1^{+0.4}_{-0.5}$	$1.1 \pm 0.2^{+0.3}_{-0.3}$	$0.1 \pm 0.1^{+0.1}_{-0.1}$	$1.9 \pm 0.0^{+0.6}_{-0.6}$	$0.9 \pm 0.0^{+0.3}_{-0.3}$	$2.4 \pm 1.1^{+0.7}_{-0.7}$	$7.2 \pm 1.1^{+1.3}_{-1.2}$	12
	SR 15	$0.3 \pm 0.1^{+0.2}_{-0.2}$	$0.9 \pm 0.2^{+0.3}_{-0.3}$	$0.1 \pm 0.1^{+0.0}_{-0.0}$	$0.5 \pm 0.0^{+0.1}_{-0.1}$	$0.4 \pm 0.0^{+0.1}_{-0.1}$	$3.2 \pm 1.5^{+1.0}_{-1.0}$	$5.5 \pm 1.5^{+1.0}_{-1.1}$	6
on-Z	SR 1	$10.7 \pm 0.4^{+5.5}_{-5.5}$	$77.2 \pm 1.6^{+21.4}_{-21.7}$	$0.9 \pm 0.7^{+0.5}_{-0.9}$	$7.8 \pm 0.1^{+1.8}_{-1.8}$	$0.3 \pm 0.0^{+0.1}_{-0.1}$	$14.8 \pm 2.9^{+4.5}_{-4.5}$	$111.8 \pm 3.4^{+23.4}_{-23.8}$	110
	SR 2	$2.2 \pm 0.2^{+1.2}_{-1.2}$	$15.3 \pm 0.7^{+4.4}_{-4.2}$	$0.1 \pm 0.1^{+0.0}_{-0.0}$	$2.2 \pm 0.0^{+0.5}_{-0.5}$	$0.1 \pm 0.0^{+0.0}_{-0.0}$	$2.8 \pm 1.6^{+0.9}_{-0.9}$	$22.7 \pm 1.7^{+4.8}_{-4.7}$	24
	SR 3	$2.1 \pm 0.2^{+1.1}_{-1.1}$	$12.6 \pm 0.6^{+3.4}_{-3.4}$	-	$1.5 \pm 0.0^{+0.4}_{-0.4}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$2.2 \pm 0.6^{+0.7}_{-0.7}$	$18.5 \pm 0.9^{+3.8}_{-3.8}$	26
	SR 4	$0.6 \pm 0.1^{+0.3}_{-0.3}$	$5.1 \pm 0.4^{+1.4}_{-1.4}$	-	$0.5 \pm 0.0^{+0.1}_{-0.1}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$1.0 \pm 1.0^{+0.3}_{-0.3}$	$7.3 \pm 1.1^{+1.5}_{-1.5}$	8
	SR 5	$5.3 \pm 0.2^{+2.7}_{-2.7}$	$6.5 \pm 0.4^{+1.8}_{-1.8}$	$0.1 \pm 0.1^{+0.1}_{-0.0}$	$16.1 \pm 0.1^{+3.5}_{-3.6}$	$0.8 \pm 0.0^{+0.2}_{-0.2}$	$9.8 \pm 1.6^{+3.0}_{-3.0}$	$38.7 \pm 1.7^{+6.2}_{-6.2}$	37
	SR 6	$1.1 \pm 0.1^{+0.6}_{-0.6}$	$1.2 \pm 0.2^{+0.3}_{-0.4}$	$0.1 \pm 0.1^{+0.0}_{-0.0}$	$3.9 \pm 0.0^{+0.9}_{-0.9}$	$0.3 \pm 0.0^{+0.1}_{-0.1}$	$0.6 \pm 0.4^{+0.2}_{-0.2}$	$7.2 \pm 0.4^{+1.3}_{-1.3}$	9
	SR 7	$0.9 \pm 0.1^{+0.5}_{-0.5}$	$1.5 \pm 0.2^{+0.4}_{-0.4}$	-	$3.8 \pm 0.0^{+0.9}_{-0.9}$	$0.1 \pm 0.0^{+0.0}_{-0.0}$	$0.9 \pm 0.4^{+0.3}_{-0.3}$	$7.3 \pm 0.5^{+1.2}_{-1.2}$	11
	SR 8	$0.3 \pm 0.0^{+0.1}_{-0.1}$	$0.6 \pm 0.1^{+0.2}_{-0.2}$	-	$1.1 \pm 0.0^{+0.3}_{-0.2}$	$0.1 \pm 0.0^{+0.0}_{-0.0}$	$0.6 \pm 0.4^{+0.2}_{-0.2}$	$2.6 \pm 0.4^{+0.4}_{-0.4}$	2
	SR 9	$2.1 \pm 0.1^{+1.1}_{-1.1}$	$0.5 \pm 0.1^{+0.1}_{-0.1}$	-	$12.5 \pm 0.1^{+2.8}_{-2.8}$	$0.7 \pm 0.0^{+0.2}_{-0.2}$	$2.6 \pm 1.1^{+0.8}_{-0.8}$	$18.4 \pm 1.2^{+3.3}_{-3.3}$	19
	SR 10	$0.2 \pm 0.0^{+0.1}_{-0.1}$	$0.2 \pm 0.1^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$1.8 \pm 0.0^{+0.4}_{-0.4}$	$0.1 \pm 0.0^{+0.0}_{-0.0}$	$0.4 \pm 0.3^{+0.1}_{-0.1}$	$2.8 \pm 0.3^{+0.5}_{-0.5}$	3
	SR 11	$0.4 \pm 0.0^{+0.2}_{-0.2}$	$0.1 \pm 0.1^{+0.0}_{-0.1}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$2.6 \pm 0.0^{+0.6}_{-0.6}$	$0.1 \pm 0.0^{+0.0}_{-0.0}$	$0.4 \pm 0.2^{+0.1}_{-0.1}$	$3.6 \pm 0.2^{+0.7}_{-0.7}$	3
	SR 12	$0.1 \pm 0.0^{+0.1}_{-0.1}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	-	$0.7 \pm 0.0^{+0.2}_{-0.2}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.3}_{-0.0}$	$0.9 \pm 0.0^{+0.2}_{-0.2}$	1
	SR 13	$0.2 \pm 0.0^{+0.1}_{-0.1}$	$0.1 \pm 0.1^{+0.0}_{-0.0}$	-	$1.5 \pm 0.0^{+0.4}_{-0.4}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.2 \pm 0.1^{+0.0}_{-0.0}$	$2.0 \pm 0.1^{+0.4}_{-0.4}$	1
	SR 14a	$1.9 \pm 0.1^{+1.0}_{-1.0}$	$5.9 \pm 0.4^{+1.6}_{-1.6}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$2.7 \pm 0.0^{+1.8}_{-1.8}$	$0.1 \pm 0.0^{+0.0}_{-0.0}$	$2.0 \pm 1.3^{+0.6}_{-0.6}$	$12.6 \pm 1.4^{+2.8}_{-2.8}$	12
	SR 14b	$0.8 \pm 0.1^{+0.4}_{-0.4}$	$3.4 \pm 0.3^{+1.0}_{-1.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$1.2 \pm 0.0^{+0.8}_{-0.8}$	$0.1 \pm 0.0^{+0.0}_{-0.0}$	$1.1 \pm 1.0^{+0.3}_{-0.3}$	$6.7 \pm 1.1^{+1.5}_{-1.5}$	5
	SR 15a	$0.4 \pm 0.1^{+0.2}_{-0.2}$	$1.3 \pm 0.2^{+0.4}_{-0.4}$	-	$0.5 \pm 0.0^{+0.1}_{-0.1}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.3}_{-0.0}$	$2.2 \pm 0.2^{+0.5}_{-0.5}$	5
	SR 15b	$0.6 \pm 0.1^{+0.3}_{-0.3}$	$3.7 \pm 0.3^{+1.0}_{-1.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.6 \pm 0.0^{+0.3}_{-0.3}$	$0.1 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.3}_{-0.0}$	$5.1 \pm 0.4^{+1.2}_{-1.2}$	7

Appendix – Part II

G Readout chip and single chip module samples

Figure G.5 (a) shows a close-up photograph of a single-chip module (SCM) sample after irradiation to 4.2 MGy. The almost square-shaped dark component in the middle of the picture is the silicon sensor, which is connected to the high-voltage sensor bias with the three wire-bonds at its lower right corner. The ROC controller and interface block (RCI) of the ROC extends for about 1 mm past the lower edge of the sensor. Its pads for input and output signals, supply voltages, and ground connections are wirebonded to the printed circuit board (PCB) to allow connecting them to the digital test board (DTB) via a custom-made adapter and a 33-pin ribbon cable, which is shown in Figure G.5 (b). The discolored area around the sample itself indicates the part of the PCB that has been exposed to the 23 MeV proton beam during the irradiation of the sample. The remainder of the PCB has been shielded by an aluminum plate with cutouts for the samples (c.f. Figure 15.4).

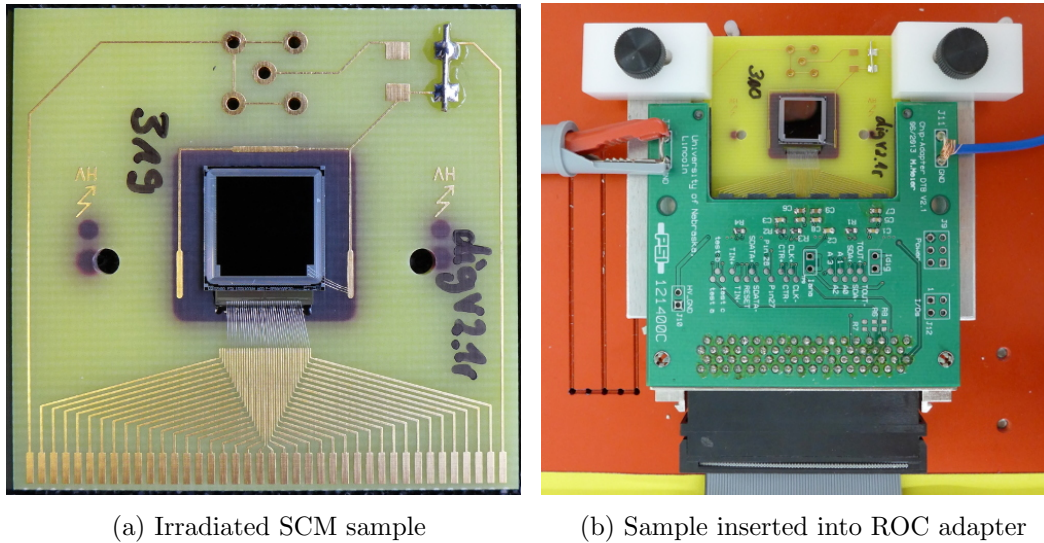


Figure G.5: Photograph of one of the tested SCM samples after irradiation to 4.2 MGy (a). In order to connect the sample to the DAQ system, the sample holding PCB is inserted into an adapter to connect it to the digital test board via a 33-pin ribbon cable (b).

Figure G.6 shows photographs of the irradiated SCM (top) and ROC samples (bottom) that have been investigated in the present thesis. All samples feature the final version of the layer 2–4 ROC *PSI46digV2.1respin*. While the SCM samples have been glued onto the sample holding PCB, the ROCs without sensor are fixed with Kapton foil to relieve the wire-bond connections from mechanical strain. The accumulated irradiation doses are indicated at the lower edge of the photographs.

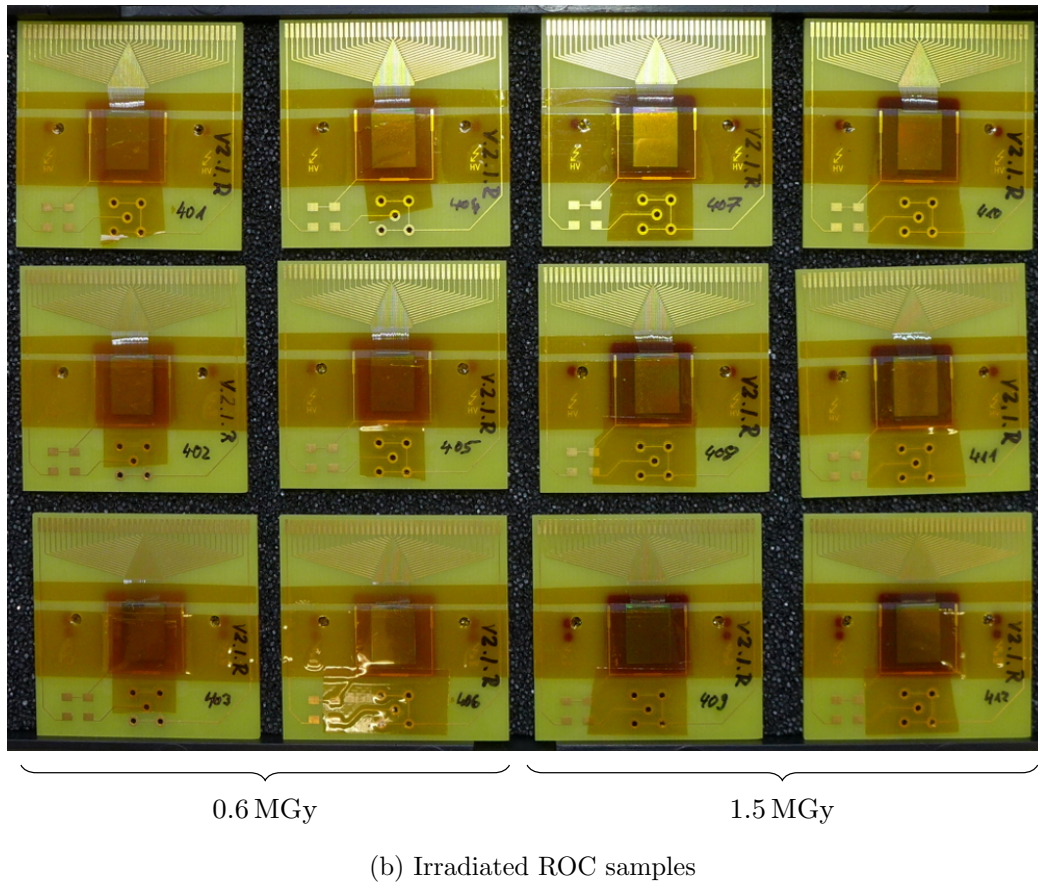
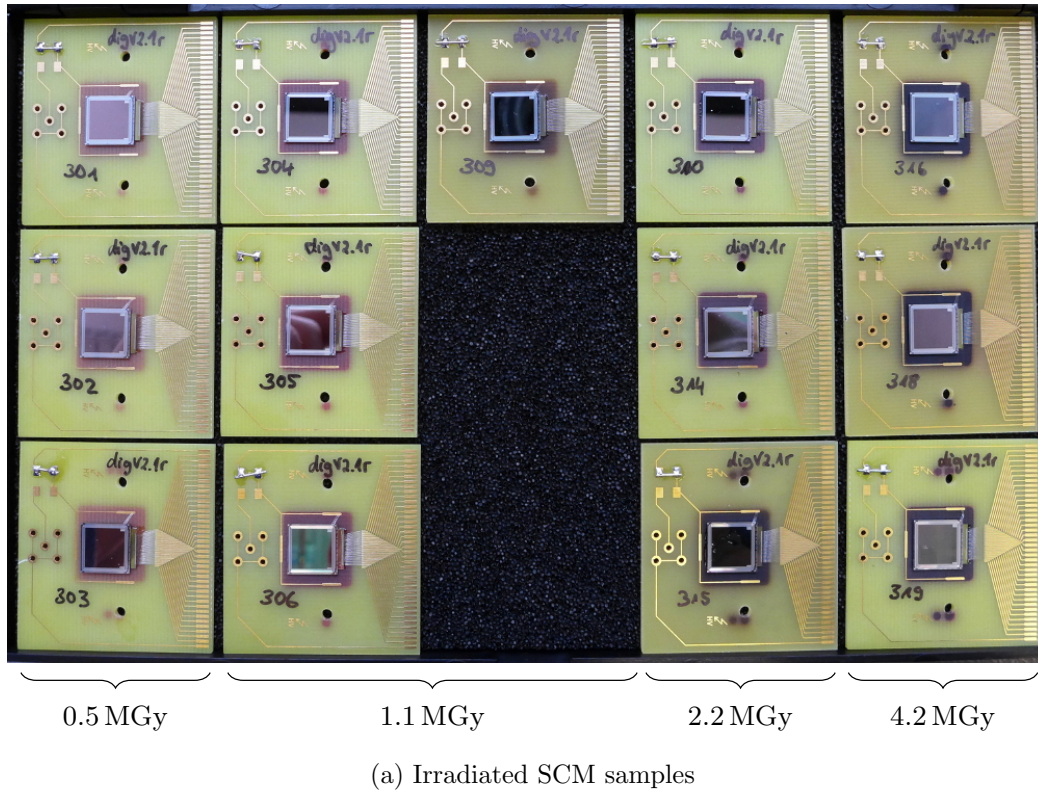
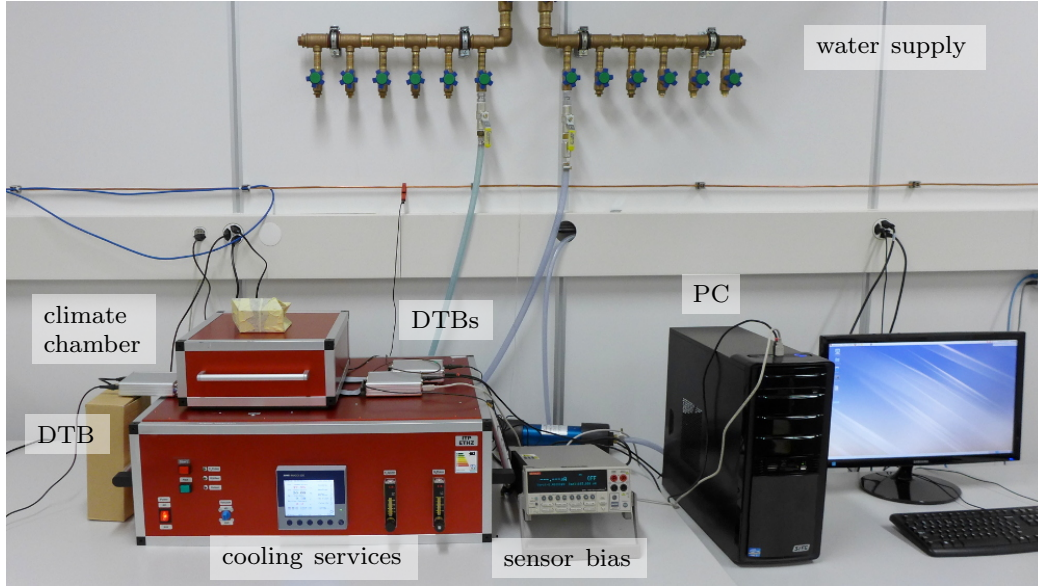
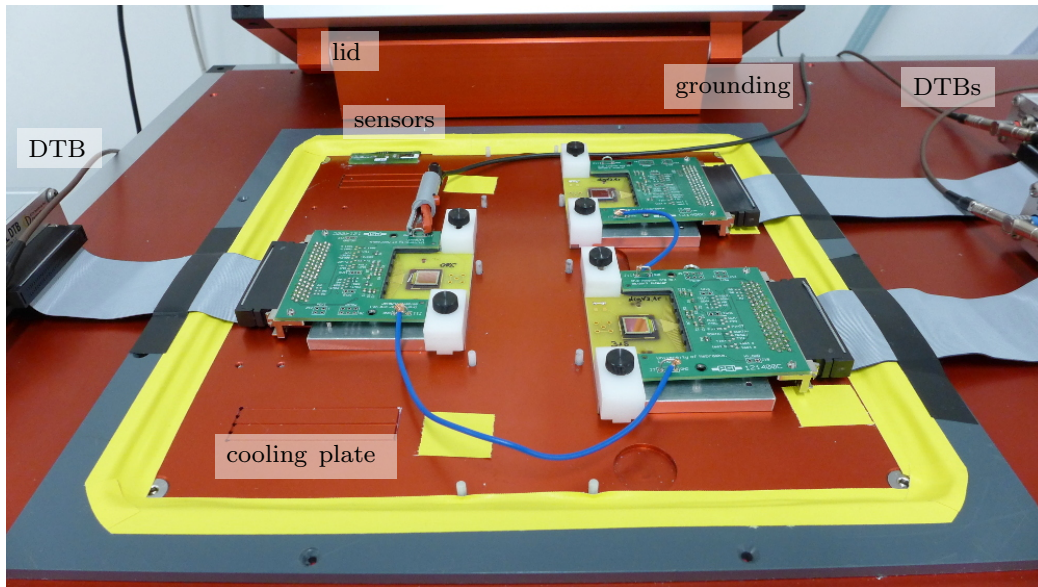


Figure G.6: Photographs of irradiated single chip module samples (a) and readout chip samples (b). The sample holding PCB exhibits a clearly visible discoloration after being exposed to the 23 MeV proton beam. The doses accumulated by the respective samples are indicated at the bottom of the pictures.

H Climate chamber setup



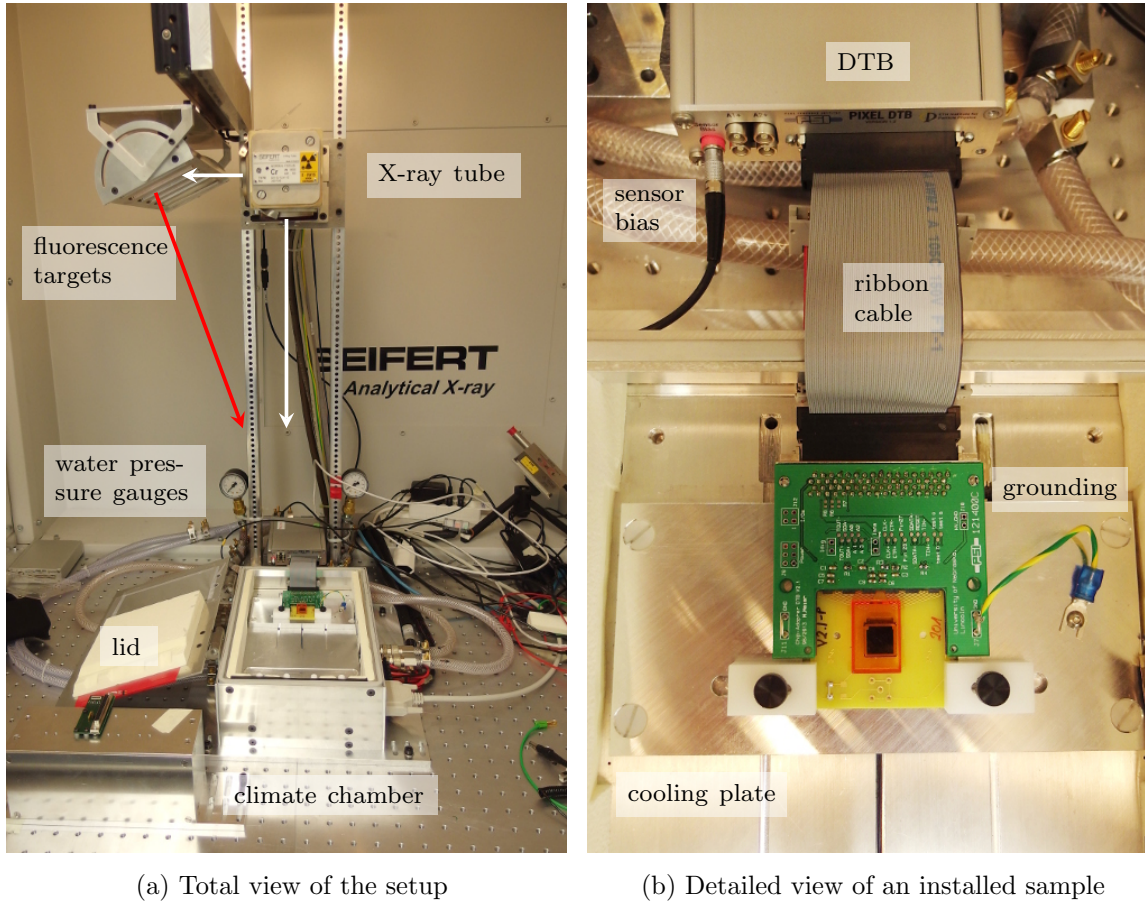
(a) Total view of the setup



(b) Detailed view of the cooling plate with three SCM samples

Figure H.7: Photographs of the climate chamber setup. The climate chamber itself and the associated services for cooling and dry air supply are hosted in the small and big red box, respectively (a). Additionally, three digital test boards in their aluminum casings, a power supply that provides the sensor bias voltage, and a PC for running the readout software can be seen. The hoses in the background provide water for cooling the hot side of the thermoelectric elements, which stabilize the temperature of the cooling plate. Within the climate chamber, three samples are installed (b). The aluminum sockets underneath the samples provide thermal contact to the cooling plate and the ROC adapters are connected to ground potential through the connection with the clamp and the blue cable. The green PCB in the upper left corner of the cooling plate hosts a temperature and a humidity sensor.

I X-ray test stand



(a) Total view of the setup

(b) Detailed view of an installed sample

Figure I.8: Photographs of the X-ray test stand. The device under test is hosted in the aluminum box, shown in the lower part of Figure (a), which serves as a climate chamber. Its temperature is stabilized by thermoelectric cooling and the testing volume is flushed with dry air to prevent condensation. The lid of the climate chamber features a window covered with thin aluminum foil, which seals the testing volume while minimizing the absorption of the incident X-radiation generated by a 1.8 kW X-ray tube, which is installed above the climate chamber. The electron retardation spectrum of the tube can be directed either directly onto the sample, or onto one of the X-ray fluoresce targets that are installed on a movable holder on the left-hand side of the X-ray tube. Monochromatic X-radiation emitted by these targets is used for charge calibrations of the readout chip. Hoses and cables that connect to the climate chamber provide cooling water and power to the thermoelectric elements and serve to read out the temperature and humidity sensors of the climate chamber. The connection of the sample (here an non-irradiated sample with a protection cap) to the digital test board via the ROC adapter and a 33-pin ribbon cable is identical as in the climate chamber setup (b).

J ROC and DTB operation parameters

Table J.10 lists DAC settings and supply voltages used to operate the ROCs before and after irradiation to various dose levels. The second column of the table presents the DAC settings corresponding to the low-power start-up mode of the ROC, while the third column indicates the pre-irradiation settings in the nominal mode of operation. DAC settings that are optimized on a per-chip level are presented as mean $\pm$ standard deviation of the setting of all tested samples at a given dose. Settings that have not been modified after irradiation are omitted from columns indicating the post-irradiation values. Their respective pre-irradiation value as listed in the third column also applies after irradiation.

Table J.10: ROC operation parameters and supply voltages in the low-power mode and in the nominal mode of operation before and after irradiation to doses between 0.5 MGy and 4.2 MGy.

	Low-power	0 MGy	0.5 MGy	1.1 MGy	1.5 MGy	2.2 MGy	4.2 MGy
VDIG	15	6	6	15	15	15	15
VANA	0	87.2 ± 8.8	70.6 ± 7.4	76.5 ± 13.2	61.0 ± 7.2	73.7 ± 4.6	60.3 ± 8.3
VSH	0	30					
VCOMP	0	12					
VWLLPr	255	220					
VWLLSh	255	220	60	10	10	0	0
VHLDDEL	0	250					
VTRIM	0	118.1 ± 14.2	100.3 ± 18.0	133.3 ± 27.3	105.0 ± 16.8	157.3 ± 18.3	187.7 ± 55.5
VTHRComp	0	77.1 ± 7.1	51.9 ± 12.4	51.5 ± 15.0	60.5 ± 13.8	46.7 ± 4.9	158.3 ± 80.5
VIBIASBUS	0	30					
PHOFFSET	0	135.2 ± 7.1	132.6 ± 9.0	101.0 ± 63.9	-	-	-
VCOMPADC	0	50					
PHSCALE	0	116.1 ± 6.4	59.7 ± 22.0	41.0 ± 38.5	-	-	-
VICOLOR	0	100					
CALDEL	0	129.6 ± 11.7	141.7 ± 11.9	137.3 ± 21.0	133.8 ± 14.7	137.3 ± 11.7	124.0 ± 36.6
WBC	0	100					
V_A (V)	1.6	1.6	1.6	1.6	1.6	1.7	1.8
V_D (V)	2.4	2.4	2.4	2.5	2.5	2.5	2.5

Table J.11 shows the delay settings for the DTB, used to read out ROC and SCM samples before and after irradiation. Shown are the additional delay between successive executions of the pattern generator loop D_{PG} (c.f. Section 15.4.1) and delays which are used to adjust the relative phases of the clock, the control, trigger, reset (CTR), the SDA, and the token-in signals of the DTB. The deser160phase setting allows to adjust the sampling point of the 160 Mbit/s data stream of the ROC in the DTB.

Table J.11: Delay settings in the digital test board used for reading out ROC and SCM samples before and after irradiation. All delays except D_{PG} are given in units of one eighth of a 25 ns clock cycle.

Delay	0 MGy	0.5 MGy	1.1 MGy	1.5 MGy	2.2 MGy	4.2 MGy
D_{PG} (clk cycles)	0	0	50	50	200	600
clk	4			1		
ctr	4			1		
sda	19			16		
tin	9			6		
deser160phase	4			4		

The following bullet list briefly recapitulates the reasons for the respective dose dependent change of the operation parameters listed in Tables J.10 and J.11.

- The increase of V_{DIG} maximizes the hit detection efficiency under high rate and mitigates the radiation induced limitation in the pulse height (PH) sampling ADC.
- The readjustment of V_{ANA} serves to maintain $I_{ana} = 24\text{ mA}$ after the radiation induced drift of band gap reference voltage increased the output of the current regulator.
- Lowering of V_{WLLSH} counteracts the radiation induced increase of the recovery time of the pulse shaper in the pixel unit cell after processing a pulse.
- Modified $V_{THRCOMP}$ and V_{TRIM} values correspond to the settings obtained after re-optimizing the pixel threshold after irradiation. In particular the lowering of the $V_{THRCOMP}$ settings has to be considered to prevent a too pronounced drop of the threshold after irradiation.
- Re-optimizing the response of the PH sampling ADC after irradiation entails a dose dependent variation of the PH_{OFFSET} and PH_{SCALE} DAC settings. No values are reported for doses beyond 1.1 MGy since the radiation induced limitation of the PH ADC can no longer be mitigated by increasing the digital voltage. The resulting binary readout of the ROC renders an optimization of the PH DACs obsolete.
- Slightly increased $CALDEL$ settings after irradiation are related to the drift of the band gap reference voltage, leading to a change of the test pulse delay of about 10%.
- Elevated analog supply voltages are required to achieve $I_{ana} = 24\text{ mA}$ for highly irradiated samples because of the dose dependent increase of the drop-out voltage of the V_{ANA} regulator.
- The elevation of the digital supply voltage by 100 mV is required after irradiation to a dose of 1.1 MGy to maximize the response efficiency to test pulse injections under high hit rates and to mitigate the limitation in the PH ADC.
- The dose dependent increase of the D_{PG} delay is required to allow the pulse shaper to recover between successive test pulse injection once the V_{WLLSH} DAC setting hits the lower limit of its adjustable range.
- The relative phase of the clock signal generated by the DTB has to be shifted by $3/8$ of a 25 ns clock cycle to read out irradiated samples. The phases of the CTR, the SDA, and the token-in signals are adjusted accordingly. No modification is required for the `deser160phase` setting.

List of Acronyms

ADC analog-to-digital converter

ATLAS A Toroidal LHC Apparatus

BPix barrel pixel detector

BSM beyond the standard model

CCE charge collection efficiency

CERN European Organization for Nuclear Research

CKM Cabibbo-Kobayashi-Maskawa

CMOS complementary metal-oxide semiconductor

CMS Compact Muon Solenoid

cMSSM constraint minimal supersymmetric standard model

CTR control, trigger, reset

DAC digital-to-analog converter

DAQ data acquisition

DCCD dynamic cluster column drain

DCI double column interface

DCol double column

DTB digital test board

DUT device under test

DY Drell-Yan

ECAL electromagnetic calorimeter

FEC front-end controller

FED front-end driver

FPix forward pixel detector

FSR final-state radiation

GMSB	gauge-mediated supersymmetry breaking
GUT	grand unified theory
HCAL	hadronic calorimeter
HDI	high-density interconnect
HL-LHC	High-Luminosity Large Hadron Collider
HLT	high-level trigger
IC	integrated circuit
IP	interaction point
ISR	initial-state radiation
JEC	jet energy correction
L1	level-1
LEP	Large Electron-Positron Collider
LHC	Large Hadron Collider
LHE	Les Houches Event
LNT	loose-not-tight
LO	leading order
LS	long shutdown
LSP	lightest supersymmetric particle
MC	Monte Carlo
MIP	minimum ionizing particle
MOSFET	metal-oxide-semiconductor field-effect transistor
MSSM	minimal supersymmetric standard model
MSUGRA	minimal supergravity
MVA	multi-variate discriminant
NLO	next-to-leading order
nMSSM	next-to-minimal supersymmetric standard model
OSSF	opposite-sign, same-flavor
PCB	printed circuit board
PDF	parton distribution function
PF	particle-flow
PH	pulse height

PLL	phase-locked loop
PMSB	Planck-scale-mediated supersymmetry breaking
pMSSM	phenomenological minimal supersymmetric standard model
PS	Proton Synchrotron
PUC	pixel unit cell
QCD	quantum chromo dynamics
QED	quantum electro dynamics
QFT	quantum field theory
RCI	ROC controller and interface block
ROC	readout chip
S&H	sample-and-hold
SBC	select bunch crossing
SCM	single-chip module
SEU	single event upset
SM	standard model
SMS	simplified model spectrum
SPS	Super Proton Synchrotron
SR	signal region
SUSY	supersymmetry
TBM	token bit manager
TID	total ionizing dose
UE	underlying event
WBC	write bunch crossing
WIMP	weakly interacting massive particle

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