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Searches for Dark Matter and Large Extra Dimensions
in Monojet Final States with the ATLAS Experiment



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Abstract

This thesis presents searches for evidence for Weakly Interacting Massive Particles (WIMPs) and Extra Dimensions in proton-proton collisions recorded by the ATLAS experiment at the CERN Large Hadron Collider (LHC). The WIMP is one of the main candidates to constitute the particle content of Dark Matter. Extra Dimensions are introduced in several theories in order to explain the apparent weakness of gravity when compared to the other interactions in Nature. Theories with WIMPs as well as Extra Dimensions can manifest themselves at the LHC, with experimental signatures characterized by an energetic hadronic jet associated with large missing momentum. These signatures are known as monojet signatures, and are investigated in this thesis.

The first analysis is performed using $L = 20.3 \text{ fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$ recorded in the ATLAS Run 1. The second analysis is performed using $L = 3.2 \text{ fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ recorded in the ATLAS Run 2. No significant excess over the expected background is found in either of the analyses. New exclusion limits are set at 95% confidence level on Dark Matter particle production. New limits are also set on graviton production in the so-called ADD scenario with Extra Dimensions.

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Olle, May 2016

List of Acronyms

ADC	Analog to Digital Converter
ADD	Arkani-Hamed, Dimopolous, Dvali (authors)
BBN	Big Bang Nucleosynthesis
BLUE	Best Linear Unbiased Estimate
BSM	Beyond the Standard Model
CDM	Cold Dark Matter
CL, CL_s	Confidence Level, Modified Frequentist Confidence Level
CMB	Cosmic Microwave Background
CSC	Cathode Strip Chambers
DM	Dark Matter
EF	Event Filter
EFT	Effective Field Theory
EM	Electromagnetic
GUT	Grand Unified Theory
HDM	Hot Dark Matter
HFN	High Frequency Noise
HLT	High Level Trigger
HG	High Gain
ID	Inner Detector
JVT	Jet Vertex Tagger
L1 (L2)	Level 1 (Level 2) Trigger
LAr	Liquid Argon
LFN	Low Frequency Noise
LG	Low Gain
LH	Likelihood(-based identification)
LHC	Large Hadron Collider
LKP	Lightest Kaluza-Klein Particle
LO, NLO, NNLO	Leading Order, Next-to Leading Order, Next-to-Next-to Leading Order
LSP	Lightest Supersymmetric Particle
LVPS	Low Voltage Power Supply
MC	Monte Carlo
MDT	Monitored Drift Tube
ML	Maximum Likelihood
MS	Muon Spectrometer
MSSM	Minimal Supersymmetric Standard Model
NCB	Non Collision Background
OF	Optimal Filtering
pdf	Probability Density Function
PDF	Parton Distribution Function
PMT	Photo-Multiplier Tube
QCD	Quantum Chromodynamics
QED	Quantum Electrodynamics
RS	Randall, Sundrum (authors)
SCT	Semiconductor Tracker
SM	(the) Standard Model
SUSY	Supersymmetry
TileCal	Tile Calorimeter
TDAQ	Trigger and Data Acquisition
TRT	Transition Radiation Tracker
UED	Universal Extra Dimensions
WIMP	Weakly Interacting Massive Particle

Preface

Overview

The field of particle physics studies the properties and interactions of the smallest constituents of matter. The study of elementary particles is driven by fundamental questions concerning the basis of the physical world. Probing the smallest scales in Nature also contributes to our knowledge of the interactions of matter on the largest scales. Particle physics thus contributes not only to our understanding of the microscopic world, but also provides insights about the Universe itself - what it consists of, what it originated in and how it will evolve in the future.

One way of studying elementary particles is to construct particle accelerators. These allow particle interactions to take place at energies otherwise only associated with galactic scales. The accelerators open windows to observe the particle scale under the conditions that characterized the early Universe. Accelerators allow for large numbers of new particles to be produced in the lab, and for the fundamental interactions to reveal features yet unseen.

The Large Hadron Collider, located at the facilities of CERN, is the most powerful particle accelerator ever built, in terms of its center-of-mass energy and the number of collisions it produces. In 2015 it provided proton-proton collisions at the world record center-of-mass energy of 13 TeV, with a luminosity (a measure of the rate of particle collisions) close to $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The ATLAS detector is a general purpose detector located at one of the interaction points of the Large Hadron Collider beam. The goal of ATLAS is to make full use of the discovery potential offered by the collider, through the observation of the processes taking place at these unprecedented energies. ATLAS is designed to measure the energies and momenta of the produced particles, providing the information to calculate fundamental quantities such as their masses, charges

and spins. Through meticulous study of the measured particles, we may analyze the data from the detector in the search for new phenomena.

The current framework for understanding the particles on the elementary level is the so called Standard Model of particle physics. Since its first formulation in the late 1960's, it has been extensively tested, and proved to be exceptionally successful in terms of precise predictions of measurements subsequently made. However, a number of observations reveals phenomena that the Standard Model cannot explain. Two such phenomena calling for new physics beyond the Standard Model are its lack of a particle level description of gravity, and the fact that it offers no explanation to the abundance of Dark Matter in the Universe. The experimental tests of models that solve these problems of the Standard Model are the topic of this thesis.

The analysis of proton-proton collisions in the ATLAS detector producing a "monojet" final state with a highly energetic hadronic jet and large missing transverse momentum provides the opportunity to test several theories that could explain the relative weakness of gravity or the existence of Dark Matter. This thesis presents two analyses of ATLAS data in the search for such events, one using data recorded at 8 TeV center-of-mass energy in 2012, and one using data recorded at 13 TeV center-of-mass energy in 2015.

About This Thesis

This thesis contains data analysis and detector studies performed on data collected with the ATLAS detector.

Part I contains a theoretical overview of the physics and models tested in this thesis, as well as a review of the current experimental constraints on these models. Chapter 1 contains a description of the Standard Model. It describes the elementary particles and their interactions, and gives a brief introduction to the gauge theories used to derive the full theory. This chapter also contains a section highlighting a few selected problems in the Standard Model, motivating the searches for new physics. Chapter 2 is a more detailed review on theories targeting two specific problems within the Standard Model. The first subject is theories with large extra dimensions that make the gravitational interaction stronger. The second is the Dark Matter problem. The chapter reviews some of the theory behind models with Extra Dimensions or Dark Matter, and contains an overview of the experimental constraints from colliders, as well as from astrophysical observations.

In Part II the experimental facilities are described. Chapter 3 contains a description of the Large Hadron Collider, its run parameters and the conditions under which the measurements in the thesis are performed. It also describes the ATLAS experiment, its various subsystems and the data acquisition process. Chapter 4 gives a more detailed description of the ATLAS Tile Calorimeter, and presents a study of the electronic noise in this calorimeter. Chapter 5 describes particle reconstruction in ATLAS and how physical observables such as particle four-vectors are reconstructed using the energy deposition in the different detector subsystems. Finally Chapter 6 gives the basic principles of simulations of physics events, used to estimate backgrounds as well as signal yields from new physics models.

Part III is devoted to the searches for new physics with the monojet analysis. Chapter 7 introduces the analysis, the event selection criteria and the main Standard Model background processes. In Chapter 8 the simulations of background and signal for this analysis are described. Special emphasis is on the generation of the signal samples with the ADD Extra Dimensions model. Chapter 9 describes the data-driven methods used to estimate the Standard Model background yield. The main backgrounds come from the decay of Z and W bosons into leptons, and the main part of the chapter concerns the control regions constructed to estimate these backgrounds and how the results from the control regions are used.

Finally Part IV contains the comparison of the observed events to the background estimates. Chapter 10 includes these comparisons, along with the limits on new physics calculated from these results. Chapter 11 contains some general conclusions drawn from the thesis.

The author of this thesis is also the author of the following publications:

O. Lundberg on behalf of the ATLAS Collaboration, *The Calibration Systems of the ATLAS Tile Calorimeter*, in Proceedings of the XXXII International Symposium on Physics in Collision, 2013 [1].

O. Lundberg, *Studies of the TileCal Electronic Noise in 2011 and Early 2012 Data*, ATLAS internal note, CERN 2013.

The ATLAS Collaboration, *Search for New Phenomena in Final States with an Energetic Jet and Large Missing Transverse Momentum in pp Collisions at $\sqrt{s}=8$ TeV with the ATLAS Detector*, Eur. Phys. J. C. (2015), 75:299 [2].

The ATLAS Collaboration, *Search for New Phenomena in Final States with an Energetic Jet and Large Missing Transverse Momentum in pp Collisions at $\sqrt{s} = 13$ TeV Using the ATLAS Detector*. arXiv:1604.07773 [hep-ex] (2016). Submitted to Phys. Rev. D. [3]

The Author's Contribution

I started my work as an ATLAS doctoral student at Stockholm University, under the supervision of Docent Christophe Clément and Professor Barbro Åsman, in March 2011. My first task was to study the electronic noise of the Tile Calorimeter. My studies focused on the variations of noise levels over time and on comparisons of noise conditions in different parts of the calorimeter. My work also included a study of a specific hardware upgrade, the replacement of several Low Voltage Power Supplies of Tile Calorimeter modules. This was done as part of a larger detector performance related task, that of keeping the noise constants in the calorimeter conditions database up-to-date and accurate. This task also included producing accurate noise conditions for the Monte Carlo simulations of the detector. My work was to develop and run programs that produce noise constants from so called pedestal runs, which are dedicated no-beam measurements of the Tile Calorimeter. These studies are summarized in an internal note. Reference [1] includes some of my own noise studies, but as part of a larger presentation of the entire calibration procedure of the Tile Calorimeter. The results in Ref. [1] were presented on behalf of the ATLAS collaboration on the annual Physics in Collision conference held in Štrbské Pleso, Slovakia, in autumn 2012. Parts of this work are found in Chapter 4.

Since early 2013, my work has been dedicated to the analysis of physics data from the ATLAS detector, where I have contributed to the ATLAS monojet analysis and the search for new physics beyond the Standard Model. This work has led to two publications, Ref. [2] using the 8 TeV center-of-mass energy data from LHC Run 1, and Ref. [3] using the 13 TeV center-of-mass energy data from LHC Run 2.

In the analysis of 8 TeV data in Ref. [2] I was responsible for studying the control regions with electrons, as described in Chapter 9. My studies of the multi-jet contamination and electron isolation in the single electron control region led to the adoption of electron isolation criteria as suggested by me. Without such isolation criteria this region would not have been useful to the analysis due to the large systematic uncertainties associated with the multi-jet

background. As part of the Stockholm monojet group I also performed studies of the dielectron control region, and among other things established that these electrons did not need to be isolated. Furthermore I studied the systematic uncertainties associated with the top contamination in the single electron and single muon control regions, and found that they were larger than previously estimated. Lastly I contributed to the studies of control regions with muons where the Stockholm group provided independent cross-checks of results from other analyzers. This work is summarized in Part III of this thesis.

In the analysis of 13 TeV data in Ref. [3] I was responsible for the ADD Large Extra Dimensions signal model interpretation of the experimental analysis. I performed studies on the parameters used as input to the signal simulation to optimize them for the 13 TeV analysis. The use of optimized scale and mass parameters increased the simulation efficiency and improved the missing transverse momentum distribution in graviton production events. The results of these studies are found in Chapter 8. Furthermore I performed studies of how sensitive the analysis selection was to these signal models. These studies included evaluating the improvement when going from an optimized single signal region analysis like the one used in Run 1, to the shape analysis used in Run 2. I found that the sensitivity of our analysis to the ADD models increased when using a small amount of 13 TeV data, even when compared to the full 8 TeV dataset. These results were part of the motivation for performing the analysis with the data collected in 2015. I was also responsible for the calculation of limits on the model parameters for the different ADD signals. The numbers and the figure describing the limits in the paper were produced by me. I contributed to the studies of the electron definitions and the uncertainties associated with the diboson background. As part of the Stockholm group we independently implemented the full background analysis, working in tandem with other analyzers and performed and provided limit calculations for the paper. Thus all Run 2 background figures in Part III are produced using our analysis framework and are fully consistent with Ref. [3].

The thesis is based in part on my Licentiate thesis [4]. This applies in particular to Chapter 4 and Section 9.1.3, which contain shortened versions of similar texts in the Licentiate thesis. The parts of Chapter 3 that concern Run 1 are taken from the Licentiate thesis. Finally parts of Chapter 2 about Dark Matter are based on similar sections in the Licentiate thesis. This particularly applies to Secs. 2.3.1- 2.3.3.

Part I

Theory and Previous Research

...of a certainty there is yet above us some higher, purer region, whither thou dost surely purpose to lead me [...] some yet more spacious Space, some more dimensionable Dimensionality, from the vantage-ground of which we shall look down together upon the revealed insides of Solid things...

Edwin A. Abbot, *Flatlands*

Oh, don't get me started on gravity.

Phoebe Buffay, *Friends*

Chapter 1

The Standard Model of Particle Physics

1.1 Introduction

Elementary particle physics deals with the elementary constituents of matter and their interaction with each other. Which particles are considered elementary has so far in the history of science regularly been subject to evolution. As physicists gain deeper knowledge, perform more precise observations and develop the technology to conduct experiments at increasing energies or to cast light on obscure phenomena in previously unobserved galaxies, theories that previously described the known Universe become approximations, and new processes and particles become fundamental.

The best theoretical framework available to describe fundamental interactions in Nature is the Standard Model (SM) [5, 6, 7] of particle physics. The SM is a quantum field theory that explains all elementary microscopic processes using the properties and interactions between a limited number of elementary particles. This chapter shortly describes these elementary particles, their interactions, and finally points out the weaknesses within the model and the motivation for looking for physics beyond the SM (BSM). The derivations in this chapter follow those of Refs. [8, 9, 10]. Chapter 2 deals in more detail with some relevant BSM theories.

Throughout this thesis, unless otherwise stated, we operate with "natural" units [10], i.e. $c = \hbar = 1$. Once these units are fixed, many of the other basic physical quantities can now be expressed in units of energy, and we choose eV as this base unit. In natural units, mass and time have unit eV^{-1} .

1.2 Particles and Interactions - an Overview

In the framework of the SM, all matter in the visible Universe is made up of two kinds of elementary particles: *leptons* and *quarks*. These are assumed fundamental in the sense that they are treated as point-like and lacking underlying substructure. Both leptons and quarks are *fermions*, with half-integer spin. They interact through three different fundamental interactions: the *strong*, *weak* and *electromagnetic* interactions. Each of these interactions is associated with the exchange of spin-1 *gauge bosons*, or force carriers.

The gauge boson mediating the electromagnetic interaction is the photon, denoted by γ , coupling to all particles carrying electric charge. The photon is massless, and the electromagnetic interaction is therefore infinite in range.

The gauge bosons that mediate the weak interactions are the electrically charged $W^\pm$ bosons and the electrically neutral Z boson. These couple to the third component of weak isospin T_3 and the weak hypercharge Y , where the latter is a combination of electric charge and T_3 . Leptons and quarks only have $T_3 \neq 0$ if they are left-handed. At high energies the electromagnetic and weak interactions are combined into a single *electroweak* interaction.

The strong interaction is mediated by the *gluon*, which is massless. The charge corresponding to the strong interaction is called color, and comes in three color states called *green*, *red* and *blue*. The gluon is itself color charged, allowing it to self-interact. This has the effect that although the gluons are massless, the strong interaction is short-range. This is described in more detail in Sec. 1.4.

The strength with which the particles couple to the respective interactions is parametrized in terms of dimensionless *coupling* strengths, allowing comparisons between them.

The three fundamental interactions described by the SM are listed in Table 1.1 along with their respective mediator particle(s) and also their relative strength. The table also gives the fourth interaction observed in Nature, gravity, and the hypothetical corresponding mediator particle called a *graviton*. Gravity is not part of the SM, and this apparent short-coming is discussed in more detail in Sec. 1.6 and Chap. 2.

Both leptons and quarks exist in three different generations. Each generation of quarks consists of two quarks, one with electric charge $+2/3$ denoted as "up-type", and one with electric charge $-1/3$ denoted as "down-type". Left-handed up-type quarks have $T_3 = +1/2$ while left-handed down-type quarks have $T_3 = -1/2$. The right-handed quarks have $T = T_3 = 0$. The up-type quarks are the

Interaction	Mediator particle(s)	Relative strength
Strong	Gluon	1
Electromagnetic	Photon	10^{-2}
Weak	$W^\pm, Z$	10^{-6}
Gravity	Graviton	10^{-42}

Table 1.1: The four fundamental interactions of Nature. The strength of the interaction is given in relation to the strong interaction. The graviton is a hypothetical spin-2 quantum gravity mediator.

up (u), *charm* (c) and *top* (t) quarks, and the down-type quarks are the *down* (d), *strange* (s) and *bottom* (b) quarks. All quarks carry color charge, while anti-quarks carry the corresponding anti-colors. Each generation of lepton consists of one negatively charged lepton, and one neutral lepton known as a *neutrino*. The charged leptons each have electric charge -1. The electrically charged leptons are the *electron* (e^-), *muon* (μ^-) and *tau* (τ^-). The corresponding neutrinos are known as the electron neutrino (ν_e), the muon neutrino (ν_μ) and the tau neutrino (ν_τ). All the fermions have an associated anti-particle, with opposite electric charge and opposite T_3 . The anti-quarks carry anti-color charge. Antiparticles are denoted by putting bars on the quarks and neutral leptons, or exchanging the charge sign on the charged leptons.

The SM assumes the neutrinos to be massless. There is however evidence of neutrino oscillations [11], indicating that the neutrinos are massive. The neutrino flavor eigenstates ν_e , ν_μ and ν_τ are all linear superpositions of neutrino mass eigenstates, denoted ν_1 , ν_2 and ν_3 . The neutrinos can oscillate between all three eigenstates. It is thus not trivial to talk about the "masses" of the neutrinos, since the flavor eigenstates that are observable in experiments are linear combinations of the mass eigenstates. The so called *mixing angles*, related to the probabilities for a neutrino of a given flavor to oscillate into another flavor, are used to determine the mass difference between the mass eigenstates. While neutrino oscillations are evidence that at least two neutrino mass eigenstates have non-zero mass, the absolute mass scales of neutrinos are not known.

The last SM particle to be discovered is the Higgs boson, a massive, neutral spin-0 particle. It was discovered in 2012 by the ATLAS [12] and CMS collab-

orations [13]. The role of the Higgs boson in the SM is to give masses to the otherwise massless $W^\pm$ and Z bosons [14, 15].

The Higgs boson couples to the $W^\pm$ and Z but does not couple to the photon and thus leaves it massless. This broken symmetry between the masses of the electroweak gauge bosons is called electroweak symmetry breaking. The masses of the $W^\pm$ and Z bosons lead to the fact that electromagnetic and weak interactions manifest as two different interactions though at a fundamental level they constitute one single *electroweak* interaction. The SM particles are presented in Table 1.2.

1.3 Symmetries in Gauge Theories

The SM is a quantum field theory, in which the Lagrangian densities of the SM fields are required to be invariant under certain specific transformations. Noether's theorem stipulates that each such invariance under a symmetry transformation is associated with a conserved current. The invariance of the fields under spatial translational and rotational transformations is associated with the conservation of linear and angular momentum. The invariance under time translations is associated with the conservation of energy. Invariance under global phase transformations associated with a specific symmetry group provides a conserved charge associated with the symmetry. In the simple case of Quantum Electrodynamics (QED), represented by the $U(1)$ symmetry group, this conserved current is identified with the electric charge.

In the SM, the interactions between fields are described in terms of local gauge theories. The Lagrangian densities are required to be invariant under certain local gauge transformations. In order to ensure local gauge invariance, the gauge boson vector fields are introduced. This is illustrated below for QED. The Lagrangian for a free spin-1/2 field ψ with mass m is written

$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi \quad (1.1)$$

where ∂_μ is the relativistic notation indicating differentiation with respect to time, minus the three spatial derivatives. Treating ψ and the adjoint field $\bar{\psi}$ as independent and applying the Euler-Lagrange equation to $\bar{\psi}$,

$$\frac{\partial\mathcal{L}}{\partial\bar{\psi}} = \frac{\partial\mathcal{L}}{\partial(\partial_\mu\bar{\psi})} \quad (1.2)$$

Type	Name	Symbol	Charge	Mass (MeV)
Quarks (Spin 1/2)	Up	u	+2/3	2.3
	Down	d	-1/3	4.8
	Strange	s	-1/3	95
	Charm	c	+2/3	1280
	Bottom	b	-1/3	4180
	Top	t	2/3	$173 \cdot 10^3$
Leptons (Spin 1/2)	Electron	e	-1	0.511
	Electron neutrino	ν_e	0	$< 2 \cdot 10^{-6}$
	Muon	μ	-1	105.7
	Muon neutrino	ν_μ	0	< 0.19
	Tau	τ	-1	1776.9
	Tau neutrino	ν_τ	0	< 18.2
Vector Bosons (Spin 1)	Photon	γ	0	0
	Gluon	g	0	0
	W boson	$W^\pm$	± 1	$80.39 \cdot 10^3$
	Z boson	Z^0	0	$91.188 \cdot 10^3$
Scalar Boson (Spin 0)	Higgs Boson	H	0	$125.1 \cdot 10^3$

Table 1.2: The elementary particles of the SM and some of their properties. The electric charge is given in fraction of the elementary charge e ($= 1.602 \cdot 10^{-19}$ C). The particle masses are taken from Ref. [16]. The listed quark masses are the estimated *bare* masses, while the effective masses might be considerably higher for the lighter quarks. For the neutrino flavor eigenstates only experimental upper limits are given for the masses.

yields the Dirac equation for a free spin-1/2 particle ψ with mass m

$$(i\gamma^\mu \partial_\mu - m)\psi = 0 \quad (1.3)$$

As previously stated the Lagrangian in Eq. 1.1 is invariant under the global phase transformation $\psi \rightarrow \psi' = e^{i\theta}\psi$. The electric charge is the conserved charge associated with this global symmetry. However the Lagrangian is not a priori invariant under a local phase transformation $\psi(x) \rightarrow \psi'(x) = e^{-iq\lambda(x)}\psi(x)$, where q is the charge of the particle, $\lambda(x)$ is some differentiable function of space and time and ψ is now explicitly written as a function of x . The non-invariance can be seen by inserting ψ' into Eq. 1.3:

$$(i\gamma^\mu \partial_\mu - m)\psi'(x) = q\gamma^\mu \partial_\mu \lambda(x)\psi'(x) + e^{-iq\lambda(x)}(i\gamma^\mu \partial_\mu - m)\psi(x) \quad (1.4)$$

Identifying the second term with the left-hand side in Eq. 1.3 times $e^{-iq\lambda(x)}$ means Eq. 1.4 becomes

$$(i\gamma^\mu \partial_\mu - m)\psi'(x) = q\gamma^\mu \partial_\mu \lambda(x)\psi'(x) \neq 0 \quad (1.5)$$

If we demand local invariance to the phase transformation, we need to replace the derivatives in the Lagrangian by the *covariant derivative*,

$$D_\mu \equiv \partial_\mu + iqA_\mu \quad (1.6)$$

where A_μ is a massless vector field transforming as $A_\mu \rightarrow A'_\mu + \partial_\mu \lambda(x)$ under the same local phase transformation. This provides the local invariance, e.g. in the transformation in Eq. 1.4 all the derivative terms from the transformation of ψ are cancelled by the simultaneous transformation of A_μ . In this way the equation

$$(i\gamma^\mu D_\mu - m)\psi(x) = 0 \quad (1.7)$$

is invariant under the coordinated transformation of ψ and A , and so is the QED Lagrangian, which is now written including the new vector field as

$$\mathcal{L}_{QED} = [\bar{\psi}\gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi] - \left[\frac{1}{16\pi} F^{\mu\nu} F_{\mu\nu} \right] - (q\bar{\psi}\gamma^\mu \psi)A_\mu \quad (1.8)$$

where $F^{\mu\nu}$ is the antisymmetric field tensor, and the full second term is the free field equation for a massless vector (spin-1) boson identified with the photon. The requirement of local gauge invariance thus provides a theory of a conserved charge q and free fermion fields (leptons) interacting with massless vector fields (photons).

The same principle of global phase invariance generating a conserved charge, and local gauge invariance generating interactions, can be extended to the full electroweak and strong sector. The symmetry under which the SM Lagrangian is invariant is called $SU(3) \otimes SU(2)_L \otimes U(1)$. The index L shows that the weak interaction only couples to left-handed fermions. The photon field is one of four generators of the $SU(2)_L \otimes U(1)$ group associated with the electroweak theory. The other three generators correspond to the $W^\pm$ and Z bosons, which without any further additions to the SM would also be massless, in clear violation with experimental observations. The Brout-Englert-Higgs mechanism is introduced to give masses to these bosons.

The $SU(3)$ symmetry group of the strong interaction has eight generators, corresponding to eight different gluon fields. Some of the phenomena associated with the strong interaction and $SU(3)$ are introduced in the following section.

1.4 Quantum Chromodynamics

Quantum Chromodynamics (QCD) describes the interactions of quarks and gluons, the particles that carry color charge. The particles carrying color charge are also referred to as partons, so named after Feynman's parton theory [17] which preceded QCD. The QCD Lagrangian is quark flavor independent in its formulation, in the sense that the coupling strength of the different quarks is independent of the quark flavor. The gluon is not neutral to the field it mediates, which means there is a gluon-gluon interaction term in the QCD Lagrangian. This makes the strength of the strong interaction increase with distance, creating a unique phenomenology described in the following section.

1.4.1 Long and Short Distance Behavior

The strength of the strong interaction depends on the energy in the interaction. The strong coupling constant α_s is said to be *running*. The running of α_s can be parametrized in terms of the momentum transfer Q of an interaction:

$$\alpha_s(Q) = \frac{12\pi}{(33 - 2n_f) \log \frac{Q^2}{\Lambda^2}} \quad (1.9)$$

where n_f is the number of quark flavors accessible at the given scale, and Λ is an arbitrary scale chosen to be one at which α_s is assumed to be known. It is most often chosen to be the mass scale of the Z boson, at which $\alpha_s(m_Z) = 0.1181$ [16]. Some measurements of α_s at various values of Q are shown along with a parametrization in Fig. 1.1. It clearly shows the running of the strong coupling constant, from asymptotically free at the high Q -end, to strongly constrained and non-perturbative at low values of Q .

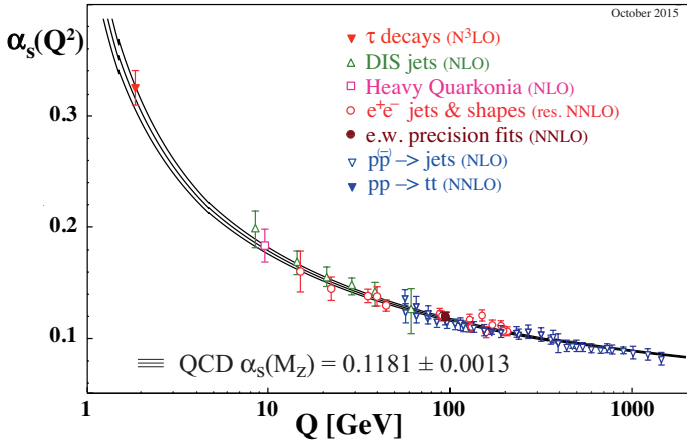


Figure 1.1: Measured values of the strong coupling constant α_s as a function of the momentum transfer Q . From Ref. [16].

At high enough Q , corresponding to distances < 1 fm, the running of the strong coupling constant can qualitatively be understood from the gluon-gluon interaction term in the QCD Lagrangian. As distances increase (and Q decreases) the gluon-gluon interaction increases in importance. The gluon polarization of the vacuum augments the color field, which leads to an *anti-screening*

effect, which grows with distance. At higher Q on the other hand, the quarks are not anti-screened from the color field and thus quasi-free. This effect is known as *asymptotic freedom*.

At larger distances, corresponding to lower values of Q in Fig. 1.1, the strong coupling constant grows stronger, until at ~ 1 fm the perturbative approach breaks down.

1.4.2 Confinement

A characteristic of the strong interaction is the observation of color *confinement*. Quarks and gluons are confined to exist within bound states which are, when the color quantum numbers are added up, colorless. These bound states are called *hadrons*. Two types of hadrons exist. The first are *baryons* which contain three quarks with different color charge. The second are *mesons* which contain a quark with a given color, and an anti-quark with the corresponding anti-color. If quarks or gluons gain enough kinetic energy to break the confinement potential, the potential energy in the gluon field is instead transferred into the creation of pairs of quarks and antiquarks which form new hadronic bound states, a process called *hadronization*. If two colored states move away from each other at energies that are large compared to the energy required to break the confinement of a hadron, a chain of hadronization processes form a number of collimated hadrons called a *hadronic jet*.

The long-distance regime in which quarks could break free from the color potential of a hadron is non-perturbative. Thus confinement is a concept constructed to account for the fact that naked color charge has never been observed, rather than a property derived from first principles.

1.5 Perturbative Method and Feynman Diagrams

The SM Lagrangian can be split into one part $\mathcal{L}_0$ that describes the free fields of the particles and one part $\mathcal{L}_I$ that describes their interactions,

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_I \quad (1.10)$$

Exemplifying with QED, the first two terms in Eq. 1.8 are the free field equations for electrons, positrons and photons, while the last term is the interaction term. When calculating the probability of some initial state $|i\rangle$ evolving at

some later time into a final state $|f\rangle$, the transition amplitude $\langle f|S|i\rangle$ is calculated, where S is the *scattering matrix*. The S -matrix can be calculated through a Dyson expansion in terms of the interaction Lagrangian density, to which perturbation theory is applied to find the transition amplitude at a given order in the expansion. This is performed using a diagrammatic technique known as Feynman diagrams.

Feynman diagrams are constructed by drawing all initial and final state particles as lines, going from left to right in time order, and connected by vertices corresponding to the interactions. Vertices must respect the conservation of all conserved charges. Arrows indicate if fermions are regular particles or anti-particles by pointing forwards or backwards in time. The basic building block in the case of QED is the three-legged diagram in Fig. 1.2. By rotating the diagrams and changing the direction of the time flow the diagrams for scattering, annihilation and creation of fermions can be obtained.

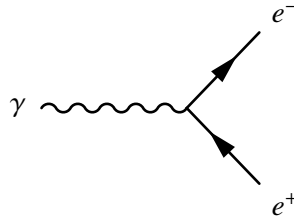


Figure 1.2: First-order building block of QED Feynman diagrams: A vertex between one photon and two electrons or positrons. Time runs from left to right. An arrow pointing forwards in the time-direction indicates a standard particle, and an arrow pointing backwards in the time-direction indicates an anti-particle.

The first-order diagram in Fig. 1.2 is not physically realizable on its own, since it cannot conserve both momentum and energy. At least two such diagrams must be combined in order to create a proper physical process. Thus the lowest order QED Feynman diagrams that correspond to processes realized in Nature are exemplified in Fig. 1.3, where an internal photon line connects an initial e^+e^- state to a final e^+e^- state.

To actually calculate the transition amplitude, all diagrams with initial state $|i\rangle$ and final state $|f\rangle$ must be added up. The contribution from each diagram is calculated using a set of Feynman rules derived from the Lagrangian. The terms for the propagators are derived from $\mathcal{L}_0$ and the terms for the vertices

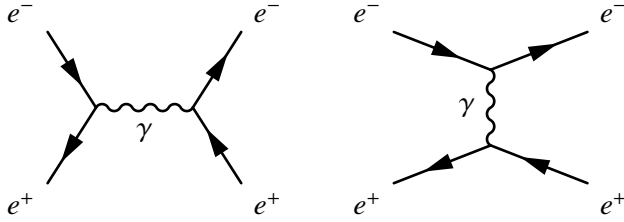


Figure 1.3: Two $e^+e^- \rightarrow e^+e^-$ Feynman diagrams with an internal photon propagator line. The left diagram corresponds to annihilation followed by pair production, while the right one corresponds to electron-positron scattering.

are derived from $\mathcal{L}_I$. The vertex terms are thus proportional to the coupling strength of the interaction. To leading order, the amplitude of the $e^+e^- \rightarrow e^+e^-$ is estimated by adding up all diagrams going from the initial state to the final state that only contain two internal vertices. This amplitude is often denoted by $\mathcal{M}$ and known as the *Matrix Element* of the process. Higher order diagrams include more internal lines, such as the diagram in Fig.1.4, which includes a fermion loop.

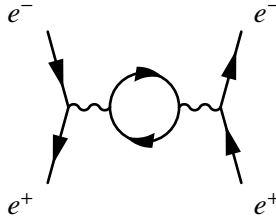


Figure 1.4: An $e^+e^- \rightarrow e^+e^-$ Feynman diagram including a fermion loop.

Extending this from QED into the full SM implies adding up all possible interactions when also including the weak and strong interactions. The e^+e^- amplitude in the examples of this section thus receives a contribution from the process in which a Z boson is exchanged instead of a photon.

The transition probability for a given process in a particle collider is given in terms of the *cross section* σ of the given process. Fermi's Golden Rule states that the transition rate is calculated by taking the $|\mathcal{M}|^2$ times the available phase space, i.e. integrating over all final state four-momenta that conserve energy and produce on-shell outgoing particles.

1.6 Shortcomings of the Standard Model

As a whole, the SM has been exceptionally successful in its predictions of experimental results. Many of the particle discoveries since the formulation of the SM around 1970 have been predicted by theory. This includes the discovery of the $W^\pm$ [18, 19] and Z boson [20] by the UA1 and UA2 experiments, the discovery of the top quark by the CDF [21] and DØ [22] experiments, and the discovery of the tau neutrino by the DONUT experiment [23]. QED is the most precise physics theory ever developed, with precision measurements confirming theoretical predictions with an accuracy of better than 1 part in 10^{12} [24]. Nonetheless, the SM is *not* a theory of everything, as there are observations it offers no explanation to. There are also theoretical issues which appear to lack a more fundamental explanation. So far the only observation on the particle level that can be said to be somewhat in conflict with the SM as originally formulated is the existence of non-zero neutrino masses described shortly in Sec. 1.2. The SM assumes neutrinos to be massless which has been shown experimentally to be false. Including the neutrino masses into the SM is however a matter of adjusting the Lagrangian [25], and does not undermine the theory as such (though the nature of the mechanism providing neutrino masses might open doors to new physics). A number of other observations and unanswered questions however seem to indicate that the SM is a low-energy approximation of some more fundamental theory. In this section a small selection of these issues is described, chosen for relevance to the searches for new physics presented in this thesis. Possible models that solve these issues are described in more detail in Chap. 2.

1.6.1 Dark Matter and Dark Energy

There is compelling evidence that the visible matter, particles we know and can observe, constitutes a minor part of the total mass in the Universe. Studies of the Cosmic Microwave Background [26] show that only 4.9% of the energy content consists of the regular SM matter particles, while 26.8% consists of some other, hitherto unknown matter type, denoted as Dark Matter (DM). The Standard Model offers no explanation for the DM, making new BSM physics necessary. This is covered in more detail in Chap. 2.

The remainder of the energy content of the Universe (68.3%) is often called Dark Energy, and is less understood than the DM. It is inferred to explain observations of e.g. supernovae showing that the expansion of the Universe takes place at an accelerating pace [27]. The Dark Energy is often assumed to be a

property of empty space, which is not diluted when the Universe expands. This would mean that the Dark Energy content of the Universe as a whole increases with its expansion and accelerates it.

1.6.2 Gravity

An obvious issue with the SM is the absence of a universally accepted way of including gravity. The large difference in interaction strength between gravity and the other forces is not understood, and has implications for the naturalness of the theory, as discussed in the next section. The hypothetical mediator particle of gravity is the graviton that couples to the energy-momentum tensor. By construction it must thus be a spin-2 particle, since the energy-momentum tensor is a rank-2 tensor. Gravity is observed to have infinite range, so the graviton is generally considered massless. The recent observation of gravitational waves with a given wavelength can be interpreted as an experimental constraint on the mass of the graviton of $m_G < 1.22 \times 10^{-22}$ eV [28]. Gravity is expected to become as strong as the other interactions at the Planck scale energies at around 10^{19} GeV, which, as shown in Table 1.1, means there is a difference of 36 orders of magnitude between gravity and the weak scale. The weakness of the gravitational coupling also means gravity cannot be studied in collider experiments. Some theories predict gravity to be much stronger than we have observed, and that studying gravity at microscopical scales could in fact reveal new features setting the scale of gravity closer to the other forces.

1.6.3 Fine Tuning

The fine tuning problem, or the hierarchy problem, arises because of the large gap between the energy scale typically associated with electroweak interactions around 100 GeV, and the Planck scale at around 10^{19} GeV. The Higgs boson mass can be regarded as a sum of two contributions: a so called bare mass term, and a term arising from quantum corrections from virtual effects of every particle that couples to the Higgs boson (see Fig. 1.5):

$$m_H^2 = (m_{H,0})^2 + \frac{kg^2\Lambda^2}{16\pi} \quad (1.11)$$

where k is a constant, and g is the coupling strength of the fermion-Higgs coupling. These corrections are on the order of the *cut-off scale* Λ where we

expect new physics to change the high-energy behavior of the model, which unless we find any new physics beyond the electroweak scale is the Planck scale. If the new physics appears at the TeV scale, the observed Higgs mass and the correction terms would be roughly of the same order, which would then also be true for the bare mass term. If the cut-off scale instead truly is the Planck scale, the correction terms and thus also the bare mass term are 17 orders of magnitude larger than the observed Higgs mass. The bare mass term of the Higgs boson should be completely independent of the Planck scale. However, in order to obtain the observed Higgs mass of 125.1 GeV using Planck-scale corrections, the bare mass needs to "conspire" with these corrections in order to exactly cancel them out. Theories of strong gravity remove the fine tuning problem by lowering the Planck scale to a value closer to the electroweak scale.

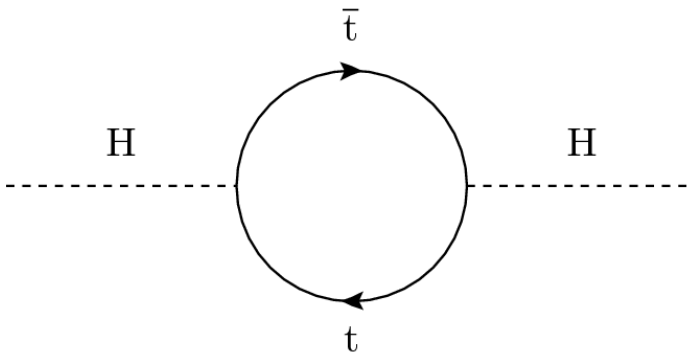


Figure 1.5: A correction term to the observed Higgs mass: A loop diagram with a $t\bar{t}$ pair.

1.6.4 Grand Unification?

The unification of electricity and magnetism in a single theory of electromagnetism as formulated by Maxwell in the 1860's is one of the most important achievements in the history of physics. Roughly 100 years later the high-energy unification of the weak and electromagnetic forces into the electroweak interaction was one of the building blocks in what was to become the SM of particle physics. The aspiration towards unification is driven by a reductionist philosophy in which fundamental physics are imagined to be ruled by a minimal number of laws and contain as few free parameters as possible. In this sense, the four

forces and 19 free parameters of the SM are not ideal. The observation that the strong force becomes weaker at high energies (Fig. 1.1), while the weak and electromagnetic forces become stronger, has led theorists to pursue the idea of *Grand Unification*. Above a hypothesized Grand Unified Theory (GUT) energy scale, there would be a single coupling strength. In a GUT the three observed interactions at low energies are different manifestations of a single fundamental interaction.

Apart from the aesthetic principle of unifying the forces, many unification schemes also try to answer the question of why charge is quantized in exactly such a way that the electron and proton charges are equal. This seemingly coincidental relation between the quark and lepton sector seems to indicate some more fundamental symmetry, of which the $SU(3)$ and $SU(2)_L \otimes U(1)$ are subgroups. One such proposition is the symmetry group $SU(5)$, proposed by Glashow and Georgi [29], setting the GUT scale at $O(10^{16})$ GeV. This theory predicts a number of new mediators that couple leptons to (anti)-quarks, and are thus called *leptoquarks*. Observations set severe constraints on this theory. In particular, $SU(5)$ predicts the decay of protons, but no such decays have yet been observed. The Super-Kamiokande detector sets lower limits on the half-life of the proton decay in various channels to $6.6\text{--}8.2 \times 10^{33}$ years [30], while the simplest $SU(5)$ theory [29] predicts a proton half-life on the order of 10^{31} years.

Chapter 2

Beyond the Standard Model

2.1 Introduction

Following the shortcomings of the SM introduced in Sec. 1.6, this chapter introduces models for BSM physics, solving some of the problems in the SM. The experimental part of this thesis, Part. III, presents searches using an energetic jet and large missing momentum as the detector signature of new physics. The theories highlighted in this chapter are theories that predict such a signature.

2.2 Extra Spatial Dimensions

The notion of introducing extra spatial dimensions to unify the gravitational force with other interactions is older than the SM. In 1921 Theodor Kaluza [31] proposed a 5-dimensional spacetime in which the two known forces at the time, gravity and electromagnetism, were unified. The main assumption apart from assuming the fifth dimension itself, is the assumption that the first derivative of all physical quantities with respect to the fifth dimension must be zero,

$$\frac{\partial f(x)}{\partial x^5} = 0, \tag{2.1}$$

imposed in order to explain why the fifth dimension was not visible. This argument was refined by Oscar Klein [32, 33], who interpreted it to mean that the fifth dimension is compactified on a cylindrical space, with dimension $\sim 10^{-30}$ cm. Compactification means that the fifth dimension is closed and periodic, so that

$x_5 = x_5 + 2\pi R$, where R is the radius of the fifth dimension. The independence with respect to the fifth coordinate (Eq. 2.1) is known as the *cylindrical condition*, and explains why the full 5-dimensional space is not visible to the underlying 4-dimensional subspace. In Klein's version of Kaluza's original theory, the standard 4-dimensional metric is rewritten in five dimensions as,

$$\tilde{g}_{AB} = \begin{bmatrix} g_{\mu\nu} + A_\mu A_\nu & A_\mu \\ A_\nu & 1 \end{bmatrix} \quad (2.2)$$

where $g_{\mu\nu}$ is the standard 4-dimensional metric, and A_μ is the electromagnetic 4-potential. Here the standard is to use greek letters for 4-dimensional objects and latin letters for higher dimensions. It can be shown that the geodesic equations of this metric reproduce the Lorentz force, and Kaluza and Klein identified the component of velocity along the fifth axis with electric charge.

The theories of compactified extra dimensions were implemented into string theories in the later half of the previous century, for example the 11-dimensional M-theory [34]. String theories generally try to unify all forces, including gravity, by replacing the point-like particles of ordinary particle physics with 1-dimensional strings, or in more general formulations with p -dimensional *branes*. These fundamental strings, through their different vibrational states, give rise to all the observed particles and forces. String theories only make predictions for observable phenomena in energies far beyond the reach of any current experiment.

Theories with extra dimensions yielding measurable effects on the TeV-scale have been proposed, inspired by concepts developed in string theory. One of these is the theory proposed by Arkani-Hamed, Dimopolous and Dvali [35], which is covered in more detail below.

2.2.1 Large Extra Dimensions in the ADD Scenario

In the ADD model [35] n compact extra dimensions are added to the 3+1 space-time dimensions. Gravity is allowed to propagate in these extra dimensions, sometimes denoted as the *bulk*, while the SM particles are only allowed to propagate in the standard 3+1-dimensions, denoted as the *brane*. This leads to gravity appearing to be weak over long distances, but on very short distances it is as strong as the other interactions. This theory is often referred to as a theory with Large Extra Dimensions, since for certain model parameters it may include compactified extra dimensions with radii up to μm -scale.

Following the example of Ref. [35] we assume n extra spatial dimensions of radius R . We denote the Planck scale of such a $(4+n)$ -dimensional theory M_D . Two bodies with masses m_1 and m_2 , positioned at a distance $r \ll R$ from each other will experience a gravitational potential (using Gauss' law):

$$V(r) \sim \frac{m_1 m_2}{M_D^{n+2}} \frac{1}{r^{n+1}} \quad (2.3)$$

If the test masses are instead put at a distance $r \gg R$, their gravitational flux lines can no longer propagate into the extra dimensions, and the potential becomes

$$V(r) \sim \frac{m_1 m_2}{M_D^{n+2} R^n} \frac{1}{r} \quad (2.4)$$

and the standard $1/r$ -dependence is retrieved. This means the effective Planck scale $\bar{M}_P = M_P/8\pi$ observed at long distances is

$$\bar{M}_P^2 \sim M_D^{n+2} R^n \quad (2.5)$$

where the left hand side is now the standard effective Planck mass, and M_D^{n+2} is the fundamental Planck mass in $4 + n$ dimensions.

If gravity is to manifest itself at energy scales close to the electroweak scale m_{EW} we simply set the fundamental $(4+n)$ -dimensional Planck scale to be $M_D \sim m_{EW}$. This yields for R

$$R \sim 10^{\frac{30}{n}-17} \text{cm} \times \left(\frac{1 \text{TeV}}{m_{EW}} \right)^{1+\frac{2}{n}} \quad (2.6)$$

The ADD model for gravity solves two fundamental problems of the SM. It provides an explanation for the apparent weakness of gravity. It also sets the fundamental Planck scale close to the electroweak scale leading to the elimination of the fine-tuning problem, since the cut-off scale providing the magnitude of the corrections to the Higgs mass, is now on the same order of magnitude as the electroweak scale (and thus the same order of magnitude as the Higgs mass itself).

2.2.2 Other Models with Extra Dimensions

Another extra-dimension model is the Randall-Sundrum (RS) theory in which a *warped* fifth dimension is added to the 3+1 space-time dimensions [36]. This theory introduces a special non-factorizable metric, where the 4-dimensional subspace of the 5-dimensional theory is x_5 -dependent. The RS models predict two different branes, and whereas all other SM fields only reside on one, gravity lives on both. This dilutes the gravitational strength in the normal four dimensions much like the ADD model, while the fundamental scale of gravity is on the same order of magnitude as the weak scale. Furthermore there are models known as Universal Extra Dimensions (UED), which are briefly discussed in the context of Dark Matter in Sec. 2.3.3. Even if these specific theories of extra dimensions are not necessarily realized in Nature, they have the merit of being new ways of exploring possible reconciliation between gravity and the microscopic world.

2.2.3 ADD Collider Phenomenology

For $n = 1$, in order to obtain M_D at the TeV-scale, R must be of the order 10^{13} m, yielding effects that would be noticeable at the scale of the solar system. This is excluded by observations. For $n > 1$ however, the scale of the extra dimensions would be less than 1 mm, a region in which gravity has not been fully studied before the LHC-era. An effective theory for the ADD scenario is outlined in Ref. [37], including the relevant inclusion of gravitons in the QED and QCD Lagrangians. This theory considers the interaction of the SM fields with a spin-2 graviton that can propagate in all $(4 + n)$ dimensions and mediates the gravitational interaction. The 4-dimensional projection of the massless graviton from the compactified extra dimensions gives rise to so called Kaluza-Klein tower of massive graviton modes. These massive graviton states appear as solutions to the free field equations of any particle in compactified extra dimensions. We illustrate this below for the 5-dimensional Klein-Gordon equation for a massless spin-0 particle.

$$(\partial_A \partial^A) \Phi(x_A) = (\partial_\mu \partial^\mu - \partial_5^2) \Phi(x_\mu, x_5) = 0 \quad (2.7)$$

Now we add the periodic boundary condition that $x_5 = x_5 + 2\pi R$, and Fourier expand the field to obtain

$$\Phi(x_\mu, x_5) = \sum_{k=-\infty}^{\infty} \phi_k(x_\mu) e^{\frac{ikx_5}{R}} \quad (2.8)$$

After this dimensional decomposition the equation of motion Eq. 2.7 yields for each of the fields ϕ_k :

$$\partial_\mu \partial^\mu \phi_k = \frac{k^2}{R^2} \phi_k \quad (2.9)$$

This is now an infinite *tower* of 4-dimensional fields with an extra mass term $m_k = \frac{k^2}{R^2}$, representing a discrete spectrum of mass modes. The same principle can be applied to any field, including the spin-2 graviton [38]. The difference in mass Δm between two mass modes m_k and m_{k+1} depends on the size of the extra dimensions.

The full expression for the mass splittings in the ADD scenario is given by Ref. [37]:

$$\Delta m \sim \frac{1}{R} = M_D \left(\frac{M_D}{M_P} \right)^{2/n} \sim \left(\frac{M_D}{\text{TeV}} \right)^{\frac{n+2}{2}} 10^{\frac{12n-31}{n}} \text{eV} \quad (2.10)$$

yielding for $M_D = 1 \text{ TeV}$ and $n = 2, 4$ or 6 a mass splitting of 0.3 meV , 20 keV and 7 MeV respectively.

The graviton modes couple to the energy-momentum tensor of the SM fields, and the interaction Lagrangian for a graviton field $G_{\mu\nu}^{(k)}$ is given by

$$\mathcal{L}_I = -\frac{1}{M_P} G_{\mu\nu}^{(k)} T^{\mu\nu} \quad (2.11)$$

where $T^{\mu\nu}$ is the energy-momentum tensor of the SM fields.

The production of gravitons is suppressed by the fact that they only couple to the SM fields gravitationally. However, the large multiplicity of KK modes given by the small mass splitting in Eq. 2.10 makes the n-dimensional phase-space factor large enough to compensate for this.

The decay of the graviton is suppressed by a factor proportional to $\bar{M}_P^2/m_k^3$ where m_k is the mass of the graviton mode, and it is therefore stable on the time scales associated with detection in colliders. The gravitons will thus appear as a tower of massive, stable, non-interacting particles, and the means of searching for them is to look for missing momentum in events where a graviton is produced in association with a SM particle. Emission of a single graviton violates momentum conservation in directions transverse to the standard 3+1-dimensional space-time brane. This is however expected since the brane itself breaks the translational invariance in the n non-brane dimensions, which means momentum is not generally conserved in these directions.

Figure 2.1 shows the main s-channel modes of production of gravitons at the LHC. While this is not a complete set of LO diagrams, it illustrates all initial ($q\bar{q}$, qg and gg) and final (gG and qG) states. For experiments performed in this thesis, only models with $n \leq 6$ are considered. For $n > 6$ there is no region of M_D where the effective field theory used remains perturbative at the same time as the LHC can produce a visible signal [37].

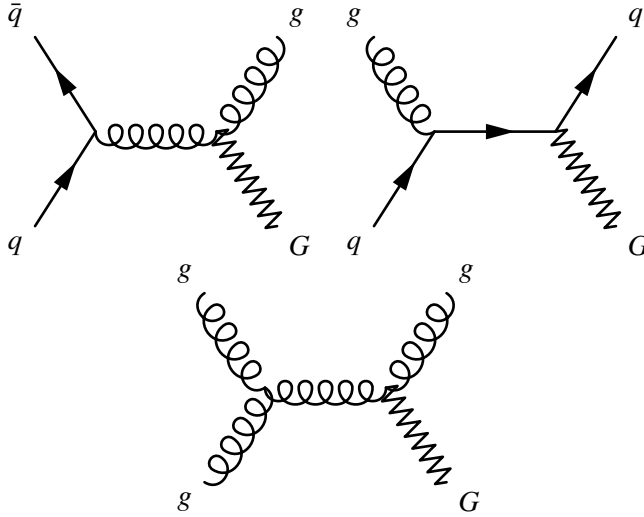


Figure 2.1: The main s-channel modes of production of gravitons in the ADD scenario at LHC.

2.2.4 Status of Experimental Searches for Extra Dimensions

Direct Measurements of Gravity

The best tabletop experiment limits on the small-distance behavior of gravity come from experiments with torsion pendulums, probing the Newtonian $1/r^2$ law to hold down to a distance of $\sim 55\mu\text{m}$ [39].

Collider Searches

The search for BSM phenomena is one of the main physics goals for the LHC experiments in the post-Higgs discovery era. Collider tests of the predictions based on the ADD theory have been performed by searching for events with a single energetic jet or photon and large missing momentum in proton-antiproton collision events with the CDF experiment [40] and the $D\bar{O}$ experiment [41] at the Tevatron, and in searches for events with photons and large missing momentum in electron-positron collision events with the LEP experiments [42] L3, OPAL, ALEPH and DELPHI.

In the experiments with the multi-purpose experiments CMS and ATLAS (see Chap. 3) at the Large Hadron Collider the searches for extra dimensions fall in three general categories: mono-X searches, searches for virtual graviton exchange and searches for black holes. Black holes appear in most theories of quantum gravity for energies above the Planck scale [43], and for TeV-scale gravity the LHC should thus be able to produce them once above some production threshold M_{th} . The presence of a black hole signal would be striking - the production cross section increases sharply as a function of energy after the threshold is reached, and the decay products may violate lepton and baryon number. With the 13 TeV dataset, ATLAS has performed searches in the dijet [44], the multi-jet [45] and the photon + jet [46] channels. The CMS experiment has performed searches for black holes in RS extra dimensions using dijet events with 13 TeV data [47]. These analyses generally set limits in the plane of M_{th} and M_D . As an example the lower limit on M_{th} is set to between 9.0-9.7 TeV depending on M_D for $n = 6$ in the ATLAS dijet analysis [44].

For the ADD model the production of a lepton pair through the exchange of a virtual graviton would appear as an excess or deficit of events at high invariant mass of the two leptons. The excess or deficit would depend on whether or not the graviton exchange interferes constructively or destructively with the Z/γ^* exchange. An example of such a search is the dilepton search at ATLAS [48].

This search sets limits on the so called string scale $M_S \approx 4M_D$ at 4-5 TeV for $n = 2-6$, which is weaker than the limits set by the mono-X searches. For the RS model, the production of diboson or dilepton final states through exchange of the lowest excited state of the graviton would manifest itself as a resonant peak in invariant mass spectra of the produced particles. The best collider limits on the mass of the lowest excited graviton mass are set by dilepton [49, 50] and diphoton [51] searches with the LHC 8 TeV data. The diphoton searches with LHC 13 TeV data from ATLAS [52] and CMS [53] both report an excess of events for resonances in the diphoton mass spectrum around 750 GeV. The ATLAS search has the highest significance and reports a 3.9σ local significance for a spin-0 signal model, and 3.6σ local significance for a spin-2 signal model.

The mono-X type searches look for signatures with a high energy jet or photon in association with missing momentum. The monophoton searches of ATLAS [54, 55] and CMS [56] generally set weaker limits than the monojet searches, because of the higher production cross section associated with the strong interaction when compared to the electromagnetic. The strongest limits from monojet searches prior to the publication of the papers on which this thesis is based are the 8 TeV limits from the CMS experiment [57], which are an upper limit on M_D at 2.99 TeV for $n=6$ and 5.09 TeV for $n=2$ (the limits for intermediate n are set between these two). The strongest ATLAS limits were the 7 TeV limits [58] between 2.51 for $n=6$ and 4.17 TeV for $n = 2$.

Cosmological and Astrophysical Constraints

For the models of Big Bang Nucleosynthesis (BBN) [59] to provide accurate predictions for the observed light elements, the influence of the extra dimensions must be negligible. This means that at some temperature T_* the extra dimensions should have a negligible energy content. The recovery of BBN requires $T_* > 1$ MeV, which we treat as a lower bound on this temperature. At this temperature the energy density ρ_{grav} stored in gravitons must be low enough as to not overclose the Universe due to the KK mode masses, and this sets the constraint that $M_D > 6.5$ GeV for $n=2$ [60].

The gravitons produced at this temperature will typically decay, with a lifetime longer than the present age of the Universe, into photons and neutrinos. The decay into photons sets further constraints on the parameters of the model, since a too low value of M_D would enhance the spectrum of the diffuse gamma radiation. Observations using the COMPTEL instrument [61] interpreted in Ref. [60]

set this lower limit at $M_D > 110$ GeV for $n=2$ and at $M_D > 5$ GeV for $n = 3$. For higher dimensionality the limits from cosmology are much lower than what can be set by colliders.

The observed energy loss from the Supernova SN1897A core collapse very well fits models in which most of the kinetic energy is carried away by neutrinos. Thus any new channel carrying away energy must be weak enough to preserve the agreement between neutrino observations and theory. This sets upper limits on the cross section for the process of nucleon-nucleon "gravi-strahlung", $N + N \rightarrow N + N + G$ in which the graviton propagates to extra dimensions, which in turn can be used to set upper limits on M_D . The lower limits using SN1897A are $M_D > 8.9$ TeV for $n=2$ and below 1 TeV for all $n > 2$ [62]. The same argument can be used to derive upper limits from neutron stars, where the gravitons produced in gravi-strahlung are gravitationally trapped around the neutron star. The gravitons slowly decay to photon pairs, which can be observed using telescopes. The non-observation of excesses in gamma-ray signals again sets limits on M_D . This has been done using data with EGRET [63] and Fermi-LAT [64] experiments. The best limit for $n=2$ (Fermi-LAT are $M_D > 230$ TeV, and for $n=3$ both set limits on the order 15-20 TeV. For $n > 3$ the limits are worse than the above quoted limits from the CMS 8 TeV analysis.

In summary, the astrophysical observations tend to be significantly more sensitive than the LHC for $n=2$, somewhat more sensitive for $n=3$, whereas for $n > 3$ colliders provide better sensitivity. However, since analyses of collider data as well as astrophysical data all use effective models with many assumptions, these searches should be seen as complementary. As this field is quickly evolving, the review in this section is subject to change.

2.3 Dark Matter

2.3.1 Observational Evidence

There is compelling evidence that the visible matter, particles we know and can observe, constitutes a minor part of the total mass in the Universe. It was observed already in the 1930's that the Coma galaxy cluster seems to rotate too fast around its center of mass compared to what is predicted from the mass of the luminous matter in the cluster [65]. In the 1970's it was shown that also the rotational velocities of individual galaxies are much too high, and tend to increase with larger radius with respect to the galactic center [66], which violates

the Keplerian laws when applied to the visible matter in the galaxy. This is illustrated below in Fig. 2.2. Gravitational lensing studies of galaxy clusters such as the so-called bullet cluster of galaxies show that the center of gravity is not always correlated with the center of visible mass [67]. The Planck satellite mapping of the Cosmic Microwave Background (CMB) [26] sets the matter content of the Universe at around 32%, while studies of BBN in turn set the amount of SM matter of the Universe close to 4.9% [68]. Together these results independently of each other point to the presence of another type of matter which has not been detected, indicating it is not interacting electromagnetically or strongly, and thus it cannot be explained by any SM particle. This Dark Matter constitutes approximately 26.8% of the energy content in the universe.

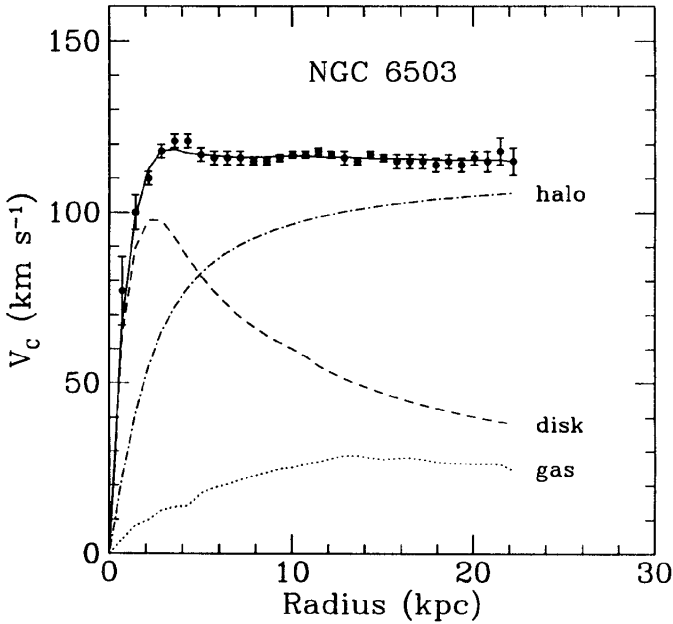


Figure 2.2: Rotational velocity as function of radius from the galactic center, for the NGC 6503 galaxy. The dashed and dotted lines represent expected contributions using only the luminous disk, using only using the gas content of the galaxy, or using only a dark matter halo. The full line is the combination of these three, which matches the observed data very well. From Ref. [69].

2.3.2 Weakly Interacting Massive Particles

Studies of structure formation in presence of DM indicate that the vast majority of the DM must be non-relativistic, and thus massive (GeV scale or heavier) [70]. This type of dark matter is usually denominated Cold Dark Matter (CDM), as opposed to Hot Dark Matter particles (HDM) which are light and relativistic. HDM is not favored by current experimental constraints. Thus unless alternative gravitational dynamics are introduced, the most favored dark matter particle candidates are particles that are non-baryonic, non-relativistic and do not interact strongly or electromagnetically.

In the very early Universe, when the temperature remained higher than m_{DM} of the DM particles, SM particles could freely annihilate into DM particles and vice versa. When the temperature dropped below m_{DM} , the creation of new DM particles became exponentially suppressed while their annihilation into SM particles continued. As long as the two particle species remained in chemical equilibrium, this process continued, gradually decreasing the DM content of the Universe. As the Universe expanded, the expansion and its corresponding dilution of DM particles eventually came to dominate the annihilation rate, and their number density thus became sufficiently small for interaction between them to cease. After this point the DM particles are said to be decoupled.

Knowing the number density at decoupling it is possible to calculate the thermally averaged annihilation rate $\langle \sigma v \rangle$ such that the result is the observed relic density. The annihilation rate is defined as the product of the cross section and the relative velocity, when averaged over the DM velocity distribution. A striking result of such calculations is that assuming a particle mass of around 1 TeV, the annihilation rate associated with the weak interaction, $\sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$, yields results very close to the observed amount of DM. The Weakly Interacting Massive Particle (WIMP) DM candidate fulfills both the requirements of CDM and provides the correct relic DM density. The coincidence between weak interaction strength and thermal relic density is often referred to as the *WIMP miracle* [71].

Some relevant WIMP DM candidates are introduced in Sec. 2.3.3, while experimental strategies are introduced in Sec. 2.3.4. Finally the phenomenology of collider DM searches is introduced in Sec. 2.3.5

2.3.3 WIMP Candidates

Supersymmetric Dark Matter

Supersymmetry (SUSY) is arguably the most popular family of BSM theories. It predicts a supersymmetric so called super-partner particle for each of the SM particles (a *sparticle*) [72]. Each fermion has an integer-spin bosonic partner, and each boson has a half-integer spin fermionic partner. SUSY is not a perfectly unbroken symmetry of Nature, since that would indicate that the supersymmetric particles have the same mass as their SM partners.

The smallest supersymmetric extension to the SM is called the Minimal Supersymmetric Standard Model (MSSM). For each gauge boson this model introduces a fermionic *gaugino*, for each quark a bosonic *squark* and for each lepton a bosonic *slepton*. An additional SM Higgs doublet must be introduced, leading to five physical Higgs states, whereof three neutral and two charged Higgs bosons. For each of these states a supersymmetric spin-1/2 fermionic Higgsino is introduced. A new quantum number, R-parity, is introduced to explain why the proton does not decay. SM particles have R-parity of +1 and supersymmetric particles have R-parity of -1. If R-parity is conserved, SUSY particles cannot decay to odd numbers of SM particles and SUSY particles can only be produced in pairs from SM particles.

There are several appealing characteristics to SUSY models. On a theoretical level, SUSY solves the fine-tuning problem since the contribution to the Higgs mass from each sparticle exactly cancels out the contribution from its corresponding SM particle, provided that the mass difference between the SM sector and the supersymmetric sector is not too large [72].

As long as R-parity is not violated the Lightest Supersymmetric Particle (LSP) is stable and can only be destroyed through pair annihilation. This makes it an excellent WIMP DM candidate. For MSSM, this LSP can be a number of different particles. To be consistent with astrophysical observations however, it must be either the lightest *neutralino* or the *gravitino*. The *neutralino* is in the MSSM a linear superposition of the four superpartners of the neutral electroweak gauge bosons and the neutral Higgs bosons. We denote this lightest neutralino state $\tilde{\chi}_1^0$. The gravitino is the supersymmetric partner of a hypothetical spin-2 graviton.

Heavy Neutrinos

The SM contains three fermions that only interact weakly - the neutrinos. For some time the SM neutrinos were regarded as viable DM candidates. One great advantage of the neutrino over other DM candidates is the simple fact that neutrinos are known to exist [68]. In the light of recent upper limits on neutrino masses, the idea of light neutrinos as DM has been shown to be inconsistent with the structure formation in the early Universe. Thus it has been proposed that there could exist neutrinos much heavier than the three known neutrino flavors. To overcome the constraints set by direct detection experiments such models must include some mechanism that suppresses the interaction of these heavy neutrinos and the Z boson [73]. Neutrino-type particles called *sterile* neutrinos have also been proposed as DM candidates [74]. These are proposed to lack couplings to the strong, electromagnetic *and* weak interactions and only interact gravitationally, apart from also mixing with the non-sterile neutrino flavors.

Universal Extra Dimensions

Some models of extra dimensions introduce extra dimensions to which all particles can propagate, so called Universal Extra Dimensions (UED) [75]. These dimensions are considerably smaller than those in the ADD model, $R \sim 10^{-18}$ m. The conservation of momentum in these extra dimensions leads to a similar symmetry as R-parity, denoted as KK-parity (since the same Kaluza-Klein tower phenomenology applies also for these extra dimensions). The conservation of KK-parity yields a DM candidate, the lightest Kaluza-Klein particle referred to as the LKP. This particle is a viable WIMP candidate if it's a photon¹⁾ or a neutrino [76], carrying extra-dimensional momenta. Though not interacting through the weak interaction, the phenomenology of the universal extra dimensions can, given the right interaction strengths and masses of the KK states, reproduce the same decoupling and relic density as a WIMP-type particle. In Sec. 2.3.5 the possibility of the production of LKP pairs will be treated as one of the possible WIMP-type particles that could be produced at the LHC.

2.3.4 Complementary Search Strategies

The nature (and of course even the answer to the question of the existence) of WIMPs is still obscure. Not knowing their mass or the nature of their interaction

¹⁾More specifically the U(1) hypercharge boson B^0 .

with SM particles, means a wide range of search strategies must be employed - to find them or set as strong limits as possible on the parameter space they might inhabit.

One approach to WIMP searches is so called *direct detection*. If the Universe is filled with WIMPs they should constantly be passing through the Earth, and it should be possible to measure e.g. the recoil energy from scattering of a WIMP by a nucleus if the WIMP-SM couplings are non-zero. The scattering can be either elastic, which would be the case for a WIMP-nucleus recoil. It could also be inelastic if the WIMP instead scatters off an electron in the atom and ionizes the atom, or interacts with the nucleus in a way that leaves it in an excited state. For interactions that are independent of the spin of the interacting particles, the cross section increases dramatically with the mass of the recoil nuclei. This is not the case for interactions dependent on the spin, and modern direct detection experiments with very heavy nuclei are thus not as sensitive to spin-dependent as to spin independent interactions. Experiments that probe the spin-independent interactions include scintillator crystals, Si and Ge semiconductor detectors looking for electronic as well as phonon signals, and finally large volume noble gas (Xe or Ar) detectors. To probe the spin-dependent interactions of WIMPs, direct detection experiments such as PICO [77, 78] and SIMPLE [79] instead use detectors with fluids in superheated states just below their boiling point. When struck, they form bubbles which can be photographed with CCD cameras. The target fluids often include fluorine, with an unpaired number of protons, making them sensitive to spin-dependent interaction

Another approach is *indirect detection*, i.e. to look for signals of SM particles from WIMP annihilations, typically in regions of space where dark matter is thought to cluster. Such regions could be inside the sun, in the galactic center or in so called dwarf satellite galaxies to the Milky Way. The signals are typically gamma-rays, neutrinos, positrons or anti-protons. This is performed using a large variety of telescope techniques. These include satellite gamma-ray telescopes such as Fermi-LAT [80], Imaging Atmospheric Cherenkov Telescopes such as H.E.S.S. [81] and MAGIC [82], and neutrino telescopes such as Ice-Cube [83] and ANTARES [84].

The same Feynman diagram that gives WIMP-WIMP annihilations must exist in reverse, therefore production of WIMPs must be possible at colliders as illustrated in Fig 2.3. Thus the high center-of-mass energy of the LHC opens a window to a third search strategy complementary to direct and indirect searches. This third strategy is the basis of the DM interpretation of ATLAS data in this

thesis. The complementarity is illustrated by a Feynman diagram of the effective interaction between SM particles and WIMPs. Collider experiments can probe very light WIMP regions more effectively than direct detection experiments, since direct detection experiments are limited by lower sensitivity to the recoils of light WIMPs, whereas the cross section for producing WIMPs in the LHC instead increases for lower masses.

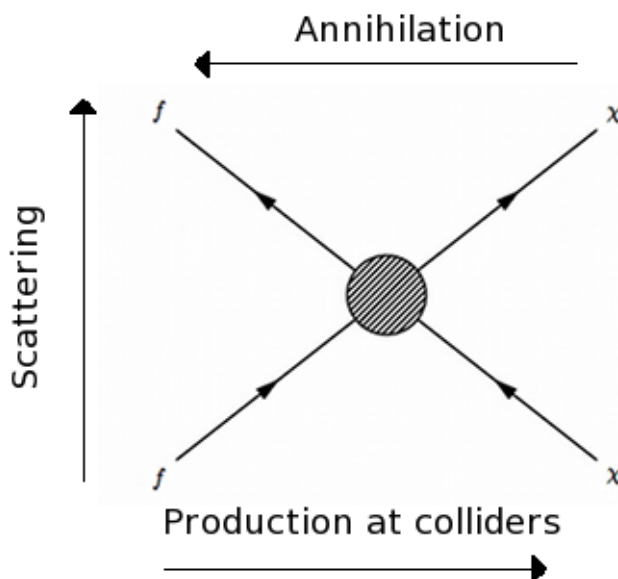


Figure 2.3: An illustration of the complementarity of WIMP searches. Scattering, production and annihilation are all possible from the invariance of the physics under time reversal. The arrow indicates time flow.

2.3.5 Collider Phenomenology

A WIMP appears to a detector as invisible, since it does not interact strongly or electromagnetically. In an event in which two WIMPs are produced, as illustrated in Fig. 2.3, there is nothing to be detected. The detection of an event requires that one of the initial colliding particles radiates a SM particle which can be measured in the detector. ATLAS and CMS have performed several such analyses, searching for radiation of several different SM particles in associa-

tion with WIMP pair production. A short review of these searches is given in Sec. 2.3.6. In this section the theoretical models used to analyze the results of these searches are outlined. These are grouped into *Effective Field Theories* (EFT) and *Simplified Models*.

Effective Field Theories for Collider Searches

In this section an EFT is introduced to describe the possible interaction between SM particles and WIMPs. EFTs are used as a tool to describe the low-energy behavior of a complete theory, while making a minimal amount of assumptions about this theory [85]. Assuming the energy scales involved experimentally to be well below some cut-off scale Λ associated with characteristic energies of the complete theory, it is possible to integrate any interaction above Λ out of the action. Any information about heavier degrees of freedom is contained in the couplings of the *effective* Lagrangian $\mathcal{L}_{\text{eff}}$,

$$\mathcal{L}_{\text{eff}} = \sum_i c_i O_i \quad (2.12)$$

where O_i are effective operators constructed using the lighter fields, and information about heavier couplings is hidden in the coupling constants c_i . For the pair production of WIMPs the assumptions concerning the nature of the model parameters as well as their interactions with SM particles follow Refs. [86, 87]:

- The WIMPs are fermions of either Dirac or Majorana type, or spin-0 (scalar) particles.
- If they are fermions they have spin-1/2.
- There are no additional dark sector particles available at the LHC energies, hence the mediator particle is too heavy to be produced directly.
- The SM-WIMP interaction is mediated by a particle heavier than twice the WIMP mass and we can assume the interaction to be point-like.
- The WIMP is parity-odd under some new parity (such as R-parity or KK-parity), and can only be produced in even numbers. Unless otherwise stated it is assumed that the WIMPs are pair produced.

These assumptions generate a contact interaction between the DM and SM sectors, analogous to Fermi theory of weak interaction. At energies below the mass of the W boson the weak decay of a neutron to a proton can be approximated by a four-body contact interaction. It can be modeled by an EFT with a combination of a vector and an axial-vector type interaction.

Each type of possible interaction in the EFT is ascribed an effective operator (listed in Table 2.1) and for each type of interaction there is a parameter M_* setting the strength of the interaction. Given that the mediator particle of mass M_{med} is too heavy to be produced directly, the mapping of the scale M_* to M_{med} is an expression of the type

$$M_* \sim M_{\text{med}} \sqrt{g_{\text{SM}} g_{\text{DM}}} \quad (2.13)$$

where g_{SM} and g_{DM} are the couplings of the mediator to the DM and SM particles respectively.

Some relevant effective operators are listed in Table 2.1, selected from a complete list in Ref. [86]. Each of the seven operators in the table is chosen as representative of a given type of interaction. The operators listed here are those that will be analyzed in Part III.

Name	Operator	Type of interaction
D1	$\frac{m_q}{M_*^3} \bar{\chi} \chi \bar{q} q$	scalar, quark
D5	$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q$	vector, quark
D8	$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$	axial-vector, quark
D9	$\frac{1}{M_*^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$	tensor, quark
D11	$\frac{\alpha_s}{(4M_*)^3} \bar{\chi} \chi G_{\mu\nu} G^{\mu\nu}$	scalar, gluon
C1	$\frac{m_q}{M_*^2} \chi^\dagger \chi \bar{q} q$	scalar, quark
C5	$\frac{\alpha_s}{4M_*^2} \chi^\dagger \chi G_{\mu\nu} \tilde{G}^{\mu\nu}$	scalar, gluon

Table 2.1: Operators coupling Dirac fermion (D) and scalar (C) WIMPs to SM quarks or gluons, selected from a complete list found in Ref. [86] for their relevance to the analysis in Part III. Operators for Majorana fermions can be obtained by rescaling the Dirac fermion operators.

The effective operators all fall into four main types of DM-SM interactions :

- **Scalar** type interaction. In this thesis this corresponds to the operator D1 and C1 when the interacting SM particles are quarks, and D11 and C5 when the SM particles are gluons. When comparing to direct detection experiments this operator corresponds to spin-independent interactions.
- **Vector** type interaction. This interaction is only non-zero if the WIMP is a Dirac fermion (e.g. a fourth generation Dirac neutrino). Majorana fermions, such as the neutralino, do not have vector type interactions with quarks [70]. In this thesis this corresponds to the operator D5. When comparing to direct detection experiments this operator corresponds to spin-independent interactions.
- **Axial-vector** type interaction. In this thesis this corresponds to the operator D8. When comparing to direct detection experiments this operator corresponds to spin-dependent interactions.
- **Tensor** type interaction. In this thesis this corresponds to the operator D9. When comparing to direct detection experiments this operator corresponds to spin-dependent interaction cross-section.

Each non-vector Dirac fermion operator in Table 2.1 has an equivalent Majorana fermion operator obtained by dividing the operator by a factor two [87]. This factor arises as a consequence of the degeneracy in the pair production of Dirac fermions. For these models, defined by their effective operator, limits can be set on the production cross section and M_* . In Chap. 10 such limits are shown for the ATLAS experiment.

Studies of WIMP pair production in colliders allow us to set limits on the WIMP-nucleon interaction cross-section, in the spin-dependent and the spin-independent case. These can be translated into constraints on direct and indirect detection cross-sections for each of these operators owing to the equations provided by Ref. [86].

Simplified Models

In a direct detection experiment, the momentum transfer in a nuclear recoil is of the order of 10 keV and the EFT is a good approach. It is not clear however if this holds true for the TeV-scale momentum transfers that can take place at

the LHC. Depending on the true value of the cut-off scale Λ in relation to the transferred momenta in the collisions, the contact type interaction assumed in the EFT might no longer be valid. Issues related to EFT interpretations are treated in more detail in Sec. 2.4. To circumvent the problem of non-validity of the EFT an alternative solution is to introduce another framework for the analysis. These alternative models are called *simplified models*, and are characterized by the inclusion not only of the mass of the WIMP m_χ , but also by the explicit inclusion of the mediator mass M_{med} , width Γ and couplings g_{SM} and g_{DM} to the SM particles and WIMPs respectively. These models represent the minimal possible assumptions about the underlying theory, while at the same time providing full validity over the experimental energy scales. The simplified models used in the analyses presented in Part. III include a massive neutral vector mediator denoted Z' , exchanged in the s-channel and described in detail in Ref. [88]. This vector mediator can have vector and axial-vector couplings to the interacting quarks and DM, described by the interaction Lagrangian terms [89]

$$\mathcal{L}_v = g_q \sum_q Z'_\mu \bar{q} \gamma^\mu q - g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi \quad (2.14)$$

$$\mathcal{L}_{\text{av}} = g_q \sum_q Z'_\mu \bar{q} \gamma^\mu \gamma^5 q - g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi \quad (2.15)$$

for vector and axial-vector interaction respectively. In these equations g_q is the coupling of the mediator to quarks, assumed equal for all flavors, g_{DM} is the coupling of the mediator to the WIMPs. The Z' , χ and $\bar{\chi}$ terms are the mediator and WIMP fields. The sum extends over all quark flavors. For colliders the two couplings give a very similar phenomenology, but in the non-relativistic limit of direct detection experiments they are very different. Vector interactions are spin-independent while axial-vector interaction are spin-independent.

2.3.6 Brief Overview of the Current Status of WIMP Searches

Direct Detection

A handful of hints of DM particle detection have been reported over the last decade. The DAMA and DAMA/LIBRA experiments use NaI(Tl) crystal scintillator detectors, and have been gathering data over 14 annual cycles. They

report a signal with 9.3σ significance [90] corresponding to the annual modulation expected from WIMPs. This signal corresponds to a 10-15 GeV WIMP for scattering off sodium, or a 60-100 GeV WIMP for scattering of iodine. The CoGeNT experiment uses germanium detectors, and with 3.4 years of gathered data reports a modulation of the annual rate of detections, corresponding to the expectation to a WIMP signal with a significance of 2.2σ [91]. The signal best fit corresponds to a WIMP mass around 8 GeV. Independent analyses using the same data but with other background models do not however find a significant signal [92]. The CDMS-II experiment use germanium and silicon *bolometers*, searching for charge or scintillation signals as well as phonon signals. The silicon detector, measuring 23.8 kg·d, finds three events above the expected background [93]. The WIMP+background hypothesis is favored over the background-only hypothesis with a p-value of 0.19%. The signal best corresponds to a WIMP with mass 8.6 GeV. Finally the CRESST-II experiment, using a calcium tungstate scintillator searching for scintillation and phonon signals, finds an excess of events corresponding to a signal significance of 4.2σ and 4.7σ for a WIMP mass of 11.6 GeV or 25.3 GeV respectively [94].

Recent data from several other experiments completely exclude the parameter space which the detection claims inhabit. The best current limits on the spin-independent WIMP-nucleon interaction cross section for WIMPs above 6 GeV are set by the LUX experiment. The LUX detector is a liquid Xenon detector, measuring scintillation as well as an ionization charge. LUX sets an upper limit on the spin-independent WIMP-nucleon cross section down to $6 \times 10^{-46} \text{ cm}^2$ for 33 GeV WIMPs [95]. Other experiments that completely exclude the parameter space of the signal hints, in the spin-independent case, include the SuperCDMS [96], Xenon-100 [97] and Panda-X [98] experiments. The tension is illustrated by the current limits of direct detection experiments and the WIMP parameters reported by the experiments claiming signal observations in Fig. 2.4. Below a WIMP mass of 6 GeV the best limits on this cross section are set by the CDMS-lite experiment [99], which uses a single germanium semiconductor crystal. This experiment sets an upper limit on the spin-independent scattering cross section around 10^{-41} cm^2 for 3 GeV WIMPs.

For the spin-dependent case the best limits from a direct detection experiment on the scattering cross section for low-mass WIMPs are set by the PICO experiment. PICO operates two bubble chambers, one consisting of 2.9 kg of C_3F_8 [77] and one consisting of 36.8 kg of CF_3I [78]. PICO sets the upper limit for the spin-dependent WIMP-nucleon cross-section at $9 \times 10^{-40} \text{ cm}^2$ for 40 GeV

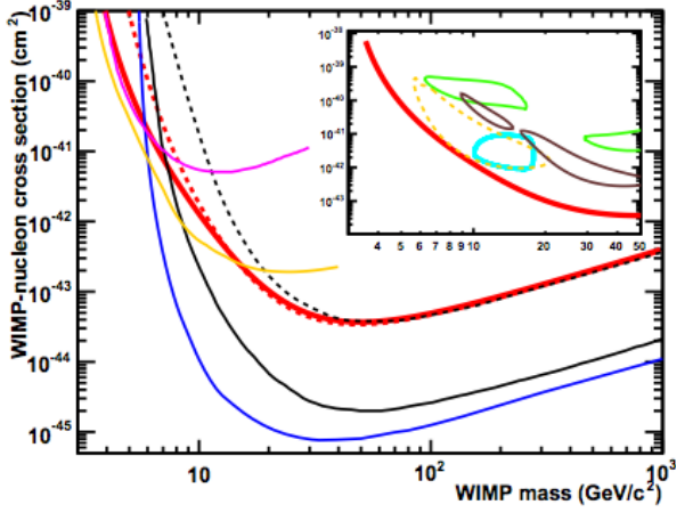


Figure 2.4: Upper limits on the spin-independent WIMP-nucleon cross section σ_{SI} from recent experiments as a function of the WIMP mass m_χ . In the large frame: LUX [100] (blue), Xenon-100 [97] (black), Super-CDMS [96] (yellow), Panda-X [98] (red) and CDEX [101] (magenta). The inset is a close-up of the best fits to the discovery hints from DAMA/LIBRA [90] (green), CoGeNT [91] (cyan), CDMS II-Si [93] (dashed yellow) and CRESST-II [94] (brown), compared to the exclusion limits from Panda-X (red). Figure from Ref. [98].

WIMPs [77]. The best limits on these cross sections are set by neutrino observatories, above 100 GeV the best limits are set by the IceCube [83] experiment, and below 100 GeV by the Super-Kamiokande [102] experiment. These are neutrino telescopes, and analyze the annihilation signal from WIMPs that have been captured inside the sun. Equilibrium between the capture and annihilation rates in the sun is assumed, and under this assumption, the rate of annihilation will depend on WIMP scattering off protons in the sun. This makes it possible to set limits on the spin-dependent interaction cross-section. In particular, the sensitivity to spin-dependent interactions in this type of experiment is typically stronger than WIMP-nucleus recoil experiments. These limits are illustrated along with the limits from PICO in Fig. 2.5.

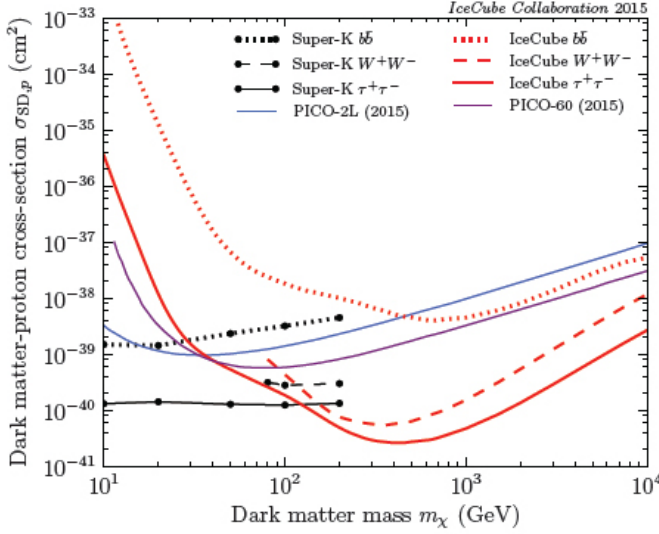


Figure 2.5: Upper limits on the spin-dependent WIMP-nucleon cross section σ_{SD} from recent experiment as function of the WIMP mass m_χ . Included are limits from IceCube [83] (red), Super-Kamiokande [102] (black) and PICO [77, 78] (blue and purple). The different line styles for the neutrino observatories illustrate different annihilation channels. Figure from Ref. [83].

Indirect Detection

Some recent indirect detection experiments report observations of an anomalous abundance of cosmic positrons on a level that might fit a WIMP annihilation model [103, 104, 105]. The analysis of data from Chandra and XMM-Newton observations of the Andromeda galaxy and the Perseus galaxy cluster shows a faint, unidentified X-ray line at around 3.5 keV [106], which might be possible to fit with a sterile neutrino model. Another interesting observation from indirect detection experiments is the observation of a gamma ray component from the galactic center seen by the Fermi [107] telescope. This feature is a gamma ray line with energy between 1-3 GeV, and can be fit with a 36-51 GeV dark matter particle annihilating primarily to $b\bar{b}$ quark pairs [108], consistent with the annihilation rate associated with the relic DM density. However all these

observed anomalies in indirect detection experiments could be related to the presence of standard but unaccounted for astrophysical sources.

The strongest limits on the WIMP-WIMP annihilation rate are set for low WIMP masses (below a few hundred GeV) by the Fermi-LAT gamma-ray telescope, from studies of the Milky Way halo [109] and Dwarf Spheroidal Galaxies around the Milky Way [110]. The latter analysis completely excludes the best fitted parameter space for the 1-3 GeV gamma ray line mentioned earlier. For WIMP masses above a few hundred GeV the best limits are set by the H.E.S.S. Imaging Atmospheric Cherenkov Telescope studies of the galactic halo [111].

Colliders

The mono-X type analysis, described briefly in Sec. 2.2.3, is a search for the process in Fig. 2.3, when read from left to right. In order to measure such events in the detector, one of the initial partons must radiate a SM particle. A final state with only invisible particles will remain undetected. The searches in this thesis are performed looking for the Initial State Radiation (ISR) of a gluon or a quark.

The monophoton final state also described in Sec. 2.2.3, in which the radiation of a parton is replaced by a photon, is also used to search for WIMP pair production. Using the 8 TeV dataset, ATLAS also performs searches in signatures where a W or Z boson is radiated from the initial state quarks. These searches are performed with both the leptonic [112, 113] and hadronic decay channels [114]. CMS performs searches in the leptonic decay channels of the mono- W and mono- Z [115, 116]. Finally ATLAS performs searches in the mono-Higgs final state, with the Higgs boson decaying to either a diphoton [117] or a $b\bar{b}$ [118] final state.

Models such as Higgs portal models or MSSM include WIMPs, and both ATLAS and CMS have a wide search program for such models. These searches generally make predictions and set experimental constraints that are only valid within the assumptions of the probed model. In contrast, the mono-X final states provides an agnostic search for WIMPs, in which as few assumptions as possible are made concerning the full underlying model. The multitude of final states provide as broad scans of the parameter space of the WIMPs as possible, which is in line with an agnostic search philosophy. It also provides the possibility to understand and measure the properties of WIMPs as exactly as possible if discovered.

2.4 On the Validity of Effective Theories

An underlying assumption of the effective theories used both in the ADD and DM searches is that the cut-off scale Λ of the underlying theory is much higher than the scales involved in the interaction in the collider experiment. If the momentum transfer Q in a LHC proton-proton collision is high enough for on-shell production of the mediator particle, the effective theory is no longer valid. To extend the analogy with Fermi theory from Sec. 2.3.5, this would represent the momentum transfer at which the W boson can be produced on-shell, and where it is thus no longer possible to assume contact interaction.

The cut-off scale is model dependent, and not known until the underlying theory has been uncovered. For the DM EFTs the minimum requirement that $M_{\text{med}} > Q$, i.e. the requirement that the mediator is not produced on-shell, is used as a measure of validity. Since the exact value of M_{med} is integrated out of the effective theory, the relation of M_{med} to M_* from Eq. 2.13 is used to re-introduce it to the theory. This means some values of the couplings between the DM and SM sectors must first be assumed. For the ADD EFTs the cut-off scale Λ is assumed to be close to the fundamental Planck scale M_D . This can be dealt with by either removing or weighting down events in simulations for which $Q > M_D$. This procedure is known as truncation. Both these methods and their respective results are described in more detail in Chap. 10.

Part II

Experimental Facilities

Du ska inte längre slita i ditt anletes svett -
Du ska ägna dig åt vetenskap och konst.

Kjell Höglund, *Maskinerna är våra vänner*

Äh det gör man, man plockar isär cykeln i molekyler och sen
sätter man ihop den igen.

Sudden, *NileCity 105.6*

Chapter 3

Experiment

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a particle accelerator with two beam pipes at the European Center for Nuclear Research (CERN) [119]. It has a circumference of 26.8 km, and is situated below ground on the French-Swiss border near Geneva. Protons are accelerated through a Linear Accelerator (LINAC 2) to 50 MeV, after which they are inserted into the Proton Synchrotron Booster, where they are accelerated further to 1.4 GeV. After the booster the protons are inserted into the Proton Synchrotron (PS) where they are accelerated to 25 GeV. Finally the Super Proton Synchrotron (SPS) accelerates the protons to 450 GeV at which point they are inserted into the LHC. The LHC ring has four interaction points at which the two counter rotating beams are made to cross. The main LHC experiments ALICE, ATLAS, CMS and LHCb are placed at these interaction points. A number of smaller experiments also use the proton beams. The LHC complex is illustrated in Fig. 3.1.

The two counter rotating beams are made to cross at the interaction points, where particle physics experiments are placed. The aim of the collider is to perform proton-proton and heavy ion collisions with unprecedented high energy and luminosity. The operating center-of-mass energies in proton-proton collisions have so far been 7 TeV in 2010-2011, 8 TeV in 2012 and 13 TeV in 2015. The 7 and 8 TeV periods together make out the LHC *Run 1*, while the 13 TeV period is called the LHC *Run 2*. The collisions take place between so called proton *bunches*, which were spaced by 50 ns in 2010-2012, and by 25 ns from 2015 and on. The machine instantaneous luminosity is given in units of $\text{b}^{-1} \text{s}^{-1}$

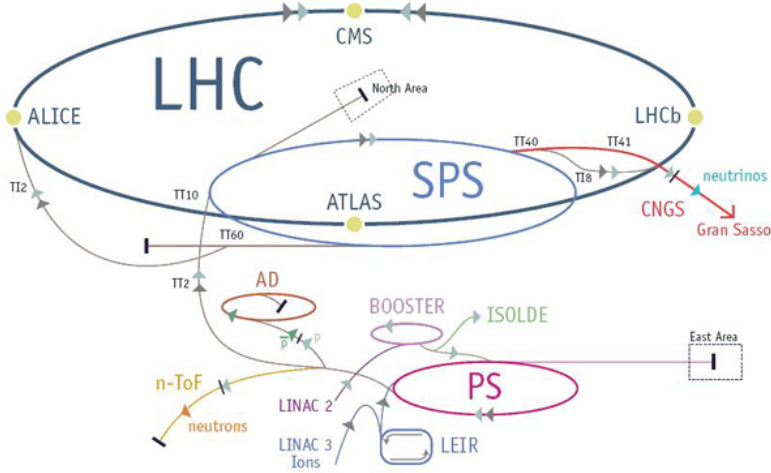


Figure 3.1: The LHC complex, in which protons are accelerated through a series of accelerators and made to collide at the four main experiments.

(or more commonly in the field $\text{cm}^{-2} \text{s}^{-1}$, since $1 \text{ b} = 10^{-24} \text{ cm}^2$), and can be written as

$$\mathcal{L} = \frac{N^2 k_b f \gamma}{4\pi \epsilon_n \beta^*} F \quad (3.1)$$

where

- N is the number of particles (protons or heavy ions) per bunch.
- k_b is the number of bunches.
- f is the revolution frequency.
- γ is the relativistic γ -factor.
- ϵ_n is the normalized emittance. The emittance ϵ is a measure of the average spread in the position-and-momentum phase space of the beam. The normalized emittance is written $\beta_L \gamma \epsilon$, where β_L and γ are the standard Lorentz factors.

- β^* is the value of the amplitude function β at the interaction point. This function is related to the spread σ of the beam through $\beta^* = \sigma^2/\epsilon$, where σ is the spread of the bunch in the transverse plane.
- F is a geometrical reduction factor related to the angle of interaction between the two beams.

For physics analysis, the interesting quantity is the total integrated luminosity L , obtained by integrating the delivered instantaneous luminosity $\mathcal{L}$ given in Eq. 3.1 over periods when the detector was actually recording data with nominal detection conditions over time,

$$L = \int \mathcal{L} dt \quad (3.2)$$

The expected number of collision events of a given process generated in these collisions can be written

$$N_{\text{event}} = L\sigma \quad (3.3)$$

where L is the integrated luminosity, and σ the cross section for the process, given in units of barn.

The total integrated luminosity delivered by the LHC in 2012 proton-proton runs is 23.1 fb^{-1} and the total integrated luminosity recorded by ATLAS with good detection conditions is 20.3 fb^{-1} . The total integrated luminosity of the 2015 physics run is just over 4 fb^{-1} , and the integrated luminosity recorded by ATLAS with good detector conditions is 3.2 fb^{-1} .

The LHC beam parameters in 2012 and 2015 are presented in Tab 3.1. The instantaneous luminosity between the two runs is very similar. The number of bunches is doubled in Run 2 with respect to Run 1, while the number of protons per bunch is decreased.

3.2 The ATLAS Detector

ATLAS [122] is a general purpose detector able to identify photons, electrons, muons, taus, hadrons and b-hadrons and measure their four-vectors. This capability allows it to fully exploit the discovery potential of the LHC. To achieve

Parameter	2012	2015
Energy (TeV)	4	6.5
$\mathcal{L}$ ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	0.7	0.5
N	1.6×10^{11}	1.15×10^{11}
k_b	1374	2244
f	11245 Hz	11245 Hz
Bunch spacing (ns)	50	25
ϵ_n (μm)	2.5	3.5
$\beta^*(m)$	0.60	0.80
F	0.8	0.8

Table 3.1: Run parameters of the LHC in 2012 and 2015. These values are typical values for the runs with best achieved performance [120, 121].

multi-particle identification ATLAS is made up of three major detector systems, which are in turn made up of subdetectors. This section aims to give an overview of the three detector systems, as well as a brief description of all of the subdetectors.

3.2.1 Overall Geometry

The ATLAS detector is approximately cylindrical, built around the LHC interaction point with the LHC beam pipe as its principal axis. It has a radius close to 11 m, a length of 44 m and weighs around 7000 tonnes. Figure 3.2 shows an illustration of the detector. The subdetectors can be grouped into three major systems:

- The Inner Detector (ID) [124] situated closest to the beam pipe, measures charge, transverse momentum and direction of charged particles. It is also used to determine the exact position of the proton-proton interaction, and to identify which hadrons contain heavy quarks (b and c), which typically decay before reaching the calorimeters.
- The calorimeter system [125, 126] situated around the ID, measures the energy and direction of photons, electrons and hadrons. The information is combined with information from the ID to identify these particles as

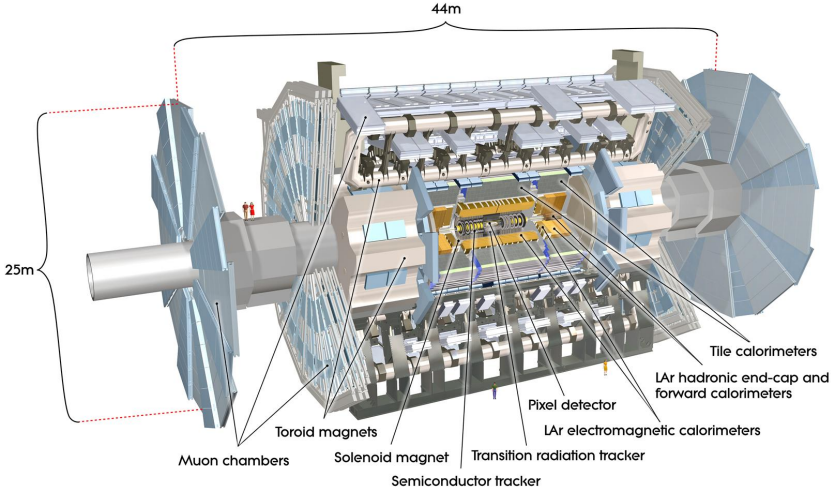


Figure 3.2: A cut-away illustration of ATLAS with the different subsystems indicated.

well as τ leptons and identifying which jets come from decay of heavy flavor quarks (primarily b , but also c). The calorimeters also provide fast read-out for trigger decisions at 40 MHz.

- The Muon Spectrometer (MS) [127], situated furthest out from the beam pipe, identifies muons and measures their momentum and direction.

The subdetectors are arranged in concentric layers, with the interaction point situated in the center, as illustrated in Fig. 3.3.

Two different coordinate systems are employed to define a position in the detector, one cartesian and one polar cylindrical. The cartesian coordinate system is defined with its z -axis along the beam pipe, its x -axis in the horizontal plane pointing radially towards the LHC center and its y -axis pointing upwards. The cylindrical coordinate system shares the z -axis with the cartesian system, ϕ is the azimuthal angle defined by rotation around the z -axis and θ the polar

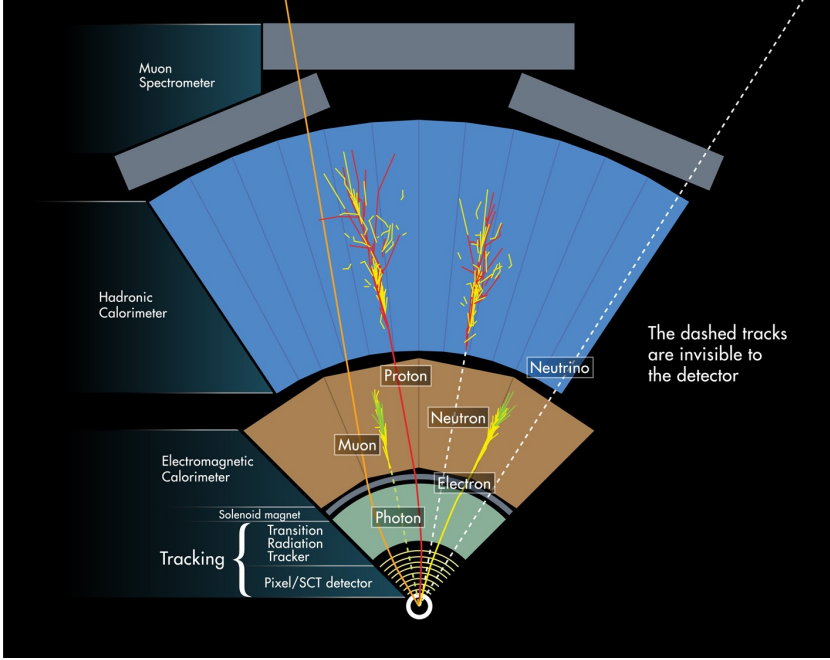


Figure 3.3: An illustration of a vertical cross section of one hemisphere of the ATLAS detector, with the detectors arranged around the beam pipe which is in this figure situated at the bottom. The way different particles interact in different subsystems is illustrated. From Ref. [123].

angle defined by rotation around the x-axis. To map a point in the cylindrical coordinate system θ is replaced by the pseudo-rapidity η defined by

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right) \quad (3.4)$$

which is preferred since particle flow is close to uniform per unit in η . The distance between two points in the detector is described in the pseudorapidity-azimuthal space by

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \quad (3.5)$$

which is invariant under Lorentz transformation along z . The part of the detector with $\eta > 0$ is denoted as the *A side* and the part with $\eta < 0$ is denoted as the *C side*. This denomination is particularly used in Chap. 4.

Though the momentum of the protons in the LHC beams is well-known, the interaction takes place between quarks or gluons for which the z -component of the momentum is unknown. The momentum perpendicular to the beam axis however is known to be zero. Because of the unknown z -component of the momentum involved in the parton collision we choose to describe momenta in the *transverse* xy -plane. We will denote the projection of quantities onto the transverse plane with a subscript T , such as for the transverse momentum p_T .

3.2.2 The Inner Detector

The ID is 6.2 m in length and has a diameter of 2.1 m. The purpose of the ID is to precisely measure the tracks of charged particles as they pass through the detector. It is used to determine momenta, directions and electric charge of these particles. It is also used to find the primary vertices from proton-proton collisions as well as secondary vertices from the decay of long-lived particles. The ID is surrounded by a solenoid magnet setting up a 2 Tesla magnetic field bending charged particles in the transverse plane. The bending radius of the particle is used to determine its momentum. The acceptance of the detector is $|\eta| < 2.5$, and tracks with momentum as low as 100 to 200 MeV can be reconstructed. Figure 3.4 shows the layout of the ID which consists of three subdetectors:

- The Pixel Detector is located closest to the interaction point and provides the most accurate position measurement in the whole of ATLAS. The original setup, used in 2012, has around 80 million read-out channels, each one being a silicon pixel diode with an area of $40 \times 500 \mu\text{m}^2$ and a thickness of $250 \mu\text{m}$ organized in a three-layer barrel and five end-cap disks at high $|\eta|$. In the long shutdown between Run 1 and Run 2, a fourth pixel barrel layer was installed, known as the Insertable B-layer (IBL) [128]. This adds another 12 million pixel read-out channels to the system. The innermost read-out channels were situated 50.5 mm from the beam axis in the three-layer setup, and are now situated 32.7 mm from the beam axis. The IBL significantly improves sensitivity to identifying b-jets, as well as the measurements of impact parameters of tracks.

- The Semiconductor Tracker (SCT) is located outside of the Pixel Detector. It consists of 6.4 million channels where the active material is silicon strips. It has four layers in the barrel region and nine disks in each end-cap at high $|\eta|$. The innermost layer is situated at 30 cm from the beam axis, and the outermost layer is situated at 51.4 cm from the beam axis.
- The Transition Radiation Tracker (TRT) is the outermost part of the ID. It consists of thin, 4 mm diameter gas-filled drift straws, each with a gold-tungsten wire at its middle. There are around 50 000 straws in the barrel, and around 320 000 straws in the end-cap. It extends from around 55 cm to 108 cm in radial distance from the beam axis. The TRT contributes to the momentum and direction measurement, but also to the particle identification. Ultra-relativistic particles traversing the straw tubes produce transition radiation, and the amount of radiation produced is proportional to the relativistic Lorentz factor γ . This makes the TRT able to discriminate between electrons and charged hadrons.

3.2.3 The Calorimeters

The purpose of the calorimeters is to measure the energy and direction of photons, electrons and hadrons. They are able to measure a large range of energies, from tens of MeV to several TeV. Much of the physics studied at ATLAS depends on accurate measurements of the missing transverse momentum from escaping particles, such as neutrinos (or hypothetical BSM particles), thus it is important that the calorimeters provide hermetic coverage in both η and ϕ . The calorimeters cover a range in pseudo rapidity of $|\eta| < 4.9$. The calorimeters are divided into five separate sections depicted in Fig. 3.5: the Liquid Argon (LAr) Electromagnetic (EM) Barrel, the LAr EM End-Cap, the LAr Hadronic End-Cap, the LAr Forward Detector and finally the hadronic barrel calorimeter, the Tile Calorimeter (TileCal) which consists of a Long Barrel and an Extended Barrel part.

The main purpose of the EM calorimeters is to identify and measure the properties of electrons and photons. These calorimeters consist of absorber materials with high atomic number and argon as the active material. The basic functional unit is a liquid-argon filled gap between two parallel plate absorbers. Any photon or electron traversing the calorimeters will interact with the detector material leading to photon conversions and bremsstrahlung, creating a shower of

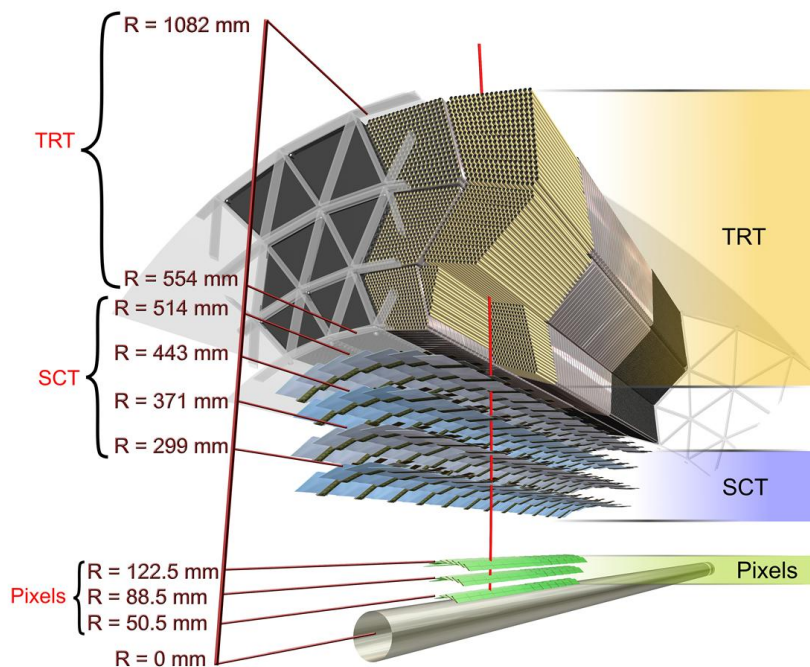


Figure 3.4: An illustration of a charged particle (red line) traversing the different layers of the inner detectors, and their respective dimensions. R denotes the distance from the center of the beam pipe.

electrons and photons. As the electrons in the shower pass through the detector they ionize the argon, and this electric signal created by the drift of argon ions towards an anode read-out electrode is measured. The different physical objects have different shower shapes. Photons can be distinguished from charged particles since they do not leave a track in the ID unless they convert early in the ID. The treatment of photons that convert to an electron-positron pair before reaching the calorimeter is described in Sec. 5.5.

The barrel EM calorimeter covers the area $|\eta| < 1.475$. The granularity of the read-out cells is fine enough to allow for discrimination between for example single photons, and boosted decays of π^0 to two photons. The inner layer has a cell width of $\Delta\eta = 0.0031$. The end-cap part is a two-wheel structure covering $1.375 < |\eta| < 2.5$ and $2.5 < |\eta| < 3.2$.

The hadronic calorimeters are the TileCal, covering $|\eta| < 1.7$, the LAr hadronic end-cap covering $1.5 < |\eta| < 3.2$, and finally the LAr Forward calorimeter covering $3.1 < |\eta| < 4.9$. Since parts of the research presented in this thesis concern TileCal, a more detailed description of this calorimeter is found in Chap. 4.

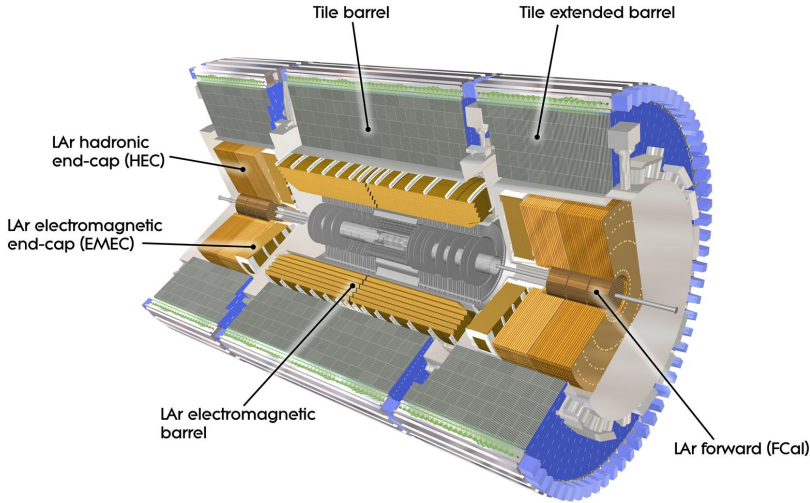


Figure 3.5: A cut-away illustration of the ATLAS calorimeter system.

3.2.4 The Muon Spectrometer

The MS is installed outside the calorimeters, and is the largest subsystem of the ATLAS detector. Its purpose is to identify muons with $p_T > 3$ GeV and measure their transverse momentum. The MS is located both inside and outside eight toroidal magnetic coils that bend the trajectory of the muon. By determining at least three points along the muon path, the radius of the curvature can be deter-

mined, which yields the muon momentum. The MS consists of four subdetectors as shown in Fig. 3.6:

- Monitored Drift Tube Chambers (MDT), used to accurately measure muon tracks with $|\eta| < 2.7$. The innermost end-cap layer only covers up to $|\eta| < 2.7$.
- Cathode Strip Chambers (CSC), used to measure muon tracks in the range $2.0 < |\eta| < 2.7$.
- Resistive Plate Chambers, which provide information for the trigger for central muons with $|\eta| < 1.05$.
- Thin Gap Chambers, which provide information for the trigger for muons in the range $1.05 < |\eta| < 2.4$.

Around 1200 MDT chambers form the backbone of the MS, positioned in three layers situated at radii of 5, 7.5 and 10 meters from the z-axis respectively. In the end-cap the MDT chambers form large wheels (Fig. 3.6).

3.2.5 Triggers and Data Acquisition

With a bunch spacing of 25 ns, the bunch crossing frequency of the LHC is 40 MHz. If every ATLAS event was recorded, it would mean writing terabytes of data every second, with most of these events being of limited interest for the LHC physics program. To avoid this, events need to meet some prerequisites in order to be recorded. The ATLAS trigger and data acquisition system (TDAQ) select events that survive a multi-level trigger. In Run 1 the trigger consists of three steps:

- The Level 1 (L1) trigger uses a sub-set of the detector systems to identify events with electrons, muons, photons, jets and hadronically decaying tau leptons. Only the Thin Gap Chambers and Resistive Plate Chambers are used for the muon system, and the calorimeter information is read out using a special read-out electronic path with reduced granularity. Inner detector information is not used as it is too time-consuming to process. The simplification of the detector information at level 1 of the trigger is necessary to ensure that trigger decisions can be made very fast and can be applied to every single bunch crossing at 20 MHz in Run 1 and 40 MHz

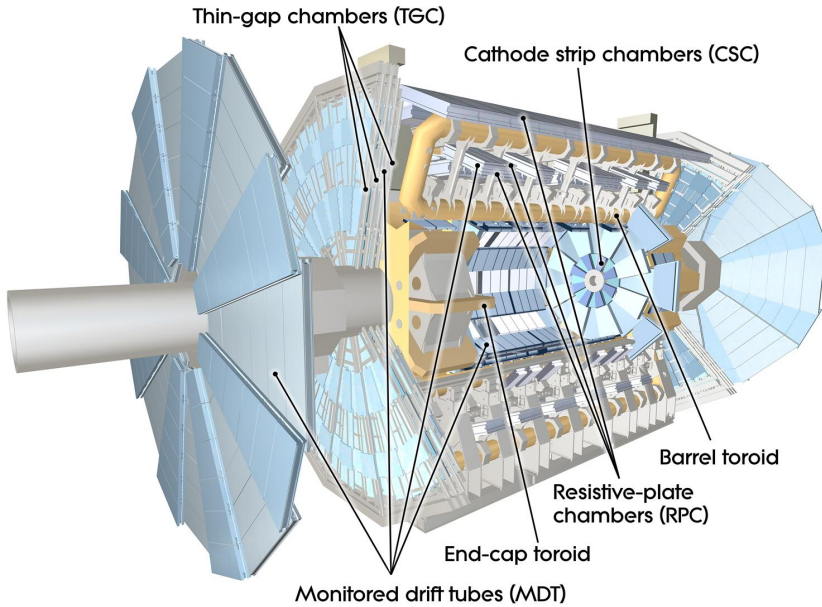


Figure 3.6: A cut-away illustration of the ATLAS muon system.

in Run 2. The highest output event rate allowed from L1 in physics runs is ~ 100 kHz.

- The Level 2 (L2) trigger refines the trigger decision from L1 by looking at the regions of interest defined by L1. L2 has access to the full ATLAS detector information, including the ID and the precision muon chambers, within the regions of interest. L2 has better signal over background discrimination and sets tighter thresholds for quality of physics objects than L1. The Level 2 trigger reduces the event rate to $O(1)$ kHz.
- The Level 3, or Event Filter (EF) is applied to events that survive L2. It uses the full ATLAS detector information in all regions and uses similar algorithms to those used offline to reconstruct physics objects. This reduces the output rate to ~ 400 Hz.

In Run 2 the L2 and EF steps have been merged into a unified High-Level Trigger (HLT) step. This allows the computing resources available to both systems to be shared optimally. This change is made possible by a combination of

hardware upgrades to the different trigger systems and an increased bandwidth in the read-out system. It provides an increase of the allowed output rate of from the HLT to $O(1)$ kHz.

In Run 1 events that passed a trigger were sorted into inclusive *data streams*, depending on which objects were found in the HLT. The major streams for data analysis were `Egamma` (if the event passed an electron or photon trigger), `JetTauEtmiss` (if it passed either a jet, tau or a missing energy trigger) and `Muon` (if it passed a muon trigger). In Run 2 a single physics data stream is used. The search for new physics presented in Part III of this thesis uses a missing energy trigger in the signal region, and electron triggers in the control regions used to estimate backgrounds to the signal region. The Run 1 data analysis presented in Part III relies on the `JetTauEtmiss` and `Egamma` streams.

Chapter 4

Electronic Noise in the Tile Calorimeter

The ATLAS Tile Calorimeter (TileCal) constitutes the section with $|\eta| < 1.7$ (see Fig. 3.5) of the ATLAS hadron calorimeter. Its purpose is to correctly identify jets and to measure their momenta. It also plays an important role in determining the missing momentum associated with invisible particles such as neutrinos or possible BSM particles. In order to do this with good accuracy the performance of TileCal must be carefully monitored. One important parameter to keep under control is the electronic noise. The known level of electronic noise is a crucial input parameter to allow for reconstruction of jets and is also used as input to the calculation of missing transverse momentum. Monitoring the noise levels is also used as a general check of the performance and health of calorimeter electronics. A brief introduction to calorimetry and the physics of hadron showers is given in Sec. 4.1. The calorimeter itself is introduced in Sec. 4.2. The later sections of this chapter are devoted to the description and studies of the TileCal electronic noise.

4.1 Hadron Showers and Calorimetry

A high-energy hadron traversing a block of matter will produce a shower of particles, mainly hadrons but also leptons and photons produced in hadron decays. The large variety of hadron interaction processes leads to a complex shower development. The hadron can interact with a nucleus via inelastic collisions in the detector. The interaction produces a set of new hadrons, which in turn will travel through the detector and interact further. Low energy neutral hadrons such as neutrons are in general not detected [129].

Sampling hadron calorimeters¹⁾ are constructed using an active detector material, where the energy deposited in the detector is measured, interleaved with a heavy absorber material where the hadrons interact strongly and shower. The energy deposited by the hadron shower in the active material is measured. Hadron calorimeters are positioned outside EM calorimeters because of the deeper reach of hadron showers compared to the reach of electrons and photons.

When a hadron interacts with a nucleus and breaks it up, the energy needed to overcome the binding energy of the nucleus is lost to the measurement. Energy will also be lost in the elastic scattering between nuclei, where the recoil in the target material cannot be measured. Thus during the hadronic showering, some of the energy of the original hadron is invisible to the detector. This component of invisible energy makes measuring the energies of hadrons inherently more difficult than measuring the energies of photons and electrons.

4.2 The ATLAS Tile Calorimeter

TileCal covers an η - ϕ region of $|\eta| < 1.7$ and $0 < \phi < 2\pi$. It uses iron absorbers and plastic scintillators as the active material. Scintillators respond to energy depositions by scintillating, i.e. emitting light that in turn is detected by the use of Photo-Multiplier Tubes (PMT) that convert the light into electric pulses. The TileCal is designed as one Long Barrel (LB) and two Extended Barrels (EB) of cylindrical shape, all divided into 64 modules placed as wedges in the azimuthal direction (Fig. 4.1).

The LB is divided into two partitions, one on each of the A and C sides (see Sec. 3.2.1). Hence the four TileCal partitions (in order of position from negative to positive coordinate along the beam axis) are EBC, LBC, LBA and EBA. The light produced in the scintillating tiles is read out on two radial sides by wavelength shifting fibers which are bundled together in groups that form read-out cells. The readout cells resulting from the bundling of fibers from the tiles are shown in Fig. 4.2. Most cells are read out by two readout channels which can each be read out in high gain (HG) or low gain (LG) amplification depending on the signal strength. In total TileCal has 5184 readout cells, comprising 9856 channels [126].

TileCal is divided into three longitudinal layers, denoted A, BC and D ordered by increasing distance from the beam pipe, as shown in Fig. 4.3. The

¹⁾Sampling calorimeters are calorimeters in which the interaction takes place in another material than the active detector material.

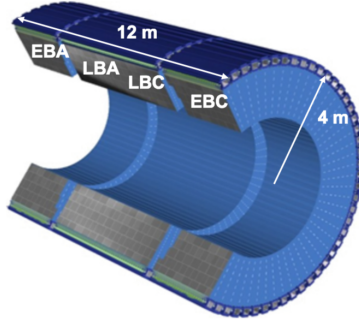


Figure 4.1: An illustration of the Tile Calorimeter. Each partition is divided into 64 modules, placed as wedges in the azimuthal direction. The text implies the scale of the detector and shows the four partitions.

D cells are located deepest into the calorimeter. The A and BC layers have a granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ while the D layer has a granularity of $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$. In the gaps between long and extended barrels additional scintillators are introduced. These are called gap or crack scintillators, and are denoted as E layer cells. These provide the information necessary to correct the reconstructed energies for energy deposited in the dead material in the crack regions.

The energy resolution σ_E for a hadron of energy E depositing energy in TileCal is given by:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad (4.1)$$

where the $\oplus$ denotes a square summation²⁾. The different terms in the equations are the following:

- a is $0.5 \text{ GeV}^{\frac{1}{2}}$, representing stochastic processes such as how much of the shower fluctuates into invisible particles or how much energy is lost inside the absorbers, and leakage of shower energy into dead parts of the detector.

²⁾ $p \oplus q = \sqrt{p^2 + q^2}$

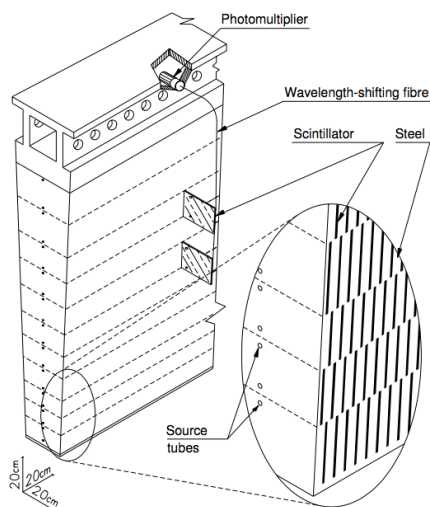


Figure 4.2: The mechanical assembly and readout for a TileCal module, positioned as a wedge in ϕ . The tiles are oriented normal to the beam. The indicated source tubes are used to circulate radioactive Cs sources for calibration purposes, as briefly discussed in Sec. 4.3

- b is a noise term originating from pile-up and electronic noise. Its exact size depends on the size of the cell clusters used to compute the hadron energy as well as the noise in each individual cell. It is a small contribution already at low energies, and since its influence on the resolution does not depend on energy, its relative effect on the $\frac{\sigma_E}{E}$ term becomes negligible at higher energies.
- c is 3% and stems from non-uniformities in the detector response.

The relative resolution becomes better with increasing energy, but can never be lower than the constant term of 3%.

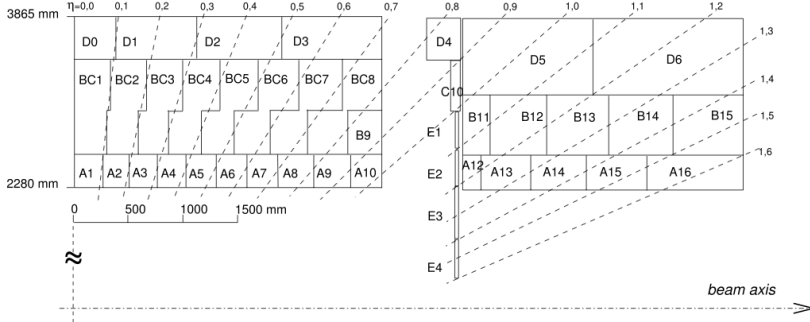


Figure 4.3: A cutout view in the Rz plane of TileCal, showing the segmentation in depth and η of TileCal modules in the $\eta > 0$ part of the LB (left) and the EB (right). The cell types are, in order from low to high R , the A, BC and D cells. The E cells are visible in the gap between the LB and EB. Figure from Ref. [126].

4.3 Signal Reconstruction in the Tile Calorimeter

Each signal pulse from the PMTs is read out by one electronic channel. The pulse is sampled by an Analog to Digital Converter (ADC) at 40 MHz. For each event that passes the L1 trigger, seven consecutive samples are read out. The digitized values are expressed in ADC counts and denoted S_i where i ranges from 1 to 7. The amplitude is amplified in two separate amplification schemes, using a high and a low gain. Which one is read out depends on the amplitude. There is a factor 64 between the two amplifications.

The seven samples are used to reconstruct the time and amplitude of the pulse using the Optimal Filtering (OF) method [130, 131]. This method is a technique for linearly combining the seven samples S_i describing a pulse to obtain the amplitude A and the time t in the following way:

$$A = \sum_{i=1}^7 a_i \cdot S_i \quad (4.2)$$

$$t = \frac{1}{A} \sum_{i=1}^7 b_i \cdot S_i \quad (4.3)$$

where the a_i and b_i are linear coefficients that minimize electronic noise. The OF comes in two versions:

- Iterative OF, for which the information of the position of the pulse within the given time window is not needed, and instead found iteratively,
- Non-iterative OF where the position of the pulse is fixed to a known position in time (phase) with respect to the sampling clock, the phase can be predetermined by some timing calibration process.

TileCal currently operates with the non-iterative OF method, partly because it is faster and partly because it is less sensitive to collision pile-up.

When calculating the noise levels in TileCal cells, the signal reconstruction in Eqs. 4.2 and 4.3 is performed in dedicated runs performed in periods with no beam. In the following sections of this chapter, the non-iterative OF reconstruction is used to calculate the cell noise unless otherwise stated. It has been shown that this choice of reconstruction algorithm lowers the noise when compared to the iterative OF [132].

Three different calibration systems are combined to convert the pulse amplitude expressed in ADC counts to a pulse amplitude in MeV. The reconstructed channel energy used by the High Level Trigger and offline is calculated as

$$E_{\text{channel}} = A \cdot C_{\text{ADC} \rightarrow \text{pC}} \cdot C_{\text{pC} \rightarrow \text{GeV}} \cdot C_{\text{Cs}} \cdot C_{\text{Laser}} \quad (4.4)$$

where $C_{\text{ADC} \rightarrow \text{pC}}$ is the conversion factor from ADC counts to charge determined for each channel by the Charge Injection System (CIS) which measures the ADC response to a calibrated charge delivered by precision condensators. The conversion factor $C_{\text{pC} \rightarrow \text{GeV}}$ from charge to energy in GeV was measured in test beam for a subset of TileCal modules via the response to electrons with well-defined energy. The conversion factor $C_{\text{pC} \rightarrow \text{GeV}}$ transforms measured charge to actually deposited energy. The factor C_{Cs} corrects for remaining response non-uniformities in the optical part of the system after the gain equalization of all channels has been performed by the Cs radioactive source system. C_{Laser} corrects for non-linearities of the PMT response measured by the Laser calibration system. The last two factors are applied in order to preserve the electromagnetic energy scale of TileCal [133] as defined in the test beam.

The energy in a cell is the sum of the reconstructed calibrated energy of its readout channels.

4.4 Electronic Noise: Definition and Usage

4.4.1 Noise in the Tile Calorimeter

In signal theory the noise is defined as an unwanted signal perturbing a transition or a recording of an input signal. In TileCal the input signal is produced in the scintillating plastic tiles. The electronic noise is defined to be any perturbation in the transition of the true signal in its passage from the wavelength shifting fibres up to and including the front-end ADCs. Electronic noise in TileCal is derived using so called pedestal runs. A run is a set of recorded ATLAS events. Pedestal runs are recorded in absence of beam. In a standard pedestal run 10^5 empty events are triggered randomly, and the energy in the channels is read out in the same way as for a physics run. The PMTs are read out in both high and low gain for each of these events so that the noise can be computed specifically for each amplification gain. The data from the pedestal run is used to evaluate the fluctuation in the calorimeter signal in absence of beam, thus allowing us to measure the electronic noise.

4.4.2 Usage

The pedestal runs defined above are used to compute two sets of noise constants:

- *Digital Noise* computed for each channel and gain and measured in ADC counts.
- *Cell Noise* constants corresponding to the noise of each calorimeter cell and gain combination, measured in MeV.

Noise from TileCal is measured over time and kept up-to-date in a database for a number of reasons. The most important application is its usage as input to the calorimeter cell clustering algorithm which in turn is used for jet reconstruction. Topological clustering [134] is the baseline algorithm to identify real energy deposits in the calorimeter and discriminate against fake deposits from random signal fluctuations. This algorithm groups neighboring cells with significant with significant signal over noise into clusters. Cells with measured energy deposit above a 4σ threshold are used as seeds, where σ is the measured cell noise for the specific cell. The algorithm then iterates to find neighboring cells with signal 2σ above the noise and finally in a third step adds all immediate neighbors to clustered cells regardless of the deposited energy. Electronic noise parameters are also used as input to the ATLAS trigger system [135]. Finally digital noise is used to monitor the detector performance at the channel level. Both the digital and the cell noise are used to accurately model the noise in ATLAS detector simulations.

4.5 Digital Noise

The digital noise constants are stored in the ATLAS conditions database. The noise constants consist of:

- The High Frequency Noise (HFN). It is determined for each channel by computing the RMS of the S_i of every event in the pedestal run, then taking the mean of all these RMS values in the pedestal run.
- The RMS of S_1 of each event, denoted Low Frequency Noise (LFN).

Dead channels are masked in this process and are not used.

4.6 Cell Noise

The cell noise is calculated after OF reconstruction of the energy following Eqs. 4.2 and 4.3, and calibration following Eq. 4.4, in pedestal runs. It is thus a combination of the two readout channels. Since most cells are read out by two channels there are four possible gain combinations for each cell: High Gain-High Gain (HGHG), Low Gain-Low Gain (LGLG) and the two combinations (HGLG and LGHG) where one channel is read out in Low Gain and one in High Gain. All four combinations need to be stored in the ATLAS conditions database for later use.

Figure 4.4 shows the mean ratio RMS/σ for 40 TileCal modules. The values of σ for the blue squares are obtained by fitting a Gaussian function to the energy distribution of the events in pedestal run 192130, recorded on October 31, 2011. For a perfectly Gaussian distribution $\text{RMS}/\sigma = 1$, but it is clear from the figure that for some channels this ratio is ~ 2 . Because of this non-Gaussian nature, using the standard deviation of a Gaussian distribution to define calorimeter cell seeds implies a degradation of the performance of the calorimeter. If a single Gaussian parametrization would be used in simulations, this would mean a large discrepancy between the number of topological clusters formed in data and in Monte Carlo simulations. For this reason the estimation of the significance of the energy deposition has to be modeled using a double Gaussian distribution function with three independent parameters to fit the energy distribution. The following double Gaussian pdf is used:

$$f_{2\text{gpdf}}(x) = \frac{1}{1+R} \left(\frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{x^2}{2\sigma_1^2}} + \frac{R}{\sqrt{2\pi}\sigma_2} e^{-\frac{x^2}{2\sigma_2^2}} \right) \quad (4.5)$$

where σ_1 and σ_2 are the standard deviations of the narrow and wide Gaussian respectively, and R is their relative normalization. As input to the topological clustering algorithm an equivalent standard deviation $\sigma_{\text{eq}}(E)$ is used, such that $\int_{-\sigma_{\text{eq}}}^{\sigma_{\text{eq}}} = 0.68$. This means there is a common unit for noise description for TileCal and LAr cells, so that the topological clustering algorithm is able to seamlessly cluster cells in three dimensions in both calorimeters even though the LAr calorimeter uses a single Gaussian description of the noise. The input to the topological clustering is σ_{eq} if $0.9\sigma_1 < E_{\text{cell}} < 7.5\sigma_2$. Otherwise the input is E/σ of the narrow (if $E_{\text{cell}} < \sigma_1$) or the wide (if $E_{\text{cell}} > 7.5\sigma_2$) Gaussian.

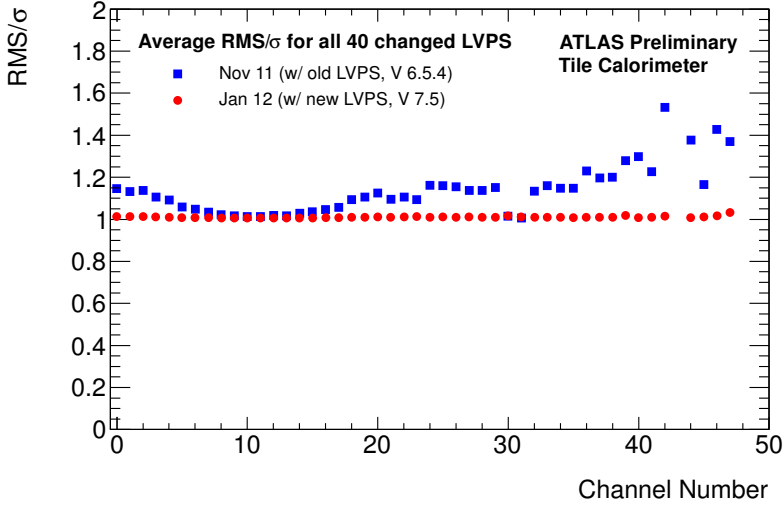


Figure 4.4: Ratio RMS/σ in all channels in the 40 version 7 LVPS (see Sec. 4.8) compared to when still using version 6.

4.7 Noise for ATLAS Monte Carlo Simulations

Monte Carlo simulations of TileCal cover the entire process from the simulation of particles interacting with the calorimeter material to the cell energy reconstruction. The process is divided into three steps: simulation, digitization and reconstruction (see Chap. 6 for more detail), and incorporates electronic noise. In the simulation step a hadronic shower is produced. It is then convoluted with the detector response and pulse shape function to simulate seven samples for each channel, after which the random noise is added to the energy in each cell in the digitization step. To simulate the electronic noise of a channel, random numbers are generated according to the double Gaussian pdf given in Eq. 4.5. Thus double Gaussian constants are needed on the channel level, while for real data taking double Gaussian constants are determined at the cell level.

The noise constants for simulations must be derived from data. Thus digital noise (HFN and LFN) and double Gaussian cell noise constants are produced from the pedestal run. The cell noise constants are then used to derive double Gaussian channel noise constants by reverting the energy reconstruction and calibration scheme presented in Sec. 4.3.

The channel level double Gaussian constants are then used to perform a detailed simulation of pedestal run events. The output of this simulation is used to re-measure noise constants for MC on the cell level. This procedure is necessary in order to maintain consistency between the MC digital noise and the MC cell noise. A closure test of the procedure is to check that the cell noise constants produced directly from the pedestal run are approximately the same as the cell noise constants produced from the digitization-reconstruction method described above.

Figure 4.5 shows the cell noise constants in the version of ATLAS simulation used in the searches for new physics in Part III of this thesis, denoted MC12. The simulated noise closely resembles the noise in real data taken in early 2012.

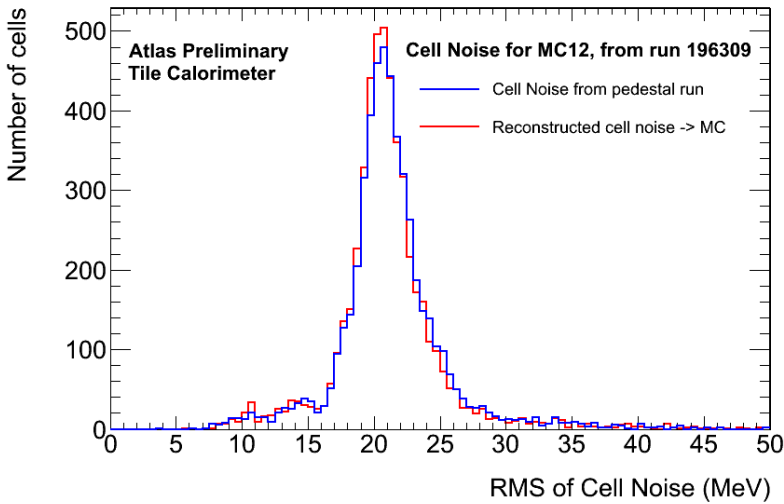


Figure 4.5: Comparison between cell noise in 2012 ATLAS data and in ATLAS Monte Carlo production MC12.

4.8 TileCal Low Voltage Power Supplies

In early measurements of electronic noise of TileCal performed during ATLAS test beam, with temporary Power Supplies, the shape of electronic noise was Gaussian. However, for the LVPS actually used in ATLAS between 2009-2012 (denoted as version 6), the noise increased. Furthermore the noise tails were

large, meaning the distribution of noise fluctuations was significantly differing from Gaussian behaviour and coherent among cells with similar values of $|\eta|$ inside a given TileCal module.

During the december 2010 LHC shutdown five new LVPS of version 7 were installed. The main reason to change the LVPS was to get rid of the high number of trips (more than six thousand in 2011). Tests of the LVPS version 6 show that one of the main factors contributing to the trips is the electronic noise. In version 6 transients originating in the switching procedure between readout voltage were seen. This led the LVPS to trip at lower current than expected. One of the design goals of the power supplies of version 7 was to reduce the noise by a number of techniques, among them improved grounding and implementation of noise filtering [136].

Studies of the noise in cells powered by these new power supplies show that the noise is lower, and that the shape is significantly more Gaussian. Only one trip from the new power supplies was recorded in 2011. In the december 2011 LHC shutdown an additional forty new LVPS of version 7 were installed. Thirty-nine of these were installed in LB modules, and one in an EB module. These forty modules are the subject of studies summarized in Sec. 4.10 where they are compared both to the performance of the same modules before the exchange, and to the 211 modules in which modules still had LVPS of version 6 in 2012. The five modules where LVPS were installed already in 2010 are not included in these studies. In addition to lower noise, version 7 does not suffer from the frequent spontaneous trips of version 6. These studies are summarized in Sec. 4.10.

4.9 Electronic Noise in 2011

Figure 4.6 shows the η -dependence of the cell electronic noise in the HGHG combinations. Each point is the mean value over all cells of a certain type (A, BC, D or E), at a given value of η . Differences among different cell types appear clearly. Only models with older LVPS of version 6 are shown in this figure. The mean RMS in HGHG is 23.5 MeV. However some cells have much higher values. These values can be compared to the energy deposited by a 10-30 GeV muon in a D cell, which is around 500 MeV [133]. Notably the cells with $|\eta| \sim 1$ have higher noise than cells near $|\eta| = 0$. This is true both for LB and EB cells, but more pronounced in the LB, where the cells of type A10 (located closest to the gap among LB cells) have a mean value close to 40 MeV. This structure

originates from the fact that the corresponding readout channels are closest to the LVPS and thus more susceptible to noise originating in these. Readout in HGHG is relevant when the deposited energy is below ~ 15 GeV and LGLG when above.

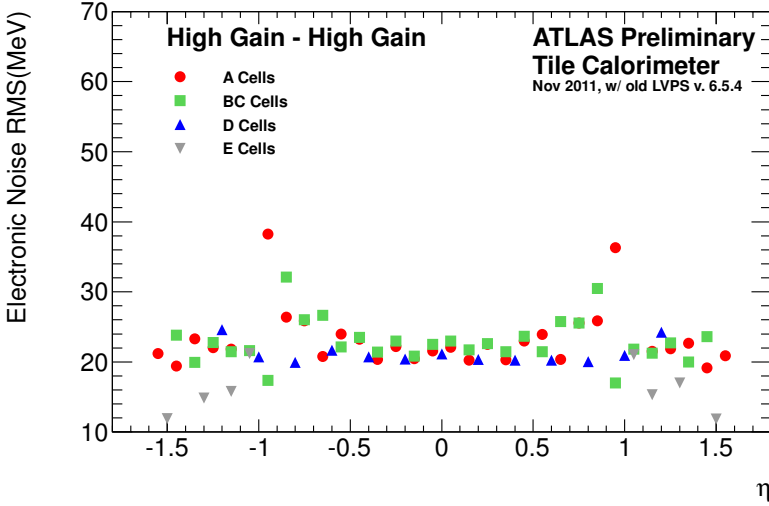


Figure 4.6: Cell noise as a function of η for the HGHG gain combination. Each point is the cell noise, averaged over all cells at a given η over all ϕ . The E cells with only one readout channel are read out in HG.

4.10 Electronic Noise with New LVPS

In this section we present the noise performance measured in 40 version 7 LVPS in 2011 data.

Noise Levels

As stated in Sec. 4.9 the average cell noise for modules with LVPS version 6 is 23.5 MeV. In run 195843 taken after the exchange of LVPS the average cell noise for these same cells is around 20.5 MeV, corresponding to a decrease of 13%. This is shown in Fig. 4.7. Another feature of the modules with version 7 appears in this figure, namely the absence of the high energy tail. The lowering

of the average cell noise is predominantly an effect of decreasing the number of cells with very high noise. The noisier channels have their electronics physically closer to the LVPS, this is also where cell noise decreases more sharply. If one considers the six cells closest to the LVPS³⁾ the average noise decreases by 22%.

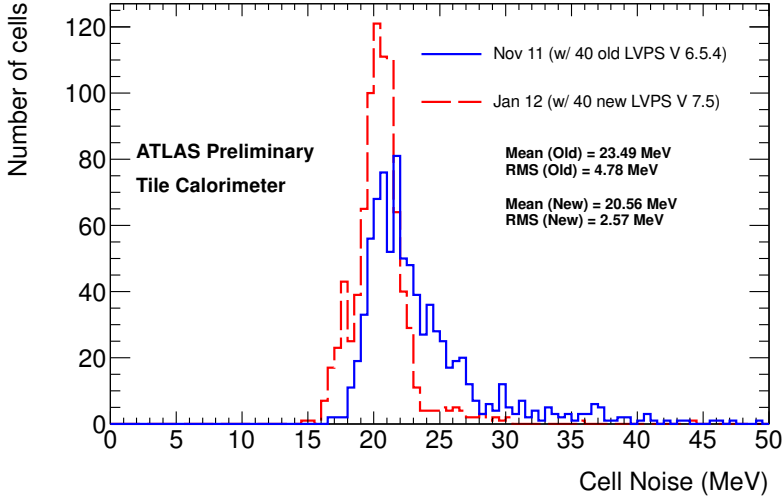


Figure 4.7: RMS of noise in cells in HGHG readout in the 40 modules with version 7 LVPS compared to the same modules in a run taken with version 6.

Noise Distribution

In the modules with new LVPS the noise appears to be closer to a Gaussian distribution. Figure 4.8 shows an illustration of this effect. The figure shows reconstructed energy in two pedestal runs 192130 and 195843, before and after the change of LVPS, for a single previously very noisy channel, channel 47 in LBC41. The distribution is clearly more Gaussian with version 7 LVPS. The RMS of cell noise in this particular channel is decreased by nearly a factor two.

Figure 4.4 shows that the ratio RMS/σ decreases for almost all channels in modules with LVPS version 7. Most channels now have a close to Gaussian noise distribution. It also shows that the improvement is greater for the channels

³⁾Cells of type A8, A9, A10, BC8, B9 and D3

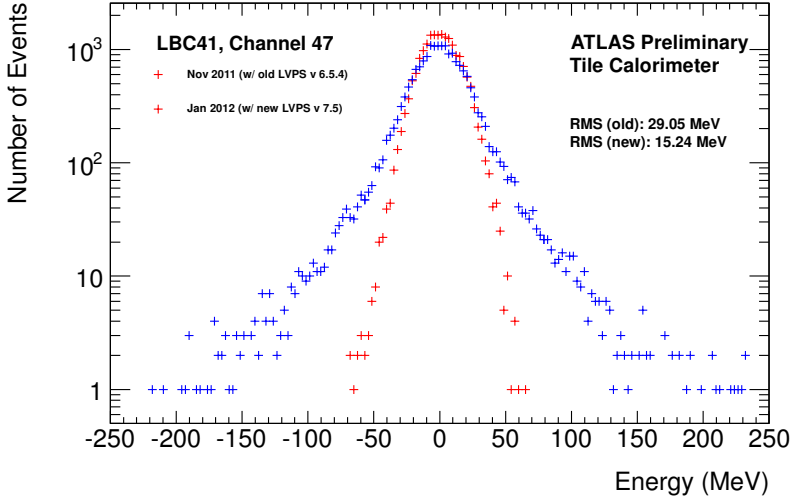


Figure 4.8: A comparison of reconstructed energy in pedestal runs in channel 47 LBC41 with LVPS version 7 and the older version 6.

close to the LVPS, in agreement with the conclusions of the previous section.

The improvement in the LVPS version 7 is also illustrated in Fig. 4.9 which shows the η -dependence of the mean electronic noise in the LB in the thirty-nine LB modules that were changed. This figure can be compared to Fig. 4.6. The LVPS are located at $|\eta| \sim 1.0$. It shows that with the new LVPS the noise is less η -dependent and more uniform over η and cell-type.

4.11 Conclusions and Further Developments

Measurements of the electronic noise in TileCal are used for monitoring the detector, as input to the topological clustering algorithm both in the trigger and offline, and to accurately model the ATLAS detector in Monte Carlo simulations.

Electronic noise in modules with LVPS version 6 differs between different cell types. The highest noise levels are found in cells around $|\eta| \sim 1$, i.e. closest to the power supplies. The cell noise ranges from 18 to 40 MeV in the HG HG gain combination. During these studies it was also found that the electronic noise does not change significantly over time.

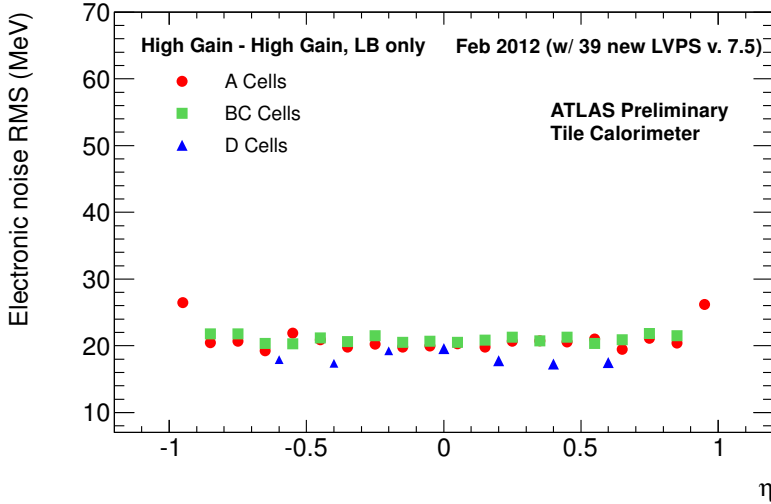


Figure 4.9: Cell noise as a function of η for the thirty-nine modules with version 7 LVPS in HGHG gain combination. The distributions is much flatter than in Fig. 4.6.

In the forty modules in which the Low Voltage Power Supplies have been exchanged to version 7 the noise is lower, and more closely follows a Gaussian distribution. The noise has on average been reduced by 13%. Both of these improvements are more pronounced in the high $|\eta|$ regions where the noise was previously the highest. After the change of LVPS, there is no longer a distinct correlation between high $|\eta|$ and high electronic noise. In the scope of this study it is also checked that the electronic noise in modules which did not have their LVPS changed remained at the same levels as before, in order to rule out any other source of the improvements.

A later more detailed study performed by members of the Tile collaboration shows that even with the new LVPS there are cells with high noise tails, and that the double Gaussian description is therefore still necessary.

During the 2012 data taking, one single trip was recorded from a Tile module with version 7 LVPS. This is to be compared with more than 6000 trips recorded in the modules still running with version 6. In the LHC Long Shutdown 1 in 2013-2014, all remaining modules had their LVPS changed to the newer version. The same kind of studies shown in this chapter have been performed, now

looking at all modules. When comparing the electronic noise after the shutdown to before, it is now on average lower, more Gaussian, and shows less correlation between neighboring channels. The frequent LVPS trips, which was one of the main issues with the performance of TileCal in Run 1, do not occur at all in Run 2.

Chapter 5

Particle Identification with ATLAS

This chapter introduces the physical objects used for the data analysis in this thesis, and describes how the detector systems and sub-detectors are used to identify and characterize different particles. We also introduce some of the quantities and variables that are specific to the monojet analysis.

5.1 Primary Vertices

A primary vertex is the point in space where a proton-proton interaction takes place. It is effectively found by looking for points where at least two tracks intersect close to the beam axis. In the monojet analysis an event is required to have at least one primary vertex. The primary vertex for which the sum of p_T of the associated tracks is the highest is considered as the vertex of interest, or "hard interaction vertex", for the analysis.

There is a high probability for each bunch crossing to have multiple proton-proton collisions - the expected number of collisions for each bunch crossing was 20.7 and 13.7 in 2012 and 2015 respectively. For each event selected for physics analysis there are energy deposits in the detector that originate in secondary interactions, so-called in-time pile-up interactions, that are not associated with the studied proton-proton interaction.

Additional contributions from pile-up can be received from earlier and later bunch crossings due to the fact that the detector read out windows are multiples of the bunch spacing, giving a probability that a process occurring in an event subsequent to the interesting collision will be recorded in the same event. These multiple collisions are called out-of-time pile-up.

5.2 Electrons

Electron candidates consist of a deposition of energy (cluster) in the EM calorimeter matched to a track in the ID. In order to find significant energy deposits the $\eta - \phi$ space of the EM calorimeter is divided into a grid of $N_\eta \times N_\phi = 200 \times 256$ towers, each covering 0.025×0.025 in $\eta \times \phi$. For each tower the energy in all cells in all longitudinal layers is summed to calculate the tower energy. These towers are then scanned using a sliding-window algorithm [134] in which a window of fixed size of 3×5 in $\eta - \phi$ space [137] is moved across the tower grid, and if the transverse energy of all towers contained in the window is a local maximum and exceeds a threshold of 2.5 GeV, a seed cluster is formed. If such a cluster can be matched to a track with sufficient number of hits in the ID, the cluster with its associated track is considered an electron candidate. If several tracks can be associated with the same cluster, a primary track is selected among those with hits in the Pixel detector based on the closeness in ΔR between track and cluster.

Electron objects are constructed from the seed clusters with associated tracks. This is done in all four layers of the EM calorimeter, by clustering $N_\eta \times N_\phi = 3 \times 7$ calorimeter cells in each layer, centered around the pre-cluster. The four-momentum of central electrons ($|\eta| < 2.47$) is computed using information from both the primary track and the EM cluster. After the electron object is reconstructed its energy is calibrated with correction factors derived from the decay of Z and J/Ψ to electrons in data.

5.2.1 Identification

Not all electron candidates are interesting for analysis. To determine if an electron is a signal-like object and not a background-like object such as a converted photon or a hadronic jet with a high fraction of electrons and photons, a number of algorithms for electron identification are applied. There are two types of identification algorithms used in ATLAS, *cut-based* and multivariate *likelihood-based* (LH) variants. They have in common the use of discriminating quantities based on shower shapes and widths in the various EM calorimeter layers, the number and quality of tracks in the ID, the fraction of high-threshold tracks in the TRT, the track-cluster matching and the hadronic leakage into the EM calorimeter.

The cut-based identification is based on sequential selections combined to classify the electrons as being loose, medium or tight, where medium is a subset

of loose and tight is a subset of medium. Tighter definitions mean the efficiency for identification is lower, but the purity of "true" electrons is higher. These cuts are optimized in 10 bins in $|\eta|$ and 11 bins in p_T to fully account for the difference in shower shapes depending on the amount of material passed by the electron before entering the calorimeter. The cut-based identification categories medium and tight are used in the 8 TeV analysis.

The LH identification instead uses the signal and background probability density functions of the discriminating variables. Using these a total probability of the candidate to be signal or background is calculated. The background and signal likelihoods are combined into an overall discriminant $d_{\mathcal{L}}$ defined as

$$d_{\mathcal{L}} = \frac{\mathcal{L}_S}{\mathcal{L}_S + \mathcal{L}_B} \quad \mathcal{L}_S(\mathbf{x}) = \prod_{i=1}^n P_{s,i}(x_i) \quad (5.1)$$

where $\mathbf{x}$ is the vector of discriminating variables applied and $P_{s,i}$ is the value of the signal pdf of the i^{th} variable evaluated at x_i . $\mathcal{L}_B$ is defined in the same way using the background pdf. The LH selection was developed to reject background events, while retaining the same efficiency of identifying electrons as the cut-based selection. Three different cut selections are defined, approximately as efficient as their cut-based equivalents. We refer to these as looseLH, mediumLH and tightLH. They yield 95%, 90% and 80% identification efficiency respectively at $p_T \sim 40$ GeV [138]. Each cuts on a combined LH discriminant defined by different discriminating variables. The LH-based identification categories looseLH and tightLH are used in the 13 TeV analysis.

5.2.2 Isolation

Electrons detected in the EM calorimeter may have different origins. There are the *prompt* electrons from the primary proton-proton interaction, and *non-prompt* electrons from secondary decays. In order to select prompt electrons, we require that they are separated from other particles. This will reject electrons that are produced by hadron decays within jets from heavy quarks as well as non-prompt electrons from highly electromagnetic hadron showers, since these will tend to have large depositions in calorimeter cells surrounding the reconstructed electron candidate. Thus isolation requirements are particularly important in regions in which processes faking electrons are more frequent. In the analysis described in Part III several different regions with different selection criteria

are defined. In some of these regions electron isolation is required in order to suppress background processes with non-prompt electrons. In others isolation would be redundant and isolation criteria are thus not applied to electron objects. Two complementary methods to find isolated electron objects are available:

- **Track isolation:** We define $p_T^{\text{cone},R}$ as the scalar sum of the p_T of the tracks within R around the electron, excluding the electron track. In Run 2 a slightly modified version of track isolation is used, in which the cone size is variable, and we thus define $p_T^{\text{vcone},R}$ as the scalar sum of the p_T of the tracks within $\Delta R = \min(R, 10 / p_T)$, where the p_T is expressed in GeV. The use of a variable cone size is to ensure not to cut too hard on very boosted topologies in which objects typically end up close to each other in the detector.
- **Calorimetric isolation:** We define $E_T^{\text{cone},R}$ as the energy deposited in calorimeter cells within ΔR around the electron object, excluding the energy deposit from the electron itself. This quantity is corrected for leakage from the reconstructed electron object into the cone and for pile-up.

When using the calorimetric isolation in Run 1 an additional correction for pile-up is performed. We define a new calorimetric isolation quantity I_{cal} as

$$I_{\text{cal}} = (E_T^{\text{cone},0.3} - a \cdot nVtx) / p_T \quad (5.2)$$

where $nVtx$ is the number of primary vertices with at least five associated tracks. The $a \cdot nVtx$ term corrects for pile-up events depositing energy in the calorimeter cells. The a constant is different for data and MC simulations to account for the mismodeling of isolation in simulations. This correction takes into account the difference in dependence of isolation on pile-up in data and MC.

In Run 1 the isolation variables are selected to maximize the sensitivity of the analysis, a procedure which is described in greater detail in Chap. 9. For Run 2 special isolation working points have been derived, where the exact cut values are defined in bins of p_T and $|\eta|$ of the electrons in such a way that a total efficiency to identify good electrons is obtained. The working point used in the Run 2 analysis is the *VeryLooseTrackOnly* isolation which only uses the $p_T^{\text{vcone},0.2}$ isolation variable, and has an identification efficiency of 99%.

5.2.3 Electron Kinematics

In order to further ensure that electron candidates originate from the primary vertex associated with the hard scatter, selection criteria with respect to the *impact parameters* may be applied. The transverse impact parameter d_0 and the longitudinal impact parameter z_0 are the distances of the point of closest approach of the extrapolated electron track to the primary vertex, in the transverse and longitudinal plane respectively. In the transverse plane a cut is applied to make sure d_0 does not deviate significantly from zero, by requiring the quantity $d_0/|\sigma_{d_0}|$ to be smaller than some threshold value. Here σ_{d_0} is the uncertainty (one standard deviation) on d_0 . In the longitudinal plane the cut is applied on the quantity $z_0 \sin\theta$ in order to avoid rejecting very forward tracks which are expected to have larger errors. No cuts on these parameters are used in the electron definitions in Run 1¹⁾, but are included in the definitions for Run 2. Unless otherwise stated the electrons are required not to be in the region $1.37 < |\eta| < 1.52$. This is the so-called crack region of the EM calorimeters where the electron purity is lower.

5.2.4 Electron Definitions

In Part III of this thesis several different categories of electrons are used to perform the analysis. They differ somewhat since they are defined within the scope of two different analyses, at 8 and 13 TeV. Additionally each analysis uses several electron definitions for different purposes. In this section a brief outline to the three general categories of electrons is given.

Generally we may divide the electron definitions into three categories, based on their function:

- The Veto electrons. This is the loosest category, used to veto events from processes with leptonic final states. They have very loose selection requirements and are not required to be isolated. The purpose of these loose requirements is to provide the most efficient rejection of background processes with electrons, such as production of leptonically decaying W or Z bosons in association with jets, diboson production or top quark production.
- The Z electrons, used to identify electrons from the decay of Z bosons in the CR2e_{corr} control region used in Run 1, and described in Chap. 9. These

¹⁾That is to say no *explicit* cuts are included, though it is worth mentioning that one of the discriminating quantities for electron identification is d_0

generally have tighter requirements than the Veto electrons, but may still be fairly loose due to the relative purity of such events in this region. Since this region also selects events using electron triggers with implicit cuts on the p_T , the p_T of the Z electrons must be higher than the Veto electrons. The Run 2 analysis does not use such a control region

- The W electrons, used to identify electrons from the decay of W bosons in order to construct the $\text{CR1e}_{\text{corr}}$ and CR1e control regions described in Chap. 9. These have tight requirements since the regions are more easily contaminated by non- W processes. Control regions based on a single electron can in particular be contaminated by multi-jet events where one jet is misreconstructed as an electron. This means harder isolation criteria are required to define the W electrons.

In the Tables 5.1 and 5.2 we summarize the electron definitions in the two analyses.

Parameter	Veto electron	Z electron	W electron
p_T [GeV]	>7	>20	>25
$ \eta $	< 2.47	< 2.47	< 2.47
Identification	Medium	Medium	Tight
Track Isolation	None	None	$p_T^{\text{cone},0.3} < 0.05 \times p_T^e$
Calorimeter Isolation	None	None	$I_{\text{cal}} < 0.05$
In Crack	Keep	Discard	Discard

Table 5.1: Summary of electron definitions used in the Run 1 analysis. "Keeping" Veto electrons in the crack region means that events with electrons in the crack will not be selected in the analysis.

5.3 Muons

A muon is identified by using track information from the ID and the MS. In this thesis two different procedures can be used to reconstruct a muon. One is the *combined* muon reconstruction, where tracks are reconstructed independently in the MS and the ID. A combined muon track is then formed if the match between the two is significant enough. The momentum of a combined muon is

Parameter	Veto Electron	W Electron
p_T [GeV]	> 20	> 20
$ \eta $	< 2.47	< 2.47
Identification	LooseLH	TightLH
Isolation	None	VeryLooseTrackOnly
$d_0/ \sigma_{d_0} $	-	< 5
$z_0\sin\theta$	-	< 5 mm

Table 5.2: Summary of electron definitions used in the Run 2 analysis. An important note is that for any electron definition using the TightLH identification, this is only used for electrons with $p_T < 300$ GeV, because of poor MC modeling of the TightLH for high p_T electrons in data. Above this threshold the LooseLH identification is used.

calculated using a weighted combination of the momentum of the ID track and the momentum of the MS track.

The other procedure is the *segment tagged* reconstruction. A track in the ID that is not associated to a combined muon is extrapolated to the MS, and if there are matching track segments in the MDT or CSC the candidate is identified as a muon. The momentum of such a muon is measured with ID track.

The combined reconstruction yields a purer muon sample, and the segment tagged reconstruction complements the combined reconstruction for low energy muons. For the analysis described in Part III of this thesis, both muon categories are used in the Run 1 analysis. The Run 2 analysis only uses combined muons. This means that the maximum $|\eta|$ allowed for muons in Run 2 is 2.5, whereas muons up to $|\eta| = 2.7$ are allowed in Run 1. After the muon object is reconstructed it is calibrated by correction factors derived from the decay of Z and J/Ψ to muons in data.

Quality requirements on the number of hits in the ID described in Ref.[139] are applied in both analyses. In Run 2 the Medium identification criteria described in Ref. [140] are applied. Muons are required to have at least three hits in at least two layers of the MDT chambers. Very central muons with $|\eta| < 0.1$ are excepted from these requirements, for these muons only three hits in at least one layer are required. The looser criterion for the central muons is to compensate for the lower sensitivity of the MDT in this region. In the Run 1 analysis

the muons are further required to be isolated so that the tracks inside a cone of $\Delta R < 0.2$ of the muon, excluding the muon itself, must have a summed p_T below 1.8 GeV. We denote this requirement as $p_T^{\text{cone},0.2} < 1.8$ GeV. In Run 2 no such isolation is required.

It is possible to categorize the various muon definitions into Veto, Z and W muons. In Run 1 the Z and W muon definitions are the same, and in Run 2 the Veto and Z muon definitions are the same. The similarity of muon definition is partly because of the use of a calorimeter-based trigger in the selections presented in Part III, which means that unlike the electrons, events do not have to pass a muon trigger. The similarity is also partly due to the fact that the CR1 μ Control Region introduced in Chap. 9 does not have a significant background from multi-jets, as opposed to the CR1e_{corr} Control Region.

In Run 2 similar requirements on the impact parameters $d_0 / |\sigma_{d_0}|$ and $z_0 \sin \theta$ as described for the electrons in Sec. 5.2.3 are included for the W muons to ensure they come from the primary interaction.

In Tabs. 5.3 and 5.4 the muon definitions used in the analysis in Part III are summarized.

Parameter	Veto Muon	Z/W Muon
p_T [GeV]	> 7	> 20
$ \eta $		< 2.7
Reconstruction	Combined or Segment Tagged	
Isolation	$p_T^{\text{cone},0.2} < 1.8$ GeV	

Table 5.3: Summary of muon definitions used in the Run 1 analysis

5.4 Jets

The base unit to reconstruct a hadronic jet is the topological cluster described in more detail in Sec. 4.4.2. These clusters are grouped into jets using the anti- k_t algorithm [141, 142] with radius parameter $D = 0.4$. This algorithm identifies as seed the highest- p_T cluster, and then proceeds to calculate the distance parameter

$$d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \left(\frac{\Delta R_{ij}}{D} \right)^2, \quad (5.3)$$

Parameter	Veto/Z Muon	W Muon
p_T [GeV]	>10 GeV	
$ \eta $	< 2.5	
Reconstruction	Combined	
$d_0/ \sigma_{d_0} $	-	< 3
$z_0\sin\theta$	-	< 5 mm

Table 5.4: Summary of muon definitions used in the Run 2 analysis.

between the seed cluster i and the closest ungrouped cluster j . If this is smaller than the distance parameter

$$d_{iB} = p_{T,i}^{-2} \quad (5.4)$$

between the seed and the beam axis the two clusters are combined to a new cluster which takes the role as seed. If not, i is called a jet and removed from the list of mergeable clusters. The highest cluster which is not already part of a jet takes the role as new seed, and the process continues until all clusters are part of jets.

After being constructed, the energy of the jet is corrected for leakage out of the jet object and for pile-up. Jets are calibrated for the non-compensating nature of hadron calorimetry, for the amount of dead material in the detector and for the leakage of energy from the jet out of the calorimeter. This is done using the Jet Energy Scale (JES) correction, which is a function of the pseudo-rapidity and transverse momentum of the jet.

5.4.1 Jet Quality

In order to distinguish jets originating in proton-proton collisions from misidentified jets from other sources, a number of cleaning criteria are defined. The main sources of such non-collision fake jets are beam induced background due to protons lost before the interaction point, cosmic-ray showers, and calorimeter noise, in particular from coherent noise in the LAr hadronic endcap. These sources are denominated Non-Collision Background [143]. Cleaning criteria that reject calorimeter noise include quality cuts on the pulse shapes in the HEC cells, as well as cuts on the total energy from cells with negative reconstructed

energy, which is indicative of jets with high levels of electronic noise and pile-up. The other criteria that reject NCB are

- The jet charge fraction f_{ch} , defined as the ratio of the scalar sum of the p_{T} of the tracks coming from the primary vertex associated with the jet, and the jet p_{T} . This is expected to be high for collision jets and low for non-collision jets.
- The electromagnetic fraction f_{EM} , defined as the fraction of the deposited jet energy that is deposited in the electromagnetic calorimeter. Collision jets have a very smooth distribution over the entire f_{EM} spectrum, while non-collision jets tend to have very high or very low f_{EM} .
- The maximum energy fraction deposited in any single calorimeter layer f_{max} , expected to be low for collision jets and high for non-collision jets.

In the analyses introduced in Part III requirements on these three quantities, as well as quality cuts on pulse shapes in the LAr detector are applied on all jets with $p_{\text{T}} > 20$ GeV according to the BadLoose criteria defined in Ref. [144]. Jets that pass these cleaning cuts are considered *Baseline* jets. Any event with a jet object with $p_{\text{T}} > 20$ GeV that does not pass these cleaning criteria is discarded from the analysis. A baseline jet with $p_{\text{T}} > 30$ GeV is considered a *good* jet, provided it also fulfills $|\eta| < 4.5$ in Run 1, or $|\eta| < 2.8$ in Run 2.

For the highest p_{T} jet in the event the additional requirement $f_{\text{ch}} / f_{\text{max}} < 0.1$ is added [144]. This requirement was introduced in the 8 TeV monojet analysis [2] because of the similarity in event topology between the monojet-type event and the NCB.

In order to reject jets from pile-up events baseline jets in the Run 2 analysis are also required to pass a cut on the Jet Vertex Tagger variable [145]. This variable is a multivariate combination of two variables that suppress jets from pileup. The result is a 2-dimensional likelihood, where one variable is the fraction of track p_{T} associated with the jet that originates in the hard scatter vertex, and the other is the ratio of the sum of the track p_{T} associated with the jet to the fully calibrated and pile-up corrected p_{T} of the jet object. From this likelihood the JVT distribution for hard-scatter and pile-up jets is calculated, and efficient cuts are constructed. The JVT efficiency does not depend on the number of primary vertices in the collision event, which makes it a robust pile-up discriminant. In the 13 TeV analysis presented in Part III all baseline jets with

$p_T < 50$ GeV and $|\eta| < 2.4$ must have $JVT > 0.64$ which corresponds to a 92% efficiency for hard-scatter jets and a 2% fake rate. Above $p_T > 50$ GeV the probability that the jet originates in pileup is negligible.

5.4.2 Identification of B-jets

The identification of jets containing b-hadrons is denoted b-tagging, and has many important applications. In the 8 TeV monojet analysis it is used to estimate the uncertainties associated with top quark production. In the 13 TeV analysis it is not used. Algorithms for b-tagging exploit the long lifetime of b-hadrons, as well as their high mass and high jet multiplicity. The working point selected for the 8 TeV analysis has an efficiency of 90% to identify b-jets, and is calculated using the artificial neural network MV1 algorithm [146].

5.5 Photons

Photons are reconstructed as isolated objects with most of their energy deposited in the EM calorimeter. The photons are categorized as being converted or unconverted depending on if the first conversion to an e^+e^- pair takes place before or inside the EM calorimeter. The former will have tracks in the ID pointing to the cluster, whereas the latter will not. Photon reconstruction begins just like the electron reconstruction described in Sec. 5.2 with the identification of a cluster in the EM calorimeter and a subsequent attempt to match this cluster to tracks in the ID. If no such track is found the object is treated as an unconverted photon. If there are tracks consistent with a photon conversion in the ID, the object is reconstructed as a converted photon. In the analyses presented in Part III, photons are never explicitly used, but they form part of the missing transverse momentum in Sec. 5.7.

5.6 Overlapping Object Removal

The reconstruction algorithms described in the previous sections are not mutually exclusive. It is possible for a single deposit in the detector to be reconstructed as several different objects, and thus be added to several collections. This ambiguity must be remedied by removing one or both of the overlapping objects. In the Run 1 analysis presented in Part III the only overlap removal performed is a removal of any jet in an electron control region that is within

$\Delta R < 0.2$ from an electron. In the Run 2 analysis the following objects are removed:

- Any baseline jet within $\Delta R(e, j) < 0.2$ with respect to an electron of at least Veto quality.
- Any electron of at least Veto quality within $0.2 < \Delta R(e, j) < 0.4$ with respect to a baseline jet.
- Any baseline jet with less than three tracks within $\Delta R(\mu, j) < 0.4$ with respect to a muon of at least Veto quality.
- Any muon of at least Veto quality within $\Delta R(\mu, j) < 0.4$ with respect to a baseline jet with at least three tracks.

5.7 Missing Transverse Momentum

The missing transverse momentum E_T^{miss} is defined as the magnitude of the 2-dimensional negative vector sum of the momenta of all reconstructed objects and deposits in the detector for a given event, in the plane perpendicular to the beam. This vector sum is written:

$$\mathbf{E}_T^{\text{miss}} = - \sum \mathbf{p}_T^{\text{jet}} - \sum \mathbf{p}_T^e - \sum \mathbf{p}_T^\mu - \sum \mathbf{p}_T^\gamma - \sum \mathbf{p}_T^{\text{soft}} \quad (5.5)$$

where the $\sum \mathbf{p}_T^{\text{soft}}$ are deposits in the detector which are not associated to any muon, photon, electron or jet. The p_T of each object is the final calibrated p_T of reconstructed objects. The soft term is calculated in two different ways in the two different analyses in Part III. In the Run 1 analysis the soft term only makes use of the calorimetric depositions not associated to an electron, muon, photon or jet. In Run 2 this is instead replaced by a track-based algorithm [147] which identifies tracks that pass some basic quality cuts but are not associated to a reconstructed particle. The use of the track-based soft term makes the calculation less sensitive to pile-up than using the calorimeter soft term, but on the other hand does not include contributions from soft neutral hadrons.

The importance of the E_T^{miss} variable can be understood from the fact that while the p_z of the incoming partons is unknown, conservation of momenta in the transverse plane means that the transverse vector momenta of the outgoing particles after a proton-proton collision should sum to zero within detector resolution. If the E_T^{miss} is not zero, some momentum is carried by particles invisible

to the detector. These particles might be neutrinos, or other weakly interacting particles such as the WIMPs described in Sec. 2.3.2 or the gravitons described in Sec. 2.2.1.

In the search for new physics presented in this thesis, the muon term in the sum of Eq. 5.5 is left out. This definition of missing transverse momentum is thus a quantity measured only by using the calorimetric energy depositions. We define the quantity $E_{T,\text{calo}}^{\text{miss}}$ as the magnitude of the following vector.

$$\mathbf{E}_{T,\text{calo}}^{\text{miss}} = - \sum \mathbf{p}_T^{\text{jet}} - \sum \mathbf{p}_T^e - \sum \mathbf{p}_T^\gamma - \sum \mathbf{p}_T^{\text{soft}} \quad (5.6)$$

In an event with a Z boson decaying to two neutrinos the E_T^{miss} will be equivalent to the transverse momentum of the Z boson, provided all momenta are measured perfectly. In the data-driven background estimation methods presented in Chap. 9 we introduce control regions where specific selection criteria are applied to select events in which a W or Z boson decays to final states with electrons. In order to use these events to measure the boson p_T , the electrons are removed from the $E_{T,\text{calo}}^{\text{miss}}$ to yield a new quantity $E_{T,\text{corr}}^{\text{miss}}$, which becomes a proxy for the momentum of W and Z boson when they decay to electrons. The $E_{T,\text{corr}}^{\text{miss}}$ is the magnitude of the vector

$$\mathbf{E}_{T,\text{corr}}^{\text{miss}} = - \sum \mathbf{p}_T^{\text{jet}} - \sum \mathbf{p}_T^\gamma - \sum \mathbf{p}_T^{\text{soft}} \quad (5.7)$$

5.8 Invariant and Transverse Mass

The invariant mass is a characteristic of the energy and momentum of a system of particles. In the lab reference frame, the square of the invariant mass M_{12} of two particles denoted as particle 1 and 2 becomes

$$M_{12}^2 = (E_1 E_2 - \mathbf{p}_1 \mathbf{p}_2) \quad (5.8)$$

where E is the kinetic energy and $\mathbf{p}$ is the momentum 3-vector. In the ultra-relativistic limit the masses of electrons and muons are negligible in relation to the momenta and energies.

The *transverse mass* of two Lorentz vectors is defined as [148]

$$M_T = \sqrt{2p_T^1 p_T^2 (1 - \cos(\Delta\phi))} \quad (5.9)$$

where $\Delta\phi$ is the separation in azimuthal angle ϕ between the two. This variable is useful in cases when one of the two decay products is invisible, for example in the case of a W decay to a charged lepton and a neutrino, in which case Eq. 5.10 becomes

$$M_T = \sqrt{2E_T^{\text{miss}} p_T^l (1 - \cos(\Delta\phi_{l,E_T^{\text{miss}}}))} \quad (5.10)$$

In this case the transverse mass of the charged lepton vector and the E_T^{miss} vector has a kinematic edge at the W mass. The invariant and transverse mass variables are used to select events consistent with the decay of Z or W bosons in the control regions defined in Chap. 9.

5.9 Systematic Uncertainties

Several systematic uncertainties are associated with the identification and reconstruction of physics objects, the calibration scale of the detector subsystems and the luminosity and pile-up conditions. These are referred to as experimental systematic uncertainties. The following categories of experimental systematic uncertainties are defined:

- The *Jets/ E_T^{miss}* category includes uncertainties from the reconstruction and calibrations of jets and E_T^{miss} . For jets there is an uncertainty associated with the knowledge of the jet energy scale calibration, and additionally an uncertainty from the jet resolution. The uncertainties associated uniquely with the E_T^{miss} come from the uncertainty on energy calibration and resolution of the soft E_T^{miss} term in Eq. 5.6. Finally this term also contains the uncertainty on the amount of pile-up, affecting calorimeter corrections to jets and electrons.
- The *Leptons* category includes uncertainties associated with the selection of electrons and muons. It includes the uncertainty on electron identification and reconstruction efficiency as well as on the energy measurement of electrons, the efficiency of the electron trigger and the momentum and identification efficiency of muons.
- *Luminosity* is the uncertainty on the absolute recorded luminosity. This uncertainty is estimated as 2.8% for the full Run 1 integrated luminosity,

and 5% in for the Run 2 2015 data integrated luminosity. The chosen strategies for estimation of backgrounds presented in Chap. 9 lead to a minimal impact of luminosity uncertainty on the analysis

The impact of these uncertainties on the analyses performed in Part III is calculated by independently varying the different parameters in the simulated background and signal samples up and down by one standard deviation, and for each such variation re-performing the event selection of the analysis. The variations are also propagated to the E_T^{miss} estimations.

Chapter 6

Physics Simulations in ATLAS

6.1 Introduction

To properly estimate the backgrounds to any analysis as well as provide precise estimates of signal yield for a given theoretical model for BSM physics, Monte Carlo simulation methods are used. In this section the event generation process is described, introducing many of the concepts applied in Chap. 8 when studying the specific generation process for ADD models. The first step is the event generation, which is described in Sec. 6.3. In this step the collision between two partons is simulated, and the output is a number of four-vectors that describe the energy and momenta of final state particles. There are various schemes to generate events, much of it comes down to which order in the expansion of the scattering matrix described in Sec. 1.5 to include. Thus generation may take place at leading order (LO), next-to-leading order (NLO), next-to-next-to-leading order (NNLO), or sometimes a mixture of these depending on what process is simulated. This chapter also describes the various scales involved in these interactions, and the complications involved when combining simulations at these widely differing scales.

The description of event generation is followed by a brief description of the steps in which the particles produced in the event generation step are used in simulations of the detector response and finally reconstructed with the same algorithms used for real collision events in Sec 6.4.

6.2 Describing the Proton at High Momentum Transfer

The proton is a baryon consisting of three *valence quarks*. Each of these quarks carries a part of the proton momentum, denoted x . Experimentally it is found that around half the momentum of the proton is carried by virtual gluons and virtual quark-antiquark pairs inside the proton. The distribution of the momentum among the partons (quarks and gluons) must fulfill

$$\int_0^1 x \sum_i f_i(x) dx = 1 \quad (6.1)$$

where $f_i(x)dx$ is the probability of finding a parton of type i carrying a fraction of the proton momentum between x and $x + dx$, called a Parton Distribution Function (PDF). The PDF is not predicted by QCD, but instead parametrized to fit measured data. Figure 6.1 shows the PDFs of the proton, measured at $Q^2 = 10 \text{ GeV}^2$ and $Q^2 = 10 \text{ TeV}^2$.

There are a number of PDF sets available, all based on precision measurements at various energy scales. Several of the sets are used to estimate various processes in the analysis presented in Part III. The details are presented in Chap. 8.

6.3 Event Generation

Exact determinations of the multi-particle final states of high-momentum particle collisions beyond the first few orders in perturbation theory is not possible in practice due to the very cumbersome calculations. Thus the last few decades have seen a development of a multitude of Monte Carlo simulation techniques to provide as accurate computations as possible [150].

The momentum scales of the different physical processes involved in a proton-proton collision are very different, from the scale of the primary interaction which in the LHC ranges all the way up to several TeV, to the $\sim \text{GeV}$ scale of hadronization. The former represents a scale at which QCD is perturbative and the matrix elements can be calculated using the methods described in Sec. 1.5, while the latter is non-perturbative and can only be phenomenologically modeled. These two distinctly different scales are connected by parton showering. This is the process in which the partons formed in the primary interaction and the initial state partons radiate additional partons until the relative momenta are at hadronization-levels.

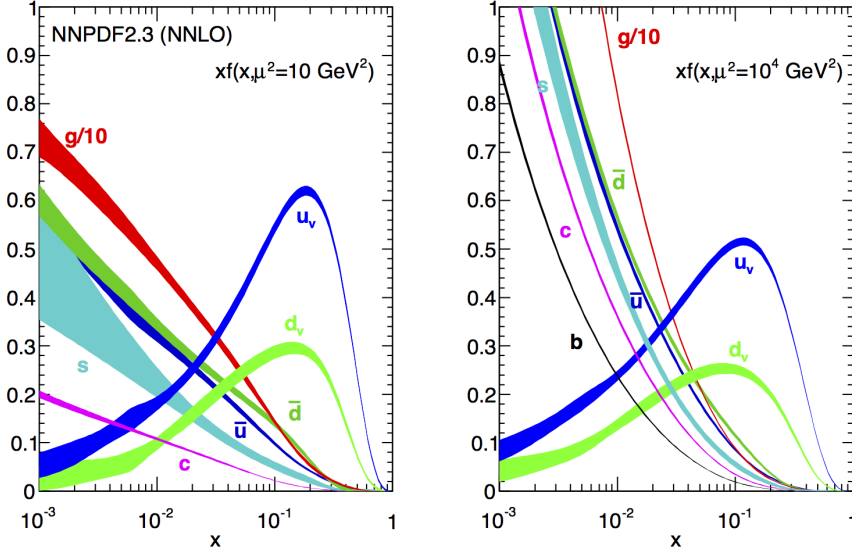


Figure 6.1: The distribution of x times the PDF for the different parton flavors, at momentum transfer $Q^2 = 10 \text{ GeV}^2$ (left) and $Q^2 = 10 \text{ TeV}^2$ (right). For $q_i \neq u, d$, the PDF for the quark is taken to be equal to that of the antiquark. Figure from Ref. [149].

6.3.1 The Primary Interaction

Any collider simulation is built around the hard primary interaction. The hard process is specified by the user, and is generated using the matrix element from the underlying theory and according to the available phase space. This can be done using the LO terms for the given processes, but some generators also include loop corrections to NLO. The cross section for a process $ab \rightarrow n$ at a hadron collider can be given by [151]

$$\sigma = \sum_{a,b} \int_0^1 dx_a dx_b \int f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) d\hat{\sigma}_{ab \rightarrow n} \quad (6.2)$$

where f_a^h is the PDF describing the probability to find parton a in hadron h carrying a fraction x_a of the hadron's total momentum, given a *factorization scale* μ_F . The factorization scale is a parameter added to factorize the long-

distance, low momentum and collinear part of the theory, from the high momentum, short distance and non-collinear part [152]. The first piece is factorized into the PDF part of the cross section calculation. Finally, $\hat{\sigma}_{ab \rightarrow n}$ denotes the parton level cross section for production of a final state n given the initial state partons a and b , and can be rewritten to yield Eq. 6.2 on the form

$$\sigma = \sum_{a,b} \int_0^1 dx_a dx_b \int d\Phi_n f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) \times \frac{1}{2\hat{s}} |\mathcal{M}_{ab \rightarrow n}|^2(\Phi_n; \mu_F, \mu_R). \quad (6.3)$$

Here the second integral is now over the final-state phase space Φ_n , the matrix element $|\mathcal{M}_{ab \rightarrow n}|$ is averaged over all initial spin and color degrees of freedom, $\hat{s}$ is the squared center-of-mass energy of the colliding hadrons and μ_R is the *renormalization scale*. The renormalization scale is introduced as a cut-off to prevent divergences in the ultraviolet high-energy limit.

The cross section in Eq. 6.2 depends on the chosen factorization and normalization scales. The choice of scale is arbitrary - from theory there is no specific scales that are more correct than any other. We should however select such scales that are reasonable from the QCD phenomenology [150]. More "natural" scales are typically those already built into the interaction, such as the momentum transfer or the transverse energies of the final state partons.

The LO cross sections are often corrected by a so-called K-factor, which is the rate of the full NLO cross section to the full LO cross section. Thus, though the kinematics may still be calculated only at LO, the overall normalization can actually be from a NLO calculation.

6.3.2 Adding More Jets

Colored or charged particles present in the initial or final state can radiate gluons and photons. A radiated gluon can split into a quark and antiquark, while a quark can radiate gluons. Final state radiation of a generated two-body final state means going through an evolution of successive radiation and splitting of partons, from the initial hard scale to the non-perturbative hadronization scale $Q_0 = \mathcal{O}(1 \text{ GeV})$. Two approaches exist to describe this evolution [153]. The first is a complete matrix element treatment in which all Feynman diagrams are calculated. This, however exact, is very difficult for higher orders. Instead

the parton shower approach is usually used, in which the matrix elements are approximated via simplifications of the kinematics in the radiative process.

Initial state radiation is modeled in a similar way as final state radiation, but the showering is worked out through a backwards evolution in time. After the initial state is produced, the probability that each initial state parton originally came from a parton with a higher momentum is calculated. This is iterated until the full initial state showers are produced [153, 150].

Parton showering is an empirical model, which works very well for the low p_T part but tends to underestimate the number of high p_T jets. In practice a compromise is often struck between the cumbersome but exact matrix element calculations and the faster but less precise parton showers, in that the first few radiated jets are calculated up to NLO, while the rest of the radiation is added through parton shower. This is the case for many of the processes described in Chap. 8.

Combining the matrix element description of the hard process to the shower without double counting parts of phase space is a non-trivial challenge. This process is known as *matching*, and several matching schemes are extensively described in Ref. [150].

6.3.3 Hadronization

Hadronization in event generators is the process to form final state hadrons from the partonic final state of the parton shower. Perturbation theory does not apply, and instead a phenomenological, probabilistic model must be applied. The PYTHIA event generator uses the Lund string model [154]. The starting point for this model is the confinement at large distances in QCD, as described in Sec. 1.4. For a quark-antiquark pair moving apart, the strong force between them is approximated to increase linearly with distance. This is modeled by a color flux tube of hadron size, stretching between the two. As the partons at distance r move further apart, the potential $V(r) = \kappa r$ increases, until it breaks when the potential energy stored in the string is large enough to produce a quark-antiquark pair, thus forming new hadrons. The string constant κ is ~ 1 GeV/fm. Production of heavier quarks (c and b) is not allowed at the string breaks, but they can exist at the string endpoints if such flavors are present at the start of hadronization.

After the hadrons are formed, the final step in the event generation is the decay of such hadrons whose decay length is much shorter than the size of the

detector. Hadrons with long enough lifetimes are propagated to the detector elements where the interaction with matter is simulated, as described in Sec. 6.4.

6.4 From Generated Events to Reconstructed Objects

The output of the event generation is a four-vector for each final state particle. These are used as input to detector simulation, the first step in a chain that leads to particles identified in the ATLAS detector:

- In the *Detector Simulation* step the output hadrons from the hadronization are taken as input. In this step the interaction of the generated particles with the detector material is simulated. This is done using GEANT4 [155]. By stepwise calculating the interaction of the particles with the matter, the energy deposition in every part of the detector is simulated. The energy deposits is the output of the detector simulation step.
- The *Digitization* step converts these energy deposits into detector read-out signals. Detector effects such as electronic noise or pile-up events from secondary proton-proton interactions are added to the detector signals.
- Finally, in the *Reconstruction* step the simulated detector read-out is processed by the same algorithms that are employed by ATLAS to process the raw detector data to identify particle such as electrons, muons, tau leptons, photons, hadrons and jets. The physics observables are constructed, and the events are stored in similar data structures as real data.

Part III

The Monojet Analysis

The language of the Pythia illustrates what mathematicians mean by calling a straight line the shortest between the same points; it makes no bending, or curve, or doubling or ambiguity; it lies straight towards truth; it takes risks, its good faith is open to examination, and it has never yet been found wrong...

Plutarch, *Why the Pythia does not Now Give Oracles in Verse*
(from *Moralia*)

You're trying to deliver a message to your team that things are OK back here. This end of the ice is pretty well cared for.

Ken Dryden, *The Game*

Chapter 7

New Physics in the Monojet Final State

7.1 Introduction

Searches for new particles at particle colliders is a wide field with many possible final states. When searching for new heavy particles that promptly decay, there are two broad main classes of particles. Those whose decay products are all detectable by the detector, and those where some of the final state particles are undetectable. The first category is usually addressed by looking for a peak in the invariant mass of the decay products, while the second category relies on the presence of missing transverse momentum in combination with detectable objects (such as leptons or jets). The kinematics of the visible objects is the only information that can be used in the ATLAS trigger to record the event.

It can for certain processes occur that there are no detectable final state particles in the event. This is the case if the final state particles have momenta that are too low to be measured by ATLAS, or if there are simply no detectable particles in the final state. This type of events calls for a third category of search where the invisible particles is required to recoil against some initial state radiation. The recoil will provide a boost to the low momentum final states and in the most extreme cases only the recoiling ISR object can be seen as recoiling against a visible object in the detector.

Monojet events appear in models with pair production of two invisible particles, which is a process in the third category with a jet in the final state. They also appear in models allowing the production of a single quark or gluon together with one or more invisible particle. In these models the events fall in the second

category, as the simplest possible search with missing transverse momentum and detectable objects.

Monojet events are characterized by a highly energetic hadronic jet and high missing transverse momentum in the final state. Such events constitute a simple and clean signature when searching for physics beyond the Standard Model at colliders. The absence of such events above the SM expectations can constrain the parameter space of a number of scenarios for new physics.

The ATLAS monojet results are interpreted in the following scenarios:

- The ADD model for large extra spatial dimensions described in Sec. 2.2.1. In this framework, a parton is produced in association with a graviton which is invisible to the detector.
- Pair production of WIMPs as described in Sec. 2.3.5, in association with the initial state radiation of a jet.
- Searches for supersymmetry. The Run 1 ATLAS analysis [2] sets limits on Gauge Mediated Symmetry Breaking models with a final state gravitino [156]. The Run 2 ATLAS analysis [3] sets limits on supersymmetric models in which the mass gap between the two lightest particles is very small. The small mass gap implies that the final state jets produced in the decay of the NLSP to the LSP are very soft, meaning ATLAS SUSY searches for final states with multi-jets and missing transverse momentum lack sensitivity to this type of signature. If the production of supersymmetric particles is associated with the initial state radiation of a hard jet, the monojet analysis will be sensitive to these final states. This search is interpreted in terms of production of the supersymmetric partners of the four lightest quarks as well as in terms of production of the supersymmetric partners of the SM bottom and top quarks. In all these models the squarks are assumed to decay directly to SM quarks and neutralinos.
- Searches for invisibly decaying Higgs bosons in association with initial state radiation of a jet. This search is so far only performed with the ATLAS Run 1 data.

The last two interpretations lie outside the scope of this thesis, but the background estimations calculated in the following chapters are also used for these model interpretations in the two ATLAS monojet papers [2, 3]. Figure 7.1 show

Feynman diagrams illustrating graviton production, WIMP production and production of SUSY particles in association with an ISR jet.

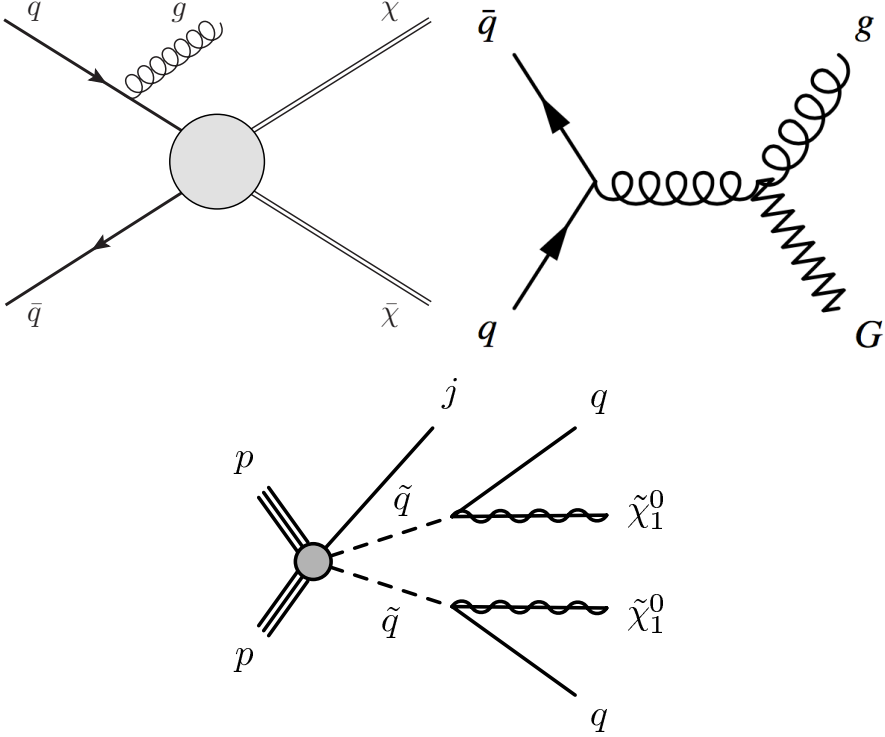


Figure 7.1: Example Feynman diagrams for WIMP pair production in the EFT framework (upper left), graviton production in the ADD scenario (upper right) and an illustration of a SUSY scenario with production of squarks which decay to neutralinos and quarks, with radiation of an ISR jet (lower).

This part of the thesis is dedicated to searches for gravitons in the ADD scenario and WIMPs. The remainder of Chap. 7 is dedicated to definitions of observables and event selection defining the signal regions in the two analyses at 8 and 13 TeV LHC center-of-mass energy respectively. This chapter also briefly introduces the main SM backgrounds to the sought BSM signals.

Chapter 8 introduces the simulations used in the background estimations, as well as the simulations of signals from specific models. The emphasis in this chapter is on the ADD signal simulations, since these were performed by

the author of this thesis for the Run 2 analysis. Systematic errors specifically associated with theoretical uncertainties in the simulation process are introduced and estimated.

Chapter 9 describes the process of estimating the SM backgrounds as well as their impact on the sensitivity of the analysis. The main background to the monojet signal comes from the decay of Z and W bosons to leptons and neutrinos, in association with jets. This background is modeled using dedicated control regions, similar in construction to the signal region, but enriched in W and Z decays to charged leptons. The main focus of the chapter is the construction of these control regions, as well as the methods to extrapolate the results from the control regions to the signal region. Special attention is given to the control regions with electrons used in the Run 1 analysis, as the construction of these was studied and proposed by the author of this thesis. Chapter 9 also briefly describes the methods used to estimate other backgrounds, and introduces the systematic errors on background and signal processes from experimental uncertainties.

The results using the estimated signal and background yields with the monojet selection are interpreted as limits on new physics in Part IV.

7.2 Data Collection

The data used in this thesis was collected using the ATLAS detector in 2012 and 2015. The 2012 data was collected in the JetTauEtmis data stream, and selected using the trigger EF_xe80_tclcw. The suffix tclcw indicates that topological clusters are constructed throughout the detector and used as input to the E_T^{miss} calculation used for the trigger decision. This trigger selects events with $E_{T,\text{calo}}^{\text{miss}} > 80$ GeV reconstructed in the high level trigger, and is more than 95% efficient for events with $E_{T,\text{calo}}^{\text{miss}} > 150$ GeV after calibration of all objects. The data collected in 2012 corresponds to a total integrated luminosity of 20.3 fb^{-1} . The 2015 data was selected using the trigger HLT_xe70 which selects events with $E_{T,\text{calo}}^{\text{miss}} > 70$ GeV, and is more than 99% efficient for events with $E_{T,\text{calo}}^{\text{miss}} > 250$ GeV. The data collected in 2015 corresponds to a total integrated luminosity of 3.2 fb^{-1} .

7.3 Signal Region Definitions

The monojet analysis is a search for events with very high $E_{T,\text{calo}}^{\text{miss}}$ back-to-back with a highly energetic jet. Beyond these baseline selection criteria, dedicated

cuts are applied to reduce SM backgrounds while retaining as many events as possible from the BSM signals. The two analyses performed with 8 TeV and 13 TeV data use somewhat different selection criteria, partially due to the difference in LHC center-of-mass energy, and partially due to the different signal models considered in the two analyses. The selection criteria that are common to the two analyses are:

- There must be at least one primary vertex. This suppresses backgrounds not originating in a proton-proton collision.
- Events must have high $E_{T, \text{calo}}^{\text{miss}}$, at least 150 GeV in the analysis of 8 TeV data and 250 GeV in the analysis of 13 TeV data.
- There must be a highly energetic jet, with $p_T > 120$ GeV in the analysis of 8 TeV data, and $p_T > 250$ GeV in the analysis of 13 TeV data.
- The highest p_T jet of the event must fulfill the baseline criteria defined in Sec. 5.4, as well as the harder cuts devised in the same section to suppress NCB events (see Sec. 5.4.1). It must also be central, with $|\eta| < 2.0$ in the 8 TeV analysis and $|\eta| < 2.4$ in the 13 TeV analysis.
- Events are discarded if there is any jet with $p_T > 20$ GeV present which does not fulfill the baseline cleaning criteria defined in Sec. 5.4.1.
- A minimal azimuthal angular difference between the $E_{T, \text{calo}}^{\text{miss}}$ vector and any good jet is required. This selection is imposed to suppress multi-jet events with misreconstructed E_T^{miss} . The angular difference is required to be $\Delta\phi > 1.0$ in the 8 TeV analysis and $\Delta\phi > 0.4$ in the 13 TeV analysis.
- Events are discarded if they contain one or more electrons or muons of Veto quality, as defined in Secs. 5.2.4 and 5.3. This suppresses events with W and Z bosons decaying to leptons.

Monojet analyses conducted prior to the 8 TeV analysis all had an upper limit on the number of allowed jets. The ATLAS analysis using the 4.7 fb^{-1} of data with 7 TeV center-of-mass energy collected in 2011 [58] did not consider any events with three or more good jets (as defined in Sec. 5.4.1). To increase the sensitivity to BSM models with high jet multiplicity the selection for the 8 TeV analysis has no limit on the number of jets. Nevertheless to ensure a

monojet topology still dominated by the leading jet in the 8 TeV analysis, and to reduce the background from hadronically decaying top quarks, the leading jet is required to fulfill $p_T/E_{T,\text{calo}}^{\text{miss}} > 0.5$.

For the 13 TeV analysis events are required to have no more than four good jets. Thus the cut on the ratio of leading jet p_T and $E_{T,\text{calo}}^{\text{miss}}$ is no longer needed.

To further suppress backgrounds from W and Z bosons decaying to leptons, events with isolated, good quality tracks with $p_T > 10$ GeV are vetoed in the 8 TeV analysis. A track is considered isolated if there is no other track with $p_T > 3$ GeV in a cone of radius $\Delta R < 0.4$ around it. This selection removes events with isolated leptons missed by the lepton veto. More importantly it also reduces the background from hadronically decaying tau leptons, for which the lepton veto is less effective.

From this baseline selection, several signal regions are created by increasing the $E_{T,\text{calo}}^{\text{miss}}$ threshold. In the 8 TeV analysis these signal regions are inclusive, meaning that each region is a sub-region of all the regions with a lower $E_{T,\text{calo}}^{\text{miss}}$ selection threshold. These lower thresholds range from 150 to 700 GeV. For each signal model the region with the highest sensitivity when comparing the expected background and signal yield is used in the analysis. In the 13 TeV analysis the regions are exclusive and disjoint: each region is bounded from above by the lower bound for the next bin, except the region with the highest $E_{T,\text{calo}}^{\text{miss}}$ threshold which has no upper bound. The lower thresholds range from 250 to 700 GeV. This analysis combines the information from all signal regions to maximize the sensitivity to new physics. These methods are described in more detail in Chap. 9.

A summary of the signal region definitions can be found in Table 7.1. The $E_{T,\text{calo}}^{\text{miss}}$ thresholds of the signal regions used in the two analyses are given in Tables 7.2 and 7.3.

7.4 Backgrounds

Several processes within the Standard Model can produce the monojet final state. These need to be well understood and estimated as precisely as possible in order to maximize the sensitivity to new physics. Background processes considered in the analysis are, in order of importance:

- Production of a W or Z boson in association with at least one jet, where the boson decays into leptons. Most important is the decay of a Z boson into

Selection	8 TeV	13 TeV
Primary vertices	> 0	> 0
$E_{T,\text{calo}}^{\text{miss}}$	$> 150 \text{ GeV}$	$> 250 \text{ GeV}$
Leading jet	$ \eta < 2.0, p_T > 120 \text{ GeV}$	$ \eta < 2.4, p_T > 250 \text{ GeV}$
No. of Good Jets	No Limit	< 5
Jet Cleaning	✓	✓
$\Delta\phi(E_{T,\text{calo}}^{\text{miss}}, j_1)$	> 1.0	> 0.4
Lepton Veto	e, μ , isolated track	e, μ
$p_T(j_1) / E_{T,\text{calo}}^{\text{miss}}$	> 0.5	-

Table 7.1: The baseline definitions of signal regions in the 8 and 13 TeV monojet analyses.

Run 1 signal regions					
Name	SR1	SR2	SR3	SR4	SR5
$E_{T,\text{calo}}^{\text{miss}} [\text{GeV}]$	> 150	> 200	> 250	> 300	> 350
Name	SR6	SR7	SR8	SR9	
$E_{T,\text{calo}}^{\text{miss}} [\text{GeV}]$	> 400	> 500	> 600	> 700	

Table 7.2: The $E_{T,\text{calo}}^{\text{miss}}$ thresholds for the nine signal regions used in the 8 TeV analysis.

two neutrinos, which forms an irreducible background for the signal. The decay of W bosons to one neutrino and one charged lepton which escapes detection constitutes most of the remaining background. As previously mentioned, the hadronic decay of the tau lepton makes the W decay to a tau and a neutrino particularly hard to reduce. The decay of W or Z to a pair of charged leptons constitutes a minor background.

- Background originating from production of $t\bar{t}$ quark pairs and single top quarks. The final state of such events will have multiple jets and may also have missing transverse momentum. This background is reduced by the upper bound on the number of jets and the lepton veto.

Run 2 signal regions				
Name $E_{T,\text{calo}}^{\text{miss}}$ [GeV]	SR1	SR2	SR3	SR4
	250-300	300-350	350-400	400-500
Name $E_{T,\text{calo}}^{\text{miss}}$ [GeV]	SR5	SR6	SR7	
	500-600	600-700	> 700	

Table 7.3: The $E_{T,\text{calo}}^{\text{miss}}$ thresholds for the seven signal regions used in the 13 TeV analysis.

- Production of multiple heavy gauge bosons, i.e. the production of two or more gauge bosons in association, may yield final states with jets and missing energy. For the signal region the most important process is the production of a W and a Z boson, where the Z decays to neutrinos and the W decays to a quark-antiquark pair.
- Background from non-collision events (NCB): cosmic showers, detector noise or background induced by the beam - all leading to fake jets and thus large E_T^{miss} .
- QCD multi-jet production is the most common process at the LHC. A small fraction of these events can have misreconstructed jets or semi-leptonic decays of heavy quarks leading to missing energy.

With the exception of the top and diboson background, the magnitudes of all these backgrounds are calculated using data-driven techniques. These techniques are described in Chap. 9. The top and diboson uncertainties are instead estimated using Monte Carlo simulations. The details of the simulation of these background samples, as well as the estimation of uncertainties associated with simulations, are given in Chap. 8.

Chapter 8

Monte Carlo Simulations

Monte Carlo simulations are used to estimate background event yields in the signal and control regions, either directly (in the case of top and diboson) or as input to various data-driven methods (in the case of W and Z plus jets). They are also used to estimate expected BSM signal yields that can be compared to observations in order to constrain or exclude for the signal models. This chapter describes the Monte Carlo generation of background and signal samples, with special emphasis on the generation of the signal samples for the ADD interpretation, since these dedicated studies were performed by the author. Finally the chapter describes the systematic uncertainties associated with the simulations and provides estimates of their magnitude.

8.1 Background Samples

This section outlines how the MC simulation samples for backgrounds are produced. The top and diboson backgrounds are in both analyses taken directly from simulations. In the 8 TeV analysis all background from the decay of Z bosons to pairs of charged leptons are also taken from simulation, while in the 13 TeV analysis this is only true for the $Z/\gamma^* \rightarrow ee$ process. All other processes are calculated using various data-driven techniques described in Chap. 9. These however still require some degree of input from simulations.

8.1.1 Event Weights

To estimate the event yield in a given control or signal region, the raw number of Monte Carlo events that survives the event selection is normalized as

$$N = \sigma L \epsilon = \sigma L \frac{\sum_i^{Region} w_i}{\sum_i^{All} w_i} \quad (8.1)$$

where σ is the cross section, corrected when relevant with a K-factor, L is the integrated luminosity and ϵ is the efficiency. The efficiency for MC is the ratio of events surviving an event selection over the total number of events before selection. The number of events after a certain selection is the sum of the so-called Monte Carlo event weights for each event inside the region. The sum over the index in Eq. 8.1 runs over the events in the selection region (numerator) and over all events before selection (denominator). The total weight for each event is the product of the following weights:

- Monte Carlo weights, provided by some generators depending on how likely the various events are.
- Lepton weights, reflecting the different efficiencies of lepton identification and reconstruction between data and MC. These weights are dependent on p_T and η of the leptons.
- Trigger weights, reflecting the different trigger efficiencies in data and MC. These are also dependent on kinematics. In the analyses in this thesis it only applies to the regions selected with electron triggers. In the other regions the $E_{T,calo}^{miss}$ threshold regions is chosen such that the trigger is 100% efficient for both data and MC.
- Pile-up weights, included to properly describe the pile-up conditions measured in the data. Events are generated with a specific pile-up distribution, and are then reweighted to shape this distribution to match the observed pile-up distribution. Pile-up weights are not used in the 13 TeV analysis.

8.1.2 W or Z Plus Jets Production

For both the 8 TeV and 13 TeV analysis SHERPA [157] is used to generate the Z and W plus jets background samples. Each leptonic final state, $Z \rightarrow \nu\nu$, $W \rightarrow \tau\nu$, $W \rightarrow \mu\nu$, $W \rightarrow e\nu$, $Z/\gamma^* \rightarrow \tau\tau$, $Z/\gamma^* \rightarrow \mu\mu$ and $Z/\gamma^* \rightarrow ee$ are generated separately. The production is split into intervals of the boson p_T in order to obtain sufficient amounts of simulated events in the high boson p_T region. For the 8 TeV analysis, SHERPA-1.4.1 is used to generate the samples, with up to four jets included at LO. The absence of higher order radiative corrections leads to a mismodeling of the p_T of the bosons, especially in the high p_T end of the spectrum [158]. The transfer factor method described in Chap. 9 cancels most of this effect for the background estimates in the signal regions, but the mismodeling complicates the validation of the high E_T^{miss} control regions. In the 13 TeV analysis these samples are generated using SHERPA-2.1.1 where 0, 1 and 2 jets are included at NLO, and the third and fourth jet are included at LO. This improves the modeling of the high p_T bosons. The simulated samples are all normalized to NNLO predictions, calculated using the perturbative QCD calculator DYNNLO [159].

8.1.3 Top Quark Production

In order to simulate $t\bar{t}$ pair production in the 8 TeV analysis the MC@NLO [160] generator is used, with the parton shower implemented in HERWIG [161] and JIMMY [162]. For single top production the ACERMC [163] and MC@NLO generators are used. The single top production simulation is split into s-channel and t-channel production. For the 13 TeV analysis the POWHEG [164] generator is used for both the single and pair produced top quarks, with the parton shower implemented in PYTHIA 6 [153]. The top mass is consistently set to 172.5 GeV in both analyses.

8.1.4 Diboson Plus Jets Production

The diboson production is divided into different sub-categories depending on which bosons are produced, and to which final state these bosons decay. In the 8 TeV analysis the generation of all diboson final states is performed using SHERPA-1.4.1, with all matrix elements at LO accuracy. In the 13 TeV analysis they are instead produced using SHERPA-2.1.1. For the fully leptonic final states the matrix elements are included at NLO accuracy, so far as to including an extra

parton at NLO for the $4l$ and $2l2\nu$ final states. For final states with hadrons the matrix elements are still at LO accuracy.

8.1.5 Multi-jet and γ Plus Jets

The simulated multi-jet samples are not used to estimate the multi-jet background, neither in the signal region nor in any control regions, but they provide the shapes of the multi-jet background for several figures presented in later chapters of this thesis. In these figures the yield is normalized to the jet smearing or matrix method estimates described in Chap. 9. The production of a photon in association with jets is a negligible background in the signal region. However in the control region $\text{CR1e}_{\text{corr}}$ constructed to select events from $W \rightarrow e\nu$ events in the 8 TeV analysis, there is a non-negligible contribution from such processes, in which the photon (or a jet) is misidentified as an electron. This background is even more important to take into consideration in the dedicated multi-jet enriched control region used to estimate the multi-jet contamination in the $\text{CR1e}_{\text{corr}}$ (Sec. 9.1.3). Both the multi-jet production and the γ + jet production are performed using PYTHIA8 [165].

8.2 ADD Signal Samples

Simulated signal samples are used for the optimization of signal region definitions and as input to the calculations of limits on new physics. In this section the process of simulating ADD large extra dimension samples is presented. The signal sample production in the ADD production is performed with PYTHIA8, using the CT10 [166, 167] and NNPDF [149, 168] as input PDF sets for the 8 TeV and 13 TeV analyses respectively. The free parameters of the model itself are the number of extra dimensions n and the fundamental Planck scale M_D . The sizes of the extra dimensions as well as the effective masses of the gravitons are set by the choice of n and M_D , as described in Secs. 2.2.1 and 2.2.3. While the choice of M_D is important for the estimate of the production cross section, it has no effect on the kinematics of the generated signal. The kinematics are instead determined by the choice of n , the PDF, and the selection of the factorization and renormalization scales. A summary of the parameters used to generate the 13 TeV samples is found in Table 8.1.

Fundamental Planck Scale

In the 8 TeV Monojet analysis the value of M_D for a given cross section is obtained from interpolating between three generated samples for each value of n , for which the cross sections are calculated by PYTHIA itself. The values of M_D in the generated samples are all chosen to lie between 2.0 and 4.5 TeV, close to the upper limits on M_D from the 7 TeV ATLAS Monojet analysis [58].

The correspondence between the production cross section and M_D is known to be [37]

$$\sigma \propto \frac{C_n}{M_D^{n+2}} \quad (8.2)$$

where C_n is some constant for a given n at a given center-of-mass energy. The rescaling parameter C_n can be calculated using the PYTHIA cross section and M_D for one single signal point, and then used to calculate the cross section for any other value of M_D at constant n . Thus the simulation of three different samples per value of n in the 8 TeV analysis is redundant, and for the 13 TeV analysis only one sample per value of n is simulated. Values of M_D close to those excluded in Run 1 are chosen for the 13 TeV analysis.

n	M_D [GeV]	m_0 [GeV]	Γ [GeV]	σ_{13} [pb]	σ_8 [pb]	N_{gen}
2	5300	800	750	1.55	0.23	100 000
3	4100	1500	1000	1.82	0.24	75 000
4	3600	2200	1100	2.29	0.19	55 000
5	3200	2800	1100	4.18	0.22	55 000
6	3000	3300	1300	7.22	0.24	55 000

Table 8.1: Summary of generation parameters for ADD samples in the 13 TeV analysis, along with the production cross sections at 8 and 13 TeV obtained with PYTHIA8. The mass parameters m_0 and Γ are the approximated central value and width of the distribution of KK graviton mass states. The number of generated events N_{gen} for each sample is given in the last column.

Graviton KK-mode Masses

The graviton mass is assumed to be zero, but the mass distribution of the KK gravitons is entirely determined by the choice of n and M_D , as explained in Sec. 2.2.3. Despite the fact that the KK-mode mass is not a free parameter of the model, PYTHIA still requires the user to provide the standard mass parameters m_0 and Γ which normally regulate the center and width of a Breit-Wigner peak. In the case the ADD model graviton, these parameters now describe the starting point for the generation of KK-mode masses by PYTHIA8. Once generated, the events are reweighted by PYTHIA to recreate the proper theoretical KK-mode mass distribution. In the Run 1 analysis the values $m_0 = 200$ GeV and $\Gamma = 50$ GeV were used for all generated ADD samples.

Figure 8.1 shows the different mass distributions for the graviton KK-modes for $n = 2-6$, with M_D set to the values in Table 8.1. Both the average graviton mass and the width of the mass distribution increase with n . The method outlined in Ref. [169] for effective simulation is to first generate enough events to be able to plot the mass distribution, and then select m_0 and Γ to cover this distribution as well as possible. The generation time is reduced by the use of mass parameters that better describe the theoretical values. It also reduces the average MC weights of the sample, making the distribution less prone to statistical fluctuations. Changing the mass distribution does not however change the production cross section or the kinematics.

In order to check that the input PYTHIA graviton mass parameters do not affect the sample normalization, the production cross section is computed for $n=6$ and $M_D=3000$ GeV, with different values of m_0 and Γ . The results are given in Table 8.2. It is clear that the cross sections are consistent with each other within errors. Comparing these values to Fig. 8.1 shows that selecting masses and widths that better fit the distribution reduces the error on the cross section and increases the generator efficiency, defined as the fraction of generated events that is accepted by the generator. Both these parameters improve by an order of magnitude by using the optimized values when compared to the values used in the 8 TeV analysis. Thus for the samples used in the 13 TeV analysis the values in Table 8.1 are selected for the graviton masses.

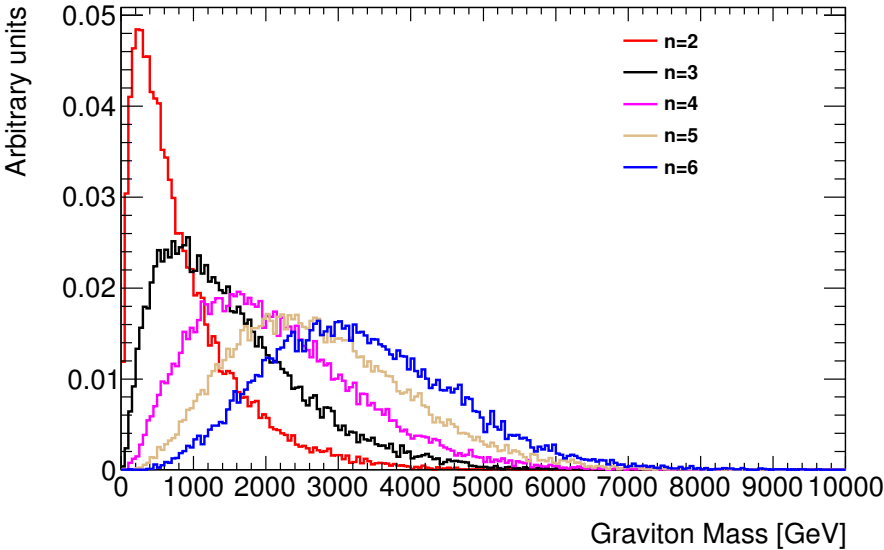


Figure 8.1: Simulated distribution of KK graviton masses, for the five different values of n at 13 GeV center-of-mass energy. All samples have been normalized to unit area.

m_0 [GeV]	Γ [GeV]	Cross section [pb]	Gen. efficiency
200	50	7.0 ± 0.4	0.006
200	200	7.5 ± 0.4	0.002
200	2000	6.9 ± 0.2	0.02
2500	50	7.3 ± 0.1	0.01
2500	200	7.2 ± 0.1	0.02
2500	2000	7.08 ± 0.07	0.06
3300	1100	7.22 ± 0.03	0.07

Table 8.2: Production cross section and generation efficiency for the signal point defined by $n = 6$ and $M_D = 3000$ GeV, for different values of the PYTHIA8 input parameters m_0 and Γ of the graviton. The final row in the table is close to the values ($m_0 = 3300$ GeV, $\Gamma = 1300$ GeV) used in the analysis.

PDF Sets

In Run 1 the ADD signal is generated using the CT10 PDF set. In a first set of simulations of 13 TeV samples, the MSTW [170] set was used. For the analysis in this thesis the NNPDF is used, as recommended by the ATLAS Monte Carlo simulation group. Figure 8.2 is a comparison of the shapes of several kinematic variables between NNPDF and MSTW, showing very small differences. The only distribution in which there is a visible discrepancy is in the distribution of the number of good jets. This is however in the tail where the number of events is very low. In the 13 TeV analysis only events with less than five jets are selected, meaning this discrepancy is not very important for the final results. The different PDFs are associated with differences in the production cross sections of around 30%, with NNPDF having the highest and MSTW the lowest. For $n = 2$, $M_D = 4000$ GeV, the cross section is 3.9 ± 0.1 pb with MSTW whereas using NNPDF it is 4.7 ± 0.1 pb.

Renormalization Scale

The factorization and renormalization scales in PYTHIA are parameters that can be set to any value. As this is a leading order generator the choice of scale is important in order to produce reliable predictions. Some "natural" choices are offered as pre-defined selections in PYTHIA. In Run 1, the renormalization scale is set to the arithmetic mean of the two squared transverse energies of the parton and graviton, i.e. $\mu_R = \frac{(p_{T,G}^2 + m_G^2) + (p_{T,p}^2 + m_p^2)}{2}$, where index G indicate the final state graviton and p indicate final state parton. The PYTHIA8 default option for a $2 \rightarrow 2$ process such as graviton+jet production is instead to use for the renormalization scale the geometric mean of the squared transverse energies of the two produced particles, i.e. $\mu_R = \sqrt{(p_{T,G}^2 + m_G^2)(p_{T,p}^2 + m_p^2)}$. The difference between the two options is small, hence in the 13 TeV analysis the geometric mean is used as it is the PYTHIA default option.

Factorization Scale

In the Run 1 ATLAS analysis the graviton signal is produced with the factorization scale set to the arithmetic mean of the two squared transverse energies, $\mu_F = \frac{(p_{T,G}^2 + m_G^2) + (p_{T,p}^2 + m_p^2)}{2}$. The default PYTHIA option is to use the minimum squared transverse energy, $\mu_F = \min(p_{T,G}^2 + m_G^2, p_{T,p}^2 + m_p^2)$. The large mass

difference between the graviton modes and the partons mean that the default setting will almost always choose the transverse energy of the parton to be μ_F . It also means the Run 1 settings generally sets μ_F much higher than the PYTHIA8 default settings. As the factorization scale regulates the phase space available for ISR, a higher scale will mean more radiation. The higher phase space available to ISR provides a higher average boost of the graviton and the p_T of the graviton will be higher. Another possible source of discrepancies between using the two settings is that when determining the ATLAS2014 (A14) tune, which is used as input to these simulations, the default PYTHIA8 settings were used. The tune is a set of variables which have been optimized using data-driven methods to make the Monte Carlo simulations better describe data. This particular tune was derived using Run 1 ATLAS data.

Figure 8.3 shows the p_T of the final state graviton as a function of the truth p_T of the graviton at the production step (before ISR). Because of ISR a completely linear correspondence between the two is supposed to be somewhat lost. For the PYTHIA8 default settings we see a linear correspondence smeared around the central value. For the settings used in Run 1, the low p_T spectrum instead show an almost flat distribution of final state graviton p_T . There are events with initial state p_T well below 200 GeV that result in final state graviton p_T (and thus $E_{T,\text{calo}}^{\text{miss}}$) of more than 1 TeV. This could be due to the fact that more phase space is available to ISR, but it could also be due to the fact that one uses a scale that was not used when optimizing the tune.

Figure 8.4 shows a similar distribution, using the Run 1 settings, but for a sample generated with $50 < \hat{p}_T < 80$ GeV, where $\hat{p}_T$ denotes a cut on the p_T of the parton and graviton at matrix element level. It is clear that even with this low matrix element p_T , there are gravitons with a p_T of more than 1 TeV in the final state. This is far from the linear correspondence we expect, and it also has practical consequences for the analysis. In the ADD generation for the Run 1 analysis a phase space cut of $\hat{p}_T > 80$ GeV is introduced in order to produce more events in the high $E_{T,\text{calo}}^{\text{miss}}$ tail. This cut is assumed to be fully efficient in the lowest signal region with $E_{T,\text{calo}}^{\text{miss}} > 150$ GeV, in the sense that no events with $\hat{p}_T < 80$ GeV would pass this cut. However Figs 8.3 and 8.4 show that this assumption does not hold. This effect would be even larger if this choice of scale had been used for the 13 TeV analysis. Thus for the 13 TeV analysis, the more robust choice of using the minimum transverse energy of graviton and parton is used. A phase space cut at $\hat{p}_T > 150$ GeV is introduced. This cut is fully efficient at $E_{T,\text{calo}}^{\text{miss}} \gtrsim 350$ GeV.

Run 2 Scale Settings in the Run 1 Analysis

A dedicated study is performed to find what the possible impact on the 8 TeV analysis the scale settings used in the 13 TeV analysis would have. For this purpose two samples with 25000 events each are produced, with the settings used in Run 1 and Run 2 respectively. These are studied after the generator step, without any detector simulation. Both samples are renormalized to their respective production cross section and an event selection very like the 8 TeV analysis selection is performed. It is found that the effect using the $E_{T,calo}^{miss} > 500$ GeV region which is used in the 8 TeV analysis, the effect is a slightly lower signal yield prediction, 3.6% lower for $n=2$ and 2.8% lower with $n=6$. This is well within the signal uncertainties described later in this chapter and thus negligible. This very small difference is despite the fact that the production cross section is $\sim 25\%$ larger for $n=2$ and $\sim 225\%$ larger for $n=6$ using the Run 2 settings with respect to the settings used in Run 1. The increase in production cross section is cancelled by the decrease in acceptance using the Run 1 settings to give this very small final effect on the yield in the signal region. Hence the Run 1 results are still considered valid.

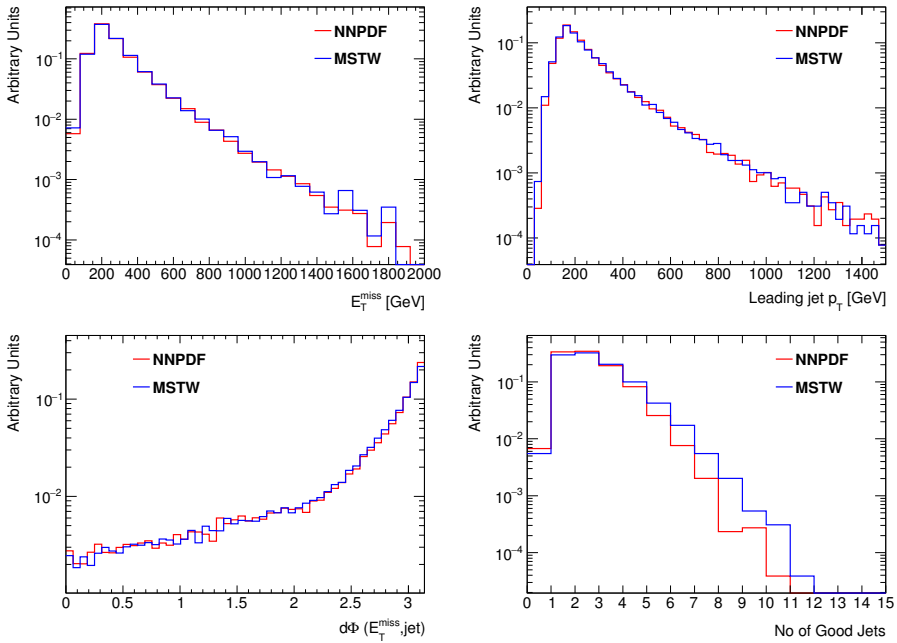


Figure 8.2: Comparison of the shapes of kinematic variables for the same signal point ($n=2$), using the PDF sets MSTW and NNPDF. The different variables are E_T^{miss} (upper left), leading jet p_T (upper right), $\Delta\phi$ between E_T^{miss} and leading jet (lower left) and jet multiplicity (lower right). All samples have been normalized to an area of 1.

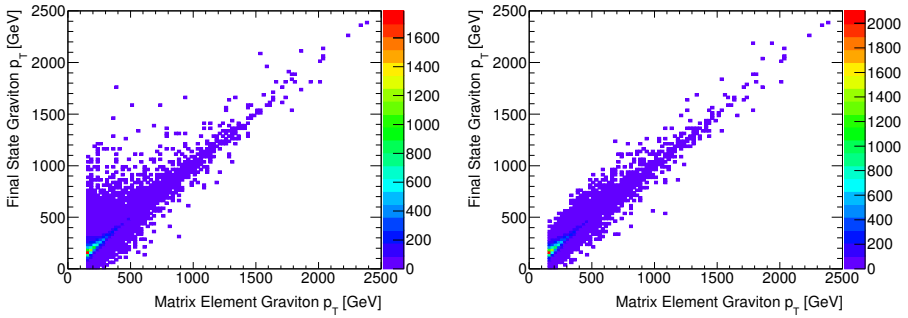


Figure 8.3: Figures showing the p_T of final state gravitons as a function of the matrix element p_T of the same gravitons. The colored axis show how many events are in a given bin. The matrix element p_T is before the graviton p_T has been modified due to ISR. These figures compare the same signal ADD signal point ($n = 2$, $M_D = 4000$ GeV) for the settings for the factorization scale that are default in PYTHIA6 (left) (used in Run 1), and the default settings in PYTHIA8 (right) (used in Run 2). The Run 1 settings in the left picture generally yield a higher factorization scale. Both distributions are generated with 13 GeV center-of-mass energy. For both configurations a phase space cut of $\hat{p}_T > 150$ GeV is imposed, which is clearly visible in the low end of the spectrum.

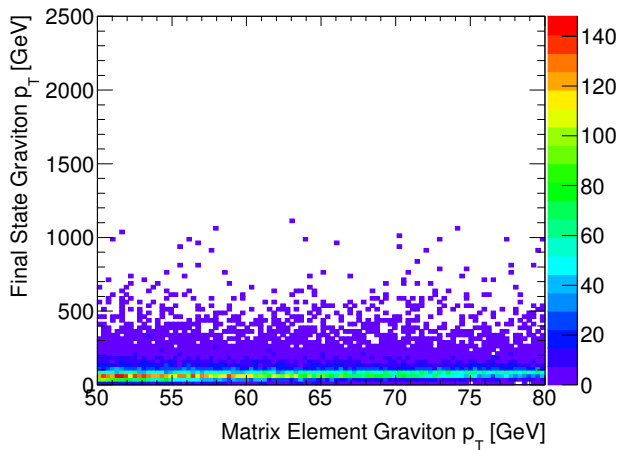


Figure 8.4: Final state p_T of gravitons as a function of the matrix element p_T of the same gravitons, using only events generated with $50 < \hat{p}_T < 80$ GeV and using the settings for the factorization scale that are default in PYTHIA6 and used in the Run 1 analysis, but with 13 TeV center-of-mass energy. The colored axis shows how many events are in a given bin.

Production Cross Section and Kinematics in 8 and 13 TeV

In order to estimate the improved sensitivity of the 13 TeV analysis when compared to the 8 TeV analysis, samples with $n=2$ and $n=6$ are generated, both with the values of M_D used in the 13 TeV analysis (see Table 8.1). Figure 8.5 shows comparisons of $E_{T,\text{calo}}^{\text{miss}}$ distributions at truth level between generation at 8 and 13 TeV, for $n=2$ and $n=6$. The E_T^{miss} spectra for 13 TeV are harder. The samples are generated using the NNPDF PDF set. Table 8.1 shows the production cross sections at 8 and 13 TeV. Since M_D is chosen to be close to the excluded values in the 8 TeV analysis, the production cross sections at 8 TeV are very similar for all models. The table shows a significant increase in production cross section for all values of n when the center-of-mass energy is increased. The increase in cross section is higher for the high values of n . For $n=2$ the cross section increases by a factor 6.7, while for $n=6$ the cross section increases by a factor 31.

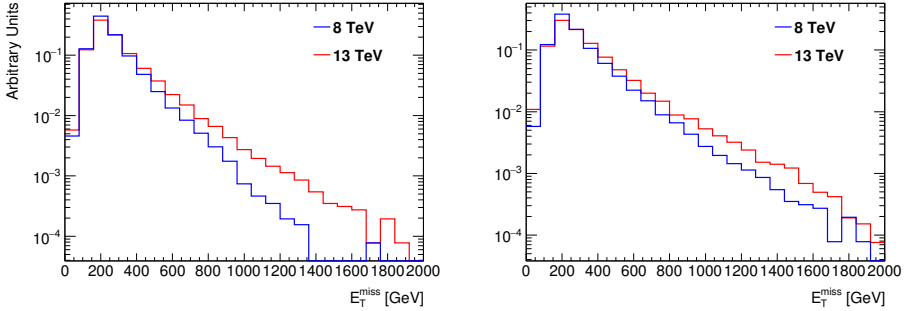


Figure 8.5: Comparison of E_T^{miss} distributions with center-of-mass energy of 8 and 13 TeV respectively, for $n = 2$ at $M_D = 5300$ GeV (left) and for $n = 6$ at $M_D = 3000$ GeV (right). All distributions are normalized to unit area.

8.3 WIMP Dark Matter Samples

8.3.1 EFT Generation

The WIMP Effective Field Theory models are only used in the 8 TeV analysis, as described in Sec. 2.3.5. The generation of EFT models in the 8 TeV analysis is performed using MADGRAPH5 [171] to yield a final state with WIMPs and

up to two partons, interfaced with PYTHIA6 for the parton shower evolution and using the MSTW2008 PDF set. The three parameters of interest are the suppression scale M_* , the WIMP mass m_χ and the effective operator mediating the interaction. In analogy with M_D for the ADD models, the choice of M_* scales the production cross section, but has no effect on the kinematics of the generated events. For all generated EFT samples M_* is set to 1 TeV. Finally the choice of effective operators follow Table 2.1. The collider kinematics of the operator D8 (axial-vector) are identical to the kinematics of the operator D5 (vector). Thus only one of these (D5) needs to be used in generation, and results for D8 are obtained from rescaling the results for D5. The operators used to generate samples are listed in Table 8.3 along with the mass range for m_χ .

Operator	m_χ [GeV]	Interaction Type
D1	50-1300	Scalar, quark)
D5	50-1300	Vector, quark
D9	10-1300	Tensor, quark
D11	50-1300	Scalar, gluon
C1	10-1300	Scalar, quark
C5	10-1300	Scalar, gluon

Table 8.3: The generated WIMP signal models. Each operator class gives the type of operation, and the SM particles involved in the production. Operators with a D couple to Dirac fermion WIMPs, and operators with a C couple to complex scalar WIMPs.

8.3.2 Simplified Model Generation

The simplified models used in the 8 TeV and 13 TeV analyses are more complex than the EFTs. The suppression scale is replaced by the mass of the mediator M_{med} , its couplings to the SM and DM particles g_q and g_χ , and its width Γ . For both analyses a spin-1 heavy Z-like mediator is studied, which could either interact through vector or axial-vector interaction. Somewhat different strategies for generating signal points are chosen for the two analyses. They are described below.

The 8 TeV Analysis

For the 8 TeV analysis two values of m_χ are generated, $m_\chi = 50$ GeV and $m_\chi = 400$ GeV. For both these, point, M_{med} is varied between 50 GeV and 30 TeV. Each combination of m_χ and M_{med} is generated with two different values of the width, $\Gamma = M_{\text{med}}/3$ and $M_{\text{med}}/8\pi$. The first of these represents a large width, and the second is the minimum allowed by the SM, as suggested in Ref. [172]. The coupling strengths are set to $\sqrt{g_{\text{SM}}} = g_{\text{DM}} = 1$ in the generation. For simplicity the results of the analysis are presented as limits on the product of the two couplings, $\sqrt{g_\chi g_q}$. Just like the EFT signal the simplified model signal samples are generated using MADGRAPH5 interfaced with PYTHIA6.

The 13 TeV Analysis

In the 13 TeV analysis M_{med} is varied between 10 GeV and 2 TeV. The generated masses are selected to be roughly equidistant on a logarithmic scale. The WIMP masses m_χ are varied between 1 GeV and 1 TeV, selected to be relevant at the given mediator mass. The full grid is implemented as outlined by the ATLAS-CMS Dark Matter Forum [89]. The couplings are fixed to $g_q = 1/4$ and $g_\chi = 1$. For models with $g_q = g_\chi$ it is found that dijet searches looking for resonant production of heavy mediators decaying into quarks have already excluded large parts of the interesting M_{med} ranges [173]. Mono-X searches are more sensitive to the parameter space where $g_q < g_\chi$. The width Γ is fixed to the minimal width allowed by these choices of the couplings. The results of the analysis are presented as limits in the m_χ - M_{med} plane. The generation of the signal samples is performed using POWHEG Box [174], which generates the process at NLO precision. It is interfaced with PYTHIA8 for the parton showering.

8.4 Modeling Systematic Uncertainties

Several different uncertainties are associated with the Monte Carlo sample generation. These will affect the production cross section as well as the kinematics of the generated event, and thus also the acceptance of the analysis. These uncertainties are associated with all Monte Carlo samples, but the top and diboson backgrounds are treated slightly differently and they are covered in the last part of this section. The final estimates of the systematic uncertainties also include the experimental uncertainties described in Sec. 5.9.

8.4.1 Uncertainties from Event Generation

Theoretical uncertainties on signal cross section and acceptance are treated differently in Chap. 10, and therefore accounted for separately in this section.

PDF Uncertainties

Two types of uncertainties associated with the PDF are considered:

- Uncertainties on acceptance and cross section when the chosen PDF is varied by its uncertainties, or "intra-PDF" uncertainties.
- Uncertainties on acceptance and cross section when the PDF is replaced by one or more other PDFs, or "inter-PDF" uncertainties.

The intra-PDF uncertainties are determined by re-simulating each signal sample while shifting each PDF parameter by its uncertainty up and down. This is done using the LHAPDF reweighting tool [175]. The three families used to evaluate the inter-PDF uncertainties are the NNPDF, the CT10 and the MSTW sets for the 8 TeV analysis, while for the 13 TeV analysis the MSTW set is exchanged for the MMTH [176] PDF set. The intra-PDF uncertainties are, for all samples where this is applicable, found to be smaller than the inter-PDF uncertainties. Therefore the final uncertainty from the PDF sets is chosen to be the envelope of the error bands from all sets. The PDF uncertainty is divided into one part that affects the production cross section, and one part that affects the acceptance. Figure 8.6 illustrates the procedure for the PDF uncertainties on the ADD signal with $n=2$, in the 13 TeV analysis. Each point shows the signal yield when performing a specific parameter variation in the PDF. The colored bands show the uncertainty band for each of the sets.

Scale Uncertainties

The uncertainties on the scales associated with the generation of MC samples are estimated by re-generating the samples, while simultaneously varying the renormalization and factorization scales μ_R and μ_F by a factor 2 and 0.5. Systematic uncertainties due to the choice of the shower-to-parton matching scale between matrix element partons and the parton shower are also obtained by varying the matching scale by 2 and 0.5. These uncertainties are generally smaller than those from factorization and normalization scale variations.

ISR/FSR Uncertainties

The uncertainty associated with the initial and final state radiation is obtained by varying parameters associated with showering probabilities. These parameters are jet structure effects such as shapes and substructure of jets, effects associated with the probability of showering, such as the strong coupling constant α_s and the tri-jet to di-jet production probability ratio. In Run 2 these uncertainties also include uncertainties from effects associated with the underlying event and the probability of multi-parton interaction in the same proton. These uncertainties only affect the kinematics of the simulated event.

Summary of Generator Uncertainties

Tables 8.4 and 8.5 summarize the uncertainties on the acceptance for some representative DM and ADD samples, for the 8 TeV and 13 TeV analyses respectively. For ADD the uncertainties tend to increase with higher values of n . For the DM the uncertainties on the production cross section grow with higher values of m_χ . The operators mediating interactions between gluons and DM tend to have higher uncertainties than the operators mediating interactions between quarks and DM. For the generation of W/Z + jets, the combined uncertainty associated with MC generation is provided along with other theory uncertainties in Chap. 9.

8.4.2 Top Production Modeling Uncertainties

To estimate the uncertainty associated with the MC estimate of the top background, two different strategies are used in the two different analyses.

In the 8 TeV analysis the uncertainty on the top background is determined by constructing two specific control regions, enriched in $t\bar{t}$ events. These regions are denoted $\text{CR1}\mu_{\text{top}}$ and $\text{CR1}e_{\text{top}}$ and are defined by the same selection as the signal regions (Sec. 7.3), with the following modifications:

- Events must contain exactly one muon of W quality in $\text{CR1}\mu_{\text{top}}$ and exactly one electron of W quality in $\text{CR1}e_{\text{top}}$. Events with additional electrons or muons of at least Veto quality are vetoed.
- The region $\text{CR1}e_{\text{top}}$ is defined using $E_{\text{T,corr}}^{\text{miss}}$ instead of $E_{\text{T,calo}}^{\text{miss}}$, and selected using the single electron triggers described more thoroughly in Sec. 9.1.3. In this region $E_{\text{T,calo}}^{\text{miss}}$ is required to fulfill $E_{\text{T,calo}}^{\text{miss}} > 25 \text{ GeV}$.

Process	Scales		PDF		ISR/FSR
	$\Delta\sigma$	ΔA	$\Delta\sigma$	ΔA	ΔA
ADD ($n=2$)	20%	4-11%	16%	8-31%	2-11%
ADD ($n=6$)	26%	2-30%	29%	9-29%	11-21%
D5 ($m_\chi=50$ GeV)	6%	1-5%	5%	2-21%	1-4%
D5 ($m_\chi=1300$ GeV)	16%	1-3%	36%	3-28%	0.3-1.1%
$M_{\text{med}}=1$ TeV, $m_\chi=200$ GeV	7%	0.4-5%	6%	6-17%	0.3-1.2%

Table 8.4: Estimated systematic uncertainties on the production cross section ($\Delta\sigma$) and acceptance (ΔA) for various signal samples, in the 8 TeV analysis. The uncertainties on the acceptance are the lowest and highest uncertainty on a single signal region. The uncertainties on the acceptance are always lower in the low $E_{T,\text{calo}}^{\text{miss}}$ signal regions, and higher in the high $E_{T,\text{calo}}^{\text{miss}}$ signal regions. For the ADD samples, the two given models are the ones with lowest ($n=2$) and highest ($n=6$) average uncertainties. For the DM samples three representative samples are shown, two EFT models with quark-quark interaction and one simplified model.

- The transverse mass of the lepton and the full E_T^{miss} (here corresponding to the p_T of the neutrino) is required to be $40 < M_T < 110$ GeV to select events from W decays.
- The requirement of leading jet $p_T/E_{T,\text{calo}}^{\text{miss}} > 0.5$ is not applied.
- Events must contain at least two b-tagged jets, defined by the MV1 working point described in Sec. 5.4.2.

Fig. 8.7 shows the $E_{T,\text{calo}}^{\text{miss}}$ distribution in $\text{CR1}\mu_{\text{top}}$. The figure illustrates that the region is dominated by $t\bar{t}$ events, and that the MC@NLO [160] modeling at high $E_{T,\text{calo}}^{\text{miss}}$ overestimates data. The uncertainty on the simulated top samples is estimated by assuming that the ratio of data over MC should be one within the statistical uncertainties. Deviations from that are taken as uncertainties on the top event yield. These uncertainties are summarized in Table 8.6.

In the 13 TeV analysis the uncertainties on the top production are calculated by performing five different variations in the generator step: varying the factorization and renormalization scales up and down, changing the matrix element

Process	Scales		PDF		ISR/FSR
	$\Delta\sigma$	ΔA	$\Delta\sigma$	ΔA	ΔA
ADD ($n=2$)	23%	1-5%	16%	6-18%	2-6%
ADD ($n=6$)	36%	4-14%	42%	2-20%	3-5%
$M_{\text{med}}=1 \text{ TeV}, m_\chi=250 \text{ GeV}$	4%	1-6%	7%	2-13%	6-14%

Table 8.5: Estimated systematic uncertainties on the production cross section ($\Delta\sigma$) and acceptance (ΔA) for various signal samples, for the 13 TeV analysis. The estimates given for the acceptance in the case of the ADD signal models are the lowest and highest uncertainty on a single signal region. The uncertainties on the acceptance are always lower in the low $E_{T,\text{calo}}^{\text{miss}}$ signal regions, and higher in the high $E_{T,\text{calo}}^{\text{miss}}$ signal regions. For the ADD samples, the two given models are the ones with lowest ($n=2$) and highest ($n=6$) average uncertainties. For the DM samples a representative sample is shown.

generator to MC@NLO (instead of PowHEG), changing the parton shower generator to HERWIG (instead of PYTHIA6) and finally changing the tune, which corresponds to changing the different ways extra jets can be produced (see the previous section on ISR/FSR uncertainties). The uncertainties from each of these are added in quadrature, and a parametrization of the top uncertainty as a function of $E_{T,\text{calo}}^{\text{miss}}$ is obtained. These uncertainties are between 30 and 40% on the nominal value. The uncertainties are summarized in Table 8.6.

8.4.3 Diboson Production Modeling Uncertainties

The strategy to estimate the background from diboson production also differs between the 8 TeV analysis and the 13 TeV analysis. In the 8 TeV analysis the uncertainties associated with the factorization, normalization and matching scales are estimated using dedicated SHERPA samples. This is performed for all control regions and the signal regions. The systematic uncertainties are parametrized as a function of $E_{T,\text{calo}}^{\text{miss}}$, and the results are given in Table 8.6.

For the 13 TeV the combined uncertainties from scales and PDF amount to around 6%. To this is added an uncertainty from comparing the nominal SHERPA generation to samples generated with PowHEG Box. These uncertainties grow with $E_{T,\text{calo}}^{\text{miss}}$, from 8% to 26% in the range used for the analysis. The

total modeling uncertainty is lower than in the 8 TeV analysis, due to the NLO generation described earlier in this chapter. These results are also summarized in Table 8.6.

Analysis	Top uncertainties	Diboson uncertainties
8 TeV	20-100%	20-80%
13 TeV	30-40%	8-26%

Table 8.6: Estimated range of modeling systematic uncertainties associated with the production of top and diboson samples in the 8 and 13 TeV analyses respectively. The higher values are associated with signal and control regions at the highest E_T^{miss} for the two analyses, and the lowest is associated with the lowest E_T^{miss} regions.

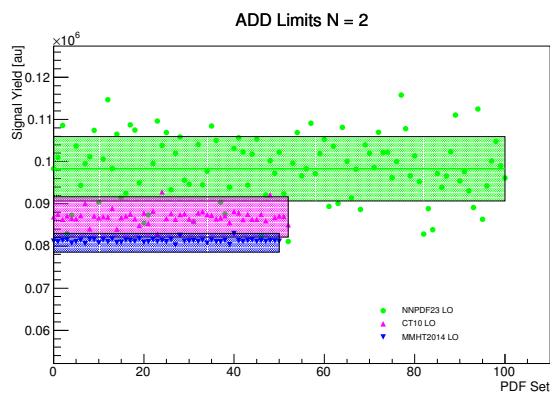


Figure 8.6: Illustration of the method for calculating the uncertainty on the production cross section from the choice of the PDF set on the generated ADD signal for $n=2$, generated at 13 TeV center-of-mass energy with PYTHIA8 . The signal yields (without any selection) from three different PDF families are compared. The final uncertainty on the cross section is the envelope that contains all three families with their respective error bands.

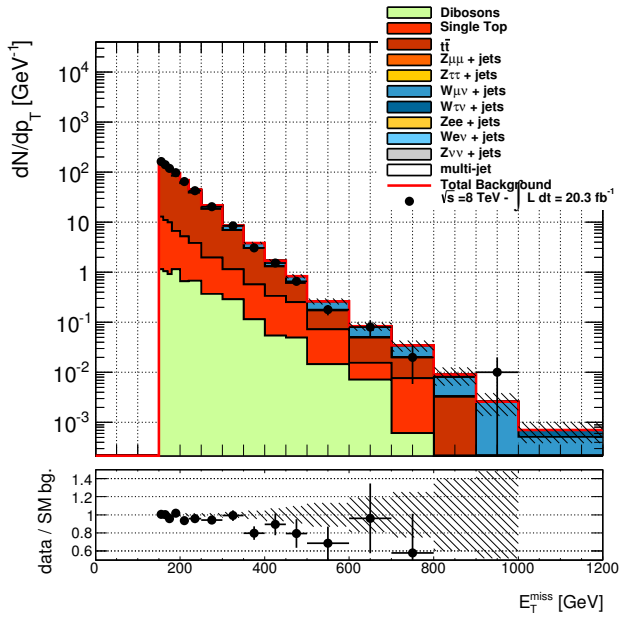


Figure 8.7: Distribution of $E_{T,\text{calo}}^{\text{miss}}$ in the top control region $\text{CR1}\mu_{\text{top}}$ used in the 8 TeV analysis, selecting exactly one muon and at least two b-tagged jets. The lower panel is the ratio of the number of events in data over MC. The error bands represent the statistical error on the background estimation.

Chapter 9

Data Driven Background Estimations

The goal of any new search for physics is to either make a definite statement of discovery, or in the absence of such a statement set the hardest possible constraints on the parameter space allowed for new physics models. The methodology of such searches is to compare the background only hypothesis to the data in a region that probes the new physics signal. These regions are constructed by making the expected sensitivity to the new models as high as possible, and by minimizing the uncertainties associated with signal and background. The signal region design is described in Chap. 7, and the uncertainties associated with the signal event yield are described in Chap. 8. This chapter describes the process of estimating the main backgrounds, Z and W plus jets production, in the signal regions as precisely as possible, in order to get the best possible sensitivity to any model for new physics.

The methods for estimating the minor backgrounds from multi-jet production and non-collision sources are also shortly described. In Part IV these results are compared to data, and interpreted in terms of the ADD and DM signal models.

9.1 W Plus Jets and Z Plus Jets Backgrounds

Background from the $Z \rightarrow \nu\nu$ Process

The main SM background in the monojet signal region is the production of W and Z bosons in association with jets. The decay of a Z boson to neutrinos is the single largest background and is irreducible. The decay of W bosons into one

charged lepton and one neutrino also constitutes a major background. These backgrounds are estimated using data-driven methods. The $E_{T,\text{calo}}^{\text{miss}}$ variable introduced in Sec. 5.7 defining the signal regions in both analyses is equal to the Z boson p_T within detector resolution in $Z \rightarrow \nu\nu$ plus jets events. Since $E_{T,\text{calo}}^{\text{miss}}$ is a calorimetric quantity which does not account for muon momenta, this is also true for the Z boson p_T in $Z/\gamma^* \rightarrow \mu\mu$ plus jets events, and for the W boson p_T in $W \rightarrow \mu\nu$ plus jets events.

The $E_{T,\text{corr}}^{\text{miss}}$ variable described in Sec. 5.7 is the equivalent of $E_{T,\text{calo}}^{\text{miss}}$ for Z and W bosons decaying to electrons. The data-driven methods used to estimate the $Z \rightarrow \nu\nu$ background in the two analyses are based on this relation between the E_T^{miss} and the p_T of the bosons. Dedicated control regions in which Z decays to charged leptons, and W decays to an electron or muon plus a neutrino are constructed. These are used to estimate the relation between observed events in data and simulated events as a function of boson p_T , i.e. how accurately the Monte Carlo simulations model the data. This relation between simulations and data in events with leptonically decaying W or Z bosons is extrapolated to the signal region in which it is used to estimate the $Z \rightarrow \nu\nu$ background.

Background from $W \rightarrow \tau\nu$ and $W \rightarrow e\nu$ Processes

The background from W decays to tau or electron plus neutrino is estimated in a similar way. A control region enriched in such events is constructed for each of the analyses. In this region the $E_{T,\text{calo}}^{\text{miss}}$ is not corrected for the electron from the W decay, since the events that are modeled are events that pass the signal region $E_{T,\text{calo}}^{\text{miss}}$ criteria.

Control Region Philosophy

The control regions are constructed to be as pure as possible in the processes they are constructed to select, in order to reduce the systematic error from other contaminating processes. At the same time, it is important to retain a high number of events in order to reduce the statistical uncertainty on the estimate, since this uncertainty will also be associated with the extrapolation to the signal region.

Two strategies for using the results of the control regions are presented in this section. One is used in the 8 TeV analysis, and one in the 13 TeV analysis. The definitions of the control regions in the two analyses are presented, as well as some of their strengths and weaknesses. Special emphasis is given to the control

regions with electrons used in the 8 TeV analysis, since these were studied and suggested in their final form by the author of this thesis.

In the following sections unless otherwise stated, the purpose of the described strategies are to estimate the event yield of the W and Z plus jets background processes in the signal region.

9.1.1 Run 1 Strategy

In the 8 TeV analysis four different control regions with leptons are constructed for each signal region, to estimate the $Z \rightarrow \nu\nu$ background. These are a one electron control region ($\text{CR1e}_{\text{corr}}$), a dielectron control region ($\text{CR2e}_{\text{corr}}$), a one muon control region ($\text{CR1}\mu$) and a dimuon control region ($\text{CR2}\mu$). The "corr" subscript indicates that the control region uses the $E_{\text{T,corr}}^{\text{miss}}$ variable instead of $E_{\text{T,calo}}^{\text{miss}}$. The $\text{CR1}\mu$, enriched in $W \rightarrow \mu\nu$ events, is also used to estimate the $W \rightarrow \mu\nu$ background. In order to compute the $W \rightarrow e\nu$ and $W \rightarrow \tau\nu$ backgrounds an additional control region CR1e is created. Table 9.1 lists the different electroweak backgrounds to the signal region and how each of these is estimated. The type of $E_{\text{T}}^{\text{miss}}$ used to construct each control region is listed, along with the trigger used to select events in the region. The control regions are constructed for each of the signal regions in Table 7.2. The decay of a Z boson into a pair of charged leptons is estimated from Monte Carlo simulations, since these backgrounds are very small.

Background	Control Region	$E_{\text{T}}^{\text{miss}}$ type	Control Region Trigger
$Z \rightarrow \nu\nu$	$\text{CR1e}_{\text{corr}}$	$E_{\text{T,corr}}^{\text{miss}}$	Single electron
	$\text{CR2e}_{\text{corr}}$	$E_{\text{T,corr}}^{\text{miss}}$	Single electron
	$\text{CR1}\mu$	$E_{\text{T,calo}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}}$
	$\text{CR2}\mu$	$E_{\text{T,calo}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}}$
$W \rightarrow e\nu$	CR1e	$E_{\text{T,calo}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}}$
$W \rightarrow \tau\nu$			
$W \rightarrow \mu\nu$	$\text{CR1}\mu$	$E_{\text{T,calo}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}}$

Table 9.1: The W and Z background processes and their associated control regions together with the type of trigger and $E_{\text{T}}^{\text{miss}}$ variable used to model the W or Z p_{T} .

Each background contribution to the signal region $N_{\text{est}}^{\text{SR}}$ is estimated by

$$N_{\text{est}}^{\text{SR}} = (N_{\text{data}}^{\text{CR}} - N_{\text{NON-W/Z}}^{\text{CR}}) \times \frac{N_{\text{MC}}^{\text{SR}}}{N_{\text{MC}}^{\text{CR}}} \quad (9.1)$$

where

- $N_{\text{est}}^{\text{SR}}$ is the predicted event count for the estimated process (e.g. $Z \rightarrow \nu\nu$) in the signal region,
- $N_{\text{data}}^{\text{CR}}$ is the observed event count in data in the given control region,
- $N_{\text{NON-W/Z}}^{\text{CR}}$ is the contamination from processes other than W and Z production, namely top, diboson, γ + jets and multi-jet events, inside the control region,
- $N_{\text{MC}}^{\text{SR}}$ is the estimated event count in the given process in the signal region obtained directly from Monte Carlo simulations,
- $N_{\text{MC}}^{\text{CR}}$ is the W and Z event count in the control region in Monte Carlo simulations.

The ratio $\frac{N_{\text{MC}}^{\text{SR}}}{N_{\text{MC}}^{\text{CR}}}$ is called a transfer factor. The use of transfer factors effectively means that the Z and W boson p_T are extracted from the control regions and used in the signal region to model the Z boson p_T in the process $Z \rightarrow \nu\nu$.

The use of the transfer factor helps to minimize the detector systematic uncertainties due to potential Monte Carlo mis-modeling of the data, since the same variable is varied simultaneously in the numerator and the denominator. In $\frac{N_{\text{MC}}^{\text{SR}}}{N_{\text{MC}}^{\text{CR}}}$ both the numerator and denominator have signal region-like jet and E_T^{miss} cuts, but differ in lepton activity. Hence Monte Carlo simulations are relied on mostly for the modeling of the lepton acceptance, which is well understood in ATLAS.

The $N_{\text{NON-W/Z}}^{\text{CR}}$ is estimated using simulations, with one exception: the large contamination of multi-jet events in the $W \rightarrow e\nu$ control region. This is poorly modeled by simulation and thus a data-driven method is used for its estimation. This method is described in Sec. 9.1.3.

Combining Results

The $Z \rightarrow \nu\nu + \text{jets}$ background in the signal region is given by four different control regions, giving four independent estimates. These are statistically combined to obtain a best estimate of the $Z \rightarrow \nu\nu$ background in the signal region. This statistical combination is performed using a Best Linear Unbiased Estimate (BLUE), as outlined in Ref. [177, 178]. The method consists in looking for an unbiased estimate $\hat{y}$ which is a linear combination of the individual estimates y_i and minimizes the variance on $\hat{y}$, denoted σ^2 . A linear combination of the individual estimates can be written

$$\hat{y} = \sum_{i=1}^4 \alpha_i y_i \quad (9.2)$$

where i runs over the four measurements of the $Z \rightarrow \nu\nu$ background, and α_i are weighting factors. For Eq. 9.2 to be unbiased it is required that

$$\sum_{i=1}^4 \alpha_i = 1 \quad (9.3)$$

The total uncertainty on the final estimate y is written

$$\sigma^2 = \sum_{i=1}^4 \sum_{j=1}^4 \alpha_i \alpha_j V_{ij} \quad (9.4)$$

where V_{ij} is the covariance matrix for the total uncertainty on the measured y_i . This matrix contains the variance on the individual estimates on the diagonal, while the off-diagonal elements contains correlation terms between pairs of individual measurements. The weights α_i are derived by minimizing a generalized χ^2 on the form

$$\chi^2 = \sum_{i=1}^4 \sum_{j=1}^4 [y_i - (\mathbf{U}\hat{y})_i] V_{ij}^{-1} [y_j - (\mathbf{U}\hat{y})_j] \quad (9.5)$$

where $\mathbf{U}$ is a vector of length 4, whose elements are all unity. This yields for the weighting factors α

$$\alpha = \frac{V^{-1}\mathbf{U}}{\mathbf{U}^T V^{-1}\mathbf{U}} \quad (9.6)$$

The four control regions are statistically independent. The covariance matrix V^{-1} is constructed assuming systematic uncertainties to be either 0% or 100% correlated between the different estimates. Detector uncertainties of the same origin between the four control region are assumed 100% correlated. These are the uncertainties associated with jets, E_T^{miss} and the track veto. Uncertainties associated with leptons are assumed to be 100% correlated between the two electron control regions, and between the two muon control regions, and assumed to be uncorrelated between a muon and an electron control region. The theory uncertainties described in Sec. 8.4 are correlated because of the use of a common generator, a common PDF and common methods to assess the scale and shower uncertainties. The exact correlation is not known, and they are assumed to be fully correlated. Finally all estimates have the same term $N_{\text{MC}}^{\text{SR}}$ in Eq. 9.1 whose statistical error is therefore fully correlated among the four background estimates. The results of this combination are found in Sec. 9.4.

9.1.2 Run 2 Strategy

Control Regions in Run 2

The $Z \rightarrow \nu\nu$ background in the signal region is estimated in the 13 TeV analysis by the use of a one muon control region denoted CR1 μ , similar to the CR1 μ used in the 8 TeV analysis. To estimate the $W \rightarrow \tau\nu$, $W \rightarrow e\nu$ and $Z/\gamma^* \rightarrow \tau\tau$ backgrounds a one electron control region denoted CR1e is also constructed, similar to the CR1e region in the 8 TeV analysis. A dimuon region denoted CR2 μ is used to estimate the background from $Z/\gamma^* \rightarrow \mu\mu$. This region is very similar to the CR2 μ in the 8 TeV analysis. These three control regions are constructed using the same exclusive bins in $E_{T,\text{calo}}^{\text{miss}}$ as the signal regions (Table 7.3).

Combined Fits

The control regions are all used in a global simultaneous fit using HistFactory [179], interfaced through the HistFitter software framework [180]. This

Background process	Scale Factor	Primary control region
$Z \rightarrow \nu\nu$ $W \rightarrow \mu\nu$	$\mu_{\nu\nu}$	CR1 μ
$W \rightarrow \tau\nu$ $W \rightarrow e\nu$ $Z/\gamma^* \rightarrow \tau\tau$	$\mu_{e\tau}$	CR1 e
$Z/\gamma^* \rightarrow \mu\mu$	μ_{ll}	CR2 μ
$Z/\gamma^* \rightarrow ee$	Monte Carlo	-

Table 9.2: The background processes and their associated scale factors, and the primary control region for setting these scale factors. The background from Z decay to two electrons is taken from Monte Carlo simulations.

fit is possible since all control regions are disjoint from each other, and from the signal regions. The global fit takes into account all signal regions and control regions in a combined likelihood and takes into account all the error correlations between the regions. The possibility of a signal is part of the likelihood through a signal strength parameter μ_{sig} which scales the signal yield from Monte Carlo simulations.

To illustrate the method we consider a simplified version of the fit where a single region CR1 μ is used to estimate the yield in a single signal region. We also assume that the signal region background is composed only of $Z \rightarrow \nu\nu$ events and that the control region is composed only of $W \rightarrow \mu\nu$ events. In this case the likelihood of a certain signal strength given the number of observed events in the signal and control regions can be written by starting with the product of the two Poisson probabilities

$$P(O|E) = P(O_{\text{SR}}|E_{\text{SR}}) \times P(O_{\text{CR}}|E_{\text{CR}}) = \frac{E_{\text{SR}}^{O_{\text{SR}}} \exp(-E_{\text{SR}})}{O_{\text{SR}}!} \times \frac{E_{\text{CR}}^{O_{\text{CR}}} \exp(-E_{\text{CR}})}{O_{\text{CR}}!} \quad (9.7)$$

where O and E are the observed and expected number of events in the two regions. The expected values are written

$$E_{\text{SR}} = \mu_{\text{BG}} N_{\text{Z,SR}}^{\text{MC}} + \mu_{\text{sig}} N_{\text{sig,SR}}^{\text{MC}} \quad , \quad E_{\text{CR}} = \mu_{\text{BG}} N_{\text{W,CR}}^{\text{MC}} + \mu_{\text{sig}} N_{\text{sig,CR}}^{\text{MC}} \quad (9.8)$$

where μ_{BG} is a normalization factor common to the background processes in the signal and control region and μ_{sig} is the signal strength parameter scaling the expected signal yield $N_{\text{sig}}^{\text{MC}}$ for a given model. The control region is selected so that its expected signal yield $N_{\text{sig,CR}}^{\text{MC}} = 0$. The probability in Eq. 9.7 can be rewritten as a likelihood of the model parameters when observing O ,

$$L(\mu_{\text{sig}}, \mu_{\text{BG}} | O) = P(O | \mu_{\text{sig}}, \mu_{\text{BG}}) \quad (9.9)$$

In the illustrative example in Eqs. 9.8 and 9.9 the only free parameters are the rescaling factor for the background μ_{BG} and the signal strength μ_{sig} . The global fit amounts to finding the values of the free parameters maximizing the likelihood function in Eq. 9.7. These are denoted $\hat{\mu}_{\text{sig}}$ and $\hat{\mu}_{\text{BG}}$ and are the *maximum likelihood* estimators of the true values of μ_{sig} and μ_{BG} .

Combined Fit for the Monojet Analysis

We now go back to the full complexity of the monojet analysis. Constructing the full likelihood includes all backgrounds in all signal and control regions. The processes $W \rightarrow \mu\nu$ and $Z \rightarrow \nu\nu$ are normalized by a scale factor $\mu_{\nu\nu}$, the processes $W \rightarrow e\nu$, $W \rightarrow \tau\nu$ and $Z/\gamma^* \rightarrow \tau\tau$ are normalized by a scale factor $\mu_{e\tau}$ and the $Z/\gamma^* \rightarrow \mu\mu$ process is normalized by a scale factor μ_{ll} . Each signal region $E_{\text{T,calo}}^{\text{miss}}$ bin has its own $\mu_{\nu\nu}$, μ_{ll} and $\mu_{e\tau}$ shared between the signal region and the control regions within the same $E_{\text{T,calo}}^{\text{miss}}$ range. The signal strength parameter μ_{sig} is the only scale factor that is common to all signal and control regions.

The systematic uncertainties are modeled by so-called nuisance parameters. Each systematic uncertainty k is modeled by a nuisance parameter θ_k , which is varied using the estimated $\pm 1\sigma$ impact of the auxiliary measurements associated with the systematic uncertainty. The final likelihood is the product of the Poisson likelihood factors from all control and signal regions, and a specific combined probability density function for the systematic uncertainties. The full likelihood function is written

$$\begin{aligned}
L(\mu_{\text{sig}}, \boldsymbol{\mu}_p, \boldsymbol{\theta}) = & \prod_{i=1}^7 \left[P(n_{\text{SR}_i} | \lambda_{\text{SR}_i}(\mu_{\text{sig}}, \boldsymbol{\mu}_{p,i}, \boldsymbol{\theta})) \times \prod_{j \in \text{CR}_i} P(n_{\text{CR}_{i,j}} | \lambda_{\text{CR}_{i,j}}(\mu_{\text{sig}}, \boldsymbol{\mu}_{p,i}, \boldsymbol{\theta})) \right] \\
& \times C_{\text{syst}}(\boldsymbol{\theta}^0, \boldsymbol{\theta}) \quad (9.10)
\end{aligned}$$

where i denotes one of the seven signal regions, j denotes one of the three control regions defined for each value of i , $\boldsymbol{\mu}_{p,i}$ is the set of three scale factors defined for each value of i , λ_{SR} and λ_{CR} here denote the predicted yield in each region, and finally C_{syst} is the product of the probability density functions corresponding to each systematic uncertainty, typically Gaussian distributions with standard deviations given by the auxiliary measurements and mean value of zero. The auxiliary measurements are essentially measurements from calibration studies performed by ATLAS to determine the size of the systematic uncertainties associated to detector measurements introduced in Sec. 5.9.

Discussion

In contrast to the Run 1 analysis, the global fit approach means no single control region sets the scale of a given background. Instead all regions in which a given process appears will affect the scale factor for that process. However, the three control regions CR1 μ , CR2 μ and CR1e are designed to be complementary, in that they constrain different background processes in the signal region. Once the fit is complete and the μ values have been determined, the total number of events in every region in each $E_{\text{T,calo}}^{\text{miss}}$ bin i is composed by

$$\begin{aligned}
N_{\text{est},i}^{\text{SR}} = & \mu_{\text{sig}} N_{\text{sig},i}^{\text{MC}} + \\
& + \mu_{\nu\nu,i} (N_{Z\nu\nu,i}^{\text{MC}} + N_{W\nu\nu,i}^{\text{MC}}) + \mu_{e\tau,i} (N_{W\tau\nu,i}^{\text{MC}} + N_{W e\nu,i}^{\text{MC}} + N_{Z\tau\tau,i}^{\text{MC}}) + \mu_{ll,i} N_{Z\mu\mu,i}^{\text{MC}} + \\
& + N_{\text{Other},i} \quad (9.11)
\end{aligned}$$

where $N_{\text{Other},i}$ represents the minor backgrounds that are not scaled in the global fit.

To validate the global fit, a dedicated low- p_{T} validation region is used. This region is defined using the same selection as the signal regions in Sec. 7.3, but

with $E_{T,\text{calo}}^{\text{miss}}$ limited to 150-250 GeV. Corresponding control regions in the same range of $E_{T,\text{calo}}^{\text{miss}}$ are constructed to perform this fit, in which the signal strength μ_{sig} is assumed to be zero.

9.1.3 Control Regions with Electrons

This section describes the different control regions with electrons used in the analyses. As outlined in the previous sections, the 8 TeV analysis uses three different control regions with electrons, the $\text{CR1e}_{\text{corr}}$, the $\text{CR2e}_{\text{corr}}$ and the CR1e , whereas the 13 TeV analysis only uses the CR1e .

The $\text{CR1e}_{\text{corr}}$ in the 8 TeV Analysis

The $\text{CR1e}_{\text{corr}}$ is used in the 8 TeV analysis to estimate the $Z \rightarrow \nu\nu$ background in the signal region. The event selection is identical to the signal region with the following modifications:

- The control regions are defined using $E_{T,\text{corr}}^{\text{miss}}$ instead of $E_{T,\text{calo}}^{\text{miss}}$.
- Since the $E_{T,\text{calo}}^{\text{miss}}$ in this region is not required to be high enough for events to be selected efficiently with the signal region trigger, these events are instead selected with single electron triggers. Events must pass a logical OR between EF_e24vhi_medium1 , requiring one isolated electron with p_T of 24 GeV, and EF_e60_medium1 that requires $p_T > 60$ GeV, without isolation requirement.
- Events are required to have exactly one W electron (as defined in Sec 5.2.4). Events with additional electrons of at least Veto quality are vetoed.
- The transverse mass of the electron and the full E_T^{miss} is required to be $40 < M_T < 110$ GeV to select events from W decays.
- $E_{T,\text{calo}}^{\text{miss}}$, here effectively the neutrino p_T , is required to be $E_{T,\text{calo}}^{\text{miss}} > 25$ GeV, to remove multi-jet events.

The $\text{CR1e}_{\text{corr}}$ has the lowest purity in its main process of the four control regions used to estimate the $Z \rightarrow \nu\nu$ backgrounds. The semileptonic decay of top quark pairs to one electron, one neutrino and multiple jets amounts to more than 10% of the region for the low $E_{T,\text{corr}}^{\text{miss}}$ regions. There are non-negligible background contributions from $W \rightarrow \tau\nu$, single top quark and diboson production.

There is a minor contamination from events with photons produced in association with jets, in which the photon or a jet is misreconstructed as an electron. These are all estimated from Monte Carlo simulations. Finally there is a contamination from multi-jet events where one of the jets is misreconstructed as an electron. This contamination cannot be safely estimated with simulations, for two reasons. The low acceptance of these backgrounds in the signal and control regions means it is impossible within a reasonable computing budget to generate Monte Carlo simulated samples that provide sufficient statistics, and the systematic uncertainties associated with modeling the calorimeter effects for such samples are expected to be large. Instead a data-driven method is used. These data-driven estimates are however also associated with high systematic uncertainties. It is therefore important to find selection criteria that reduce this contamination.

Estimating the Multi-Jet Background

The region $\text{CR1e}_{\text{corr}}$ is contaminated by multi-jet events where one jet is misreconstructed as an electron. These electrons from multi-jet events are denoted as *fake* electrons, emphasizing that these electrons are not prompt electrons, but either misreconstructed objects such as jets, or electrons from secondary hadron decays. To estimate the number of fake electron events from multi-jets a matrix method is implemented. This method uses the following system of equations:

$$N_{\text{loose}} = N_{\text{fake}} + N_{\text{real}} \quad (9.12)$$

$$N_{\text{tight}} = \epsilon_{\text{fake}} N_{\text{fake}} + \epsilon_{\text{real}} N_{\text{real}} \quad (9.13)$$

where N_{tight} is the number of events in the region $\text{CR1e}_{\text{corr}}$. N_{loose} is the number of events in a looser control region defined as $\text{CR1e}_{\text{corr}}$, with the modification that no isolation criteria are applied to the electrons. The factor ϵ_{fake} is the probability for a fake electron to pass the W electron requirement in Table 5.1, and ϵ_{real} is the probability for a prompt electron to pass the W electron requirement. N_{real} and N_{fake} are the numbers of real and fake electrons in the data sample without the isolation.

These equations can be solved for N_{fake} , yielding

$$N_{\text{fake}} = \frac{\epsilon_{\text{real}} N_{\text{loose}} - N_{\text{tight}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}} \quad (9.14)$$

The yield of non-prompt electrons in the tight region is thus $\epsilon_{\text{fake}} N_{\text{fake}}$.

The efficiency ϵ_{fake} for a non-prompt electron to pass the tight electron cuts is calculated by defining a multi-jet enriched control region denoted CRMJ and defined by the same cuts as the $\text{CR1e}_{\text{corr}}$, but with two modifications:

- $E_{\text{T,calo}}^{\text{miss}} < 25 \text{ GeV}$
- $M_{\text{T}}(e, E_{\text{T,calo}}^{\text{miss}}) < 40 \text{ GeV}$

These selections enhance the multi-jet content by removing $W \rightarrow e\nu$ and top events. In this region ϵ_{fake} is estimated as the ratio of the number of events with one W electron to the number of events with one *loose* electron, i.e. an electron that fulfills all requirements on W electrons, except isolation.

In Fig. 9.1 the distribution of the number of jets in the CRMJ is shown, using the loose and W electron definitions on the left and right panels respectively. In these figures for illustrative purposes, the multi-jet background is estimated by Monte Carlo simulations, and the error bands are statistical only. It is clear that the region is dominated by multi-jet events, and that requiring isolated electrons reduces the amount of fake electrons. This also illustrates the large errors associated with the simulation of multi-jet events.

The efficiency ϵ_{real} for a real electron to pass the tight electron cut is estimated from $W \rightarrow e\nu$ simulations using data-driven efficiencies to estimate the Monte Carlo efficiencies. A conservative systematic uncertainty of 100% is taken on the multi-jet contamination in the $\text{CR1e}_{\text{corr}}$. This takes into account impurities in the CRMJ, uncertainties on the real electron identification and modeling uncertainties of the isolation cuts in Monte Carlo simulations compared to data.

Minimizing the Multi-Jet Background

If the isolation requirement on the electrons is not tight enough, the fraction of multi-jet events in the $\text{CR1e}_{\text{corr}}$ can be well over 10%. This is the case if the electron isolation criteria used in the ATLAS monojet analysis of 7 TeV data [58]

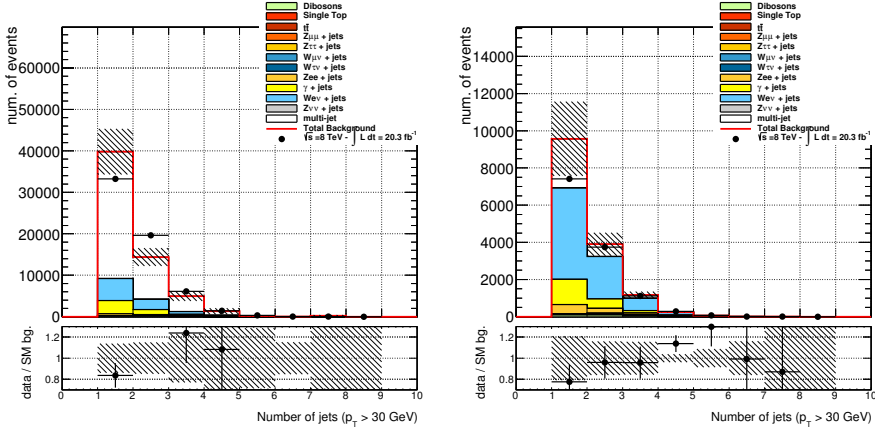


Figure 9.1: Distribution of the number of jets in events in the CRMJ, using loose (left) and W (right) electrons. Here the multi-jet background is from Monte Carlo simulations generated with PYTHIA8. The region is dominated by multi-jet events. The error bands represent the statistical error on the background estimation. The lower panels show the ratio of events in data and Monte Carlo simulations.

are applied. Given the 100% systematic uncertainty on this background, it is important to find selection criteria that reduce this background well below the 10% level.

In order to devise such selection criteria we study the nature of the multi-jet contamination. This is done by looking at the distribution of the angular separation $\Delta\Phi(e, \text{jet1})$ between the leading jet and the leading electron in the left plot of Fig. 9.2. It shows that the events from multi-jet production cluster around π in this variable. The right plot shows the contamination to be primarily located at low $E_{T, \text{calo}}^{\text{miss}}$, as expected for multi-jet production. In order to illustrate these trends the electron isolation in Fig. 9.2 is set to the looser criteria defined in Table 9.3. Together the two figures show that the contamination comes from back-to-back jets arranged such that the $E_{T, \text{calo}}^{\text{miss}}$ is just above the cut at 25 GeV.

Figure 9.2 indicates that a higher $E_{T, \text{calo}}^{\text{miss}}$ threshold can remove most of the contamination, but at the expense of also significantly reducing the number of $W \rightarrow e\nu$ events available for the data-driven background calculations. A dedicated study of the optimal isolation criteria and $E_{T, \text{calo}}^{\text{miss}}$ cuts is performed for

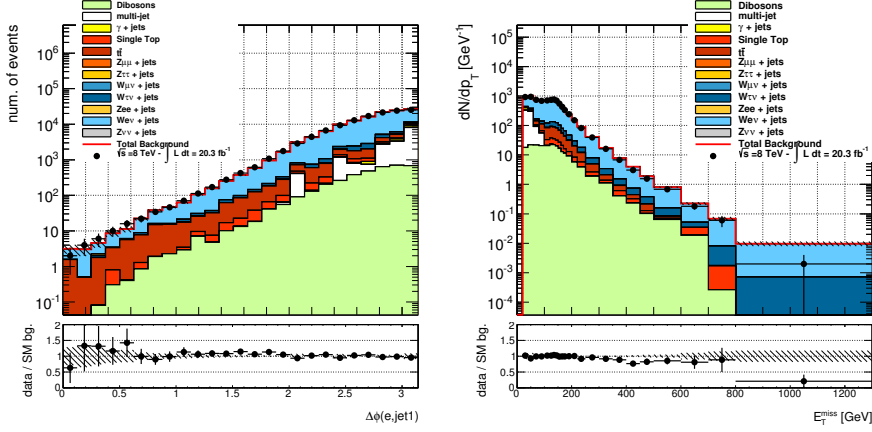


Figure 9.2: Distribution of $E_{T,\text{calo}}^{\text{miss}}$ (left) and $\Delta\phi$ between the leading jet and the leading electron (right), for the $\text{CR1e}_{\text{corr}}$ using the looser electron definition in Table 9.3. The multi-jet contamination is from Monte Carlo simulations generated with PYTHIA8. The lower panels show the ratio of events in data and simulations.

the 8 TeV analysis [4], in which 2-dimensional scans of calorimetric isolation and track isolation variables in a simplified version of the control region are performed. This study assumes a simplified model of the $\text{CR1e}_{\text{corr}}$, assuming it consists of $W \rightarrow e\nu$ and multi-jet backgrounds only. In this study the figure of merit is the total error on the estimated number of $Z \rightarrow \nu\nu$ events in the signal region, taking into account the available event statistics as well as the multi-jet contamination and its associated error. For the $W \rightarrow e\nu$ yield a 5% flat systematic uncertainty is assumed in this study (close to what was found in the 7 TeV analysis [58]), and for the multi-jet yield a conservative 100% uncertainty is assumed. Several different isolation variables are tested, with varying cone sizes and different pile-up correction methods. The main result regardless of which variables were used is that the electron isolation should be tightened in order to decrease the error on the $Z \rightarrow \nu\nu$ estimate. No significant differences in performance between the different variables are found, and in the end the $p_T^{\text{cone},0.3}/p_T$ and I_{cal} variables described in Sec. 5.2.2 are selected on the merit of having been used in other ATLAS analyses.

The main result of the study is that for the lowest E_T^{miss} regions, the optimal cuts on these two isolation variables are in the range 0.1-0.15, which is in the same order of magnitude as in the 7 TeV analysis [58], while for signal regions above 250-300 GeV the optimal cuts for both track isolation and calorimetric isolation are always much harder, between 0.01-0.05. This is the motivation for the isolation criteria defined in Sec. 5.2.2. These criteria are thus optimized for the high $E_{T,\text{calo}}^{\text{miss}}$ regions where the sensitivity to new physics is higher.

Table 9.3 summarizes the main results of the study, and highlight some key parameters for the multi-jet contamination. The table lists a comparison between using the W electron definition and using a looser set of parameters ($I_{\text{cal}} < 0.18$, $p_T^{\text{cone},0.3}/p_T < 0.16$). This table lists control region yields in data and the multi-jet contamination estimated with the matrix method. It shows that the tighter isolation criteria decrease the multi-jet background by almost 90%, while only decreasing the overall yield by 12%.

Isolation	CR Yield	N_{MJ}	ϵ_{fake}	ϵ_{real}
$I_{\text{cal}} < 0.18, p_T^{\text{cone},0.3}/p_T < 0.16$	128851	14147 (11.0%)	0.23	0.92
$I_{\text{cal}} < 0.05, p_T^{\text{cone},0.3}/p_T < 0.05$	113683	1528 (1.3%)	0.03	0.86

Table 9.3: Multi-jet contamination estimates for two different isolation criteria applied to $\text{CR1e}_{\text{corr}}$. CR yield is the number of events in data in the $\text{CR1e}_{\text{corr}}$. N_{MJ} is the matrix method estimate of fake electrons in the control region, and the number in parentheses is the fraction of the total yield estimated to be from fake electrons in the $\text{CR1e}_{\text{corr}}$.

Figure 9.3 shows comparisons for the $\text{CR1e}_{\text{corr}}$ region, using the final selection described earlier in this section and with $E_{T,\text{corr}}^{\text{miss}} > 150$ GeV. In these figures the W and Z backgrounds have been normalized to make the Monte Carlo yield equal to the observed number of events in data. The figure shows that the shape of data and Monte Carlo agree well, but as introduced in Sec. 8.1.2 for high $E_{T,\text{corr}}^{\text{miss}}$ the simulated backgrounds tend to overshoot the data.

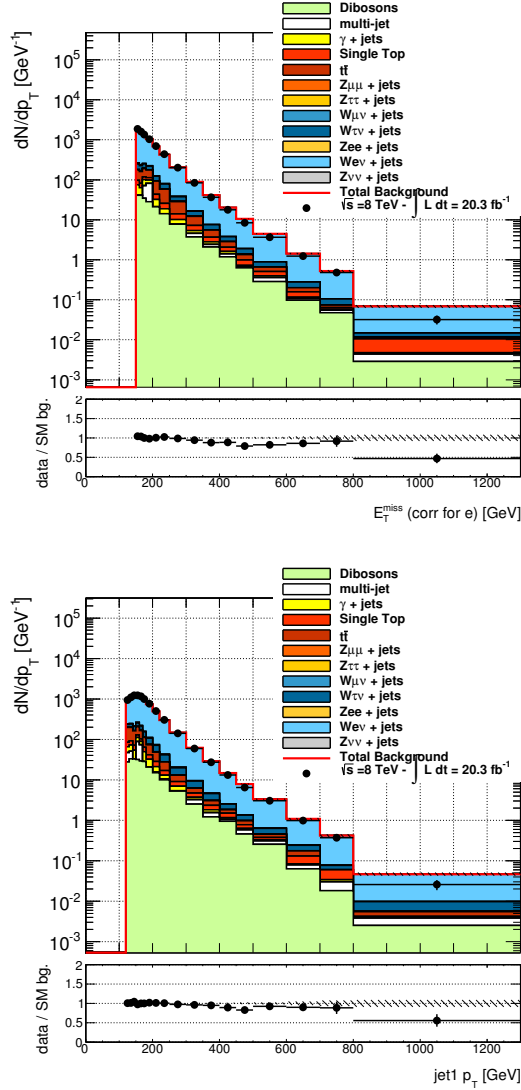


Figure 9.3: Data to simulation comparisons for $E_{T,\text{corr}}^{\text{miss}}$ (upper) and leading jet p_T (lower), in the CR1e_{corr} with $E_{T,\text{corr}}^{\text{miss}} > 150 \text{ GeV}$. The lower panels show the ratio of events in data and Monte Carlo simulations. The error bands correspond to statistical errors only. The W and Z processes have been rescaled so that the total background match the data. The shape of the multi-jet background is taken from Monte Carlo simulations, and rescaled to the number of multi-jet events predicted by the matrix method.

The CR2e_{corr}

The CR2e_{corr} is one of the regions used in the 8 TeV analysis to estimate the $Z \rightarrow \nu\nu$ background in the signal region. This control region is defined by the same cuts as the signal region with the following modifications:

- The control region is defined using $E_{T,\text{corr}}^{\text{miss}}$ which models the Z boson p_T in decays to two electrons. The $E_{T,\text{corr}}^{\text{miss}}$ thresholds are the same as the ones specified for the signal regions in Table 7.2.
- Since there is no lower threshold for the $E_{T,\text{calo}}^{\text{miss}}$ in this region, events can not be selected efficiently with the signal region trigger. Events are instead selected with single electron triggers. Events must pass a logical OR between EF_e24vhi_medium1, requiring one isolated electron with p_T of 24 GeV, and EF_e60_medium1 that requires $p_T > 60$ GeV, without isolation requirement.
- Events are required to have exactly two Z electrons (as defined in Table 5.1). Events with additional electrons of at least veto quality are vetoed.
- In order to select events from Z decays, the invariant mass of the two electrons is required to be $66 < M_{ee} < 116$ GeV.

In comparison to the CR1e_{corr}, the CR2e_{corr} is less contaminated by other processes, but contains significantly fewer events, thus leading to a larger statistical uncertainty on the provided $Z \rightarrow \nu\nu$ estimation. Figure 9.4 shows data to simulation comparisons for the CR2e_{corr} with $E_{T,\text{corr}}^{\text{miss}} > 150$ GeV. The purity is higher than in CR1e_{corr}, and the total number of events is lower. The figure shows good agreement between the shapes of the observed data and the Monte Carlo simulations.

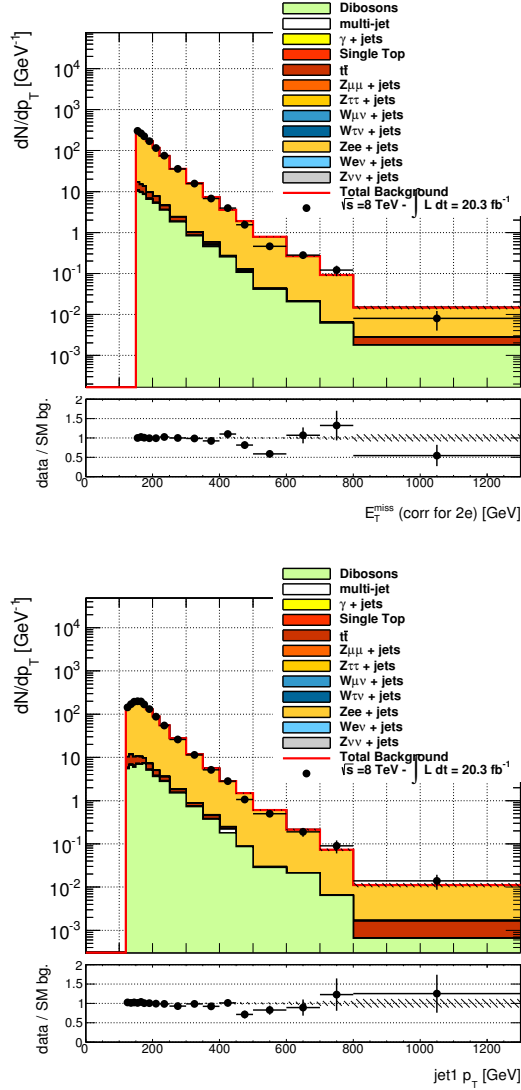


Figure 9.4: Data to Monte Carlo simulation comparisons for $E_{T,\text{corr}}^{\text{miss}}$ (upper) and leading jet p_T (lower), in the CR2_{e_{corr}} control region with $E_{T,\text{corr}}^{\text{miss}} > 150$ GeV. In these figures the W and Z backgrounds have been normalized to make the Monte Carlo yield equal to the observed number of events in data. The lower panels show the ratio of events in data and Monte Carlo simulations. The error bands correspond to statistical errors only.

The CR1e

The CR1e is constructed to estimate the $W \rightarrow \tau\nu$ and $W \rightarrow e\nu$ backgrounds in both analyses, and additionally the $Z/\gamma^* \rightarrow \tau\tau$ backgrounds in the 13 TeV analysis. Most of the $W \rightarrow \tau\nu$ and $Z/\gamma^* \rightarrow \tau\tau$ background in the signal region comes from events where the tau decays hadronically, meaning these are events where the energy associated with the tau is deposited in the calorimeters. The CR1e is constructed to measure the W boson p_T in such events, defined by a deposit in the calorimeter and high $E_{T,\text{calo}}^{\text{miss}}$.

This control region has the same event selection as the signal region, with the following modifications:

- Exactly one Z electron in the 8 TeV analysis, as described in Table 5.1 ¹⁾, or exactly one W electron in the 13 TeV analysis, as described in Table 5.2.
- The transverse mass of the electron and the full E_T^{miss} is in the 8 TeV analysis required to be $40 < M_T < 110$ GeV to select events from W decays. This requirement is removed in the 13 TeV analysis, in order to allow a higher contribution of $W \rightarrow \tau\nu$ events.

The missing transverse energy variable used in this region is $E_{T,\text{calo}}^{\text{miss}}$, in order to select the same $W \rightarrow l\nu$ processes that the regions is used to estimate in the signal region.

Figure 9.5 shows CR1e data to Monte Carlo simulation comparisons, for both analyses. For the 13 TeV analysis this figure shows the distribution after global fit. In the 8 TeV analysis the Monte Carlo simulation tends to overshoot the data at high $E_{T,\text{calo}}^{\text{miss}}$, due to the LO-only generation of extra partons. This effect is not present in the 13 TeV analysis.

¹⁾The hard cut on $E_{T,\text{calo}}^{\text{miss}}$ means there is no significant multi-jet contamination in this control region and the isolated W electron definition is not needed.

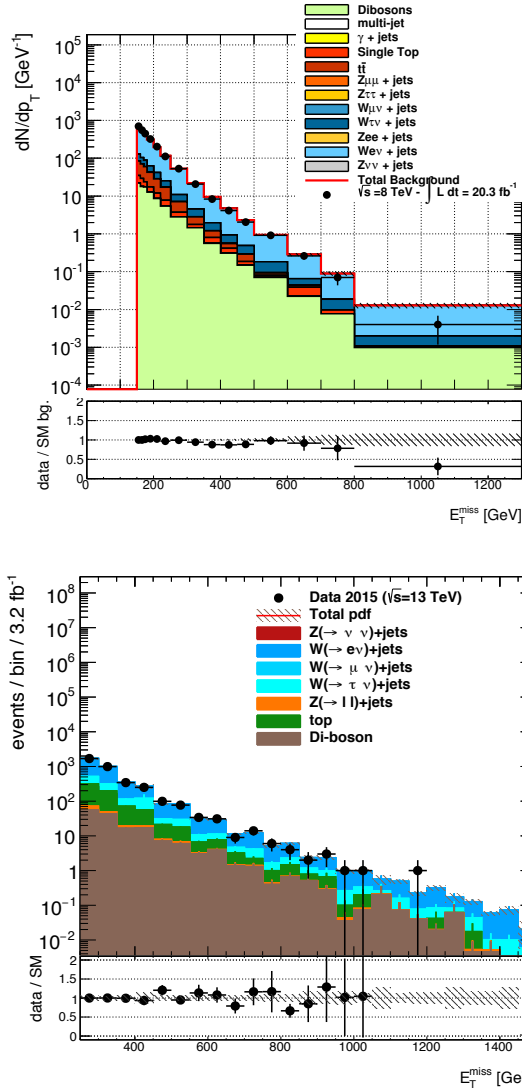


Figure 9.5: Data to Monte Carlo simulation comparisons for $E_{T,\text{calo}}^{\text{miss}}$ in the CR1e, in the 8 TeV (upper) and 13 TeV (lower) analysis. The upper figure shows the control region in the 8 TeV analysis with $E_{T,\text{calo}}^{\text{miss}} > 150$ GeV. The W and Z processes have been rescaled for the total background to match data. The lower figure shows all the control regions in the 13 TeV analysis, after the global fit. The lower panels show the ratios of events in data and Monte Carlo simulation. The error bands correspond to statistical errors only.

9.1.4 Control Regions with Muons

The control regions with muons have the advantage over the control regions with electrons that the $E_{T,\text{calo}}^{\text{miss}}$ does not need to be corrected for the leptons since $E_{T,\text{calo}}^{\text{miss}}$ considers the muons as invisible. This also means that the same $E_{T,\text{calo}}^{\text{miss}}$ -based trigger used for the signal region selection can be used to select control region events, which significantly reduces the systematic uncertainties associated with the trigger. The CR1 μ is not contaminated by multi-jet events to nearly the same extent as the CR1e_{corr} control region described in Sec. 9.1.3.

The CR1 μ

In the 8 TeV analysis this is one of the four regions used for the $Z \rightarrow \nu\nu$ background estimation. It is also used to estimate the $W \rightarrow \mu\nu$ background. In the 13 TeV analysis this region is the primary source of data-driven constraints on the $Z \rightarrow \nu\nu$ and $W \rightarrow \mu\nu$ backgrounds. The $W \rightarrow \mu\nu$ control region is defined by the same selection as the signal region, with the following modifications:

- Events are required to have exactly one muon, in the 8 TeV analysis of the W/Z quality defined in Table 5.3, and in the 13 TeV analysis of the W quality defined in Table 5.4. Events with additional muons of at least Veto quality or electrons are vetoed.
- The transverse mass computed with the muon momentum and the full E_T^{miss} is required to be in a window around the W mass, $40 < M_T < 110$ GeV in the 8 TeV analysis and $30 < M_T < 100$ GeV in the 13 TeV analysis.

Figure 9.6 shows data to Monte Carlo simulation comparisons in the CR1 μ , in both analyses. For the 13 TeV analysis these figures show the distribution after the global fit. For the 8 TeV analysis the Z and W backgrounds from Monte Carlo simulations have been rescaled to match the observed total yield in data. In the 8 TeV analysis the Monte Carlo prediction can be seen to overshoot the data at high $E_{T,\text{calo}}^{\text{miss}}$. This effect is not present in the 13 TeV analysis.

The CR2 μ

In the 8 TeV this is one of the four regions used to estimate the $Z \rightarrow \nu\nu$ background in the signal region. In the 13 TeV analysis it is used to estimate the

$Z/\gamma^* \rightarrow \mu\mu$ background in the signal region. The region is defined by the same selection as the signal region, with the following modifications:

- Events are required to have exactly two muons, in the 8 TeV analysis of the W/Z quality defined in Table 5.3. In the 13 TeV analysis the muons are required to be of the Z quality defined in Table 5.4. Events with additional muons of Veto quality are removed.
- The invariant mass of the two muons is required to be in a window around the Z mass, $66 < M_{\mu\mu} < 116$ GeV.

Figure 9.7 shows data to Monte Carlo simulation comparisons in the CR2 μ , in both analyses. For the 13 TeV analysis this shows the distribution after the global fit. For the 8 TeV analysis the Z and W backgrounds from Monte Carlo simulations have been rescaled to match the observed total yield in data. In the 8 TeV analysis the background estimates overshoot data at high $E_{T,calo}^{miss}$. For both analyses these regions are purer than the CR1 μ control regions, but the total number of events is lower.

9.1.5 Systematic Uncertainties Associated with Transfers

Both analyses rely on Monte Carlo simulations to predict the ratio between background components in the control region and the signal region. While this greatly reduces uncertainties associated with each of the background processes, the assumption that the ratio is predicted accurately by simulation is only true to a certain degree. Two specific systematic uncertainties are associated with this. The first is associated with the modeling of the $E_{T,calo}^{miss}$ in regions with W and Z bosons. This uncertainty is estimated [181] by comparing several different E_T^{miss} distributions using only Monte Carlo simulations, both by comparing Z to W boson p_T at matrix element level, and after the reconstruction step by comparing $E_{T,calo}^{miss}$ with and without muons. It is found that most of the deviations between estimates using Z and W bosons respectively are within an envelope of 3%, which is thus assumed to be the magnitude of this uncertainty.

A second systematic uncertainty is introduced to take into account that the W and Z boson p_T differ in the true production process. These differences are due to radiative corrections, especially at high boson p_T , and described in detail in Ref. [158]. These boson p_T -dependent corrections are transformed into $E_{T,calo}^{miss}$ -dependent corrections to be inserted in the 8 TeV and 13 TeV analyses. The

corrections to the W and Z production are not used to correct the prediction of $Z \rightarrow \nu\nu$ events, instead uncertainties of the same magnitude are introduced. These uncertainties range from 1 to 4% in both analyses.

These two systematic uncertainties are implemented in such a way that the ratio of W or Z event yields between the control and signal region can deviate from the ratio predicted by the Monte Carlo simulation, within these errors.

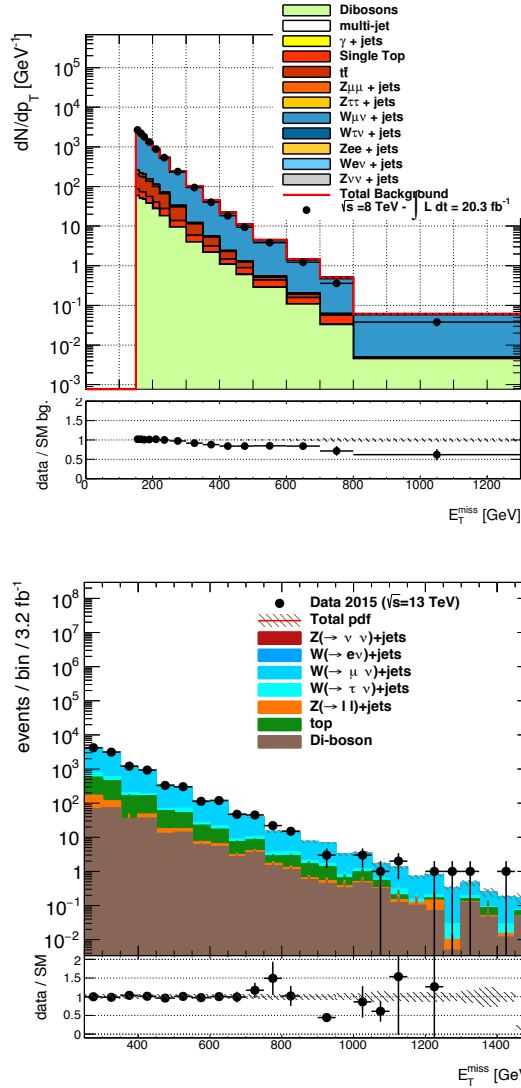


Figure 9.6: Data to Monte Carlo simulation comparisons for $E_{T,\text{calo}}^{\text{miss}}$ in the CR1 μ control region. The upper figure shows the control region in the 8 TeV analysis with $E_{T,\text{calo}}^{\text{miss}} > 150$ GeV. The W and Z processes have been rescaled for the total background to match data. The lower figure shows all the control regions in the 13 TeV analysis, after the global fit. The lower panels show the ratios of events in data and Monte Carlo simulation. The error bands correspond to statistical errors only.

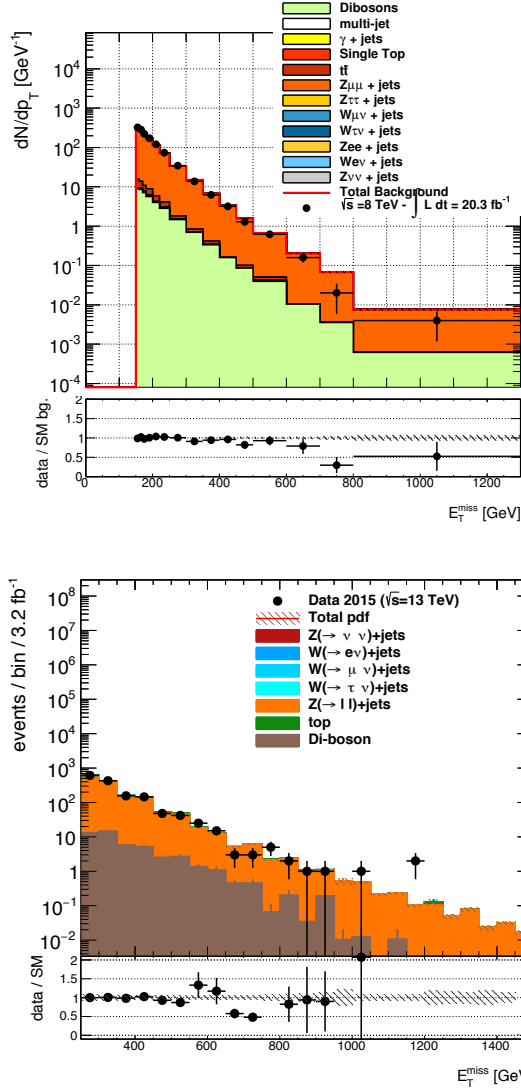


Figure 9.7: Data to Monte Carlo simulation comparisons for $E_{T,\text{calo}}^{\text{miss}}$ in the $Z/\gamma^* \rightarrow \mu\mu$ control region. The upper figure shows the control region in the 8 TeV analysis with $E_{T,\text{calo}}^{\text{miss}} > 150$ GeV. The W and Z processes have been normalized for the total background to match data. The lower figure shows all the control regions in the 13 TeV analysis, after the global fit. The lower panels show the ratios of events in data and Monte Carlo simulations. The error bands correspond to statistical errors only.

9.2 Multi-Jet Background in the Signal Regions

As discussed in the context of the $\text{CR1e}_{\text{corr}}$, the multi-jet background cannot be computed reliably from Monte Carlo simulations. For the signal region estimate a data-driven technique is used in both analyses, known as jet smearing, described in more detail in Ref. [182]. The method follows the following steps:

1. Events with jets and low $E_{\text{T}}^{\text{miss}}$ are selected from data to obtain events where the jets are well-measured (the reconstructed jet p_{T} is close to the true p_{T}). These are used as *seed* events for the smearing.
2. The jet *response function* in Monte Carlo simulations is calculated as $R = p_{\text{T}}^{\text{reco}} / p_{\text{T}}^{\text{truth}}$, where $p_{\text{T}}^{\text{reco}}$ is the reconstructed jet p_{T} , and $p_{\text{T}}^{\text{truth}}$ is the generator p_{T} . This response function is used to smear the seed events to generate pseudo-data. The original response function is then modified until the pseudo-data accurately describe the data in dedicated control regions. These control regions are defined using the same selection as the signal regions, but with the cut on $\Delta\phi$ between the $E_{\text{T}}^{\text{miss}}$ and the leading jet inverted to select events with $\Delta\phi(E_{\text{T,calo}}^{\text{miss}}, \text{jet}) < 1.0$ in the 8 TeV analysis, and $\Delta\phi(E_{\text{T,calo}}^{\text{miss}}, \text{jet}) < 0.4$ in the 13 TeV analysis, to enrich the region in multi-jet events with misreconstructed $E_{\text{T}}^{\text{miss}}$. In this analysis the jet response function is extracted as $E_{\text{T,calo}}^{\text{miss}}$ -dependent scale factors.
3. These data-constrained jet response functions are used to smear the seed events in the signal regions to estimate the multi-jet contribution.

A 100% uncertainty is conservatively assumed on all the multi-jet background estimates.

9.3 Non-Collision Background

The non-collision background to the signal region is estimated using a data-driven technique. Almost all of the NCB to the monojet signal is estimated to be muons from beam halo background, misidentified as jets. These are identified using beam-induced-background tagging techniques, which try to match deposits in the calorimeters on both the A and the C side to tracks in the CSC or MDT that are nearly parallel to the beam pipe. The specific methods between the two analyses differ somewhat. The 8 TeV analysis method uses timing information to distinguish between jets from collisions and non collision-jets, while

the 13 TeV analysis only uses the topology of the event. To evaluate the impact of non-collision background on this analysis, a region enriched in non-collision background, here denoted CR_{NCB} , is constructed by inverting the requirement that the leading jet must pass the tight cleaning criteria described in Sec 5.4.1, i.e. for this region it is required that $f_{\text{ch}} / f_{\text{max}} > 0.1$. The efficiency of the beam-tagging is computed in data as the ratio between the tagged events in this region and the total number of events in the region:

$$\epsilon_{\text{tag}} = \frac{N_{\text{tag}}^{\text{CR}_{\text{NCB}}}}{N^{\text{CR}_{\text{NCB}}}} \quad (9.15)$$

The number of non-collision background events in the signal region $N_{\text{NCB}}^{\text{SR}}$ is obtained by counting in data how many events $N_{\text{tag}}^{\text{SR}}$ that are beam-tagged inside the signal region. From the efficiency of the beam-tagging algorithm ϵ_{tag} derived in Eq. 9.15, the total number of non-collision background events in the signal region can be obtained as follows:

$$N_{\text{NCB}}^{\text{SR}} = \frac{N_{\text{tag}}^{\text{SR}}}{\epsilon_{\text{tag}}} \quad (9.16)$$

The tagging efficiency varies between 0.22 and 0.45. For the low $E_{\text{T,calo}}^{\text{miss}}$ signal regions, this contamination is $\sim 0.5\%$. A 100% systematic uncertainty is assumed on the estimated number of non-collision background events. For $E_{\text{T,calo}}^{\text{miss}}$ regions above 250 GeV in the 8 TeV analysis, and above 500 GeV in the 13 TeV analysis, this background is estimated to be zero.

9.4 Run 1 Results

The estimate of the $Z \rightarrow \nu\nu$ background in the signal region is calculated with the four different control regions using Eq. 9.1, and combined using the BLUE method described in Sec. 9.1.1. The result is shown in Table 9.4. The systematic uncertainties are the experimental uncertainties on jets, $E_{\text{T}}^{\text{miss}}$ and leptons introduced in Sec. 5.9. All uncertainties introduced in Chap. 8 associated with event generation, as well as the uncertainties associated with the transfer between regions described in Sec. 9.1.5 are collected in the common category "Theory". The top and diboson uncertainties are the modeling uncertainties described in

Sec. 8.4.2 and Sec. 8.4.3. The multi-jet uncertainties are the 100% systematic uncertainties associated with the data-driven multi-jet estimates from the matrix method and the jet smearing method.

The combined value using BLUE has a lower systematic error than the measurements based on the individual control regions. All the four individual estimates of $Z \rightarrow \nu\nu$, as well as the combined estimate, are consistent with each other within errors. For the signal region with $E_{T,\text{calo}}^{\text{miss}} > 500$ GeV given in the table, the estimates from the Z and W control regions have total errors of roughly the same magnitude. The Z control regions are at this cut on $E_{T,\text{calo}}^{\text{miss}}$ dominated by statistical errors, while the W control regions are dominated by systematics. For lower $E_{T,\text{calo}}^{\text{miss}}$ regions, the Z regions have lower uncertainties and are more important for the combined estimate. For higher $E_{T,\text{calo}}^{\text{miss}}$ regions, the W regions instead have lower uncertainties and become more important.

Process	Nominal	Stat.	Theory	Top/Diboson	Multi-jet	Jets/MET	Leptons	Total Syst.
$Z \rightarrow \nu\nu(\text{CR1}\mu)$	760	± 90	23	80	-	+11 -11	+7 -4	80
$Z \rightarrow \nu\nu(\text{CR1e}_{\text{corr}})$	760	± 110	23	90	17	+22 -35 +30	+17 -18 +9	100
$Z \rightarrow \nu\nu(\text{CR2}\mu)$	790	± 120	6	24	-	-7 +10	-10 +21	29
$Z \rightarrow \nu\nu(\text{CR2e}_{\text{corr}})$	690	± 90	80	25	-	-8.9 +7	-20 +9	33
$Z \rightarrow \nu\nu(\text{BLUE})$	740	± 60	40	40	1.0	-5 +8.0	-9 +2.5	40
$W \rightarrow \tau\nu$	140	± 19	15	11	-	-0.28 +2.0	-2.0 +1.2	12
$W \rightarrow e\nu$	40	± 6	5	3.2	-	-0.90 +1.6	-0.6 +0.5	4
$W \rightarrow \mu\nu$	35	± 5	2.2	4	-	-0.46 +0.84	-0.4 +0.5	4
$Z/\gamma^* \rightarrow \tau\tau$	0.5	± 0.1	0.08	-	-	-0.031	-0.05	0.06
$Z/\gamma^* \rightarrow ee$	-	-	-	-	-	-	-	-
$Z/\gamma^* \rightarrow \mu\mu$	2.1	± 0.2	0.010	-	-	+0.060 -0.010 +1.0	+0.10 -0.10 +0.14	0.10
$t\bar{t}$	3.8	± 4.2	1.3	4	-	-0.28 +1.1	-0.28 +0.12	4
Single Top	2.9	± 3.4	1.7	2.9	-	-0 +3.2	-0.12 +0.6	2.9
Diboson	70	± 30	4	25	-	-5.6	+0.8 +0.08	25
Multi-jet	1.3	± 1.3	-	-	1.3	-	-0.08	1.3
Total [$Z \rightarrow \nu\nu(\text{BLUE})$]	1030	± 60	50	35	1.6	+13 -3	+11 -11	40

Table 9.4: Full summary of background processes estimated in the 8 TeV analysis for SR7, with $E_{\text{T}}^{\text{miss}} > 500$ GeV. There are five different estimates of the $Z \rightarrow \nu\nu$ background, one using each control region individually and one using the BLUE combination. The sum of all backgrounds is given using only the combined estimate of $Z \rightarrow \nu\nu$. The "Stat." column contains the estimated statistical error, which depends on the Monte Carlo statistics as well as on the control region yield in data. Systematic errors are given for the categories defined in the text. The last column contains the total systematic error. The errors given in this column, as well as the total uncertainty on the nominal estimate is obtained by first symmetrizing all the asymmetric errors around the nominal, and adding the symmetrized error in quadrature with the other errors. The systematic uncertainties associated with different background processes may be correlated, so the uncertainty on the total estimate is not necessarily the quadratic sum of the individual errors.

9.5 Run 2 Results

The background estimate of Run 2 is performed using the combined fit described in Eq. 9.10, with the scale factors in Table 9.2. Table 9.5 shows the expected yields after the fits, in an inclusive region with $E_{T,calo}^{miss} > 250$ GeV. The expected yields in this region correspond to a fit to the background only hypothesis, i.e. where μ_{sig} is fixed to zero in the fit. The use of the combined fit means that the background estimate is dependent on the assumed signal model, which means the numbers in the table are slightly different when including μ_{sig} in the fit.

The systematic errors in Run 2 are similar to those reported in Run 1. The dominant sources of systematic uncertainties are thus still those that in the previous section was categorized as "Theory", which amount to between 3 and 5% in the different signal regions. Uncertainties associated with the modeling of the top background lead to an uncertainty on the total background estimate of $\sim 3\%$ in all signal regions. Uncertainties associated with jets and E_T^{miss} lead to an uncertainty on the total background of 1 to 2% in the different signal regions. Uncertainties associated with leptons lead to an additional 0.1-3% uncertainty on the total background. The uncertainty from the modeling of the diboson background has been reduced since Run 1, and is now on the same level as the uncertainty from the multi-jet background, between 0.1 and 0.4%. All here listed systematic uncertainties increase with higher $E_{T,calo}^{miss}$. The lower bins are dominated by systematic uncertainties. For the high $E_{T,calo}^{miss}$ signal regions the statistical uncertainty instead dominates, and in SR7 ($E_{T,calo}^{miss} > 700$ GeV) the statistical uncertainty is $\sim 10\%$.

Table 9.6 shows the scale factors used in the analysis, derived from a background only fit. These are again produced under the assumption of $\mu_{sig} = 0$. They are with a few exceptions consistent with 1. The errors grow with higher $E_{T,calo}^{miss}$, this is particularly true for the μ_{ll} scale factor, because of the higher statistical error associated with these regions. The table shows that even for the higher $E_{T,calo}^{miss}$ regions the Monte Carlo estimates are consistent with data. In the 8 TeV analysis the Monte Carlo estimates for high $E_{T,calo}^{miss}$ regions instead generally overshoot the observation in data. This improvement is caused by the inclusion of more jets at NLO in SHERPA-2.1.1 when compared to SHERPA-1.4.1, which gives better modeling of high p_T W and Z bosons.

Total background	21700 ± 900
$Z \rightarrow \nu\nu + \text{jets}$	12500 ± 700
$W \rightarrow \tau\nu + \text{jets}$	3980 ± 310
$W \rightarrow \mu\nu + \text{jets}$	1950 ± 170
$W \rightarrow e\nu + \text{jets}$	1710 ± 170
$Z/\gamma^* \rightarrow \tau\tau + \text{jets}$	48 ± 7
$Z/\gamma^* \rightarrow \mu\mu + \text{jets}$	76 ± 30
$Z/\gamma^* \rightarrow ee + \text{jets}$	-
$t\bar{t}$, single top	780 ± 240
Diboson	510 ± 50
Multi-jet	50 ± 50
Non-Collision Background	110 ± 110

Table 9.5: Background processes estimated for an inclusive signal region with $E_{T,\text{calo}}^{\text{miss}} > 250$ GeV. Errors include both statistical and systematic errors.

Region	$\mu_{\nu\nu}$	$\mu_{e\tau}$	μ_{ll}
SR1	1.03 ± 0.09	0.87 ± 0.10	1.09 ± 0.12
SR2	1.00 ± 0.09	0.90 ± 0.12	0.89 ± 0.11
SR3	1.10 ± 0.11	0.94 ± 0.13	0.98 ± 0.11
SR4	0.98 ± 0.11	0.66 ± 0.13	1.06 ± 0.12
SR5	0.95 ± 0.12	0.81 ± 0.14	1.20 ± 0.19
SR6	1.15 ± 0.16	0.75 ± 0.20	0.94 ± 0.27
SR7	0.86 ± 0.16	0.95 ± 0.25	1.18 ± 0.36

Table 9.6: All scale factors used in the different $E_{T,\text{calo}}^{\text{miss}}$ regions, obtained using a background-only fit.

Part IV

Results and Conclusions

Nu har vi tydligen inte råd med äkta sanningar längre, utan vi får nöja oss med sannolikhetskalkyler. Det är synd det, för dom håller lägre kvalitet än sanningar. Dom är inte lika pålitliga. Dom blir till exempel väldigt olika före och efter.

Tage Danielsson, *Om Sannolikhet*

It was still snowing as he stumped over the white forest track, and he expected to find Piglet warming his toes in front of his fire, but to his surprise he saw that the door was open, and the more he looked inside the more Piglet wasn't there.

A. A. Milne, *The House at Pooh Corner*

Chapter 10

Interpretations and Limits

10.1 Introduction

This chapter presents the results of the search for WIMPs and ADD scenario gravitons in the two analyses, comparing the observed data yield in the signal regions to the estimates presented in the previous chapter. Setting limits on new physics models requires a statistical test involving background predictions and observations in data. These comparisons are found in Sec. 10.2. In the absence of a significant excess in the signal region, when compared to the background-only predictions, the number of events in the signal regions is used to set exclusion limits. This is done using a profile likelihood method [183], in which the various signal model hypotheses are included in a combined global fit of backgrounds and signal, and then compared to the background-only hypothesis. Limits are set using the CL_s approach [184], a modified frequentist method specifically adapted to high energy physics. These statistical tests, the profile likelihood method and the CL_s approach are described in Sec. 10.3. Model-independent limits on the cross section times acceptance are presented in Sec. 10.4. Results in terms of graviton production in the ADD scenario are presented in Sec. 10.5. Results in terms of WIMP pair production are presented in Sec. 10.6.

10.2 Comparison of Observed Data to Expectation

10.2.1 The 8 TeV Analysis

The observed data yields in the inclusive signal regions of the 8 TeV analysis are compared to the SM expectations in Table 10.1. The background estimates are based on the data-driven calculations described in Chap 9. As each signal region only has a lower threshold on the $E_{T, \text{calo}}^{\text{miss}}$, each observation and expectation is a subset of all lower signal regions. The observed data are consistent with the SM prediction. The largest deviation is a 1.7σ excess of data above the expectation in SR9.

Signal Region	SR1	SR2	SR3
Observed events	364378	123228	44715
SM expectation	372900 ± 9900	126000 ± 2900	45300 ± 1100
Signal Region	SR4	SR5	SR6
Observed events	18020	7988	3813
SM expectation	18000 ± 500	8300 ± 300	4000 ± 160
Signal Region	SR7	SR8	SR9
Observed events	1028	318	126
SM expectation	1030 ± 60	310 ± 30	97 ± 14

Table 10.1: Data and SM prediction for the nine inclusive signal regions defined in Sec. 7.3 for the 8 TeV analysis. The error on the SM expectation contains both statistical and systematic errors.

Figures 10.1 and 10.2 show data to MC comparisons SR1 and SR7 respectively. There is no significant deviation in data compared to the SM expectations in these regions. Figure 10.2 shows that though more jets than one are allowed for, most selected events still have a leading jet which is very energetic when compared to sub-leading jets.

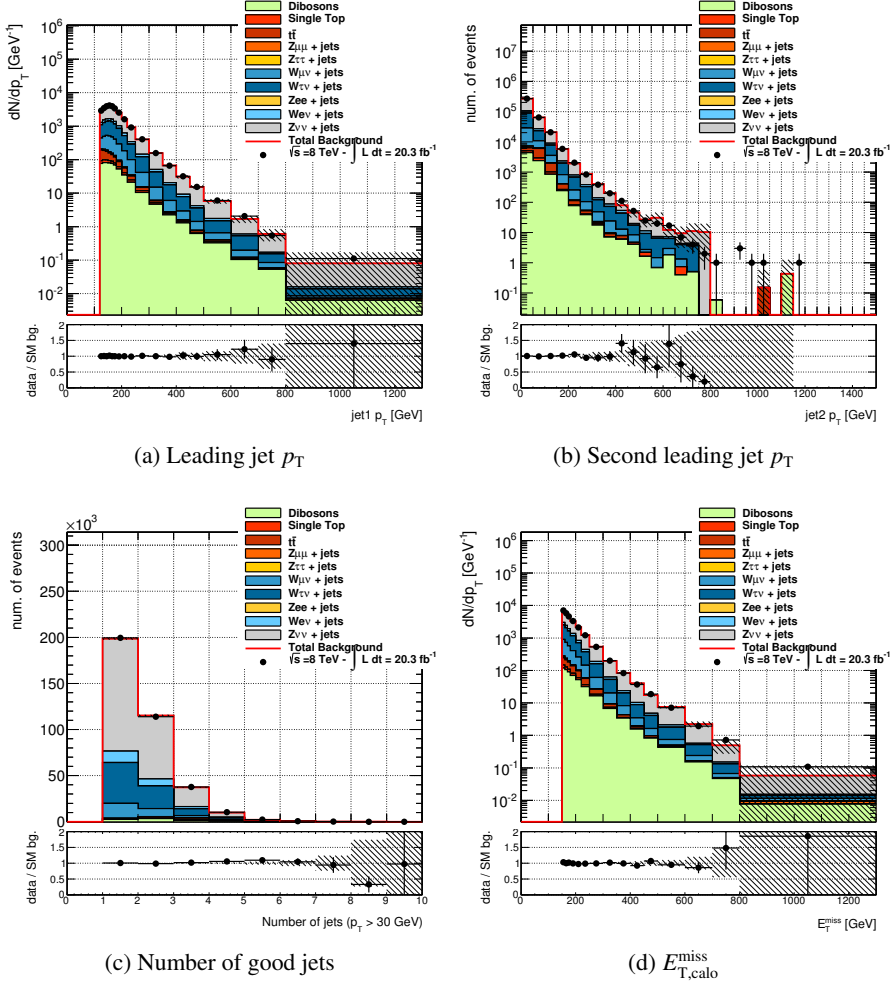


Figure 10.1: Data to background comparisons in the 8 TeV analysis, p_T (upper left), second leading jet p_T (upper right), number of good jets (lower left) and $E_{T, \text{calo}}^{\text{miss}}$ (lower right), in SR1, where $E_{T, \text{calo}}^{\text{miss}} > 150$ GeV. The lower panel is the ratio of data events and expected events. The error bands correspond to the statistical error and the total systematic error on the background estimation. The per mil level multi-jet background is not shown.

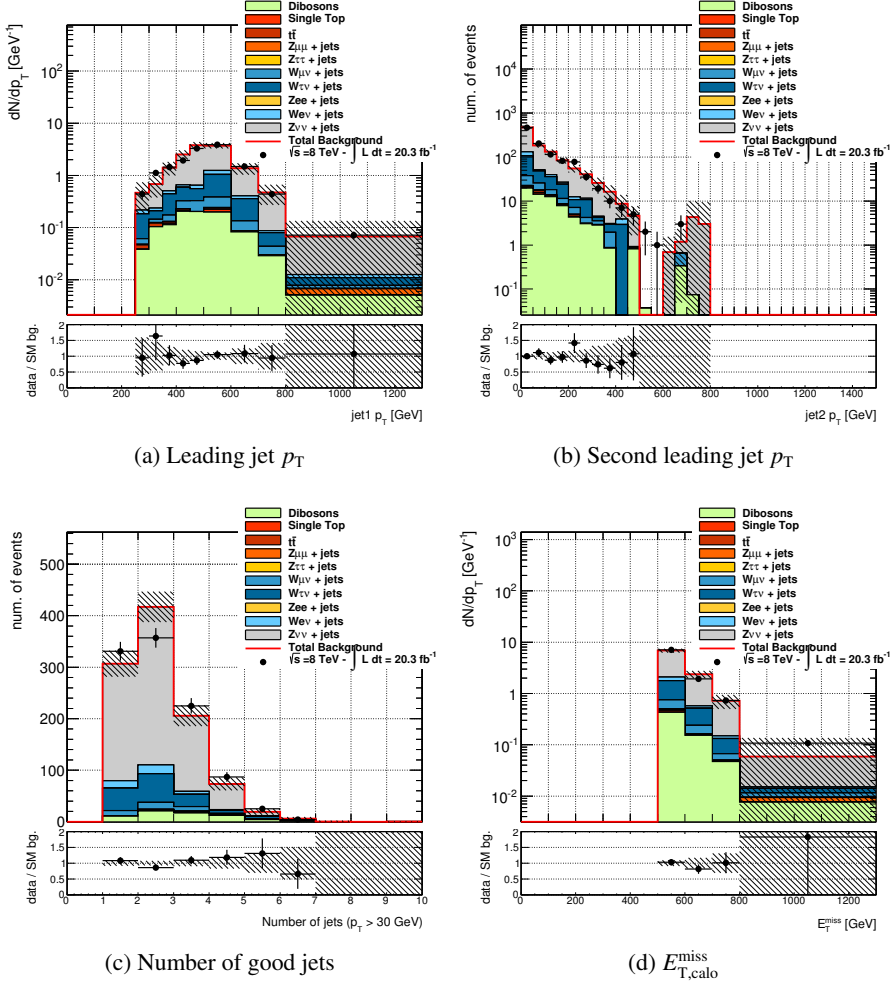


Figure 10.2: Data to background comparisons in the 8 TeV analysis for leading jet p_T (upper left), second leading jet p_T (upper right), number of good jets (lower left) and $E_{T, \text{calo}}^{\text{miss}}$ (lower right), in SR7, where $E_{T, \text{calo}}^{\text{miss}} > 500$ GeV. The lower panel is the ratio of data events and expected events. The error bands correspond to the statistical error and the total systematic error on the background estimation. The per mil level multi-jet background is not shown.

10.2.2 The 13 TeV Analysis

The observed data yield in the different exclusive signal regions of the 13 TeV analysis is compared to the SM expectations in Table 10.2. These numbers are based on a background-only fit, in which Eq. 9.10 is modified so that the signal region is not part of the fit, and μ_{sig} is assumed to be zero. The background scale factors are extracted from the control regions and applied to the signal region, as opposed to the full fit that includes signal, in which the signal region is part of the combined fit. The observed number of events from these estimates is consistent with the SM prediction. The largest deviation is a 1.5σ deficit of data to the expectation in SR3.

Signal Region	SR1	SR2	SR3	SR4
Observed events	9472	5542	2939	2324
SM expectation	9400 ± 400	5770 ± 260	3210 ± 170	2260 ± 140
Signal Region	SR5	SR6	SR7	
Observed events	747	238	185	
SM expectation	690 ± 50	271 ± 28	167 ± 20	

Table 10.2: Data and SM prediction for the seven different exclusive signal regions defined in Sec. 7.3 for the 13 TeV analysis. The error on the SM expectation contains both statistical and systematic errors.

Figure 10.3 shows data to MC comparisons for all signal regions combined, after the global fit has been performed. It shows no significant deviations from the SM predictions.

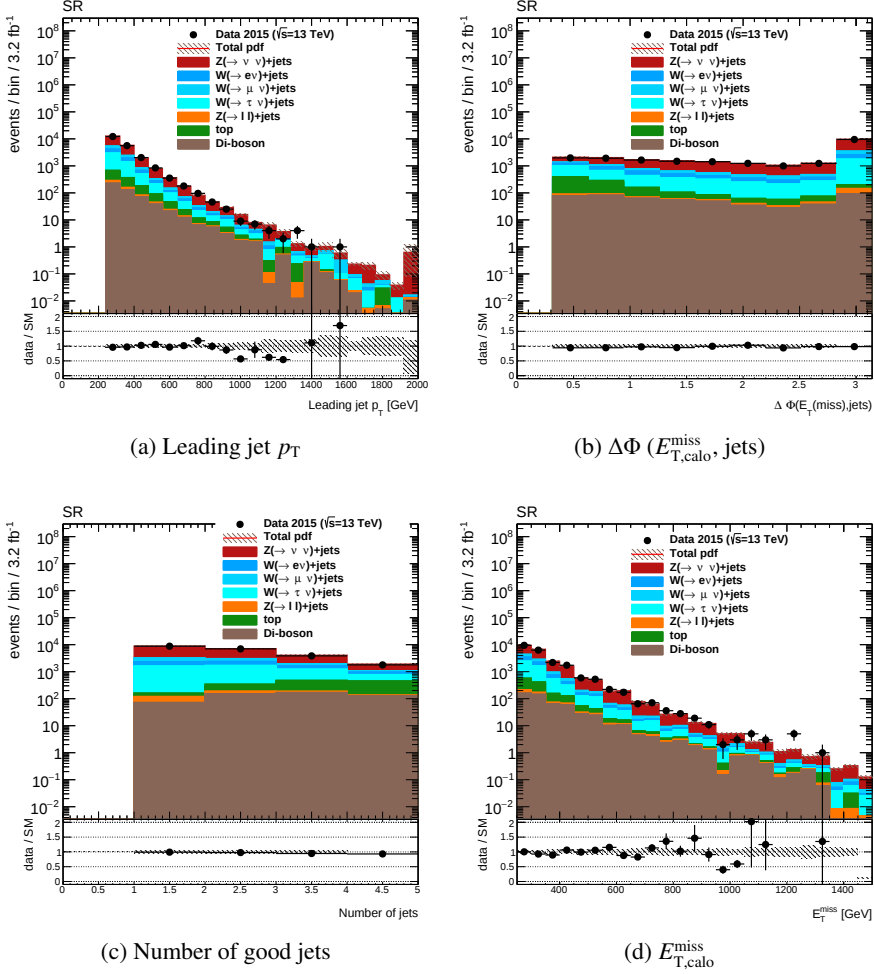


Figure 10.3: Data to background comparisons in the 13 TeV analysis, after the global fit has been performed, for leading jet p_T (upper left), minimum $\Delta\Phi$ between $E_{T,\text{calo}}^{\text{miss}}$ and any jet, number of good jets (lower left) and $E_{T,\text{calo}}^{\text{miss}}$ (lower right), in an inclusive combination of all signal regions, i.e using the signal region selection with $E_{T,\text{calo}}^{\text{miss}} > 250$ GeV. The lower panel is the ratio of data events and expected events. The error bands correspond to the statistical error and the total systematic error on the background estimation.

10.3 Statistical Hypothesis Tests

10.3.1 Test Statistic

In the absence of excess in the observed data with respect to the SM expectations, the observation is used to set limits on the parameter space for new physics. Under a signal-plus-background hypothesis, the expectation value of observed events n can be written $n = \mu_{\text{sig}}s + b$, where b is the expected background and s the nominal signal yield. The exclusion of a new physics model proceeds by using the signal-plus-background hypothesis, and then finding for which values of μ_{sig} this null-hypothesis can be excluded at 95% CL. The parameter μ_{sig} is the strength of the signal process, where $\mu_{\text{sig}} = 0$ corresponds to the background-only hypothesis and $\mu_{\text{sig}} = 1$ corresponds to the nominal signal strength for a given sample. To test a hypothesized value of μ_{sig} a profile likelihood ratio is introduced,

$$\lambda(\mu_{\text{sig}}) = \frac{L(\mu_{\text{sig}}, \hat{\hat{\theta}})}{L(\hat{\mu}_{\text{sig}}, \hat{\theta})} \quad (10.1)$$

Here $\hat{\hat{\theta}}$ is the *conditional* Maximum Likelihood (ML) estimator of θ . This is the estimator of θ which maximizes the likelihood for the specific value of μ_{sig} , and therefore a function of the hypothesized signal strength. The denominator is the unconditional likelihood, so $\hat{\mu}_{\text{sig}}$ and $\hat{\theta}$ are the standard ML estimators of the parameters. The likelihood functions in the 13 TeV analysis are introduced in Eq. 9.10. For the 8 TeV analysis the likelihood only consists of one signal region selected for sensitivity, with its associated systematic uncertainties.

For convenience a test statistic $q(\mu_{\text{sig}})$ is defined such that higher values of q represent greater incompatibility between data and the hypothesized μ :

$$q(\mu_{\text{sig}}) = -2 \ln \lambda(\mu_{\text{sig}}) \quad (10.2)$$

For calculations of upper limits on signal strengths this is modified somewhat to

$$q(\mu_{\text{sig}}) = \begin{cases} -2 \ln \lambda(\mu_{\text{sig}}), & \mu_{\text{sig}} \geq \hat{\mu}_{\text{sig}} \\ 0, & \mu_{\text{sig}} < \hat{\mu}_{\text{sig}} \end{cases} \quad (10.3)$$

The second line of Eq. 10.3 represents the cases in which the best estimator of μ_{sig} is larger than the tested value of μ_{sig} , which is not included in the region which will be rejected by the test [183] (as we are not setting lower limits on μ_{sig}). To quantify the level of agreement between the observation and the hypothesized μ_{sig} , one calculates the p-value, the probability under the signal-plus-background hypothesis of observing an outcome of lesser probability than the data outcome:

$$p(\mu_{\text{sig}}) = \int_{q_{\mu,\text{obs}}}^{\infty} f(q_{\mu}|\mu_{\text{sig}}) dq_{\mu} \quad (10.4)$$

where $f(q_{\mu}|\mu_{\text{sig}})$ denotes the pdf of $q(\mu_{\text{sig}})$ under the assumption of signal strength μ_{sig} . Section 10.3.3 describes how this test statistic and the p-value are used in practice. Before that however, the modified frequentist CL_s method is introduced in Sec. 10.3.2.

10.3.2 The CL_s Method

The standard frequentist p-value approach is to treat any signal-plus-background hypothesis with a p-value (as formulated in Eq. 10.4) below some given value α , as excluded with a confidence level (CL) of $1 - \alpha$. In particle physics at very high energies, the cross sections tend to be very small and thus both background and signal predictions may be small numbers of events. This can lead to unwanted outcomes of the standard approach. For instance a downward fluctuation in the number of observed events could lead to the exclusion of models for which the experiment is not truly sensitive. The CL_s method [184] is introduced to mitigate these effects, and this is done by weighting the standard CL by a weight depending on the probability of the result being compatible with the background-only hypothesis. The compatibility of observed data with the background-only hypothesis is written

$$p_b = 1 - \int_{q_{\mu,\text{obs}}}^{\infty} f(q_{\mu}|0) dq_{\mu} \quad (10.5)$$

where $f(q_{\mu}|0)$ uses the conditional likelihood under the condition that $\mu_{\text{sig}} = 0$. The CL_s significance is now written

$$p_{CL_s} = \frac{p_{\mu}}{1 - p_b} \quad (10.6)$$

which decreases the significance in the case where the observation is neither compatible with the signal-plus-background nor with the background-only hypothesis. A signal is regarded as excluded with confidence α if $p_{CL_s} < 1 - \alpha$. Since the denominator in Eq. 10.6 is always less than 1, this is a conservative approach. If the data is not compatible with the background-only hypothesis, the denominator is close to zero and the value of p_{CL_s} is increased, reducing the sensitivity. In the results of this thesis, α values of 0.9 and 0.95 are used.

10.3.3 Expected and Observed Limits

The expected limits on the signal strength for a given signal model are the limits obtained by assuming the number of data events to be equal to the expected number of background events, while the observed limits are the limits obtained by using the actual number of observed events in data. In the 8 TeV analysis the choice of which signal region to use for each signal model is based on which region sets the strongest expected limits on μ_{sig} for this specific signal model.

In the 8 TeV analysis the full frequentist procedure with 10 000 toy experiments is used for each tested value of μ_{sig} . The toy Monte Carlo experiments are used to construct the pdf of q_μ for the background-only hypothesis, as well as the signal-plus-background hypothesis for the different hypothesized values of μ_{sig} . All nuisance parameters are fixed to the conditional ML estimators when generating each toy MC, but are allowed to float in the fits that evaluate the test statistic for each value of μ_{sig} . In the 13 TeV analysis the full frequentist method is approximated by the asymptotic formulae introduced in Ref. [183].

10.4 Model Independent Limits

Using the CL_s method, the results in Chap. 9 can be interpreted as limits on any model with a monojet final state. These allows to set an upper bound on the cross section of the process times the acceptance of the detector times the efficiency of the cuts, $\sigma \times A \times \epsilon$, sometimes called the *visible* cross section, yielding the number of events $n = \mu_{\text{sig}} s + b$ mentioned in Sec. 10.3.1. Such limits are called model independent limits, since they do not depend on a specific signal model. Upper limits at 95% confidence level on the visible cross section from the 8 TeV analysis are presented in Table 10.3. The signal region with $E_{\text{T,calo}}^{\text{miss}} > 700$ GeV excludes visible cross sections as low as 3.4 fb.

$E_{T,\text{calo}}^{\text{miss}}$ [GeV]	$\sigma \times A \times \epsilon$ (obs.) [fb]	$\sigma \times A \times \epsilon$ (exp.) [fb]
> 150	727	934
> 200	194	271
> 250	90	106
> 300	45	51
> 350	21	29
> 400	12	17
> 500	7.2	7.2
> 600	3.8	3.6
> 700	3.4	1.8

Table 10.3: Model independent upper limits 95% CL on the visible cross section for the different signal regions defined in Table 7.2, in the 8 TeV analysis. Observed limits are given in the middle column, expected limits are given in the right column.

For the 13 TeV analysis the shape fit means model-independent limits are not fully comparable to the model-dependent limits, because from Eq. 9.10 it is clear that the choice of signal model will affect the background estimates in each of the regions. The model-independent limits in the 13 TeV analysis are instead calculated using inclusive $E_{T,\text{calo}}^{\text{miss}}$ signal regions like the ones used in the 8 TeV analysis. Table 10.4 presents the expected and observed model-independent limits for various regions with the 13 TeV analysis. It is observed that the model-independent limits are worse in the 13 TeV analysis. The main reason is the lower statistics in the 13 TeV analysis when compared to the 8 TeV analysis. The improvement in the model-dependent limits presented later in this chapter depend on the fact that the increase in production cross section for the signal models under investigation is much higher than the increase in production cross section for the background processes.

10.5 ADD Graviton Production

Limits on the ADD model parameters are presented as a lower limit on the fundamental Planck scale M_D in n dimensions, at 95% CL, as a function of the number of extra dimensions n . These limits are obtained from the upper limits on μ_{sig} using the known relations between μ_{sig} , the production cross section σ

$E_{T,\text{calo}}^{\text{miss}}$ [GeV]	$\sigma \times A \times \epsilon$ (obs.) [fb]	$\sigma \times A \times \epsilon$ (exp.) [fb]
>250	553	582
>300	308	368
>350	196	217
>400	153	125
>500	61	51
>600	23	26
>700	19	15

Table 10.4: Model independent limits on the visible cross sections at 95% CL, for different inclusive $E_{T,\text{calo}}^{\text{miss}}$ thresholds corresponding to the lower thresholds on the signal regions defined in Table 7.3 for the 13 TeV analysis. Observed limits are given in the middle column, expected limits are given in the right column.

and M_D . Since $\mu_{\text{sig}} = 1$ is associated with the signal strength with the nominal production cross section σ_{nom} found in Table 8.1, the lower limit on μ_{sig} is associated with an upper limit on the production cross section σ_{excl} through

$$\sigma_{\text{excl}} = \mu_{\text{sig}} \sigma_{\text{nom}} \quad (10.7)$$

Using the relation $\sigma = \frac{C_n}{M_D^{n+2}}$ from Eq. 8.2 with Eq. 10.7, the lower limit on M_D given the upper limit on μ_{sig} is written

$$M_{D,\text{excl}} = \frac{M_{D,\text{nom}}}{\mu_{\text{sig}}^{\frac{1}{n+2}}} \quad (10.8)$$

Using this equation the extracted upper limit on μ_{sig} is translated into a lower limit on M_D

10.5.1 The Validity of the Effective Theory

As presented in Sec. 2.4, the analysis is probing a region of phase space in which the effective theory cannot be trusted. Two sets of observed limits are calculated, one in which the effective theory is assumed to be valid, and another in which the limit of validity is taken into account for events with $\hat{s}$ above the lower limit

on M_D . In the second case the lower limit is truncated by weighing down signal events for which $\hat{s} > M_D$ with a weight $M_D^4 / \hat{s}^2$ [2, 58]. For each value of the lower limit M_D a suppression factor is derived, with which the limit on the visible cross section can be scaled down depending on the actual value of the excluded M_D .

The upper panel of Fig. 10.4 shows the $\hat{s}$ -distribution for $n = 6$ in the 13 TeV analysis, in the signal region with $500 < E_{T,\text{calo}}^{\text{miss}} < 600$ GeV. A straight line close to the excluded limit on M_D before any truncation is also shown. The figure shows that a large part of the generated events with $\hat{s}$ -values are in the region where the effective theory cannot necessarily be trusted. The lower panel of Fig. 10.4 shows the visible cross section for $n = 6$ with and without truncation as a function of M_D , if only this signal region would be used. The truncated visible cross section goes to 0 at $M_D = 0$, since all events have $\hat{s} > 0$ and thus all events get weighted down. The horizontal line represents a typical model independent limit on the visible cross section, for purpose of illustration (this limit is not actually used in the analysis). The point where the cross section of the model intersects the horizontal line indicates the lower limit on M_D . However in the combined fit only the ratio between the continuous line and dashed line are used to reduce the visible signal event yield in each signal bin as function of the limit on M_D .

For the 8 TeV analysis this suppression factor is simply applied to the upper limit on the production cross section, which yields a truncated value that is translated into a truncated lower limit on M_D .

For the 13 TeV analysis the suppression function, essentially the ratio of the dashed line over the full line in the lower panel of Fig. 10.4, will be different for the various signal regions used in the global fit, since the shape of the $\hat{s}$ distribution depends on $E_{T,\text{calo}}^{\text{miss}}$. For this analysis, after computing the lower limit on the M_D , the signal yield in each signal region bin is weighted by a suppression factor derived for that specific region. The limit setting procedure is repeated using the truncated signal yield, and new lower limits on M_D are obtained. In order to also account for the fact that the excluded value of M_D is lowered after truncation, the suppression factors are recomputed for the new value of M_D . The limits before and after truncations are compared, and if the difference between them is more than $0.1\sigma_{\text{exp}}$ (where σ_{exp} is the error on the expected limit), the truncation is repeated.

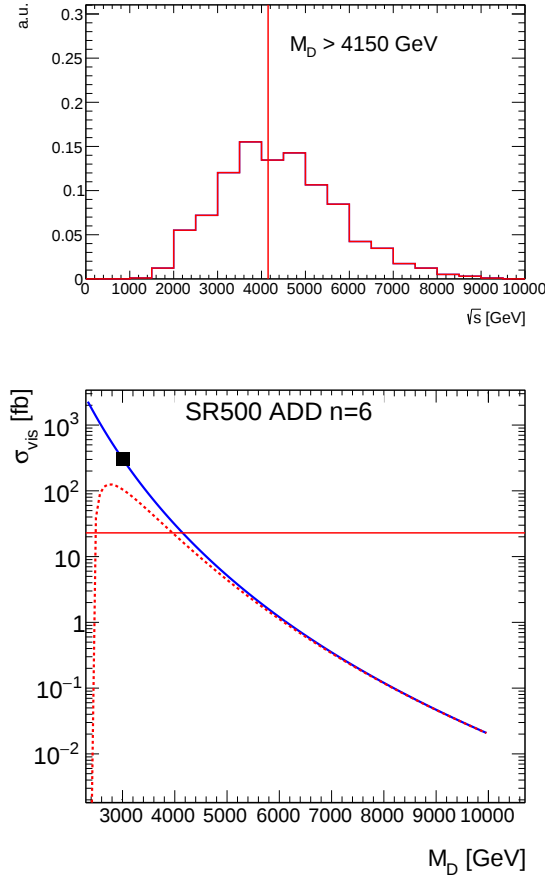


Figure 10.4: Upper: Distribution of generated $\hat{s}$, for $n = 6$ in the signal region with $500 < E_{T, \text{calo}}^{\text{miss}} < 600$ GeV. The straight line is placed close to the excluded limit on M_D before truncation. Lower: The visible cross section for $n = 6$ as a function of M_D , with and without truncation in the signal region with $500 < E_{T, \text{calo}}^{\text{miss}} < 600$ GeV. The horizontal line indicates the upper limit on the production cross section if limits are set using this region only. The black square indicates the nominal value from the generated signal sample.

10.5.2 Results of the 8 TeV Analysis

In the 8 TeV analysis, SR7 yields the best expected limits for the ADD models, and is used to set the lower limits on M_D . Figure 10.5 shows how the vis-

ible cross section depends on M_D for three different values of n , in SR7. It is compared to the model-independent limit for the same signal region. Any model predicting a visible cross section above the model-independent limit is excluded. The experimental errors on the background and the signal model, as well as the errors from the signal generation that affect the acceptance of the model, are included in the error band around the model-independent limit. The systematic errors that only affect the production cross section of the model are included in the model error bands.

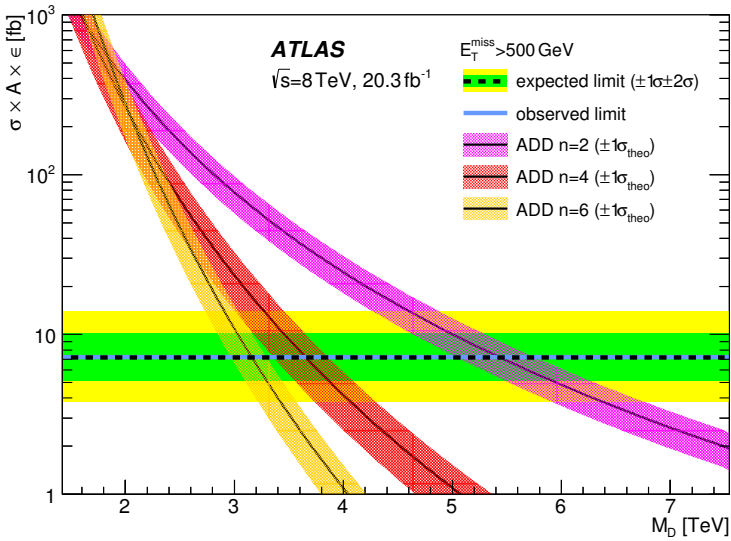


Figure 10.5: 8 TeV analysis 95% CL upper limit on $\sigma \times A \times \epsilon$ for SR7, with $E_T^{\text{miss}} > 500\text{ GeV}$, as a function of the reduced Planck scale M_D . This is compared to the model-independent observed and expected limits on the visible cross section for this signal region.

Table 10.5 summarizes the limits on the ADD models for all n from the 8 TeV analysis. The observed limits are presented with and without truncation. The experimental errors include those signal model uncertainties that affect the acceptance to the model. The theory uncertainties include those signal model uncertainties. Figure 10.6 shows the 95% CL lower limits on M_D . The experimental uncertainties, shown as a yellow and green error band on the expected

limit in the figure, include all experimental uncertainties, as well as those theoretical uncertainties that affect the acceptance of the model. The theoretical uncertainties that only affect the cross section are included in the σ_{theory} term in the table.

The limits constitute an improvement over the analysis using the 7 TeV data [58].

n extra dimensions	95% CL Observed Limit [TeV]		95% CL Expected Limit [TeV]	
	Nominal (Truncated)	$\pm 1 \sigma_{\text{theory}}$	Nominal	$\pm 1 \sigma_{\text{exp}}$
2	5.25 (5.25)	$+0.31$ -0.38	5.25	$+0.59$ -0.58
3	4.11 (4.11)	$+0.25$ -0.30	4.11	$+0.38$ -0.36
4	3.57 (2.56)	$+0.33$ -0.29	3.57	$+0.26$ -0.25
5	3.27 (3.24)	$+0.17$ -0.25	3.27	$+0.23$ -0.21
6	3.06 (2.96)	$+0.13$ -0.19	3.06	$+0.20$ -0.18

Table 10.5: 95% CL observed and expected limit on the fundamental Planck Scale M_D for $n = 2-6$ extra dimensions, with 20.3 fb^{-1} of collected data at 8 TeV. The observed limits after truncation is given in parentheses.

10.5.3 Results of the 13 TeV Analysis

In order to derive the 13 TeV analysis limits the binned approach described in Sec. 9.1.2 is slightly modified. The $\hat{p}_T > 150 \text{ GeV}$ cut defined in Sec. 8.2 in the generation of the signal models makes the analysis selection fully efficient only at $E_{\text{T,calo}}^{\text{miss}} > 350 \text{ GeV}$, and for this reason only the four signal regions SR4-SR7 are used. Figure 10.7 shows the results of scans of μ_{sig} for $n=2$ and $n=6$. These scans amount to testing values of μ_{sig} using the test statistic introduced in Sec. 10.3, and using the CL_s method to calculate their compatibility with the observed yield in data. Values of μ_{sig} for which the p-value is below 0.05 are excluded at 95% CL or higher. The excluded μ_{sig} for the two models are 0.41 and 0.055, where $\mu_{\text{sig}} = 1$ corresponds to the M_D for the nominal ADD models presented in Table 8.1.

Table 10.6 summarizes the limits on M_D for all n . It includes the limits on M_D after truncation. The effect of truncations is larger for higher values of n . For $n=2$ the effect is negligible, while for $n=6$ the truncation corresponds to a 5% decrease of the observed lower limits. Figure 10.8 shows the expected, observed and truncated limits at 95% CL for all n . Included in this figure for reference are also the observed limits from the 8 TeV analysis, and it is clear

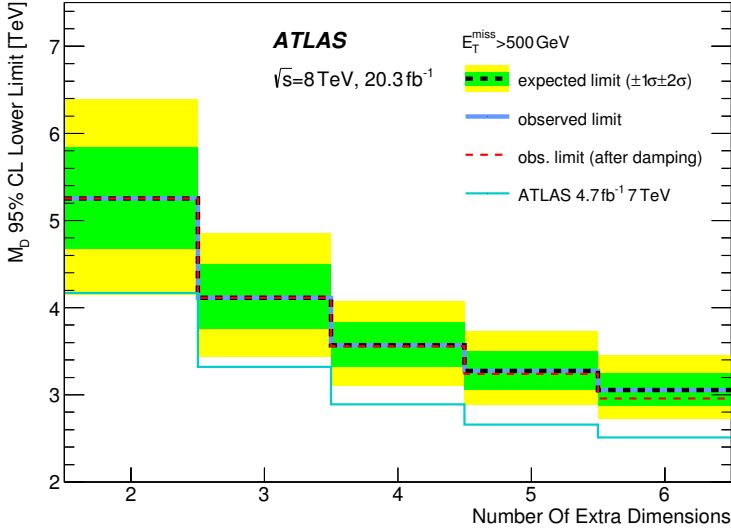


Figure 10.6: 95% CL limits on M_D as a function of the number of extra dimensions n for a signal region with $E_{T,\text{calo}}^{\text{miss}} > 500$ GeV, from the 8 TeV analysis. In this figure the expected and observed limits overlap. The dashed red line represents the truncated limits using the truncation method described in Sec. 10.5.1. The limits are compared to those set by the ATLAS monojet search using 4.7 fb^{-1} of 7 TeV data [58].

that the 13 TeV limits constitute a significant improvement. These limits on the fundamental Planck scale in $4 + n$ dimensions also sets upper limits on the size of the extra dimensions through Eq. 2.5. The upper limit on the size of new extra dimensions range from $11 \mu\text{m}$ for $n = 2$ to 3.8 fm for $n = 6$.

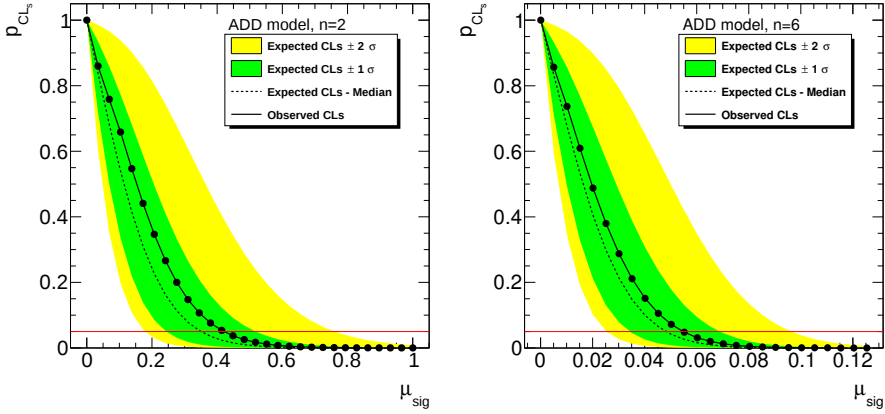


Figure 10.7: p -values using the CL_s approach, as a function of μ_{sig} , for $n=2$ (left) and $n=6$ (right) in the 13 TeV analysis. The green and yellow bands represent $\pm 1 \sigma$ on the expected limits. The red line shows $p = 0.05$. The crossing of the observed line with this line indicates the upper limit on μ_{sig} .

n extra dimensions	95% CL Observed Limit [TeV]		95% CL Expected Limit [TeV]	
	Nominal (Truncated)	$\pm 1 \sigma_{\text{theory}}$	Nominal	$\pm 1 \sigma_{\text{exp}}$
2	6.58 (6.58)	$+0.52$ -0.42	6.88	$+0.65$ -0.64
3	5.46 (5.44)	$+0.45$ -0.34	5.67	$+0.41$ -0.41
4	4.81 (4.74)	$+0.41$ -0.29	4.96	$+0.29$ -0.23
5	4.48 (4.34)	$+0.41$ -0.26	4.60	$+0.23$ -0.19
6	4.31 (4.10)	$+0.41$ -0.24	4.38	$+0.19$ -0.19

Table 10.6: 95% CL observed and expected lower limit on the fundamental Planck Scale M_D for $n = 2$ -6 extra dimensions, with 3.2 fb^{-1} of collected data at 13 TeV. The 95% CL observed limits after the truncation of the signal cross section are also given.

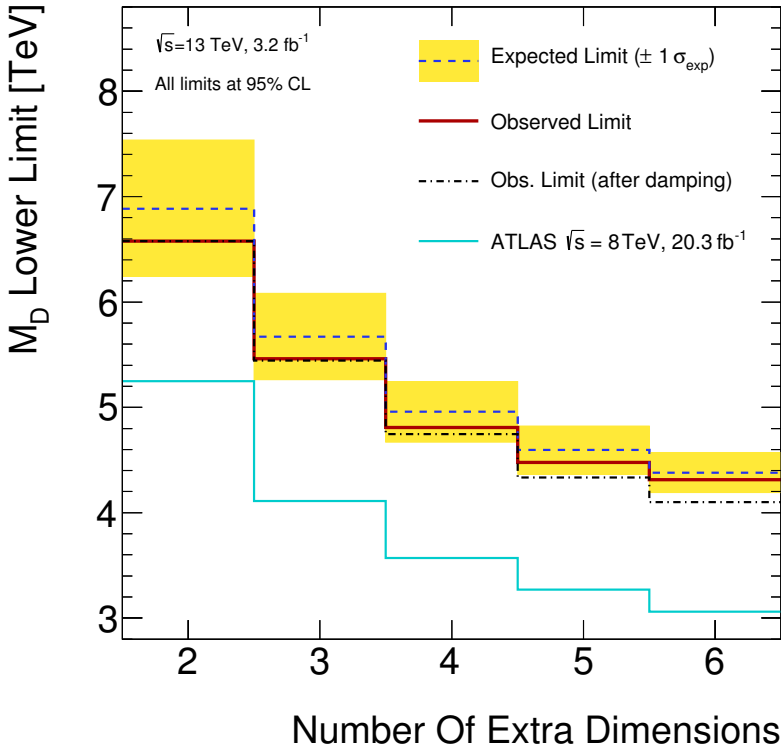


Figure 10.8: 95% CL lower limits on M_D as a function of the number of extra dimensions n , with the 13 TeV analysis. The dashed black line represents the truncated limits using the truncation method described in Sec. 10.5.1. The 8 TeV limits presented in Fig. 10.6 are included for comparison.

10.6 WIMP Pair Production

10.6.1 Results of the 8 TeV Analysis

Limits are set on the parameters of WIMP pair production models, both in the EFT framework and in the simplified model framework presented in Sec. 2.3.5, using the signal models described in Sec. 8.3. In the EFT framework limits on the signal strength are interpreted as limits on the production cross section for each signal model. These are turned into limits on the suppression scale M_* as a function of the WIMP mass m_χ . This is performed for each of the effective operators in Table 2.1. For the 8 TeV WIMP analysis the signal region with the best expected limits is different for different WIMP signals, because of differences in the kinematics of the different signals. For the operators D1, D5 and D8 SR7 is optimal, for D9, D11 and C5 SR9 is optimal, and finally for C1 SR4 is optimal.

For each signal point the limits are truncated according to the criterion introduced in Sec. 2.4 by requiring that $Q < M_{\text{med}}$. A detailed study to find a relation between M_* and M_{med} and the implications for the validity of the EFT is performed in the 8 TeV paper [2], following what is outlined in Ref. [185]. Here we summarize it by stating some important results:

- The relation between M_* and M_{med} depends on the coupling strengths g_{SM} and g_{DM} . Since the full theory is treated as unknown, what values of these couplings that are justified is also unknown. Thus in the following we make two different assumptions. The first is the so-called natural scale assumption, $g_{\text{SM}} = g_{\text{DM}} = 1$, and the second is to assume the maximum value of the couplings while the theory is still perturbative. What the maximum value is depends on the operator, but it is always higher than the natural scale assumption.
- Using the relation $M_* \sim M_{\text{med}} \sqrt{g_{\text{SM}} g_{\text{DM}}}$ from Eq. 2.13 with given coupling constants, we require that events fulfill $Q < M_{\text{med}}$ to be considered valid. The limit setting procedure is then repeated using only events considered valid under this assumption.
- Since $Q > 2m_\chi$, the fraction of valid events is reduced with higher WIMP masses.
- The different operators turn out to have quite different fractions of validity. For the complex scalar operators C1 and C5 there are no points in the

parameter space where the fraction of validity is not zero. For the Dirac fermion operators there is still a significant fraction of valid events used to set the truncated limits in Fig. 10.9.

Figure 10.9 shows the lower limits on M_* as a function of m_χ for four different effective operators. It is clear from these plots that the truncation scheme affects the models very differently. The operators providing the lowest limits are also the ones most affected by the truncation. For the operator D1 almost no signal points pass the truncation criteria, so in the assumption of truncated limits the experiment cannot set limits on this model. On the other hand, for the D9 operator, neither truncation scheme has a significant effect. The lower limits range from a non-truncated value of 40 GeV for the D1 operator, to a truncated value of 1.4 TeV using the natural scale assumption for the D9 operator.

In the simplified models with a Z' -like mediator limits, the limits on signal strengths are translated into upper limits on the production cross sections, which in turn are translated into upper limits on the coupling strengths. For each point in the m_χ/M_{med} plane 95% CL upper limits are set on $\sqrt{g_{\text{SM}}g_{\text{DM}}}$. This is performed for both of the generated mediator widths. Figure 10.10 shows these limits, for the width $\Gamma = M_{\text{med}}/3$. The figure shows that the strongest limits on the couplings are obtained at low mediator and WIMP masses.

In order to compare the simplified models to the EFT, the limits on $\sqrt{g_{\text{SM}}g_{\text{DM}}}$ are translated into limits on $M_* = M_{\text{med}}/\sqrt{g_{\text{SM}}g_{\text{DM}}}$. These limits are shown in Fig. 10.11, where they are also compared to the EFT results using the D5 operator corresponding to the same vector interaction. The figure shows that the EFT tends to overestimate the lower limit on M_* when compared to the UV-complete theory for the lowest mediator masses, and tends to underestimate them in the intermediate region in which the WIMPs can be produced resonantly. For mediator masses above ~ 5 TeV the EFT results overlap with the results from the simplified theory, which is what is expected since this region matches the heavy mediator assumption of the EFT.

10.6.2 Results of the 13 TeV Analysis

In the 13 TeV analysis all signal and control regions are used in global fits to set limits on the parameters of the simplified Z' -like models described in Sec. 8.3.2. The widths and coupling strengths are fixed. The p-value for each signal point in the generated mass grid is calculated, and an exclusion contour in the $m_\chi - M_{\text{med}}$ plane is drawn. This is shown in Fig. 10.12. Under the assumptions of this

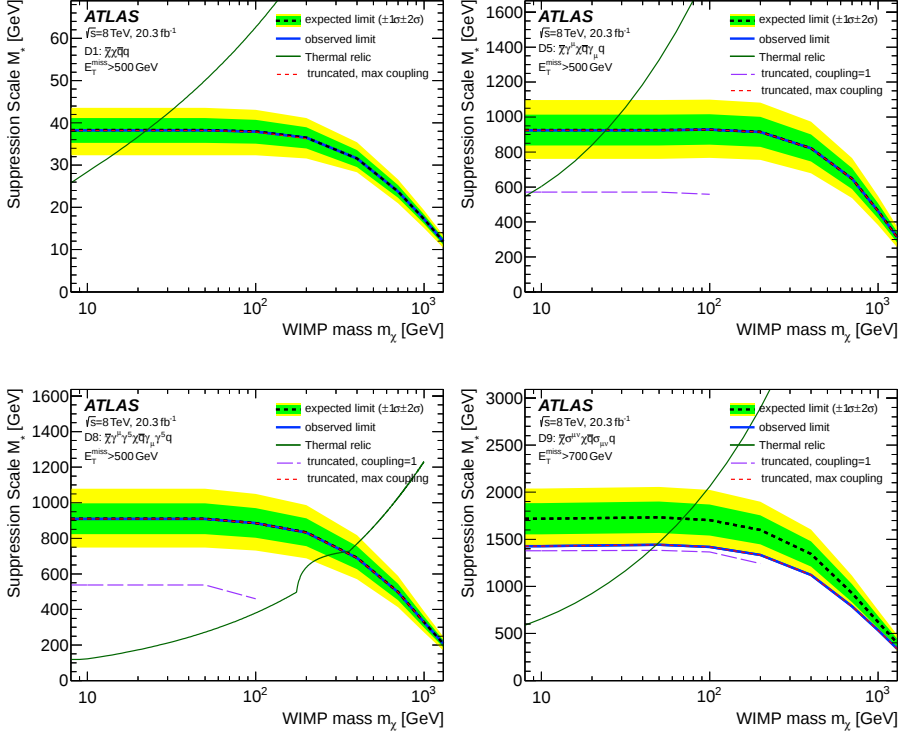


Figure 10.9: 95% CL lower limits on the suppression scale M_* as a function of the WIMP mass m_χ , for the effective operators D1 (top left), D5 (top right), D8 (bottom left) and D9 (bottom right). Expected and observed limits are shown as dashed and solid lines. The green lines are the values at which WIMPs of the given mass would result in the relic density measured by the WMAP experiment [186], assuming the annihilation of DM from the early universe took place exclusively through the mediation of this operator. Also included are the effects of the two different truncation schemes on the observed limit. Figure from Ref. [2].

analysis, WIMP masses up to $m_\chi = 300$ GeV and mediator masses up to $M_{\text{med}} = 1 \text{ TeV}$ are excluded.

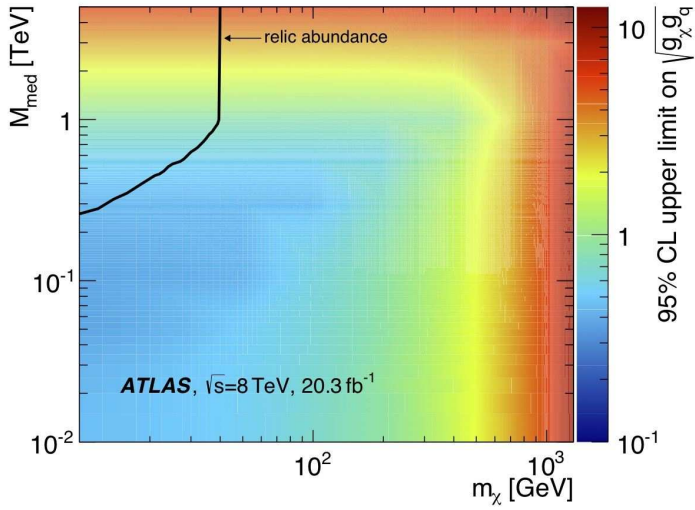


Figure 10.10: 95% CL upper limits on the DM-SM coupling strengths $\sqrt{g_{\text{SM}} g_{\text{DM}}}$ in the simplified model framework of the 8 TeV analysis, as a function of the mediator mass M_{med} and WIMP mass m_χ . Values leading to the relic density observed by the Planck experiment [187] are illustrated by the solid lines. Figure from Ref. [2].

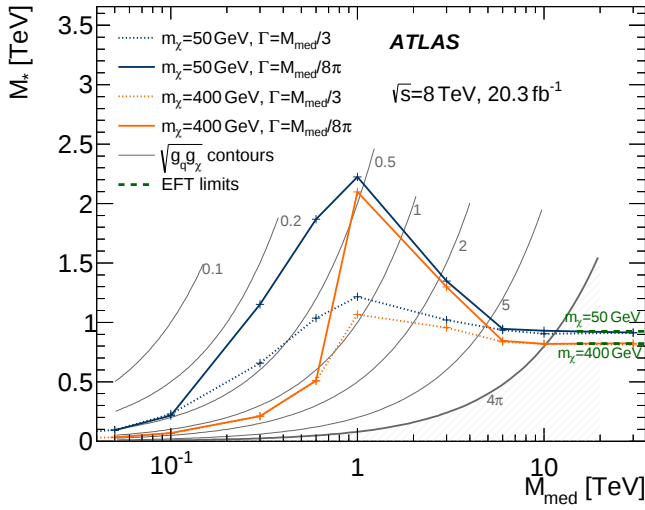


Figure 10.11: 95% CL limits on M_* , when comparing the limits using the D5 effective operator to the limits using the simplified theory, in the 8 TeV analysis. For the simplified theory the M_* limits are obtained by multiplying the limits on $\sqrt{g_{\text{SM}} g_{\text{DM}}}$ by M_{med} . The gray lines show the contours of constant $\sqrt{g_{\text{SM}} g_{\text{DM}}}$. Figure from Ref. [2].

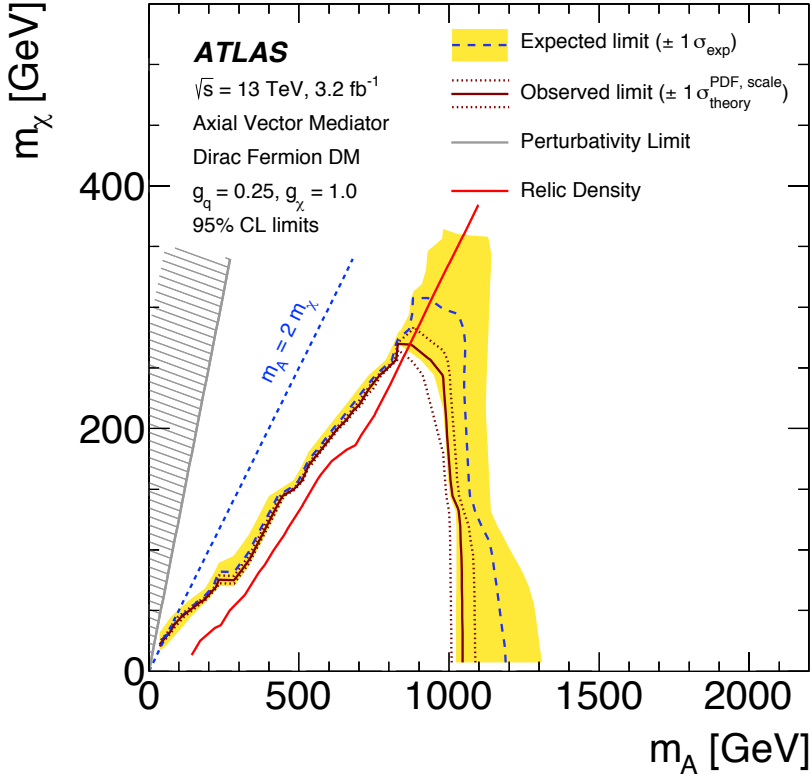


Figure 10.12: 95% CL exclusion contours in the $M_{\text{med}} - m_\chi$ (M_{med} here denoted m_A) plane, for a simplified model with an axial-vector mediator in the 13 TeV analysis. The red curve corresponds to the parameters producing the correct relic matter density with the chosen couplings. From Ref. [3]

10.6.3 Comparison to Direct and Indirect Detection Experiments

The limits on the WIMP pair production cross sections are translated into limits on the spin-independent and spin-dependent WIMP-nucleon scattering cross sections, as well as into limits on the WIMP-WIMP annihilation rate, introduced in Sec. 2.3. For the 8 TeV EFT results this process is performed using equations from Ref. [86], and for the 13 TeV simplified model using the prescription from Ref. [88]. Figure 10.13 shows the comparison of the 8 TeV EFT limits to relevant limits from indirect and direct detection experiments. It also shows the impact of the different truncation schemes. Regardless of which truncation scheme used, these figures show that the limits set by this analysis are competitive at low WIMP masses for the spin-independent interaction cross sections. For the spin-dependent scattering cross section and the annihilation cross section, ATLAS sets competitive limits over the entire investigated range of WIMP masses.

Figure 10.14 shows the comparison of the 13 TeV simplified model limits to some relevant direct detection experiments, comparing the spin-independent WIMP-nucleon scattering cross section. For light WIMPs ATLAS sets upper limits at 10^{-42} cm^2 for $m_\chi < 300 \text{ GeV}$. The loss of sensitivity in the region where the WIMPs can be produced off-shell leads to the turn of the exclusion line at $m_\chi \approx 300 \text{ GeV}$. The limits from simplified models are only valid within the context of the given model. For this specific model the figure shows that at low WIMP masses ATLAS sets much harder constraints on the production cross section than any of the direct detection experiments.

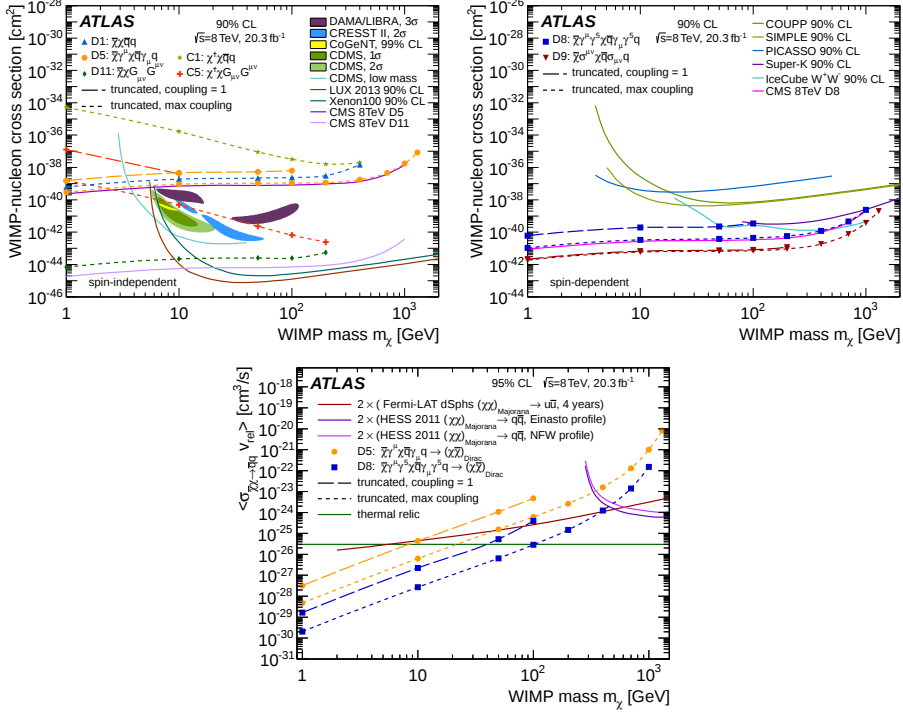


Figure 10.13: 90% CL upper limits from the 8 TeV analysis on the spin-independent WIMP-nucleus scattering cross section (upper left), the spin-dependent WIMP-nucleus scattering cross section (upper right), and the WIMP-WIMP annihilation rate (lower). Each line color represents an effective operator, whereas the different line styles represent the two different truncation schemes. The points are the generated signal points. These numbers are compared to results from DAMA/LIBRA [188], CRESST [94], CoGeNT [92], CDMS [189, 93], LUX [100], XENON100 [97], CMS [57], COUPP [190], SIMPLE [79], PICASSO [191], Super-K [102], IceCube [192], Fermi-LAT [193] and H.E.S.S [81]. In the WIMP-WIMP annihilation figure the relic density annihilation rate from Planck [187] is shown for comparison. Figures from [2].

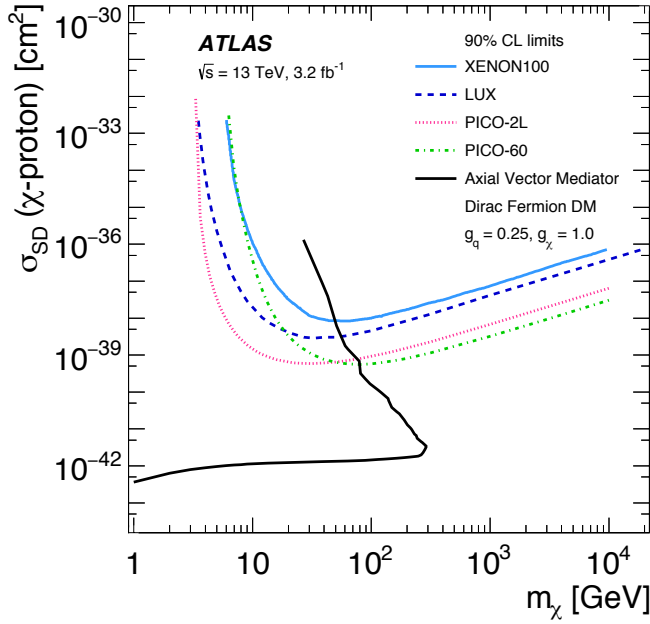


Figure 10.14: 90% CL exclusion limits on the spin-independent WIMP-nucleus scattering cross section in the 13 TeV analysis, calculated from the limits in Fig. 10.12 (black line). The limits are compared to comparable limits from direct detection experiments: Pico [77, 78] (red dotted and green dash-dotted), LUX [194] (dashed blue) and XENON100 [195] (solid light blue). The comparison is only valid for the simplified model described in this thesis. From Ref. [3]

Chapter 11

Conclusions

Despite the great success of the Standard Model of particle physics in the last four decades, there are fundamental questions that are still unanswered. Two issues that occupy both theoretical and experimental physicists are how to unify quantum mechanics and gravity, and how to detect the Dark Matter we can indirectly observe to make up around five sixths of all matter. The energies available at the Large Hadron Collider make it possible to study these issues in particle collisions in the laboratory.

In order to make as accurate measurements as possible concerning new observations, as well as to increase our sensitivity to new physics, the detector must perform optimally. We also need to understand the conditions of the detector during the recording of data to be able to reproduce its performance in simulations. This thesis presents studies of one area where a detailed knowledge of detector performance is needed, namely the levels and distributions of electronic noise in the Tile Calorimeter. This noise is used to monitor detector performance, to provide input to the topological clustering algorithm used to reconstruct hadronic jets and to accurately model the ATLAS detector in Monte Carlo simulations. It has been shown that the noise decreased, and now more closely follows a Gaussian distribution, after a hardware exchange was performed in December 2011. The 40 modules in which the Low Voltage Power Supplies were exchanged for a new version have 13% lower electronic noise after the change.

Searches for Dark Matter and Extra Dimensions have been performed by looking for excesses of events with an energetic hadronic jet and high missing transverse momentum. Two such analyses have been presented, one using all

the LHC Run 1 data with 8 TeV center-of-mass energy proton-proton collisions, and one using 3.2 fb^{-1} of LHC Run 2 data where the energy is 13 TeV. The main background to this type of signal is the production of a Z boson in association with a jet, where the Z boson decays to a pair of neutrinos. Understanding and correctly modeling this background is essential to the sensitivity of the analysis to new physics. The two analyses use slightly different methods to estimate backgrounds associated with W and Z boson production, both however relying on the construction of control regions from which auxiliary measurements are used to perform extrapolations to the signal region.

This thesis introduces a control region with a W boson decaying to an electron and a neutrino, used in the 8 TeV analysis. This control region typically has a large multi-jet contamination leading to large systematic uncertainties on the final estimate of the $Z \rightarrow \nu\nu$ background in the signal region. However it has been shown in this thesis that this contamination can be greatly reduced to the point that this region can be used in the analysis, by using tighter isolation criteria on the electrons in the control region. Using isolation criteria introduced in this thesis, the control region can provide as good estimates of the number of $Z \rightarrow \nu\nu$ background events as any of the control regions used in previous versions of the analysis, or even better. The main advantage of using control regions with W bosons as compared to Z bosons, is that once their contamination is under control they have higher statistics, which make them especially useful at high E_T^{miss} . This is also where most of the studied signal models predict new physics.

For the 13 TeV analysis, this thesis presents studies performed to optimize the Monte Carlo generation of ADD large extra dimensions signal samples. It is demonstrated that the production cross section greatly increases when going from 8 to 13 TeV center-of-mass energy, meaning already with 3.2 fb^{-1} of collected data, the sensitivity to these models is higher than with the full 20.3 fb^{-1} of 8 TeV data collected in 2012. Furthermore it is shown that optimizing the settings for mass distributions of KK graviton modes as well as for renormalization and factorization scales, makes the physics more predictable and the Monte Carlo generation more efficient.

We use data-driven methods to calculate the Standard Model expectation and find that there is no significant excess in data compared to this estimation, in either of the two analyses. Model-independent limits calculated using these results have been presented. The results are also interpreted as limits on new physics. In this thesis we present limits on specific models with Extra Dimen-

sions where the scale of gravity is set close to the weak scale. The lower limits on the reduced Planck scale M_D are set between 5.3 and 3.1 TeV for models with two to six extra dimensions in the 8 TeV analysis, and between 6.6 and 4.3 TeV in the 13 TeV analysis. We also present limits on models with pair produced weakly interacting massive particles, which are one of the main dark matter candidates. In the 8 TeV analysis this is performed in the frameworks of effective field theories as well as in a simplified model, whereas in the 13 TeV analysis only the simplified model framework is analyzed. The 8 TeV analysis sets limits on the suppression scale M_* of the theory for several different effective operators. These limits range from 40 GeV for the scalar operator D1 to 1.4 TeV for the tensor operator D9. In terms of the simplified models presented in the 13 TeV analysis, we set limits on the WIMP mass m_χ up to ≈ 270 GeV for mediator mass M_{med} of 1 TeV. Compared to direct and indirect detection experiment it is shown that under the assumptions of the signal models, this analysis sets competitive limits at low masses for the spin-independent WIMP-nucleon scattering cross section, and for the entire investigated mass range for the spin-dependent WIMP-nucleon scattering cross section and the WIMP-WIMP annihilation rate.

Sammanfattning på svenska

Elementarpartikelfysik är vetenskapen om naturens minsta beståndsdelar - vilka de är, vilka egenskaper de har och hur de växelverkar med varandra. Studiet av dessa partiklar är grundläggande för att förstå den fysiska världen och allt vi kan observera. Kunskapen om det allra minsta ger oss samtidigt verktyg att förstå naturens allra största fenomen. Kunskap om elementarpartiklarnas växelverkan låter oss sålunda förstå det universum vi lever i, vad det består av, hur det en gång tog sin början och hur det kommer utvecklas i framtiden.

Den teoretiska modell vi använder för att beskriva elementarpartiklarna och deras växelverkan kallas Standardmodellen. Standardmodellen är en kvantfältteori där elementarpartiklarna kan delas in i två kategorier: Materiepartiklar (fermioner) som bygger upp all materia och kraftförmedlare (bosoner) som förmedlar interaktion mellan partiklar. Standardmodellen har sedan den formulerades i slutet av 1960-talet varit oerhört framgångsrik, såväl vad gäller att beskriva observerade fenomen, som att förutse nya. Flera av de upptäckter av nya partiklar som skett de senaste 40 åren har föregåtts av teoretiska förutsägelser. Den senaste av dessa är Higgs-bosonen som förutsågs redan 1964 av Higgs, Brout och Englert, och observerades av ATLAS- och CMS-experimenten 2012. Trots Standardmodellens stora framgångar finns det mycket som talar för att den inte är en slutgiltig, komplett "teori om allt". Den innehåller svårförklarliga teoretiska problem, dessutom finns ett flertal observationer som inte kan förklaras inom ramarna för modellen. En av dessa är frånvaron av en allmänt accepterad teori för gravitationell växelverkan på partikelnivå. Detta problem är tätt förknippat med den hittills obesvarade frågan om varför gravitationen är så svag jämfört med de andra formerna av växelverkan. Ett annat problem är de många observationerna av mörk materia, som enligt de senaste uppskattningarna utgör fem sjättedelar av all materia i universum. Standardmodellen saknar svar på vad denna materia består av.

Ett sätt att studera elementarpartiklar är att bygga acceleratorer. Large Hadron Collider (LHC) är en proton-proton-kolliderare på det europeiska kärnforskningscentret CERN utanför Genève. LHC är världens mest kraftfulla partikelaccelerator vad gäller såväl rörelseenergin hos de kolliderande partiklarna som luminositeten, det vill säga den mängd partiklar som kolliderar varje sekund. 2015 kolliderades protoner med världsrekordenergin 13 TeV, vilket med hjälp av Einsteins ekvation $E = mc^2$ låter oss skapa långt tyngre partiklar än de protoner som kolliderar. Varje sekund kolliderar ungefär en miljard protoner, vilket ökar sannolikheten att producera nya tunga partiklar. För att maximalt utnyttja den potential till nya upptäckter som denna energi och luminositet medför finns fyra stora detektorer, en vid varje punkt där protonstrålarna kolliderar med varandra. En av dessa är ATLAS. ATLAS-detektorn är byggd för att så noggrant som möjligt kunna mäta egenskaper hos de partiklar vi redan känner till, och för att kunna söka efter nya, hittills okända partiklar.

I denna avhandling presenteras två analyser av ATLAS-data, en med masscentrumsenergin 8 TeV och en med 13 TeV. I denna data analyseras så kallade monojet-händelser. Dessa kännetecknas av en högenergetisk hadronskur som detekteras samtidigt som ingenting detekteras på motsatt sida av detektorn. Denna obalans i den transversella rörelsemängden tyder på att stora delar av rörelseenergin i kollisionen överförs till partiklar som är osynliga för detektorn. Sådana detektorsignaturer förutsågs av flera modeller för ny fysik bortom Standardmodellen. En av dessa är den s.k. ADD-modellen, där nya, små rumsdimensioner introduceras utöver de 3+1 vanliga rumtidsdimensionerna. I denna modell tillåts gravitationens kraftförmedlare gravitonen propagera i de nya dimensionerna, medan den vanliga materian är begränsad till att röra sig i de vanliga dimensionerna. Det får som effekt att gravitationen upplevs som svag på stora avstånd, men på väldigt korta avstånd är den av samma storleksordning som de övriga krafterna. En annan modell som monojet-analysen kan undersöka är produktionen av svagt växelverkande massiva partiklar, s.k. WIMPs. Dessa hypotetiska partiklar är idag de hetaste kandidaterna till att utgöra universums mörka materia.

För att förstå om de händelser vi observerar är en signal från ny fysik bortom Standardmodellen, behöver vi förstå dels hur en sådan signal skulle se ut i detektorn, och dels den bakgrund till vår hypotetiska signal som kommer från processer inom Standardmodellen. För att förstå hur en signal ser ut utför vi simuleringar med Monte Carlo-metoder. Denna avhandling presenterar en förbättring av simulerade händelser där en graviton produceras i ett scenario med

extra rumsdimensioner. För att förstå bakgrunden från processer inom Standardmodellen introducerar denna avhandling en ny bakgrundsberäkning som gör analysen känsligare för ny fysik.

Då de detekterade händelserna inte uppvisar något överskott gentemot den uppskattade bakgrunden kan vi sätta gränser på parametrar för modeller bortom Standardmodellen.

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