

Search for Supersymmetry in final states with one Photon and Jets at the CMS Detector

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1 Introduction

For thousands of years, mankind has been seeking answers to the question of the origin of everything and how our universe evolved to its present form. The understanding of elementary particles and their interactions is the best way to come closer to these answers, because our universe is made up of and can be described with these. Many theories are invented to describe elementary particles, and experiments are performed to rule them out or enhance our believe in these theories.

The Standard Model of particle physics (SM) has proven to be the most successful theory describing subatomic physics. Particle properties and interactions can be predicted and agree with many high-energy measurements. With the discovery of the Higgs boson by CMS [1] and ATLAS [2], all SM particles are observed.

Even so, the hierarchy problem and astrophysical observations suggest the presence of physics beyond the SM. The Supersymmetry (SUSY) theory predicts a symmetry of bosons and fermions, which leads to new particles and specific decay chains that can be observed if SUSY is realized in nature.

A possible scenario for SUSY is Gauge Mediated Symmetry Breaking (GMSB), in which final states with photons, jets and gravitinos can occur. Gravitinos do not interact with the detector, but missing transverse energy is a hint for the presence of such particles.

As high energies are needed to produce and observe new heavy particles, the Large Hadron Collider was build to accelerate protons to a center-of-mass energy of up to $\sqrt{s} = 14$ TeV. These high energetic protons collide at several points, including the center of the Compact Muon Solenoid (CMS) detector. This thesis uses data corresponding to an integrated luminosity of 19.8 fb^{-1} , recorded with the CMS detector at $\sqrt{s} = 8$ TeV in 2012.

The main background arises from jets faking photons or prompt photons in combination with an imbalance of transverse energy due to mismeasured jets. In addition, electrons can be misidentified as photons. Both backgrounds are estimated from data. The small, irreducible background from hard photon radiation in events with real missing transverse energy, like γW , $\gamma t\bar{t}$ or $\gamma Z \rightarrow \gamma \nu \nu$ is estimated from simulation. Event yields and background prediction are compared in intervals of missing transverse energy. The compatibility of data with various GMSB signal hypotheses is tested, and exclusion limits depending on significant variables in the GMSB model are calculated. To develop and prove the validity of the background estimation methods, and to not be influenced by possible signal, the analysis is performed with simulated events first. After the methods are found to be precise and accurate, they are applied to data.

A similar analysis has been performed with data corresponding to an integrated luminosity of 4.93 fb^{-1} at $\sqrt{s} = 7$ TeV from 2010 [3] and with data corresponding to an integrated luminosity of 4.04 fb^{-1} at $\sqrt{s} = 8$ TeV from 2011 [4]. The change of the photon definition and other recent developments in the search presented here lead to several adjustments. The modifications with respect to the former analyses and the full analysis upgrade will be presented in this thesis.

The ATLAS collaboration studied final states with two photons [5], one photon and a bottom quark [6] or non prompt neutralino decays [7], but did not publish any inclusive

single photon search.

This thesis is structured as follows: After the introduction, the theoretical foundations are presented in Section 2. This is followed by the description of the experimental setup, especially the detector in Section 3. In Section 4, the reconstruction of particles and events is explained. Using these events, the background estimation strategy and the signal contamination are presented in Section 5. Signal studies are shown in Section 6. The results and expected limits are described in Section 7 and the conclusion is presented in Section 8.

2 Standard Model and Supersymmetry

In this chapter, the theoretical foundations of this work are presented. To simplify calculations and notation, the reduced Plack constant $\hbar$ and the velocity of light c are set to one:

$$\hbar = c = 1$$

Therefore, energy, momentum, and mass have the unit GeV. For lengths and time the metric system is used.

2.1 Standard Model

This chapter describes the most important properties of the Standard Model relevant for this thesis [8, 9].

The Standard Model of particle physics (SM) is a renormalizable gauge quantum field theory, which describes the electroweak and the strong force. Keystone of this theory are the symmetries of the unitary product group $SU(3) \times SU_L(2) \times U_Y(1)$.

Quantum Chromodynamics

Quantum Chromodynamics (QCD) is the $SU(3)$ component of the SM and describes the strong force. As representation of generators for $SU(3)$, the eight Gell-Mann matrices are used, which are interpreted as a gluon octet. The fundamental triplet is interpreted as color charge. The gluon (spin-1 particle) carries one color and one anti-color, whereas the quarks only carry one color. Interactions between color charged particles can be described by rotations in $SU(3)$.

Three generations of quarks have been observed. The mass eigenstates are related to the gauge eigenstates by the Cabibbo–Kobayashi–Maskawa mixing matrix. The most important properties of the resulting mass eigenstates of the quarks are stated in Table 2.1.

The gauge eigenstates mix by Instead of the gauge eigenstate, the mass eigenstate is used more often and is obtained by a rotation of the gauge eigenstates

Table 2.1: Approximate mass and electric charge of the mass eigenstates of quarks [8].

Generation	Name	Mass [GeV]	Electric Charge [e]
I	up	0.002	2/3
	down	0.005	−1/3
II	charm	1.3	2/3
	strange	0.10	−1/3
III	top	173	2/3
	bottom	4.2	−1/3

For each quark, there is an anti-quark with same mass, lifetime, and spin, but opposite other quantum numbers. If not explicitly stated, the quark’s name is used for both quark and anti-quark.

Free quarks have not been observed since they decay or are confined to color neutral hadrons on small timescales. Quark – anti-quark states are called mesons, states of three bound quarks are called baryons. A proton, for example, is a baryon with two up and one down valence quarks. The quarks are bound by gluons, which can interact with other gluons and can split into further gluons or quark – anti-quark pairs. These latter quarks in bound states are called sea-quarks. Quarks and gluons are also called partons.

Electroweak theory

The electroweak theory is based upon symmetries in the $SU_L(2) \times U_Y(1)$ gauge group. The corresponding gauge bosons are the W^0, W^1, W^2 bosons and the B^0 boson, with the corresponding coupling constants g and g' .

To assign mass to particles, the potential

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad \mu^2 < 0 \text{ and } \lambda > 0$$

is added to the SM lagrangian [10, 11]. ϕ is a doublet of complex fields. The ground state $\nu^2 = |\phi|^2 = -\mu^2/\lambda$ is not symmetric with respect to $SU_L(2)$ transformation. This spontaneous symmetry breaking leads to new Goldstone particles. The Goldstone particles and the electroweak bosons mix to massive vectorial particles and one scalar particle, the Higgs boson.

The mass eigenstates and masses of the neutral gauge bosons, i.e. the Z boson and the photon field A, can be obtained as

$$\begin{aligned} Z &= \frac{gW^0 - g'B^0}{\sqrt{g^2 + g'^2}}, & m_Z &= \frac{1}{2}\nu\sqrt{g^2 + g'^2} \\ A &= \frac{g'W^0 + gB^0}{\sqrt{g^2 + g'^2}}, & m_A &= 0, \end{aligned}$$

and the charged bosons $W^\pm$ as

$$W^\pm = (W^1 \mp W^2)/\sqrt{2}, \quad m_W = \frac{1}{2}\nu g.$$

Quarks and leptons interact with the electroweak force. There are three generations of leptons, which are stated in Table 2.2. The mixing to their mass eigenstates is described by the Pontecorvo–Maki–Nakagawa–Sakata matrix [12]. In each generation, there is a neutral mass eigenstate with extremely small mass and a charged eigenstate.

Table 2.2: Listing of the three lepton generations. There is a heavy charged lepton and a very light neutral lepton in each generation. The generations are sorted by lepton masses [8].

Generation	Name	Mass [GeV]	Electric Charge [e]
I	e	$5.1 \cdot 10^{-4}$	-1
	ν_e	$< 2 \cdot 10^{-9}$	0
II	μ	0.11	-1
	ν_μ	$< 2 \cdot 10^{-9}$	0
III	τ	1.8	-1
	ν_τ	$< 2 \cdot 10^{-9}$	0

On small energy scales, the electroweak theory can be separated into electromagnetic and weak theory. The electromagnetic theory can be modeled by an $U_{\text{em}}(1)$ group alone and affects charged particles only.

Similar as for the quarks, there is an anti-fermion to each fermion with same mass, lifetime, and spin, but opposite other quantum numbers. If not explicitly stated, the fermion's name is used for both fermion and anti-fermion.

2.2 Motivation for Physics Beyond the Standard Model

Although the SM predictions agree with many measurements and can explain many phenomena, there still remain some open questions:

Observations in Astrophysics: The mass of galaxies and galaxy clusters estimated by gravitational effects is much larger than the mass of the luminous matter for these objects. Matter which interacts gravitationally, but not through the strong or the electromagnetic force could explain this phenomenon and is called Dark Matter. The only particles in the SM that neither anticipate in the strong nor the electromagnetic interaction are neutrinos, but their contribution to Dark Matter is only small [13]. Even if there is indirect evidence for Dark Matter [14], no Dark Matter particle was found yet.

Much more matter than anti-matter is observed (for example much more positrons than electrons [15]). There has to be a mechanism that explains the excess of matter in comparison to anti-matter.

Multiplicity of generations: It is unknown why there are exactly three generations of quarks and leptons. Searches for additional generations were unsuccessful so far [16].

Unification of interactions: The electronic and the magnetic forces could be unified to a single theory [17]. Similar, the electromagnetic and weak forces can be described by the electroweak theory [11]. Unification is not only a more elegant way to formulate laws of nature from a mathematical point of view, but improves the understanding of nature [18]. Is it possible to unify the strong and electroweak force as well, so do they have the same origin?

Description of gravity: Gravity is well measured on astronomical to atomic scales, but its description is not part of the SM. Can the description of gravitation, formulated in a gauge quantum field theory, be related to the SM?

Hierarchy problem: The hierarchy problem is the fact that the mass scale of loop corrections to the SM Higgs boson mass can be much larger than the Higgs-boson mass itself [18].

Figure 2.1a shows the loop correction for a Dirac fermion f to the Higgs mass. With the coupling $-\lambda_f H \bar{f} f$ to the fermion, the correction for the Higgs mass is

$$\Delta m_H^2 = -\frac{2|\lambda_f|^2}{16\pi^2} \Lambda_{UV}^2 + \dots \quad (2.1)$$

For a scalar particle with mass m_S like in Fig. 2.1b and a coupling of $-\lambda_S |H|^2 |S|^2$ a correction of

$$\Delta m_H^2 = +\frac{\lambda_S}{16\pi^2} \Lambda_{UV}^2 - \frac{m_S^2 \lambda_S}{8\pi^2} \ln(\Lambda_{UV}/m_S) + \dots \quad (2.2)$$



Figure 2.1: Feynman diagrams for Higgs mass corrections with a fermion (a) and a scalar (b).

is obtained. Λ_{UV} is the ultraviolet momentum cutoff parameter. For the SM to be valid up to the Planck scale ($\Lambda_P = (4\pi G_{\text{Newton}})^{-1/2} = 2.4 \cdot 10^{18} \text{ GeV}$), the ultraviolet cutoff parameter needs to be of the same order. This leads to corrections to the Higgs-boson mass of the order of Λ_P , while the Higgs-boson mass is about 125 GeV and therefore many orders of magnitude smaller than the correction. This difference is considered to be “unnatural”.

2.3 Supersymmetry

One way to solve many of the problems mentioned above is to introduce a symmetry between fermions and bosons called Supersymmetry [18, 19]. The operator Q transforms a bosonic state in a fermionic state and vice versa.

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

Each particle and its superpartner are grouped in a supermultiplet. A chiral supermultiplet consists of a single fermion (with two helicity states) and two real scalars, which are grouped in a complex scalar field. All SM fermions with their superpartners can be grouped in this way. The name of the new resulting scalars is obtained by prepending an s to the SM particles’ name. They all have spin 0.

A gauge supermultiplet contains a massless¹ spin-1 vector boson and a spin-1/2 superpartner, which is called gaugino, each with two helicity states. If gravity is included, the graviton (gauge boson for gravitational force with spin 2) and its superpartner, the gravitino, form a supermultiplet.

Since the superpotential must be holomorphic, two chiral supermultiplets are needed: H_u^+, H_u^0 give mass to the up-like quarks and H_d^0, H_d^- to the down-like quarks and the charged leptons. The SM Higgs boson is a combined state of the neutral H_u^0 and H_d^0 . The superpartners are called higgsinos.

The particle content of the Minimal Supersymmetric extension of the SM (MSSM) is shown in Table 2.3. SUSY particles are marked with a tilde.

The introduction of these new particles solves the hierarchy problem, as can be seen by comparing Eq. (2.1) and Eq. (2.2). The leading order of the Higgs mass correction cancels for $\lambda_S = |\lambda_f|^2$ and two scalars corresponding to one fermion with two helicity states.

¹ The gauge bosons and their superpartners are massless before spontaneous symmetry breaking.

Table 2.3: SUSY particles of the MSSM. The squarks and sleptons appear in three generations, in similar ways as in the SM. The ellipses represent the second and third generation. After electroweak symmetry breaking, the bino and the neutral wino mix to photino and zino.

Name	Symbol	spin
squark	$\tilde{q} = (\tilde{u}_L \tilde{u}_R \tilde{d}_L \tilde{d}_R \dots)$	0
slepton	$\tilde{\nu} \tilde{e}_L \tilde{e}_R \dots$	0
higgsino	$\tilde{H}_u^+ \tilde{H}_u^0 \tilde{H}_d^0 \tilde{H}_d^-$	1/2
gluino	$\tilde{g}$	1/2
wino	$\tilde{W}^0 \tilde{W}^1 \tilde{W}^2$	1/2
bino	$\tilde{B}^0$	1/2
gravitino	$\tilde{G}$	3/2

2.3.1 R-Parity

In SUSY, new interactions are possible allowing baryon number² B or lepton number L violation [20]. Since no lepton or baryon number violation was observed [21], the multiplicative quantum number P_R is introduced and assumed to be conserved:

$$P_R = (-1)^{3(B+L)+2s},$$

where s is the spin of the particle. SM and superpartners can be distinguished by

$$P_R = \begin{cases} 1 & \text{for SM particle} \\ -1 & \text{for a superpartner.} \end{cases}$$

Conservation of P_R has some interesting phenomenological consequences:

- Sparticles are produced in even numbers.
- If a sparticle decays, there is an odd number of supersymmetric daughter particles, so at least one daughter particle is supersymmetric.
- The lightest supersymmetric particle cannot decay further and is stable.

2.3.2 Gauge Mediated Symmetry Breaking

If SUSY particles would have the same mass as their SM partners, their discovery would be trivial. Since no such discovery was made [22], the masses of SUSY particles must be larger than the masses of their SM partners. Hence SUSY must be a broken symmetry. The hierarchy problem is not completely solved but reduced to the “little Hierarchy problem”. To solve it, sparticle masses must therefore not be much larger than particle masses.

One of the theories of how SUSY breaking could be realized in nature is the Gauge Mediated Symmetry Breaking (GMSB) [23, 24]. The symmetry breaking is mediated via gauge interactions. As an effect of symmetry breaking, the neutral higgsinos ($\tilde{H}_u^0$ and $\tilde{H}_d^0$) and the neutral gauginos ($\tilde{B}^0$ and $\tilde{W}^0$) mix to four mass eigenstates called neutralinos ($\tilde{\chi}_{1,2,3,4}^0$). Likewise, the charged higgsinos ($\tilde{H}_u^+$ and $\tilde{H}_d^-$) and the charged gauginos ($\tilde{W}^1$ and

² B and L are additive quantum numbers. For a (anti-)lepton, L is +1 (−1) and for a (anti-)quark B is 1/3 (−1/3).

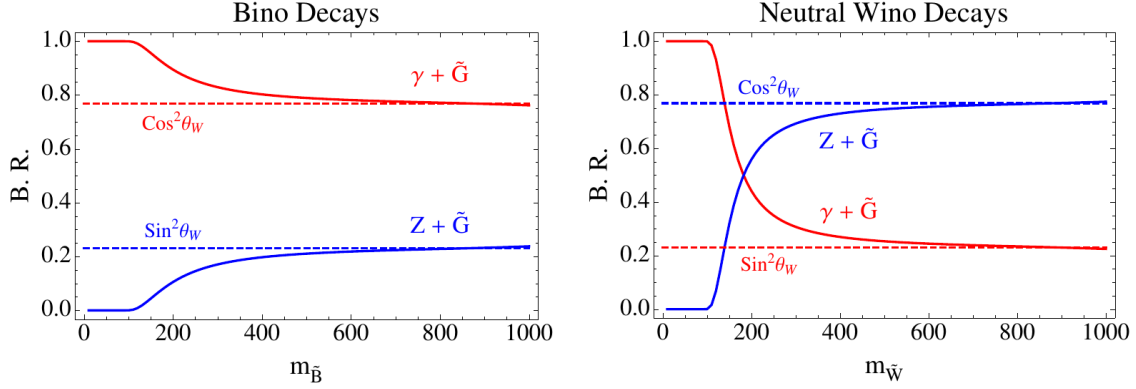


Figure 2.2: Branching fraction for a pure wino- or bino-like NLSP to photons and Z bosons as a function of the NLSP mass. θ_W is the Weinberg angular [25].

$\tilde{W}^2$) mix to four mass eigenstates called charginos ($\tilde{\chi}_{1,2}^\pm$). The neutralinos and charginos are ordered by mass, so that $m_{\tilde{\chi}_1} < m_{\tilde{\chi}_2} < m_{\tilde{\chi}_3} < m_{\tilde{\chi}_4}$.

If the neutralinos have a short lifetime, they decay in the center of the detector, which allows an easy measurements of the decay products. The sort of decay products indicates the mixing of the decaying neutralino. In addition, a short lifetime of the neutralinos implies a small gravitino mass. The gravitino is assumed to be the lightest supersymmetric particle (LSP). The next to lightest stable particle (NLSP) is the lightest neutralino.

The branching fractions of the neutral gauginos are shown in Fig. 2.2. For small gaugino masses, the decay into the massive Z boson is suppressed. The bino state favours the decay into a photon, while the wino favours the decay into a Z boson. The decay partner is always the gravitino.

If the lightest neutralino is wino-like, the lightest chargino is also wino like. Since the mass difference of the NLSP and the lightest chargino is small, the lightest chargino will directly decay into a W boson and a gravitino.

2.3.3 Signal Scenarios

In this analysis, a pure wino- or a pure bino-like neutralino mixing scenario is studied. A specialized analysis for higgsino-like neutralinos is under development. A dominant decay chain for the bino-like neutralino mixing scenario is shown in Fig. 2.3. The neutralinos are produced via gluinos and squarks, and decay mainly into photons and gravitinos.

Possible decay chains for a wino-like neutralino mixing scenario are shown in Fig. 2.4. With increasing neutralino mass, the decay into a Z and a gravitino is enhanced, but the decay to a photon is still possible (see Fig. 2.4a). In Fig. 2.4b the upper gluino decays via a squark and a neutralino into a photon, while the lower gluino decays via a squark into a chargino. The chargino decays into a gravitino and a W boson, which decays into two SM fermions.

Since the production is dominated by the strong interaction, there are many quarks and gluons in the final state, and their hadronization products are clustered to jets. The gravitinos are light, have no color and no electric charge and are stable. They cannot be detected and lead to an imbalance of the events transverse momentum. A search for events with a high energy photon can be sensitive to the wino- and bino-like neutralino mixing scenarios.

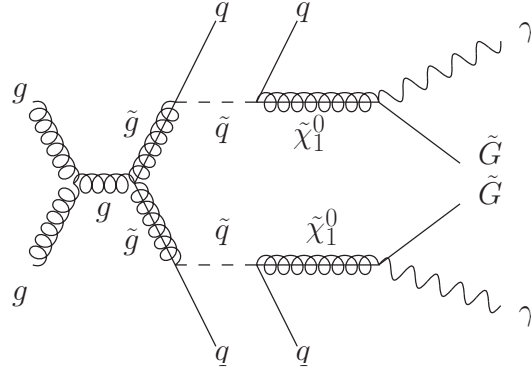


Figure 2.3: Production of two gluinos, which are decaying via squarks and neutralinos into photons and gravitinos. This is a typical process if the neutralino is bino-like.

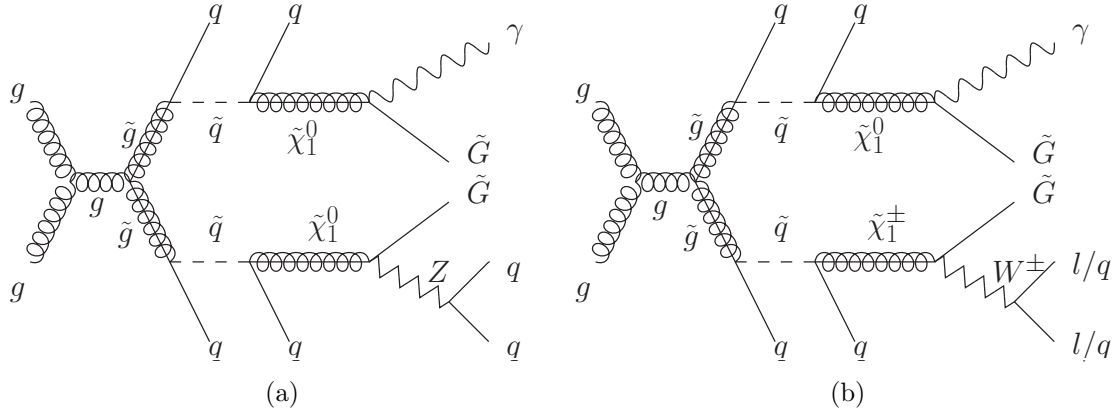


Figure 2.4: Production of two gluinos. One of them decays via squarks and a neutralino into a photon. This is a typical process if the neutralino is wino-like.

Previous publications [3, 4] showed that a similar analysis searching for SUSY with a final state with one photon is the most sensitive analysis for wino-like neutralino mixtures in the CMS collaboration. For the bino-like neutralino mixing scenarios, the analysis has similar sensitivity as the two-photon analysis [4], despite the larger SM background in this analysis.

3 Experimental Setup

Searches for physics beyond the SM at former colliders with center-of-mass energies up to 1.96 TeV were unsuccessful [26–28]. In addition, the Higgs boson was expected to be discovered using a larger center-of-mass energy. To find the Higgs boson and hints for physics beyond the SM, the Large Hadron Collider was constructed. In this thesis, a search for SUSY with the Compact Muon Solenoid detector at the Large Hadron Collider is presented.

3.1 Large Hadron Collider

The Large Hadron Collider (LHC) is a proton-proton and heavy ion collider located at the European Organization for Nuclear Research (CERN) [29]. The 27 km tunnel, in which the LHC was built, is 45 m to 170 m below ground near Geneva. From 1989 till 2000, this tunnel was used by the Large Electron–Positron (LEP) collider.

There are two general purpose detectors located at approximately opposite positions in the ring: The Compact Muon Solenoid (CMS) [30] and A Torodial LHC ApparatuS (ATLAS) [31]. The two other large detectors are the Large Hadron Collider beauty experiment (LHCb) [32], which is specialized in measuring b quark dominated events and A Large Ion Collider Experiment (ALICE) [33], which is optimized to study heavy ion collisions. The arrangement of these experiments and the LHC can be seen in Fig. 3.1.

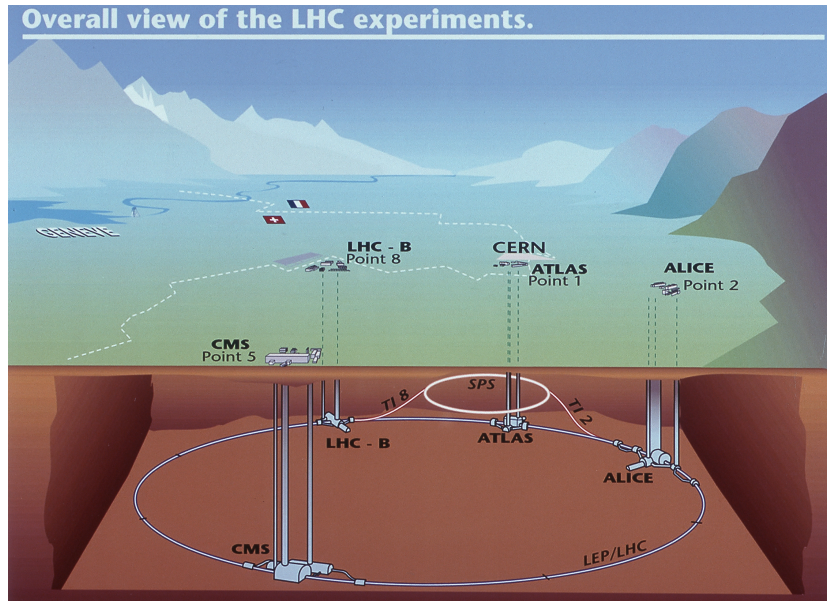


Figure 3.1: Sketch of the LHC tunnel below the Franco-Swiss boarder near Geneva. The location of the four main experiments CMS, ATLAS, LHCb, and ALICE is shown [34].

Table 3.1: Maximum center-of-mass energy of the LHC in different years.

Year	2011	2012	2015 (planned)	design value
$\sqrt{s}$ [TeV]	7	8	13	14

The protons gain kinetic energy in several preaccelerators: The Linac2, Proton Synchrotron Booster, Proton Synchrotron and Super Proton Synchrotron. In the LHC, protons are accelerated in counter-rotating beams to higher center-of-mass energies. The maximal energy was increased during the years of operation as can be seen in Table. 3.1. Since this thesis describes the evaluation of data of 2012, only parameters valid for this run range with a center-of-mass energy of $\sqrt{s} = 8$ TeV are stated in the following.

Protons are accelerated in bunches of approximately $N_b = 10^{11}$ protons. Up to $n_b = 1380$ bunches are injected per beam. With the revolution frequency f_{rev} , an instantaneous luminosity

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F$$

of up to $7.7 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ was achieved [35]. γ_r is the relativistic gamma factor, ϵ_n the normalized transverse beam emittance, β^* the beta function at the collision point, and F the geometric luminosity reduction factor due to the crossing angle at the interaction point. $\mathcal{L}_{\text{int}}$ is the luminosity integrated over time. It can be used as quantity to express the amount of data.

In total, an integrated luminosity of 21.79 fb^{-1} have been recorded in 2012. This corresponds to 93% of the delivered integrated luminosity. The timeline is shown in Fig. 3.2.

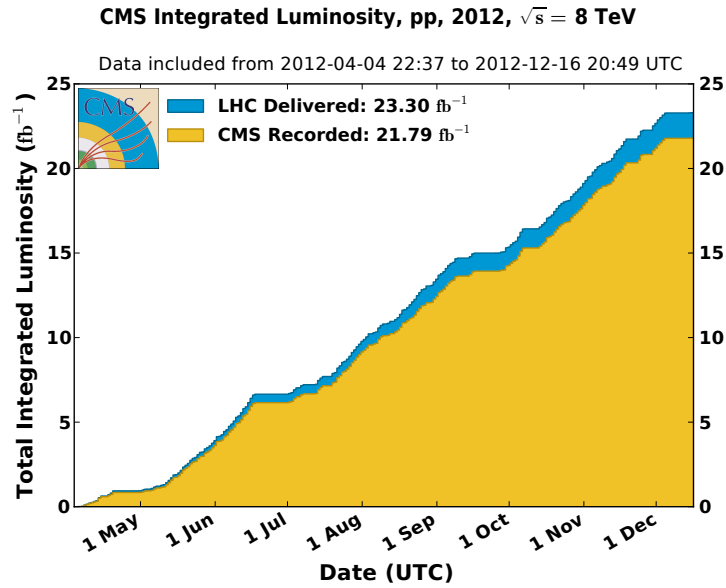


Figure 3.2: Delivered integrated luminosity by LHC (blue) and recorded integrated luminosity by CMS (yellow) in 2012 over time [35].

3.2 Compact Muon Solenoid Detector

The Compact Muon Solenoid [30] is a cylindrical detector with a barrel and two endcaps with the beam pipe as the symmetry axis. From inside to outside there is the beam pipe, the silicon pixel and the silicon strip detector, the electromagnetic and the hadron calorimeter, the superconducting solenoid and the muon chambers, as can be seen in Fig. 3.3.

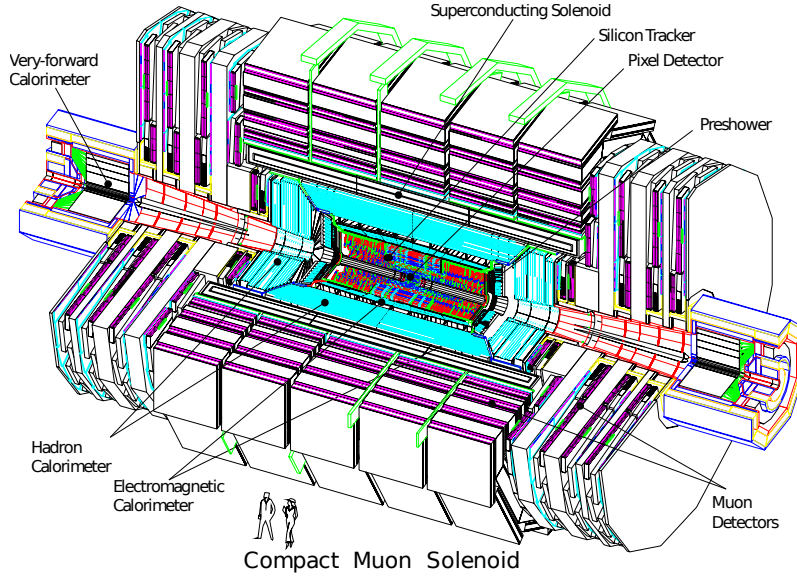


Figure 3.3: Overview of the CMS detector with labeled subdetectors. To visualize the scale, two people are shown at the bottom [30].

The detector is 21.6 m long and has a diameter of 14.6 m. In total, it weighs about 12 500 t.

During the LHC runs in the past years, the CMS detector performed excellently. Having been analyzed and studied by physicists for a long period of time, the detector is understood in many details. Precision measurements, observations and limits on new physical models are published in over 300 papers.

3.2.1 Coordinate System

The origin of the coordinate system of CMS is in the center of the detector near the point of collision.

The x -axis is pointing towards the center of the LHC, the y -axis is pointing vertically upwards, and the z -axis lies in the direction of the beam pipe to form a right-handed coordinate system. The distance r to the z -axis is defined as $\sqrt{x^2 + y^2}$. The azimuthal angle ϕ is measured in the x - y plane from the x -axis, ranging from $-\pi$ to π . The polar angle θ is measured from the positive z -axis. The pseudorapidity is defined as

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

For particles moving close to the speed of light, it is a good approximation to the rapidity. Rapidity is used in theoretical predictions since rapidity differences are invariant under

lorentz transformations along the z -axis. Using the rapidity

$$y = \frac{1}{2} \ln \left(\frac{E + |\vec{p}|}{E - |\vec{p}|} \right)$$

is difficult in experiments, since the mass of particle candidates is often unknown.

Distances in the ϕ - η plane are measured in $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$.

As is the case for all hadron colliders, the longitudinal momenta of the initial partons are not known. Since the initial transverse momenta are small, and the total transverse momentum is conserved, the total transverse momentum of all final states is small as well. Transverse momenta for final states are therefore more expressive than the absolute value of the momentum. The transverse momentum is defined as

$$p_T = |\vec{p}| \cdot \sin \theta.$$

Similarly, the transverse energy is defined as

$$E_T = E \cdot \sin \theta.$$

3.2.2 Inner Tracking System

The inner tracking system is a silicon detector with about 200 m^2 of active silicon sensors. The system has a length of 5.8 m and a diameter of 2.5 m and surrounds the interaction point and the beam pipe. The cross section of the pixel detector and the silicon strip tracker can be seen in Fig. 3.4.

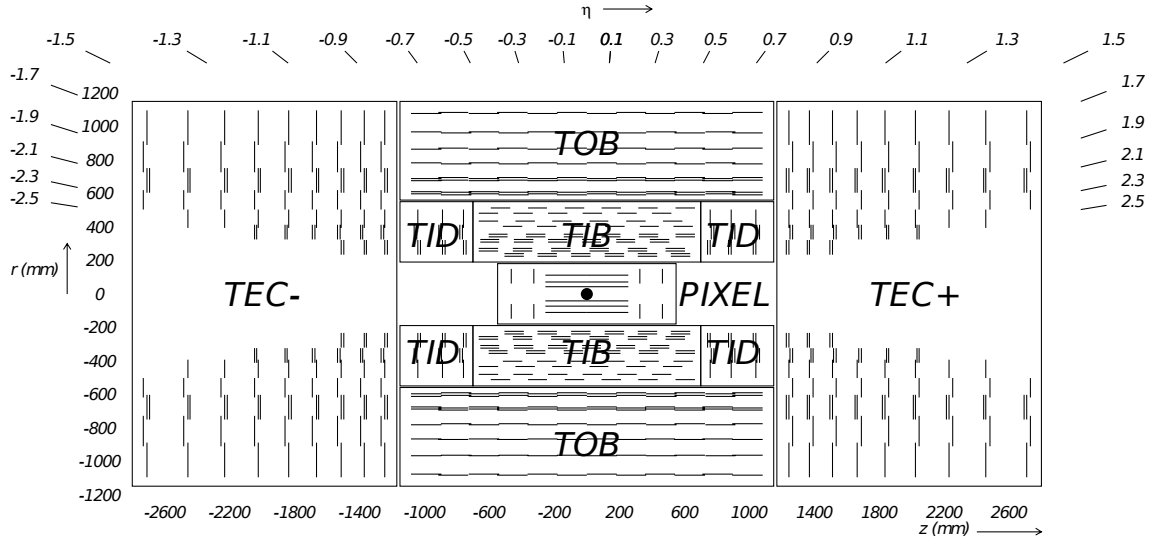


Figure 3.4: Schematic cross section through the CMS tracking detector. The Tracker Outer Barrel (TOB) and the Tracker Inner Barrel (TIB) surround the pixel detector. The vertical Tracker Inner Disk (TID) and Tracker End Cap (TEC) are perpendicular to the barrel detectors [30].

The pixel detector is the innermost detector of CMS. Three cylindrical layers of pixels surround the pipe at radii between 4.4 and 10.2 cm, each with a length of 53 cm. At $z = \pm 37.5$ and $z = \pm 46.5$ cm, two endcap discs are located with diameters between 12 and 30 cm. The 48 million pixels in the barrel and 18 million pixels in the endcaps have a

size of $100 \times 150 \mu\text{m}^2$ in $r\phi \times z$ and cover a pseudorapidity range of $|\eta| < 2.5$. A n+ pixel on n-substrate design is chosen to allow an operation at very high particle fluences.

The Tracker Inner Barrel consists of four cylindric strip detector layers at radii between 25.5 and 49.8 cm and has a length of 140 cm in z . Three disks between $z = \pm 80$ cm and ± 90 cm form the Tracker Inner Disks. Strip pitches of $80 \mu\text{m}$ and $120 \mu\text{m}$ are used.

The Outer Tracker Barrel is built of six layers at radii from 60.8 cm to 108 cm, each with a length of 236 cm. From $z = \pm 124$ cm to ± 280 cm nine disks of the Tracker End Caps are installed.

The readout electronics and sensor leakage current lead to heat, which has to be transported out of the detector. To minimize radiation damage, the detector is also cooled down. The sensors and the electronics are radiation hard to work for several years without significant losses in acceptance.

For high p_T tracks, the transverse impact parameter resolution reaches $10 \mu\text{m}$. The nominal momentum resolution is 0.7% (5%) at 1 GeV (1 TeV) and the primary vertex resolution is $60 \mu\text{m}$ ($500 \mu\text{m}$) for vertices with many tracks (few tracks with low p_T) [36].

3.2.3 Electromagnetic Calorimeter

Like the inner tracker, the electromagnetic calorimeter (ECAL) can be separated into the barrel at $|\eta| < 1.479$ and the endcap at $1.479 < |\eta| < 3.0$, which can be seen in Fig. 3.5. The ECAL barrel is granulated 360-fold in ϕ and 2×85 -fold in η , resulting in a total of 61 200 crystals. The scintillation crystals are made of tungstate PbWO_4 because of the material's high density of 8.28 g/cm^3 , short radiation length of $X_0 = 0.89 \text{ cm}$ and small Molière radius of 2.2 cm. Additionally, they have a fast response: 80% of the light is emitted in 25 ns, the designed time between two proton-proton bunch crossings. The crystals in the barrel have a front cross section of 0.0174×0.0174 in $\eta \times \phi$ at a radius of 129 cm from the beam pipe. This corresponds to $2.2 \times 2.2 \text{ cm}^2$, which is the square of the Molière radius. The crystals are tapered and have a rear cross section of $2.6 \times 2.6 \text{ cm}^2$. Their length is 23 cm, corresponding to $25.8 X_0$.

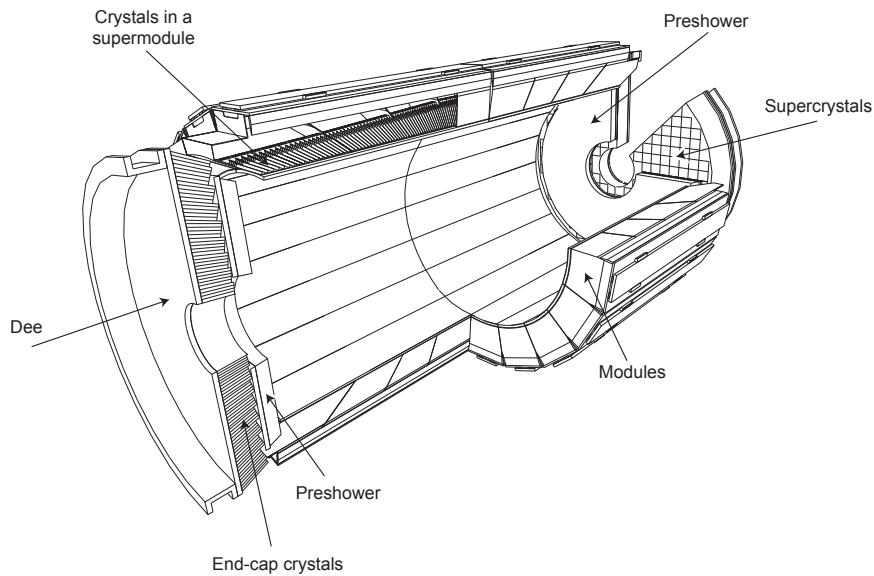


Figure 3.5: Sketch of the electromagnetic calorimeter [37].

An avalanche photodiode (APD) (n-type silicon bulk behind the p-n junction) with an effective area of $0.5 \times 0.5 \text{ cm}^2$ is mounted at the rear side of each ECAL crystal in the barrel. They are able to operate in a 3.8 T magnetic field and have a quantum efficiency of 75% at the typical scintillation wavelength of 430 nm. In order to be insensitive to particles traveling through them, the effective thickness is $6 \mu\text{m}$.

The front sides of the ECAL endcaps are located at $z = \pm 315.4 \text{ cm}$. They are divided into two halves, called Dees, each containing 3662 crystals. The crystal cross section is $2.862 \times 2.862 \text{ cm}^2$ (front) to $3 \times 3 \text{ cm}^2$ (rear) and the length is 22 cm ($= 24.7 X_0$). The scintillation light is measured with vacuum phototriodes. To reduce the misidentification probability of neutral pions as photons, a preshower detector is installed in front of the ECAL endcaps.

Since the response varies strongly with temperature ($(-3.8 \pm 0.4)\%/^\circ\text{C}$), the crystals and the silicon avalanche photodiodes are water-cooled to $(18 \pm 0.05)^\circ\text{C}$.

Two calibrations are performed: A global calibration for the absolute energy scale and a crystal-to-crystal calibration, taking into account the different light yields for each crystal.

To measure and correct for the transparency loss in the crystals due to radiation, a laser monitoring system is installed.

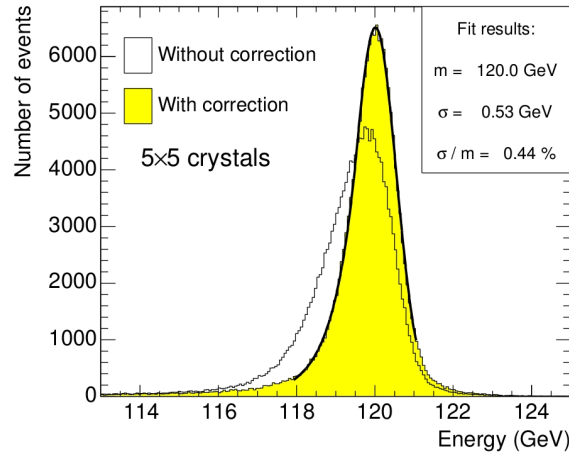


Figure 3.6: Measured energy of electrons with an energy of 120 GeV with a 5×5 cluster of ECAL crystals. The energy is corrected for leaking energy due to gaps and the electron's incident position. A gauss function is fitted to the corrected distribution [38].

The total energy resolution of the ECAL can be parametrized as

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2,$$

where S is the stochastic term dominated by photostatistics and event-to-event fluctuations and N is the term describing electronic, digitization and pile-up noise. C is the constant term taking intercalibration errors, non-uniformity of the longitudinal light collection and leakage of energy from the back of the crystal into account. A typical energy resolution for the ECAL in CMS was measured using electron beams with momenta between 20 and 250 GeV to

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E [\text{GeV}]}}\right)^2 + \left(\frac{12\%}{E [\text{GeV}]}\right)^2 + (0.3\%)^2.$$

Using electrons with an energy of 120 GeV, the energy resolution of the ECAL barrel is measured to be 0.44% (see Fig. 3.6), which is in agreement with the formula above.

3.2.4 Hadron Calorimeter

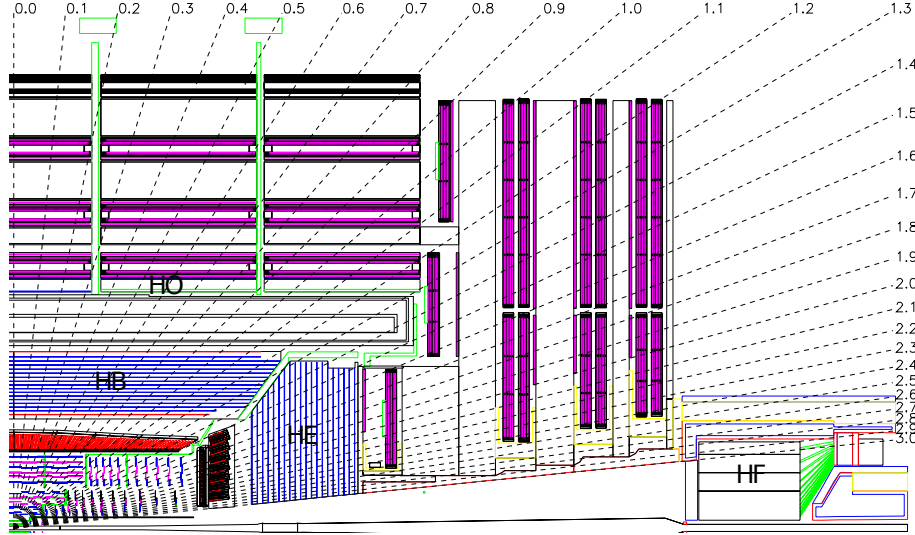


Figure 3.7: Schematic cross section through the CMS detector showing the hadron barrel (HB), endcap (HE), outer (HO) and forward calorimeter (HF) [30].

The Hadron calorimeter (HCAL) surrounds the ECAL and consists of several subdetectors. This can be seen in Fig. 3.7.

The hadron barrel (HB) covers the pseudorapidity range $|\eta| < 1.3$ and consists of 36 azimuthal wedges. The wedges are constructed of flat brass absorber plates and of plastic scintillators. The HB effective thickness increases from 5.82 interaction lengths at $\eta = 0$ to 10.6 interaction lengths at $|\eta| = 1.3$. The size of a sector is 0.087×0.087 in $\eta \times \phi$. Cracks between wedges are minimized to less than 2 mm.

The hadron endcaps (HE) cover the pseudorapidity range $1.3 < |\eta| < 3$. The wedges consist of the same material as the ones in the HB. For $|\eta| < 1.6$, the sectors have the same size in $\eta \times \phi$ as the sectors in the HB. For $|\eta| \geq 1.6$, the size of the sectors is 0.17×0.17 .

Since space inside the solenoid is limited, the HCAL's outer layer, which is called Hadron Outer calorimeter (HO), is installed outside the solenoid and uses the solenoid as an additional absorber. It covers the pseudorapidity range of $|\eta| < 1.3$, the size and positions of the tiles mapping the layers of HB.

At large absolute values of pseudorapidity, the Hadron Forward calorimeter (HF) is placed. Since most of the energy in a proton-proton interaction is deposited in the HF, it is designed to be very radiation hard.

3.2.5 Superconducting Solenoid

The solenoid is a 220 t heavy 4-layer winding of stabilized reinforced NbTi. It has a length of 12.5 m and a diameter of 6 m. In order to be superconducting, the cold mass is cooled down to 4.5 K. In this state, it can store 2.6 GJ of energy and generates a magnetic field of 3.8 T.

The magnetic field bends charged particle trajectories in ϕ direction. The high magnetic field allows charge and momentum measurements even at high energies. Thus the transverse momentum of 1 TeV muons can be measured with a momentum resolution of less than 10% [39].

3.2.6 Muon System

Like most of the other detector parts, the muon system consists of a barrel ($|\eta| < 0.9$) and two endcaps ($0.9 < |\eta| < 2.4$). In the barrel, between the iron yokes of the magnet, through which the magnetic flux is returned, drift tubes are used. In the endcaps cathode strip chambers are used because of the higher background. To improve the trigger time measurement, resistive plate chambers are installed in $|\eta| < 1.6$, which are fast, but lack the spatial resolution of the cathode strip chambers or the drift tubes.

The standalone muon momentum resolution for muons with $p_T = 1$ TeV varies from 15% to 40% depending on $|\eta|$. The combination of all detector components can decrease the resolution by one order of magnitude.

3.2.7 Trigger

Reading out all channels of the detector results in a data size of approximately 1 Mbyte per event. The LHC beam crossing interval in 2012 was 50 ns, leading to 20 Tbyte/s which would have to be stored. Since no such data-streams are available, it is not possible to readout and store all events. The decision whether an event is saved or not is made by the Level 1 (L1) Trigger, followed by the High Level Trigger (HLT).

The L1 Trigger is implemented largely in programmable electronics and is designed to reduce the event rate from 20 MHz to 30 kHz. It consists of three steps: In the first step, the trigger primitive generator sums up the transverse energy from an ECAL or HCAL trigger tower. Then the regional calorimeter trigger determines regional electrons/photons, τ -veto bits and isolation. Lastly, the global calorimeter trigger can combine this information and calculate more complex observables using all of the calorimeter. In parallel, a second chain triggers muons.

The HLT is a software system implemented in a computer farm, which reduces the rate to the order of 100 Hz. It can be easily customized and is able to reconstruct objects similarly to the off-line reconstruction.

4 Event Reconstruction and Selection

In this section, an overview of the used data and simulation is given, and event reconstruction and processing are explained.

4.1 Recorded Datasets

The data is divided into different runs. In each run, the data is grouped in luminosity sections. Only luminosity sections in which the detector is in a good state are processed. In addition, the events have to be triggered. The L1 Trigger requires transverse energy sum

$$\sum_{\text{trigger tower}} E_T \geq 24 \text{ GeV}$$

in a trigger tower of 5×5 ECAL crystals.

The HLT requires at least one object with the following properties:

- Transverse energy in a cluster of ECAL crystals of at least 70 GeV
- Shower width¹ in η smaller than 0.014 (0.035) in the ECAL barrel (endcap)
- Ratio of the HCAL energy in a cone around the ECAL cluster of $\Delta R = 0.14$ to the ECAL cluster energy smaller than 0.1
- Hadronic activity of at least 400 GeV

Hadronic activity is calculated as the sum of transverse energies for all jets in $|\eta| < 3$, which have at least $E_T > 40$ GeV. With this trigger named "HLT_Photon70_CaloIdXL_PFHT400" an integrated luminosity of 5.3 fb^{-1} was recorded for the first runs.

For subsequent runs, this trigger was replaced by the "HLT_Photon70_CaloIdXL_PFN0PUHT400" trigger. This newer trigger uses an improved jet clustering algorithm, by neglecting charged particles not coming from the primary vertex. The data collected with this trigger corresponds to an integrated luminosity of 14.5 fb^{-1} . So in total

$$\mathcal{L}_{\text{int}} = 19.8 \text{ fb}^{-1}$$

are used.

The luminosity is measured as ratio of event rate to visible total cross section [40]. The event rate is estimated from the number of pixel clusters. The visible cross section is defined as

$$\sigma_{\text{vis}} = \frac{2\pi \Sigma_x \Sigma_y \langle n \rangle_{\Delta=0}}{N_1 N_2},$$

¹The shower width will be defined in Section 4.4.2 in more detail.

where $\Sigma_x \Sigma_y \langle n \rangle_{\Delta=0}$ is determined using the Van der Meer scan technique and $N_1 N_2$ is measured by the LHC beam current transformers (DCBCT and FBCT). The Hadron Forward Calorimeter is used as an independent measurement for the luminosity. This measurement is used for cross checks and for estimating systematic uncertainties of the first method.

4.2 Event Simulation

SM and signal processes are simulated in three steps: Hard scattering, hadronization and detector simulation. The Monte Carlo technique is used to compute high dimensional integrals, especially in the hard scattering process.

For SM processes, **Madgraph** [41] is used for the hard scattering, **Pythia** [42] for the hadronization and the detector is simulated by **Geant4** [43]. The hard scattering for signal processes and hadronization are calculated using **Pythia**. To reduce computing time, an approximation of the detector and physical processes [44] is used for the detector simulation for signal events. The distribution of partons in the initial protons is described by the CTEQ6.1 parton distribution function [45] for all simulated events.

Because of the high instantaneous luminosity, more than one proton-proton interaction may occur in a single bunch crossing. To account for this in simulation, several minimum bias events, called “pile-up events”, are added to the hard scattering. Since the probability distribution for the number of pile-up events was unknown when the datasets were simulated, the number of pile-up events could only be estimated. The number of estimated pile-up events is shown in Fig. 4.1.

The number of pile-up events in data is measured by the product of total inelastic proton-proton cross section times instantaneous luminosity per bunch crossing. To account for the different pile-up distribution in data, the simulated events are weighted to match the number of pile-up events in data.

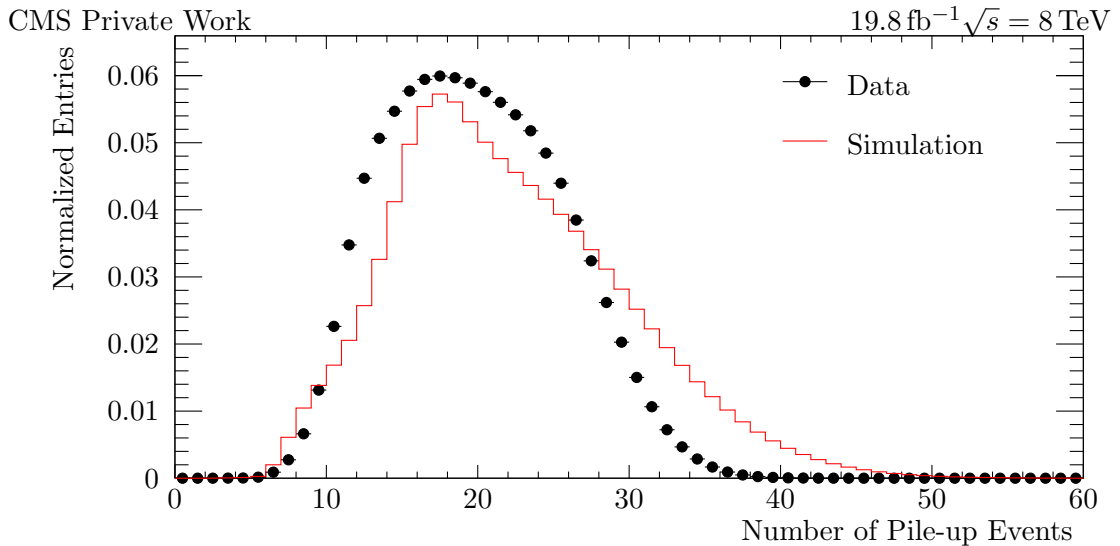


Figure 4.1: Probability distribution for the number of pile-up events per bunch crossing for data and simulation.

Statistical uncertainties of the simulation do not target to match the statistical uncertainties of the data, but are aimed to be minimized. This is done by simulating more events. For processes with larger cross sections, this is problematic due to the high amount of computing time needed.

Each simulated event is weighted by

$$\frac{\mathcal{L}_{\text{int}} \cdot \sigma}{N_{\text{generated}}} = \frac{\mathcal{L}_{\text{int}}}{\mathcal{L}_{\text{int}}^{\text{sim.}}},$$

where $\mathcal{L}_{\text{int}}$ is the measured integrated luminosity of the data, σ the cross section and $N_{\text{generated}}$ the number of generated events for a given process.

Cross sections are calculated using perturbation theory. For most simulated processes in this analysis, only the leading order (LO) cross section is known and taken as an approximation. For some simulated samples, the next-to-leading order (NLO) cross section has been calculated and is used in this analysis.

Since most distributions are steeply falling with energy, and regions of high energy are interesting for many analyses, process simulation is binned in hadronic activity H_T^{gen} or the photon's transverse momentum p_T^{gen} . H_T^{gen} and p_T^{gen} are computed for hard scattering, without taking detector effects into account. Therefore H_T^{gen} and p_T^{gen} do not match exactly the reconstructed H_T or p_T .

This procedure reduces the statistical uncertainty of the simulation and computing time. The number of generated events, cross sections and the integrated luminosities corresponding to the simulation are shown in Table 4.1 for all used simulations of SM processes in this thesis.

Table 4.1: Cross section, number of generated events, and corresponding integrated luminosity for various simulated SM samples. The full CMS database names can be seen in Table A.2. The $t\bar{t}$ and $\gamma t\bar{t}$ cross sections are NLO, all other cross sections are LO.

Process	Range [GeV]	σ [pb]	$N_{\text{generated}}$ [10^6]	$\mathcal{L}_{\text{int}}^{\text{sim.}}$ [fb^{-1}]
Multijet+ γ	$200 < H_T^{\text{gen}} < 400$	960.5	59	61
	$400 < H_T^{\text{gen}}$	107.5	42	390
Multijet	$250 < H_T^{\text{gen}} < 500$	276000.0	26	0.094
	$500 < H_T^{\text{gen}} < 1000$	8426.0	30	3.6
	$1000 < H_T^{\text{gen}}$	204.0	13	64
W	$250 < H_T^{\text{gen}} < 300$	48.0	4.9	100
	$300 < H_T^{\text{gen}} < 400$	38.3	5.1	133
	$400 < H_T^{\text{gen}}$	25.2	3.9	155
$t\bar{t}$	inclusive	225.2	6.9	31
Z	$200 < H_T^{\text{gen}} < 400$	41.49	9.7	234
	$400 < H_T^{\text{gen}}$	5.274	5.1	965
γW	$50 < p_T^{\text{gen}} < 130$	1.17	1.1	940
	$130 < p_T^{\text{gen}}$	0.2571	0.47	1828
$\gamma t\bar{t}$	inclusive	2.166	2.4	903
$\gamma Z \rightarrow \gamma \nu \nu$	$130 < p_T^{\text{gen}}$	0.074	0.49	66216

Signal parameter have been suggested to cover many GMSB signal scenarios, for which experiments at the LHC could be sensitive [25, 46]. Sparticle parameters not essential

for the production of the signature of interest are decoupled to simplify the models. The signal parameters and branching fractions are documented in [47]. Signal processes are simulated with the mass of the lightest neutralino $\tilde{\chi}_1^0$ of 375 GeV. The lightest neutralinos are either pure wino-like or pure bino-like. The lifetime of the neutralinos is fixed to 0.1 mm/c. The squark mass $m_{\tilde{q}}$ is varied from 400 GeV to 2000 GeV and the gluino mass $m_{\tilde{g}}$ from 420 GeV to 2020 GeV in steps of 100 GeV. The masses of all other SUSY particles are set to 3500 GeV. The ratio of the vacuum expectation values of the Higgs bosons is $\tan \beta = \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle} = 2$, and the higgsino mass parameter is set to $\mu = 3500$ GeV to avoid the mixing of higgsinos to the lightest neutralino.

The NLO production cross sections for wino-like and bino-like $\tilde{\chi}_1^0$ as function of the gluino and squark mass are shown in Fig. 4.2. The cross sections are decreasing with gluino and squark masses in both wino- and bino-like $\tilde{\chi}_1^0$ mixing scenarios. Wino-like neutralinos can also be produced in association of a chargino via for example a W boson. This process, called electroweak production, is much smaller than the production of wino-like neutralinos via the strong interaction for low squark and gluino masses, but is the dominating process for large squark and gluino masses. Electroweak production is suppressed in bino-like $\tilde{\chi}_1^0$ mixing scenarios. Hence the production cross section for high gluino and squark masses is much larger for bino-like than wino-like $\tilde{\chi}_1^0$ mixing scenarios.

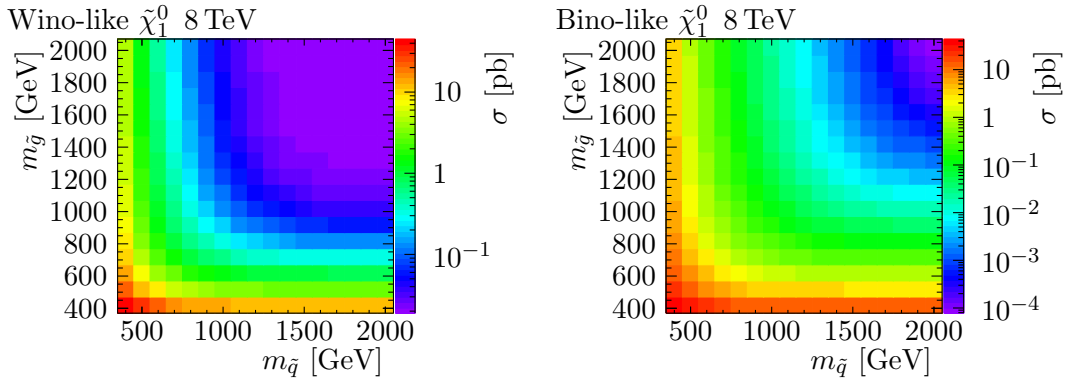


Figure 4.2: NLO cross sections for the production of wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios as a function of squark and gluino mass.

4.3 Computing and Software

If an event passes the HLT decision, all information belonging to this bunch crossing is stored in RAW format at CERN, and security copies are made. Most of these events are promptly reconstructed at the Tier0 computing center at CERN in the RECO format. Other events are saved and reconstructed later. To simplify access to physic objects and reduce the storage size of events, the event information is grouped to form object candidates and stored as AOD files [30]. These files together with simulated events are distributed to various Tier1 computing centers worldwide via the Worldwide LHC Computing Grid [48]. After the shutdown of the LHC in January 2013, the Tier0 and several Tier1s were used to reprocess recorded events with the latest reconstruction algorithms, corrections and calibrations. This resulted in the reconstruction version 22Jan2013ReReco.

The CMS Remote Analysis Builder (CRAB) tool [49] is used to access the huge amount

of data and build `SusyNtuples`, a data format used by many SUSY photon groups in CMS [50]. The processing is done in CMS Software (CMSSW) version 5.3.8 Patch3.

The final processing is done with a self-developed framework [51], which is more flexible than the framework used for previous publications. The analysis is performed with two independent frameworks to cross check the analysis code by comparing results. The framework is used to develop, study and test object definitions, methods and event topologies, and to visualize data. C++ of the GNU Compiler Collection 4.8.2 and the ROOT [52] library version 5.34/11 are used in combination with Python [53] 2.7.6 for this framework.

4.4 Object Reconstruction

The detector's output has to be interpreted in terms of physical particles and objects to obtain information about the initial processes in the collisions. The detector information are grouped into variables, which are combined to reconstruct objects and candidates for particles.

4.4.1 Jets

Quarks cannot exist as free particles, since the strong force increases with distance: If quarks are separated, secondary particles are produced. These secondary particles may radiate gluons and produce further particles (fragmentation). Two or three quarks hadronize to hadrons. These hadrons follow the original direction of the quark in a narrow cone, called jet.

Particles are reconstructed with the Particle-flow algorithm [54], which combines information from different subdetectors to improve identification and discrimination power. Charged particles which do not come from the primary vertex are excluded in order to reduce sensitivity to pile-up events [55]. The primary vertex is defined as the vertex with the highest sum of p_T^2 of charged particles coming from it. As many particles with low p_T are expected for secondary pile-up vertices, the squared transverse momentum is used to improve the sensitivity to non pile-up events.

Charged particles associated to the primary vertex and neutral particles are combined to jets using the anti- k_T algorithm [56] with a distance parameter of 0.5. Up to four steps are done successively to correct the jet's energy [57]:

- **Pile-up correction:** For each event the energy density per unit area is determined using k_T clustered jets with a distance parameter of 0.6. Under the assumption that pile-up energy is distributed uniformly in the detector, the jets are corrected depending on their actual area.
- **Relative jet correction:** To cover non uniform response in η , the energy is corrected to jets in the central region.
- **Absolute jet correction:** The non-linearity of the jet's energy response in the hadronic calorimeter is corrected back to the parton level.
- **Residual correction:** This correction is applied to data only and covers differences between simulation and data which remain after all other corrections are applied.

The correction factors for pile-up, relative, and absolute jet corrections are measured in data and are cross checked with simulation. The residual corrections are derived from the difference of measured to simulated multijet events.

Jets are also required to fulfill the following quality criteria [58]: The neutral hadron fraction and the neutral electromagnetic fraction should not exceed 99%. Also, the jet should consist of two or more particles. If the jet is in the endcap, the charged electromagnetic fraction should be smaller than 99%. A minimum of charged hadron energy is required and at least one charged particle is needed.

4.4.2 Photons

Unconverted photons do not interact with the tracker and deposit most of their energy in the ECAL. Because of the high granularity of the ECAL, the position of energy deposits can be measured well [38]. To suppress light neutral hadrons (e.g. neutral pions) to be misidentified as photons, a photon-like shower shape is required. As many photons are produced in the fragmentation of partons into jets, unisolated photons are discarded. The high resolution of the inner tracker allows to reject charged particles, but the material needed for this high resolution increases the material budget at the same time and therefore the probability of conversion of prompt photons or Bremsstrahlung from electrons. Important variables for identifying photons are:

Isolation cone energy: A clear hint for a photon is a single energy deposit in the ECAL without any other detector activity nearby. If so, the photon candidate is “isolated”. To measure the isolation, the sum of transverse momenta of particles near a photon candidate is computed. Particles are reconstructed using the Particle-flow algorithm and ordered in five categories: charged hadrons, neutral hadrons, electrons, muons, and photons. In a cone of $\Delta R = 0.3$, the transverse momenta of charged hadrons, neutral hadrons and photons (excluding the photon for which the isolation is calculated) are summed up, leading to three isolation variables: Charged hadron isolation cone energy ($\text{Iso}_{\pm}$), neutral hadron isolation cone energy (Iso_0) and neutral electromagnetic isolation cone energy (Iso_{γ}). They are pile-up corrected by subtracting the photons’ effective area times the hadronic activity per unit area. The effective areas vary between 0.01 and 0.148, depending on η only.

Even if the correct term for these isolation variables would be “additional transverse momenta in $\Delta R < 0.3$ ”, the term “isolation cone energy” is used in the following.

By requiring small values of isolation cone energies, the contribution of jets with a high electromagnetic component are suppressed.

This is one of the major changes with comparison to the former analysis [4], in which the isolation was calculated detector based and not particle based.

Hadronic energy fraction H/E : The energy deposited in the HCAL tower directly behind the supercluster’s seed crystal in the ECAL should be small compared to the energy stored in the supercluster. Taking only one tower minimizes pile-up dependencies.

This suppresses neutral hadrons that have a similar shower shape as photons.

In the former analysis [4], the hadronic energy fraction was calculated more similar to the definition of the trigger.

Supercluster width $\sigma_{i\eta i\eta}$: The width of the shower in the ECAL is computed by summing weighted η differences in a 5×5 grid around the seed crystal at $\bar{\eta}$ with the highest

energy.

$$\sigma_{i\eta i\eta}^2 = \frac{\sum_i^{5 \times 5} w_i (\eta_i - \bar{\eta})^2}{\sum_i^{5 \times 5} w_i}, \quad w_i = \max \left(0, 4.7 + \ln \frac{E_i}{E_{5 \times 5}} \right),$$

where E_i is the energy deposit in ECAL crystal i . $E_{5 \times 5}$ is the total energy of the 5×5 grid around the seed crystal. η_i is the η position of the crystal i . More ECAL crystals than the 5×5 grid are taken into account in cases of gaps between ECAL crystals. The width in ϕ is not used since charged particles in the shower are bent due to the magnetic field in ϕ direction.

This requirement suppresses jets that have a larger shower width due to the amount of different particles they consist of.

Number of pixel seeds $N_{\text{pixel seeds}}$: To suppress electrons being misidentified as photons, the activity in the tracker between the interaction point and the ECAL supercluster must be small.

To find track candidates fitting to the energy deposit in the ECAL, the energy in the ECAL cluster is used to estimate the position and curvature of possible tracks for the electron or positron hypothesis. The combination of two or three hits in the pixel detector that can be extrapolated from the primary vertex to the ECAL cluster, is called pixel seed. Photons can be selected by requiring no pixel seed.

To increase the photon selection efficiency in other CMS analyses, a “conversion safe electron veto” is often used instead of the pixel seed veto². Photon candidates are rejected, if a track without missing hits on the inner layers of the tracker from the vertex to the cluster in the ECAL is found. This procedure increases the selection efficiency, but also the probability of misidentifying an electron as a photon. Since this analysis is aiming at a small contamination of electrons being misidentified as photons, the pixel seed veto is preferred.

For this analysis, three different **electromagnetic objects** γ_{tight} , γ_{loose} and γ_{pixel} are defined. This definition is the major change to the previous publication [4]. It is more efficient in the enhanced pile-up environment and the used variables are better suited to define a control region with few real photons. γ_{tight} is used for the signal selection, while γ_{loose} and γ_{pixel} are used to define the control regions for the background estimation methods.

The definition of the objects is as follows:

γ_{tight} : The tightly isolated electromagnetic object γ_{tight} has a shower width compatible with photons, small photon energy depositions in the HCAL and no pixel seed. This definition is identical to the photon definition in many CMS analyses, except for the fact that the conversion safe electron veto is replaced by the pixel seed veto.

$$\text{Iso}_{\pm} < 2.6 \text{ GeV}$$

$$\text{Iso}_0 < 3.5 \text{ GeV} + 0.04 \cdot p_T$$

$$\text{Iso}_{\gamma} < 1.3 \text{ GeV} + 0.005 \cdot p_T$$

$$H/E < 0.05$$

$$\sigma_{i\eta i\eta} < 0.012$$

$$N_{\text{pixel seeds}} = 0$$

² An example of such an analysis is the search for a Higgs boson with the decay into two photons [59].

γ_{pixel} : Electromagnetic objects with pixel seeds are identical to γ_{tight} except that the pixel seed veto is reversed. Since electrons and photons are expected to shower similarly in the calorimeters, most of these objects are electrons.

$$\begin{aligned} \text{Iso}_{\pm} &< 2.6 \text{ GeV} \\ \text{Iso}_0 &< 3.5 \text{ GeV} + 0.04 \cdot p_T \\ \text{Iso}_{\gamma} &< 1.3 \text{ GeV} + 0.005 \cdot p_T \\ H/E &< 0.05 \\ \sigma_{i\eta i\eta} &< 0.012 \\ N_{\text{pixel seeds}} &> 0 \end{aligned}$$

γ_{loose} : The loosely isolated electromagnetic object γ_{loose} is defined similarly to γ_{tight} , except that a minimum of isolation cone energy is required and the maximal isolation cone energy is allowed to be larger. Since isolation variables are hard to simulate, the values are not optimized to tune the significance or the performance of the background estimation method. Isolation cone energies must be at least a tenth of the γ_{tight} 's isolation cone energy cut value and may not exceed 10 times the γ_{tight} 's isolation cone energy cut value. Additionally, one of the γ_{tight} isolation cone energy requirements has to fail. This is needed to distinctly identify objects either as γ_{tight} or γ_{loose} . Most of the selected objects are loosely isolated photons or jets. Figure 4.3 visualizes the separation of γ_{tight} and γ_{loose} .

$$\begin{aligned} 0.26 \text{ GeV} &< \text{Iso}_{\pm} < 26 \text{ GeV} \\ 0.35 \text{ GeV} + 0.004 \cdot p_T &< \text{Iso}_0 < 35 \text{ GeV} + 0.4 \cdot p_T \\ 0.13 \text{ GeV} + 0.0005 \cdot p_T &< \text{Iso}_{\gamma} < 13 \text{ GeV} + 0.05 \cdot p_T \\ H/E &< 0.05 \\ \sigma_{i\eta i\eta} &< 0.012 \\ N_{\text{pixel seeds}} &= 0 \\ \text{Iso}_{\pm} \geq 2.6 \text{ GeV} \text{ or } \text{Iso}_0 \geq 3.5 \text{ GeV} + 0.04 \cdot p_T \text{ or } \text{Iso}_{\gamma} \geq 1.3 \text{ GeV} + 0.005 \cdot p_T \end{aligned}$$

All electromagnetic objects are defined without overlap. The naming γ_{tight} , γ_{loose} and γ_{pixel} of electromagnetic objects should underline the similarities between most selection variables. γ_{tight} is the only definition efficiently identifying real photons (γ), while the definitions of γ_{loose} and γ_{pixel} target to exclude real photons.

Since SUSY particles are expected to be heavy, most of the available initial energy is used to create such heavy particles. Little energy is available for boosting the system, therefore central final states are more likely. So electromagnetic objects are limited to be reconstructed in the barrel with a marginal of two ECAL crystals ($|\eta| < 1.4442$). In addition, the barrel is much better suited for measuring and identifying photons. To further suppress soft photon radiation, high transverse energies of the electromagnetic objects are required (see below).

Redefinition of the electromagnetic object's transverse momentum

For the background estimation method, similar spectra of transverse momentum for γ_{tight} and γ_{loose} are an advantage as will be discussed in Section 5.1.

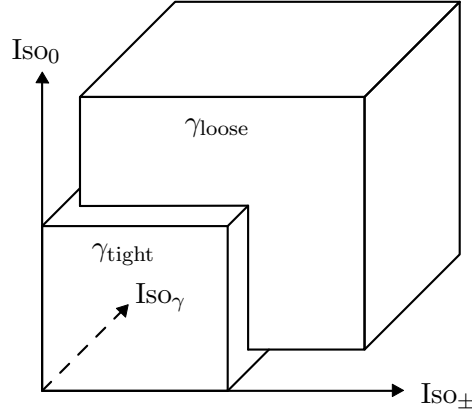


Figure 4.3: Sketch showing how γ_{tight} and γ_{loose} are separated with respect to their different isolation cone energy criteria. The p_T dependencies of the isolation cone energy cuts are neglected here. The objects in the interception of both rectangular solids are assigned to γ_{tight} .

The distribution of the transverse momenta of γ_{tight} and γ_{loose} can be seen in Fig. 4.4a. Especially for high transverse momenta, the distributions differ. Throughout there is no reason why the spectra of photons (identified as γ_{tight}) and jets (identified as γ_{loose}) must have a similar distribution of transverse momentum, it can be tried to improve the agreement.

As an independent way to measure the photon's energy, the jet algorithm described in Section 4.4.1 is used. Most electromagnetic objects are also reconstructed as jets with similar energy and position, which can be seen in Fig. 4.5. The $\eta\phi$ -distance and the ratio of the jet's p_T to the electromagnetic object's p_T is shown for each pair of γ_{tight} and jet in Fig. 4.5a and for each pair of γ_{loose} and jet in Fig. 4.5b.

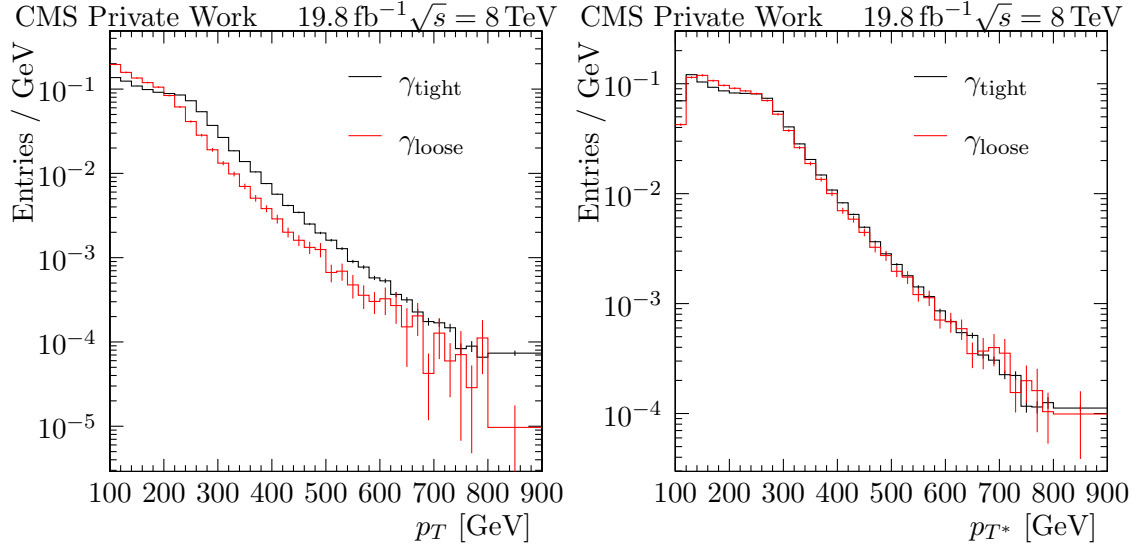
Jets with an $\eta\phi$ -distance larger than the jet's distance parameter 0.5 are clearly no matching candidates for electromagnetic objects. Most suitable jets are reconstructed with small $\eta\phi$ -distances to the electromagnetic objects and with approximately the same transverse momentum.

The mean $\eta\phi$ -distance increases with increasing momentum ratio. A reason for this is the decrease of the neutral energy fraction of jets: Jets with high neutral energy fraction are reconstructed near the electromagnetic object. If the neutral energy fraction decreases, the jet has a higher component of charged particles. Since the position of the jet is estimated by charged particles and the neutral energy depositions, the jet is reconstructed with a larger distance to its' neutral depositions. Hence the mean $\eta\phi$ -distance increases with increasing ratio of the jet's p_T to the electromagnetic object's p_T .

The p_T of a matching jet includes the p_T of the electromagnetic objects and isolation cone energy. Since the isolation cone energy of a γ_{tight} is smaller than the isolation cone energy of a γ_{loose} , the ratio of the jet's p_T to the electromagnetic object's is smaller for γ_{tight} as for γ_{loose} . Therefore more events with γ_{loose} have a larger p_T ratio in Fig. 4.5.

A jet is considered to match a photon if the $\eta\phi$ -distance is smaller than 0.2 and the p_T ratio is larger than 0.8 and smaller than 3 (red box in Fig. 4.5).

If a jet is assigned to an electromagnetic object, the p_T of the jet is used instead the p_T of the electromagnetic object. If no jet matched, the p_T of the electromagnetic object is



(a) Probability density function for the transverse momentum of γ_{tight} and γ_{loose} . The isolation cone energy is not included in the momentum.

(b) Probability density function for the transverse momentum of jets matched to γ_{tight} and γ_{loose} where possible.

Figure 4.4: The photon's kinematic variables for γ_{tight} and γ_{loose} . On the left hand side the energy is measured by the ECAL alone, whereas the new definition on the right hand side includes information from all subdetectors by using jets. Because of the slightly different distributions of hadronic activity H_T (defined in Section 4.4.6) of γ_{tight} and γ_{loose} , the γ_{loose} distribution is weighted to match the H_T distribution of the γ_{tight} events. This is only done in this figure to exclude the influence of the different response in hadronic activity and not necessary for the background estimation methods. This will be shown in Section 5.1. Without weighting the γ_{loose} distribution, the agreement for both p_T and p_{T^*} would decrease equally.

used. The modified transverse momentum is called p_{T^*} :

$$p_{T^*} = \begin{cases} \text{jet } p_T & \text{if jet matches} \\ \text{electromagnetic object } p_T & \text{else.} \end{cases}$$

In case no jet is matched to a γ_{loose} , the γ_{loose} object is discarded.

The resulting distribution of p_{T^*} , the kinematic variable for the photon which is used from now on, is shown in Fig. 4.4b for γ_{tight} and γ_{loose} . The agreement has improved with respect to Fig. 4.4a, especially for high energies. A perfect matching is not required since the background estimation method does not rely on a perfect matching.

4.4.3 Electrons

Hits in the tracker are combined to tracks using the Gaussian Sum Filter algorithm [60]. By combining these tracks to matching energy depositions in the ECAL, electron candidates are obtained.

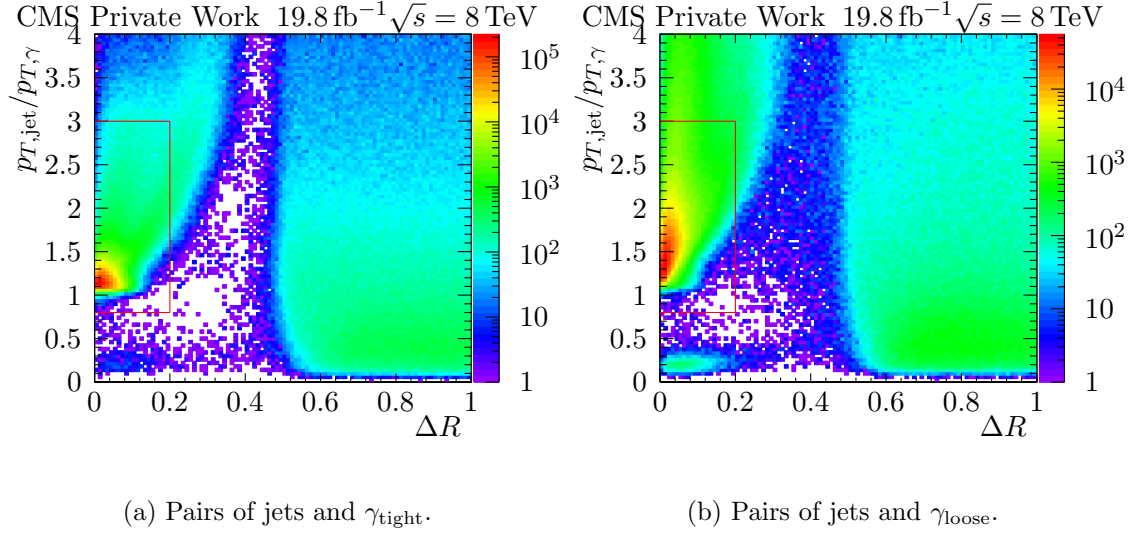


Figure 4.5: For each γ_{tight} (left) and γ_{loose} (right) the $\eta\phi$ -distance to a jet and the ratio of the jet's p_T and the electromagnetic object's p_T is plotted. On the z-axis the number of pairs of an electromagnetic object and a jet is drawn. Jets within the red box are assigned to the electromagnetic object.

To suppress jets being misidentified as electrons, the electron candidates must fulfill following quality criteria [61]: The transverse isolation energy in a cone of $\Delta R < 0.3$ must be smaller than 15% of the electron's p_T . The track of the electron must cross the center of the detector within 0.2 cm along the beam axis and 0.004 cm in perpendicular direction. The shower width in η must not exceed 0.01 (0.03) in the barrel (endcap). The energy deposit has to match the charged track within 0.007 (0.01) in η and 0.8 (0.7) in ϕ for the barrel (endcap). In the barrel, the energy deposit in the corresponding HCAL tower must not be more than 15% of the energy deposit in the ECAL.

Electrons are required to have a transverse momentum of at least 15 GeV and are reconstructed in barrel or endcap ($|\eta| < 2.5$).

Electrons in an $\eta\phi$ -distance $\Delta R < 0.3$ to an electromagnetic object are not considered, in order to avoid double counting of objects. This affects especially the γ_{pixel} objects, since many of them are reconstructed as electrons, too.

4.4.4 Muons

The Kalman Filter algorithm [62] is used to reconstruct muon candidates in the muon detectors [39]. Muons are required to have consistent tracks in both the inner and the outer tracker and a fitting energy deposit in the calorimeters. To select isolated muons, the transverse isolation energy in a cone of $\Delta R < 0.3$ must be smaller than 15% of the muon's p_T . Like electrons, muons are required to have a transverse momentum of at least 15 GeV and are reconstructed in barrel or endcap ($|\eta| < 2.4$).

4.4.5 Missing Transverse Energy

The initial transverse momentum of an event is given by the transverse momentum of the quarks and gluons in the protons that collide. It is expected to be small compared to the longitudinal momenta. Because of conservation of linear momentum, the total transverse

momentum of all particles in the final state has to be small as well. If a particle such as a neutrino or a gravitino leaves the detector undetected, the vectorial sum of the transverse momenta of all reconstructed particles points in the opposite direction relative to the undetected particle in the $x - y$ plane. If an object is misreconstructed, either in direction or energy, the vectorial sum of all transverse momenta can have large values, too.

Since most particles have high momenta, the transverse energy is used instead of the transverse momentum. Missing transverse energy is measured as absolute value of the sum of all reconstructed particle's transverse energies [63].

$$\cancel{E}_T = \left| \vec{\cancel{E}}_T \right| = \left| - \sum_i \vec{E}_{T,i} \right|$$

Particles used for the $\cancel{E}_T$ calculation are reconstructed using the Particle-flow algorithm.

4.4.6 Hadronic Activity

Two main aspects have to be kept in mind when defining the hadronic activity H_T :

The analysis' H_T definition should be similar to the criteria defined in the HLT. With a closer agreement between the analysis' and the trigger's H_T definition a higher trigger-efficiency for more events can be archived (as will be explained in Section 4.5).

For the background estimation method it is crucial that H_T is compatible for events with γ_{tight} and for events with γ_{loose} . The reason therefore will be discussed in Section 5.1.

The hadronic activity is defined as scalar sum of all jets' transverse energies and electromagnetic objects' transverse momenta p_{T^*} .

$$H_T = \sum_{\text{jets}} E_T + \sum_{\substack{\text{electromagnetic} \\ \text{objects}}} p_{T^*}$$

The jets have to be reconstructed in $|\eta| < 3$ and have to have a transverse energy of at least 40 GeV, which are the trigger requirements for jets.

Using only the jets and not the electromagnetic objects would introduce a bias between events with γ_{tight} and events with γ_{loose} . γ_{loose} have a higher probability of being reconstructed as jet than γ_{tight} , so H_T would be larger for events with γ_{loose} . To solve this problem, the transverse energy of all electromagnetic objects is added. To avoid double counting, only jets with a distance of $\Delta R \geq 0.3$ to electromagnetic objects are used.

4.5 Event Selection

At least one well defined primary vertex within 24 cm along the beam axis from the center and 2 cm in the perpendicular direction is required per event. Events with clear sources of noise, especially single noisy ECAL crystals or beam induced background, are rejected. To suppress dijet events with one jet being reconstructed as electromagnetic object, at least two jets with $p_T > 30$ GeV and $|\eta| < 2.5$ are required. These jets must not overlap with an electromagnetic object within $\Delta R < 0.3$. Events with electrons or muons are rejected to decrease the background. A separate analysis is used to search for SUSY in final states with a photon and leptons [64].

The signal trigger consists of two parts: The H_T requirement and the requirement of a photon candidate. The probability that an event is triggered (trigger efficiency) is

factorized in the probability that the event fulfills the H_T requirement given it passed the photon candidate requirement, and the probability that the event fulfills the photon candidate requirement given it passed the H_T requirement.

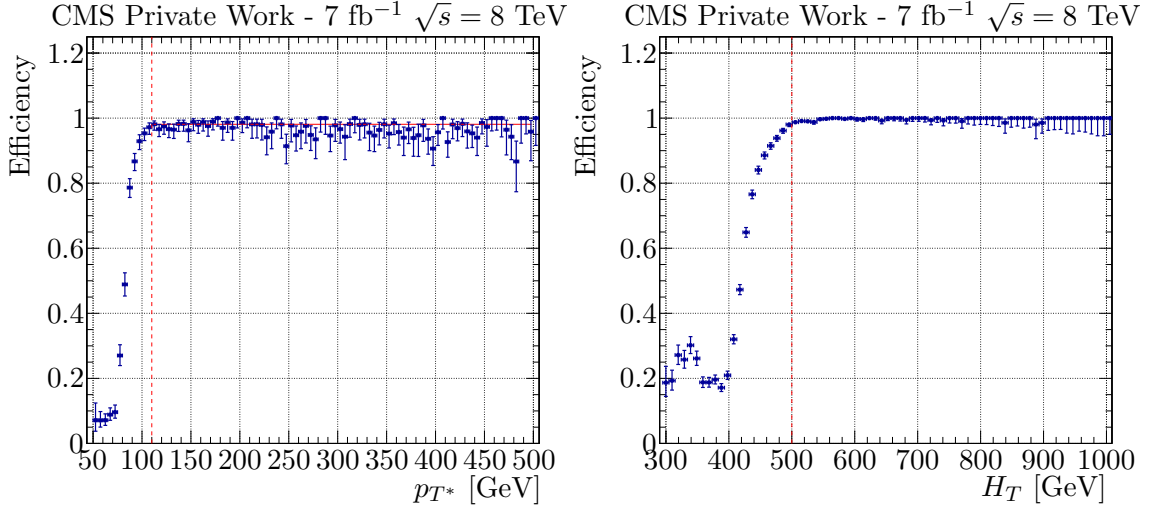


Figure 4.6: Trigger efficiency for the p_{T^*} requirement (left) and for the H_T requirement (right). The vertical red lines symbolize the selection values, and the horizontal red line symbolizes the value of the trigger efficiency for the selected region [65].

The efficiency for the photon candidate part of the trigger is measured using a cross trigger with no photon candidate requirement. In this case a trigger requiring $H_T \geq 650$ GeV is used as cross trigger, so the H_T requirement of the signal trigger is exceeded. The number of events passing the signal trigger and the cross trigger is divided by the number of events passing the cross trigger. This is shown on the left-hand side in Fig. 4.6 as function of p_{T^*} . For low values of p_{T^*} , hardly any events fulfill the signal trigger, but many the cross trigger, leading to a small trigger efficiency. For large values of p_{T^*} , nearly all events which are triggered by the cross trigger are triggered by the signal trigger, too. A high trigger efficiency can be obtained by only selecting events with an electromagnetic object with $p_{T^*} \geq 110$ GeV.

The efficiency for the H_T part of the trigger is measured in a similar way, using a cross trigger which requires an electromagnetic object with $p_T \geq 150$ GeV. The efficiency for this part is shown on the right-hand side in Fig. 4.6. By requiring $H_T \geq 500$ GeV, a high trigger efficiency is acquired.

Since the trigger efficiency for the H_T part is close to one, the total trigger efficiency is approximately the trigger efficiency of the p_{T^*} part, and is measured to 0.981 ± 0.003 [65].

The trigger is not included in the simulation of events. To have meaningful comparisons of data to simulation, the selection H_T and p_{T^*} selection is applied to both data and the simulation. The trigger efficiency is needed for the statistical interpretation in Section 7.4.

Depending on the electromagnetic object's type, events are sorted in three groups:

- γ_{tight} events,
- γ_{loose} events, and

- γ_{pixel} events.

For events with two or more electromagnetic objects of different types, the event is classified by the leading object in p_{T^*} . This approach reduces the probability, that a signal event is interpreted as SM event and used for the estimation of the background.

In Fig. 4.7, the numbers of electromagnetic objects of each type per event are shown. There are only few events with more than one type of electromagnetic objects compared to the number of events with a single type of electromagnetic object.

Since gravitons in signal events lead to large values of $\cancel{E}_T$, the selection $\cancel{E}_T \geq 100$ GeV is used to discriminate between signal region and background region. The selection of the signal region can be summarized as follows:

- γ_{tight} event with $p_{T^*} \geq 110$ GeV and the electromagnetic object being reconstructed in $|\eta| < 1.4442$
- $H_T \geq 500$ GeV
- $n_{\text{jets}} \geq 2$
- Veto events with electrons or muons
- $\cancel{E}_T \geq 100$ GeV

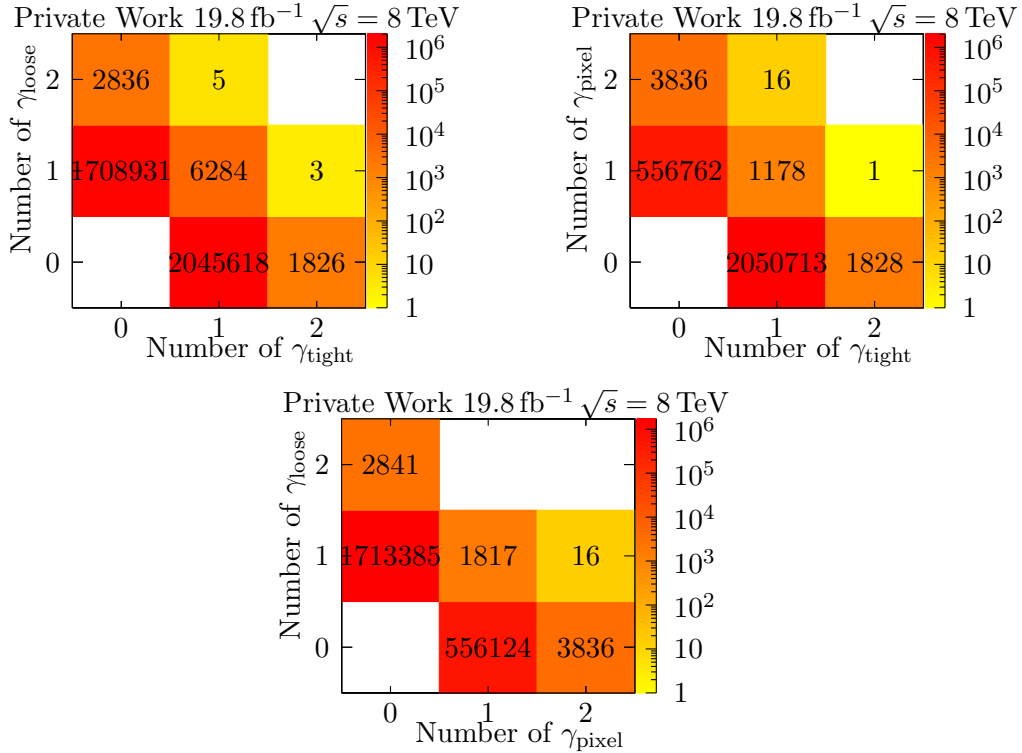


Figure 4.7: Number of events with various types of electromagnetic objects. The assignment of events with more than one type of electromagnetic object is done by the leading electromagnetic object in p_{T^*} . To increase the amount of data, no selection in $\cancel{E}_T$, H_T , or in the number of jets is applied for these plots.

5 Background Estimation

Direct comparison shows that simulation does not match the data perfectly. Especially multijet events with and without prompt photons are difficult to simulate, due to their large cross section. Despite the immense effort and calculation time to simulate the background, only few events pass the signal selection because of the large $\cancel{E}_T$ requirement. In addition, for most of the cross sections only the leading order of perturbation theory is calculated. Hence the cross sections have large uncertainties.

To decrease uncertainties, data-driven background estimation methods are used where possible. The dominant backgrounds from multijet events with prompt photons or with a jet faking a photon, and electrons faking photons are extracted from data. The contribution of hard photon radiation to the background is simulated.

5.1 Jets Faking Photons and Prompt Photons in Association with Jets

The total proton-proton cross section at the LHC is dominated by events with strong interaction in the hard processes. These processes are often called “QCD” or multijet events. Final states are dominated by jets and hardly any undetectable particles. Missing transverse energy is therefore caused by mismeasured jets or jet resolution, and the $\cancel{E}_T$ spectrum is steeply falling.

Processes with photons are suppressed by at least the electromagnetic coupling constant and further reduced by requiring a large transverse momentum of the photon in this analysis. Jets with a high neutral fraction and few components may also be misidentified as photons. The misidentification probability is small, but the jet production cross section is very large, leading to a significant contribution to the background. Both of these processes are very similar, therefore they are treated together. Nevertheless, the method is working for both processes individually as well as will be shown in the following.

The estimation of this background is done by extrapolating the ratio of the number of loosely to the number of tightly isolated photons for small values of $\cancel{E}_T$ to the signal region with high values of $\cancel{E}_T$.

As discussed in Section 4.4.2, most important to this method is the definition of γ_{loose} . It selects photon-like jets with few real photons. It must not overlap the γ_{tight} definition to unambiguously discriminate between these two objects. To further suppress real photons being misidentified as γ_{loose} , minimal values of isolation cone energy are required. Since the isolation cone energy distribution has a steeply falling spectrum, the upper limit is not crucial. It is set to ten times the γ_{tight} limit to exclude unphysical spikes that may appear in the data. Other discriminants were found to be useless: There are few events with H/E values larger than the selection for γ_{tight} and the trigger efficiency would be reduced since the trigger is using a similar variable. Loosening the $\sigma_{i\eta i\eta}$ selection would also introduce a lower trigger efficiency, since the trigger is already requiring some shower shape. In addition, $\sigma_{i\eta i\eta}$ is correlated with $\cancel{E}_T$, and therefore not usable for this method.

Events are grouped in four classes:

- γ_{tight} events with $\cancel{E}_T \geq 100$ GeV (signal region)
- γ_{tight} events with $\cancel{E}_T < 100$ GeV
- γ_{loose} events with $\cancel{E}_T \geq 100$ GeV
- γ_{loose} events with $\cancel{E}_T < 100$ GeV

Assuming that the isolation and $\cancel{E}_T$ are uncorrelated for SM processes, the ratio of the number of γ_{tight} to γ_{loose} events with $\cancel{E}_T \geq 100$ GeV should be equal the ratio of the number of γ_{tight} to γ_{loose} events with $\cancel{E}_T < 100$ GeV. This can be used to estimate the SM background in the signal region by calculating the ratio of number of γ_{tight} events with $\cancel{E}_T < 100$ GeV to γ_{loose} events with $\cancel{E}_T < 100$ GeV and multiplying it with the number of γ_{loose} events with $\cancel{E}_T \geq 100$ GeV.

Most signal events are expected to be reconstructed in the signal region. Possible contamination of signal events to other regions is discussed in Section 6.

The contribution of other SM processes for small $\cancel{E}_T$ is negligible due to the high multijet cross section.

5.1.1 Calculation of Weights in a Control Region

For multijet events with and without prompt photons, isolation cone energies of electromagnetic objects and $\cancel{E}_T$ are slightly correlated. This is shown in Fig. 5.1 for data with small values of $\cancel{E}_T$, which is dominated by multijet events and does not contain possible signal.

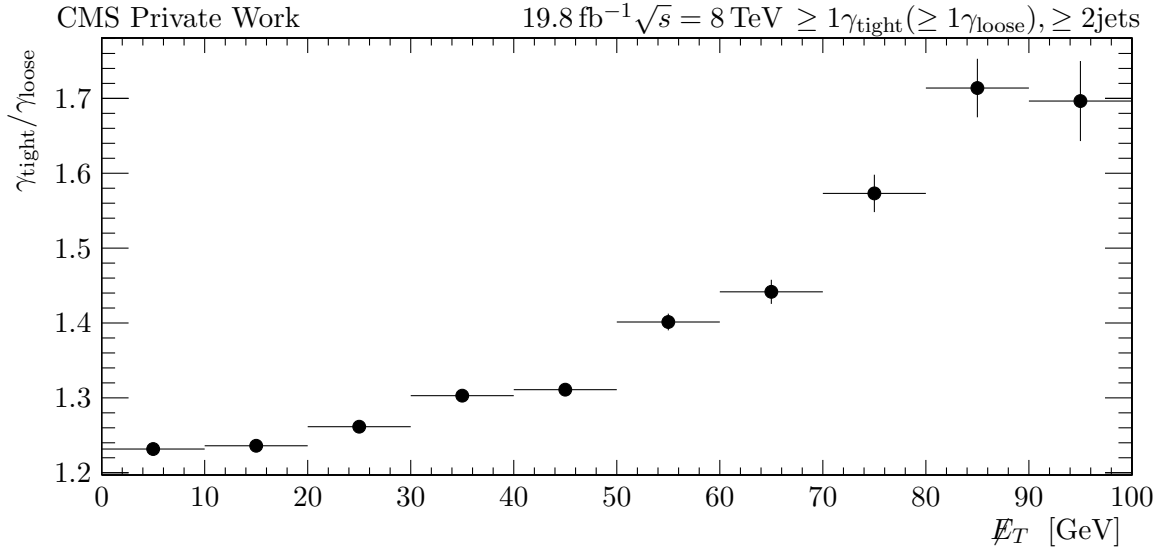


Figure 5.1: Ratio of γ_{tight} events to γ_{loose} events with $\cancel{E}_T < 100$ GeV.

To reduce the influence of the correlation, the background estimation method is performed in small intervals of p_{T^*} and H_T . The weights are defined as

$$w_i = \frac{\text{number of } \gamma_{\text{tight}} \text{ events } (p_{T^*}, H_T)_i}{\text{number of } \gamma_{\text{loose}} \text{ events } (p_{T^*}, H_T)_i} \Big|_{\cancel{E}_T < 100 \text{ GeV}}$$

in each interval i of p_{T^*} and H_T . w_i as a function of p_{T^*} and H_T is shown in Fig. 5.2.

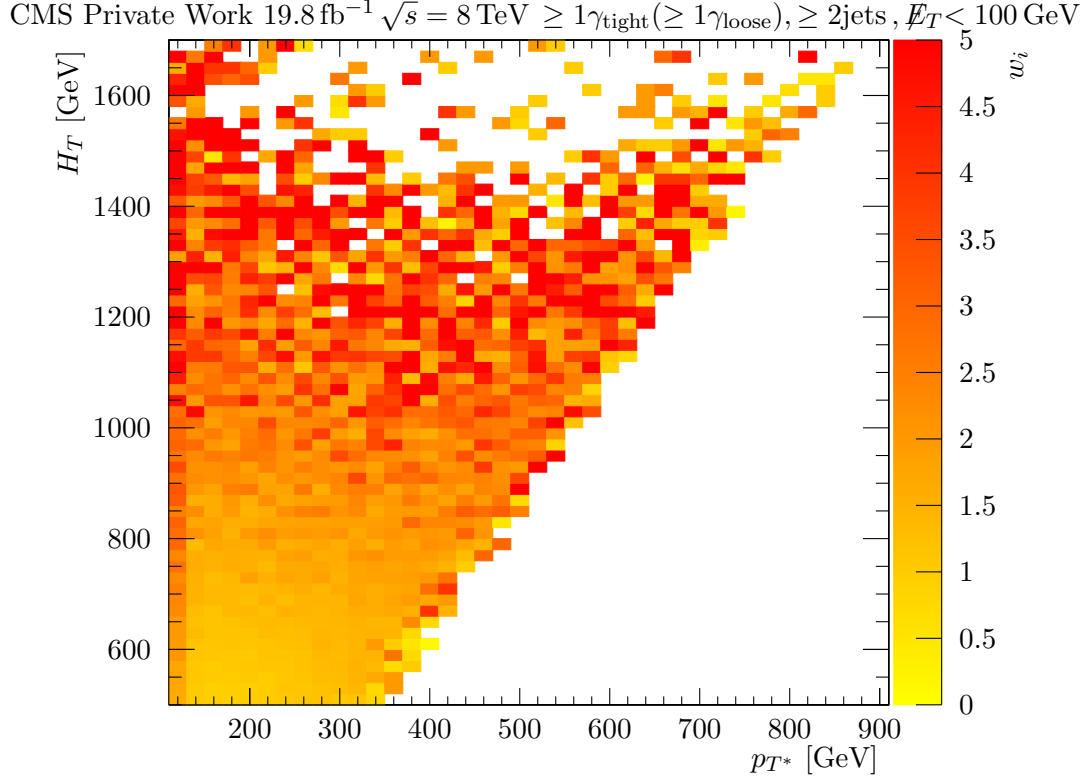


Figure 5.2: The weights w_i as a function of H_T and p_{T^*} for data.

Due to the H_T definition used in this analysis, H_T is always larger than p_{T^*} , so no entries can be below the diagonal. Even if p_{T^*} would not be directly included into H_T , a large correlation between H_T and p_{T^*} would arise, since H_T is a variable sensitive to the momentum transfer at the hard scattering, as is p_{T^*} . This second dependency leads to a non strict edge at $H_T \propto 2 \cdot p_{T^*}$. In the heavily populated region for small p_{T^*} and H_T , most w_i are smaller than one. Small values of w_i decrease the uncertainty of the prediction, since the uncertainty of the unweighed prediction is scaled by w_i . The weights w near the edge are often much larger, but they also have a larger uncertainty, as can be seen in Fig. 5.3. In the heavily populated region for small p_{T^*} and H_T , the relative uncertainty is about 20%.

Increasing the number of p_{T^*} and H_T intervals leads to larger statistical uncertainties of w . Decreasing the number of intervals reduces the statistical uncertainty, but increases the correlation between the isolation and $\cancel{E}_T$, causing the method to fail. A slight change in the interval size leads to negligible changes.

For large values of H_T or the phase space near the edge, no events are found in the control region $\cancel{E}_T < 100 \text{ GeV}$ for some p_{T^*}, H_T intervals. This leads to a weight of 0, in these intervals, so γ_{loose} events with $\cancel{E}_T \geq 100 \text{ GeV}$ in these intervals do not contribute to the background estimation. γ_{tight} events with $\cancel{E}_T \geq 100 \text{ GeV}$ in these intervals are not rejected, so the background is predicted too small. To test the influence of this effect, the analysis is repeated with an artificial weight of 1 ± 1 in these intervals, which corresponds approximately to the mean weight with a relative uncertainty of 100%. The change in predicted background events is taken as uncertainty and is of the order of 1.5 – 2% and therefore much smaller than the total uncertainty of 10 – 20%.

To predict the multijet background with and without prompt photons in the signal

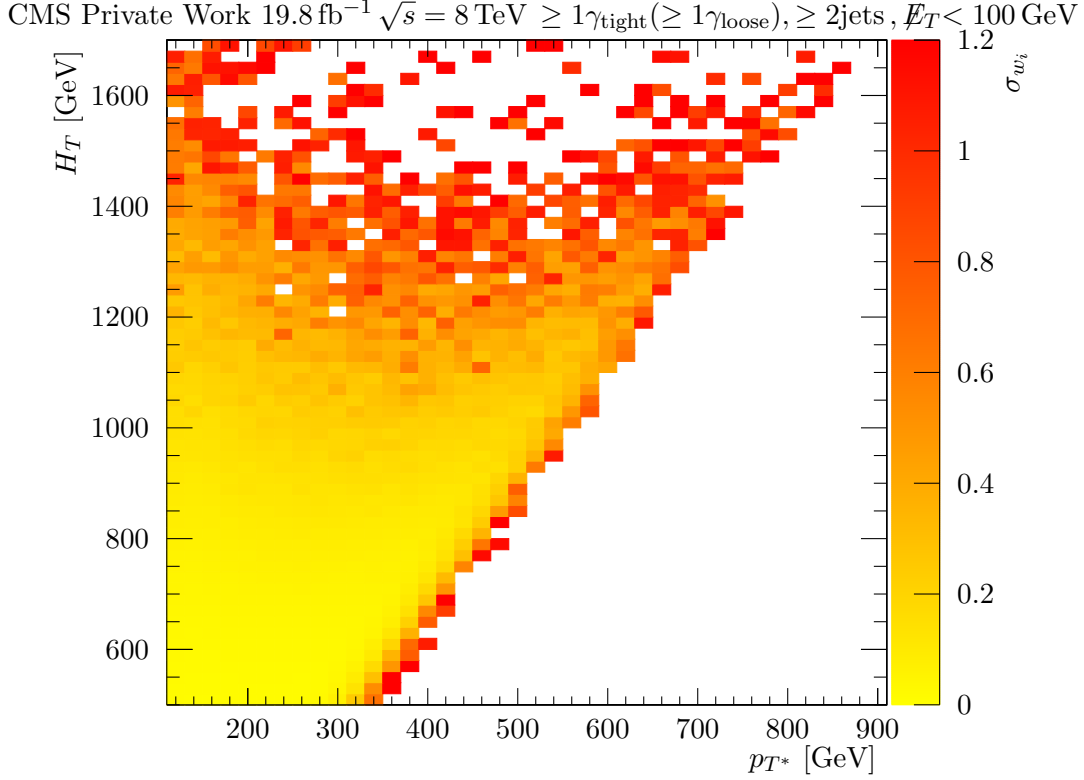


Figure 5.3: Relative statistical uncertainty of w_i as a function of H_T and p_{T^*} for data.

region, all γ_{loose} events are weighted according to their p_{T^*} and H_T . With the number of γ_{loose} events N_i and the weight w_i in a specific p_{T^*}, H_T interval i , the prediction for the multijet background can be calculated as

$$\text{Prediction} = \sum_{(H_T, p_{T^*})_i} N_i w_i.$$

The uncertainty of the prediction can be separated into two parts: The one due to the statistical uncertainty of γ_{loose} events with $\cancel{E}_T \geq 100$ GeV is calculated as

$$\sigma_{\text{stat}}^2 = \sum_{(H_T, p_{T^*})_i} \sigma_{N_i}^2 w_i^2.$$

Since the event yields in each interval are expected to be Poisson distributed, $\sigma_{N_i}^2 = N_i$ is used. The uncertainty of the prediction due to w_i is calculated as

$$\sigma_w^2 = \sum_{(H_T, p_{T^*})_i} N_i^2 \sigma_{w_i}^2.$$

w_i is always calculated for $\cancel{E}_T < 100$ GeV, while the prediction can be done for an arbitrary subset of the events. In the following, the prediction is done in disjoint intervals of $\cancel{E}_T$. σ_{stat} is uncorrelated between various $\cancel{E}_T$ intervals, since the number of γ_{tight} events in various $\cancel{E}_T$ intervals is uncorrelated. σ_w is fully correlated between bins in the prediction and is therefore handled as a systematic uncertainty.

5.1.2 Test of the Method on Simulation

To validate the method's performance, it is applied to simulated multijet events with and without prompt photons. In Fig. 5.4, the $\cancel{E}_T$ distribution for γ_{tight} events is compared to the prediction described above. The binning of $\cancel{E}_T$ is the same as will be used in the statistical interpretation of the results. The rightmost bin is the overflow bin that contains all events with $\cancel{E}_T \geq 350$ GeV.

The integrals of direct simulation and prediction for $\cancel{E}_T < 100$ GeV must agree within the systematic uncertainties, since this region is used to calculate w_i .

In the upper part of Fig. 5.4, σ_{stat} is shown as red vertical line, while the hatched area corresponds to σ_w . For the most sensitive bins with high $\cancel{E}_T$, σ_w is of the same order as σ_{stat} . In the ratio plot at the bottom, the vertical bars correspond to the total statistical uncertainty, which is uncorrelated, while the hatched area is the same as in the plot above and is fully correlated between the $\cancel{E}_T$ intervals.

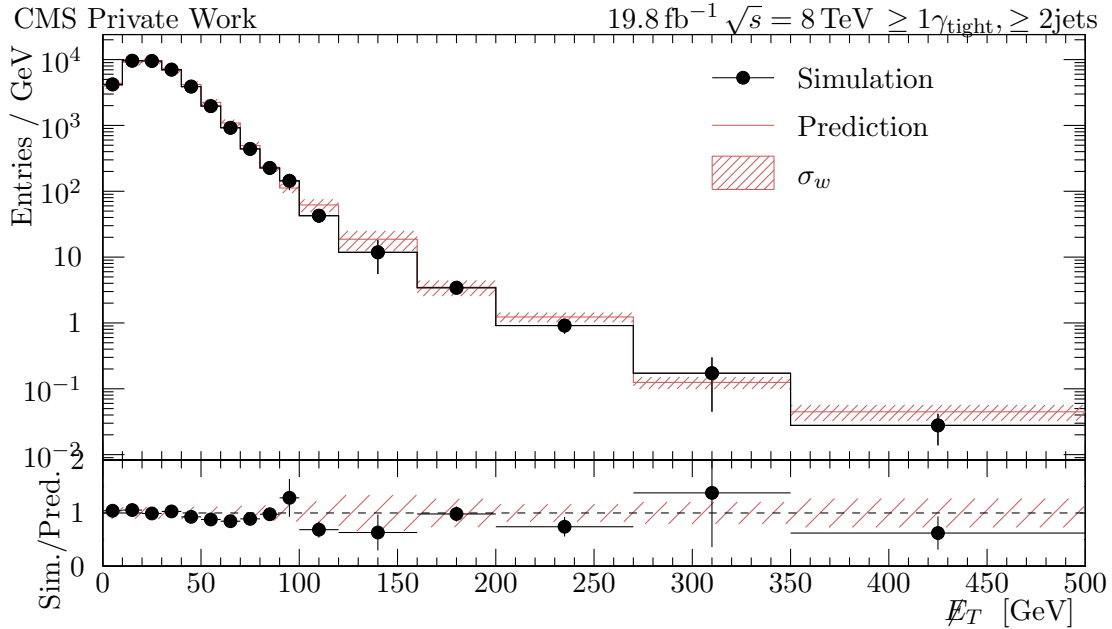


Figure 5.4: Application of the background estimation method on simulated multijet events with and without prompt photon radiation. The direct simulation (black) is compared to the prediction (red). The systematic uncertainty is drawn as hatched area. In the ratio plot at the bottom, the vertical error bars represent the total statistical uncertainties of the prediction and the direct simulation. The hatched area is represents the systematic uncertainty and is correlated between different intervals.

The prediction of this method is in statistical agreement with direct simulation, so the method is working well.

In Fig. 5.5, the test is repeated with simulated multijet events without prompt photons, and in Fig. 5.6, the test is done for simulated multijet events with prompt photons. The prediction is in agreement with the direct simulation, so the method is independent of the relative contribution of both processes.

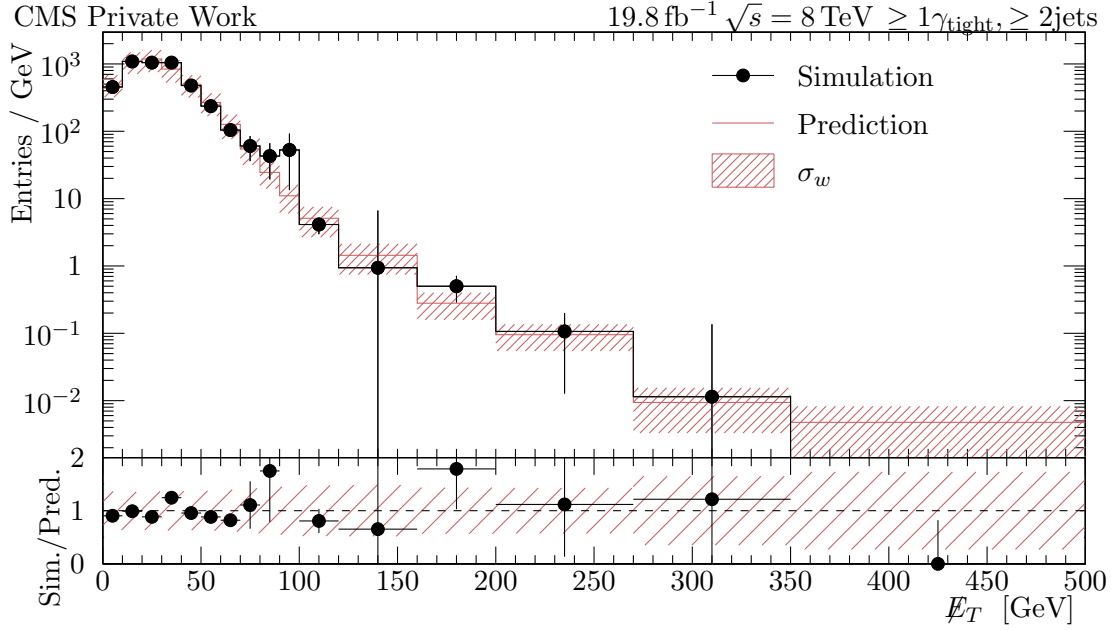


Figure 5.5: Application of the background estimation method on simulation for multijet processes without prompt photons only. The labels are explained in Fig. 5.4. Large uncertainties arise in bins which are dominated by few events with large luminosity weights (see Section 4.2). For empty bins, the one-sided Poisson uncertainty for zero entries is used.

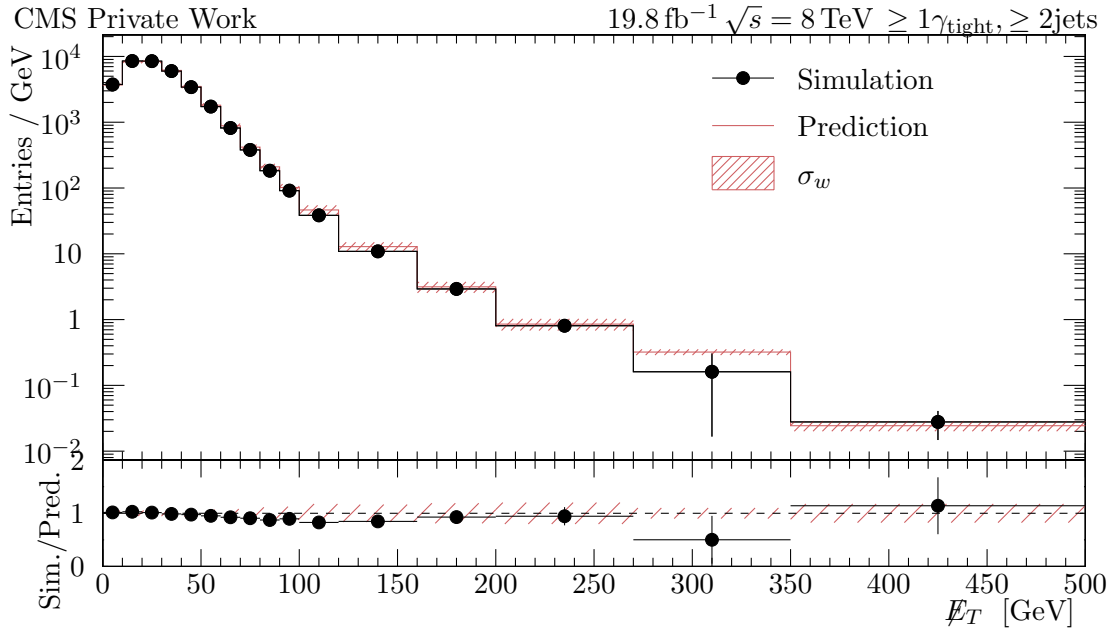


Figure 5.6: Application of the background estimation method on simulation for prompt photon production in multijet processes only. The labels are explained in Fig. 5.4.

5.2 Electrons Faking Photons

Isolation cone energies and shower shape in the calorimeters are similar for photons and electrons. The distinguishable feature used to separate between electrons and photons is the tracker activity. Photons do not interact with the silicon detectors and leave no track, because they are neutral. Since electrons are ionizing particles, they are registered by the tracking system by producing electron-hole pairs in the silicon sensors. In this analysis, the number of pixel seeds is used to discriminate between electrons and photons. Few real photons are discarded this way, but some electrons may be misidentified as photons by the inefficiency of the pixel detector.

To estimate this effect, the probability of an electron faking a photon (fake rate) is measured in a control region [66]. A second control region is defined by replacing γ_{tight} events with γ_{pixel} events in the signal region. To predict the background of electrons faking photons, the fake rate is applied to this control region.

5.2.1 Estimation of the Fake Rate

The fake rate is the probability of an electron being misidentified as a photon. It is measured as

$$f_{e \rightarrow \gamma} = \frac{\#\gamma_{\text{tight}} \text{ events}}{\#\gamma_{\text{tight}} \text{ events} + \#\gamma_{\text{pixel}} \text{ events}}, \quad (5.1)$$

with γ_{tight} and γ_{pixel} being electrons. To find out if a reconstructed γ_{tight} or γ_{pixel} originates from a real electron, the tag-and-probe method is used in events containing a Z boson. Virtual photon or Z-boson production in hadron colliders is also called Drell-Yan. Z bosons are produced and recorded with a high frequency, leading to small statistical uncertainties. The events have small values of $\cancel{E}_T$, so the overlap with the signal region is negligible. If the Z boson decays into two electrons, the invariant mass of both electrons peaks at $m_Z = 91.2 \text{ GeV}$. Vice versa, if the invariant mass of a good identified electron (tag) and an electromagnetic object (probe) is near the Z resonance, the electromagnetic object is very likely an electron.

For events triggered with a double photon trigger, one well identified electron (e) is required. The invariant mass for this electron and a $\gamma_{\text{pixel}}(\gamma_{\text{tight}})$ is shown in Fig. 5.7 on the left (right). In both distributions, the Z-boson resonance can be seen.

Combinatoric background to both spectra of $m_{e\gamma_{\text{pixel}}}$ or $m_{e\gamma_{\text{tight}}}$ can come from two W bosons or $t\bar{t}$ decays. Additional combinatoric background arises if a jet or a photon is identified as a γ_{pixel} or a γ_{tight} . All these backgrounds can also occur with muons, so the invariant mass of one γ_{tight} or γ_{pixel} with one muon is computed. A kernel density estimator is used to extract the background shape using these events with muons.

For the signal shape, a convolution of a Breit-Wigner function and a Crystal Ball function is used. The Breit-Wigner function describes the resonance of the Z boson, and the Crystal Ball function describes the resolution and the radiative losses. A detailed definition of the Crystal Ball function can be found in appendix C.

To get the number of real electrons being reconstructed as γ_{tight} or γ_{pixel} , the sum of the signal and background shape is fitted to the invariant mass distribution. The integral of the signal function in the plotted region is used to count the number of γ_{tight} and γ_{pixel} events.

For simulated events, the fake rate can be measured directly by using the generator information. Reconstructed γ_{tight} and γ_{pixel} are checked for a generated electron in an

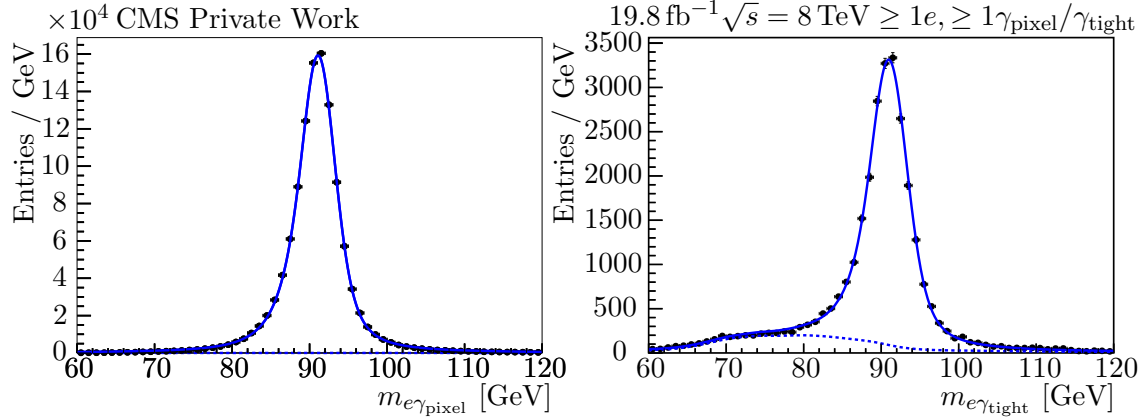


Figure 5.7: Invariant mass m of a well identified electron (e) and a γ_{pixel} (left) or γ_{tight} (right) [66]. A convolution of a Breit-Wigner function and a Crystal ball function plus a background shape extracted from $\mu\gamma_{\text{pixel}}$ (left) or $\mu\gamma_{\text{tight}}$ (right) events is fitted to the spectrum. The background is drawn as a dashed line, the total fit as a solid line.

$\eta\phi$ -distance of $\Delta R < 0.1$. If a generated electron is found, the object is kept, and used to calculate the fake rate with Eq. 5.1.

The dependency of the fake rate on the electromagnetic object's p_T can be seen in Fig. 5.8 for various simulated processes. For W boson, $t\bar{t}$ and Drell-Yan processes, the electromagnetic objects are matched to a generated electron. For Drell-Yan, the tag-and-probe method is used in addition. For W boson and $t\bar{t}$ this tag-and-probe method cannot be used since electrons are not produced in correlated pairs. Some deviations for simulated Drell-Yan processes between the tag-and-probe method and the method using generator information are expected, but the disagreement between them could also hint to an underestimated uncertainty for the more sophisticated tag-and-probe method.

In addition, the fake rate is different for various processes. Recent studies [67] suggest that this is due to the different activity near the electron vertex. This dependency is not taken into account here. These studies indicate a better agreement of the fake rates for different samples. Since this new method is under development, the legacy and established method is used here. To account for the differences when applying the fake rate in different samples, an additional uncertainty of 50% is used to take the deviations into account.

For electromagnetic objects with $p_T \geq 80$ GeV, the fake rate estimated with the tag-and-probe method is

$$\begin{aligned} f_{e \rightarrow \gamma}[\%] &= 0.84 \pm 0.05(\text{stat.}) \pm 0.02(\text{sys.}) \pm 0.42(\text{add.}) && \text{for simulation and} \\ f_{e \rightarrow \gamma}[\%] &= 1.48 \pm 0.05(\text{stat.}) \pm 0.08(\text{sys.}) \pm 0.74(\text{add.}) && \text{for data [66].} \end{aligned}$$

In Fig 5.9, the fake rate measured in data is shown for various p_T intervals.

The systematic uncertainty arises from the background shape uncertainty. The additional uncertainty taking the deviations between processes into account is the dominating one.

Using the definition of the fake rate $f_{e \rightarrow \gamma}$, the prediction for electrons being reconstructed as γ_{tight} in the signal region is

$$\frac{f_{e \rightarrow \gamma}}{1 - f_{e \rightarrow \gamma}} \times \#\gamma_{\text{pixel}} \text{ events.}$$

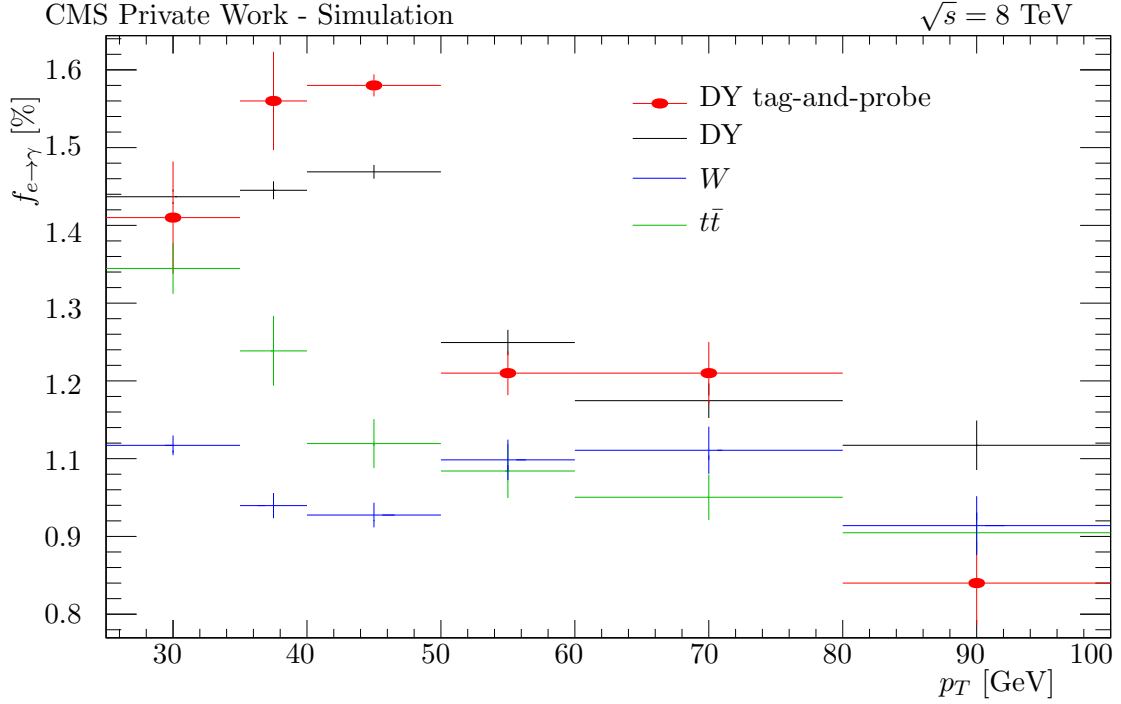


Figure 5.8: Fake rate as a function of p_T for various simulated processes. For W boson, $t\bar{t}$ and Drell-Yan processes, the electromagnetic objects are matched to a generated electron. For Drell-Yan, the tag-and-probe method is used in addition [66]. The error bars represent statistical uncertainties only.

5.2.2 Test of the Method on Simulation

To check the background estimation method's performance, it is applied to simulation. A control region is defined similar to the signal region, except that γ_{pixel} events instead of γ_{tight} events are used. The fake rate is extracted from simulated Drell-Yan processes and applied to this control region. Since the generated particles in simulation are known, the prediction is compared to reconstructed γ_{tight} which originate from generated electrons.

In Fig. 5.10 the prediction is shown in red and the γ_{tight} from generated electrons in black for simulated W bosons (left) and for simulated $t\bar{t}$ decays (right). The fake rate is measured in Drell-Yan simulation only. For both processes the curves agree within their uncertainty, so the method is working for both processes. The $\cancel{E}_T$ intervals shown are the ones used for statistical interpretation of the results. The rightmost bin is the overflow bin, containing all events with $\cancel{E}_T \geq 350$ GeV.

To test the influence of other SM processes, the $\cancel{E}_T$ distribution for γ_{pixel} is shown in Fig. 5.11a for simulation. For $\cancel{E}_T \geq 100$ GeV, which corresponds to the signal region, the dominating processes are $t\bar{t}$ and W -boson production. Other SM processes contaminate the control region only by a small percentage. This has no impact on the performance of the method as can be seen in Fig. 5.11b. The total prediction for electrons faking γ_{tight} is in agreement with γ_{tight} from generated electrons for all simulated SM processes. Contamination from signal is small as well and will be covered in more detail in Section 6.

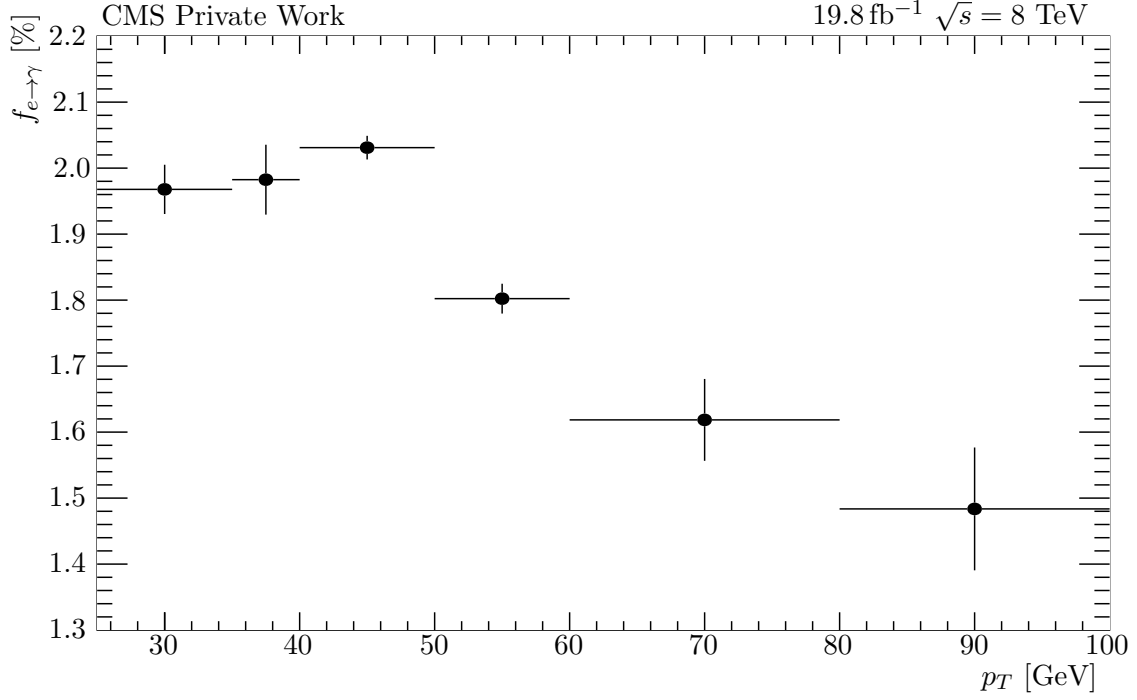


Figure 5.9: Fake rate as a function of p_T measured with the tag-and-probe technique on data. [66]. The last interval contains all electrons with $p_T \geq 80$ GeV. The error bars represent statistical uncertainties only.

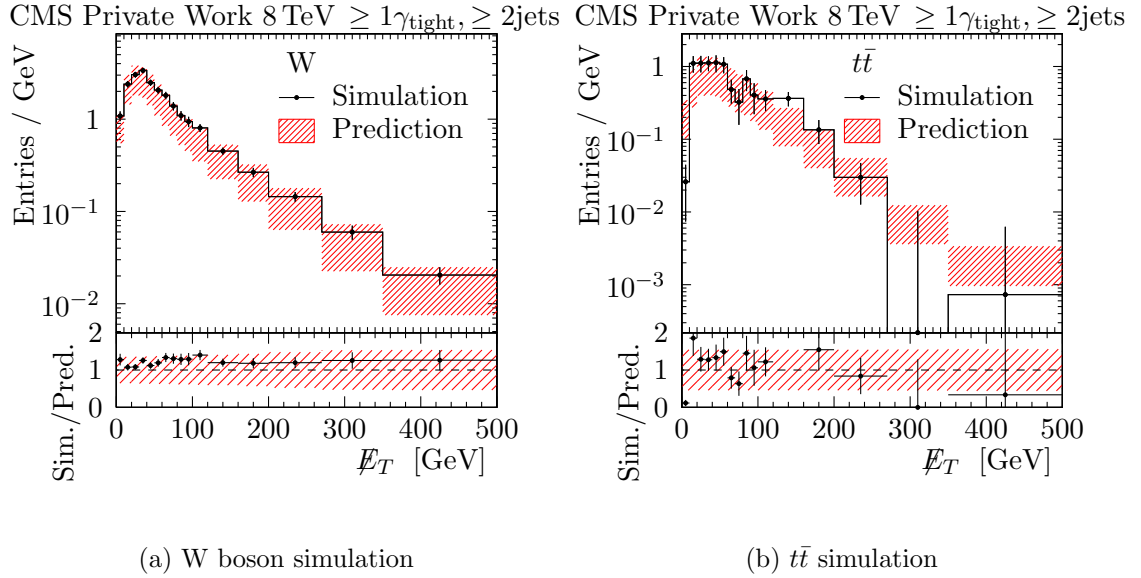
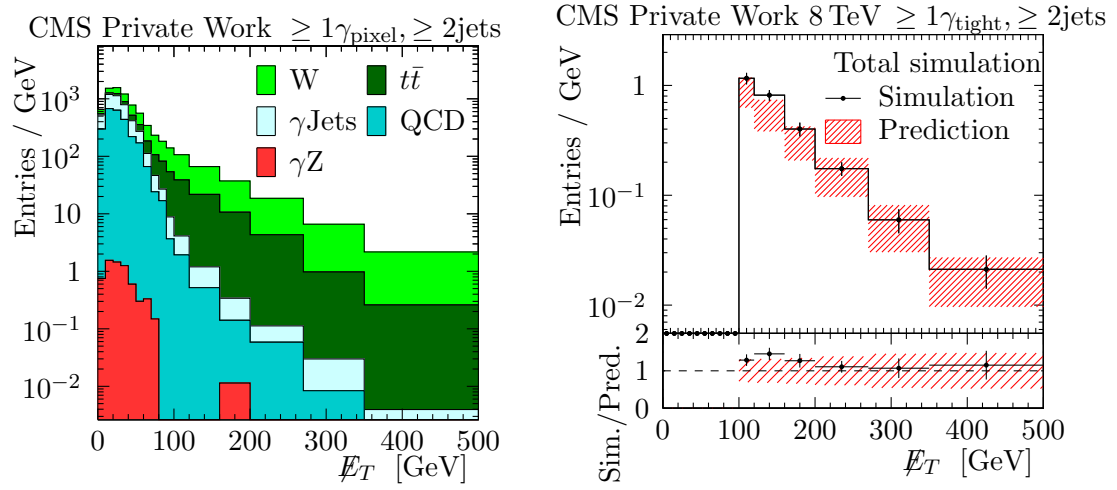


Figure 5.10: Application of the background estimation method on simulation. The direct simulation (black) is compared to the prediction. The hatched area covers the statistical and systematical uncertainties.



(a) Stacked E_T distribution of γ_{pixel} events for various simulated SM processes. (b) Application of the background estimation method on SM simulation in the signal region.

Figure 5.11: E_T distribution for γ_{pixel} events (left) and the comparison of real electrons being reconstructed as γ_{tight} to the prediction

5.3 Hard Photon Radiation

Photon radiation is a common process in the SM, but high energetic photons are rare. To contribute significantly to the signal region, processes must also have high values of $\cancel{E}_T$. Three SM processes are found to contribute significantly to the background of this analysis:

γW

High energetic photons can be produced in initial or final state radiation in association with a W boson. Two simulated samples are available to predict the contribution of this background: The inclusive W sample used in Section 5.2 and a sample in which the production of a photon is simulated in the hard scattering. Since reconstructed γ_{tight} in the inclusive W sample might be misidentified electrons, jets or real photons, only γ_{tight} which are matched to a generated photon must be considered. Other γ_{tight} are already predicted by the data-driven background estimation methods described in Section 5.1 and 5.2.

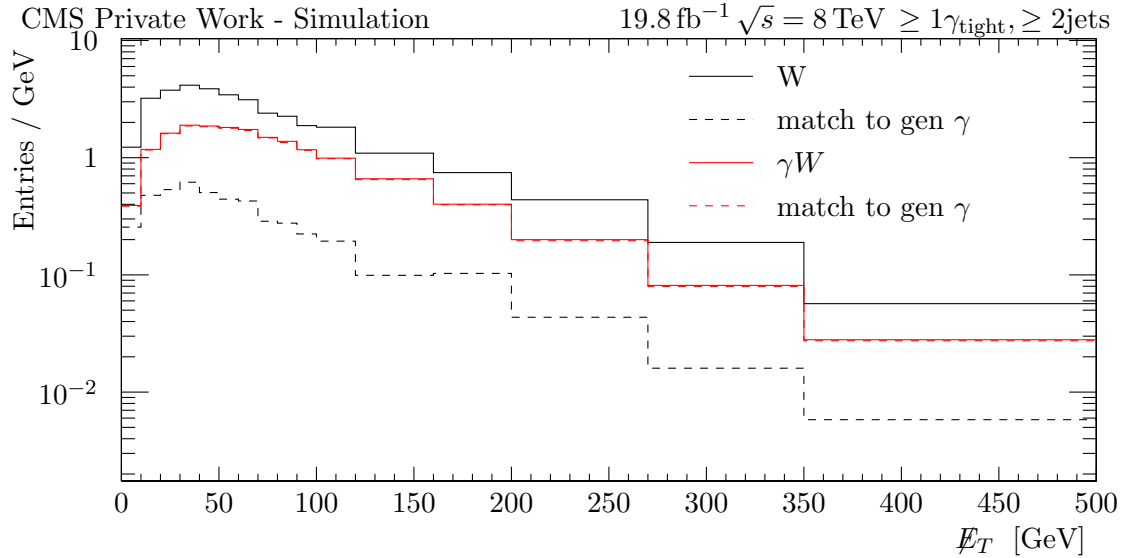


Figure 5.12: Simulated $\cancel{E}_T$ distribution for an inclusive W sample (black) and a simulated γW sample (red). In addition, the distributions in which the γ_{tight} is matched to a generated photon are drawn.

In Fig. 5.12, the $\cancel{E}_T$ distribution for both samples is shown. The $\cancel{E}_T$ distribution for γ_{tight} which are matched to a generated photon are plotted with dashed lines. In the simulated γW sample, nearly all reconstructed γ_{tight} are matched to a generated photon. This is due to the high matching efficiency and the large numbers of prompt photons with large p_{T^*} . Far less γ_{tight} are matched to generated photons in the inclusive W sample. The photons are not generated in the hard scattering, but in the subsequent simulation steps. Both cross sections are calculated in leading order. As prediction for this background, the prompt photon simulation in the hard scattering is used (γW). This way it is not necessary to rely on a way to match the reconstructed γ_{tight} to a generated photon. An overall uncertainty of 50% is used.

$\gamma t\bar{t}$

The prediction of photons in association to $t\bar{t}$ is similar to the method described in the section above. Here the inclusive $t\bar{t}$ sample used in Section 5.2 and a sample in which the production of a photon is simulated in the hard scattering are used. The $\cancel{E}_T$ distributions with and without match to a generated photon for both samples are shown in Fig. 5.13. Both cross sections are NLO. The $\gamma t\bar{t}$ sample is used with an uncertainty of 50%.

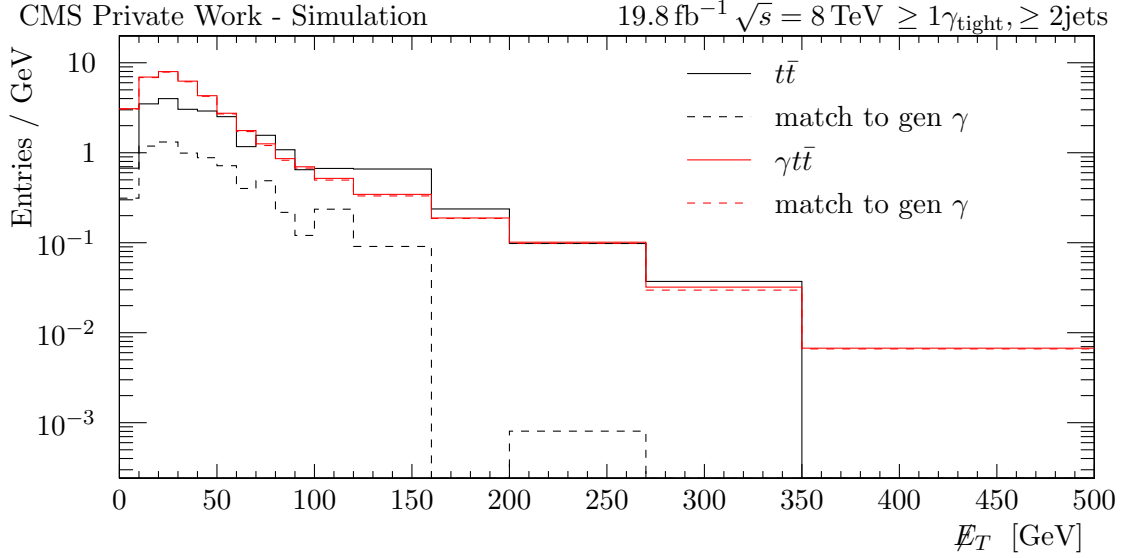


Figure 5.13: Simulated $\cancel{E}_T$ distribution for an inclusive $t\bar{t}$ sample (black) and a simulated $\gamma t\bar{t}$ sample (red). In addition, the distributions in which the γ_{tight} is matched to a generated photon are drawn.

γZ

Initial state particles radiate a photon, and a Z boson is produced. If the Z boson decays into two neutrinos, which leads to $\cancel{E}_T$. Two simulated samples are available for now: The simulation of γZ , with a photon p_T^{gen} threshold of 130 GeV and a simulation of $Z \rightarrow \nu\nu$ decays.

In Fig. 5.14, both processes are compared in the same way as in Fig. 5.12 and Fig. 5.13, only for photons with $p_T > 130$ GeV. As for W and $t\bar{t}$ initial state radiation, nearly all γ_{tight} in the prompt photon simulation γZ are matched to a generated photon. The discrepancy between both distributions can be explained with the arguments above.

Fig. 5.15 shows the same as Fig. 5.14, except that the photon is not required to have a transverse momentum of at least 130 GeV for the inclusive simulation. The prompt photon simulation γZ distributions are exactly the same as in Fig. 5.14. Even with the harder restriction for the γZ simulated processes, it exceeds the prediction with Z decays using a match to a generated photon. To cover all possible scenarios and to be consistent to the methodology above, the simulated γZ sample is used with an uncertainty of 70%. The uncertainty is 20% larger than for the other hard radiation samples, because events with photons with $p_T < 130$ GeV are not included in the simulation.

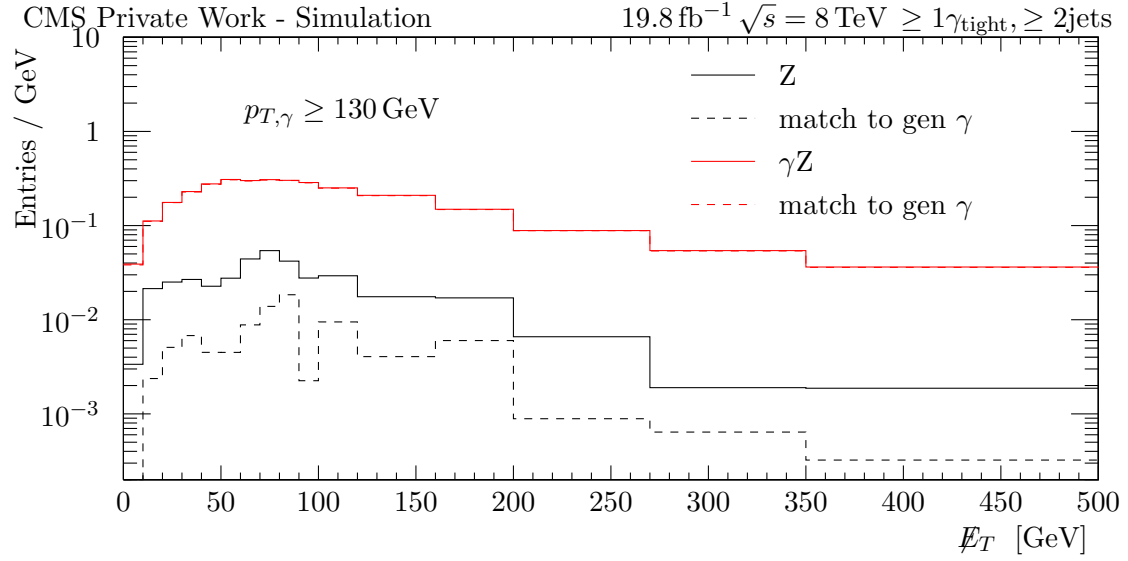


Figure 5.14: Simulated E_T distribution for an inclusive Z sample (black) and a simulated γZ sample (red). In addition, the distributions in which the γ_{tight} is matched to a generated photon are drawn. The photons are required to fulfill $p_T > 130 \text{ GeV}$.

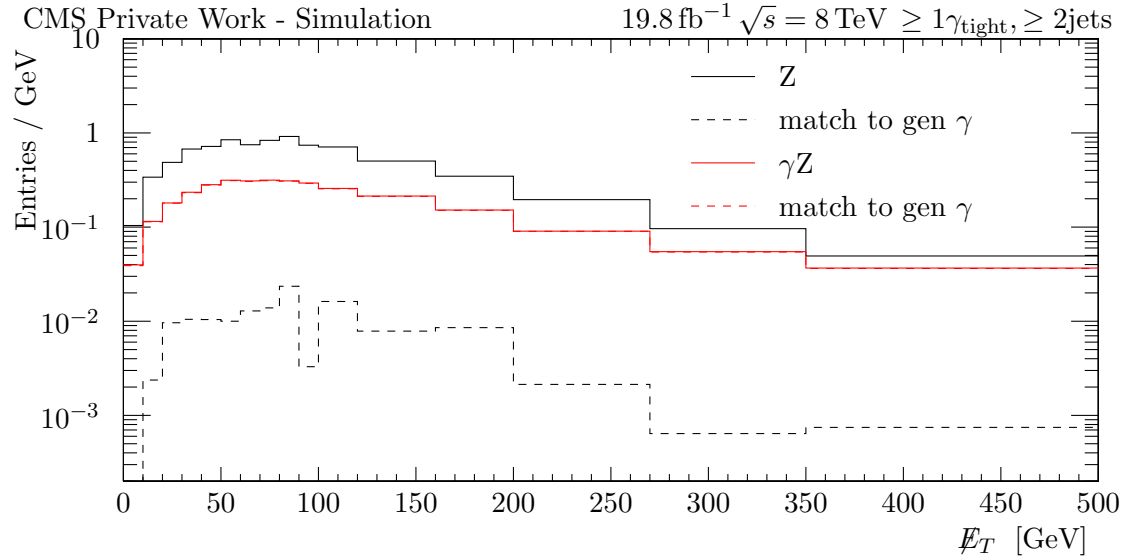


Figure 5.15: Simulated E_T distribution for an inclusive Z sample (black) and a simulated γZ sample (red). In addition, the distributions for the γ_{tight} is matched to a generated photon are drawn.

6 Selection of Signal Events

Although most signal events are expected to be reconstructed with at least one γ_{tight} and with large values of $\cancel{E}_T$, there are some events which do not fulfill these requirements. In this chapter the reasons are examined and the impact on the analysis is discussed.

6.1 Signal Acceptance

The signal region is defined in Section 4.5 as:

- γ_{tight} event with $p_{T^*} \geq 110$ GeV and the electromagnetic object being reconstructed in $|\eta| < 1.4442$
- $H_T \geq 500$ GeV
- $n_{\text{jets}} \geq 2$
- Veto events with electrons or muons
- $\cancel{E}_T \geq 100$ GeV

The ratio of the number of signal events reconstructed in the signal region to the total number of generated signal events is called acceptance. It is shown in Fig. 6.1 for wino-like and bino-like $\tilde{\chi}_1^0$ mixing scenarios. The total acceptance is lower in the wino-like $\tilde{\chi}_1^0$ mixing scenario, since the decay to a Z boson instead of a photon is enhanced (see Fig. 2.2).

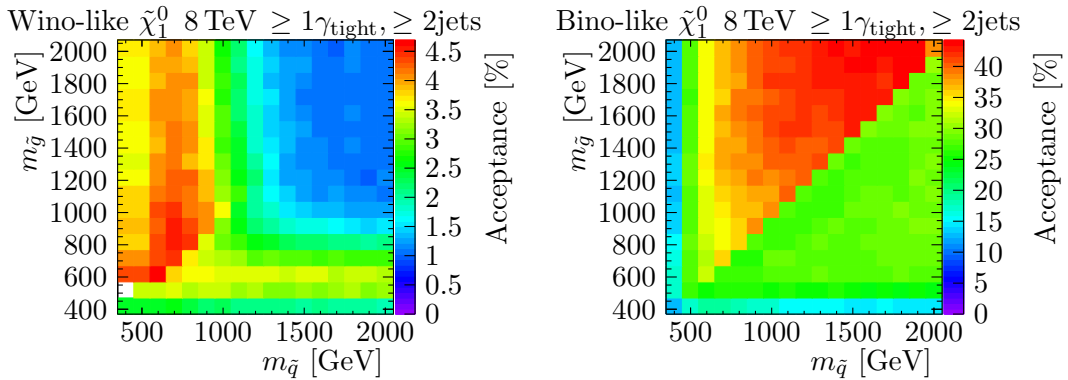


Figure 6.1: Acceptance for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios as a function of squark and gluino mass.

For both wino- or bino-like $\tilde{\chi}_1^0$ mixing scenarios, the signal acceptance drops for low squark or gluino masses near 400 GeV, which is close to the simulated lightest neutralino mass of 375 GeV. In this case, the mass difference between the squark or the gluino and the neutralino is about 25 GeV, which is less than the jet p_T requirement. Therefore, less jets are reconstructed for these signal events, leading to a small acceptance.

For the wino-like $\tilde{\chi}_1^0$ mixing scenario, the acceptance drops for large squark or gluino masses. For low squark and gluino masses, wino-like neutralinos are dominantly produced via squarks and gluinos, which decay into jets and increase H_T . For high squark and gluino masses, the production of wino-like neutralinos via W bosons gets more dominant. This reduces H_T (Fig. 6.2) and the number of jets (Fig. 6.3).

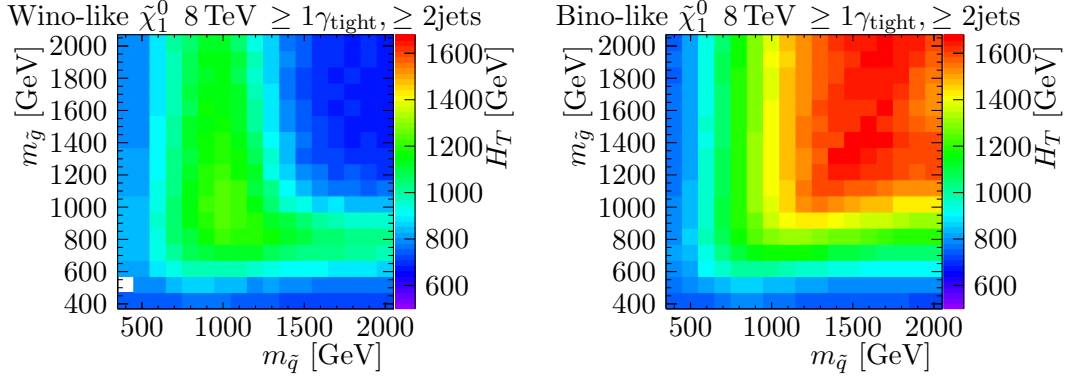


Figure 6.2: Mean H_T in the signal region for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios as a function of squark and gluino mass.

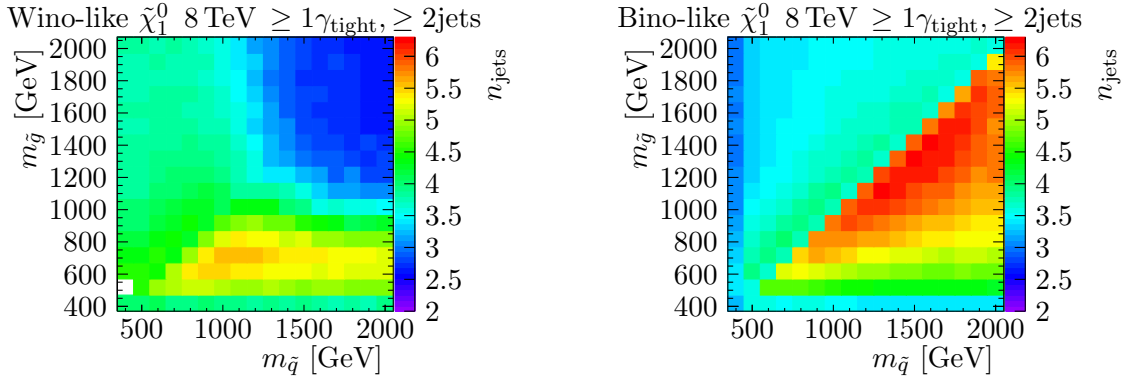


Figure 6.3: Mean number of jets in the signal region for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios as a function of squark and gluino mass.

In the bino-like $\tilde{\chi}_1^0$ mixing scenario, the type of initially produced supersymmetric particles is more important than in the wino-like $\tilde{\chi}_1^0$ mixing scenario. If the squark mass is larger than the gluino mass, the probability for initial gluino production is increased (Fig. 6.4a). Gluinos cannot decay directly into a neutralino, since they are color charged. They must first decay to a squark and a quark. If the gluino is heavier than the squark, squark production is more likely (Fig. 6.4b). Squarks can decay to a neutralino and a quark. Decay chains are therefore shorter, leading to less jets, but more energy is transferred to the $\tilde{\chi}_1^0$ and thus to the photon (Fig. 6.6) and to the gravitino (Fig. 6.5). Hence the acceptance is enhanced if the gluino mass is larger than the squark mass.



Figure 6.4: Production of neutralinos via gluinos (left) and squarks (right).

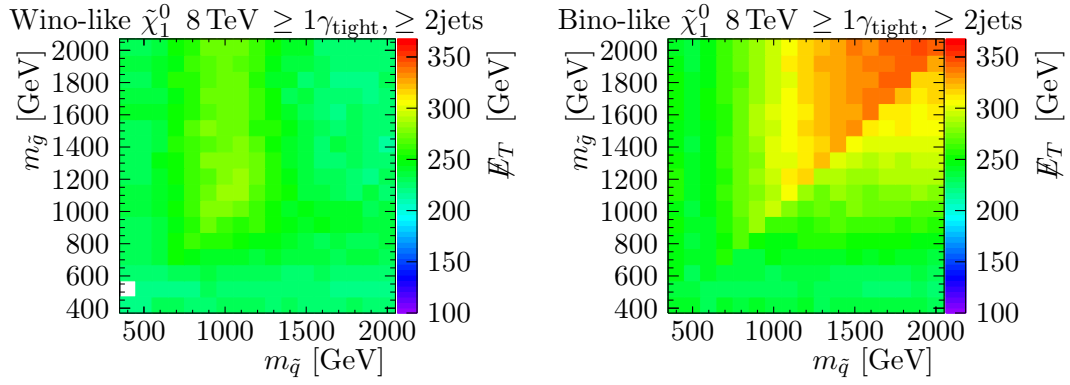


Figure 6.5: Mean $\cancel{E}_T$ in the signal region for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios as a function of squark and gluino mass.

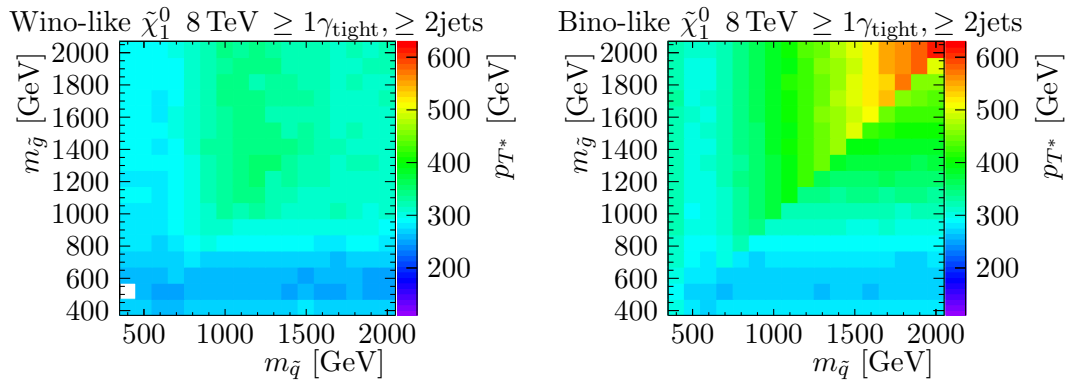


Figure 6.6: Mean p_{T^*} in the signal region for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios as a function of squark and gluino mass.

6.2 Signal Contamination in Control Regions

If a signal event is reconstructed with a γ_{tight} or a γ_{loose} and with $\cancel{E}_T < 100$ GeV, it is used to calculate the weights w_i for the multijet background estimation. The multijet background exceeds possible signal for events with $\cancel{E}_T < 100$ GeV by far. Most signal events are expected to be reconstructed with large values of $\cancel{E}_T$, so the influence to w_i is negligible.

There are two effects reducing the sensitivity if a signal event is reconstructed with $\cancel{E}_T \geq 100$ GeV but as a γ_{loose} or γ_{pixel} event and not as a γ_{tight} event: Firstly, the event is not reconstructed as a signal event, so the acceptance drops. Secondly, the event increases the background prediction, since it is weighted with $f_{e \rightarrow \gamma}$ or w_i . The background prediction originating from γ_{loose} signal events (as described in Section 5.1) is denoted as $b_{\text{signal}}^{\text{QCD}}$, the background prediction originating from γ_{pixel} signal events (as described in Section 5.2) as $b_{\text{signal}}^{e \rightarrow \gamma}$. The sum of these background predictions normalized to the number of signal events s in the signal region is called signal contamination and defined as

$$\frac{b_{\text{signal}}}{s} = \frac{b_{\text{signal}}^{\text{QCD}}}{s} + \frac{b_{\text{signal}}^{e \rightarrow \gamma}}{s}.$$

It reduces the sensitivity as will be shown in Section 7.2.

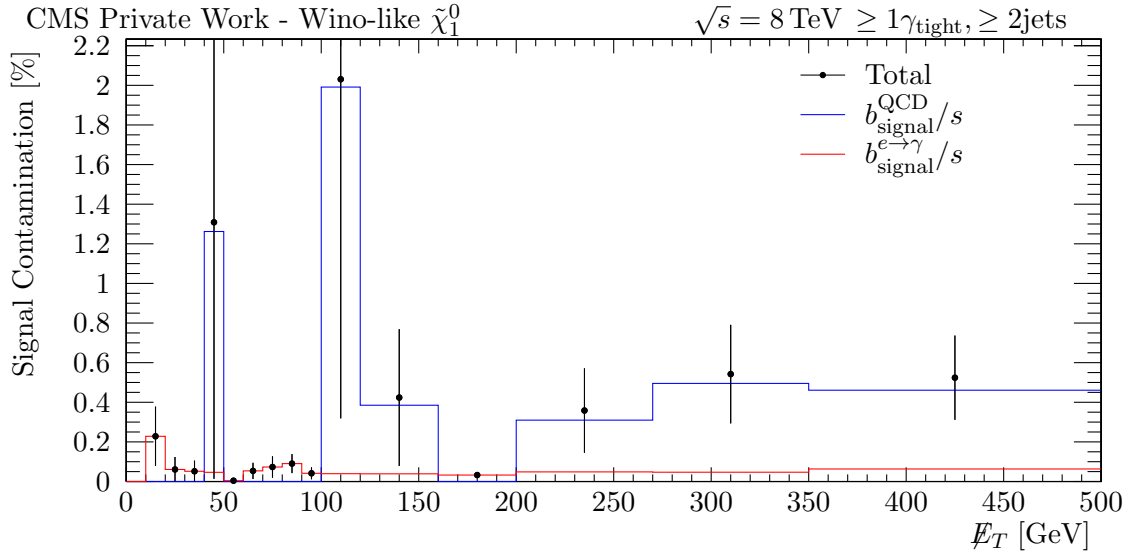


Figure 6.7: Signal contamination for a wino-like $\tilde{\chi}_1^0$ mixing scenario, with $m_{\tilde{q}} = 1000$ GeV and $m_{\tilde{g}} = 1220$ GeV. In addition, the signal contamination for both data-driven background estimation methods is plotted separately.

The signal contamination in the $\cancel{E}_T$ intervals used for the statistical interpretation is shown in Fig. 6.7 for a wino-like $\tilde{\chi}_1^0$ mixing scenario with $m_{\tilde{q}} = 1200$ GeV and $m_{\tilde{g}} = 1220$ GeV. Signal events with $\cancel{E}_T < 100$ GeV are negligible since the multijet background in this region is many orders of magnitudes larger.

There are few electrons expected in the signal leading to a small contribution of $b_{\text{signal}}^{e \rightarrow \gamma}/s$ to the signal contamination. It is about 0.1% in all bins. $b_{\text{signal}}^{\text{QCD}}/s$ is the dominant contri-

bution to the signal contamination and is about 0.5%, but with large uncertainties. No trend for the shape can be observed for different squark or gluino mass points.

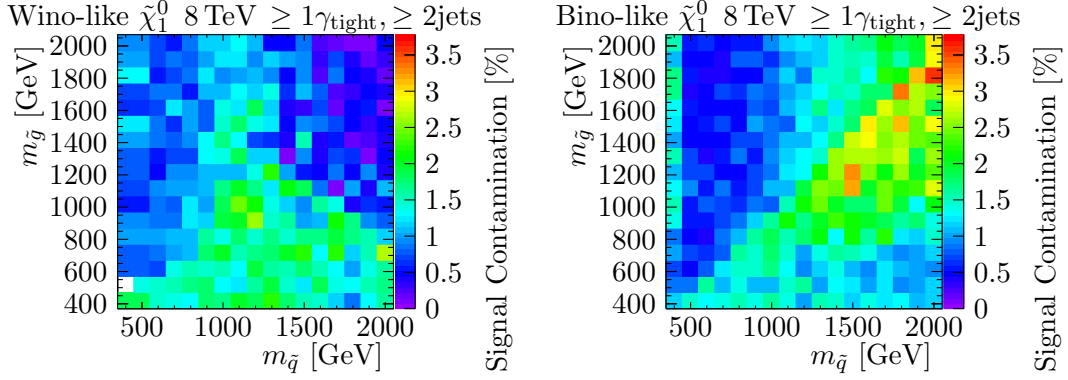


Figure 6.8: Signal contamination for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios as a function of squark and gluino mass.

The total signal contamination for different squark and gluino masses is shown in Fig. 6.8. For both the wino- and the bino-like $\tilde{\chi}_1^0$ mixing scenario, the signal contamination increases with the number of jets (see Fig. 6.3). Some of these jets are identified as γ_{loose} , which leads to an enhanced prediction of the background. The signal contamination is of the order of a few percent, which is more than a magnitude better than in previous analyses [4]. This is the main improvement coming along with the improved photon identification: Instead of computing a detector-based isolation cone energy, a particle-based isolation cone energy for photon candidates is computed. Since jets consists of several particles, but signal photons are isolated, the discrimination between jets and photons is more effective. Photons in the control region defined by γ_{loose} can be rejected by requiring minimal values for the isolation cone energy.

7 Results

All background estimation methods and signal scenarios have been discussed. Now the developed methods are combined to search for physics beyond the SM. The event yields in data are therefore compared to the total background prediction and are then interpreted in the GMSB model.

7.1 Event Yields and Background Predictions

Firstly, all background estimation methods are tested on simulation only. Secondly, the analysis is performed using already published data corresponding to 4 fb^{-1} . After this, data corresponding to 19.8 fb^{-1} and simulation is used to predict the background.

7.1.1 Simulation only

To test the interference of all background estimation methods, all methods are simultaneously applied to a mix of simulated events in Fig. 7.1. The simulation includes multijet events with and without prompt photons, inclusive $t\bar{t}$ events, $\gamma t\bar{t}$ events, W boson events, γW events and γZ events. The multijet simulation was used in Section 5.1 to test the multijet background estimation method, and the W boson and the $t\bar{t}$ simulation was used in Section 5.2 to test the background estimation method for electrons being misidentified as photons. The overlap between the $\gamma t\bar{t}$ and $t\bar{t}$ sample, and the overlap between the γW and the W boson sample was found to be negligible in Section 5.3 and is not subtracted.

This mixture of simulated events is treated as data. The weights w_i are calculated intervals of H_T and p_{T^*} with these simulated events and applied to all γ_{loose} events. In the following plots, this prediction is labeled as “Multijet”. The number of γ_{pixel} events in the same mix of simulation is used to predict the background labeled with $e \rightarrow \gamma$ using the fake rate $f_{e \rightarrow \gamma}$ estimated with simulation. For prompt photon production in association with $t\bar{t}$, a W or a Z boson, plain simulation (γW , $\gamma t\bar{t}$ and γZ) is used. The sum of these backgrounds is compared to the signal selection without a $\cancel{E}_T$ requirement.

Good agreement between the background prediction and the direct simulation is observed. In Section 5, the background estimation methods are shown to work for separate simulated processes. Here, the performance of the interference of the background estimation methods is shown. γ_{loose} events in other processes than multijet events, for example γ_{loose} events in W or $t\bar{t}$ simulation, do not influence the performance of the methods.

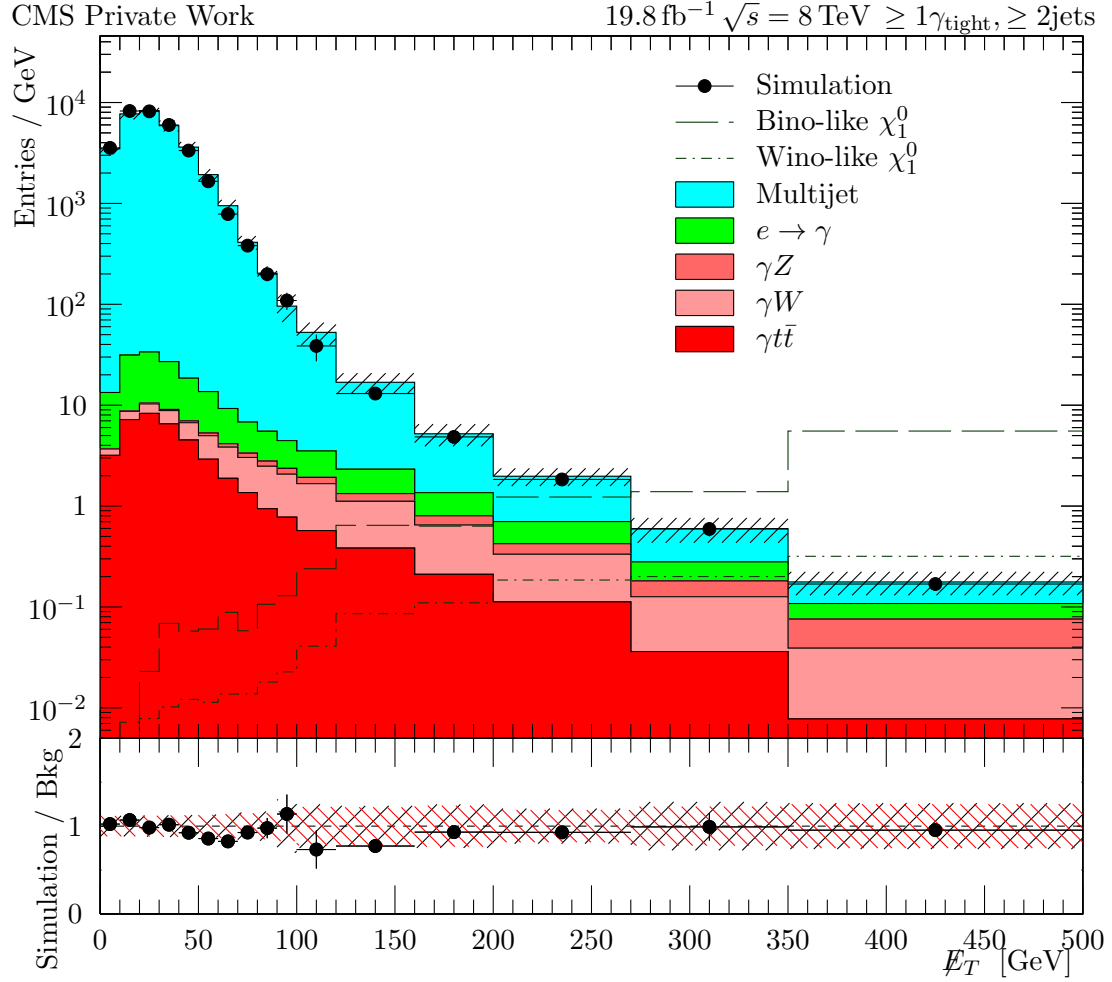


Figure 7.1: Stacked background prediction extracted from simulated events compared to simulation in intervals of E_T . The distribution for wino-like and bino-like $\tilde{\chi}_1^0$ mixing scenarios with $m_{\tilde{q}} = 1300$ GeV and $m_{\tilde{q}} = 1320$ GeV are drawn in addition. In this and in all following E_T distributions, the rightmost bin contains all events with $E_T \geq 350$ GeV. The ratio plot below shows the total background uncertainty as hatched black area and the fully correlated systematical uncertainty only as hatched red area.

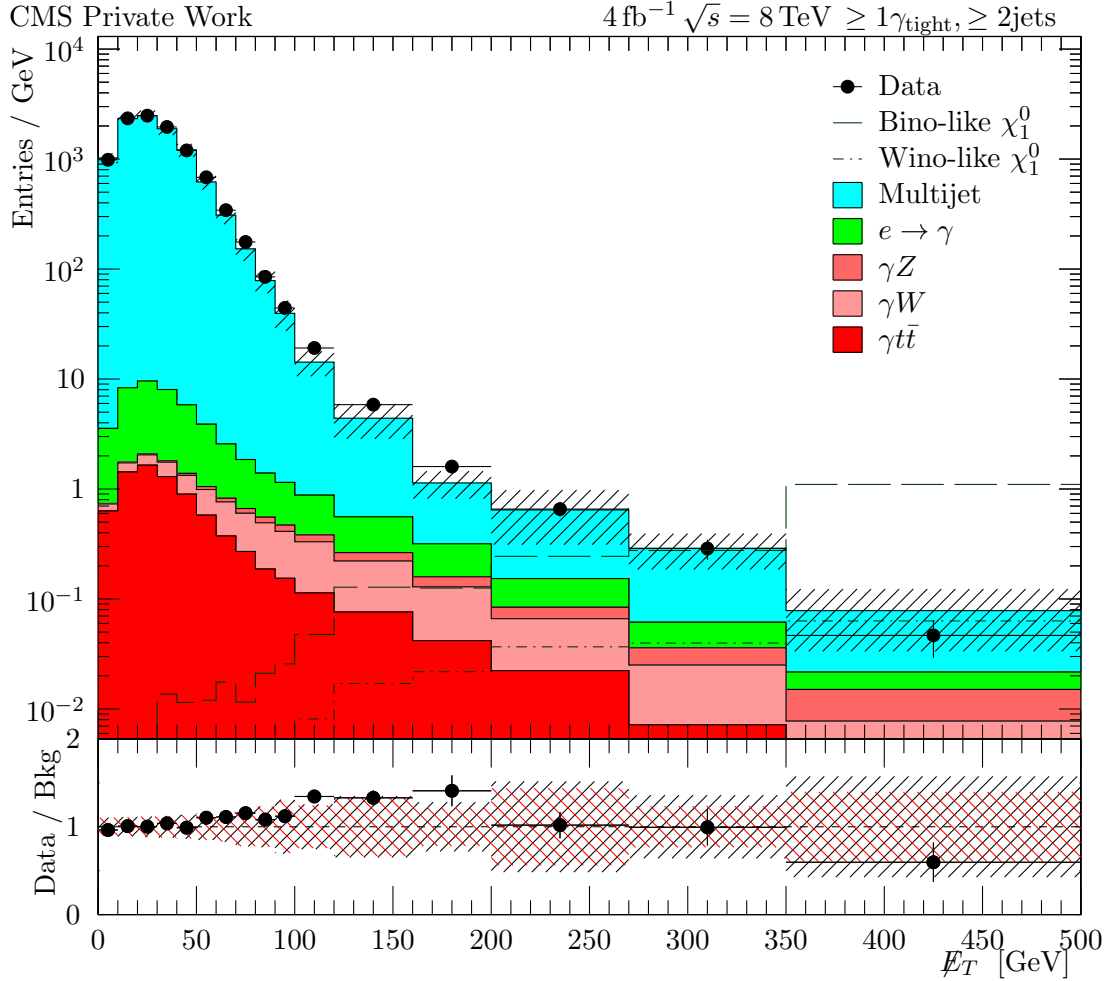
7.1.2 Data corresponding to 4 fb^{-1} 

Figure 7.2: Stacked background prediction extracted from data (Multijet and $e \rightarrow \gamma$) and simulation (γZ , γW , $\gamma t\bar{t}$) compared to data corresponding to 4 fb^{-1} . The distribution for wino-like and bino-like $\tilde{\chi}_1^0$ mixing scenarios with $m_{\tilde{q}} = 1300 \text{ GeV}$ and $m_{\tilde{g}} = 1320 \text{ GeV}$ are drawn in addition. The ratio plot below shows the total background uncertainty as hatched black area and the fully correlated systematical uncertainty only as hatched red area.

From the full data at $\sqrt{s} = 8 \text{ TeV}$ and a corresponding integrated luminosity of 19.8 fb^{-1} , the first runs of data were analysed by a similar analysis, which is published [4]. The analysis described in this thesis is now applied to these published runs. The integrated luminosity for these runs was measured to be 4.04 fb^{-1} with the prompt reconstruction. With the new luminosity measurement technique described in Section 4.1, the new reconstruction, and the new good-run list, the same run range corresponds to 3.93 fb^{-1} , which is well within the uncertainties.

The data yields and the background estimation in the E_T intervals used in the statistical interpretation is shown in Fig. 7.2, using data corresponding to 3.93 fb^{-1} only. The multijet

background and the background of real electrons faking photons is extracted from data, while the background of prompt photon radiation in association with $t\bar{t}$, W or Z bosons is simulated and scaled to the luminosity of 3.93 fb^{-1} .

The observed data is in agreement with the estimated background, and no excess can be observed. Since the object definitions and the kinematic requirements changed in comparison to the published analysis [4], the $\cancel{E}_T$ distributions are not compatible. The largest uncertainty is the multijet background prediction, which was optimized to yield acceptable uncertainties for data corresponding to 19.8 fb^{-1} .

In Fig. 7.2 the $\cancel{E}_T$ distribution for a wino-like and a bino-like $\tilde{\chi}_1^0$ mixing scenario is drawn in addition. Since the branching fraction to photons is larger for bino-like $\tilde{\chi}_1^0$ than for wino-like $\tilde{\chi}_1^0$, the signal yields for the bino-like $\tilde{\chi}_1^0$ mixing scenario exceeds the signal yields for the wino-like $\tilde{\chi}_1^0$ mixing scenario. The bino-like $\tilde{\chi}_1^0$ mixing scenario shown here is excluded by this and the published analysis [4], while the wino-like $\tilde{\chi}_1^0$ mixing scenario is not.

7.1.3 Background prediction for data corresponding to 19.8 fb^{-1}

The data-driven background estimation methods applied on all data recorded at $\sqrt{s} = 8 \text{ TeV}$ are shown in Fig. 7.3. Until now, the signal region has not been looked at in order not to be influenced by possible signal or deviation when developing the analysis. After the analysis has been presented to the SUSY group of CMS, and all upcoming questions are answered, we will proceed to unblind the signal region.

Since the event yields in each interval are expected to be Poisson distributed, the relative statistical uncertainty of the data-driven background methods decreases with respect to the relative statistical uncertainties for the already published data. As the systematic uncertainty is dominated by σ_w , the relative systematic uncertainty decreases as well. The relative uncertainties for the simulation are unaffected by the increase of integrated luminosity. The ratio of the contributions of the SM background is the same within the uncertainties.

The background prediction of prompt photon production in association with $t\bar{t}$, W or Z bosons is the same as the prediction in Fig. 7.1. The background from misidentified electrons estimated in simulation (Fig. 7.1) agrees with the background prediction from misidentified electrons in data (Fig. 7.3), especially for large values of $\cancel{E}_T$. The estimation of the multijet background in data (Fig. 7.3) exceeds the multijet background estimation in simulation (Fig. 7.1) by a factor of 1.8 for the $\cancel{E}_T$ interval with lowest $\cancel{E}_T$, and by a factor of 3.6 for events with $\cancel{E}_T \geq 350 \text{ GeV}$. As discussed in Section 5, these derivations are due to the large uncertainties of multijet event simulation with high values of $\cancel{E}_T$. The use of a data-driven background estimation, as described in this thesis, is therefore crucial.

In Table 7.1, the predictions and uncertainties are listed. Multijet events with and without prompt photons are the main background for this analysis. The smallest uncertainty for this background is the one arising from unpopulated H_T, p_{T^*} phase space for $\cancel{E}_T < 100 \text{ GeV}$, which is about 2%. The most dominant uncertainty is σ_w . Since the latter two effects are fully correlated within the $\cancel{E}_T$ intervals, the uncertainties are added and will be referenced as systematic uncertainty. Nevertheless, this uncertainty is of statistical origin. The statistical uncertainty is uncorrelated among the $\cancel{E}_T$ intervals. In the interval for large values of $\cancel{E}_T$, the statistic uncertainty is of the order of the systematic uncertainty.

The second largest background is the one arising from electrons being reconstructed as

Table 7.1: Predictions for 19.8fb^{-1} of the $\sqrt{s} = 8\text{TeV}$ data for the first and the last $\cancel{E}_T$ interval in the signal region. The uncertainties for multijet with or without prompt photon events are separated in statistical uncertainty ($\sigma_{\text{stat.}}$), uncertainty propagated from events with $\cancel{E}_T < 100\text{GeV}$ (σ_w) and uncertainty taking into account unpopulated phase space of H_T, p_{T^*} for $\cancel{E}_T < 100\text{GeV}$. The uncertainty for the background of misidentified electrons is separated in statistical uncertainty of the control sample with γ_{pixel} events, the statistical and the systematical uncertainty of the fake rate measurement, and the additional uncertainty taking into account the difference of $f_{e \rightarrow \gamma}$ for different processes. For photon radiation, the statistical and the systematical scaling uncertainty is stated.

	$100 \leq \cancel{E}_T [\text{GeV}] < 120$	$350 \leq \cancel{E}_T [\text{GeV}]$
Multijet	$1521 \pm 61 \pm 266 \pm 20$	$45 \pm 13 \pm 14 \pm 1$
$e \rightarrow \gamma$	$44.52 \pm 0.81 \pm 1.50 \pm 2.41 \pm 22.26$	$4.91 \pm 0.27 \pm 0.17 \pm 0.27 \pm 2.46$
γW	$21.92 \pm 0.53 \pm 10.96$	$4.70 \pm 0.25 \pm 2.35$
$t\bar{t}$	$11.43 \pm 0.48 \pm 5.72$	$1.17 \pm 0.16 \pm 0.58$
γZ	$5.69 \pm 0.37 \pm 3.99$	$5.51 \pm 0.52 \pm 3.85$
Sum	$1604 \pm 61 \pm 268$	$62 \pm 13 \pm 15$

photons. The statistical and systematical uncertainties of the fake rate measurement are small compared to the additional uncertainty taking into account different processes.

The bino-like $\tilde{\chi}_1^0$ mixing scenario shown here is expected to be excluded by this analysis, while the wino-like $\tilde{\chi}_1^0$ mixing scenario is not.

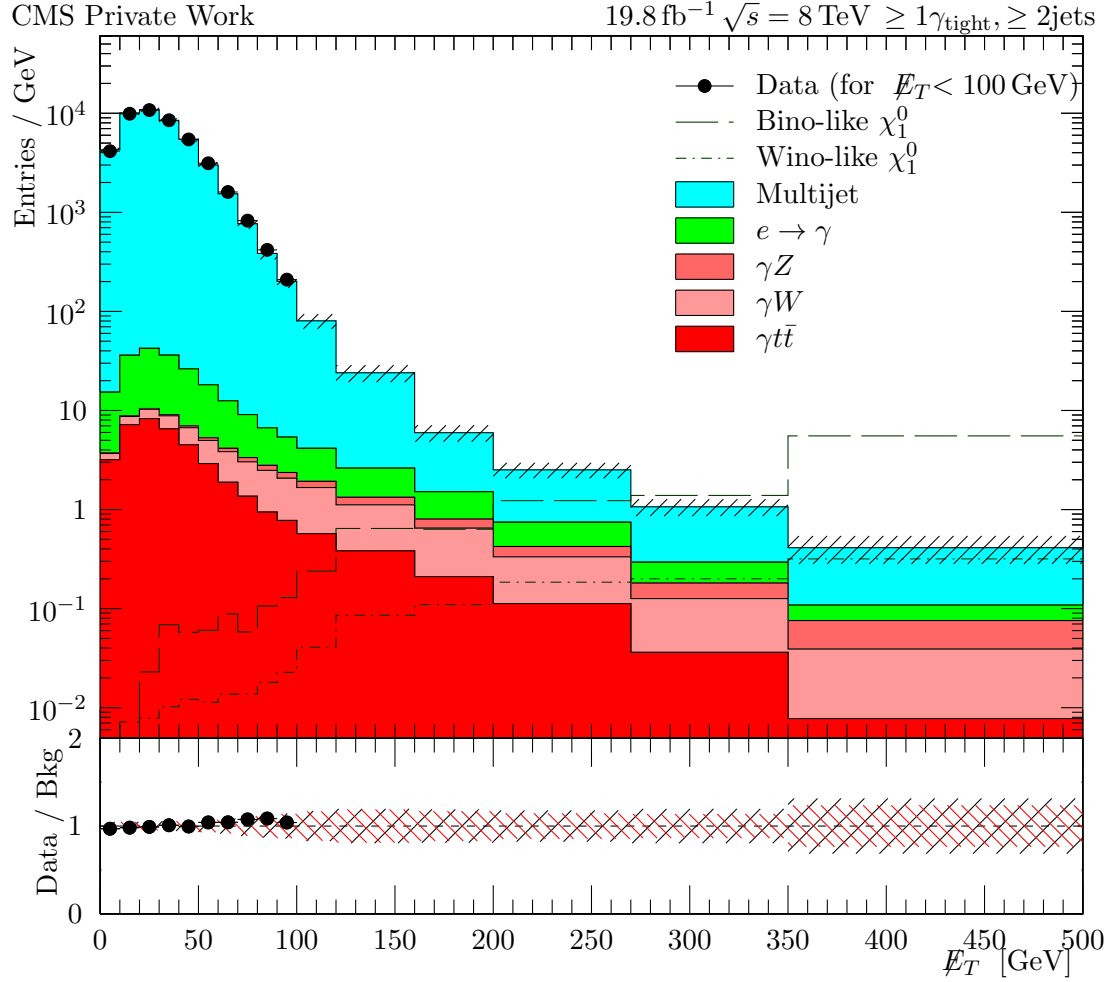


Figure 7.3: Stacked background prediction extracted from data (Multijet and $e \rightarrow \gamma$) and simulation (γZ , γW , $\gamma t\bar{t}$) compared to data corresponding to 19.8 fb⁻¹. Since the analysis is not yet approved by the CMS collaboration at the time of writing, the event yields for the signal region are not shown. The distribution for wino-like and bino-like $\tilde{\chi}_1^0$ mixing scenarios with $m_{\tilde{q}} = 1300$ GeV and $m_{\tilde{g}} = 1320$ GeV are drawn in addition. The ratio plot below shows the total background uncertainty as hatched black area and the fully correlated systematical uncertainty only as hatched red area.

7.2 Limit Calculation

In order to compare the analysis to the previously published results, observed and expected limits are computed based upon data corresponding to the published run range. To evaluate the sensitivity for the full data at $\sqrt{s} = 8$ TeV, expected limits are calculated. This is done using the modified frequentists CL_s [68] method, which is briefly described in the following.

The method follows the combination of the searches for the Higgs boson by ATLAS and CMS [69], is implemented using RooStats [70] libraries, and was used for the previous publication as well [4].

Different channels, in this analysis different intervals of $\cancel{E}_T$, can be combined easily. In each channel, a likelihood for the signal+background hypothesis and the background only hypothesis is computed. A signal can be excluded at a certain confidence level, if the probability that an observed number of events fits to the signal+background hypothesis is small.

To calculate the limits, uncertainties are broken down into uncorrelated, fully positively correlated or fully negatively correlated uncertainties. They are handled by nuisance parameters θ . The signal yields s and the background yields b are both functions of θ . The true value of θ , $\tilde{\theta}$ is unknown, but the systematic uncertainties may be described as a probability density function $p(\tilde{\theta}|\theta)$. The signal strength modifier μ is the scale for the signal cross. The likelihood is constructed as

$$\mathcal{L}(n|\mu, \theta) = \prod_{i=1}^{N_{\cancel{E}_T \text{ intervals}}} \frac{(\mu s_i + b_i)^{n_i}}{n_i!} e^{-(\mu s_i + b_i)} \cdot p(\tilde{\theta}|\theta), \quad (7.1)$$

where s_i is the signal yield, b_i the background yield and n_i is the (pseudo) data yield in each channel. The Poisson distributions for each channel i are multiplied. By transforming $\mathcal{L}$ to the test statistics

$$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(n|\mu, \hat{\theta}_\mu)}{\mathcal{L}(n|\hat{\mu}, \hat{\theta})}, \text{ with } 0 \leq \hat{\mu} \leq \mu,$$

the product of exponential terms is transformed to a sum which decreases computing time. In addition this distribution can be approximated by the χ^2 distribution for large values of n . $\hat{\mu}$ and $\hat{\theta}$ are the parameters corresponding to the global maximum of the likelihood. $\hat{\theta}_\mu$ maximizes the likelihood for a given signal strength. Since the studied SUSY models do not interfere destructively with the SM, one-sided confidence intervals are calculated by requiring $\hat{\mu} \leq \mu$. For a given signal strength modifier μ , $\tilde{q}_\mu^{\text{obs}}$ is calculated and $\hat{\theta}_0^{\text{obs}}$ and $\hat{\theta}_\mu^{\text{obs}}$ are the values which maximize the likelihood for the background only $\mu = 0$ and the signal+background hypothesis. Toy Monte Carlo simulation is used to construct the probability density functions $f(\tilde{q}_\mu|\mu, \hat{\theta}_\mu^{\text{obs}}, \text{signal+background})$ and $f(\tilde{q}_\mu|\mu, \hat{\theta}_0^{\text{obs}}, \text{background})$. The values

$$CL_{s+b}(\mu) = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} | \text{signal+background}) \text{ and} \\ CL_b(\mu) = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} | \text{background})$$

are the probabilities to obtain a larger test statistics $\tilde{q}_\mu$ than the observed one for the signal+background and the background only hypothesis, respectively. Signal points are

excluded if the probability of the signal+background hypothesis is small compared to the background only hypothesis probability. Usually 95% confidence upper limits are stated:

$$CL_s(\mu) = \frac{CL_{s+b}}{CL_b} \leq (1 - 95\%) = 0.05.$$

For each signal, this inequality is solved for μ . If for a certain signal $\mu \leq 1$, then this signal is said to be excluded at 95% confidence level.

To calculate the expected limit and the 1σ and 2σ bands, pseudo data is generated on the basis of the background expectation. Since the distribution of the test statistics does not depend on μ , only one set of test statistics is generated to save CPU time.

Signal contamination is subtracted from the signal yields in the signal+background hypothesis. In Eq. 7.1, s_i is substituted by $s_i(1 - b_{\text{signal},i}/s_i)$, so the discrimination power between background only and signal+background hypothesis decreases.

7.3 Systematic Uncertainties for Signal Events

Since the signal events used to calculate exclusion limits are simulated, but possible signal in data is not simulated but measured, differences in data and simulation have to be taken into account.

Signal events are scaled by the trigger efficiency [65] of

$$0.981 \pm 0.003.$$

The luminosity is measured with an uncertainty of 2.5%(stat.) and 0.5%(syst.) [40], and as the signal events are weighted to match the integrated luminosity, the uncertainties are propagated to the signal yields. To correct for different efficiencies in data and simulation, the simulated signal samples are weighted by the ratio of photon efficiency in data to photon efficiency in simulation. The ratio excluding the pixel seed veto is measured in Drell-Yan processes [71] to

$$0.9966 \pm 0.0072(\text{stat.}) \pm 0.0195(\text{syst.}).$$

To measure the effect of the pixel seed veto on the efficiency, the decay chain $Z \rightarrow \mu\mu \rightarrow \mu\mu\gamma$ is used. Photons can be selected with a high purity if requiring the invariant mass of $\mu\mu\gamma$ to be close to the Z-boson mass. The scale factor describing differences for the pixel seed veto in simulation and data is measured [72] to

$$0.990 \pm 0.075(\text{stat.}) \pm 0.007(\text{syst.}).$$

The NLO cross section uncertainties are of the order of a few percent in the region of the limit and are shown in Fig. 7.4.

The parton density function used for simulating signal events is the same as for simulating SM processes. The uncertainties due to the parton density function can be seen in Fig. 7.5 for signal simulation.

All of these uncertainties are neglected for simulated SM processes. The total uncertainty for simulated SM processes assigned in Section 5.3 should cover all of the uncertainties discussed in this Section.

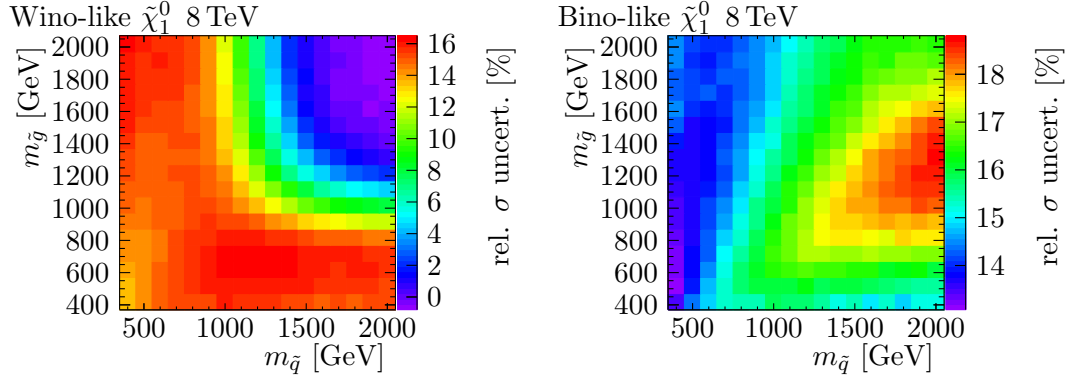


Figure 7.4: Relative cross section uncertainty for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios as a function of squark and gluino mass [73–76].

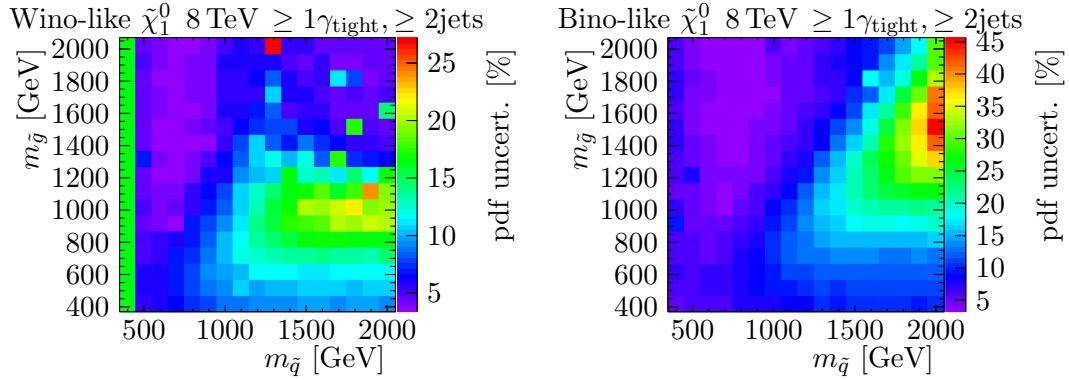


Figure 7.5: Added cross section and signal acceptance uncertainty due to the parton distribution function (pdf) for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios as a function of squark and gluino mass [77].

7.4 Interpretation of the Results

For each signal point, the signal strength modifier μ is found, so that the observation is just in agreement with the background only hypothesis at 95% confidence level. Signal points with $\mu \leq 1$ can be excluded. The contour line with $\mu = 1$ is called limit and marks the excluded region.

7.4.1 Interpretation for data corresponding to 4 fb^{-1}

To compare this analysis' sensitivity to the published analysis, the expected and observed limits for data corresponding to an integrated luminosity of 4 fb^{-1} are shown in Fig. 7.6. In addition, the expected limit of the previous analysis [4] is drawn. For both bino- and wino-like $\tilde{\chi}_1^0$ mixing scenarios, the expected limits do not exceed the previous limits. The reason is that the relative uncertainties are increased by approximately a factor of 1.8. In addition, the signal acceptance dropped due to harder H_T and p_{T^*} requirements. Furthermore, the photon identification, the electron and muon veto the selection of good luminosity sections and the reconstruction version was changed. Which of these effects decreased the exclusion limit is not known at the time of writing, but will be studied

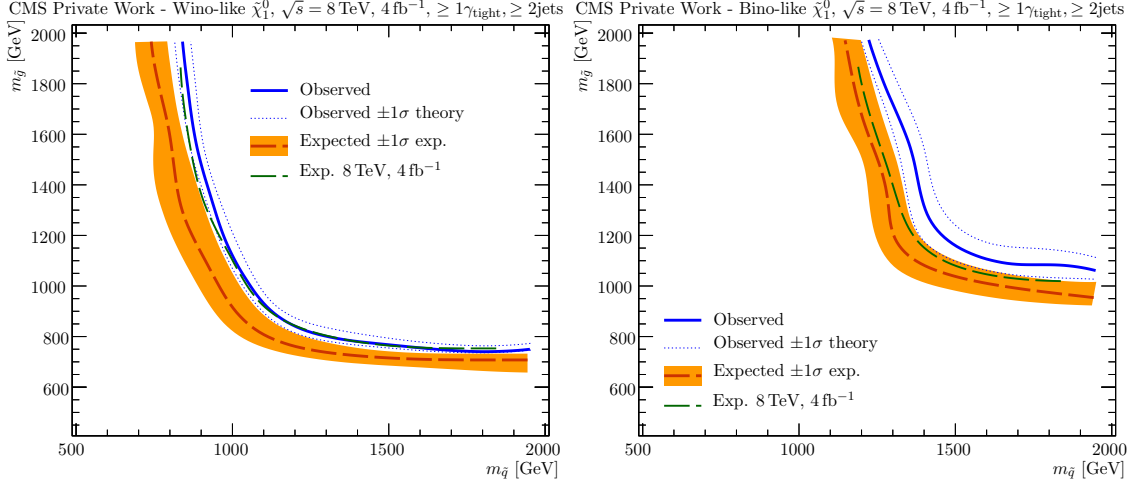


Figure 7.6: Expected and observed limit contours for data corresponding to 4 fb^{-1} is shown for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios. In addition, the expected limit contour of the previous publication [4] is shown. The low $m_{\tilde{g}}$ low $m_{\tilde{q}}$ phase space is excluded.

soon to improve the analysis.

The observed limit for both scenarios exceeds the expected limit, since the background prediction exceeds the signal yields in the most sensitive $\cancel{E}_T$ interval. The observed limit is in agreement with the expected limit.

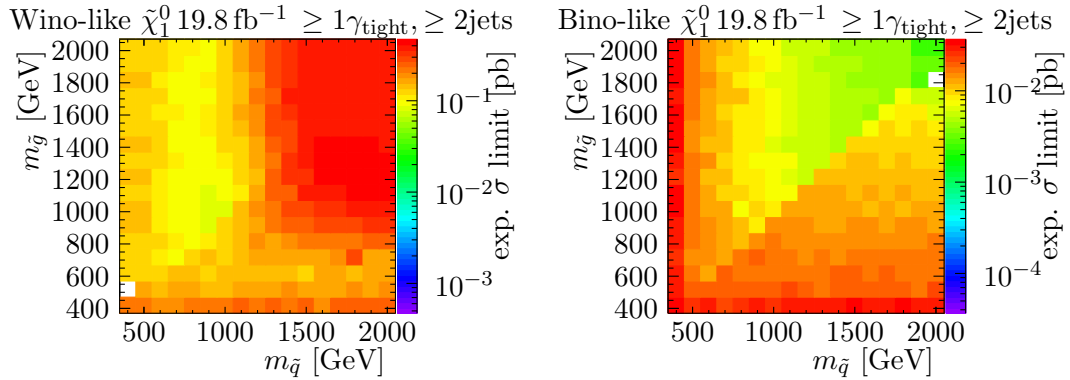


Figure 7.7: Expected cross section limits for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios as a function of squark and gluino mass.

7.4.2 Interpretation for data corresponding to 19.8 fb^{-1}

To obtain cross section limits, the signal strength modifier is multiplied by the cross section (Fig. 4.2) for each signal point. The resulting expected cross section limits can be seen in Fig. 7.7 for data corresponding to 19.8 fb^{-1} . The features are similar to the ones in the

acceptance plots (Fig 6.1). Signal points with a large acceptance can be excluded with smaller cross sections.

The smaller acceptance for wino-like $\tilde{\chi}_1^0$ mixing scenario compared to bino-like $\tilde{\chi}_1^0$ mixing scenario discussed in Section 6, leads to a larger expected cross section limit for the wino-like $\tilde{\chi}_1^0$ mixing scenario.

The expected limit contour for data corresponding to 19.8 fb^{-1} is shown in Fig. 7.8. In addition, the observed limit of the previous publication [4] is shown. The expected limits for the analysis described in this thesis are estimated to exceed the previous limits for the bino-like $\tilde{\chi}_1^0$ mixing scenario by approximately 50 GeV. For the wino-like $\tilde{\chi}_1^0$ mixing scenario, there is no improvement. As discussed before, studies are ongoing trying to improve the analysis' sensitivity for physics beyond the SM.

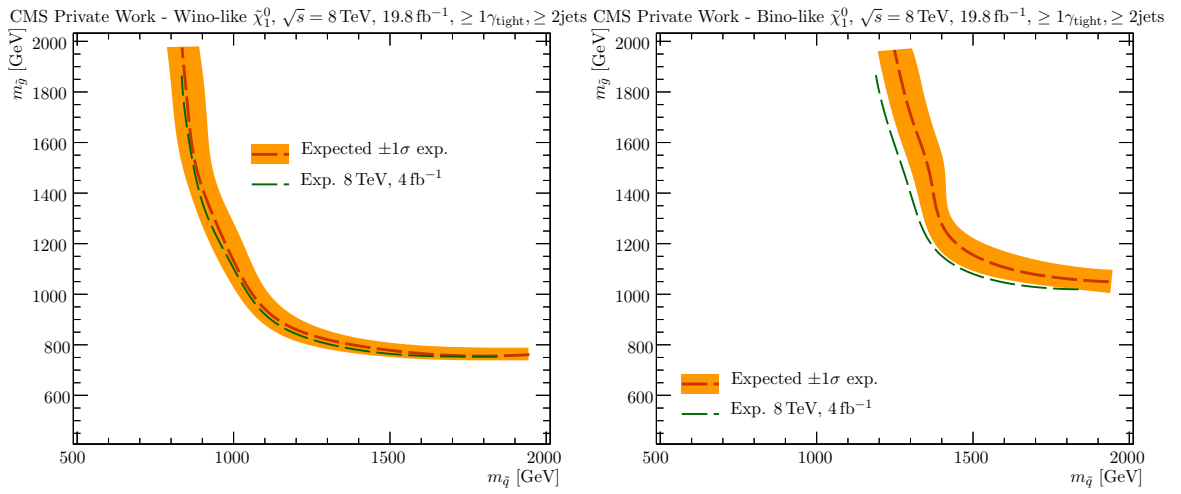


Figure 7.8: Expected and observed limit contours for data corresponding to 19.8 fb^{-1} is shown for wino-like (left) and bino-like (right) $\tilde{\chi}_1^0$ mixing scenarios. In addition, the expected limit contour of the previous publication [4] is shown. The low $m_{\tilde{q}}$ low $m_{\tilde{g}}$ phase space is excluded.

Even if this thesis focuses on supersymmetric theories, this analysis is sensitive to similar realizations of physics beyond the standard model in nature with increased photon and $\cancel{E}_T$ production in association with jets.

8 Conclusion

A search for Supersymmetry in events with at least one photon, two jets, hadronic activity, and missing transverse energy was performed. The GMSB model predicts events with such final states. In this model, neutralinos are produced via squarks or gluinos, and depending on their mixture, they decay to photons and gravitinos. Gravitinos do not interact with the detector and lead to missing transverse energy, while the gluinos and squarks radiate jets, which lead to hadronic activity. Data corresponding to 3.93 fb^{-1} and 19.8 fb^{-1} of proton-proton collisions were used, recorded by CMS at a center-of-mass energy of 8 TeV.

97% of the Standard Model backgrounds in this search were estimated from data. Photon production in association with jets, and jets being reconstructed as photons were estimated by extracting the ratio of tightly isolated photons to loosely isolated photons for small values of $\cancel{E}_T$ and applying this ratio to loosely isolated photons with large values of $\cancel{E}_T$. The probability of electrons faking photons was measured in data in a control region. This probability is used to predict the number of electrons being reconstructed as photons in the signal region. Additional photon radiation was estimated from simulation. All methods were adjusted to a new photon definition. The methods' performance and validity was tested in simulated collisions.

Two signal scenarios were studied and a reduction of additional background estimation due to signal events by a factor of 10 was archived in comparison to the previously published analysis.

The methods were applied to the already published data runs and the results are in agreement with the former analyses. All background estimation methods were also applied to the full data range, but the signal region is still kept blind until official approval by the CMS collaboration. The limits are expected to exceed the previous limits by 25 to 100 GeV, if no signal is present in the data.

After comparing the yields in the signal region to the background estimation, this search will find or constrain the parameter space for gauge mediated SUSY breaking models, in which the lightest neutralino decays into a photon and a gravitino.

A Used Datasets

For all recorded events, the 22Jan2013ReReco version is used. The valid runs are documented in `Cert_190456-208686_8TeV_22Jan2013ReReco_Collisions12_JSON.txt`. Several filters are applied to filter noise. Table A.1 shows how many events were rejected in the preselection due to filters.

Table A.1: Filters applied to exclude noise. The first row is not a filter, but are the events which pass all filters. Filtered events are normalized to this number.

Filter name	filtered events	normalized events [%]
Passing all filters	1106448	100.000
EcalDeadCellBE	19664	1.777
CSCBeamHalo	5025	0.454
EcalLaserCorr	3433	0.310
HcalNoise	2648	0.239
EcalDeadCellTP	1168	0.106
GreedyMuon	216	0.020
InconsistentMuon	132	0.012
ManyStripClus53X	43	0.004
TooManyStripClus53X	42	0.004
TrackingFailure	2	0.000
EEBadSC	0	0.000
HcalLaserOccupancy	0	0.000
HcalLaserEventList	0	0.000
HcalLaserRECOUserStep	0	0.000
LogErrorTooManyClusters	0	0.000
LogErrorTooManyTripletsPairs	0	0.000
LogErrorTooManySeeds	0	0.000
EERingOffFire	0	0.000

Table A.2: Name and path in the CMS bookkeeping system DBS [78] for simulated datasets used for this analysis. For the generator H_T^{gen} binned samples an influence of lower H_T^{gen} bins is negligible in this analysis.

Sample name	CMS database path
Multijet+ γ	/GJets_HT-200To400_8TeV-madgraph_v2/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
	/GJets_HT-400ToInf_8TeV-madgraph_v3/ Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
Multijet	/QCD_HT-250To500_TuneZ2star_8TeV-madgraph-pythia6/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
	/QCD_HT-500To1000_TuneZ2star_8TeV-madgraph-pythia6/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
	/QCD_HT-1000ToInf_TuneZ2star_8TeV-madgraph-pythia6/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
W	/WJetsToLNu_HT-250To300_8TeV-madgraph_v2/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
	/WJetsToLNu_HT-300To400_8TeV-madgraph_v2/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
	/WJetsToLNu_HT-400ToInf_8TeV-madgraph_v2/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
$t\bar{t}$	/TTJets_MassiveBinDECAY_TuneZ2star_8TeV-madgraph-tauola/ Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
Z	/ZJetsToNuNu_200_HT_400_TuneZ2Star_8TeV-madgraph_(ext)/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
	/ZJetsToNuNu_400_HT_inf_TuneZ2Star_8TeV-madgraph_(ext)/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
γW	/WGToLNuG_PtG-50-130_8TeV-madgraph/ Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
	/WGToLNuG_PtG-130_8TeV-madgraph-pythia6-tauola/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
$\gamma t\bar{t}$	/TTGJets_8TeV-madgraph/ Summer12_DR53X-PU_S10_START53_V19-v1/AODSIM
γZ	/ZG_Inclusive_8TeV-madgraph_v2/ Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM

B Matching Reconstructed Objects to Generated Particles

The particle's type and four-momentum is saved for simulated events, as well as the simulated energy deposits in the calorimeters and the simulated hits in tracker. To match the energy deposits to the information of the generator, the four-momentum extracted by the simulated detector information is compared to the generated four-momentum.

For this analysis, a match to generated photons is important. For each photon candidate, the $\eta\phi$ -distance and normalized p_T difference to all generated photons in each event is shown in Fig. B.1 to Fig. B.3 for various simulated processes. The z -axis symbolizes number of generated photons for all events.

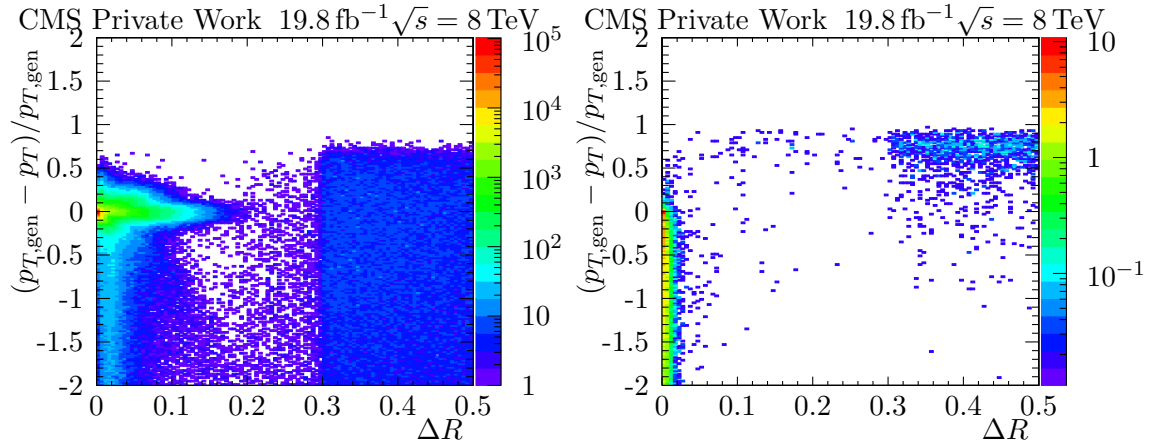


Figure B.1: $\eta\phi$ -distance and normalized p_T difference between photon candidates and generated photons for events with Z bosons. Photons are generated in hadronization simulation (left and right) and in the simulation of the hard scattering (left).

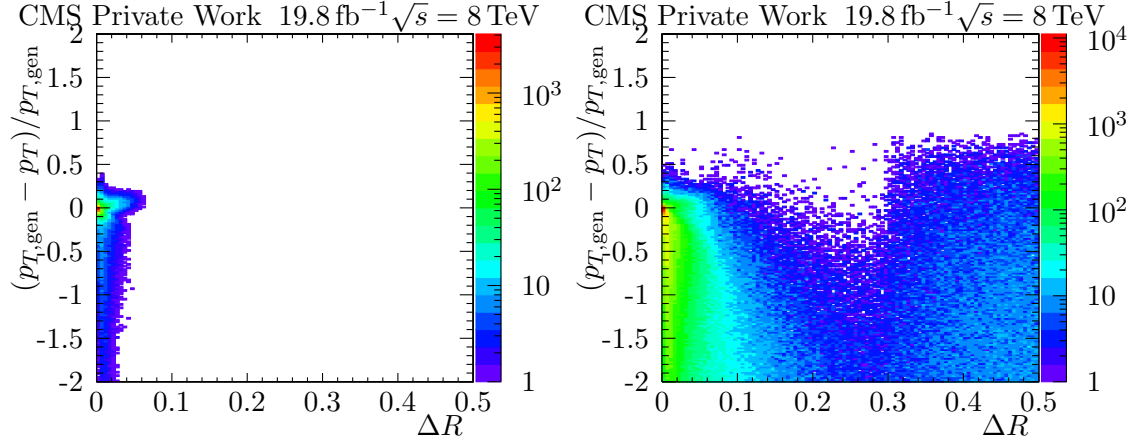


Figure B.2: $\eta\phi$ -distance and normalized p_T difference between photon candidates and generated photons for $t\bar{t}$ events. Photons are generated in hadronization simulation (left and right) and in the simulation of the hard scattering (left).

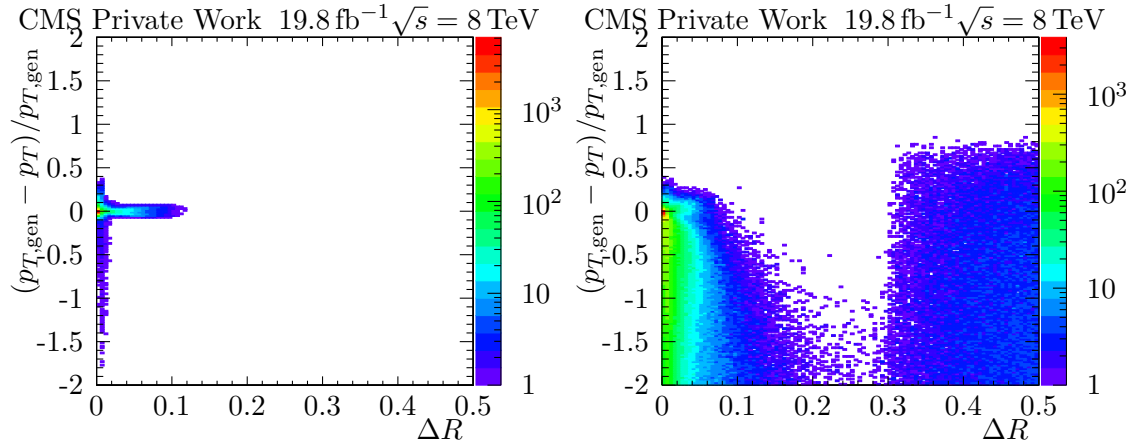


Figure B.3: $\eta\phi$ -distance and normalized p_T difference between photon candidates and generated photons for events with W bosons. Photons are generated in hadronization simulation (left and right) and in the simulation of the hard scattering (left).

C Crystal Ball function

The crystal ball function is a probability density function used to model a lossy Gaussian resonance. It is a composite function of an exponential function and a Gauss distribution:

$$f(x|\bar{x}, \sigma, \alpha, n) = \begin{cases} A_1 \cdot \left(B - \frac{x-\bar{x}}{\sigma}\right)^{-n} & \text{for } \frac{x-\bar{x}}{\sigma} < -\alpha \\ A_2 \cdot \exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right) & \text{else} \end{cases}$$

The parameters A_1 , A_2 , and B are determined by requiring f to be continuous, continuous differentiable and normalized to 1. $\bar{x}$ is the mean of the Gaussian, σ its' width, and n describes the slope of the exponential part of the function. By the use of α , the abscissa $\bar{x} - \alpha\sigma$, where the functions merge, is set.

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Erklärung

Ich versichere, dass ich die Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie Zitate kenntlich gemacht habe.

Aachen, den 09.03.2014

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