

Search for gauge-mediated supersymmetry in events with photons and a Z boson at CMS

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The understanding of the world around us is one of the main reasons for science. Driven by the urge for knowledge and striving to combine all observed phenomena in a unified description gave rise to more and more successful and comprehensive models in all fields of physics.

The state-of-the-art understanding in particles physics is characterized by the standard model (SM), which describes all observations in high energy particle physics successfully. Essential parameters of the SM have been studied at particle accelerators for years with very high precision. It provides a combined description of three of the four fundamental forces and a classification of all building blocks of matter. The most recent remarkable success of the standard model is the observation of a Higgs boson in 2012 [1–3]. Since then, the properties and couplings of the Higgs boson have been studied also with great interest and effort.

Nevertheless, the SM is not capable of explaining various physical observations, such as the existence of neutrino masses or the origin of dark matter. Several theoretical extensions to the SM could supply answers to the different shortcomings. Driven by the attractive concept of symmetry [4] in theory, one possible solution is supersymmetry (SUSY). SUSY postulates partner particles to each particle of the SM, introducing a symmetry between fermions and bosons, although the supersymmetric partners must be much heavier in mass compared to their SM equivalents.

Bigger and more complex, and such more expensive, experiments are needed to study elementary particles at the high energy frontier. The currently largest and most powerful particle accelerator is the Large Hadron Collider (LHC) at CERN near Geneva. Here, billions of protons are accelerated to almost the speed of light and are collided every second. The large amount of data arising thereby is recorded with the Compact Muon Solenoid (CMS) detector located at one of the four collision points of the LHC. The data sample being analyzed in this thesis consists of events recorded in 2016 based on proton-proton collisions with a center-of-mass energy of 13 TeV. CMS shows an excellent performance with regard to event reconstruction and particle identification, based on the combined reconstruction from all CMS subdetectors, such as the tracking system, the electromagnetic and hadronic calorimeters, and the muon system.

Supersymmetric particles are expected to have masses that might be accessible at the LHC. In order to difference between the masses of the SM particles and their partners, a symmetry breaking mechanism needs to be introduced. One scenario is gauge-mediated supersymmetry breaking (GMSB), where the second lightest supersymmetric particle is expected to decay to SM bosons, such as the Z boson and the photon, and the lightest supersymmetric particle (LSP)

which is the gravitino (\tilde{G}). The LSP is supposed to be undetectable, thus leading to a imbalance in the measured transverse momentum sum, called missing transverse momentum. These theoretical models are mainly motivating the presented search.

Searches for SUSY with photons in the final states have been carried out using the 2016 data set [5–8], but in this thesis a new independent final state is investigated, complementing the existing searches. By targeting events with photons, a Z boson decaying to charged leptons, and missing transverse momentum, the search is sensitive to various production channels for SUSY particles, and is able to study also phase space regions, where not so much energy is transferred to the final state particles, due to low requirements on the lepton and photon momenta.

The analyzed data set is based on events where at least two same-flavor opposite-charge leptons are reconstructed, being a part of the total 2016 data set corresponding to a total integrated luminosity of 35.9 fb^{-1} .

Standard model processes leading to the same final state are considered as background throughout this thesis, and they are estimated using an approach based on MonteCarlo simulated events that are normalized to data in various control regions. In the signal sensitive region, a counting experiment is performed, comparing SM prediction with supersymmetric signal expectations. The considered SUSY signals are based on three different signal scenarios, all established within the General Gauge Mediation (GGM) framework.

This analysis has been endorsed by the CMS collaboration, and is documented in detail in an official CMS analysis note [9].

This thesis is structured as follows. Firstly, a theoretical introduction to the SM and supersymmetry is given in Section 2, where SUSY in general is discussed, before in particular gauge-mediated supersymmetry breaking is explained, and the relevant signal models are introduced. Afterwards, the Large Hadron Collider and the CMS experiment are presented in Section 3. In Section 4 the basic event processing, including reconstruction and triggering, together with event simulation is explained, and properties of the used data sets are introduced. Moreover, the identification principle of physical objects, the definition of important high level variables, as well as the event selection and trigger efficiency measurement are discussed. The basic analysis strategy and background prediction is explained in detail in Section 5, while the definition of the control, validation and signal regions are given. In addition, the estimation of the background and validation of the background estimation are discussed. The determination of systematic uncertainties is also presented. Final results are discussed in Section 6 together with their interpretation in the context of various signal models. In Section 7, the thesis is briefly summed up, and conclusions are made.

Theoretical introduction and motivation

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2.1. System of units

For simplicity, the unit system commonly used in particle physics is the natural unit system [10]. In natural units, the reduced Planck constant \hbar and the speed of light c are set to unity:

$$\hbar = c = 1. \quad (2.1)$$

The observables used most frequently in particle physics are the energy, the momentum, and the mass. They are given in magnitudes of eV in the natural unit system. For other variables, such as length and time, the metric unit system is used. Cross sections are given in barn ($1 \text{ b} = 10^{-28} \text{ m}^2$). Integrated luminosities are therefore given in b^{-1} . Electric charges are given in dependence of the elementary charge e .

2.2. The standard model of particle physics

The standard model of particle physics (SM) is a gauge theory describing three of the four fundamental forces, namely the electromagnetic, the weak, and the strong interactions [11]. The gravitational force is described by general relativity [12], which is not described in a quantum field theory as the other three forces.

All particles can be divided into two categories: Particles of integer spin, called bosons, and particles of half-integer spin, called fermions.

The matter content is given by the fermions. Fermions are divided into two subgroups, called quarks and leptons. Leptons take part only in electroweak interactions, while quarks carry also a color charge and therefore interact via the strong force. There are three generations of fermions, which include each two leptons and two quark flavors. The quark flavors are the down, up, strange, charm, bottom, and top quarks, while the lepton flavors are made up of three electrically charged particles, the electron (e), the muon (μ), and the tau lepton (τ), as well as three electrically neutral leptons, called neutrinos (ν_e, ν_μ, ν_τ). Of the quarks, there are up-type quarks, the up, charm, and top quark, carrying an electric charge of $+\frac{2}{3}e$, and down-type quarks, the down, strange, and bottom quark, carrying an electric charge of $-\frac{1}{3}e$.

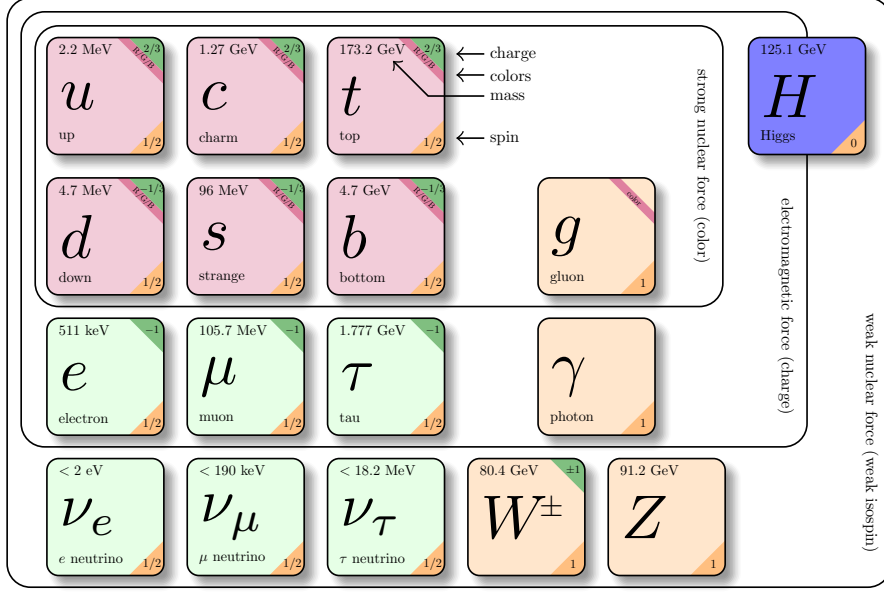


Figure 2.1.: Complete particle content of the standard model [13]. For each particle important properties such as mass, spin, and charges are given. The values are taken from [14].

The SM is based on the symmetry group $SU(3) \otimes SU(2) \otimes U(1)$. Interactions are described via the exchange of spin-1 gauge bosons. In case of the strong force these are 8 massless gluons, which carry color charge and couple to it. The mediator of the electromagnetic interaction is the massless photon, coupling to the electric charge of particles. For the weak interaction the responsible mediator particles are the three massive bosons W^\pm and Z , which couple to the weak isospin.

An illustration of the complete SM particle content with its properties is shown in Figure 2.1. For each particle, a corresponding antiparticle exists with same mass and inversed quantum numbers. Throughout this thesis particles and antiparticles are treated the same way, and both will be labeled with the name of the particle.

The strong interaction between color charged particles is described by the quantum field theory of quantum chromodynamics (QCD). The corresponding mediators of the non-abelian gauge group $SU(3)_C$ are the eight gluons, which each carry the color-charge C of an anticolor and a color, giving rise to the self-coupling of gluons. Due to the confinement of quarks [15], quark-antiquark pairs will be produced out of the vacuum, if particles with color charge are being separated, since the potential energy density of the strong force includes constant terms, and the potential energy rises with increasing distance. This principle is responsible for the existence of only color-neutral bound states of two (mesons) or three (baryons) quarks, called hadrons. Indications for hadrons made up of or five quarks have also been found recently (pentaquarks [16]). Based on the same principle, color charged particles are not observed as single particles. In the hadronization process, gluons and quarks, lead to the generation of large aggregations of color charged particles while transversing the detector material. These clusters are called jets.

The electromagnetic and weak forces are unified in the electroweak theory [17–20], represented

by the gauge group $SU(2)_L \otimes U(1)_Y$. The indices L and Y indicate, that the weak isospin T couples only to left-handed $SU(2)_L$ doublets of fermions, while the right-handed $SU(2)_L$ singlets carry no isospin, and the symmetry of the $U(1)_Y$ corresponding to the weak hypercharge Y . The three mediators of the $SU(2)_L$ group are the W^1, W^2 , and W^3 bosons, and the gauge boson of the $U(1)_Y$ group is the B^0 boson. These four bosons mix to the W^\pm and Z bosons and the photon γ :

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos(\theta_W) & \sin(\theta_W) \\ -\sin(\theta_W) & \cos(\theta_W) \end{pmatrix} \cdot \begin{pmatrix} B \\ W^3 \end{pmatrix}, \quad (2.2)$$

$$W^\pm = \frac{1}{\sqrt{2}} (W^1 \mp iW^2), \quad (2.3)$$

where $\theta_W \approx 0.231$ [14] is the weak-mixing angle, also referred to as Weinberg angle. The resulting weak interaction is parity violating [21, 22]. The W^\pm bosons only couple to left-handed fermions, while the neutral Z boson couples to both left-handed and right-handed particles, but with different strength.

In this theory the gauge bosons are not allowed to have dirac mass terms in the Lagrangian since it would break local gauge symmetry. However, since the Z boson mass is measured to be 91.2 GeV [14] and the W boson mass to be 80.4 GeV [14], the Higgs mechanism is introduced [23–25]. In its simplest representation, it predicts a complex scalar Higgs doublet with a potential, that is symmetric, but has a non zero vacuum expectation value. Therefore, the deviation from zero is responsible for the spontaneous symmetry breaking of the $SU(2)_L \otimes U(1)_Y$ gauge group. The Higgs field can be represented by the complex scalar $SU(2)_L$ doublet

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi_1 + i\Phi_2 \\ \Phi_3 + i\Phi_4 \end{pmatrix} \quad (2.4)$$

with the potential

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2. \quad (2.5)$$

For $\mu^2 < 0$ it results in the non-zero vacuum expectation value of

$$v = \frac{|\mu|}{\sqrt{\lambda}}. \quad (2.6)$$

The field can be reformulated without loss of generality by expanding around the vacuum expectation value and transforming to unitary gauge as

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \quad (2.7)$$

where h is a scalar field. Thereby, three of the four degrees of freedom of the field are consumed to give mass terms to the W and Z bosons. The remaining degree of freedom is the spin-0 Higgs boson. For consistency, leptons and quarks acquire also masses in the SM via Yukawa interactions with the Higgs field. Such a neutral boson has been observed in proton-proton collisions at the LHC in 2012 [1, 2], and its mass has been determined to be 125.09 ± 0.24 GeV. Measurements regarding the Higgs boson are in good agreement with SM predictions [26], and recently also the couplings of Higgs bosons to the top quark [27], and decays of Higgs bosons to bottom quarks and tau leptons have been observed [28, 29], strengthening the presumption, that the found Higgs boson is the postulated SM Higgs boson.

2.2.1. Indications for physics beyond the standard model

Although the SM describes all phenomena observed at high energy particle colliders successfully, different observations and theoretical arguments indicate that there must exist physics beyond the standard model (BSM):

1. Precise measurements of the cosmic microwave background and theoretical interpretations suggest, that only 4.9% of the universe consists of ordinary matter, while the remainder is composed of dark energy and dark matter [30]. The existence of dark matter is also observed in gravitational lensing effects [31] and in the velocity of rotation curves of spiral galaxies [32]. Inside the SM there exists no particle, that could explain the total amount of dark matter in the universe.
2. It is assumed, that in the early age of the universe there was the same amount of matter and antimatter. But, today we observe the existence of much more matter than antimatter [33, 34]. In order to explain this discrepancy, different conditions, such as \mathcal{CP} -violation and baryon number violation, must be fulfilled [35]. However, in the SM there are no known sources of \mathcal{CP} -violation effects large enough to give rise to such big differences, while baryon number conservation is not violated at all.
3. In the SM, neutrinos are predicted to be massless particles. But, the observation of neutrino oscillations are only explicable if neutrinos are massive particles [14, 36].
4. The observation of a Higgs boson in 2012 on the one hand marks the great success of the SM, but on the other hand directly leads to a issue concerning the Higgs mass, which is known as the "Hierarchy Problem". The Higgs boson couples to all massive particles, with coupling strengths proportional to their masses. But unlike for all other particles, the correction to the Higgs boson mass is quadratically divergent at low energies, caused by virtual loop corrections. The cut-off scale for these corrections can be as large as the validity scale of the SM. Thus, the Higgs boson mass can be enlarged to the order of the Planck scale (10^{19} GeV). Since its mass was measured at the LHC to be approximately 125 GeV, and due to the large difference between the electroweak scale (10^2 GeV) and the Planck scale, these correction terms need to cancel extremely precise over 32 orders of magnitude. This is considered "unnatural", leading to the expectation that new physics exists in the energy range between the electroweak and the Planck scale.
5. Driven by the electroweak unification, the unification of all forces except for gravity in a grand unified theory (GUT) is well motivated. While the couplings of the forces in the SM do not lead to a unification at very high energies [14], a possible extension of the SM with additional new particles could realize such a unification of the electroweak and strong interactions, see Figure 2.2.

2.3. Supersymmetry

Supersymmetry (SUSY) [37, 38] is one of the most popular BSM theories and was developed in the 1970s [39, 40]. It is well motivated with regard to the theory, because it is the only possible extension of space time symmetry. Since then, many different SUSY models have been developed, all based on the same principle: SUSY connects fermions with bosons and the other way around by introducing supersymmetric partners for SM particles. These superpartners differ only in spin by $\pm 1/2$, all other quantum numbers are equal. With the help of generators Q , bosonic and fermionic states can be transformed into each other:

$$Q |fermion\rangle = |boson\rangle, \quad Q |boson\rangle = |fermion\rangle. \quad (2.8)$$

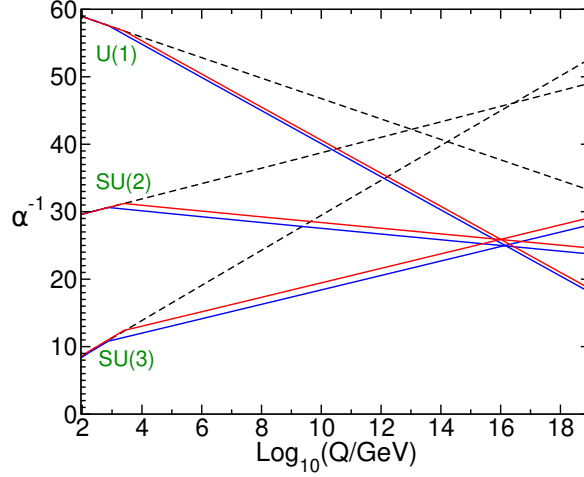


Figure 2.2.: Running couplings for all three fundamental forces in case of the SM (dashed lines) and the minimal supersymmetric standard model (solid lines) for two different particle mass scales (750 GeV and 2.5 TeV) [37].

Advantages of SUSY are, e.g., that multiple models directly provide candidates for dark matter particles, and it realizes the unification of forces, and solves the Hierarchy Problem without fine tuning of physical parameters to match the observation.

The simplest model of SUSY regarding the extension of the particle content is the minimal supersymmetric standard model (MSSM), where only exactly one Q exists. Within the MSSM, for each left and right-handed fermion in the SM exactly one supersymmetric scalar bosons is introduced. To differentiate between SM and SUSY particles, the names of supersymmetric partners are those of the SM particles prepended with an "s-" in case of the fermions. Thus the partners are called sfermions, and, e.g., the partner of the electron is the selectron. The names of superpartners of bosons are constructed by appending the SM name with an "-ino", making them bosinos, so the gluon's superpartner for example is called gluino. In general, superpartners are called sparticles, and are labeled the same as their SM counterparts, but with a tilde (e.g. $\mu \rightarrow \tilde{\mu}$). Also, the couplings between all sparticles are the same as of their SM partners.

To realize mass terms in the spontaneous symmetry breaking for all particles, including both up- and down-type fermions, the SM higgs sector needs to be extended to two complex scalar doublets:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}. \quad (2.9)$$

The H_d gives masses to the down-type quarks and charged leptons, while the H_u is responsible for the masses of up-type quarks. Four higgsinos as superpartners are introduced in the MSSM. As a consequence, there are eight degrees of freedom in the Higgs sector instead of four, related to the two Doublets, and giving rise to an expanded Higgs sector consisting of five particles: the two neutral scalars h^0 and H^0 , the two charged scalars H^\pm , and the neutral pseudoscalar A^0 . The remaining three degrees of freedom give masses to the gauge bosons as in the SM. The observed Higgs boson at the LHC can be identified as one of the two neutral scalars, where the lightest boson, the h^0 , is chosen by convention.

The gauginos and higgsinos mix, similar to the mixing in the electroweak sector, to eight mass eigenstates, which are the four neutral neutralinos $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \text{ and } \tilde{\chi}_4^0$, and the four charged charginos $\tilde{\chi}_1^\pm \text{ and } \tilde{\chi}_2^\pm$.

The total particle content of the MSSM is shown in Figure 2.3. To include gravity, the SM is extended by the graviton G , and the SUSY sector is extended by its superpartner, the gravitino \tilde{G} .

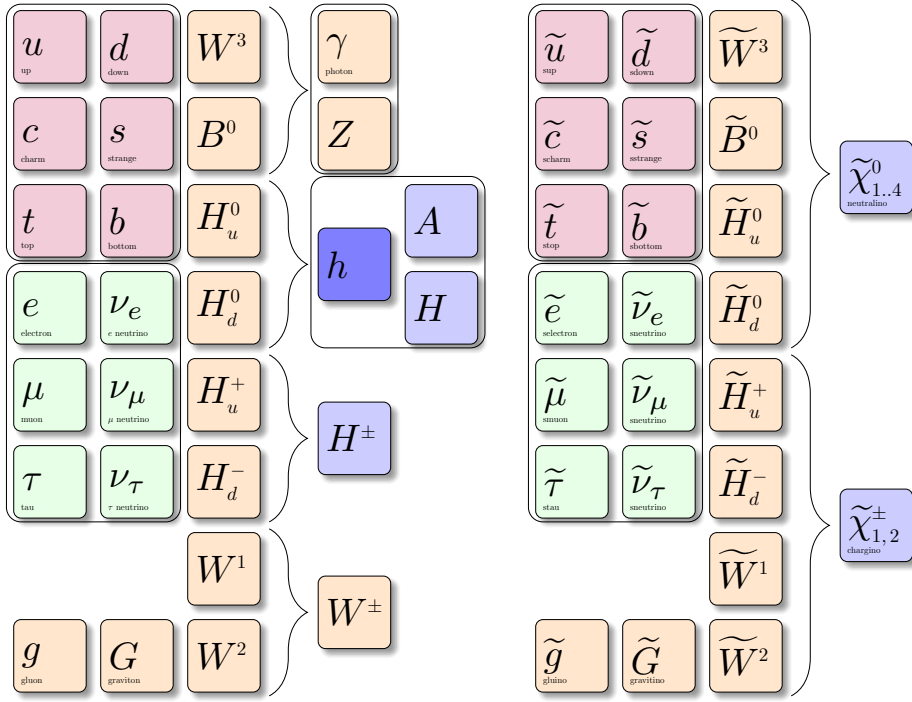


Figure 2.3.: The particle content of the MSSM extended with the graviton and gravitino. Mixings to mass eigenstates are indicated with the brackets.

In unbroken SUSY the particles and their corresponding sparticles should have the same masses, and those SUSY particles should have been found easily in the past (considering, e.g., a selectron with a mass of 511 keV). Therefore, SUSY must be a broken symmetry. Many different theories have been developed over time to explain different breaking scenarios. Attractive approaches are models where gravity is responsible for the SUSY breaking [37], anomaly breaking scenarios [41], and in particular gauge-mediated supersymmetry breaking, which will be discussed in the next section.

SUSY can provide Dark Matter candidates, if the lightest supersymmetric particle (LSP), is stable, electrically neutral, and colorless. R-parity

$$R = (-1)^{3B+L+S} \quad (2.10)$$

is therefore introduced as a new conserved quantum number, where S is the spin, B the Baryon number, and L the lepton number. The R-parity is -1 for sparticles, and $+1$ for particles, respectively.

It is not fundamentally necessary, that the LSP is stable. In R-Parity violating scenarios, decays of all SUSY particles into SM particles are allowed. Hence, the conservation of the Baryon number, or the lepton number is violated. R-parity conserving scenarios however are motivated by many precision measurements, such as the life time measurement of protons [42]. In this thesis, only R-parity conserving scenarios are considered. Therefore SUSY particles can only be produced in pairs and the LSP needs to be stable.

2.3.1. General Gauge Mediation

The phenomenology of SUSY is very rich. While in many models gravity is responsible for SUSY breaking, a different approach, motivating this search, is general gauge mediation (GGM). It

is based on the assumption of gauge mediated supersymmetry breaking (GMSB) [43], where an additional "hidden sector" is introduced, that is responsible for the breaking. This sector is mainly decoupled, and the possible interactions between the visible and the hidden sector are only achieved by messenger fields mediated by gauge interactions. In the studied GMSB models, the LSP is the gravitino \tilde{G} . This particle is assumed to be very light ($\ll 1$ GeV). Therefore, the next-to-lightest supersymmetric particle (NLSP), which basically can be any sparticle, decays promptly. Since the gravitino is stable because of R-parity conservation, electrically and color neutral, it will leave the detector undetected, causing an imbalance in the measured total transverse momentum in proton-proton collisions at the LHC.

In all models considered throughout this thesis, the NLSP is assumed to be the lightest neutralino ($\tilde{\chi}_1^0$). The mixing of the NLSP can include bino, wino, and higgsino components, each enabling different decay channels.

2.3.2. Signal scenarios

The signal scenarios considered in this thesis are discussed in the following. In general, very different production channels for SUSY particles, such as electroweak and strong production, are possible. In case of the LHC proton-proton collisions, SUSY particles can be produced directly in the hard scattering processes of the partons, leading to cascade decays down to the decays of the NLSP to the gravitino and a SM boson. The branching fractions of the lightest neutralino to different SM bosons depends on its mixing

$$\tilde{\chi}_1^0 = \sum_{i=1}^N N_{1i} \tilde{\psi}_i^0, \quad (2.11)$$

where $\tilde{\psi}_i^0 = (\tilde{B}, \tilde{W}, \tilde{H}_d^0, \tilde{H}_u^0)$ [44]. The mass eigenvectors N_{1i} are defined by four parameters, namely the bino mass M_1 and the wino mass M_2 at the messenger scale, the supersymmetric Higgs mass term μ , and $\tan \beta$, the ratio of the up-type to down-type Higgs vacuum expectation values. In GGM, a neutralino NLSP has three possible decay branches, all involving the \tilde{G} [44]:

$$\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma) = |N_{11}c_W + N_{12}s_W|^2 \mathcal{A} \quad (2.12)$$

$$\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} + Z) = \left(|N_{12}c_W - N_{11}s_W|^2 + \frac{1}{2}|N_{13}c_\beta - N_{14}s_\beta|^2 \right) \left(1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2} \right)^4 \mathcal{A} \quad (2.13)$$

$$\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} + h) = \frac{1}{2}|N_{13}c_\beta + N_{14}s_\beta|^2 \left(1 - \frac{m_h^2}{m_{\tilde{\chi}_1^0}^2} \right)^4 \mathcal{A} \quad (2.14)$$

Here, c_W , s_W , c_β , and s_β are abbreviations for $\cos(\theta_W)$, $\sin(\theta_W)$, $\cos(\beta)$, and $\sin(\beta)$, respectively. The formulae hold in cases of on-shell Z and h production. \mathcal{A} is a parameter responsible for the NLSP lifetime [45, 46]:

$$\mathcal{A} = \frac{m_{\tilde{\chi}_1^0}^5}{16\pi F_0^2} \approx \left(\frac{m_{\tilde{\chi}_1^0}}{100 \text{ GeV}} \right)^5 \left(\frac{100 \text{ TeV}}{\sqrt{F_0}} \right)^4 \frac{1}{0.1 \text{ mm}}, \quad (2.15)$$

where F_0 is the scale of SUSY breaking, its range is given by $10 \text{ TeV} \lesssim \sqrt{F_0} \lesssim 10^6 \text{ TeV}$, and it is related to the gravitino mass via

$$m_{\tilde{G}} = \frac{F_0}{\sqrt{3}M_{Planck}}. \quad (2.16)$$

Branching fractions for pure bino-, wino-, or higgsino-like NLSPs are shown in Figure 2.4. Since

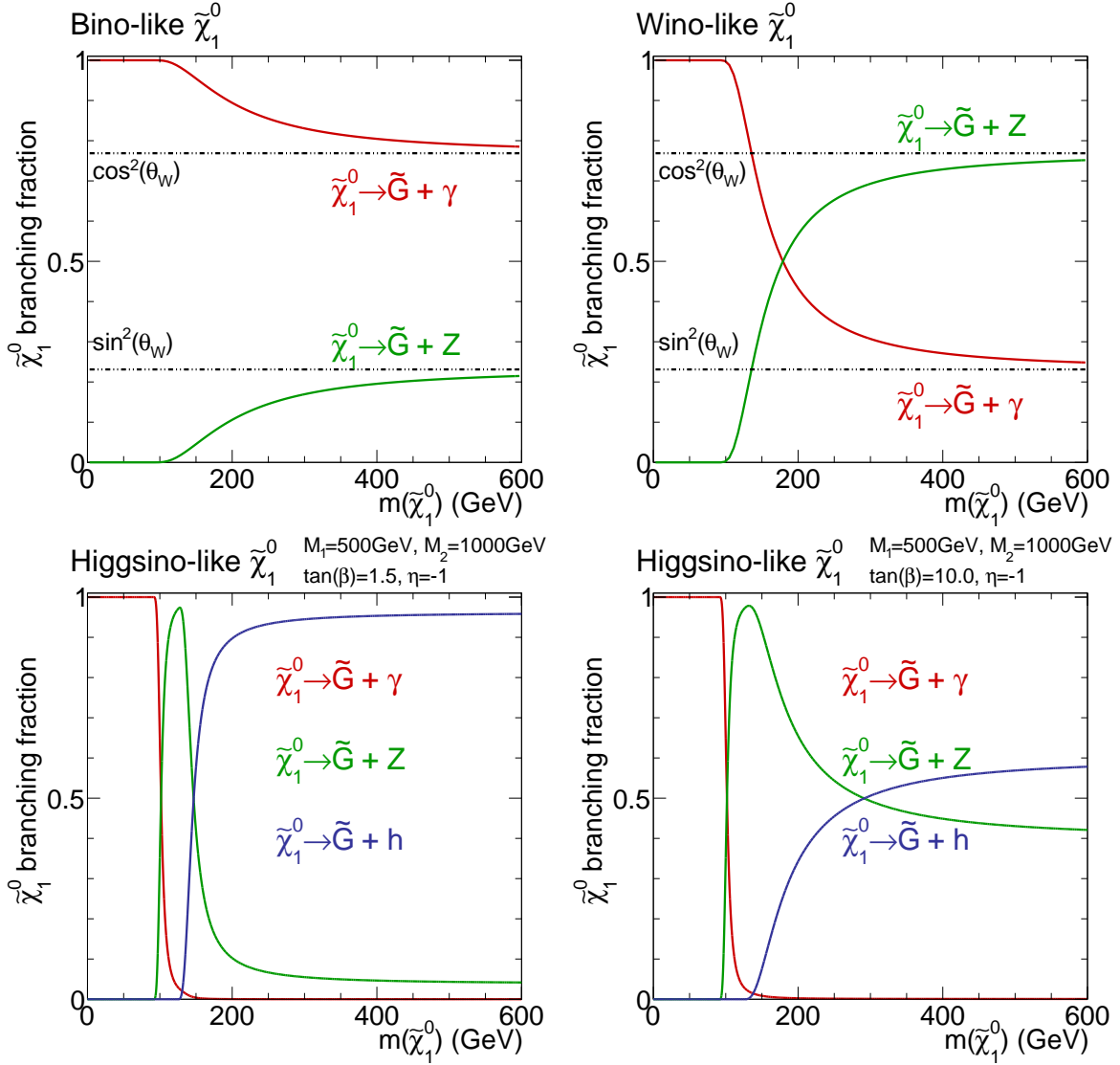


Figure 2.4.: Branching fractions for pure bino (top left), wino (top right), and two higgsino-like (bottom) NLSP scenarios with different parameters. The parameter η is defined as $\eta = \text{sgn}(\mu)$.

the final state investigated in this analysis consists of a Z boson and a photon, the search is sensitive in particular to bino- and wino-like NLSP scenarios.

One scenario used in the development of this search is a consistent GGM model, where the NLSP is the $\tilde{\chi}_1^0$, and it is assumed to be bino-like. The heavier neutralino $\tilde{\chi}_2^0$ and the lightest chargino $\tilde{\chi}_1^\pm$, are assumed to be wino-like. Therefore, the bino mass equals the mass of the lightest neutralino, while the $\tilde{\chi}_1^+$ and the $\tilde{\chi}_2^0$ are mass degenerate and their mass equals the wino mass. Higgsinos are decoupled, i.e., set to very high masses. Squarks and gluinos are also decoupled in this scenario, allowing only electroweak production modes. For the most dominant process a diagram is shown in Figure 2.5. The signal cross section depends only on the wino mass, since $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^\mp \tilde{\chi}_1^\pm$ production are by far the most dominant production channels. The branching fractions of the gauginos are given by the gaugino masses and their gauge eigenstates, and behave as shown in Figure 2.4. The mass of the neutralinos and the lightest chargino directly influence the transverse momenta in the final state. As can be seen in Figure 2.5, larger mass differences between the NLSP mass and the wino mass will lead to higher momenta of the produced bosons

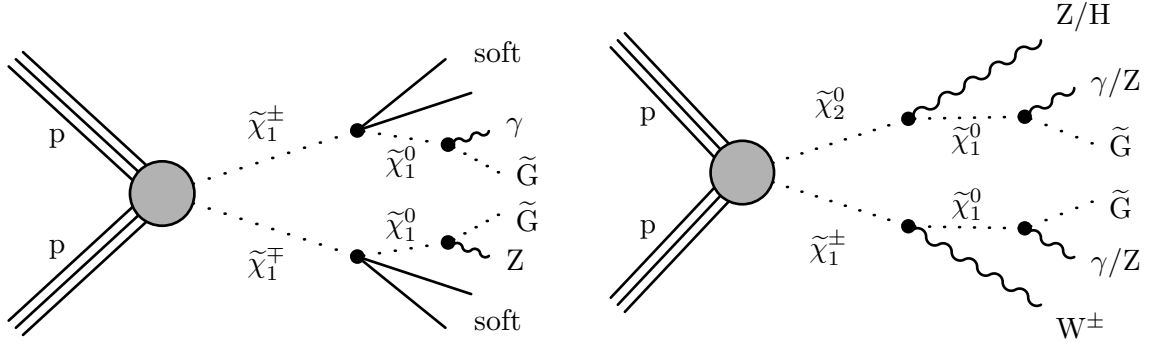


Figure 2.5.: Diagram of the TChiZG scenario (left) with chargino pair production, where the charginos decay to neutralinos under soft emission of off-shell W bosons. Also, the chargino-neutralino production is possible. The most dominant production process with a wino-like $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ of the full GMSB model (right).

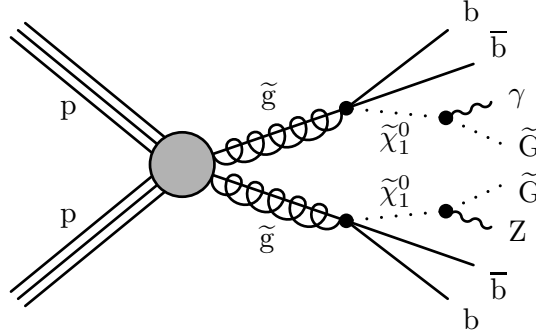


Figure 2.6.: The Feynman diagram for the T5bbbbZG scenario with pair production of gluinos in the hard process, decaying to neutralinos under the emission of b quarks.

in the cascades. The mass of the NLSP is directly responsible for the momenta of the SM bosons and the gravitino in the final state, and therefore the missing transverse momentum in an event. A very different approach in regard to full theoretical models are simplified models (SMS)[47]. Here, only a limited particle content is assumed with simplified assumptions on the production and decay channels, providing a more model independent result by probing distinct final states. These results can be reinterpreted in various models [48]. In this thesis two simplified models are considered, one with electroweak gaugino production, and the other one with a strong gaugino production channel.

The electroweak model is the TChiZG SMS, in which only neutralino-chargino associated and chargino-chargino production is assumed. The lightest chargino and lightest neutralino are assumed to have nearly the same mass, leading to soft emissions of off-shell W bosons in the decays of the charginos to the NLSP. The branching fractions of the lightest neutralino to a gravitino and a photon or a Z boson are fixed to 50% each, i.e., $\mathcal{BR}(\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}) = \mathcal{BR}(\tilde{\chi}_1^0 \rightarrow Z \tilde{G}) = 0.5$. A diagram for the process can be found in Figure 2.5. The squarks and gluinos are decoupled.

The strong model considered here is the T5bbbbZG SMS. A diagram is depicted in Figure 2.6. In this model, gluino pairs are produced in the hard interaction, leading to decays to the NLSP under the emission of bottom quark pairs. The branching fractions for the $\tilde{\chi}_1^0$ to photons and Z bosons are again set to 50% each.

2.3.3. Status of SUSY searches at the Large Hadron Collider

Searches for SUSY have been performed at the LEP experiment [49], the Tevatron collider [50], and using the LHC RunI data [51]. Although some promising excesses with respect to the SM expectation have been observed for example in the opposite-sign dilepton channel [52], no clear evidences for SUSY or other BSM theories have been confirmed. Currently SUSY is also constrained by precision measurements of the Higgs boson properties as mentioned above, and by measurements of rare decay processes, such as the $B_S^0 \rightarrow \mu^- \mu^+$ decay observed by the CMS and LHCb collaborations [53]. In the SM this decay is helicity suppressed, whereas in the MSSM or other extensions to the SM this decay may receive large enhancements.

Direct searches for SUSY in terms of SMS interpretations excluded gluino pair production up to gluino masses of around 2 TeV [54], squark pair production up to squark masses of roughly 1500 GeV, and sbottom (stop) masses of approximately 1500 GeV [55] (1200 GeV [56]), respectively. The production of electroweakinos (electroweak gauge bosinos) is excluded for chargino and neutralino masses up to around 1.1 TeV [57]. Regarding GMSB scenarios, the currently most stringent exclusion limits set by the CMS collaboration [58] are shown in Figure 2.7. The presented results are based on the proton-proton collision data recorded with the CMS detector in 2016, corresponding to an integrated luminosity of 36 fb^{-1} with a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. Searches similar to the one presented in this thesis exclude electroweakino production scenarios up to roughly 980 GeV, when final states tagged with a high-energy photon and large missing transverse momentum are analyzed [6]. Searches targeting the single lepton plus photon final state [8] have set lower limits. Strong exclusions for gluino and squark pair production scenarios are set by searches targeting events with large hadronic activity and photons [5] and searches investigating events with photons together with high b-jet multiplicity [7] over the whole parameter space. They set limits up to approximately 2.2 TeV for gluino masses and 1.8 TeV for squark masses.

Despite the high exclusion limits set by CMS and ATLAS analyses [60–62] in comparable ways, large regions of phase space remain unexplored. But since there are many different SUSY models, and the phenomenology of SUSY is very rich, including scenarios with R-parity violation, compressed mass spectra, long-lived particles and displaced vertices, all described in different breaking scenarios, many studies and searches are yet to be performed. Nevertheless, although the sparticle masses are not predicted by theory, natural SUSY scenarios without great fine tuning should lead to sparticle masses in the order of $\mathcal{O}(\text{TeV})$, which are accessible at the LHC [63].

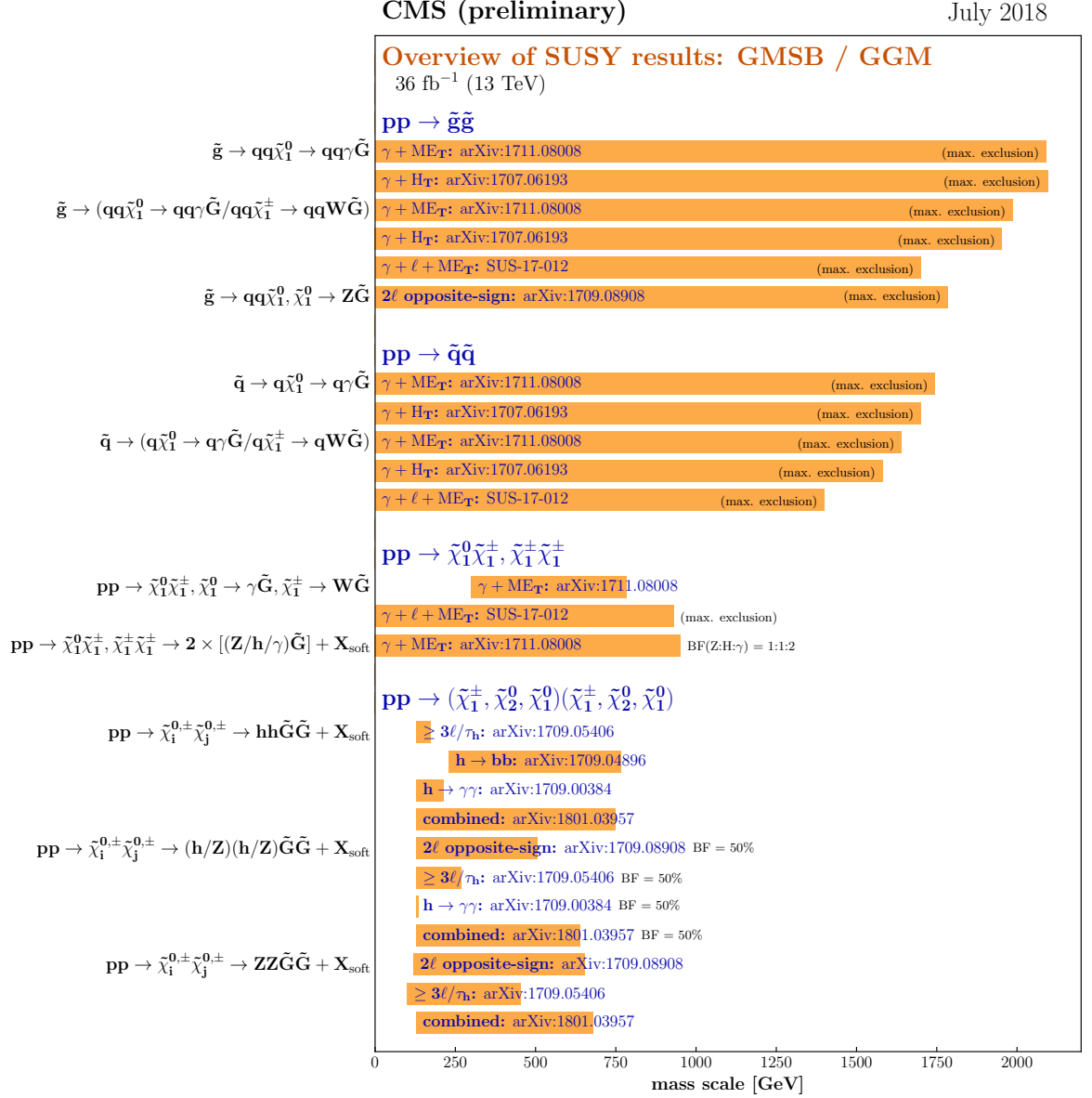


Figure 2.7.: Mass exclusion limits for simplified models in the context of GMSB [59].

The experiment

Contents

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In this chapter, the relevant experimental setup is discussed. Beginning with the description of the Large Hadron Collider (LHC), which accelerates the proton beams, thereafter the Compact Muon Solenoid (CMS) experiment and detector with all important subdetector components are explained.

3.1. The Large Hadron Collider

The Large Hadron Collider [64, 65], located at the European Organization of Nuclear Research (CERN) near Geneva in Switzerland, is the worlds largest and most powerful hadron collider. The design center-of-mass energy for proton-proton collisions is $\sqrt{s} = 14$ TeV, while the LHC started operating in 2010 with an center-of-mass energy of 7 TeV. The energy was increased afterwards for the 2012 run period to 8 TeV. After the end of Run I and the first long shutdown, the LHC started operating again in 2015 with an increased center-of-mass energy of 13 TeV. This energy was maintained trough the whole Run II for pp collisions until the end of 2018. In the near future, the LHC will be upgraded again in the long shutdown II, so that with the beginning of 2021 operations with the design energy of 14 TeV are planned. The LHC is also capable of accelerating lead ions and xenon ions with an energy of around 2.7 TeV per nucleon. The LHC is a synchrotron collider built in a tunnel with a circumference of 27 km, which was already used for the Large Electron Positron collider (LEP) [66] in the past. The proton beams are accelerated using various pre-accelerators, such as the Booster, Proton Synchrotron (PS), and the Super Proton Synchrotron (SPS), accelerating protons to an energy of 450 GeV before entering the main storage ring. Four main experiments are located at the LHC, each built around one collision point. These are: ALICE (A Large Ion Collider Experiment) [67], ATLAS (A Toroidal LHC Apparatus) [68], CMS (Compact Muon Solenoid) [58], and LHCb (LHC Beauty) [69]. CMS and ATLAS are designed to be independent experiments by using different detector layouts, searching both for BSM physics, measuring precisely properties of the SM, and improve the knowledge of the Higgs sector. Besides those tasks, they also analyze lead ion collisions to gain a deeper understanding of the strong interaction. Initially ATLAS and CMS were mainly designed to find the SM Higgs boson. The tasks of ALICE include studies of the quark-gluon-plasma, where the confinement is abrogated, leading to asymptotically free quarks and gluons. LHCb investigates mainly mesons that include charm and bottom quarks, to perform precision measurements of the SM and look for \mathcal{CP} -violation and hints for new physics. The asymmetric detector design of LHCb favors such studies, since the forward region with particles flying close

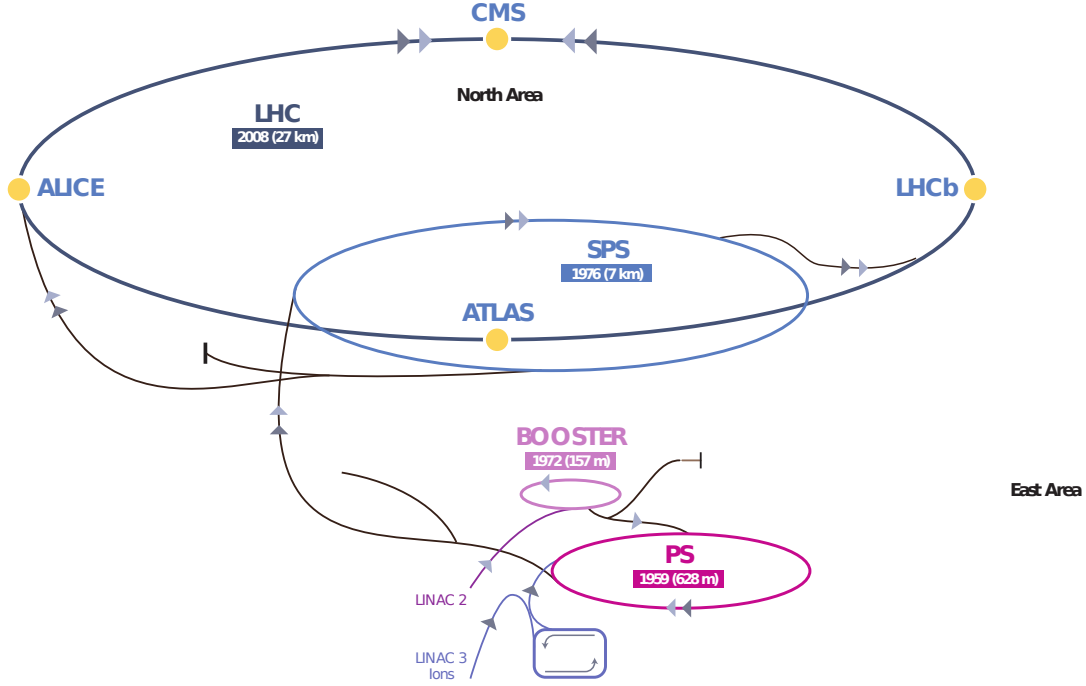


Figure 3.1.: A sketch of the total LHC accelerator complex [70] including the preaccelerators. The four main experiments are marked as yellow dots.

to the beam axis, is enriched with such events. A schematic sketch of the LHC apparatus including the four big experiment locations at the interaction points and the preaccelerators is shown in Figure 3.1.

As the protons are accelerated to an energy of 450 GeV, they are injected in bunches of approximately $N_b = 1.1 \cdot 10^{11}$ particles into the two beam pipes counter rotating in bunch spacings of 25 ns. To achieve a center-of-mass energy of 13 TeV, each beam has to reach an energy of 6.5 TeV. Therefore, superconducting cavities operating at 400 MHz accelerate the protons, and dipole magnets force the beams on their orbital path. Higher order multipoles are needed to focus the beam and correct for different beam and magnetic effects, such as quadrupoles perform a geometrical and sextupoles a momentum dependent orbital correction. One important quantity to characterize a collider is the instantaneous luminosity L , because the rate of any scattering process is proportional to L . It can be defined as

$$L = \frac{N_b^2 n_b f_{rev}}{4\pi\sigma_x\sigma_y} F, \quad (3.1)$$

where N_b is the number of particles per bunch, n_b the number of bunches, f_{rev} the revolution frequency, σ_x and σ_y are the widths of Gaussian distributed beam profiles in x- and y-direction, and F is a geometrical factor accounting for the crossing angle of the beams [71]. The integrated Luminosity \mathcal{L}_{int} is connected to L via

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

The number of events N for a given process with cross section σ is given by

$$N = \mathcal{L} \cdot \sigma. \quad (3.3)$$

In 2016, the LHC provided a total integrated luminosity of 40.8 fb^{-1} , while the CMS detector recorded 37.8 fb^{-1} , and 35.9 fb^{-1} were validated as good to be used for physics analysis [72].

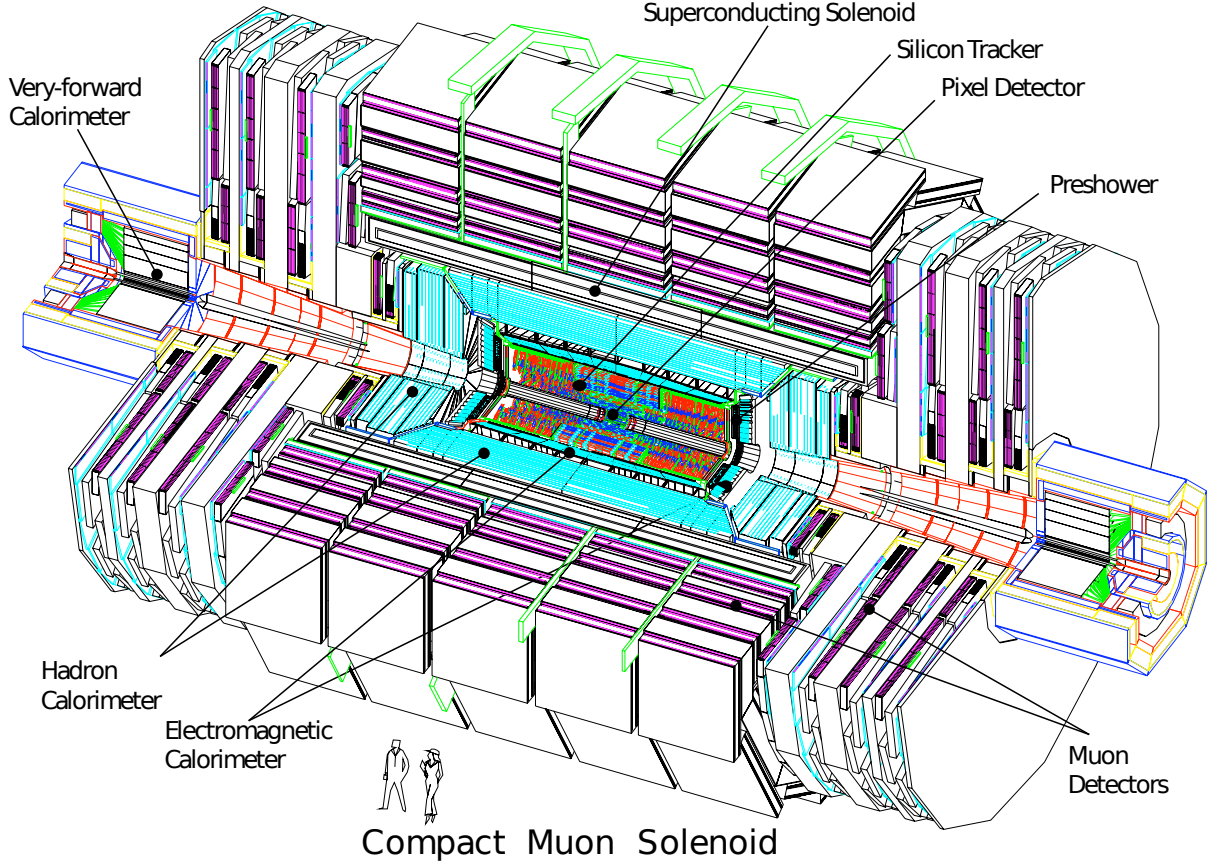


Figure 3.2.: A sketch of the CMS detector showing all subdetectors. [73]. The innermost part of the detector is the tracker system, composed of the pixel and silicon strip detectors. Outside the tracking system the electromagnetic and hadron calorimeters are placed within the solenoid magnet. The outermost part of the detector is the muon system.

3.2. The Compact Muon Solenoid

The data used in this thesis were recorded by the CMS detector [58, 73] in 2016. The CMS detector is a multi-purpose detector housing different subdetectors. From inside to outside these are the tracker system including a pixel and the silicon strip detector, the electromagnetic calorimeter, the hadronic calorimeter, followed by the solenoid magnet and the muon system. A sketch of the CMS detector is shown in Figure 3.2. In the following, at first the used coordinate system to describe the detector will be introduced and afterwards each subdetector and the trigger system will be briefly explained. The coordinate system used to describe the detector has its origin located at the interaction point, and the z -axis points in the direction of the beam axis westwards toward the Jura mountains. The y -axis points upwards, while the x -axis points to the center of the LHC ring. To exploit the underlying symmetry of the detector, a transformation to an angular coordinate system is chosen. The azimuthal angle ϕ is measured in the x - y plane, where $\phi = 0$ equals the direction of the x -axis, and ϕ ranges from $-\pi$ to π . The polar angle θ is measured from the positive z -axis, and the pseudorapidity η is introduced as

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

The advantage in using η instead of θ is, that differences in η are invariant under Lorentz-boosts along the beam axis, and in the limit of massless particles the pseudorapidity equals the rapidity.

In proton proton collisions, the initial total momentum of the colliding partons is unknown, since they carry only a fraction of the proton energy. In contrast, the transverse momentum in the initial state is negligible, and therefore, the transverse momentum

$$p_T = |\vec{p}_T| = |\vec{p} \cdot \sin(\theta)| \quad (3.5)$$

is a widely used quantity. Most of the subdetectors are divided into a low η part (barrel), and two high η parts (endcaps). Each of the subdetectors is designed to measure certain properties of different particle types, to ensure both a good particle distinction and identification, and precise measurements of energy, momenta, and trajectories.

3.2.1. The tracker system

The innermost part of the CMS detector is the inner tracker, which consists of two main components, a silicon pixel and a silicon strip detector¹. Both components enclose parts parallel to the beam pipe in the barrel, and parts orthogonal to the beam axis in the endcaps. They cover a length of 5.8 m and a diameter of 2.5 m. A sketch of the inner tracker with all subparts is shown in Figure 3.3. The tracker is designed to perform precise measurements of particle trajectories and an identification of primary and secondary vertices. Therefore, a high granularity and fast response is needed. The silicon pixel subcomponent is built of three barrel layers (the closest at a radial distance of 4.4 cm to the center of the beam pipe) and two endcap disks, covering a total area size of around 1 m². Each of the approximately 66 million silicon pixel cells has a size of $100 \times 150 \mu\text{m}^2$. This provides good granularity for all track directions.

The silicon strip detector consists of four strip layers in the inner (TIB), and six layers in the outer part (TOB). In the direction of the endcaps, it is built of three inner disk layers (TID), and nine layers in the outer part (TEC).

The inner tracker in total covers a range of $|\eta| < 2.5$ and the sensing system has a surface area of around 200 m². The performance of the tracker yields a momentum resolution for muons with a transverse momentum of around 100 GeV of 1 – 3% in the pseudorapidity range of $|\eta| < 1.6$. At higher pseudorapidities and momenta the momentum resolution decreases.

¹The silicon pixel detector was replaced at the end of the 2016 run. Since in this thesis only 2016 data is used, only the former detector is discussed.

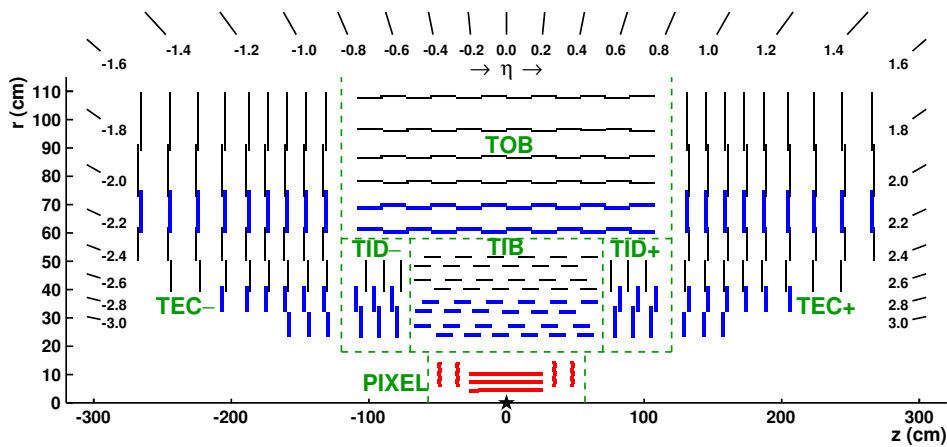


Figure 3.3.: A sketch of one quadrant of the CMS tracker [74]. It is composed of the inner pixel detector (red) and of the strip detector. The silicon strip detector is divided into the TIB, TOB, TID, and TEC.

3.2.2. The electromagnetic calorimeter

Built around the tracker, the second subdetector of CMS is the electromagnetic calorimeter (ECAL). Its main purpose is to measure the energy of electrons and photons, which produce similar electromagnetic showers in the calorimeter. Only with the combined measurements of the tracker, a differentiation between electrons and photons can be performed. The ECAL is made up homogeneously of lead-tungstate (PbWO_4) crystals and their light emission is proportional to the deposited energy of traversing particles in an electromagnetic shower. The emitted light in the visible spectrum is measured by photodiodes and phototriodes. The material of lead-tungstate was chosen due to its high density, short Molière radius of 2.2 cm characterizing the shower width, and short radiation length of 0.89 cm. Another big advantage of PbWO_4 is the short scintillation time. In a time window of 25 ns most of the visible light (approximately 80%) is emitted, which agrees with the bunch spacing of 25 ns. The ECAL is divided into a barrel (EB: $|\eta| < 1.479$) and an endcap part (EE: $1.479 < |\eta| < 3.0$), as can be seen in Figure 3.4. The 61200 crystals mounted in the barrel have a length of 23 cm, corresponding to 25.8 radiation lengths, and a cross section of $22 \times 22 \text{ mm}^2$ matching the Molière radius of PbWO_4 . In each ECAL endcap, 3662 crystals are placed, having a larger cross section of $28.6 \times 28.6 \text{ mm}^2$ and a length of 22 cm. To prevent particle trajectories from aligning with the orientation of ECAL crystal borders, the crystals (in EB) are tilted in an angle of 3 degree with respect to their orientation toward the interaction point. In the EE, the tilting varies between 2 – 8 degree in dependence of η . So both a compact format and a high granularity is maintained. The energy resolution of the ECAL is determined to be

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E[\text{GeV}]}}\right)^2 + \left(\frac{12\%}{E[\text{GeV}]}\right)^2 + (0.3\%)^2, \quad (3.6)$$

where the first term covers stochastic effects due to the Poissonian distributed number of created scintillation photons and the second term combines noise effects both from the electronics and multiple collisions per bunch-crossing (pileup). The third term covers constant effects, such as intercalibration effects between the crystals and energy leakage. All values were obtained in test beam setups [76]. The energy resolution was designed to be optimal at energies of around 50 GeV to maximize the sensitivity for the Higgs boson discovery, where photons from the Higgs boson decay were expected.

An additional preshower detector is installed in front of the ECAL endcap, to identify photons coming from meson decays, such as the π^0 .

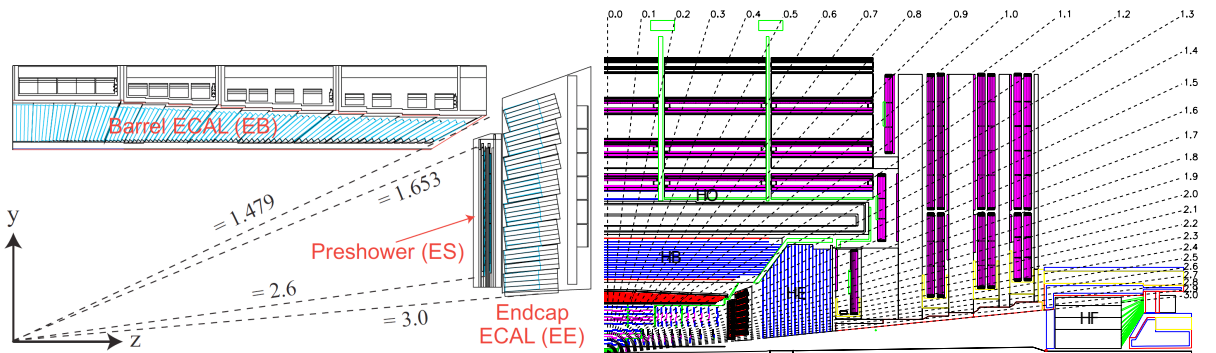


Figure 3.4.: A sketch of one quadrant of the CMS detector for the ECAL (left) [75], and the whole detector (right) [58]. The subparts of the HCAL, the HE HB HO, and HF are indicated separately.

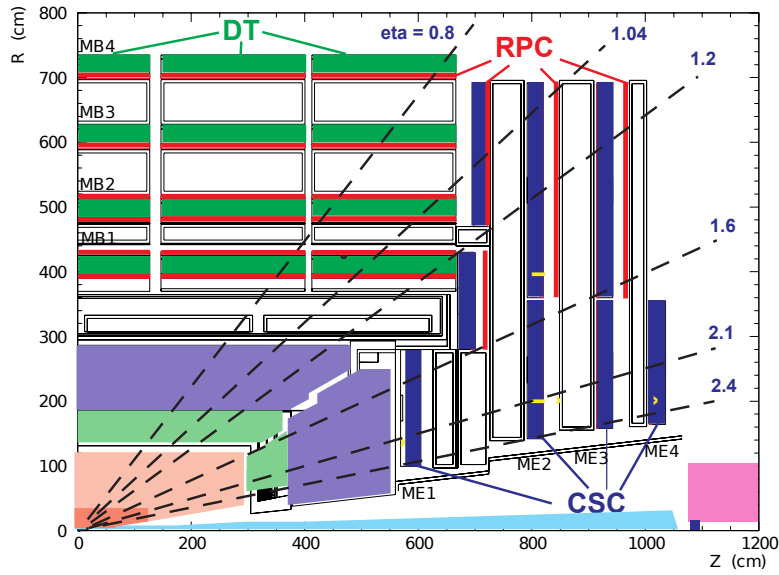


Figure 3.5.: A sketch of one quadrant of the CMS detector with the main detector components [73], especially the different muon detectors, is shown.

3.2.3. The hadron calorimeter

The hadron calorimeter (HCAL), which is designed for the energy measurement of hadrons, consists also of a barrel (HB) and endcap parts (HE). It is placed between the ECAL at a radius of 1.77 m and the magnet coil at a radius of 2.95 m. An additional outer barrel part with lower granularity (HO) extends the HCAL outside of the solenoid magnet, making use of its stopping power, while the hadron forward (HF) is installed to cover high pseudorapidity ranges. The barrel part covers pseudorapidities in the range of $|\eta| < 1.4$, while the HCAL endcap together with the outer HCAL covers the range of $1.3 < |\eta| < 3$.

In contrast to the homogeneous ECAL, the HCAL barrel is a so-called sampling calorimeter, consisting of alternating layers of brass absorbers and plastic scintillator material. The front and backplates are made of steel. Hence, the brass plates stop incoming particles, and their energy deposition is measured in the form of hadronic showers creating scintillation light in the plastic layers, which is measured afterwards by hybrid photodiodes. The outer HCAL makes use of the same principle, but uses in addition the stopping power of the solenoid. The hadron forward, covering pseudorapidity ranges of $3 < |\eta| < 5.2$, needs to be more radiation hard in comparison to the rest of the HCAL, since the energy deposit in the forward region is much higher. It is therefore constructed as a Cherenkov detector made of quartz fibres. A total sketch of the HCAL can be seen in Figure 3.4.

3.2.4. The solenoid magnet

To measure the momentum of charged particles properly, it is crucial to have bent trajectories. The resolution of momentum measurements at very high energies is directly proportional to the particle momenta and inverse proportional to the magnetic field strength. Thus, for a precise measurement of the curvature of the trajectory, a strong magnetic field is needed. In case of the CMS detector, this is provided by a superconducting NbTi magnet, cooled to 4.8 K, inducing a magnetic field of 3.8 T inside the solenoid. Outside, in the muon chambers discussed in the next section, the magnetic field is weaker (approximately 2 T). By choosing a solenoid with a length of 12.5 m and a diameter of 6.3 m, the solenoid defines the CMS detector design, especially with regard to the limited space for the tracking system, the ECAL, and HCAL.

3.2.5. The muon system

The outermost part of the CMS detector is the muon system. Because all other charged particles beside muons should be stopped in the inner layers, muons are the only particles entering the muon system and leaving a signature there. Three different types of detectors are used to measure and identify muons. The barrel part ($|\eta| < 1.2$) is covered by four stations of drift tubes (DT). Cathode strip chambers (CSC) are covering the endcap at pseudorapidity $0.9 < |\eta| < 2.4$, because in this region a higher muon rate is expected, and CSCs in contrast to DTs have a faster response time and are more radiation hard. The muon momentum resolution, dependent on the η region, varies between 10% in the barrel region to around 20% in the endcap region for muons reconstructed standalone by the muon system with a transverse momentum above 15 GeV. In a combined reconstruction with the tracker information, the resolution is of the order of 1 – 6% for muons with momenta lower than 100 GeV and 10% for TeV muons [77]. Again, the energy resolution was designed to be at its maximum at around 50 GeV, where muons from the diboson Z decays of the Higgs boson were expected.

Additional detector components, namely six layers of resistive plate chambers (RPC), are installed in the pseudorapidity range of $|\eta| < 1.8$. Because they show both good time resolution and fast response time, they are mainly used for triggering purposes. The structure of the muon system can be seen in Figure 3.5.

3.2.6. The trigger system

As bunch crossings take place every 25 ns, and therefore at a rate of 40 MHz, it is not achievable to read out and store all events. To keep only physically interesting events and reduce the rate of events to be saved, a trigger system consisting of two stages is implemented [78]. It is composed of the hardware based level 1 (L1) triggers, and the software based high level triggers (HLT). Since the L1 trigger system needs to deliver decisions in a very short time window, it uses only information provided by the calorimeters and the muon chambers. Usually first requirements on the event, such as a minimal deposited transverse energy, and the presence of first estimates for electron and muon candidates, are imposed. The L1 trigger reduces the event rate to a rate of approximately 100 kHz.

More complex decisions are made by the HLT trigger system. It has full access to the complete readout of all subdetectors, and therefore performs selections close to the offline analysis. It reduces the event rate to $\mathcal{O}(1 \text{ kHz})$ [79].

Using the decisions of the HLT, events are categorized into different subsets, based on event kinematics and the trigger objects, called primary data sets (PD).

Simulation, data processing, and event reconstruction

Contents

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The data sets, based on the proton-proton (pp) collisions recorded with the CMS detector, are centrally provided in the MINIAOD format [80]. This format contains only parts of the original event and detector information relevant for most of the physics analyses. An analysis looking for deviations from expectations from the SM is supposed not to be biased while development. Thus, SM and signal simulations are performed, and are centrally provided by the CMS collaboration. These are also provided in the MINIAOD format with extended generator information. All available data sets, including measured data and simulation, are further processed with the help of the CMS software framework (CMSSW¹) [81], the CMS Remote Analysis Builder (CRAB3) [82], and the resources of the Worldwide LHC Computing Grid (WLCG) [83], to obtain files with significantly reduced size. The obtained reduced information is stored in the ROOT [84] file format, and can be used by analysts with self-developed software ².

In this chapter, at first the used data samples are introduced. Thereafter, an overview of simulation is given, while the simulated samples used in this analysis are reviewed. After that, the event reconstruction performed on all data sets is explained. A more detailed view is given on the reconstruction and identification of physics objects.

Protons are objects composed of many different quarks and gluons. The probability to find a distinct parton of a proton with a specific momentum in a deep-inelastic-scattering is given by parton distribution functions (PDFs)[85], that need to be extracted from fits to data, since they are not predicted by QFT. A interaction between two partons of the colliding protons is described in the hard interaction. The products and quantities of these interactions contain the most interesting physical information. Due to the structure of protons, many different lower energy particles can be produced in interactions between additional partons (multi-parton-interactions). These remnants of the scattering process, together with reconstructed remnants of the protons, are denoted as the underlying event. More important for proton-proton colliders

¹Version 8.0.26

²Usually composed of parts developed in C/C++ and Python

is pileup, which denotes interactions between additional protons in the same bunch crossing as the hard interaction.

4.1. Data sets

This analysis uses different data sets based on the pp-collisions of the LHC with a center-of-mass energy of 13 TeV in 2016 and recorded with the CMS detector, corresponding to an integrated luminosity of 35.9 fb^{-1} . Each primary data set is a composition of events recorded with similar HLT trigger paths. The `DoubleMuon` and `DoubleEG` PDs are used in the central part of the analysis for the signal selection, since they contain events with at least two muons or electrons, respectively. `MET` and `HT` PDs are used for trigger efficiency measurements, and the `MuonEG` PD is used to extract a selection relevant for the background prediction. For a list of used triggers see Section 4.6.

The different PDs are separated into several single samples for different run eras throughout 2016. The paths of the used samples, available via the CMS data set bookkeeping service (DBS) [86] are listed in Table A.1 in the additional material.

4.2. Monte-Carlo simulation

The simulation process for SM background and SUSY signal samples can be divided into three major steps, which are very similar for both cases. At first, for a specific process events are simulated with an event generator. The event generators used for the generation of the samples considered in this analysis are MADGRAPH 5 in leading order (LO) configuration [87–89], MADGRAPH_MC@NLO in next-to-leading order (NLO) [87, 90], PYTHIA [91] for both cases of accuracy, or POWHEG [92, 93]. Matrix elements for the contributing diagrams are computed, and via convolving with PDFs, cross sections are calculated. These cross sections later can be used to rescale the simulation event yield to a given integrated luminosity. Thus, the simulation can be performed with much higher statistics than data in order to minimize the statistical uncertainty of the simulation.

Depending on the choice of the chosen generator, a separate generator for the simulation of hadronic showers must be used. This is done with PYTHIA. A matching with the MLM [88] (LO) or FxFX [90] (NLO) matching schemes is performed, so that partons generated in matrix element calculations corresponding to the hard interaction, and partons generated with PYTHIA in the showering for, e.g., initial state radiation (ISR), are not double counted. The hadronization of the partons (quarks and gluons) is simulated also with PYTHIA, based on the confinement of color charged particles. This, together with the underlying event and pileup, is all covered by the CUETP8M1 generator tune [94]. It is based on 7 TeV proton-proton CMS and proton-antiproton CDF measurements. The PDFs used for the generation of the MC samples are provided by the NNPDF 3.0 sets [95].

The big next step, which is the most time and resource consuming part, is the simulation of the detector response. A full model of the CMS detector was constructed with the GEANT4 [96] package. Hence, it allows a precise simulation of the detector response for the events generated with the procedure described above. In the GEANT4 package, material and particle properties, detector effects, and decay structures are considered in the simulation process. Since this procedure is very time consuming, but leads to a high accuracy, a different method is chosen for signal processes. For the generation of SUSY samples, where theoretical uncertainties dominate and events for many different signal points for each model need to be generated, the CMS FASTSIM package is used [97]. It is based on a simplified geometry and parametrizations, yielding a reduction in runtime of the factor ≈ 100 . If the "FullSim" and "FastSim" performances are

compared [98], a agreement within $\approx 10\%$ for all distributions, such as momenta of particles or jet multiplicity, is observed.

All simulated processes used in this analysis are listed in Table 4.1 together with their corresponding cross sections used to rescale the samples later on. The DBS paths are given in the appendix in Table B.1.

Table 4.1.: All SM simulated samples used in the analysis with their cross sections. For their corresponding accuracy refer to the text. Additional k-factors to obtain NNLO cross sections for the ZZ samples are applied per event in dependence of the p_T of the diboson system. All samples are of the MINIAODSIM format.

process	σ [pb]	process	σ [pb]
ttbar		diboson	
$t\bar{t} \rightarrow \ell^+ \nu b + \ell^- \bar{\nu} \bar{b}$	87.31	$Z\gamma \rightarrow 2\ell\gamma$ ($p_T^\gamma < 130$ GeV)	124.936
ttbarGamma		$Z\gamma \rightarrow 2\ell\gamma$ ($p_T^\gamma > 130$ GeV)	0.1488
$t\bar{t}\gamma \rightarrow 2\ell 2\nu 2b\gamma$	1.679	WZ	4.9125
$t\bar{t}\gamma \rightarrow 4q 2b\gamma$	3.482	$ZZ \rightarrow 2\ell 2\nu$	$0.5644 \cdot k(p_T^{ZZ})$
$t\bar{t}\gamma \rightarrow \ell\nu 2b 2q\gamma$	2.509	$WW \rightarrow 2\ell 2\nu$	12.178
DrellYan		$Wg \rightarrow \ell\nu\gamma$	489
$Z/\gamma^* \rightarrow 2\ell$	5765.4	W jets	
single top		$W + jets$	61526.7
$W^+ \rightarrow t\bar{b}$	3.36	triboson	
$q\bar{b} \rightarrow q'\bar{t}$	80.95	$WW\gamma$	0.2147
$qb \rightarrow q't$	136.02	$WZ\gamma$	0.04123
$\bar{b} \rightarrow W^+\bar{t}$	11.7		
$b \rightarrow W^-t$	11.7		

The Drell-Yan (DY) Z/γ process, as well as the diboson $Z\gamma$ and $W\gamma$ processes, and triboson production of $WW\gamma$ and $WZ\gamma$ are generated with MADGRAPH_MC@NLO with NLO accuracy. Top pair production in association with a photon ($t\bar{t}\gamma$) and the production of a W boson in association with jets are also simulated using the MADGRAPH_MC@NLO generator with NLO accuracy. Top pair production with leptonic decays ($t\bar{t} \rightarrow 2\ell 2\nu 2b$), diboson production of WZ, ZZ, WW, and all single top production processes are generated using POWHEG. Diboson WW and $W\gamma$ production, $W + jets$ production, triboson $WW\gamma$ and $WZ\gamma$ production, and all single top production channels are grouped together and denoted as "other" in the following. Cross sections calculated with NLO and next-to-next-to-leading order (NNLO) accuracy [99–107] are used for the normalization of the samples.

The generator used for the signal simulation production is MADGRAPH_MC@NLO for the simplified models, and PYTHIA 8 for the full GGM model. The corresponding DBS paths are also listed in the appendix in Table B.2. The cross sections used in the signal normalization are calculated at NLO accuracy for the full GGM scenario, and at NLO+next-to-leading logarithmic (NLL) accuracy for the two simplified models [108–116]. For the electroweak SMS, the applied cross sections are calculated for the $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production channels with squarks and gluinos decoupled, and the sum of both is used. In the cross section calculations of gluino pair production for the other SMS, squark decoupling is assumed. The applied cross sections for the GGM scenario are obtained using a full model, thus being different from the ones used for the electroweak SMS.

For the GGM model, signal points are generated with wino masses ranging from 215 GeV to

1015 GeV, and bino masses ranging from 205 GeV to $m(\widetilde{W}) - 10$ GeV in intervals of 25 GeV. In case of the TChiZG SMS, points are generated with NLSP masses in the range of 300 – 1300 GeV in steps of 25 GeV. The grid of points generated for the T5bbbbZG strong production SMS includes gluino masses in the range of 800 GeV to 2500 GeV, while the NLSP mass range is scanned from 10 GeV to $m(NLSP) = m(\widetilde{g}) - 10$ GeV in non equidistant steps.

As mentioned above, the number of generated events N_{Gen} is very high. Thus, with the measured integrated luminosity \mathcal{L} and a given cross section σ , a global event weight of

$$w = \frac{\mathcal{L} \cdot \sigma}{N_{Gen}} \quad (4.1)$$

is used to rescale the simulation to the physical expectation.

Additional event weights are applied on the simulation to account for differences in the pileup distribution between data and simulation. To improve on the MADGRAPH modeling of the multiplicity of additional jets arising from initial state radiation, SUSY SMS events are reweighted as a function of N_{jet}^{ISR} or the transverse momentum of the ISR system, to improve the agreement with observations in data. The latter is based on studies of the transverse momentum of Z events. [117]. The differences to unity for the reweighting factors are considered as systematic uncertainties later on. The POWHEG $t\bar{t}$ simulation is also reweighted as a function of the transverse momentum of the top system, based on studies in top pair production cross section measurements [118–121] to improve the agreement of the transverse momentum of the top quark with data.

Overlap removal

Because a very special phase space region is investigated in this analysis, effects play a role, where different physical processes described in higher orders lead to a redundant modeling of distinct diagrams in the matrix element calculation. For each of these processes distinct simulated samples are available, and multiple ones will be used in order to achieve a precise modeling of the phase space region of interest with low statistical uncertainties. Since these samples are produced for a distinct process only, e.g., $t\bar{t}$ pair production, NLO contributions in this case overlap with the stand-alone $t\bar{t}\gamma$ samples, because photon radiation in the initial state on the one hand is an NLO contribution for $t\bar{t}$ production, but on the other hand also describes $t\bar{t}\gamma$ production in LO. The same holds for the Drell-Yan $Z\gamma^*$ process and the NLO $Z\gamma$ diboson production. To avoid double counting of events, these overlaps need to be removed.

Therefore, the MC simulation for those processes was studied on generator level, to understand which event signatures are exactly produced in both samples. Events that have a signature like in samples where photons are produced in the LO matrix element calculations, are removed from the inclusive samples, to achieve a common higher order description of the selected phase space. Since different generators are used to simulate the different processes, different strategy to remove the overlaps were studied, to ensure that all samples can be used without concerns, and double counting of diagram contributions is rejected.

4.3. Event reconstruction and particle identification

To maintain both a precise and robust particle reconstruction, and flexibility in the identification of physical objects, such as electrons or photons, based on the global reconstruction, particle reconstruction and identification is divided in two major parts. This is needed, since different types of analyses, such as searches or SM precision measurements have different needs for the requirements of their selected particles in terms of efficiency, misidentification, and resolution.

In the global event reconstruction, at first, particles and their properties, such as momentum, energy, and trajectory, are reconstructed with the Particle Flow (PF) algorithm [122] by combining information from all CMS subdetectors. After that, identification criteria determined by specialized CMS physics objects groups (POGs) are applied, dependent on the choice of the analyst regarding the demands mentioned above.

In the following the PF algorithm is briefly introduced by explaining its main features, whereafter more detailed definitions of the physical objects are given.

4.3.1. Particle flow

Traditionally, particles in multi-purpose high energy detectors are identified by their information collected in a certain subdetector component. Electrons for example are identified by measuring the deposited energy in the ECAL, and jets consisting of neutral and charged hadrons and photons are measured independently from informations of the tracker and the muon chambers just with the help of the measurements of the calorimeters. To compensate the only sufficient HCAL performance of the CMS detector, a different method is applied, where all information of all subdetectors are combined and global particle elements are identified. Thus, the excellent performance of the CMS tracking system, the high granularity of the ECAL, and the highly efficient muon tracking system can be exploited. This yields the basis of the particle flow event reconstruction, which showed great performance for the first time in its application in the CMS experiment.

The PF reconstruction and identification procedure is divided in multiple subtasks. Firstly, tracks and clusters are reconstructed separately. Afterwards, they are combined by a linking algorithm. Finally, so-called PF blocks are formed out of the links, and final decisions are made on the type of the particle.

A combinatorial track finding algorithm based on Kalman Filtering [123] is used to reconstruct tracks in three stages. Firstly, seeds are generated that are compatible with tracker hits and therefore with a trajectory of a charged particle. Secondly, trajectories are built by using all tracker layers. Finally, the particle properties, such as momentum and direction, are determined in a fit. The tracking procedure is optimized to maintain a high efficiency by keeping a low misidentification rate. Solely by using this approach, e.g., a tracking efficiency of 99% for muons, and around 70 – 80% for charged pions is achieved. To further increase the efficiency while retaining the misidentification rate as low as possible, an iterative tracking procedure is realized, where each step has a lower efficiency compared to the approach discussed before, but quality criteria requirements ensure a low misidentification rate.

For electrons another separate track reconstruction is realized. In contrast to the tracker based approach described above, an approach based on reconstructed ECAL clusters is used. Thereby, extrapolations back to the inner tracker are realized based on the cluster energy and position. The muon tracking is also different, since here in addition the muon system can be used to gain further information and increase the efficiency and lower the misidentification rate. Three types of muon tracks are reconstructed. The first are standalone muon tracks, where only information from the muon system, in particular seeds built of hits in the DTs and CSCs, is used to reconstruct a muon trajectory through all muon system subcomponents. Global muon tracks are standalone muon tracks, that can be matched to hits in the inner tracker. Tracker muon tracks are obtained by extrapolating inner tracker tracks to the muon system, and are only considered if at least one muon segment hit matches the extrapolation.

The aforementioned clustering algorithm is performed in each subcalorimeter separately. It is used to measure the energy and direction of neutral particles such as photons and neutral hadrons, and distinguish them from charged hadrons and photons originating from electron bremsstrahlung. Thereafter, a fit based on the assumption of Gaussian-distributed cell entries in

topological clusters is realized to obtain the energy and position of each cluster via determination of cluster seeds, where the energy deposits are maximal compared to the neighboring cells.

The last important part of the PF based reconstruction is the linking procedure, where all gained information is combined, based on the nature of each particle. Multiple links are then summed up to a particle flow block, in which separately the final decisions are made. After each identification step, the used subdetector informations, such as tracks and clusters, are removed from the PF block.

Muons are identified first, driven by the high reconstruction efficiency and low misidentification rate using the muon system. Except for jet remnants entering the muon system, called punch through, muons are the only particles leaving a signature in the muon system.

Electrons and prompt photons are identified next, since they produce very similar signatures in the ECAL due to electromagnetic showers, and also in the tracker, if photons are converted to electron-positron pairs. Finally neutral and charged hadrons, and non prompt photons, e.g., originating from meson decays, are identified.

Based on the PF reconstruction, an analysis-specific physical object selection can be performed on top of the PF objects, which will be discussed in the following.

4.3.2. Primary vertex

The primary vertex of an event is defined by the vertex with the largest sum of associated transverse momenta squared determined by vertex reconstruction algorithms [124], and needs to be reconstructed within a distance of 24 cm in z direction, and 2 cm in the x-y-plane.

4.3.3. Muons

Muons are required to have a transverse momentum larger than 15 GeV. Because the muon chambers extend only to a pseudorapidity range of $|\eta| < 2.4$, muons need to be reconstructed within this region. In addition, muons have to pass quality requirements suggested by the CMS collaboration, yielding a $\approx 98\%$ efficiency [125].

A muon candidate needs to be reconstructed as a PF muon, and either as a global muon or a tracker muon. If it is reconstructed as a global and as a tracker muon, the segment compatibility, which is a measure for the comparability between the tracker tracks and an extrapolation to the muon system, has to be larger than 0.303. In addition, more than 80% of the inner track layers need to be used in the track fit, the normalized goodness of fit ($\chi^2/ndof$) needs to be less than 3, the match between the standalone muon position and the tracker muon must have $\chi^2 < 12$, and the maximum χ^2 found by a kink finding algorithm, which tries to separate the track into two independent tracks, needs to be smaller than 20. If the muon is reconstructed exclusively as a tracker muon, only the segment compatibility needs to be greater than 0.451, and the other requirements on the track quality are removed.

Besides the identification requirements, conditions on the position of the track relative to the reconstructed primary vertex are imposed. In the transverse direction (d_{xy}), muon tracks need to be closer than 0.05 cm to the vertex, and in the longitudinal direction (d_z), the distance needs to be smaller than 0.1 cm. To quantify the dominance of an object with respect to its surrounding particles in its vicinity, the concept of isolation is introduced. A cone dependent isolation is used, called mini isolation, where the cone size in the $\phi - \eta$ plane is calculated relative to the transverse momentum of the particle as follows:

$$R = \max \left(0.05, \min \left(0.2, \frac{10 \text{ GeV}}{p_T} \right) \right). \quad (4.2)$$

Pileup corrections are also taken into account in the mini isolation calculation. The determined energy deposited in the cone around the muon must not exceed 10% of the transverse momentum of the particle.

Table 4.2.: Identification criteria for muons, spread for muons being reconstructed as solely tracker and as tracker and global muons.

Variable	Value	
	tracker and global muon	tracker muon
segment compatibility	> 0.303	> 0.451
fraction of valid inner tracker hits	> 0.8	-
normalized χ^2 of global track fit	< 3	-
chi2localposition (track standalone position match)	< 12	-
kink finder	< 20	-
p_T	$> 15 \text{ GeV}$	
η	< 2.4	
mini isolation	< 0.1	
d_{xy}	$< 0.05 \text{ cm}$	
d_z	$< 0.1 \text{ cm}$	

Table 4.3.: Identification criteria for electrons given separately for reconstructed electrons in the barrel and endcap.

Variable	Value	
	EB	EE
$\sigma_{i\eta i\eta}$	< 0.00988	< 0.0298
$\Delta\eta_{Seed}$	< 0.00311	< 0.00609
$\Delta\phi_{In}$	< 0.00311	< 0.00609
H/E	< 0.253	0.0878
relative combined PF isolation	< 0.0695	< 0.0821
$ \frac{1}{E} - \frac{1}{p} $	< 0.134	< 0.13
# missing inner hits	≤ 1	≤ 1
Photon conversion veto	true	true
p_T	$> 15 \text{ GeV}$	
η	< 2.4	
mini isolation	< 0.2	
d_{xy}	$< 0.05 \text{ cm}$	
d_z	$< 0.1 \text{ cm}$	

4.3.4. Electrons

The list of requirements imposed on the electron selection is driven by a symmetric approach between the two lepton selections. The same conditions on the distance to the primary vertex, ($d_{xy} < 0.05$, $d_z < 0.1$), pseudorapidity ($|\eta| < 2.4$), and transverse momentum ($p_T > 15 \text{ GeV}$) need to be fulfilled. The mini isolation criterion is relaxed to 20%.

The identification requirements determined by the CMS Collaboration [126] separately for electrons reconstructed in the ECAL barrel (EB: $|\eta_{Supercluster}| < 1.479$) and endcap (EE: $|\eta_{Supercluster}| > 1.479$) region are listed in Table 4.3. Here, $\sigma_{i\eta i\eta}$ is a quantity characterizing the width of the electromagnetic shower shape in the ECAL in η direction. It is calculated as the weighted variance of energy deposits in the full 5x5 pixel ECAL supercluster. Since jets emerging from hadrons have a wider shower in the ECAL than electrons, a differentiation can be achieved. Consistency between the information of the reconstructed track at the vertex, and the supercluster is required, by setting conditions on $\Delta\eta$, $\Delta\phi$, and the supercluster energy E

and track momentum p . To further separate electrons from hadrons, more energy should be deposited in the ECAL, rather than in the HCAL (H/E). An isolation requirement based on the PF determined isolation, assures that prompt electrons are separated from electrons coming from, e.g., jets. Photons misidentified as electrons are suppressed by imposing a requirement on the number of missing inner hits in the tracker, and an additional veto for photon conversions to electron-positron pairs determined in an χ^2 fit.

4.3.5. Photons

Photons are required to have a transverse momentum larger than 20 GeV. Because in the considered SUSY signal scenarios the sparticles typically have high masses, central collisions are needed to produce these in the proton-proton interactions. Therefore, the sparticles decay mainly in rest, and the photons originating from the decays are produced more centrally in comparison to SM processes. Hence, only photons reconstructed in the ECAL barrel are considered ($|\eta| < 1.4442$). Additional identification criteria determined by the CMS Collaboration [127] are listed in Table 4.4. Similar to the requirements on $\sigma_{i\eta i\eta}$ and H/E for the electron selection,

Table 4.4.: Identification criteria for photons reconstructed in the ECAL barrel.

Variable	Value
$\sigma_{i\eta i\eta}$	< 0.01031
H/E	< 0.0597
PF charged hadron isolation	< 1.295
PF neutral hadron isolation	$< 10.910 + 0.0148 \cdot p_T + 0.000017 \cdot (p_T)^2$
PF photon isolation	$< 3.630 + 0.0047 \cdot p_T$
η	< 1.4442
p_T	$> 20 \text{ GeV}$
# Pixel Seeds	0

these conditions in the photon identification ensure the suppression of selecting hadrons faking the photon signature. Additional different isolation criteria lower the amount of selected photons originating from neutral and charged hadrons, and photons created from light meson decays. Requirements on the minimum distance in the $\eta - \phi$ plane between the photon and selected lepton candidates ($\Delta R(\gamma, \ell) > 0.3$) significantly reduce contributions from final state radiation (FSR) photons. By requiring that no pixel seed can be assigned to a trajectory between ECAL supercluster and interaction point, a clear differentiation between electrons and photons is achieved.

4.3.6. Jets

Jets are complicated objects due to the complexity of the hadronization and fragmentation processes. Therefore, a sophisticated clustering algorithm is needed to identify them and measure their energy properly. Jets are clustered with the anti- k_T algorithm [128] included in the FAST-JET package [129, 130] with a distance parameter of $R = 0.4$. In the clustering procedure, each PF object is considered a pseudojet, and these pseudojets are summed up iteratively until a certain breaking condition is fulfilled. The final jet momentum is defined as the sum of the momenta of the constituents of the jet. Charged hadrons not emerging from the primary vertex are not considered in the clustering. The jet energy is corrected for effects originating from pileup and the detector response, tuned with the help of different data control selections and simulation [131]. Reconstructed jets are required to pass loose identification criteria proposed by the CMS Collaboration [132], to have a transverse momentum larger than 30 GeV, and their

pseudorapidity must not exceed $|\eta| = 3$. In addition, jets overlapping with photon or lepton candidates in a cone with radius $R = 0.4$ in the $\eta - \phi$ -plane, are removed from the selection to avoid double counting of objects.

4.4. Definition of observables

Throughout this thesis, different observables are used to define different phase space regions, in particular the signal region and control and validation regions important for the background prediction. All these high level variables are defined based on low level quantities such as the p_T of different objects.

4.4.1. Missing transverse momentum

Missing transverse momentum p_T^{miss} is one of the most important observables in searches for BSM physics. In typical SUSY models, see Section 2.3, significant p_T^{miss} is expected in the events due to the LSP leaving the detector undetected. In SM processes only neutrinos and mismeasurements of, e.g., the jet energies lead to missing transverse momentum, because before a collision the transverse momentum of the colliding protons is nearly negligible. In such SUSY events, the LSP gains a lot of energy in its production in the decays of sparticles with higher masses. Therefore, much more p_T^{miss} is expected to be produced in SUSY events as in SM processes. Missing transverse momentum quantifies the imbalance of all reconstructed particles in an event and is defined as

$$p_T^{\text{miss}} = |\vec{p}_T^{\text{miss}}| = \left| - \sum_{P \text{ Objects}} p_{T,i} \right|. \quad (4.3)$$

Jet energy corrections are propagated to the missing transverse momentum vector to avoid a bias in events with large hadronic activity.

Total hadronic activity H_T

The hadronic activity H_T is defined as the scalar sum of the transverse momenta of all jets, that are clustered with the procedure above, and fulfill $|\eta| < 3$ and $p_T > 30 \text{ GeV}$

$$H_T = \sum_{\text{Jets}} |\vec{p}_{T,i}|. \quad (4.4)$$

Invariant dilepton mass $m_{\ell\ell}$

The invariant dilepton mass $m_{\ell\ell}$ is defined as the absolute value of the sum of both lepton four momenta

$$m_{\ell\ell} = |\mathbf{p}_{\ell_1} + \mathbf{p}_{\ell_2}|. \quad (4.5)$$

The transverse mass m_T

If particles decay to invisible and visible objects, the invariant mass of the mother particle cannot be fully reconstructed. In contrast to the calculation of the invariant dilepton mass introduced above, invisible decay products are not measured in the detector. Only the missing transverse energy p_T^{miss} can be measured, and is only reasonable to be defined in the transverse plane. In such cases, the transverse mass m_T of the mother particle can be reconstructed by using only transverse components of all involved fourmomenta.

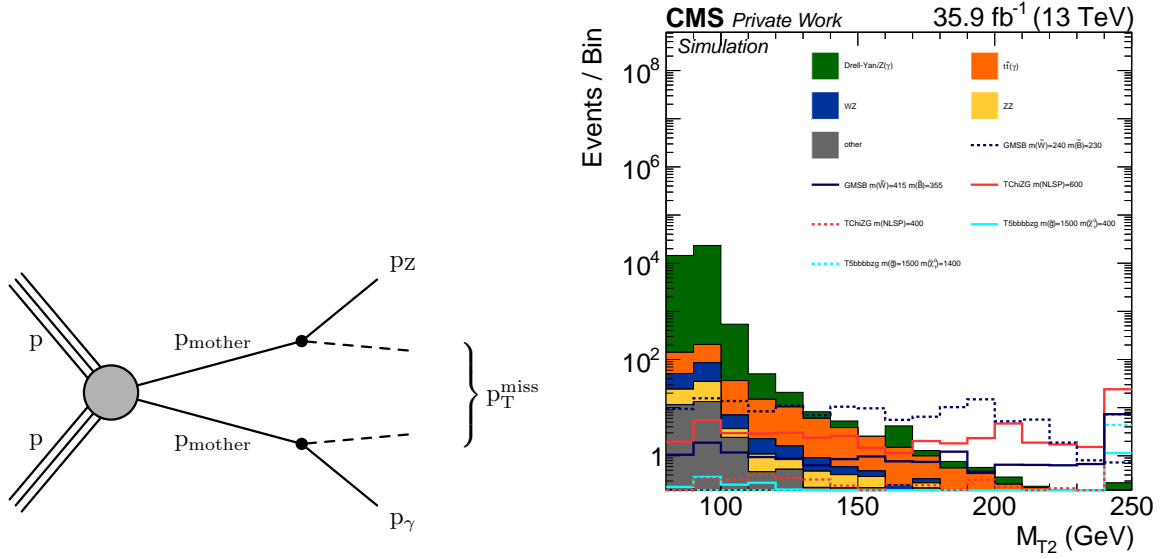


Figure 4.1.: Sketch of decays of pair produced particles to p_T^{miss} and a Z boson or photon respectively (left). Stacked background and different signal points against the transverse mass M_{T2} (right). Both are obtained from simulation. For each signal model two different signal points are shown. For their masses refer to the legend in the plot.

The transverse mass of two objects with transverse momentum \vec{p}_T^A and \vec{p}_T^B yields the transverse mass of the mother particle if both particle emerge from the same decay. It is defined as

$$m_T(\vec{p}_T^A, \vec{p}_T^B) = \sqrt{2|\vec{p}_T^A||\vec{p}_T^B|(1 - \cos(\Delta\phi))}, \quad (4.6)$$

where $\Delta\phi$ is the angle between \vec{p}_T^A and \vec{p}_T^B in the transverse plane.

In cases of one invisible decay product, m_T is calculated assuming that p_T^{miss} describes the p_T of the invisible decay product. By definition it has an upper limit at the actual mass of the mother particle, and yields therefore good estimate for the total mother particle mass.

The transverse mass M_{T2}

In case of two identical particles, each decaying to one invisible and one visible particle, the transverse mass M_{T2} [133, 134] is a useful generalization of m_T . In this analysis it is calculated to estimate the mass of the NLSP, which decays to an invisible object, the gravitino, and one visible particle, a Z boson or a photon. It is defined as

$$M_{T2} = \min_{\tilde{p}_T^{\tilde{G}1} + \tilde{p}_T^{\tilde{G}12} = \vec{p}_T^{\text{miss}}} \left(\max \left[m_T(\vec{p}_T^Z, \vec{p}_T^{\tilde{G}1}), m_T(\vec{p}_T^\gamma, \vec{p}_T^{\tilde{G}12}) \right] \right), \quad (4.7)$$

where the final value is determined via minimization as indicated by min in the equation. Descriptively, the algorithm tries to estimate the transverse masses of the mother particles under the assumption, that p_T^{miss} is composed of exactly one massless particle from each decay branch. For decays of the NLSP in all signal models, the M_{T2} distribution has a upper limit at the mass of the lightest neutralino, while for all SM backgrounds M_{T2} yields much lower values in comparison to the high SUSY masses. See Figure 4.1 for a visualization of the described decay structure and a M_{T2} distribution.

4.5. Lepton pair selection and quality requirements

In the analysis, different datasets selected with different dilepton triggers are combined, see Section 4.1. Therefore it is possible, that an event is contained in more than one data set. Hence, it is assured with the following procedure, that no event is double counted. At first, all leptons per event are sorted by their transverse momenta. The leading and subleading³ lepton are identified. Their flavor combination then determines the classification of the event as "dielectron", "dimuon", or "electron-muon". For instance, a dielectron event is classified as such, if the event originates from the DoubleEG sample, both the leading and the trailing lepton are electrons, and it is selected by at least one of the dielectron triggers. This set of conditions ensures the exclusivity of the three selections.

In addition, there are some requirements imposed on the dilepton system. The trailing and leading lepton need to be separated at least by a distance of $\Delta R = 0.1$ in the transverse plane, and the invariant dilepton mass $m_{\ell\ell}$ should be larger than 50 GeV. The first requirement provides a cleaning between the lepton collections and ensures, that no lepton candidate is counted twice, while the latter threshold is introduced, because the simulation of the Drell-Yan simulation does not include events with lower dilepton masses. Events with lower invariant dilepton masses are not of interest for this analysis, since in the following only leptons originating from a Z boson decay are selected, resulting in an invariant dilepton mass around the Z boson mass of ≈ 91 GeV. Hereafter, the dielectron and dimuon selections are combined to a dilepton selection to increase the statistics in the validation, and especially in the signal region.

Additional leptons need to pass the same selection as the trailing lepton.

Also, several event quality filters are applied to reject contaminated events [135]. The rejected events consist mainly of events with faulty detector signals caused by noise or anomalies, spurious energy deposits in ECAL endcap crystals, cosmic muons, muons being misidentified as charged hadrons, or muons produced in scattering processes with the beam halo.

4.6. Triggers and trigger efficiency measurement

As pointed out in Section 4.1, the events are recorded with various dilepton triggers. For each dilepton combination ($ee, \mu\mu, e\mu$) multiple triggers are used because of the changing instantaneous luminosity over the 2016 run period, and different triggers were active at different times. The main trigger paths are isolated dilepton triggers, while non-isolated trigger paths are added to increase the efficiency for boosted topologies of the dilepton system. A list of all used HLT trigger paths is given in the appendix in Table C.1 and Table C.2. While the same-flavor dilepton triggers ($ee, \mu\mu$) are used as signal triggers, the different-flavor triggers ($e\mu$) are used to select events needed for the background prediction of the top pair production ($t\bar{t}(\gamma)$) background. This is explained in more in detail in Section 5.2.1. The various dilepton triggers altogether have transverse momentum thresholds for the dileptons of around 17 – 33 GeV for the leading lepton, and 8 – 33 GeV for the trailing one. Additional triggers with hadronic activity (H_T) or p_T^{miss} thresholds are relevant for the trigger efficiency measurement, which will be presented in the following.

Trigger efficiency measurement

A trigger efficiency curve is characterized by an inefficient part, a more or less sharp transition ("Turn On") to the efficient part, that is ideally located at the nominal threshold of the trigger path, and a flat efficient part.

Measuring the trigger efficiency is essential to obtain appropriate transverse momentum require-

³Called trailing from now on.

ments for the dilepton system. In the signal simulation using the FASTSIM package no trigger simulation is performed, while it is done for the SM background samples. Therefore, the efficiency needs to be measured also on simulation, such that the signal simulation can be scaled accordingly. In addition, the SM simulation samples will be weighted with a factor, correcting for differences in the efficiency between data and simulation.

A logical OR combination of all dilepton triggers with the same-flavor requirements is used. Thus, for an event only one of the used triggers has to be fired to be selected for the key analysis. The combined trigger efficiency ε is measured using a baseline trigger. An appropriate baseline trigger has to be chosen, meaning that it needs to be uncorrelated to the signal trigger which efficiency is being measured. In addition, the baseline trigger needs to provide a sufficient number of events to ensure a sample of events large enough to reduce the statistical uncertainty of the measurement. The signal trigger efficiency is defined as the number of events passing baseline and signal trigger, divided by the number of events passing only the baseline trigger:

$$\varepsilon = \frac{\#(baseline \wedge signal)}{baseline}. \quad (4.8)$$

As a consequence, the efficiency of the baseline trigger cancels, and the pure signal trigger efficiency is maintained. As baseline triggers, a combination of various triggers with H_T thresholds is used. These thresholds range from 200 – 800 GeV. Therefore, the measurement is not performed on the dilepton data streams, but on the H_T datasets. The event selection consists of the lepton pair selection introduced in Section 4.5 with an additional $H_T > 200$ GeV requirement to ensure, that the baseline triggers are efficient. An additional matching between the selected leptons and the trigger objects responsible for the firing of the triggers is performed.

Since dilepton triggers are used, the threshold of the efficient part needs to be determined for each lepton trigger leg separately. Resulting efficiency curves for all three dilepton combinations measured both on data and simulation are shown in Figure 4.2 against the p_T of the trailing lepton. The statistical uncertainties of the individual bins are calculated using 68% confidence level (CL) Clopper-Pearson intervals [136]. The measurements suffer mainly from the available sample size in the H_T triggered data set, while the available number of simulated events is very high per definition. The electron-muon channel is affected the most by this effect. However, the efficiency curves show the structure of multiple transitions into efficient phases, as it is expected from a combination of triggers with very different ranges of thresholds. As indicated by the dotted lines in the plots, the lepton p_T cut was determined to be 20 GeV for the trailing lepton, and 25 GeV for the leading one. Although the dielectron and electron-muon triggers are not yet fully efficient at this threshold, as it is the case for the dimuon trigger, this requirement is imposed also on the other two selections in order to obtain a symmetric lepton selection. The mean plateau efficiencies are shown as gray bands with their statistical uncertainties in the plots. The mean efficiency is also measured on simulation, and all efficiency values are given in Table 4.5. These are obtained by requiring both leptons to pass the 25 GeV and 20 GeV threshold, respectively. As can be seen, these values do not differ very much from the values quoted in the plots, where no lepton p_T requirement in the selection is imposed. Thus, the leading lepton leg is nearly fully efficient, when the trailing lepton has a p_T larger than 20 GeV. Additional efficiency values for the same triggers obtained with a p_T^{miss} baseline selection, that are discussed in the following, are given, too. The efficiency curves after applying the p_T cuts, are also studied in various other distributions to assure the stability of the used triggers.

In addition the agreement between rescaled simulation by the factor $\varepsilon' = \varepsilon_{Data}/\varepsilon_{MC}$ and data is shown in the ratio plots beneath the efficiency curves. It can be concluded, that the efficiencies agree within the systematic uncertainty, which is set to cover differences between data and simulation. It is determined to be 3%, and is indicated with the red uncertainty band in the plots.

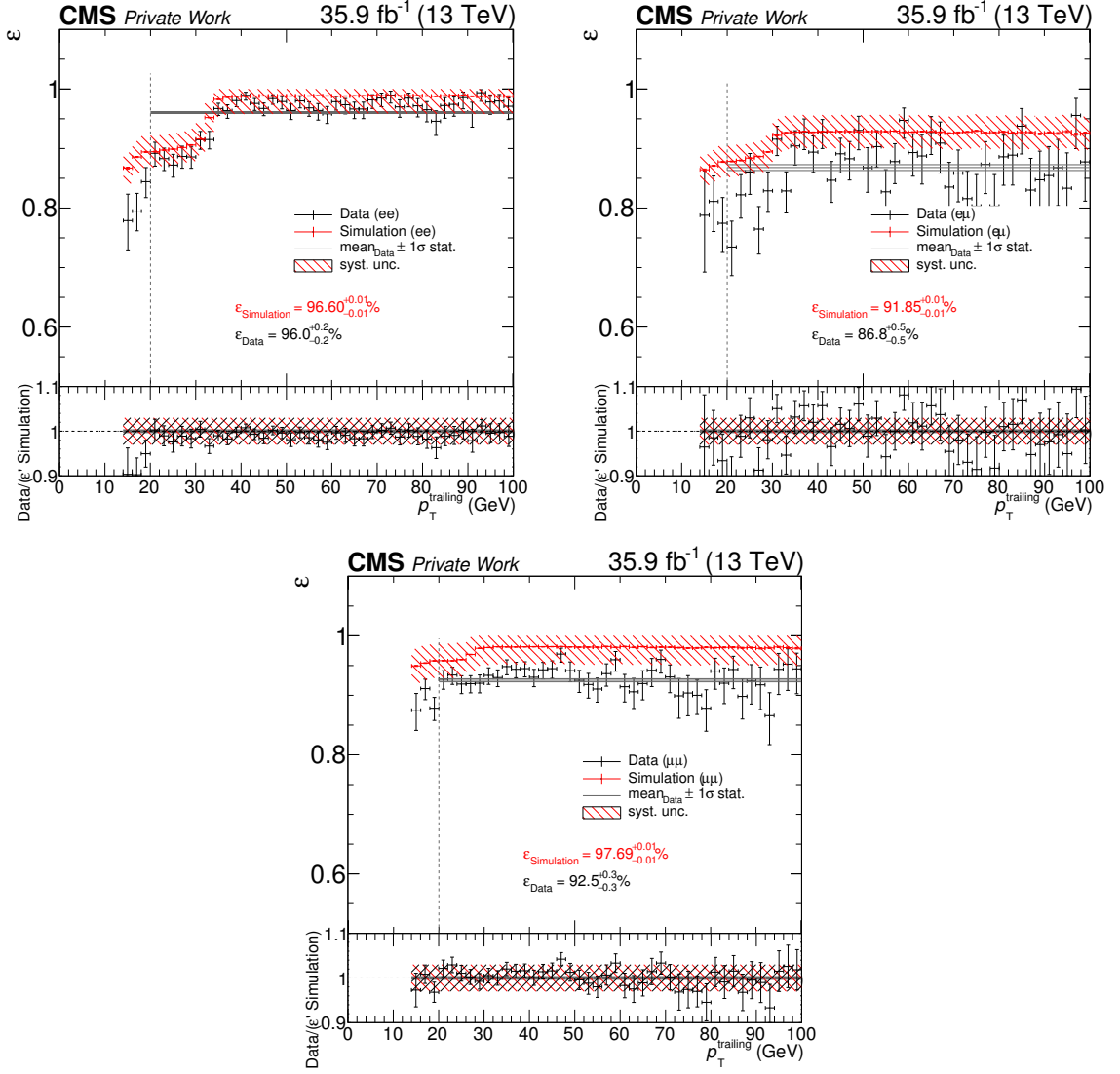


Figure 4.2.: Measurement of the combined efficiency for all dilepton trigger combinations on data (black) and simulation (red) for the ee (top left), $e\mu$ (top right), and $\mu\mu$ (bottom) channels. The measurement is performed using various H_T baseline triggers, while the selection consists of the lepton pair preselection, and a $H_T > 200$ GeV requirement. The mean of the data efficiency with its statistical uncertainty (gray band), and the 3% systematic uncertainty on the measurement (red band) are also shown.

As an additional independent check, the whole trigger efficiency measurement was performed also on p_T^{miss} datasets with p_T^{miss} baseline triggers, that have thresholds of around 110 – 600 GeV. This selected phase space region should be more or less orthogonal the H_T selection. It is also closer to the phase space of the final signal region, since the signal region selection contains a p_T^{miss} threshold, see Section 5.1.2. Because the efficiency in the low H_T region cannot be studied with the H_T baseline selection due to the inherent inefficiency of these triggers, with the p_T^{miss} baseline selection this region can be covered. As can be read from Table 4.5, the values obtained from this method are also in agreement with the efficiencies measured using the H_T selection. Moreover, the pure simulated trigger efficiency was investigated in dependence of H_T , to confirm the reliability of the simulation.

Table 4.5.: Trigger efficiencies determined both on data and simulation for both baseline trigger configurations for the ee , $e\mu$, and $\mu\mu$ channels.

baseline trigger	Data		Simulation	
	H_T	p_T^{miss}	H_T	p_T^{miss}
ee	$96.1^{+0.2\%}_{-0.2\%}$	$93.8^{+0.3\%}_{-0.3\%}$	$96.62^{+0.01\%}_{-0.01\%}$	$96.79^{+0.02\%}_{-0.02\%}$
$e\mu$	$86.9^{+0.5\%}_{-0.5\%}$	$86.8^{+0.3\%}_{-0.3\%}$	$91.92^{+0.01\%}_{-0.01\%}$	$91.46^{+0.05\%}_{-0.05\%}$
$\mu\mu$	$92.6^{+0.3\%}_{-0.3\%}$	$93.9^{+0.3\%}_{-0.3\%}$	$97.71^{+0.01\%}_{-0.01\%}$	$97.63^{+0.02\%}_{-0.02\%}$

Analysis strategy and background estimation

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Processes producing SUSY particles have significantly smaller cross sections than most SM processes. Therefore, a sophisticated understanding of the relevant production and decay scenarios is needed in order to separate the potential interesting events from the huge amount of SM background. Since this search is targeting SUSY scenarios with bino- and wino-like NLSPs, final states with photons and Z bosons are expected. Choosing the dileptonic decay of the Z boson, there are not many SM background processes leading to the investigated final state. Especially the requirement of a photon and missing transverse momentum p_T^{miss} in the events reduces most of the background, such that, e.g., the QCD background becomes negligible. Left over are processes producing two same-flavor opposite-charge (SFOC) leptons, one photon and missing transverse momentum. The most important ones are $t\bar{t}(\gamma)$ production, Drell-Yan/ $Z(\gamma)$, ZZ, and WZ diboson production. This will be discussed in more detail in Section 5.2.

The key strategy of this analysis is to impose as little requirements as necessary, to obtain an inclusive event selection, so that many model scenarios can be investigated. Hence, only the existence of all expected final state particles is required, where the Z boson is reconstructed from the two selected leptons. Therefore, loose requirements on the lepton and photon energies can be imposed. Not many additional requirements are needed in the following to obtain a sensitive signal region selection.

In the final selection a counting experiment is performed, where predicted and observed data yields are compared, and the result is interpreted in different signal models.

5.1. Event Selection

In this section, the event selection is discussed, including region definitions important for the background prediction, which is based on simulation. In those control regions, each enriched with a specific type of background events and suppressed signal contribution, the simulation is tuned to match the measured data. In an additional validation region, the background prediction will be examined, and finally a two bin counting experiment is performed in the signal region. But first, the preselection will be introduced.

5.1.1. Preselection

The preselection acts as a first rough definition of the phase space that is of interest, and rejects inefficient parts of the used triggers. The preselection imposed on the dilepton triggered events is defined as follows:

- exactly one SFOC lepton pair (ee or $\mu\mu$) as defined in Section 4.3,
- $p_T > 25$ GeV for the leading lepton,
- $p_T > 20$ GeV for the trailing lepton,
- at least one photon,
- $\Delta R(\ell_1, \gamma) > 0.3$ and $\Delta R(\ell_2, \gamma) > 0.3$,
- $81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$.

The first four conditions imply the existence of the final state particles, including the definition of the physics objects and lepton pair selection explained above, and the p_T requirements determined in the trigger efficiency measurement. The fifth requirement reduces contributions of final state radiation photons, that are radiated off by the leptons in electromagnetic showers. The invariant dilepton mass requirement ensures that both leptons originate from an on-shell Z boson decay, and reduces different contributions of SM backgrounds that produce dileptons with an invariant mass not in agreement with a Z boson.

5.1.2. Signal region

The signal region (SR) selection is optimized to maintain high sensitivity for various SUSY scenarios both with electroweak and strong production. In the considered models, see Section 2.3.2, the NLSP ($\tilde{\chi}_1^0$) can decay to a Z boson or a photon in combination with gravitinos \tilde{G} , which are undetectable and create missing transverse momentum in the event. Therefore, the requirement of p_T^{miss} being larger than in most of the SM background processes enables a good separation between SM background and SUSY signal. The p_T^{miss} threshold is not supposed to be too high, in order to maintain sensitivity to low neutralino masses as well. Additional high separation power is given by the transverse mass M_{T2} , because it yields a good estimate of the NLSP mass. Also, there is no known SM particle which can decay into photons or a Z boson accompanied with neutrinos creating an momentum imbalance in the detector. Therefore, M_{T2} on average is much larger for SUSY processes than for SM processes. Both the M_{T2} and p_T^{miss} distributions of events fulfilling the preselection are shown in Figure 5.1 for the total background and signal points of each model. Hence, the SR is defined by the following criteria:

- $p_T^{\text{miss}} > 150 \text{ GeV}$,
- $M_{T2} > 100 \text{ GeV}$.

The final SR is binned in two search bins in the p_T^{miss} distribution, one ranging from 150 to 200 GeV, and the second one ranging from 200 GeV to infinity, see Section 6.1.

5.1.3. Control regions

Different control regions (CRs) are defined for the four main background processes, in order develop a background prediction for each background process. These CRs are built such that they are fully orthogonal to the signal region and among each other and include a large amount of events for precise studies and high purity. The main groups of backgrounds are $t\bar{t}(\gamma)$, $DY/Z(\gamma)$, WZ, and ZZ production.

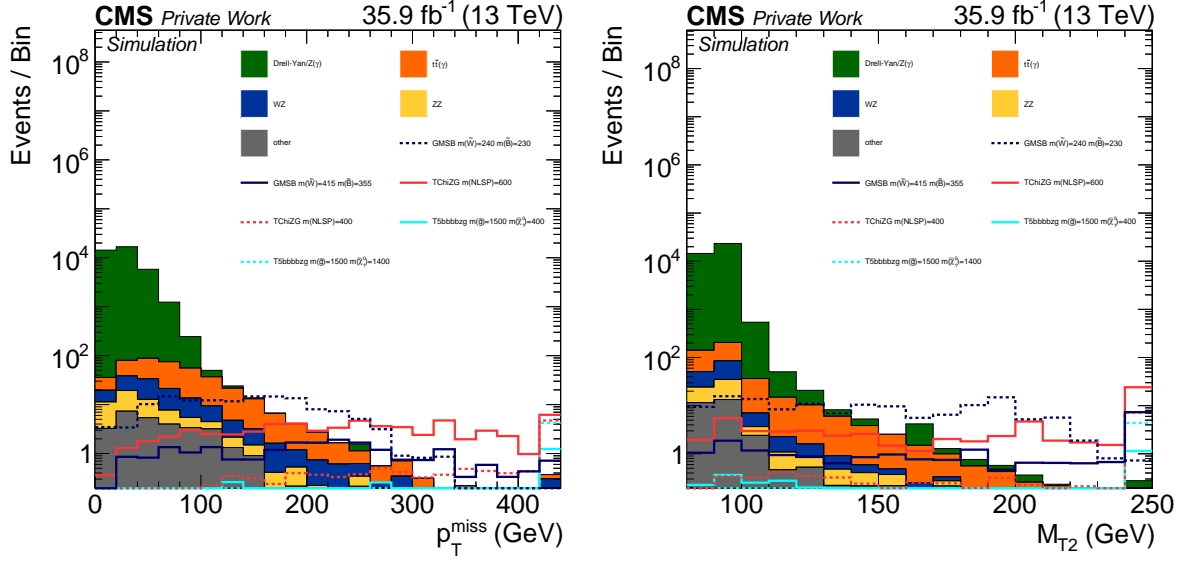


Figure 5.1.: Stacked background and different signal points against p_T^{miss} (left) and the transverse mass M_{T2} (right). Both are obtained from simulation. For each signal model two different signal points are shown. For their mass parameters refer to the legend in the plots.

$t\bar{t}(\gamma)$ - control region

To obtain a CR for the $t\bar{t}(\gamma)$ background, the flavor symmetry of the process is exploited. The two top quarks can decay independently with the same probability to an electron or a muon, resulting in an equal number of same-flavor and different-flavor final state events. The different-flavor triggers are needed to guarantee a basis data set containing a sufficient number of events. In addition, the background can be studied in the same high p_T^{miss} and M_{T2} regions where the SR is defined due to the underlying symmetry of the dilepton production. The preselection criteria need to be adjusted accordingly, resulting in a CR definition of

- exactly one different-flavor opposite-charge (DFOC) lepton pair ($e\mu$),
- at least one photon,
- $\Delta R(\ell_1, \gamma) > 0.3$ and $\Delta R(\ell_2, \gamma) > 0.3$.

The invariant dilepton mass window requirement is removed from the preselection, since the reconstructed dilepton mass is not in coincidence with the Z boson mass. In contrast, it shows a broad distribution because the leptons are not originating from the same mother particle. The requirement being responsible for the orthogonality to the SR is the different dilepton flavor requirement.

Drell-Yan/Z(γ) - control region

The Drell-Yan/Z(γ) background has nearly the same phenomenological topology as the SUSY signal, except for lower missing transverse momentum, since it is mainly present due to mismeasurements of jets. Therefore, the p_T^{miss} distribution of the Drell-Yan/Z(γ) background is defined by the p_T^{miss} resolution of the detector and reconstruction. The final control region definition on top of the preselection is

- $p_T^{\text{miss}} < 100$ GeV.

This region is orthogonal to the SR per definition due to the inverted p_T^{miss} requirement.

WZ - control region

In order to obtain a high purity WZ control region, the SFOC dilepton criteria are adjusted such that the fully leptonic decay of the diboson system is studied. As in the preselection, a SFOC lepton pair is required, but the additional lepton veto is inverted. Hence, the existence of third lepton is required. This ensures exclusivity between the SR and this CR. Since the $W \rightarrow 2\ell\nu$ boson decays are selected, with the help of additional p_T^{miss} and m_T requirements the purity of the selection of WZ diboson production events is enhanced. The transverse mass m_T is calculated using the third lepton and the missing transverse momentum, and is therefore an estimate for the W boson mass. In the identification of the lepton pair belonging to the decayed Z boson, all combinations fulfilling flavor and charge requirements are tested. In case of multiple valid combinations, the combination with the invariant dilepton mass closest to the Z boson mass is chosen. To ensure a selection with a suitable amount of data, since the cross section for diboson production is rather low, the existence of at least one photon from the preselection is removed. The final region selection is

- exactly one SFOC lepton pair (ee or $\mu\mu$),
- exactly one additional third lepton (e or μ),
- $\Delta R(\ell_1, \gamma) > 0.3$ and $\Delta R(\ell_2, \gamma) > 0.3$,
- $81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$,
- $p_T^{\text{miss}} > 70 \text{ GeV}$,
- $m_T(\vec{p}_T^{\text{miss}}, p_{\ell_3}) > 50 \text{ GeV}$.

ZZ - control region

The strategy to achieve a pure ZZ diboson selection that does not overlap with the SR selection is very similar to the WZ CR selection described above. By selecting events, where both Z bosons decay leptonically to charged leptons (ee or $\mu\mu$), per definition an exclusive control region is obtained. As in the WZ CR selection, flavor and charge requirements are considered to construct Z boson candidates from the four selected leptons. In cases, where multiple valid solutions for the reconstruction of two Z bosons exist, the possibility with the first Z boson candidate mass closest to the nominal Z boson mass is chosen. The second Z boson candidate has to fulfill a looser mass agreement compared to the first one. Also, the existence of a photon in the event is not required. In total, the selection criteria is

- exactly two SFOC lepton pairs (ee or $\mu\mu$),
- $\Delta R(\ell_1, \gamma) > 0.3$ and $\Delta R(\ell_2, \gamma) > 0.3$ for the first pair,
- $76 \text{ GeV} < m_{\ell\ell} < 106 \text{ GeV}$ for the mass of the first Z boson candidate,
- $50 \text{ GeV} < m_{\ell\ell} < 130 \text{ GeV}$ for the mass of the second Z boson candidate.

5.1.3.1. Validation region

An additional validation region (VR) is constructed, where the developed background predictions are verified by performing data to background prediction comparisons. Therefore, it is convenient to choose the VR close in phase space to the SR. This is achieved by applying the same selection requirements as for the SR, but demanding either the p_T^{miss} the M_{T2} requirement to fail. Hence, the VR is built as a sideband to the SR. The VR must also not overlap with the DY/Z(γ) CR, thus a minimal p_T^{miss} requirement needs to be imposed. The selection requirements for the VR in addition to the preselection are the following:

- $p_T^{\text{miss}} > 100 \text{ GeV}$,

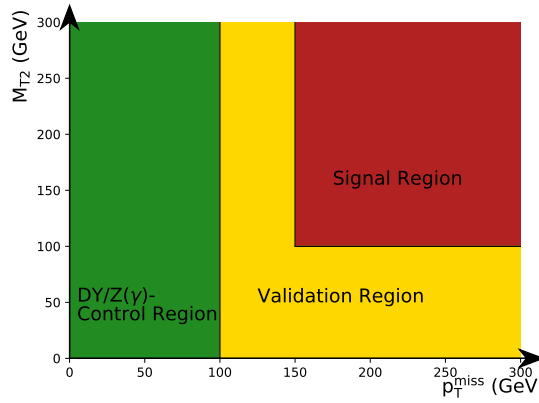


Figure 5.2.: Visualization of the definition of the signal, validation and DY/Z(γ) control region in the M_{T2} - p_T^{miss} plane.

- either $p_T^{\text{miss}} < 150$ GeV or $M_{T2} > 100$ GeV.

A visualization of the signal, validation, and DY/Z(γ) control region definitions in the M_{T2} - p_T^{miss} plane can be found in Figure 5.2. Two dimensional histograms for the number of expected events motivating the region definitions are shown in Figure 5.3 for all background processes, together with distributions of different benchmark points for all three considered signal models. These distributions show also specific features of the considered signal models regarding important kinematic observables. Because the TChiZG model is a one parameter scan, and the only free parameter is the NLSP mass, it directly determines the maximum amount of transverse momentum for the decay products and thus directly the Z boson p_T and the p_T^{miss} originating from the gravitinos. Hence, p_T^{miss} and M_{T2} calculated from the bosons and p_T^{miss} are strongly correlated. Also, the endpoints of the p_T^{miss} and M_{T2} distributions are of the same order and coincide with the NLSP mass.

In case of the strong SMS, it is not directly the case. Since this is a two dimensional parameter scan, the event kinematics also depend on the mass difference of the gluino and the NLSP mass, as discussed in Section 2.3.2. In cases where the mass difference is small, the kinematics evolve similar as for the EWK SMS, while for larger mass differences, as shown in Figure 5.3, the correlation between M_{T2} and p_T^{miss} is much weaker and the distributions are much broader. The distributions of the GMSB model behave like a mixture of the two SMSs, depending on the wino and bino masses.

And most importantly, the signal events mainly populate the SR for all models, with small contributions in the CRs and the VR, while the majority of the background events contribute to the DY/Z(γ) CR and a minor part to the VR. Only a minority of the background events are expected in the SR. Hence, in total a good separation between background and signal is achieved.

5.2. Background estimation

In this section, the used background estimation methods are discussed, including the study of systematic effects. The total background is put together of $t\bar{t}(\gamma)$ production, Drell-Yan and Z(γ) events, WZ and ZZ diboson production, and a remaining group of backgrounds, composed of, e.g., single top and triboson production (See Section 4.2 and Section 5.1.3). The relative contributions for all background processes in the two SR bins are depicted in Figure 5.4. The most dominant background is $t\bar{t}(\gamma)$, followed by WZ, ZZ, and Drell-Yan/Z(γ).

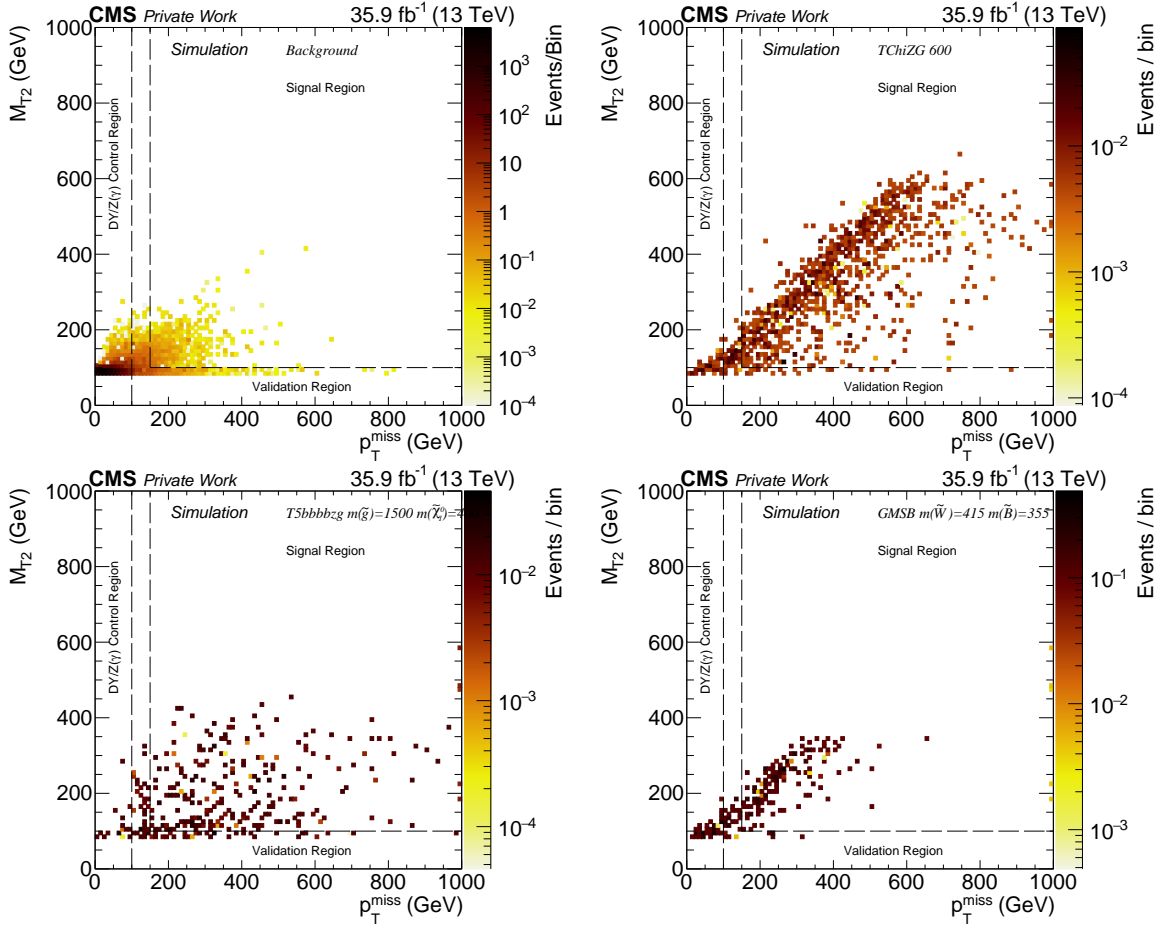


Figure 5.3.: Distribution of the total number of expected background events in the M_{T2} - p_T^{miss} plane (upper left). Distributions for the number of expected signal events for the TChiZG SMS with an NLSP mass of 600 GeV (upper right), the T5bbbbZG SMS with a gluino mass of 1.5 TeV and a neutralino mass of 400 GeV (bottom left), and the GMSB model with $m(\tilde{W}) = 415$ GeV and $m(\tilde{B}) = 355$ GeV (bottom right).

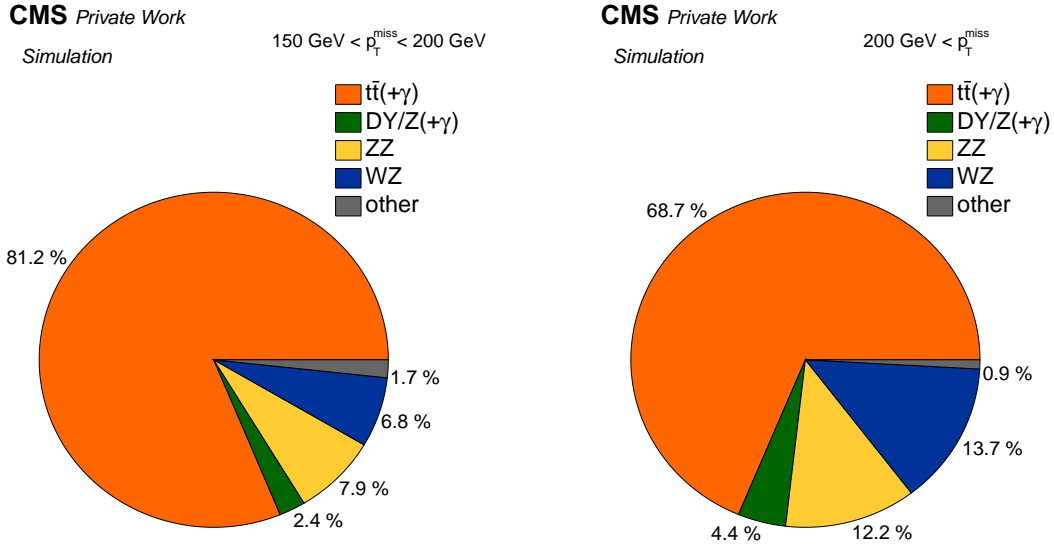


Figure 5.4.: Relative amounts for all group of considered backgrounds for the two search bins in the SR.

The leptonic decays of the top pairs generated in association with a photon significantly contribute to the SR, because the final state signatures appear very similar to those of the SUSY models and the production cross section is very high. If both W bosons decay leptonically, a SFOC lepton pair in connection with neutrinos can be produced, creating a large amount of p_T^{miss} in the detector. Prompt photons can be produced in the hard interaction, or can be radiated off in the initial or the final state by participating charged particles. Due to the high cross section of the $t\bar{t}(\gamma)$ production, there is a sufficient probability to measure an invariant dilepton mass close to the Z boson mass although the two leptons do not emerge from it.

In the Drell-Yan process, in context with FSR or ISR, and in $Z\gamma$ production, directly an on-shell Z boson is produced, thus the $m_{\ell\ell}$ requirement for the dileptons in the SR is fulfilled. Although additionally a photon is produced, this background does not contribute significantly to the SR, because only nongenuine p_T^{miss} is generated in the process due to mismeasurements and therefore the p_T^{miss} distribution drops steeply.

WZ production is also an important background for this search, since the W boson can decay leptonically and therefore creates a sufficient amount of genuine p_T^{miss} to pass the SR requirements, but is also suppressed by the M_{T2} requirement. While a photon can be generated in all possible radiation processes, an additional electron or jet originating from the W boson can fake a photon signature in the detector. In cases of appearance of photons, the additional lepton can also be lost in the reconstruction.

Lastly, the ZZ event signature can be very similar to the one expected from the considered SUSY signals. One boson can decay to a pair of charged leptons, while the other decays to neutrinos leading to a large amount of p_T^{miss} in the event. Together with FSR or ISR of a photon, it mimics the signal topology in many ways.

If the different background processes are compared, the diboson processes have more similar event kinematics than the $t\bar{t}(\gamma)$ process, but due to the lower diboson production cross sections the $t\bar{t}(\gamma)$ background dominates the other contributions. The strategy to perform a sophisticated background prediction is based on simulation for all backgrounds. As mentioned in Section 5.1.3, different CRs are developed, that are enriched with corresponding background events. In those CRs, scale factors (SF) α_i are calculated by scaling the simulation to the measured data yield. Contributions of other backgrounds in the CR are considered in the calculation by fixing their

contribution. The SFs are calculated via the following formula:

$$1 = \frac{\#Data}{\#FixedBackground + \alpha_i \cdot \#BackgroundToScale} \quad (5.1)$$

$$\Rightarrow \alpha_i = \frac{\#Data - \#FixedBackground}{\#BackgroundToScale}. \quad (5.2)$$

Due to the used method, which is performed similarly in each CR, possible uncertainties on the normalization of the predicted distributions cancel, and only uncertainties on the shape need to be considered, see Section 5.3. The uncertainty arising from the SF calculation is purely of statistical origin, and is calculated via error propagation

$$\sigma_{\alpha_i}^2 = \sigma_D^2 \cdot \left(\frac{D}{B}\right)^2 + \sigma_F^2 \cdot \left(\frac{F}{B}\right)^2 + \sigma_B^2 \cdot \left(\frac{D-F}{B^2}\right)^2, \quad (5.3)$$

where $B = \#BackgroundToScale$, $F = \#FixedBackground$, $D = \#Data$, and σ_i are the corresponding statistical uncertainties. These are assumed to be uncorrelated Poissonian uncertainties, and can be calculated via $\sigma_i = \sqrt{N_i}$, where N is the associated total integral in the selection. In the case of simulation, for the calculation of the SF the normalized event yield is used, whereas in the error calculation the pure MC event count is considered to reflect the underlying statistical precision of the simulation. This method is referred to as the "integral method" in the following.

In each CR, all other backgrounds have of course an influence, since their contributions are not negligible. Therefore, the order of SF determination can introduce a bias. To minimize this effect, the SFs are calculated in descending order of the purity of the background sample. At first, the ZZ SF is determined, followed by DY/Z(γ), $t\bar{t}(\gamma)$, and WZ. However, the background estimations are discussed in a different order, starting with the most important background, $t\bar{t}(\gamma)$. The systematic uncertainty arising from the choice of order is discussed in Section 5.3.

To strengthen the confidence in the outcome, Kolmogorov-Smirnov [137] tests are performed to study the shape agreement, which are based on the largest deviation between the two compared distributions. Resulting KS-values from the tests results are quoted on the corresponding plots for each individual distribution in the related sections. KS-values $\ll 1$ indicate disagreement between the input distributions, otherwise the distributions are considered to match.

In order to study a possible bias of observables not well modeled within the simulation, additional cross checks are performed. Similar to the SF calculation in the integral method, SFs are determined via χ^2 minimization in the same CRs. Albeit this method is somewhat correlated to the method explained above, it enables the possibility to study influences of different distributions in different binnings. Therefore, α_i is varied in a range in small steps for each binning and distribution, and for every iteration the simulation was scaled and the χ^2 was calculated, which is defined as:

$$\chi^2 = \sum_i^{N_{bins}} \frac{(N_{i,bin}^{obs} - N_{i,bin}^{predicted})^2}{N_{i,bin}^{predicted}}. \quad (5.4)$$

The best fit value is determined to be at the minimum of the χ^2 distribution, which is obtained by fitting a polynomial of fourth grade to the measured points. The uncertainty of the χ^2 -fit method, that is also of statistical origin, is calculated by taking the difference between the best fit value and the values, where $\chi^2 = \chi_{BestFit}^2 + 1$. An example fit in the p_T^{miss} distribution is shown in Section 5.2.1 in the discussion of the $t\bar{t}(\gamma)$ background estimation. The number of degrees of freedom (ndf) is given by the number of bins used to obtain the χ^2 distribution reduced by the number of parameters that are being optimized. The only free parameter is α_i , so ndf

equals the number of bins subtracted by unity.

After determining all SFs, the background prediction is tested in the VR. Therefore, the simulated backgrounds in the VR are scaled accordingly, and the result is investigated, see Section 5.2.6.

5.2.1. Top pair production in association with a photon

As shown in Figure 5.4, the main background contribution is $t\bar{t}(\gamma)$, which is composed of standard top pair production with and without photon radiation, and top-pair production in association with a photon, while the latter dominates. Both compositions are determined together by rescaling the simulation, such that the integral of events of the simulation in the CR matches the integral of events in data as explained in Section 5.2. The overall purity of the selection is of the order of 84.62%. With the integral method applied, the SF given in Equation (5.5) is obtained.

$$\alpha_{t\bar{t}(\gamma)} = 0.803 \pm 0.033(stat.) [\hat{=} 4.07\%]. \quad (5.5)$$

After application of $\alpha_{t\bar{t}(\gamma)}$, the numbers of events in data and total simulation match per definition.

Since the analyzed final state in this CR is very sensitive to higher order effects such as jet and photon radiation, and complex matrix elements are needed to describe the hard interaction, and these are very hard to model in the simulation, a SF differing from unity is not unexpected. Because the generation of simulation in general is time and resource consuming, simplifications are made on, e.g., radiation effects, and not all aspects of a specific process are calculated and generated at NLO, although MC@NLO was used for the generation of the $t\bar{t}\gamma$ sample. NNLO electroweak effects can cause negative corrections for example due to destructive terms in higher order corrections. The uncertainty of the order of 4% indicates, that a sufficient number of events is present in the corresponding CR.

The resulting prediction shows a good agreement with data, as can be seen from the p_T^{miss} and M_{T2} distributions in the CR after rescaling in Figure 5.5. The uncertainty of the fit method is of statistical origin, and is treated as a systematic in the following. The agreement of additional important observables, such as the transverse momentum of the photon and both leptons, is also investigated, and no systematic deviation was found. Additional statistical checks, such as Kolmogorov-Smirnov tests and χ^2 -fits, as explained above are also performed. The resulting KS-values of the Kolmogorov-Smirnov tests quoted in each plot indicate a good shape agreement.

The resulting curves of the χ^2 -fit distributions, see Figure 5.6 left for an example fit in the p_T^{miss} distribution, are smooth, indicating a proper performance of the fit. A comparison of all obtained SFs for the different setups and the SF obtained by the integral method is shown in Figure 5.6 right. No significant deviation is observed, and all SFs are in agreement with each other. Hence, the scaling of the $t\bar{t}(\gamma)$ background seems stable and well described in the CR.

Further studies

Since the $t\bar{t}(\gamma)$ background is the most dominating one, further studies are realized in which the underlying MC simulation samples and their combination are examined. Different overlap removal procedures, see Section 4.2, and different available cross sections are used, while the fit procedure itself is varied. In addition, available corrections to improve the modeling of jet radiation in the initial state, and corrections to enhance the description of the top quark p_T distribution, that are used both to correct the LO samples and the samples that are generated with POWHEG (see Section 4.2), are applied in different combinations. The used fit methods include a χ^2 -template fit, where the ratio between the fractions of the $t\bar{t}$ and $t\bar{t}\gamma$ simulation is left free as an additional parameter, and a fit where only the $t\bar{t}\gamma$ simulation is made use of.

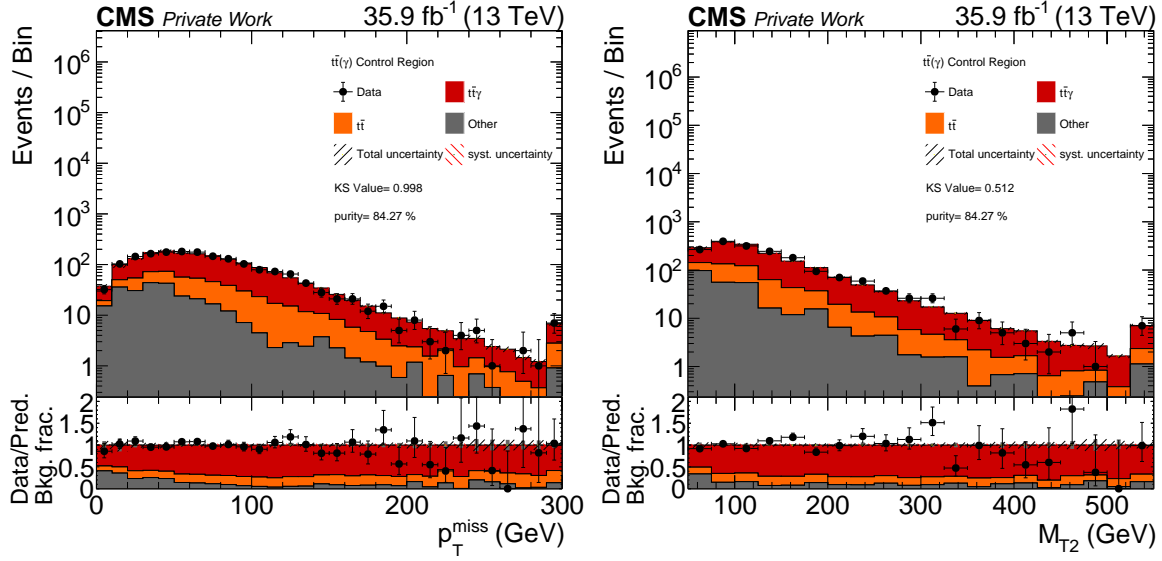


Figure 5.5.: Comparisons between data and rescaled simulation in the $t\bar{t}(\gamma)$ CR in the p_T^{miss} and M_{T2} distribution. Below each plot, a ratio between data and prediction is shown. The uncertainty bands correspond to the systematic (red) and total uncertainty (gray). In addition, in the ratio plot the relative composition of the backgrounds is visualized. KS-values for the performed Kolmogorov-Smirnov test are also quoted.

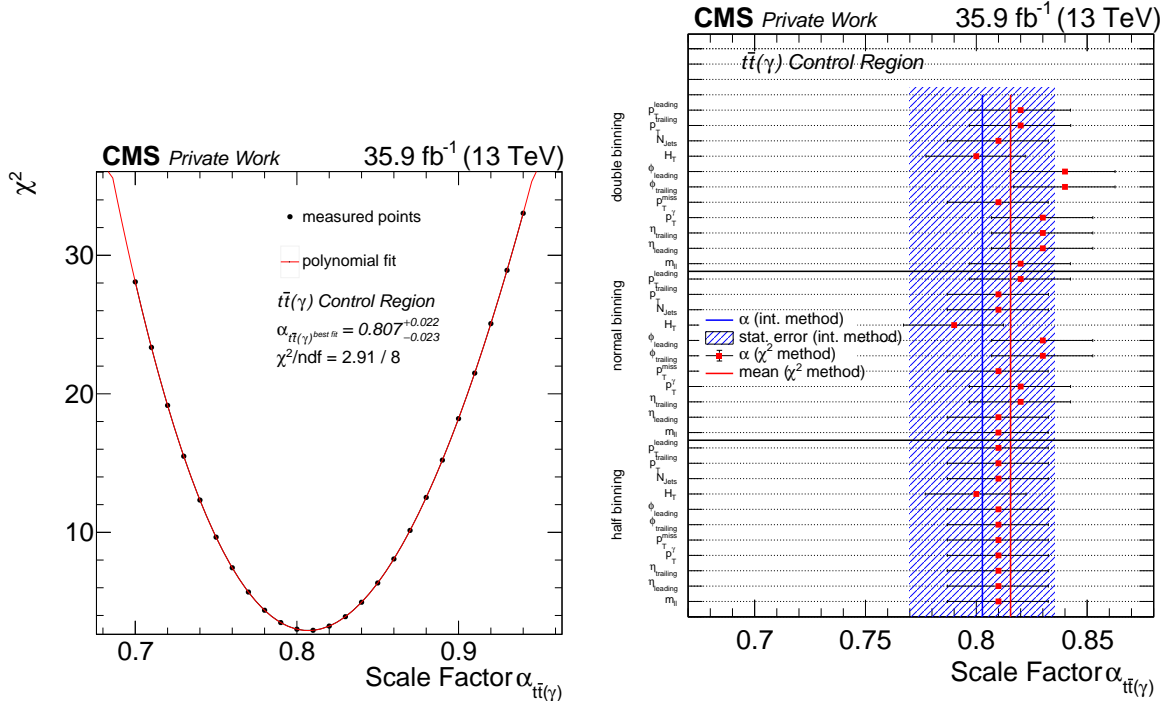


Figure 5.6.: Example χ^2 fit in the $t\bar{t}(\gamma)$ CR in the p_T^{miss} distribution (left) with the polynomial fit. All fit results compared with the SF obtained from the integral method in different binnings and variables (right.)

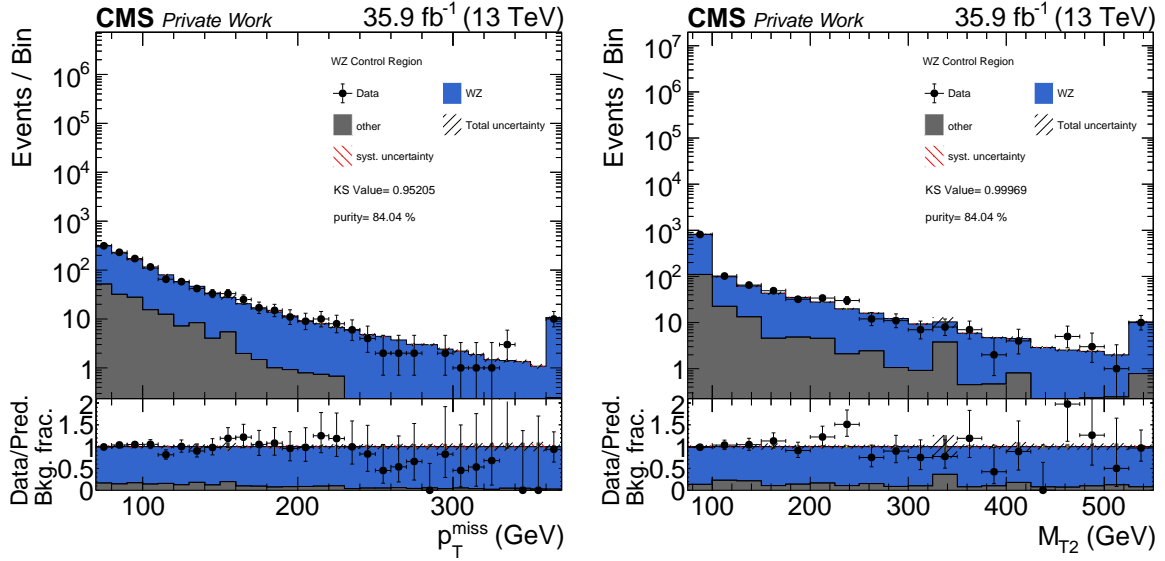


Figure 5.7.: Comparisons between data and rescaled simulation in the WZ CR in the p_T^{miss} and M_{T2} distribution. Below each plot, a ratio between data and prediction is shown. The uncertainty bands correspond to the systematic (rand) and total uncertainty (gray). In addition, in the ratio plot the relative composition of the backgrounds is visualized. KS-values for the performed Kolmogorov-Smirnov test are also quoted.

Eventually, no substantial differences are observed, and the best performance and stability is provided by the initial approach explained above in detail.

5.2.2. WZ diboson production

The diboson production of WZ pairs is the second important background contribution for this analysis. It is also tuned to agree with the measurement in the WZ CR, while the SF α_{WZ} is calculated with the integral method. The expected purity of selected WZ events in this CR is about 84%. The agreement beforehand is also very good, considering this background is a higher order process and is therefore simulated at NLO, see Section 4.2, which includes several complicated effects the event generator needs to handle properly. The SF $\alpha_{DY/Z(\gamma)}$ is determined to be

$$\alpha_{\text{WZ}} = 1.138 \pm 0.037(\text{stat.}) [\hat{=} 3.23\%], \quad (5.6)$$

which indicates that usage of NNLO cross sections for the WZ samples is nearly sufficient enough to describe the background. Of course higher order effects can lead to larger cross sections, thus it is not unexpected to obtain a SF varying $\approx 12\%$ from unity. Resulting distributions of the description of the p_T^{miss} and M_{T2} variables are shown in Figure 5.7. As can be seen, the predicted shape is in consistency over the whole range with the observed data, also in the high p_T^{miss} and M_{T2} regime. This is further confirmed by the additional cross checks, that are also realized in the other two CRs described above. The KS-values close to one strengthen the trust in the background estimation method. The χ^2 -fit studies lead to the same outcome, the uncertainties seem to be well estimated and of statistical origin, since no large shape deviation can be observed in the performed fits, as can be seen in Figure 5.8 right. Each individual χ^2 -fit seems to behave properly, see Figure 5.8 left for an example in the p_T^{miss} distribution.

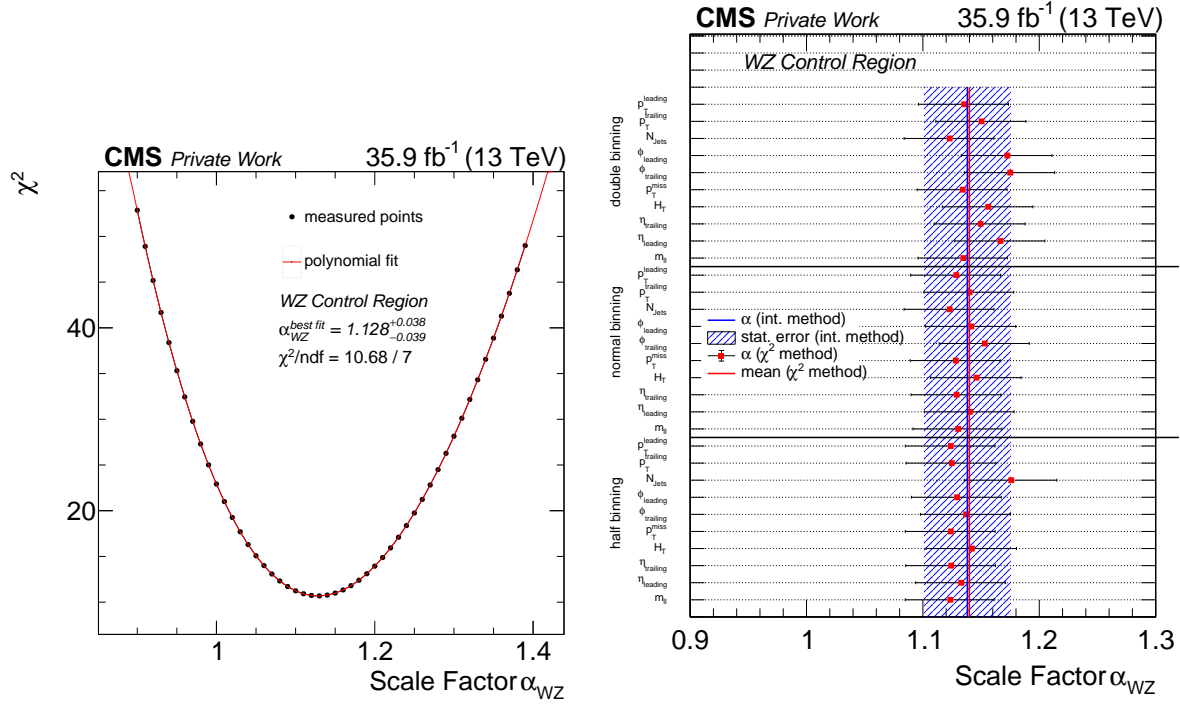


Figure 5.8.: Example χ^2 fit in the WZ CR in the p_T^{miss} distribution (left) with the polynomial fit. All fit results compared with the SF obtained from the integral method in different binnings and variables (right.)

5.2.3. ZZ diboson production

The third biggest background contribution is ZZ diboson production, where both Z bosons decay leptonically, one to charged leptons such as electrons or muons, and the other one to neutrinos. To simplify the construction of a dedicated CR, as explained in Section 5.1.3, the assumption is made, that there is no difference for the generator to generate neutral or charged leptons. Only the detector response should differ. Therefore, ZZ can be well estimated in a four lepton CR. A pure selection of ZZ events can be established, although the statistics in data is quite low due to small cross section and the low branching fraction for the $Z \rightarrow \ell\ell$ decay. The selection purity is nearly 100%. With the integral method applied, a SF α_{ZZ} stated in Equation (5.7) is determined, being relatively close to one.

$$\alpha_{\text{ZZ}} = 1.109 \pm 0.064(\text{stat.}) [\simeq 5.74\%]. \quad (5.7)$$

Post-fit distributions to show the good agreement in the p_T^{miss} distribution and invariant dilepton mass distribution of the second Z boson can be found in Figure 5.9. As mentioned, the precision is limited by the low statistics of the selected sample, but nevertheless is sufficient enough to establish a stable background prediction. The shapes agree very well, as it is additionally indicated by the KS-values printed on the plots. The properties of the $\text{ZZ} \rightarrow 4\ell$ processes does not allow to study the prediction in the high p_T^{miss} regime, since only nongenuine p_T^{miss} is produced. However, the agreement of distributions of the third and fourth leptons, such as $m_{\ell_3\ell_4}$, can be translated into the agreement of the p_T^{miss} in the $\text{ZZ} \rightarrow 2\ell 2\nu$ background, that is generated with the same event generator. There, also no χ^2 -fit studies, see Figure 5.10, are performed as for the other three background estimations discussed above, and yield the same conclusion, although some fluctuations in the choice of the variable or binning are present due to the lower total event count in the observed data. All in all also this background estimation method is stable.

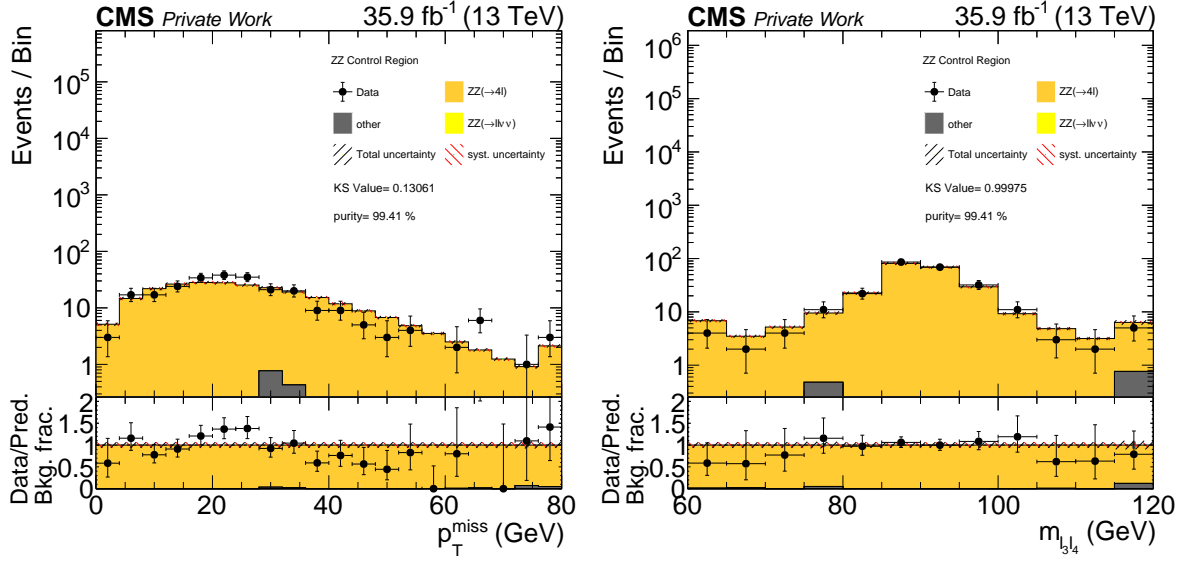


Figure 5.9.: Comparisons between data and rescaled simulation in the ZZ CR in the p_T^{miss} and $m_{\ell_3\ell_4}$ distribution. Below each plot, a ratio between data and prediction is shown. The uncertainty bands correspond to the systematic (red) and total uncertainty (gray). In addition, in the ratio plot the relative composition of the backgrounds is visualized. KS-values for the performed Kolmogorov-Smirnov test are also quoted.

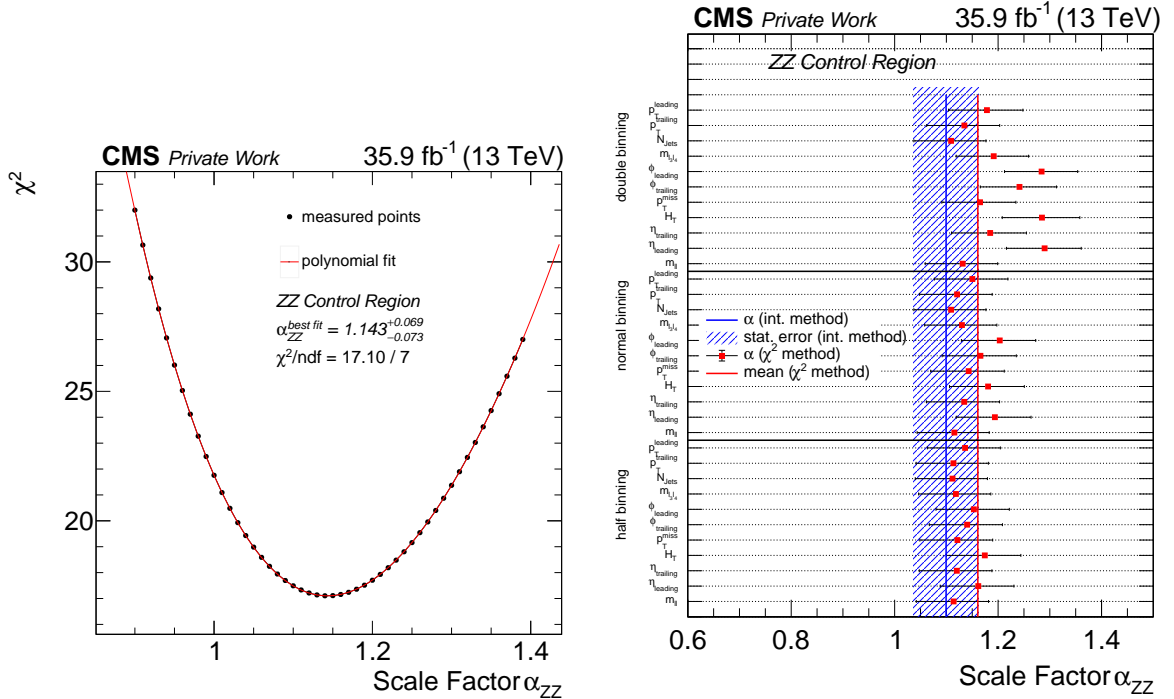


Figure 5.10.: Example χ^2 fit in the ZZ CR in the p_T^{miss} distribution (left) with the polynomial fit. All fit results compared with the SF obtained from the integral method in different binnings and variables (right.)

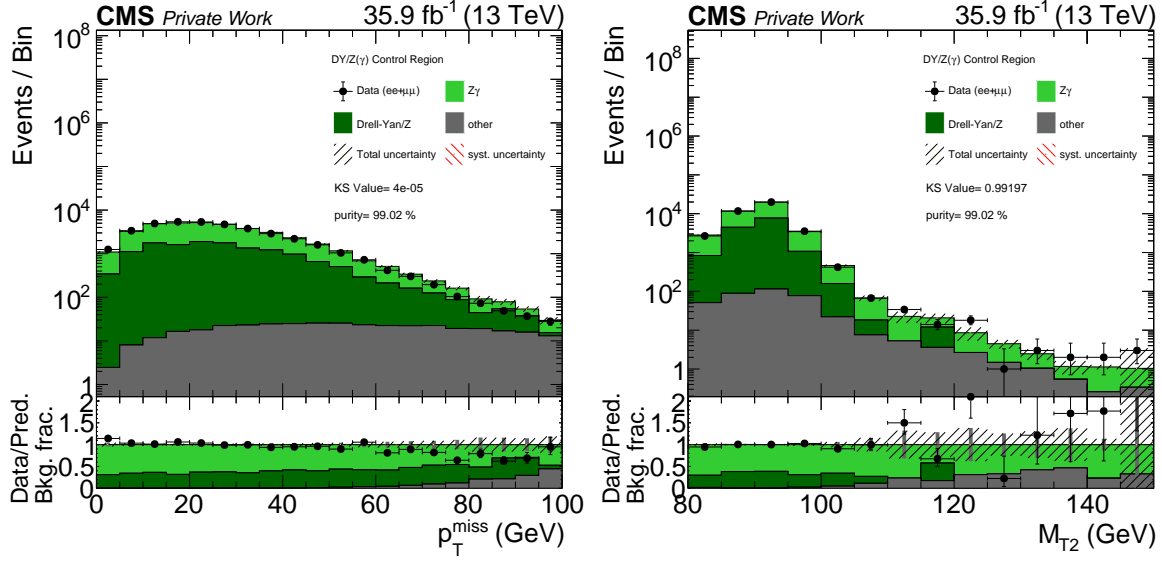


Figure 5.11.: Comparisons between data and rescaled simulation in the DY/Z(γ) CR in the p_T^{miss} and M_{T2} distribution. Below each plot, a ratio between data and prediction is shown. The uncertainty bands correspond to the systematic (red) and total uncertainty (gray). In addition, in the ratio plot the relative composition of the backgrounds is visualized. KS-values for the performed Kolmogorov-Smirnov test are also quoted.

5.2.4. Drell-Yan and $Z\gamma$ diboson production

Although contribution from the Drell-Yan and dibosonic $Z\gamma$ backgrounds is admittedly small in the two SR bins, its contribution is the fourth largest. Hence, it needs to be assured, that the background is modeled well. As in the case of the $t\bar{t}(\gamma)$ background, it is composed of two major parts, the Drell-Yan process, where quarks annihilate to off-shell leptons or Z bosons and generate leptons in their decays, and the diboson production of $Z\gamma$ pairs. The integral method as explained above is used to determine the SF $\alpha_{DY/Z(\gamma)}$ in the dedicated CR defined in Section 5.1.3. The resulting SF is stated in Equation (5.8). With a purity of about 99%, and a total event count that large, a precise SF determination is feasible, as can be concluded also from the small statistical uncertainty of $\approx 1\%$. The agreement between simulation and data is very good even before application of $\alpha_{DY/Z(\gamma)}$, since the SF equals nearly unity. The post-scaling distributions of p_T^{miss} and M_{T2} are shown in Figure 5.11. They show overall a good agreement, only in the high M_{T2} region there are some fluctuations due to the limited statistics being present both in data and simulation. The same cross checks as for the $t\bar{t}(\gamma)$ background are made, including the Kolmogorov-Smirnov tests, and the additional χ^2 -fits with variable bin size in different observables. All in all the KS-values indicate a very good matching between predicted and observed shape, albeit the Kolmogorov-Smirnov test provides a very small KS value for the consistency between the p_T^{miss} distributions. This is mainly due to the high statistics in data and therefore a higher absolute discrepancy, in contradiction to the lower statistics in simulation, leading to larger fluctuations. These discrepancy is also visible in the ratio shown under the plot, but is consistent with the shown total uncertainty.

$$\alpha_{DY/Z(\gamma)} = 1.066 \pm 0.001(\text{stat.}) [\triangleq 0.87\%]. \quad (5.8)$$

The χ^2 -fit studies, shown in Figure 5.12 together with an example fit in the p_T^{miss} distribution, show good agreement over all variations. Hence, the background estimation is reliable also in

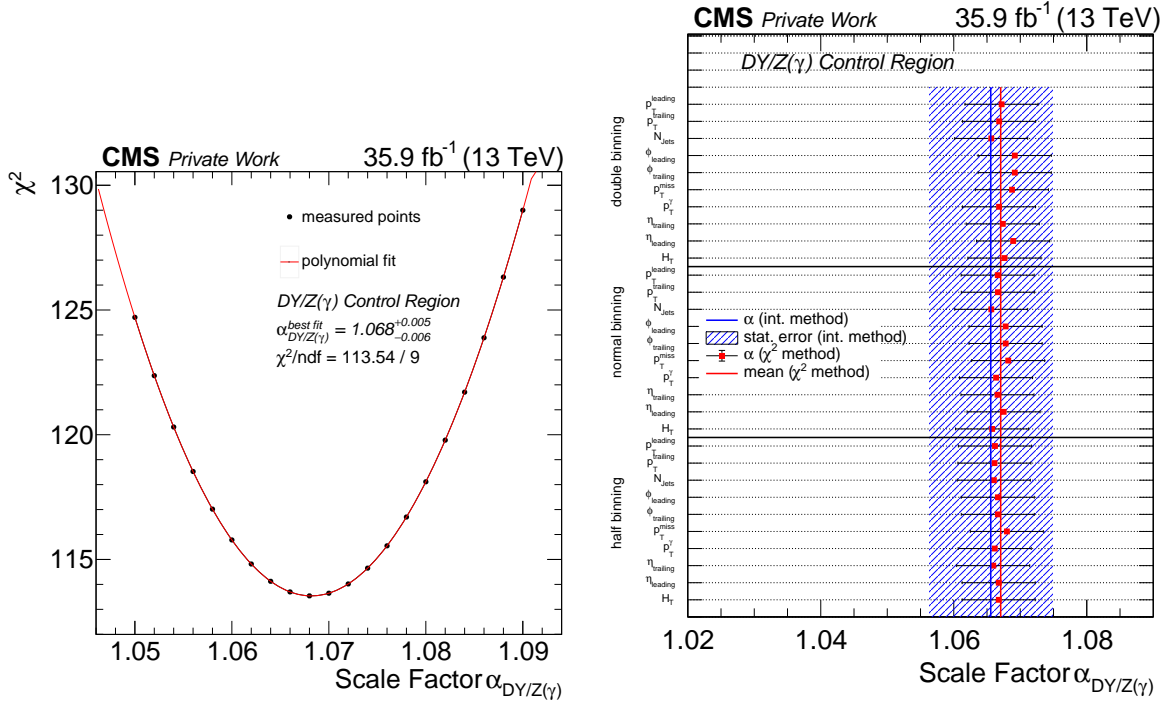


Figure 5.12.: Example χ^2 fit in the $DY/Z(\gamma)$ CR in the p_T^{miss} distribution (left) with the polynomial fit. All fit results compared with the SF obtained from the integral method in different binnings and variables (right.)

the $DY/Z(\gamma)$ CR.

5.2.5. Other standard model backgrounds

Additional minor backgrounds, such as triboson processes as $WZ\gamma$, $WW\gamma$, diboson WW and $W\gamma$ production, the production of W bosons in association with jets, and single top processes as listed in Table 4.1, are taken from plain simulation after reweighting them as described in Section 4.2 to the measured luminosity and NLO and NNLO cross sections.

5.2.6. Validation of the background estimation

After all main backgrounds are estimated using the corresponding CRs where the SFs are determined the background prediction is validated in the VR defined in Section 5.1.3. The VR is very close in phase space to the SR where the background prediction shall work sufficiently well, and therefore the VR is ideal to study the obtained background prediction.

Resulting comparisons between prediction and observed data in different distributions are shown in Figure 5.13 for the most important variables, such as p_T^{miss} and M_{T2} , together with p_T distributions of the leading and trailing lepton. Comparisons for the photon p_T and the invariant dilepton mass $m_{\ell\ell}$ distributions are shown in Figure 5.14.

Overall, the agreement is very good in all distributions, although being limited by the low statistics in some kinematic regions. The same Kolmogorov-Smirnov tests as for the different CRs are performed to gain more trust in the background prediction. As can be read from the resulting KS-values, each quoted on the corresponding plot, the shape agreement considering statistical uncertainties and systematic uncertainties originating from the statistical ones from the integral method, is very good. With 97 data events measured and 93.9 predicted, the total agreement is very good.

Therefore, the background prediction is assumed to be stable also in the SR due to the similar

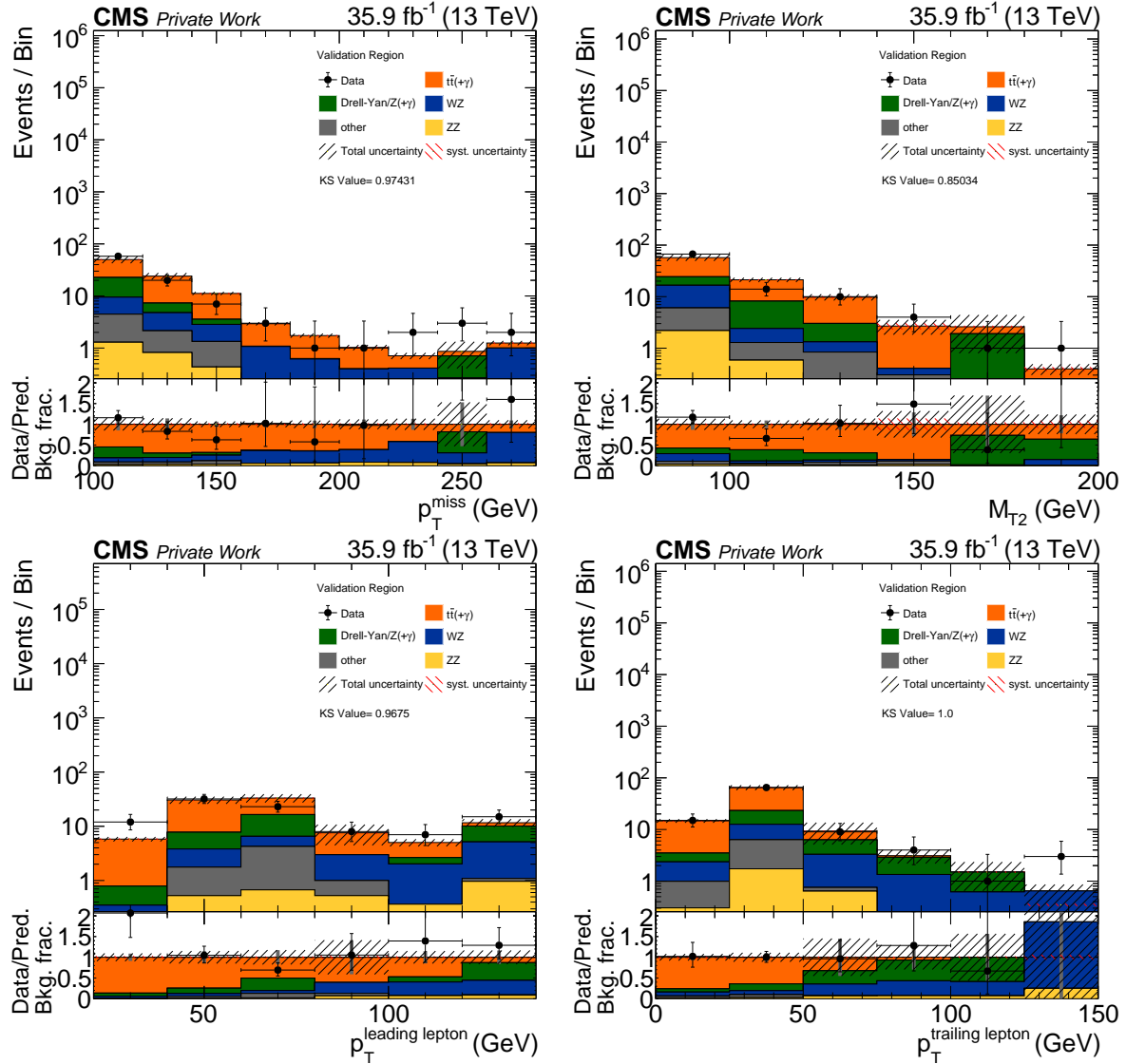


Figure 5.13.: Comparisons between data and rescaled simulation in the VR in the p_T^{miss} , M_{T2} , and lepton p_T distributions. Below each distribution, a ratio between data and prediction is shown. The uncertainty bands correspond to the systematic (red) and total uncertainty (gray). In addition, in the ratio plot the relative composition of the backgrounds is visualized. KS-values for the performed Kolmogorov-Smirnov test are also quoted.

kinematics in the VR based on the design as a kinematic sideband in p_T^{miss} and M_{T2} .

5.2.7. Signal contamination

If SUSY was realized in nature, it would not only produce events in the SR, but also some of them may appear in the CRs that are used to determine a proper background prediction. To account for this effect, the so-called signal contamination of the background CRs is not considered in the background estimation itself, but is rather translated into a reduction of the predicted signal yield in the SR. Hence, at first the signal contamination needs to be measured for each signal point of all samples individually in all CRs.

Therefore, the fraction of expected signal events relative to the total number of background events in each CR is measured. Examples for the contamination of the TChZG SMS in the

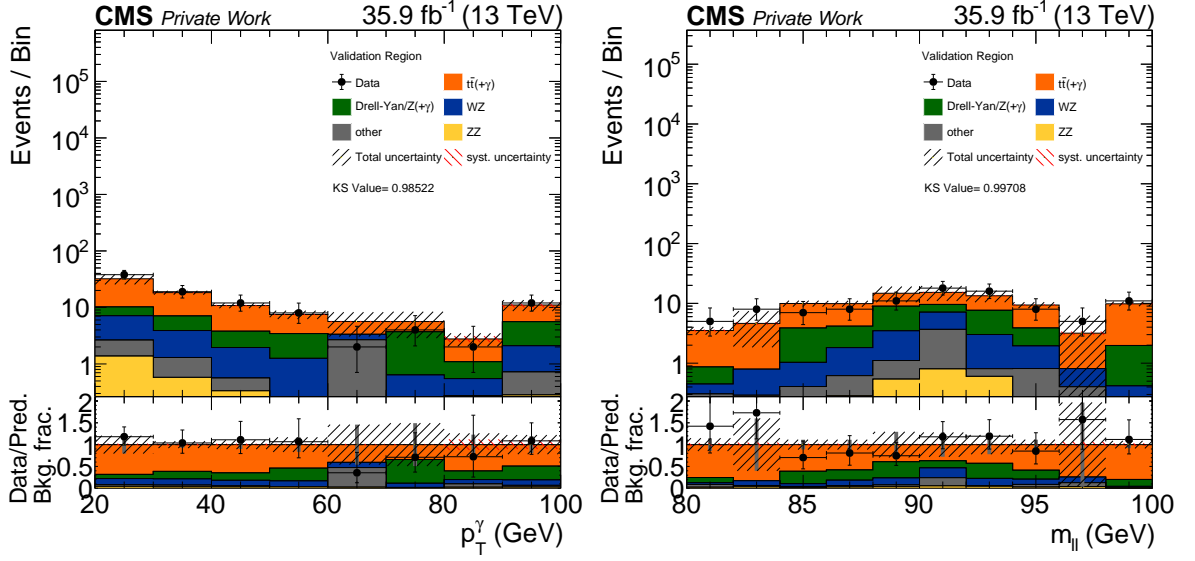


Figure 5.14.: Comparisons between data and rescaled simulation in the VR in the photon p_T and invariant dilepton mass distribution. Below each distribution, a ratio between data and prediction is shown. The uncertainty bands correspond to the systematic (red) and total uncertainty (gray). In addition, in the ratio plot the relative composition of the backgrounds is visualized. KS-values for the performed Kolmogorov-Smirnov test are also quoted.

DY/Z(γ) CR and the GMSB model in the WZ CR are shown in Figure 5.15, because they are the largest ones observed. As can be seen, the contributions of signal events are mainly negligible, although the signal contamination reaches $\approx 3\%$ for very low bino and wino masses in the GMSB model.

To account for those effects, these relative fractions are used to lower the signal expectation in each SR bin individually. This can be accomplished in a simple way, since the background prediction method is based on simulation which is rescaled with constant SFs. If ρ is the fraction of signal events in the CR, in each SR bin the absolute signal event yield reduced with the following formula

$$\#signal_{after} = \#signal_{before} - \rho \cdot \#background, \quad (5.9)$$

where $\#signal_{before}$ and $\#signal_{after}$ are the total number of signal events per bin before and after the correction, and $\#background$ is the number of predicted background events in this bin.

In total, the influence of signal contamination to the final result is rather negligible, because for most of the signal points the contributions to all CRs are very low. In cases where they exceed the level of some percent, their influence will not matter in the final interpretation, since for those low SUSY mass signal points, the expectation for the signal yield in the SR is sufficiently high.

5.3. Study of systematic uncertainties

In addition to the statistical uncertainties coming from the background prediction method itself, various systematic effects and their impact on the final prediction need to be evaluated.

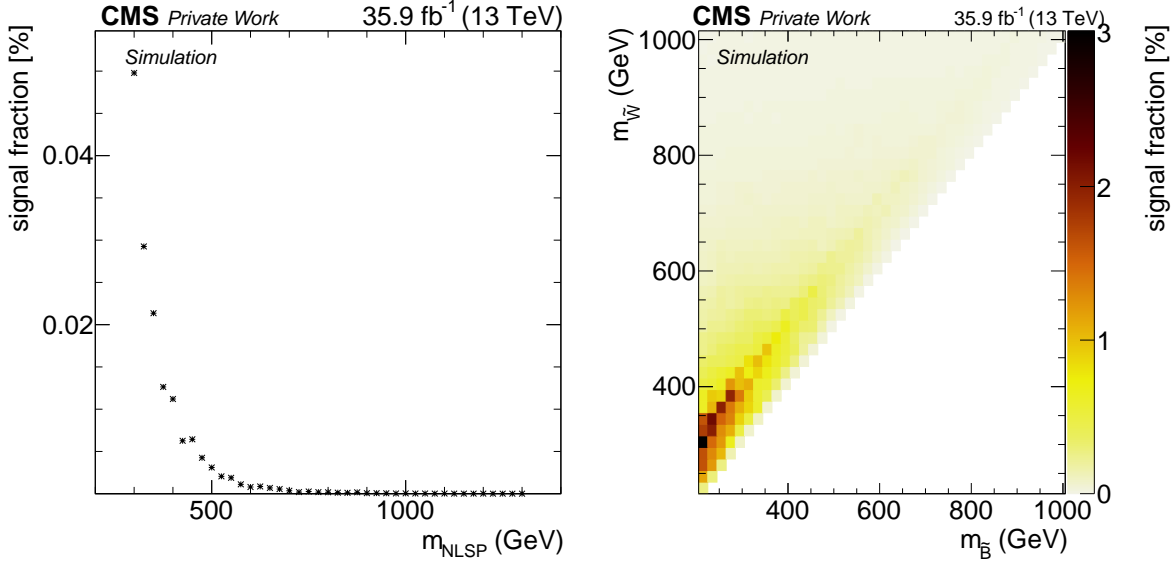


Figure 5.15.: Signal fraction for different signal points of the TChiZG in the DY/Z(γ) CR (left) and the GMSB model in the WZ CR (right).

5.3.1. Background uncertainties

Systematic uncertainties arise from the measured pileup distribution, which is needed to rescale the simulated samples as explained in Section 4.2, the measurement of the total integrated luminosity, the measurement of the jet energy scale (JES) and the jet energy resolution (JER), that are important for the $p_{\text{T}}^{\text{miss}}$ description, the measured trigger efficiencies as discussed in Section 4.6, corrections for a different photon and lepton reconstruction in simulation and data, the PDF used in the simulation process, and the factorization scale and renormalization scale. These measurements and underlying effects all contribute systematic uncertainties on the final background prediction. Cross section, trigger, and luminosity uncertainties cancel for the four main background contributions due to the applied method, but are relevant for the other minor contributions as a relative uncertainty. They are assumed to be 50% to account for the biggest differences between the measurement and theoretical prediction, and to consider the circumstance, that only a special phase space is used in the analysis.

The uncertainty on the luminosity measurement with 2.5% [138] and the uncertainty on the trigger efficiency, that is estimated to be 3% (see Section 4.6), propagate directly as relative uncertainties to the final prediction.

All other uncertainties are uncertainties on the shapes of the predicted spectra, and need to be determined another way. In order to estimate the impact of the JEC and JER, the pileup reweighting, and the lepton and photon identification and reconstruction corrections, the background prediction is performed again with the underlying quantities shifted one standard deviation up and down. Hence, two additional predictions for each SR bin are obtained, and half of the difference between those, relative to the nominal prediction, is taken as the systematic uncertainty.

To estimate the effect on the choice of the renormalization scale μ_R and factorization scale μ_F , these two are varied in combinations of the factors 0.5, 1, and 2, and nine new background predictions are obtained. The half of the difference between the two outliers, relative to the nominal prediction, is treated as the systematic uncertainty.

To determine the systematic uncertainty arising from the used PDFs, one hundred different PDF variations are studied, and for each the background prediction method is performed again, thus one hundred different predictions for the SR are obtained. From this distribution of predicted

Table 5.1.: Systematic uncertainty ranges for all background predictions in the signal region.

	$t\bar{t}(\gamma)$	DY/Z(γ)	WZ	ZZ	Other
PDF	0.8 – 1.5%	2.6 – 3.3%	0.5 – 0.7%	2.2 – 2.4%	1.1 – 1.2%
Renorm. and fact. scale	3.3 – 7.1%	18.2 – 22.5%	4 – 6%	3.7 – 4.1%	2.1 – 9.3%
JES	4.6 – 6.5%	4.4 – 5%	2.8 – 4.8%	1 – 1.9%	0 – 50.7%
JER	1.6 – 3.1%	0.7 – 16.1%	1 – 1.8%	0.2 – 1.4%	0 – 50.7%
Lepton ID and reco.	2.8 – 2.9%	2.2 – 3.4%	3.3%	1.8%	4.2%
Photon ID and reco.	0.7 – 0.8%	1.4 – 1.5%	1 – 1.1%	0.9%	0.7 – 1.9%
Luminosity	-	-	-	-	2.5%
Pileup	1.2 – 2%	1 – 5%	0.2 – 2.5%	1.5 – 1.7%	0.1 – 10%
Trigger efficiency	-	-	-	-	3%
Scale factor α_i	4.1%	0.9%	3.9%	5.7%	-
Cross section	-	-	-	-	50%

yields, the standard deviation and the mean can be calculated. The standard deviation with respect to the mean is considered as the systematic uncertainty.

The uncertainty arising from the choice of order regarding the four SFs determined in the CRs, is estimated by testing all $4! = 24$ possibilities, and calculating the largest deviation from the nominal SFs. This envelope is considered as a systematic uncertainty on the SFs on top of the statistical uncertainty. Both uncertainties are added quadratically, such that one final uncertainty for each SF is obtained. Table 5.1 lists ranges for all final systematic uncertainties for all backgrounds individually. Besides uncertainties for some backgrounds, such as DY/Z(γ) and the other composed backgrounds, exceed the level of 10%, where statistical fluctuations based on changes of different quantities play an important role, all other systematic uncertainties are of the order of some percent. This reflects the stability and robustness, that was observed in the scale factor determination itself.

5.3.2. Signal uncertainties

Whereas all derivations of systematic uncertainties on the final event yields are covered, further signal uncertainties need to be studied in order to interpret the results statistically in each SUSY model. Most of the signal uncertainty determination methods behave the same as explained above for the backgrounds, but some additional effects need to be considered, and some calculations change, since the detector response in the signal MC simulation was performed using FASTSIM.

For the determination of the pileup uncertainty, a different method is applied. The pileup distribution is split into a low PU (< 20) and a high PU (> 20) region, and the difference in the total signal acceptance is determined. Half of this difference is treated as the systematic uncertainty. Because the modeling of the p_T^{miss} distribution is very complicated, and in the FASTSIM package only a simplified detector response is parameterized, the difference between generated p_T^{miss} and reconstructed p_T^{miss} is investigated. Thus, the whole analysis is reperformed for the signal, where the reconstructed p_T^{miss} is replaced with the generated one for each event, and the difference in the acceptance is examined. Half of the deviation is taken as the systematic uncertainty.

For the signal simulation no PDF uncertainties are available. In addition, the initial state radiation dependent reweightings mentioned in Section 4.2 introduce systematic effects on the signal yield expectation. Therefore the same method as mentioned above for the identification and reconstruction uncertainties on the background prediction is performed.

Ranges for all signal uncertainties including the statistical one are given in Table 5.2 altogether for all signal models considered in the analysis. Large ranges are observable due to the limited statistics that is available for each signal point. All other systematic effects, except for the are

Table 5.2.: Ranges for all the systematic uncertainties for all signal models.

Uncertainty	Range [%]
Statistical	3.2 – 85
Luminosity	2.6
Pileup	< 0.1 – 143
JES	< 0.1 – 62
JER	< 0.1 – 63
Trigger Efficiency	3
Lepton ID and reconstruction	< 0.1 – 5.6
Photon ID and reconstruction	1.4 – 1.5
Reconstructed/generated p_T^{miss}	< 0.1 – 293
ISR Reweighting	< 0.1 – 10.5
Renorm. and fact. scale	0.1 – 10.9

correlated with the statistical uncertainty. This is due to time and resource saving reasons, since a large number of different signal points is being generated. In addition, the low available number of signal events becomes much lower, as only leptonic decay branches of the Z boson are considered and its branching fraction ($\mathcal{BR}(Z \rightarrow \ell^+ \ell^-) \approx 3.36\%$ [14]) is very low. Nevertheless, in most of the relevant signal points the uncertainties do not exceed the level of a few percent.

Results and interpretation

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Now that all backgrounds are well estimated, the background prediction is reliable in the validation region, and all uncertainties are determined, the background prediction can be applied to the SR, $p_T^{\text{miss}} > 150 \text{ GeV}$ and $M_{T2} > 100 \text{ GeV}$, and predicted and observed event counts can be compared. An excess or other significant deviations from the prediction would be indicators for BSM physics.

6.1. Results

Signal region binning

In order to perform the counting experiment, a distinct binning in one or multiple variables needs to be applied to the SR. This binning can be optimized considering different criteria, e.g., observation and exclusion power. Since the most sensitive variables are p_T^{miss} and M_{T2} , different one dimensional and two dimensional binnings are trialed. For individual benchmark points of all three signal models, simplified significances $\frac{s}{s+b}$, where s is the number of signal events and b the number of background events per bin, the binnings are varied. Because the total predicted event count in the SR is of the order of 13 events, special care has to be taken regarding this issue. Albeit many sensitive bins with lower SM prediction and high signal expectation would push expected exclusion limits, this would make reinterpretations and observations difficult due to the high statistical uncertainties of the measured data.

To take into consideration all those aspects, a binning consisting of two bins in the p_T^{miss} distribution is chosen, as already introduced in Section 5.1.2. The first bin starts at 150 GeV and ends at 200 GeV, while the second one is an overflow bin, meaning all events with $p_T^{\text{miss}} > 200 \text{ GeV}$ in the SR are counted in that bin. This binning yields good exclusion power, because the p_T^{miss} distribution is observed to be more sensitive than the M_{T2} distribution, and includes an amount of events large enough in each bin, so that the reinterpretation is not restricted by statistical uncertainties. For the same reasons, two dimensional binnings are discarded.

Possible influence of signal to the validation region

The SR and the VR are very close to each other in phase space due to the chosen sideband structure of the VR. Thus, some signal events, especially for low SUSY masses, are expected to populate also the VR. The distribution most sensitive to this effect is the p_T^γ distribution of the selected photon, as shown in Figure 6.1. At high p_T^γ ranges ($> 80 \text{ GeV}$), a considerable amount

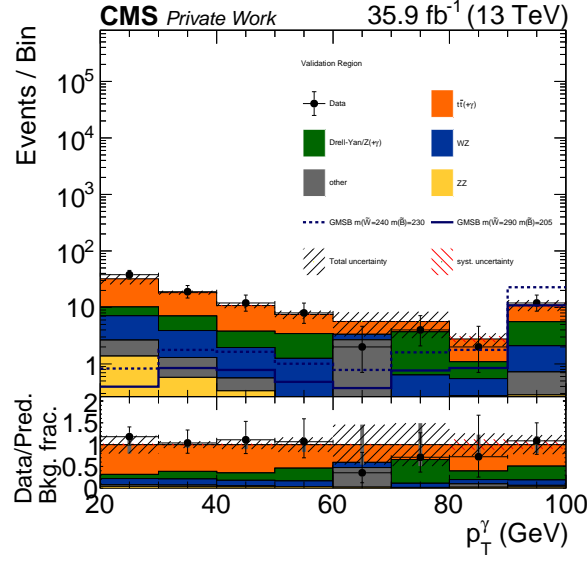


Figure 6.1.: The transverse momentum distribution of the photon in the VR. Signal benchmark points are also added to show the possible sensitivity in the high p_T^γ regime.

of signal events is measurable in the VR. Since the predicted background and observed data are already compared in the VR, and no background prediction is performed here, there is no need to account for this effect like in the other CR in terms of signal contamination.

Hence, the subtraction of this region from the VR, and the addition to the SR as a third search bin would increase the total sensitivity. But, because the number of expected signal events in the two SR bins is already high enough for the relevant signal points, this strategy does not show any improvement in the overall sensitivity, that is large enough to justify the deterioration in the simplicity of the analysis.

Event yields

The final background prediction together with the observed event yield is shown in Figure 6.2. The total background uncertainties are obtained by adding the individual uncertainties quadratically. The statistical uncertainties on the measurement are calculated using 68% confidence intervals of the Poisson distribution with the mean set to the observed yield. To show the effect of a possible signal in the counting experiment, contributions of two example signal points are drawn for comparison. The measured data yields are in good agreement with the predicted background events, thus no evidence for BSM physics is found. The measured excess corresponds to a significance of 1.3σ calculated with the discovery significance based on a profile-likelihood ratio test and Asimov approximation [139]

$$Z_A = \left[2 \left(n \ln \left[\frac{n(b + \sigma_b^2)}{b^2 + n\sigma_b^2} \right] - \frac{b^2}{\sigma_b^2} \ln \left[1 + \frac{\sigma_b^2(n - b)}{b(b + \sigma_b^2)} \right] \right) \right]^{1/2}, \quad (6.1)$$

where n is the observed yield, b the predicted background, and σ_b the total uncertainty on the prediction, including the statistical and systematic uncertainty on the background prediction. Albeit more classical approaches to calculate the observed significance, like $\frac{n-b}{\sqrt{b}}$ and $\frac{n-b}{\sqrt{b+\sigma_b^2}}$, overestimate the significance for small b , the Asimov significance yields a more confident estimate of the true significance of the observation [140]. The number of background and observed events together with their total uncertainties are given also in Table 6.1.

Figure 6.2.: Comparison between final prediction and observation with statistical and systematic uncertainties in the signal region. Two signal expectations for the TChiZG model with $m(\text{NLSP}) = 600 \text{ GeV}$ and the GMSB model with $m(\tilde{W}) = 290 \text{ GeV}$ and $m(\tilde{B}) = 205 \text{ GeV}$ are also shown.

Table 6.1.: Observed yields and final predicted background yields with the statistical and systematic uncertainties for each bin and background.

$p_{\text{T}}^{\text{miss}}$	150 – 200 GeV			200 GeV – ∞		
	yield	σ_{stat}	σ_{syst}	yield	σ_{stat}	σ_{syst}
$t\bar{t}(\gamma)$	7.16	0.32	0.60	3.31	0.23	0.37
DY/Z(γ)	0.15	0.06	0.04	0.04	0.02	0.01
WZ	0.69	0.08	0.06	0.59	0.08	0.05
ZZ	0.60	0.02	0.05	0.67	0.02	0.06
Other	0.22	0.22	0.19	0.21	0.21	0.11
Total	8.82	0.40	0.63	4.82	0.32	0.40
Data	9			8		

6.2. Statistical interpretation

No evidence for BSM physics is found, but the results can be interpreted in various SUSY models in terms of exclusion of available model parameter space.

6.2.1. Limit calculation

Upper cross section limits are calculated for signal points in the parameter space of simplified models with both electroweak and strong production, and a consistent GMSB model, as introduced in Section 2.3.2. All limits are calculated using the modified frequentist CL_s approach [141–143] with a likelihood test statistics and asymptotic formulae [144] at a confidence level (CL) of 95%. The compatibility of the background only (b) and signal plus background ($s + b$) hypotheses with the results is tested. Therefore, the signal strength modifier μ is introduced, in order to express both hypotheses in a uniform way $\mu s + b$, where $\mu = 0$ yields the background only hypotheses, and $\mu > 0$ corresponds to the $s + b$ hypotheses.

To account for systematic uncertainties, for each signal or background uncertainty a nuisance parameter θ is introduced, and signal and background yield are rewritten as functions of θ : $s(\theta)$ and $b(\theta)$. Different probability density functions (pdf) $p(\tilde{\theta}|\theta)$ are also implemented in the likelihood, to reflect the degree of belief in the true value of the nuisance parameter θ , where $\tilde{\theta}$ is the default value of the nuisance parameter. Different pdfs are used to describe the uncertainties, such as the log normal or log uniform distributions. The total likelihood function $\mathcal{L}(\text{data}|\mu, \theta)$ reads

$$\mathcal{L}(\text{data}|\mu, \theta) = \text{Poisson}(\text{data}|\mu \cdots (\theta + b(\theta))) \cdot p(\tilde{\theta}|\theta). \quad (6.2)$$

Here, data represents the actual experimental observation, and $\text{Poisson}(\text{data}|\mu \cdots (\theta + b(\theta)))$ stands for the probability to observe n_i events in i bins:

$$\text{Poisson}(\text{data}|\mu s + b) = \prod_i \frac{(\mu s_i + b_i)^{n_i}}{n_i!} e^{-\mu s_i - b_i}. \quad (6.3)$$

A test statistics \tilde{q}_μ is introduced as a likelihood ratio, because according to the Neyman-Pearson Lemma [145], this is the discriminator suited best for the testing of two alternative statistical hypotheses while minimizing the rate of wrongly rejected true hypotheses and accepted false

hypotheses:

$$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}, \text{ with } 0 \leq \hat{\mu} \leq \mu. \quad (6.4)$$

Here, $\hat{\theta}_\mu$ refers to the conditional maximum likelihood estimators of θ , given the signal strength μ and the data observation. The parameters $\hat{\theta}$ and $\hat{\mu}$ correspond to the global maximum of the likelihood. The constraints on $\hat{\mu}$ ensure, that only positive signal rates are considered, and a one sided confidence interval is guaranteed.

The probability to obtain values of $\hat{\theta}_\mu$ larger than observed in data ($\hat{\theta}_\mu^{\text{obs}}$) is given by CL_b for the background only hypothesis and CL_{s+b} for the signal plus background hypothesis. Now the ratio CL_s can be calculated

$$CL_s = \frac{CL_{s+b}}{CL_b}. \quad (6.5)$$

The $(1 - \alpha) = 95\%$ CL upper limit is found by varying μ until $CL_s = \alpha = 0.05$ is reached.

The limits on μ can be translated into cross section upper limits by multiplying it with the cross section that was used to determine the expected signal yield.

The calculation is performed using the Higgs Combine tool [143], while all systematic uncertainties are treated as fully correlated over all bins and background, except for the statistical uncertainties. Additional expected upper limits are calculated using pseudo-data, that are useful to show the maximum sensitivity of the analysis, since statistical fluctuations are not considered.

6.2.2. Exclusion limits

Three different SUSY models are used to interpret the results of the counting experiment discussed above individually for each masspoint. If the given theoretical cross section exceeds the calculated limit, the points is considered as excluded. In cases of two dimensional parameter scans, exclusion contours can be determined.

Limits on electroweak production of charginos and neutralinos

Two different models are used to interpret the results for EWK SUSY production. For the TChiZG SMS, expected (dashed line) and observed upper limits shown in Figure 6.3 (left) as a function of the NLSP mass parameter. The theoretical cross section together with the uncertainty band is plotted as the blue curve. The error band of the expected limit reflects all uncertainties of the analysis.

This analysis is capable of excluding NLSP masses below 600 GeV in this scenario. Due to the excess of data in the second SR bin, which is the most sensitive one for all signal points of this parameter scan, the observed limit is approximately one standard deviation weaker than the expected limit of 675 GeV.

Upper cross section limits for the two dimensional GMSB model are shown in Figure 6.3 (right) together with the expected limit contour (red) and the observed limit contour (black). The uncertainty band of the expected limit represents all analysis specific uncertainties, while the uncertainty band of the observed limit reflects theoretical cross section uncertainties. The limits are shown in the wino-bino mass plane, where the wino mass corresponds to the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ mass, and the bino mass corresponds to the NLSP $\tilde{\chi}_1^0$ mass, as discussed in Section 2.3.2. The analysis has the highest sensitivity in cases where the bino and wino mass differ by around 90 GeV, so that Z boson production in the decays of the wino is enhanced, as can be seen by the off-diagonal structure in the cross section limit plane. The sensitivity weakens for lower and higher wino masses, since the available energy is split between all decay products. For degenerate bino and wino masses, the sensitivity increases again, because nearly all energy is transferred into the final decay products, the gravitinos and the selected bosons. Due to the

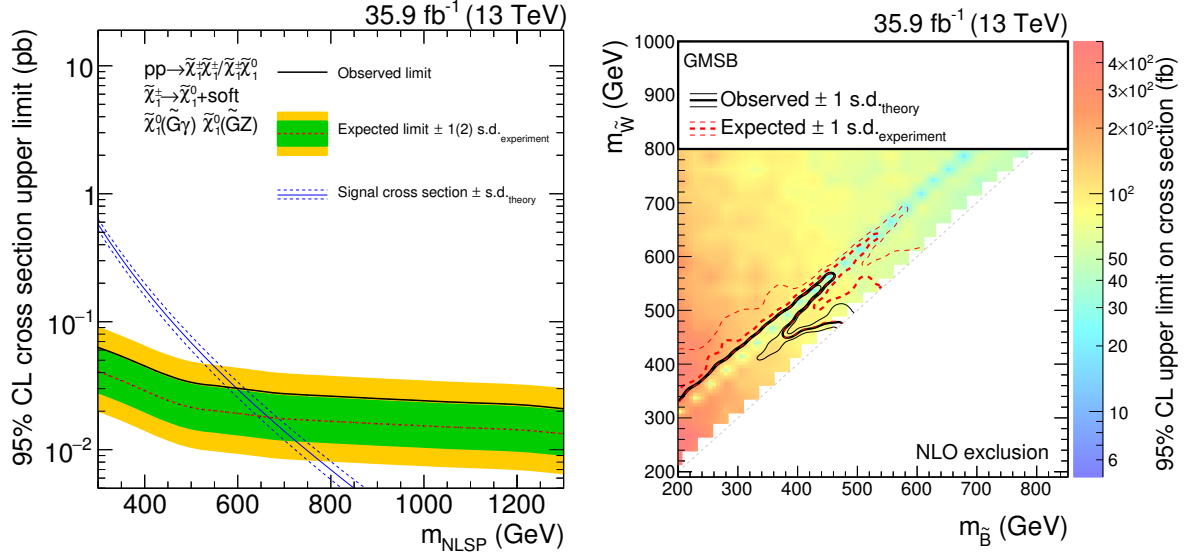


Figure 6.3.: Expected and observed upper limits for the TChiZG electroweak SMS (left) and the full GMSB model (right).

cross section increase for larger bino masses, the sensitivity loses there. In total the analysis excludes bino and wino masses in a range up to 400 – 500 GeV depending on the wino mass. The exclusion contours show the same behavior as for the one dimensional exclusion discussed above, due to the overfluctuation in data in the second SR bin. Therefore, the observed limit is weaker than the expected limit.

Limits on strong production of gluinos

In addition to the limits on EWK SUSY production, the results are interpreted in a SMS with gluino pair production. The cross section upper limits are shown in Figure 6.4 in the gluino-NLSP mass plane.

The analysis can exclude gluino masses up to 1.4 TeV, depending on the mass of the NLSP ($\tilde{\chi}_1^0$), and thus the mass splitting between them. For NLSP masses lower than 150 GeV, the sensitivity drops because of the applied M_{T2} threshold of 100 GeV and its poor mass resolution due to the difficulty in the interpretation of p_T^{miss} . With increased $\tilde{\chi}_1^0$ masses the sensitivity rises, since the final state products carry more energy. Again, the same effect between expected and observed limit contour is observable.

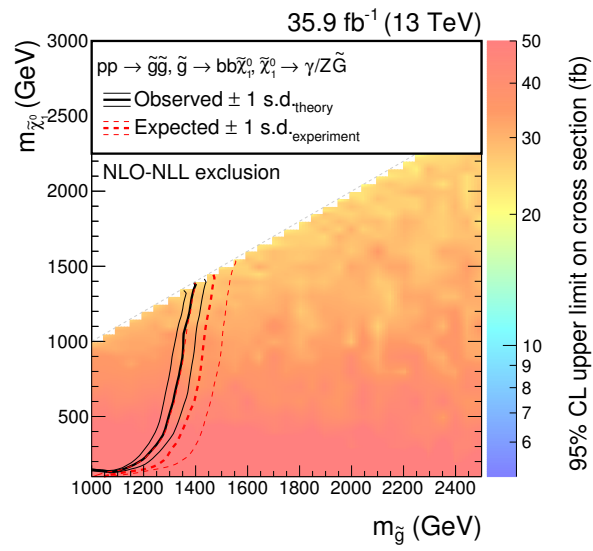


Figure 6.4.: Expected and observed upper limits for the T5bbbbZG SMS with strong production.

Summary & Conclusion

A search for gauge-mediated supersymmetry in final states with missing transverse momentum p_T^{miss} , a Z boson decaying to charged leptons ($Z \rightarrow \mu\mu/\text{ee}$), and photons based on a data set of proton-proton collisions with a center-of-mass energy of 13 TeV recorded with CMS in 2016 has been presented. The data set corresponds to an integrated luminosity of 35.9 fb^{-1} , and the relevant events are selected using same flavor dilepton triggers.

Events with photons, Z bosons, and p_T^{miss} are expected in gauge-mediated supersymmetry breaking scenarios, where the next-to-lightest supersymmetric particle is bino- or wino-like, and the NLSP decays to these SM bosons and the LSP, the gravitino \tilde{G} . The gravitino is predicted to be stable in R-parity conserving SUSY scenarios and leaves the detector undetected, thus giving rise to a significant amount of p_T^{miss} in the event.

The search was developed such, that is complementary to other CMS GMSB SUSY searches targeting different scenarios including photons. Therefore, this is the first CMS SUSY analysis investigating $Z(\rightarrow \ell\ell) + \gamma$ events. In addition, the analysis is designed to be sensitive to different production channels of gauginos, including strong and electroweak production channels. By restricting the search to events including three final state particles and p_T^{miss} , not many additional selection criteria are needed to reduce standard model background contributions. The usage of the transverse mass M_{T2} reconstructed from the Z boson candidate, the photon, and the missing transverse momentum, enables good discrimination between background and SUSY signals by estimating the NLSP mass.

The main background contributions for the search are $t\bar{t}(\gamma)$, $DY/Z(PGg)$, WZ , and ZZ production, while $t\bar{t}(\gamma)$ is by far the most important background, making up 70 – 80% of the total SM background in the signal region. Each of those backgrounds is estimated with a data driven approach based on Monte-Carlo simulation, where each background is normalized to the observation in a dedicated control region. The agreement between data and prediction in each control region is good, and further studies such as χ^2 -fits are performed to investigate the modeling of different observables within the simulation.

The final background prediction is validated in a validation region, which is constructed as a sideband region to the signal region, by requiring the events to fail one of the two signal region requirements. The agreement between data and prediction in the validation region is also good, indicating that the background estimations behaves properly.

In the signal region a counting experiment is performed comparing predicted and observed event yields in each of the bins of the p_T^{miss} distribution. No significant deviation is observed,

though in one of the bins, a 1.3σ upward deviation is present.

Upper cross section and exclusion limits are calculated at 95% confidence level for three different signal models. The results are interpreted within a electroweak model based on the General Gauge Mediation framework, excluding bino and wino masses up to 400 – 560 GeV. Additional simplified models are used for interpretation, excluding NLSP neutralino masses up to 600 GeV in case of electroweak gaugino production. In cases of gluino pair production, gluino masses lower than 1.4 TeV are excluded.

The results presented throughout this thesis are documented in [9]. The exclusion limits are comparative to different CMS SUSY searches [6] in the low bino and wino mass regions of the GMSB model, but are not as sensitive as other analyses for the simplified models discussed above due to the low $Z \rightarrow \ell\ell$ branching fraction. Since the analysis investigates a new final state with respect to all other CMS GMSB SUSY searches [5–7], it can be useful for a future statistical combination of analyses, which is under development [146] at the time of writing. With the full Run II data recorded at CMS in the years 2015-2018, a reperformance of this search on the much larger data set would be interesting, as the larger data set enables possibilities to optimize the background prediction, and especially the search region definitions.

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In Table A.1 the DBS paths for all used data sets in the analysis are given. The data sets are divided into several primary datasets (PD), where the same-flavor datasets are used for the signal selection, the different-flavor data sets is used for the background prediction, and the p_T^{miss} and H_T data sets are used for the trigger efficiency measurement. Each group of data sets is subdivided into several run eras (B-H), and the 2017 version of reconstruction is used.

Table A.1.: DBS paths for the datasets used in the analysis. Their paths are similar, only the PD names vary. The dilepton data sets are used for the key analysis, whereas the H_T and p_T^{miss} datasets are used for the trigger efficiency measurement, see Section 4.6.

PDs	DoubleEG
	DoubleMu
	MuonEG
	HT
	MET
DBS path	/PD/Run2016B-03Feb2017_ver2-v2/MINIAOD
	/PD/Run2016C-03Feb2017-v1/MINIAOD
	/PD/Run2016D-03Feb2017-v1/MINIAOD
	/PD/Run2016E-03Feb2017-v1/MINIAOD
	/PD/Run2016F-03Feb2017-v1/MINIAOD
	/PD/Run2016G-03Feb2017-v1/MINIAOD
	/PD/Run2016H-03Feb2017_ver2-v1/MINIAOD
	/PD/Run2016H-03Feb2017_ver3-v1/MINIAOD

Simulated data sets

Simulated standard model data sets

In Table B.1 DBS paths of the used SM simulated data sets are given together with their cross sections used for the normalization of the processes. In cases where NLO to NNLO k-factors are used, this is also stated in the table.

Table B.1.: All SM MC samples used in the analysis with their cross section. In the case k-factors are applied, they are given separately. {...} stands for RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TracheIV_v6 in abbreviation. All samples are of the MINIAODSIM format.

process	data set	$\sigma \cdot k [\text{pb}]$
ttbar		
$t\bar{t} \rightarrow \ell^+ \nu_b + \ell^- \bar{\nu}_b$	/TTTo2L2Nu_Tune*_ttHtranche3_13TeV-powheg-pythia8/{...}-v1	87.31
ttbarGamma		
$t\bar{t}\gamma$	/TTGamma_Dilept_Tune*_13TeV-amcatnlo-pythia8/{...}-v2	1.679
	/TTGamma_Hadronic_Tune*_13TeV-amcatnlo-pythia8/{...}-v2	3.482
	/TTGamma_SingleLeptFromT_Tune*_13TeV-amcatnlo-pythia8/{...}-v2	2.509
	/TTGamma_SingleLeptFromTbar_Tune*_13TeV-amcatnlo-pythia8/{...}-v2	2.509
DrellYan		
$Z/\gamma^* \rightarrow 2\ell$	/DYJetsToLL_M-50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/{...}_ext2-v1	5765.4
diboson		
$Z\gamma \rightarrow 2\ell\gamma$	/ZGTo2LG_Tune*_13TeV-amcatnloFXFX-pythia8/{...}_ext1-v1	117.864 · 1.06
	/ZGTo2LG_Tune*_13TeV-amcatnloFXFX-pythia8/{...}-v1	117.864 · 1.06
	/ZGTo2LG_PtG-130_Tune*_13TeV-amcatnloFXFX-pythia8/{...}-v1	0.1404 · 1.06
WZ	/WZTo3LNU_Tune*_13TeV-powheg-pythia8/{...}-v1	4.42965 · 1.109
	/WZTo3LNU_Tune*_13TeV-powheg-pythia8/{...}_ext1-v3	4.42965 · 1.109
$ZZ \rightarrow 2\ell 2\nu$	/ZZTo2L2Nu_13TeV-powheg-pythia8_ext1/{...}-v1	0.5644 · k
	/ZZTo2L2Nu_13TeV-powheg-pythia8/{...}-v1	0.5644 · k
$ZZ \rightarrow 4\ell$	/ZZTo4L_13TeV-powheg-pythia8/{...}-v1	1.212 · k
	/ZZTo4L_13TeV-powheg-pythia8_ext1/{...}-v1	1.212 · k
$WW \rightarrow 2\ell 2\nu$	/WWTo2L2Nu_13TeV-powheg/{...}-v1	12.178
$Wg \rightarrow \ell\nu g$	/WGToLNUg_Tune*_13TeV-amcatnloFXFX-pythia8/{...}_ext3-v1	489
W jets		
$W + jets$	/WJetsToLNu_Tune*_13TeV-amcatnloFXFX-pythia8/{...}_ext2-v2	61526.7
	/WJetsToLNu_Tune*_13TeV-amcatnloFXFX-pythia8/{...}-v1	61526.7
triboson		
WWg	/WWG_Tune*_13TeV-amcatnlo-pythia8/{...}_ext1-v1	0.2147
WZg	/WZG_Tune*_13TeV-amcatnlo-pythia8/{...}-v1	0.04123
single top		
$W^+ \rightarrow t\bar{b}$	/ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_*/{...}-v1	3.36
$q\bar{b} \rightarrow q'\bar{t}$	/ST_t-channel_antitop_4f_incl*Decays_13TeV-powhegV2-*pythia8_*/{...}-v1	80.95
$q\bar{b} \rightarrow q't$	/ST_t-channel_top_4f_incl*Decays_13TeV-powhegV2-*pythia8_*/{...}-v1	136.02
$\bar{b} \rightarrow W^+\bar{t}$	/ST_tW_antitop_5f_NoFullyHadronicDecays_13TeV-powheg_*/{...}_ext1-v1	11.7
$b \rightarrow W^-t$	/ST_tW_top_5f_NoFullyHadronicDecays_13TeV-powheg_*/{...}_ext1-v1	11.7

Simulated SUSY data sets

In Table B.2 the DBS paths for the used signal simulated data sets are given. Because for in each signal data set very different parameter masses are used in the generation, many cross sections are used for the rescaling of the simulation, and are not quoted in the table.

Table B.2.: All SUSY MC samples used in the analysis. $\{..\}$ stands for 80X_mcRun2_asymptotic_2016 in abbreviation. All samples are of the MINIAODSIM format.

signal	data set
electroweak	
TChiNG	/SMS-TChiNG_BF50N50G_*/RunIISpring16MiniAODv2-PUSpring16Fast_{..}_miniAODv2_v0-v1
GMSB model	/GMSB_GravitinoLSP_N1decays_*/RunIISummer16MiniAODv2-PUSummer16Fast_{..}_TrancheIV_v6-v1
strong production	
T5bbbbZG	/SMS-T5bbbbZg_*/RunIISummer16MiniAODv2-PUSummer16Fast_{..}_TrancheIV_v6-v2

Trigger paths

In Table C.1 and Table C.2 all HLT trigger paths used in the analysis are quoted. The trigger paths in the first table are relevant for the signal event selection and the background prediction, while the HLT paths stated in the second table are only needed for the trigger efficiency measurement.

Table C.1.: Trigger paths used in the analysis for the signal event selection.

trigger path
dielectron trigger
HLT_Ele17_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_DoubleEle33_CaloIdL_GsfTrkIdVL_v*
HLT_DoubleEle33_CaloIdL_GsfTrkIdVL_MW_v*
dimuon trigger
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v*
HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v*
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v*
HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v*
HLT_TkMu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v*
HLT_Mu27_TkMu8_v*
HLT_Mu30_TkMu11_v*
electron-muon trigger
HLT_Mu17_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_v*
HLT_Mu23_TrkIsoVVL_Ele8_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*
HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Mu8_TrkIsoVVL_Ele17_CaloIdL_TrackIdL_IsoVL_v*
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v*
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v*
HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
HLT_Mu30_Ele30_CaloIdL_GsfTrkIdVL_v*
HLT_Mu33_Ele33_CaloIdL_GsfTrkIdVL_v*

Table C.2.: Trigger paths used in the analysis for the trigger efficiency measurements.

trigger path
HT trigger
HLT_PFHT200_v*
HLT_PFHT250_v*
HLT_PFHT300_v*
HLT_PFHT350_v*
HLT_PFHT400_v*
HLT_PFHT475_v*
HLT_PFHT600_v*
HLT_PFHT650_v*
HLT_PFHT800_v*
MET trigger
HLT_PFMET110_PFMHT110_IDTight_v*
HLT_PFMET120_PFMHT120_IDTight_v*
HLT_PFMET170_NoiseCleaned_v *
HLT_PFMET170_HBHECleaned_v*
HLT_PFMET170_JetIdCleaned_v*
HLT_PFMET170_NotCleaned_v*
HLT_PFMET300_v*
HLT_PFMET400_v*
HLT_PFMET500_v*
HLT_PFMET600_v*

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Para. 156 StGB (German Criminal Code): False Statutory Declarations

Whoever before a public authority competent to administer statutory declarations falsely makes such a declaration or falsely
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Abs. 2 und 3 gelten entsprechend.

Para. 161 StGB (German Criminal Code): False Statutory Declarations Due to Negligence

(1) If a person commits one of the offences listed in sections 154 through 156 negligently the penalty shall be imprisonment not
exceeding one year or a fine.

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