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Search for gauge-mediated supersymmetry in events with at least one photon and missing transverse momentum in pp collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for gauge-mediated supersymmetry (SUSY) in final states with photons and large missing transverse momentum is presented. The data sample of pp collisions at $\sqrt{s} = 13\,\text{TeV}$ was collected with the CMS detector at the CERN LHC and corresponds to an integrated luminosity of $35.9\,\text{fb}^{-1}$. Data are compared with models in which the lightest neutralino has bino- or wino-like components, resulting in decays to photons and gravitinos, where the gravitinos escape detection. The event selection is optimized for both electroweak (EWK) and strong production SUSY scenarios. The observed data are consistent with standard model predictions, and limits are set in the context of a general gauge mediation model in which gaugino masses up to 980 GeV are excluded at 95% confidence level. Gaugino masses below 780 and 950 GeV are excluded in two simplified models with EWK production of mass-degenerate charginos and neutralinos. Stringent limits are set on simplified models based on gluino and squark pair production, excluding gluino (squark) masses up to 2100 (1750) GeV depending on the assumptions made for the decay modes and intermediate particle masses. This analysis sets the highest mass limits to date in the studied EWK models, and in the considered strong production models when the mass difference between the gauginos and the squarks or gluinos is small.

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*See Appendix A for the list of collaboration members

1 Introduction

The search for physics beyond the standard model (SM) is one of the key research topics of the CMS experiment at the CERN LHC. Especially after the discovery of a Higgs boson with a mass of around 125 GeV in 2012 [1–3], supersymmetry (SUSY) [4–17] is one of the theoretically favored possible extensions of the SM. Among several explanations for unsolved problems in particle physics, SUSY provides a mechanism for stabilizing the SM-like Higgs boson mass at the electroweak (EWK) scale. Since current searches are pushing the limits on strongly produced SUSY particles (sparticles) beyond the one-TeV threshold, the interest in probing gaugino masses via EWK production is growing. While searches for heavy sparticles especially profit from the increase in the center-of-mass energy due to the large increase of the production cross section, searches for EWK production benefit from a larger data set, as collected by the CMS experiment in 2016.

In this Letter, a search for SUSY focusing on gauge-mediated SUSY breaking (GMSB) [18–24] scenarios is presented. The R-parity [25] is assumed to be conserved, so that SUSY particles are always produced in pairs. The gravitino ($\widetilde{G}$) is the lightest SUSY particle (LSP) and escapes undetected, leading to missing transverse momentum (p_T^{miss}) in the detector. The next-to-LSP (NLSP) is assumed to be the lightest neutralino ($\widetilde{\chi}_1^0$). Depending on its composition, the $\widetilde{\chi}_1^0$ can decay according to $\widetilde{\chi}_1^0 \to N\widetilde{G}$, where N is either a photon (γ), an SM-like Higgs boson (H), or a Z boson. If the gauginos are nearly mass-degenerate, the chargino ($\widetilde{\chi}_1^\pm$) decays $\widetilde{\chi}_1^\pm \to W^\pm\widetilde{G}$ are also possible. The $\widetilde{G}$ is assumed to have negligible mass and the NLSP is assumed to decay promptly.

The analyzed data set was collected at the CERN LHC in proton-proton collisions at a center-of-mass energy of 13 TeV and corresponds to an integrated luminosity of 35.9 fb^{-1}. Events are required to contain at least one high-energy photon and large p_T^{miss}. In order to maintain sensitivity to EWK SUSY production, there is no explicit event selection criterion requiring hadronic energy, i.e., the presence of jets in the event. In GMSB SUSY, p_T^{miss} arises from the stable and noninteracting $\widetilde{G}$, while photons originate from $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$ decays. The energy of the photon as well as of the gravitino and thus the p_T^{miss} is governed by the $\widetilde{\chi}_1^0$ mass, and the $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$ branching fraction is determined by the neutralino's bino and wino components and its mass. Compared to analyses requiring photons and large hadronic activity, this analysis has superior sensitivity to GMSB SUSY in EWK production, and also in strong production if the squark, gluino, and the lightest gaugino masses are similar (compressed-spectrum scenarios).

An earlier version of this analysis [26] was carried out by CMS on a special 8 TeV data set recorded as part of the "parked-data" program [27] corresponding to an integrated luminosity of 7.4 fb^{-1} using a dedicated trigger and a lower photon transverse momentum (p_T) threshold of 30 GeV. The ATLAS and CMS collaborations have also searched for direct EWK production of gauginos in final states with at least one photon and one electron or muon [28, 29], and in the two-photon channel [29–31]. Single-photon and H_T-based analyses [31], where H_T is the scalar sum of hadronic jet transverse momenta, have good sensitivity for strong production in GMSB models but lack sensitivity for EWK production and compressed-spectrum scenarios.

2 Signal models

To interpret the results, a general gauge mediation (GGM) [32–37] scenario dominated by EWK production is used. Furthermore, two EWK production and four strong production simplified model scenarios (SMS) [38] are considered for interpretation. For the GGM scenario, the squark and gluino masses are set to a high scale rendering them inaccessible and strong production negligible. The bino and wino masses therefore fully determine the model point under study and are varied in the interpretation. The $\widetilde{\chi}_1^0$ is assumed to be purely bino-like, while the $\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_2^0$ are assumed to be purely wino-like. The dominant process for EWK GGM production is shown in Fig. 1 (upper left). In the GGM framework, where the gauginos are not mass-degenerate by construction, a larger $\widetilde{\chi}^\pm$–$\widetilde{\chi}_1^0$ mass difference increases the hadronic energy in the final state if the Z, H, or W bosons decay hadronically.

The EWK simplified scenario TChiWg probes associated production of mass-degenerate charginos and neutralinos ($\widetilde{\chi}_1^\pm\widetilde{\chi}_1^0$), assuming the decay modes $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$ and $\widetilde{\chi}_1^\pm \to W^\pm\widetilde{G}$, as shown in Fig. 1 (upper right). The TChiNg scenario assumes nearly mass-degenerate $\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_1^0$, but considers $\widetilde{\chi}_1^\pm\widetilde{\chi}_1^\mp$ and $\widetilde{\chi}_1^\pm\widetilde{\chi}_1^0$ production as shown in Fig. 1 (lower left and right). In this scenario, the $\widetilde{\chi}_1^\pm$ is assumed to have a slightly higher mass than $\widetilde{\chi}_1^0$, and it decays to $\widetilde{\chi}_1^0$ and low-momentum particles outside the acceptance of this analysis. The neutralinos are assumed to decay as $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$, $\widetilde{\chi}_1^0 \to Z\widetilde{G}$, and $\widetilde{\chi}_1^0 \to H\widetilde{G}$ with 50, 25, and 25% probability, respectively.

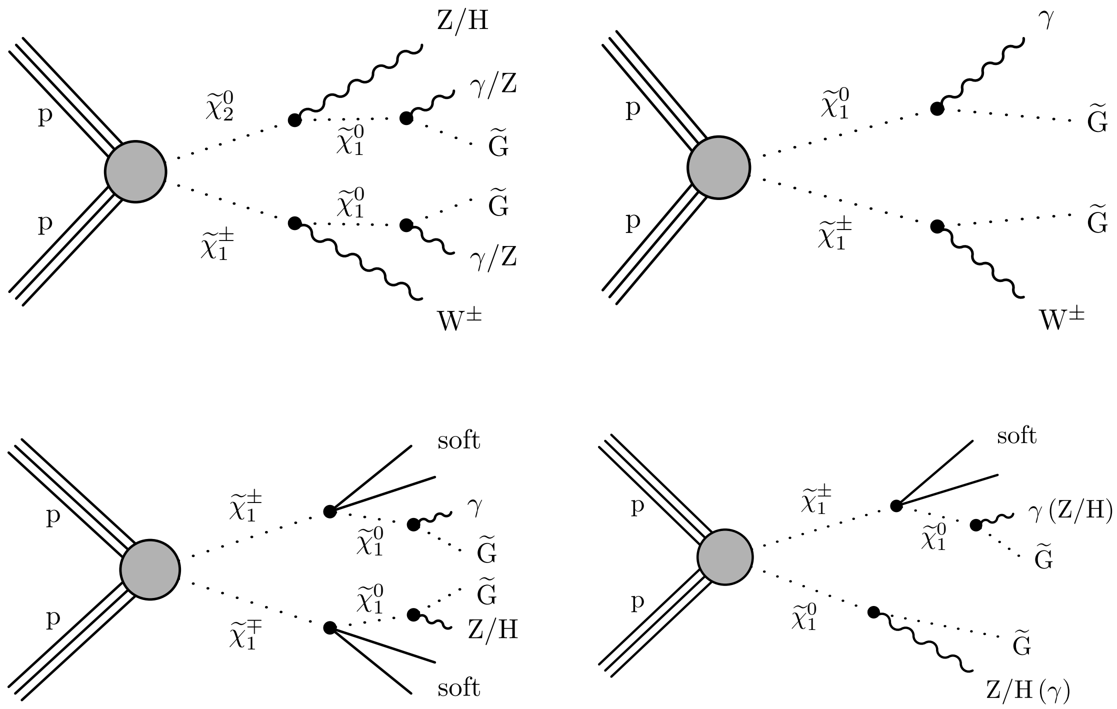

Figure 1: In the context of GGM, several production and decay channels are possible. The diagram of the dominant process $\widetilde{\chi}_2^0$–$\widetilde{\chi}_1^\pm$ production is shown (upper left), where the gaugino decays depend on the mass configuration under study. In the TChiWg model (upper right), the gauginos are mass degenerate. The TChiNg model comprises $\widetilde{\chi}_1^\pm$ pair production (lower left) and $\widetilde{\chi}_1^\pm\widetilde{\chi}_1^0$ production (lower right), where the $\widetilde{\chi}_1^\pm$ is only slightly heavier than the $\widetilde{\chi}_1^0$, so only low-momentum (soft) particles appear in the decay of $\widetilde{\chi}_1^\pm$ to $\widetilde{\chi}_1^0$.

The strong production SMS models T5gg, T5Wg, T6gg, and T6Wg are shown in Fig. 2, where T5gg and T5Wg represent gluino pair production, and T6gg and T6Wg squark pair production. The neutralino decays as $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$, while the chargino decays as $\widetilde{\chi}_1^\pm \to W^\pm\widetilde{G}$. In the T5Wg and T6Wg scenario, a branching fraction of 50% is assumed for the charged and neutral decays of the gluino or squark. The T5gg (T6gg) scenario assumes a branching fraction of 100% for $\widetilde{g} \to q\bar{q}\widetilde{\chi}_1^0$ ($\widetilde{q} \to q\widetilde{\chi}_1^0$).

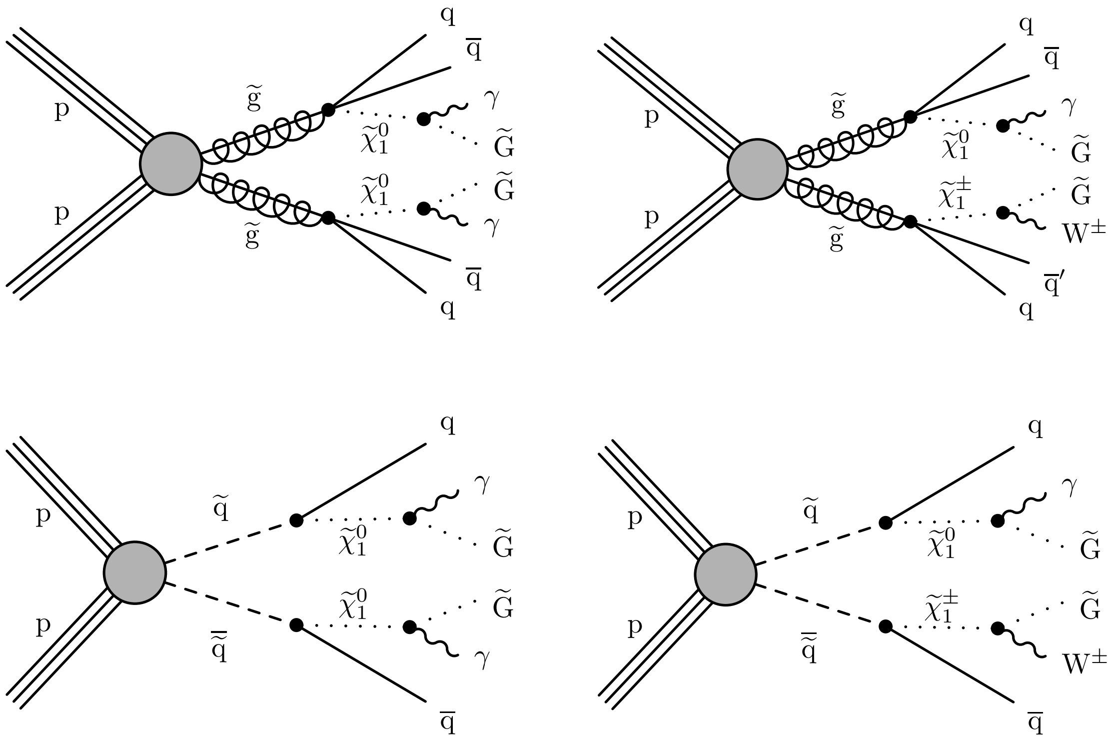

Figure 2: For strong gluino pair-production the simplified scenarios T5gg (upper left) and T5Wg (upper right) and for squark pair-production the simplified scenarios T6gg (lower left) and T6Wg (lower right) are studied. In the T5Wg (T6Wg) scenario, a branching fraction of 50% is assumed for the decays $\tilde{g} \to q\overline{q}\widetilde{\chi}_1^\pm$ and $\tilde{g} \to q\overline{q}\widetilde{\chi}_1^0$ ($\widetilde{q} \to q\widetilde{\chi}_1^\pm$ and $\widetilde{q} \to q\widetilde{\chi}_1^0$), resulting in final states with zero, one, or two photons.

3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

In the barrel section of the ECAL, an energy resolution of approximately 1% is achieved for unconverted or late-converting photons arising from the $H \to \gamma\gamma$ decay for photons with $p_T > 25\,\text{GeV}$. The remaining barrel photons have an energy resolution of about 1.3% up to a pseudorapidity of $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$. In the endcaps, the energy resolution of unconverted or late-converting photons is about 2.5%, while the remaining endcap photons have a resolution between 3 and 4% [39].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [40].

4 Object reconstruction and simulation

The particle-flow (PF) event algorithm [41] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. Fully reconstructed photon conversions are used by the PF algorithm and are included in the set of photon candidates. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

Photons are reconstructed [39] from clusters in the ECAL and are required to be isolated. The energy deposit in the HCAL tower closest to the seed of the ECAL supercluster [42] assigned to the photon is required to be less than 5% of the energy deposited in the ECAL. A photon-like transverse ECAL shower shape is required. The photon isolation is determined by computing the transverse energy in a cone centered around the photon momentum vector. The cone has an outer radius of 0.3 in $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, where ϕ is the azimuthal angle, and the contribution of the photon is removed. Corrections for the effects of multiple interactions in the same or adjacent bunch crossing (pileup) are applied to all isolation energies, depending on the η of the photon. To ensure that no photon with anomalously high a posteriori corrections populate the signal region, a requirement that at least 30% of the photon's energy be deposited in the seed crystal is imposed for all considered photons. A photon candidate must exceed a minimal p_{T} of 15 GeV. Photons are efficiently discriminated against electrons by requiring that photons have no matching pattern of energy deposits in the pixel detector.

The vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the projection onto the plane perpendicular to the beams of the negative vector sum of the momenta of all PF candidates in an event. The magnitude of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is referred to as $p_{\mathrm{T}}^{\mathrm{miss}}$.

Jets are reconstructed from PF candidates with the anti-k_{T} clustering algorithm [43] as implemented in the FastJet [44] package, using a distance parameter of 0.4. Jet energy corrections [45, 46] are derived from Monte Carlo (MC) simulation, and are confirmed with in situ measurements of the energy balance in dijet and γ+jet events. These corrections are also propagated to $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$. Jets with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 3$ are required to be geometrically isolated from identified photons, electrons, and muons, where electrons and muons have to fulfill standard identification requirements to be considered in this isolation criterion. Filters against anomalously high $p_{\mathrm{T}}^{\mathrm{miss}}$ from instrumental effects are applied [47].

The reconstructed vertex with the largest value of summed physics-object p_{T}^2 is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [43, 44] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_{T} of those jets.

The SM background processes contributing to the signal and control regions are modeled using MC simulations. The quantum chromodynamics (QCD) multijet, γ+jets, and W and Z processes are generated with MadGraph5_aMC@NLO 2.3.3 [48, 49] at leading order (LO), while the $\mathrm{t\bar{t}}(+\gamma)$ processes are generated at next-to-leading order (NLO) [48, 50]. The WW diboson production is generated with POWHEG v2 [51–55], and WZ and ZZ production are generated using PYTHIA8.205 [56]. The $Z\gamma$ sample is scaled with photon p_{T} dependent next-to-next-to-leading logarithmic (NNLL) K-factors [57], which are of the order of 1.3. A constant next-to-NLO (NNLO) K-factor of 1.34 is applied to the $W\gamma$ production cross section [57], and NLO K-factors of the order of 1.2 are applied to the W and $Z(\rightarrow \nu\nu)$ production cross sections. The diboson production cross sections are available at NLO (ZZ, WZ) and NNLO (WW) precision [58]. The $W\gamma$ and $Z\gamma$ processes, collectively denoted as $V\gamma$, are the dominant backgrounds in the signal region. A data sideband region is used to obtain additional scale factors for the $V(\gamma)$ and γ+jets samples, where $V(\gamma)$ comprises the Wand Z boson production, with and without photon radiation.

The GGM signal scan is generated with PYTHIA8, while the SMS signal scans are generated with MADGRAPH5_aMC@NLO at LO. The cross sections are calculated at NLO and NLO+NLL accuracy [59–67] for the GGM and the SMS scans, respectively, with all the unconsidered sparticles assumed to be heavy and decoupled. For the EWK models, the cross sections are computed in a limit of mass-degenerate wino $\widetilde{\chi}^0_2$ and $\widetilde{\chi}^{\pm}_1$.

All MC samples incorporate the NNPDF 3.0 [68] parton distribution functions (PDFs) and use the PYTHIA v8.205 or PYTHIA v8.212 program with the CUETP8M1 generator tune [69] to describe the parton showering and the hadronization. Double counting of the partons generated with MADGRAPH5_aMC@NLO and those with PYTHIA is removed using the MLM [49] and the FXFX [50] matching schemes, in the LO and NLO samples, respectively. The GEANT4 [70] package is used to model the detector and the detector response for SM processes, while the CMS fast simulation [71, 72] is used for signal samples. Additional pp interactions are considered in the simulation and all samples are weighted on an event-by-event basis to match the distribution of the number of interaction vertices observed in data.

5 Event selection

The data are recorded using a trigger requiring one photon that passes very loose identification criteria and has a p_{T} of at least 165 GeV [73]. The events in the subsequent analysis are required to contain at least one identified and isolated photon with $p_{\mathrm{T}} > 180$ GeV in the central barrel part of the detector ($|\eta| < 1.44$) that has been accepted by the trigger. The photons are required to have an angular distance in the $\eta-\phi$ plane of $\Delta R > 0.5$ to the nearest jet. To suppress events where the $p_{\mathrm{T}}^{\mathrm{miss}}$ mainly arises from a significant mismeasurement of a jet's energy, all jets with $p_{\mathrm{T}} > 100$ GeV must fulfill $\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet}) > 0.3$, where $\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})$ is the distance in ϕ between the jet and the $p_{\mathrm{T}}^{\mathrm{miss}}$. At least one reconstructed vertex per event is required [74]. To maintain high signal acceptance for all studied signal scenarios no selection criteria are applied on the presence or absence of jets or leptons, except for the photon isolation criteria. The photon trigger efficiency for this selection is found to be $\epsilon_{\gamma} = 94.3 \pm 0.4\%$, independent of the kinematic event variables used in the analysis.

The preselected events with at least one high-p_{T} photon are separated into a signal region and an orthogonal control region. The signal region is defined by $p_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV and $M_{\mathrm{T}}(\gamma, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) > 300$ GeV, where $M_{\mathrm{T}}(\gamma, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ is the transverse mass of the photon with the highest energy and $p_{\mathrm{T}}^{\mathrm{miss}}$, and roughly represents the NLSP mass in the SUSY scenarios containing the decay $\widetilde{\chi}^0_1 \rightarrow \gamma\widetilde{G}$. The requirement $M_{\mathrm{T}}(\gamma, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) > 300$ GeV was chosen to optimize the statistics in the control region under maximization of the signal acceptances. The region with $p_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV and $M_{\mathrm{T}}(\gamma, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) > 100$ GeV, but excluding the signal region, defines the signal-depleted data control region.

Multiple exclusive signal bins are defined with respect to $S_T^\gamma \equiv p_T^{miss} + \sum_{\gamma_i} p_T(\gamma_i)$, the scalar sum of p_T^{miss} and the p_T of all photons in the event. The region with $p_T^{miss} > 300$ GeV and $M_T(\gamma, \vec{p}_T^{miss}) > 300$ GeV, but $S_T^\gamma \leq 600$ GeV has negligible signal contamination and is used to validate the background estimation. The four S_T^γ regions 600–800, 800–1000, 1000–1300, and >1300 GeV define exclusive bins that are simultaneously interpreted in a multichannel counting experiment for best sensitivity. The full selection requirements to define each region used in this analysis are summarized in Table 1.

Table 1: Summary of the event selection criteria required for the control, validation, and signal regions.

Region	Selection
Preselection	p_T^{miss} filters At least one reconstructed vertex At least one photon with $p_T > 180$ GeV $\Delta R(\gamma, \text{jet}) > 0.5$ $\Delta\phi(\vec{p}_T^{miss}, \text{jet}) > 0.3$ rad, if $p_T(\text{jet}) > 100$ GeV
Control region	Preselection $p_T^{miss} > 100$ GeV $M_T(\gamma, \vec{p}_T^{miss}) > 100$ GeV $p_T^{miss} < 300$ GeV or $M_T(\gamma, \vec{p}_T^{miss}) < 300$ GeV
Validation region	Preselection $p_T^{miss} > 300$ GeV $M_T(\gamma, \vec{p}_T^{miss}) > 300$ GeV $S_T^\gamma < 600$ GeV
Signal region	Preselection $p_T^{miss} > 300$ GeV $M_T(\gamma, \vec{p}_T^{miss}) > 300$ GeV $S_T^\gamma > 600$ GeV

The selection differs in several aspects from the analysis using 8 TeV data [26]. The trigger used in the 8 TeV analysis allowed for very low photon p_T and p_T^{miss} selections. The "p_T^{miss} significance" that defined the signal and control regions has been replaced by p_T^{miss} for simplicity and to allow for easier reinterpretations of the results. The analysis is optimized such that no loss in sensitivity is ensured.

6 Background estimation

The SM background in the photon and p_T^{miss} final state is dominated by vector boson production with initial-state photon radiation, in particular by the $Z\gamma \to \nu\bar{\nu}\gamma$ process. Direct photon production in association with jets, γ+jets, also contributes at low values of p_T^{miss} and thus low values of S_T^γ. A subdominant background arises from electrons misidentified as photons ($e \to \gamma$). Further minor contributions originate from $t\bar{t}\gamma$ and diboson production. The most relevant backgrounds, $V(\gamma)$ and γ+jets, are modeled by MC simulation and are scaled to the data in the data control region at low values of p_T^{miss} and $M_T(\gamma, \vec{p}_T^{miss})$. The contribution from events with $e \to \gamma$ misidentification is predicted from data. All remaining minor contributions are modeled by MC simulation.

The normalization of the $V(\gamma)$ and γ+jets backgrounds is determined in the control region by a simultaneous χ^2-fit in bins of $\Delta\phi(\vec{p}_T^{miss}, \text{nearest jet}/\gamma)$, which is the angular distance in the transverse plane of the p_T^{miss} and the nearest jet or photon. The distribution of

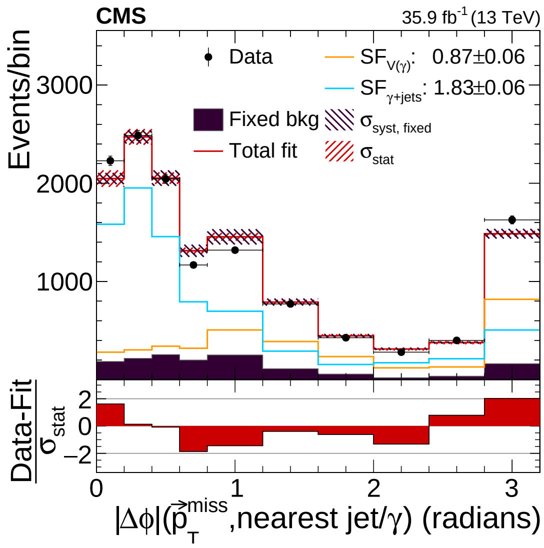

Figure 3: The post-fit distributions for the γ+jets (blue) and $\mathrm{V}(\gamma)$ (orange) background in the control region together with the fixed background (dark magenta) and the total fit distribution stacked onto the fixed backgrounds (red) are shown. The statistical uncertainty (σ_{stat}) of the post-fit distribution is shown in the red hatched area and the systematic uncertainty of the fixed background ($\sigma_{\text{syst, fixed}}$) is indicated with the dark magenta hatched area. The values $\mathrm{SF}_{\mathrm{V}(\gamma)}$ and $\mathrm{SF}_{\gamma\text{+jets}}$ in the legend are the resulting scale factors. The pull distribution only considers the statistical uncertainty.

$\Delta\phi(\vec{p}_{\mathrm{T}}^{\text{miss}}, \text{nearest jet}/\gamma)$ sufficiently separates the shapes of $\mathrm{V}(\gamma)$ and γ+jets backgrounds, so that scaling one background cannot compensate for the other. Contributions from other SM processes are small and are kept constant in the fit. Under the constraint of a fixed total yield, the scale factors for the $\mathrm{V}(\gamma)$ and γ+jets simulations are given by the minimum of the χ^2 distribution. The resulting scale factors are

$$\mathrm{SF}_{\mathrm{V}(\gamma)} = 0.87 \pm 0.06, \tag{1}$$

$$\mathrm{SF}_{\gamma\text{+jets}} = 1.83 \pm 0.06, \tag{2}$$

where the uncertainties are of statistical origin only. The post-fit distribution of $\Delta\phi(\vec{p}_{\mathrm{T}}^{\text{miss}}, \text{nearest jet}/\gamma)$ is shown in Fig. 3. The size of the measured factors is consistent with the expectations [57]. The scale factor for $\mathrm{V}(\gamma)$ is smaller than unity because EWK corrections, which are not contained in the K-factors, are smaller than unity for high photon p_{T}. The γ+jets scale factor is larger than unity since no K-factor is applied and QCD corrections for multijet backgrounds are large. The factors are found to be stable with respect to systematic variations of the method. Different control region selections, a variety of template variables, and various binnings of the template variables have been studied. Signal contamination becomes relevant if the gauginos are light because in terms of its kinematical variables the production of light gauginos is similar to that of $\mathrm{V}(\gamma)$ production and is taken into account in the statistical analysis. In the remaining phase space, signal contamination is negligible.

Electrons that are misidentified as photons create a subdominant background, which can be predicted from data with good statistical precision. The misidentification rate $f_{\mathrm{e}\to\gamma}$ is measured in data in $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ decays with the "tag-and-probe" method [75]. The dependence of the misidentification rate on the electron p_{T} and η is studied. Nonresonant $\mathrm{e}^+\mathrm{e}^-$ background from non Z boson events is estimated from $\mathrm{e}\mu$ events. The resulting misidentification rate in data is

$$f_{\mathrm{e}\to\gamma} = 2.7 \pm 1.3\%. \tag{3}$$

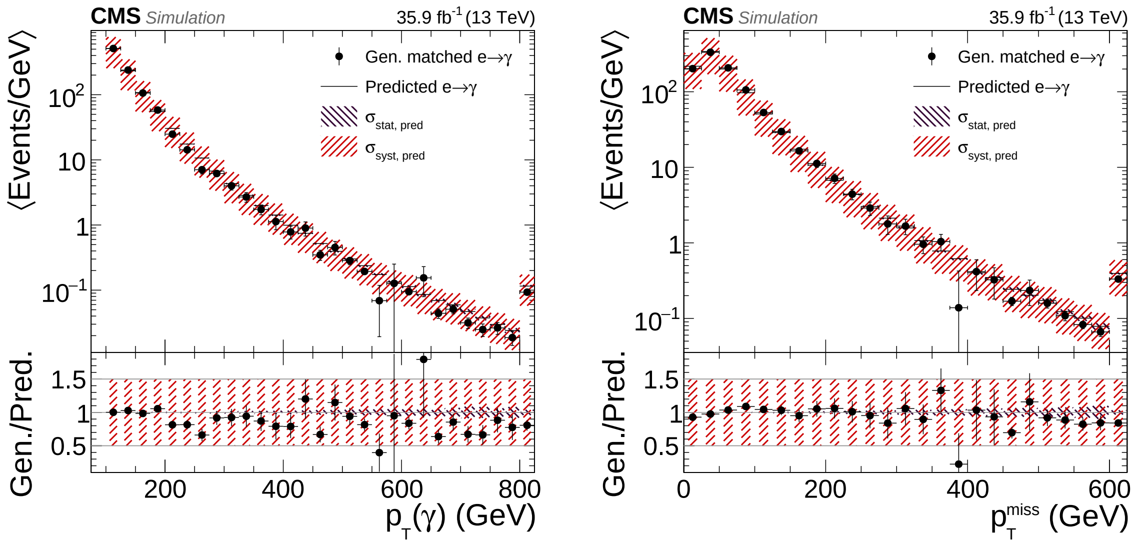

Figure 4: Validation of the electron misidentification background estimation method using MC simulation. In the selection with at least one photon with $p_T > 100\,\text{GeV}$, the prediction of the $e \to \gamma$ misidentification estimation method is compared to direct simulation in the photon p_T (left) and the p_T^{miss} (right) distributions. The black and red hatched areas represent the statistical ($\sigma_{\text{stat, pred}}$) and the 50% systematic ($\sigma_{\text{syst, pred}}$) uncertainties of the prediction, respectively. Events populating the phase space beyond the shown range are included in the last bin.

The uncertainty of 50% takes into account the variation of the misidentification rate as a function of the photon p_T, η, and several other variables.

The $e \to \gamma$ background is modeled from a data control sample with the same event selection as the signal region, but containing an identified electron instead of a photon. The sample is weighted by $f_{e\to\gamma}$. The uncertainty of this estimation is dominated by the systematic uncertainties in the misidentification rate. The statistical uncertainty is negligible because the electron selection efficiency is about 40 times larger than $f_{e\to\gamma}$. The method has been validated using MC simulation, as shown in Fig. 4.

The minor contributions from $t\bar{t}(\gamma)$ and diboson processes are modeled using MC simulation as discussed above. Events where electrons are misidentified as photons are removed at the generator level to avoid overlaps. Based on simulation studies, the background from QCD multijet events is found to be negligible.

All uncertainties that would affect the normalization are eliminated for the $V(\gamma)$ and γ+jets backgrounds by the MC normalization method. Therefore, the only remaining uncertainties originate from the simulated shape of these backgrounds. The shape uncertainty due to the choice of the renormalization and factorization scales has been determined by varying these scales in different combinations of factors 0.5, 1, and 2 and repeating the fit of the $V(\gamma)$ and γ+jets backgrounds. The prediction for each combination is compared in the four signal region bins for both backgrounds separately and bin-by-bin. The largest deviation in the respective bin is taken as the systematic uncertainty and varies in the range of 3.8–9.0% and 2.8–7.1% for the $V(\gamma)$ and γ+jets backgrounds, respectively. The LHC4PDF procedure [76] is used to determine the shape uncertainty due to the choice of the PDFs and is determined bin-by-bin in the signal region and taken as systematic uncertainty, varying in the range of 1.6–3.8% for the $V(\gamma)$ and 1.9–8.2% for γ+jets the background. Although there is no direct usage of jets, the analysis is affected by the propagation of the jet energy scale (JES) uncertainty to p_T^{miss}. The resulting uncertainty affecting the final selection is determined by propagating the upward

Table 2: Systematic uncertainties in the background prediction in percent.

	$V(\gamma)$	γ+jets	$e \rightarrow \gamma$	$t\bar{t}(\gamma)$	Diboson
Fit uncert. of statistical origin	6.9	3.3	—	—	—
Scale uncertainty in shape	3.8–9.0	2.8–7.1	—	—	—
PDF uncertainty in shape	1.6–3.8	1.9–8.2	—	—	—
JES uncertainty in shape	5.0–5.9	0.9–32	—	—	—
Tag-and-probe fit	—	—	50	—	—
Cross section, PDF, scales	—	—	—	30	30
Integrated luminosity	—	—	—	2.5	2.5
Photon eff. scale factor	—	—	—	2.0	2.0
Trigger efficiency	—	—	—	0.4	0.4

Table 3: Systematic uncertainties in the signal predictions in percent.

	Signal scenario	
Source	EWK	Strong production
Statistical MC precision per signal region	$1-28$	$2-50$
Fast simulation uncertainty in $p_{\mathrm{T}}^{\mathrm{miss}}$	$<0.1-5$	$<0.1-25$
Scale uncertainty in shape	$<0.1-1.8$	$<0.1-1.2$
Integrated luminosity	2.5	2.5
Trigger efficiency	0.4	0.4
Photon scale factor	2.0	2.0
Pileup	<0.1–0.4	<0.1–2.1
ISR reweighting	0.6–3.0	—

and downward shift of the JES to $p_{\mathrm{T}}^{\mathrm{miss}}$ and repeating the analysis using the shifted $p_{\mathrm{T}}^{\mathrm{miss}}$. The largest deviation in the prediction is taken as systematic uncertainty and varies in the range of 5.0–5.9% for the $V(\gamma)$ and 0.9–32% for the γ+jets background. The large deviation of 32% for γ+jets affects the highest bin in S_{T}^{γ}, where only approximately one γ+jets event is expected, so the absolute effect of this large uncertainty is small. A 30% uncertainty is assumed for the $t\bar{t}(\gamma)$ cross section, corresponding to a conservative estimate of the uncertainty with respect to the latest CMS measurement [77]. The uncertainty in the diboson cross section is assumed to be 30%. Further systematic uncertainties, also affecting the signal simulation, arise from the trigger efficiency (0.4%), the data to MC photon identification efficiency scale factor (2%) and the integrated luminosity (2.5%) [78].

We improve the MADGRAPH modeling of initial-state radiation (ISR), which affects the total transverse momentum ($p_{\mathrm{T}}^{\mathrm{ISR}}$) of the system of SUSY particles, by reweighting the $p_{\mathrm{T}}^{\mathrm{ISR}}$ distribution of MC SUSY events. This reweighting procedure is based on studies of the p_{T} of Z boson events [79]. The reweighting factors range between 1.18 at $p_{\mathrm{T}}^{\mathrm{ISR}} = 125\,\mathrm{GeV}$ and 0.78 for $p_{\mathrm{T}}^{\mathrm{ISR}} > 600\,\mathrm{GeV}$. We take the deviation from unity as the systematic uncertainty in the reweighting procedure.

The systematic uncertainties affecting the background prediction and the signals are summarized in Tables 2 and 3, respectively.

In Fig. 5 the signal sensitive variable S_{T}^{γ} is shown for the control selection, used to derive scale factors for the γ+jets and $V(\gamma)$ simulated samples, and for the validation selection. Good agreement is observed between the selected data and the SM background prediction.

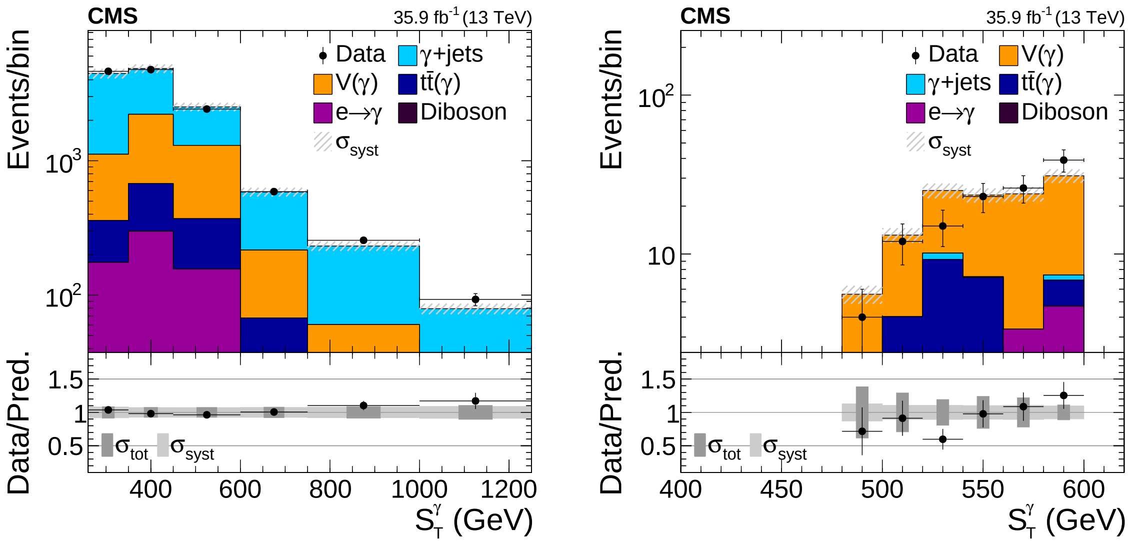

Figure 5: Data to simulation comparisons in the control region (left) and the validation region (right). Events with S_T^{γ} beyond the shown range are included in the last bin. The hatched light gray band in the upper panel, as well as the solid light gray band in the lower panel represent the total systematic uncertainty (σ_{syst}). The dark gray band in the lower panel indicates the quadratic sum of the statistical and systematic uncertainties (σ_{tot}).

7 Results and interpretation

Distributions of S_T^{γ} in the four search regions are shown in Fig. 6. The corresponding yields are given in Table 4 for each bin, also showing the contributions of the individual background components. The statistical uncertainty in the $e \to \gamma$ background is caused by the limited size of the collected data sample. All other statistical uncertainties are due to the limited number of simulated events. The total systematic uncertainty results from the quadratic sum of the systematic uncertainties of each background component. Good agreement is observed between the SM background prediction and the recorded data, without indication for the presence of new physics.

Limits are calculated in one- and two-dimensional parameter spaces for the EWK and strong production models introduced in Section 1. Upper limits on the signal cross section are calculated at 95% confidence level (CL) using a modified frequentist CL_s approach [80–82] with a profile likelihood test statistic and asymptotic formulae [83]. The 95% CL observed upper cross section limit, as well as the expected and observed exclusion contours, for the EWK GGM signal scan are shown in Fig. 7. The limits are presented in the wino-bino mass plane. The analysis reaches the highest sensitivity for nearly degenerate wino and bino masses. In this case, the analysis excludes wino and bino masses up to 980 GeV at 95% CL, improving on the former best limit of 710 GeV [26]. The sensitivity decreases with a larger wino-bino mass splitting since on average the energy of the photons and gravitinos decreases, while more energy is transfered to the other decay products of the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$.

The limits for the EWK TChiWg and TChiNg simplified models are shown as a function of m_{NLSP} in Fig. 8 together with the theoretical cross section. The analysis excludes NLSP masses below 780 GeV at 95% CL in the TChiWg scenario and below 950 GeV in the TChiNg scenario. Due to the slight excess observed with respect to the SM background prediction especially in the highest S_T^{γ} bins, the observed limits are weaker than the expected exclusion limits of 920 (1070) GeV for the TChiWg (TChiNg) scenario.

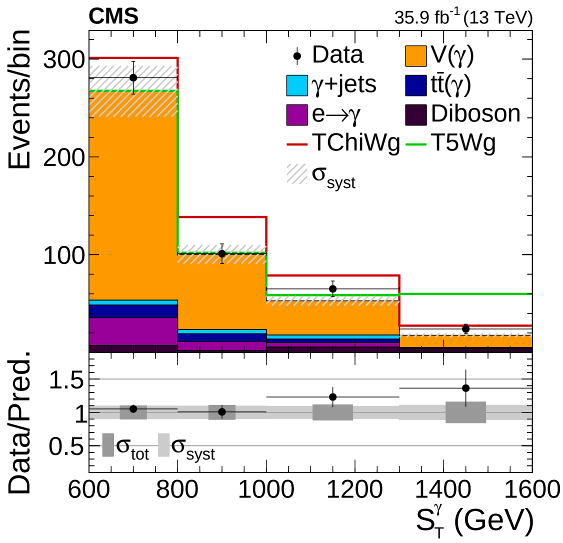

Figure 6: Comparison of the measurement and prediction in the signal region in four exclusive bins of S_T^γ. For guidance, two SUSY benchmark signal points are stacked on the SM background prediction, where the TChiWg signal point corresponds to a NLSP mass of 700 GeV and the T5Wg signal point corresponds to a gluino mass of 1750 GeV and a NLSP mass of 1700 GeV. Events with values of S_T^γ beyond the shown range are included in the last bin. The hatched light gray band in the upper panel, as well as the solid light gray band in the lower panel represent the total systematic uncertainty (σ_{syst}). The dark gray band in the lower panel indicates the quadratic sum of the statistical and systematic uncertainties (σ_{tot}).

Table 4: Background and data yields, as well as the statistical and systematic uncertainties for the separate signal region bins. For the total background uncertainty the uncertainties of the individual background components are summed quadratically.

S_T^γ: 600–800 GeV

	Yield	σ_{stat}	σ_{syst}
V(γ)	213	4.4	21.3
γ+jets	5	1.1	0.5
t$\bar{t}$(γ)	13	5.7	3.9
e $\to \gamma$	29	0.9	14.2
Diboson	7	2.8	2.1
Total	267	7.9	26.0
Data	281		

S_T^γ: 800–1000 GeV

	Yield	σ_{stat}	σ_{syst}
V(γ)	76.8	1.9	8.1
γ+jets	4.4	1.2	0.4
t$\bar{t}$(γ)	8.0	3.8	2.4
e $\to \gamma$	9.2	0.5	4.6
Diboson	1.9	1.7	0.6
Total	100.2	4.7	9.7
Data	101		

S_T^γ: 1000–1300 GeV

	Yield	σ_{stat}	σ_{syst}
V(γ)	35.0	1.3	3.9
γ+jets	4.2	1.3	0.4
t$\bar{t}$(γ)	3.5	0.9	1.1
e $\to \gamma$	4.7	0.4	2.3
Diboson	5.4	3.0	1.6
Total	52.8	3.6	5.0
Data	65		

S_T^γ: >1300 GeV

	Yield	σ_{stat}	σ_{syst}
V(γ)	12.6	0.7	1.6
γ+jets	1.1	0.5	0.4
t$\bar{t}$(γ)	0.7	0.5	0.2
e $\to \gamma$	1.5	0.2	0.8
Diboson	1.7	1.7	0.5
Total	17.6	2.0	1.9
Data	24		

The results are also interpreted in simplified models of strong production scenarios. The two

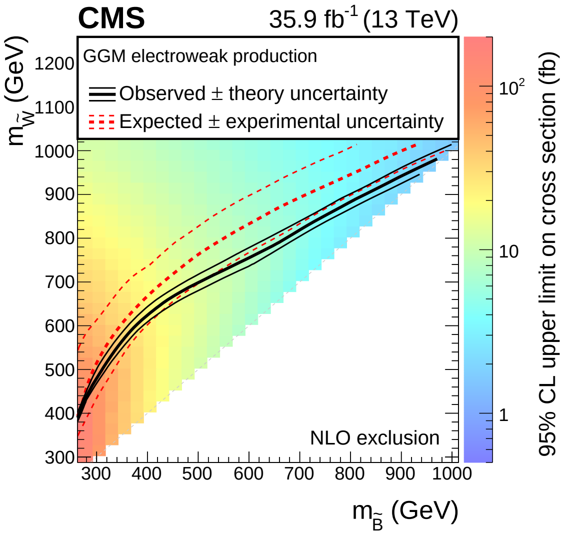

Figure 7: Observed upper cross section limit at 95% CL for the EWK GGM signal in the wino-bino mass plane. The thick lines represent the observed (black) and expected (red) exclusion contours, where the phase space closer to the diagonal is excluded by the analysis. The thin dotted red curves indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis. The thin solid black curves show the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

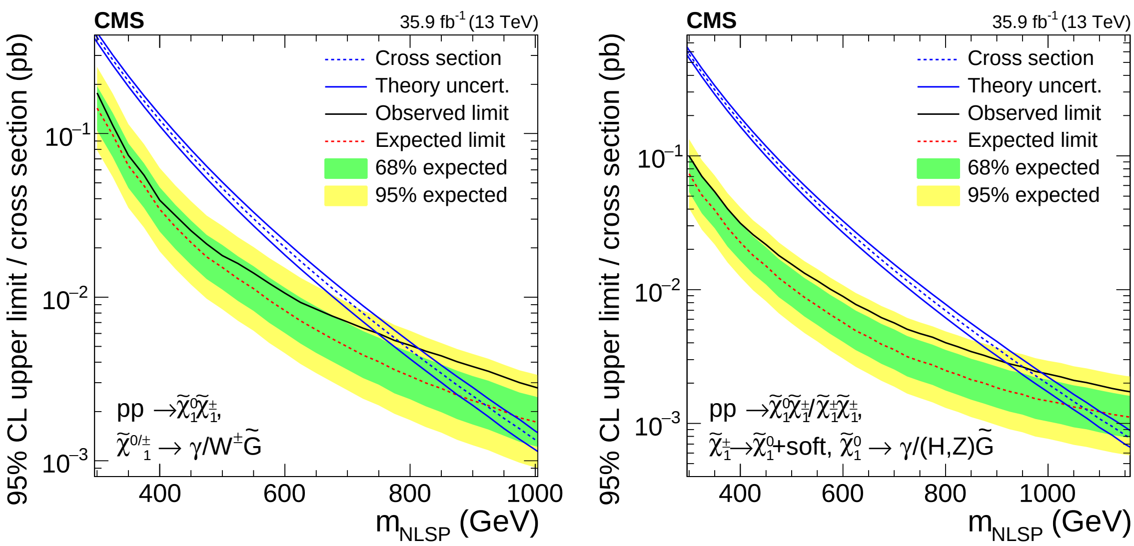

Figure 8: Observed (black) and expected (red) upper cross section limits as a function of the NLSP mass for the TChiWg (left) and TChiNg (right) model together with the corresponding theoretical cross section (blue). The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The solid blue lines represent the theoretical uncertainty in the signal cross section.

scenarios T5gg and T5Wg represent the gluino pair production with two photons and one photon and one W boson in the final state, respectively. The cross section limits and exclusion contours are shown in Fig. 9 in the $\tilde{g} - \tilde{\chi}^0_1/\tilde{\chi}^\pm_1$ mass plane. This search can exclude gluino masses of up to 2100 (2000) GeV in the T5gg (T5Wg) scenario. The limit gets weaker at low

NSLP masses because of the acceptance loss, which mostly arises from the lower energy of the photons and the gravitinos accompanied by larger hadronic activity in the event.

Similar scenarios, T6gg and T6Wg, based on squark production are also used for interpretation and are shown in Fig. 10. Here, squark masses up to 1750 (1650) GeV are excluded for T6gg (T6Wg).

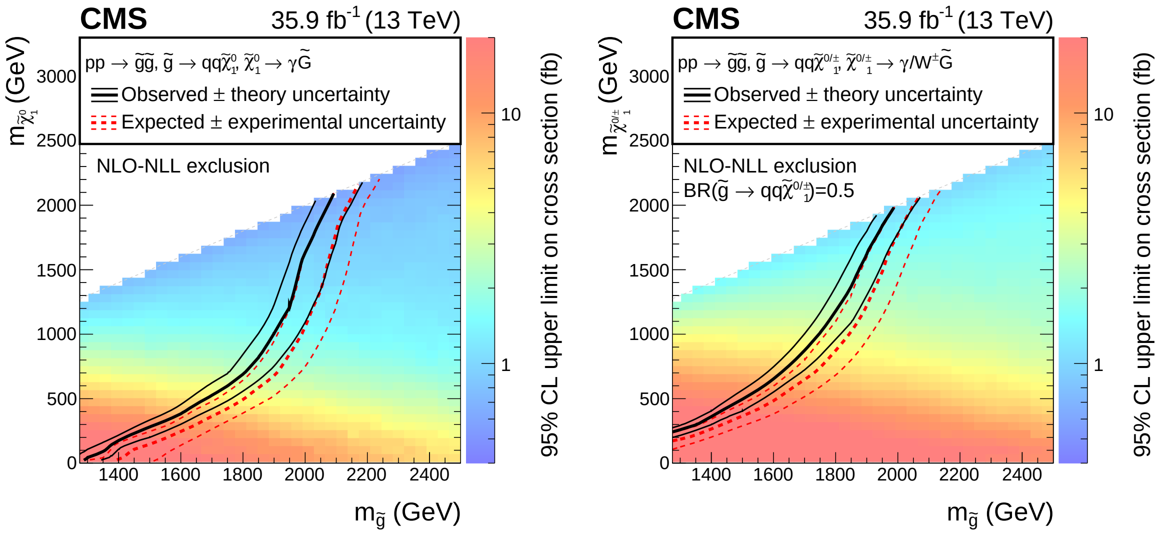

Figure 9: The 95% CL limits for the T5gg (left) and T5Wg (right) SMS models in the gluino-neutralino/chargino mass plane. The color scale encodes the observed upper cross section limit for each point. The thick lines represent the observed (black) and expected (red) exclusion contours, where the phase space of lower masses is excluded by the analysis. The thin dotted red curves indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis. The thin solid black curves show the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

The mass limits on squarks are weaker compared to those on gluinos due to the generally lower production cross section. However, for squark production the hadronic activity in the event is lower compared to gluino production, slightly reducing the dependence on the $\tilde{q} - \tilde{\chi}_1^0/\tilde{\chi}_1^\pm$ mass difference. The higher sensitivity in the T5gg and T6gg models is due to two photons contributing to S_T^γ, increasing the separation power between the signal and the SM background.

8 Summary

A search for electroweak (EWK) and strong production of gauginos in the framework of gauge mediated supersymmetry breaking in final states with photons and large missing transverse momentum has been performed. A data set recorded by the CMS experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}, was analyzed. The data were found to agree with the expectation from the standard model, without any indication of new physics.

The analysis is sensitive to EWK production of gauginos and to strong production of gluinos and squarks in particular if the mass difference between gauginos and gluinos or squarks is small. A two-dimensional EWK signal scan in the framework of general gauge mediation is used to interpret the results. In the case of similar wino and bino masses, the analysis excludes masses below 980 GeV at 95% confidence level, improving on the current best limit by

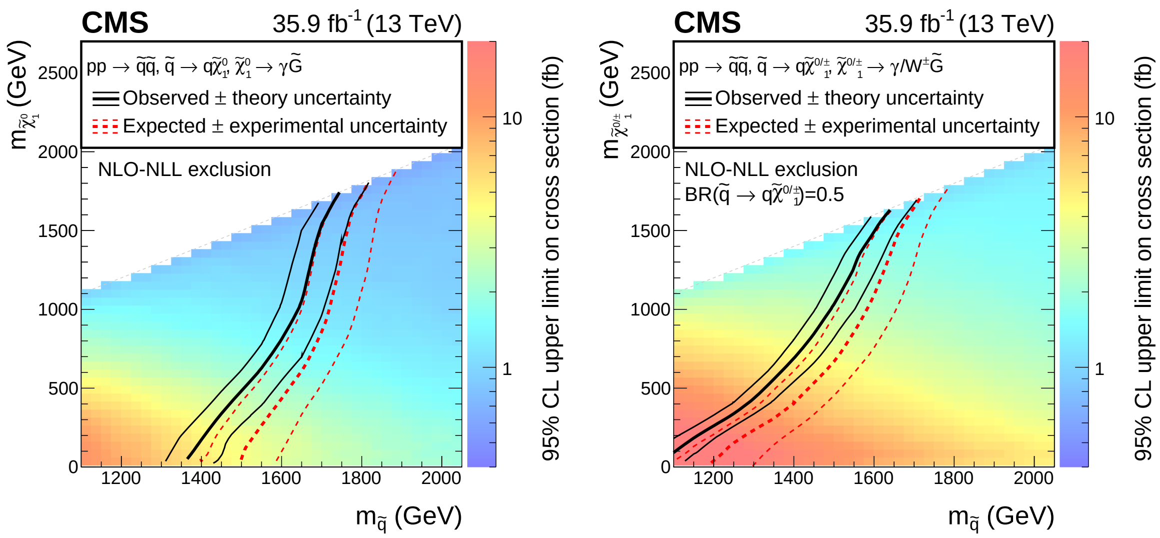

Figure 10: The 95% CL limits for the T6gg (left) and T6Wg (right) SMS models in the squark-neutralino/chargino mass plane. The color scale encodes the observed upper cross section limit for each point. The thick lines represent the observed (black) and expected (red) exclusion contours, where the phase space of lower masses is excluded by the analysis. The thin dotted red curves indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis. The thin solid black curves show the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties. For the signal production cross section five accessible mass-degenerate squark flavors for $\widetilde{q}_L$ and $\widetilde{q}_R$ were assumed.

270 GeV [26]. Two EWK simplified models are also used for the interpretation. The analysis excludes masses of the next-to-lightest supersymmetric particle $\widetilde{\chi}^0_1$ below 780 (950) GeV in the TChiWg (TChiNg) scenario. Additionally, limits are set for strong production simplified models based on gluino (T5gg, T5Wg) and squark (T6gg, T6Wg) pair production, excluding gluino (squark) masses up to 2100 (1750) GeV. This analysis complements searches in the photon+jets, diphoton, and photon+leptons final states, and sets the most stringent limits to date in the EWK production models, and in the strong production models when the gauginos are degenerate in mass with the gluino or squarks.

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