



Search for supersymmetry in events with photons and missing transverse energy in pp collisions at 13 TeV



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ABSTRACT

The results of a search for new physics in final states with photons and missing transverse energy are reported. The study is based on a sample of proton–proton collisions collected at a center-of-mass energy of 13 TeV with the CMS detector in 2015, corresponding to an integrated luminosity of 2.3 fb⁻¹. Final states with two photons and significant missing transverse energy are used to search for supersymmetric particles in models of supersymmetry (SUSY) with general gauge-mediated (GGM) supersymmetry breaking. No excess is observed with respect to the standard model expectation, and the results are used to set limits on gluino pair production and squark pair production in the GGM SUSY framework. Gluino masses below 1.65 TeV and squark masses below 1.37 TeV are excluded at a 95% confidence level.

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1. Introduction

Final states in proton–proton collisions containing photons with high transverse momentum p_T and significant missing transverse energy E_T^{miss} emerge naturally from a variety of new-physics scenarios, particularly in models of supersymmetry (SUSY) broken via gauge mediation that require a stable, weakly interacting lightest supersymmetric particle (LSP) [1–6]. The E_T^{miss} in an event, defined as the magnitude of the vector sum of the transverse momenta of all visible particles, is a consequence of undetected particles such as neutrinos or LSPs. Models with general gauge mediation (GGM) [7–14] can have a wide range of features, but typically entail a nearly massless gravitino LSP, \tilde{G} , and a next-to-lightest supersymmetric particle (NLSP) often taken to be a neutralino $\tilde{\chi}_1^0$. Photons in the final state arise when the neutralino decays to a gravitino and a photon, $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$.

In this Letter we present a search for GGM SUSY in final states involving two photons and significant E_T^{miss} . The data sample, corresponding to an integrated luminosity of 2.3 fb⁻¹ of proton–proton collisions at $\sqrt{s} = 13$ TeV, was collected with the CMS detector at the CERN LHC in 2015. The increased center-of-mass energy substantially improves the sensitivity of the analysis compared to searches performed at the LHC in Run 1 at $\sqrt{s} = 8$ TeV [15,16]. A similar analysis was performed by the ATLAS Collaboration at $\sqrt{s} = 13$ TeV [17]. For the interpretation of the re-

sults we use the T5gg and T6gg simplified models [18]. The T5gg (T6gg) simplified model assumes gluino \tilde{g} (squark \tilde{q}) pair production, with subsequent decays as shown in Fig. 1. The branching fraction of the NLSP neutralino to decay to a gravitino and a photon, $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$, resulting in characteristic events with two photons and large E_T^{miss} , is assumed to be unity. In more general GGM SUSY models, a bino-like neutralino could also decay to a gravitino and a Z boson, $\tilde{\chi}_1^0 \rightarrow \tilde{G}Z$.

Events with two photons and E_T^{miss} can also arise from several standard model (SM) processes, including direct diphoton production with initial-state radiation and multijet events (possibly with associated photon production). These processes lack intrinsic E_T^{miss} but can emulate the signal if the hadronic activity in the event is mismeasured. In the latter case, photons may be reconstructed in the event as a result of the misidentification of electromagnetically rich jets. A smaller background comes from events with intrinsic E_T^{miss} , principally $W\gamma$ and W +jet production, where an electron is misidentified as a photon in $W \rightarrow e\nu$ decays.

2. Detector, data, and simulated samples

The data were collected with the CMS detector in 2015. 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 covering the pseudorapidity region $|\eta| < 2.5$, as well as a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and

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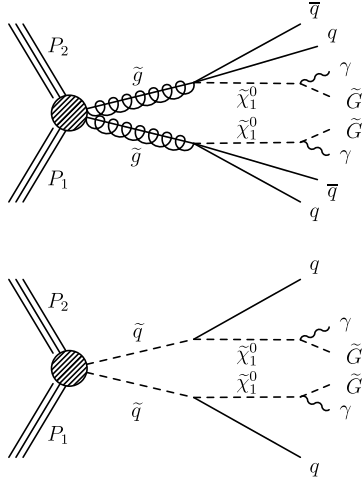


Fig. 1. Diagrams showing the production of signal events in the collision of two protons with four momenta P_1 and P_2 . In gluino \tilde{g} pair production in the T5gg simplified model (top), the gluino decays to an antiquark \bar{q} , quark q , and neutralino $\tilde{\chi}_1^0$. In squark \tilde{q} pair production in the T6gg simplified model (bottom), the squark decays to a quark and a neutralino. In both cases, the neutralino subsequently decays to a photon γ and a gravitino \tilde{G} . In the second diagram, we do not distinguish between squarks and antisquarks.

two endcap sections and covering the range $|\eta| < 3.0$. Forward calorimeters extend the coverage up to $|\eta| < 5.0$. Muons are measured in gas-ionization detectors embedded in the iron flux-return yoke outside the solenoid and cover the range $|\eta| < 2.4$. 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. [19].

The data used in this analysis were selected with a diphoton trigger requiring a leading photon with $p_T > 30$ GeV and a sub-leading photon with $p_T > 18$ GeV. In order to keep the trigger rate low and to exclude $Z \rightarrow ee$ events, a combined invariant mass $M_{\gamma\gamma} > 95$ GeV was also required. In addition, the photons were required to pass isolation and cluster shape requirements. A sample of $Z \rightarrow ee$ events for additional studies was collected with a trigger nearly identical to the diphoton trigger, but with an invariant mass requirement $M_{ee} > 70$ GeV and with the additional requirement that both electromagnetic (EM) objects be matched to a pixel detector seed (at least two measurements in the pixel detector consistent with a track from a charged particle).

Monte Carlo simulations of the signal and background processes are used to validate the performance of the analysis and determine signal efficiencies, as well as to determine the contributions of some of the smaller backgrounds, as described in Section 4. The leading-order event generator MADGRAPH 5.1.3.30 [20] is used to simulate the signal samples, which were generated with either two gluinos or two squarks and up to two additional partons in the matrix element calculation. The parton showering, hadronization, multiple-parton interactions, and the underlying event were described by the PYTHIA8 [21] event generator. The parton distribution functions are obtained from NNPDF3.0 [22]. For the background processes, the detector response is simulated using GEANT4 [23], while the CMS fast simulation [24] is used for the signal events.

The signal events were generated using the T5gg and T6gg simplified models and are characterized by the masses of the particles in the decay chain. For the gluino (squark) mass we simulate a range of values from 1.0 to 1.8 TeV (1.2 to 2.0 TeV) in steps of 50 GeV. These mass ranges were selected to overlap and expand upon the mass ranges excluded by previous searches [15–17]. For each gluino (squark) mass, the $\tilde{\chi}_1^0$ mass ranges from 100 GeV

to 1.9 TeV in 100 GeV increments, with the requirement that $M_{\tilde{\chi}_1^0} < M_{\tilde{g}}$ ($M_{\tilde{\chi}_1^0} < M_{\tilde{q}}$). We assume branching fractions of unity for the decays $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$, $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ and $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$. For the T6gg model, the gluino mass is set to 10 TeV, and t-channel production is not considered.

The production cross sections for these processes are calculated as functions of $M_{\tilde{g}}$ and $M_{\tilde{q}}$ at next-to-leading-order (NLO) accuracy including the resummation of soft gluon emission at next-to-leading-logarithmic (NLL) accuracy [25,26], and the uncertainties are calculated as described in Ref. [27].

3. Event selection

Photon, electron, muon, charged hadron, and neutral hadron candidates are reconstructed with the particle-flow (PF) algorithm [28,29], which reconstructs particles produced in a collision based on information from all detector subsystems. Photons are reconstructed from energy deposits in the ECAL. We require the shape of ECAL clusters to be consistent with that of an electromagnetic object, and we require that the energy present in the corresponding region of the HCAL not exceed 5% of the ECAL energy, as electromagnetic showers are expected to be contained almost entirely within the ECAL. In order to ensure that the photons pass the trigger with high efficiency, all photons are required to satisfy $E_T > 40$ GeV. Because the SUSY signal models used in this analysis produce photons primarily in the central region of the detector and because the magnitude of the background increases considerably at high $|\eta|$, we consider only photons within the barrel fiducial region of the detector ($|\eta| < 1.44$).

To suppress photon candidates originating from quark and gluon jets, photons are required to be isolated from other reconstructed particles. Separate requirements are made on the scalar p_T sums of charged hadrons, neutral hadrons, and electromagnetic objects in a cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ (where ϕ is the azimuthal angle measured in radians) around the photon candidate. Each momentum sum is corrected for the effect of additional proton–proton collisions in the event (pileup), and in each case the momentum of the photon candidate itself is excluded. We further require that the photon candidate have no pixel track seed, to distinguish the candidate from an electron.

Due to the similarity of the ECAL response to electrons and photons, $Z \rightarrow ee$ events are used to measure the photon identification efficiency. The selection of electron candidates is identical to that of photons, with the exception that the candidate is required to be matched to a pixel seed consistent with a track, to ensure that the selection is orthogonal to that of photons. The photon efficiency is measured via the tag-and-probe method [30] in both data and simulation. The ratio of the efficiency in data and simulation was measured as a function of the p_T and η of the electron and the ΔR separation between the electron and the nearest jet. It is determined that this ratio does not depend significantly on any measured kinematic variables, and the overall ratio is computed to be $\epsilon_e^{\text{data}}/\epsilon_e^{\text{sim}} = 0.983 \pm 0.012$.

Muon candidates, which are included among the objects counted in the photon isolation requirement, are reconstructed by performing a global fit that requires consistent hit patterns in the tracker and the muon system [31]. We require muons to have $p_T > 30$ GeV and to satisfy track quality and isolation requirements. Photons and electrons that overlap within $\Delta R < 0.3$ of any muons are rejected, but otherwise no requirement is made on the number of muons in the event. In addition, photons must be separated by $\Delta R > 0.3$ from electrons.

Jets are reconstructed from PF candidates using the anti- k_T clustering algorithm [32] with a distance parameter of 0.4. The jet

energy and momentum are corrected both for the nonlinear response of the detector and for the effect of pileup via the procedure described in Ref. [33]. Jets are required to have corrected $p_T > 30$ GeV and to be reconstructed within $|\eta| < 2.4$. In addition, jets are required to be separated from other objects in the event by $\Delta R > 0.4$.

For the purpose of defining the various control regions used in the analysis, we apply an additional set of selection criteria. Misidentified photons are defined as those photon candidates passing the photon selection but failing either the shape requirement for the ECAL clusters or the charged-hadron isolation requirement, but not both. In order to ensure that misidentified photons do not differ too much from our photon selection, upper limits are applied to both the charged-hadron isolation and cluster shape requirements.

Events are then sorted into one of four mutually exclusive categories depending on the selection of their highest- p_T electromagnetic objects: $\gamma\gamma$, ee, two misidentified (“fake”) photons (ff), and $e\gamma$. Due to the trigger requirements described in Section 2, the invariant mass of the two electromagnetic objects is required to be greater than 105 GeV. The size of the data sample limits any improvements in the sensitivity of the analysis from categorizing events by jet multiplicity. Therefore, no requirements are made on the number of jets in the event.

The signal region is defined by the events in the $\gamma\gamma$ category with $E_T^{\text{miss}} \geq 100$ GeV and is split into four bins: $100 \leq E_T^{\text{miss}} < 110$ GeV, $110 \leq E_T^{\text{miss}} < 120$ GeV, $120 \leq E_T^{\text{miss}} < 140$ GeV, and $E_T^{\text{miss}} \geq 140$ GeV. The bins are chosen in such a way that there is a sufficient amount of data in each bin in the ee and ff control samples used for background estimation. The bin with $E_T^{\text{miss}} < 100$ GeV is used as a control region.

4. Estimation of backgrounds

The dominant background for this analysis comes from multijet production from quantum chromodynamics (QCD) processes without intrinsic E_T^{miss} , where the high- E_T^{miss} signature is mimicked by the mismeasurement of the hadronic activity in the event. A subdominant contribution comes from electroweak (EWK) processes that include intrinsic E_T^{miss} from neutrino production.

The contribution from the QCD background is modeled in a fully data-driven way from the ee and ff control samples. Both of these control samples are dominated by processes without intrinsic E_T^{miss} and can therefore be used to model the E_T^{miss} in the QCD background. These control samples differ in hadronic activity from the candidate $\gamma\gamma$ sample due to different event topologies. In particular, the ee control sample has a large contribution from $Z \rightarrow ee$ events, where the electromagnetic objects come from one parent particle. In contrast, the ff control samples are primarily multijet events where the two electromagnetic objects are produced independently. To account for this difference, the di-EM p_T variable, defined as the magnitude of the vector sum of the transverse momenta of the two electromagnetic objects, is used to model the hadronic recoil in the event. Events in the ee and ff control samples are reweighted by the di-EM p_T distribution of the $\gamma\gamma$ events to correct for any differences in hadronic recoil. The E_T^{miss} distributions of these di-EM p_T reweighted control samples are then normalized to that of the $\gamma\gamma$ sample in the region $E_T^{\text{miss}} < 50$ GeV and used to predict the contribution of QCD processes to the high- E_T^{miss} signal region. A comparison of the reweighted E_T^{miss} distributions to the distribution of $\gamma\gamma$ events is shown in Fig. 2 in the sideband of the search region ($E_T^{\text{miss}} < 100$ GeV). There is an agreement within statistical uncertainties between the $\gamma\gamma$ and each of the reweighted distributions.

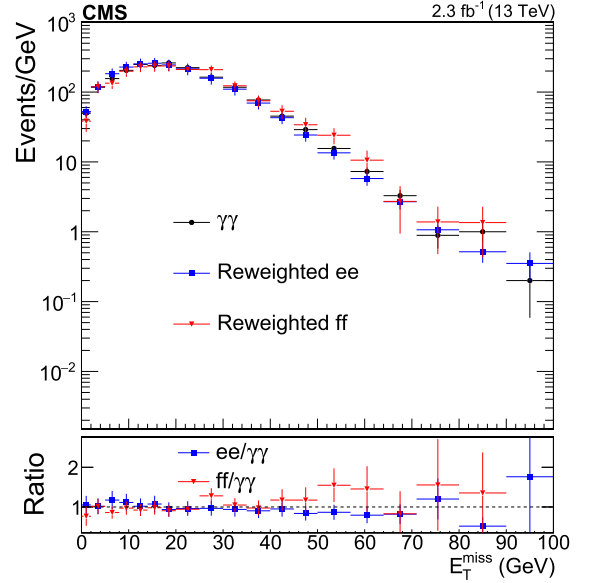


Fig. 2. The E_T^{miss} distributions of the candidate $\gamma\gamma$, reweighted ee, and reweighted ff samples in the $E_T^{\text{miss}} < 100$ GeV sideband.

Similarly, we consider differences in the E_T^{miss} distribution due to the number of jets in the event. A direct comparison of the candidate sample and the two control samples shows little dependence on the jet multiplicity N_{jets} at low E_T^{miss} , so we take the difference as a systematic uncertainty in the prediction, as described in Section 5.

In addition, there is a small contribution in the QCD control samples from comparatively rare processes with intrinsic E_T^{miss} , including $t\bar{t}$ events and $Z \rightarrow \bar{\nu} + \text{jets}$ events. Due to their small cross sections, these processes are estimated with simulation, and their contributions are subtracted from the ee and ff control samples for the final prediction.

The primary estimate of the QCD contribution comes from the reweighted ee distribution. The reweighted ff control sample serves as a cross-check, and the difference between them is taken as a symmetric systematic uncertainty on the prediction. Due to the limited number of ff events with $E_T^{\text{miss}} > 100$ GeV, a looser misidentification definition is used. In the looser definition, misidentified photons are not required to pass any photon isolation or neutral-hadron isolation cuts, and the upper limits on charged-hadron isolation and the shape requirement for the ECAL clusters are loosened further. The looser ff sample is used to obtain the shape of the ff distribution in the $E_T^{\text{miss}} > 100$ GeV signal region, while the normalization comes from the tighter, more photon-like misidentification definition.

As an additional cross-check on this background estimation method, the ratio of the candidate $\gamma\gamma$ distribution to the unweighted ff distribution as a function of E_T^{miss} is fit with different functional forms. The predicted number of QCD background events in each E_T^{miss} bin is then given by the function multiplied by the number of ff events seen in that bin. The primary prediction from the ee sample is consistent with the prediction from this cross-check within the fit uncertainties, and we conclude that the predictions from these two methods are compatible.

The electroweak background comes from $W\gamma$ events where the W decays to an electron and a neutrino, and the electron is misidentified as a photon. We estimate this misidentification rate by comparing the Z-boson mass peak in the ee invariant mass spectrum to the peak in the $e\gamma$ spectrum. The data are modeled using an extended likelihood fit to the mass spec-

Table 1
Systematic uncertainties from the QCD background estimation.

E_T^{miss} bin (GeV)	Di-EM p_T reweighting	Jet multiplicity reweighting	Shape difference between ee and ff	Statistical uncertainty of ee sample
$100 \leq E_T^{\text{miss}} < 110$	15%	34%	18%	31%
$110 \leq E_T^{\text{miss}} < 120$	17%	15%	12%	33%
$120 \leq E_T^{\text{miss}} < 140$	33%	29%	14%	42%
$E_T^{\text{miss}} \geq 140$	39%	20%	150%	71%

trum for the signal plus background hypothesis. The misidentification rate $f_{e \rightarrow \gamma}$ is then computed from the signal events as $f_{e \rightarrow \gamma} = N_{e\gamma} / (2N_{ee} + N_{e\gamma}) = (2.13 \pm 0.21)\%$. This rate is used to compute a scaling factor $f_{e \rightarrow \gamma} / (1 - f_{e \rightarrow \gamma})$, which is then applied to the sample of $e\gamma$ events with $E_T^{\text{miss}} > 100$ GeV to obtain an estimate of the electroweak background in the signal region.

5. Sources of systematic uncertainty

We evaluate systematic uncertainties from each of the background predictions, the signal efficiency, and the integrated luminosity. For each source of uncertainty, we give the uncertainty value and describe the method used for its estimation.

The largest systematic uncertainties come from the QCD background estimation method. We consider three sources of systematic uncertainty from the QCD background estimate: the di-EM p_T reweighting, the jet multiplicity dependence, and the E_T^{miss} shape difference between the ee and ff control samples. The magnitudes of these uncertainties for each of the E_T^{miss} bins in the signal region are shown in Table 1.

The uncertainty from di-EM p_T reweighting is estimated from the distributions of the di-EM p_T ratio in simulated pseudo-experiments, allowing the ratio to vary bin by bin according to a Gaussian distribution with a standard deviation computed from the statistical uncertainty of unweighted events in the bin. The E_T^{miss} distribution of the ee control sample is then reweighted by each of these distributions, and the standard deviation is determined for the prediction. The magnitude of this uncertainty ranges from 15% to 39%.

The effect of the difference in the E_T^{miss} distribution as a function of the jet multiplicity is determined directly by taking the difference between the ee estimate with di-EM p_T and N_{jets} reweighting and with di-EM p_T reweighting alone. The resulting systematic uncertainty ranges from 15% to 34% in the four signal E_T^{miss} bins. The shape uncertainty of the ee control sample is determined by fitting the high- E_T^{miss} tails of the ee and ff samples to the empirical three-parameter function $dN/dE_T^{\text{miss}} = (E_T^{\text{miss}})^{p_0} e^{p_1 (E_T^{\text{miss}})^{p_2}}$. The systematic uncertainty in the shape is symmetric and taken to be the fractional difference in each E_T^{miss} bin between these fitted functions. This yields a systematic effect between 12% and 18% in the lower three E_T^{miss} signal bins, and a systematic effect of 150% in the final bin that covers E_T^{miss} above 140 GeV.

The main source of uncertainty in the electroweak background estimate comes from the uncertainty in the extended likelihood fit used to calculate the misidentification rate. This is computed by shifting the rate up and down by its uncertainty and scaling the E_T^{miss} distribution of the $e\gamma$ control sample by the altered rates. The difference between the estimates from the two shifted misidentification rates gives the systematic uncertainty in the rate of electroweak events. Because this represents an uncertainty in the overall normalization, it is constant across E_T^{miss} bins. The uncertainty is a constant 19% across the E_T^{miss} bins.

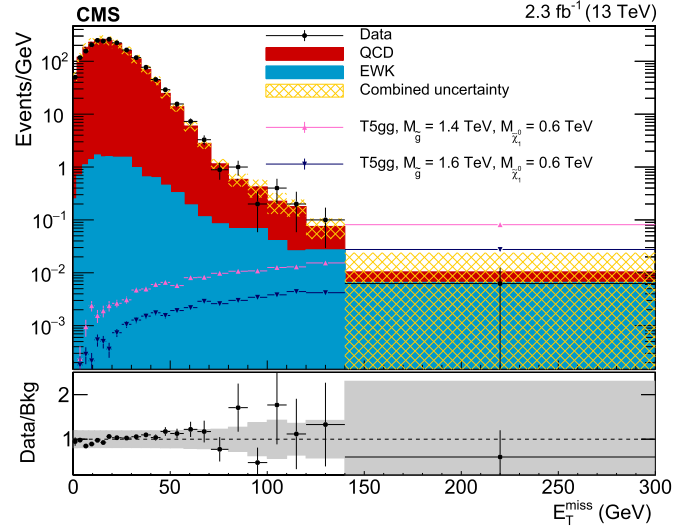


Fig. 3. Measured E_T^{miss} distribution in comparison with the background prediction. The four bins with $E_T^{\text{miss}} \geq 100$ GeV constitute the signal region, and the $E_T^{\text{miss}} < 100$ GeV bins serve mainly to normalize the background. The systematic uncertainty on the background prediction and the ratio of the data to the prediction are also shown. The last bin includes all events with $E_T^{\text{miss}} \geq 140$ GeV, but for normalization by bin width, the bin is taken to be from $140 \leq E_T^{\text{miss}} < 300$ GeV. The distributions for two signal model points are overlaid for comparison.

The signal efficiency uncertainties are related to the statistical uncertainty from the finite size of the T5gg and T6gg signal samples (0–16%), knowledge of the jet energy scale (0–23% depending on the $\tilde{g}-\tilde{\chi}_1^0$ mass difference), parton distribution function uncertainties (13–22% depending on the signal point), and photon identification and reconstruction efficiencies (2%). The uncertainty related to the integrated luminosity of the data sample is 2.7% [34].

6. Results

The measured E_T^{miss} distribution and corresponding background predictions are shown in Fig. 3. The expected number of events from the QCD and EWK backgrounds, as well as the total number of expected and observed events, are shown in Table 2 for each bin in the signal region. We observe 9 events total in the signal region, compared to an expected background of 7.2 ± 2.5 events. The number of events in the signal region agrees with the background estimate within the uncertainties.

We determine 95% confidence level (CL) upper limits on gluino pair and squark pair production cross sections using the modified frequentist CL_s method [35,36] based on a log-likelihood test statistic that compares the likelihood of the SM-only hypothesis to the likelihood of the presence of a signal in addition to the SM contributions. The likelihood function is constructed from the background and signal E_T^{miss} distributions across the four bins described in Section 3. The systematic uncertainties described in Sec-

Table 2

Numbers of expected and observed events in the signal region. The last row shows the total number of expected and observed events in the inclusive bin $E_T^{\text{miss}} \geq 100$ GeV. The expected numbers of events for two T5gg mass points are also shown. For Signal A, $M_{\tilde{g}} = 1400$ GeV and $M_{\tilde{\chi}_1^0} = 600$ GeV. For Signal B, $M_{\tilde{g}} = 1600$ GeV and $M_{\tilde{\chi}_1^0} = 600$ GeV. The uncertainties include all of the systematic uncertainties described in Section 5.

E_T^{miss} bin (GeV)	QCD	EWK	Total background	Signal A	Signal B	Observed
$100 \leq E_T^{\text{miss}} < 110$	1.9 ± 1.0	0.4 ± 0.1	2.3 ± 1.0	0.12 ± 0.01	0.04 ± 0.01	4
$110 \leq E_T^{\text{miss}} < 120$	1.5 ± 0.6	0.3 ± 0.1	1.8 ± 0.6	0.13 ± 0.02	0.04 ± 0.01	2
$120 \leq E_T^{\text{miss}} < 140$	1.0 ± 0.6	0.5 ± 0.2	1.5 ± 0.6	0.31 ± 0.04	0.08 ± 0.01	2
$E_T^{\text{miss}} \geq 140$	0.6 ± 2.2	1.0 ± 0.3	1.6 ± 2.2	13.0 ± 0.7	4.4 ± 0.2	1
$E_T^{\text{miss}} \geq 100$	5.0 ± 2.5	2.2 ± 0.3	7.2 ± 2.5	13.6 ± 0.7	4.6 ± 0.2	9

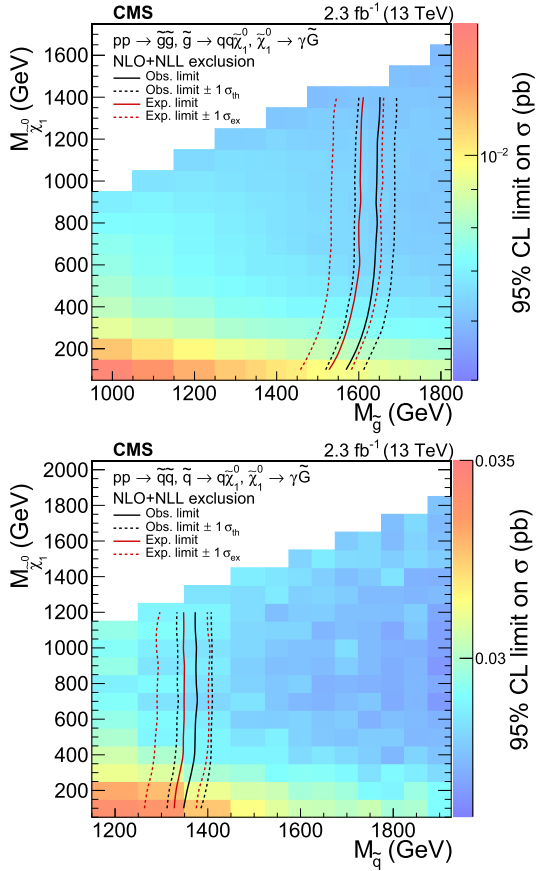


Fig. 4. The 95% CL upper limits on the gluino (top) and squark (bottom) pair production cross sections as a function of neutralino versus gluino (squark) mass. The contours show the observed and median expected exclusions assuming the NLO+NLL cross sections, with their one standard deviation uncertainties. The limit curves terminate at the centers of the bins used to sample the cross section.

tion 5 are included in the test statistic as nuisance parameters, with log-normal probability distributions.

In Fig. 4 we present 95% CL upper limits on the cross section as a function of the mass pair values for the two models considered in this analysis, $M_{\tilde{\chi}_1^0}$ versus $M_{\tilde{g}}$ and $M_{\tilde{\chi}_1^0}$ versus $M_{\tilde{q}}$ for gluino pair and squark pair production, respectively. From the NLO+NLL predicted cross sections and their uncertainties we derive contours representing lower limits in the SUSY mass plane. We also show expected limit contours based on the expected experimental cross section limits and their uncertainties. For typical values of the neutralino mass, we expect to exclude gluino masses up to 1.60 TeV and squark masses up to 1.35 TeV, and we observe exclusions of 1.65 and 1.37 TeV respectively. The excluded mass ranges for gluino pair production have been improved by approximately 300 GeV

with respect to previous searches performed at $\sqrt{s} = 8$ TeV [15, 16]. The observed exclusions are consistent with the results of the ATLAS analysis performed at $\sqrt{s} = 13$ TeV [17].

7. Summary

A search is performed for supersymmetry with general gauge mediation in proton–proton collisions yielding events with two photons and large missing transverse energy. The data were collected at a center-of-mass energy of 13 TeV with the CMS detector in 2015, and correspond to an integrated luminosity of 2.3 fb^{-1} .

The data are interpreted in the context of two simplified SUSY models with gauge-mediated supersymmetry breaking, one assuming gluino pair production and the second assuming squark pair production. In both models, the branching fraction of the NLSP neutralino to decay to a gravitino and a photon is assumed to be unity. Using background estimation methods based on control samples in data, limits are determined on the gluino and squark pair production cross sections, and those limits are used together with NLO+NLL cross section calculations to constrain the masses of gluinos, squarks, and neutralinos. Gluino masses below 1.65 TeV and squark masses below 1.37 TeV are excluded at a 95% confidence level. This represents an improvement of approximately 300 GeV with respect to previous analyses performed at a center-of-mass energy of 8 TeV [15,16] and is consistent with the results of the ATLAS analysis performed at a center-of-mass energy of 13 TeV [17].

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