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Search for supersymmetry in events with a photon, a lepton, and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract: Results of a search for supersymmetry are presented using events with a photon, an electron or muon, and large missing transverse momentum. The analysis is based on a data sample corresponding to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV, produced by the LHC and collected with the CMS detector in 2016. Theoretical models with gauge-mediated supersymmetry breaking predict events with photons in the final state, as well as electroweak gauge bosons decaying to leptons. Searches for events with a photon, a lepton, and missing transverse momentum are sensitive probes of these models. No excess of events is observed beyond expectations from standard model processes. The results of the search are interpreted in the context of simplified models inspired by gauge-mediated supersymmetry breaking. These models are used to derive upper limits on the production cross sections and set lower bounds on masses of supersymmetric particles. Gaugino masses below 930 GeV are excluded at the 95% confidence level in a simplified model with electroweak production of a neutralino and chargino. For simplified models of gluino and squark pair production, gluino masses up to 1.75 TeV and squark masses up to 1.43 TeV are excluded at the 95% confidence level.

Keywords: Hadron-Hadron scattering (experiments), Supersymmetry

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JHEP01(2019)154

Contents

1 Introduction

The search for supersymmetry (SUSY), a popular extension of the standard model (SM) of particle physics, is a central piece of the physics program at the CERN LHC. Models utilizing a general gauge-mediated (GGM) SUSY mechanism [1–6], with the assumption that R parity [7] is conserved, often lead to final states containing photons and significant transverse momentum imbalance [8–15]. Final states with an additional lepton enhance the sensitivity to the electroweak (EW) production of SUSY particles, making signatures with both leptons and photons an important part of the SUSY search program at the LHC.

In GGM SUSY models, the lightest SUSY particle (LSP), taken to be the gravitino $\widetilde{\mathrm{G}}$, is both stable and weakly interacting. It escapes detection, leading to missing momentum in the event. Except for direct LSP pair production, each produced SUSY particle initiates a decay chain that yields the next-to-lightest SUSY particle (NLSP) decaying to the LSP. The signature of the event depends sensitively on the nature of the NLSP. In most GGM models, the NLSP is taken to be a bino- or wino-like neutralino or a wino-like chargino, where the bino and wino are the superpartners of the SM U(1) and SU(2) gauge particles, respectively. Typically, a neutral NLSP $\widetilde{\chi}^0$ will decay to a photon or a Z boson, while a charged NLSP $\widetilde{\chi}^{\pm}$ will produce a W boson, where both vector bosons can decay leptonically.

In this paper, the results are presented of a search for SUSY in events with one photon γ, at least one lepton ℓ (electron or muon), and large transverse momentum imbalance. This signature suppresses many SM backgrounds, avoiding the need for additional requirements

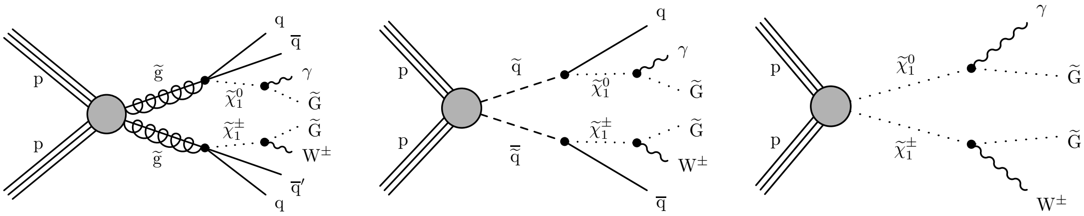

Figure 1. Diagrams showing the production and decay modes of the signal models T5Wg (left), T6Wg (center), and TChiWg (right) considered in this analysis.

such as associated jet activity. This makes it possible to include events with low jet activity, increasing the sensitivity to SUSY scenarios with EW production, in which the absence of colored SUSY particles in the decay chain leads to lower final-state jet activity in these models.

The data sample corresponds to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$ of proton-proton (pp) collision data at $\sqrt{s} = 13\,\mathrm{TeV}$, collected with the CMS detector at the LHC in 2016. Similar searches with a photon plus lepton signature were conducted by the ATLAS [16] and CMS [17, 18] experiments at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$. Searches for SUSY in GGM scenarios have also been conducted in the single-photon [19, 20] and two-photon [21] channels at $\sqrt{s} = 13\,\mathrm{TeV}$. None of these analyses observed any significant excess of events over their respective SM predictions. This paper improves the sensitivity of the previous CMS result obtained at $\sqrt{s} = 8\,\mathrm{TeV}$ [22].

The diagrams in figure 1 provide examples of the decays studied in this analysis. Simplified models [23] are used for the interpretation of the results. The three simplified models considered are denoted as T5Wg, T6Wg, and TChiWg, where T5Wg assumes gluino ($\widetilde{g}$) pair production, T6Wg squark ($\widetilde{q}$) pair production, and TChiWg the direct EW production of a neutralino and chargino. For simplicity, we assume the $\widetilde{\chi}^0$ and $\widetilde{\chi}^{\pm}$ are mass-degenerate co-NLSPs and are therefore produced at equal rates. The decay of the NLSP $\widetilde{\chi}^{\pm}$ ($\widetilde{\chi}^0$) produces a gravitino LSP with a $W^{\pm}$ (γ). We assume a 50% branching fraction to either the $\widetilde{\chi}^0$ or the $\widetilde{\chi}^{\pm}$ in the decays $\widetilde{g} \to q\overline{q}\widetilde{\chi}^0/\widetilde{\chi}^{\pm}$ and $\widetilde{q} \to q\widetilde{\chi}^0/\widetilde{\chi}^{\pm}$, and 100% branching fractions for the decays $\widetilde{\chi}^0 \to \gamma\widetilde{G}$ and $\widetilde{\chi}^{\pm} \to W^{\pm}\widetilde{G}$.

The paper is organized as follows. In section 2, we describe the CMS detector used to collect the data. The data samples and object definitions used in the analysis are described in section 3, and the details of the event selection are given in section 4. The methods for estimating the backgrounds in the analysis are discussed in section 5, the systematic uncertainties in section 6, and the results in section 7. Conclusions are summarized in section 8, including our exclusion limits in the simplified-model framework.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid with an internal diameter of 6 m, providing an axial magnetic field of 3.8 T. Within the solenoid volume are several subdetector systems, each composed of a cylindrical barrel closed by two endcaps.

JHEP01(2019)154

At the core is a silicon pixel and strip tracker, providing a precise measurement of the trajectories of charged particles. The energy of photons and electrons is measured by a lead tungstate crystal electromagnetic calorimeter (ECAL), covering the pseudorapidity range $|\eta| < 1.479$ in the barrel and $1.479 < |\eta| < 3.0$ in the endcap. Surrounding the ECAL is a brass and scintillator sampling hadron calorimeter (HCAL) with $|\eta| < 3.0$ coverage. Forward calorimeters extend the calorimeter coverage up to $|\eta| = 5.0$. 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 about 1% is achieved for unconverted and late-converting photons with transverse momentum $p_T \approx 10\,\text{GeV}$. The remaining barrel photons have a resolution of about 1.3% up to $|\eta| < 1.0$, rising to about 2.5% for $|\eta| = 1.4$ [24].

The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with $p_T \approx 45\,\text{GeV}$ from $Z \to e^+e^-$ decays ranges from 1.7 to 4.5%. It is generally better in the barrel region than in the endcaps, and also depends on the bremsstrahlung energy emitted by the electron as it traverses the material in front of the ECAL [25].

Muons are measured in the range $|\eta| < 2.4$, with detector elements based on three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks reconstructed in the silicon tracker results in a relative transverse momentum resolution, for muons with p_T up to 100 GeV, of 1% in the barrel and 3% in the endcaps. The p_T resolution in the barrel is better than 7% for muons with p_T up to 1 TeV [26].

A detailed description of the CMS detector, together with the definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [27].

3 Object reconstruction and simulated samples

Physics objects are defined using the particle-flow (PF) algorithm [28], which aims to reconstruct and identify each individual particle in an event via an optimized combination of information from different elements of the CMS detector. The PF candidates are classified as photons, charged hadrons, neutral hadrons, electrons, or muons. The PF method also allows the identification and mitigation of particles from additional pp interactions in the same or adjacent beam crossings (pileup).

Photons are reconstructed from clusters of energy deposits in the ECAL. To distinguish photon candidates from electrons, photon objects are rejected if a matching pixel detector track segment from the silicon tracker is identified. Photon candidates used in this analysis are identified with a set of loose quality criteria with an average selection efficiency of 90%. We require such photon candidates to be associated with an energy deposit in the HCAL having no more than 6% of the energy deposited in the ECAL, and a shower shape in the η direction consistent with that of a genuine photon. In addition, the photons are required to have more than 50% of their cluster energy deposited in the 3×3 array of crystals centered on the most energetic crystal.

JHEP01(2019)154

To further suppress the misidentification of hadrons as photons, a PF-based isolation requirement is imposed. The isolation variable is calculated by summing the magnitude of the transverse momentum of all PF charged hadrons, neutral hadrons, and other photons within a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$, where ϕ is the azimuthal angle in radians, around the candidate photon direction. We required this variable not to exceed fixed values that are set to achieve a desirable balance between identification efficiency and misidentification rate. The photon object that is being identified is not included in the isolation sums, and charged hadrons are included only if they are associated with the primary pp interaction vertex. The reconstructed vertex with the largest value of summed physics-object p_{T}^2 is taken to be the primary pp vertex. The physics objects are the jets, clustered using the jet-finding algorithm [29, 30] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector p_{T} sum of those jets.

Electrons are found by associating tracks reconstructed in the silicon tracker with ECAL clusters. The electron candidates are required to be within the fiducial region of $|\eta| < 2.5$, where the tracker coverage ends. Identification of electrons is based on the shower shape of the ECAL cluster, the HCAL-to-ECAL energy ratio, the geometric matching between the cluster and the track, the quality of the track reconstruction, and the isolation variable. To enhance the identification efficiency, the isolation variable is calculated from the transverse momenta of photons, charged hadrons, and neutral hadrons within a ΔR cone whose radius is variable depending on the electron p_{T} [31], and which is also corrected for the effects of pileup [32].

The reconstruction of muons is based on associating tracks from the silicon tracker with those in the muon system. A set of muon identification criteria, based on the goodness of the track fit and the quality of muon reconstruction, is applied to select the muon candidates, having an efficiency greater than 98% for genuine muons [26]. Muons are also required to be isolated from other objects in the event using a similar isolation variable [26] as in the electron identification.

Jets are reconstructed starting with all PF candidates that are clustered using the anti-k_{T} algorithm [29, 30] with a distance parameter that determines the nominal jet radius of $R = 0.4$. The jet energies are corrected for detector response, as well as an offset energy from pileup interactions [32]. Jet candidates considered in this analysis are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and be within the $|\eta| < 2.5$ region. Tracks associated with the jet are required to be consistent with originating from the primary vertex. The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is given by the negative vector p_{T} sum of all PF objects, with jet energy corrections [32, 33] applied. The magnitude of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is referred to as the missing transverse momentum $p_{\mathrm{T}}^{\mathrm{miss}}$. The near hermiticity of the CMS detector allows for accurate measurements of $p_{\mathrm{T}}^{\mathrm{miss}}$. Dedicated filters are applied to remove events with $p_{\mathrm{T}}^{\mathrm{miss}}$ induced by beam halo, noise in the detector, or poorly reconstructed muons [34].

Monte Carlo (MC) simulated events are used to model the SM backgrounds, validate the background estimation methods, and study the SUSY signal yields. In order to study the SM backgrounds, discussed more fully in section 5, samples of Wγ events are generated with MadGraph5_amc@nlo 2.3.3 [35] at leading order (LO), while the Zγ, Drell-Yan,

JHEP01(2019)154

WW(+γ), WZ(+γ), and $t\bar{t}$ (+γ) background processes are generated at next-to-leading order (NLO). All samples use the NNPDF 3.0 [36] parton distribution functions (PDFs). The generated events are interfaced with PYTHIA 8.205 or 8.212 [37] with the CUETP8M1 underlying event tune [38] for simulation of parton showering and hadronization. Renormalization and factorization scales and PDF uncertainties are derived with the use of the SysCalc package [39]. The Zγ, Drell-Yan, WW(+γ), WZ(+γ), and $t\bar{t}$ (+γ) samples are scaled to the integrated luminosity using the theoretical cross sections at NLO precision [35]. For the Wγ sample, a next-to-NLO (NNLO) scale factor of 1.34 [40] is applied to the LO cross section to account for higher-order corrections. The CMS detector response is simulated using a GEANT4-based [41] package. The effects of pileup are modeled in the simulation by overlaying simulated minimum-bias events on the corresponding hard-scattering event, and the distribution of the pileup vertices is reweighted to match that observed in data.

The signal events in the three simplified models introduced in section 1 are generated with MADGRAPH5_aMC@NLO at LO. The cross sections are calculated at NLO plus next-to-leading-logarithm (NLL) accuracy [42–46]. The generated events are processed with a fast simulation of the CMS detector response [47]. Scale factors are applied to compensate for any differences with respect to the full simulation.

To improve the MADGRAPH5_aMC@NLO modeling of initial-state radiation (ISR), which affects the total transverse momentum of the event, the ISR transverse momentum (p_T^{ISR}) distributions of the MC Wγ and Zγ events are weighted to agree with those in data. This reweighting procedure is based on studies of the transverse momentum of Z boson events [48]. The reweighting factors range from 1.11 for $p_T^{ISR} \approx 125$ GeV to 0.64 for $p_T^{ISR} > 300$ GeV. We take the deviation of the reweighting factors from 1.0 as an estimate of the systematic uncertainty in the reweighting procedure.

4 Event selection

The analysis is performed in both the eγ and $\mu\gamma$ channels. The eγ data sample is collected using a diphoton trigger [49] requiring at least two isolated electromagnetic objects with p_T thresholds of 30 and 18 GeV for the highest p_T and second-highest-p_T electromagnetic object, respectively, that satisfy loose identification criteria and have an invariant mass $M_{\gamma\gamma} > 90$ GeV. The trigger does not veto photon objects that can be matched to a track from the silicon tracker, allowing events with a photon and an electron to also pass the trigger selections. The $\mu\gamma$ events are collected using a combination of two muon+photon triggers, one requiring the presence of an isolated photon with $p_T > 30$ GeV and a muon with $p_T > 17$ GeV, and the other using symmetric p_T thresholds of 38 GeV for both objects, with no photon isolation criteria. With the selection criteria described below, the average trigger efficiency for the investigated SUSY signal models is found to be 96% for eγ and 94% for $\mu\gamma$.

Candidate signal events are required to contain at least one isolated photon with $p_T^{\gamma} > 35$ GeV and $|\eta| < 1.44$ and at least one isolated electron (muon) with $p_T > 25$ GeV and $|\eta| < 2.5$ (2.4). To ensure a high reconstruction efficiency, electrons in the barrel-endcap transition region $1.44 < |\eta| < 1.56$ are rejected. If more than one electron (muon) satisfies the selection criteria, the highest p_{T} candidate is selected. To suppress events with photons from final-state radiation, photon candidates are vetoed if they are within $\Delta R < 0.3$ of any reconstructed electron or muon. In addition, the highest p_{T} photon is required to be separated from the highest p_{T} lepton by $\Delta R > 0.8$. In the eγ channel, the eγ invariant mass must be at least 10 GeV greater than the world-average Z boson mass [50] to reduce the contribution of $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ events, where one of the electrons is misidentified as a photon.

For each event we compute the transverse mass m_{T} of the lepton plus $p_{\mathrm{T}}^{\mathrm{miss}}$ system to help discriminate between the SUSY signal and SM backgrounds. The quantity m_{T} is defined as $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} [1 - \cos(\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}))]}$, where p_{T}^{ℓ} is the magnitude of the lepton transverse momentum and $\Delta\phi$ is the difference in azimuthal angle between the direction of the lepton and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$. The signal region is defined as $p_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV and $m_{\mathrm{T}} > 100$ GeV. Models with strongly produced SUSY particles lead to final states with significant hadronic activity in the form of jets. To provide additional sensitivity to these models, we define the variable H_{T} as the scalar sum of the transverse momenta of all jets that are separated from both the candidate photon and candidate lepton by $\Delta R > 0.4$. The signal region is later divided into search regions as a function of $p_{\mathrm{T}}^{\mathrm{miss}}$, p_{T}^{γ}, and H_{T}.

5 Background estimation

The SM backgrounds of events with one lepton, one photon, and substantial $p_{\mathrm{T}}^{\mathrm{miss}}$ in the final state mainly arise from three sources. The first consists of events without a directly produced (prompt) photon. This includes events with a photon that does not originate from the hard-scattering event vertex, but from a nearby pileup vertex, as well as events with an object such as an electron or an electromagnetically rich jet that is misidentified as a photon. The second source of background consists of events that do not contain a prompt lepton. These typically result from the misidentification of a jet as a lepton, or from a jet caused by the hadronization of a heavy-flavor quark, which produces a lepton via the semileptonic decay of the corresponding heavy-flavor meson or baryon. The final contribution to the background comes from EW processes, primarily Wγ and Zγ production. This category also includes rarer processes such as WWγ, WZγ, and $\mathrm{t\bar{t}}\gamma$, referred to in this paper as the "rare EW" background.

The contribution from EW processes is estimated via simulation, while the backgrounds due to misidentified photons and leptons are estimated from data, as described below.

5.1 Backgrounds from misidentified photons

Photon candidates are considered misidentified if they are not produced directly in the hard-scattering process, or if they result from a misidentified object. The latter constitute the majority of misidentified photons and can occur in two cases: when a large fraction of the energy of a jet is carried by a neutral pion decaying into two almost collinear photons, or when an electron fails to register hits in the pixel tracker. In both cases, a misidentified photon is reconstructed. Signal candidate events with misidentified photons from jets can

JHEP01(2019)154

arise from the process $W(\to \ell\nu)+$ jets, where a π^0 or η meson in the jet decays to photons. Signal candidate events with misidentified photons from electrons can arise from Drell-Yan dielectron production ($q\overline{q} \to \gamma^* \to e^+e^-$), as well as $t\overline{t}$ events with an electron in the final state.

The misidentified-photon background is estimated from collision data by determining the misidentification rate from a control sample of electron-like objects and applying it to events in a control region. First, the control sample is formed by replacing the photon candidate with a photon-like object, which is obtained by inverting some of the photon identification criteria, while keeping the other selection requirements identical to those for signal candidates. Second, the misidentification rate is defined as the ratio of the number of misidentified photons to the total number of photon-like objects in the control sample. The misidentification rate is applied in a control region, defined by $p_T^{miss} < 70\,GeV$, to estimate the number of misidentified photons in the control region. This estimate is then extrapolated to the signal region.

Electron control samples are constructed by requiring a candidate photon to either be associated with a seed track in the pixel detector or be geometrically matched to a reconstructed electron within $\Delta R < 0.03$. The misidentification rate is estimated using the "tag-and-probe" method [51] on a sample of $Z \to e^+e^-$ events in data. The rate is derived in bins of three variables: the p_T and $|\eta|$ of the probe objects, and the number of vertices in the event N_{vtx}. Parameterized functions are used to model the dependence of the misidentification rate on p_T and N_{vtx}, and binned values are used for the $|\eta|$ dependence. The measured misidentification rate varies from 2.3% for $p_T = 35\,GeV$ to 1.2% for $p_T > 180\,GeV$. These misidentification rates are then applied on an event-by-event basis in the control region when estimating the misidentified-lepton backgrounds later in the signal region. To verify the correctness of this background estimation method, it is tested on simulated Drell-Yan and $t\overline{t}$/WW/WZ events. As shown in figure 2, good agreement is achieved in the p_T^{miss} distribution of these simulated background events found using the control sample e-to-γ misidentification estimation method and that found directly from the generator-level truth information.

To estimate the jet-to-photon misidentification background, a hadronic control sample is constructed by inverting one of the variables characterizing the ECAL cluster shape ($\sigma_{\eta\eta}$ in ref. [25]) and the isolation variable requirement. The misidentification rate for the hadronic control sample is determined through an assessment of the fraction of events with jet-to-photon misidentification among the photon candidates. This fraction is denoted as the "hadron fraction". The measurement is performed in the control region $p_T^{miss} < 70\,GeV$ from a fit to the isolation variable distribution based on two templates, one representing pure photons obtained from γ+jet simulated MC events and one modeling the events with jet-to-photon misidentification, where the template for those events is obtained by inverting the $\sigma_{\eta\eta}$ requirement on the signal-photon candidates. The fit to the isolation distribution is performed in bins of p_T^{γ}. The resulting hadron fraction varies from 47 to 4% for the $e\gamma$ channel and 18 to 4% for the $\mu\gamma$ channel as p_T^{γ} increases. The p_T distribution of the jet-to-photon background in the control region is obtained by multiplying the p_T distribution of the photon candidates by the hadron fraction. To extrapolate the result to high-p_T photons,

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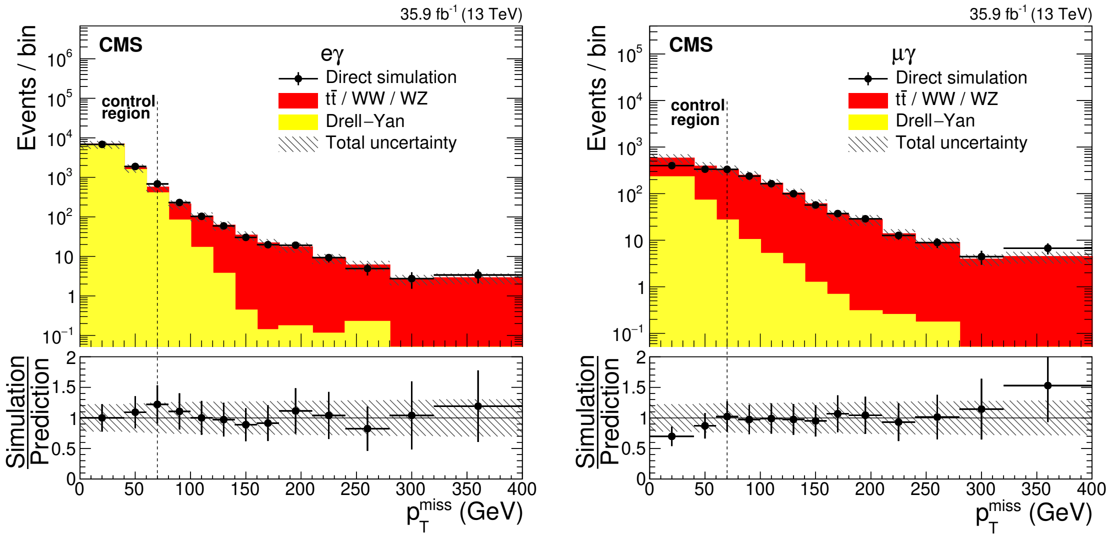

Figure 2. Verification of the e-to-γ misidentification estimation method using simulated data. The p_T^{miss} distribution for events with misidentified photons in the eγ (left) and $\mu\gamma$ (right) channels from prediction using the control sample estimation method (histograms) and direct simulation (points), as obtained from the generator-level information of the simulated data. The vertical bars on the points show the statistical uncertainty in the simulation, while the horizontal bars give the bin widths. The dashed vertical line shows the boundary between the control and signal regions. The lower panels show the ratio of the predictions from direct simulation to those estimated with control samples. The hatched areas give the quadrature sum of the statistical and systematic uncertainties in the simulated background.

the p_T shape of the jet-to-photon backgrounds and the control samples are modeled with the sum of two exponential functions, and the ratio between these two functions is used to assign event-by-event misidentification rates in the signal region. In the eγ channel, the misidentification rate varies from 28% at $p_T = 35$ GeV to 12% at $p_T = 200$ GeV. In the $\mu\gamma$ channel, it drops from 22 to 10% as p_T goes from 35 to 200 GeV.

5.2 Electroweak and misidentified-lepton backgrounds

A lepton is considered to be misidentified if it doesn't originate from a prompt W or Z boson decay. This includes leptons from heavy- and light-flavor hadron decays, misidentified jets, and electrons from photon conversions. Similar to the misidentified-photon background, the shapes of the misidentified-lepton backgrounds are modeled by control samples, which are formed by inverting the isolation requirement of the lepton while keeping other requirements unchanged. For electrons, the cluster shape and the quality of the cluster-to-track matching are also inverted to include more hadronic objects.

The SM backgrounds in final states with a lepton, a photon, and large p_T^{miss} are dominated by the production of W and Z bosons in association with a photon, denoted as Vγ production. In particular, neutrinos from the W boson leptonic decay escape the detector, producing significant p_T^{miss}. The shape of the p_T^{miss} distribution from the Vγ background is

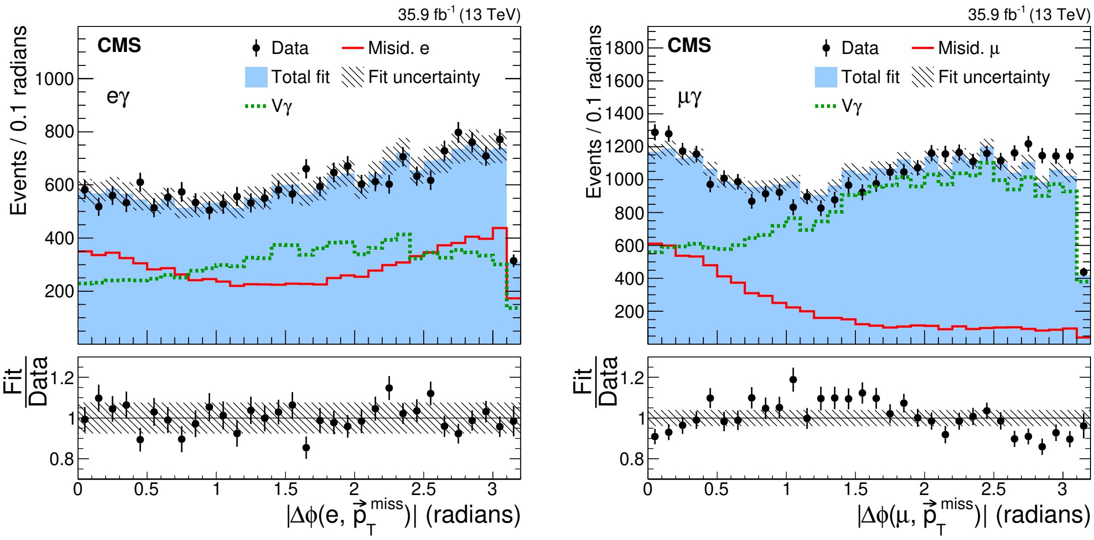

Figure 3. The $|\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})|$ distributions for the data in the $40 < p_{\mathrm{T}}^{\mathrm{miss}} < 70\,\mathrm{GeV}$ control region (points) and the estimated Vγ (dashed line) and misidentified-lepton (solid line) backgrounds for the eγ (left) and $\mu\gamma$ (right) channels. The filled histogram shows the result of the overall fit and the hatched area indicates the fit uncertainty. The vertical bars on the points represent the statistical uncertainty in the data. The lower panels show the ratio of the fit result to the data.

modeled by simulation, and the normalization factors are determined together with those of the misidentified-lepton backgrounds, as described in the next paragraph.

The normalization of the Vγ and misidentified-lepton backgrounds is determined by a two-component signal-plus-background template fit to the distribution of $|\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})|$, the azimuthal angular difference between the direction of the lepton and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ in the transverse plane. This fit is performed in the control region $40 < p_{\mathrm{T}}^{\mathrm{miss}} < 70\,\mathrm{GeV}$, where the lower bound of 40 GeV is applied to reduce the contribution of Zγ events. Expected contributions from the misidentified-photon and rare EW backgrounds such as WW$(+\gamma)$, WZ$(+\gamma)$, and $\mathrm{t\bar{t}}(+\gamma)$ processes are subtracted before the fit. The distribution of $|\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})|$ is shown in figure 3 with the fit results overlaid. The resulting scale factors (SFs) for the Vγ and misidentified-lepton backgrounds in the eγ channel are $SF_{\mathrm{V}\gamma} = 1.17 \pm 0.08$ and $SF_{\mathrm{e-misid}} = 0.24 \pm 0.02$, respectively, while the SFs for the $\mu\gamma$ channel are $SF_{\mathrm{V}\gamma} = 1.33 \pm 0.02$ and $SF_{\mu\mathrm{-misid}} = 0.62 \pm 0.02$, where the uncertainties are statistical only.

6 Systematic uncertainties

Table 1 summarizes the relative systematic uncertainties in the background estimation and signal expectation. If the relative uncertainties differ considerably in different kinematic regions because of the limited number of events available for the evaluation of the systematic uncertainties, the range of the relative uncertainty is shown. The main sources of systematic uncertainties are the SFs derived from the $|\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})|$ template fit to the Vγ and misidentified-lepton backgrounds, and the cross sections used to normalize the rare EW simulated samples. The systematic uncertainty coming from the shape of the Vγ distribu-

Uncertainty source	Background process	Background uncertainty (%)	Signal uncertainty (%)
Jet energy scale	Vγ, rare EW	0–23	0–10
Normalization scale	Vγ, jet $\to \ell$ misid.	20	—
Cross section	rare EW	50	4–37
Ident. and trigger efficiency	Vγ, rare EW	1.3–6.5	1.3–6.5
e $\to \gamma$	e $\to \gamma$ misid.	8–51	—
Jet $\to \gamma$ shape	jet $\to \gamma$ misid.	8–56	—
Misid. lepton shape	jet $\to \ell$ misid.	0–42	—
ISR corrections	Vγ	3–58	0–32
Integrated luminosity	rare EW	2.5	2.5
Pileup uncertainty	—	—	2–10
PDF, renormalization/factorization scales	—	—	0–10
Fast simulation $p_{\mathrm{T}}^{\mathrm{miss}}$ modeling	—	—	0–31

Table 1. The relative systematic uncertainties in the SM background processes (third column) and the expected SUSY signal (fourth column). The ranges refer to the uncertainties over the different kinematic regions.

tion is obtained by allowing each bin of the template to vary independently according to a Gaussian distribution. Systematic uncertainties in the magnitude of the normalization are determined by allowing the number of subtracted events from the estimated backgrounds to vary within their uncertainties, as well as the PDF and renormalization and factorization scales of the Vγ template to vary by one standard deviation around their nominal values. For the rare EW backgrounds, a 50% uncertainty is assigned to the cross sections to cover the difference between the calculated cross sections and the latest CMS measurements [52, 53].

The subdominant systematic uncertainties come from the modeling of the misidentified photons. Different choices of control samples and parameterized functions are studied to evaluate the size of these systematic effects. The uncertainties in the number of misidentified photons with $p_{\mathrm{T}} < 200\,\mathrm{GeV}$ are less than 20%. A larger uncertainty, up to 56%, is caused by the limited number of events in the control sample and applies only to the high-p_{T} bins, where the misidentified photons contribute less than 10% of the total background, resulting in a small effect on the total background prediction. For the backgrounds obtained from simulation, systematic uncertainties from the jet energy scale are evaluated by varying the corresponding scale by one standard deviation around its nominal value [54]. Uncertainties in the signal cross sections used in the simulation due to the PDFs and the renormalization and factorization scales are taken from refs. [42–46]. The additional shape uncertainty in the signal sample due to the choice of the renormalization and factorization scales is estimated by varying the scales upward and downward by a factor of two with respect to their nominal values. Finally, the uncertainty in the integrated luminosity of the data sample is 2.5% [55].

7 Results

Figure 4 shows the $p_{\mathrm{T}}^{\mathrm{miss}}$, p_{T}^{γ}, and H_{T} distributions of the observed data and predicted background, together with the systematic uncertainties in the background prediction. The

JHEP01(2019)154

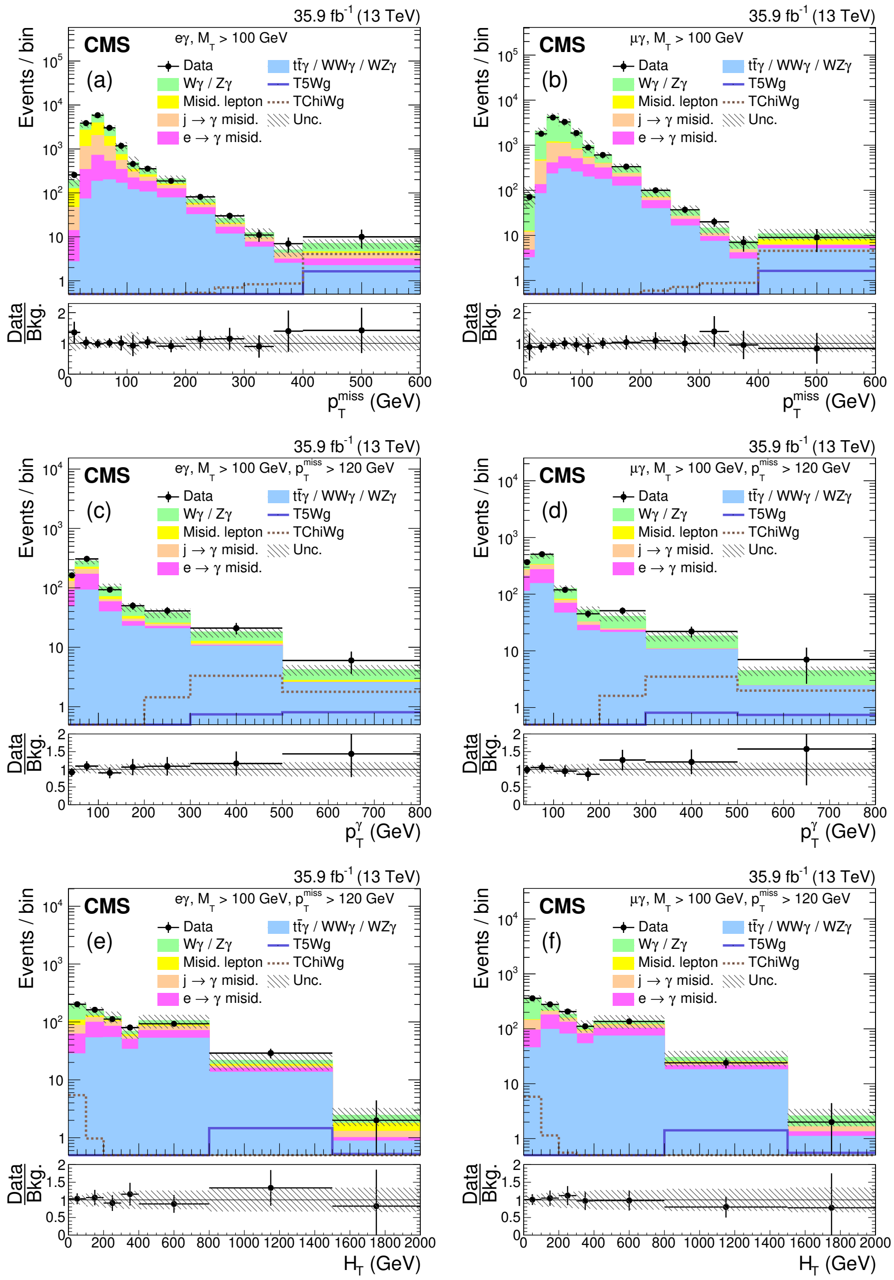

Figure 4. Distributions of $p_{\mathrm{T}}^{\mathrm{miss}}$ (a, b), p_{T}^{γ} (c, d), and H_{T} (e, f) from data (points) and estimated SM predictions (stacked histograms) for the eγ (left) and $\mu\gamma$ (right) channels. Simulated signal distributions from the TChiWg model (dotted) with $m_{\tilde{\chi}^0/\tilde{\chi}^\pm} = 800\,\mathrm{GeV}$ and the T5Wg model (solid) with $m_{\tilde{g}} = 1700\,\mathrm{GeV}$ are overlaid. The $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution includes all events with $m_{\mathrm{T}} > 100\,\mathrm{GeV}$, while the p_{T}^{γ} and H_{T} distributions only include events with $m_{\mathrm{T}} > 100\,\mathrm{GeV}$ and $p_{\mathrm{T}}^{\mathrm{miss}} > 120\,\mathrm{GeV}$. The vertical bars on the points give the statistical uncertainty in the data and the horizontal bars show the bin widths. The hatched area represents the quadratic sum of the statistical and systematic uncertainties in the simulated background. The lower panels display the ratio of the data to the total background prediction.

JHEP01(2019)154

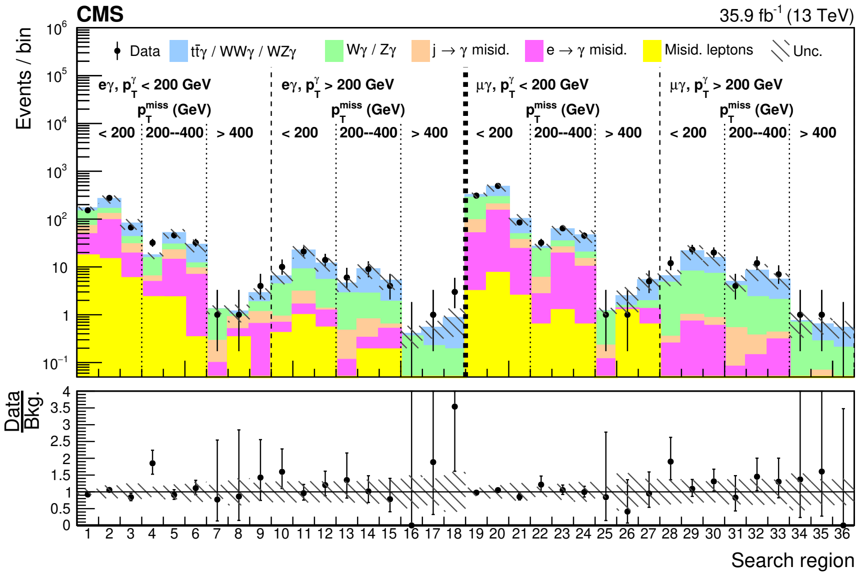

Figure 5. The number of data events (points) and predicted background events (shaded histograms) for the 18 search regions in p_T^{miss}, H_T, and p_T^γ (separated by dashed vertical lines) in the eγ (regions 1–18) and the $\mu\gamma$ (regions 19–36) channels. For each p_T^{miss} range, the first, second, and last bins correspond to the H_T regions 0–100, 100–400, and > 400 GeV, respectively. The lower panel displays the ratio of the data to the background predictions. The vertical bars on the points show the statistical uncertainty in the data, and the hatched areas give the quadrature sum of the statistical and systematic uncertainties in the simulated background.

p_T^{miss} distribution includes all events with $m_T > 100$ GeV, while the p_T^γ and H_T distributions only include events in the signal region. Two simulated signal distributions, one from the TChiWg simplified model with an NLSP mass of 800 GeV, and the other from the T5Wg model with an NLSP mass of 1000 GeV and a gluino mass of 1700 GeV, are also overlaid. The data are compatible with the estimated SM backgrounds within the uncertainties.

To improve the sensitivity for different SUSY scenarios, the signal region for each lepton channel is further divided into 18 search regions: three bins of p_T^{miss} (120–200, 200–400, and >400 GeV) in each of three H_T ranges (0–100, 100–400, and >400 GeV), and two ranges of photon p_T (35–200 and >200 GeV). The misidentified-photon and misidentified-lepton control samples are also divided into respective search regions. Figure 5 gives the event yields from data and the estimated total background in each of the search regions for the eγ (left part) and $\mu\gamma$ (right part) channels. The observed data are consistent with the background predictions in all the search regions. The largest difference is in the fourth bin of the eγ channel, which has an excess over the background prediction of 2.3 standard deviations. In the corresponding search regions of the $\mu\gamma$ channel, the data are compatible with the SM background predictions. Thus, we conclude that no significant excess of events beyond the SM expectation is observed.

JHEP01(2019)154

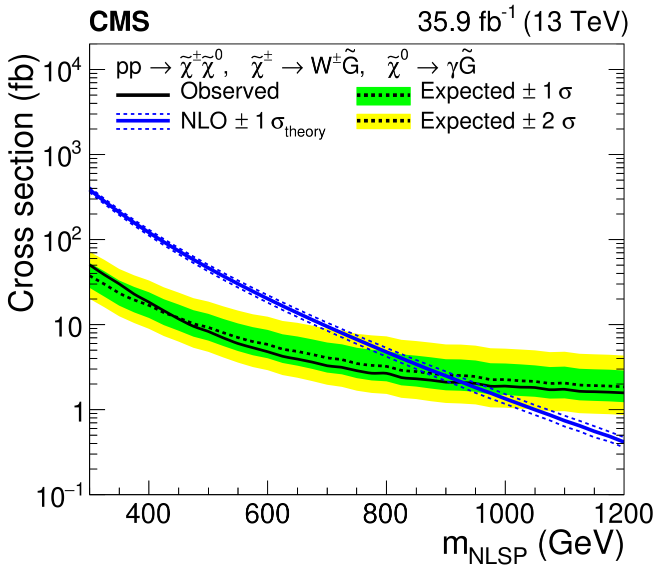

Figure 6. The observed (solid line) and expected (dashed line) 95% CL upper limits on the production cross sections for the TChiWg simplified model, together with the NLO theoretical cross sections as a function of the NLSP mass. The inner (darker) band and outer (lighter) band around the expected upper limits indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The dotted lines around the theoretical cross section gives the ±1 standard deviation uncertainty in the cross section.

8 Interpretation

The results are interpreted in the context of upper limits on the cross sections of the three simplified SUSY models introduced in section 1. For each mass point of the signal models, a 95% confidence level (CL) upper limit on the signal production cross section is obtained by calculating $\mathrm{CL_s}$ limits [56–58] using the profile likelihood as a test statistic and asymptotic formulas [59]. The SM background prediction, signal expectation, and observed number of events in each signal search region of the eγ and $\mu\gamma$ channels defined above are combined into one statistical interpretation, and studied as a multichannel counting experiment.

Figure 6 shows the observed and expected 95% CL upper limits on the cross section for the TChiWg model as a function of the NLSP mass, together with the theoretical cross section for $\tilde{\chi}^0\tilde{\chi}^\pm$ pair production. The TChiWg model is based on the direct production of $\tilde{\chi}^\pm$ and $\tilde{\chi}^0$, in which their decays are restricted to $\mathrm{W}^\pm\tilde{\mathrm{G}}$ and $\gamma\tilde{\mathrm{G}}$, respectively. The gravitino $\tilde{\mathrm{G}}$ is modeled as nearly massless. Assuming a 100% branching fraction for $\tilde{\chi}^0 \to \gamma\tilde{\mathrm{G}}$, this search excludes NLSP masses up to 930 GeV at the 95% CL.

In figure 7, we present the cross section 95% CL upper limits and mass exclusion contours for the T5Wg and T6Wg simplified models. The production cross section of the T5Wg (T6Wg) model is determined solely by $m_{\tilde{\mathrm{g}}}$ ($m_{\tilde{\mathrm{q}}}$). Nevertheless, the $m_{\tilde{\mathrm{g}}/\tilde{\mathrm{q}}} - m_{\tilde{\chi}}$ mass difference affects the H_T and $p_\mathrm{T}^\mathrm{miss}$ spectra, resulting in nontrivial exclusion-limit contours in the ($m_{\tilde{\mathrm{g}}/\tilde{\mathrm{q}}}, m_{\tilde{\chi}}$) mass plane. The branching fractions for $\tilde{\mathrm{g}} \to \mathrm{q}\bar{\mathrm{q}}\tilde{\chi}^0/\tilde{\chi}^\pm$ and $\tilde{\mathrm{q}} \to \mathrm{q}\tilde{\chi}^0/\tilde{\chi}^\pm$

JHEP01(2019)154

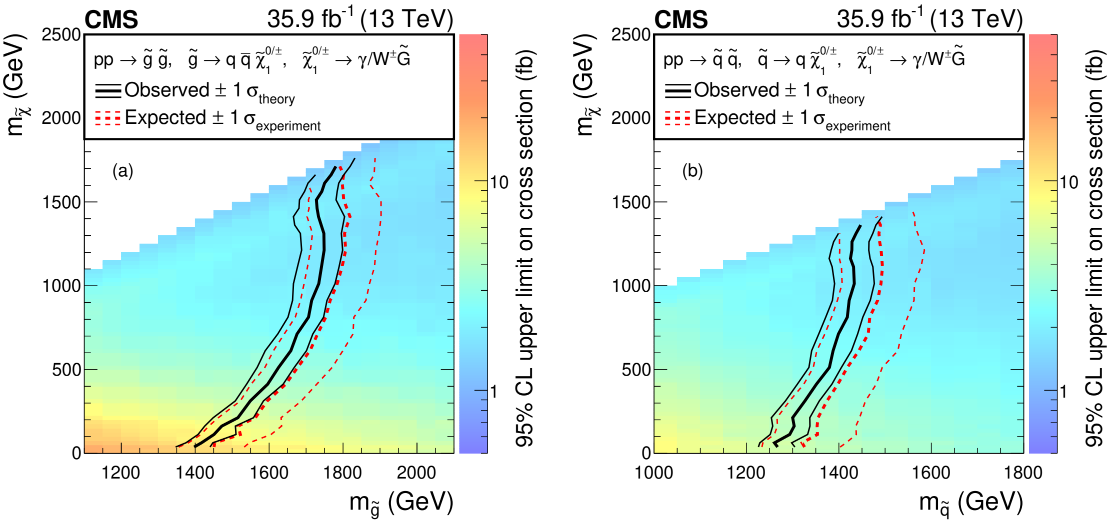

Figure 7. The observed (solid line) and expected (dashed line) 95% CL exclusion contours for (a) $m_{\tilde{g}}$ versus $m_{\tilde{\chi}}$ and (b) $m_{\tilde{q}}$ versus $m_{\tilde{\chi}}$ (regions to the left of the curves are excluded), and the 95% CL upper limits on the pair production cross sections for (a) $\widetilde{g}\widetilde{g}$ in the T5Wg and (b) $\widetilde{q}\widetilde{q}$ in the T6Wg simplified models (use the scales to the right of the plots). The upper limits on the cross sections assume a 50% branching fraction for $\widetilde{g} \to q\bar{q}\widetilde{\chi}^0/\widetilde{\chi}^\pm$ and $\widetilde{q} \to q\widetilde{\chi}^0/\widetilde{\chi}^\pm$. The bands around the observed and expected exclusion contours indicate the ± 1 standard deviation range when including the experimental and theoretical uncertainties, respectively.

are assumed to be 50%. For large $\widetilde{\chi}^0/\widetilde{\chi}^\pm$ masses, gluino (squark) masses are excluded at 95% CL up to 1.75 (1.43) TeV in the T5Wg (T6Wg) scenarios.

9 Summary

A search for supersymmetry with general gauge mediation in events with a photon, an electron or muon, and large missing transverse momentum has been presented. This analysis is based on a sample of proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$ recorded by the CMS experiment in 2016. The data are examined in bins of the photon transverse energy, the magnitude of the missing transverse momentum, and the scalar sum of jet energies. The standard model background is evaluated primarily using control samples in the data, with simulation used to evaluate backgrounds from electroweak processes. The data are found to agree with the standard model expectation, without significant excess in the search region. The results of the search are interpreted as 95% confidence level upper limits on the production cross sections of supersymmetric particles in the context of simplified models [23] motivated by gauge-mediated supersymmetry breaking. For strong production models, such as the T5Wg simplified model of gluino pair production and the T6Wg model of squark pair production, this search excludes gluinos (squarks) with masses up to 1.75 (1.43) TeV in the T5Wg (T6Wg) scenarios. The TChiWg simplified model, based on direct electroweak production of a neutralino and chargino, is excluded for next-to-lightest supersymmetric particle masses below 930 GeV, extending the current best limit by about 150 GeV [19].

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154

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JHEP01(2019)154