Search for supersymmetry in events with a photon, a lepton, and missing transverse momentum in pp collisions at √s=8 TeV

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Search for supersymmetry in events with a photon, a lepton, and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV

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ABSTRACT

A search for supersymmetry involving events with at least one photon, one electron or muon, and large missing transverse momentum has been performed by the CMS experiment. The data sample corresponds to an integrated luminosity of 19.7 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV, produced at the CERN LHC. No excess of events is observed beyond expectations from standard model processes. The result of the search is interpreted in the context of a general model of gauge-mediated supersymmetry breaking, where the charged and neutral winos are the next-to-lightest supersymmetric particles. Within this model, winos with a mass up to 360 GeV are excluded at the 95% confidence level. Two simplified models inspired by gauge-mediated supersymmetry breaking are also examined, and used to derive upper limits on the production cross sections of specific supersymmetric processes.

1. Introduction

The extension of the standard model (SM) of particle physics through the concept of supersymmetry (SUSY) [1], which imposes a symmetry between fermions and bosons, can offer a solution to some of the issues not accommodated in the SM, such as the existence of dark matter in the universe or the extreme fine tuning required to control radiative corrections to the Higgs boson mass (hierarchy problem) [2–4]. The minimal supersymmetric standard model (MSSM) [5–7] provides a calculable framework with a fully known particle content, introducing a superpartner for each SM particle. For example, squarks, gluinos, and gravitinos are the SUSY partners of quarks, gluons, and gravitons, respectively. The MSSM has guided the search program for physics beyond the SM at facilities such as the Fermilab Tevatron and CERN LHC. Existing searches have not yet found evidence for SUSY, but a large parameter space of the MSSM remains to be explored.

Within the MSSM, scenarios based on gauge-mediated SUSY breaking (GMSB) [8–18] are of particular interest because of their ability to naturally circumvent the so-called SUSY flavour problem [19]. The framework of general gauge mediation (GGM) [20] offers a clear definition of GMSB and establishes its key aspects. For example, GMSB predicts the gravitino ($\widetilde{\mathrm{G}}$) to be the lightest supersymmetric particle (LSP). The combination of this feature and the weakness of the coupling of $\widetilde{\mathrm{G}}$ to other MSSM particles has specific consequences in collider phenomenology. Under the assumption that R-parity [6] is conserved, SUSY particles are pair-produced at the LHC. Except for direct LSP pair production, each SUSY particle initiates a decay chain that yields the next-to-lightest supersymmetric particle (NLSP). Branching fraction for the SUSY particle decay involving $\widetilde{\mathrm{G}}$ is negligible except for the NLSP, leaving the decay of the NLSP to its SM partner and the $\widetilde{\mathrm{G}}$ as effectively the only gravitino production mechanism. The gravitino escapes detection, leading to missing momentum in the event. The signature of a GMSB signal is thus strongly dependent on the identity of the NLSP. In most GMSB models, the NLSP is taken to be a bino- or wino-like lightest neutralino, where a bino and wino are the superpartners of the SM U(1) and SU(2) gauge fields, respectively. Previous searches for a GMSB signal typically exploited the diphoton signature [21–29], in which each of the two bino-like neutralinos decays promptly into a photon and a gravitino. Similar scenarios with nonprompt NLSP decays have also been considered [30,31]. Thus far, no evidence for GMSB SUSY has been observed, resulting in upper limits on the production cross sections given as a function of the SUSY particle masses, the NLSP lifetime, or other model parameters.

This paper presents a search for SUSY with the CMS experiment at the LHC, and targets GGM models with wino-like NLSPs. The data sample corresponds to an integrated luminosity of 19.7 fb^{-1} of pp collision data collected in 2012 at $\sqrt{s} = 8$ TeV. In particular, we study the wino co-NLSP model [32], in which nearly mass-degenerate charged and neutral winos are significantly lighter than the other electroweakinos and constitute the lightest SUSY parti-

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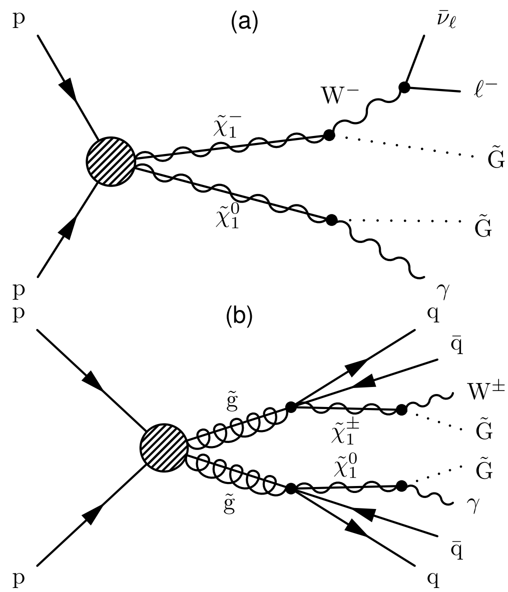

Fig. 1. Diagrams showing the production and decays of wino-like co-NLSPs ($\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$) leading to final states with a photon, an electron or muon, and missing momentum from undetected gravitinos $\tilde{G}$ (a) without and (b) with involvement of coloured SUSY particles.

cles aside from the gravitino. Although the lifetime of the NLSP is effectively a free parameter in GGM phenomenology, a prompt decay of winos is assumed in this analysis. A signature of at least one photon (γ), one electron or muon (ℓ), and large missing transverse momentum ($\vec{p}_T^{\,miss}$) is used in this search. The photon is assumed to be emitted by a neutralino NLSP, and the leptons by either a charged or neutral NLSP decaying to a W or Z boson, respectively. This signature suppresses many SM backgrounds, obviating the need for additional requirements such as associated jet activity. The diagrams in Fig. 1 provide examples of the decay chains studied in this analysis. The present search is sensitive to the direct electroweakino production mode of Fig. 1(a), where the winos are produced without involving coloured SUSY particles, but also to strong production modes such as the gluino ($\tilde{g}$) pair-production process shown in Fig. 1(b). Similar searches were conducted by the ATLAS [33] and CMS [34,35] experiments using LHC pp collision data at $\sqrt{s} = 7$ or 8 TeV, as well as the CDF experiment [36] at the Tevatron using $p\bar{p}$ collision data at $\sqrt{s} = 1.8$ TeV. None of these analyses sees an excess of events over the respective SM predictions. The wino co-NLSP model has also been probed through the signatures of three leptons or two leptons and two jets [37,38], which target the decay of the neutralino NLSP to a gravitino and a Z boson rather than to a gravitino and a photon. None of these analyses observed a significant excess of events over their respective SM predictions.

2. 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 consisting of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, can be found in Ref. [39].

In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted and late-converting photons with transverse energy $E_T \approx 10$ GeV. The remaining barrel photons have a resolution of about 1.3% up to a pseudorapidity $|\eta| < 1.0$, rising to about 2.5% for $|\eta| = 1.4$ [40].

The electron momentum is determined by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with transverse momentum $p_T \approx 45$ GeV from $Z \to e^+e^-$ decays ranges from 1.7% for non-showering electrons in the barrel region to 4.5% for showering electrons in the endcaps [41].

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. Through the matching of track segments measured in the muon detectors with tracks measured in the tracker, a transverse momentum resolution of 1.3–2.0% is achieved for barrel muons with $20 < p_T < 100$ GeV. In the endcaps, the resolution increases up to around 6%. The p_T resolution in the barrel is better than 10% for muons with transverse momentum up to 1 TeV [42].

Physics objects are defined using the particle-flow (PF) algorithm [43,44], which reconstructs and identifies individual particles through 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. Finally, the CMS detector is nearly hermetic, permitting accurate measurements of $\vec{p}_T^{\,miss}$.

3. Data collection and event selection

The search is conducted in the electron–photon (eγ) and muon–photon ($\mu\gamma$) channels. The data samples are collected using a dedicated trigger for each channel, as described below. An event is considered to be in the eγ ($\mu\gamma$) channel if it contains at least one high-energy photon and an electron (muon). Events that simultaneously satisfy the criteria for the two search channels, representing about 0.1% of the selected events, are classified as $\mu\gamma$ candidates because muon objects are less often the result of hadron misidentification than are electron objects.

The trigger for the eγ channel requires at least two isolated photon-like objects, with E_T thresholds of 36 and 22 GeV for the highest and second-highest E_T photon, respectively. The trigger does not veto photon objects that can be matched to a track, allowing events with a photon and an electron to also satisfy the trigger. The $\mu\gamma$ channel uses a muon–photon trigger with a p_T threshold of 22 GeV for both the photon and muon objects. To ensure a fully efficient trigger and a similar selection efficiency for the two channels, the subsequent analysis requires $E_T > 40$ GeV for the photon and $p_T > 25$ GeV for the electron or muon. With these requirements, the trigger efficiency for the signal models described in Section 7 is found to be 93–98% for both channels, depending on the model and SUSY mass values.

Photon candidates are reconstructed from clusters of energy in the ECAL [40]. The momentum vector of the photon points from the primary pp interaction vertex to the center of the ECAL energy cluster, under the assumption that the photon originates from the primary vertex, which is defined as the vertex with the highest $\sum p_T^2$ of associated tracks. Only photons from clusters in the pseudorapidity range $|\eta| < 1.44$ are included in this analysis. These clusters were selected as photon candidates by a set of criteria that are designed to achieve a 90% identification efficiency for true photons. For a cluster to be identified as a photon, its shape must be consistent with that expected from a photon, and the energy detected in the HCAL behind the cluster cannot exceed 5% of the ECAL energy. To further suppress the misidentification of hadrons as photons, a PF-based isolation requirement is imposed. The transverse component of the momentum sum of each of the PF photons, charged hadrons, and neutral hadrons within a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the direction of the photon candidate (where ϕ is the azimuth measured in radians) is required not to exceed fixed values defined to achieve a desirable balance between the 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 vertex. The p_T sums are corrected for contributions from additional pp interactions (pileup). To distinguish photon candidates from isolated electrons, photon objects are vetoed if a matching track segment from the inner tracker is identified.

Electron (muon) candidates must lie in the pseudorapidity range $|\eta| < 2.5\,(2.4)$. For electrons, the transition region $1.44 < |\eta| < 1.56$ between the barrel and the endcap detectors is vetoed because the reconstruction efficiency in this region is difficult to model. Electron objects are reconstructed by associating a cluster of energy deposited in the ECAL with a reconstructed track. The electron selection [45] is based on the shower shape, the matching of a track to the cluster, and isolation, where the isolation variable is calculated from the momenta of PF photons, charged hadrons, and neutral hadrons within a cone of $\Delta R = 0.3$ around the electron direction, corrected for the effects of pileup. The isolation sum is required not to exceed a fixed fraction of the electron p_T, where the selection criteria are defined to obtain an 80% electron identification efficiency. The muon selection [42], targeting a 90% efficiency for true muons, utilizes the quality of the track fit, the number of detector hits used in the tracking, and the isolation. The isolation requirement for muons is similar to that for electrons, but uses a larger cone size $\Delta R = 0.4$. Electrons and muons must originate from a primary vertex, with respective distances of closest approach for electrons (muons) of less than 0.2 mm (2 mm) in the transverse plane and < 1 mm (< 5 mm) along the beam direction.

The reconstruction of jets and $\vec{p}_T^{\,\text{miss}}$ is also based on the PF objects. All reconstructed PF candidates are clustered into jets using the anti-k_T clustering algorithm [46,47], with a distance parameter of 0.5. Jet objects are used to calculate the H_T variable, defined as the scalar p_T sum of jets. To be considered in the H_T sum, a jet must have a calibrated and pileup-corrected [48] p_T value greater than 30 GeV, $|\eta| < 2.5$, and be consistent with an origin at the primary vertex [49]. In addition, it must be no closer than $\Delta R = 0.5$ to the photon or lepton candidates. The missing momentum $\vec{p}_T^{\,\text{miss}}$ is given by the negative of the vector p_T sum of all PF objects, with jet-energy corrections applied. The magnitude of $\vec{p}_T^{\,\text{miss}}$ is referred to as E_T^{miss}.

To suppress the background from final-state radiation events with an on-shell W (Z) boson that decays to $\ell\nu\gamma$ ($\ell\ell\gamma$), the highest-E_T photon in an event must be separated by $\Delta R > 0.8$ from the highest-p_T electron or muon. Additionally, for the eγ channel, the invariant mass of the electron–photon system is required to differ by more than 10 GeV from the nominal Z boson mass [50], to reduce background from electrons misidentified as photons.

After applying the selection requirements described above, the obtained event yields are compared to expectations from SM background processes. The signal region of interest is defined by $E_T^{\text{miss}} > 120$ GeV and $M_T > 100$ GeV, where transverse mass M_T is defined by $M_T = \sqrt{2E_T^{\text{miss}} p_T^{\ell}[1 - \cos\Delta\phi(\ell, \vec{p}_T^{\,\text{miss}})]}$, with p_T^{ℓ} the transverse momentum of the highest-p_T lepton and $\Delta\phi(\ell, \vec{p}_T^{\,\text{miss}})$ the azimuthal angle between the lepton and $\vec{p}_T^{\,\text{miss}}$. The M_T requirement reduces backgrounds from processes that produce W bosons. Table 1 shows the observed number of events at different stages of the selection process. Because of a higher selection efficiency for muons, after implementing the selection requirements, the number of observed events in the $\mu\gamma$ channel is larger than in the eγ channel.

Table 1
Summary of event selection requirements and observed number of events after applying the listed selection requirements in successive order. The symbols $m_{e\gamma}$ and m_Z denote the invariant mass of the electron–photon system and the nominal Z boson mass, respectively.

Selection requirement	eγ channel	$\mu\gamma$ channel
Trigger	26 733 051	19 456 571
≥1 accepted γ	2 718 364	243 664
≥1 accepted ℓ ($\ell = $ e, μ)	70 736	32 173
$\Delta R(\gamma, \ell) > 0.8$	68 168	30 232
$\lvert m_{e\gamma} - m_Z\rvert > 10$ GeV	29 169	–
$E_T^{\text{miss}} > 120$ GeV, $M_T > 100$ GeV	110	152

4. Background estimation

Three sources of SM background are considered: misidentified photons, misidentified leptons, and electroweak backgrounds.

4.1. Misidentified-photon background

The background from misidentified photons arises from events in which a photon object does not correspond to a genuine prompt photon. The dominant background processes in this category are Drell–Yan dielectron ($q\bar{q} \to \gamma^* \to e^+e^-$) and W ($\to \ell\nu$) + jets production, in which an electron or jet, respectively, is misidentified as a photon. Minor contributions arise from $t\bar{t}$ events with leptonic top quark decays, for both the eγ and $\mu\gamma$ channels. Events with $t\bar{t}$ production also contribute to the background if a jet is misidentified as a photon. An electron can be misidentified as a photon if it fails to register track seeds due to detector inefficiencies such as non-operational sensors in the tracker. A jet can be misidentified as a photon if a large fraction of its energy is carried by mesons decaying to photons, such as $\pi^0 \to \gamma\gamma$. These two types of background are estimated from data using weighted control samples. The method proceeds in two steps. First, a control sample enriched in particles that are prone to be misidentified as photon candidates, i.e., electrons or neutral hadrons, is selected by inverting certain criteria in the photon identification, while keeping the other selection requirements identical to those for signal candidates. This control sample is called the proxy sample. The second step is to determine the transfer factor $N^{\text{misid}}/N^{\text{proxy}}$, where N^{misid} is the estimate of the number of misidentified events in the signal candidate sample and N^{proxy} is the number of events in the proxy sample. The proxy sample is then scaled by the transfer factor. The definition of the proxy sample is tuned to make its kinematic properties similar to those of events with misidentified photons. Thus, this two-step procedure takes the set of misidentified events in a control region where the SUSY signal contribution is expected to be negligible, e.g. in events with small E_T^{miss}, and utilizes it to model the distribution of the misidentified background for a given kinematic variable. In particular, from the extrapolation of the observed events in the control region, the method predicts an expectation for the number of events and corresponding kinematic distribution in the signal region. A detailed validation of this background estimation is performed by applying the method to Monte Carlo (MC) simulation samples, and comparing the outcome of this procedure to the known generated MC content. Good agreement is found in all such tests.

The proxy sample for events with an electron-to-photon misidentification is constructed by inverting the electron-seed veto in the photon identification, which turns the photon candidate into an electron proxy. The transfer factor for this proxy sample is determined by counting $Z \rightarrow e^+e^-$ decays in a separate control sample, defined by $E_T^{miss} < 70$ GeV. The ratio N_Z^{misid}/N_Z^{proxy} constitutes the transfer factor, where N_Z^{misid} is the number of $Z \rightarrow e^+e^-$ events in the control sample with an e^+ or e^- misidentified as a photon, while N_Z^{proxy} is the number of $Z \rightarrow e^+e^-$ events in the control sample with the proxy condition applied. The control sample for the $e\gamma$ channel is taken from the data set collected with the same diphoton trigger as the signal candidates, while the sample for the $\mu\gamma$ channel is from a data set based on a trigger that requires at least one isolated electron. To ensure that the samples dominantly consist of $Z \rightarrow e^+e^-$ decays, events with one high-purity electron object ("tag") are selected from the respective data sets. The photon candidate and the electron-proxy object are called "probes". For each sample of probe candidates, a fit is performed to the invariant mass distribution of the tag–probe system to extract the number of $Z \rightarrow e^+e^-$ decays.

The "tag-and-probe" method described above [51] is executed in bins of three variables: the transverse momentum of the probe object (p_T^{probe}), the track multiplicity of the primary vertex (N_{track}), and the number of reconstructed interaction vertices in the event (N_{vtx}). To account for the correlations in the distributions of the three variables, the dependence of the transfer factor on these quantities is modelled by a three-dimensional parametric function, which is then used to assign an event-by-event weight to the proxy sample. The transfer factor is a decreasing function of p_T^{probe} and N_{track}, and an increasing function of N_{vtx}. For a median value of N_{vtx}, its value varies from 0.04 for events with low p_T^{probe} and low N_{track}, to 0.007 for high p_T^{probe} and high N_{track}. The relative uncertainty in the transfer factor is typically of order 10%, which is dominated by systematic uncertainties such as those arising from the tag-and-probe fitting procedure and the parametrization of the transfer factor. The dependence of the transfer factor on N_{vtx} is approximately linear, with a value that changes from about 0.005 to 0.012 for N_{vtx} values between 5 (low pileup) and 25 (high pileup).

The estimation of the jet-to-photon misidentification background follows the same procedure of defining a proxy sample and scaling it with the transfer factor. The proxy sample for events with a jet-to-photon misidentification is constructed by inverting the requirements on the variable describing the ECAL cluster shape ($\sigma_{\eta\eta}$ in Ref. [41]) and on one of the isolation variables in the photon selection. The transfer factor for the hadronic-proxy 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". This measurement is performed in a low-E_T^{miss} control sample from a fit to the distribution of $\sigma_{\eta\eta}$ based on two templates, one representing pure photons and one modelling the events with jet-to-photon misidentification. The fit is performed with photon candidates in muon–photon events, where a very small contamination of misidentified electrons is expected in the photon sample. The pure photon template is obtained from $Z \rightarrow \mu\mu\gamma$ data by tagging two muons and requiring the three-body $\mu\mu\gamma$ invariant mass to be consistent with the Z boson mass. The template that models events with jet-to-photon misidentification is obtained by inverting the isolation requirement on the signal-photon candidates. The hadron fraction is measured in p_T bins of the photon candidate and decreases, in general, as a function of p_T. In the $e\gamma$ channel, its value varies from 0.25 ± 0.03 at $p_T = 40$ GeV to 0.08 ± 0.02 at $p_T = 120$ GeV. In the $\mu\gamma$ channel, the corresponding values are 0.30 ± 0.03 and 0.09 ± 0.02. The uncertainties are dominantly due to possible mismodelling of the fit templates. The small difference in the hadron fraction of the photon candidates between the $e\gamma$ and $\mu\gamma$ channels originates from small differences in trigger requirements on the photon object between the diphoton and muon–photon triggers used to select the $e\gamma$ and $\mu\gamma$ data sets.

The p_T distribution of the photon objects is multiplied by the hadron fractions determined as described above. In the $e\gamma$ channel, the estimated p_T distribution of misidentified electrons is subtracted first. The resulting distribution provides the estimate of the p_T shape for the events with jet-to-photon misidentification. Rather than forming the ratio of this distribution with the p_T distribution of the proxy sample, both distributions are parameterized individually by simple analytic functions. The ratio of these two parameterizations constitutes the transfer factor for the jet-to-photon misidentification.

4.2. Misidentified-lepton and electroweak backgrounds

The misidentified-lepton and electroweak (EWK) backgrounds are evaluated together, as described below. A misidentified lepton is defined as a reconstructed lepton that does not arise directly from W or Z boson decays, nor from τ decays that originate from a W or Z boson. Misidentified-lepton events arise primarily from the decay of heavy-flavour quarks and from hadrons misidentified as leptons, with other sources such as decays-in-flight constituting a much smaller contribution. Events where both the lepton and photon are misidentified, which constitute up to 30% of the total misidentified-photon background, are already accounted for by the procedure described in Section 4.1. The SM electroweak background is dominated by events with $V\gamma$ ($V = W$, Z) production. In particular, $W\gamma$ events have the same signature as signal events: an energetic photon, a lepton, and significant E_T^{miss}. The EWK background includes rare multiboson events and events with $t\bar{t}\gamma$ production, which we collectively refer to as the "rare EWK" background. Rare EWK events provide only a minor contribution to the overall background but are relevant in the high-E_T^{miss} signal region.

Similar to the determination of the misidentified-photon background, proxy samples are formed and scaled by transfer factors to estimate the contribution of misidentified leptons to the signal region. Each event in the proxy sample contains at least one candidate photon and at least one misidentified-lepton proxy, but no candidate lepton. Proxy objects that model misidentified leptons are selected by inverting the isolation condition in the lepton selection. For electrons, the track-cluster matching requirements are also inverted to further enrich the proxy sample with hadronic objects. The calculation of the transfer factor used to evaluate the misidentified-lepton background is described below.

The modelling of the EWK background is based on MC simulation. Samples of $W\gamma$, $Z\gamma$, $t\bar{t}\gamma$, and $WW\gamma$ events, listed in the order of decreasing overall background contributions, are generated with up to two additional partons using the MadGraph 5 1.3 [52] event generator. The pythia 6.4 [53] program is used to describe the parton shower and hadronization. The pythia program is further used to generate samples of $WZ\gamma$ events, which produce an even smaller background contribution than $WW\gamma$ events. All samples use the CTEQ6L1 [54] parton distribution functions (PDF). Simulated minimum-bias events are overlaid on the main hard-scattering events to simulate pileup. The generated particles are processed through the full CMS detector simulation framework based on the Geant4 [55] package, and are subjected to the same event selection procedure as the data, including the trigger requirements. Differences between simulation and data in the pileup profile, trigger efficiency, and object identification efficiency are corrected by reweighting the MC events by factors that lie within a few percent of unity. The $t\bar{t}\gamma$, $WW\gamma$, and $WZ\gamma$ samples are normalized to the integrated luminosity of the data using cross sections calculated with the event generators, which are valid to leading order (LO) in quantum chromodynamics. For the $t\bar{t}\gamma$ sample, a next-to-leading order (NLO)-to-LO scale factor of 2.0 [56] is applied to the cross section to account for higher-order contributions.

For the $V\gamma$ background, calculated cross sections are used to fix the ratio between the $W\gamma$ and $Z\gamma$ components, but the overall normalization of the combined sample is derived from data to mitigate potential uncertainties in the theoretical calculation. This is accomplished through a two-component template fit describing the $V\gamma$ and misidentified-lepton backgrounds. The templates originate from two background samples obtained using the event selection criteria for the $V\gamma$ MC sample and for the misidentified-lepton proxy sample. Distributions of the variable $\Delta\phi(\ell, \vec{p}_T^{\,\text{miss}})$ from the two background samples in the control region $40 < E_T^{\text{miss}} < 70$ GeV are employed as templates. The lower bound $E_T^{\text{miss}} = 40$ GeV is applied to reduce the contribution of $Z\gamma$ events. Expected contributions from the misidentified-photon background and rare EWK backgrounds are subtracted from the data distribution before the fit. The fit provides scale factors for the template histograms that are used directly as transfer factors for the $V\gamma$ and the misidentified-lepton proxy samples. Besides avoiding a reliance on the value of the theoretical $V\gamma$ cross section, which is observed to underestimate the measured production rate of $W\gamma$ events [57,58], this method has the benefit that it does not double count the contributions of background events with both a misidentified photon and lepton. This class of events is already accounted for in the misidentified-photon background sample, as mentioned above.

Fig. 2 shows the results of the template fit, which is performed in the $e\gamma$ and $\mu\gamma$ channels independently. The resulting scale factors for the $V\gamma$ background in the $e\gamma$ and $\mu\gamma$ channels are 1.59 ± 0.27 and 1.47 ± 0.16, respectively, which are similar to each other as expected. The uncertainties in the scale factors are estimated through toy MC studies repeating the fit after changing the contributions of the subtracted misidentified-photon and rare EWK components by their uncertainties.

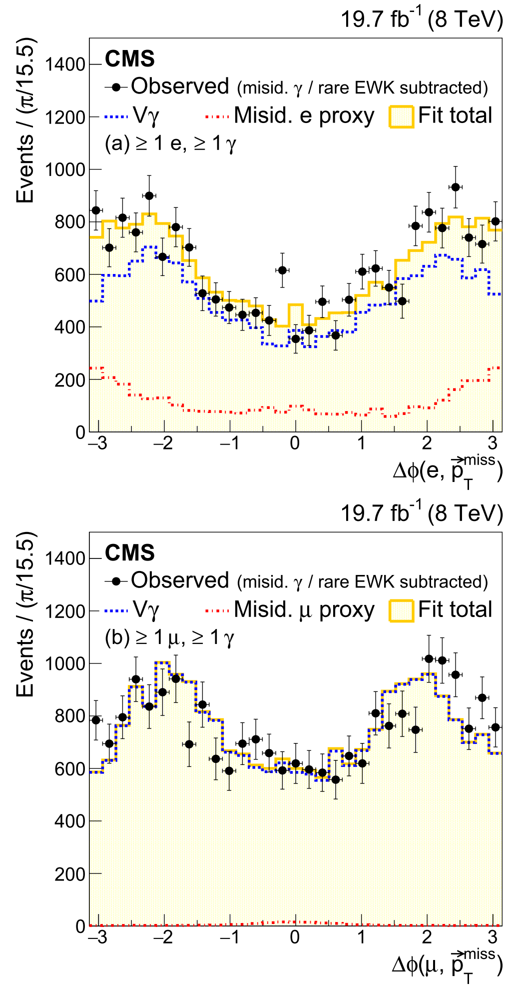

Fig. 2. Results of the $\Delta\phi(\ell, \vec{p}_T^{\,\text{miss}})$ template fit for events with $40 < E_T^{\text{miss}} < 70$ GeV, used to determine the $V\gamma$ and misidentified-lepton background for the (a) $e\gamma$ and (b) $\mu\gamma$ channels.

5. Systematic uncertainties

Table 2 summarizes the sources of systematic uncertainty for the background predictions and the signal yields. For each source, the size of the uncertainty is given (in percentage) relative to the number of events in the corresponding background or signal sample. For the background, the size of the uncertainty relative to the total number of background events is also shown. If the relative uncertainties differ significantly among background sam-

Table 2
Summary of systematic uncertainties. The third column gives the uncertainty relative to the number of events in the corresponding background or signal sample. The fourth column shows, for the background terms, the uncertainty relative to the total number of background events in the signal region.

Name	Sample	Relative uncertainty (%)	
		Sample	Total
Rare background rate	Rare EWK	50	19
$V\gamma$ scale factor	$V\gamma$	14	6
Proxy sample shape	Misidentified γ&ℓ	20–27	5
Trigger and identification efficiency	Rare EWK	8	3
JES	EWK	0–6	2
$V\gamma$ shape	$V\gamma$	5	2
Integrated luminosity	Rare EWK	2.6	1
JER	EWK	0–2	1
JES	Signal	0–22	–
JER	Signal	0–17	–
Trigger and identification efficiency	Signal	8	–
Initial-state radiation	Signal	0–5	–
Integrated luminosity	Signal	2.6	–
Renormalization scale and PDF	Signal	4–41	–

ples because of statistical fluctuations due to the limited number of events available for the evaluation of the systematic uncertainties, the range from the minimum to the maximum relative uncertainty is shown. The dominant experimental uncertainty for the background prediction is due to the normalization scale factors applied to the rare EWK and Vγ samples. For the rare EWK sample, a 50% uncertainty is assigned as a conservative approximation of the uncertainty in the NLO-to-LO cross section ratio of $t\bar{t}\gamma$ production, which is the dominant component in this sample. Also, for the rare EWK sample, we evaluate the uncertainty due to the luminosity determination [59]. Normalization uncertainties in the background estimates of events with misidentified photons or leptons are absorbed in the uncertainty of the Vγ scale factor through the uncertainty estimation in the $\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})$ template fit described above. Subdominant systematic uncertainties arise from potential mismodelling of the shapes of the Vγ and proxy samples for misidentified photons and leptons.

For simulation-based background estimates, differences with respect to the data in the jet energy scale (JES) and resolution (JER) are considered as systematic uncertainties. The uncertainty associated with the JES is evaluated by varying the scale by $\pm 1\sigma$, where σ is the half-width of the 68% confidence interval around the nominal value, and recalculating the $E_{\mathrm{T}}^{\mathrm{miss}}$, M_{T}, and H_{T} values in the Vγ and rare EWK samples, and similarly for the JER term. The shift in the expected event yield in the signal region is taken as the estimate of the systematic uncertainty.

Table 2 also lists the systematic uncertainties considered for the signal MC samples that are used for the interpretation of the result of this search. The uncertainties due to the JES and JER are evaluated using the procedure described above. In addition, for the signal samples, uncertainties in the description of initial-state radiation as well as the renormalization scale and PDF [60] are considered.

6. Results

Fig. 3 shows the observed distributions of M_{T}, $E_{\mathrm{T}}^{\mathrm{miss}}$, photon E_{T} (E_{T}^{γ}), and H_{T} in the eγ and $\mu\gamma$ channels, together with the background expectations obtained as described in Section 4. The ratio of the observed number of events to the total background expectation is displayed in the lower part of each panel. The M_{T} distribution includes all events that satisfy the event selection criteria of Table 1 except for the restrictions on M_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$. Events in the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution must additionally satisfy $M_{\mathrm{T}} > 100$ GeV, and events in the E_{T}^{γ} and H_{T} distributions $E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV and $M_{\mathrm{T}} > 100$ GeV. The uncertainty bands shown for the background estimates are the statistical and systematic terms added in quadrature. The data are seen to agree with the SM prediction within the uncertainties.

Fig. 4 shows a compilation of event yields compared to the total background expectations. To enhance the sensitivity to different SUSY scenarios, the signal region is further explored in bins of E_{T}^{γ} ([40, 80] and >80 GeV), H_{T} ([0, 100], [100, 400], and >400 GeV), and $E_{\mathrm{T}}^{\mathrm{miss}}$ (Low, Mid, and High, corresponding to [120, 200], [200, 300], and >300 GeV, respectively). The data are found to be consistent with the background prediction in all regions. Thus no significant excess of events beyond the SM expectation is observed.

7. Interpretation

The results of the search are interpreted in terms of cross section upper limits on a GMSB model and two distinct simplified models. For each parameter point of the three models, a large number of hard-scattering simulation events are generated. These events are processed with a detailed fast simulation of the CMS detector response [61]. A large number of minimum-bias interactions are superimposed on the hard-scattering process in order to reproduce the pileup profile observed in data. The event selection applied to the simulated signal events is identical to that applied to data, including the trigger requirements. The resulting event yields are weighted by correction factors to account for selection efficiency differences between data and simulation.

For each mass point of the signal models, a 95% confidence level (CL) cross section upper limit is obtained utilizing the "LHC-style" $\mathrm{CL_s}$ prescription [62–64], which calculates frequentist $\mathrm{CL_s}$ limits using the one-sided profiled likelihood as a test statistic. The SM background prediction, signal expectation, and observed number of events in each signal-region bin of the eγ and $\mu\gamma$ channels as shown in Fig. 4 are combined into one statistical interpretation, turning the analysis into a multichannel counting experiment.

7.1. Interpretation in a GMSB model

A GMSB model with wino co-NLSPs [32], which contains both electroweak and strong production as the primary SUSY production process, is examined. All SUSY particles except for the gluino and winos are considered in the limit of very large mass values such that they do not participate in the interactions. In this limit, the lightest chargino and neutralino become purely wino-like. There is no restriction on the decays, but the gluino always undergoes at least a three-body decay and the charged wino decays to a W boson and the gravitino. The neutral wino decays to a gravitino and either a photon or a Z boson, with branching fractions dictated by the weak mixing angle and the wino mass. In the generated scans, the gluino mass ($M_{\widetilde{\mathrm{g}}}$) ranges from 715 to 1415 GeV in 50 GeV steps, and the wino mass ($M_{\widetilde{\mathrm{W}}}$) from 205 GeV to [$M_{\widetilde{\mathrm{g}}} - 10$ GeV], also in 50 GeV steps.

The SUSY particle spectra and branching fractions are determined using the SuSpect 2.41 [65] and sdecay 1.3 [66] programs. pythia 6.4 is employed for the SUSY particle generation, decays, and the subsequent parton showers. The cross section for each mass point is determined to NLO accuracy in quantum chromodynamics using the prospino 2.1 [67] program. This cross section result, along with its uncertainty, is used to derive 95% CL exclusion limits on the SUSY particle masses.

Fig. 5 shows the observed 95% CL cross section upper limits with the exclusion contours overlaid. In the figure, the dashed curves are the median and ± 1 standard deviation (σ) expected exclusion contours assuming the nominal cross sections for the signal model. The solid curves represent the observed exclusion with the signal cross sections at the nominal and $\pm 1\sigma$ values. All mass points on the bottom left side of the contours are excluded. Note that the approximate one standard deviation discrepancy between the expected and observed exclusion contours toward larger values of $M_{\widetilde{\mathrm{W}}}$ is due to an upward fluctuation observed in a single bin of the signal region with $E_{\mathrm{T}}^{\gamma} > 80$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV, and an intermediate bin in H_{T} from 100 to 400 GeV.

In this inclusive GMSB model, electroweak production will always take place when the wino is light, independent of the gluino mass. Thus the exclusion curve becomes horizontal for $M_{\widetilde{\mathrm{W}}} \approx$ 360 GeV. Note that for this and for all other instances in this paper where a numerical result is quoted for a mass limit, the result is based on the theoretical prediction for the cross section minus its 1σ uncertainty. The expected distributions for signal in Fig. 3 correspond to the GMSB model for the mass point $(M_{\widetilde{\mathrm{g}}}, M_{\widetilde{\mathrm{W}}}) =$ (915, 405) GeV. This mass point has competing contributions from strong and electroweak SUSY production and exhibits a non-trivial behavior in H_{T} as can be seen in Fig. 3(g) and (h).

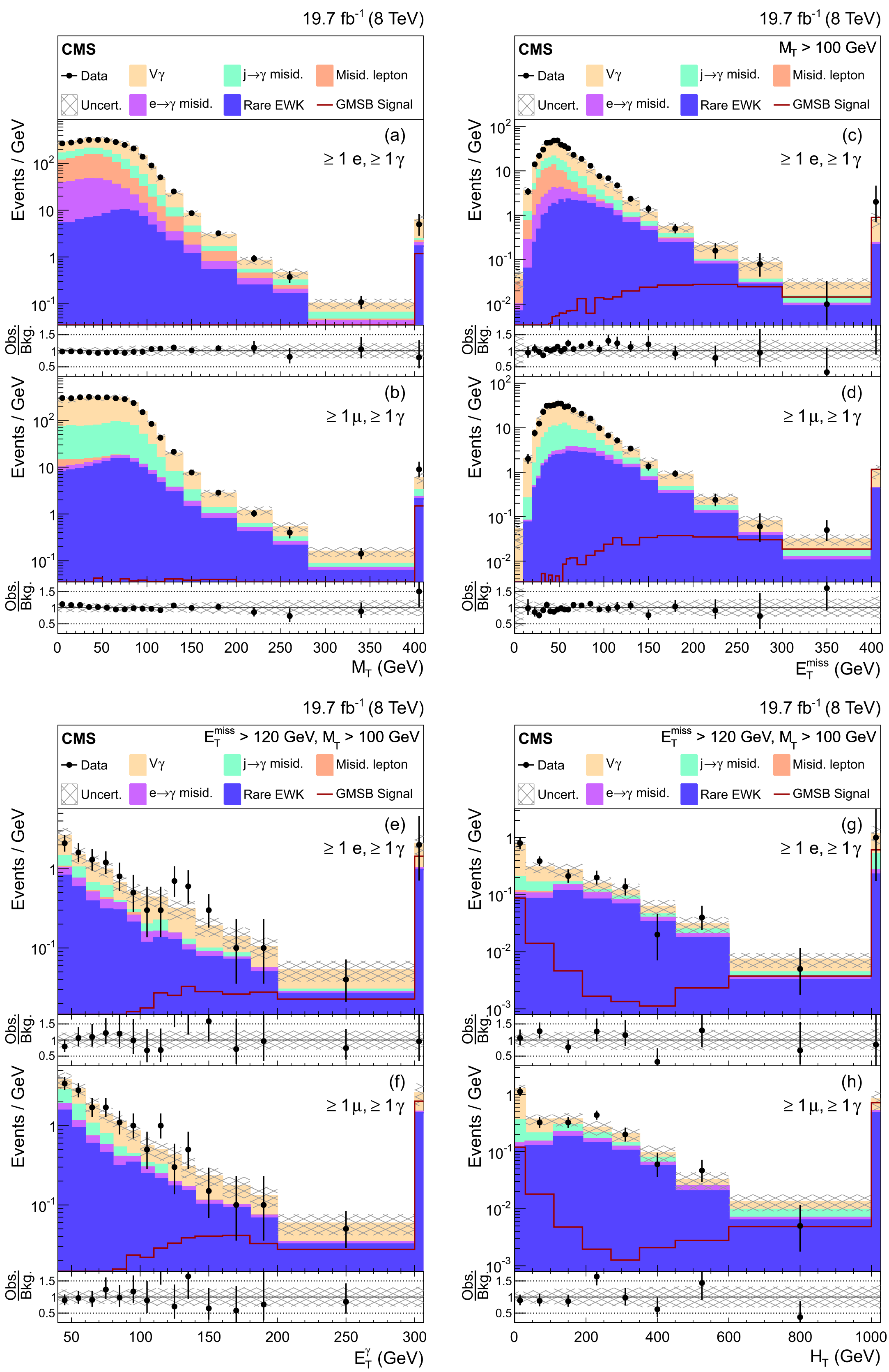

Fig. 3. Distributions of (a, b) M_T, (c, d) E_T^{miss}, (e, f) E_T^{γ}, and (g, h) H_T compared with the stacked background expectations for the (a, c, e, g) $e\gamma$ and (b, d, f, h) $\mu\gamma$ channels. See text for details of the event selections applied to these distributions. The rightmost bin of each plot shows the overflow, with contents that are not normalized by the bin width. Expected signal distributions from a GMSB model for a representative mass point $(M_{\tilde{g}}, M_{\widetilde{W}}) = (915, 405)$ GeV are overlaid. The lower part of each panel shows the ratio of the data to the predicted background. The uncertainty bands represent the statistical and systematic terms added in quadrature.

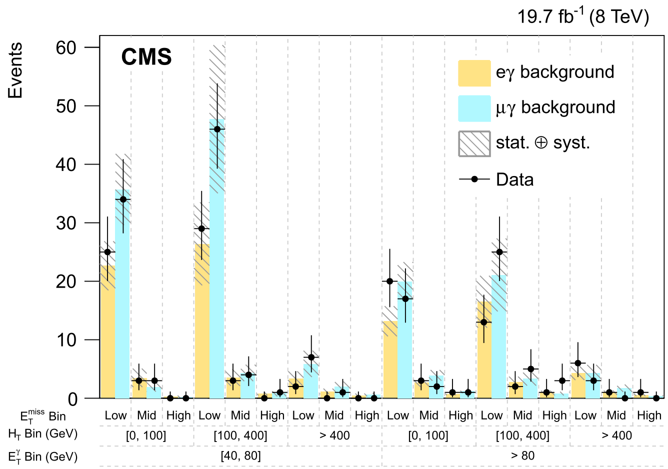

Fig. 4. Event yields in all signal region bins, compared with the combined SM background predictions. The numbers in brackets indicate the range of the bins in the signal region variables E_T^{miss}, H_T, and E_T^{γ}. For the E_T^{miss} bins, Low, Mid, and High correspond to the intervals [120, 200], [200, 300], and >300 GeV, respectively.

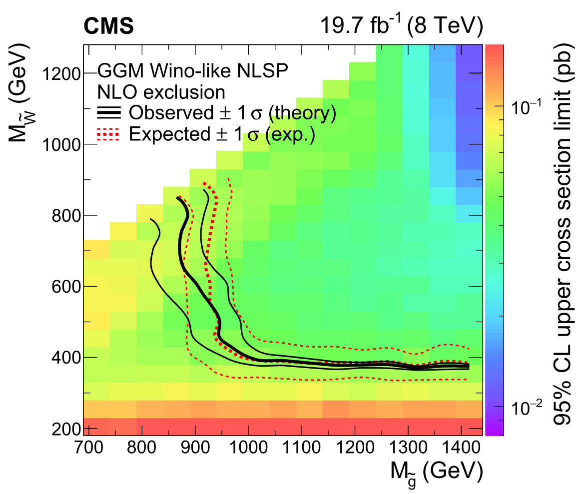

Fig. 5. Observed and expected 95% confidence level upper limits on the cross section and corresponding exclusion limits for the GMSB model.

7.2. Interpretation in simplified models

In a simplified model [68–70], a limited set of hypothetical particles and decay chains are introduced to describe a given topological signature such as the $\ell\gamma$ final state studied in this analysis. The production and decay amplitudes of these particles are parameterized in terms of the particle masses.

The two simplified models considered are denoted the TChiWg and T5Wg models. The TChiWg model is initiated by the direct production of hypothetical particles $\widetilde{\chi}^{\pm}$ and $\widetilde{\chi}^{0}$, whose decays are restricted to $W^{\pm}\widetilde{G}$ and $\gamma\widetilde{G}$, respectively. The gravitino $\widetilde{G}$ is nearly massless as in GMSB models. Thus, this model can be identified with electroweak production in the GMSB wino co-NLSP model, depicted by the diagram in Fig. 1(a), differing only in the decay branching fractions. The particles $\widetilde{\chi}^{\pm}$ and $\widetilde{\chi}^{0}$ are therefore identified with gauginos in the remainder of this paper. A mass range of $100 \le M_{\widetilde{\chi}} \le 800$ GeV is considered, where $M_{\widetilde{\chi}}$ is the degenerate mass of the gauginos. The generation of events for the T5Wg model, corresponding to the diagram in Fig. 1(b), starts with the pair production of gluinos. The two gluinos undergo three-body decays $\widetilde{g} \to q\bar{q}\widetilde{\chi}^{\pm}$ and $\widetilde{g} \to q\bar{q}\widetilde{\chi}^{0}$, followed by the decays of the $\widetilde{\chi}^{\pm}$ and $\widetilde{\chi}^{0}$ as discussed above. The T5Wg samples are generated in a mass region $700 \le M_{\widetilde{g}} \le 1400$ GeV and 25 GeV $\le M_{\widetilde{\chi}} \le [M_{\widetilde{g}} - 25$ GeV]. No other non-SM particle is involved in either model.

Events for both models are generated with the MadGraph 5 1.3 program, with up to two final-state partons in addition to the hard interaction. The events are then interfaced to pythia 6.4, which is used to describe the SUSY decay chains and parton showers. The neutralino–chargino and the gluino pair production cross sections are calculated to NLO and NLO + NLL (next-to-leading logarithm) accuracy [60], respectively, and used to derive 95% exclusion limits.

Fig. 6(a) shows the computed 95% CL cross section upper limit for the TChiWg model as a function of $M_{\widetilde{\chi}}$, together with the theoretical cross section. Assuming a 100% branching fraction for $\widetilde{\chi}^{0} \to \gamma\widetilde{G}$, the mass range $100 < M_{\widetilde{\chi}} < 540$ GeV is excluded, where the lower limit corresponds to the lowest $M_{\widetilde{\chi}}$ included in the scan. Assuming a more physically motivated branching fraction through a rescaling of the theoretical cross section by the weak mixing angle, the exclusion range is $100 < M_{\widetilde{\chi}} < 340$ GeV. The latter result is similar to the limit $M_{\widetilde{W}} < 360$ GeV obtained from the GMSB model with a wino-like NLSP.

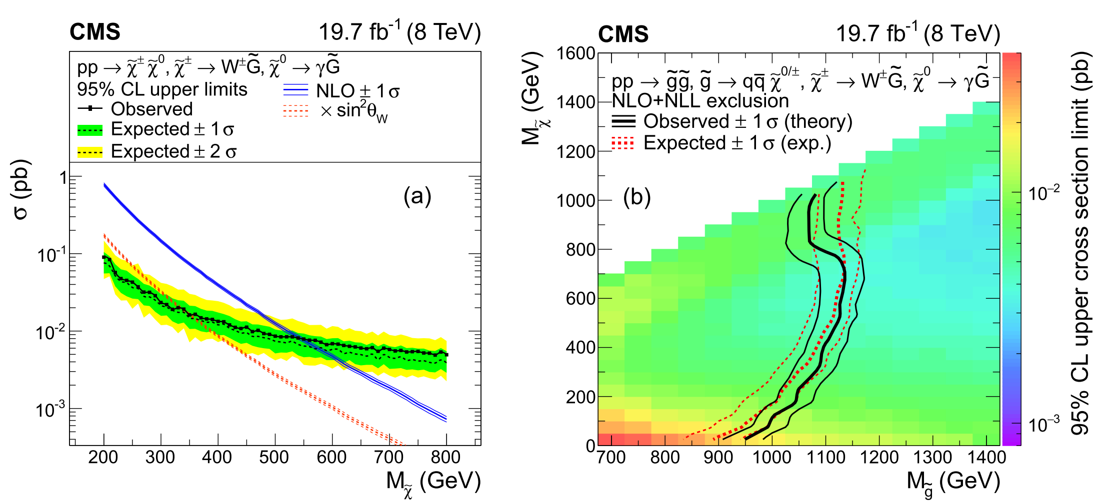

Fig. 6. Observed and expected 95% confidence level upper limits on the (a) TChiWg and (b) T5Wg simplified models. For the T5Wg model, the 95% confidence level exclusion contour is also shown.

The production cross section of the T5Wg model is determined solely by $M_{\tilde{g}}$. Nevertheless, the $M_{\tilde{g}} - M_{\tilde{\chi}}$ mass difference affects the H_T and E_T^{miss} spectra, resulting in nontrivial exclusion-limit contours in the $M_{\tilde{\chi}}$–$M_{\tilde{g}}$ plane. The 95% CL cross section upper limits and exclusion contours for the T5Wg model are shown in Fig. 6(b). For $M_{\tilde{\chi}} > 200$ GeV, pair production of gluinos is excluded for gluino masses below 1 TeV. For $500 < M_{\tilde{\chi}} < 700$ GeV, gluinos below approximately 1.1 TeV are excluded.

8. Summary

This paper presents a search for the anomalous production of events with a photon, an electron or muon, and large missing transverse momentum produced in proton–proton collisions at $\sqrt{s} = 8$ TeV. The data are examined in bins of the photon transverse energy, the magnitude of the missing transverse momentum, and H_T, 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. No excess of events above the standard model expectation is observed. The results of the search are interpreted as 95% confidence level upper limits on the production of new-physics events in the context of a gauge-mediated supersymmetry breaking (GMSB) model. The GMSB model is excluded for wino masses below 360 GeV. Results are also interpreted in the context of two simplified models inspired by GMSB, denoted TChiWg and T5Wg. The TChiWg model is excluded for gaugino masses below 540 GeV or, if the cross sections are scaled by the weak mixing angle, below 340 GeV. The T5Wg model with gaugino mass above 200 GeV is excluded for gluino masses below 1 TeV.

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