Search for supersymmetry in events with at least one photon, missing transverse momentum, and large transverse event activity in proton-proton collisions at √s = 13 TeV

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ABSTRACT: A search for physics beyond the standard model in final states with at least one photon, large transverse momentum imbalance, and large total transverse event activity is presented. Such topologies can be produced in gauge-mediated supersymmetry models in which pair-produced gluinos or squarks decay to photons and gravitinos via short-lived neutralinos. The data sample corresponds to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded by the CMS experiment at the LHC in 2016. No significant excess of events above the expected standard model background is observed. The data are interpreted in simplified models of gluino and squark pair production, in which gluinos or squarks decay via neutralinos to photons. Gluino masses of up to 1.50–2.00 TeV and squark masses up to 1.30-1.65 TeV are excluded at 95% confidence level, depending on the neutralino mass and branching fraction.

Contents

1   Introduction

The standard model (SM) of particle physics describes elementary particles and their inter-actions successfully. Nevertheless, fine tuning of fundamental physics parameters is needed to cancel large quantum corrections to the mass term in the Higgs potential [1]. This and other problems of the SM can be addressed by supersymmetry (SUSY) models [2–8], in which a SUSY partner particle is predicted for each SM particle. Gauge-mediated SUSY breaking (GMSB) models [9–15] allow for a natural suppression of flavour violations in the SUSY sector and can give rise to final states with photons and jets [16].

The conservation of R parity [17, 18] implies that SUSY particles are produced in pairs and the lightest SUSY particle (LSP) is stable. If the LSP is neutral and only weakly interacting, it can escape detection, leading to an imbalance of the total observed transverse momentum. In this analysis, R-parity conservation is assumed and the LSP is considered to be a nearly massless gravitino $\widetilde{\mathrm{G}}$. The next-to-lightest-supersymmetric particle is assumed to be a gaugino $\widetilde{\chi}_1^{0/\pm}$, which is a mixture of the superpartners of the electroweak gauge bosons and the Higgs bosons. It decays promptly to a SM boson and a gravitino. Both bino- and wino-like neutralinos $\widetilde{\chi}_1^0$ can decay to a photon and a gravitino;

wino-like charginos $\widetilde{\chi}_1^\pm$ decay typically to a W boson and a gravitino [19]. In this analysis, we assume gauginos are produced in decay chains of primary squarks or gluinos, so the events also contain jets and thus large transverse event activity.

In this paper, a search for physics beyond the standard model (BSM) in final states with at least one photon, large missing transverse momentum, and large total transverse event activity is reported. The data used in this analysis were collected with the CMS detector at the CERN LHC in 2016, and correspond to an integrated luminosity of $35.9\,\text{fb}^{-1}$ of proton-proton collisions at a centre-of-mass energy $\sqrt{s} = 13\,\text{TeV}$. Similar searches yielding no evidence for BSM physics have been performed at lower centre-of-mass energies by CMS [20] with similar and alternative selections [21, 22] and by the ATLAS Collaboration [23, 24]. The higher $\sqrt{s}$ of this dataset allows us to extend the sensitivity to more massive SUSY particles.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. The electromagnetic calorimeter consists of 75 848 lead tungstate crystals, which provide coverage in pseudorapidity $|\eta| < 1.48$ in a barrel region (EB) and $1.48 < |\eta| < 3.0$ in two endcap regions (EE). Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The jet energy resolution amounts typically to 15, 8, and 4% at 10, 100, and 1000 GeV, respectively, when combining information from the entire detector [25]. 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. [26].

3 Event reconstruction

The particle-flow (PF) algorithm reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector [27]. The energy of photons is directly obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as measured by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The momentum of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

Loose quality criteria with a selection efficiency close to 90% are applied to photons, based on the shower shape width in η, the hadronic energy fraction, and the isolation from other particles. To distinguish photons from electrons, photon candidates are not allowed to be associated with pixel seeds. Pixel seeds consist of two or three hits in the pixel detector matching to the hypothetical trajectory from the proton-proton interaction point to the energy cluster in the ECAL, taking into account positively and negatively charged electron hypotheses.

Jets are reconstructed from all PF candidates, clustered by the anti-k_T algorithm [28, 29] with a distance parameter of 0.4. To reduce the effect of additional proton-proton collisions from the same or adjacent beam crossing (pileup) other than the primary hard scattering process, charged hadrons from vertices not being the primary vertex are excluded. An offset correction is applied to jet energies to take the contribution from pileup interactions into account [30]. The jet momentum is determined as the vector sum of momenta of all PF candidates clustered into the jet. To correct for this, jet energy corrections are applied, derived from simulation and data using multijet, γ+jet, and leptonic Z+jets events.

The missing transverse momentum $\vec{p}_\mathrm{T}^{\,\mathrm{miss}}$ is defined as the negative vector sum of the transverse momenta p_T of all PF candidates in the event, and its magnitude is denoted by $p_\mathrm{T}^{\mathrm{miss}}$. In order to improve the momentum resolution, the jet energy corrections are propagated to $p_\mathrm{T}^{\mathrm{miss}}$. The total transverse momentum H_T^γ is the scalar sum of all jet momenta and the p_T of the leading photon. Only jets with $p_\mathrm{T} > 30\,\mathrm{GeV}$ and $|\eta| < 3$ are considered. In addition, if a jet is found within $\Delta R < 0.4$ from the leading photon, it is assumed that the jet p_T originates from the photon and the jet p_T is not included in the calculation of H_T^γ.

4 Signal models and event simulation

Monte Carlo (MC) generated events are used to study the SM backgrounds, develop and validate the background estimation techniques, and model signal scenarios. To generate γ+jet, multijet, Z, W, $\mathrm{t\bar{t}}$, γW, γZ, gluino pair, and squark pair events, the MAD-GRAPH5_aMC@NLO 2.2.2 [31] generator is used at leading-order (LO) accuracy, while the next-to-leading-order (NLO) accuracy is used for $\gamma\mathrm{t\bar{t}}$ events. The NNPDF3.0 [32] parton distribution functions (PDFs) are used in conjunction with PYTHIA 8.205 or 8.212 [33] with the CUETP8M1 generator tune [34] for simulating parton showering and hadronization. The LO cross sections are used for γ+jet events and events comprising solely jets produced through the strong interaction (multijet events). For all other background processes, NLO cross sections are used. The contribution of pileup events is added to the hard scattering process such that the probability of pileup events to occur is the same as that in the data, with on average approximately 23 interactions per bunch crossing.

Gluino and squark pair production cross sections are determined using NLO plus next-to-leading logarithm (NLL) calculations [35]. Four simplified models [36, 37] are considered. The T6gg model, where a first- or second-generation squark-antisquark pair is produced, followed by the (anti)squark decay into an (anti)quark and a neutralino. The neutralino

decays promptly to a photon and a gravitino, resulting in a final state with two jets, two photons, and missing transverse momentum from the two gravitinos escaping detection. The T6Wg model is similar, except the squarks decay with a probability of 50% to a quark and a neutralino, and a 50% probability to decay to a quark and a chargino. The chargino further decays to a W boson and a gravitino, resulting in signatures with at least two jets, two gravitinos, and two bosons. These two bosons can either be two photons, one photon and one W boson, or two W bosons. The T5gg and T5Wg models consist of gluino pair production. For these models, the squark masses are assumed to be much larger than the gluino mass, leading to a three-body decay of the gluino to two jets and a gaugino. For the T5gg model, the gauginos are neutralinos, while for the T5Wg model, the gluino can also decay to jets and a chargino. Branching fractions are assumed to be 100%, except the squark to neutralino branching fraction in the T6Wg model and the gluino to neutralino decay in the T5Wg model, which are 50% each. Feynman-like diagrams of these processes are shown in figure 1.

The CMS detector response is simulated using GEANT4 [38] for SM processes, while for signal events we use the CMS fast simulation [39, 40]. In the latter case, scale factors are applied to account for any differences with respect to the full simulation. Event reconstruction is performed in the same manner as for collision data.

5 Event selection and background prediction strategy

The high-level trigger system [41] selects events containing at least one photon with $p_T > 90\,\text{GeV}$ and $|\eta| < 2.5$, and $H_T^{\gamma,\text{HLT}} > 600\,\text{GeV}$, where $H_T^{\gamma,\text{HLT}}$ is defined as the scalar sum of the p_T for all jets passing the kinematic selection used to select jets for the offline H_T^{γ} calculation. The trigger does not distinguish between jets and photons. As a result, photons in the event, including the leading photon, are reconstructed as jets and thus included in the calculation of $H_T^{\gamma,\text{HLT}}$. The efficiency for both the photon and the $H_T^{\gamma,\text{HLT}}$ criterion are measured independently, and their product is estimated to be equal to $(96 \pm 4)\%$, where the uncertainty covers variations of the trigger efficiency versus time and versus photon identification variables.

Events are selected if they contain at least one photon with $p_T > 100\,\text{GeV}$ in the EB with $|\eta| < 1.4442$. To reliably predict the background, the photon is not allowed to be parallel or anti-parallel to $\vec{p}_T^{\text{miss}}$ within an azimuthal angle of $|\Delta\phi(\pm\vec{p}_T^{\text{miss}}, \vec{p}_T^{\gamma})| < 0.3$. Three high-$p_T^{\text{miss}}$ ranges (350–450, 450–600, and $\geq$600 GeV) and two H_T^{γ} selections (700–2000 and $\geq$2000 GeV) give rise to the definition of six search regions. Additional selection criteria are applied to remove events with spurious signals from instrumental noise [42]. Background contributions of multijet, γ+jet, γZ, γW, γt$\bar{\text{t}}$, W+jets, and t$\bar{\text{t}}$ events are estimated as described below.

5.1 Background contribution of events with nongenuine p_T^{miss}

A small fraction of γ+jet events can populate the signal region because of artificial p_T^{miss} generated by momentum mismeasurement in the detector. Jets have the largest transverse momentum uncertainties, and even though the probability of a large mismeasurement is
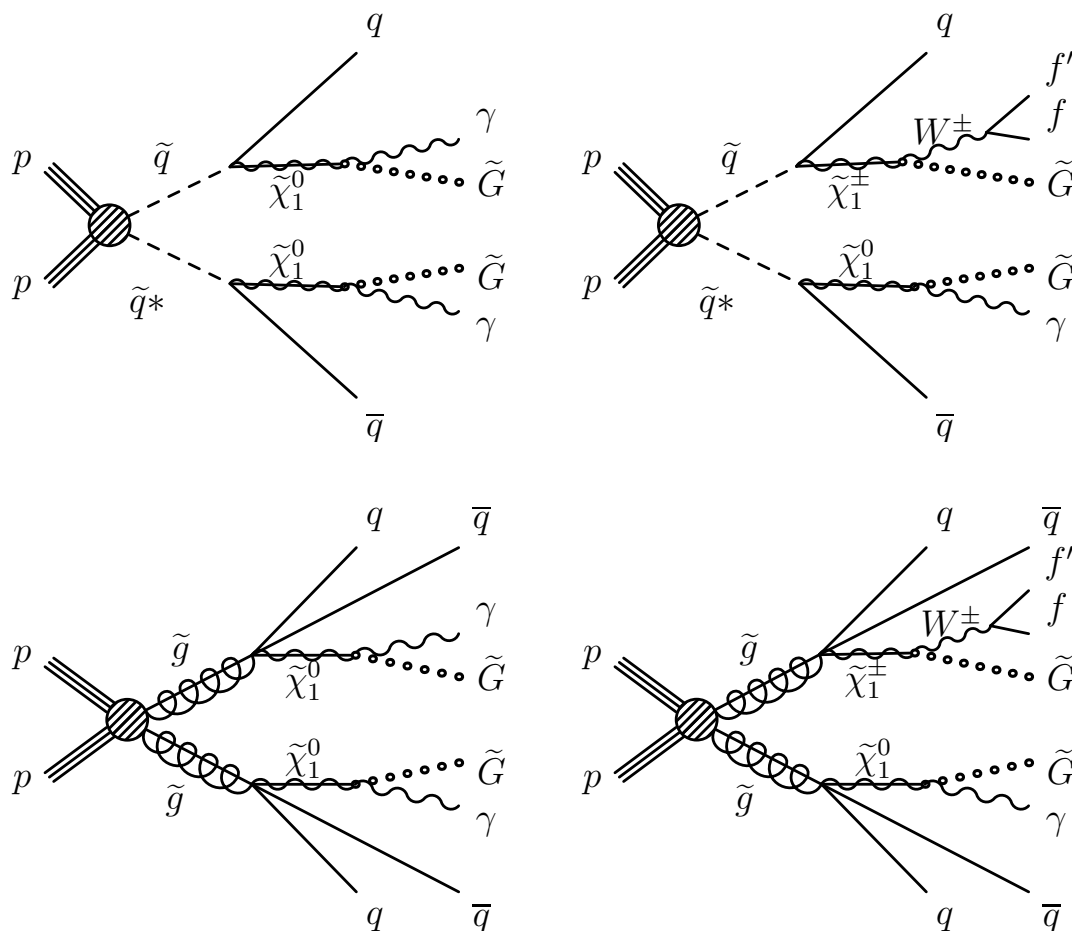
Figure 1. Feynman-like diagrams for the T6gg (top left) and the T5gg (bottom left) processes, and representative Feynman-like diagrams for the T6Wg (top right) and T5Wg (bottom right) processes. The T6Wg and T5Wg models include also diagrams with either two photons or two W bosons in the final state.

low, the large cross section of the γ+jet process leads to a nonnegligible contribution to the search region. Multijet events have an even higher cross section, and contribute to the signal selection if one of the jets is misidentified as a photon. As in γ+jet events, nonzero $p_{\mathrm{T}}^{\mathrm{miss}}$ in multijet events is caused by the finite jet momentum resolution.

Estimating these backgrounds from simulation would result in a large uncertainty for two reasons: the large cross section requires a large number of simulated events to obtain a small statistical uncertainty; in addition, small differences between the measured and simulated jet response can lead to large differences at high $p_{\mathrm{T}}^{\mathrm{miss}}$ values between measured and simulated events. A background estimation method based on control samples in data was therefore developed to achieve smaller uncertainties without relying on the simulated jet energy response. We performed this method independently for the low- and high-H_{T}^{γ} selection. The shapes of the $p_{\mathrm{T}}^{\mathrm{miss}}$ distributions in γ+jet and multijet events are found

to be similar, and their normalizations can be extracted from low-p_T^{miss} events, where no significant signal contribution should be present. This is verified using simulated event samples. We use the shape of the p_T^{miss} distribution of a multijet event sample as a prediction for events with nongenuine p_T^{miss}.

For the background estimate, the photon control region (CR) is defined by requiring the search selection, but requiring $p_T^{miss} < 100\,\mathrm{GeV}$. A jet CR is defined by selecting events with the H_T^γ criteria only, based on a trigger with only the $H_T^{\gamma,\mathrm{HLT}}$ selection. For low p_T^{miss} values, the jet CR is dominated by multijet events, but for large p_T^{miss} values, W$(\ell\nu)$+jets, Z$(\nu\nu)$+jets, and t$\bar{t}$ events can also contribute. These are subtracted using simulation. The shape of the p_T^{miss} distribution of γ+jet and multijet events in the photon CR is very similar to that in the jet CR.

To correct for residual differences between the two CRs, a correction factor is applied to the p_T^{miss} values of the jet CR. Studies showed that a constant multiplicative factor leads to the best agreement between the p_T^{miss} shapes in the two CRs. The factor is chosen such that it minimizes the χ^2 between the shapes of the p_T^{miss} distributions in the two CRs for $p_T^{miss} < 100\,\mathrm{GeV}$, and is about 0.90 (0.84) for the low- (high-) H_T^γ selection. The uncertainty in this factor is calculated as the quadratic sum of the deviation of the factor from unity and the statistical uncertainty in the χ^2 method. The p_T^{miss} distribution of the jet CR is then scaled to the p_T^{miss} distribution of the photon CR in $p_T^{miss} < 100\,\mathrm{GeV}$ to provide an estimate for the background contribution of nongenuine p_T^{miss} events in the signal selection. Several uncertainties are considered. The uncertainty associated to the shift factor is obtained by multiplying the jet CR by the factor modulated by its uncertainty. The uncertainty in the normalization is derived from the statistical uncertainty of the photon CR and the jet CR in the $p_T^{miss} < 100\,\mathrm{GeV}$ range. The statistical uncertainty assigned to the prediction due to the number of events in the jet CR at high p_T^{miss} is about as large as the systematic uncertainty.

The method is tested on simulated γ+jet and multijet events. The comparison of direct simulation results and the prediction from simulation, using this method, is shown in figure 2. In this figure and the following ones, the rightmost bin includes all events with $p_T^{miss} > 600\,\mathrm{GeV}$. The agreement between the two distributions suggests that the method is performing as expected. Further validation is discussed in section 5.4.

5.2 Background contribution from events with electrons

Electrons and photons have similar calorimetric response. If no pixel seeds are reconstructed for an electron, it can be misidentified as a photon. In W+jets or t$\bar{t}$ processes, electrons are produced in association with neutrinos, so these events tend to also have large p_T^{miss} and enter the search regions. To estimate the contribution of these processes, a CR with electrons is defined and scaled by the electron-to-photon (e $\rightarrow \gamma$) misreconstruction probability.

The electron CR is defined similar to the search selection, except that the photon candidate is required to have pixel seeds, thereby selecting events with electrons. For high p_T^{miss}, this CR is dominated by W and t$\bar{t}$ events.

The electron-to-photon misreconstruction probability is estimated with the tag-and-probe method using an event sample dominated by Z $\rightarrow$ ee events, and is 2.7% for data
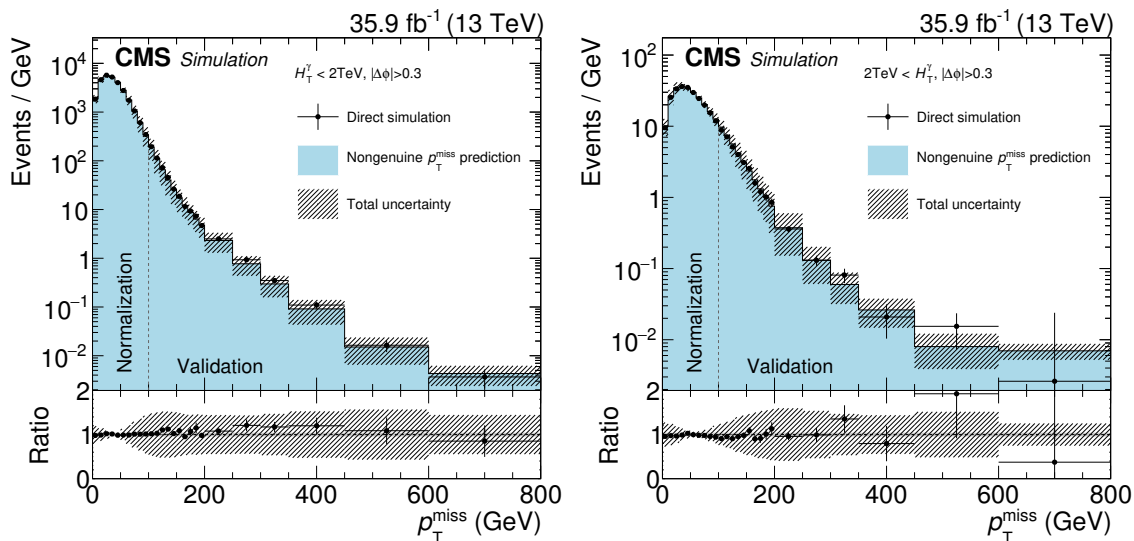
Figure 2. Validation of the nongenuine $p_\mathrm{T}^\mathrm{miss}$ background estimation method with γ+jet and multijet simulations. The direct simulation results are shown as black dots, while the prediction using the jet CR is shown as light blue histogram. The total uncertainty of the prediction is presented as shaded area. The bottom panel shows the ratio of the direct simulation to the prediction. The low- (high-) H_T^γ selection is shown on the left (right). The number of events corresponds to the expectation in data for an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$. The rightmost bin includes all events with $p_\mathrm{T}^\mathrm{miss} > 600\,\mathrm{GeV}$.

and 1.5% for simulation. For the prediction in data, the probability measured with data is used, while for the validation in simulation, the probability measured with simulated events is used. To account for differences between the misreconstruction rate determined from the Z boson resonance and the W boson dominated electron CR with high $p_\mathrm{T}^\mathrm{miss}$ and high H_T^γ, a systematic uncertainty of 30% is applied to the misreconstruction rate. The size of the uncertainty is based on studies of the variation of the misreconstruction probability versus various kinematic and geometric quantities in data and simulation.

The background estimation method is tested on simulated W+jets and $t\bar{t}$ events. The direct simulation of electrons reconstructed as photons is compared to the electron CR, scaled by the electron-to-photon misreconstruction probability as shown in figure 3, but including also low $p_\mathrm{T}^\mathrm{miss}$ events. The agreement in the search regions suggests that the method is performing as expected.

5.3 Backgrounds estimated from simulation

Also contributing to the search region are the processes $\gamma\mathrm{W}(\ell\nu)$, $\gamma\mathrm{Z}(\nu\nu)$, and $\gamma t\bar{t}$, which are estimated using simulation. Simulated events with electrons reconstructed as photons passing the event selection are omitted since they are estimated using data. The photon in the event can be produced in the hard scattering or in the shower, either as initial- (ISR) or final-state radiation, or as a jet misreconstructed as a photon. Events are simulated with and without a photon in the hard scattering process, and the overlap between the samples is removed. The reconstruction and identification efficiencies for photons are measured in
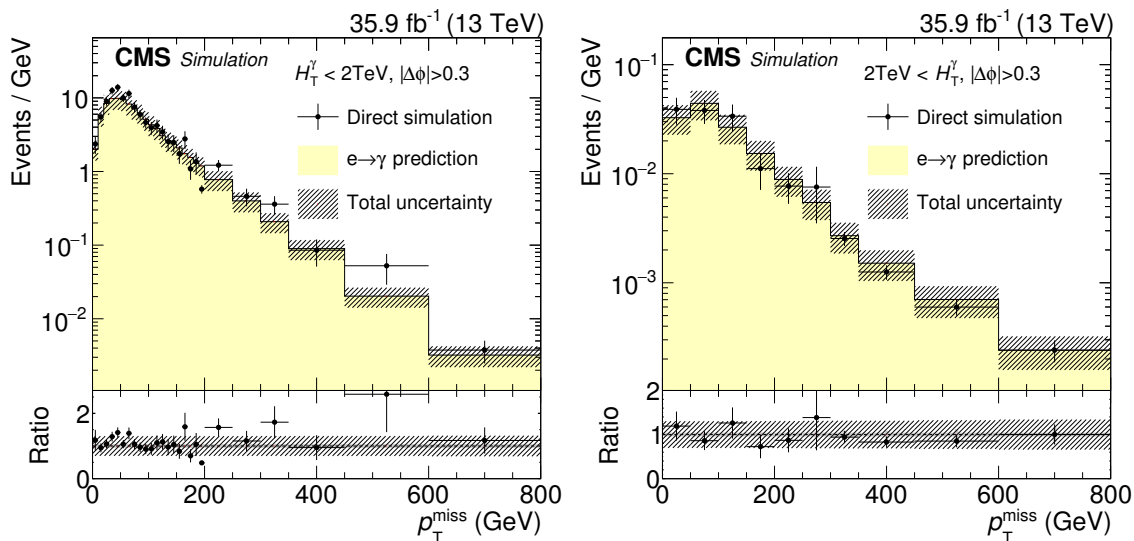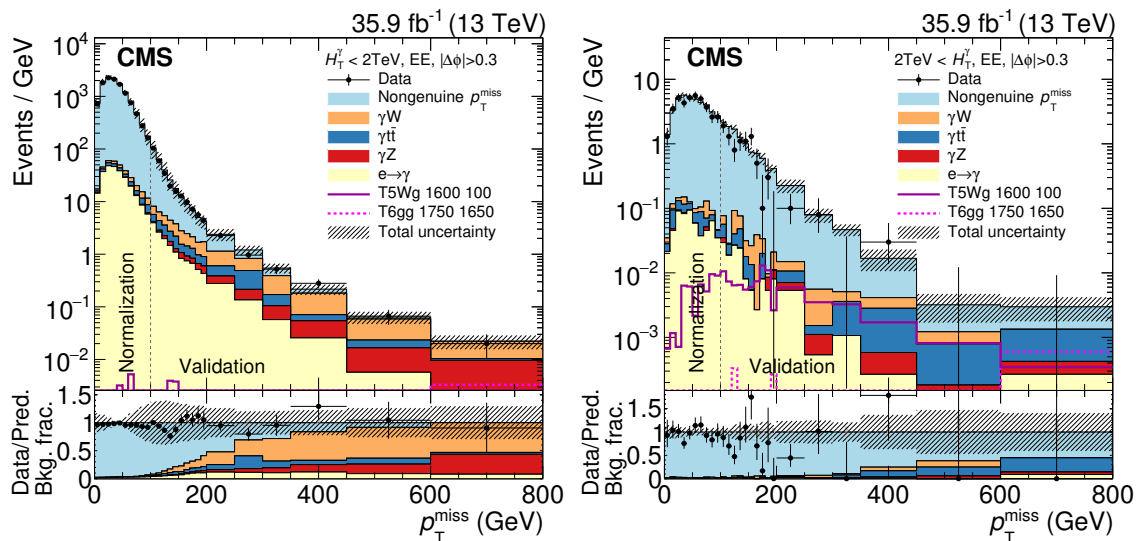
Figure 3. Validation of the background estimation method for electrons misreconstructed as photons using W+jets and $t\bar{t}$ simulation. The low- (high-) H_T^γ selection is shown on the left (right). The number of events corresponds to the expectation in data for an integrated luminosity of 35.9 fb^{-1}. The rightmost bin includes all events with $p_T^{\text{miss}} > 600$ GeV.

$Z \to ee$ and $Z \to \mu\mu\gamma$ data and simulation. The ratio of these efficiencies is consistent with unity and has an uncertainty of about 3%. Simulated events are weighted by the ratio of the efficiencies, and the uncertainty is propagated to the event yield. The NLO cross sections are used, and several uncertainties are considered, with their relative uncertainties given here in parentheses: factorization and renormalization scales (16–27%), PDFs (5–10%) [43], contribution of pileup events (0.2–6%), trigger efficiency (4%), jet resolution and energy scales (2–20%), integrated luminosity (2.5%) [44], and statistical uncertainty of the simulated samples (4–47%). For the study of the renormalization and factorization scale uncertainties, variations up and down by a factor of two with respect to the nominal values of the scales are considered. The maximum difference in the yields with respect to the nominal case is used as the uncertainty. The pileup uncertainty corresponds to the variation of the number of predicted events if the total inelastic proton-proton cross section is shifted by $\pm 5\%$.

5.4 Validation of the background estimation methods

In addition to the validation of the background estimation methods with simulated events, the methods are also validated using data from two mutually exclusive event selections. The first validation region is defined with noncentral photons. Instead of the photon being reconstructed in the EB, the leading photon must be reconstructed in the range $1.6 < |\eta| <$ 2.5. This is not the full range of the EE, but in this range the background contribution from electrons reconstructed as photons is similar to the one in the EB search region. High-mass gluinos and squarks tend to decay more centrally, leaving the EE validation region essentially free of potential signal events. The same methods as for the EB search regions
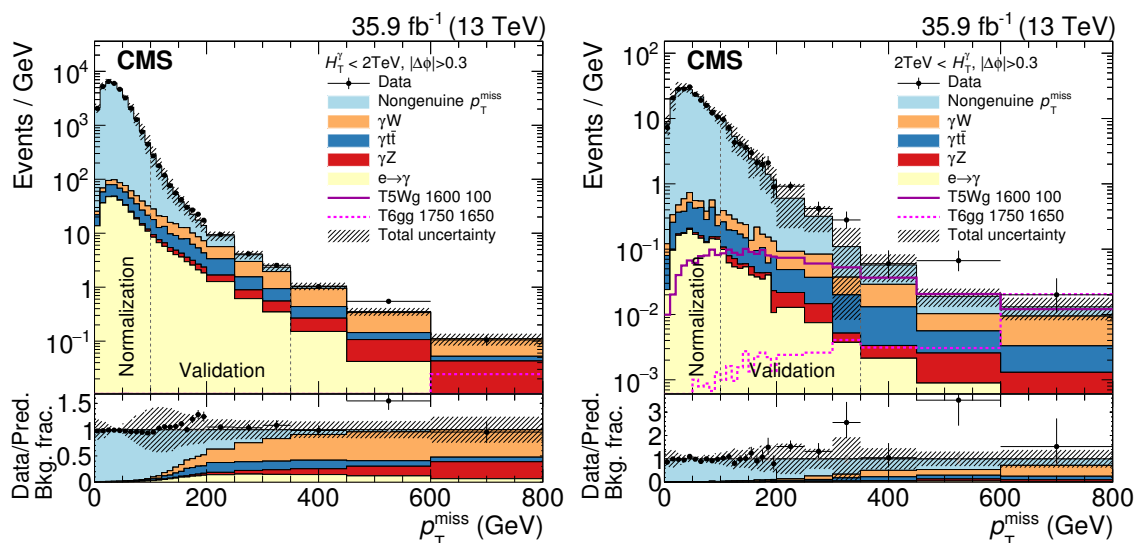
Figure 4. Validation of the background estimation methods with photons reconstructed in the EE. The expectation for the T5Wg signal scenario with a gluino mass of 1600 GeV and a gaugino mass of 100 GeV and the T6gg signal scenario with a squark mass of 1750 GeV and a neutralino mass of 1650 GeV are shown. The low- (high-) H_T^γ selection is shown on the left (right). Below the p_T^{miss} distributions, the data divided by the background prediction are shown as black dots, and the relative background components are shown as coloured areas. The rightmost bin includes all events with $p_T^{miss} > 600$ GeV.

are applied, and the resulting distributions are shown in figure 4. The p_T^{miss} distributions of two signal models are displayed as well. In the low-H_T^γ region and for large p_T^{miss} of the high-H_T^γ region, the observed number of events agrees with the prediction. The second validation region is similar to the search regions with photons reconstructed in the EB, with $100 < p_T^{miss} < 350$ GeV, which is orthogonal to both the region used to normalize the multijet background ($p_T^{miss} < 100$ GeV) as well as the signal regions ($p_T^{miss} > 350$ GeV), and is shown in figure 5. Good agreement is observed in this validation region as well.

6   Results

The predicted number of SM background events, the expected signal yield for two signal scenarios and the number of observed events in data are shown in figure 5 and table 1. The uncertainties (including the uncertainties for the signal models) are presented in table 2. The low-H_T^γ search regions are dominated by γW events and are sensitive to signal models with low squark or gluino masses. The high-H_T^γ search regions are dominated by background with nongenuine p_T^{miss} and have larger sensitivity to models with high gluino or squark masses and low gaugino masses. Overall, the number of observed events is in agreement with the prediction. The second search bin in both the low- and high-H_T^γ regions shows an excess with local significance of 1.9 and 2.7 standard deviations (σ), respectively. In the highest p_T^{miss} bins, which are more sensitive for most signal scenarios, the number of observed events is compatible with the background expectation.

Figure 5. Observed data compared to the background prediction. The expectation for the T5Wg signal scenario with a gluino mass of 1600 GeV and a gaugino mass of 100 GeV and the T6gg signal scenario with a squark mass of 1750 GeV and a neutralino mass of 1650 GeV are shown. The low- (high-) H_T^γ selection is shown on the left (right). Below the p_T^{miss} distributions, the data divided by the background prediction are shown as black dots, and the relative background components are shown as coloured areas. The last three bins in each plot correspond to the search regions. The rightmost bin includes all events with $p_T^{miss} > 600$ GeV.

H_T^γ (GeV)	<2000			>2000		
p_T^{miss} (GeV)	(350, 450)	(450, 600)	>600	(350, 450)	(450, 600)	>600
Nongenuine p_T^{miss}	$9.6 ^{+\ 11.1}_{-\ 9.6}$	$2.2 ^{+\ 5.5}_{-\ 2.2}$	< 0.1	2.83 ± 2.51	1.31 ± 0.74	$0.73 ^{+\ 0.86}_{-\ 0.73}$
γW	$51.3 \pm\ 9.7$	29.1 ± 5.5	11.6 ± 2.5	1.58 ± 0.58	0.70 ± 0.37	1.23 ± 0.43
$\gamma t\bar{t}$	$17.1 \pm\ 5.4$	5.6 ± 2.6	1.9 ± 0.4	0.97 ± 0.38	0.45 ± 0.29	0.40 ± 0.22
γZ	$11.5 \pm\ 2.4$	9.7 ± 1.8	7.1 ± 1.4	0.12 ± 0.07	0.25 ± 0.11	0.21 ± 0.10
e $\to \gamma$	$15.1 \pm\ 4.6$	6.3 ± 1.9	1.4 ± 0.5	0.21 ± 0.10	0.13 ± 0.07	0.05 ± 0.04
Total bkg.	104.6 ± 16.5	53.0 ± 8.6	22.0 ± 3.0	5.72 ± 2.60	2.84 ± 0.89	2.62 ± 0.99
Data	103	82	21	6	10	4
T5Wg 1600 100	$0.4 \pm\ 0.1$	0.8 ± 0.1	0.7 ± 0.1	3.66 ± 0.40	3.09 ± 0.40	2.41 ± 0.32
T6gg 1750 1650	$0.5 \pm\ 0.1$	0.8 ± 0.1	4.9 ± 0.4	0.31 ± 0.04	0.46 ± 0.07	4.12 ± 0.32

Table 1. Observed data compared to the background prediction and the expected signal yields for two signal scenarios. The expectations are given for the T5Wg signal scenario with a gluino mass of 1600 GeV and a gaugino mass of 100 GeV and the T6gg signal scenario with a squark mass of 1750 GeV and a neutralino mass of 1650 GeV. The quadratic sum of statistical and systematical uncertainties is given. Only experimental uncertainties for the signal model are stated.

| | Relative uncertainty (%) | |
Source	background	signal
Nongenuine p_T^{miss}	14–250	
e → γ	30	
Integrated luminosity	2.5	2.5
Photon scale factors	2	2
Trigger	4	4
PDFs	5–10	
Renormalization/factorization scales	16–27	0–1
Jet energy scale and resolution	2–20	1–6
Pileup	0.2–6	0.2–10
ISR		0–10
Fast simulation p_T^{miss} modelling		0.5–6

Table 2. Systematic uncertainties for background determined from control samples in data (first two rows) and simulation (all other rows). If two values are given, the first one is for simulated SM backgrounds, while the latter is for simulated signal. The PDF and scale uncertainties for the signal simulation affect the shape only, as the uncertainty in the rate is already considered in the overall cross section uncertainty [35].

7 Interpretation

The systematic uncertainties of the nongenuine p_T^{miss} background are fully correlated within the high- and low-H_T^γ selections, and are described in section 5.1. The systematic uncertainty in the electron misidentification background is fully correlated for all search regions, as are most uncertainties in the simulated backgrounds described in section 5.3.

To improve on the signal simulation of the multiplicity of additional jets from ISR, simulated signal events are reweighted based on the number of ISR jets (N_J^{ISR}) so as to make the jet multiplicity in simulated $t\bar{t}$ samples agree with that in data. The reweighting factors vary between 0.92 and 0.51 for N_J^{ISR} between 1 and 6. We take one half of the deviation from unity as the systematic uncertainty in these reweighting factors, correlated between all search regions. The renormalization and factorization scales, and PDF uncertainties in the cross sections for signal simulation are taken from ref. [35]. To estimate the influence of pileup in signal events, the selection is done with a high and a low number of additional interactions. The difference in selection efficiency is taken as a systematic uncertainty. Since all physics objects are included in the computation of p_T^{miss}, it can be difficult to describe accurately within the CMS fast simulation. The p_T^{miss} of the models considered, however, is dominated by the missing momentum carried away by the gravitons and not by the modelling of resolution effects. An additional systematic uncertainty of between 0.5 and 6% is assigned by calculating the mean difference between the reconstructed and generated p_T^{miss}. A summary of the uncertainties can be found in table 2.

The results are interpreted in terms of the simplified models introduced in section 4. The 95% confidence level (CL) upper limits on the SUSY cross section are calculated with
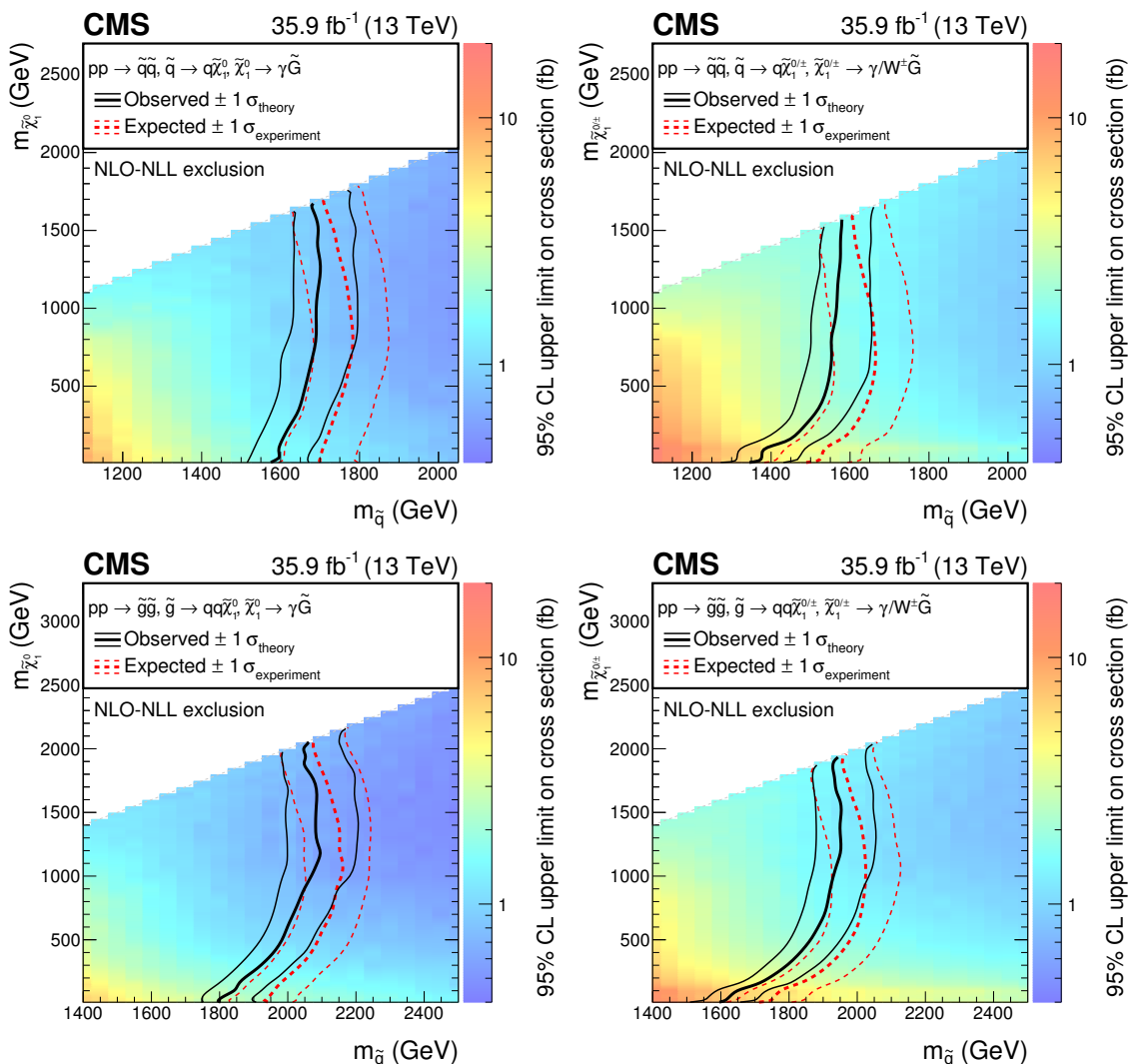
the CL_s criterion [45, 46] using the LHC-style profile likelihood ratio as test statistic [47] evaluated in the asymptotic approximation [48]. Log-normal nuisance parameters are used to describe the systematic uncertainties. The observed upper limits on cross sections, exclusion contours, and expected exclusion contours are shown in figure 6. More stringent limits can be set on models with two photons, since the probability that at least one photon is reconstructed is higher. In this case, for high gaugino masses, squarks up to 1650 GeV and gluinos up to 2000 GeV can be excluded, while for the T6Wg and T5Wg scenarios, squarks up to 1550 GeV and gluinos up to 1900 GeV can be excluded for high gaugino masses. The acceptance drops for low neutralino masses, since more energy is transferred to jets, leaving less energy available for the photon and the gravitinos, and therefore resulting in a lower value of p_T^{miss}. If the chargino mass is close to the W boson mass, less momentum is transferred to the gravitino, leading to smaller p_T^{miss} values and, therefore, lower sensitivity. This yields a squark mass exclusion of 1500 and 1300 GeV for the T6gg and T6Wg model, respectively, and a gluino mass exclusion of 1750 and 1500 GeV for the T5gg and T5Wg model, respectively. For squark pair production, the mass exclusion is determined assuming eight mass-degenerate squark states, corresponding to the SUSY partners of the left- and right-handed u, d, s, and c quarks.

8 Summary

A search for physics beyond the standard model (SM) in final states with at least one photon, large missing transverse momentum, and large total transverse event activity has been presented using data corresponding to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded by the CMS experiment at the LHC in 2016. The SM background is estimated from data and simulation, and is validated in several control regions. No significant signs of new physics beyond the SM are found, and the data are interpreted in simplified models motivated by gauge-mediated supersymmetry breaking. Gluino masses up to 1.50–2.00 TeV and squark masses up to 1.30–1.65 TeV are excluded at 95% confidence level, depending on the neutralino mass and mixture.

Figure 6. Exclusion limits at 95% CL for the T6gg (top left), T6Wg (top right), T5gg (bottom left) and T5Wg (bottom right) models. The solid black curve represents the observed exclusion contour and the uncertainty due to the signal cross section. The red dashed curves represent the expected exclusion contours and the experimental uncertainties.

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