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Search for supersymmetry in electroweak production with photons and large missing transverse energy in pp collisions at $\sqrt{s} = 8\,\text{TeV}$

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ABSTRACT

Results are reported from a search for supersymmetry with gauge-mediated supersymmetry breaking in electroweak production. Final states with photons and large missing transverse energy (E_T^{miss}) were examined. The data sample was collected in pp collisions at $\sqrt{s} = 8\,\text{TeV}$ with the CMS detector at the LHC and corresponds to $7.4\,\text{fb}^{-1}$. The analysis focuses on scenarios in which the lightest neutralino has bino- or wino-like components, resulting in decays to photons and gravitinos, where the gravitinos escape undetected. The data were obtained using a specially designed trigger with dedicated low thresholds, providing good sensitivity to signatures with photons, E_T^{miss}, and low hadronic energy. No excess of events over the standard model expectation is observed. The results are interpreted using the model of general gauge mediation. With the wino mass fixed at 10 GeV above that of the bino, wino masses below 710 GeV are excluded at 95% confidence level. Constraints are also set in the context of two simplified models, for which the analysis sets the lowest cross section limits on the electroweak production of supersymmetric particles.

1. Introduction

Supersymmetry [1–14] (SUSY) can stabilize the mass of the Higgs boson, recently measured to be around 125 GeV [15,16], and hence the electroweak scale against large quantum corrections, thus providing a solution to the gauge hierarchy problem [17]. Searches for supersymmetric partners of standard model (SM) particles with photons in the final state are already probing SUSY parameter space at the TeV scale [18–21]. There is a strong interest in probing so-called natural SUSY scenarios, where a subset of SUSY partners can remain light, while many other SUSY partners can have large masses that are inaccessible to present searches. These regions of SUSY parameter space are still largely unexplored.

In this analysis, R-parity [22,23] is assumed to be conserved, so that SUSY particles are always produced in pairs. In SUSY models of gauge-mediated SUSY breaking (GMSB) [24–30] the gravitino ($\widetilde{\text{G}}$) is the lightest SUSY particle (LSP) and escapes undetected, leading to missing transverse energy (E_T^{miss}) in the detector. In the studied cases, the next-to-lightest SUSY particle (NLSP) is the lightest neutralino ($\widetilde{\chi}_1^0$). Depending on its composition, the $\widetilde{\chi}_1^0$ can decay according to $\widetilde{\chi}_1^0 \rightarrow N\widetilde{\text{G}}$, where N is either a photon γ, a SM Higgs boson H, or a Z boson. If the gauginos are nearly mass-degenerate, chargino ($\widetilde{\chi}_1^{\pm}$) decays according to $\widetilde{\chi}_1^{\pm} \rightarrow \text{W}^{\pm}\widetilde{\text{G}}$ are also possible.

The ATLAS and CMS Collaborations have searched for direct electroweak production of gauginos. Final states with at least one photon and one electron or muon have been examined [21,31], requiring one gaugino decaying to $\gamma\widetilde{\text{G}}$ and one to $\text{W}^{\pm}\widetilde{\text{G}}$. The NLSP masses below 540 GeV in the simplified model spectra TChiWg scenario, introduced below, were excluded at the 95% confidence level (CL). In decays into any of the heavy standard model bosons (H, Z, $\text{W}^{\pm}$), higgsino (chargino) masses up to 380 GeV (210 GeV) have been excluded at the 95% CL [32–34]. Other analyses requiring two photons in the final state [19–21] probe bino-like neutralinos and within the context of general gauge mediation (GGM) [35–40] exclude electroweakly produced winos with masses up to 740 GeV, depending on the bino mass. A previous single-photon analysis [20] has set limits on bino- and wino-like neutralinos for strong production, but the search is insensitive to electroweak production because the chosen trigger requires $H_T > 500\,\text{GeV}$, where H_T is the scalar sum of transverse energy clustered in jets.

To provide sensitivity to GMSB scenarios with low gaugino masses and mass differences, this analysis uses signatures with at least one photon together with large E_T^{miss}. In signal events, hadronic energy arises only from initial-state radiation or from the

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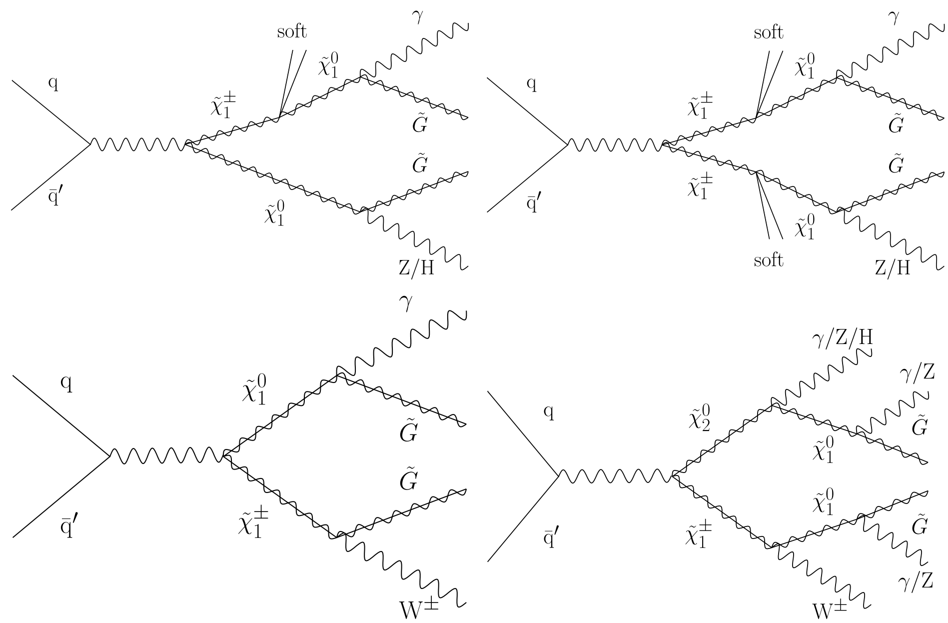

Fig. 1. Scenarios for the production and decay of charginos and neutralinos considered in this analysis. In the TChiNg scenario (top row), the charginos are only slightly heavier than the neutralinos, leading to chargino to neutralino decays accompanied by soft radiation. One neutralino decays to a photon and a gravitino, while the other decays into a Z or an H boson and a gravitino with equal probability. In the TChiWg scenario (bottom left), the gauginos are mass-degenerate and the $\widetilde{\chi}_1^0$ decays are as shown. Within GGM models, the $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$ to $\widetilde{\chi}_1^0 \to Z\widetilde{G}$ branching fraction depends on the neutralino mass. The dominant process for electroweak GGM production is shown in bottom right. A smaller amount of hadronic energy compared to strong production and at least one photon and E_T^{miss} are common features of all scenarios.

decays of a $W^\pm$ or Z boson, collectively denoted as V bosons. We concentrate on final states with only a moderate amount of H_T due to direct electroweak production of gauginos. The lightest gauginos are assumed to be either bino- or wino-like, leading to final states with E_T^{miss} and $\gamma\gamma$, γV, or VV.

We consider three signal scenarios: The scenario TChiNg models the electroweak pair and associated production of nearly mass-degenerate charginos and neutralinos, which then decay into the NLSP, as shown in Fig. 1 (top row). The branching fractions of the NLSP decay correspond here to a wino-like $\widetilde{\chi}_1^0$ of similar mass. The TChiWg scenario models associative production of mass-degenerate charginos and neutralinos, which then decay as shown in Fig. 1 (bottom left). The third scenario is electroweak production within the GGM context; the dominant production channel is shown in Fig. 1 (bottom right). Masses of the bino- and wino-like neutralinos involved in this scenario are scanned, while the squark and gluino masses are decoupled. The amount of E_T^{miss} and the photon transverse momentum (p_T) is determined by the mass of the $\widetilde{\chi}_1^0$, while the mass of the $\widetilde{\chi}^\pm$ determines the production cross section. In the GGM framework, where the gauginos are not mass-degenerate by construction, a larger $\widetilde{\chi}^\pm$–$\widetilde{\chi}_1^0$ mass difference increases the hadronic energy in the final state.

The analysis uses a special data set corresponding to an integrated luminosity of $7.4\,\text{fb}^{-1}$ recorded with a trigger requiring a photon candidate with $p_T > 30\,\text{GeV}$ measured within $|\eta| < 1.44$ and $E_T^{miss} > 25\,\text{GeV}$, where the E_T^{miss} is calculated using calorimeter information without correcting for muons. Compared to the available triggers in the full 2012 data set, which require a photon candidate with $p_T > 135\,\text{GeV}$ or events with $E_T^{miss} > 120\,\text{GeV}$, these low trigger thresholds enable a high signal sensitivity to electroweak production and compressed mass spectrum scenarios. The data set was recorded during the second half of the 2012 data-taking period but only reconstructed during the Long Shutdown 1 of the LHC as part of the so-called "parked-data" program [41].

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. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

In the barrel section of the ECAL, an energy resolution of approximately 1% is achieved for unconverted or late-converting photons arising from the $H \to \gamma\gamma$ decay. The remaining barrel photons have an energy resolution of about 1.3% up to a pseudorapidity of $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$ [42].

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. [43].

3. Object reconstruction and simulation

Photons are reconstructed [42] from clusters in the ECAL barrel with $|\eta| < 1.44$ and are required to be isolated. The energy deposit in the HCAL tower closest to the seed of the ECAL supercluster assigned to the photon divided by the energy deposit in the ECAL is required to be less than 5%. A photon-like shower shape is required. The photon isolation is determined by computing the transverse energy in a cone centered around the photon momentum vector. The cone has an outer radius of 0.3 in $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, where ϕ is azimuthal angle in radians, and the contribution of the photon is removed. Corrections for the effects of multiple interactions in the same bunch crossing (pileup) are applied to all isolation energies, depending on the η of the photon. Discrimination against electrons is achieved by requiring that photons have no matching pattern of hits in the pixel detector.

All objects used in this search, i.e. photons, electrons, muons, and jets, are reconstructed using the particle-flow (PF) algorithm [44,45]. Jets are reconstructed with the anti-k_T clustering algorithm [46] as implemented in the FastJet [47] package, using a distance parameter of 0.5. The jets are required to have transverse momenta above 30 GeV and to satisfy the requirement $|\eta| < 2.4$. Pileup corrections and corrections for the response of the detector are applied to the momenta of the jets [48,49].

The missing p_T vector is defined as the projection onto the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed particles in an event. Its magnitude is referred to as E_T^{miss}. The E_T^{miss} is calculated using all particles identified by the PF algorithm. Filters against anomalously high E_T^{miss} from instrumental effects are applied [50].

The dimensionless variable E_T^{miss}-significance ($E_T^{miss,signif}$) [50] is a measure of the probability that the E_T^{miss} in a given event arises from genuine noninteracting stable particles, such as neutrinos or gravitinos, and not as a consequence of the limited energy resolution of objects, such as jets, photons, or leptons. The $E_T^{miss,signif}$ is proportional to the logarithm of the likelihood ratio of both hypotheses. Energy and angular resolutions of the relevant objects, determined by data and simulation studies, are taken into account. For processes where the reconstructed E_T^{miss} only arises from the limited energy resolution, the $E_T^{miss,signif}$ is an exponentially falling distribution, falling by three orders of magnitude for $0 < E_T^{miss,signif} < 25$. SM processes with genuine E_T^{miss} have approximately the same decrease between 0 and 125. Electroweak SUSY processes intrinsically have high values of genuine E_T^{miss} along with a significantly lower presence of jets, which otherwise increase the energy uncertainty used in the calculation of $E_T^{miss,signif}$. Therefore, the $E_T^{miss,signif}$ distribution of those processes does not decrease monotonically, and a considerable fraction has $E_T^{miss,signif} > 200$.

The SM $t\bar{t}\gamma$ and QCD multijet production samples, as well as the TChiNg and TChiWg signal scenarios, are simulated with the MadGraph 5.1.3 generator [51]. The diboson event samples and the electroweak GGM signal scan are generated using pythia 6.4 [52]. All Monte Carlo (MC) samples incorporate the CTEQ6L1 [53] parton distribution functions (PDF) and use the pythia program to describe the parton showering and the hadronization. The Geant4 [54] package is used to model the detector and detector response. The cross sections of the electroweak GGM signal scan are calculated at next-to-leading-order (NLO) accuracy using the prospino 2.1. [55] program, the cross sections for the TChiNg and TChiWg signal points are calculated at NLO + NLL (next-to-leading logarithm) accuracy [56–58].

4. Analysis

The data are selected by a trigger with E_T^{miss} and photon p_T requirements. The events are subsequently required to contain at least one tightly isolated photon measured in the ECAL barrel with a p_T of at least 40 GeV. The E_T^{miss} is required to exceed 100 GeV. In addition, H_T is required to exceed 100 GeV, improving the signal-to-background ratio. With this selection the parked data set trigger efficiency is uniform and measured to be $86.5^{+1.0}_{-1.3}$%. No selection criteria were applied on the presence or absence of an identified lepton. All events are required to have $E_T^{miss,signif} > 80$ and a transverse mass $M_T(E_T^{miss}, p_T^{\gamma_1}) > 300$ GeV, where $p_T^{\gamma_1}$ is the transverse momentum of the photon with the highest p_T. The cut on $E_T^{miss,signif}$ strongly reduces the contribution of backgrounds without genuine E_T^{miss}, whereas the cut on $M_T(E_T^{miss}, p_T^{\gamma_1})$ affects all backgrounds but retains most of the signal events, since only in signal processes the photon and the source for E_T^{miss} are expected to originate from the same mother particle. To increase the sensitivity to higher gaugino masses, the signal region is divided into four exclusive bins defined by regions in the variables S_T^{γ} and $E_T^{miss,signif}$, where S_T^{γ} is defined by $S_T^{\gamma} = \sum_i p_T^{\gamma_i} + E_T^{miss}$. The boundaries of the bins are at $S_T^{\gamma} = 600$ GeV and $E_T^{miss,signif} = 200$.

The dominant SM backgrounds are vector-boson production with initial- or final-state photon radiation (Vγ) and direct photon production (γ + jets). The normalization of these two backgrounds is determined simultaneously by a χ^2-fit in the control region selection defined by $E_T^{miss,signif} > 10$ and $M_T(E_T^{miss}, p_T^{\gamma_1}) > 100$ GeV, but excluding the signal region defined above. The distribution of $E_T^{miss}/\sqrt{H_T}$ is chosen as template variable for the χ^2-fit, which sufficiently separates the shapes of Vγ and γ + jets, so that scaling one background cannot compensate the other. The shape of both backgrounds is simulated with MadGraph 5.1.3. Under the constraint of a fixed total yield, the scale factors for the Vγ and γ + jets simulations are given by the minimum of the χ^2/ndf distribution and found to be $f_{V\gamma} = 0.94 \pm 0.23$ and $f_{\gamma+\text{jets}} = 2.20 \pm 0.31$, respectively. Before performing the normalization, the Vγ background is scaled to the NLO cross section [59], whereas γ + jets is used with LO cross section calculated by the event generator. The upper and lower uncertainty is given by the difference of the best estimate and the scale factor corresponding to the χ^2/ndf values at the minimum of the parabola increased by unity. The measured scale factors and their uncertainties were studied and found stable with respect to systematic variations in the background prediction over different control regions, template variables, and binnings of the template variables. The anticorrelation of the Vγ and γ + jets systematic uncertainties due to the fixed total normalization is taken into account in the interpretation. Signal contamination becomes relevant if the gauginos are light because the signal kinematics for light gauginos are similar to that of Vγ production. In the examined phase space, signal contamination is negligible.

A subdominant background arises from electrons misidentified as photons ($e \to \gamma$). The misidentification rate $f_{e\to\gamma} = (1.46 \pm 0.16)\%$ is determined from $Z \to e^+e^-$ decays in data [20]. The background is estimated from a data control sample with the same event selection, but containing an identified electron instead of a photon. The prediction of electrons misidentified as photons is then obtained by scaling this control sample by $f_{e\to\gamma}/(1 - f_{e\to\gamma})$. The uncertainty of this estimation is 11%, which is dominated by the misidentification rate uncertainty. Further minor contributions from $t\bar{t}\gamma$, diboson, and QCD multijet production are estimated using MC simulations and are corrected for electrons misidentified as photons at the generator level to avoid overlaps. For the cross sections, 26%, 50%, and 100% systematic uncertainties are assigned to $t\bar{t}\gamma$, diboson, and QCD multijet backgrounds, respectively. Based on simulation studies, the background from QCD multijet events is found to be negligible.

The systematic uncertainties with respect to the choice of the PDF in the signal acceptance are determined by the difference in acceptance using different sets of PDFs [60–64] and vary from less than 1% to 11%. Further systematic uncertainties arise from the jet energy correction (0.1–2.4% for the signal, 1.3% for the background estimation) and from the integrated luminosity measurement (2.6%) [65]. When evaluating the exclusion contours for SUSY particle masses in specific models, signal cross sections (σ_s) are conservatively lowered by one standard deviation (4–8%) corresponding to the combined theoretical uncertainty in σ_s due to the choices of the renormalization and factorization scales and the PDFs. All systematic uncertainties are summarized in Table 1.

Table 1
Summary table of systematic uncertainties relevant for the analysis. Uncertainties due to the luminosity and trigger efficiency measurement apply only to the backgrounds estimated using MC simulation without data normalization, namely $t\bar{t}\gamma$, diboson, and multijet, and for the signal. The total uncertainty is dominated by the uncertainty in the Vγ background.

Source	Sample	Relative uncert. (%)	
		In sample	In total bkg
Vγ normalization	Vγ	24	19
γ + jets normalization	γ + jets	14	1
$Z \to e^+e^-$ fit	$e \to \gamma$	11	0.3
Cross section measurement	$t\bar{t}\gamma$	26	3
Cross section	Diboson	50	1
Cross section	Multijet	100	0
Integrated luminosity	Diboson, multijet, and signal	2.6	–
Trigger efficiency	Diboson, multijet, and signal	1.2	–
Jet energy scale	Diboson, multijet, and signal	1–2	–
PDF uncertainty in acceptance	Signal	<1–11	–
PDF and scale uncertainty	Signal	4–8	–

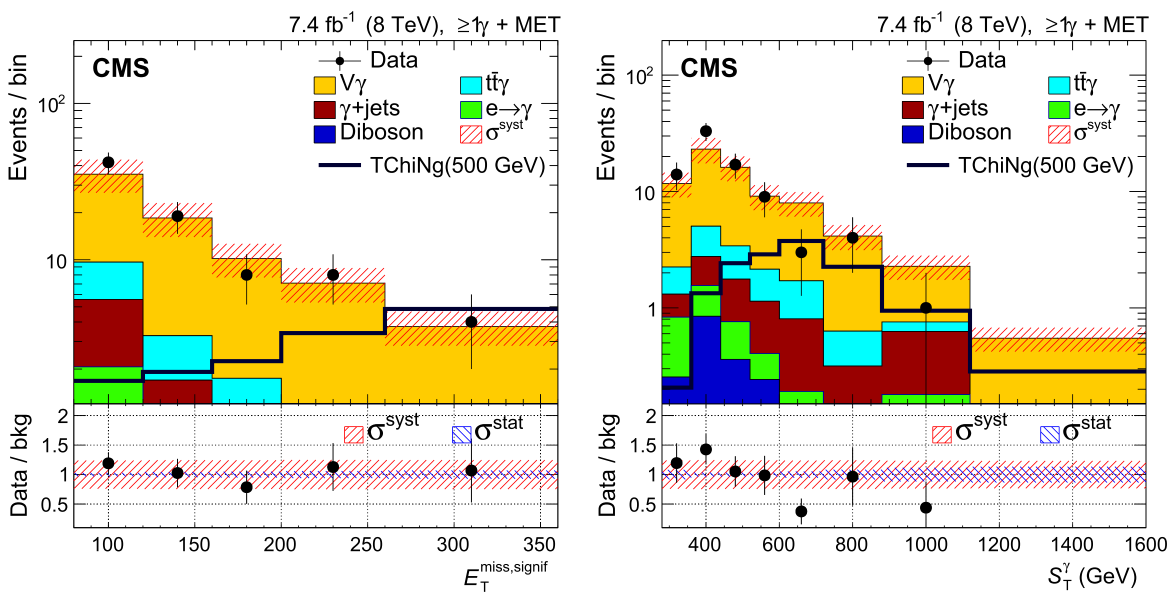

Fig. 2. The $E_T^{miss,signif}$ (left) and S_T^{γ} (right) variables are shown in the signal selection and used to define four search regions with $E_T^{miss,signif} = 200$ and $S_T^{\gamma} = 600$ GeV partitions. A benchmark TChiNg signal point with an NLSP mass of 500 GeV is shown for comparison.

5. Results and interpretation

As shown in Fig. 2, the observed data are in agreement with the total standard model background expectation within the combined statistical and systematic uncertainties. Shown are the distributions of $E_T^{miss,signif}$ (Fig. 2, left) and S_T^{γ} (Fig. 2, right) used to define the four search regions described in Section 4. The results are summarized in Table 2. No sign of new physics is observed.

Cross section limits are calculated combining the results of all four search regions defined in the S_T^{γ}–$E_T^{miss,signif}$ plane at the 95% CL, using the modified frequentist CL$_s$ criterion [66–68] with a test statistic corresponding to a profile likelihood ratio of the background-only and signal-plus-background hypotheses. Asymptotic formulae [69] are used in the calculation.

The interpretation of the TChiNg and TChiWg scenarios is shown in Fig. 3. The analysis excludes NLSP masses below 570 (680) GeV at the 95% CL in the TChiNg (TChiWg) scenario.

The 95% CL observed upper cross section limit, as well as the observed and expected exclusion contours, for the GGM signal scan in the M_{wino}–M_{bino} plane are shown in Fig. 4. For nearly mass-degenerate gauginos, i.e. for $M_{wino} = M_{bino} + 10$ GeV, wino masses up to approximately $M_{wino} = 710$ GeV are excluded.

6. Conclusion

We have searched for electroweak production of gauginos in the framework of gauge mediated supersymmetry breaking in final states with photons and E_T^{miss}. A dataset, corresponding to an integrated luminosity of 7.4 fb^{-1}, recorded with a special trigger with low thresholds is used. The data are found to agree with the SM expectation. The analysis is sensitive to electroweak production and compressed mass spectra which are characterized by minimal hadronic activity in the final state, complementing previously published searches. Limits in the TChiNg scenario are set for the first time, excluding NLSP masses below 570 GeV at 95% CL. In the TChiWg scenario, NLSP masses below 680 GeV are excluded at 95% CL, increasing the previous mass limit in this scenario [31] by 140 GeV. In the general gauge mediation model for compressed mass spectrum scenarios with e.g. $M_{wino} - M_{bino} = 10$ GeV, wino masses below 710 GeV can be excluded, increasing the previous CMS limit [19] by about 220 GeV.

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Table 2
Event yields for data corresponding to 7.4 fb^{-1} and the estimated backgrounds. The signal yields correspond to the benchmark TChiNg signal point with $M_{\text{wino}} = 500$ GeV shown in Fig. 2, also stating the acceptance times efficiency $A\varepsilon$ for each search region. The contribution from QCD multijet background is negligible in all regions.

Selection	$E_T^{\text{miss,signif}} > 200$, $S_T^{\gamma} > 600$ GeV	$E_T^{\text{miss,signif}} < 200$, $S_T^{\gamma} > 600$ GeV	$E_T^{\text{miss,signif}} < 200$, $S_T^{\gamma} < 600$ GeV	$E_T^{\text{miss,signif}} > 200$, $S_T^{\gamma} < 600$ GeV
Vγ	4.7 ± 1.2	7.0 ± 1.8	42.3 ± 10.4	5.0 ± 1.3
γ + jets	0.1 ± 0.1	1.3 ± 0.3	3.4 ± 0.7	0.0 ± 0.1
$t\bar{t}\gamma$	0.3 ± 0.1	1.1 ± 0.3	5.5 ± 1.5	0.4 ± 0.1
Diboson	0.1 ± 0.1	0.2 ± 0.1	1.5 ± 0.8	0.2 ± 0.1
$e \to \gamma$	0.1 ± 0.1	0.1 ± 0.1	1.6 ± 0.2	0.2 ± 0.1
Background	5.3 ± 1.2	9.7 ± 1.8	54.3 ± 10.6	5.8 ± 1.3
Data	4	4	65	8
Signal	6.2 ± 0.2	2.1 ± 0.1	4.6 ± 0.1	3.3 ± 0.1
$A\varepsilon$ [%]	12.2 ± 0.3	4.2 ± 0.1	9.0 ± 0.2	6.5 ± 0.2

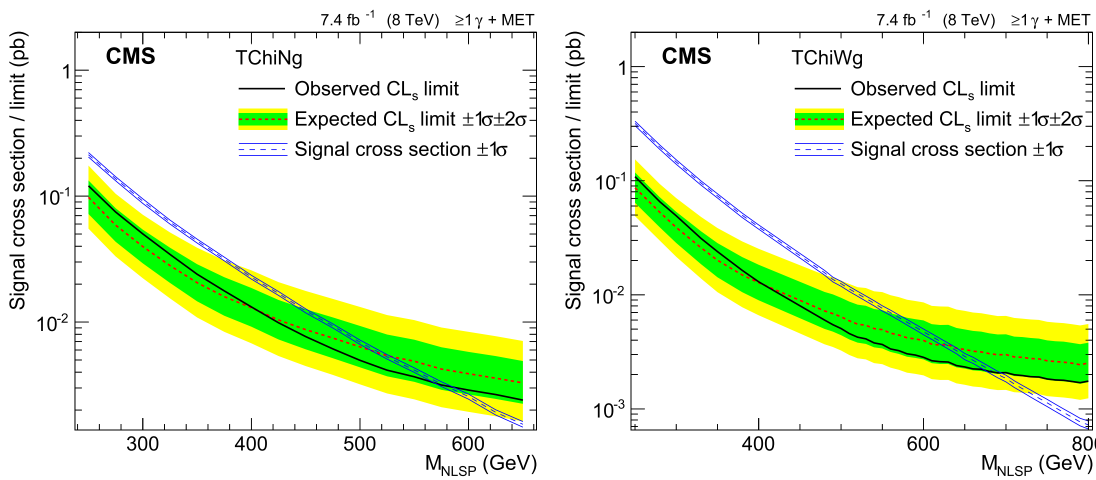

Fig. 3. Exclusion limits at 95% CL for the TChiNg (left) and TChiWg (right) scenario. In the TChiNg scenario NLSP masses below 570 GeV are excluded, in the TChiWg scenario NLSP masses below 680 GeV are excluded.

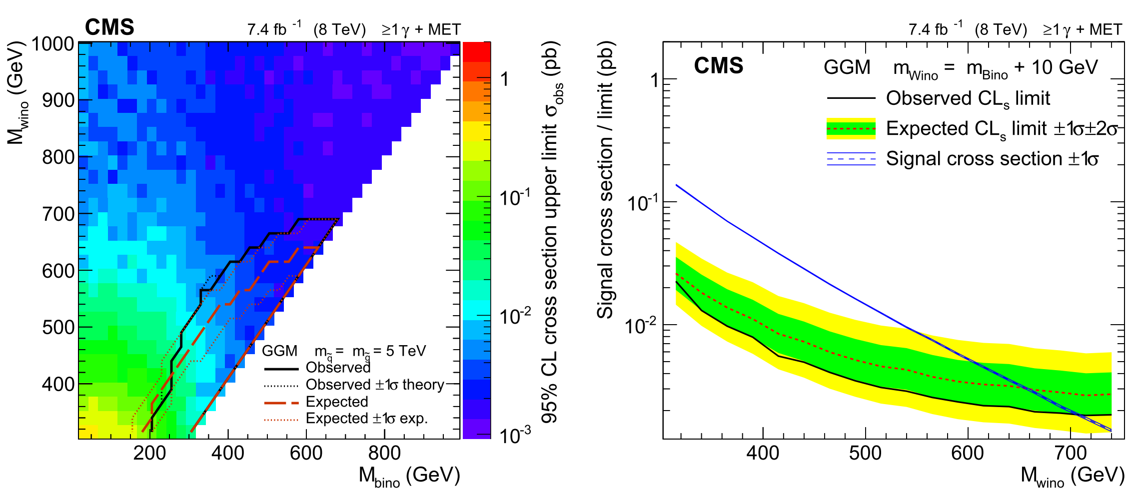

Fig. 4. Observed upper cross section CL_s limit at the 95% CL for the GGM signal points in the M_{wino}–M_{bino} plane (left). Also shown are the 95% CL expected and observed exclusion contours. The GGM signal points near the diagonal, e.g. for $M_{\text{wino}} = M_{\text{bino}} + 10$ GeV up to a wino mass of $M_{\text{wino}} = 710$ GeV are excluded (right).

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