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# Search for gauge-mediated supersymmetry in events with at least one photon and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV

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## Abstract

A search for gauge-mediated supersymmetry (SUSY) in final states with photons and large missing transverse momentum is presented. The data sample of pp collisions at  $\sqrt{s} = 13$  TeV was collected with the CMS detector at the CERN LHC and corresponds to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . Data are compared with models in which the lightest neutralino has bino- or wino-like components, resulting in decays to photons and gravitinos, where the gravitinos escape detection. The event selection is optimized for both electroweak (EWK) and strong production SUSY scenarios. The observed data are consistent with standard model predictions, and limits are set in the context of a general gauge mediation model in which gaugino masses up to 980 GeV are excluded at 95% confidence level. Gaugino masses below 780 and 950 GeV are excluded in two simplified models with EWK production of mass-degenerate charginos and neutralinos. Stringent limits are set on simplified models based on gluino and squark pair production, excluding gluino (squark) masses up to 2100 (1750) GeV depending on the assumptions made for the decay modes and intermediate particle masses. This analysis sets the highest mass limits to date in the studied EWK models, and in the considered strong production models when the mass difference between the gauginos and the squarks or gluinos is small.

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## 1 Introduction

The search for physics beyond the standard model (SM) is one of the key research topics of the CMS experiment at the CERN LHC. Especially after the discovery of a Higgs boson with a mass of around 125 GeV in 2012 [1–3], supersymmetry (SUSY) [4–17] is one of the theoretically favored possible extensions of the SM. Among several explanations for unsolved problems in particle physics, SUSY provides a mechanism for stabilizing the SM-like Higgs boson mass at the electroweak (EWK) scale. Since current searches are pushing the limits on strongly produced SUSY particles (sparticles) beyond the one-TeV threshold, the interest in probing gaugino masses via EWK production is growing. While searches for heavy sparticles especially profit from the increase in the center-of-mass energy due to the large increase of the production cross section, searches for EWK production benefit from a larger data set, as collected by the CMS experiment in 2016.

In this Letter, a search for SUSY focusing on gauge-mediated SUSY breaking (GMSB) [18–24] scenarios is presented. The  $R$ -parity [25] is assumed to be conserved, so that SUSY particles are always produced in pairs. The gravitino ( $\tilde{G}$ ) is the lightest SUSY particle (LSP) and escapes undetected, leading to missing transverse momentum ( $p_T^{\text{miss}}$ ) in the detector. The next-to-LSP (NLSP) is assumed to be the lightest neutralino ( $\tilde{\chi}_1^0$ ). Depending on its composition, the  $\tilde{\chi}_1^0$  can decay according to  $\tilde{\chi}_1^0 \rightarrow N\tilde{G}$ , where  $N$  is either a photon ( $\gamma$ ), an SM-like Higgs boson ( $H$ ), or a  $Z$  boson. If the gauginos are nearly mass-degenerate, the chargino ( $\tilde{\chi}_1^{\pm}$ ) decays  $\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{G}$  are also possible. The  $\tilde{G}$  is assumed to have negligible mass and the NLSP is assumed to decay promptly.

The analyzed data set was collected at the CERN LHC in proton-proton collisions at a center-of-mass energy of 13 TeV and corresponds to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . Events are required to contain at least one high-energy photon and large  $p_T^{\text{miss}}$ . In order to maintain sensitivity to EWK SUSY production, there is no explicit event selection criterion requiring hadronic energy, i.e., the presence of jets in the event. In GMSB SUSY,  $p_T^{\text{miss}}$  arises from the stable and noninteracting  $\tilde{G}$ , while photons originate from  $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$  decays. The energy of the photon as well as of the gravitino and thus the  $p_T^{\text{miss}}$  is governed by the  $\tilde{\chi}_1^0$  mass, and the  $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$  branching fraction is determined by the neutralino's bino and wino components and its mass. Compared to analyses requiring photons and large hadronic activity, this analysis has superior sensitivity to GMSB SUSY in EWK production, and also in strong production if the squark, gluino, and the lightest gaugino masses are similar (compressed-spectrum scenarios).

An earlier version of this analysis [26] was carried out by CMS on a special 8 TeV data set recorded as part of the “parked-data” program [27] corresponding to an integrated luminosity of  $7.4 \text{ fb}^{-1}$  using a dedicated trigger and a lower photon transverse momentum ( $p_T$ ) threshold of 30 GeV. The ATLAS and CMS collaborations have also searched for direct EWK production of gauginos in final states with at least one photon and one electron or muon [28, 29], and in the two-photon channel [29–31]. Single-photon and  $H_T$ -based analyses [31], where  $H_T$  is the scalar sum of hadronic jet transverse momenta, have good sensitivity for strong production in GMSB models but lack sensitivity for EWK production and compressed-spectrum scenarios.

## 2 Signal models

To interpret the results, a general gauge mediation (GGM) [32–37] scenario dominated by EWK production is used. Furthermore, two EWK production and four strong production simplified model scenarios (SMS) [38] are considered for interpretation. For the GGM scenario, the squark

and gluino masses are set to a high scale rendering them inaccessible and strong production negligible. The bino and wino masses therefore fully determine the model point under study and are varied in the interpretation. The  $\tilde{\chi}_1^0$  is assumed to be purely bino-like, while the  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  are assumed to be purely wino-like. The dominant process for EWK GGM production is shown in Fig. 1 (upper left). In the GGM framework, where the gauginos are not mass-degenerate by construction, a larger  $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$  mass difference increases the hadronic energy in the final state if the Z, H, or W bosons decay hadronically.

The EWK simplified scenario TChiWg probes associated production of mass-degenerate charginos and neutralinos ( $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ ), assuming the decay modes  $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$  and  $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{G}$ , as shown in Fig. 1 (upper right). The TChiNg scenario assumes nearly mass-degenerate  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$ , but considers  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  production as shown in Fig. 1 (lower left and right). In this scenario, the  $\tilde{\chi}_1^\pm$  is assumed to have a slightly higher mass than  $\tilde{\chi}_1^0$ , and it decays to  $\tilde{\chi}_1^0$  and low-momentum particles outside the acceptance of this analysis. The neutralinos are assumed to decay as  $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ ,  $\tilde{\chi}_1^0 \rightarrow Z \tilde{G}$ , and  $\tilde{\chi}_1^0 \rightarrow H \tilde{G}$  with 50, 25, and 25% probability, respectively.

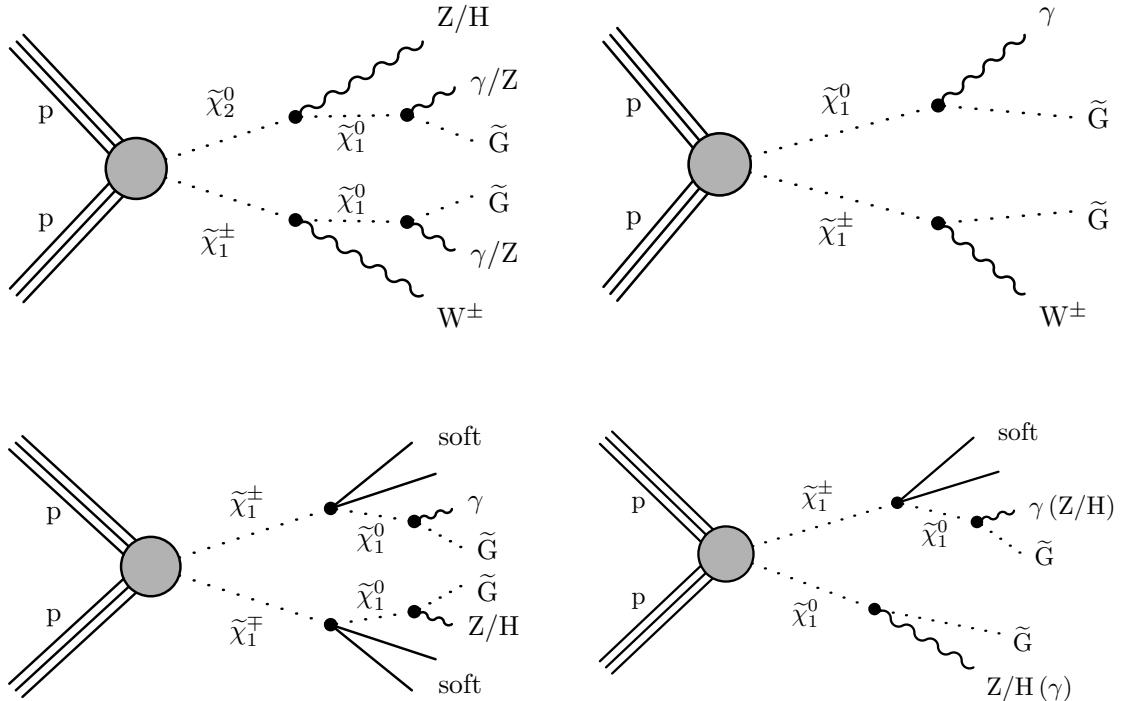


Figure 1: In the context of GGM, several production and decay channels are possible. The diagram of the dominant process  $\tilde{\chi}_2^0 - \tilde{\chi}_1^\pm$  production is shown (upper left), where the gaugino decays depend on the mass configuration under study. In the TChiWg model (upper right), the gauginos are mass degenerate. The TChiNg model comprises  $\tilde{\chi}_1^\pm$  pair production (lower left) and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  production (lower right), where the  $\tilde{\chi}_1^\pm$  is only slightly heavier than the  $\tilde{\chi}_1^0$ , so only low-momentum (soft) particles appear in the decay of  $\tilde{\chi}_1^\pm$  to  $\tilde{\chi}_1^0$ .

The strong production SMS models T5gg, T5Wg, T6gg, and T6Wg are shown in Fig. 2, where T5gg and T5Wg represent gluino pair production, and T6gg and T6Wg squark pair production. The neutralino decays as  $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ , while the chargino decays as  $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{G}$ . In the T5Wg and T6Wg scenario, a branching fraction of 50% is assumed for the charged and neutral decays of the gluino or squark. The T5gg (T6gg) scenario assumes a branching fraction of 100% for  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$  ( $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ ).

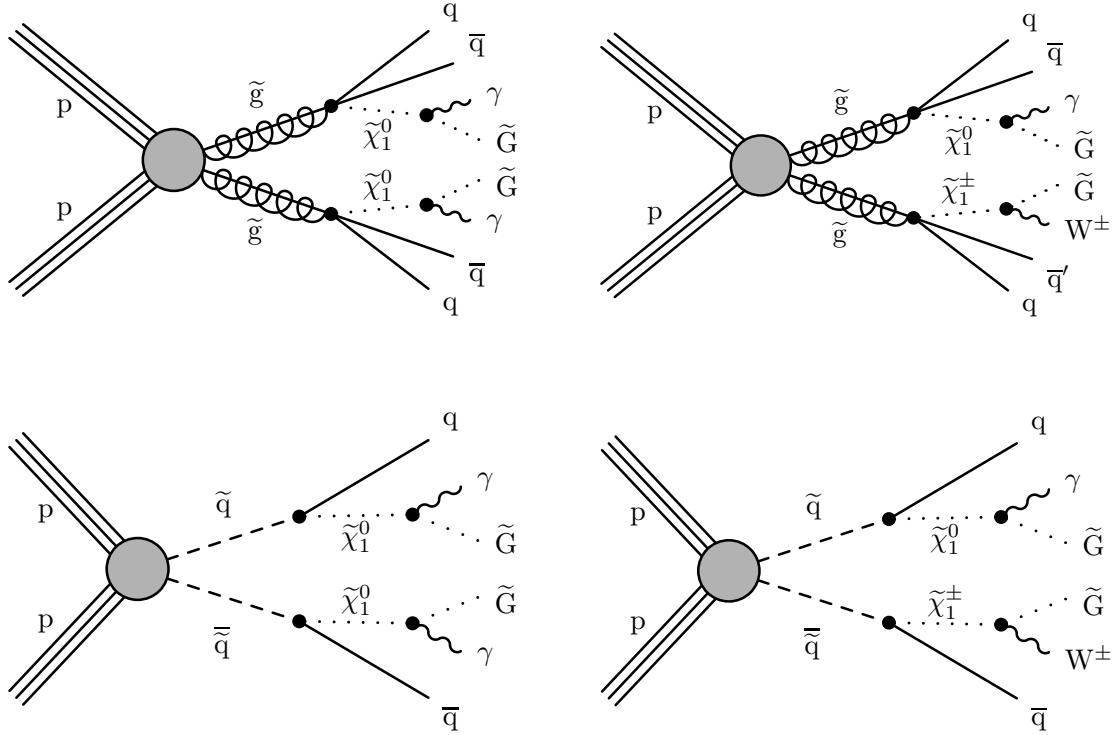


Figure 2: For strong gluino pair-production the simplified scenarios T5gg (upper left) and T5Wg (upper right) and for squark pair-production the simplified scenarios T6gg (lower left) and T6Wg (lower right) are studied. In the T5Wg (T6Wg) scenario, a branching fraction of 50% is assumed for the decays  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^\pm$  and  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$  ( $\tilde{q} \rightarrow q\tilde{\chi}_1^\pm$  and  $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ ), resulting in final states with zero, one, or two photons.

### 3 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  $H \rightarrow \gamma\gamma$  decay for photons with  $p_T > 25$  GeV. 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  $|\eta| = 1.4$ . In the endcaps, the energy resolution of unconverted or late-converting photons is about 2.5%, while the remaining endcap photons have a resolution between 3 and 4% [39].

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. [40].

## 4 Object reconstruction and simulation

The particle-flow (PF) event algorithm [41] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. Fully reconstructed photon conversions are used by the PF algorithm and are included in the set of photon candidates. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined 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 energy 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 energy.

Photons are reconstructed [39] from clusters in the ECAL and are required to be isolated. The energy deposit in the HCAL tower closest to the seed of the ECAL supercluster [42] assigned to the photon is required to be less than 5% of the energy deposited in the ECAL. A photon-like transverse ECAL 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  $\phi$  is the azimuthal angle, and the contribution of the photon is removed. Corrections for the effects of multiple interactions in the same or adjacent bunch crossing (pileup) are applied to all isolation energies, depending on the  $\eta$  of the photon. To ensure that no photon with anomalously high a posteriori corrections populate the signal region, a requirement that at least 30% of the photon's energy be deposited in the seed crystal is imposed for all considered photons. A photon candidate must exceed a minimal  $p_T$  of 15 GeV. Photons are efficiently discriminated against electrons by requiring that photons have no matching pattern of energy deposits in the pixel detector.

The vector  $\vec{p}_T^{\text{miss}}$  is defined as the projection onto the plane perpendicular to the beams of the negative vector sum of the momenta of all PF candidates in an event. The magnitude of  $\vec{p}_T^{\text{miss}}$  is referred to as  $p_T^{\text{miss}}$ .

Jets are reconstructed from PF candidates with the anti- $k_T$  clustering algorithm [43] as implemented in the FASTJET [44] package, using a distance parameter of 0.4. Jet energy corrections [45, 46] are derived from Monte Carlo (MC) simulation, and are confirmed with in situ measurements of the energy balance in dijet and  $\gamma$ +jet events. These corrections are also propagated to  $\vec{p}_T^{\text{miss}}$ . Jets with  $p_T > 30$  GeV and  $|\eta| < 3$  are required to be geometrically isolated from identified photons, electrons, and muons, where electrons and muons have to fulfill standard identification requirements to be considered in this isolation criterion. Filters against anomalously high  $p_T^{\text{miss}}$  from instrumental effects are applied [47].

The reconstructed vertex with the largest value of summed physics-object  $p_T^2$  is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [43, 44] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the  $p_T$  of those jets.

The SM background processes contributing to the signal and control regions are modeled using MC simulations. The quantum chromodynamics (QCD) multijet,  $\gamma$ +jets, and W and Z processes are generated with MADGRAPH5\_aMC@NLO 2.3.3 [48, 49] at leading order (LO), while the  $t\bar{t}(+\gamma)$  processes are generated at next-to-leading order (NLO) [48, 50]. The WW

diboson production is generated with POWHEG v2 [51–55], and WZ and ZZ production are generated using PYTHIA8.205 [56]. The  $Z\gamma$  sample is scaled with photon  $p_T$  dependent next-to-next-to-leading logarithmic (NNLL) K-factors [57], which are of the order of 1.3. A constant next-to-NLO (NNLO) K-factor of 1.34 is applied to the  $W\gamma$  production cross section [57], and NLO K-factors of the order of 1.2 are applied to the  $W$  and  $Z(\rightarrow \nu\nu)$  production cross sections. The diboson production cross sections are available at NLO (ZZ, WZ) and NNLO (WW) precision [58]. The  $W\gamma$  and  $Z\gamma$  processes, collectively denoted as  $V\gamma$ , are the dominant backgrounds in the signal region. A data sideband region is used to obtain additional scale factors for the  $V(\gamma)$  and  $\gamma+\text{jets}$  samples, where  $V(\gamma)$  comprises the  $W$  and  $Z$  boson production, with and without photon radiation.

The GGM signal scan is generated with PYTHIA8, while the SMS signal scans are generated with MADGRAPH5\_aMC@NLO at LO. The cross sections are calculated at NLO and NLO+NLL accuracy [59–67] for the GGM and the SMS scans, respectively, with all the unconsidered sparticles assumed to be heavy and decoupled. For the EWK models, the cross sections are computed in a limit of mass-degenerate wino  $\tilde{\chi}_2^0$  and  $\tilde{\chi}_1^\pm$ .

All MC samples incorporate the NNPDF 3.0 [68] parton distribution functions (PDFs) and use the PYTHIA v8.205 or PYTHIA v8.212 program with the CUETP8M1 generator tune [69] to describe the parton showering and the hadronization. Double counting of the partons generated with MADGRAPH5\_aMC@NLO and those with PYTHIA is removed using the MLM [49] and the FXFX [50] matching schemes, in the LO and NLO samples, respectively. The GEANT4 [70] package is used to model the detector and the detector response for SM processes, while the CMS fast simulation [71, 72] is used for signal samples. Additional pp interactions are considered in the simulation and all samples are weighted on an event-by-event basis to match the distribution of the number of interaction vertices observed in data.

## 5 Event selection

The data are recorded using a trigger requiring one photon that passes very loose identification criteria and has a  $p_T$  of at least 165 GeV [73]. The events in the subsequent analysis are required to contain at least one identified and isolated photon with  $p_T > 180$  GeV in the central barrel part of the detector ( $|\eta| < 1.44$ ) that has been accepted by the trigger. The photons are required to have an angular distance in the  $\eta-\phi$  plane of  $\Delta R > 0.5$  to the nearest jet. To suppress events where the  $p_T^{\text{miss}}$  mainly arises from a significant mismeasurement of a jet's energy, all jets with  $p_T > 100$  GeV must fulfill  $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{jet}) > 0.3$ , where  $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{jet})$  is the distance in  $\phi$  between the jet and the  $p_T^{\text{miss}}$ . At least one reconstructed vertex per event is required [74]. To maintain high signal acceptance for all studied signal scenarios no selection criteria are applied on the presence or absence of jets or leptons, except for the photon isolation criteria. The photon trigger efficiency for this selection is found to be  $\epsilon_\gamma = 94.3 \pm 0.4\%$ , independent of the kinematic event variables used in the analysis.

The preselected events with at least one high- $p_T$  photon are separated into a signal region and an orthogonal control region. The signal region is defined by  $p_T^{\text{miss}} > 300$  GeV and  $M_T(\gamma, \vec{p}_T^{\text{miss}}) > 300$  GeV, where  $M_T(\gamma, \vec{p}_T^{\text{miss}})$  is the transverse mass of the photon with the highest energy and  $p_T^{\text{miss}}$ , and roughly represents the NLSP mass in the SUSY scenarios containing the decay  $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ . The requirement  $M_T(\gamma, \vec{p}_T^{\text{miss}}) > 300$  GeV was chosen to optimize the statistics in the control region under maximization of the signal acceptances. The region with  $p_T^{\text{miss}} > 100$  GeV and  $M_T(\gamma, \vec{p}_T^{\text{miss}}) > 100$  GeV, but excluding the signal region, defines the signal-depleted data control region.

Multiple exclusive signal bins are defined with respect to  $S_T^\gamma \equiv p_T^{\text{miss}} + \sum_{\gamma_i} p_T(\gamma_i)$ , the scalar sum of  $p_T^{\text{miss}}$  and the  $p_T$  of all photons in the event. The region with  $p_T^{\text{miss}} > 300 \text{ GeV}$  and  $M_T(\gamma, \vec{p}_T^{\text{miss}}) > 300 \text{ GeV}$ , but  $S_T^\gamma \leq 600 \text{ GeV}$  has negligible signal contamination and is used to validate the background estimation. The four  $S_T^\gamma$  regions 600–800, 800–1000, 1000–1300, and  $> 1300 \text{ GeV}$  define exclusive bins that are simultaneously interpreted in a multichannel counting experiment for best sensitivity. The full selection requirements to define each region used in this analysis are summarized in Table 1.

Table 1: Summary of the event selection criteria required for the control, validation, and signal regions.

Region	Selection
Preselection	$p_T^{\text{miss}}$ filters
	At least one reconstructed vertex
	At least one photon with $p_T > 180 \text{ GeV}$
	$\Delta R(\gamma, \text{jet}) > 0.5$
Control region	$\Delta\phi(\vec{p}_T^{\text{miss}}, \text{jet}) > 0.3 \text{ rad}$ , if $p_T(\text{jet}) > 100 \text{ GeV}$
	Preselection
	$p_T^{\text{miss}} > 100 \text{ GeV}$
	$M_T(\gamma, \vec{p}_T^{\text{miss}}) > 100 \text{ GeV}$
Validation region	$p_T^{\text{miss}} < 300 \text{ GeV}$ or $M_T(\gamma, \vec{p}_T^{\text{miss}}) < 300 \text{ GeV}$
	Preselection
	$p_T^{\text{miss}} > 300 \text{ GeV}$
	$M_T(\gamma, \vec{p}_T^{\text{miss}}) > 300 \text{ GeV}$
Signal region	$S_T^\gamma < 600 \text{ GeV}$
	Preselection
	$p_T^{\text{miss}} > 300 \text{ GeV}$
	$M_T(\gamma, \vec{p}_T^{\text{miss}}) > 300 \text{ GeV}$
	$S_T^\gamma > 600 \text{ GeV}$

The selection differs in several aspects from the analysis using 8 TeV data [26]. The trigger used in the 8 TeV analysis allowed for very low photon  $p_T$  and  $p_T^{\text{miss}}$  selections. The “ $p_T^{\text{miss}}$  significance” that defined the signal and control regions has been replaced by  $p_T^{\text{miss}}$  for simplicity and to allow for easier reinterpretations of the results. The analysis is optimized such that no loss in sensitivity is ensured.

## 6 Background estimation

The SM background in the photon and  $p_T^{\text{miss}}$  final state is dominated by vector boson production with initial-state photon radiation, in particular by the  $Z\gamma \rightarrow \nu\bar{\nu}\gamma$  process. Direct photon production in association with jets,  $\gamma+\text{jets}$ , also contributes at low values of  $p_T^{\text{miss}}$  and thus low values of  $S_T^\gamma$ . A subdominant background arises from electrons misidentified as photons ( $e \rightarrow \gamma$ ). Further minor contributions originate from  $t\bar{t}\gamma$  and diboson production. The most relevant backgrounds,  $V(\gamma)$  and  $\gamma+\text{jets}$ , are modeled by MC simulation and are scaled to the data in the data control region at low values of  $p_T^{\text{miss}}$  and  $M_T(\gamma, \vec{p}_T^{\text{miss}})$ . The contribution from events with  $e \rightarrow \gamma$  misidentification is predicted from data. All remaining minor contributions are modeled by MC simulation.

The normalization of the  $V(\gamma)$  and  $\gamma+\text{jets}$  backgrounds is determined in the control region by a simultaneous  $\chi^2$ -fit in bins of  $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{nearest jet}/\gamma)$ , which is the angular distance in the transverse plane of the  $p_T^{\text{miss}}$  and the nearest jet or photon. The distribution of

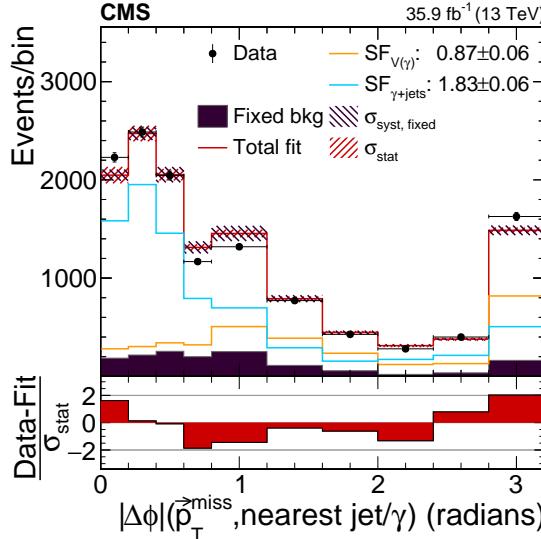


Figure 3: The post-fit distributions for the  $\gamma$ +jets (blue) and  $V(\gamma)$  (orange) background in the control region together with the fixed background (dark magenta) and the total fit distribution stacked onto the fixed backgrounds (red) are shown. The statistical uncertainty ( $\sigma_{\text{stat}}$ ) of the post-fit distribution is shown in the red hatched area and the systematic uncertainty of the fixed background ( $\sigma_{\text{syst, fixed}}$ ) is indicated with the dark magenta hatched area. The values  $SF_{V(\gamma)}$  and  $SF_{\gamma+\text{jets}}$  in the legend are the resulting scale factors. The pull distribution only considers the statistical uncertainty.

$\Delta\phi(\vec{p}_T^{\text{miss}}, \text{nearest jet}/\gamma)$  sufficiently separates the shapes of  $V(\gamma)$  and  $\gamma$ +jets backgrounds, so that scaling one background cannot compensate for the other. Contributions from other SM processes are small and are kept constant in the fit. Under the constraint of a fixed total yield, the scale factors for the  $V(\gamma)$  and  $\gamma$ +jets simulations are given by the minimum of the  $\chi^2$  distribution. The resulting scale factors are

$$SF_{V(\gamma)} = 0.87 \pm 0.06, \quad (1)$$

$$SF_{\gamma+\text{jets}} = 1.83 \pm 0.06, \quad (2)$$

where the uncertainties are of statistical origin only. The post-fit distribution of  $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{nearest jet}/\gamma)$  is shown in Fig. 3. The size of the measured factors is consistent with the expectations [57]. The scale factor for  $V(\gamma)$  is smaller than unity because EWK corrections, which are not contained in the K-factors, are smaller than unity for high photon  $p_T$ . The  $\gamma$ +jets scale factor is larger than unity since no K-factor is applied and QCD corrections for multijet backgrounds are large. The factors are found to be stable with respect to systematic variations of the method. Different control region selections, a variety of template variables, and various binnings of the template variables have been studied. Signal contamination becomes relevant if the gauginos are light because in terms of its kinematical variables the production of light gauginos is similar to that of  $V(\gamma)$  production and is taken into account in the statistical analysis. In the remaining phase space, signal contamination is negligible.

Electrons that are misidentified as photons create a subdominant background, which can be predicted from data with good statistical precision. The misidentification rate  $f_{e \rightarrow \gamma}$  is measured in data in  $Z \rightarrow e^+e^-$  decays with the “tag-and-probe” method [75]. The dependence of the misidentification rate on the electron  $p_T$  and  $\eta$  is studied. Nonresonant  $e^+e^-$  background from non  $Z$  boson events is estimated from  $e\mu$  events. The resulting misidentification rate in data is

$$f_{e \rightarrow \gamma} = 2.7 \pm 1.3\%. \quad (3)$$

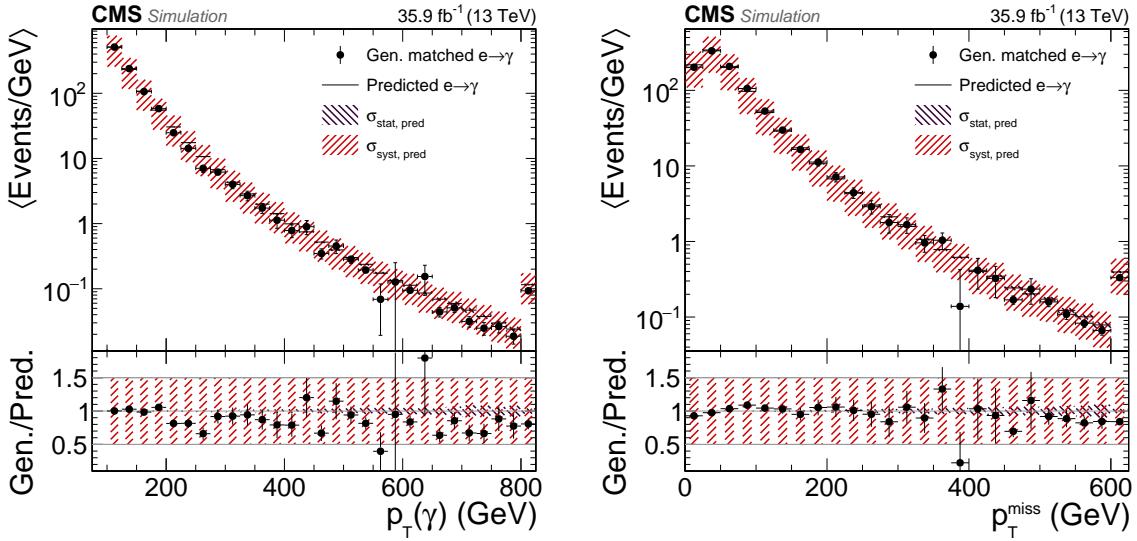


Figure 4: Validation of the electron misidentification background estimation method using MC simulation. In the selection with at least one photon with  $p_T > 100$  GeV, the prediction of the  $e \rightarrow \gamma$  misidentification estimation method is compared to direct simulation in the photon  $p_T$  (left) and the  $p_T^{\text{miss}}$  (right) distributions. The black and red hatched areas represent the statistical ( $\sigma_{\text{stat, pred}}$ ) and the 50% systematic ( $\sigma_{\text{syst, pred}}$ ) uncertainties of the prediction, respectively. Events populating the phase space beyond the shown range are included in the last bin.

The uncertainty of 50% takes into account the variation of the misidentification rate as a function of the photon  $p_T$ ,  $\eta$ , and several other variables.

The  $e \rightarrow \gamma$  background is modeled from a data control sample with the same event selection as the signal region, but containing an identified electron instead of a photon. The sample is weighted by  $f_{e \rightarrow \gamma}$ . The uncertainty of this estimation is dominated by the systematic uncertainties in the misidentification rate. The statistical uncertainty is negligible because the electron selection efficiency is about 40 times larger than  $f_{e \rightarrow \gamma}$ . The method has been validated using MC simulation, as shown in Fig. 4.

The minor contributions from  $t\bar{t}(\gamma)$  and diboson processes are modeled using MC simulation as discussed above. Events where electrons are misidentified as photons are removed at the generator level to avoid overlaps. Based on simulation studies, the background from QCD multijet events is found to be negligible.

All uncertainties that would affect the normalization are eliminated for the  $V(\gamma)$  and  $\gamma$ +jets backgrounds by the MC normalization method. Therefore, the only remaining uncertainties originate from the simulated shape of these backgrounds. The shape uncertainty due to the choice of the renormalization and factorization scales has been determined by varying these scales in different combinations of factors 0.5, 1, and 2 and repeating the fit of the  $V(\gamma)$  and  $\gamma$ +jets backgrounds. The prediction for each combination is compared in the four signal region bins for both backgrounds separately and bin-by-bin. The largest deviation in the respective bin is taken as the systematic uncertainty and varies in the range of 3.8–9.0% and 2.8–7.1% for the  $V(\gamma)$  and  $\gamma$ +jets backgrounds, respectively. The LHC4PDF procedure [76] is used to determine the shape uncertainty due to the choice of the PDFs and is determined bin-by-bin in the signal region and taken as systematic uncertainty, varying in the range of 1.6–3.8% for the  $V(\gamma)$  and 1.9–8.2% for  $\gamma$ +jets the background. Although there is no direct usage of jets, the analysis is affected by the propagation of the jet energy scale (JES) uncertainty to  $p_T^{\text{miss}}$ . The resulting uncertainty affecting the final selection is determined by propagating the upward

Table 2: Systematic uncertainties in the background prediction in percent.

	V( $\gamma$ )	$\gamma$ +jets	$e \rightarrow \gamma$	$t\bar{t}(\gamma)$	Diboson
Fit uncert. of statistical origin	6.9	3.3	—	—	—
Scale uncertainty in shape	3.8–9.0	2.8–7.1	—	—	—
PDF uncertainty in shape	1.6–3.8	1.9–8.2	—	—	—
JES uncertainty in shape	5.0–5.9	0.9–32	—	—	—
Tag-and-probe fit	—	—	50	—	—
Cross section, PDF, scales	—	—	—	30	30
Integrated luminosity	—	—	—	2.5	2.5
Photon eff. scale factor	—	—	—	2.0	2.0
Trigger efficiency	—	—	—	0.4	0.4

Table 3: Systematic uncertainties in the signal predictions in percent.

Source	Signal scenario	
	EWK	Strong production
Statistical MC precision per signal region	1–28	2–50
Fast simulation uncertainty in $p_T^{\text{miss}}$	<0.1–5	<0.1–25
Scale uncertainty in shape	<0.1–1.8	<0.1–1.2
Integrated luminosity	2.5	2.5
Trigger efficiency	0.4	0.4
Photon scale factor	2.0	2.0
Pileup	<0.1–0.4	<0.1–2.1
ISR reweighting	0.6–3.0	—

and downward shift of the JES to  $p_T^{\text{miss}}$  and repeating the analysis using the shifted  $p_T^{\text{miss}}$ . The largest deviation in the prediction is taken as systematic uncertainty and varies in the range of 5.0–5.9% for the V( $\gamma$ ) and 0.9–32% for the  $\gamma$ +jets background. The large deviation of 32% for  $\gamma$ +jets affects the highest bin in  $S_T^\gamma$ , where only approximately one  $\gamma$ +jets event is expected, so the absolute effect of this large uncertainty is small. A 30% uncertainty is assumed for the  $t\bar{t}(\gamma)$  cross section, corresponding to a conservative estimate of the uncertainty with respect to the latest CMS measurement [77]. The uncertainty in the diboson cross section is assumed to be 30%. Further systematic uncertainties, also affecting the signal simulation, arise from the trigger efficiency (0.4%), the data to MC photon identification efficiency scale factor (2%) and the integrated luminosity (2.5%) [78].

We improve the MADGRAPH modeling of initial-state radiation (ISR), which affects the total transverse momentum ( $p_T^{\text{ISR}}$ ) of the system of SUSY particles, by reweighting the  $p_T^{\text{ISR}}$  distribution of MC SUSY events. This reweighting procedure is based on studies of the  $p_T$  of Z boson events [79]. The reweighting factors range between 1.18 at  $p_T^{\text{ISR}} = 125 \text{ GeV}$  and 0.78 for  $p_T^{\text{ISR}} > 600 \text{ GeV}$ . We take the deviation from unity as the systematic uncertainty in the reweighting procedure.

The systematic uncertainties affecting the background prediction and the signals are summarized in Tables 2 and 3, respectively.

In Fig. 5 the signal sensitive variable  $S_T^\gamma$  is shown for the control selection, used to derive scale factors for the  $\gamma$ +jets and V( $\gamma$ ) simulated samples, and for the validation selection. Good agreement is observed between the selected data and the SM background prediction.

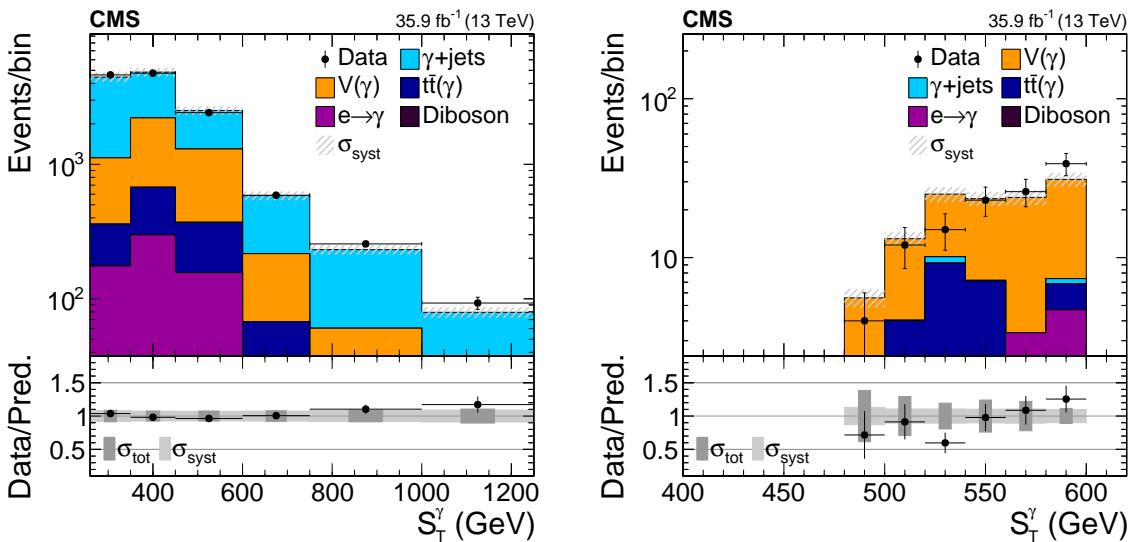


Figure 5: Data to simulation comparisons in the control region (left) and the validation region (right). Events with  $S_T^\gamma$  beyond the shown range are included in the last bin. The hatched light gray band in the upper panel, as well as the solid light gray band in the lower panel represent the total systematic uncertainty ( $\sigma_{\text{syst}}$ ). The dark gray band in the lower panel indicates the quadratic sum of the statistical and systematic uncertainties ( $\sigma_{\text{tot}}$ ).

## 7 Results and interpretation

Distributions of  $S_T^\gamma$  in the four search regions are shown in Fig. 6. The corresponding yields are given in Table 4 for each bin, also showing the contributions of the individual background components. The statistical uncertainty in the  $e \rightarrow \gamma$  background is caused by the limited size of the collected data sample. All other statistical uncertainties are due to the limited number of simulated events. The total systematic uncertainty results from the quadratic sum of the systematic uncertainties of each background component. Good agreement is observed between the SM background prediction and the recorded data, without indication for the presence of new physics.

Limits are calculated in one- and two-dimensional parameter spaces for the EWK and strong production models introduced in Section 1. Upper limits on the signal cross section are calculated at 95% confidence level (CL) using a modified frequentist CL<sub>s</sub> approach [80–82] with a profile likelihood test statistic and asymptotic formulae [83]. The 95% CL observed upper cross section limit, as well as the expected and observed exclusion contours, for the EWK GGM signal scan are shown in Fig. 7. The limits are presented in the wino-bino mass plane. The analysis reaches the highest sensitivity for nearly degenerate wino and bino masses. In this case, the analysis excludes wino and bino masses up to 980 GeV at 95% CL, improving on the former best limit of 710 GeV [26]. The sensitivity decreases with a larger wino-bino mass splitting since on average the energy of the photons and gravitinos decreases, while more energy is transferred to the other decay products of the  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$ .

The limits for the EWK TChiWg and TChiNg simplified models are shown as a function of  $m_{\text{NLSP}}$  in Fig. 8 together with the theoretical cross section. The analysis excludes NLSP masses below 780 GeV at 95% CL in the TChiWg scenario and below 950 GeV in the TChiNg scenario. Due to the slight excess observed with respect to the SM background prediction especially in the highest  $S_T^\gamma$  bins, the observed limits are weaker than the expected exclusion limits of 920 (1070) GeV for the TChiWg (TChiNg) scenario.

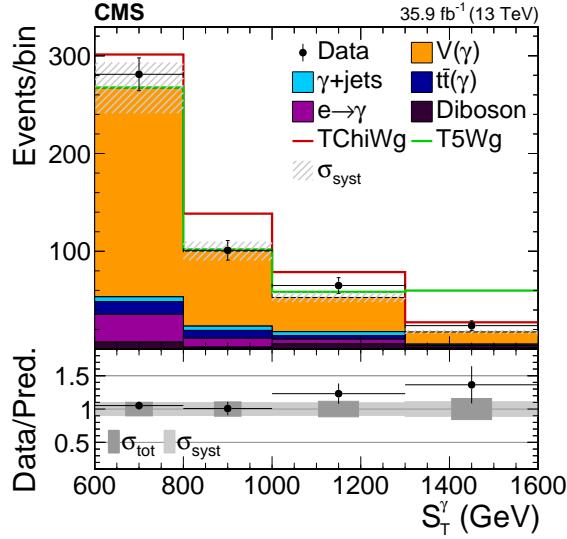


Figure 6: Comparison of the measurement and prediction in the signal region in four exclusive bins of  $S_T^\gamma$ . For guidance, two SUSY benchmark signal points are stacked on the SM background prediction, where the TChiWg signal point corresponds to a NLSP mass of 700 GeV and the T5Wg signal point corresponds to a gluino mass of 1750 GeV and a NLSP mass of 1700 GeV. Events with values of  $S_T^\gamma$  beyond the shown range are included in the last bin. The hatched light gray band in the upper panel, as well as the solid light gray band in the lower panel represent the total systematic uncertainty ( $\sigma_{\text{syst}}$ ). The dark gray band in the lower panel indicates the quadratic sum of the statistical and systematic uncertainties ( $\sigma_{\text{tot}}$ ).

Table 4: Background and data yields, as well as the statistical and systematic uncertainties for the separate signal region bins. For the total background uncertainty the uncertainties of the individual background components are summed quadratically.

$S_T^\gamma: 600\text{--}800\text{ GeV}$				$S_T^\gamma: 800\text{--}1000\text{ GeV}$			
	Yield	$\sigma_{\text{stat}}$	$\sigma_{\text{syst}}$		Yield	$\sigma_{\text{stat}}$	$\sigma_{\text{syst}}$
V( $\gamma$ )	213	4.4	21.3	V( $\gamma$ )	76.8	1.9	8.1
$\gamma$ +jets	5	1.1	0.5	$\gamma$ +jets	4.4	1.2	0.4
t $\bar{t}$ ( $\gamma$ )	13	5.7	3.9	t $\bar{t}$ ( $\gamma$ )	8.0	3.8	2.4
e $\rightarrow \gamma$	29	0.9	14.2	e $\rightarrow \gamma$	9.2	0.5	4.6
Diboson	7	2.8	2.1	Diboson	1.9	1.7	0.6
Total	267	7.9	26.0	Total	100.2	4.7	9.7
Data	281			Data	101		

$S_T^\gamma: 1000\text{--}1300\text{ GeV}$				$S_T^\gamma: >1300\text{ GeV}$			
	Yield	$\sigma_{\text{stat}}$	$\sigma_{\text{syst}}$		Yield	$\sigma_{\text{stat}}$	$\sigma_{\text{syst}}$
V( $\gamma$ )	35.0	1.3	3.9	V( $\gamma$ )	12.6	0.7	1.6
$\gamma$ +jets	4.2	1.3	0.4	$\gamma$ +jets	1.1	0.5	0.4
t $\bar{t}$ ( $\gamma$ )	3.5	0.9	1.1	t $\bar{t}$ ( $\gamma$ )	0.7	0.5	0.2
e $\rightarrow \gamma$	4.7	0.4	2.3	e $\rightarrow \gamma$	1.5	0.2	0.8
Diboson	5.4	3.0	1.6	Diboson	1.7	1.7	0.5
Total	52.8	3.6	5.0	Total	17.6	2.0	1.9
Data	65			Data	24		

The results are also interpreted in simplified models of strong production scenarios. The two

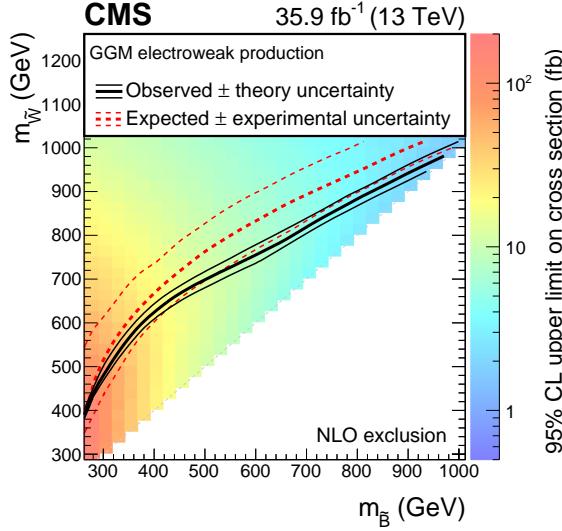


Figure 7: Observed upper cross section limit at 95% CL for the EWK GGM signal in the wino-bino mass plane. The thick lines represent the observed (black) and expected (red) exclusion contours, where the phase space closer to the diagonal is excluded by the analysis. The thin dotted red curves indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis. The thin solid black curves show the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

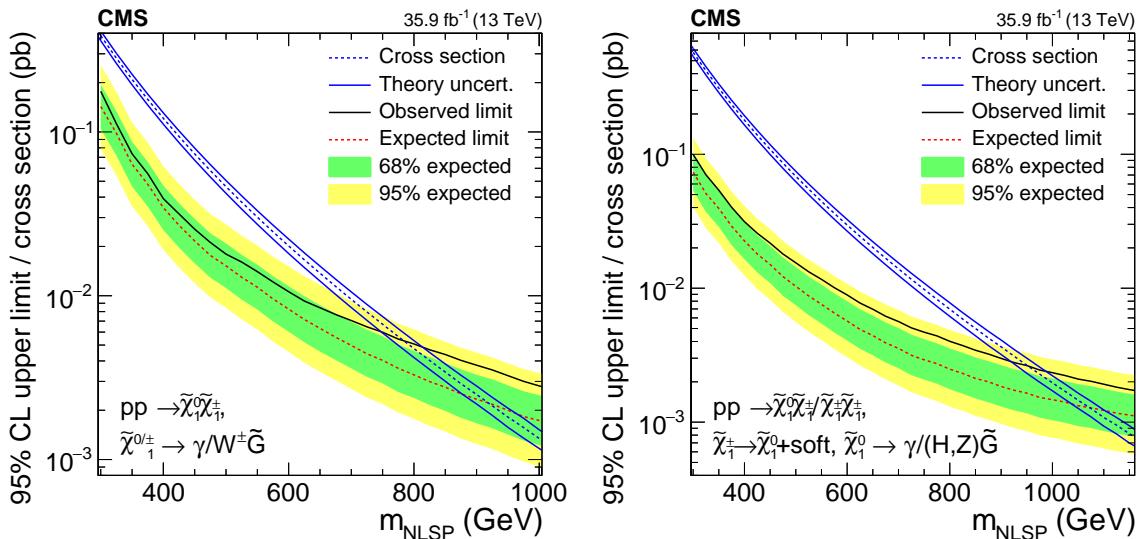


Figure 8: Observed (black) and expected (red) upper cross section limits as a function of the NLSP mass for the TChiWg (left) and TChiNg (right) model together with the corresponding theoretical cross section (blue). The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The solid blue lines represent the theoretical uncertainty in the signal cross section.

scenarios T5gg and T5Wg represent the gluino pair production with two photons and one photon and one W boson in the final state, respectively. The cross section limits and exclusion contours are shown in Fig. 9 in the  $\tilde{g} - \tilde{\chi}_1^0/\tilde{\chi}_1^\pm$  mass plane. This search can exclude gluino masses of up to 2100 (2000) GeV in the T5gg (T5Wg) scenario. The limit gets weaker at low

NSLP masses because of the acceptance loss, which mostly arises from the lower energy of the photons and the gravitinos accompanied by larger hadronic activity in the event.

Similar scenarios, T6gg and T6Wg, based on squark production are also used for interpretation and are shown in Fig. 10. Here, squark masses up to 1750 (1650) GeV are excluded for T6gg (T6Wg).

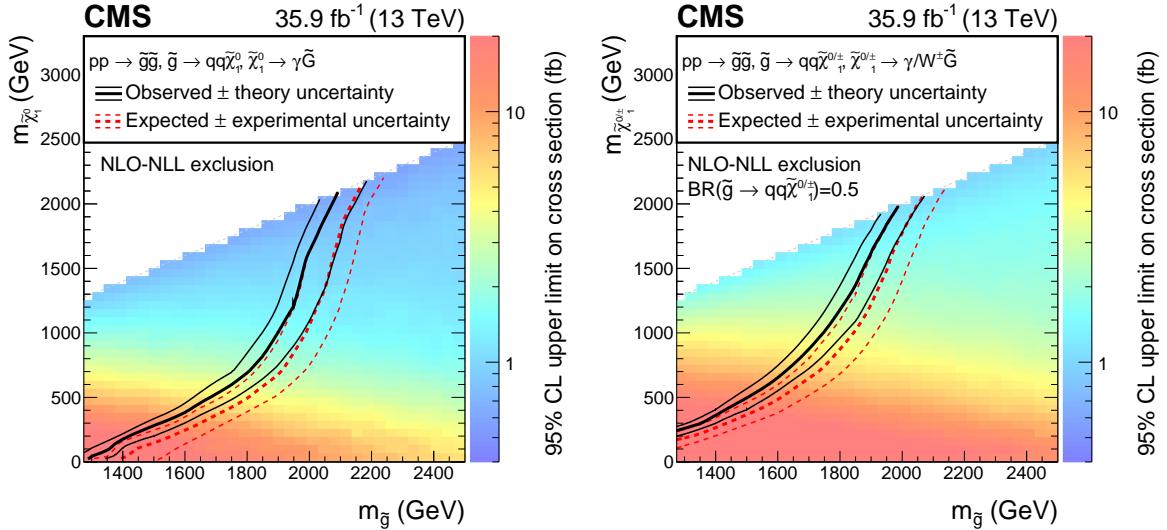


Figure 9: The 95% CL limits for the T5gg (left) and T5Wg (right) SMS models in the gluino-neutralino/chargino mass plane. The color scale encodes the observed upper cross section limit for each point. The thick lines represent the observed (black) and expected (red) exclusion contours, where the phase space of lower masses is excluded by the analysis. The thin dotted red curves indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis. The thin solid black curves show the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

The mass limits on squarks are weaker compared to those on gluinos due to the generally lower production cross section. However, for squark production the hadronic activity in the event is lower compared to gluino production, slightly reducing the dependence on the  $\tilde{q} - \tilde{\chi}_1^0/\tilde{\chi}_1^\pm$  mass difference. The higher sensitivity in the T5gg and T6gg models is due to two photons contributing to  $S_T^\gamma$ , increasing the separation power between the signal and the SM background.

## 8 Summary

A search for electroweak (EWK) and strong production of gauginos in the framework of gauge mediated supersymmetry breaking in final states with photons and large missing transverse momentum has been performed. A data set recorded by the CMS experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ , was analyzed. The data were found to agree with the expectation from the standard model, without any indication of new physics.

The analysis is sensitive to EWK production of gauginos and to strong production of gluinos and squarks in particular if the mass difference between gauginos and gluinos or squarks is small. A two-dimensional EWK signal scan in the framework of general gauge mediation is used to interpret the results. In the case of similar wino and bino masses, the analysis excludes masses below 980 GeV at 95% confidence level, improving on the current best limit by

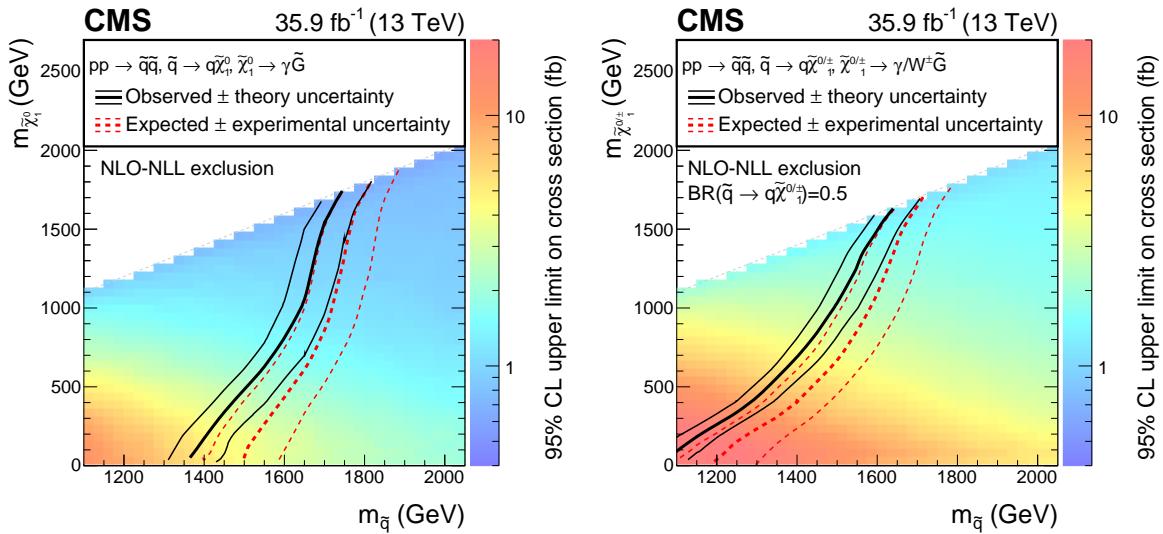


Figure 10: The 95% CL limits for the T6gg (left) and T6Wg (right) SMS models in the squark-neutralino/chargino mass plane. The color scale encodes the observed upper cross section limit for each point. The thick lines represent the observed (black) and expected (red) exclusion contours, where the phase space of lower masses is excluded by the analysis. The thin dotted red curves indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis. The thin solid black curves show the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties. For the signal production cross section five accessible mass-degenerate squark flavors for  $\tilde{q}_L$  and  $\tilde{q}_R$  were assumed.

270 GeV [26]. Two EWK simplified models are also used for the interpretation. The analysis excludes masses of the next-to-lightest supersymmetric particle  $\tilde{\chi}_1^0$  below 780 (950) GeV in the TChiWg (TChiNg) scenario. Additionally, limits are set for strong production simplified models based on gluino (T5gg, T5Wg) and squark (T6gg, T6Wg) pair production, excluding gluino (squark) masses up to 2100 (1750) GeV. This analysis complements searches in the photon+jets, diphoton, and photon+leptons final states, and sets the most stringent limits to date in the EWK production models, and in the strong production models when the gauginos are degenerate in mass with the gluino or squarks.

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## References

- [1] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) 1, doi:[10.1016/j.physletb.2012.08.020](https://doi.org/10.1016/j.physletb.2012.08.020), arXiv:[1207.7214](https://arxiv.org/abs/1207.7214).
- [2] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30, doi:[10.1016/j.physletb.2012.08.021](https://doi.org/10.1016/j.physletb.2012.08.021), arXiv:[1207.7235](https://arxiv.org/abs/1207.7235).
- [3] CMS Collaboration, “Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV”, *Eur. Phys. J. C* **75** (2015) 212, doi:[10.1140/epjc/s10052-015-3351-7](https://doi.org/10.1140/epjc/s10052-015-3351-7), arXiv:[1412.8662](https://arxiv.org/abs/1412.8662).
- [4] P. Ramond, “Dual theory for free fermions”, *Phys. Rev. D* **3** (1971) 2415, doi:[10.1103/PhysRevD.3.2415](https://doi.org/10.1103/PhysRevD.3.2415).
- [5] P. Ramond, “An interpretation of dual theories”, *Nuovo Cim. A* **4** (1971) 544, doi:[10.1007/BF02731370](https://doi.org/10.1007/BF02731370).
- [6] Yu. A. Gol'dand and E. P. Likhtman, “Extension of the algebra of Poincaré group generators and violation of P invariance”, *JETP Lett.* **13** (1971) 323.
- [7] D. V. Volkov and V. P. Akulov, “Possible universal neutrino interaction”, *JETP Lett.* **16** (1972) 438, doi:[10.1007/BFb0105270](https://doi.org/10.1007/BFb0105270).

- [8] J. Wess and B. Zumino, “Supergauge transformations in four-dimensions”, *Nucl. Phys. B* **70** (1974) 39, doi:10.1016/0550-3213(74)90355-1.
- [9] D. Z. Freedman, P. van Nieuwenhuizen, and S. Ferrara, “Progress toward a theory of supergravity”, *Phys. Rev. D* **13** (1976) 3214, doi:10.1103/PhysRevD.13.3214.
- [10] S. Deser and B. Zumino, “Consistent supergravity”, *Phys. Lett. B* **62** (1976) 335, doi:10.1016/0370-2693(76)90089-7.
- [11] D. Z. Freedman and P. van Nieuwenhuizen, “Properties of supergravity theory”, *Phys. Rev. D* **14** (1976) 912, doi:10.1103/PhysRevD.14.912.
- [12] S. Ferrara and P. van Nieuwenhuizen, “Consistent supergravity with complex spin 3/2 gauge fields”, *Phys. Rev. Lett.* **37** (1976) 1669, doi:10.1103/PhysRevLett.37.1669.
- [13] P. Fayet, “Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino”, *Nucl. Phys. B* **90** (1975) 104, doi:10.1016/0550-3213(75)90636-7.
- [14] A. H. Chamseddine, R. L. Arnowitt, and P. Nath, “Locally supersymmetric grand unification”, *Phys. Rev. Lett.* **49** (1982) 970, doi:10.1103/PhysRevLett.49.970.
- [15] R. Barbieri, S. Ferrara, and C. A. Savoy, “Gauge models with spontaneously broken local supersymmetry”, *Phys. Lett. B* **119** (1982) 343, doi:10.1016/0370-2693(82)90685-2.
- [16] L. J. Hall, J. D. Lykken, and S. Weinberg, “Supergravity as the messenger of supersymmetry breaking”, *Phys. Rev. D* **27** (1983) 2359, doi:10.1103/PhysRevD.27.2359.
- [17] G. L. Kane, C. F. Kolda, L. Roszkowski, and J. D. Wells, “Study of constrained minimal supersymmetry”, *Phys. Rev. D* **49** (1994) 6173, doi:10.1103/PhysRevD.49.6173, arXiv:hep-ph/9312272.
- [18] P. Fayet, “Mixing between gravitational and weak interactions through the massive gravitino”, *Phys. Lett. B* **70** (1977) 461, doi:10.1016/0370-2693(77)90414-2.
- [19] H. Baer, M. Brhlik, C. H. Chen, and X. Tata, “Signals for the minimal gauge-mediated supersymmetry breaking model at the Fermilab Tevatron collider”, *Phys. Rev. D* **55** (1997) 4463, doi:10.1103/PhysRevD.55.4463, arXiv:hep-ph/9610358.
- [20] H. Baer, P. G. Mercadante, X. Tata, and Y. L. Wang, “Reach of Tevatron upgrades in gauge-mediated supersymmetry breaking models”, *Phys. Rev. D* **60** (1999) 055001, doi:10.1103/PhysRevD.60.055001, arXiv:hep-ph/9903333.
- [21] S. Dimopoulos, S. Thomas, and J. D. Wells, “Sparticle spectroscopy and electroweak symmetry breaking with gauge-mediated supersymmetry breaking”, *Nucl. Phys. B* **488** (1997) 39, doi:10.1016/S0550-3213(97)00030-8, arXiv:hep-ph/9609434.
- [22] J. R. Ellis, J. L. Lopez, and D. V. Nanopoulos, “Analysis of LEP constraints on supersymmetric models with a light gravitino”, *Phys. Lett. B* **394** (1997) 354, doi:10.1016/S0370-2693(97)00019-1, arXiv:hep-ph/9610470.
- [23] M. Dine, A. E. Nelson, Y. Nir, and Y. Shirman, “New tools for low energy dynamical supersymmetry breaking”, *Phys. Rev. D* **53** (1996) 2658, doi:10.1103/PhysRevD.53.2658, arXiv:hep-ph/9507378.

- [24] G. F. Giudice and R. Rattazzi, “Gauge-mediated supersymmetry breaking”, in *Perspectives on supersymmetry*, p. 355. World Scientific, Singapore, 1998.
- [25] G. R. Farrar and P. Fayet, “Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry”, *Phys. Lett. B* **76** (1978) 575, doi:10.1016/0370-2693(78)90858-4.
- [26] CMS Collaboration, “Search for supersymmetry in electroweak production with photons and large missing transverse energy in pp collisions at  $\sqrt{s} = 8 \text{ TeV}$ ”, *Phys. Lett. B* **759** (2016) 479, doi:10.1016/j.physletb.2016.05.088, arXiv:1602.08772.
- [27] CMS Collaboration, “Data parking and data scouting at the CMS experiment”, CMS Detector Performance note CMS-DP-2012-022, (2012).
- [28] CMS Collaboration, “Search for supersymmetry in events with a photon, a lepton, and missing transverse momentum in pp collisions at  $\sqrt{s} = 8 \text{ TeV}$ ”, *Phys. Lett. B* **757** (2016) 6, doi:10.1016/j.physletb.2016.03.039, arXiv:1508.01218.
- [29] ATLAS Collaboration, “Search for photonic signatures of gauge-mediated supersymmetry in 8 TeV pp collisions with the ATLAS detector”, *Phys. Rev. D* **92** (2015) 072001, doi:10.1103/PhysRevD.92.072001, arXiv:1507.05493.
- [30] CMS Collaboration, “Search for new physics in events with photons, jets, and missing transverse energy in pp collisions at  $\sqrt{s} = 7 \text{ TeV}$ ”, *JHEP* **03** (2013) 111, doi:10.1007/JHEP03(2013)111, arXiv:1211.4784.
- [31] CMS Collaboration, “Search for supersymmetry with photons in pp collisions at  $\sqrt{s} = 8 \text{ TeV}$ ”, *Phys. Rev. D* **92** (2015) 072006, doi:10.1103/PhysRevD.92.072006, arXiv:1507.02898.
- [32] P. Meade, N. Seiberg, and D. Shih, “General gauge mediation”, *Prog. Theor. Phys. Suppl.* **177** (2009) 143, doi:10.1143/PTPS.177.143, arXiv:0801.3278.
- [33] M. Buican, P. Meade, N. Seiberg, and D. Shih, “Exploring general gauge mediation”, *JHEP* **03** (2009) 016, doi:10.1088/1126-6708/2009/03/016, arXiv:0812.3668.
- [34] J. T. Ruderman and D. Shih, “General neutralino NLSPs at the early LHC”, *JHEP* **08** (2012) 159, doi:10.1007/JHEP08(2012)159, arXiv:1103.6083.
- [35] Y. Kats, P. Meade, M. Reece, and D. Shih, “The status of GMSB after  $1 \text{ fb}^{-1}$  at the LHC”, *JHEP* **02** (2012) 115, doi:10.1007/JHEP02(2012)115, arXiv:1110.6444.
- [36] Y. Kats and M. J. Strassler, “Probing colored particles with photons, leptons, and jets”, *JHEP* **11** (2012) 097, doi:10.1007/JHEP11(2012)097, arXiv:1204.1119.
- [37] P. Grajek, A. Mariotti, and D. Redigolo, “Phenomenology of general gauge mediation in light of a 125 GeV Higgs”, *JHEP* **07** (2013) 109, doi:10.1007/JHEP07(2013)109, arXiv:1303.0870.
- [38] CMS Collaboration, “Interpretation of searches for supersymmetry with simplified models”, *Phys. Rev. D* **88** (2013) 052017, doi:10.1103/PhysRevD.88.052017, arXiv:1301.2175.
- [39] CMS Collaboration, “Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8 \text{ TeV}$ ”, *JINST* **10** (2015) P08010, doi:10.1088/1748-0221/10/08/P08010, arXiv:1502.02702.

- [40] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:[10.1088/1748-0221/3/08/S08004](https://doi.org/10.1088/1748-0221/3/08/S08004).
- [41] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:[10.1088/1748-0221/12/10/P10003](https://doi.org/10.1088/1748-0221/12/10/P10003), arXiv:[1706.04965](https://arxiv.org/abs/1706.04965).
- [42] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8 \text{ TeV}$ ”, *JINST* **10** (2015) P06005, doi:[10.1088/1748-0221/10/06/P06005](https://doi.org/10.1088/1748-0221/10/06/P06005), arXiv:[1502.02701](https://arxiv.org/abs/1502.02701).
- [43] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- $k_t$  jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:[10.1088/1126-6708/2008/04/063](https://doi.org/10.1088/1126-6708/2008/04/063), arXiv:[0802.1189](https://arxiv.org/abs/0802.1189).
- [44] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:[10.1140/epjc/s10052-012-1896-2](https://doi.org/10.1140/epjc/s10052-012-1896-2), arXiv:[1111.6097](https://arxiv.org/abs/1111.6097).
- [45] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Phys. Lett. B* **659** (2008) 119, doi:[10.1016/j.physletb.2007.09.077](https://doi.org/10.1016/j.physletb.2007.09.077), arXiv:[0707.1378](https://arxiv.org/abs/0707.1378).
- [46] CMS Collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, *JINST* **6** (2011) 11002, doi:[10.1088/1748-0221/6/11/P11002](https://doi.org/10.1088/1748-0221/6/11/P11002), arXiv:[1107.4277](https://arxiv.org/abs/1107.4277).
- [47] CMS Collaboration, “Performance of the CMS missing transverse momentum reconstruction in pp data at  $\sqrt{s} = 8 \text{ TeV}$ ”, *JINST* **10** (2015) P02006, doi:[10.1088/1748-0221/10/02/P02006](https://doi.org/10.1088/1748-0221/10/02/P02006), arXiv:[1411.0511](https://arxiv.org/abs/1411.0511).
- [48] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:[10.1007/JHEP07\(2014\)079](https://doi.org/10.1007/JHEP07(2014)079), arXiv:[1405.0301](https://arxiv.org/abs/1405.0301).
- [49] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:[10.1140/epjc/s10052-007-0490-5](https://doi.org/10.1140/epjc/s10052-007-0490-5), arXiv:[0706.2569](https://arxiv.org/abs/0706.2569).
- [50] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:[10.1007/JHEP12\(2012\)061](https://doi.org/10.1007/JHEP12(2012)061), arXiv:[1209.6215](https://arxiv.org/abs/1209.6215).
- [51] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:[10.1088/1126-6708/2004/11/040](https://doi.org/10.1088/1126-6708/2004/11/040), arXiv:[hep-ph/0409146](https://arxiv.org/abs/hep-ph/0409146).
- [52] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:[10.1088/1126-6708/2007/11/070](https://doi.org/10.1088/1126-6708/2007/11/070), arXiv:[0709.2092](https://arxiv.org/abs/0709.2092).
- [53] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:[10.1007/JHEP06\(2010\)043](https://doi.org/10.1007/JHEP06(2010)043), arXiv:[1002.2581](https://arxiv.org/abs/1002.2581).
- [54] T. Melia, P. Nason, R. Rontsch, and G. Zanderighi, “ $W^+W^-$ ,  $WZ$  and  $ZZ$  production in the POWHEG BOX”, *JHEP* **11** (2011) 078, doi:[10.1007/JHEP11\(2011\)078](https://doi.org/10.1007/JHEP11(2011)078), arXiv:[1107.5051](https://arxiv.org/abs/1107.5051).

- [55] P. Nason and G. Zanderighi, “ $W^+W^-$ ,  $WZ$  and  $ZZ$  production in the POWHEG-BOX-V2”, *Eur. Phys. J. C* **74** (2014) 2702,  
doi:10.1140/epjc/s10052-013-2702-5, arXiv:1311.1365.
- [56] T. Sjöstrand, S. Mrenna, and P. Z. Skands, “PYTHIA 6.4 physics and manual”, *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.
- [57] G. Bozzi et al., “Production of Drell–Yan lepton pairs in hadron collisions: Transverse-momentum resummation at next-to-next-to-leading logarithmic accuracy”, *Phys. Lett. B* **696** (2011) 207, doi:10.1016/j.physletb.2010.12.024, arXiv:1007.2351.
- [58] T. Gehrmann et al., “ $W^+W^-$  production at hadron colliders in next-to-next-to leading order QCD”, *Phys. Rev. Lett.* **113** (2014) 212001,  
doi:10.1103/PhysRevLett.113.212001, arXiv:1408.5243.
- [59] W. Beenakker, R. Hopker, M. Spira, and P. M. Zerwas, “Squark and gluino production at hadron colliders”, *Nucl. Phys. B* **492** (1997) 51,  
doi:10.1016/S0550-3213(97)80027-2, arXiv:hep-ph/9610490.
- [60] A. Kulesza and L. Motyka, “Threshold resummation for squark-antisquark and gluino-pair production at the LHC”, *Phys. Rev. Lett.* **102** (2009) 111802,  
doi:10.1103/PhysRevLett.102.111802, arXiv:0807.2405.
- [61] A. Kulesza and L. Motyka, “Soft gluon resummation for the production of gluino-gluino and squark-antisquark pairs at the LHC”, *Phys. Rev. D* **80** (2009) 095004,  
doi:10.1103/PhysRevD.80.095004, arXiv:0905.4749.
- [62] W. Beenakker et al., “Soft-gluon resummation for squark and gluino hadroproduction”, *JHEP* **12** (2009) 041, doi:10.1088/1126-6708/2009/12/041, arXiv:0909.4418.
- [63] W. Beenakker et al., “Squark and gluino hadroproduction”, *Int. J. Mod. Phys. A* **26** (2011) 2637, doi:10.1142/S0217751X11053560, arXiv:1105.1110.
- [64] C. Borschensky et al., “Squark and gluino production cross sections in pp collisions at  $\sqrt{s} = 13, 14, 33$  and  $100\text{ TeV}$ ”, *Eur. Phys. J. C* **74** (2014) 3174,  
doi:10.1140/epjc/s10052-014-3174-y, arXiv:1407.5066.
- [65] W. Beenakker et al., “Production of charginos, neutralinos, and sleptons at hadron colliders”, *Phys. Rev. Lett.* **83** (1999) 3780, doi:10.1103/PhysRevLett.83.3780, arXiv:hep-ph/9906298. [Erratum: *Phys. Rev. Lett.* **100** (2008) 029901, doi:10.1103/PhysRevLett.100.029901].
- [66] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, “Gaugino production in proton-proton collisions at a center-of-mass energy of 8 TeV”, *JHEP* **10** (2012) 081, doi:10.1007/JHEP10(2012)081, arXiv:1207.2159.
- [67] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, “Precision predictions for electroweak superpartner production at hadron colliders with RESUMMINO”, *Eur. Phys. J. C* **73** (2013) 2480, doi:10.1140/epjc/s10052-013-2480-0, arXiv:1304.0790.
- [68] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.

- [69] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [70] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [71] CMS Collaboration, “The fast simulation of the CMS detector at LHC”, volume 331, p. 032049. 2011. doi:10.1088/1742-6596/331/3/032049.
- [72] CMS Collaboration, “Recent developments in CMS fast simulation”, in *Proceedings, 38th International Conference on High Energy Physics (ICHEP 2016)*, p. 181. Chicago, Illinois, USA, August, 2016. arXiv:1701.03850. [PoS(ICHEP2016)181].
- [73] CMS Collaboration, “The CMS trigger system”, *J. Instrum.* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020.
- [74] CMS Collaboration, “Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid”, CMS Technical proposal CERN-LHCC-2015-010, CMS-TDR-15-02, CERN, 2015.
- [75] CMS Collaboration, “Measurement of the inclusive W and Z production cross sections in pp collisions at  $\sqrt{s} = 7 \text{ TeV}$ ”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.
- [76] J. Butterworth et al., “PDF4LHC recommendations for LHC Run II”, *J. Phys. G* **43** (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
- [77] CMS Collaboration, “Measurement of the semileptonic  $t\bar{t} + \gamma$  production cross section in pp collisions at  $\sqrt{s} = 8 \text{ TeV}$ ”, *JHEP* **10** (2017) 006, doi:10.1007/JHEP10(2017)006, arXiv:1706.08128.
- [78] CMS Collaboration, “CMS luminosity measurements for the 2016 data taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.
- [79] CMS Collaboration, “Search for top-squark pair production in the single-lepton final state in pp collisions at  $\sqrt{s} = 8 \text{ TeV}$ ”, *Eur. Phys. J. C* **73** (2013) 2677, doi:10.1140/epjc/s10052-013-2677-2, arXiv:1308.1586.
- [80] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [81] A. L. Read, “Presentation of search results: the  $CL_s$  technique”, in *Durham IPPP Workshop: Advanced Statistical Techniques in Particle Physics*, p. 2693. Durham, UK, March, 2002. [*J. Phys. G* **28** (2002) 2693]. doi:10.1088/0954-3899/28/10/313.
- [82] ATLAS, CMS, and LHC Higgs Combination Group collaborations, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report CMS-NOTE-2011-005. ATL-PHYS-PUB-2011-11, 2011.
- [83] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

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38: Also at P.N. Lebedev Physical Institute, Moscow, Russia  
39: Also at California Institute of Technology, Pasadena, USA  
40: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia  
41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia  
42: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia  
43: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy  
44: Also at National and Kapodistrian University of Athens, Athens, Greece  
45: Also at Riga Technical University, Riga, Latvia  
46: Also at Universität Zürich, Zurich, Switzerland  
47: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria  
48: Also at Istanbul Aydin University, Istanbul, Turkey  
49: Also at Mersin University, Mersin, Turkey  
50: Also at Cag University, Mersin, Turkey  
51: Also at Piri Reis University, Istanbul, Turkey  
52: Also at Gaziosmanpasa University, Tokat, Turkey  
53: Also at Izmir Institute of Technology, Izmir, Turkey  
54: Also at Necmettin Erbakan University, Konya, Turkey  
55: Also at Marmara University, Istanbul, Turkey  
56: Also at Kafkas University, Kars, Turkey  
57: Also at Istanbul Bilgi University, Istanbul, Turkey  
58: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom  
59: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom  
60: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain  
61: Also at Utah Valley University, Orem, USA  
62: Also at Beykent University, Istanbul, Turkey  
63: Also at Bingol University, Bingol, Turkey  
64: Also at Erzincan University, Erzincan, Turkey  
65: Also at Sinop University, Sinop, Turkey  
66: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey  
67: Also at Texas A&M University at Qatar, Doha, Qatar  
68: Also at Kyungpook National University, Daegu, Korea