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Search for supersymmetry in events with a lepton, a photon, and large missing transverse energy in pp collisions at $\sqrt{s} = 7$ TeV

The CMS collaboration

Abstract: A search is performed for an excess of events, over the standard model expectations, with a photon, a lepton, and large missing transverse energy in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$. Such events are expected in many new physics models, in particular a supersymmetric theory that is broken via a gauge-mediated mechanism, when the lightest charged and neutral gauginos are mass degenerate. The data sample used in this search corresponds to an integrated luminosity of 35 pb^{-1} collected with the CMS detector at the LHC. No evidence of such an excess above the standard model backgrounds, dominated by Wγ production, is found. The results are presented as 95% confidence level upper limits on the cross section for a benchmark gauge-mediated scenario, and are then converted into exclusion limits on the squark, gluino, and wino masses.

Keywords: Hadron-Hadron Scattering

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Contents

1 Introduction

Supersymmetry (SUSY) is one of the best studied scenarios for physics beyond the standard model (SM). It alleviates the hierarchy problem and may provide a path to the grand unification of forces. Of particular interest is a scenario with gauge-mediated SUSY breaking [1–9], which elegantly addresses the SUSY flavour problem. In the gauge mediation scenario, SUSY breaking occurs at energy scales much smaller than the Planck scale, resulting in the gravitino ($\tilde{G}$) as the lightest SUSY particle (LSP), which would escape detection and result in an imbalance of momentum in the plane transverse to the beam direction ($E_{\mathrm{T}}^{\mathrm{miss}}$). In one scenario of general gauge-mediated (GGM) SUSY [10, 11], the next-to-lightest SUSY particles (NLSP) are mostly the superpartners of the $\mathrm{SU}(2)_L$ gauge fields (winos). This scenario results in a small mass splitting between the charged ($\tilde{\mathrm{W}}^{\pm}$) and neutral ($\tilde{\mathrm{W}}^{0}$) winos. The charged wino decays promptly into a gravitino and a W boson, and the neutral wino into a gravitino and a photon or a Z boson [12]. If R-parity is conserved, coloured SUSY particles are pair-produced, resulting in the presence of two NLSPs and multiple jets per event. An example process is shown in figure 1. The event topologies of interest therefore contain, in addition to $E_{\mathrm{T}}^{\mathrm{miss}}$, one of the following signatures: two photons (γ); lepton(s) (ℓ) and one photon; lepton(s) and jets; one photon and jets; or all jets. Final states with two or more leptons are suppressed because of the W and Z leptonic branching fractions.

In this paper, we perform the first search for SUSY in the $\ell + \gamma + E_{\mathrm{T}}^{\mathrm{miss}} + X$ final state produced in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ at the Large Hadron Collider (LHC). The ℓ denotes an electron or a muon. The X represents the production of additional particles, such as jets, which are not explicitly required in this analysis in order to encompass a wide range of possible scenarios. Previous searches for anomalous production of such events were performed at the Fermilab Tevatron [13–15].

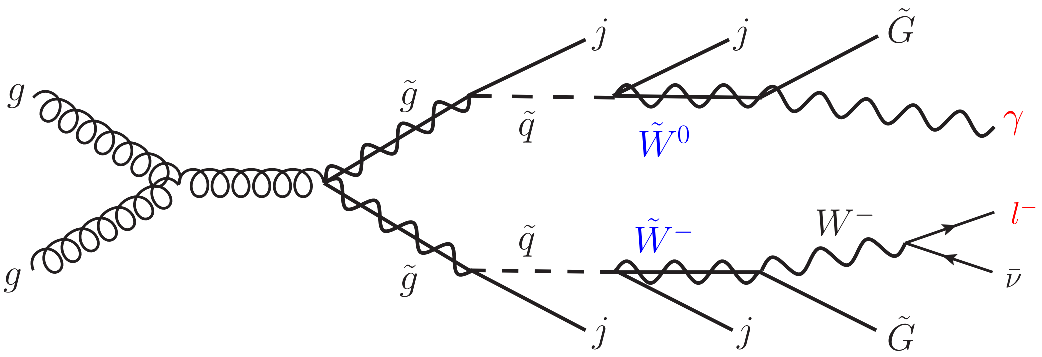

Figure 1. Feynman diagram for an example of a process with strong production of charged and neutral winos ($\tilde{\mathrm{W}}^{\pm}$ and $\tilde{\mathrm{W}}^0$) as co-NLSP with multiple jets (j), resulting in the signature $\ell + \gamma + E_{\mathrm{T}}^{\mathrm{miss}} + X$.

2 The CMS detector

The Compact Muon Solenoid (CMS) is a nearly hermetic, multipurpose detector and is described in detail elsewhere [16]. Charged particle trajectories are measured with silicon pixel and strip tracking detectors encompassed by a 3.8 T superconducting solenoid, with full azimuthal coverage and $|\eta| < 2.5$. The azimuthal angle ϕ is defined in the plane transverse to the beam direction. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the counterclockwise proton beam direction, with the origin at the center of the detector. Energy deposits of particles are measured with lead-tungstate crystal electromagnetic (ECAL) and brass/scintillator ($|\eta| < 3$) or iron/quartz-fiber ($3 < |\eta| < 5$) hadronic (HCAL) calorimeters. Muon candidates are identified in gas-ionisation detectors embedded in the steel return yoke of the magnet.

3 Candidate event selection

We use the data sample collected by the CMS detector at the LHC from March to November 2010 corresponding to an integrated luminosity of 35 pb^{-1} [17]. Events are required to have at least one high transverse momentum (p_{T}) electron or muon, in addition to a photon. Events are selected and recorded using a two-tiered trigger system. We use a suite of single-electron and single-muon triggers with several thresholds changing to match the rapidly increasing instantaneous luminosity of the LHC. The electron candidates are reconstructed from clusters of energy in the ECAL barrel ($|\eta| < 1.479$) and endcaps ($1.479 < |\eta| < 3$) and are required to match charged tracks reconstructed in the silicon tracking detectors. Muons are reconstructed as charged tracks matched to hit patterns in the muon detectors. We further require the leading electron or muon to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $|\eta| < 2.1$ and to satisfy a set of identification and isolation criteria [18]. For electrons, the region from $1.44 < |\eta| < 1.57$ is excluded since it contains services and cables exiting between the transition of the barrel and endcap calorimeters and leads to lower quality reconstructed clusters.

Events in which the electron is consistent with having originated from a photon conversion are rejected. The efficiency of the triggers for events with an electron (muon) with p_{T} above 20 GeV is measured to be 0.98 ± 0.01 (0.968 ± 0.004). Lepton identification and reconstruction efficiencies are measured in data using $\mathrm{Z} \to \ell^+\ell^-$ decays. The ratio of the lepton efficiencies measured in data to those from Monte Carlo (MC) simulation (described below) is found to be 0.928 ± 0.015 (0.990 ± 0.001) for an electron (muon). We require the presence of at least one photon with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 1.44$, spatially separated from the lepton by $\Delta R(\ell, \gamma) = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$. The reconstruction of photon candidates in the calorimeter is similar to that of the electrons, with the additional requirement that they do not have associated hit patterns in the pixel detector consistent with a track. The data/MC scale factor for the photon efficiency is 0.97 ± 0.02. We demand that the lepton and the photon candidates be isolated from any other activity in the tracker, ECAL, or HCAL. The events are required to contain at least one reconstructed primary vertex within 24 cm of the geometric center of the detector along the beamline and a transverse distance with respect to the reconstructed beam axis of less than 2 cm. These selections define our candidate sample, which consists of 264 (126) events in the $\mathrm{e}\gamma$ ($\mu\gamma$) channel. Finally, in order to minimise the number of expected background events while retaining high signal efficiency, we select events with $E_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is reconstructed using calorimeter energy deposits and is corrected for the contribution from the muons and for the expected calorimeter response for each reconstructed hadron track [19].

4 Background estimation

The dominant background process is $\mathrm{W}\gamma$ production, with the W boson decaying leptonically. This background is estimated using the MADGRAPH MC generator [20] with parton showering using PYTHIA [21]. The result is scaled from the leading-order (LO) to the next-to-leading-order (NLO) cross section obtained from the WGRAD NLO $\mathrm{W}\gamma$ generator [22, 23] and using the CTEQ6.6 NLO parton distribution function (PDF) sets [24]. For example, for a photon with $p_{\mathrm{T}} = 50\,\mathrm{GeV}$ the NLO/LO K factor is 2.3. The NLO calculation is in good agreement with the $\mathrm{W}\gamma$ production cross section measured by the CMS collaboration [25], over the relevant phase space of that measurement, giving confidence in the NLO prediction used here. The MC events are processed with the full CMS detector simulation based on the Geant4 [26] package. To estimate the uncertainty on the K factor due to higher-order corrections, we vary the factorisation and renormalisation scales by a factor of two and observe a variation in the cross section of approximately 20%. Additional systematic uncertainties on this background estimate include the uncertainties on the trigger efficiencies and data/MC scale factors described above, the PDF set estimated using the PDF4LHC working group procedure (2%) [27], and the integrated luminosity measurement (4%) [17].

The next most important instrumental background originates from SM processes that have misidentified leptons and photons. Data-driven methods are used to determine all backgrounds involving object misidentification [28]. We consider sources of background in which a jet or an electron is misidentified as a photon (jet $\to \gamma$ and $\mathrm{e} \to \gamma$) or in which a jet is misidentified as a lepton. The dominant SM processes that contribute to the jet

$\to \gamma$ misidentification background include W+jets and QCD multijet production. The jet $\to \gamma$ background is determined by selecting a sample of events that satisfy the criteria of our $\ell\gamma$ candidate sample except that the photon is required to fail either the isolation or electromagnetic shower shape criterion. We then weight this sample by the probability of misidentifying a jet as a photon [29] to estimate the total contribution of this background to the signal sample. The SM processes contributing to the e $\to \gamma$ misidentification background are predominantly Z and $t\bar{t}$ production. The e $\to \gamma$ background is determined in a similar way to the jet $\to \gamma$ background, by selecting a sample of events that satisfy the criteria of our $\ell\gamma$ candidate sample but with the additional requirement that the photon be matched to a pattern of hits in the pixel tracker. We then weight this sample by the probability of misidentifying an electron as a photon (f_{γ_e}) to estimate the total contribution of this background to the signal sample. The probability, f_{γ_e}, is determined from Z $\to$ e$^+$e$^-$ data to be 0.014 ± 0.004.

The strategy for determining QCD contributions which have poorly measured $E_{\mathrm{T}}^{\mathrm{miss}}$ is to select events with kinematic properties similar to the candidate events, but which are known to have no genuine $E_{\mathrm{T}}^{\mathrm{miss}}$. A control sample of events dominated by Z $\to$ e$^+$e$^-$ decays is used. These events are further reweighted to reproduce the $\ell\gamma$ sample kinematics. In particular, we reproduce the $\ell\gamma$ transverse energy distribution and, therefore, the transverse energy of the hadronic recoil against the $\ell\gamma$ candidates, ensuring a correct description of the $E_{\mathrm{T}}^{\mathrm{miss}}$. In order to describe the distribution of the transverse mass of the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ system, defined as $M_T = \sqrt{2 \cdot p_{T_\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos(\phi_\ell - \phi_{E_{\mathrm{T}}^{\mathrm{miss}}}))}$, the lepton p_T distribution is also reweighted. We determine the background contribution by normalising the control sample in such a way that the total background matches the number of selected events in data with $E_{\mathrm{T}}^{\mathrm{miss}}$ less than 30 GeV. Tables 1 and 2 summarise the breakdown of the backgrounds for $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV and for our optimal selection of $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV. The dominant sources of systematic uncertainties are due to the limited precision of the data-driven methods and the uncertainties on the corresponding misidentification rate measurements.

5 Results

The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution is shown in figure 2 (top) for the eγ and $\mu\gamma$ channels combined, together with the sum of the expected background contributions, as well as the expectation of the signal from a SUSY benchmark point (referred to as GMC, described below) for comparison. Figure 2 (bottom) shows the M_T distribution. The data agree well with the SM expectations and do not exhibit any evidence for an excess of events with high $E_{\mathrm{T}}^{\mathrm{miss}}$.

We performed several cross-checks to support our modeling of the SM backgrounds. For example, events with M_T above 70 GeV have small QCD background, as shown in figure 2 (bottom), and we verified that we can describe all the kinematic distributions in these events with the sum of the expected backgrounds, except the contribution from QCD. We also checked that the photon candidates have a timing consistent with having originated from the primary vertex, to verify that non-collision backgrounds are negligible. Finally, we verified that our QCD background determination procedure works in the presence of a

	No $E_{\mathrm{T}}^{\mathrm{miss}}$ selection	$E_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$
Wγ	44.5 ± 9.2	16.1 ± 3.4	1.68 ± 0.42
jet$\rightarrow \gamma$	20.3 ± 4.5	3.1 ± 0.9	0.02 ± 0.02
e $\rightarrow \gamma$	70.5 ± 19.1	0.3 ± 0.1	0.04 ± 0.03
QCD	134 ± 28	0.4 ± 0.2	0.00 ± 0.00
Total background	269 ± 18	19.9 ± 3.7	1.74 ± 0.43
data	264	16	1
SUSY GMC prediction	3.94 ± 0.79	3.76 ± 0.75	2.79 ± 0.56

Table 1. Event counts for data and expected background in the eγ channel. The uncertainty on the total background includes the anti-correlation between the uncertainties on the individual components due to the scaling of the QCD background to the events with $E_{\mathrm{T}}^{\mathrm{miss}} < 30\,\mathrm{GeV}$ as described in the text. The expected event yields from the SUSY benchmark point GMC (section 5) are also shown.

	No $E_{\mathrm{T}}^{\mathrm{miss}}$ selection	$E_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$
Wγ	44.8 ± 9.3	15.9 ± 3.4	1.40 ± 0.37
jet$\rightarrow \gamma$	18.0 ± 4.0	3.7 ± 1.1	0.10 ± 0.09
e $\rightarrow \gamma$	1.2 ± 0.4	0.6 ± 0.2	0.09 ± 0.04
QCD	58.3 ± 15.1	0.2 ± 0.1	0.00 ± 0.00
Total background	122.3 ± 12.3	20.4 ± 3.7	1.59 ± 0.39
data	126	27	1
SUSY GMC prediction	5.12 ± 1.02	4.84 ± 0.96	3.66 ± 0.73

Table 2. Event counts for data and expected background in the $\mu\gamma$ channel. The uncertainty on the total background includes the anti-correlation between the uncertainties on the individual components due to the scaling of the QCD background to the events with $E_{\mathrm{T}}^{\mathrm{miss}} < 30\,\mathrm{GeV}$ as described in the text. The expected event yields from the SUSY benchmark point GMC (section 5) are also shown.

large range of SUSY signals by mixing simulated SUSY events into the data sample and recalculating the QCD background; the change in its value was found to be negligible.

Since we observe no evidence of an excess of events with high $E_{\mathrm{T}}^{\mathrm{miss}}$ compared to the SM expectations, we interpret our results by placing 95% confidence level (CL) lower limits on GGM SUSY particle masses in a benchmark model. The GGM SUSY [12] signal is simulated using the PYTHIA [21] MC generator version 6.420 with tune D6T [30], and assuming that the squark mass ($m(\tilde{q})$) is approximately equal to the gluino mass ($m(\tilde{g})$), with the charged and neutral winos as co-NLSPs, $\tan\beta = 2$, and the gravitino mass $m(\tilde{G}) = 1\mathrm{eV}$. This search focuses on the $m(\tilde{W}^0) > 100\,\mathrm{GeV}$ region, which is beyond the sensitivity of the previous collider experiments [13–15, 31]. We therefore generate points with $m(\tilde{g})$ and $m(\tilde{q})$ in the range of 350–800 GeV and $m(\tilde{\mathrm{W}}^0) \approx m(\tilde{\mathrm{W}}^{\pm})$ in the range of 100–

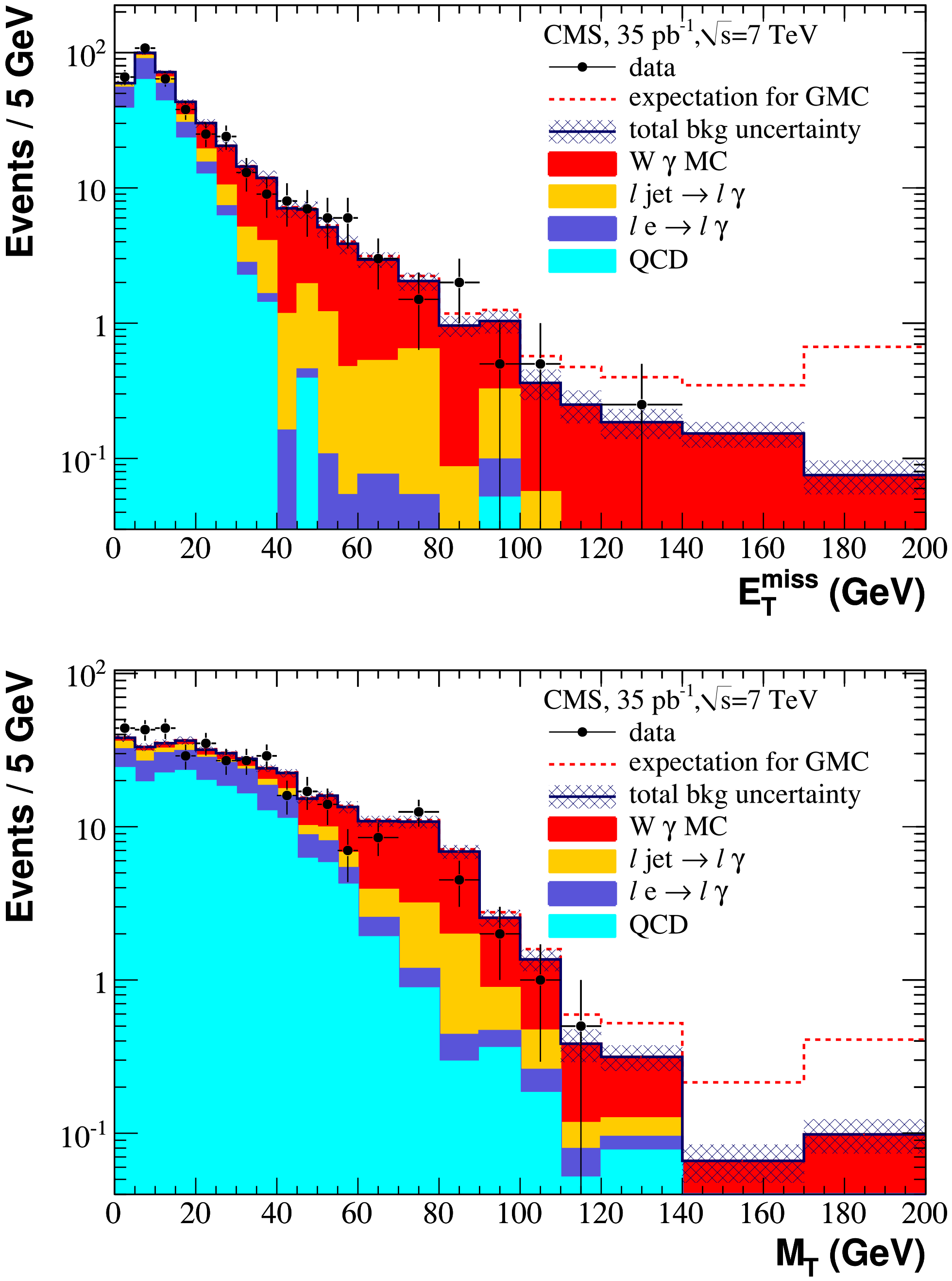

Figure 2. The $E_T^{\rm miss}$ (top) and M_T distributions (bottom) for the combined eγ and $\mu\gamma$ samples, with logarithmic scales on the vertical axes; the last bin shown in both distributions includes the overflow events. The black points represent the 35 pb^{-1} data sample, and the coloured histograms show the individual background components. The total background and its uncertainty are represented by the shaded band. The expectation from the SUSY benchmark point GMC is shown by the red dashed line.

480 GeV. The generated events are processed with the full CMS detector simulation using the Geant4 package. The NLO K factors were calculated using PROSPINO [32] and are found on average to be 1.4 with a $\sim 20\%$ variation. As an example of a SUSY benchmark model, we use the point generated with $m(\tilde{g}) = m(\tilde{q}) = 450\,\mathrm{GeV}$ and $m(\tilde{\mathrm{W}}^0) \approx m(\tilde{\mathrm{W}}^{\pm}) = 195\,\mathrm{GeV}$, referred to as GMC.

We use a Bayesian approach to determine the 95% CL upper limits on the cross sections in the benchmark SUSY model described above, combining the likelihoods of the eγ and $\mu\gamma$ channels. The inputs for both channels are the sum of the data-driven backgrounds, the Wγ background as determined from the MC simulation and corrected by the appropriate data/MC scale factors, and, for each MC SUSY point, the efficiency times acceptance, corrected for the appropriate data/MC scale factors. Each of these inputs for a given channel has log-normal distributed nuisance parameters that vary by the uncertainty in each quantity. We consider the 4% uncertainty on the luminosity as an additional nuisance parameter. As an example of the calculation, the efficiency times acceptance times branching ratio for the GMC benchmark point for eγ ($\mu\gamma$) is 0.0063 ± 0.0003 (0.0083 ± 0.0004). The 95% CL upper limit on the cross section obtained for this point is 8.7 pb. The limit is less than the predicted NLO cross section for this point, (12.7 ± 2.6) pb, with uncertainties due to the PDF [27] (10%) and the renormalization scale (18%). We therefore exclude this point with more than 95% confidence. The observed 95% CL upper limits on the cross section are shown in figure 3 as a function of the squark / gluino and the wino masses for the kinematic selections applied in this analysis (an electron with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $|\eta| < 1.44$ or $1.57 < |\eta| < 2.1$; a muon with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.1$; a photon with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 1.44$; events with $E_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$). Figure 4 displays the resulting 95% CL exclusion region in the squark / gluino and wino mass plane, where masses in the area below the curve are excluded. The shaded region around the central value of the exclusion contour represents the variation of the predicted cross section by one standard deviation. Also shown is the expected 95% CL exclusion as well as the the region excluded by previous searches at the Tevatron in the same channel [13–15], as interpreted in [31].

6 Conclusions

We performed the first search in proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ for an excess of events with a photon, a lepton, and large $E_{\mathrm{T}}^{\mathrm{miss}}$ over the SM expectation. Using a data sample corresponding to an integrated luminosity of 35 pb^{-1}, collected with the CMS detector at the LHC, we find no evidence of such an excess. Our results are interpreted as 95% CL lower limits on GGM SUSY particle masses in a benchmark model. Additionally, the 95% CL upper limits on the cross sections of generic SUSY production as a function of squark / gluino and wino masses are also provided, allowing other SUSY scenarios to be constrained. These limits are the most stringent to date for a large range of parameters in this GGM SUSY scenario.

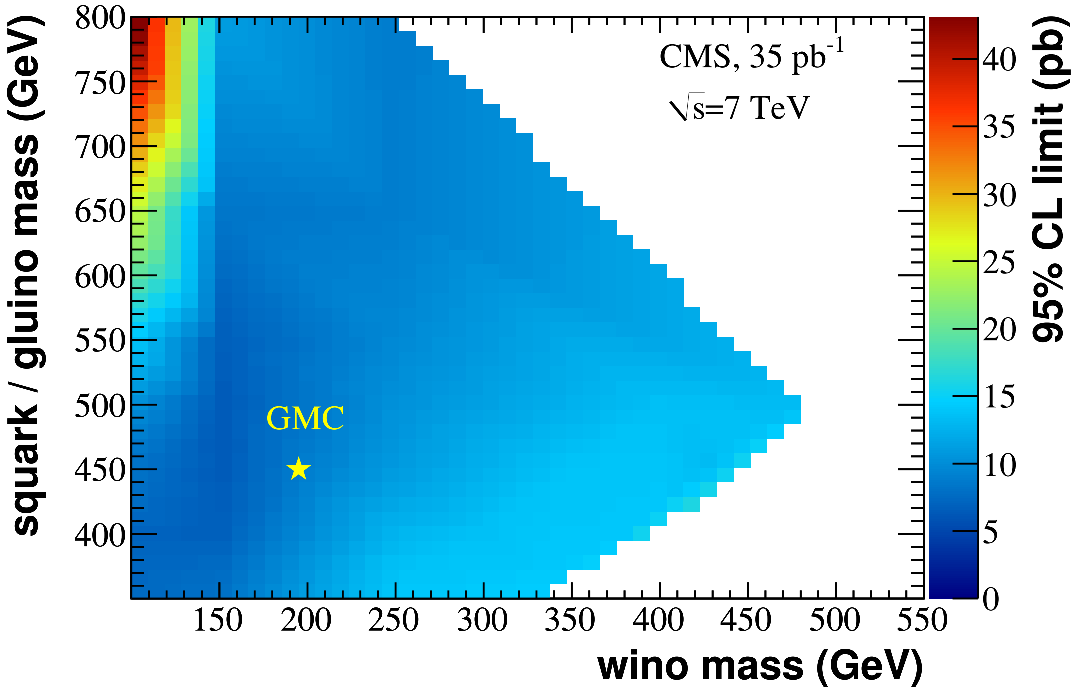

Figure 3. The observed 95% CL upper limits on the cross section as a function of the squark / gluino mass (since $m(\tilde{q}) \approx m(\tilde{g})$) and the wino mass is shown for the range of MC points generated for this analysis. The star indicates the SUSY benchmark point GMC.

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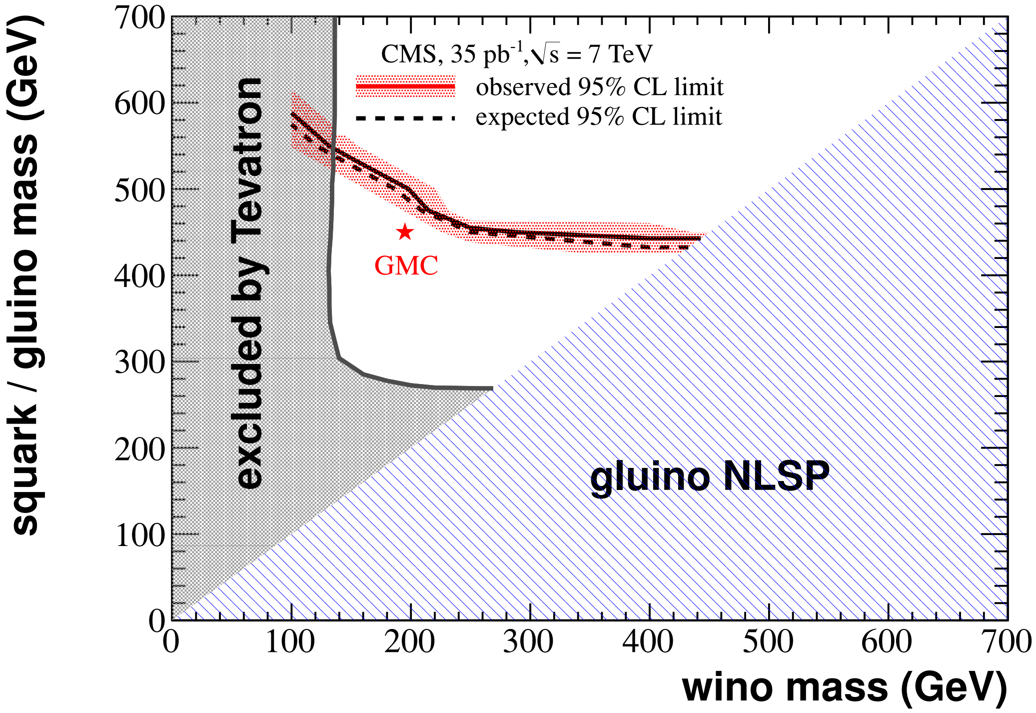

Figure 4. The 95% CL exclusion region as a function of the squark / gluino mass (since $m(\tilde{q}) \approx m(\tilde{g})$) and the wino mass. The area below the curve is excluded by this analysis. The shaded region around the central value of the exclusion contour reflects the uncertainty in the NLO predicted cross section. The dashed line represents the expected 95% CL limit from the MC simulation. The region excluded by the Tevatron in this channel [13–15] as interpreted in [31] is also shown. The star indicates the SUSY benchmark point GMC, which lies in the excluded region. The region for the scenario of the gluino as the NLSP is specified by the hatched area, which is not accessible to this analysis.

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