EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2012-342
2013/05/09

CMS-EXO-11-035

Search for long-lived particles in events with photons and missing energy in proton-proton collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

Results are presented from a search for long-lived neutralinos decaying into a photon and an invisible particle, a signature associated with gauge-mediated supersymmetry breaking in supersymmetric models. The analysis is based on a 4.9 fb^{-1} sample of proton-proton collisions at $\sqrt{s} = 7$ TeV, collected with the CMS detector at the LHC. The missing transverse energy and the time of arrival of the photon at the electromagnetic calorimeter are used to search for an excess of events over the expected background. No significant excess is observed, and lower limits at the 95% confidence level are obtained on the mass of the lightest neutralino, $m > 220$ GeV (for $c\tau < 500$ mm), as well as on the proper decay length of the lightest neutralino, $c\tau > 6000$ mm (for $m < 150$ GeV).

Submitted to Physics Letters B

*See Appendix A for the list of collaboration members

1 Introduction

New, heavy particles with long lifetimes are predicted in many models of physics beyond the standard model (SM), such as hidden valley scenarios [1] or supersymmetry (SUSY) with gauge-mediated supersymmetry breaking (GMSB) [2]. Under the assumption of R-parity conservation [3], strongly-interacting supersymmetric particles would be pair-produced at the Large Hadron Collider (LHC). The decay chain may include one or more quarks and gluons, as well as the lightest supersymmetric particle (LSP), which escapes detection, giving rise to a momentum imbalance in the transverse plane. A GMSB benchmark scenario, commonly described as 'Snowmass Points and Slopes 8' (SPS8) [4] is used as the reference in this search. In this scenario, the lightest neutralino ($\widetilde{\chi}_1^0$) is the next-to-lightest supersymmetric particle, and can be long-lived. It decays to a photon (or a Z boson) and a gravitino ($\widetilde{\mathrm{G}}$), which is the LSP [5]. If $\widetilde{\chi}_1^0$ consists predominantly of the bino, the superpartner of the $U(1)$ gauge field, its branching fraction to a photon and gravitino is expected to be large. If $\widetilde{\chi}_1^0$ is wino-like, the superpartner of the $SU(2)$ gauge fields, its branching fraction to a photon and gravitino is reduced. Figure 1 shows several diagrams of possible squark and gluino pair-production processes that result in a single-photon or diphoton final state.

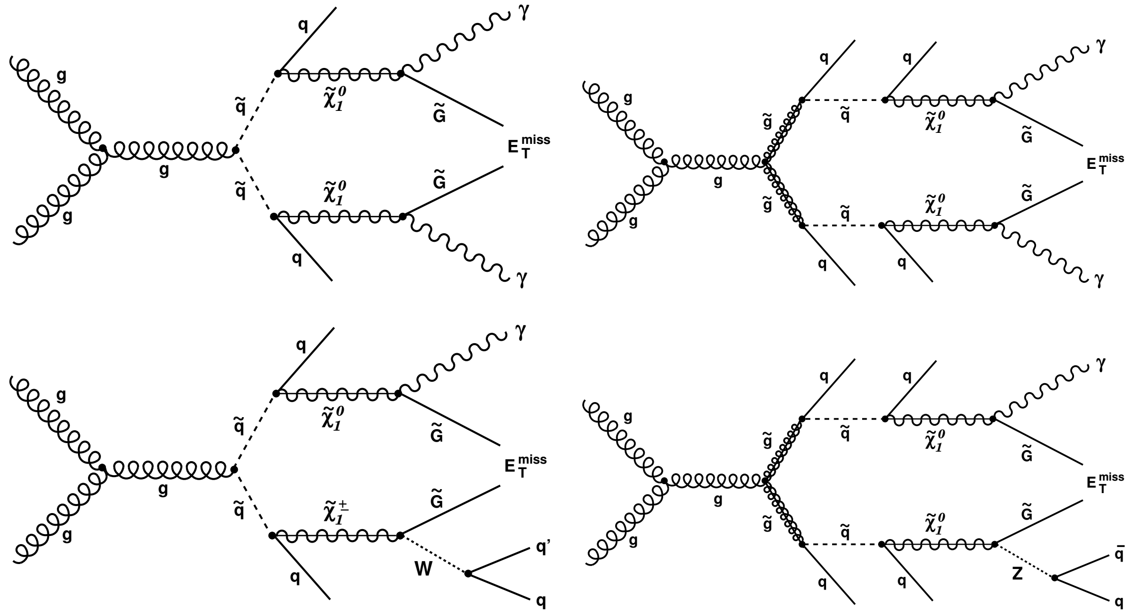

Figure 1: Example diagrams for SUSY processes that result in a diphoton (top) and single-photon (bottom) final state through squark (left) and gluino (right) production at the LHC.

The search criteria require only one identified photon in order to be sensitive to scenarios with a large branching fraction for the neutralino decay to a Z boson and a gravitino. For a long-lived neutralino, the photon from the $\widetilde{\chi}_1^0 \to \gamma\widetilde{\mathrm{G}}$ decay is produced at the $\widetilde{\chi}_1^0$ decay vertex, at some distance from the beam line, and reaches the detector at a later time than the prompt, relativistic particles produced at the interaction point. In addition, the geometric shape of the energy deposit produced by such photons is typically different from that of a prompt photon. The time of arrival of the photon at the detector and the missing transverse energy are used to discriminate signal from background.

A search for a long-lived neutralino, decaying to a photon and a gravitino, is performed with a novel technique using the excellent time measurement with the electromagnetic calorimeter. Previous searches for long-lived neutralinos have been performed by the CMS Collaboration [6], using the impact parameter of converted photons relative to the beam collision point, and by the CDF [7] collaboration, using only the missing transverse energy in the event. Other searches with prompt photons, by the ATLAS [8] and D0 [9] collaborations, place lower limits on the mass of the $\widetilde{\chi}_1^0$ at 280 GeV and 175 GeV, respectively, in the SPS8 scenario, assuming $\mathcal{B}(\widetilde{\chi}_1^0 \rightarrow \gamma\widetilde{\mathrm{G}}) = 100\%$.

2 Detector and data samples

A detailed description of the Compact Muon Solenoid (CMS) detector can be found elsewhere [10]. The detector's central feature is a superconducting solenoid providing a 3.8 T axial magnetic field along the beam direction. Charged particle trajectories are measured by a silicon pixel and strip tracker system with full azimuthal coverage within $|\eta| < 2.5$; the pseudo-rapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, with θ being the polar angle with respect to the counterclockwise beam direction. A lead-tungstate (PbWO4) crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL) surround the tracker volume. The ECAL is a high-granularity device. The barrel region consists of 61 200 crystals with a frontal area of approximately $2.2 \times 2.2\,\mathrm{cm}^2$ corresponding to roughly 0.0174×0.0174 in η-ϕ space. Each of the two endcap sections consist of 3662 crystals with a frontal area of $2.68 \times 2.68\,\mathrm{cm}^2$. A typical shower spans approximately 10 crystals with energy deposits above the threshold. Muons are measured in gas-ionization detectors embedded in the steel return yoke of the magnet. The detector is nearly hermetic, allowing reliable measurement of transverse momentum imbalance to be performed. The time of arrival of electromagnetic particles can be measured to excellent precision using the CMS ECAL [11]. The time reconstruction method is described in more detail in Section 3.1.

The analysis is performed on the proton-proton collision data at a center-of-mass-energy of 7 TeV recorded by the CMS detector at the LHC, corresponding to an integrated luminosity of $4.9 \pm 0.1\,\mathrm{fb}^{-1}$. Events with at least one high transverse momentum (p_T) isolated photon in the barrel region ($|\eta| < 1.44$) and at least three jets in the final state are selected in this analysis. The data were recorded using the CMS two-level trigger system. Several trigger selections have been used due to the increasing instantaneous luminosity during the data taking. The first $0.20\,\mathrm{fb}^{-1}$ of data were collected with a trigger requiring at least one isolated photon with $p_\mathrm{T} > 75\,\mathrm{GeV}$. For the second $3.8\,\mathrm{fb}^{-1}$, the p_T threshold was increased to 90 GeV. In the remaining $0.89\,\mathrm{fb}^{-1}$, the trigger selection required at least one isolated photon with $p_\mathrm{T} > 90\,\mathrm{GeV}$ in the barrel region and at least three jets with p_T greater than 25 GeV. All offline selection requirements are chosen to be more restrictive than the trigger selection.

Signal and background events are generated using Monte Carlo (MC) packages PYTHIA 6.4.22 [12] or MADGRAPH 5 [13] with the CTEQ6L1 [14] parton distribution functions (PDFs). The response of the CMS detector is simulated using the GEANT4 package [15]. Decays of secondary τ leptons, coming from W and Z productions, are simulated with TAUOLA [16]. The SUSY GMSB signal production follows the SPS8 proposal, where the free parameters are the SUSY breaking scale (Λ) and the average proper decay length ($c\tau$) of the neutralino. The $\widetilde{\chi}_1^0$ mass explored is in the range of 140 to 260 GeV (corresponding to Λ values from 100 to 180 TeV), with proper decay lengths ranging from $c\tau$ = 1 mm to 6000 mm. These free parameters are varied to cover the range of experimental phase space allowed by inner radius of the barrel section of the ECAL (1.29 m).

There is a non-negligible probability that several collisions may occur in a single bunch crossing due to the high instantaneous luminosities at the LHC. The presence of multiple interaction vertices in an event (pile-up) affects the resolution of the transverse momentum measurement and the performance of photon isolation requirements. To account for the effects of pile-up, simulated events are re-weighted so that the distribution of the number of interaction vertices matches that in the data.

3 Analysis technique

This section, outlining the analysis technique, starts with a description of the physics object reconstruction followed by a brief explanation of the event selection criteria. Finally, the definitions of the key discriminating variables related to the ECAL cluster shape and the time of impact of the photon on the surface of the ECAL are discussed. The signal and background yields are determined with a binned maximum likelihood fit to the two-dimensional distribution in these variables.

3.1 Object reconstruction

Photons are reconstructed by identifying energy deposits in the ECAL using the method explained in Ref. [17]. Photons that are found to have converted into an electron-positron pair in the detector material are not used in the analysis. Electron or positron candidates are reconstructed starting from a cluster of energy deposits in the ECAL which is then matched to the momentum associated with a track in the silicon tracker. Electron candidates are required to have $|\eta| < 1.44$ or $1.56 < |\eta| < 2.5$ to avoid the region of transition between the barrel and endcap sections. Photons are required to be spatially separated from electrons by at least $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.25$, where $\Delta\eta$ and $\Delta\phi$ are, respectively, differences between the photon and the electron directions in pseudorapidity and azimuthal angle.

Jets are reconstructed from objects identified using the Particle-Flow (PF) algorithm [18] with anti-k_{T} clustering [19] and a distance parameter of 0.5. In this analysis, the missing transverse energy ($\not\!\!E_{\mathrm{T}}$) is defined as the magnitude of the vector sum of the transverse momentum of all particles identified in the PF algorithm in the event excluding muons.

The time of impact, T_{raw}, for the photon on the surface of the ECAL is the weighted time of impact measured in the crystals within the cluster associated with a photon candidate. An event-by-event correction (T_{prompt}) is applied to T_{raw} to account for possible biases due to the jitter in the trigger system, and to the imperfect knowledge of the time of the interaction within the bunch crossing. This correction is computed using the time of impact of all crystals in the event, excluding those belonging to the two most energetic photon candidates, which are typically due to prompt jets, low-energy prompt photons, and photons from π^0 and η decays. The new calibrated ECAL timing is defined as $T_{\mathrm{calib}} = T_{\mathrm{raw}} - T_{\mathrm{prompt}}$. With this definition, a particle produced at the interaction point has a time of arrival of zero, whereas a delayed photon has a non-zero T_{calib}. The distributions in data for T_{raw} and T_{calib}, after the nominal selection, are shown in Fig. 2. The width of the main, Gaussian, component of T_{calib} is slightly smaller than that of T_{raw}, while there is some increase in the tails. For the dominant background processes, the tails are taken into account by using control samples in data, as described in Section 4. In the determination of the yield, the distribution of T_{calib} in simulated signal events is used as a template for the signal contribution. This distribution is narrower in simulation than in the data, because the uncertainties in the time inter-calibration constants are not emulated. A convolution with a Gaussian, whose parameters vary as a function of the photon energy, is performed to reproduce the T_{calib} resolution observed in data.

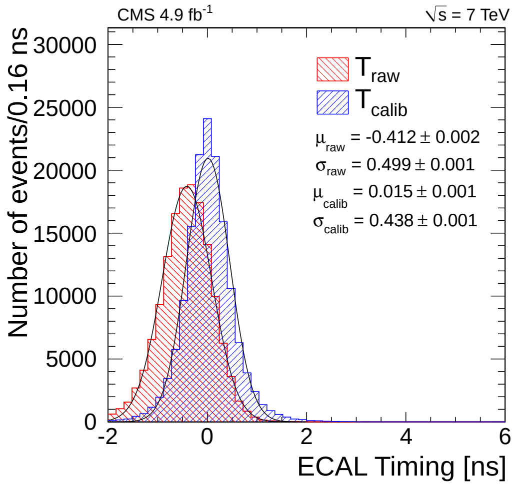

Figure 2: The ECAL timing distribution for data, before and after calibration, overlaid with the results of the Gaussian fits.

One of the distinctive features of a photon is the shape of the energy deposits it leaves in the ECAL. Prompt photons have a roughly circular projected energy deposit on the ECAL surface, while the energy deposits from jets typically have a larger width along the η direction. Non-prompt photons are expected to have an elliptical shape along an arbitrary direction, as illustrated in Fig. 3, therefore the width of the energy deposit along the η direction is not optimal for the discrimination of jets. In this search, the shape of the energy deposit is characterized by the minor axis (S_{Minor}) of its projection on the internal ECAL surface. The axis S_{Minor} is computed using the geometrical properties of the distribution of the energy deposit, and is defined as

$$S_{\text{Minor}} = \frac{(S_{\phi\phi} + S_{\eta\eta}) - \sqrt{(S_{\phi\phi} - S_{\eta\eta})^2 + 4S_{\phi\eta}^2}}{2}, \quad (1)$$

where $S_{\phi\phi}$, $S_{\eta\eta}$, and $S_{\phi\eta}$ are the second moments of the spatial distribution of the energy deposit in the ECAL in η-ϕ coordinates. A large fraction of QCD multijet events can be rejected by applying requirements on S_{Minor} as illustrated in Fig. 4, where the normalized distributions of S_{Minor} for simulated signal and QCD multijet background events are shown.

3.2 Event selection

Events must have a primary vertex with at least four associated tracks and a position less than 2 cm from the center of the CMS detector in the direction transverse to the beam and 24 cm in the direction along the beam. Events are also required to have at least three jets with $p_{\mathrm{T}} > 35\,\text{GeV}$ and spatially separated from photons by at least $\Delta R = 0.5$.

Photon candidates are required to have $p_{\mathrm{T}} \geq 100\,\text{GeV}$ and $|\eta| \leq 1.44$ and to be isolated in the HCAL, the ECAL, and the tracker. An absolute isolation parameter is defined as the scalar sum of the transverse energies of tracks or calorimeter deposits in a cone of aperture 0.3 around the photon direction, excluding the contribution from the photon itself. A relative isolation parameter is defined as the ratio of the absolute isolation and the photon p_{T}. In the tracker, the relative isolation is required to be less than 0.1. In the ECAL and the HCAL, the relative isolation is required to be less than 0.05 and the absolute isolation less than 2.4 GeV. Thresholds on both absolute and relative isolation are set in the ECAL and HCAL to avoid imposing requirements that are more restrictive than the noise level. The energy deposit by a photon candidate

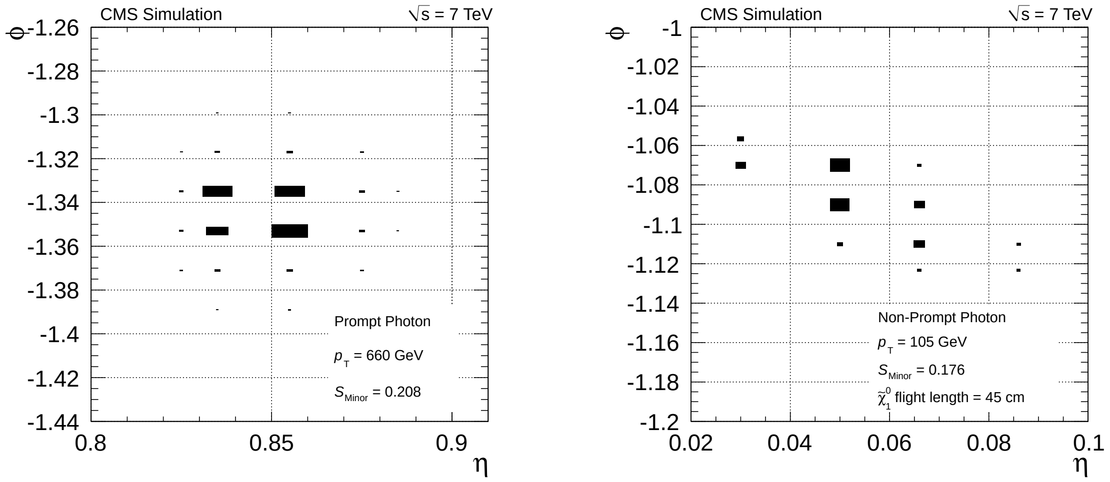

Figure 3: The distribution of energy deposition in the ECAL crystals for a prompt (left) and a non-prompt (right) photon. Each rectangle represents an ECAL crystal and has a size that is proportional to the energy deposited in that crystal. The non-prompt illustration is for a $\tilde{\chi}_1^0$ flight length of 45 cm.

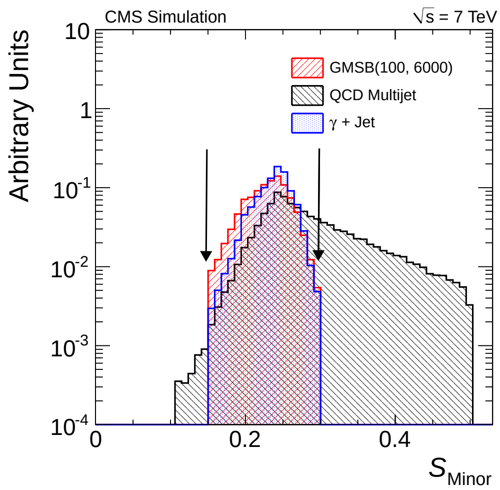

Figure 4: Normalized distribution of S_{Minor} for simulated signal, $\gamma +$ jets, and QCD multijet events. The arrows indicate the S_{Minor} selection interval.

is required to have $0.15 < S_{\mathrm{Minor}} < 0.30$. This requirement is optimized to select candidates that are more likely to be real photons.

The signal efficiencies for selecting one photon and at least three jets are summarized in Table 1 for proper decay lengths between 1 mm and 6000 mm and for Λ between 100 TeV and 180 TeV. The efficiency drops by a factor of two between $c\tau = 1$ mm and 6000 mm, since, with increasing decay time, the probability of the $\tilde{\chi}_1^0$ to decay outside the detector is enhanced.

4 Background estimation

The primary sources of background in the analysis are QCD multijet events and $\gamma +$ jets events, which together make up 99% of the sample. Improper reconstruction of jets can give rise to fake

Table 1: Selection efficiency in percent. The reported uncertainties include the contributions of systematic effects, for various signal samples.

Λ (TeV)	$M_{\tilde{\chi}_1^0}$ (GeV)	$c\tau = 1\,\text{mm}$	$c\tau = 250\,\text{mm}$	$c\tau = 2000\,\text{mm}$	$c\tau = 6000\,\text{mm}$
100	140	18.7 ± 0.3	18.4 ± 0.2	8.4 ± 0.2	3.3 ± 0.1
120	170	24.9 ± 0.4	24.6 ± 0.3	15.1 ± 0.4	6.6 ± 0.1
140	200	30.4 ± 0.3	31.3 ± 0.3	22.2 ± 0.4	11.4 ± 0.3
160	230	35.5 ± 0.3	36.1 ± 0.6	29.4 ± 0.4	17.0 ± 0.4
180	260	40.1 ± 0.7	38.0 ± 0.5	36.0 ± 0.5	22.2 ± 0.4

missing transverse energy, while photons produced in the decays of hadrons (mostly energetic π^0 and η) can sometimes pass the isolation criteria.

A large fraction of $\gamma +$ jets events, characterized by a smaller jet multiplicity compared to signal, are rejected by requiring at least three jets in the event. The residual contribution of these backgrounds is estimated from the data.

In addition, there are other (non-QCD) processes with genuine $\not\!\!E_{\mathrm{T}}$, largely comprised of $\mathrm{W/Z} + \gamma +$ jets and $\mathrm{t\bar{t}}$ events, where the W boson decays into a lepton and a neutrino. There is also a small contribution from Drell–Yan processes. These events make up less than 1% of the total sample but are taken into account since they can play a role in the tails of the $\not\!\!E_{\mathrm{T}}$ distribution where signal is expected. Simulated events are used to estimate the contribution of these processes.

Finally, additional backgrounds from events not originating from proton-proton collisions, including cosmic rays and beam-halo muons, are also expected. The contribution of these events is reduced to negligible levels by requiring T_{calib} of the most energetic photon candidate to be greater than $-2\,\text{ns}$, and the event to have an identified primary vertex and at least three jets.

Because of the difficulty of accurately predicting cross sections and jet multiplicities for multijet and $\gamma +$ jets processes, their contribution is estimated with methods based on the data. The QCD multijet control sample is obtained by selecting events with at least three jets and a photon candidate passing a less stringent identification requirement but failing the nominal photon selection criteria. The $\gamma +$ jets control sample consists of events with one photon which satisfies the nominal selection. Events with the angle in the transverse plane between the highest-p_{T} jet (leading jet) and the photon smaller than $2/3\,\pi$ are rejected. The ratio of the transverse momenta of the leading jet to that of the photon is required to be between 0.6 and 1.4, while for the subleading jet the ratio is required to be less than 0.2. The contribution of non-QCD and signal events to these two control samples is estimated to be, respectively, 1% and less than 0.01%.

To estimate the number of background and signal events in data, a maximum likelihood fit is performed to the two-dimensional distribution of $\not\!\!E_{\mathrm{T}}$ and T_{calib}. The correlation coefficient between $\not\!\!E_{\mathrm{T}}$ and T_{calib} is 0.05 for events with $\not\!\!E_{\mathrm{T}} > 100\,\text{GeV}$ and $T_{\text{calib}} > 0.5\,\text{ns}$, and 0.001 when all events are considered. Binned shape templates are derived from simulated events for signal and non-QCD backgrounds. Templates for QCD multijet and $\gamma +$ jets are derived from data control samples as described earlier. The relative normalization of the QCD multijet and $\gamma +$ jets components is fixed to 67% and 33%, respectively, based on studies with simulated events. The normalization of the non-QCD templates are fixed in the fit according to the measured cross sections (statistical uncertainties in the cross sections are less than 3%) and the integrated luminosity of the data sample. Studies have been performed with pseudo-experiments to confirm the stability of the fit and to verify that the fit results are unbiased. The measured signal and background yields in data, obtained with the likelihood fit, are summarized in Table 2. The one-dimensional projections of $\not\!\!E_T$ and T_{calib} for the data and expected backgrounds, as determined from the fit, are illustrated in Fig. 5. No excess of events is observed beyond the SM backgrounds and the fitted signal yield is compatible with zero. It should be noted that the discriminating power of individual variables is not apparent in these projections because the largest sensitivity to signal is in the region with both large $\not\!\!E_T$ and large T_{calib}. The improved background discrimination is visible in Fig. 6 where the one-dimensional projection of $\not\!\!E_T$ for events with $T_{calib} > 0.5$ ns is illustrated.

Table 2: The measured signal and background yields determined with the maximum likelihood fit to the data. The relative composition of QCD multijet and $\gamma +$ jets backgrounds have been normalized to 67% and 33% with respect to each other. The expected signal yields are 211 events for the GMSB(100,250) benchmark point and 96 for GMSB(100,2000). The GMSB(100,250) benchmark point corresponds to $\Lambda = 100$ TeV, $c\tau = 250$ mm and the GMSB(100,2000) benchmark point corresponds to $\Lambda = 100$ TeV, $c\tau = 2000$ mm. The reported uncertainties are statistical only and are determined in the fit.

	Events
GMSB (100, 250)	6 ± 8
GMSB (100, 2000)	4 ± 4
QCD multijet and $\gamma +$ jets	$80\,900 \pm 300$
$t\bar{t}$ + jets (fixed)	73
$W \to e\nu +$ jets (fixed)	116
Drell–Yan + jets (fixed)	67
$W/Z +$ jets $+ \gamma$ (fixed)	215
Total background	$81\,400 \pm 300$
Data	81 382

5 Systematic uncertainties

Several sources of systematic uncertainty have been considered and their contributions are summarized in Table 3. The largest single contribution to the systematic uncertainties derives from the uncertainty in the modeling of the background shape. A bin-by-bin variation of the background shape template according to the Poisson uncertainty is used to determine the contribution of each type of background. An additional uncertainty is assessed for the QCD multijet and $\gamma +$ jets processes using simulated events, by comparing the shapes of $\not\!\!E_T$ and T_{calib} for the control sample and for a sample obtained with the nominal selection criteria. The difference observed in simulation is used to re-weight the shapes obtained in data control samples. The dominant contribution is due to the difference in the $\not\!\!E_T$ distributions. The small tails in the distribution of T_{calib} are accounted for by using data control samples to derive the templates, rather than relying on simulation. The uncertainty in the relative fraction of QCD multijet and $\gamma +$ jets events is estimated to be 33%. The main contribution to this uncertainty is due to the next-to-leading correction for the $\gamma +$ jets cross section. Additional contributions are included to take into account the the observed difference between the number of events in the $\gamma +$ jets control sample in data and the expected number of events according to PYTHIA (10%), and to the QCD multijet events misidentified as $\gamma +$ jets events (10%).

The main contributions to the uncertainty in the signal shape modeling derive from the uncertainty in the $\not\!\!E_T$ resolution and the determination of T_{calib}. The contribution of the $\not\!\!E_T$ resolution uncertainty is estimated by smearing the $\not\!\!E_T$ distribution of simulated signal events. A sys-

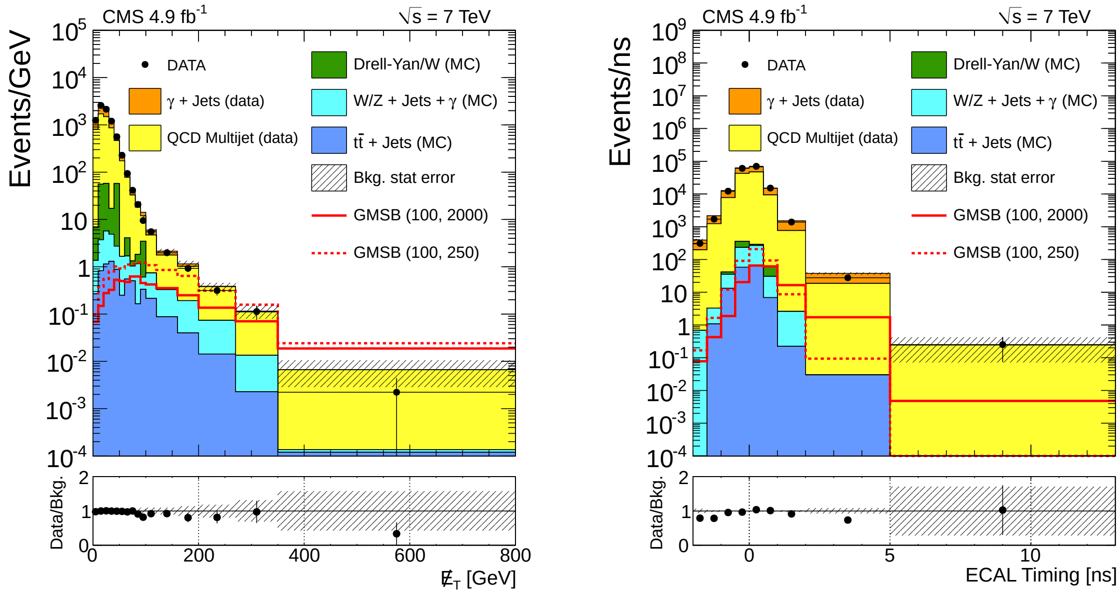

Figure 5: The one-dimensional projection for $\not\!\!E_T$ (left) and for ECAL timing (right), after all selection requirements. The multijet and $\gamma+$jets backgrounds are normalized to the yields from the fit. The rest of the backgrounds are fixed according to the integrated luminosity of the data. The GMSB(100,2000) benchmark point corresponds to $\Lambda = 100$ TeV, $c\tau = 2000$ mm and the GMSB(100,250) benchmark point corresponds to $\Lambda = 100$ TeV, $c\tau = 250$ mm.

tematic uncertainty of 0.1 ns is assigned to the measurement of the time of impact T_{calib}. This uncertainty is determined using a sample of $\gamma+$jets events by measuring the difference between the average T_{calib} values in data and simulation, as a function of the photon p_T.

The uncertainty in the luminosity determination is 2.2% [20]. The remaining sources of systematic uncertainty affecting the signal acceptance are the following. The calorimeter response to different types of particles is not perfectly linear and hence corrections are made to properly map the measured jet energy deposition. The uncertainty on this correction is referred to as the uncertainty on the jet energy scale and varies as a function of position and transverse momentum of the jet. Similarly, the uncertainty on the photon energy scale in the barrel is estimated to be 1.0%, based on the final-state radiation measurement with Z bosons [21]. Following the recommendations of the PDF4LHC group [22], PDF and the strong coupling constant (α_s) variations of the MSTW2008 [23], CTEQ6.6 [24] and NNPDF2.0 [25] PDF sets are taken into account and their impact on the signal acceptance is estimated.

6 Results

The observed event yield in data is consistent with the SM background prediction, and upper limits are obtained on the production cross section of a long-lived neutralino in the context of the GMSB model, assuming $\mathcal{B}(\tilde{\chi}^0_1 \to \gamma\tilde{G}) = 100\%$. Exclusion limits are computed with a modified frequentist CL_s method [26–28], using the asymptotic approximation for the test statistic as described in Ref. [29]. The background normalization and the corresponding uncertainty are taken from the fit to the data. The uncertainties in the shapes are taken into account by vertical interpolation of the templates. The shapes are interpolated quadratically for shifts below one

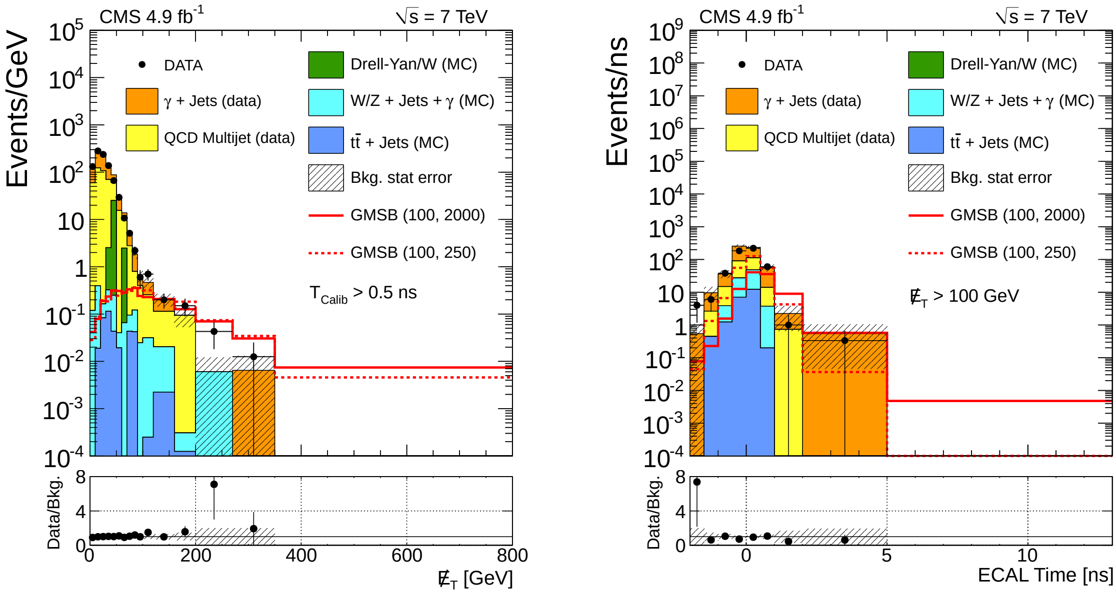

Figure 6: The one-dimensional projection after all selection requirements for $\not\!\!E_{\mathrm{T}}$ for events with $T_{\text{calib}} > 0.5\,\text{ns}$ (left) and for ECAL timing (right) for events with $\not\!\!E_{\mathrm{T}} > 100\,\text{GeV}$. The multijet and $\gamma +$jets backgrounds are normalized to the yields from the fit. The rest of the backgrounds are fixed according to the integrated luminosity of the data. The GMSB(100,2000) benchmark point corresponds to $\Lambda = 100\,\text{TeV}$, $c\tau = 2000\,\text{mm}$ and the GMSB(100,250) benchmark point corresponds to $\Lambda = 100\,\text{TeV}$, $c\tau = 250\,\text{mm}$.

standard deviation and linearly beyond. Log-normal multiplicative corrections are used for the normalization, the signal acceptance, and the integrated luminosity. Fig. 7 shows the observed and expected 95% confidence level (CL) upper limits on the cross section for GMSB production in terms of $\tilde{\chi}_1^0$ mass (left), and proper decay length (right). The signal cross section is computed at leading order precision and the theoretical uncertainty is evaluated by using the PDF4LHC recommendation for the PDF uncertainty. The one-dimensional limits are combined to provide exclusion limits in the mass and proper decay length plane of the long-lived $\tilde{\chi}_1^0$ in Fig. 8.

7 Summary

The CMS experiment has performed a search for long-lived particles produced in association with jets using LHC proton-proton collision data at a center-of-mass energy of 7 TeV corresponding to an integrated luminosity of $4.9 \pm 0.1\,\text{fb}^{-1}$. A GMSB scenario with a long-lived neutralino decaying to a photon and a gravitino is used as the reference. The missing transverse energy and the timing information from the ECAL are used to search for an excess of events over the expected SM background prediction. A fit to the two-dimensional distribution in these variables yields no significant excess of events beyond the SM contributions, and upper limits at 95% CL are obtained on the GMSB production cross section in the SPS8 model of GMSB supersymmetry. In this scheme, we obtain an exclusion region as a function of both the neutralino mass and its proper decay length, assuming $\mathcal{B}(\tilde{\chi}_1^0 \to \gamma\tilde{G}) = 100\%$. The mass of the lightest neutralino is then restricted to values $m(\tilde{\chi}_1^0) > 220\,\text{GeV}$ (for neutralino proper decay length $c\tau < 500\,\text{mm}$) at 95% CL, and the neutralino decay length $c\tau$ must be greater than 6000 mm (for $m(\tilde{\chi}_1^0) < 150\,\text{GeV}$). These limits are the most stringent for long-lived neutralinos.

Table 3: Summary of the systematic uncertainties in the background and signal shapes, as well as in the signal acceptance $\times$ efficiency. The signal uncertainties are evaluated individually for every signal point, although only the maximum and minimum values associated with each source are quoted.

Source	Uncertainty (%)
Background	
Shape	10
Normalization	0.3
Multijet/$\gamma+$jets fraction	0.8
Signal shape	
$\not\!\!E_{\mathrm{T}}$ resolution	0.2–2
ECAL timing uncertainty	1–5
Signal acceptance $\times$ efficiency	
Photon energy scale	0.5–3
Jet energy scale	0.02–0.05
Jet energy resolution	0.01–2
PDF uncertainties	0.1–2

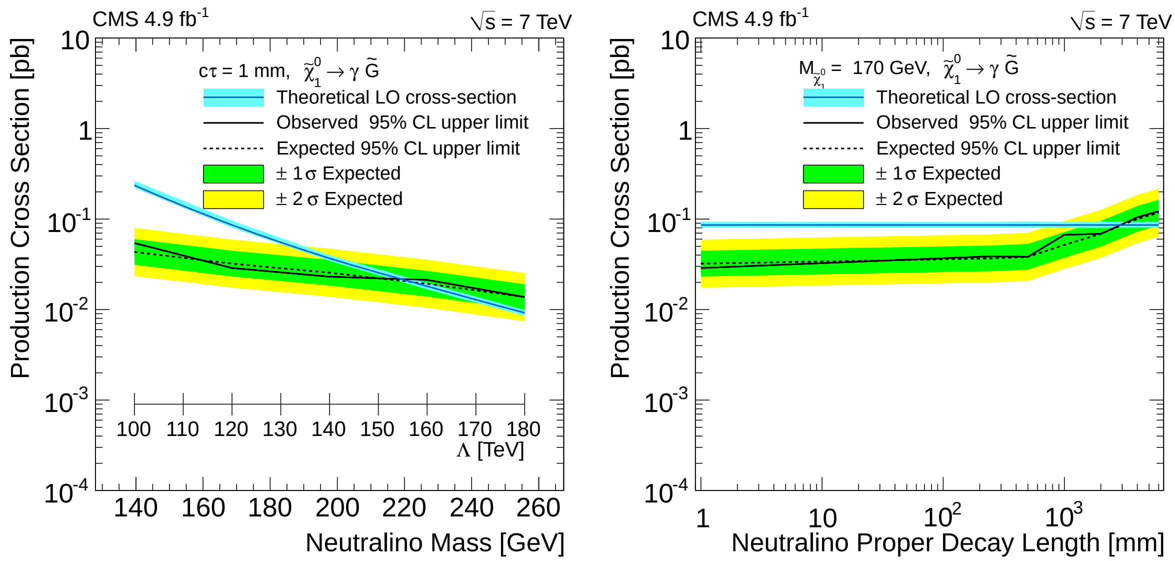

Figure 7: Upper limits at the 95% CL on the cross section as a function of the $\tilde{\chi}_1^0$ mass for $c\tau = 1\,\mathrm{mm}$ (left), and for the $\tilde{\chi}_1^0$ proper decay length for $M_{\tilde{\chi}_1^0} = 170\,\mathrm{GeV}$ (right) in the SPS8 model of GMSB supersymmetry.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MEYS (Bulgaria); CERN; CAS,

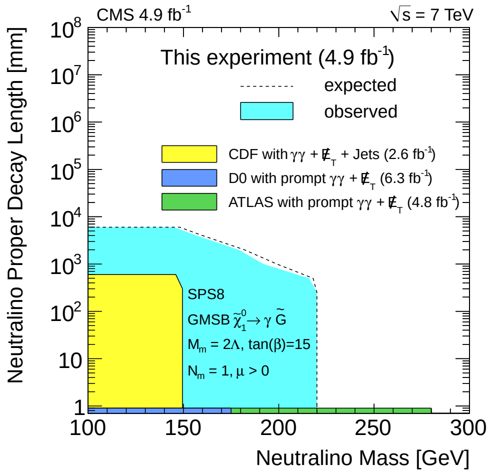

Figure 8: The observed exclusion region for the mass and proper decay length of the long-lived $\tilde{\chi}_1^0$ in the SPS8 model of GMSB supersymmetry.

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