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

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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 ($\tilde{\chi}_1^0$) is the next-to-lightest supersymmetric particle, and can be long-lived. It decays to a photon (or a Z boson) and a gravitino ($\tilde{G}$), which is the LSP. If $\tilde{\chi}_1^0$ 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 $\tilde{\chi}_1^0$ is wino-like, the superpartner of the $SU(2)$ gauge fields, its branching fraction to a photon and gravitino is reduced.

Fig. 1 shows several diagrams of possible squark and gluino pair-production processes that result in a single-photon or diphoton final state.

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 $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ decay is produced at the $\tilde{\chi}_1^0$ decay vertex, at some distance from the beam line, and reaches the detector at a later time than the prompt, relativistic particles produced in the event. 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 Collaboration [7], 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 $\tilde{\chi}_1^0$ at 280 GeV and 175 GeV, respectively, in the SPS8 scenario, assuming $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}) = 100\%$. 

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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 $\eta$ is defined as $\eta = -\ln[\tan(\theta/2)]$, with $\theta$ 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 61200 crystals with a frontal area of approximately $2.2 \times 2.2$ cm$^2$ corresponding to roughly $0.0174 \times 0.0174$ in $\eta-\phi$ space. Each of the two endcap sections consists of 3662 crystals with a frontal area of 2.68 $\times$ 2.68 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 $4.9 \pm 0.1$ 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 fb$^{-1}$ of data were collected with a trigger requiring at least one isolated photon with $p_T > 75$ GeV for the second 3.8 fb$^{-1}$, $p_T$ threshold was increased to 90 GeV. In the remaining 0.89 fb$^{-1}$, the trigger selection required at least one isolated photon with $p_T > 90$ 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 $\tau$ leptons, coming from $W$ and $Z$ productions, are simulated with TAUOLA [16]. The SUSY CMSB signal production follows the SP8 proposal, where the free parameters are the SUSY breaking scale ($\Lambda$) and the average proper decay length ($\tau$) of the neutralino. The $\tilde{\chi}^0_1$ mass explored is in the range of 140 to 260 GeV (corresponding to $\Lambda$ values from 100 to 180 TeV), with proper decay lengths ranging from $\tau = 1$ 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 have been found to convert 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 ($E_T$) 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, $T_{\text{raw}}$, 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 ($T_{\text{prompt}}$) is applied to $T_{\text{raw}}$ 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 $\pi^0$ and $\eta$ decays. The new calibrated ECAL timing is defined as $T_{\text{calib}} = T_{\text{raw}} - T_{\text{prompt}}$. 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 $T_{\text{calib}}$. The distributions in data for $T_{\text{raw}}$ and $T_{\text{calib}}$ after the nominal selection, are shown in Fig. 2. The width of the main, Gaussian component of $T_{\text{calib}}$ is slightly smaller than that of $T_{\text{raw}}$, 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 $T_{\text{calib}}$ 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 $T_{\text{calib}}$ resolution observed in data.

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 $\eta$ 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 $\eta$ direction is not optimal for the discrimination of jets. In this search, the shape of the energy deposit is characterized by the minor axis ($S_{\text{Minor}}$) of its projection on the internal ECAL surface. The axis $S_{\text{Minor}}$ is computed using the geometrical properties of the distribution of the energy deposit, and is defined as

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

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 $\eta$–$\phi$ coordinates. A large fraction of QCD multijet events can be rejected by applying requirements on $S_{\text{Minor}}$ as illustrated in Fig. 4, where the normalized distributions of $S_{\text{Minor}}$ 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.
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 $E_T$, largely comprised of W/Z + $\gamma$ + jets and tt 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 $E_T$ 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 $-2$ 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 $2/3\tau$ 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 $E_T$ and $T_{calib}$. The correlation coefficient between $E_T$ and $T_{calib}$ is 0.05 for events with $E_T > 100$ GeV and $T_{calib} > 0.5$ 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 $E_T$ 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.
The measured signal and background yields determined with the maximum likelihood fit to the data. The relative composition of QCD multijet and $\gamma + \text{jets}$ 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, $c_T = 250$ mm and the GMSB (100, 2000) benchmark point corresponds to $\Lambda = 100$ TeV, $c_T = 2000$ mm. The reported uncertainties are statistical only and are determined in the fit.

<table>
<thead>
<tr>
<th>Events</th>
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<tbody>
<tr>
<td>GMSB (100, 250)</td>
</tr>
<tr>
<td>GMSB (100, 2000)</td>
</tr>
<tr>
<td>QCD multijet and $\gamma + \text{jets}$</td>
</tr>
<tr>
<td>$t\bar{t} + \text{jets}$ (fixed)</td>
</tr>
<tr>
<td>$W \rightarrow e + \text{jets}$ (fixed)</td>
</tr>
<tr>
<td>Drell–Yan $+ \text{jets}$ (fixed)</td>
</tr>
<tr>
<td>$W/Z + \gamma + \text{jets}$ (fixed)</td>
</tr>
<tr>
<td>Total background</td>
</tr>
<tr>
<td>Data</td>
</tr>
</tbody>
</table>

because the largest sensitivity to signal is in the region with both large $E_T$ and large $T_{\text{calib}}$. The improved background discrimination is visible in Fig. 6 where the one-dimensional projection of $E_T$ for events with $T_{\text{calib}} > 0.5$ ns is illustrated.

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 $\gamma + \text{jets}$ processes using simulated events, by comparing the shapes of $E_T$ and $T_{\text{calib}}$ 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 $E_T$ distributions. The small tails in the distribution of $T_{\text{calib}}$ 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 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 $E_T$ resolution and the determination of $T_{\text{calib}}$. The contribution of the $E_T$ resolution uncertainty is estimated by smearing the $E_T$ distribution of simulated signal events. A systematic uncertainty of 0.1 ns is assigned to the measurement of the time of impact $T_{\text{calib}}$. This uncertainty is determined using a sample of $\gamma + jets$ events by measuring the difference between the average $T_{\text{calib}}$ 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 ($\alpha_s$) 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.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td>10</td>
</tr>
<tr>
<td>Normalization</td>
<td>0.3</td>
</tr>
<tr>
<td>Multijet/$\gamma + jets$ fraction</td>
<td>0.8</td>
</tr>
<tr>
<td>Signal shape $E_T$ resolution</td>
<td>0.2–2</td>
</tr>
<tr>
<td>ECAL timing uncertainty</td>
<td>1–5</td>
</tr>
<tr>
<td>Signal acceptance × efficiency</td>
<td></td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>0.5–3</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.02–0.05</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.01–2</td>
</tr>
<tr>
<td>PDF uncertainties</td>
<td>0.1–2</td>
</tr>
</tbody>
</table>

### 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 ± 0.1 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 the long-lived $\tilde{\chi}_1^0$ mass, proper decay length for $\tilde{\chi}_1^0$ mass (top), and proper decay length (bottom). 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.
both the neutralino mass and its proper decay length, assuming $\mathbb{B}(\tilde{\chi}^0_1 \rightarrow \gamma G) = 100\%$. The mass of the lightest neutralino is then restricted to values $m(\tilde{\chi}^0_1) > 220$ GeV (for neutralino proper decay length $c\tau < 500$ mm) at 95% CL, and the neutralino decay length $c\tau$ must be greater than 6000 mm (for $m(\tilde{\chi}^0_1) < 150$ GeV). These limits are the most stringent for long-lived neutralinos.

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References


Fig. 8. The observed exclusion region for the mass and proper decay length of the long-lived $\tilde{\chi}^0_1$ in the SPS8 model of GMSB supersymmetry. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

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