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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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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).

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 ($\widetilde{\chi}^0_1$) is the next-to-lightest supersymmetric particle, and can be long-lived. It decays to a photon (or a Z boson) and a gravitino ($\widetilde{G}$), which is the LSP [5]. If $\widetilde{\chi}^0_1$ 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 $\widetilde{\chi}^0_1$ 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 $\widetilde{\chi}^0_1 \to \gamma\widetilde{G}$ decay is produced at the $\widetilde{\chi}^0_1$ 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 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 $\widetilde{\chi}^0_1$ at 280 GeV and 175 GeV, respectively, in the SPS8 scenario, assuming $\mathcal{B}(\widetilde{\chi}^0_1 \to \gamma\widetilde{G}) = 100\%$.

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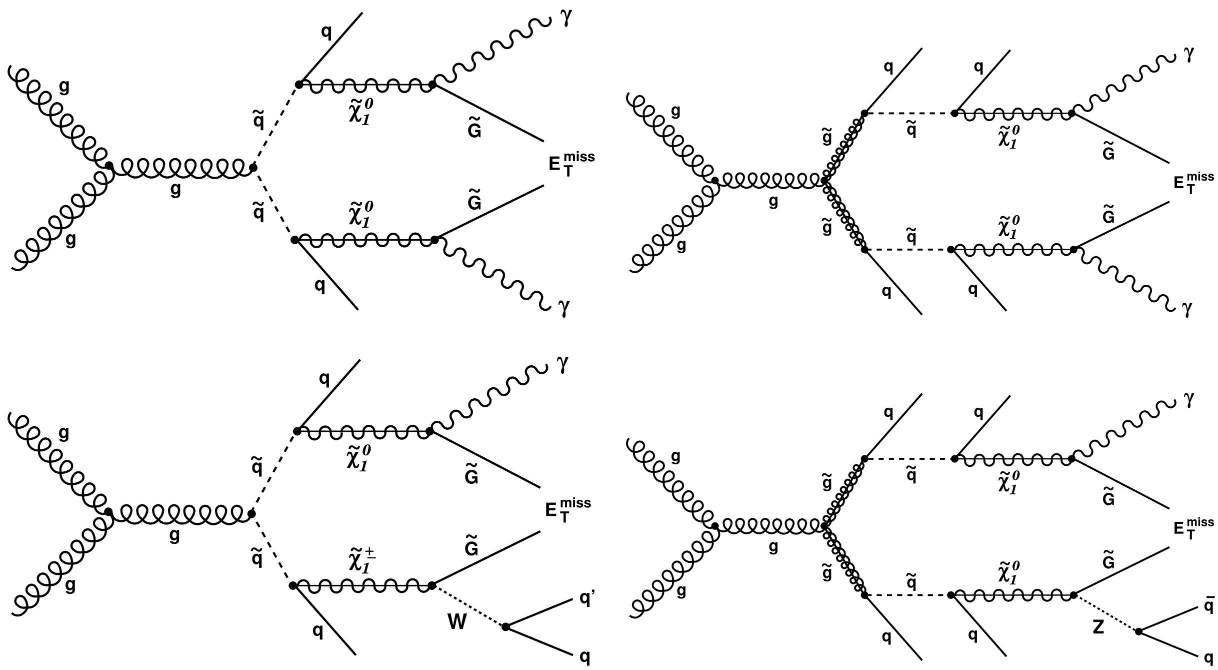

Fig. 1. Example diagrams for SUSY processes that result in a diphoton (top) and single-photon (bottom) final state through squark (left) and gluino (right) production at the LHC.

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 2.2×2.2 cm^2 corresponding to roughly 0.0174×0.0174 in η–ϕ space. Each of the two endcap sections consists of 3662 crystals with a frontal area of 2.68×2.68 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 ± 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}, the 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 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.