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Search for long-lived particles using delayed photons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search for long-lived particles decaying to photons and weakly interacting particles, using proton-proton collision data at $\sqrt{s} = 13$ TeV collected by the CMS experiment in 2016–2017 is presented. The data set corresponds to an integrated luminosity of $77.4\,\text{fb}^{-1}$. Results are interpreted in the context of supersymmetry with gauge-mediated supersymmetry breaking, where the neutralino is long-lived and decays to a photon and a gravitino. Limits are presented as a function of the neutralino proper decay length and mass. For neutralino proper decay lengths of 0.1, 1, 10, and 100 m, masses up to 320, 525, 360, and 215 GeV are excluded at 95% confidence level, respectively. We extend the previous best limits in the neutralino proper decay length by up to one order of magnitude, and in the neutralino mass by up to 100 GeV.

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1 Introduction

The results of a search for long-lived particles (LLP) decaying to a photon and a weakly-interacting particle are presented. Neutral particles with long lifetimes are predicted in many models of physics beyond the standard model (SM). In this paper, a benchmark scenario of supersymmetry (SUSY) [1–14] with gauge-mediated SUSY breaking (GMSB) [15–23] is employed, commonly referred to as the "Snowmass Points and Slopes 8" (SPS8) benchmark model [24]. In this scenario, pair-produced squarks and gluinos undergo cascade decays as shown in Fig. 1, and eventually produce the lightest SUSY particle (LSP), the gravitino ($\widetilde{G}$), which is stable and weakly interacting. The phenomenology of such decay chains is primarily determined by the nature of the next-to-lightest SUSY particle (NLSP). In the SPS8 benchmark, the NLSP is the lightest neutralino, $\widetilde{\chi}^0_1$, and the mass of the NLSP is linearly related to the effective scale of SUSY breaking, Λ [15, 25].

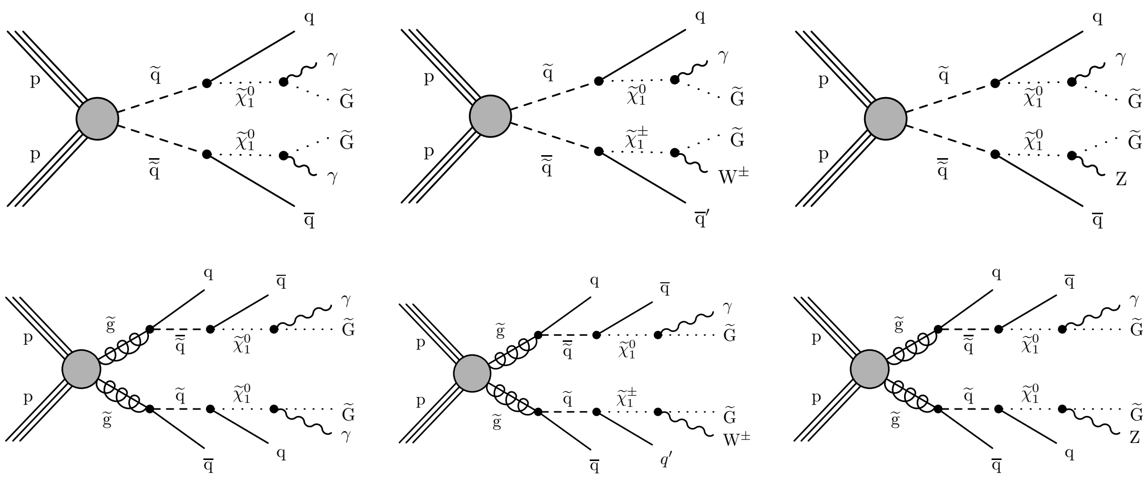

Figure 1: Example Feynman diagrams for SUSY processes that result in diphoton (left) and single photon (middle and right) final states via squark (upper) and gluino (lower) pair-production at the LHC.

In the SPS8 model, Λ is a free parameter whose value determines the primary production mode and decay rate of SUSY particles. Depending on the value of Λ, the coupling of the NLSP to the gravitino could be very weak and lead to long NLSP lifetimes. The dominant decay mode of the NLSP is to a photon and a gravitino, resulting in a final state with one or two photons and missing transverse momentum ($p_{\mathrm{T}}^{\text{miss}}$). The dominant squark-pair and gluino-pair production modes also result in additional energetic jets. If the NLSP has a proper decay length that is a significant fraction of the radius of the CMS tracking volume (about 1.2 m), then the photons produced at the secondary vertex tend to exhibit distinctive features. Because of their production at displaced vertices and their resulting trajectories, the photons have significantly delayed arrival times (order of ns) at the CMS electromagnetic calorimeter (ECAL) compared to particles produced at the primary vertex and traveling at the speed of light. They also enter the ECAL at non-normal impact angles.

The present search makes use of these features to identify potential signals of physics beyond the SM. We select events with one or two displaced or delayed photons, and three or more jets. Signal events are expected to produce large $p_{\mathrm{T}}^{\text{miss}}$ as the LSP escapes the detector volume without detection. In the case of very long-lived NLSPs, one of the NLSPs may completely escape the detector, further increasing the $p_{\mathrm{T}}^{\text{miss}}$. Previously, similar searches for LLPs decaying to displaced or delayed photons have been performed by the CMS [26] and ATLAS [27]

Collaborations using LHC collisions at a center-of-mass energies of 7 and 8 TeV, respectively. Past LHC searches for invisible Higgs boson decays in association with photons [28] also have sensitivity to such models.

2 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 ECAL, and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity 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.

The ECAL is highly granular and consists of 61 200 crystals in the barrel region, each with an area of approximately $2.2{\times}2.2\,\mathrm{cm}^2$ corresponding to roughly $0.0174{\times}0.0174$ in η-ϕ space, where η is the pseudorapidity and ϕ the azimuthal angle (in radians) of the coordinate system [29]. Each of the two endcap sections consist of 7324 crystals, each crystal having an area of $2.68{\times}2.68\,\mathrm{cm}^2$. A typical electromagnetic shower spans approximately 10 crystals with energy deposits above noise threshold. The barrel and endcap ECAL components cover the regions with $|\eta| < 1.5$ and $1.5 < |\eta| < 2.5$, respectively. The best possible time resolution for each ECAL channel is measured to be between 70 and 100 ps, depending on detector aging.

The first level of the CMS trigger system [30], composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than $4\,\mu$s. The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage. 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. [29].

3 Event samples

This analysis uses data sets of proton-proton (pp) collisions collected by the CMS experiment at the LHC in 2016 and 2017, corresponding to integrated luminosities of 35.9 and $41.5\,\mathrm{fb}^{-1}$, respectively. Simulated samples are used to study the SM background and signal contributions, primarily for the purpose of optimizing the event selection and the binning in the photon time and $p_{\mathrm{T}}^{\mathrm{miss}}$ observables. The MADGRAPH5_aMC@NLO v2.2.2 generator [31] is used at next-to-leading order (NLO) in quantum chromodynamics (QCD) to simulate events originating from single top quark and top quark pair production, and at leading order (LO) to simulate events originating from QCD multijet, γ+jets, W+jets, and Z+jets production. Simulated samples of diphoton events are generated using SHERPA v2.2.4 [32, 33], and include Born processes with up to three additional jets, as well as box processes at LO precision. The particle spectra of each GMSB SPS8 signal model are tabulated in a SUSY Les Houches accord (SLHA) file using ISASUGRA as part of ISAJET v7.87 [34]. The SLHA files are then used to generate benchmark signal model samples using PYTHIA v8.212 (v8.230) [35] for the 2016 (2017) data analysis.

For all simulated samples discussed above, the fragmentation and parton showering are modeled using PYTHIA v8.212 with the CUETP8M1 underlying event tune [36, 37] (PYTHIA v8.230 with the CP5 [38] tune) for the 2016 (2017) data analysis. The NNPDF3.0 [39] and NNPDF3.1 [40] parton distribution function (PDF) sets are used for the 2016 and 2017 simulated samples, respectively. The signal and background samples are processed through a simulation of the CMS detector based on GEANT4 [41] and are reconstructed with the same algorithms as used for data. Additional pp interactions in the same or adjacent bunch crossings, referred to as pileup, are also simulated.

4 Trigger and event selection

The unique signature of delayed photons is best exploited with specialized triggers and dedicated photon reconstruction and identification criteria. There is a difference between the search selections for the 2016 and 2017 data sets, primarily because of the introduction of a targeted HLT algorithm implemented for the 2017 data set, which superseded a general diphoton trigger used for the 2016 data set.

4.1 Trigger selection

For the 2016 data set, events are selected by the standard diphoton trigger, requiring transverse momenta (p_{T}) larger than 42 and 25 GeV for the leading and subleading photons, respectively. Loose identification criteria are imposed on the photon shower width in the ECAL and on the ratio of the energies recorded in the ECAL and HCAL to reduce the rate of background from jets misidentified as photons.

For the 2017 data set, a dedicated HLT algorithm was developed to select events with a single photon satisfying requirements consistent with production at a displaced vertex. Such photons tend to strike the front face of the barrel ECAL at a non-normal incidence angle, resulting in a more elliptical electromagnetic shower in the η-ϕ plane [26]. In addition to standard requirements on the shower width and electromagnetic to hadronic energy ratio, requirements on the major and minor axes of the shower are also imposed. This allows the identification of the elliptical shower shape, described in greater detail in Sec. 4.2. Loose requirements on the amount of energy around the direction of the photon in the CMS subdetectors (isolation) are also imposed on trigger photon candidates, and the photon p_{T} is required to exceed 60 GeV. Electrons misidentified as photons are suppressed by requiring the candidate photon to be geometrically isolated from charged-particle tracks. Relaxing the trigger requirement from two photons to only one photon increases the background rate, and in order to reduce the trigger rate to a level acceptable for the operation of the HLT the scalar p_{T} sum of all jets (H_{T}) is required to exceed 350 GeV. For signals with neutralino proper decay length larger than 10 m, the signal acceptance is improved by about a factor of two compared to the 2016 data set.

4.2 Object reconstruction and selection

A particle-flow (PF) algorithm [42] is used to reconstruct and identify each individual particle in an event using an optimized combination of information from the various elements of the CMS detector. The candidate 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 candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_{T} of those jets.

Photon candidates are reconstructed from energy clusters in the ECAL [45] and identified based on the transverse shower width, the hadronic to electromagnetic energy ratio, and the degree of isolation from charged particle tracks. Photons are required to satisfy $|\eta| < 2.5$ and to not fall in the transition region between the barrel and endcap of the ECAL ($1.444 < |\eta| < 1.566$), where the photon reconstruction is not optimal. For the 2016 data set, photon candidates that share the same energy cluster as an identified electron associated with the primary vertex are vetoed following the procedure detailed in Ref. [45]. To remain consistent with the HLT selection, photons matched geometrically to charged-particle tracks are vetoed for the 2017 data set as well.

Because of algorithms designed to reject noise and out-of-time pileup, the default photon reconstruction vetoes photons delayed by more than 3 ns. To evade this veto, a second set of out-of-time (OOT) photons is therefore defined, in which the clustering starts from ECAL deposits whose signals are delayed by more than 3 ns. The remainder of the reconstruction algorithm for OOT photons is identical to the standard photon reconstruction described in the previous paragraph. In addition to being delayed, signal photons tend to impact the front face of the barrel ECAL at a non-normal incidence angle, and yield electromagnetic showers that are more elliptical in the η-ϕ plane. To make use of this discriminating feature, we define the OOT photon identification criteria including selection requirements on the S_{major} and S_{minor} observables defined as:

$$\begin{aligned} S_{\mathrm{major}} &= \frac{S_{\phi\phi} + S_{\eta\eta} + \sqrt{(S_{\phi\phi} - S_{\eta\eta})^2 + 4S_{\eta\phi}^2}}{2}, \\ S_{\mathrm{minor}} &= \frac{S_{\phi\phi} + S_{\eta\eta} - \sqrt{(S_{\phi\phi} - S_{\eta\eta})^2 + 4S_{\eta\phi}^2}}{2} \end{aligned} \tag{1}$$

where $S_{\phi\phi}$, $S_{\eta\eta}$, and $S_{\eta\phi}$ are the second central moments of the spatial distribution of the energy deposits in the ECAL in η-ϕ coordinates, and are proportional to the squared lengths of the semimajor and semiminor axes of the elliptical shower shape. The full set of criteria for the OOT photon selection additionally includes requirements on the transverse shower width and isolation and was obtained through a separate optimization that maximizes the discrimination between displaced signal photons and background photons associated with the primary vertex.

Hadronic jets are reconstructed by clustering PF candidates using the anti-k_{T} algorithm with a distance parameter of 0.4 [43, 44]. Further details of the performance of the jet reconstruction can be found in Ref. [46]. Jets used in any selection of this analysis are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 3.0$.

The negative vector p_{T} sum of all the PF candidates in an event is defined as $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, and its magnitude is denoted as $p_{\mathrm{T}}^{\mathrm{miss}}$ [47]. The $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event. Because OOT photons are not part of the standard PF candidate reconstruction used to compute the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, we correct the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ by adding the negative momentum of an OOT photon if it is selected in the event. Anomalous high-$p_{\mathrm{T}}^{\mathrm{miss}}$ events can arise because of a variety of reconstruction failures, detector malfunctions, or noncollision backgrounds. Filters for vetoing such anomalous events are applied [47].

4.3 Photon time reconstruction

Photons from signal events tend to arrive at the ECAL up to 10 ns later than particles produced at the primary vertex. Therefore measuring the photon time of arrival delay with respect to a photon produced at the primary vertex and traveling at the speed of light helps to discriminate between signal and background. The time of arrival of a photon at the ECAL, t_{ECAL}, is calculated based on a weighted sum of the arrival times reconstructed from the signal pulse in each ECAL crystal comprising the photon cluster:

$$t_{\mathrm{ECAL}} = \frac{\sum_i \frac{t_{\mathrm{ECAL}}^i}{\sigma_i^2}}{\sum_i \frac{1}{\sigma_i^2}}, \tag{2}$$

where t^i_{ECAL} is the timestamp of the signal pulse in crystal i [48]. The estimated time resolution of the signal pulse in crystal i is σ_i and is parametrized as:

$$\sigma_i^2 = \left(\frac{N}{A_i/\sigma_{\mathrm{N}_i}}\right)^2 + C^2, \tag{3}$$

where A_i is the amplitude of the signal detected by crystal i, σ_{N_i} is the pedestal noise for crystal i, and N and C are constants fitted from a dedicated measurement of the time resolution of the crystal sensors.

To measure the crystal sensor time resolution, we follow a procedure similar to that described in Refs. [48, 49]. We first apply a very loose selection on photons using S_{major} and S_{minor} in order to reject jets. Pairs of crystals from the same photon cluster are selected by requiring that their energies are within 20% of each other, are nearest neighbors either in the η or ϕ directions, and are within the same 5×5 grid of crystals defining a trigger tower. The distributions of time differences measured in such crystal pairs are fitted using Gaussian functions in bins of the effective amplitude $A_{\mathrm{eff}}/\sigma_{\mathrm{N}}$, and the standard deviation of each fitted Gaussian function is trended as a function of $A_{\mathrm{eff}}/\sigma_{\mathrm{N}}$. The effective amplitude is obtained combining the signals in the two crystals and is denoted by:

$$A_{\mathrm{eff}}/\sigma_{\mathrm{N}} = \frac{(A_1/\sigma_{\mathrm{N}_1})(A_2/\sigma_{\mathrm{N}_2})}{\sqrt{(A_1/\sigma_{\mathrm{N}_1})^2 + (A_2/\sigma_{\mathrm{N}_2})^2}}. \tag{4}$$

The results for the 2016 and 2017 data sets are shown in Fig. 2. These resolution measurements are fitted with the functional form given by Eq. (3), and the N and C parameters are extracted and summarized in Table 1. These parameters are then used to calculate the weights for the photon timestamp in Eq. (2). The observed worsening of the constant term to the time resolution in 2017 may be due to a progressive loss of transparency of the crystals from radiation damage.

Table 1: The fitted ECAL timing resolution parameters for the 2016 and 2017 data sets.

Parameters	2016 Data set	2017 Data set
N	31.6 ± 1.2 ns	30.4 ± 1.2 ns
C	0.077 ± 0.001 ns	0.095 ± 0.001 ns

To calibrate the photon timestamp response, electrons from $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ decays with an invariant mass between 60 and 150 GeV are reconstructed as photons. For each such photon candidate, the t_{ECAL} is adjusted for the time-of-flight between the primary vertex and the location of the impact of the photon on the front face of ECAL. The timestamp for each photon is recorded, and the mean and RMS parameters of the resulting distribution are extracted as a function of the photon energy. The time response mean is adjusted to zero for both data and simulation, and the timestamps in the simulated events are smeared by an additional Gaussian-distributed random variable such that the resolution in simulation matches that measured in data. The calibrated photon arrival time is denoted as t_γ. These calibrations are applied to simulated signal samples in order to accurately predict the signal response, and their uncertainties are propagated to the predicted shape of the t_γ distribution for the signal as a systematic uncertainty. The time resolution of a single photon candidate is roughly 400 ps. The resolution is constant up to a photon timestamp of 25 ns, the upper boundary of t_γ used during the signal extraction.

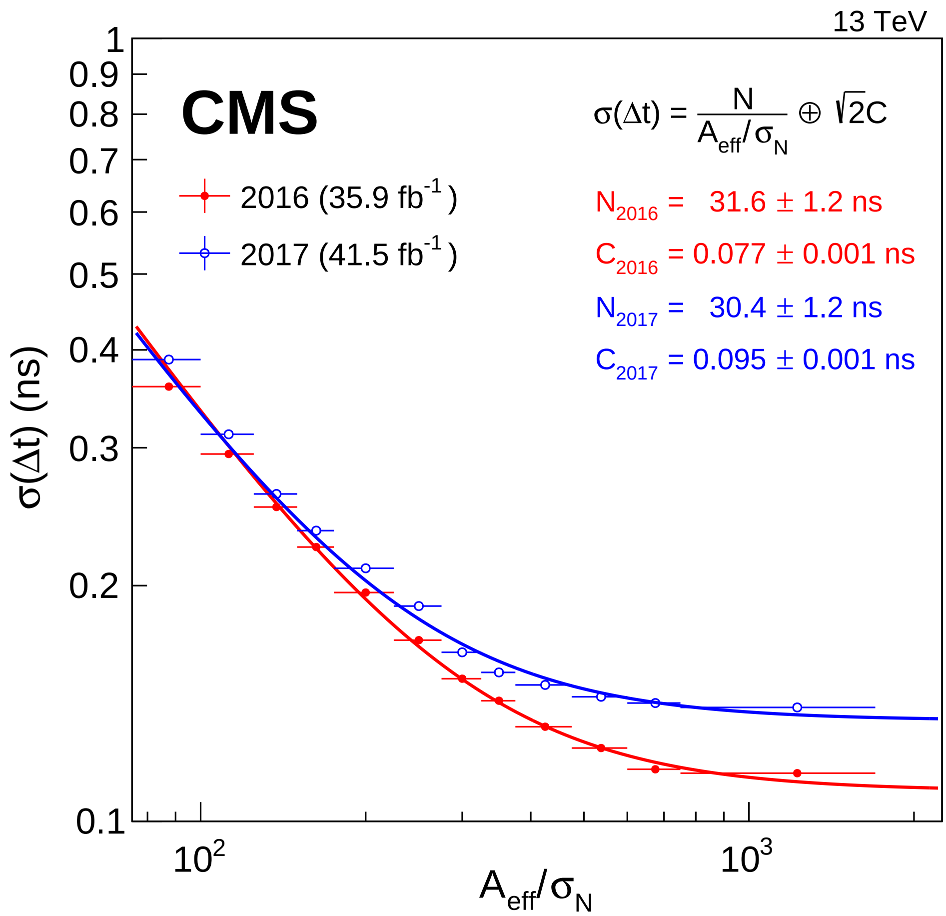

Figure 2: The time resolution between two neighboring ECAL crystals as a function of the effective amplitudes of the signals in the two crystals for the 2016 and 2017 data sets. The lines shown reflect the fits described in the text. The horizontal bars on the data represent the bin widths, which are treated as uncertainties in the fit.

4.4 Event selection

Events with at least one photon in the barrel region of the detector ($|\eta| < 1.444$) with p_{T} larger than 70 GeV are selected. Standard photons [45] and OOT photons are required to pass the "tight" working points. Both photon identifications are tuned to have an average efficiency of about 70%. Furthermore, a displaced photon identification requirement based on the S_{major} and S_{minor} variables is imposed. The calibrated arrival time of this tight photon, t_γ, is used as one of the final discriminating observables to distinguish signal from background. For the dominant squark-pair and gluino-pair production modes shown in Fig. 1, the NLSP is generally produced in association with several jets, and therefore we also require events to have three or more jets with p_{T} larger than 30 GeV.

In order to remain compatible with the respective HLT selection, slightly different event selection criteria are imposed on the 2016 and 2017 data sets. For the 2016 data set, triggered by a diphoton HLT, a second photon with p_{T} larger than 40 GeV is required to match the analogous HLT requirement. For the 2017 data set, the first category, referred to as the 2017γ category, requires events with no subleading photon or events where the subleading photon does not pass the photon identification criteria. The second category requires events to have a subleading photon satisfying the photon identification criteria, and is referred to as the 2017$\gamma\gamma$ category. The second-photon requirement helps to reduce background by one to two orders of magnitude, while the signal yield remains high for low to intermediate lifetimes. Finally, for the 2017 data set, the H_{T} is required to be larger than 400 GeV in order to match the requirements of the HLT and to reach the plateau of the trigger efficiency.

For the 2016 and 2017$\gamma\gamma$ analyses, for a given neutralino proper decay length, the signal yield increases as a function of the SUSY breaking scale, Λ, by roughly a factor of two over the range considered for this analysis (Λ from 100 to 400 TeV). The product of signal efficiency and acceptance for the lowest Λ is roughly $10.0 \pm 0.1\%$ and $0.15 \pm 0.01\%$ for neutralino proper decay lengths of 0.1 and 100 m, respectively. For the 2017γ analysis, the product of signal efficiency and acceptance varies as a function of Λ from 5.5 ± 0.1 to $10.4 \pm 0.2\%$ for a neutralino proper decay length of 0.1 m, and from 0.22 ± 0.03 to $0.65 \pm 0.05\%$ for a neutralino proper decay length of 100 m. These trends can be explained by the harder photon spectrum and increase in jet activity that result from an increase in Λ, while an increase in the neutralino proper decay length results in either one or both of the NLSPs decaying outside the fiducial region of ECAL.

Figures 3 and 4 show the $p_{\mathrm{T}}^{\text{miss}}$ (t_γ) distribution in data for low and high t_γ (low and high $p_{\mathrm{T}}^{\text{miss}}$), for the 2016, 2017$\gamma$, and 2017$\gamma\gamma$ event selections. In addition, the distribution of events for a representative signal point (GMSB: $\Lambda = 200$ TeV, $c\tau = 2$ m) is also shown, scaled by the product of the production cross section and the integrated luminosity in the regions most sensitive to this signal benchmark: large $p_{\mathrm{T}}^{\text{miss}}$ and t_γ.

5 Signal extraction and background estimation

The $p_{\mathrm{T}}^{\text{miss}}$ and t_γ variables are used as the final discriminating observables to distinguish signal from background. Standard model background events can populate the signal-enriched regions with large values of $p_{\mathrm{T}}^{\text{miss}}$ and t_γ because of imperfect resolution. Four bins are defined based on the values of the $p_{\mathrm{T}}^{\text{miss}}$ and t_γ observables. Bin A has low $p_{\mathrm{T}}^{\text{miss}}$ and low t_γ; bin B has high $p_{\mathrm{T}}^{\text{miss}}$ and low t_γ; bin C has high $p_{\mathrm{T}}^{\text{miss}}$ and high t_γ; and bin D has low $p_{\mathrm{T}}^{\text{miss}}$ and high t_γ. Signals with large lifetimes are concentrated in bin C, while signals with shorter lifetimes tend to occupy bin B. In contrast, backgrounds are concentrated in bin A. In general, bin C is the most sensitive, with largest signal to background ratio. After the offline selection is ap-

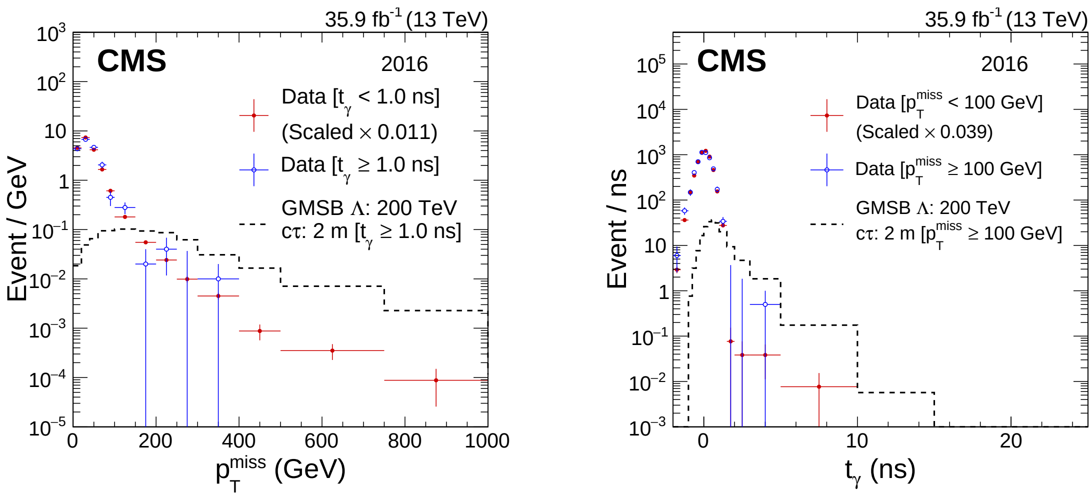

Figure 3: The $p_{\mathrm{T}}^{\mathrm{miss}}$ (left) and t_{γ} (right) distributions for the 2016 event selection, shown for data and a representative signal benchmark (GMSB: $\Lambda = 200\,\mathrm{TeV}, c\tau = 2\,\mathrm{m}$). The $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution for data is separated into events with $t_{\gamma} \geq 1\,\mathrm{ns}$ (blue, darker) and $t_{\gamma} < 1\,\mathrm{ns}$ (red, lighter), scaled to match the total number of events with $t_{\gamma} \geq 1\,\mathrm{ns}$. The t_{γ} distribution for data is separated into events with $p_{\mathrm{T}}^{\mathrm{miss}} \geq 100\,\mathrm{GeV}$ (blue, darker) and $p_{\mathrm{T}}^{\mathrm{miss}} < 100\,\mathrm{GeV}$ (red, lighter), scaled to match the total number of events with $p_{\mathrm{T}}^{\mathrm{miss}} \geq 100\,\mathrm{GeV}$. The signal (black, dotted) is shown in the left plot only for events with $t_{\gamma} \geq 1\,\mathrm{ns}$, and in the right plot only for events with $p_{\mathrm{T}}^{\mathrm{miss}} \geq 100\,\mathrm{GeV}$. The entries in each bin are normalized by the bin width. The horizontal bars on data indicate the bin boundaries. The last bin in each plot includes overflow events.

plied, the main background contribution is from pp collision processes with high $p_{\mathrm{T}}^{\mathrm{miss}}$, which have the same timing distribution as low-$p_{\mathrm{T}}^{\mathrm{miss}}$ collider data, ensuring that the two discriminating variables are independent for background processes. This includes proton collisions from satellite bunches spaced $\sim 2.5\,\mathrm{ns}$ apart from the main bunches. The noncollision backgrounds, which include cosmic ray muons, beam halo muons, and electronic noise deposits, are reduced to a negligible level by the jet multiplicity requirement and the photon selections.

As the $p_{\mathrm{T}}^{\mathrm{miss}}$ and t_{γ} observables are statistically independent for background processes, the background distribution can be factorized into the product of the distributions of these two observables. This permits the use of the so called "ABCD" method to predict the background yield in the signal-enriched bin C as $N_{\mathrm{C}} = (N_{\mathrm{D}} N_{\mathrm{B}}) / N_{\mathrm{A}}$, where N_{X} is the number of background events. In order to account for potential signal contamination in bins A, B, and D, a modified ABCD method is used where a binned maximum likelihood fit is performed simultaneously in the four bins, with the signal strength included as a floating parameter that scales the signal yield uniformly in each bin. The background component of the fit is constrained to obey the standard ABCD relationship, within the bounds of a small systematic uncertainty derived from a validation check of the method in a control region (CR). Systematic uncertainties that impact the signal and background yields are treated as nuisance parameters with log-normal probability density functions.

For each point in the signal model parameter space (Λ and $c\tau$ in Table 2), the boundaries in $p_{\mathrm{T}}^{\mathrm{miss}}$ and t_{γ} that define the A, B, C, and D bins are chosen to yield optimal expected sensitivity. For the optimization procedure, in order to remain unbiased by the observed data in the signal-enriched regions, we estimate the background yields using only the observed yield in data for bin A (N_{A}) as follows. Template shapes for the observable $p_{\mathrm{T}}^{\mathrm{miss}}$ (t_{γ}) are derived from data requiring that $|t_{\gamma}| < 1\,\mathrm{ns}$ ($p_{\mathrm{T}}^{\mathrm{miss}} < 100\,\mathrm{GeV}$). These regions are defined to have negligible signal

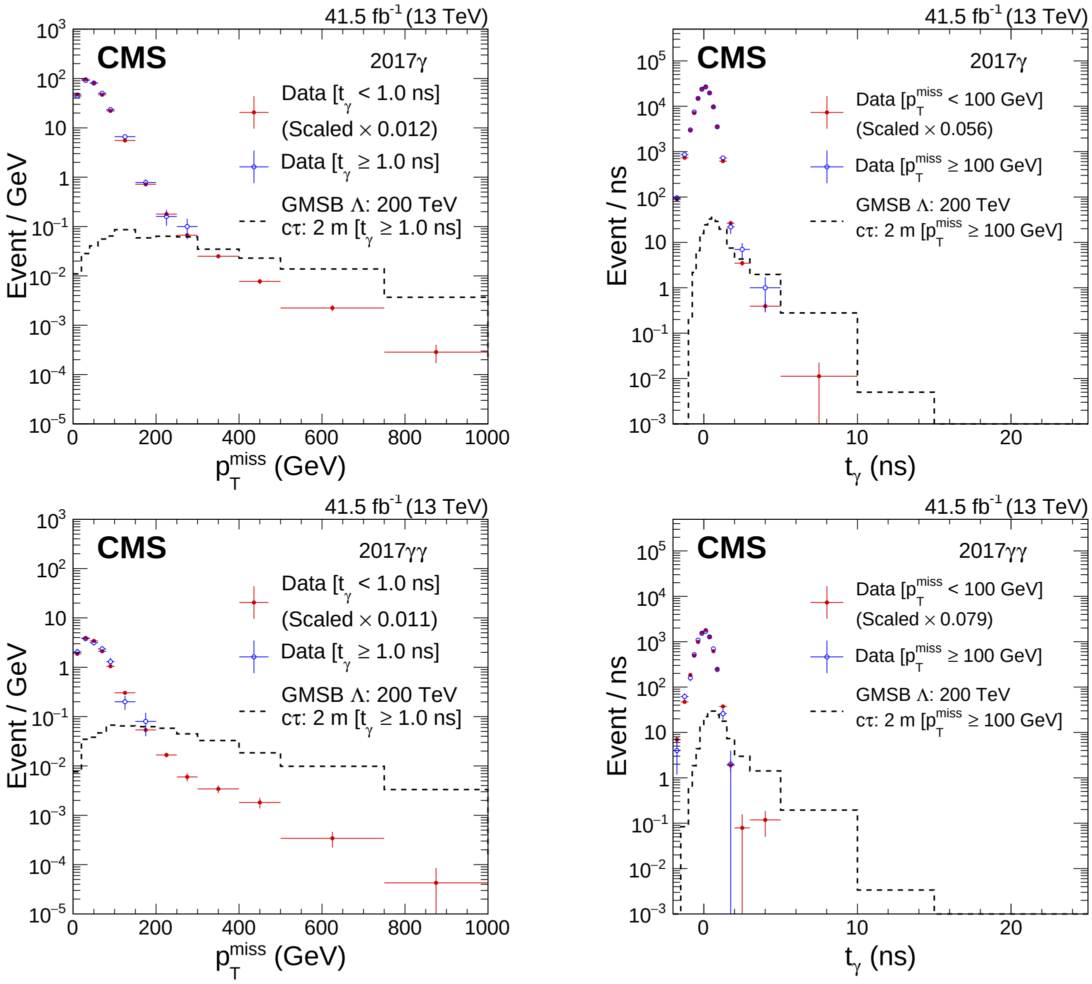

Figure 4: The $p_{\mathrm{T}}^{\mathrm{miss}}$ (left) and t_γ (right) distributions for the 2017γ (upper row) and 2017$\gamma\gamma$ (lower row) event selections shown for data and a representative signal benchmark (GMSB: $\Lambda = 200\,\mathrm{TeV}, c\tau = 2\,\mathrm{m}$). The $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution for data is separated into events with $t_\gamma \geq 1\,\mathrm{ns}$ (blue, darker) and $t_\gamma < 1\,\mathrm{ns}$ (red, lighter), scaled to match the total number of events with $t_\gamma \geq 1\,\mathrm{ns}$. The t_γ distribution for data is separated into events with $p_{\mathrm{T}}^{\mathrm{miss}} \geq 100\,\mathrm{GeV}$ (blue, darker) and $p_{\mathrm{T}}^{\mathrm{miss}} < 100\,\mathrm{GeV}$ (red, lighter), scaled to match the total number of events with $p_{\mathrm{T}}^{\mathrm{miss}} \geq 100\,\mathrm{GeV}$. The signal (black, dotted) is shown in the left plots only for events with $t_\gamma \geq 1\,\mathrm{ns}$, and in the right plots only for events with $p_{\mathrm{T}}^{\mathrm{miss}} \geq 100\,\mathrm{GeV}$. The entries in each bin are normalized by the bin width. The horizontal bars on data indicate the bin boundaries. The last bin in each plot includes overflow events.

yield. We obtain the ratios $r_{\mathrm{B/A}}$ ($r_{\mathrm{D/A}}$) by dividing the number of events with $p_{\mathrm{T}}^{\mathrm{miss}}$ ($|t_\gamma|$) larger than the given bin boundary by the number of events with $p_{\mathrm{T}}^{\mathrm{miss}}$ ($|t_\gamma|$) smaller than the bin boundary. The background yields in bins B, D, and C are calculated as $N_{\mathrm{A}} r_{\mathrm{B/A}}$, $N_{\mathrm{A}} r_{\mathrm{D/A}}$, and $N_{\mathrm{A}} r_{\mathrm{B/A}} r_{\mathrm{D/A}}$, respectively. The resulting optimized bin boundaries in t_γ and $p_{\mathrm{T}}^{\mathrm{miss}}$ are obtained by choosing the bin boundaries that yield the best expected limit and are summarized in Table 2 for all the SPS8 model parameter space points considered. To simplify the analysis, groups of similar signal model parameters share the same optimized bin boundaries.

It should be noted that we set the lower and upper boundaries in t_γ to be -2 ns and 25 ns, respectively. The lower boundary is set by five times the single photon candidate time resolution, while the upper boundary is set to avoid contamination from the next LHC bunch crossing.

Table 2: The optimized bin boundaries for t_γ (first number, in units of ns) and $p_{\mathrm{T}}^{\mathrm{miss}}$ (second number, in units of GeV), for different GMSB SPS8 signal model benchmark points considered in the search and for each data set category.

$c\tau$ (m)	$\Lambda \leq 300$ TeV			$\Lambda > 300$ TeV		
	2016	2017γ	2017$\gamma\gamma$	2016	2017γ	2017$\gamma\gamma$
(0, 0.1)	0 , 250	0.5 , 300	0.5 , 150	0 , 250	0.5 , 300	0.5 , 200
(0.1 , 100)	1.5 , 100	1.5 , 200	1.5 , 150	1.5 , 150	1.5 , 300	1.5 , 200

To verify that the $p_{\mathrm{T}}^{\mathrm{miss}}$ and t_γ observables are independent, we define CRs that isolate different SM processes that are similar to the backgrounds expected in the signal region (SR). The γ+jets CR, dominated by the γ+jets process, is defined as events satisfying the same requirements as the SR, but having fewer than three jets. The multijet CR, dominated by QCD multijet production, comprises events satisfying the same requirements as the SR, but with an inverted isolation requirement on the leading photon. We measure the correlation coefficients between $p_{\mathrm{T}}^{\mathrm{miss}}$ and t_γ to be less than 1% for both the γ+jets CR and multijet CR, supporting their independence. A closure test on the predicted background yield in these CRs is propagated as a systematic uncertainty, as discussed further in Sec. 6.

6 Systematic uncertainties

The dominant uncertainty in the search is the statistical uncertainty in the background prediction of the modified ABCD method. There are several subdominant systematic uncertainties that affect the prediction of the signal yield in all four bins. These systematic uncertainties include the uncertainty in the integrated luminosity measurement [50, 51], in the energy scale and resolution of the photons and jets, and in the trigger and photon identification efficiencies. For all these cases, dedicated measurements are performed that evaluate corrections and uncertainties in the efficiencies and energy scales in simulated signal events, and these uncertainties are propagated to the signal yield predictions as an uncertainty in the predicted shapes of the distributions of the discriminating observables $p_{\mathrm{T}}^{\mathrm{miss}}$ and t_γ. The calibration of the timestamp discussed in Sec. 4.3 has associated uncertainties that affect both the offset and the resolution in t_γ, and are propagated in the shape prediction for the t_γ distribution for the signal benchmarks. As we use $\mathrm{Z} \to \mathrm{e^+e^-}$ events to measure the photon identification efficiency, the corresponding systematic uncertainty includes the impact of the difference in detector response between an electron and a photon. Table 3 provides a summary of the systematic uncertainties in the analysis and their assigned values for each data set, as well as additional information about the correlations between the uncertainties.

As the modified ABCD method for estimating the background requires that the discriminating observables $p_{\mathrm{T}}^{\mathrm{miss}}$ and t_{γ} are independent, we propagate a systematic uncertainty for any potential interdependence of these observables. We select events in the γ+jets and multijet CR and separate events into the same A, B, C, and D bins defined for the signal region. We compare the background yield in bin C predicted by the ABCD method with the observed yield, and propagate the difference as a systematic uncertainty. This systematic uncertainty is referred to as "the closure" in Table 3. For the cases with neutralino proper decay length smaller than 0.1 m, this systematic uncertainty is relatively small, at 4% or less. For the cases with neutralino proper decay length larger than 0.1 m, the data yields in bin C of the CRs are small and are limited by statistical uncertainty. As a result, a relatively large systematic uncertainty of 90% of the predicted background yield is propagated.

Table 3: Summary of systematic uncertainties in the analysis. Also included are notes on whether each source affects signal yields (Sig) or background (Bkg) estimates, to which bins each uncertainty applies, and how the correlations of the uncertainties between the different data sets are treated. We assign different values for the uncertainty in the closure of the background prediction for short and long lifetime signal models. The column labeled 2017 includes both the 2017γ and 2017$\gamma\gamma$ categories.

Systematic uncertainty	Sig/Bkg	Bins	2016	2017	Correlation
Integrated luminosity	Sig	A,B,C,D	2.5%	2.3%	Uncorrelated
Photon energy scale	Sig	A,B,C,D	1%	2%	Correlated
Photon energy resolution	Sig	A,B,C,D	1%	1%	Correlated
Jet energy scale	Sig	A,B,C,D	1.5%	2%	Correlated
Jet energy resolution	Sig	A,B,C,D	1.5%	1.5%	Uncorrelated
Photon time bias	Sig	A,B,C,D	1.5%	1%	Correlated
Photon time resolution	Sig	A,B,C,D	0.5%	0.5%	Correlated
Trigger efficiency	Sig	A,B,C,D	2%	$<$1%	Uncorrelated
Photon identification	Sig	A,B,C,D	2%	3%	Correlated
Closure in bin C ($c\tau \leq 0.1$ m)	Bkg	C	2%	3.5%	Correlated
Closure in bin C ($c\tau > 0.1$ m)	Bkg	C	90%	90%	Correlated

7 Results and interpretation

Tables 4 and 5 list the yields and postfit background predictions for the background-only fit in each of the four bins of the 2016, 2017γ, and 2017$\gamma\gamma$ categories, respectively, for all the t_{γ}-$p_{\mathrm{T}}^{\mathrm{miss}}$ bin boundaries used. No statistically significant deviation from the background expectation is observed. The search result is interpreted in terms of limits on the neutralino production cross section for scenarios in the GMSB SPS8 signal model set.

The modified frequentist criterion $\mathrm{CL_s}$ [52–54] with the profile likelihood ratio test statistic determined by toy experiments is used to evaluate the observed and expected limits at 95% confidence level (CL) on the signal production cross sections. The limits are shown in Fig. 5 as functions of the mass of the neutralino NLSP $\tilde{\chi}_1^0$ (linearly related to the SUSY breaking scale, Λ) and the proper decay length of the neutralino. The two-photon category (2016 and 2017$\gamma\gamma$) and the one-photon category (2017γ) are complementary as the sensitivity at small proper decay length is better for the 2016 and 2017$\gamma\gamma$ categories because of the extra background suppression from requiring two photons, while the sensitivity at large proper decay lengths is better for the 2017γ analysis because of the significantly improved signal acceptance from the dedicated displaced single-photon trigger. As a result, the sensitivity to signal models with proper lifetimes greater than the ECAL timing resolution for a single photon candidate is improved

Table 4: Observed number of events ($N_{\mathrm{obs}}^{\mathrm{data}}$) and predicted background yields from the background-only fit ($N_{\mathrm{bkg}}^{\mathrm{postfit}}$) in bins A, B, C, and D in data for the 2016 category and for the different t_γ and $p_{\mathrm{T}}^{\mathrm{miss}}$ bin boundaries summarized in Table 2. In addition, the predicted postfit yields from the background-only fit not including bin C ($N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$) are provided as a test of the closure. Uncertainties in the $N_{\mathrm{bkg}}^{\mathrm{postfit}}$ and $N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$ values are the postfit uncertainties. The propagation of the systematic uncertainties is handled during the fit and therefore they are included in the postfit uncertainties.

		2016 category			
Bin boundary [t_γ (ns), $p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)]		A	B	C	D
(0, 250)	$N_{\mathrm{obs}}^{\mathrm{data}}$	16 139	41	62	18 826
	$N_{\mathrm{bkg}}^{\mathrm{postfit}}$	$16\,130 \pm 110$	47.5 ± 4.8	55.6 ± 5.6	$18\,830 \pm 130$
	$N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$	$16\,140 \pm 110$	41.0 ± 6.5	47.8 ± 7.7	$18\,830 \pm 130$
(1.5, 100)	$N_{\mathrm{obs}}^{\mathrm{data}}$	33 760	1302	1	5
	$N_{\mathrm{bkg}}^{\mathrm{postfit}}$	$33\,760 \pm 160$	1303 ± 37	0.29 ± 0.28	5.7 ± 2.2
	$N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$	$33\,760 \pm 160$	1302 ± 37	0.19 ± 0.21	5.0 ± 2.1
(1.5, 150)	$N_{\mathrm{obs}}^{\mathrm{data}}$	34 595	467	0	6
	$N_{\mathrm{bkg}}^{\mathrm{postfit}}$	$34\,600 \pm 170$	467 ± 22	0.08 ± 0.08	5.9 ± 2.3
	$N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$	$34\,600 \pm 170$	467 ± 22	0.08 ± 0.09	6.0 ± 2.3

compared to previous results. For the neutralino proper decay lengths $c\tau$ of 0.1, 1, 10, and 100 m, masses up to about 320, 525, 360, and 215 GeV are excluded at 95% CL, respectively.

8 Summary

A search for long-lived particles that decay to a photon and a weakly interacting particle has been presented. The search is based on proton-proton collisions at a center-of-mass energy of 13 TeV collected by the CMS experiment in 2016–2017. The photon from this particle's decay would enter the electromagnetic calorimeter at non-normal impact angles and with delayed times, and this striking combination of features is exploited to suppress backgrounds. The search is performed using a combination of the 2016 and 2017 data sets, corresponding to a total integrated luminosity of 77.4 fb^{-1}. Both single-photon and diphoton event samples are used for the search, with each sample providing a complementary sensitivity at larger and smaller long-lived particle proper decay lengths, respectively. The results are interpreted in the context of supersymmetry with gauge-mediated supersymmetry breaking, using the SPS8 benchmark model. For neutralino proper decay lengths of 0.1, 1, 10, and 100 m, masses up to about 320, 525, 360, and 215 GeV are excluded at 95% confidence level, respectively. The previous best limits are extended by one order of magnitude in the neutralino proper decay length and by 100 GeV in the mass reach.

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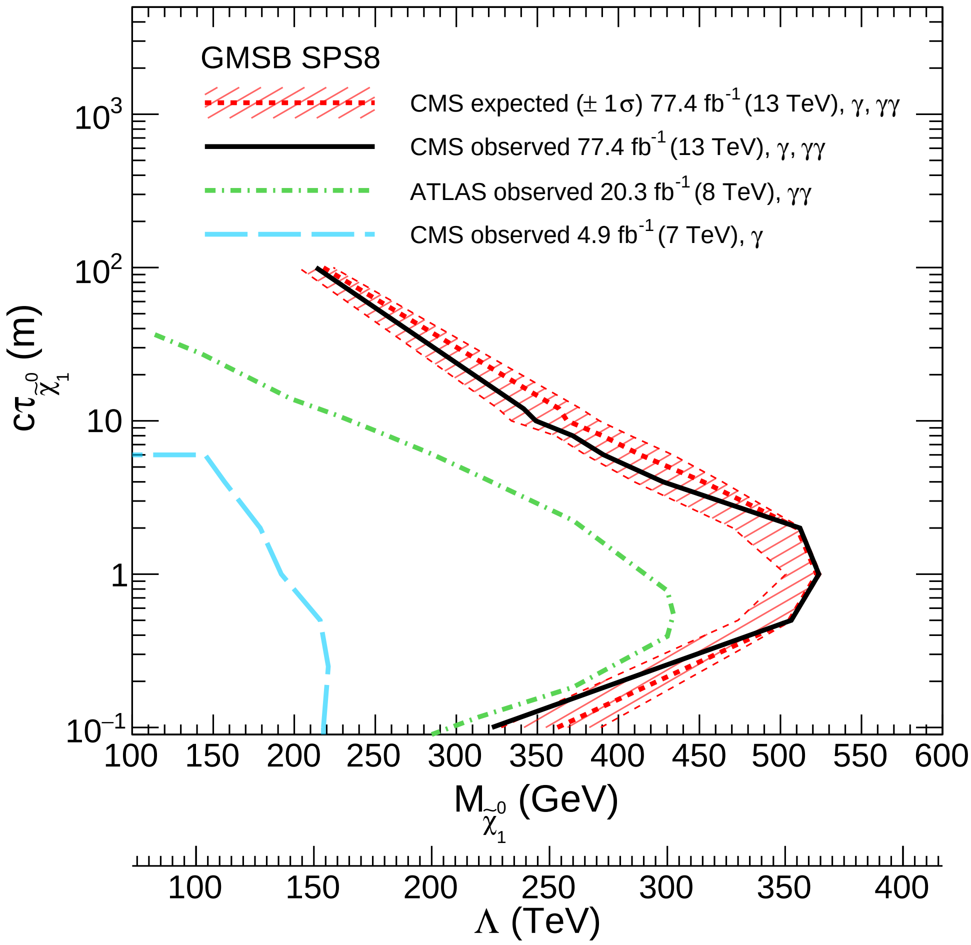

Figure 5: The 95% CL exclusion contours for the GMSB neutralino production cross section, shown as functions of the neutralino mass, or equivalently the SUSY breaking scale, Λ, in the GMSB SPS8 model, and the neutralino proper decay length, $c\tau_{\tilde{\chi}_1^0}$.

Table 5: Observed number of events ($N_{\mathrm{obs}}^{\mathrm{data}}$) and predicted background yields from the background-only fit ($N_{\mathrm{bkg}}^{\mathrm{postfit}}$) in bins A, B, C, and D in data for the 2017γ (upper table) and 2017$\gamma\gamma$ (lower table) categories and for the different t_γ and $p_{\mathrm{T}}^{\mathrm{miss}}$ bin boundaries summarized in Table 2. Additional details are described in the caption of Table 4.

Bin boundary [t_γ (ns), $p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)]		A	B	C	D
		2017γ category			
(0.5, 300)	$N_{\mathrm{obs}}^{\mathrm{data}}$	458 372	281	41	67 655
	$N_{\mathrm{bkg}}^{\mathrm{postfit}}$	$458\,370 \pm 660$	281 ± 15	41.4 ± 2.4	$67\,660 \pm 280$
	$N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$	$460\,369 \pm 660$	281 ± 16	41.5 ± 2.7	$67\,660 \pm 280$
(1.5, 200)	$N_{\mathrm{obs}}^{\mathrm{data}}$	524 652	1364	1	332
	$N_{\mathrm{bkg}}^{\mathrm{postfit}}$	$524\,650 \pm 710$	1364 ± 36	0.9 ± 0.8	330 ± 20
	$N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$	$524\,650 \pm 700$	1364 ± 35	0.9 ± 1.0	330 ± 20
(1.5, 300)	$N_{\mathrm{obs}}^{\mathrm{data}}$	525 694	322	0	333
	$N_{\mathrm{bkg}}^{\mathrm{postfit}}$	$525\,690 \pm 700$	322 ± 17	0.19 ± 0.21	330 ± 20
	$N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$	$525\,690 \pm 700$	322 ± 17	0.20 ± 0.24	330 ± 20
		2017$\gamma\gamma$ category			
(0.5, 150)	$N_{\mathrm{obs}}^{\mathrm{data}}$	21 640	362	56	3201
	$N_{\mathrm{bkg}}^{\mathrm{postfit}}$	$21\,640 \pm 140$	364 ± 17	54.0 ± 3.0	3200 ± 60
	$N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$	$21\,640 \pm 140$	362 ± 18	53.6 ± 3.3	3200 ± 60
(0.5, 200)	$N_{\mathrm{obs}}^{\mathrm{data}}$	21 863	139	24	3233
	$N_{\mathrm{bkg}}^{\mathrm{postfit}}$	$21\,860 \pm 140$	142 ± 11	21.1 ± 1.7	3240 ± 60
	$N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$	$21\,860 \pm 140$	139 ± 11	20.6 ± 1.8	3230 ± 60
(1.5, 150)	$N_{\mathrm{obs}}^{\mathrm{data}}$	24 824	418	0	17
	$N_{\mathrm{bkg}}^{\mathrm{postfit}}$	$24\,820 \pm 150$	420 ± 20	0.25 ± 0.28	16.7 ± 4.4
	$N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$	$24\,820 \pm 150$	420 ± 20	0.29 ± 0.36	17.0 ± 4.4
(1.5, 200)	$N_{\mathrm{obs}}^{\mathrm{data}}$	25 079	163	0	17
	$N_{\mathrm{bkg}}^{\mathrm{postfit}}$	$25\,080 \pm 150$	163 ± 12	0.11 ± 0.12	16.9 ± 4.4
	$N_{\mathrm{bkg(no\ C)}}^{\mathrm{postfit}}$	$25\,080 \pm 150$	163 ± 12	0.11 ± 0.14	17.0 ± 4.4

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