

DRAFT

CMS Physics Analysis Summary

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Search for long-lived neutral particles in the final state of delayed photons and missing energy in proton-proton collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration

Abstract

A search for long-lived neutral particles decaying into a photon and an un-detectable particle such as gravitino, is performed using 19.1 fb^{-1} of proton-proton collision data at $\sqrt{s} = 8 \text{ TeV}$. We present a method which exploits its long-lived feature by using the time measurement from the CMS Electromagnetic calorimeter. The method is sensitive to a range of lifetimes (τ) from 1.6 ns to 34 ns and is nearly free from standard model background. Taking the Gauge Mediated Supersymmetry Breaking model as a benchmark and applying our method to the data, no significant excess is observed above background expectation. An exclusion region of neutralino mass and lifetime at 95% C.L. is set.

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1 Introduction

The observation of the 125 GeV neutral boson at the LHC provides strong evidence for the Higgs mechanism of the standard model (SM). Despite the many successes of the standard model, the theory suffers from fine-tuning problems stemming from the Higgs sector [1] and has no explicit prediction for the unification of the gauge couplings and the role of gravity. With solutions for these questions, supersymmetry (SUSY) is one of the most compelling theories beyond the standard model. In addition, the Lightest Supersymmetric Particle (LSP) can be a stable particle making it a good candidate for dark matter. This scenario further motivates searches for the evidence of SUSY.

In the model of Gauge Mediated Supersymmetry Breaking (GMSB) [2], the gravitino (\tilde{G}) is the LSP. Under the assumption of R-parity conservation [3], the gravitino is stable and couples weakly to the other SUSY particles. Strongly interacting supersymmetric particles with higher masses, such as the squarks and gluinos produced in proton-proton collisions at the LHC, provide large cross sections for SUSY production while at the same time through their prompt decays allow for lighter SUSY particles to be produced. The Next-to-Lightest Supersymmetric Particle (NLSP) is considered, in this analysis, to be the lightest of the promptly produced SUSY particles initiated by squark or gluino decays.

The NLSP for a range of GMSB model parameters will decay in a non-prompt manner, into the gravitino and SM particle(s). Depending on the choice of mass parameters, the NLSP can be a neutralino ($\tilde{\chi}_0$), stau or sneutrino. The mass, decay modes and lifetime of the NLSP depends on the SUSY breaking scale (Λ). If the NLSP is the neutralino, it has three different two-body decay channels with the gravitino produced with a photon, Z boson or a Higgs boson. The branching ratio (BR) for each channel depends on the choice of SUSY parameters. In this study, we choose the 'Snowmass Points and Slopes 8' (SPS8) [4] scenario as our benchmark model. In this scheme, the neutralino decay to a photon and a gravitino has the largest branching ratio [5](Table 1). Its lifetime is proportional to

$$\tau \propto \frac{M_P^2 m_{\tilde{G}}^2}{m_{\tilde{\chi}_0}^5} \quad (1)$$

Λ (TeV)	BR
100	0.9444
120	0.9042
140	0.8711
160	0.8464
180	0.8282
220	0.8043

Table 1: The branching ratio of $\tilde{\chi}_0 \rightarrow \gamma + \tilde{G}$

where M_P is the Planck mass. The neutralino mass ($m_{\tilde{\chi}_0}$) and the gravitino mass ($m_{\tilde{G}}$) are related to the SUSY breaking scale Λ . For example, the gravitino mass is given by

$$m_{\tilde{G}} = \frac{c_{grav} \Lambda M}{\sqrt{3} M_P} \quad (2)$$

where M is the mass of the messenger particle responsible for mediating SUSY breaking from the so-called *hidden sector* to a much lower energy scale where SUSY breaking is felt and c_{grav} is

a free parameter which influences the gravitino mass thus adjusting the lifetime of neutralino for a given energy scale. In this search, we focus on a non-prompt decay of the neutralino. When the decay lifetime of the neutralino is sufficiently long, the arrival time of the resulting photon can be measurably later than normal prompt photons from proton interactions and this can be used to search for neutralino decays. We explore the parameter space covering possible neutralino lifetimes from 1 ns to 30 ns at different SUSY breaking scales.

The neutralinos are produced mainly when squarks or gluinos are pair produced. The cascade decay chain of a squark or gluino will lead to a neutralino as the NLSP and other quarks in the final state. Many of these events should have at least one late arriving photon, a few jets as well as missing energy from un-detectable gravitino.

CMS electromagnetic calorimeter (ECAL) consists of 75848 $PbWO_4$ scintillation crystals, and with its fine granularity and excellent timing as well as energy resolution, it is a powerful tool to search for the delayed photon signal. In addition, the absence of any known SM physics process at the TeV energy scale in proton-proton collisions which would produce a delayed photon, makes it possible to use ECAL timing measurements to perform a search with nearly zero background. Previous searches [6–9] have set the neutralino mass lower limits as high as 250 GeV/ c^2 for different lifetime ranges between 0.25 ns to 50 ns.

2 Data and Monte Carlo samples

The data used in the analysis were collected during the 2012 runs with an integrated luminosity of 19.1 fb^{-1} . They are selected by an off-line trigger processor (HLT) which requires at least one isolated ECAL cluster (a collection of crystals with associated energy deposit) with E_T greater than 65 GeV and E_T^{miss} greater than 25 GeV.

The signal Monte Carlo (MC) samples are generated by PYTHIA 6 [10] with an external SLHA (Supersymmetry Les Houches Accord) file which describes SUSY parameters and mass spectrum. Those parameters are calculated by ISAJET [11]. The generation for signal samples adopts SUSY GMSB scheme where Λ , and c_{grav} are varied to cover a range (1.67 ns to 34 ns) of neutralino lifetime. The SUSY breaking scale, Λ , ranges from 100 TeV to 220 TeV where this analysis is most sensitive to according to the predicted cross-sections from GMSB.

The γ + jets samples simulate photons radiated from a quark in the QCD process. The events are generated in different transverse momentum ranges with respect to the quark (denoted as p_T). These samples are just used to study timing calibration and resolution in MC and data. Background arises from mis-measured collision events so-called spike hits (section 6.3), and beam-halo and cosmic ray-induced processes. Since their contributions must be estimated using data samples, we do not use any Monte Carlo sample for this purpose.

3 Event and Object Selection

As described briefly in section 1, neutralinos are pair produced from the cascade decays of two sparticles. As a result, our signal events are expected to have at least one photon and at least two jets. Another common feature in various models is the missing energy. Since gravitino is undetectable, a significant amount of missing energy is expected. A cut on Missing Transverse Energy (E_T^{miss}) is useful to lower the rate from the standard model backgrounds like γ + jets process and QCD events.

Photons are reconstructed using a clustering algorithm to build a cluster of clusters (super-

cluster) [12], which extends the cluster size in ϕ in order to recover energy spread due to strong magnetic fields for photons which convert into positron-electron pairs. Photon candidate should have corresponding HCAL energy deposit less than 5 percent of ECAL energy deposit. Because ECAL crystals are pointing to the center of the CMS detector, the prompt photons have a circular distribution of energy deposit and the displaced photons could have an elliptical shape. Therefore, the major and minor axis of the spatial distribution of the energy deposit can be constructed and defined as S_{major} and S_{minor} . In this search, we require S_{minor} of the photon should be between 0.12 and 0.38 and no constraint on S_{major} . Figure 1 shows the distribution for late photon from signal Monte Carlo events.

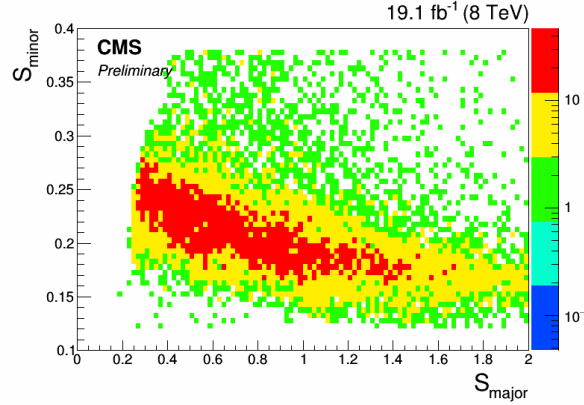


Figure 1: The distribution of S_{major} and S_{minor} from GMSB Monte Carlo events. The ECAL time of the photons is greater than 3 ns and the Δt_2 (defined in section 4) is greater than 0.5 ns.

We use only photons from the ECAL barrel in this analysis. We require that the transverse momentum (p_T) of the leading photon of the event must be greater than 80 GeV and other photon candidates must have p_T greater 45 GeV. Photon isolation requires no track with p_T greater than 3 GeV exists within a cone of $\Delta R = 0.6$. An event is classified as a late timing event if one of the selected photon with ECAL time greater than 3 ns. An early timing event is similar except the photon with ECAL time less than -3 ns.

For jets and E_T^{miss} reconstruction, the particle-flow (PF) algorithm [13] is used because it takes information from all sub-detectors into account to reconstruct each particle before jet clustering. The PF jets are found to have the highest purity and lowest fake rate to pass the jet quality criteria [14]. In this analysis, we select PF jets that pass a p_T threshold of 35 GeV and $|\eta| < 2.4$. A $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ separation between a jet and a photon should be at least 0.3 to avoid counting the same object as a photon and jet.

PF ignores out-of-time energy deposits readout from ECAL crystals for the E_T^{miss} calculation and includes it as isolation energy deposits if it is part of a photon cluster. In this analysis, since out-of-time photons are a legitimate part of events, the photon E_T needs to be included in the E_T^{miss} calculations. Therefore, we correct the E_T^{miss} for events with out-of-time photons by subtracting the photon E_T vector from the E_T^{miss} vector and define a variable called $E_{T no\gamma}^{miss}$ which is the vector sum of E_T^{miss} and photon E_T . For signal events, not only E_T^{miss} but also $E_{T no\gamma}^{miss}$ is large unless the p_T sum of two gravitinos is back-to-back with photon E_T . For non-collision backgrounds, out-of-time photons from background sources do not belong to the event. If taking them into account for E_T^{miss} calculation of otherwise small E_T^{miss} collision event, the E_T^{miss} will be back to back with photon p_T in the same magnitude. Therefore, $E_{T no\gamma}^{miss}$ is small and E_T^{miss} is large in this type of events. Collision backgrounds behave in the opposite way since

QCD events are dominated.

In summary, our signal events should have at least one photon and at least two jets. Both estimates of the missing transverse energy, E_T^{miss} and $E_{T \text{ no } \gamma}^{\text{miss}}$, are required to be greater than 60 GeV. Zero and one jet events are dominated by background and are particularly useful to study various sources of them.

4 ECAL Timing and Delayed Photon

The photon arrival time in ECAL is the main observable that we use to distinguish signal from background in this study (Figure 2a). The arrival time is estimated from 10 pulse-height measurements recorded every 25 ns over a 250 ns period from before and until after photons deposit energy in ECAL. The rising part of the shaped pulse depends on the relaxation time of the $PbWO_4$ crystal scintillation process, while the falling part of the pulse is determined by the front-end electronics time constants. The pulse timing relative to the clock pulse uniquely determines the ratio of pulse heights from two consecutive measurements. We invert this relationship and use the pulse height ratio to estimate the pulse timing relative to the LHC beam clock which is distributed to each crystal. Typically, samples 1 through 3 are pedestals, so the useful ratios are sample 4/sample 5, through sample 7/sample 8. The remaining ratios arising from the tail of the pulse are insensitive to the pulse timing. We calculate weighted average of typically 3 measurements of pulse timing obtained this way as the pulse timing for each crystal. Even though the uncertainty in the ratio measurements is anti-correlated, its effect on the crystal timing estimate turns out to be less than 10% of the uncertainty estimate. Since the clock pulse delivery system has its own delays relative to the actual collision time and they vary from crystal to crystal, we calibrate the timing using actual prompt relativistic particles so that their arrival time is defined to be zero. The resolution and linearity of the time measurement have been studied with test beam electrons, cosmic rays and beam splash events. Results show that the resolution is 595 ps if the pulse peak is within 10 ns range of the mean measured absolute time and the linearity is verified up to 14 ns [15].

Since each photon deposits energy in a cluster of crystals, we have considered both using the timing measurement from the crystal with the highest energy deposit (seed crystal), and also a weighted average of multiple timing measurements in the cluster. Even though the latter could have a narrower rms width of the core timing distribution at zero, they are more susceptible to spurious measurements since if one measurement is “bad”, the average is affected. The gain in the core resolution is negligible because a significant part of the resolution is due to systematic uncertainties arising from common sources among neighbor crystals, which are not reduced by averaging. Finally, it is also easier to understand the behavior of background processes and estimate their effects on our search when we use the seed crystal timing because some of the background sources affect individual crystals differently.

Therefore, we use the timing measurements from the seed crystal. However, we reject photon candidates whose timing measurements from multiple crystals are inconsistent (normalized $\chi^2 > 4$) because we are able to minimize the effect of one bad timing measurement in the seed crystal with minimum loss in the efficiency for real off-time timing measurements as the events in the left plot of figure 2b, showing the quadratic dependence of the χ^2 . The quadratic correlations happen mostly when a particle deposits significant energy in the photo-detector itself rather than the scintillation light from the crystal which populate mostly negative times. The distribution of normalized χ^2 for times around 0 sample demonstrate that the efficiency for those photon candidates whose normalized $\chi^2 > 4$ due to timing mismeasurements of crystals is 99.2%.

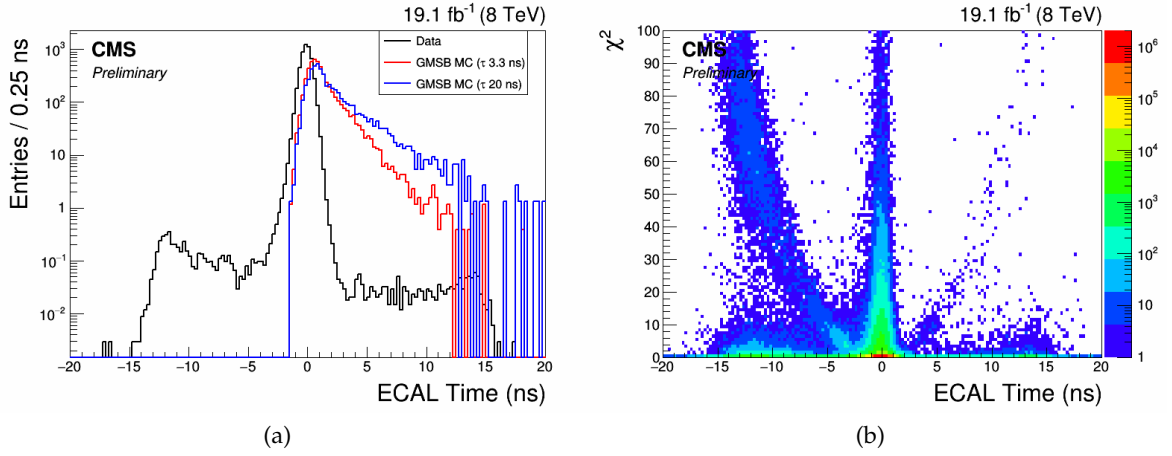


Figure 2: The left plot shows the timing distribution of GMSB MC and data. All samples pass event selection criteria. The right plot is the correlation between ECAL time of seed crystal and χ^2 of the ECAL cluster. The quadratic-like correlation in data indicates the inconsistency in the timing measurements from seed crystal and other crystals in the cluster.

There are two reasons why the photon from a neutralino arrives at the ECAL later than the photons hitting ECAL directly. Many of the neutralinos are expected to be moving slower than the speed of light, so if the decay length ($L1$ in Figure 3) is significant or the velocity very low, this causes delays. In addition, if the photon is emitted from the neutralino in directions much different from the neutralino direction as illustrated in Figure 3, the two paths, $L1$ and $L2$, will be much longer than the direct path, $L3$, from the main interaction point to the same ECAL crystal. In order to show this, we calculate Δt_1 and Δt_2 which represent delays in the photon arrival due to these two reasons and defined below.

- $\Delta t_1 = (L1/c\beta) - (L1/c)$
- $\Delta t_2 = (L1 + L2 - L3)/c$

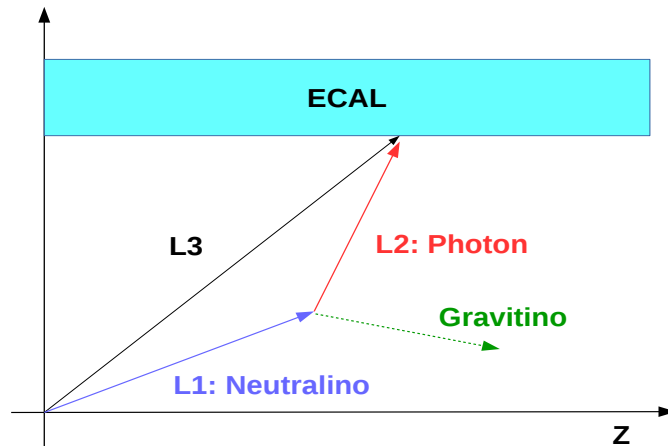


Figure 3: The schematic drawing of long-lived neutralino decay. The normal photon reconstruction uses $L3$ as its trajectory. $L1$ is the decay length of neutralino and $L2$ is the photon trajectory.

Figure 4 shows a scatter plot of these quantities for a sample of Monte Carlo events where neutralinos are produced. The mass of the neutralino is 256 GeV and the neutralino lifetime is 20 ns. Since the radius of the ECAL is about 1.5 m which is smaller than the decay length in this scenario, those neutralino which decay inside ECAL tend to have small transverse momenta, and the slowness of the neutralino is the main cause of late photons as indicated by the red region along the abscissa in Figure 4.

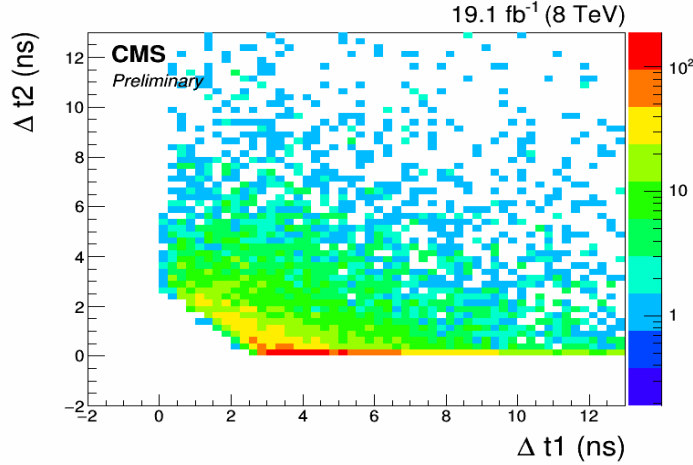


Figure 4: Δt_1 and Δt_2 distribution of GMSB sample (Λ 180 TeV and τ 20 ns) with ECAL time > 3 ns.

5 Efficiency

Because the barrel ECAL is 1.5 meters in radius, the efficiency to detect photons from neutralino decays is highly dependent on the transverse decay length (perpendicular to the proton beam direction) of the neutralino in the CMS lab frame. Since the main feature of the signal event is the delayed timing, we examined the efficiency to detect a late photon. The efficiency is defined as the fraction of photons that arrive later than the collision by 3 ns or more and the photons pass the photon selection criteria.

Figure 5 shows the efficiency as a function of the neutralino transverse decay length. The efficiency is higher for longer lifetime. This is because the neutralinos have higher p_T for shorter lifetime scenario which results in less delay in timing. The efficiency peaks around 1 m and levels off above 1.4 m or even starts increasing again. This observation can be explained using the two mechanisms for the photon from the neutralino decay to delay as discussed in section 4. The efficiency for large angle decayed neutralinos peaks around the middle of tracker (about 0.7 m) but the efficiency for slow neutralinos increases monotonically that gives the peak at the outer edge of the ECAL (1.6 m). There is very rare cases where neutralinos decay outside ECAL and the photons are emitted backwards to reach ECAL.

6 Background Estimation

Three major background sources are beam halo, cosmic-rays and ECAL spikes. Methods to identify photons arising from these sources are developed using the off-time photon sample ($t > 2$ ns and $t < -3$ ns). The residual of non-collision background and collision backgrounds

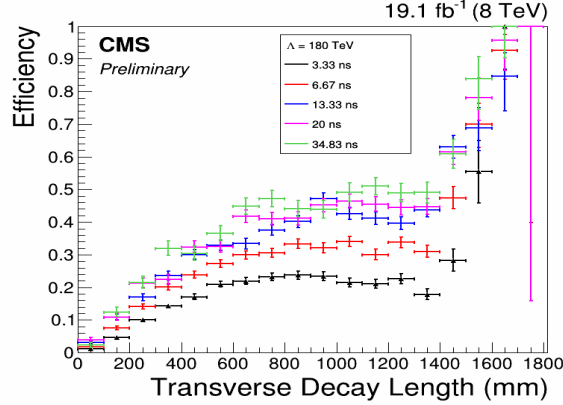


Figure 5: The photon time acceptance ($t > 3$ ns) as a function of the transverse decay length in different lifetime models

are estimated using the so-called the ABCD method. An alternative estimation of collision background using Z events shows that the in-time contribution is small.

6.1 Halo Photon

Beam halo muons are created when a beam proton collides with beam gas or scratches collimators upstream of the CMS detector. The muons travel in the proton beam optics where because their momenta are lower than the beam protons, they get overbent by the dipole magnets and tend to be deflected in the horizontal plane once the effects for quadrupole and other magnets are taken into account. Some of these muons approach ECAL more or less parallel to the proton beams, and radiate photons near or in ECAL. Since the photons are created by halo muons, a muon track segment is often found in the Cathode Strip Chambers (CSC) of the endcap muon system which covers the same radial region as the barrel ECAL. Figure 6 shows a clear matching between a track segment found in CSC and an ECAL cluster for a large fraction of the off-time events.

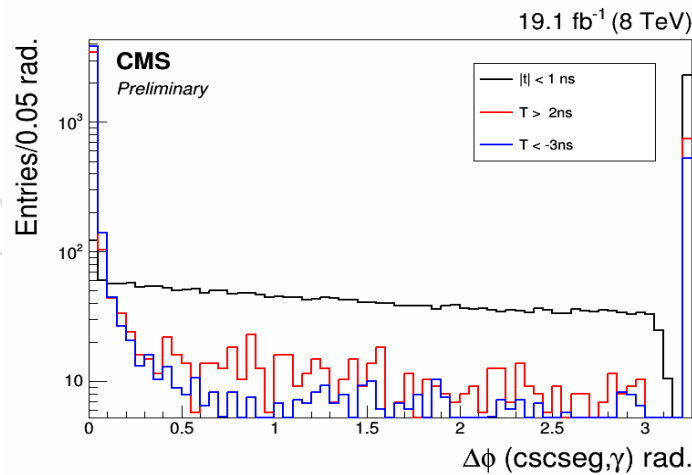


Figure 6: CSC $\Delta\phi(\text{cscsegment}, \gamma)$ distributions of in-time (black) and off-time (red and blue) samples. The events in the last bin are those without any CSC segment information available.

Due to the 400 MHz RF frequency of the LHC, it provides 9 additional LHC buckets for protons to fill beside each of the nominal LHC RF buckets. These so-called satellite bunches are thus

formed when a part of proton beam is captured in one of these incorrect RF buckets at each stage of beam transfers from an earlier accelerator to the later one. The existence of satellite bunch halo can be observed from the endcap ECAL system and identified by selecting the photon clusters each of which is matched to a CSC segment. A clear pattern of 2.5 ns structure can be seen in Figure 7. Because the CSC does not cover most of the high η region of the endcap ECAL, the efficiency for finding a CSC match for these photons is low and limited to the low η part of the endcap ECAL. This suggests that the halo from these satellite proton beams are expected to contribute photons which arrive later than the photons from the main bunch collisions.

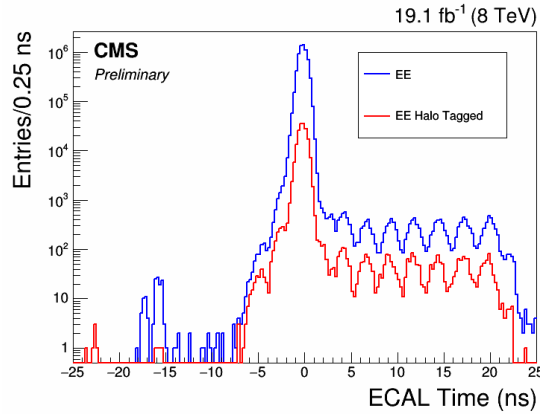


Figure 7: The ECAL time of photons from ECAL endcap (right). The periodic pattern is from the halo of satellite bunches. The red histogram is the ECAL time from photons tagged by CSC $\Delta\phi$ matching.

Using the off-time control sample, we find that most halo-induced photons are associated with a CSC track segment. Therefore, a photon would be vetoed if a CSC segment with $|\eta| > 1.6$ is found within 0.05 rad of the azimuthal angle with the photon cluster.

6.2 Cosmic-Ray

Like halo muons, cosmic-ray muons can initiate showers in the ECAL. The existence of cosmic-muon-induced photons can be found by looking at the $\Delta\phi$ and $\Delta\eta$ between a Drift Tube (DT) cosmic-ray muon segment [16] and an ECAL cluster. Due to the large space between the Muon Barrel system and ECAL, the actual DT position used in the difference calculation is a projection of the muon trajectory using the direction of the DT segment to the outer surface of ECAL. Figure 8a shows the $\Delta\phi$ and $\Delta\eta$ 2D distribution for the off-time sample where there is a clear enhancement at the small $\Delta\phi$ and $\Delta\eta$ corner of the plot while Figure 8b does not show such an enhancement for the in-time sample. This demonstrates that the off-time sample contains a significant fraction of cosmic-muon-induced photon candidates.

To confirm this finding, we use a cosmic dataset (no proton beams are colliding) to produce Figure 9. When there is one or more DT track segments and one ECAL supercluster in an event, we observe that 75.5% of those superclusters are associated with the projection of a DT track segment within the range of $|\Delta\eta| < 0.1$ and $|\Delta\phi| < 0.1$. Since these events are triggered by DT hits, this tagging rate should be considered an upper limit for the efficiency.

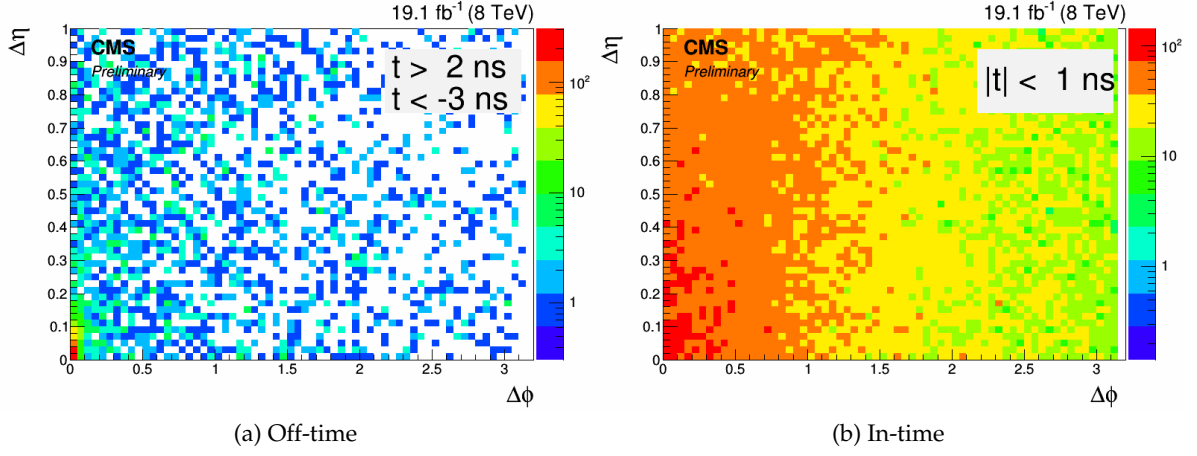


Figure 8: DT $\Delta\eta - \Delta\phi$ distributions of in-time (left) and off-time (right) photon samples.

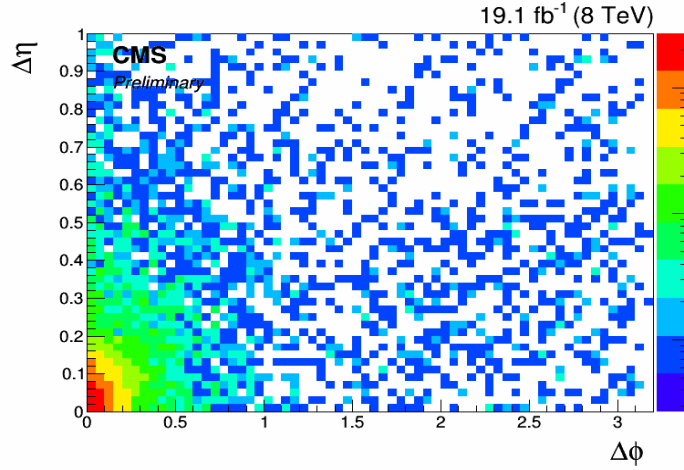


Figure 9: The $\Delta\eta$ and $\Delta\phi$ distribution of DT segments and ECAL superclusters for cosmic-ray data.

6.3 Anomalous ECAL Spike

ECAL spikes are due to direct energy deposition by particles in the Avalanche Photo-Diode (APD) [17] which are attached to the $PbWO_4$ crystals to collect scintillation light. The ECAL spikes often appear as apparent isolated energy deposits in one crystal and can be rejected if the spike candidate energy (E_1) and the sum of its neighboring four crystals (E_4) satisfies this equation:

$$1 - \frac{E_4}{E_1} > 1 - (0.04 \times \log E_1 - 0.024) \quad (3)$$

for E_1 greater than 4 GeV. The anomalous ECAL spike will not be used to form a cluster in the PF reconstruction process. Occasionally, however, some of the spike hits are surrounded by some energy deposits either by coincidence, or the charge particle which created the spike hit is associated with other particles which deposit sufficient energies so that the isolation test of the spike fails equation 3. This component can be identified in the negative timing sample where

we don't find any correlation with muon system segments for either halo-induced photons or cosmic-muon-induced photons.

Due to its production mechanism, when a non-isolated spike hit forms an ECAL cluster, its size is expected to be smaller than the size of regular photons. Figure 10a shows the distribution of S_{Major} vs S_{Minor} for the above spike-enhanced sample. The dense area at small S_{Major} as well as S_{Minor} is due to spikes since they are not accompanied by energetic hits very often. The $1 - \frac{E_4}{E_1}$ values for the spike-enhanced sample is also compared with the values from the nominal photon sample (Figure 10b). It also indicates higher $1 - \frac{E_4}{E_1}$ values for spike-enhanced sample. Based on these observations, we use a tighter $1 - \frac{E_4}{E_1}$ cut (> 0.9). In addition, we also veto photons with $S_{Major} < 0.6$ and $S_{Minor} < 0.17$.

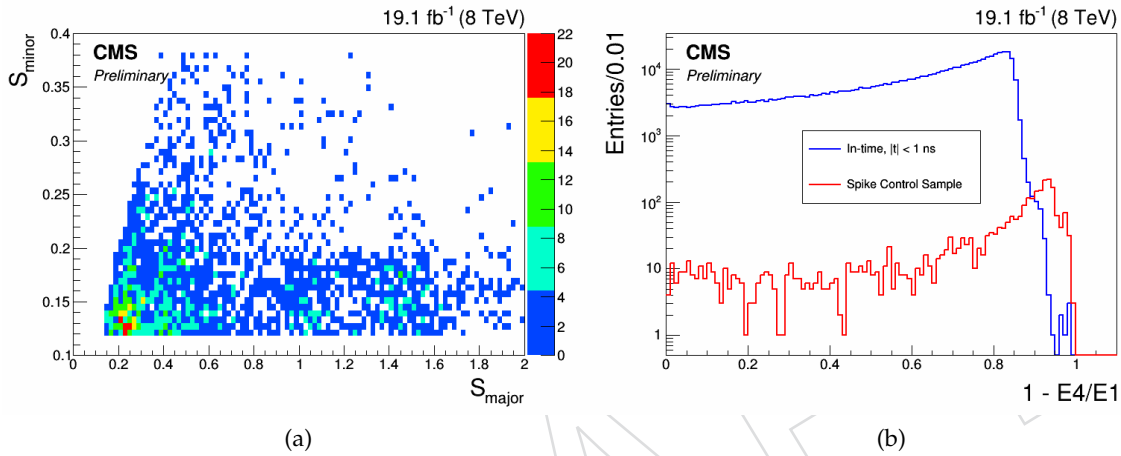


Figure 10: S_{Major} and S_{Minor} distribution (left) of spike control sample. The right plot shows the $1 - \frac{E_4}{E_1}$ distributions of in-time photons and the photons from spike control sample.

6.4 ABCD Method for Non-Collision Background

By applying the methods to veto background events from three sources, we can reduce the background contributions significantly. Figure 11 shows the ECAL timing distribution of the 0- and 1-jet data sample. The plot shows three major background components which are tagged by our tagging methods. Halo contributes the most in the off-time area. Cosmic-rays and the ECAL spike background also have the expected shape from the tagged components. However, the remaining photons after removing all the tagged backgrounds still have a significant number of photons with $|t| > 3$ ns since the tagging efficiencies are not 100%. We use the so-called ABCD method to estimate how many of these photons are due to untagged background contributions.

We seek signal in the ECAL timing window between 3 and 13 ns and $E_T^{miss} > 60$ GeV, which suppress normal photons arising from proton collisions in the regular RF buckets. Our signal events have a large E_T^{miss} since a gravitino cannot be detected. However, background photons from the three sources we have discussed in section 3 will have large E_T^{miss} since the photon does not arise from a regular collision and they will have small $E_{T no \gamma}^{miss}$, when taking the photon out of E_T^{miss} calculation.

The ABCD regions are defined from ECAL time and $E_{T no \gamma}^{miss}$, as shown in Table 2, where E_T^{miss} is required to be greater than 60 GeV to suppress photons from the collision-type events. A and B regions are signal-free regions since there is no signal with $t < -3$ ns. Region C ($E_{T no \gamma}^{miss} <$

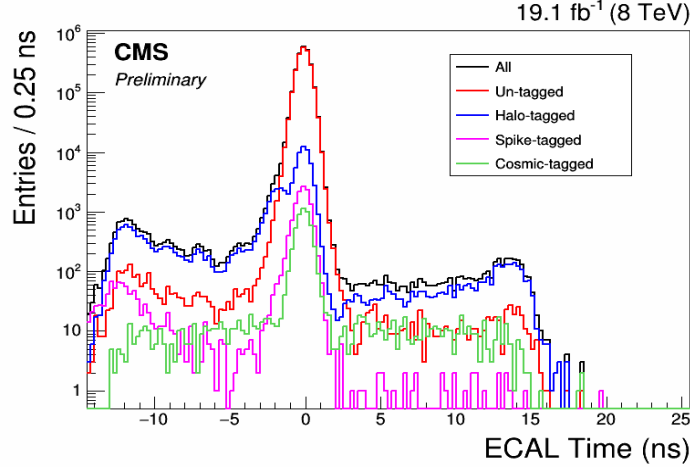


Figure 11: ECAL time distribution from 0- and 1-jet events. Three tagged background sources and the remaining background-subtracted event counts are shown in different colors.

60 GeV) is also signal free, and photons from collisions should be suppressed because most of them should have large $E_{T\text{no}\gamma}^{\text{miss}}$. Thus, the non-collision background in signal region D can be estimated from this relationship:

$$\text{Non-collision background in D} = \frac{B}{A} \times C \quad (4)$$

	$E_{T\text{no}\gamma}^{\text{miss}} < 60 \text{ GeV}$	$E_{T\text{no}\gamma}^{\text{miss}} > 60 \text{ GeV}$
$t > 3 \text{ ns}$	C	D
$t < -3 \text{ ns}$	A	B

Table 2: ABCD definition for non-collision background estimation. All events pass $E_T^{\text{miss}} > 60 \text{ GeV}$ requirement.

6.5 ABCD Method for Collision Background

The main sources of delayed photons are photon candidates which are not from normal collisions. As for possible contamination from collision events, another ABCD method using ECAL time and E_T^{miss} is developed. This method is aimed at estimating the collision events in each of the ABCD regions defined in the previous section. As collision events are suppressed in A and C regions and non-collision backgrounds dominate in these two regions ($E_T^{\text{miss}} > 60 \text{ GeV}$ and $E_{T\text{no}\gamma}^{\text{miss}} < 60 \text{ GeV}$), this estimation is only necessary for B and D regions. We use events with $E_{T\text{no}\gamma}^{\text{miss}} > 60 \text{ GeV}$ to estimate collision background in these two regions to minimize non-collision background. Since ECAL time from collision-type events should be around zero, the $|t| < 2 \text{ ns}$ region can be used as the control region to extract the ratio for collision events with large and small E_T^{miss} values. The ABCD regions are defined in Table 3. The collision background in D region is estimated by this equation:

$$Q_d(\text{Collision background in D}) = \frac{F}{F'} \times D' \quad (5)$$

Similar to the collision background in D, the same formula is also applicable to B region.

$$Q_b(\text{Collision background in B}) = \frac{F}{F'} \times B' \quad (6)$$

	$E_T^{\text{miss}} < 60 \text{ GeV}$	$E_T^{\text{miss}} > 60 \text{ GeV}$
$t > 3 \text{ ns}$	D'	D
$ t < 2 \text{ ns}$	F'	F
$t < -3 \text{ ns}$	B'	B

Table 3: ABCD region definition for collision background estimation. All events pass $E_{T \text{ no } \gamma}^{\text{miss}} > 60 \text{ GeV}$ requirement.

6.6 Collision Background From Z Events

Because all known standard model events from pp collisions of the LHC are all in-time, the Gaussian tail of ECAL time distribution is also a possible source of background for delayed photon signal. Since ECAL time is a variable which is un-correlated to the kinematics of SM processes, we use $Z \rightarrow e^+e^-$ events as a control sample to estimate the percentage of the out-of-time events from SM processes. We select events with at least two electrons with p_T greater than 30 GeV. The electron isolation is not applied because the algorithm handles off-time ECAL crystals inappropriately for our purpose in the isolation energy calculation. We use the distinct Z mass peak in the invariant mass distribution of two electrons and count the excess number of di-electron pairs in the range between 76 GeV and 104 GeV to estimate in-time and late electrons.

The goal is to estimate the probability that the timing measurement of an electron from the Z sample is out-of-time ($t > 3 \text{ ns}$ or $t < -3 \text{ ns}$). It represents the probability to mis-measure an object from in-time collision. Therefore, we define three samples based on the timing of the electrons from the Z sample.

- In-time events. Both electrons are within $|t| < 2 \text{ ns}$ region (Figure 12).
- Late timing events. The arrival time of at least one of the electrons is $t > 3 \text{ ns}$ (Figure 13a).
- Early timing events. The arrival time of at least one of the electrons is $t < -3 \text{ ns}$. If one electron is early and the other is late, the event is classified as late timing (Figure 13b).

In order to estimate the number of Zs in each of the above samples, we first fit the sideband (50 to 76 GeV and 104 to 130 GeV) with a fourth-order polynomial function to estimate the background under the Z peak. By subtracting the background represented by the integral of the background function in the peak region, we can estimate the number of pure Z events in these samples.

Three events with both electrons late are found presumably because these Z bosons are produced in satellite bunch collisions. Since the satellite bunch intensity is roughly 10^{-3} times the main bunch intensity, their collision luminosity is expected to be 10^{-6} [18]. This is consistent with the observed three Z candidates with late electron daughters out of 1.35 million in-time Z bosons. Therefore, we calculate the probability of one late timing measurement $(29.40/(1352383.40 \times 2) = (1.09^{+0.28}_{-0.23}) \times 10^{-5}$, denoted as p_1 in equation 7) as well as the probability of a late collision events $(3.00/1352383.40 = (2.22^{+1.7}_{-0.96}) \times 10^{-6}$, denoted as p_2 in equation 7).

Using these probabilities, we can predict the number of collision background in $t > 3 \text{ ns}$ by

$$N = n_1 \times p_1 + n_2 \times (2p_1(1 - p_1) + p_1^2) + n_1 \times p_2 + n_2 \times p_2 \quad (7)$$

where n_1 is the number of in-time one photon events (28208) and n_2 is the number of in-time two photon events (38) from the F region, defined in section 6.5. The estimated background is $0.370^{+0.092}_{-0.070}$. This is larger than the result ($0.093^{+0.093}_{-0.047}$) from the collision ABCD method, but both methods estimate a small contribution (less than 1 event predicted) from collision events to off-timing region. Since $Z \rightarrow e^+e^-$ method can tell us the composition of the particle with late time measurements, we choose $Z \rightarrow e^+e^-$ method as the default estimate of the background arising from collision events.

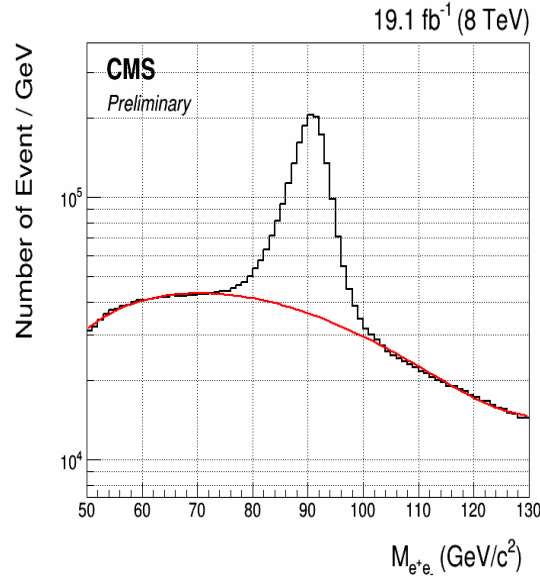


Figure 12: The invariant mass of two in-time ($|t| < 2$ ns) electrons. The red curve is the background estimation by fitting the sideband.

6.7 Combined ABCD Method and Closure Test

Based on the results of two estimations for collision background, we choose the value from $Z \rightarrow e^+e^-$ events since it suggests a larger value for collision background. Combining the non-collision and collision backgrounds, the final background in the signal region is estimated by

$$\text{Total background in D} = \left(\frac{B - Q_b}{A} \times C \right) + Q_d \quad (8)$$

$$(9)$$

where Q_b and Q_d are the collision components in the B and D regions.

A closure test is done by using 0- and 1-jet events, where we don't expect any signal events, so the background estimates for the D region should agree with the actual number of events in the D region. The yields in each region can be found in Tables 5 and 6. The uncertainty is calculated based on the statistical nature of each region and the method of Pearson's χ^2 interval [19]. The estimated background in the D region for 0- and 1-jet events is $16.41^{+3.00}_{-2.59}$ which

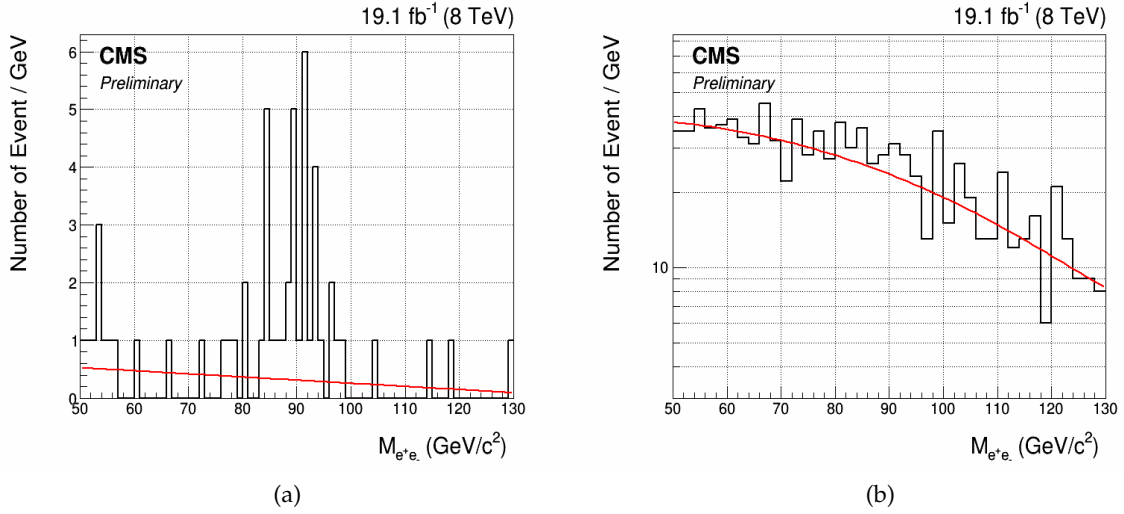


Figure 13: The Z mass distribution from late timing (left) and early timing (right) events. The red curves are the background estimation by fitting the sideband.

is compatible with the observed value of 10. The uncertainty from collision background has negligible effect because the ratio of out-of-time and in-time photon is small.

$$D = \left(\frac{38 - 0.64}{851} \times 359 \right) + 0.46 = 16.41^{+3.00}_{-2.59} \quad (10)$$

$$Q_d = 0.46^{+0.11}_{-0.09} \quad (11)$$

$$Q_b = 0.64^{+0.35}_{-0.34} \quad (12)$$

7 Systematic Uncertainties

This analysis relies on photons above 80 GeV in p_T , jets above 35 GeV in E_T and E_T^{miss} larger than 60 GeV. So the efficiency estimated using MC samples must simulate these quantities well, and any uncertainties on how these quantities match between data and Monte Carlo will lead to systematic uncertainties in the efficiency.

We compare data and $\gamma + \text{jets}$ samples to study the timing simulation for photons. Both samples require one isolated photon, one or two jets and E_T^{miss} less than 30 GeV in events that are statistically independent of the data used for the delayed photon search. The difference in the mean values and resolutions from the fit of the ECAL timing distribution are applied to correct the GMSB samples and considered as systematics. In addition to ECAL timing, we also estimate the uncertainties due to the uncertainties in the jet energy scale, jet energy resolution, electron-to-photon energy scale and unclustered energy for E_T^{miss} .

We vary their $1\text{-}\sigma$ deviation with respect to the nominal values. The results are summarized in Table 4. The time scale has most significant impact on the result since our method is a pure counting method on ECAL time. The second largest source of uncertainty comes from unclustered energy uncertainty of E_T^{miss} . It has biggest effect on the E_T^{miss} scale.

Given the same τ , the systematic uncertainties usually have higher impact on lower SUSY breaking scale cases. This is due to the fact that there are fewer events detected for lighter

neutralino (i.e. smaller Λ) and the statistical uncertainties of the systematic effects are large. Photon decays from lighter neutralino have softer p_T spectrum and therefore lower efficiency for passing the photon p_T requirement. In addition, lighter neutralinos are more boosted than heavier neutralinos, which also results in lower efficiency since there are fewer slow moving neutralinos on which our analysis relies.

Other general factors such as luminosity [20] and parton distribution function [21] are adopted from the official CMS study. These factors are all then applied in the statistical analysis as nuisance parameters.

Because the background estimation uses a pure data-driven method, most effects from these systematic uncertainties are canceled out ($< 1\%$ impact). The systematic uncertainty on background estimation is quoted from the statistical uncertainty of the $Z \rightarrow e^+e^-$ method. The fluctuation can be 105% higher or 19% less on current estimation. Due to low statistic counts, the background uncertainty is large. However, it does not impact the final result as significantly as the uncertainties of signal efficiency.

Source	Uncertainty(%)
Time scale	6 ~ 10
Unclustered Energy	4 ~ 10
ECAL time resolution	2 ~ 5
Jet energy scale	3 ~ 9
Jet energy resolution	2 ~ 9
Photon energy scale	2 ~ 4
Luminosity	2.6
PDF	< 1

Table 4: Systematic uncertainties for signal efficiency

8 Result

Only one event is observed in the signal region. The event contains one photon and two jets. The photon in the event has transverse momentum 224 GeV and ECAL time 12.17 ns. Its S_{major} and S_{minor} are 2.82 and 0.16. The final background estimation is $0.37^{+0.39}_{-0.07}$. The non-collision background is zero due to zero observation in the C region. The uncertainty of the zero non-collision background is estimated using Pearson's Chi-square interval and also taken into account when combining with collision background. The numbers used in background estimation are presented in Table 5 and Table 6.

$$D = \left(\frac{1 - 0.51}{3} \times 0 \right) + 0.37 = 0.37^{+0.39}_{-0.07} \quad (13)$$

$$Q_d = 0.37^{+0.09}_{-0.07} \quad (14)$$

$$Q_b = 0.51^{+0.28}_{-0.27} \quad (15)$$

With no significant excess of events over estimated background, we find an upper limit of 4.07 photon events at 95% C.L. using the CLs method [22]. Assuming the GMSB model and the SUSY breaking scale is 180 TeV, this corresponds to a cross section of 14.07 fb for the neutralino production of photon plus gravitino channels and the lifetime of the neutralino (τ) is either less than 4.33 ns or larger than 14.93 ns (Figure 14).

Taking GMSB as a benchmark model, the exclusion region at 95% C.L. in neutralino mass is up to 300 GeV. The excluded lifetime range is about 3 ns to 40 ns for a low mass neutralino and the excluded interval shrinks when the mass increases (Figure 15a). This is mainly due to the smaller expected cross-section of neutralino production at higher Λ (or neutralino mass) values.

	0- and 1-jet	≥ 2 -jet
A	851	3
B	38	1
C	359	0
D	10	1

Table 5: Numbers used in non-collision background estimation for closure test (0- and 1-jet events) and signal analysis (≥ 2 -jet events). All events pass $E_T^{\text{miss}} > 60$ GeV cut.

	0- and 1-jet	≥ 2 -jet
B'	8	3
D'	2	1
F'	144525	6049584
F	35271	28246

Table 6: Numbers used in collision background estimation for closure test (0- and 1-jet events) and signal analysis (≥ 2 -jet events). All events pass $E_T^{\text{miss}} > 60$ GeV cut.

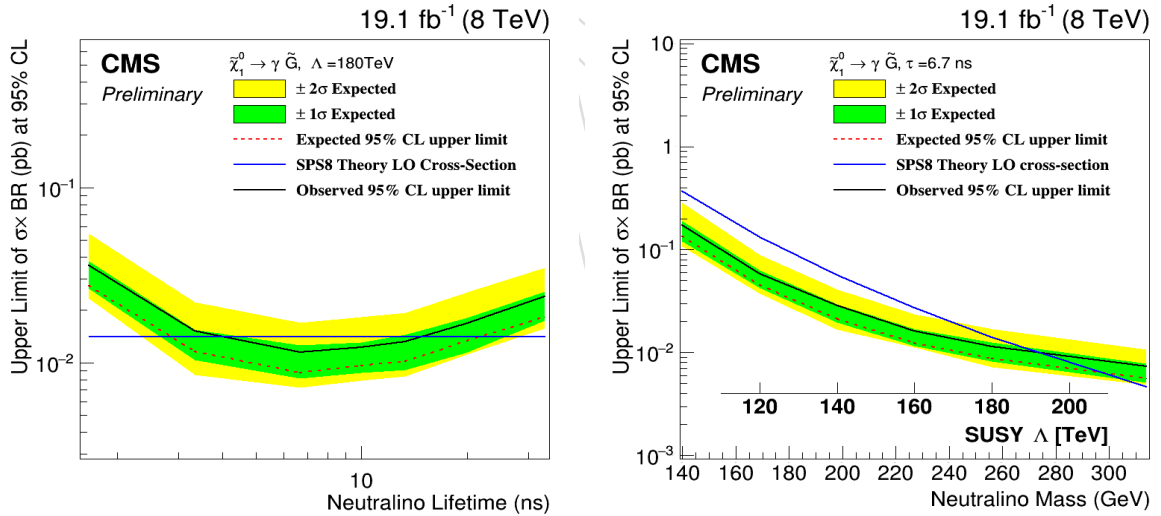


Figure 14: Upper limit at 95 % C.L. for $\Lambda = 180$ TeV for different lifetimes and $\tau = 6.7$ ns for different Λ values using CLs method.

9 Conclusion

We develop an effective method using ECAL timing to search for a delayed photon signal in the CMS experiment. We apply it to long-lived neutral particles decaying to a photon and gravitino using data with an integrated luminosity 19.1 fb^{-1} from LHC proton-proton collision at 8 TeV center-of-mass energy in 2012. The upper limit of cross-section times branching ratio is obtained with respect to different lifetimes and masses of the neutral particle (Figure 15b).

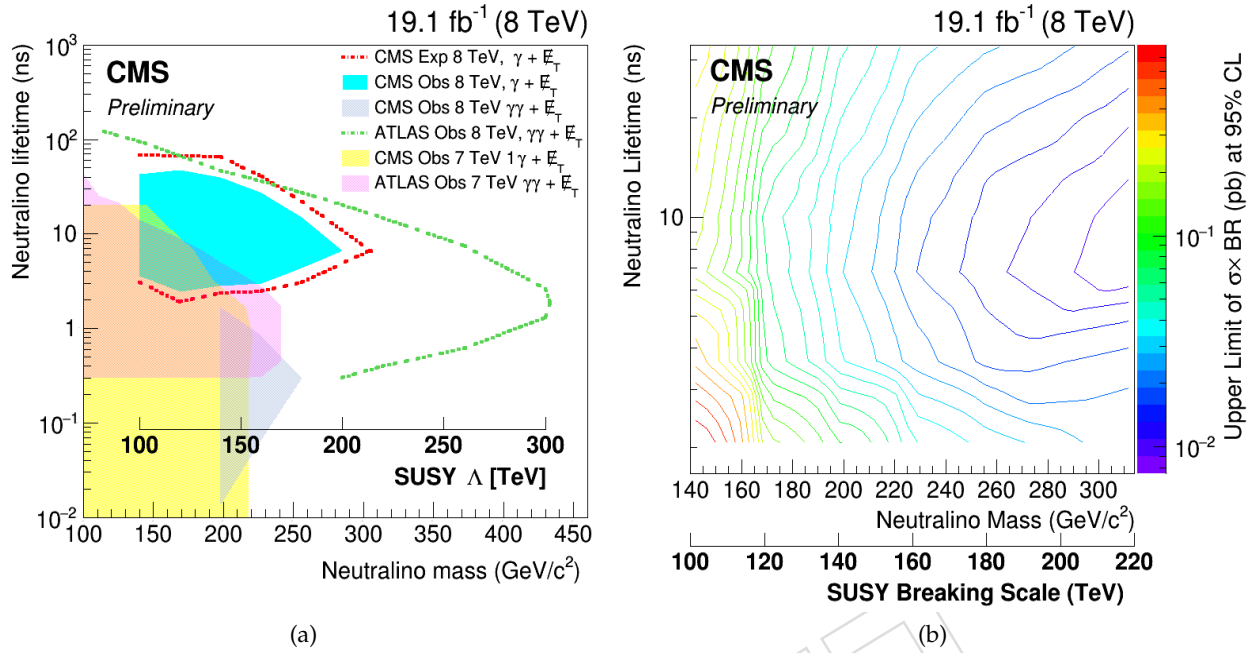


Figure 15: Exclusion region for the mass and lifetime of neutralinos in the SPS8 model (left) and cross-section limit for the mass and lifetime of neutralinos using 8 TeV data with integrated luminosity 19.1 fb⁻¹ (right).

Comparing with the previous searches [7, 8] in the CMS experiment, the ECAL timing method provides a broader search spectrum for long-lived neutralinos and the result is scalable for different theoretical interpretations.

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