

DRAFT

CMS Physics Analysis Summary

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2015/02/24

Head Id: 278587

Archive Id: 270582:278587MP

Archive Date: 2015/02/24

Archive Tag: trunk

Search for long-lived neutral particles decaying to photons with missing energy in proton-proton collision at $\sqrt{s} = 8$ TeV

The CMS Collaboration

Abstract

A search for long-lived neutral particle (neutralino) decaying into photon and an undetectable 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 detector (ECAL). The method is sensitive in a range of lifetime ($c\tau$) from 0.5 up to 13 m with nearly free standard model background. Taking GMSB as a benchmark model and applying our method to data, no significant excess is observed above background expectation. An exclusion region of neutralino mass and lifetime at 95% C.L. is set by using CLs method.

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PDFAuthor:	Shih-Chuan Kao, Yuichi Kubota
PDFTitle:	Search for long-lived neutral particles decaying to photons
PDFSubject:	CMS
PDFKeywords:	CMS, physics, LHC, SUSY, Exotica, GMSB, Long-Lived, Photons, Displaced, neutralino

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1 Introduction

The observation of the new neutral boson at LHC provides strong evidence for the existence of the standard model higgs. What is left from the standard model are the fine-tuning problems and the unification of the gauge couplings and gravity. With solutions for both questions, *supersymmetry* (SUSY) has been one of the popular theories beyond the standard model. In addition, the Lightest Supersymmetry 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 Gauge Mediated Supersymmetry Breaking (GMSB) [1] which provides a viable mechanism to break SUSY, gravitino (\tilde{G}) is the LSP. Under the assumption of R-parity conservation, the gravitino is stable and couple to the other SUSY particles only weakly, thus, other supersymmetric particles with higher mass like squarks and gluino produced in proton-proton collisions at the LHC, will promptly decay to a Next-to-Lightest Supersymmetry Particle (NLSP) and the NLSP could 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 of the NLSP also depends on the SUSY breaking scale (Λ) and the choice of Λ has significant impact on the decay modes and the lifetime of NLSP.

If the NLSP is the neutralino, it has three different decay channels; photon, Z boson and higgs. The decay width for each channel depends on the choice of SUSY parameters. In this study, we choose the 'Snowmass Points and Slopes 8' (SPS8) [2] scenario as our benchmark model. In this scheme, the neutralino decays to a photon and a gravitino has the largest branching ratio [3](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 (BR) of $\tilde{\chi}_0 \rightarrow \gamma + \tilde{G}$

where M_P is the Plank 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 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, ($c\tau$), from several tenths of a meter to 10 meters at different SUSY breaking scale, Λ .

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. Many of these events should have at least one late arriving photon, a few jets as well as missing energy from un-detectable gravitino. This is because many of the neutralinos are slow moving and when their flight lengths are long enough, the arrival time of the photons arising from the neutralino decays are measurably later than normal photons.

CMS's electromagnetic calorimeter (ECAL) consists of about 80 thousands of PbWO scintillation crystals, and with its fine granularity and excellent timing as well as energy resolution, it is a powerful tool to search for delayed photon signal. In addition, the absence of any known SM physics process at the TeV energy scale proton-proton collisions which would produce delayed photon, makes it possible to use ECAL timing measurements to perform a search with nearly zero background.

Previous searches ([4–7]) has set the neutralino mass lower limits as high as 250 GeV/ c^2 for different lifetime ranges between 0.25 ns to 50 ns (0.075 m to 15 m).

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 were selected by an off-line trigger processor(HLT) which required at least one isolated ECAL cluster (cluster of crystals with 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 [8] with an external SLHA (Supersymmetry Les Houches Accord) file which describes SUSY parameters and mass spectrum. Those parameters are calculated by ISAJET [9]. The generation for signal samples adopts SUSY GMSB scheme where the SUSY breaking scale (Λ), and c_{grav} are varied to cover a range (0.15 m to 10 m) 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 GMSB.

The γ + jets samples simulate photon radiated from a quark in the QCD process. The events were generated in different p_T spectrums with respect to the quark (denoted as \hat{p}_T). This sample is 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 sample, we did 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, significant amount of missing energy is expected. A cut on E_T^{miss} is useful to lower the rate from the standard model backgrounds like γ + jets process and QCD events. Based on the above consideration, we have developed our selection.

Photons are reconstructed using clustering algorithm to build a cluster of clusters (supercluster) [10], which extends cluster size in ϕ in order to recover energy spread due to strong mag-

netic field for photons which produce positron-electron pairs. We use only photons from ECAL barrel ($\eta < 1.47$) in this analysis. We require that the 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. Because particle-flow (PF) algorithm [11] considers off-timing photon as part of isolation energy deposit, the out-of-time photon will not be particle-flow isolated. As a result, we did not implement PF isolation criteria for photon objects but require no tracks around the selected photon within $\Delta R = 0.6$ range and corresponding HCAL energy deposit less than 5 percent of ECAL energy deposit.

For jets and \cancel{E}_T reconstruction, the particle-flow (PF) algorithm [11] is used because it takes all sub-detectors information into account to reconstruct each particle before jet clustering. The PF jets are found to have highest purity and lowest fake rate to pass the jet quality criteria [12]. In this analysis, we select PF jets pass 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. If a jet candidate is closer to a photon, it was not counted as a jet.

Since most out-of-time energy deposits are from machine induced backgrounds, PF ignores out-of-time energy deposit from ECAL crystal from E_T^{miss} calculation and includes it as anti-isolation energy deposit if it is part of photon cluster. In this analysis, since they are 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. On the other hand, 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 and be the same in magnitude. Therefore, we define a variable called $E_{T \text{ no } \gamma}^{\text{miss}}$ which is the vector sum of E_T^{miss} and photon E_T . For signal events, $E_{T \text{ no } \gamma}^{\text{miss}}$ is also large unless the p_T sum of two gravitinos is back-to-back with photon E_T . Table 2 shows how events arising from various sources behave in terms of these two variables effectively. A threshold of 60 GeV for the E_T^{miss} and $E_{T \text{ no } \gamma}^{\text{miss}}$ is found to suppress QCD and non-collision backgrounds.

Event Type	E_T^{miss}	$E_{T \text{ no } \gamma}^{\text{miss}}$
Signal	Large	Large
W or Top events	Large	Large
QCD events	Small	Large
Non-collision backgrounds	Large	Small
Low p_T non-collision backgrounds	Small	Small

Table 2: E_T^{miss} and $E_{T \text{ no } \gamma}^{\text{miss}}$ signature of different types of events.

In summary, our signal events should have at least one photon and at least two jets. The two ways to estimate 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 background.

4 Delayed Photon and ECAL Timing

The photon arrival time in ECAL is the main observable we use to distinguish signal from background in this study. ECAL crystals have time resolution less than 500 ps and linearity compatible with unity [13]. The timing measurement from the crystal with the highest energy deposit (seed crystal) is used in this analysis. Since each photon deposit energies in a cluster of crystals, the χ^2 calculated from the timing measurements in all crystals indicates the legitimacy

of photon time.

Figure 1 shows a two dimensional distribution of the seed time with respect to normalized χ^2 of the timing measurements in each ECAL cluster. Most of them have the ECAL timing around zero, but many of the clusters with non-zero timing have large χ^2 values, which is expected when the timing measurements of non-seed crystals are around zero and inconsistent with the seed crystal timing measurement. Based on this observation, we reject those photon candidates with χ^2 greater than 4.

Most of the rejected events have negative times because they are the result of a spike hit, which usually have a negative time, surrounded by crystals with time measurements of around zero which is expected regular energy deposits. The distribution of χ^2 for time around 0 sample demonstrates that the efficiency for those photon candidates whose $\chi^2 > 4$ due to timing mis-measurements of non-seed crystals is 99.2%.

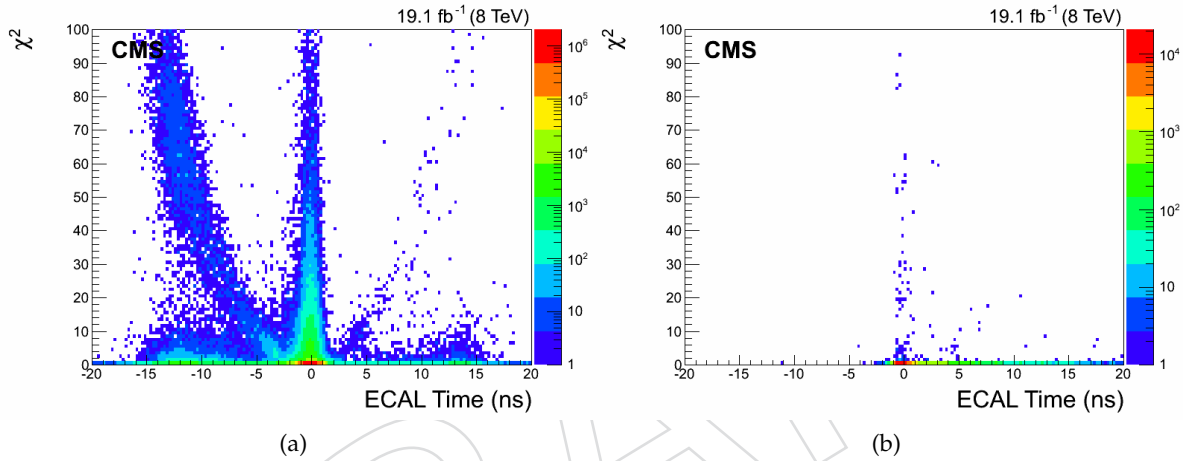


Figure 1: The correlation between ECAL time of seed crystal and χ^2 of the cluster. The quadratic-like correlation in data (left plot) indicates the inconsistency in the timing measurements from seed crystal and other crystals in the cluster. MC samples (right plot) do not show this correlation for out-of-time photons.

There are two reasons why the photon from a neutralino arrives at 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 2) is significant, 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 2, 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 shows a scatter plot of these quantities for a sample of Monte Carlo events where neutralinos are produced. The mass of neutralino is 256 GeV and the neutralino lifetime is 20 ns. Since the radius of CMS ECAL is about 1.5 m which is smaller than the lifetime in this scenario, those neutralino which decay inside ECAL tend to have small transverse momenta (less time dilation), and this is the main cause of late photons as indicated by the red region

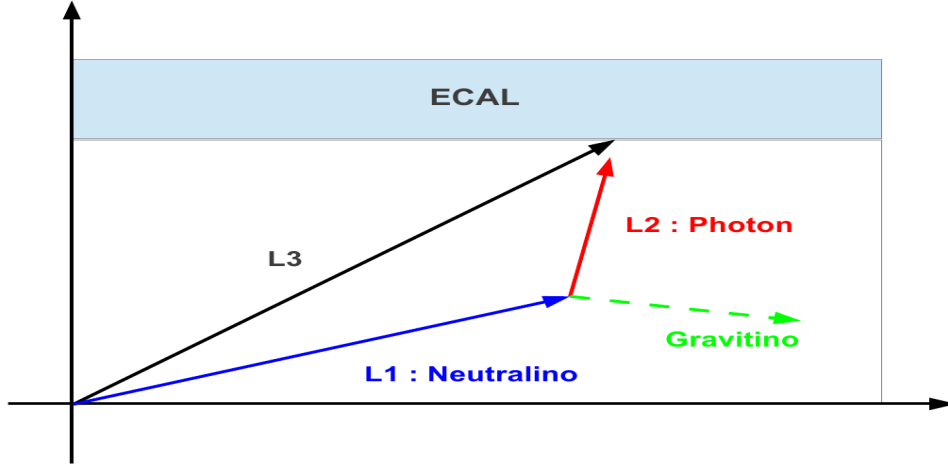


Figure 2: The schematic drawing of long-lived neutralino decay. The normal photon reconstruction uses L3 as its trajectory. L1 is the decay length of neutralino and L2 is the real photon trajectory.

136 along the abscissa in Figure 3.

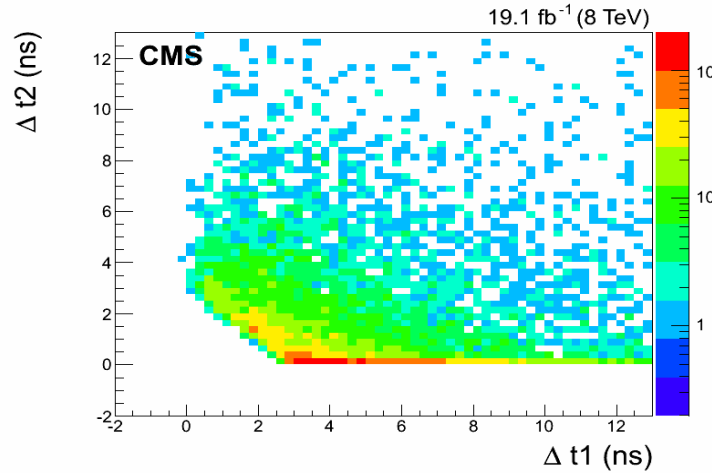


Figure 3: Δt_1 and Δt_2 distribution of GMSB sample (Λ 180 TeV and $c\tau$ 6 m) with ECAL time $> 3\text{ns}$

137 5 Efficiencies

138 Because the barrel ECAL is 1.5 meters in radius, the efficiency to detect photons from neutralino
 139 decays is highly dependent on the transverse decay length (perpendicular to the proton beam
 140 direction) of the neutralino in the CMS lab frame. Figure 4a shows our estimates of efficiencies
 141 of photon reconstruction and photon selection as a function of the neutralino decay length.
 142 The efficiency drops sharply around the decay length of 1.5 m which corresponds to where the
 143 outer surface of ECAL detector is. It shows little variation among different $c\tau$ models at the
 144 same SUSY breaking scale.

145 Figure 4b shows that the efficiency decreases for the same lifetime if the SUSY breaking scale
 146 Λ decreases. This is because if the neutralino mass is heavier, the p_T of the photon and the

147 missing energy due to the undetected gravitino are harder and more decays pass our photon
 148 p_T and E_T^{miss} requirements.

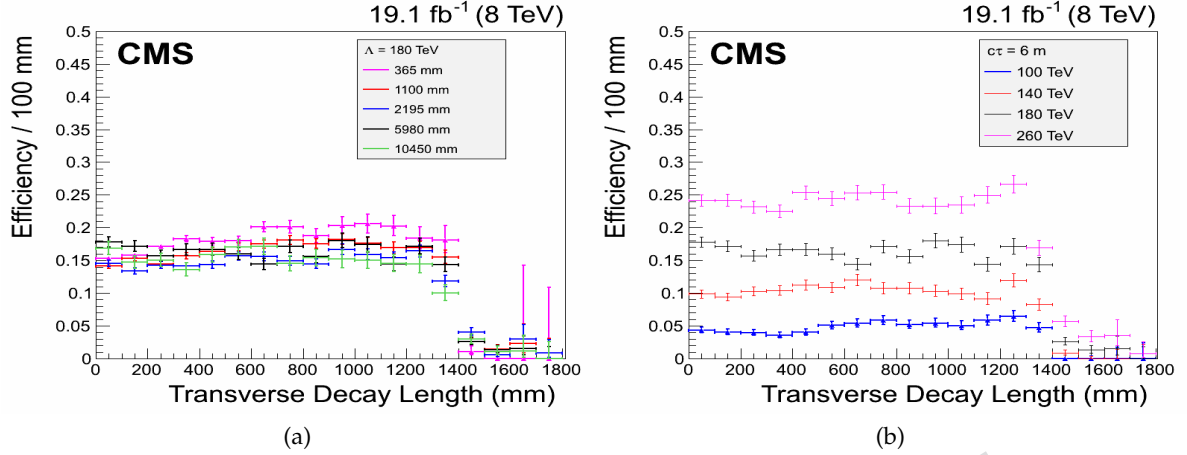


Figure 4: The efficiency of reconstruction and event selection with respect to transverse decay length for different $c\tau$ values (in mm) at Λ 180 TeV (left). Under the same $c\tau$ scenario ($c\tau$ 6m), the efficiency shows dependence on SUSY breaking scale (right plot).

149 Figure 5a shows the time acceptance of ECAL time selection for photons that they arrives
 150 later than the collision by 3 ns or more as a function of the neutralino transverse decay length.
 151 The time acceptance is higher for higher values of $c\tau$. This is because for larger $c\tau$ scenario,
 152 we are more sensitive to lower p_T neutralinos which there are more of. The acceptance peaks
 153 around 1 m and levels off above 1.4 m or even starts increasing again. This observation can
 154 be explained using the two mechanisms for the photon from the neutralino decay to delay
 155 as discussed in section 4. Figure 5b shows the acceptance when $\Delta t_2 < 0.5$, *i.e.* the delay is
 156 mainly due to the slowness of the neutralino, and $\Delta t_2 > 0.5$, *i.e.* the delay is mainly due to the
 157 long paths of the neutralino and photon. The acceptance of the former increases monotonically
 158 while the latter peaks around 0.8 m.

159 6 Background Estimation

160 The main sources of delayed photons are photon candidates which are not from normal colli-
 161 sions. We compare an in-time photon sample ($|t| < 1$ ns) as well as an off-time photon sample
 162 ($t > 2$ ns and $t < -3$ ns) and conclude that three major background sources are beam halo,
 163 cosmic-rays and ECAL spikes. Methods to identify photons arising from them are developed
 164 using the off-time sample. The residual of non-collision background and collision backgrounds
 165 are estimated using the so-called the ABCD method. An additional estimation of collision back-
 166 ground using Z events shows that its contribution is negligible.

167 6.1 Halo Photon

168 Beam halo muons are created when a beam proton collides with beam gas or scratches colli-
 169 mator upstream of CMS. They travel in the proton beam optics where because their momenta
 170 are lower than the beam protons, they get overbent by the dipole magnets and tend to be de-
 171 flected in the horizontal plane once the effects for quadrupole and other magnets are taken into
 172 account. Some of these muons approach ECAL more or less in parallel to the proton beams,
 173 and radiate photons near or in ECAL. Since they are created by halo muons, a muon track is

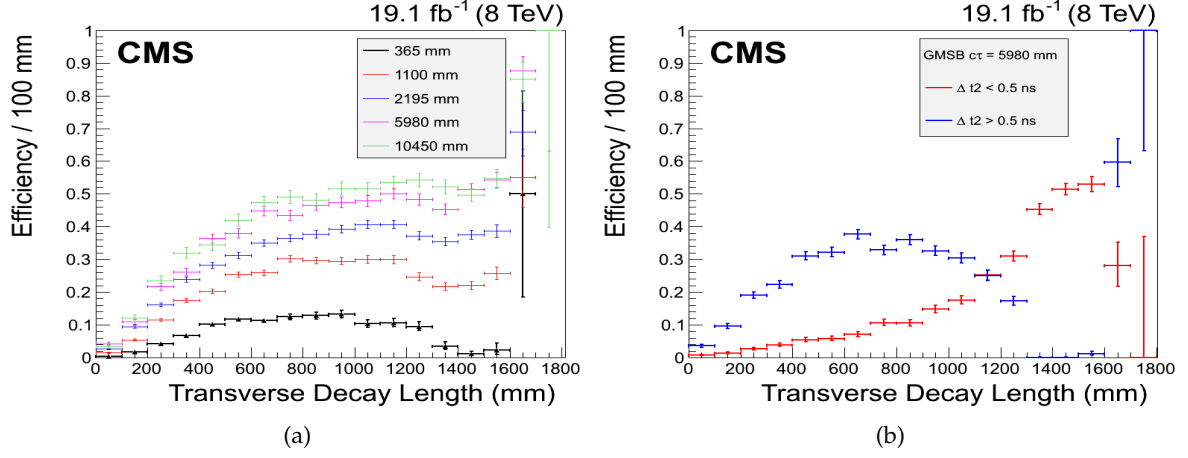


Figure 5: The photon time acceptance ($t > 3$ ns) as a function of the transverse decay length in different $c\tau$ models (left). The acceptance has two components where the main cause of the delay is the slowness of the neutralino ($\Delta t_2 < 0.5$ ns, red) and large decay angle ($\Delta t_2 > 0.5$ ns, blue)

often found in the CSC 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 ECAL cluster for a large fraction of the off-time events.

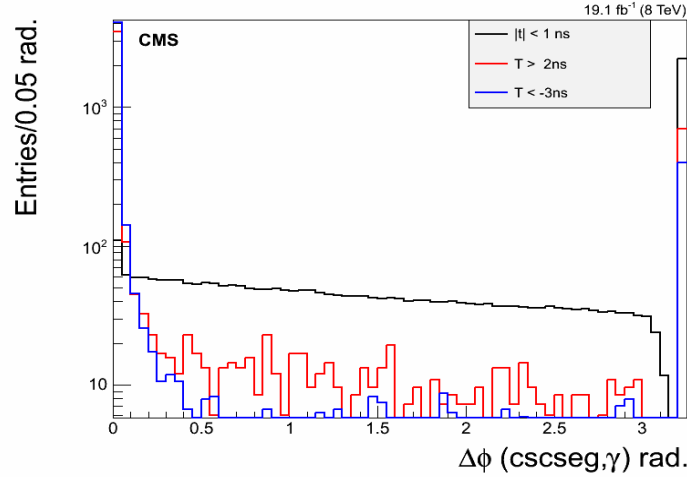


Figure 6: CSC $\Delta\phi$ distributions of in-time (black) and off-time (red and blue) samples. The events in the last bin are those without any CSC segment information available.

The timing of the arrival of these halo-induced photons show a very characteristic η dependence. A simple approximation for the arrival timing of the halo induced photon relative to photons produced in p-p interactions is given by.

$$t_{ECAL} = \frac{\rho}{c} \left(\frac{1}{\tan \theta} - \frac{1}{\sin \theta} \right) \quad (3)$$

$$= -\frac{\rho}{2c} \tan(\theta/2) = -\frac{\rho}{2c} \exp^{-\eta} \quad (4)$$

where ρ is the transverse radius with respect to beam pipe, r is the distance between the main interaction point and photon cluster, z is the z position of the photon cluster, c is the speed of light, and θ is the polar angle.

The above result predicts that the ECAL arrival time of halo-induced photons is a function of η and always earlier than the time of normal photons from the associated bunch crossing. The 2D distribution of ECAL timing *vs.* η for data in Figure 7a shows that there are a number of photon candidates which exhibit the η -ECAL timing correlation derived above and indicated by two red curves.

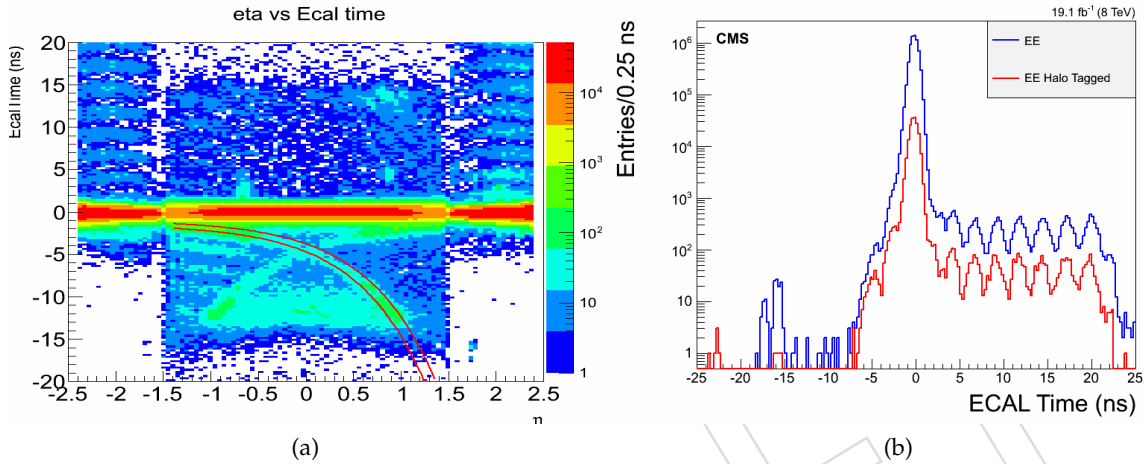


Figure 7: The η *v.s.* ECAL time for inclusive photon samples (left). The red curves show the fitting range to select halo control sample. The ECAL time of photons from ECAL Endcap (right). The periodic pattern is from the halo of satellite bunches. The red histogram is the ECAL time from photons tagged by $\text{CSC}\Delta\phi$.

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 7b. Because 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.

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 radian of the azimuthal angle with the photon cluster ($\text{CSC}\Delta\phi < 0.05$). A 91% veto efficiency and 3% mis-tagging rate are found by applying this requirement.

6.2 Cosmic-Ray

Like halo muons, cosmic-ray muons can initiate showers in ECAL. Their existence can be found by looking at the $\Delta\phi$ and $\Delta\eta$ between a DT cosmic-ray muon segment [14] and an ECAL cluster. Due to the large space between Muon Barrel system and ECAL, the actual DT positon 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 8b 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 8a does not show such an enhancement for in-time sample. This demonstrates that the off-time sample contains significant fraction of cosmic muon-induced photon candidates.

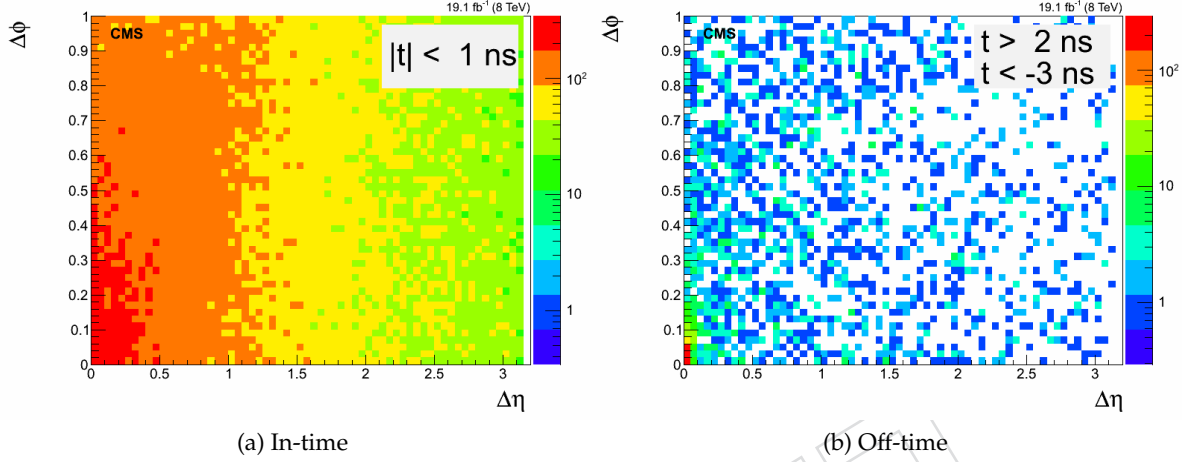


Figure 8: DT $\Delta\eta - \Delta\phi$ distributions of in-time (left) and off-time (right) photon samples.

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 segment and one ECAL supercluster in an events, we observe that 75.5% of those superclusters are associated with the projection of 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. Using the normal photon sample from displaced photon dataset where the events pass the regular event selection and the ECAL time is within an 1 ns window ($|t| < 1$ ns), we obtain a mis-tagging rate of 1.4%.

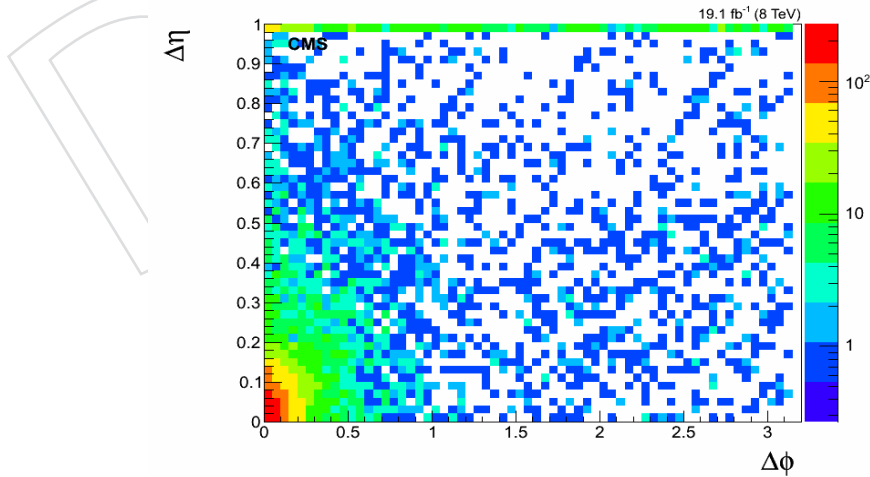


Figure 9: The $\Delta\eta$ and $\Delta\phi$ distribution of DT segment and ECAL supercluster for cosmic-ray data.

6.3 Anomalous ECAL Spike

ECAL spikes is due to direct energy deposit by particle in the Avalanche Photo-Diode (APD) [15]. They are often isolated apparent energy deposit in one crystal, they can be rejected if the spike candidate energy ($E1$) and the sum of its neighboring four crystals ($E4$) satisfies equation 5

$$1 - \frac{E4}{E1} > 1 - (0.04 \times \log E1 - 0.024) \quad (5)$$

while $E1$ greater than 4 GeV. It also will not be used to form a cluster in the particle-flow reconstruction process. Occasionally, however, some of the spike hits are surrounded by some energy deposit either by coincidence, or the charge particle which created the spike hit is associated with other particles which deposit sufficient energies so that it is not considered a spike. 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 photon.

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 10 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 "swiss-cross" values for the spike-enhanced sample is also compared with the values from nominal photon sample. It also indicates higher swiss-cross values for spike-enhance sample. Based on these observations, we use a tighter swiss-cross cut ($1 - \frac{E4}{E1} > 0.9$). In addition, we also veto photons with $S_{Major} < 0.6$ and $S_{Minor} < 0.17$.

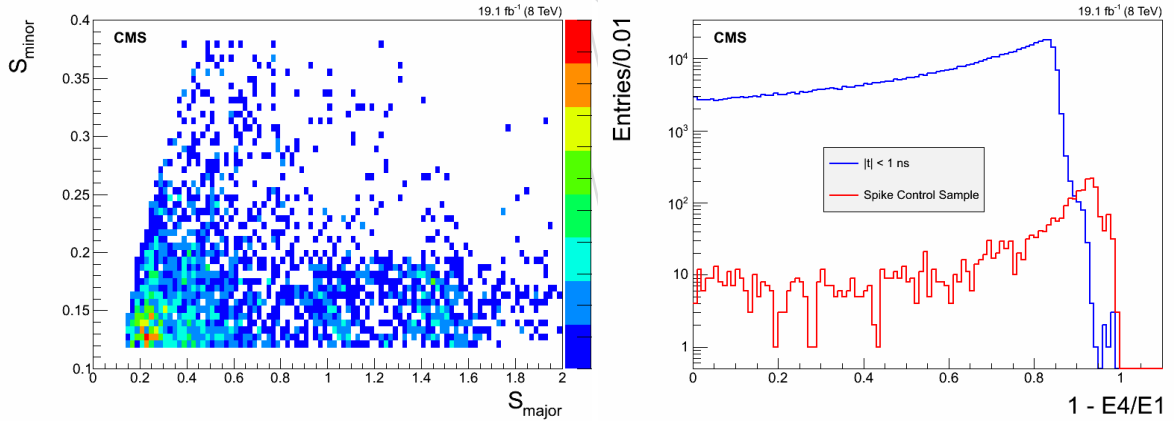


Figure 10: S_{Major} and S_{Minor} distribution of spike control sample.

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 ECAL spike background also have expected shape from the tagged components. However, the remaining photons after removing all the tagged backgrounds still have 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.

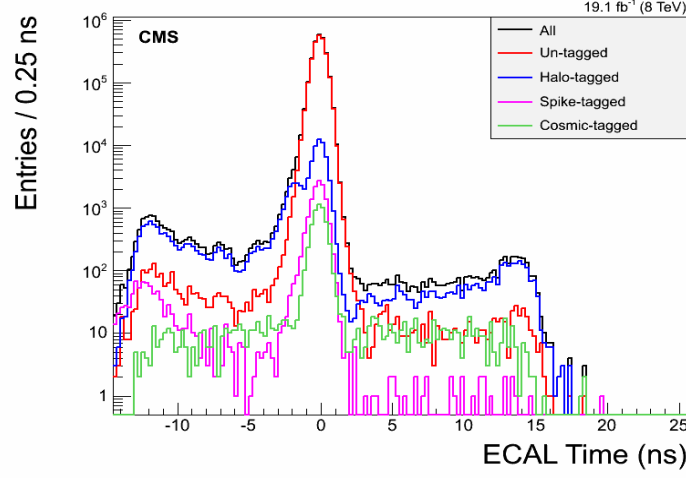


Figure 11: ECAL time distribution from 0 and 1-jet events. Three tagged background sources and the remaining are shown in different color.

We seek signal in the ECAL timing window between 3 and 13 ns and $E_T^{\text{miss}} > 60$ 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 $E_{T \text{ no } \gamma}^{\text{miss}}$ if taking photon out of E_T^{miss} calculation.

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

$$\text{Non-collision background in D} = \frac{B}{A} \times C \quad (6)$$

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

Table 3: ABCD definition for non-collision background estimation. All events pass $E_T^{\text{miss}} > 60$ GeV requirement.

6.5 ABCD Method for Collision Background

As for possible contamination from collision events, another ABCD method using ECAL time and E_T^{miss} is developed. This method is aimed as estimating the collision events in each of ABCD regions defined in previous section. As collision events are suppressed in A and C region and non-collision backgrounds dominate in these two regions ($E_T^{\text{miss}} > 60$ GeV and $E_{T \text{ no } \gamma}^{\text{miss}} < 60$ GeV), this estimation is only necessary for B and D regions. We use events with $E_{T \text{ no } \gamma}^{\text{miss}} > 60$ 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 $|t| < 2$ ns

region can be used as the control region to extract ratio for collision events with large and small E_T^{miss} values. The ABCD regions are defined in Table 4. The collision background in D region is estimated by

$$Q_d(\text{Collision background in D}) = \frac{F}{F'} \times D' \quad (7)$$

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

$$Q_b(\text{Collision background in B}) = \frac{F}{F'} \times B' \quad (8)$$

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

Table 4: ABCD Region definition for collision background estimation. All events pass $E_{T \text{ no } \gamma}^{\text{miss}} > 60 \text{ GeV}$ requirement.

6.6 Combined ABCD Method and Closure Test

Combining the ABCD methods for non-collision and collision backgrounds, the final background in the signal region is estimated by

$$\text{Total background in D} = \left(\frac{B - Q_b}{A} \times C \right) + Q_d \quad (9)$$

$$Q_d = \frac{F}{F'} \times D' \quad (10)$$

$$Q_b = \frac{F}{F'} \times B' \quad (11)$$

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 and the number of vetoed backgrounds can be found in Tables 5 and 6. The estimated background in the D region for 0 and 1-jet events is $16.35^{+3.04}_{-2.63}$ which is compatible with the observed value of 10. The uncertainty from collision background has negligible effect because the ratio F/F' is small.

$$D = \left(\frac{39 - 0.20}{852} \times 359 \right) + 0.05 = 16.40^{+3.04}_{-2.63} \quad (12)$$

$$Q_d = \frac{35464}{1446522} \times 2 = 0.05^{+0.05}_{-0.02} \quad (13)$$

$$Q_b = \frac{35464}{1446522} \times 8 = 0.20^{+0.08}_{-0.06} \quad (14)$$

	Spikes	Halo	Cosmic	Yield
D	0	22	30	10
C	9	1508	368	359
B	1	300	17	39
A	65	5075	237	852
F	-	-	-	35464

Table 5: Numbers used in closure test of the 0 and 1-jet events. Numbers in Spikes/Halo/Cosmic columns are the counts vetoed by corresponding background tagging in each defined region. F region is dominated by collision backgrounds. Therefore only the yield is shown.

	Spikes	Halo	Cosmic	Yield
B'	0	1	1	8
D'	0	0	0	2
F'	-	-	-	1446522

Table 6: Closure test from 0 and 1-jet events for collision background estimation. The first three columns are the vetoed backgrounds.

6.7 Cross-Check From Z Events

A cross-check for collision events is done using $Z \rightarrow e^+e^-$ events. This study uses Z mass spectrum and its sideband to extract Z events and the background sample. Since Z decays promptly, the timing from the electrons must be in-time. The majority of the background is Drell-Yan process, which also have in-time electrons in the final state. However, any off-time electron could also pass event selection and present in the Z mass spectrum as well (Figure 12). Therefore, the time distribution from the Z mass sideband provides a background template with proper scale of two background sources, Drell-Yan and random electron pairs.

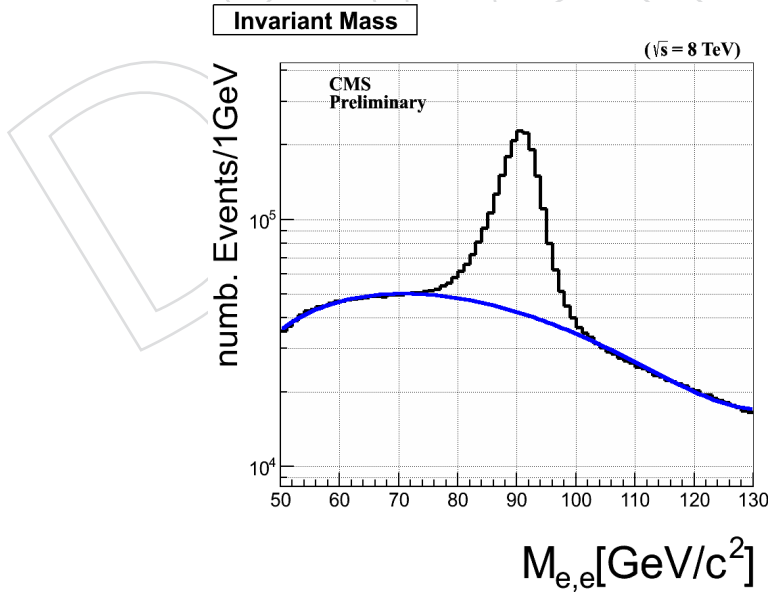


Figure 12: The invariant mass of two electrons. The blue curve is the background estimation by fitting the sideband.

The events requires at least two electrons with p_T greater than 30 GeV. The electron isolation

is not applied because the algorithm included off-time ECAL crystal in isolation energy calculation. The Z sample is chosen by requiring the invariant mass between 76 GeV and 100 GeV of two leading electrons. For the background template, the sample events with invariant mass between 50 to 76 GeV and 100 to 130 GeV are used. By fitting the sideband in Z mass spectrum using a polynomial function, the background contamination in the Z sample area can be estimated and the background timing distribution template can be normalized accordingly.

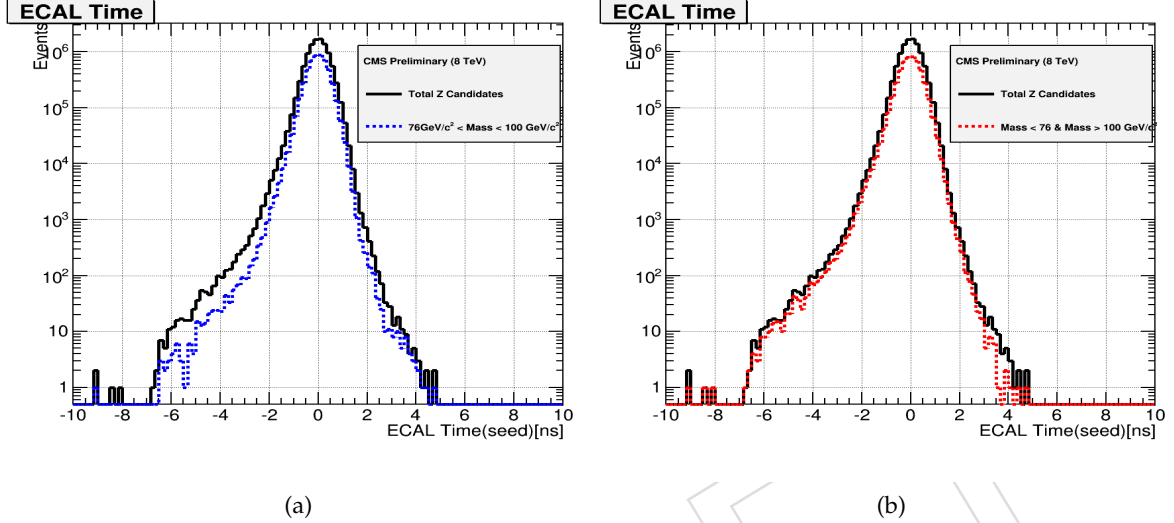


Figure 13: The time distribution of the Z signal (left, mass range is 76 GeV < mass < 100 GeV) is indicated in blue and the whole mass region in black. The time distribution of the Z sideband (right, mass ranges are 50 GeV < Mass < 76 GeV and 100 GeV < Mass < 130 GeV) is indicated in red.

By subtracting this background time distribution (Figure 13b) from the Z sample's (Figure 13a), a time distribution of pure Z events can be obtained (Figure 14). Based on this pure Z time distribution, a ratio $(1.293^{+0.374}_{-0.325} \times 10^{-5})$ of $|t| < 2$ ns and $t > 3$ ns can be obtained. The ratio can be multiplied to the number from the F region define in the result section (28283) to give an estimate of collision background in the D region, which equals $0.366^{+0.106}_{-0.092}$ photons. This is larger than the result $(0.093^{+0.093}_{-0.047})$ from the collision ABCD method, but both methods suggest negligible controbution (less than 1 event predicted) from collision events to off-timing region.

7 Systematic Uncertainties

This analysis relies on photons above 80 GeV in p_T , jet above 35 GeV in E_T and E_T^{miss} larger than 60 GeV. So the efficiency estimated using MC sample 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 estimate the uncertainties due to the uncertainties in the jet energy scale, jet energy resolution, electron-gamma energy scale, unclustered energy for E_T^{miss} as well as photon timing resolution. We vary their $1\text{-}\sigma$ deviation with respect to the nominal values. The results are summarized in table 7. The timing bias has most significant impact to 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 $c\tau$, the systematic uncertainties usually have higher impact to lower SUSY

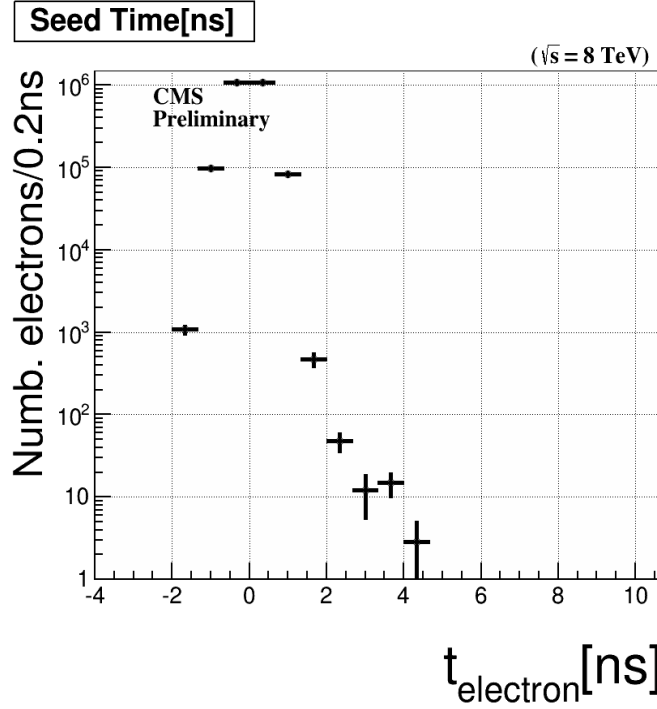


Figure 14: The time distribution of Z events

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 decay from lighter neutralino has softer p_T spectrum and causes lower efficiency for passing the photon p_T requirement. In addition, lighter neutralino is more boosted than heavier neutralino, which also results in lower efficiency since there are fewer slow motion neutralinos on which our analysis relies.

Other general factors such as luminosity [16] and parton distribution [17] function are adopted from the official CMS study. These factors are all then applied in the statistic 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 as upward 223% and 51% downward by using the statistic uncertainty of the ABCD method. Due to low statistic counts, the background uncertainty is large. However, it does not impact to the final result as significant as the uncertainties of 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 0.093 ($^{+0.301}_{-0.047}$). The vetoed backgrounds and the numbers used in background estimation are presented in Table 8 and Table 9.

Source	Uncertainty(%)
Time zero	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 7: Systematic uncertainties for signal efficiency

$$D = \left(\frac{1 - 0.14}{3} \times 0 \right) + 0.093 = 0.093^{+0.301}_{-0.047} \quad (15)$$

$$Q_d = \frac{28283}{605496} \times 2 = 0.093^{+0.093}_{-0.047} \quad (16)$$

$$Q_b = \frac{28283}{605496} \times 3 = 0.140^{+0.108}_{-0.061} \quad (17)$$

336 With no significant excess event over estimated background, we find an upper limit of 4.22
 337 photon counts at 95% C.L. using CLs method [18]. Assuming the GMSB model and the SUSY
 338 breaking scale is 180 TeV, this corresponds to a cross section of 12.42 fb for the neutralino pro-
 339 duction of photon channels and the lifetime of the neutralino ($c\tau$) is either less than 71 cm or
 340 larger than 552 cm (Figure 15).

341 Taking GMSB as a benchmark model, the exclusion region at 95% C.L. in neutralino mass is up
 342 to 300 GeV. The excluded lifetime range is about 70 cm to 1000 cm for low mass neutralino
 343 and the excluded interval shrinks when the mass increases (Figure 17). This is mainly due
 344 to smaller expected cross-section of neutralino production at higher Λ (or neutralino mass)
 345 values.

	Spikes	Halo	Cosmic	Yield
D	0	0	0	1
C	0	2	1	0
B	1	1	1	1
A	0	6	0	3
F	-	-	-	28283

Table 8: Final background estimation for signal candidates. All events pass $E_T^{\text{miss}} > 60$ GeV cut.

	Spikes	Halo	Cosmic	Yield
D'	0	0	0	2
B'	0	0	0	4
F'	-	-	-	669013

Table 9: Final background estimation for at least one photon and two jets events. All events pass $E_T^{\text{miss}} > 60$ GeV cut.

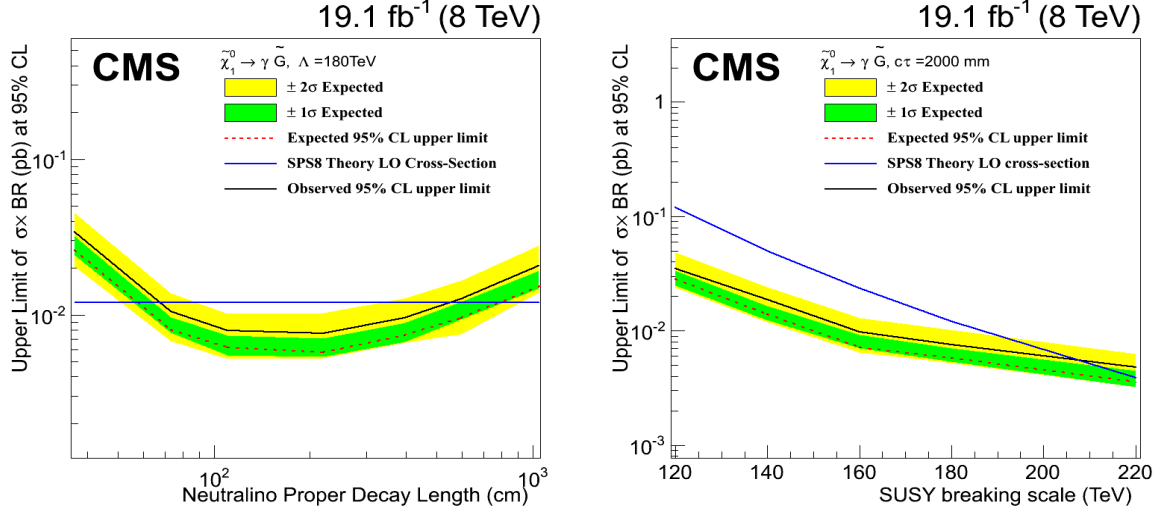


Figure 15: The upper limit at 95 % C.L. for Λ 180 TeV in different $c\tau$ and $c\tau$ 6000 mm in different Λ values using CL_s method

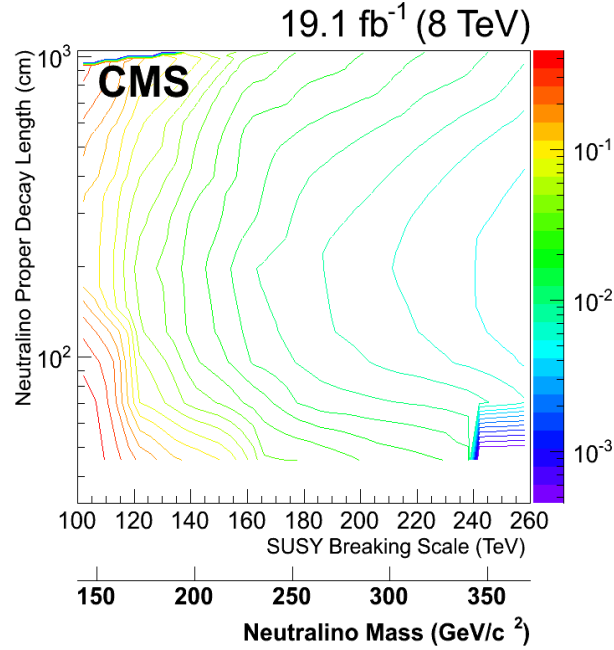


Figure 16: The cross-section limit for the mass and lifetime of neutralino in the SPS8 model

9 Conclusion

We have developed an effective method using ECAL timing to search for delayed photon signal in the CMS experiment. The application of long-lived neutral particle decaying to photon and gravitino is performed using the data with an integrated luminosity 19.1 fb⁻¹ from the 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 lifetime and mass of the neutral particle (Figure 16). Comparing with the previous searches [5, 6] in CMS experiment, the CMS ECAL timing method provides broad search spectrum for long-lived neutralino.

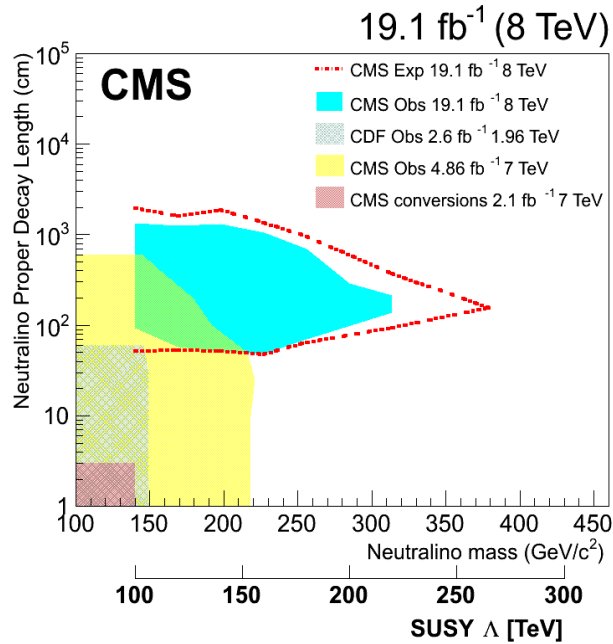


Figure 17: The exclusion region for the mass and lifetime of neutralino in the SPS8 model

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