Search For Delayed Photons Using Timing.

Shih-Chuan Kao[1] Yuichi Kubota[1] Tambe E. Norbert[1] Roger Rusack[1]

[1]University Of Minnesota

Long-Lived Meeting, January 7, 2015

Outline

Where are we now?

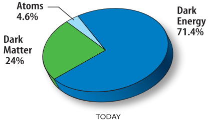
The Universe Set

The set $S = \{\cdots \mathbf{0}, \frac{1}{2}, 1, \frac{3}{2}, 2 \cdots\} \cdot \hbar$

where s is the spin of a particle. represents our past, current and probably future understanding of the universe around us. As of the moment Currently we know:

- $\mathbf{s} = \mathbf{\frac{1}{2}}\hbar$ Describes all the matter in our universe.
- $\mathbf{s} = \mathbf{1}\hbar$ Describes gauge interactions.
- $\mathbf{s} = \mathbf{0}\hbar$ Responsible for giving mass.
- $\mathbf{s} = \mathbf{2}\hbar$ Describes gravity (gauged?).
- $\mathbf{s} = \mathbf{\frac{3}{2}}\hbar$?? **Dark Matter**?

However, this magic set only describes $\approx 4.6\%$ of our total universe.

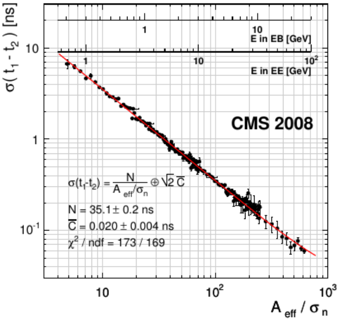


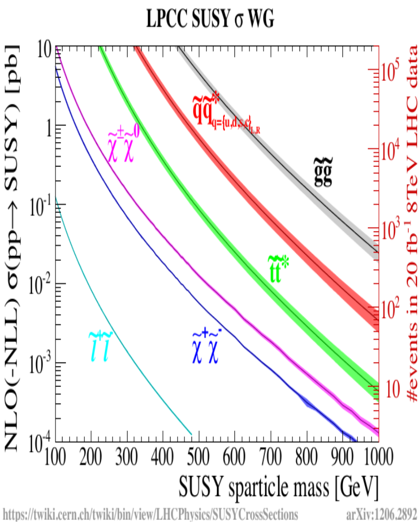
Introduction

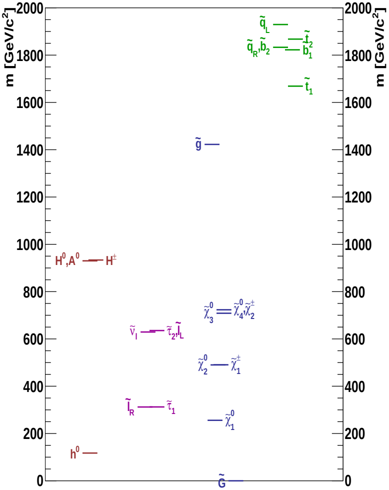
- **Long-Lived Particle Models**
  - ⋆ Gauge Mediated Supersymmetry Breaking (GMSB)
    - ▷ Next-to-lightest SUSY (NLSP) is Neutralino ($\tilde{\chi}_1^0$)
    - ▷ $eV - keV$ Lightest-SUSY particle (LSP) is Gravitino ($\tilde{G}$).
    - ▷ Gravitino is a Dark Matter Candidate.
  - ⋆ General Gauge Mediation (GGM)
    - ▷ NLSP is a mixture of fermions (Bino, Wino, Higssino).
    - ▷ Several SUSY particles can be NLSP.
- **ECAL Resolution**

† ECAL timing resolution $\sigma_t < 500$ ps.

† Use timing to identify photons and electrons from long-lived decay.

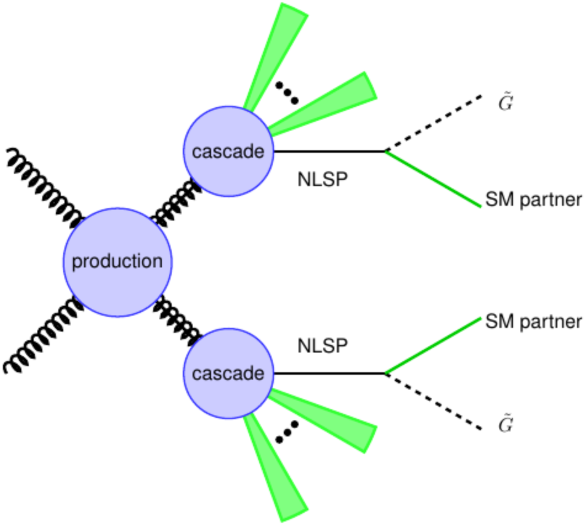






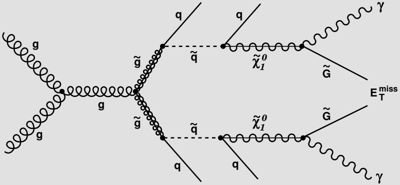
SUSY production mostly in strong interactions at LHC.

Cascade Decay Chain



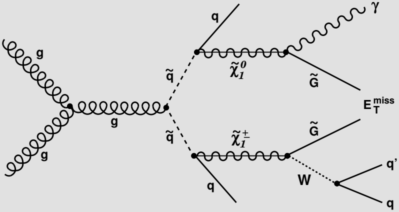
Y. Kats et al: arXiv:1110.6444v2

Double Photon



2 Photons, Jets, Large MET

Single Photon



1 Photon, Jets, Large MET

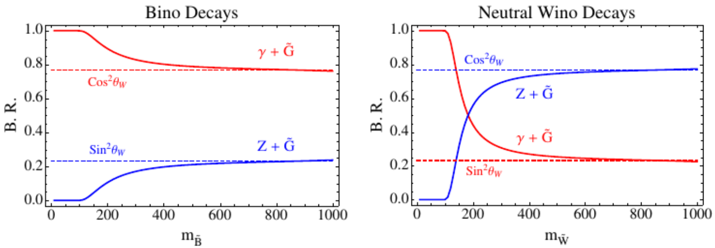
Tranverse Decay Distance

Distance Travelled

$$\mathrm{L}_T = c\tau \cdot (\gamma\beta_T) = c\tau \cdot \left(\frac{p_T}{m}\right)$$

Proper Decay Length

$$c\tau_{\texttt{NLSP}} = C_{\texttt{grav}}^2 \frac{1}{\kappa} \left(\frac{m_{\texttt{NLSP}}}{GeV}\right)^{-5} \left(\frac{\sqrt{\mathrm{F}}}{TeV}\right)^4$$



J. Ruderman, D. Shih arXiv:1103.6083

- **Data ($19.1 fb^{-1}$)**

Dataset Name	Recorded Luminosity $[fb^{-1}]$
/Run2012B/SinglePhoton/EXODisplacedPhoton-PromptSkim-v3	5.1
/Run2012C/SinglePhoton/EXODisplacedPhoton-PromptSkim-v3	6.9
/Run2012D/SinglePhoton/EXODisplacedPhoton-PromptSkim-v3	7.1
/Run2012C/Cosmics/Run2012C-22Jan2013-v1/RECO	3130384(events)
/Run2012D/Cosmics/Run2012C-22Jan2013-v1/RECO	52430 (events)
/SingleElectron/Run2012A-22Jan2013-v1/AOD	5.2
/DoubleElectron/Run2012C-22Jan2013-v1/AOD	4.8

- **Signal MC [GMSB (SPS8)]**

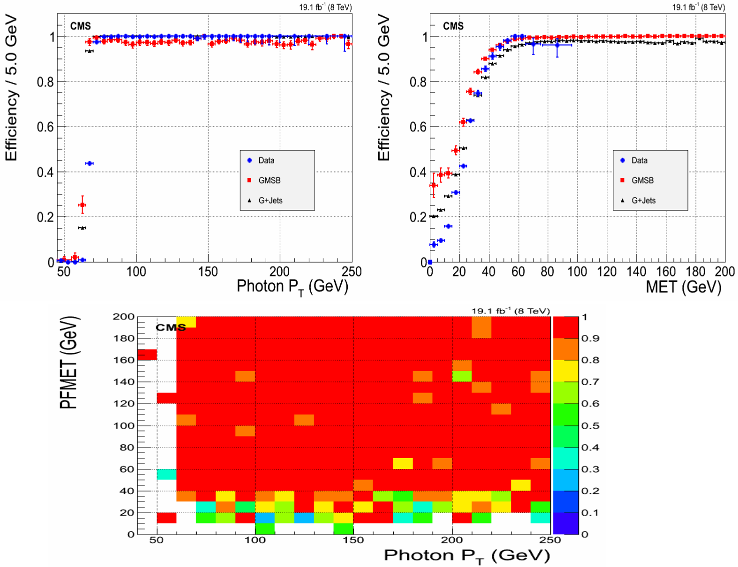
Λ [TeV]	100	120	140	160	180	300
$M_{\tilde{\chi}_1^0}$ $[GeV/c^2]$	140	169	198	227	256	430
$c\tau$	215	325	130	245	185	
(mm)	425	645	515	490	365	495
	1700	1290	1030	975	730	
	3400	1935	2060	1945	1100	995
	5100	2955	2920	2930	2195	2960
	6000	3870	3985	3910	3950	
	9300	5985	6000	5875	5980	6000
		9825	10450	9815	10450	10450

- **$\gamma+$ Jets MC**

$\hat{p}_T$ [GeV /c]	σ_{LO} (pb)	Number of events
$50 - 80$	3322.3	1995062
$80 - 120$	558.3	1992627
$120 - 170$	108.0	2000043
$170 - 300$	30.1	2000069
$300 - 470$	2.1	2000130
$470 - 800$	0.212	1975231

HLT Trigger

- **HLT_DisplacedPhoton65_CaloIdVL_IsoL_PFMET25**
  - HLT_Photon50_CaloIdVL_IsoL (Study Trigger)

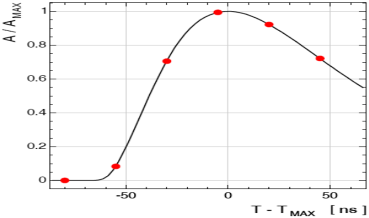


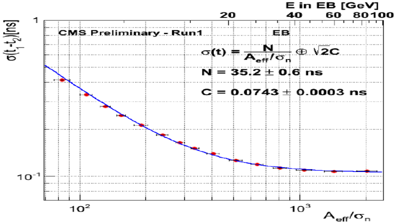
ECAL Timing

- **Time Reconstruction**
  - 10 digitized samples used.
  - Fit and Weighted methods used to extract time.
- **Time Measurement**

$$T_{MAX} = \frac{\sum_i \frac{T_{MAX,i}}{\sigma_i^2}}{\sum_i \frac{1}{\sigma_i^2}}$$

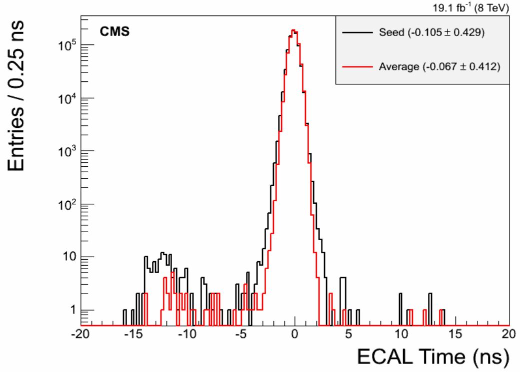
- **Time Performance**
  - Time resolution better than 200 ps for $E > 30$ GeV





ECAL Timing(2)

- **Photon Timing**
  - $T_\gamma =$ Average Time of all Crystals.
  - $T_\gamma =$ Seed (most energetic) Crystal Time.



- Similar behavior seen in Seed and Average Time.
- We use seed time as Photon Measured Time in this analysis.

ECAL Timing(3): MC Vs Data

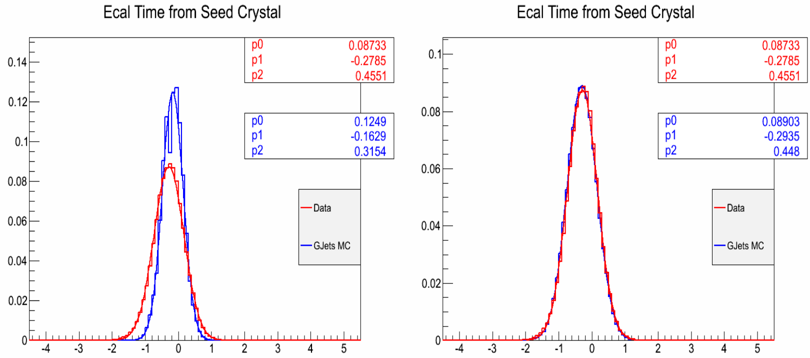
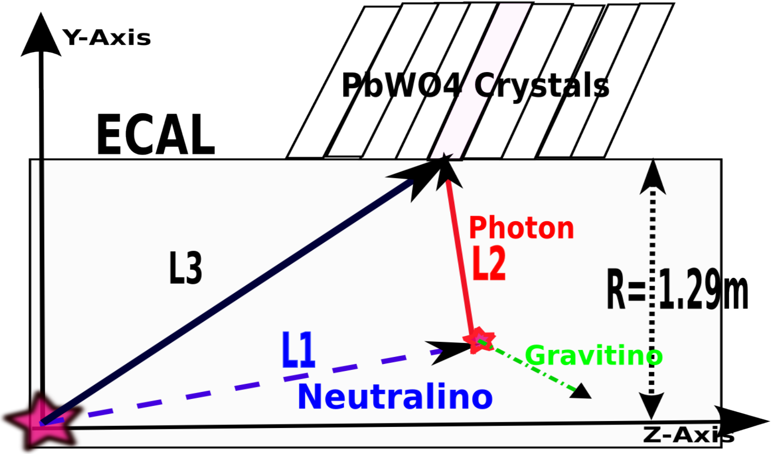


Figure : (LEFT): Before (RIGHT): After

- Timing corrections from data applied to $\gamma+$ Jets MC.
- $\gamma+$ Jets MC timing aligns better with data after corrections are applied.

Long-Lived Decay

- **Source of Delayed Photon?**
  - Slow moving particle; $\beta << 1$,
  - Non-nominal flight path,
  - Stopped in subdetectors,

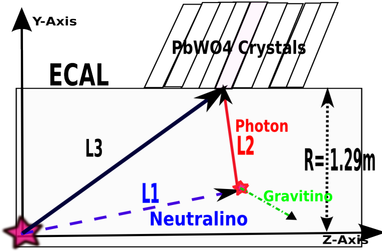


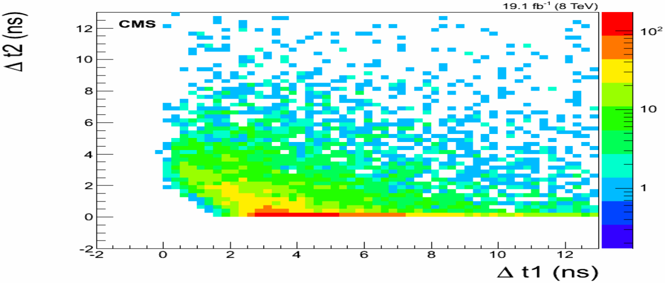
Slow Vs Off-Pointing Decay

Photon Arrival Time

$$\Delta t_1 = (L1/c\beta) - (L1/c)$$

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





Delayed photons mostly from slow moving neutralino decays.

Event Selection

Object Selection Criteria

Variable	Selection Cuts
Photon $p_T(\gamma^{1(2)})$	$> 80(45)$ GeV
$\lvert\eta_\gamma\rvert$,(EB only),	$< 3.0(< 1.5)$
Semi-minor axis(S_{Minor})	$0.12 \leq S_{Minor} \leq 0.38$
H/E	< 0.05
Track Vito,$\Delta R(\gamma, track)$	> 0.6
HCAL,ECAL, Track, Isolation	$< 4.0, < 4.5, < 0.2$
Cone Size(Iso γ) $\Delta R(\gamma, SC)$	< 0.4
Spike Swiss-Cross	$1 - E_4/E_1) < 0.98$
Jets must satisfy	JetID Requirements
Leading Jet p_T	> 35 GeV
Number Of Constituents	> 1
$\Delta R(\gamma, jet) = \sqrt{(\phi_\gamma - \phi_{jet})^2 + (\eta_\gamma - \eta_{jet})^2}$	> 0.3
E_T^{miss}	> 25 GeV

Kinematics Distribution

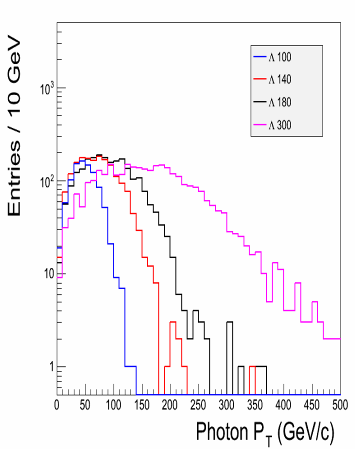


Figure : Photon p_T

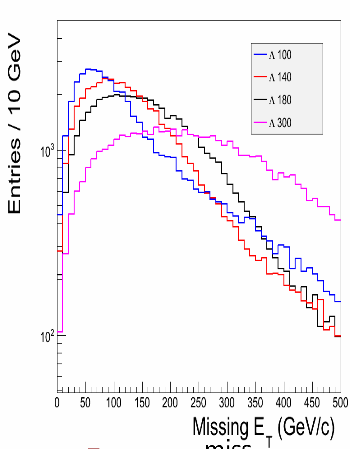


Figure : E_T^{miss}

- Different Λ values with the same $c\tau$(10 m). Photon p_T is harder with higher values of Λ.

Signal Efficiency and Acceptance

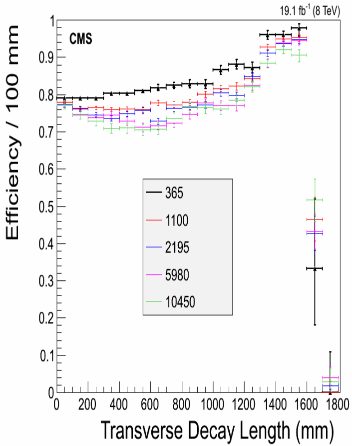


Figure : Efficiency

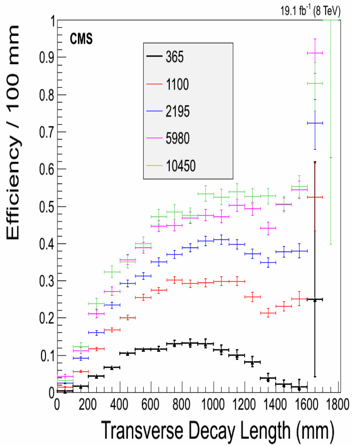


Figure : Acceptance

Sharp drop in efficiency immediately beyond ECAL radius for slow moving neutralino decay as source of delayed photon.

Signal Efficiency and Acceptance(II)

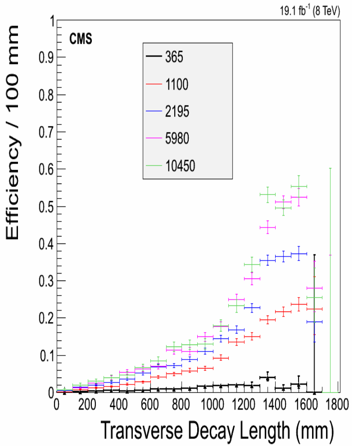


Figure : Slow Moving

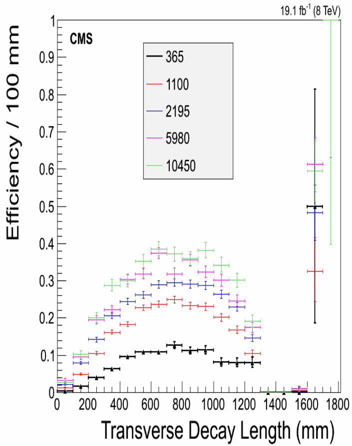


Figure : Off-Pointing

Acceptance peaks at transverse decay length 800 mm with delayed photons from off-pointing neutralino decays.

Signal Efficiency and Acceptance(III)

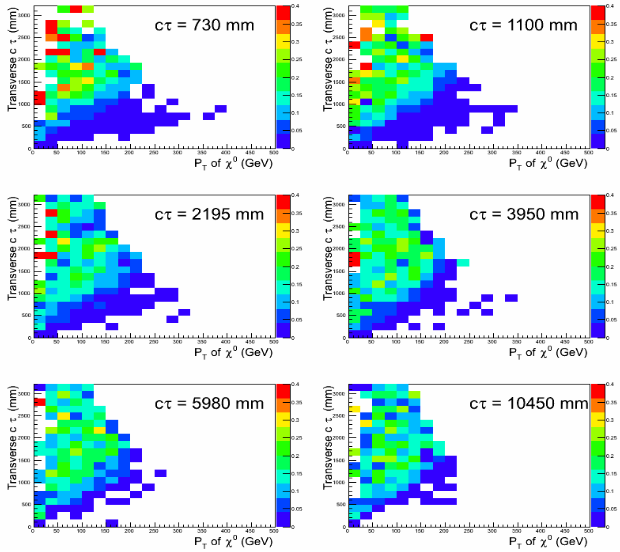
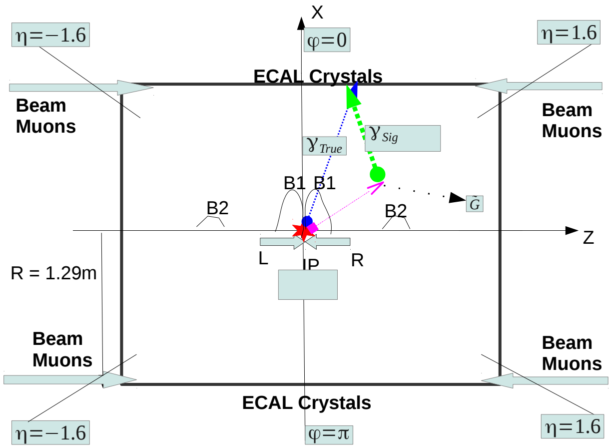


Figure : 2 Dim Efficiency

Analysis Strategy

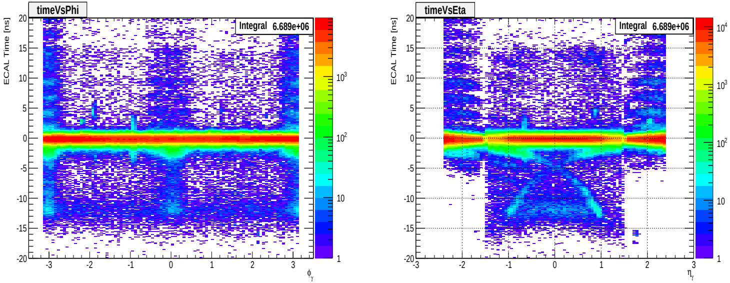
- **Background Source**
  - **Collision**:Mis-measured time of $Z/W/top$ events.
  - **Non-Collision**:Out-time events from LHC proton Beam/Cosmic/Anomalous Spikes.
- **Strategy**
  - I Identify, tag and reject Non-Collision events.
  - II Perform ABCD background estimation technique on residual non-collision events.
  - III Perform ABCD background estimation technique on collision events.
  - IV Performed a combined ABCD background estimation technique.
- **Clusure Test**:Verify background estimation methodology by performing a combined ABCD technique on a control sample.
- **Cross-Check**:Background estimation of collision events on another Control Sample.

Sources Of Background



Events Cleaning

- Non-collision events like proton Beam Induced Background (BIM or Halos)/Cosmic/Anomalous spikes contribute towards delayed photons ECAL timing.
- Need to defined a cleaning mechanism for identifying and rejecting non-collision events.



Features around $\phi = 0, \pm\pi$ and η-dependence shows that background sources originate from both collision and non-collision events.

In-Time Vs Out-Of-Time Events

We estimate these background by defining two Control samples.

In-time events Control Sample (IT-CS)
Out-of-time events Control Sample (OT-CS)

Control Sample (In-time Events)

IT-CS: > 2 Jets Events with photon ECAL time, $t \in [-1, 1]$ ns.

Control Sample (Out-Of-time Events)

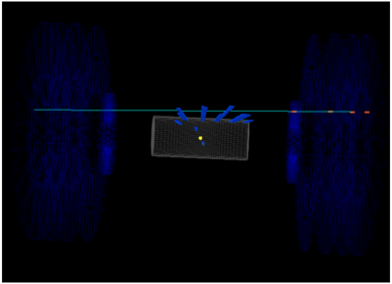
OT-CS: 0 Jet Events with photon ECAL time, $t < -3$ ns or $t > 2$ ns.

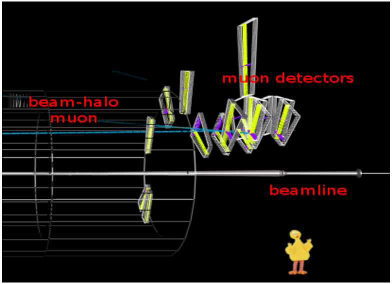
Events from above CSs provide a unique approach to estimate possible background contribution in signal.

Beam Halo Muons

- Proton beam interacting with gas/air particles in the beam pipe,
- Proton beam colliding with the collimators upstream prior to entering the CMS detector.

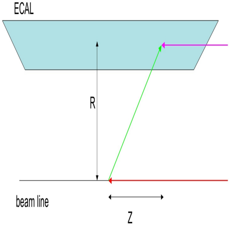
will produce energetic muons traveling parallel with main proton beam and showering in the Calorimeters.





Halo Photon (II)

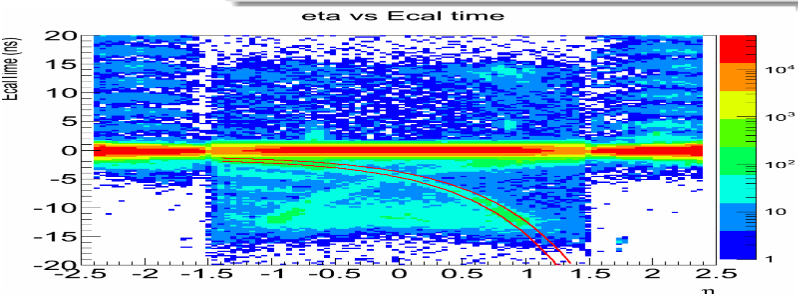
Using Halo kinematics, We can tag and estimate halo photons produced from halo muons showering in ECAL as follows:



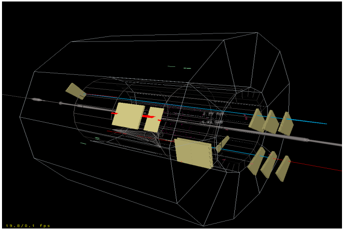
Halo Expected ECAL Time

$$t_0 = \frac{\rho}{c} = \frac{R}{\sin\theta}\frac{1}{c}, \quad t_{halo} = \frac{Z}{c} = \frac{R}{\tan\theta}\frac{1}{c}$$

$$\Delta t_H^{exp} = t_{halo} - t_0 = -\frac{R}{2c}\exp^{-\eta}$$

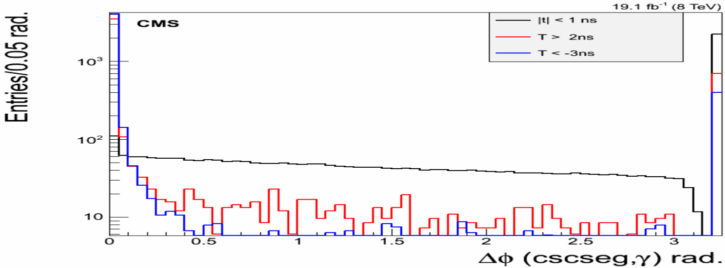


Additionally, using halo muon hits from CSC segment matched in ϕ to Superclusters in ECAL, we can in additionally identify, tag and remove halo photon events with large timing.



Halo Photon Matching

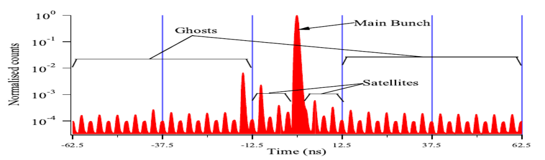
$$\Delta\phi(CSCSeg, \gamma) = |\phi_{CSCSeg} - \phi_{\gamma}|$$



Satellite/Ghost Beam Halos

- Fill empty RF buckets.
- Trail main bunches by ≈ 5 ns.
- 10^{-5} protons compared to main bunches.
- Can contribute to main collision photons.
- Show a 2.5 ns pattern in EE,
- Tagged using $\Delta\phi(CSCseg, \gamma)$.

LHC LDM Proton Beam Profile



Halo Photon (V)

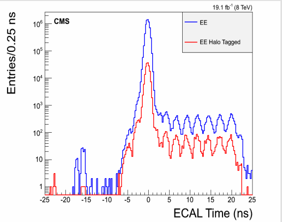
Halo Photon Event Properties

- Halo photons populate around $\phi = 0, \pm\pi$
- ECAL time mostly < -3 ns but can also arrive late(ghosts).
- Halo events most contain no jets (0-jet events).
- Rare cases can be associated with "pile-up" events.

Halo Photon Tagging Criteria

- Use $\Delta\phi(CSCseg, \gamma) < 0.05$ randians.
- Shower shape($0.8 < S_{Major} < 1.65$ and $S_{minor} < 0.2$)

Ghost/Satellite EE



HP Tagging Efficiency/mis-Tag Rate

Halo Photon Tagging Efficiency

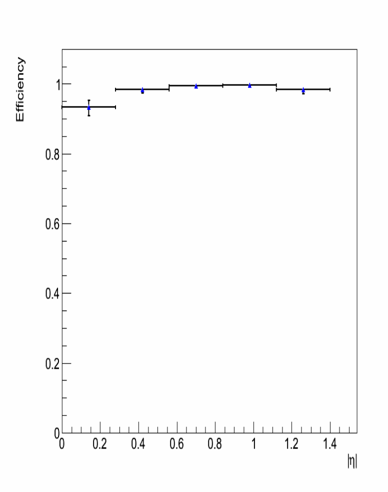
- Control Sample Selection,
  - $\Delta\phi(CSCseg, \gamma) < 0.05$ randians
  - Same $\Delta t_{H}^{exp} = -\frac{R}{2c}\exp^{-\eta}$ ECAL time Vs η dependence.
- Efficiency evaluated in 5η bins for S_{Major} η dependence.

Halo Photon mis-Tag Rate

- Control Sample Selection:
  - $>=$ 2-jets events with $E_T^{miss} < 60$ GeV
  - ECAL time, $|t| < 1$ ns.
- mis-tag rate eveluated in 5η bins for S_{major} η dependence.

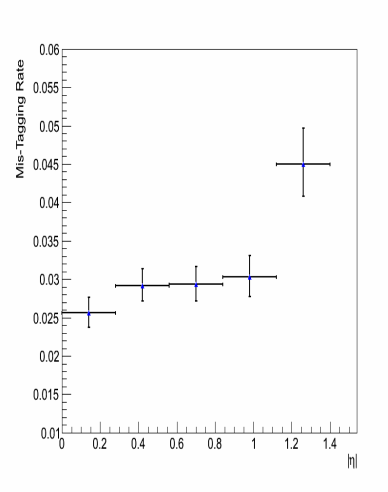
HP Tagging Efficiency/mis-Tag Rate(I)

Tagging Efficiency



- Tagging Efficiency $\approx 98\%$

mis-Tag Rate

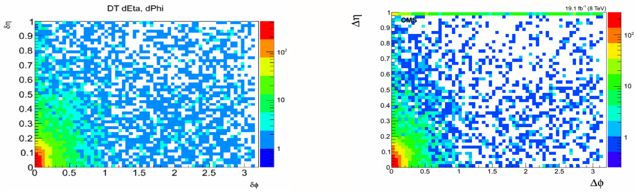


- mis-tag rate $\approx 3\%$

Cosmic Muons

- Muons from cosmic rays in CMS detector.
- Hits in muon detectors (DT/CSC) and shower in ECAL.
- Produce energetic photons with out-of-time.
- Using DT segment matched to ECAL cluster position in $\delta\eta$ and $\delta\phi$ can eliminate cosmic events.

$DT(\delta\eta, \delta\phi)$ **Cosmic Muon dataset(left) and Data(Right)**



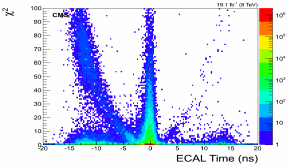
$DT(\delta\eta, \delta\phi)$ tagging of cosmic muons in data and a pure cosmic sample(without LHC proton beam) is comparable.

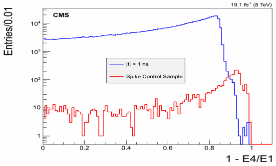
Anomalous ECAL Spike

ECAL Spikes

- Energetic particles(neutrons) from proton collision directly hitting APDs/VPTs.
- Associated with hadronic activity.
- Observed as photons with early time due to no crystal scintillation.
- Can produced late ECAL timing photons with small shower shape.
- ID and rejected requiring $1 - \frac{E_4}{E_1} < 0.9$ of crystal energy deposit and χ^2 from pulse shape fitting.

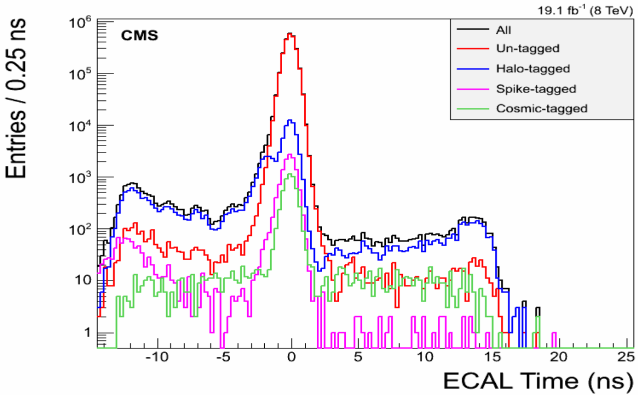
Spike Identification and Rejection





After tagging and cleaning Halo/Cosmic/Spike events, We apply ABCD background estimation technique on residual Non-collision background events to estimate their contribution to possible signal.

Event Tagging and Cleaning Performance



PF-E_T^{miss}(PF-MET) Adjustment

$E_T^{\text{miss}}(\gamma)$

PF-MET calculation fails to take into consideration E_T from out-of-time photons. We make PF-MET adjustment by taking into account the E_T of out-of-time photons for E_T^{miss} measurements. This new PF-MET is called $E_T^{\text{miss}}(\gamma)$.

As a result our signal selection criteria is defined as:

Signal Selection Criteria

SIGNAL: $\geq 1\gamma + \geq 2Jets + E_T^{\text{miss}} > 60, E_T^{\text{miss}}(\gamma) > 60$ GeV

ABCD Technique: Non-Collision Background

Assume similar distribution in earlier and delayed ECAL time for untagged non-collision events.

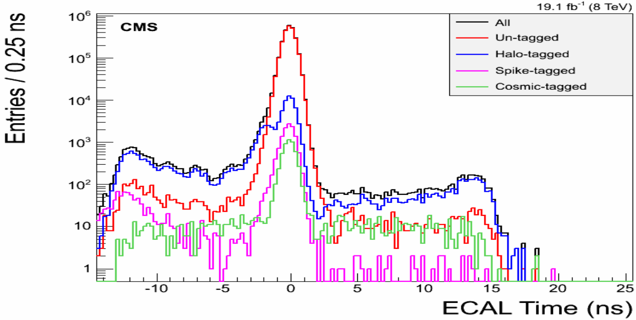
$E_T^{\text{miss}} > 60$ **GeV**

	$E_T^{\text{miss}}(\gamma) < 60$	$E_T^{\text{miss}}(\gamma) > 60$
$t < -3$ ns	A	B
$t > 3$ ns	C	D

$\frac{D}{C} = \frac{B}{A}, \Rightarrow$

$$\mathbf{D} = \frac{\mathbf{B}}{\mathbf{A}} \cdot \mathbf{C}$$

Picture Explaining non-collision untagged background



ABCD Technique: Collision Background

Assume similar distribution in earlier and in-time, in-time and delayed ECAL time for collision events.

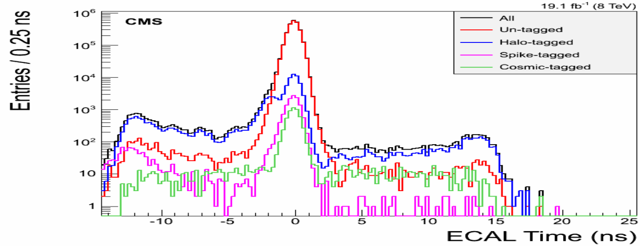
$E_T^{\textbf{miss}}(\gamma) < 60$ **GeV**

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

$$\frac{Q}{D'} = \frac{F}{F'}, \Rightarrow$$

$$\mathbf{Q_d} = \frac{\mathbf{F}}{\mathbf{F'}} \cdot \mathbf{D'}$$

Picture Explaining collision background



Equations and Results.

Closure Test Results: $0,1$-Jet Events

Results Of Background Estimation

Background Estimation Cross-Check

Using $Z \to ee$ events.

Systematics

Background estimation is Data driven. Thus, most of a systematics come from signal,including:

Experimental Systematics

- Definition of Absolute or Zero time,
- ECAL time Resolution,
- Unclustered Energy,
- Jet energy scale,
- Jets energy resolution,
- Photon energy scale,
- Luminosity. We use standard CMS luminosity uncertainty.

Theoretical Systematics

- Choice of PDF.
- Re-normalization group equations.

Systematics(II)

Systematic Uncertainties

Source	Uncertainty(%)
Absolute time(Zero time)	$10 \sim 6$
Unclustered Energy	$10 \sim 4$
Photon Energy Scale	$4 \sim 2$
ECAL Time Resolution	$5 \sim 2$
Jet Energy Scale	$9 \sim 3$
Jet Energy Resolution	$9 \sim 2$
Luminosity	2.6
Choice of PDF	< 1

- Systematics is obtained by studying the effects of varying by a few amount of a particular source of systematic on the total number of objects passing object selection cuts.

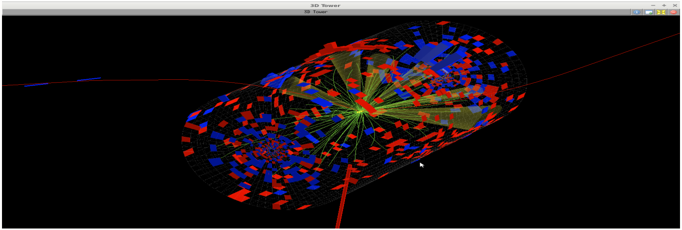
Results

Events Passing Final Selection

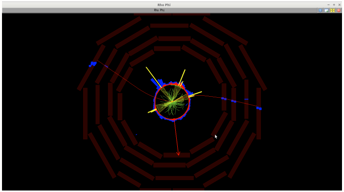
Sample	**Lifetime($c\tau$)[mm]**	**Number Of Events**
GMSB $\Lambda = 180$ TeV	10500	
GMSB $\Lambda = 180$ TeV	6000	
GMSB $\Lambda = 180$ TeV	4000	
GMSB $\Lambda = 180$ TeV	3000	
GMSB $\Lambda = 180$ TeV	2000	
GMSB $\Lambda = 180$ TeV	1000	
GMSB $\Lambda = 180$ TeV	500	
Data	1.00	
Background Total	0.014	

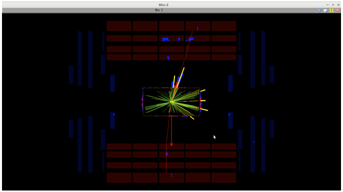
Observed Event

3-D View



Transverse (left) and $\rho - Z$ (Right) View





Exclusion Limits

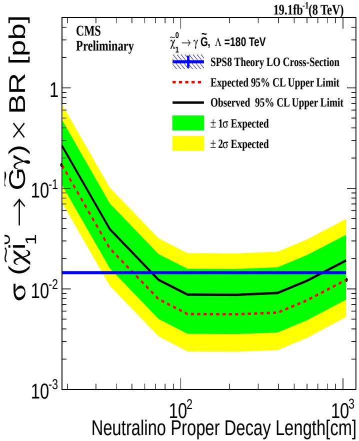


Figure : $c\tau$ Limits

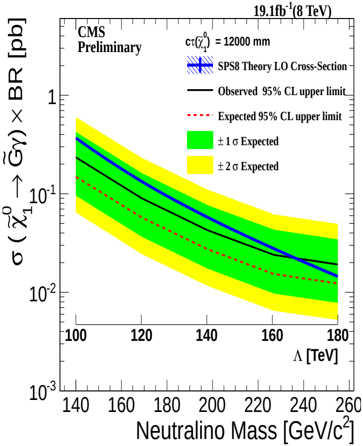
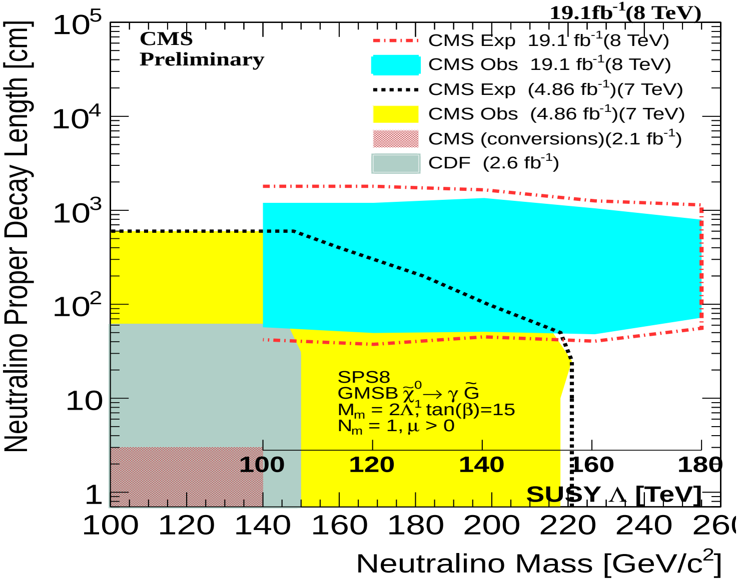


Figure : Mass Limit

sample is $c\tau = 12000$ mm but we measure $c\tau \approx 10500$ mm

$c\tau$-Mass Limits



Summary

Back Up