Search For Delayed Photons Using Timing.

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Outline

Where are we now?

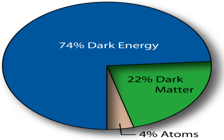
The Universe Set

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 $\approx 4\%$ of our total universe.

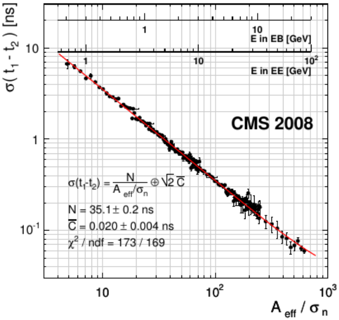


Introduction

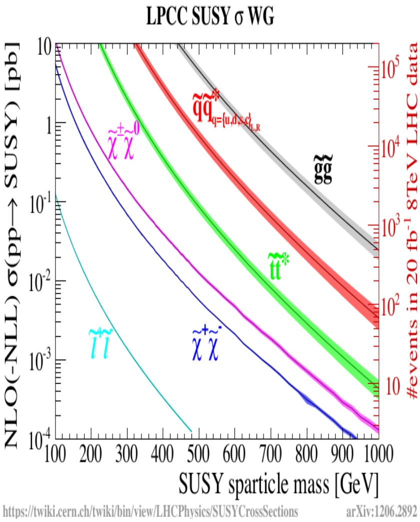
- **Long-Lived Particle Models**
  - ⋆ Gauge Mediated Supersymmetry Breaking (GMSB)
    - ▷ Next-to-lightest SUSY (NLSP) is Neutralino ($\tilde{\chi}_1^0$)
    - ▷ $eV - keV$ Lightest-SUSY particle (LSP) is Gravitino ($\tilde{G}$).
    - ▷ Gravitino is a Dark Matter Candidate.
  - ⋆ General Gauge Mediation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

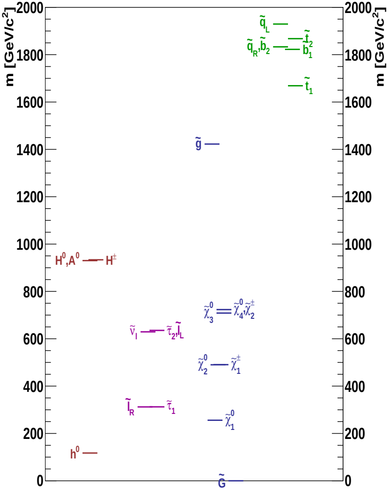
† ECAL timing resolution $\sigma_t < 500$ ps.

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



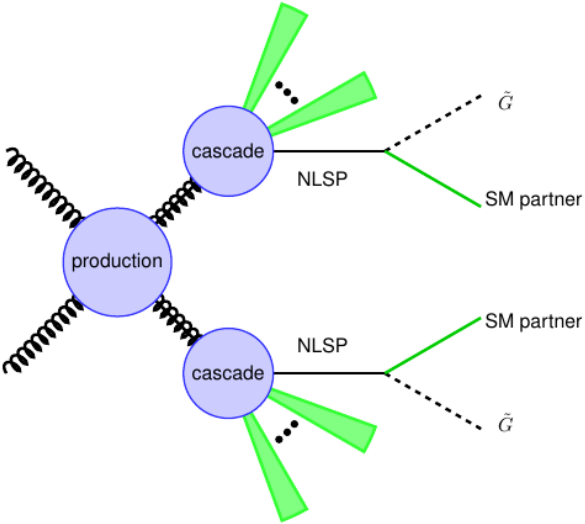
LHC Supersymmetry Production





SUSY production mostly in strong interactions at LHC.

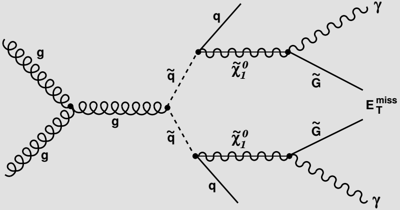
Cascade Decay Chain



Y. Kats et al: arXiv:1110.6444v2

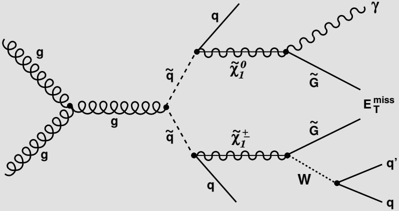
Delayed Photon Production

Double Photon



2 Photons, 2 Jets, Large MET

Single Photon



1 Photon, Jets, Large MET

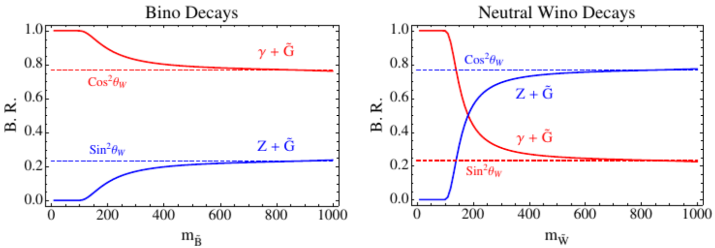
Tranverse Decay Distance

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

Datasets

- **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)]**

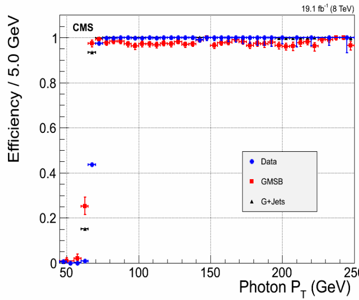
Λ [TeV]	100	120	140	160	180	300
$M_{\tilde{\chi}_1^0}$ $[GeV/c^2]$	140	169	198	227	256	430
$c\tau$	215	325	130	245	185	
(mm)	425	645	515	490	365	495
	1700	1290	1030	975	730	
	3400	1935	2060	1945	1100	995
	5100	2955	2920	2930	2195	2960
	6000	3870	3985	3910	3950	
	9300	5985	6000	5875	5980	6000
		9825	10450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

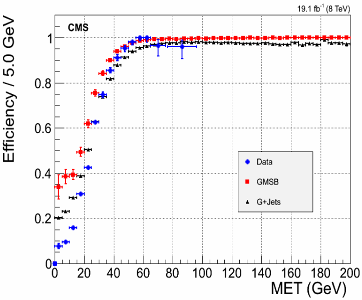
- $\gamma+$ **Jets MC**

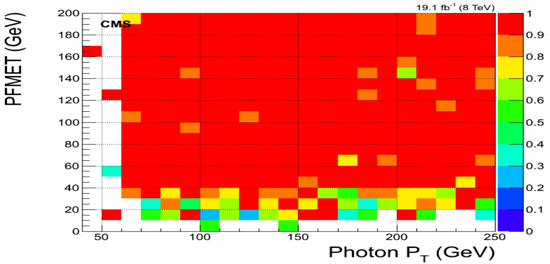
$\hat{p}_T$ [GeV /c]	σ_{LO} (pb)	Number of events
$50 - 80$	3322.3	1995062
$80 - 120$	558.3	1992627
$120 - 170$	108.0	2000043
$170 - 300$	30.1	2000069
$300 - 470$	2.1	2000130
$470 - 800$	0.212	1975231

HLT Trigger

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





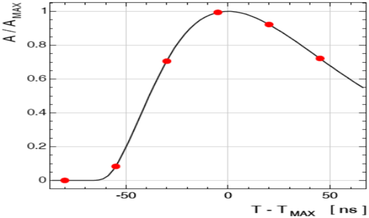


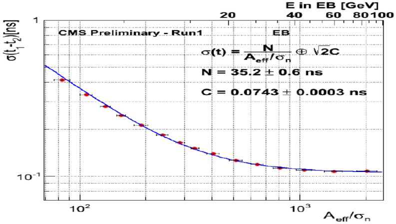
ECAL Timing

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

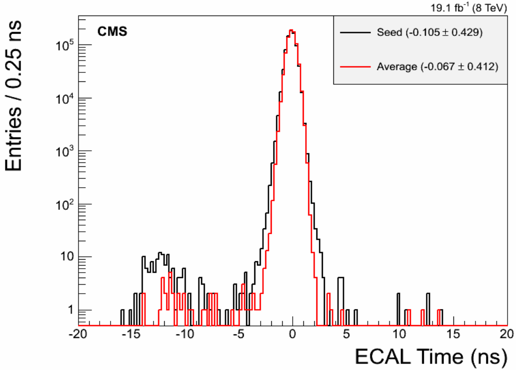
$$T_{MAX} = \frac{\sum_i \frac{T_{MAX,i}}{\sigma_i^2}}{\sum_i \frac{1}{\sigma_i^2}}$$

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





- **Photon Timing**
  - T_γ = Average Time of all Crystals.
  - T_γ = 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

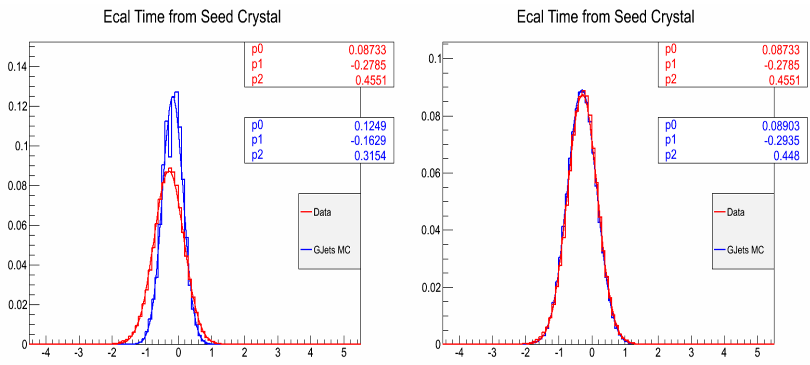
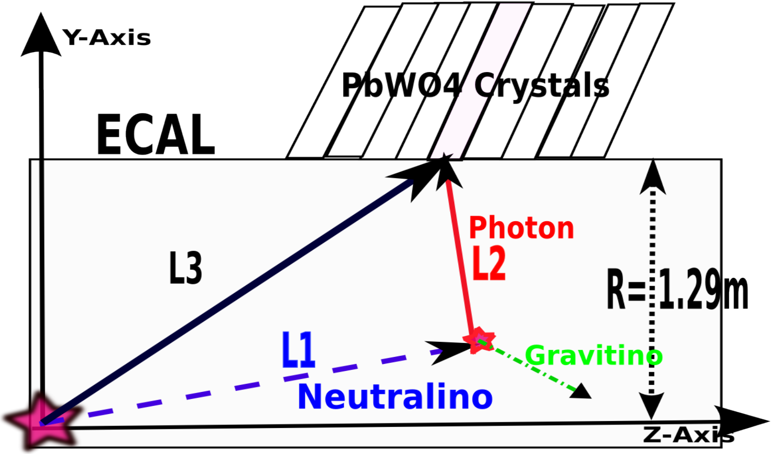


Figure: (LEFT): Before (RIGHT): After

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

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

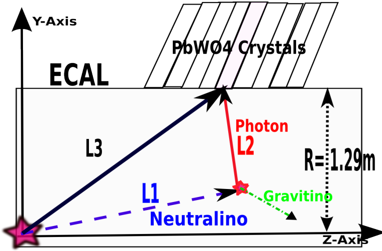


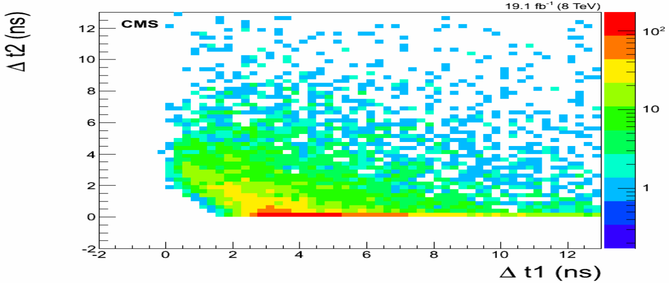
Slow Vs Off-Pointing Decay

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
$\|\eta_\gamma\|$,(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

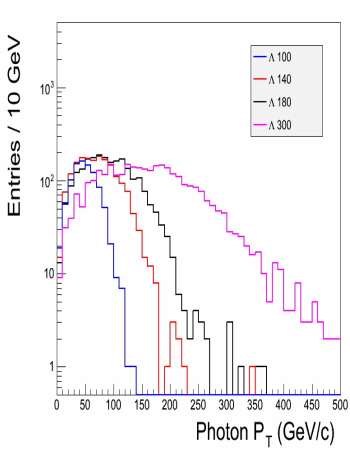


Figure: Photon p_T

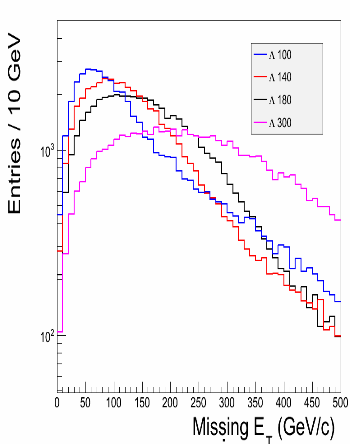


Figure: E_T^{miss}

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

Signal Efficiency and Acceptance

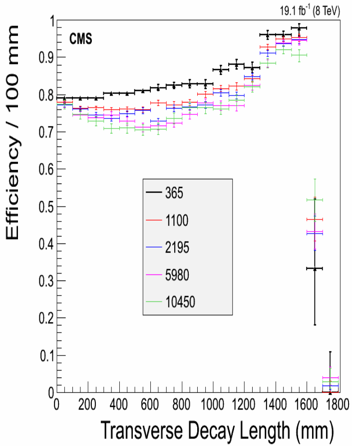


Figure: Efficiency

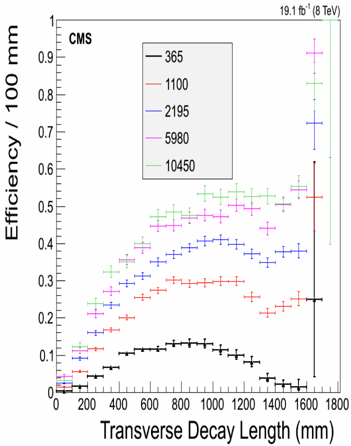


Figure: Acceptance

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

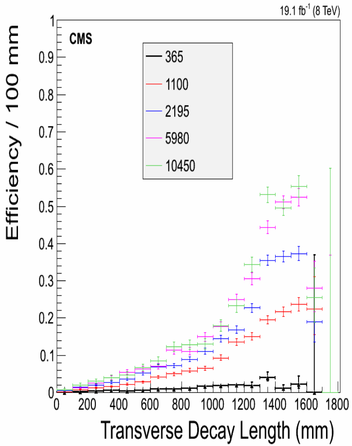


Figure: Slow Moving

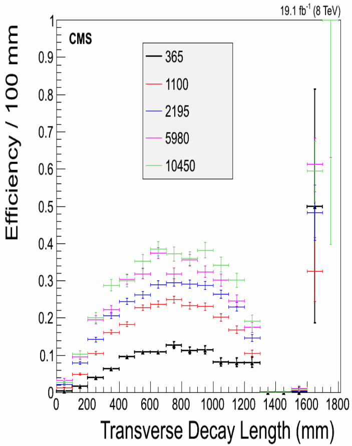


Figure: Off-Pointing

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

Signal Efficiency and Acceptance(III)

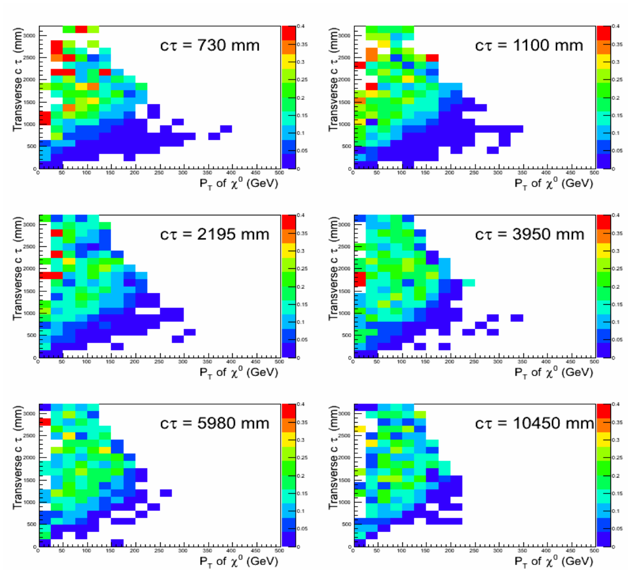
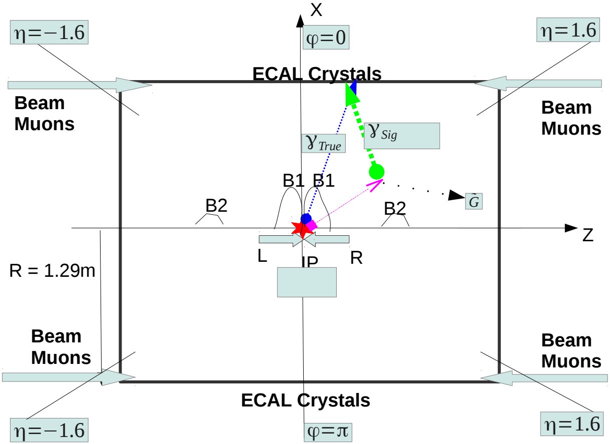


Figure: 2 Dim Efficiency

Analysis Strategy

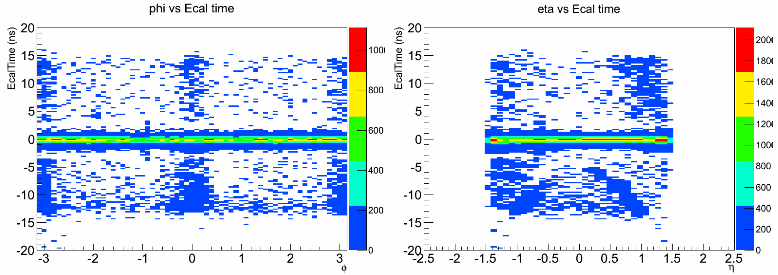
- **Background Source**
  - **Collision**:Mis-measured time of $Z/W/top$ events.
  - **Non-Collision**:Out-time events from LHC proton Beam/Cosmic/Anomalous Spikes.
- **Strategy**
  - I Identify, tag and reject Non-Collision events.
  - II Perform ABCD background estimation technique on residual non-collision 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.


X
η=−1.6
φ=0
η=1.6
ECAL Crystals
Beam Muons
Beam Muons
γ Sig
γ True
B1 B1
B2
B2
G̃
Z
L
IP
R
R = 1.29m
Beam Muons
Beam Muons
ECAL Crystals
η=−1.6
φ=π
η=1.6

Background Estimation

Main sources of background to delayed photons are:

- Photons of events produced from Non-collision,
- Photons of events produced from collision with mis-measured ECAL time.



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)

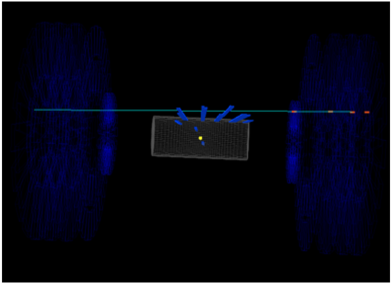
OT-CS: 0 Jet Events with photon ECAL time, $t < -3$ ns or $t > 2$ ns.

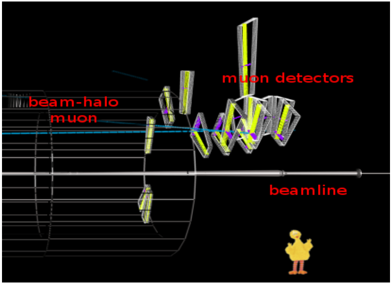
Events from above CSs provide a unique approach to estimate possible background contribution in signal.

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.

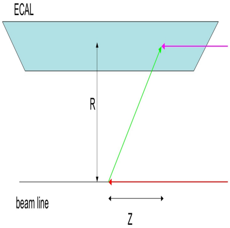
will produce energetic muons traveling parallel with main proton beam and showering in the Calorimeters.





Halo Photon (II)

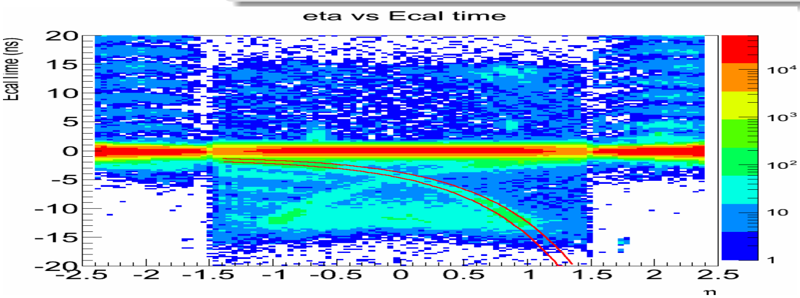
Using Halo kinematics, We can tag and estimate halo photons produced from halo muons showering in ECAL as follows:



Halo Expected ECAL Time

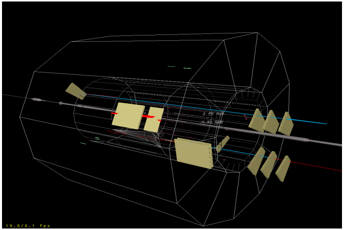
$$t_0 = \frac{\rho}{c} = \frac{R}{\sin\theta}\frac{1}{c}, \quad t_{halo} = \frac{Z}{c} = \frac{R}{\tan\theta}\frac{1}{c}$$

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



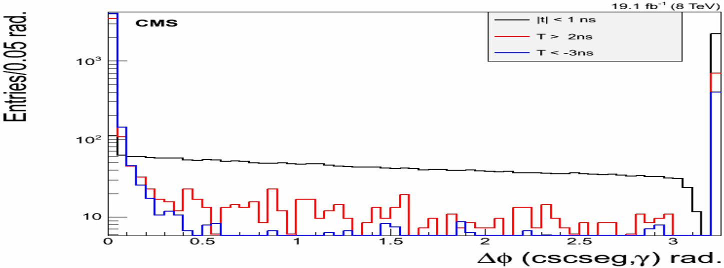
Halo Photon (III)

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

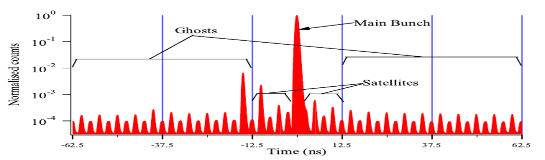
$$\Delta\phi(CSCSeg, \gamma) = |\phi_{CSCSeg} - \phi_{\gamma}|$$



Satellite/Ghost Beam Halos

- Fill empty RF buckets.
- Trail main bunches by ≈ 5 ns.
- 10^{-5} protons 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



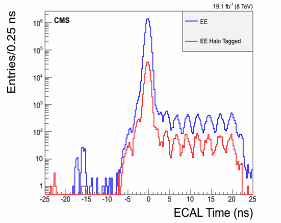
Halo Photon Event Properties

- 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

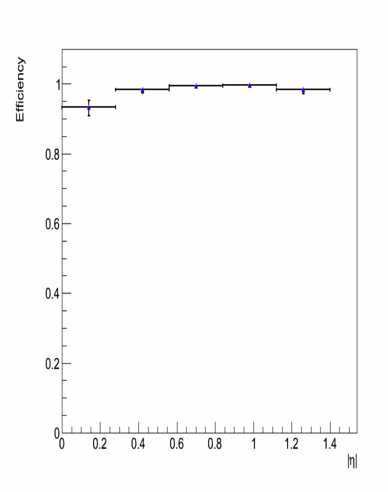
Halo Photon Tagging Efficiency

- 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 eveluated in 5η bins for S_{major} η dependence.

Halo Photon mis-Tag Rate

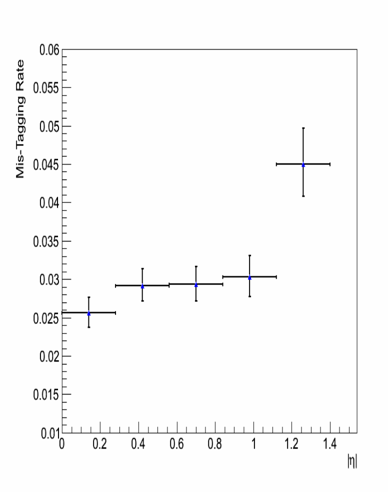
- Control Sample Selection:
  - $>=2$-jets events with $E_T^{miss} < 60$ GeV
  - ECAL time, $|t| < 1$ ns.
- mis-tag rate eveluated in 5η bins for S_{major} η dependence.

Tagging Efficiency



- Tagging Efficiency $\approx 98\%$

mis-Tag Rate



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

Cosmic Muons

Anomalous ECAL Spike

ABCD Technique: Collision Background

Equations and Results.

Closure Test: Events with $1 - jet$.

Using $Z \rightarrow ee$ 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.

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	

CLs Upper Limits

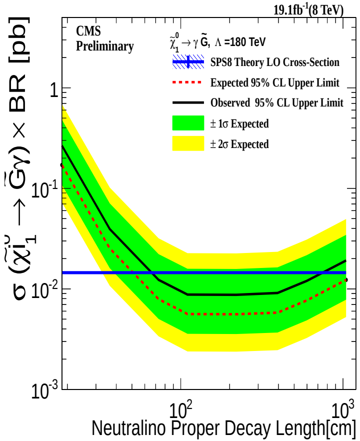


Figure: $c\tau$ Limits

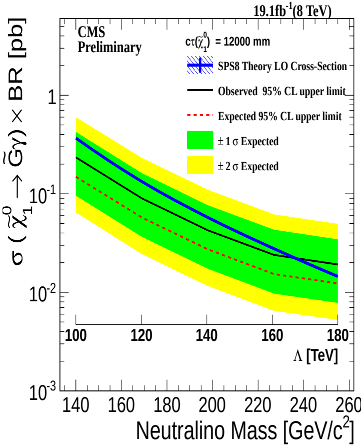
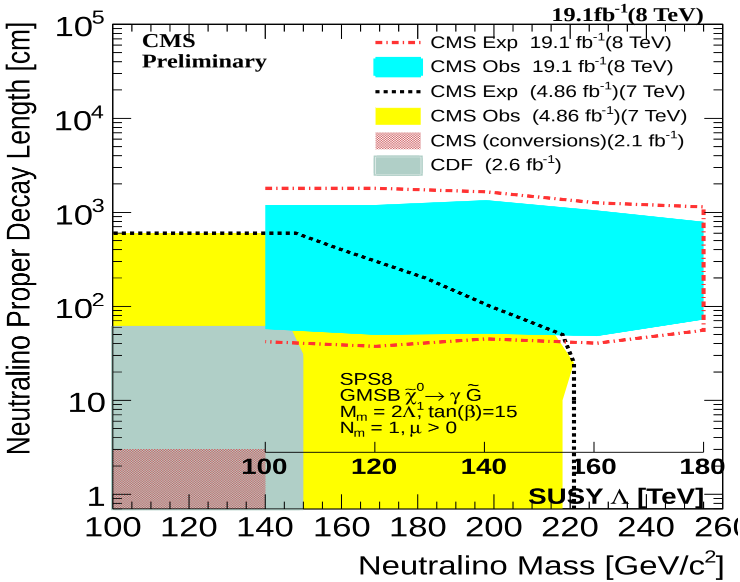


Figure: Mass Limit

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

$c\tau$-Mass Limits



Summary