

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

# Search For Delayed Photons Using Timing With CMS

PhD Oral Exam

Tambe E. Norbert  
University Of Minnesota

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

1 INTRODUCTION

2 ECAL TIMING

3 SEARCH ANALYSIS

4 RESULTS

5 SUMMARY



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

# INTRODUCTION

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

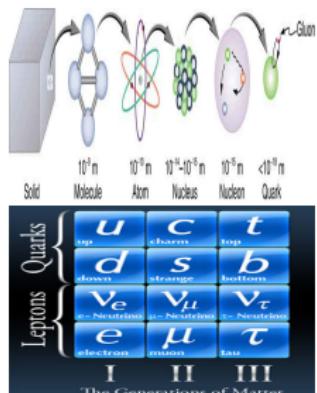
The **Standard Model** recipe of:

- **Particle Physics:** physics of **very small** and **Cosmology:** physics of **very large**
- best describes the universe with **unprecedented precision**. Studying particle properties like,
- Mass, Charge, Magnetic Moment, Spin, and **Lifetime.**

Particle Classification table of our universe.

- **Incomplete Recipe**

- 6 quarks and leptons(3 Gen) only?
- Forceful spices not a single spice?
- Recipe can also prepare Dark Matter?
- Is this list of ingredients complete?
- Origin of these ingredients?



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

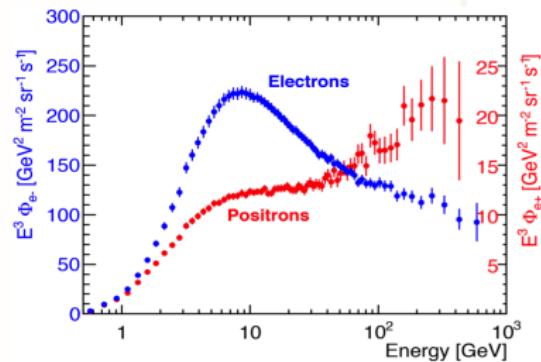
ECAL  
TIMING

SEARCH  
ANALYSIS

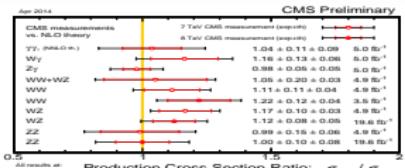
RESULTS

SUMMARY

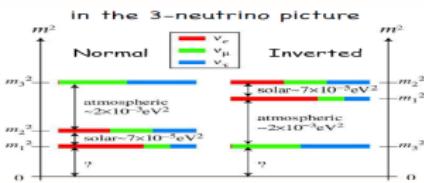
## AMS Experiment on ISS



## ZZ, WW Production



## Neutrino Masses.



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

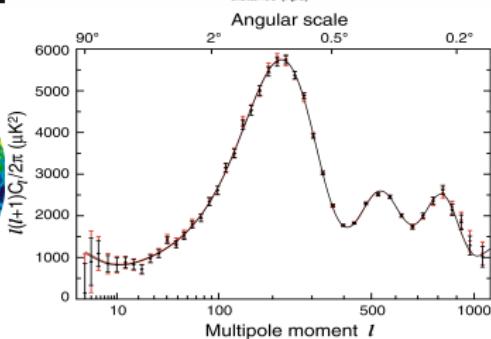
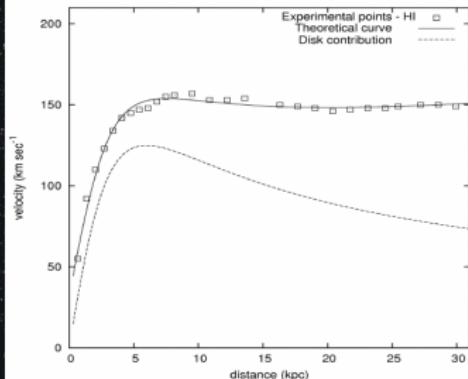
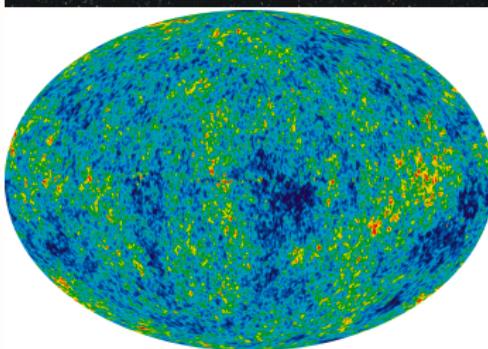
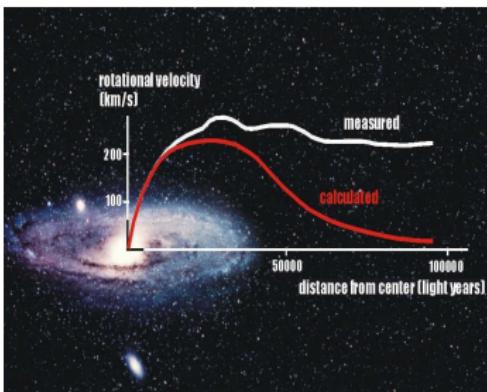
ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

## Dark Matter.



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

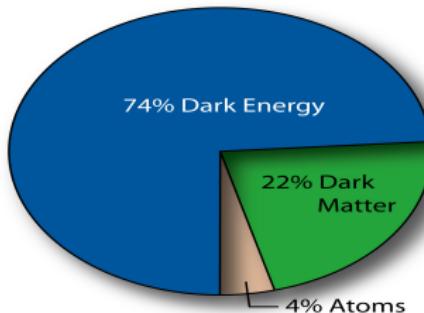
ECAL  
TIMING

SEARCH  
ANALYSIS

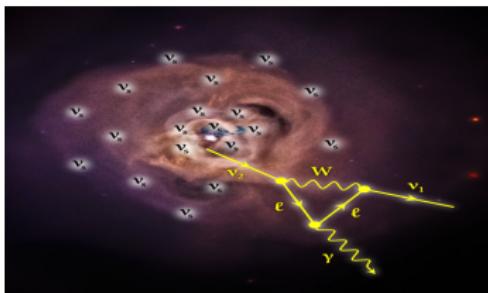
RESULTS

SUMMARY

## Universe Matter Budget.



## Dark Matter in our Galaxy?.



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTORY

ECAL  
TIMING

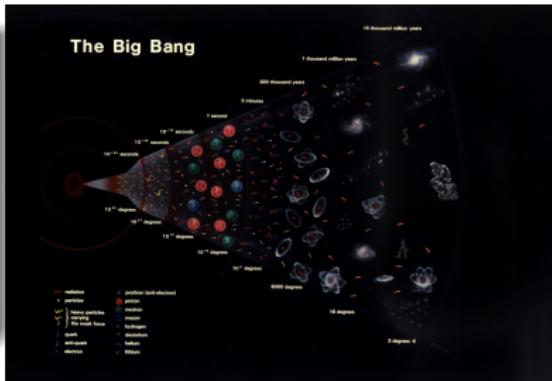
SEARCH  
ANALYSIS

RESULTS

SUMMARY

## The Universe Spin Set

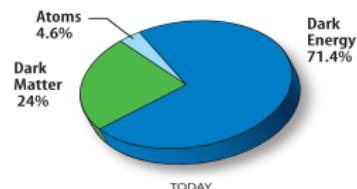
$$S = \{0, \frac{1}{2}, 1, \frac{3}{2}, 2 \dots\} \hbar$$



Our current understanding:

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

- $s = \frac{3}{2}\hbar$  ?? Dark Matter?



This *magic* set describes only  $\approx 4.6\%$  of our total universe

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

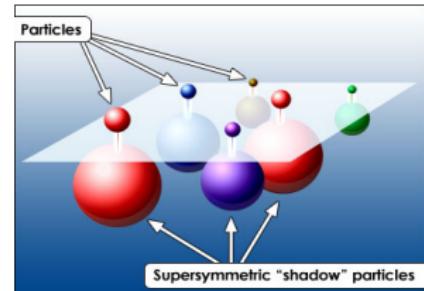
RESULTS

SUMMARY

Supersymmetry allows for  
**Bosons**  $\xleftrightarrow{\text{SUSY}}$  **Fermions**.

$$Q | \text{Bosons} \rangle = | \text{Fermions} \rangle$$

$$Q | \text{Fermions} \rangle = | \text{Bosons} \rangle$$



## SUSY Motivation

- Stabilizes the Higgs mass and explains energy scale hierarchy.
- Allows for unification of fundamental forces.
- Predicts long-lived and stable particles which could describe Dark Matter.
- Natural frame work for unifying gravity and Quantum Mechanics.

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

## ● Long-Lived Particle SUSY 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.

## ● R-Parity Conserving GMSB Models

- † Few Parameters.  $\{\Lambda, \mathbf{M}_{\text{mess}}, \mathbf{N}_5, \tan(\beta), \text{sgn}(\mu), C_{\text{grav}}\}$   $R = (-1)^{3(B-L)+2S}$
- † R-Parity conserved, LSP is Dark Matter candidate.  $R |SM\rangle = +1 |SM\rangle$   $R |SUSY\rangle = -1 |SUSY\rangle$

**SPS8 GMSB Model**

<b>M<sub>mess</sub></b>	<b>N<sub>5</sub></b>	<b>sgn(μ)</b>	<b>tan(β)</b>	<b>Λ</b>	<b>C<sub>grav</sub></b>	
2.Λ	1	1	15	varies	varies	

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Delayed  
Photons  
Using  
Timing  
With CMS  
  
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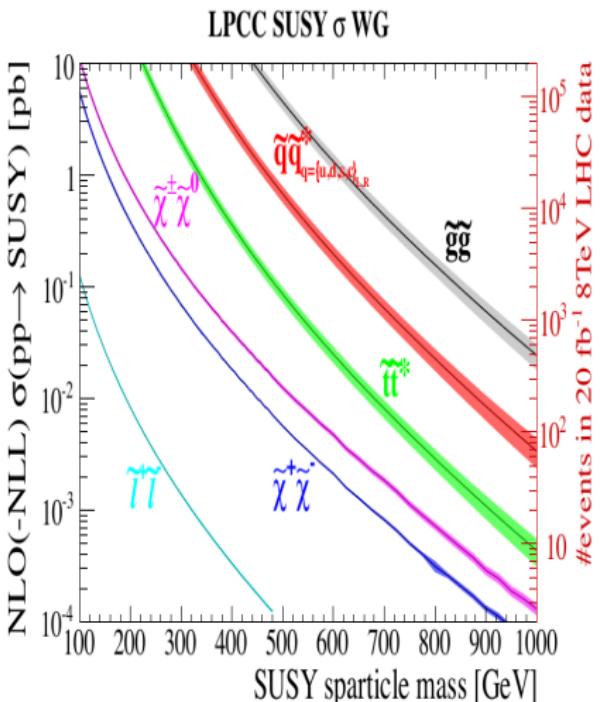
MENU

INTRODUCTION

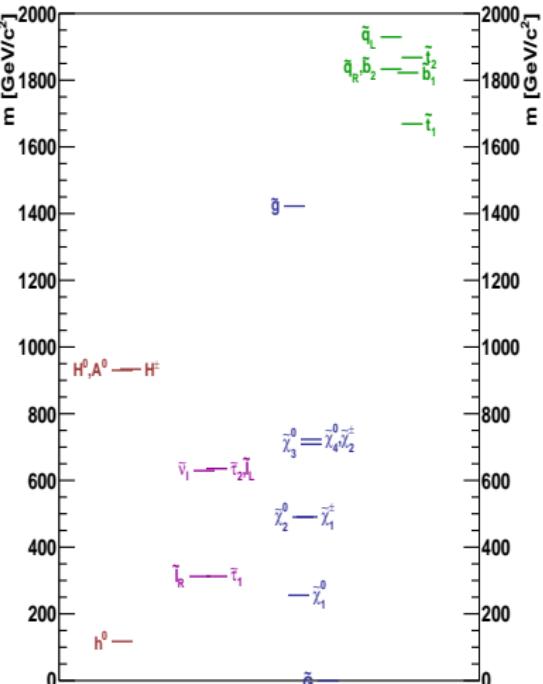
ECAL  
TIMINGSEARCH  
ANALYSIS

RESULTS

SUMMARY

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections>

arXiv:1206.2892



SUSY production mostly in strong interactions at LHC.

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

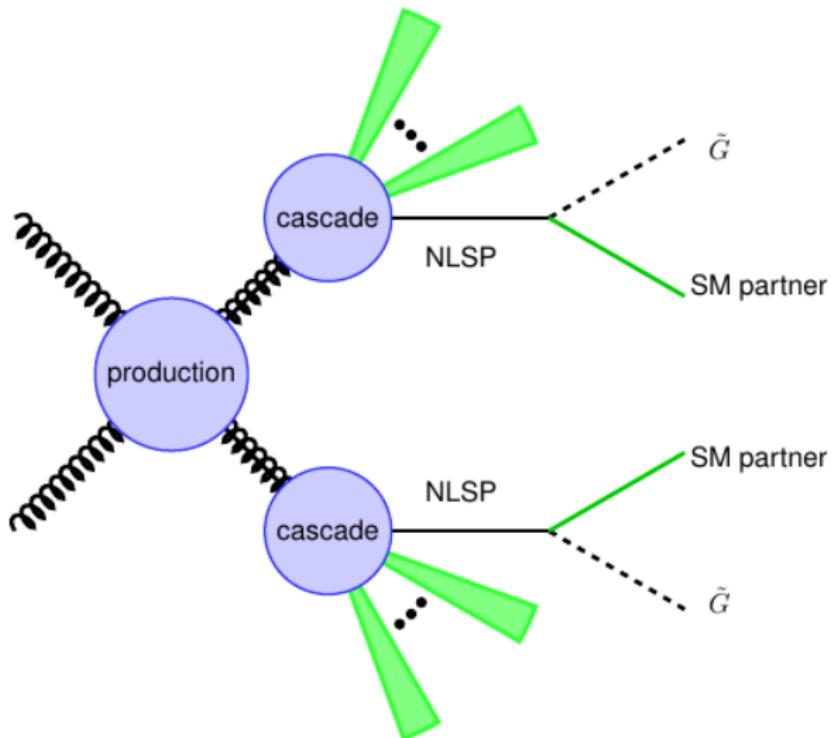
INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTORY

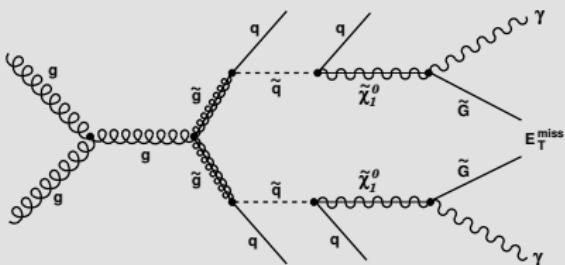
ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

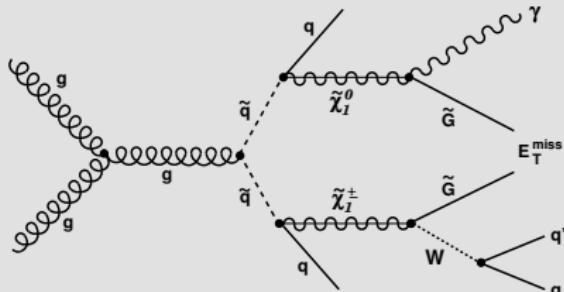
SUMMARY

## Double Photon



2 Photons, Jets, Large MET

## Single Photon



1 Photon, Jets, Large MET

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
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MENU

INTRODUCTORY

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

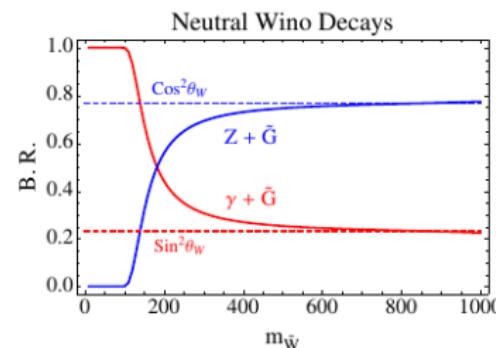
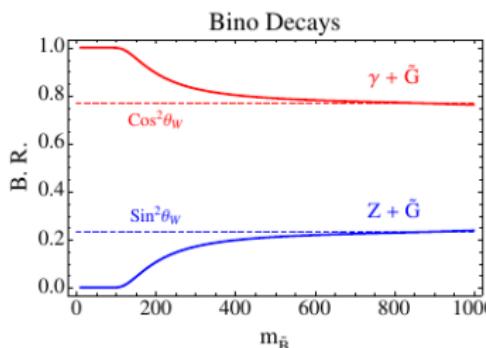
SUMMARY

## Distance Travelled

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

## Proper Decay Length

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



# Previous Search Experiments



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

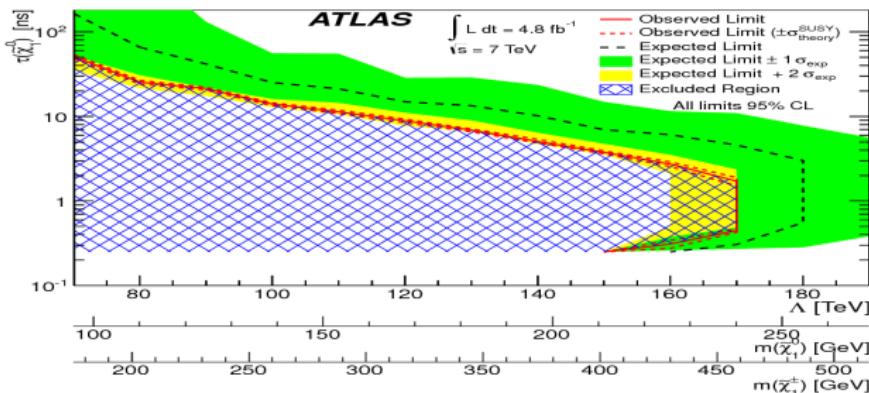
ECAL  
TIMING

SEARCH  
ANALYSIS

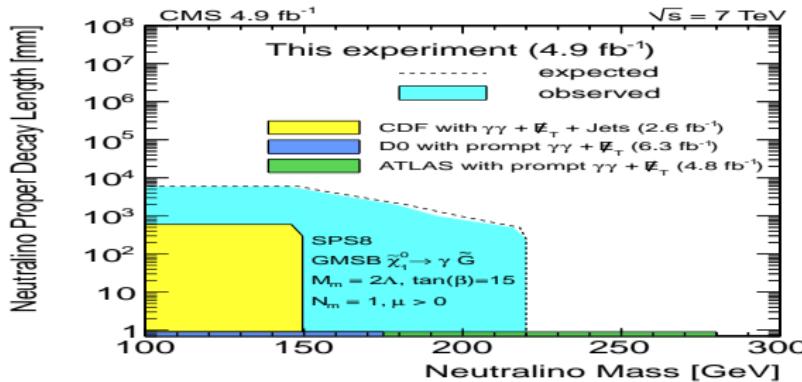
RESULTS

SUMMARY

## ▷\* ATLAS



## ▷\* DO, CDF, CMS



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

# ECAL TIMING



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

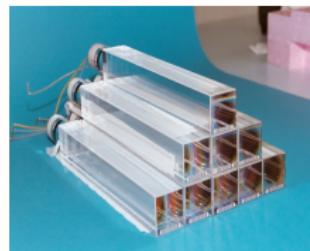
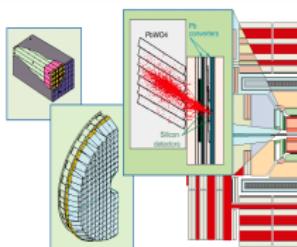
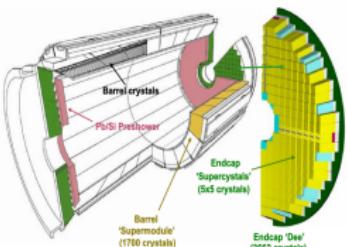
ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

## ECAL Detector.



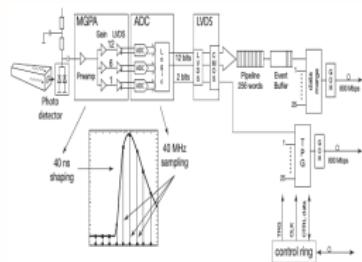
**Barrel Detector (EB):**  $|\eta| < 1.475$ .

**Endcap Detectors (EE):**  $1.5 < \eta < 3.0$ ..

## ECAL Properties.

- ▷ 760000 Lead Tungstate crystals.
- ▷ Crystals measure Energy and Time.
- ▷ Showers in crystal generates light detected with:
  - ▷ Avalanche Photo-Diodes(APD)
  - ▷ Vacuum Photo-Triodes(VPT)
- ▷ Readout with custom ASICs in 250 nm CMOS.

## Readout Chain.



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

ECAL  
TIMING

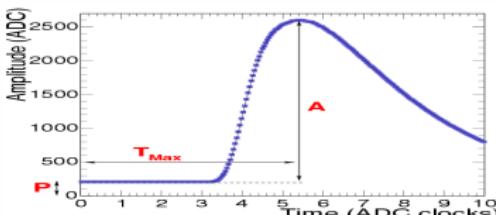
SEARCH  
ANALYSIS

RESULTS

SUMMARY

## Time Reconstruction

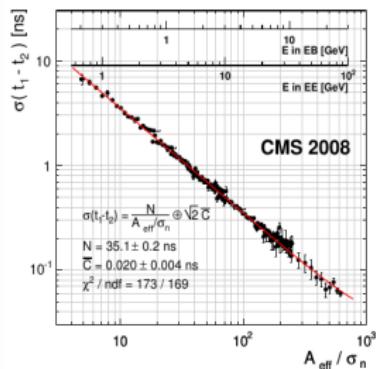
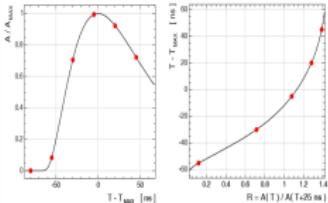
- ▷\* 10 digitized samples.
- ▷\* Extract time using Fit or Weighted algorithm.



## Time Measurement

- ▷\* Error Weighted
- ▷• Fit Method

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



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

ECAL  
TIMING

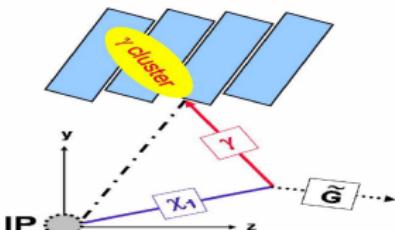
SEARCH  
ANALYSIS

RESULTS

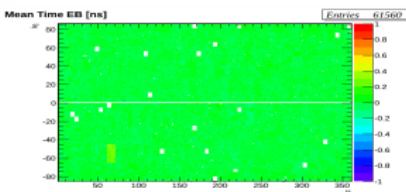
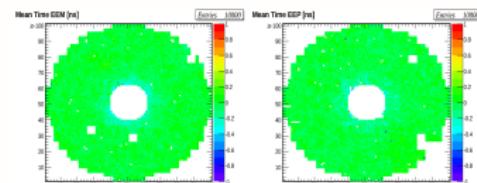
SUMMARY

## Calibration Procedure

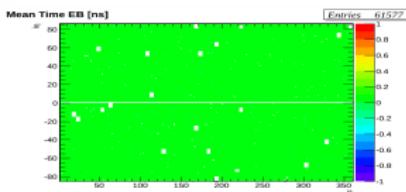
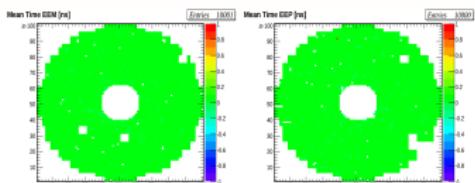
- ▷\* Adjust Crystal time such that  $\langle t_{crys}^\gamma \rangle \approx 0$
- ▷\* Average is over events(*rechits*)/crystal.



### Before Calibration



### After Calibration



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

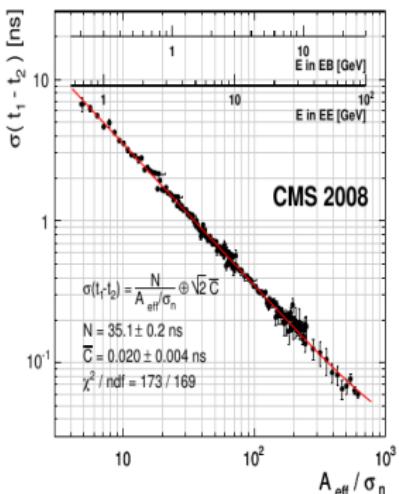
RESULTS

SUMMARY

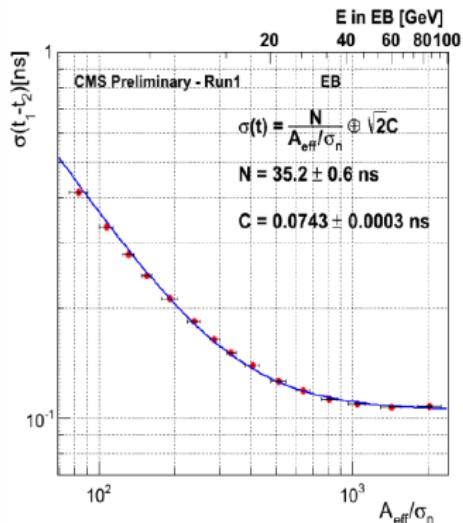
## ECAL Timing Resolution

► Time resolution better than 150 ps for  $E > 50$  GeV

### Test Beam



### LHC RUN I



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
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MENU  
INTRODUCTION

ECAL  
TIMING

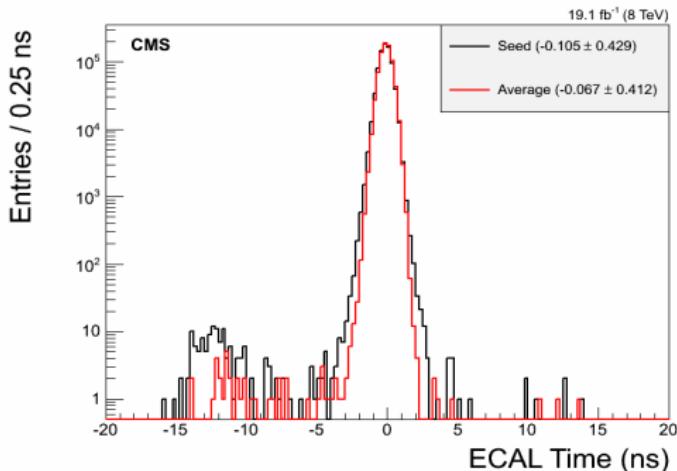
SEARCH  
ANALYSIS

RESULTS

SUMMARY

- ➊  $T_\gamma$  = Error weighted average time of crystals in photon.
- ➋  $T_\gamma$  = Seed (most energetic) crystal time.

## Photon Arrival Time



- ▷\* Similar time in seed and average.
- ▷\* Photon time = Seed crystal time.

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTORY

ECAL  
TIMING

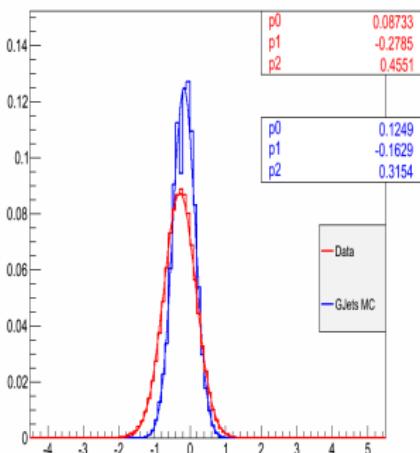
SEARCH  
ANALYSIS

RESULTS

SUMMARY

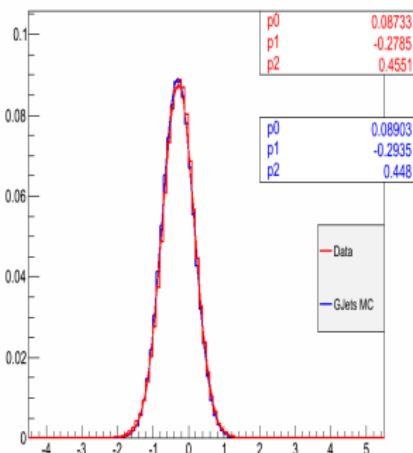
## Before Correction

Ecal Time from Seed Crystal



## After Correction

Ecal Time from Seed Crystal



- ▷\* Timing corrections from data applied to  $\gamma +$  Jets MC.
- ▷\* Data/MC better agreement with corrections applied.

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

# SEARCH ANALYSIS



# Datasets



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU  
INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

## • 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)]

$\Lambda$ [TeV]	100	120	140	160	180	300
$M_{\tilde{\chi}_1^0}$ [GeV/c <sup>2</sup> ]	140	169	198	227	256	430
$c\tau$ (mm)	215	325	130	245	185	
	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]	$\sigma_{LO}$ (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

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

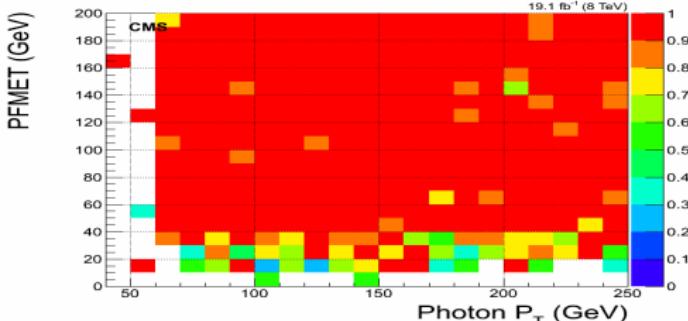
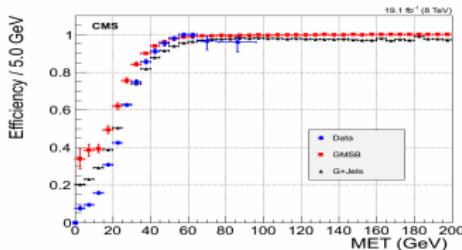
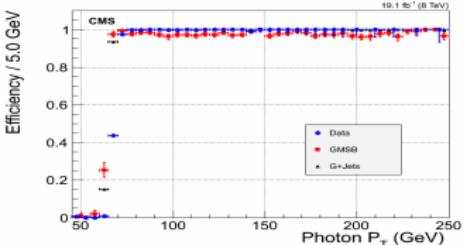
ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

## HLT\_DisplacedPhoton65\_CaloIdVL\_IsoL\_PFMET25



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU

INTRODUCTION

ECAL  
TIMING

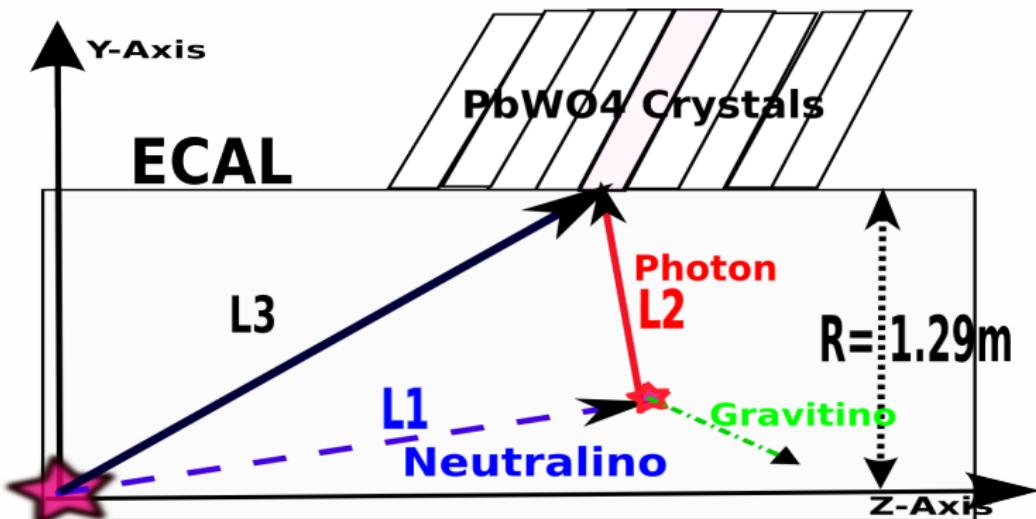
SEARCH  
ANALYSIS

RESULTS

SUMMARY

## Source of Delayed Photons?

- Decay of slow moving particles;  $\beta \ll 1$ ,
- Non-nominal photon flight path,
- Stopped particles in detector.



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

Tambe E.  
Norbert

MENU  
INTRODUCT

ECAL  
TIMING

SEARCH  
ANALYSIS

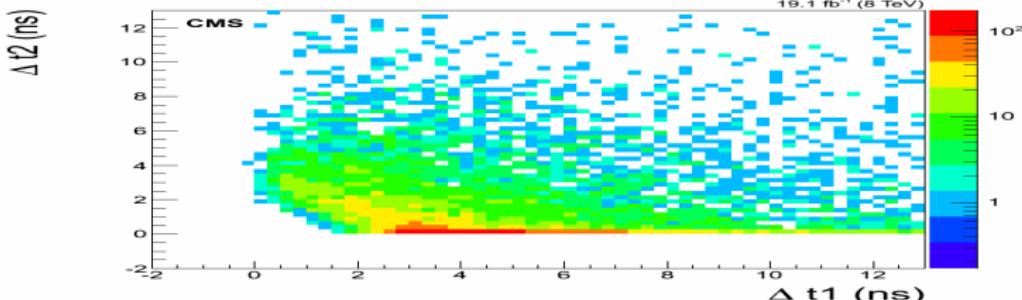
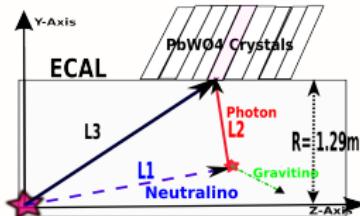
RESULTS

SUMMARY

## Photon Measured Time

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

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



- Delayed photons mostly from slow moving decay.



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

## Object Selection Criteria

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

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Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

## PF-Missing Transverse Energy( $E_T^{\text{miss}}$ )

Standard PF-MET calculation excludes  $E_T$  from out-of-time photons. We adjust for this by taking into account the  $E_T$  of out-of-time photons in  $E_T^{\text{miss}}$  measurements. This PF-MET with photon is  $E_T^{\text{miss}\gamma}$ .

- $E_T^{\text{miss}}$ : PF-MET.
- $E_T^{\text{miss}\gamma}$ : PF-MET with photon  $E_T$ .

## Signal Selection Criteria

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

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Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

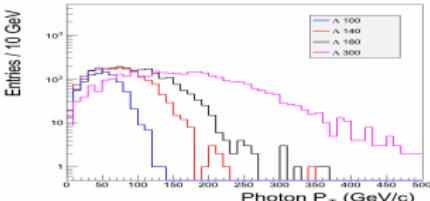
ECAL  
TIMING

SEARCH  
ANALYSIS

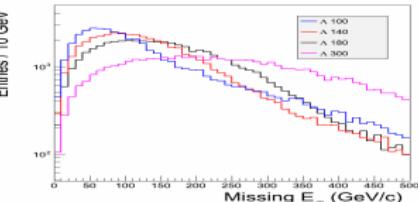
RESULTS

SUMMARY

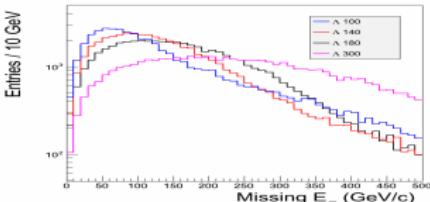
## Photon $p_T$



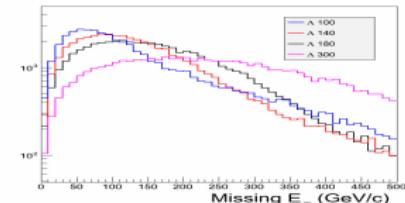
## Neutralino $c\tau$



## $\text{MET}(E_T^{\text{miss}})$



## NJets



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

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Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

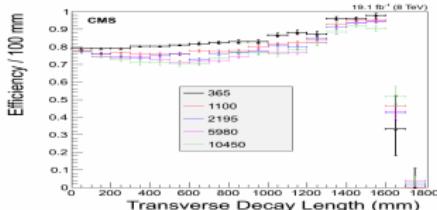
ECAL  
TIMING

SEARCH  
ANALYSIS

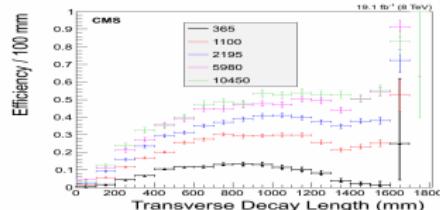
RESULTS

SUMMARY

## Efficiency

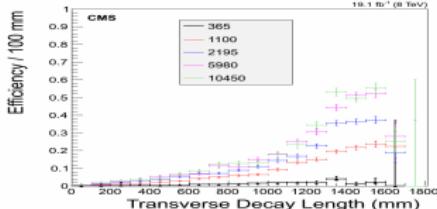


## Acceptance

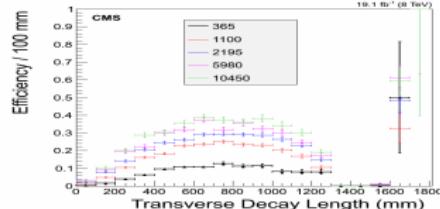


- Slow moving neutralino decay causes sudden efficiency drop.

## Slow moving



## Off-Pointing



- Peak Acceptance at transverse decay length= 800 mm.

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Delayed  
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Using  
Timing  
With CMS

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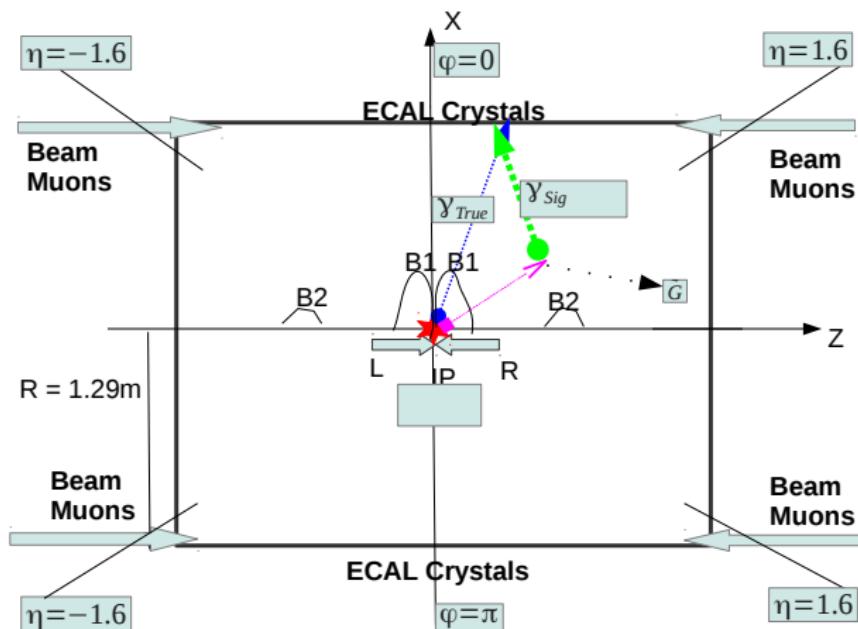
INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY



## ● Background Events

- **Collision:** Mis-measured time of  $Z/W/\text{top}$  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

Another check on background estimation of collision events on a separate control sample.

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Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

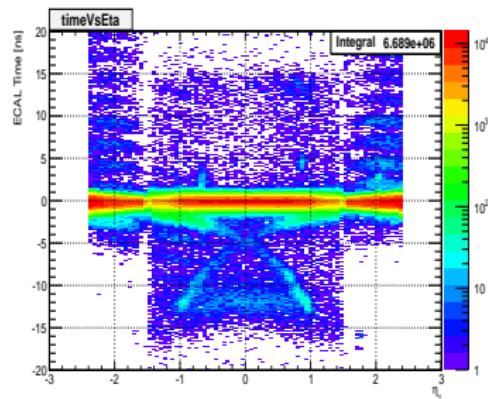
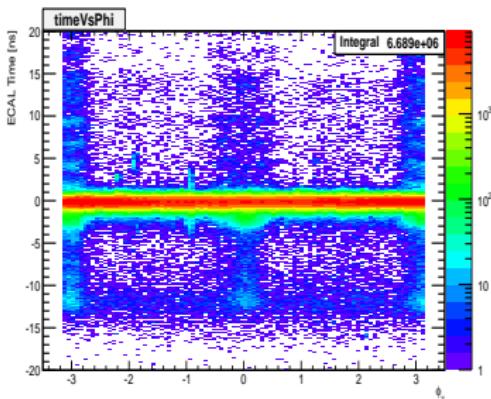
ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

- ▶ 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.

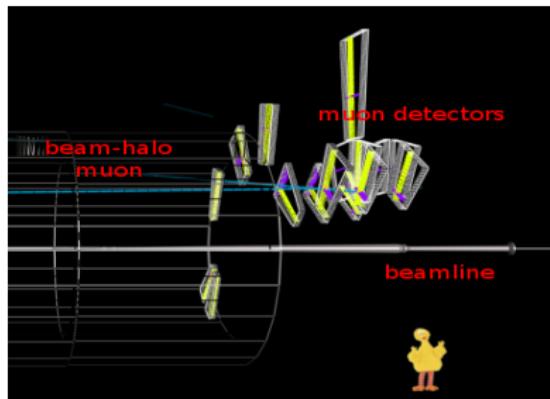
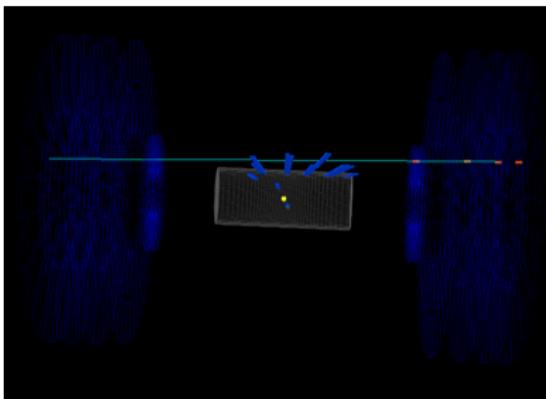


Features around  $\phi = 0, \pm\pi$  and  $\eta$ -dependence shows that background sources originate from both collision and non-collision events.

## 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.



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

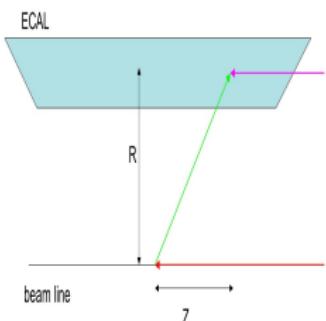
INTRODUCT

ECAL  
TIMING

SEARCH  
ANALYSIS

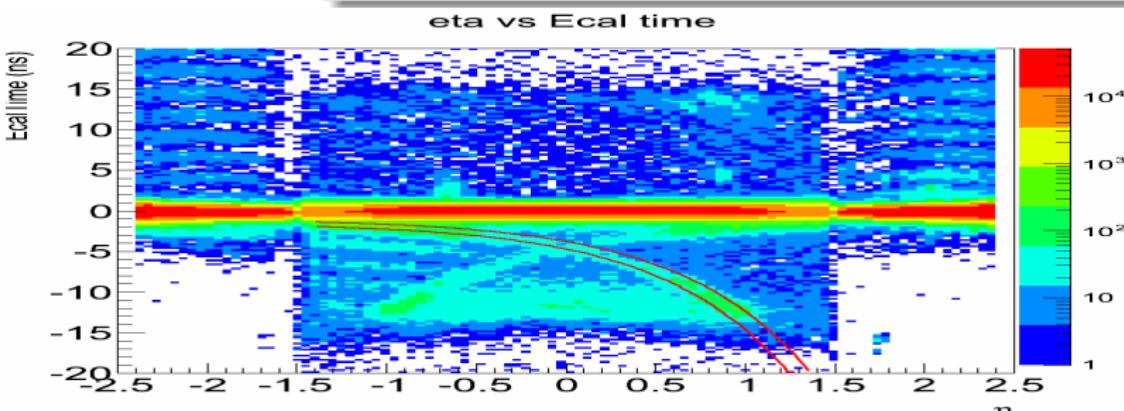
RESULTS

SUMMARY



### 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)



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Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

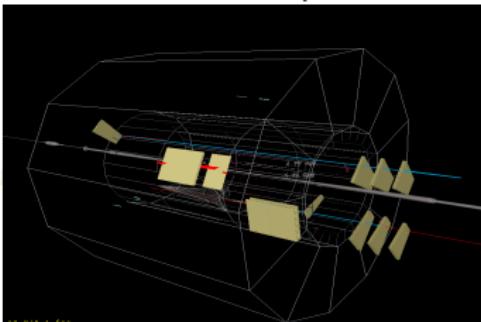
ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

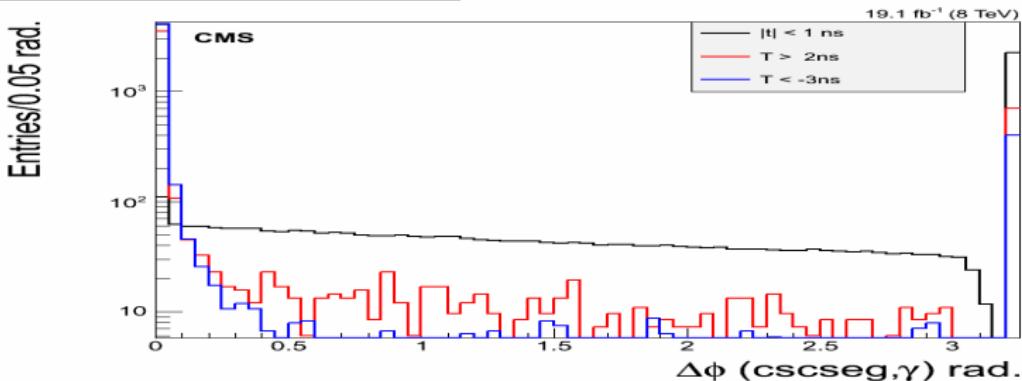
SUMMARY

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



## Halo Photon Matching

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



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

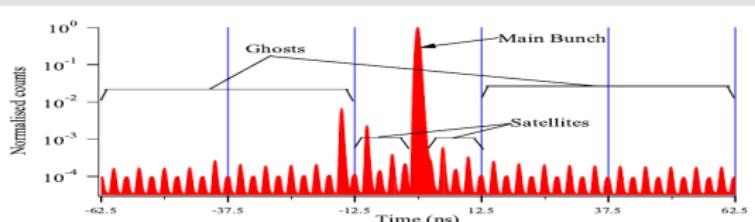
RESULTS

SUMMARY

## Satellite/Ghost Beam Halos

- Fill empty RF buckets.
- Trail main bunches by  $\approx 5$  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



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

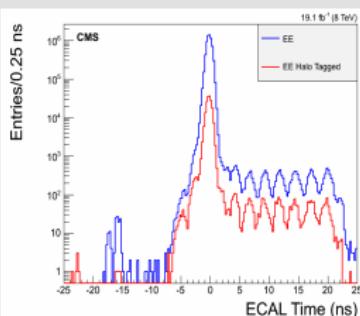
## Halo Photon Event Properties

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

## Ghost/Satellite EE



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

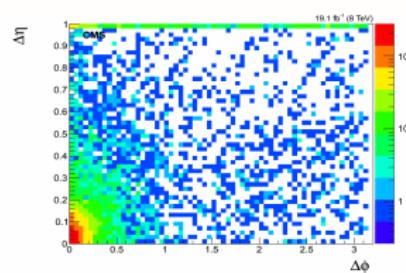
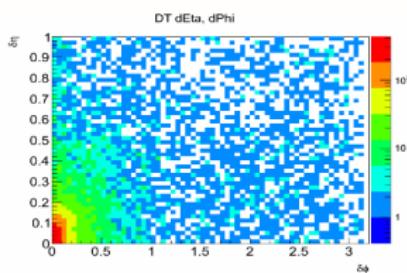
RESULTS

SUMMARY

## 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.

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

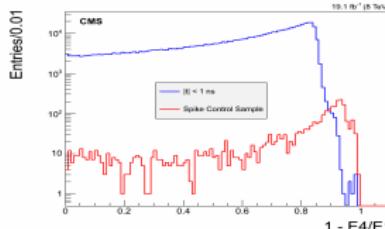
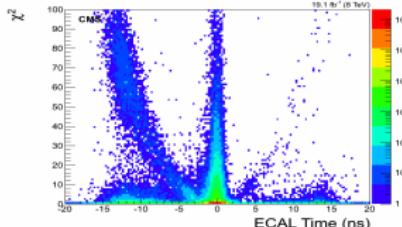
RESULTS

SUMMARY

## 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 produce 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  $\chi^2$  from pulse shape fitting.

### Spike Identification and Rejection



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCT

ECAL  
TIMING

SEARCH  
ANALYSIS

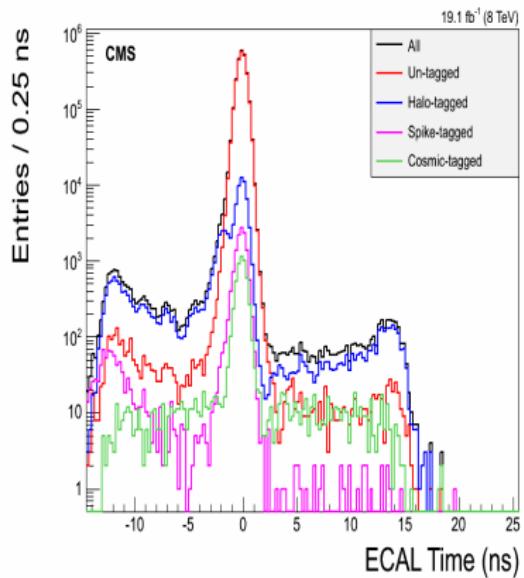
RESULTS

SUMMARY

## Mis-Tag Rates

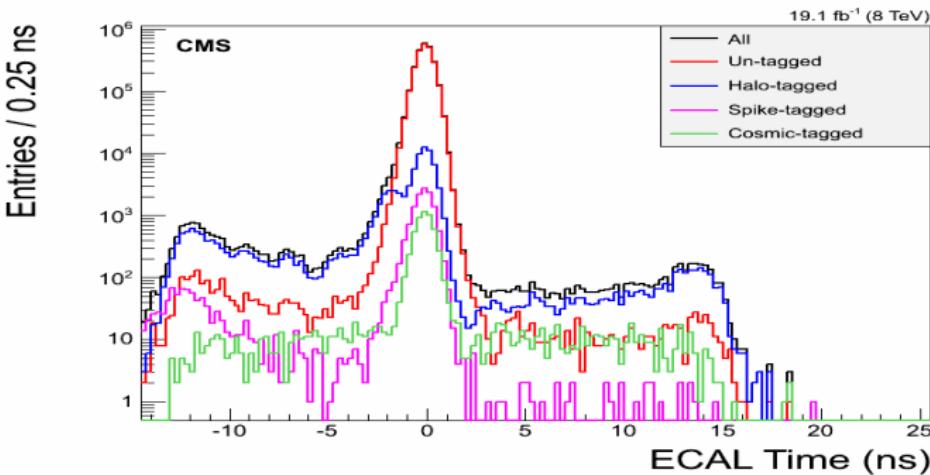
Halo	$\approx 5\%$
Cosmic	$\approx 6\%$
Spike	$\approx 1.5\%$

## Tagging Performance



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



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

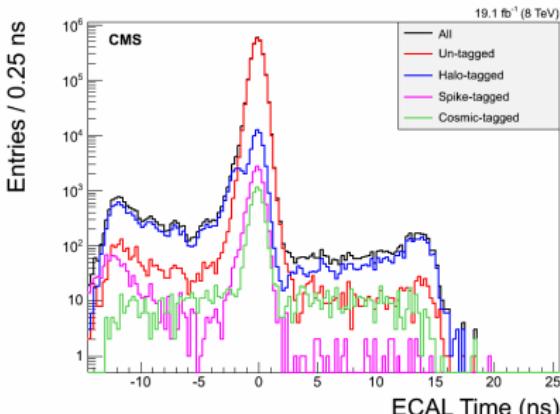
RESULTS

SUMMARY

## Non-Collision Events.

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

	$E_T^{\text{miss}\gamma} < 60$	$E_T^{\text{miss}\gamma} > 60$
$-10 < t < -3 \text{ ns}$	A	B
$3 < t < 13 \text{ ns}$	C	D



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

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

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

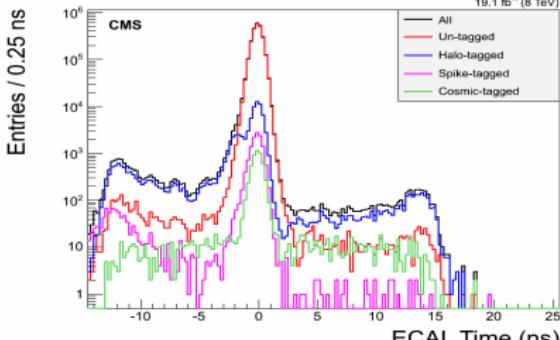
RESULTS

SUMMARY

## Collision Events.

$$E_T^{\text{miss}} \gamma < 60 \text{ GeV}$$

	$E_T^{\text{miss}} < 60$	$E_T^{\text{miss}} > 60$
$-10 < t < -3 \text{ ns}$	$B'$	$B$
$ t  < 2 \text{ ns}$	$F'$	$F$
$3 < t > 13 \text{ ns}$	$D'$	$D$



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

$$\mathbf{Q}_d = \frac{\mathbf{F}}{\mathbf{F}'} \cdot \mathbf{D}'$$

$$\mathbf{Q}_b = \frac{\mathbf{F}}{\mathbf{F}'} \cdot \mathbf{B}'$$

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

## Combined Background Estimation.

$$D = \frac{B - Q_b}{A} \cdot C + Q_d$$

### Closure Test: < 2-Jets Events

$E_T^{\text{miss}} < 60 \text{ GeV}$

	$E_T^{\text{miss}} < 60$	$E_T^{\text{miss}} > 60$
$-10 < t < -3 \text{ ns}$	$B'$	$B$
$ t  < 2 \text{ ns}$	$F'$	$F$
$3 < t > 13 \text{ ns}$	$D'$	$D$

## Closure Test: < 2-Jets Events

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

	$E_T^{\text{miss}} < 60$	$E_T^{\text{miss}} > 60$
$-10 < t < -3 \text{ ns}$	A	B
$3 < t < 13 \text{ ns}$	C	D



# Background Estimation Cross-Check



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

## Control Sample $Z \rightarrow ee$ Events

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTORY

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

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.

## Systematic Uncertainties

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

- We obtained our systematics 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.

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

# RESULTS





# Results



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

- Observed **1 Event**
- Expected **0.0886 Events**

## 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	0.0886	

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

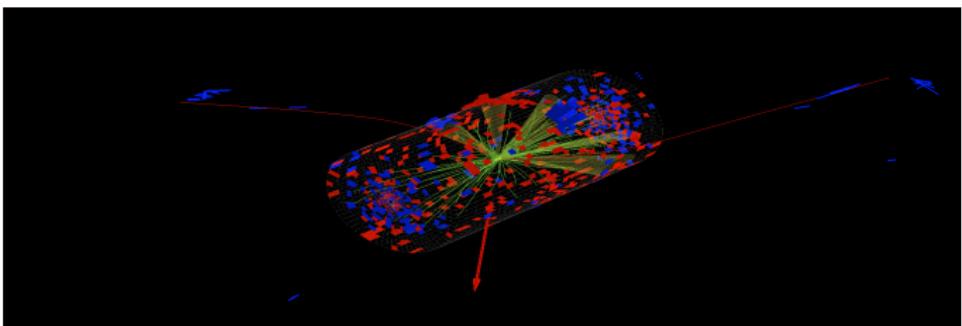
ECAL  
TIMING

SEARCH  
ANALYSIS

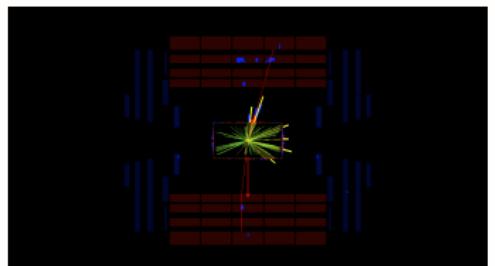
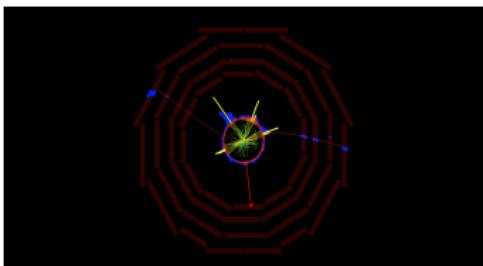
RESULTS

SUMMARY

## 3-D View



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



# Exclusion Limits

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

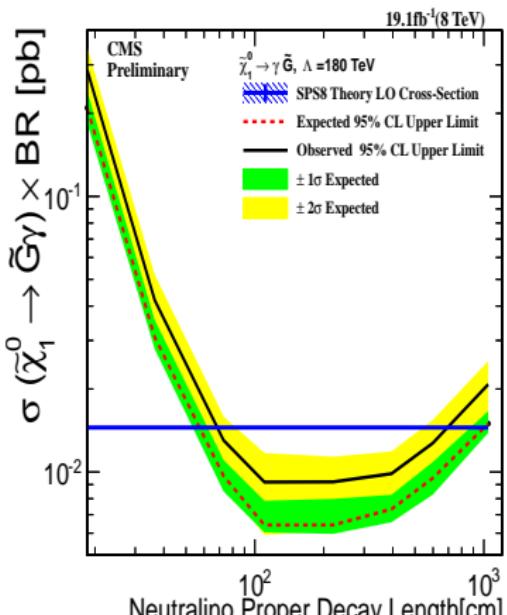


Figure :  $c\tau$  Limits

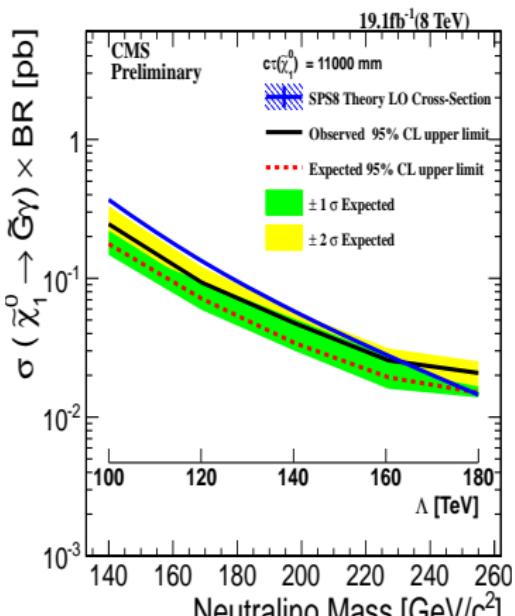


Figure : Mass Limit

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Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

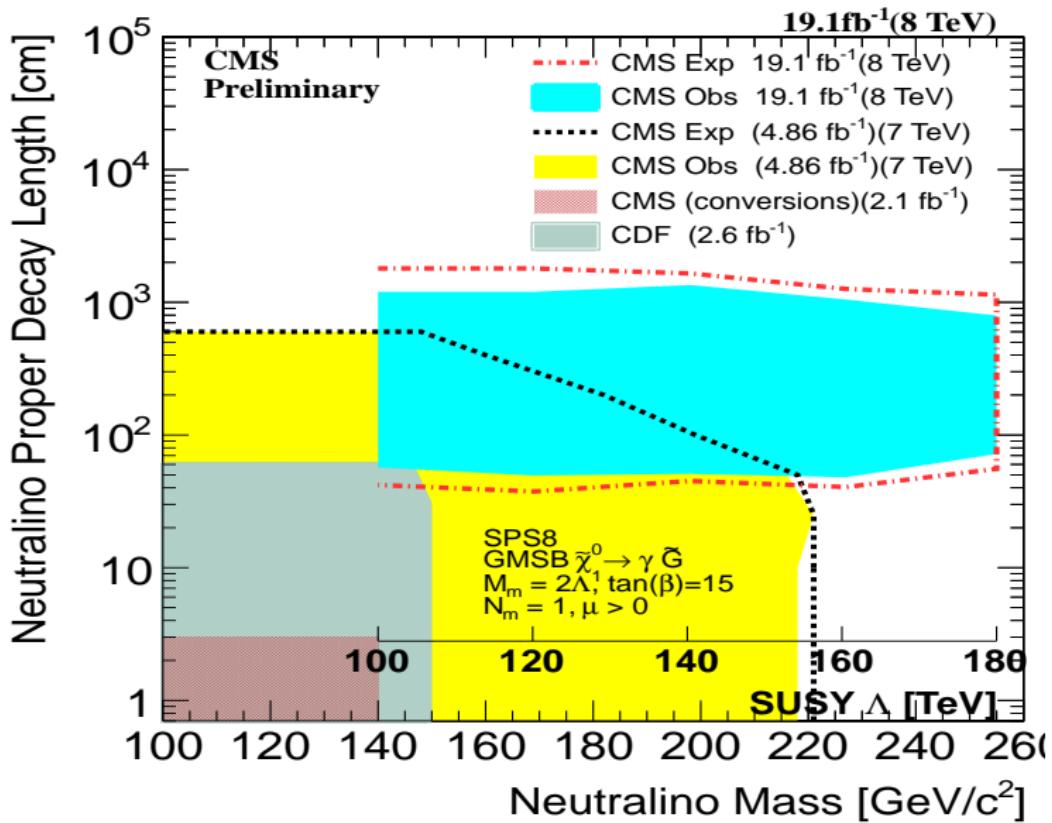
INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

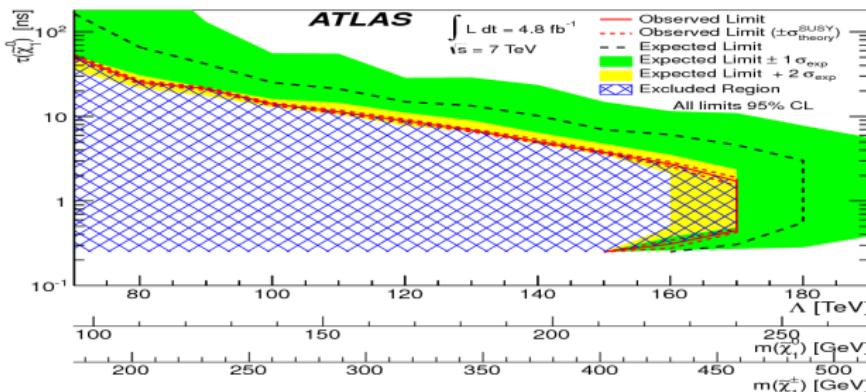
ECAL  
TIMING

SEARCH  
ANALYSIS

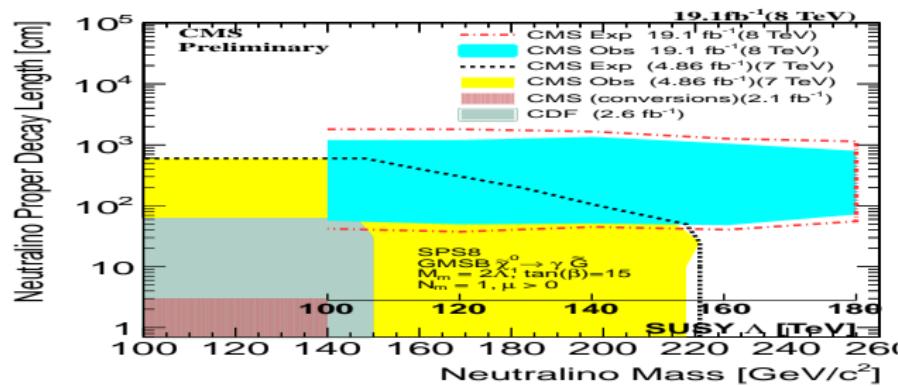
RESULTS

SUMMARY

## ▷\* ATLAS



## ▷\* CMS 8 TeV



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

# SUMMARY





# Summary



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

- Discuss Motivation for New Physics.
- Discuss ECAL Timing.
- Discuss Search for Long-Lived Particles using ECAL Time.
- Looking forward to LHC Run II Results on this Analysis.

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Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

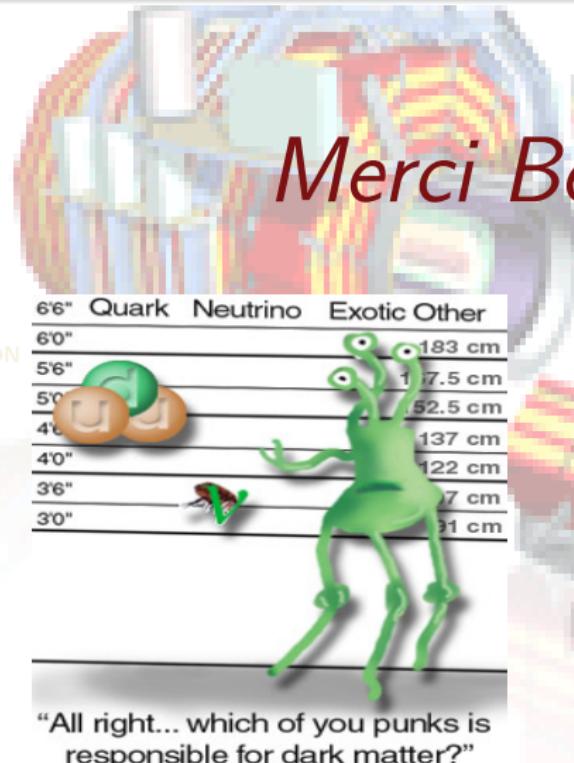
INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY



"Vacuums, black holes, antimatter - It's the elusive and intangible which appeals to me."

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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Norbert

MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

# BACK UP



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Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY



Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

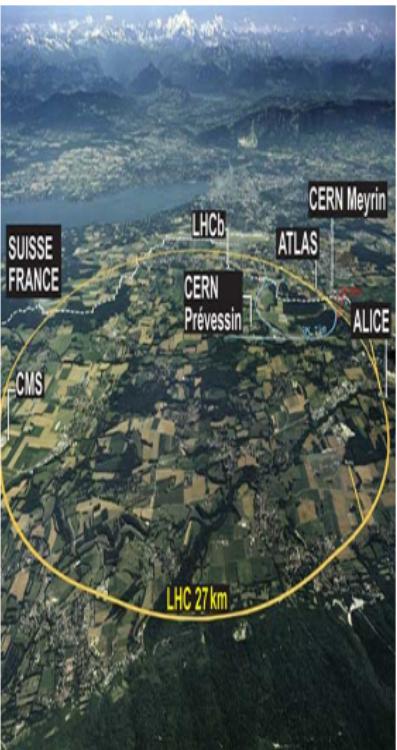
ECAL  
TIMING

SEARCH  
ANALYSIS

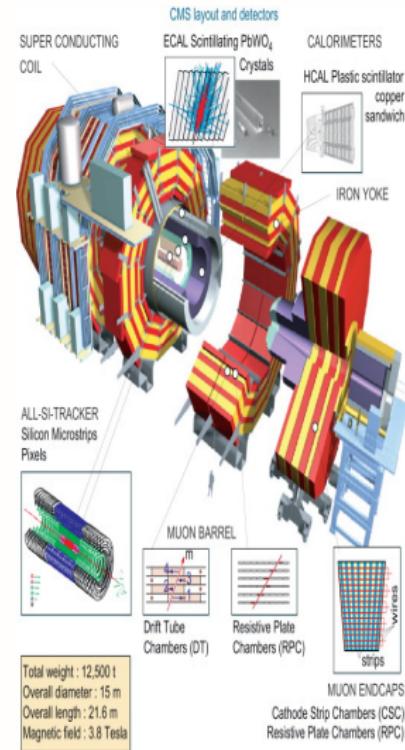
RESULTS

SUMMARY

## LHC



## CMS Detector



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Using  
Timing  
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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

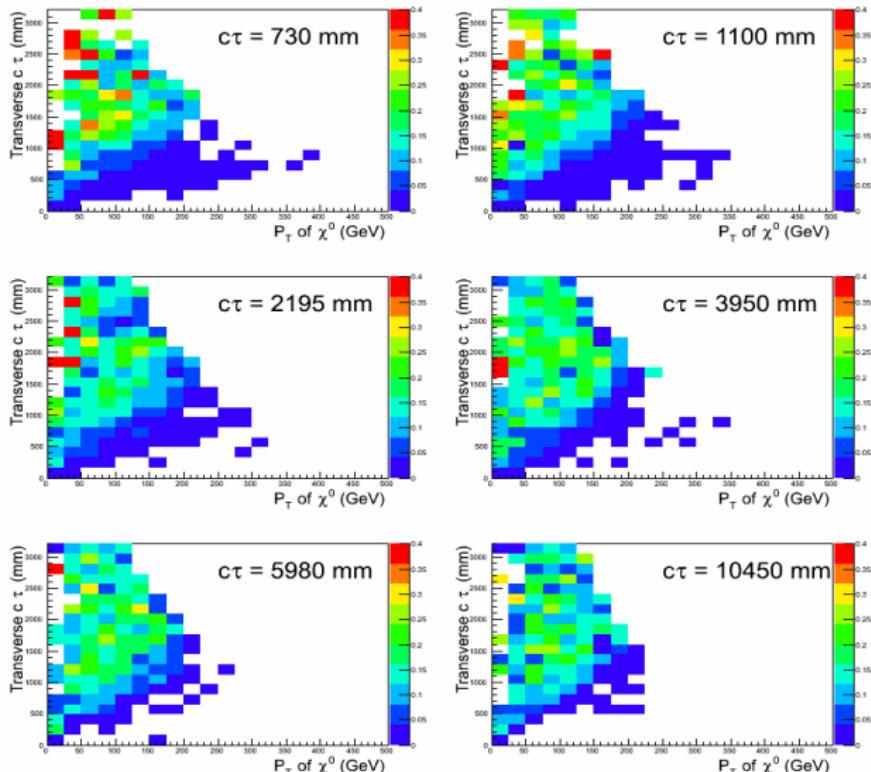


Figure : 2 Dim Efficiency

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Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

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.

Search For  
Delayed  
Photons  
Using  
Timing  
With CMS

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MENU

INTRODUCTION

ECAL  
TIMING

SEARCH  
ANALYSIS

RESULTS

SUMMARY

## Halo Photon Tagging Efficiency

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

## Halo Photon mis-Tag Rate

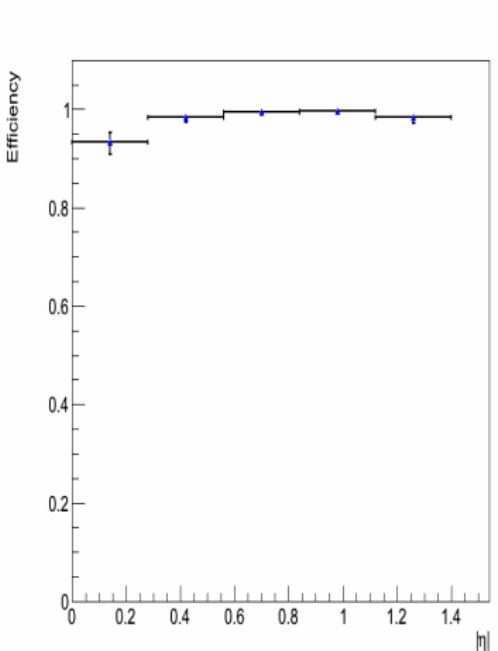
- Control Sample Selection:
  - $\geq 2$ -jets events with  $E_T^{miss} < 60$  GeV
  - ECAL time,  $|t| < 1$  ns.
- mis-tag rate evaluated in  $5\eta$  bins for  $S_{major}$   $\eta$  dependence.

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Delayed  
Photons  
Using  
Timing  
With CMS

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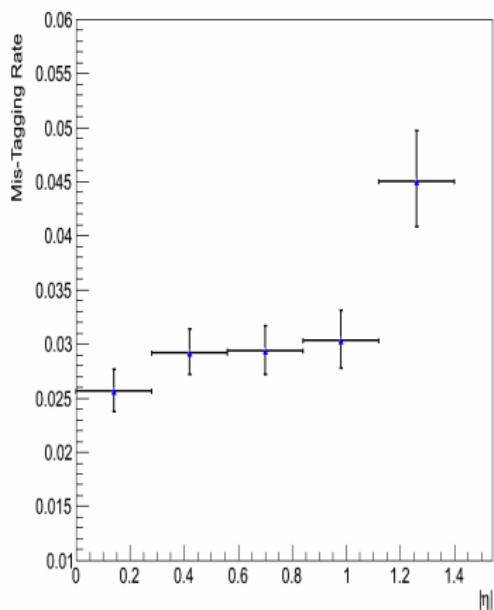
MENU  
INTRODUC  
ECAL  
TIMING  
SEARCH  
ANALYSIS  
RESULTS  
SUMMARY

## Tagging Efficiency



- Tagging Efficiency  $\approx 98\%$

## mis-Tag Rate



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