



Search For  
Long-Lived  
Neutral  
Particles in  
Final  
States with  
Delayed  
Photon  
and  
Missing  
Transverse  
Energy  
from  $pp$   
Collisions  
at  $\sqrt{S} =$   
8 TeV

# Search For Long-Lived Neutral Particles in Final States with Delayed Photon and Missing Transverse Energy from $pp$ Collisions at $\sqrt{S} = 8$ TeV

PhD Oral Exam

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University Of Minnesota

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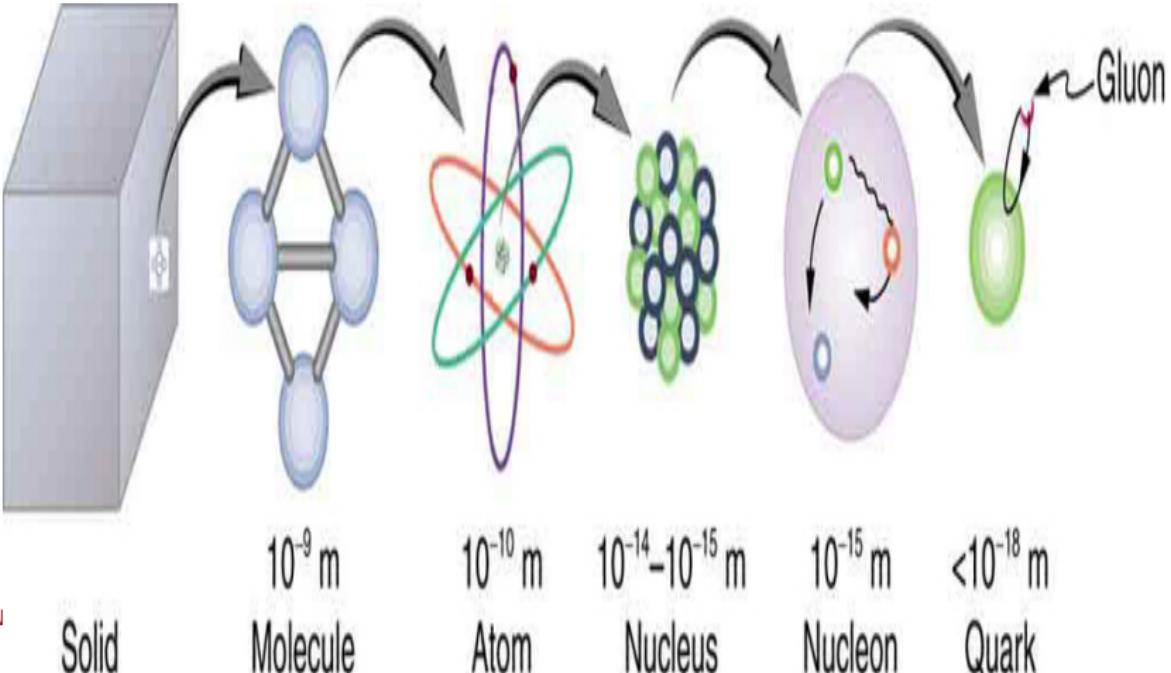
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Matter at lengths from  $10^{-18}$  m to  $10^{26}$  m

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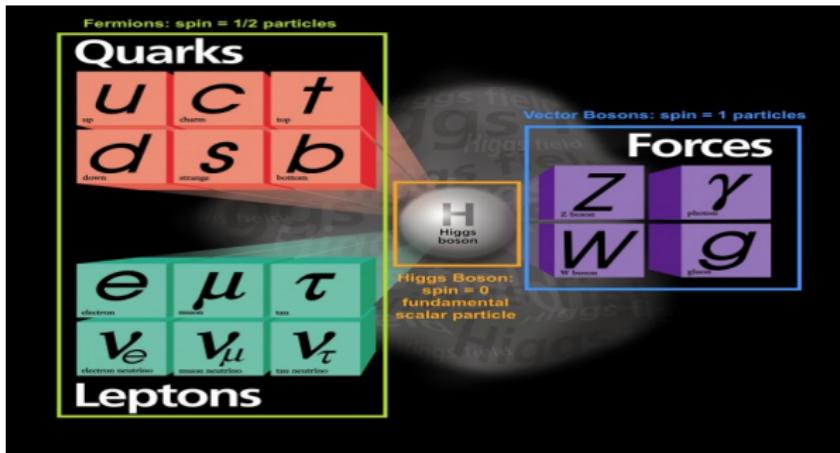
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## • Reality Recipe

- 6 quarks and leptons,
- 4 force mediators,
- 1 Higgs Boson.



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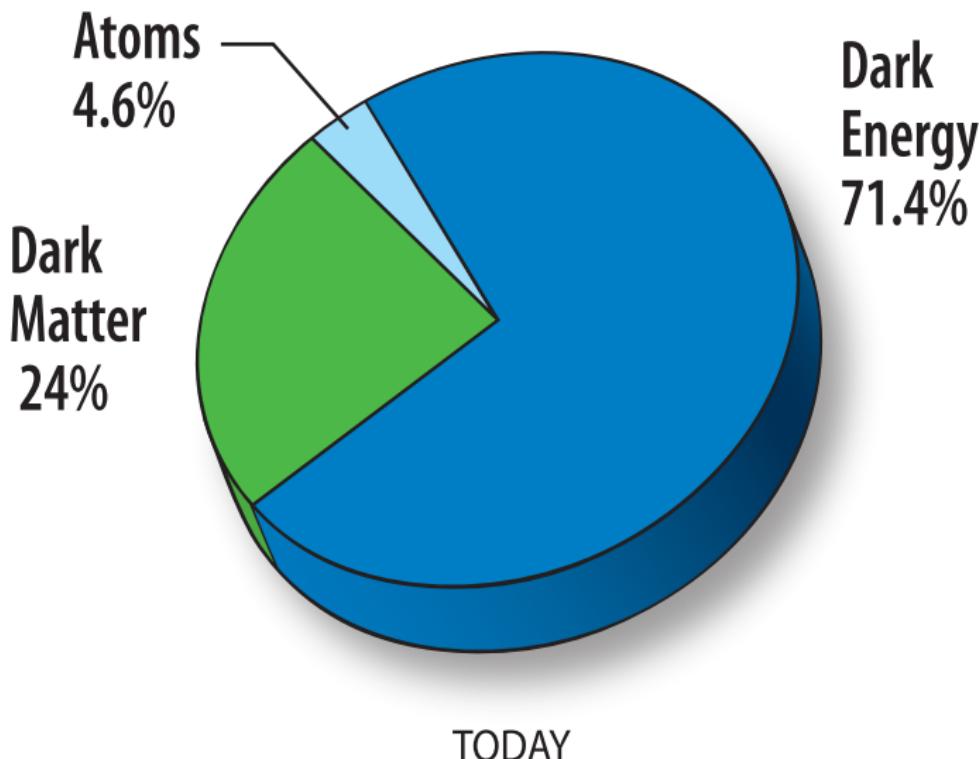
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What are the fundamental constituents of the Universe?

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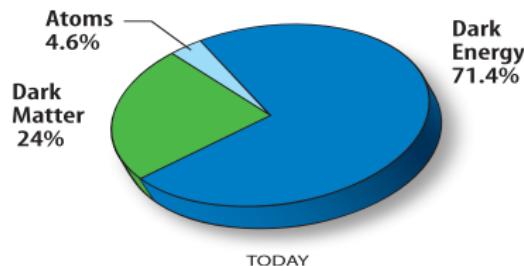
## The Universe Spin Set

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

- $s = \frac{1}{2}\hbar$  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?).

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

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



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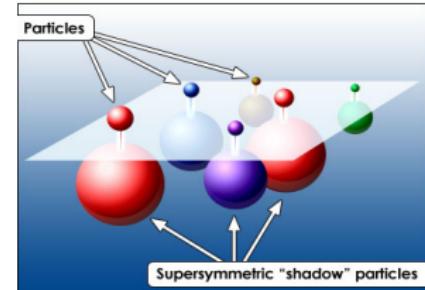
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Supersymmetry(SUSY) allows for  
**Bosons**  $\xleftrightarrow{\text{SUSY}}$  **Fermions.**

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

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



## Supersymmetry Motivation

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



# Interaction Life Time



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## GMSB Models

- ▷ Next-to-lightest SUSY (NLSP) is Neutralino ( $\tilde{\chi}_1^0$ ),
- ▷  $eV - keV$  mass Lightest-SUSY particle (LSP) is Gravitino ( $\tilde{G}$ ),
- ▷ Gravitino is a Dark Matter Candidate.

## R-Parity Conserving Models

- † R-Parity conserved, LSP is Dark Matter candidate.  $R = (-1)^{3(B-L)+2S}$
  - † Proton decay is consistent.  $R |SM\rangle = +1 |SM\rangle$
  - † Few Parameters.  $R |SUSY\rangle = -1 |SUSY\rangle$
- $$\{\Lambda, M_{\text{mess}}, N_5, \tan(\beta), \text{sgn}(\mu), C_{\text{grav}}\}$$

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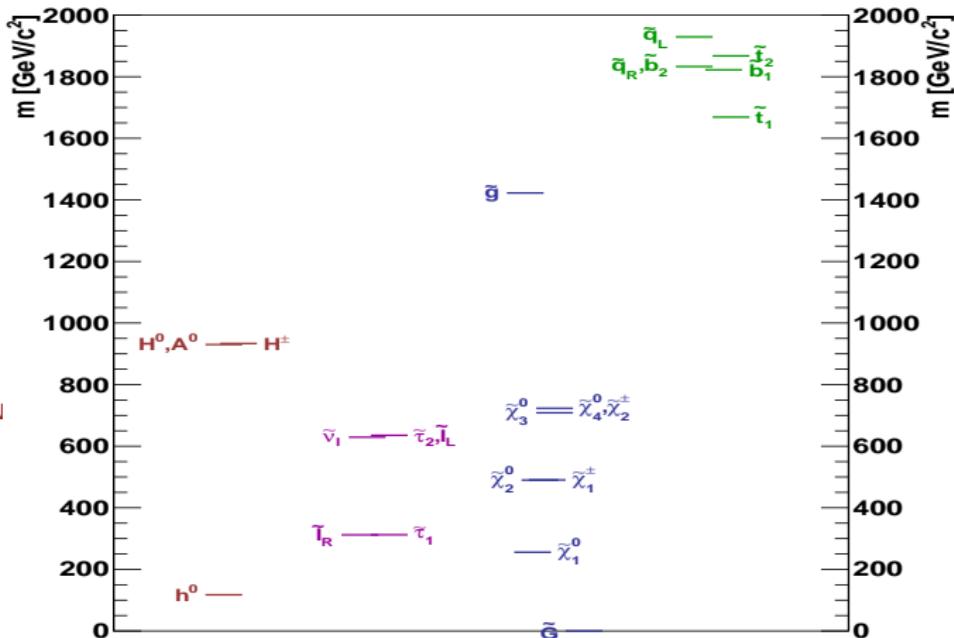
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### SPS8 GMSB Model

$M_{mess}$	$N_5$	$sgn(\mu)$	$\tan(\beta)$	$\Lambda$	$C_{grav}$	
$2.\Lambda$	1	1	15	varies	varies	



# Supersymmetry Production

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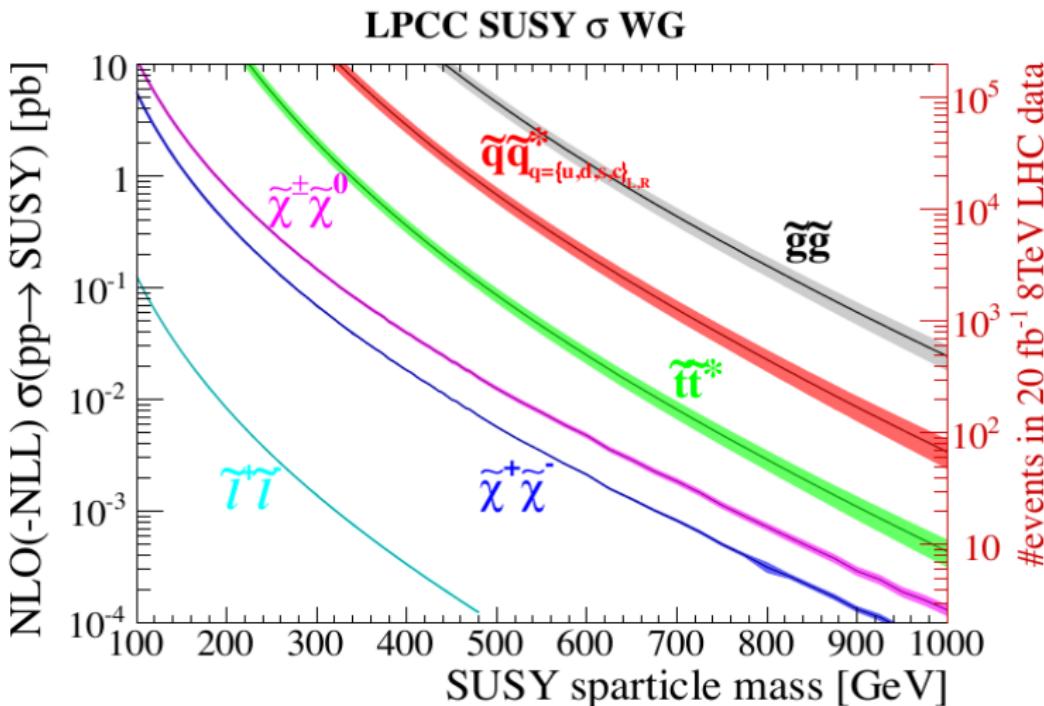
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<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections>

arXiv:1206.2892

SUSY production mostly in strong interactions at LHC.

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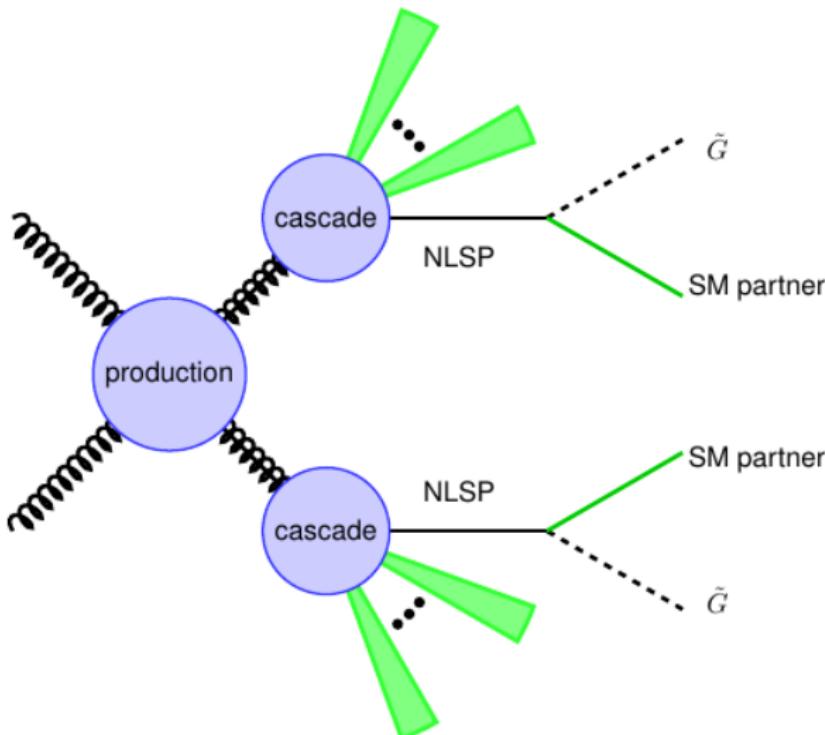
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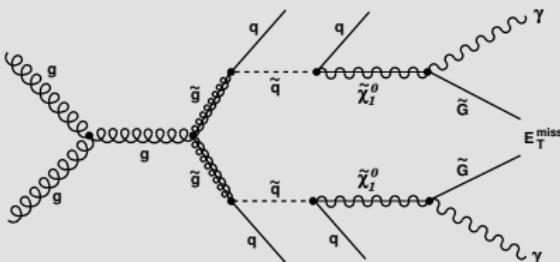
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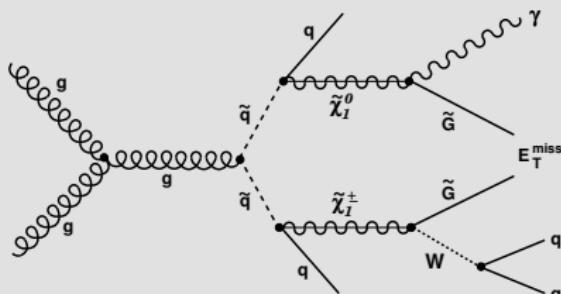
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## Double Photon



2 Photons, Jets, Large MET

## Single Photon



1 Photon, Jets, Large MET

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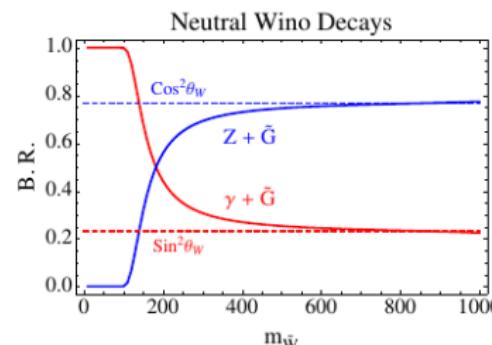
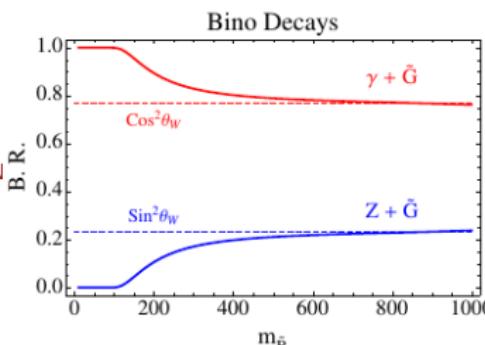
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## Distance Travelled

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

## Proper Decay Length

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



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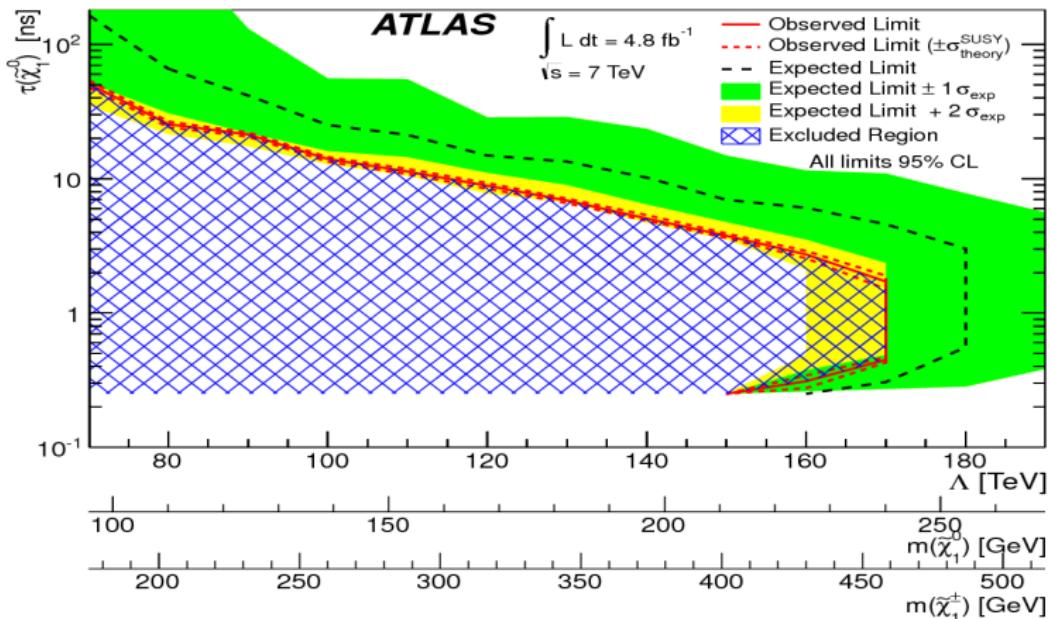
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## ATLAS



Excluded: Mass > and  $c\tau >$ .

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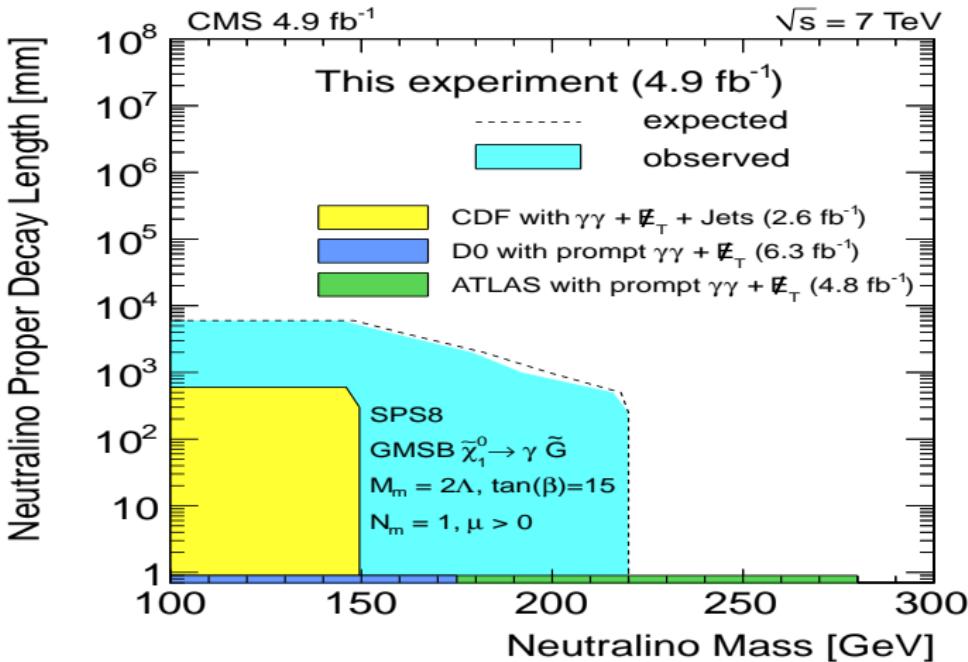
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## CMS, CDF, DO



Excluded: Mass > and  $c\tau >$ .

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# ECAL TIMING



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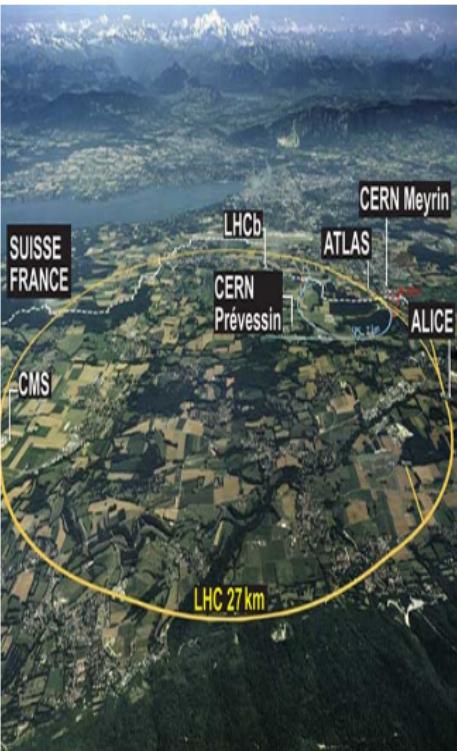
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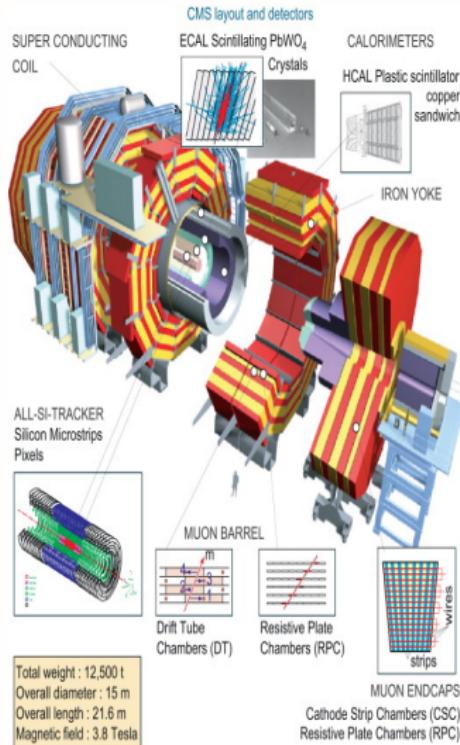
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## LHC



## CMS Detector

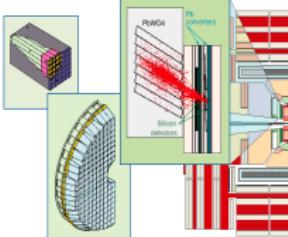
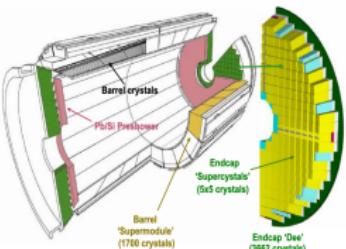


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## ECAL Subdetector



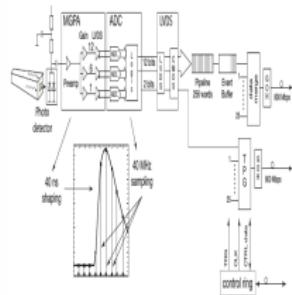
**Barrel Detector (EB):**  $|\eta| < 1.475$ .

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

## ECAL Properties

- ▷ 75,848 Lead Tungstate crystals,
- ▷ Crystals measure energy and time,
- ▷ Shower in crystal generates lights detected using:
  - ★ Avalanche Photo-Diodes(APD) in EB,
  - ★ Vacuum Photo-Triodes(VPT) in EE
- ▷ Readout with custom ASICs.

## Readout Chain



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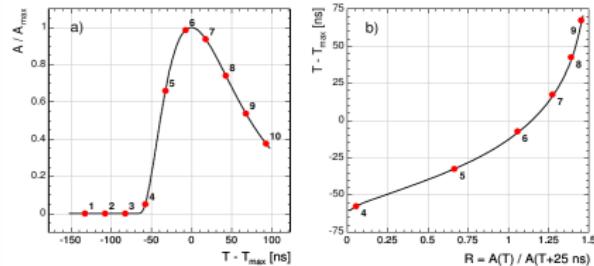
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## Time Reconstruction

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



## Time Measurement

- ▷\* Error Weighted

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

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## Time Resolution Equation and parameter Definitions.

# Test Beam Performance

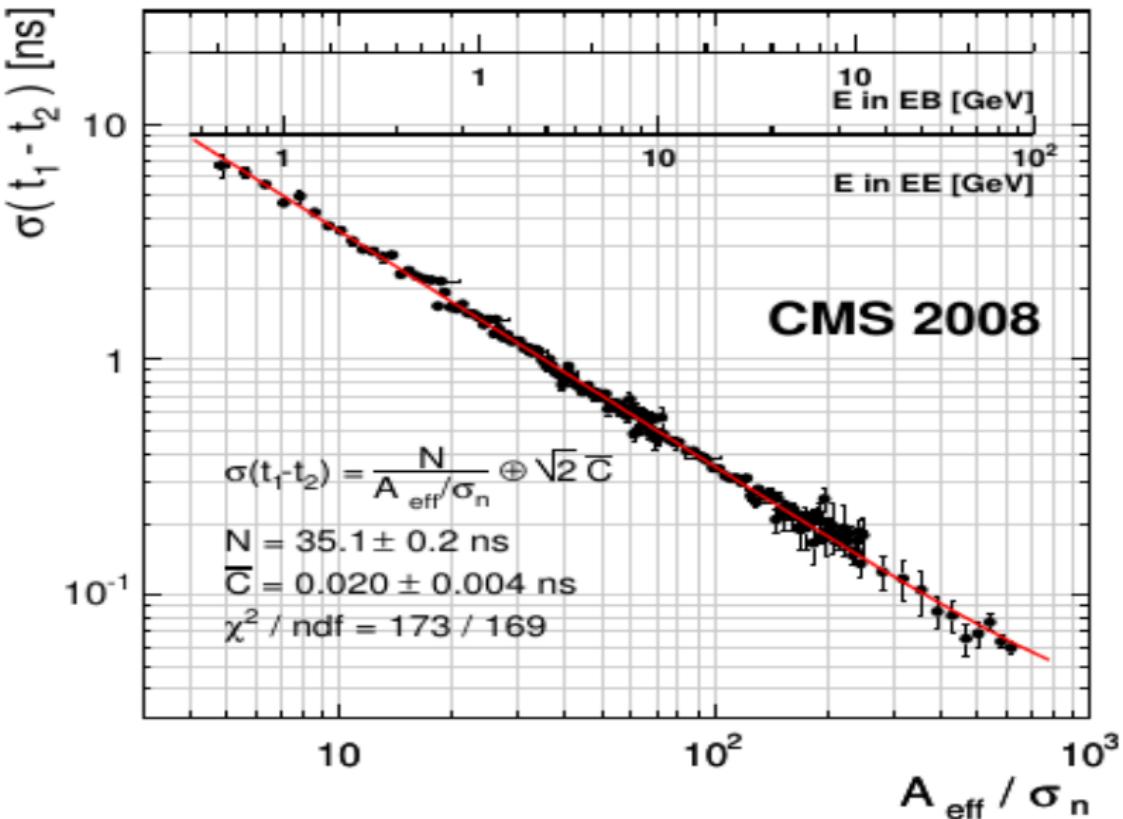
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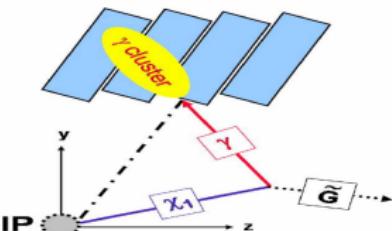
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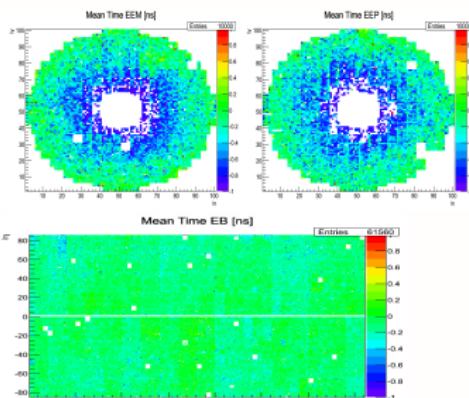
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## Calibration Procedure

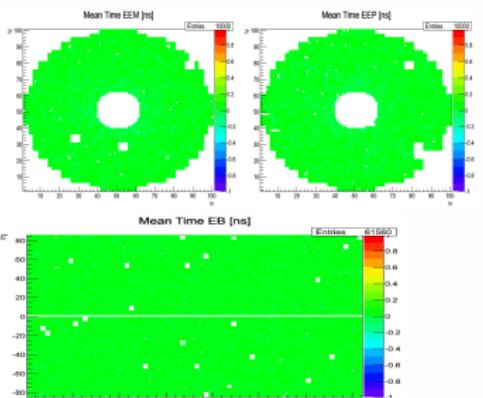
- ▷\* Adjust Crystal time such that  $\langle t_{crys}^{\gamma} \rangle \approx 0$
- ▷\* Average is over events(*rechits*)/crystal.



### Before Calibration



### After Calibration



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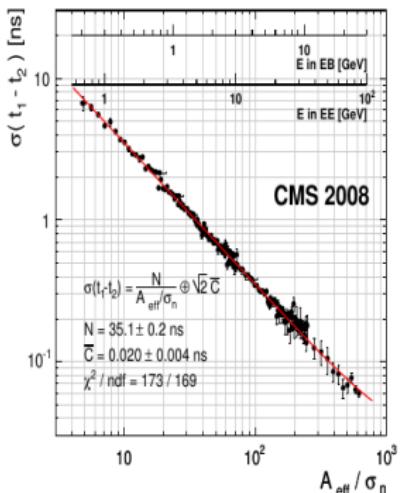
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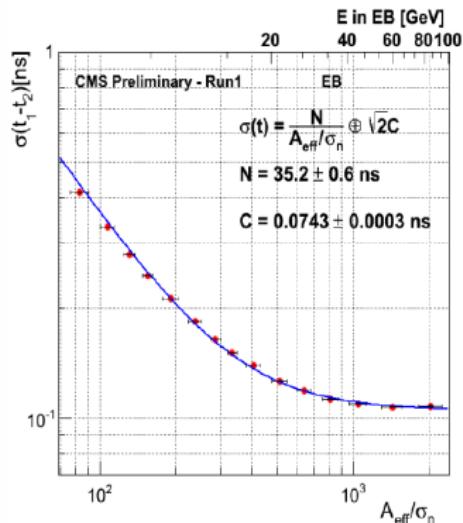
## ECAL Timing Resolution

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

### Test Beam



### LHC RUN I



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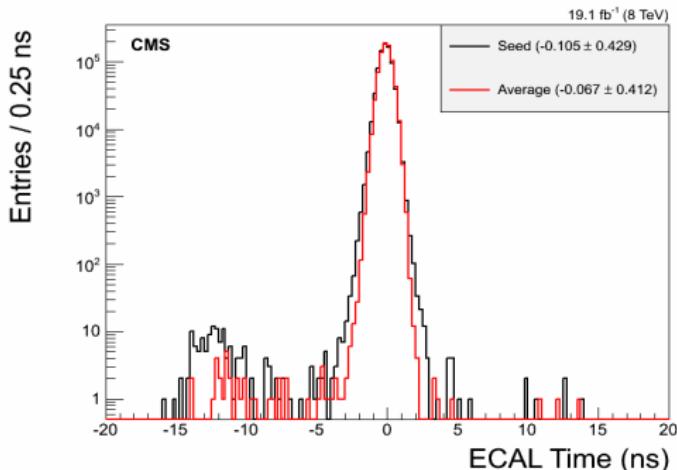
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- ➊  $T_\gamma$  = Error weighted average time of crystals in photon.
- ➋  $T_\gamma$  = Seed (most energetic) crystal time.

## Photon Arrival Time



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

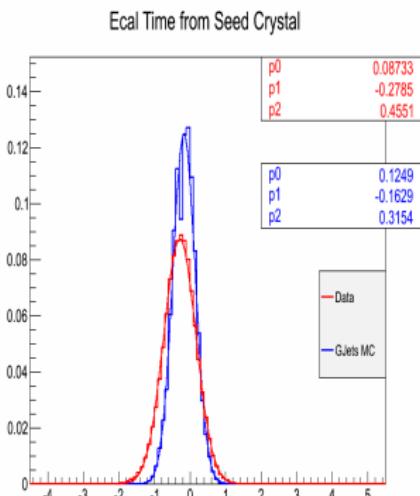
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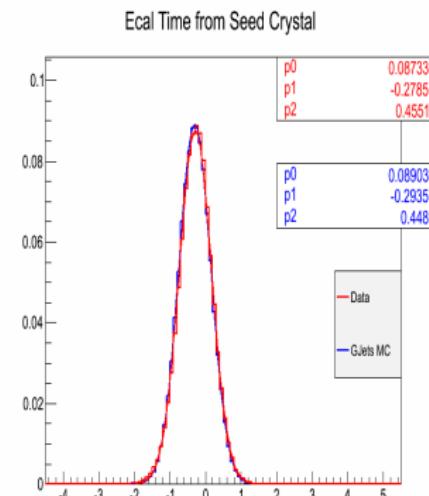
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## Before Correction



## After Correction



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

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# SEARCH ANALYSIS





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at  $\sqrt{S} =$   
8 TeV

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## • 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 $^2$ ]	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]	$\sigma_{LO}$ (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

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Collisions  
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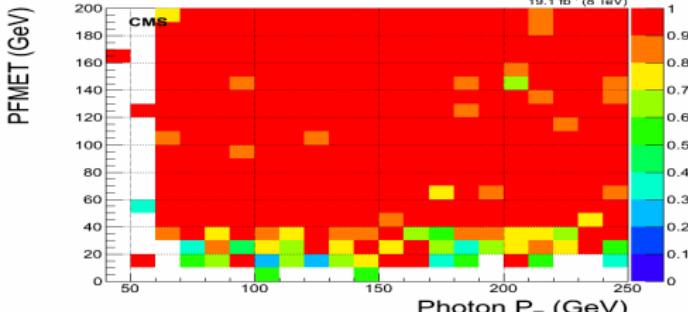
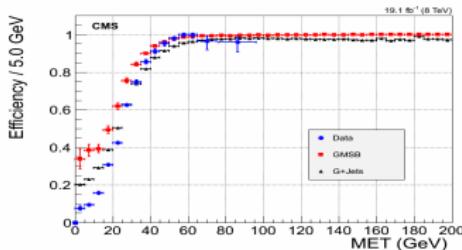
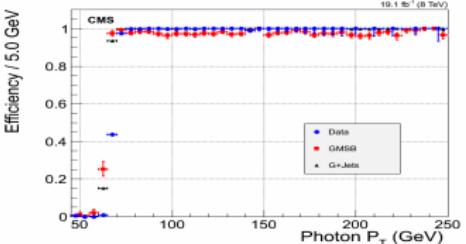
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## HLT\_DisplacedPhoton65\_CaloIdVL\_IsoL\_PFMET25



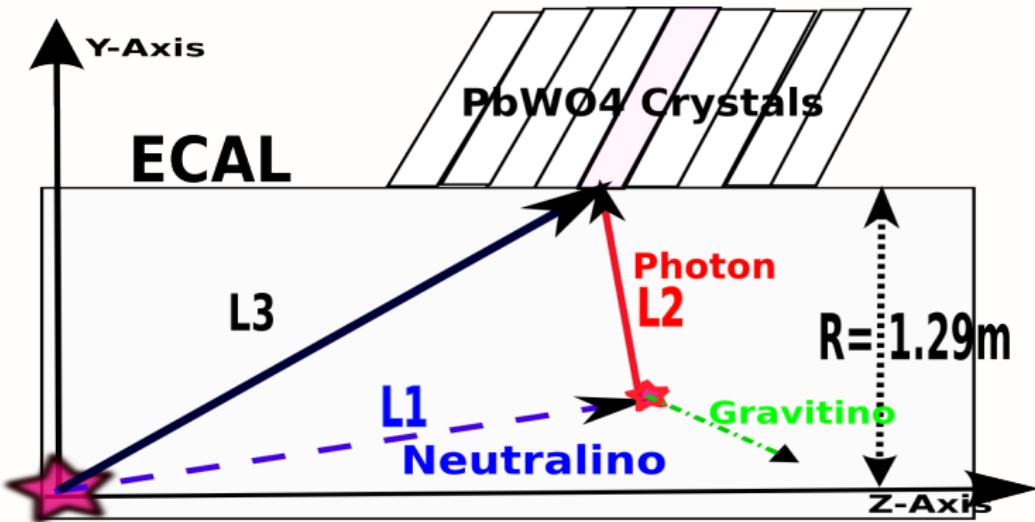
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## Source of Delayed Photons?

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



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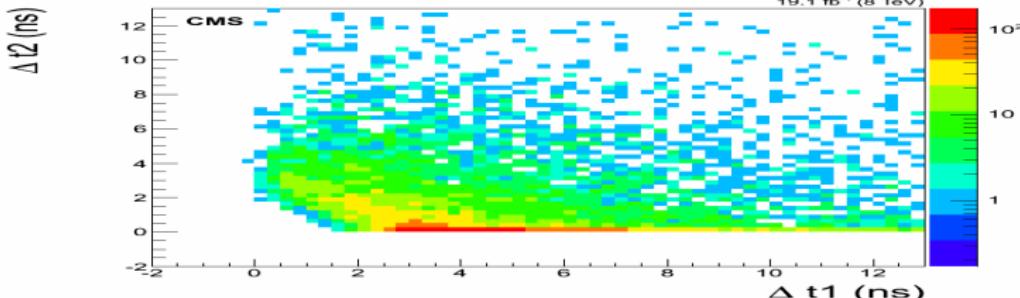
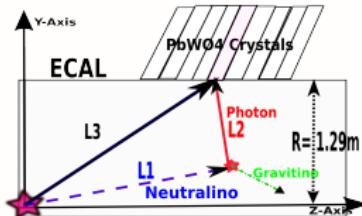
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## Photon Measured Time

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

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



- Delayed photons mostly from slow moving decay.

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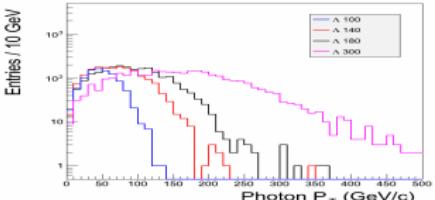
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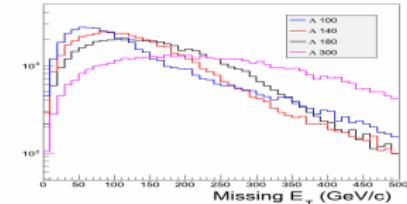
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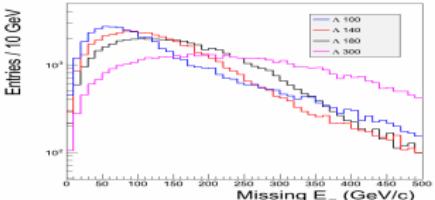
## Photon $p_T$



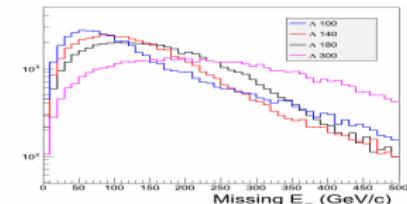
## Neutralino $c\tau$



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



## NJets



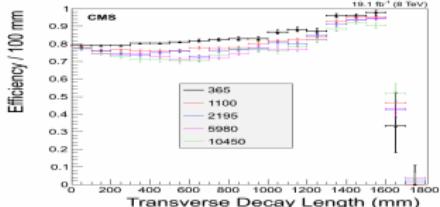
- Different  $\Lambda$  values with the same  $c\tau(10 \text{ m})$ . Photon  $p_T$  is harder with higher values of  $\Lambda$ .

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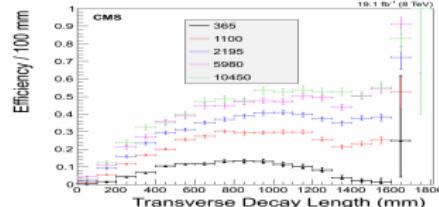
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## Efficiency

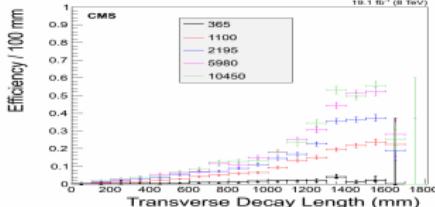


## Acceptance

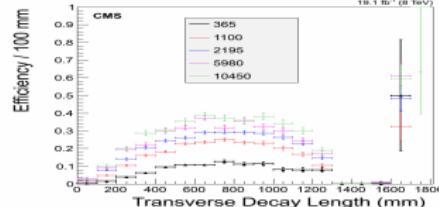


- Slow moving neutralino decay causes sudden efficiency drop.

## Slow moving



## Off-Pointing



- Peak Acceptance at transverse decay length= 800 mm.

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## Signal Events

## Background Events

- **Collision:** mis-measured time of  $Z/W/top$  events.
- **Non-Collision:** Out-time events from LHC proton Beam/Cosmic/Anomalous Spikes.

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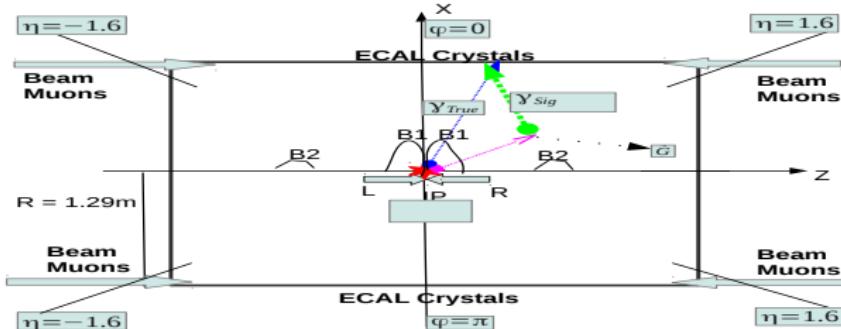
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## ● Background Sources



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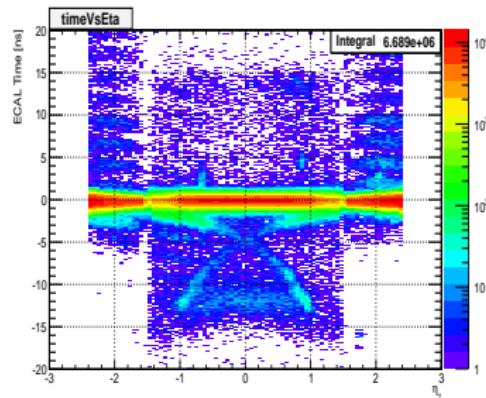
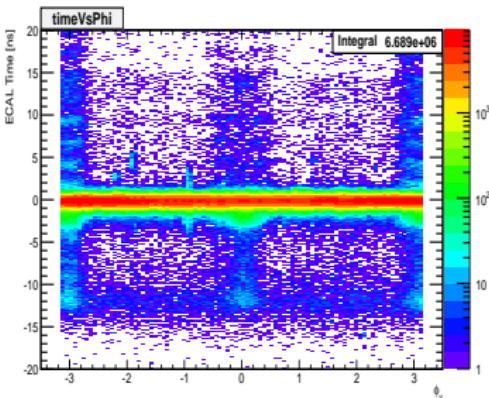
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- ▶ Non-collision events like proton Beam Induced Background (BIM or Halos)/Cosmic/Anomalous spikes contribute towards delayed photons ECAL timing.
- ▶ Need to defined a cleaning mechanism for identifying and rejecting non-collision events.



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

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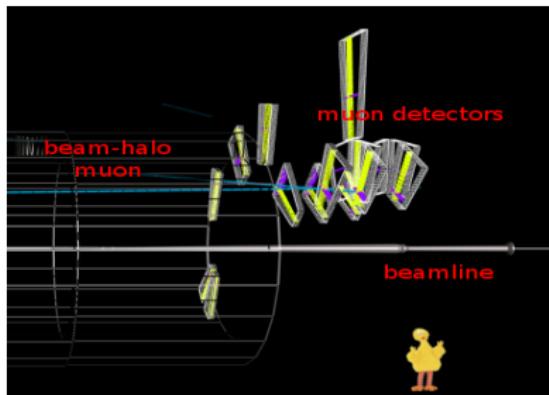
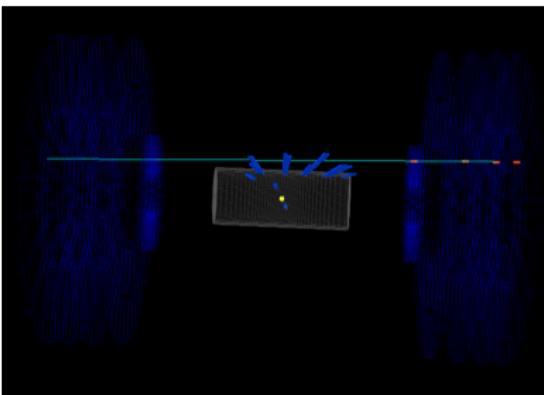
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## Beam Halo Muons

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

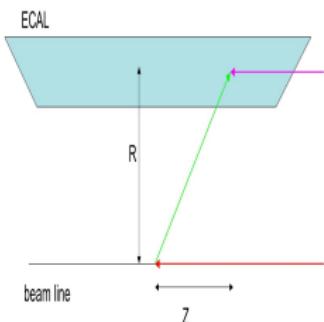
will produce energetic muons traveling parallel with main proton beam and showering in the Calorimeters.



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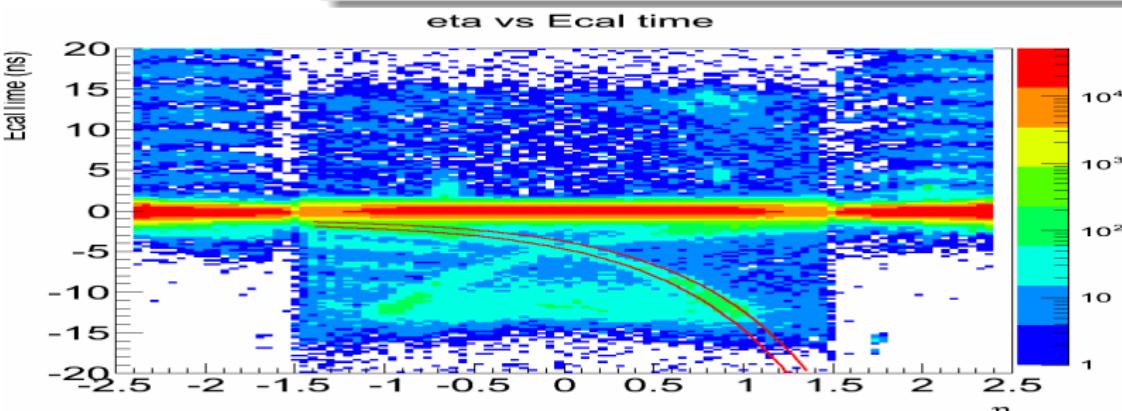
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### Halo Expected ECAL Time

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

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



# Halo Photon (III)



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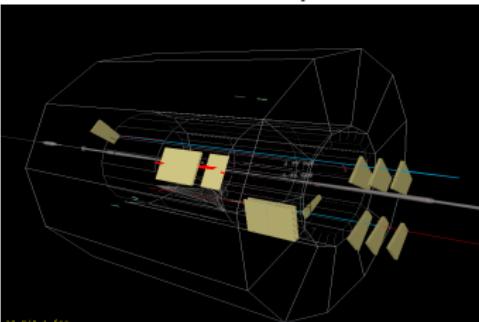
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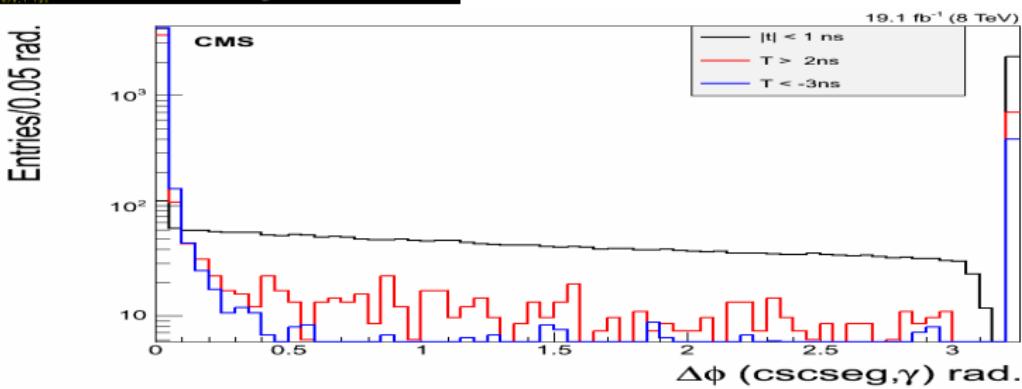
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Additionally, using halo muon hits from CSC segment matched in  $\phi$  to Superclusters in ECAL, we can in addition identify, tag and remove halo photon events with large timing.



## Halo Photon Matching

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



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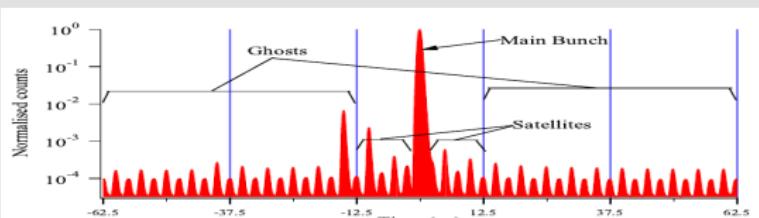
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## Satellite/Ghost Beam Halos

- 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



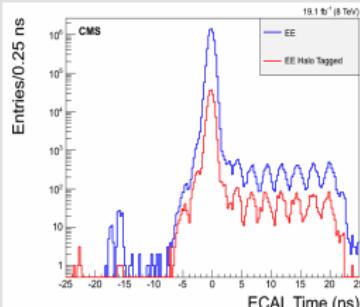
## Halo Photon Event Properties

- 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



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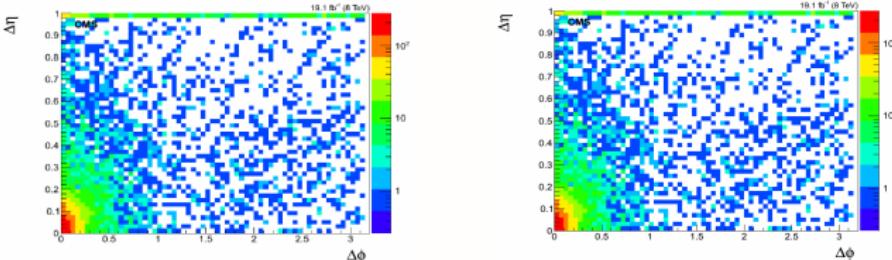
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## Cosmic Muons

- 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.

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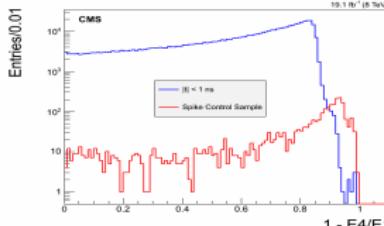
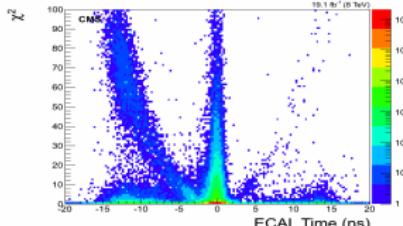
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## ECAL Spikes

- 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



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



# Event Selection



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## 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 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 $p_T$	$> 35$ GeV
Number Of Constituents	$> 1$
$\Delta R(\gamma, jet) = \sqrt{(\phi_\gamma - \phi_{jet})^2 + (\eta_\gamma - \eta_{jet})^2}$	$> 0.3$
$E_T^{\text{miss}}$	$> 25$ GeV

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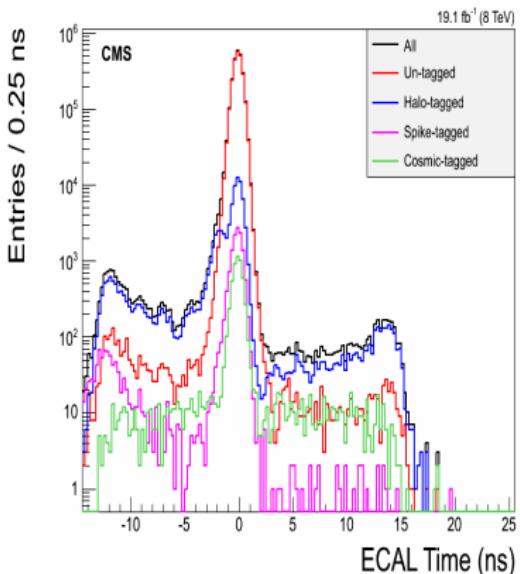
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## Mis-Tag Rates

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

- Tagging reliable but not 100% efficient.

## Tagging Performance



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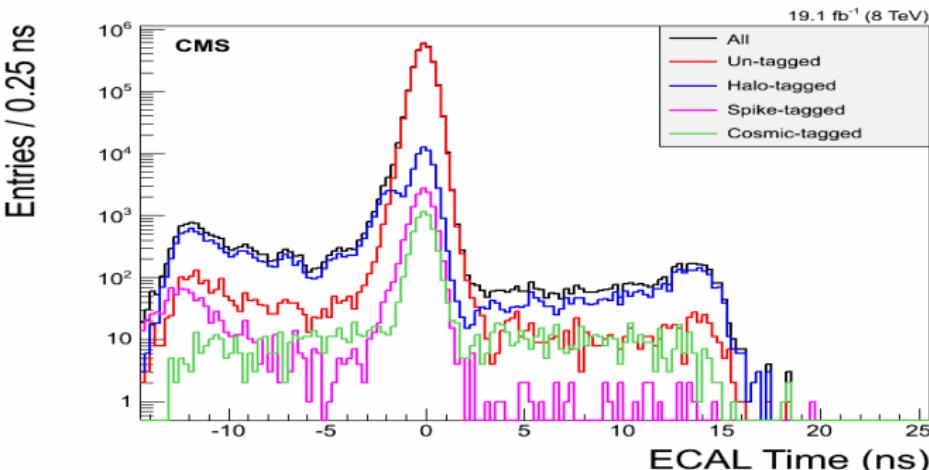
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After tagging and cleaning Halo/Cosmic/Spike events, We apply ABCD background estimation technique on residual Non-collision background events to estimate their contribution to possible signal.

### Event Tagging and Cleaning Performance

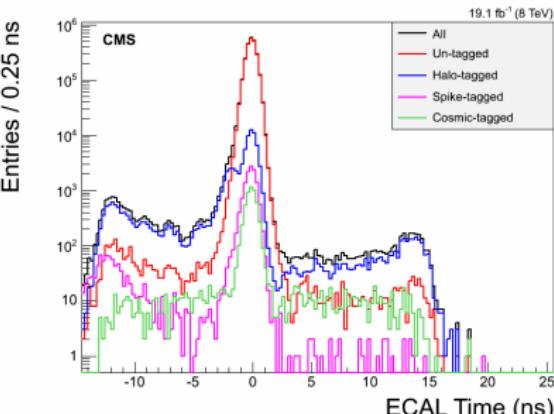


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at  $\sqrt{S} =$   
8 TeV

## 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  
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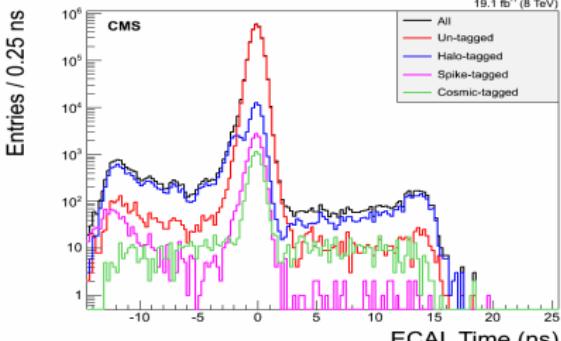
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## Collision Events.

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

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



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

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

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

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## 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}$	$F'$	$F$
$3 < t > 13 \text{ ns}$	$D'$	$D$

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## 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

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## Control Sample $Z \rightarrow ee$ Events

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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.

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## 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.

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# RESULTS





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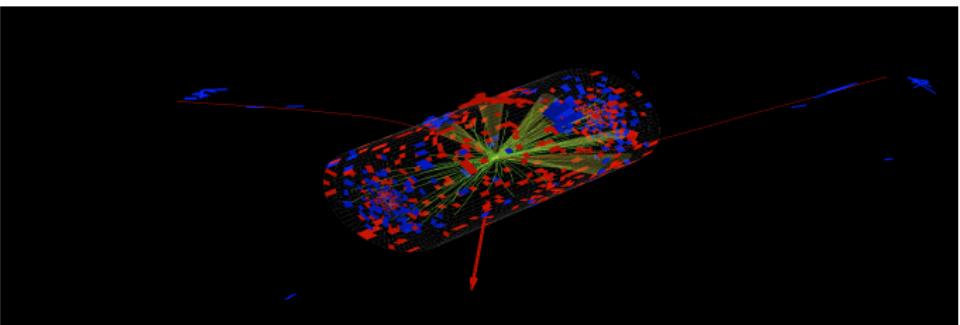
- Observed **1 Event**
- Expected **0.0886 Events**

## Events Passing Final Selection

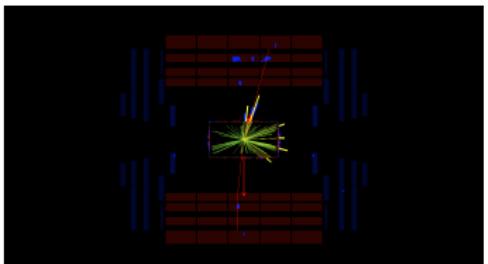
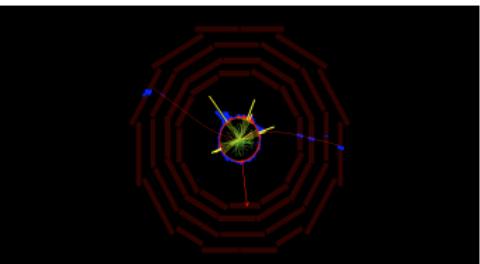
Sample	Lifetime( $c\tau$ )[mm]	Number Of Events
GMSB $\Lambda = 180$ TeV	10500	
GMSB $\Lambda = 180$ TeV	6000	
GMSB $\Lambda = 180$ TeV	4000	
GMSB $\Lambda = 180$ TeV	3000	
GMSB $\Lambda = 180$ TeV	2000	
GMSB $\Lambda = 180$ TeV	1000	
GMSB $\Lambda = 180$ TeV	500	
Data	1.00	
Background Total	0.0886	

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### 3-D View



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



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# Exclusion Limits

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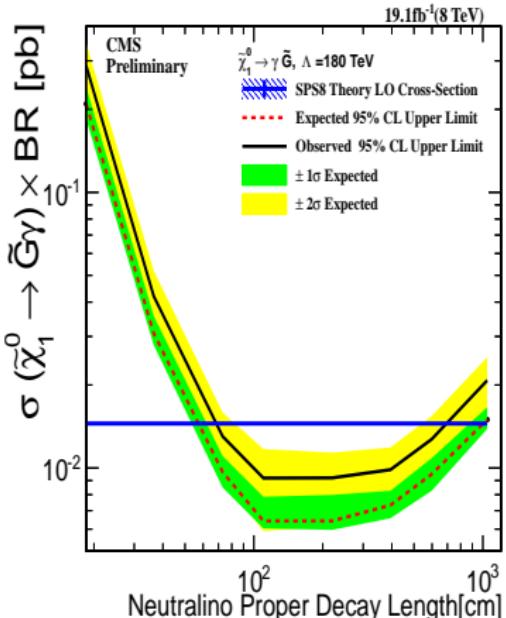


Figure :  $c\tau$  Limits

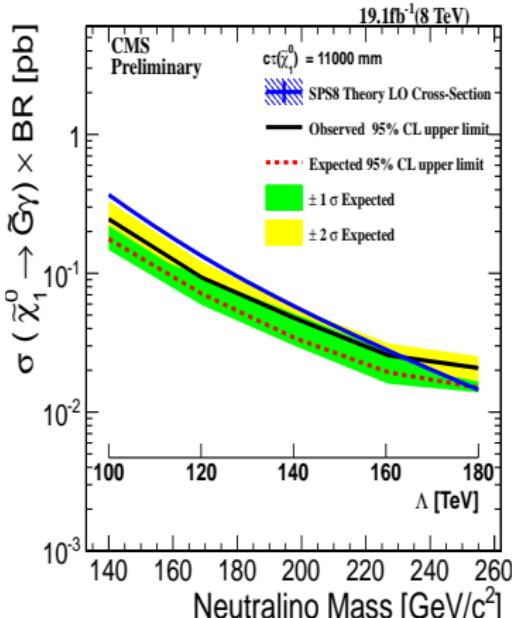


Figure : Mass Limit

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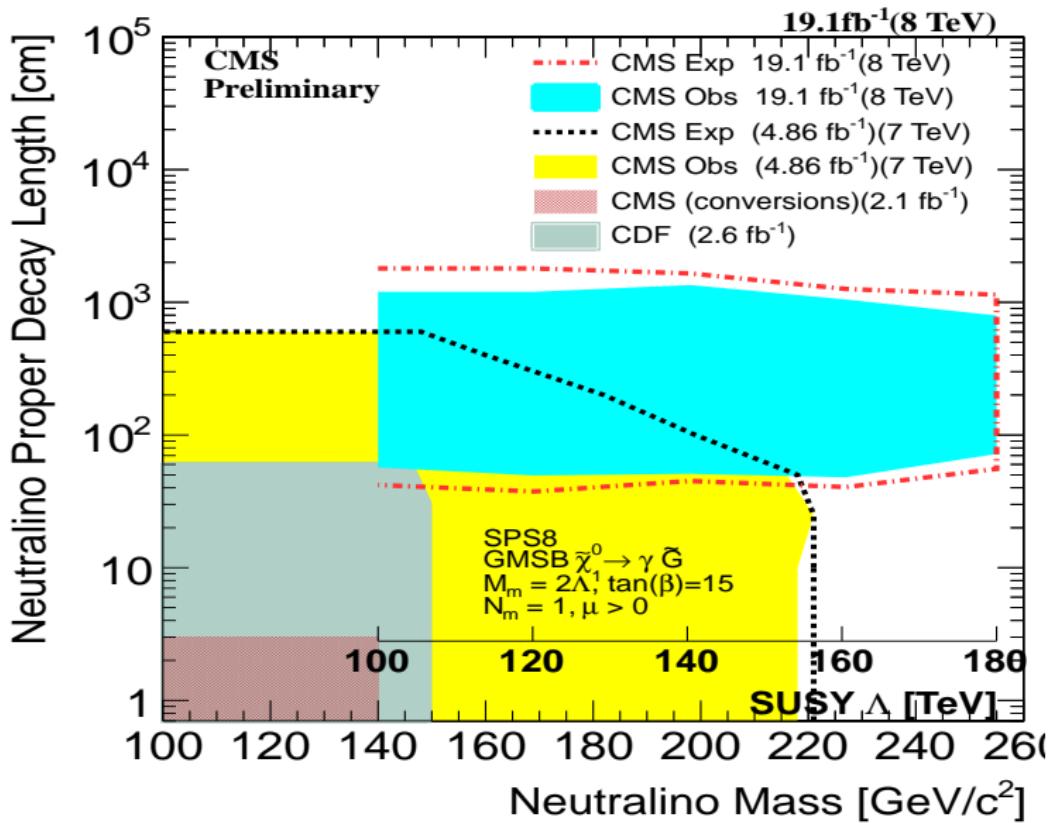
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# Comparison To Other Search Experiments



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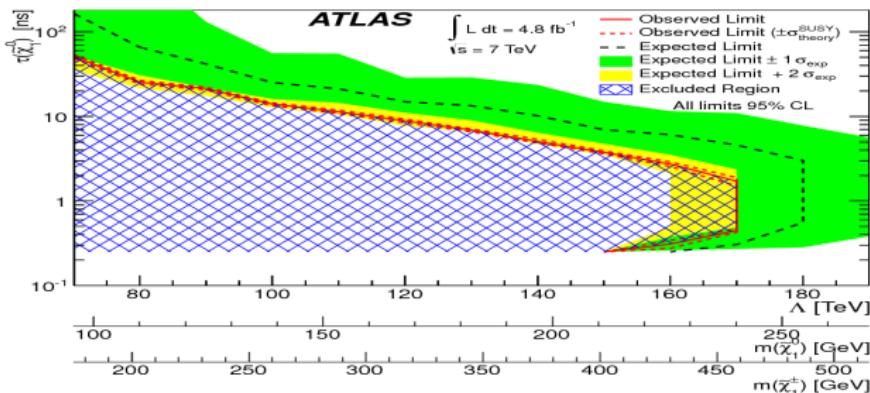
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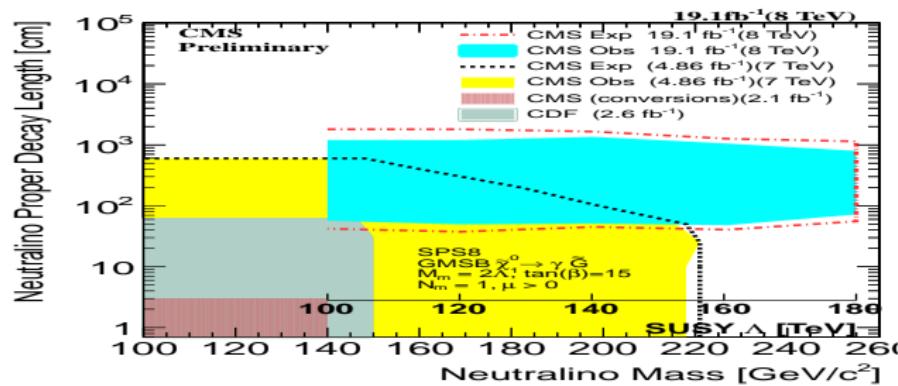
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## ▷\* ATLAS



## ▷\* CMS 8 TeV



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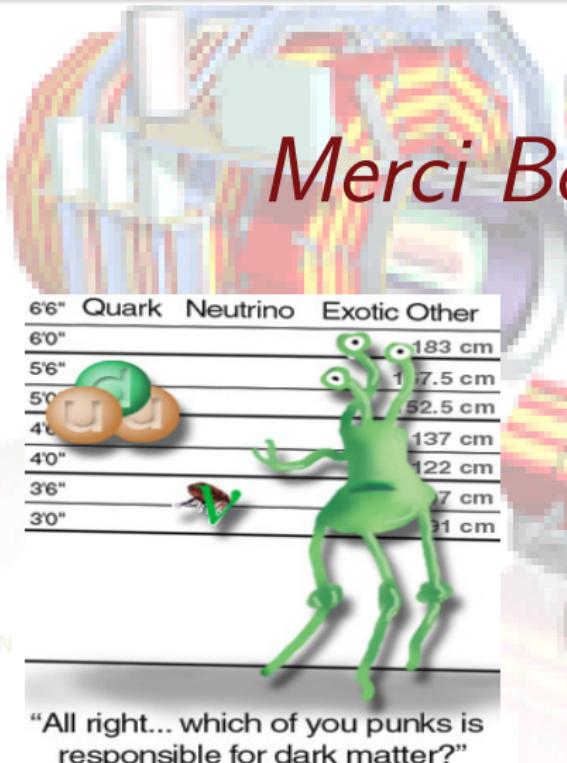
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"Vacuums, black holes, antimatter - It's the elusive and intangible which appeals to me."

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# BACK UP



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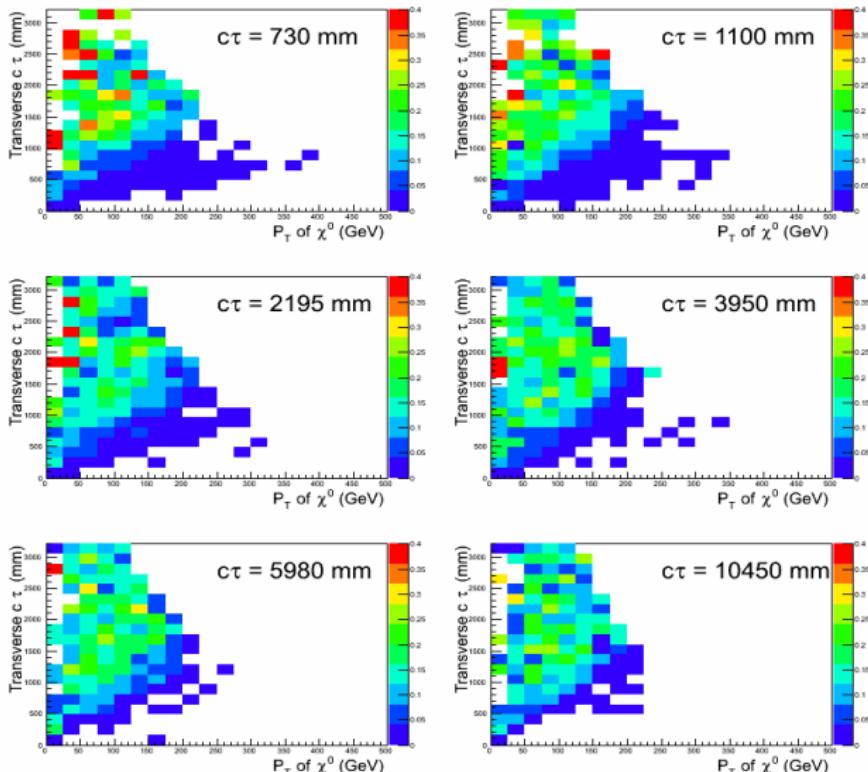


Figure : 2 Dim Efficiency

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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.

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## 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

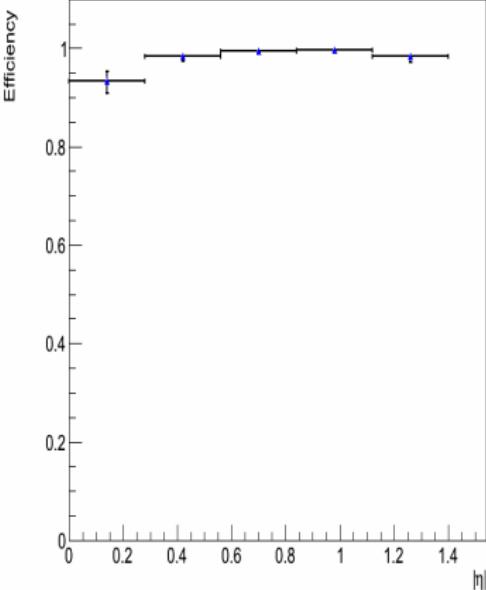
- Control Sample Selection:
  - $\geq 2$ -jets events with  $E_T^{miss} < 60$  GeV
  - ECAL time,  $|t| < 1$  ns.
- mis-tag rate evaluated in  $5\eta$  bins for  $S_{major}$   $\eta$  dependence.

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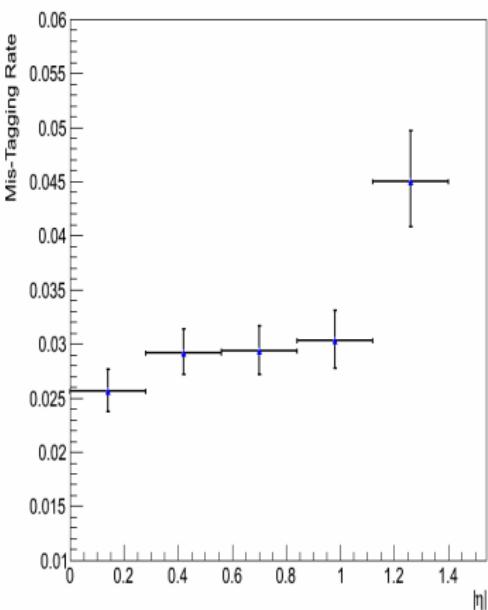
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## Tagging Efficiency



## mis-Tag Rate



- Tagging Efficiency  $\approx 98\%$

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

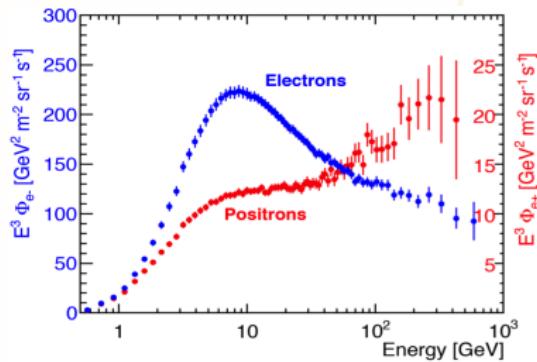
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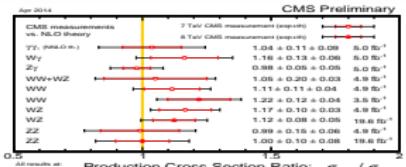
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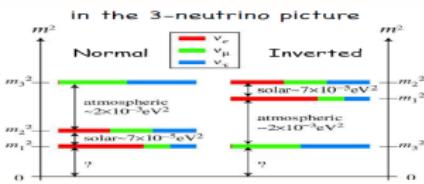
## AMS Experiment on ISS



## ZZ, WW Production



## Neutrino Masses.



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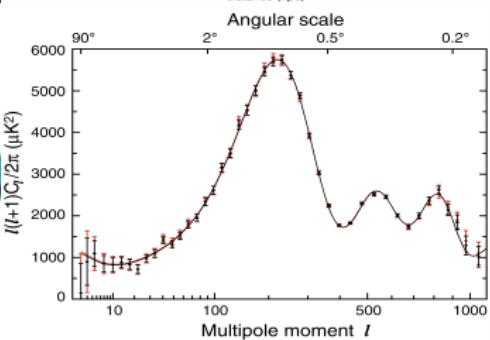
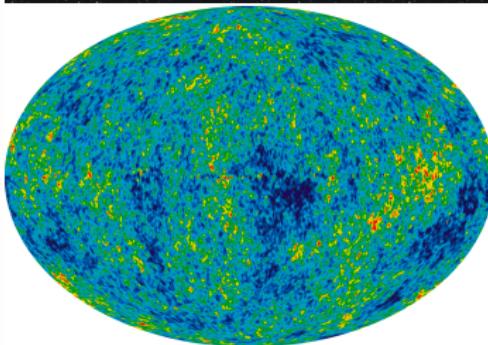
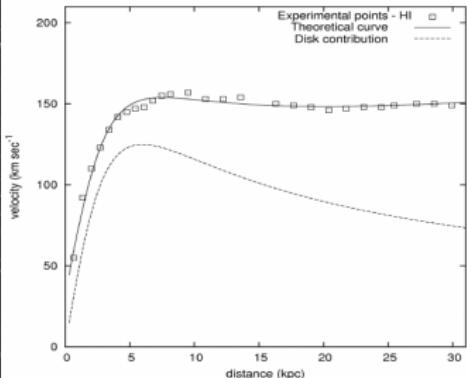
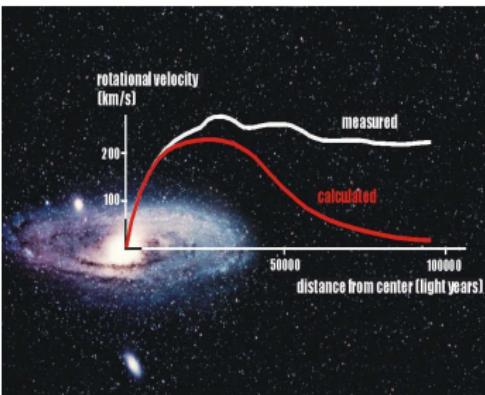
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## Dark Matter.



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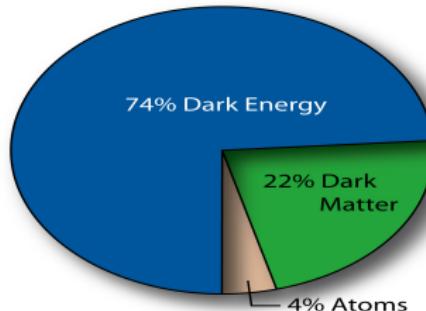
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## Universe Matter Budget.



## Dark Matter in our Galaxy?.

