Search For New Massive Long-Lived Neutral Particles Decaying To Photons In CMS

PhD Oral Exam

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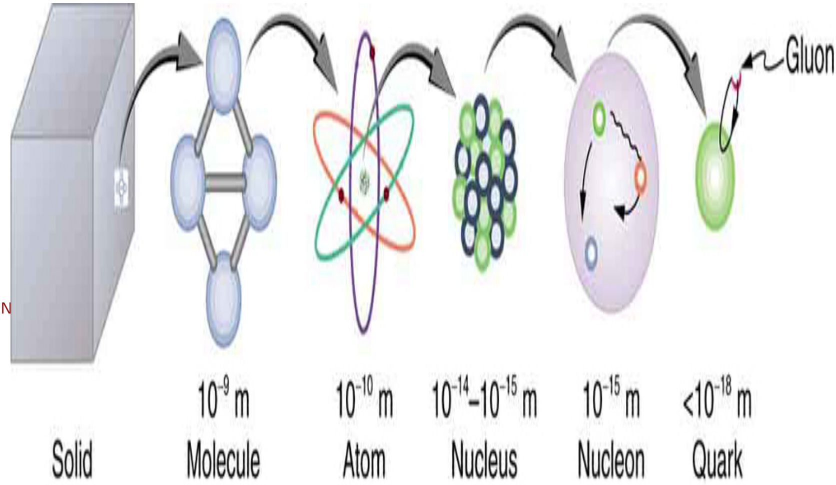
MENU

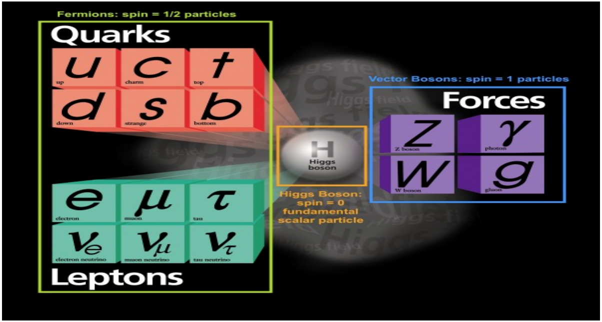
INTRODUCTION

Modern Particle Physics



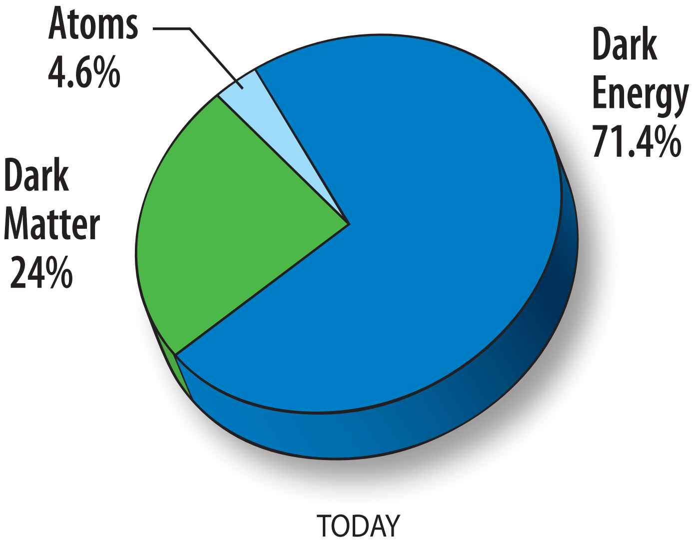
Matter at lengths from 10^{-18} m to 10^{26} m

Standard Model Recipe



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

The Universe



What are the fundamental constituents of the Universe?

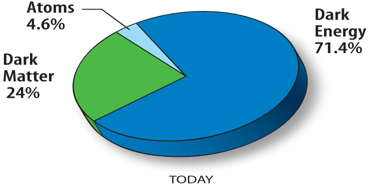
The Universe Spin Set

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

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

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

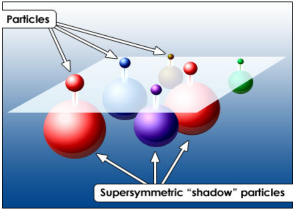
- $\mathbf{s} = \frac{\mathbf{3}}{\mathbf{2}}\hbar$?? **Dark Matter?**



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

$$Q\,|\mathbf{Bosons}\rangle = |\mathbf{Fermions}\rangle$$

$$Q\,|\mathbf{Fermions}\rangle = |\mathbf{Bosons}\rangle$$



Supersymetry 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.**

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.

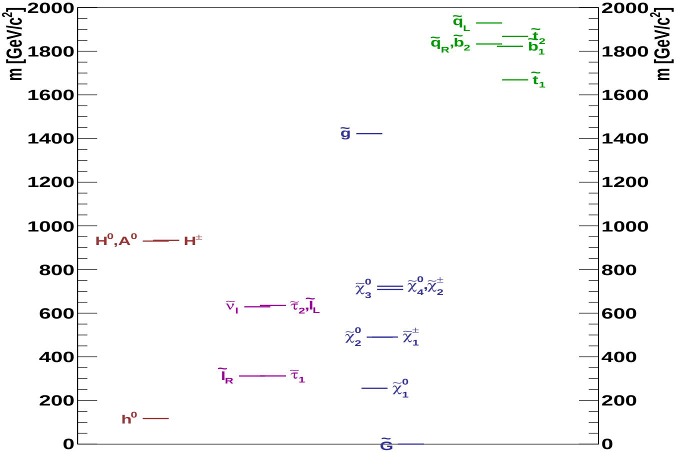
R-Parity Conserving Models

- R-Parity conserved, LSP is Dark Matter candidate.
- Proton decay is consistent.
- Few Parameters. $\{\mathbf{\Lambda}, \mathbf{M}_{\text{mess}}, \mathbf{N}_5, \tan(\beta), sgn(\mu), C_{grav}\}$

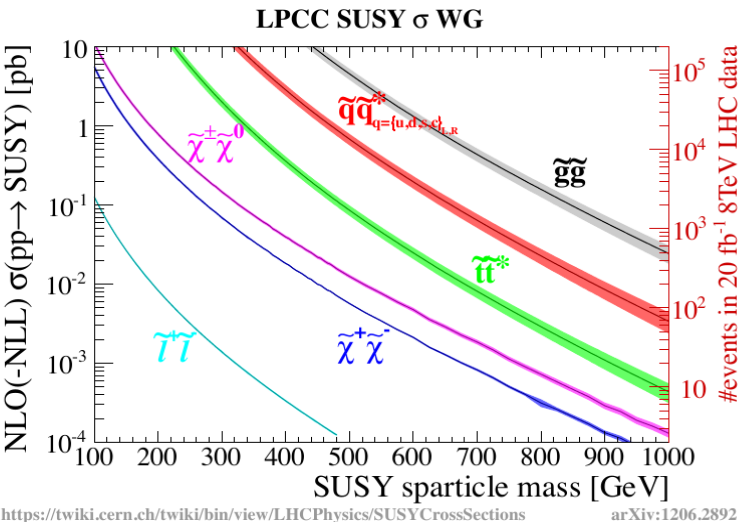
$$\mathrm{R} = (-1)^{3(B-L)+2S}$$
$$\mathrm{R}\,|SM\rangle = +1\,|SM\rangle$$
$$\mathrm{R}\,|SUSY\rangle = -1\,|SUSY\rangle$$

GMSB Model:SPS8

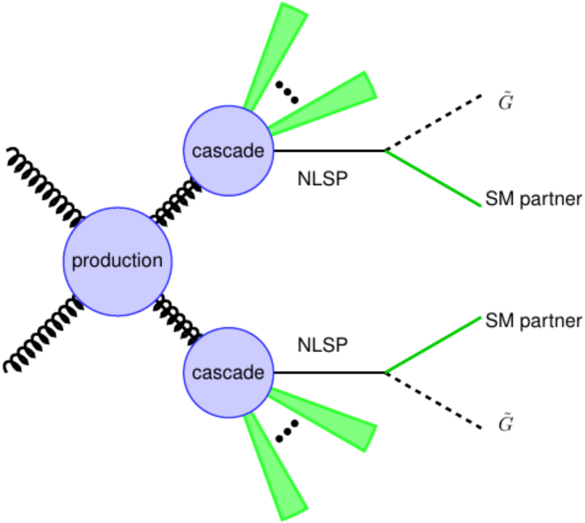
SPS8 GMSB Model						
$\mathbf{M}$mess	N_5	$sgn(\mu)$	$\tan(\beta)$	$\boldsymbol{\Lambda}$	C_{grav}	
$2.\boldsymbol{\Lambda}$	1	1	15	varies	varies	



Supersymmetry Production



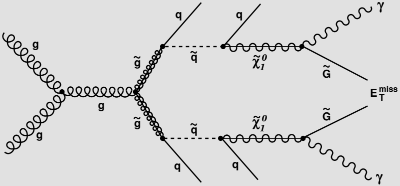
SUSY production mostly in strong interactions at LHC.



production
cascade
cascade
NLSP
NLSP
$\tilde{G}$
$\tilde{G}$
SM partner
SM partner

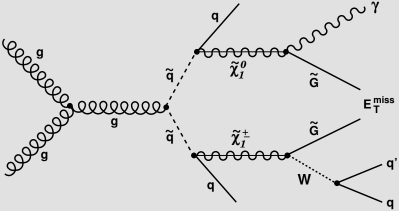
Delayed Photon Production

Double Photon



2 Photons, Jets, Large MET

Single Photon



1 Photon, Jets, Large MET

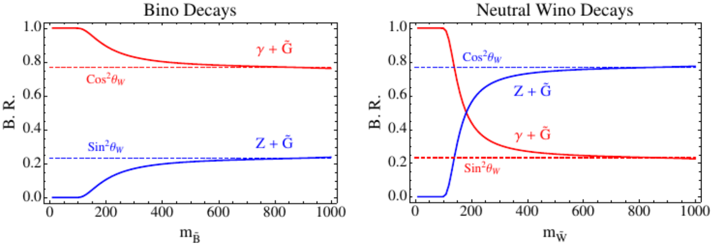
Tranverse Decay Distance

Distance Travelled

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

Proper Decay Length

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



J. Ruderman, D. Shih arXiv:1103.6083

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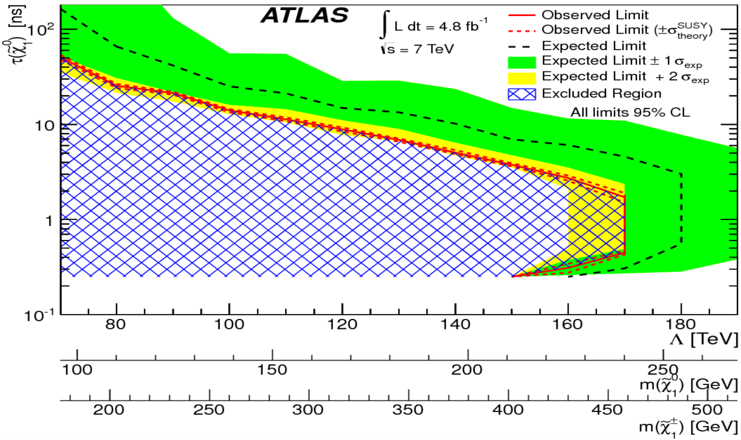
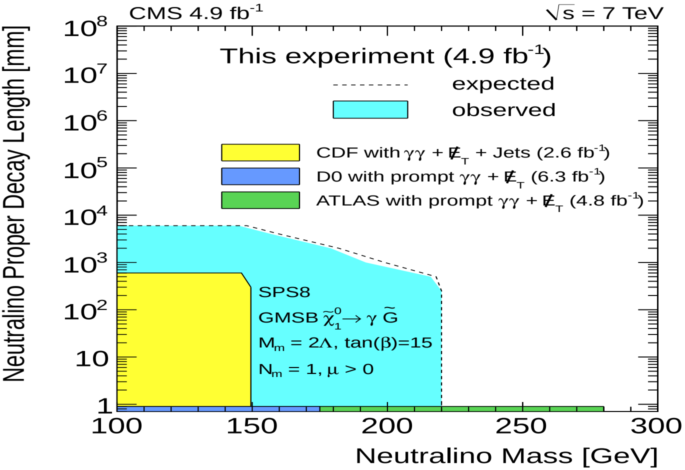
SEARCH ANALYSIS
RESULTS
SUMMARY

ATLAS



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

CMS, CDF, DO

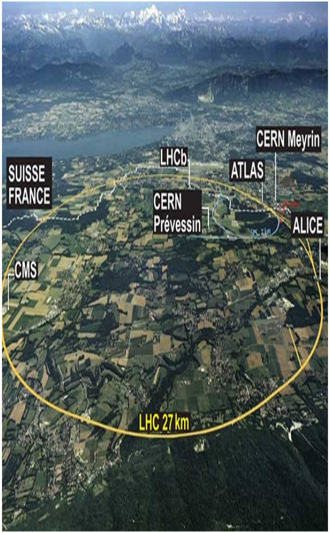


Excluded: Mass $>$ and $c\tau >$.

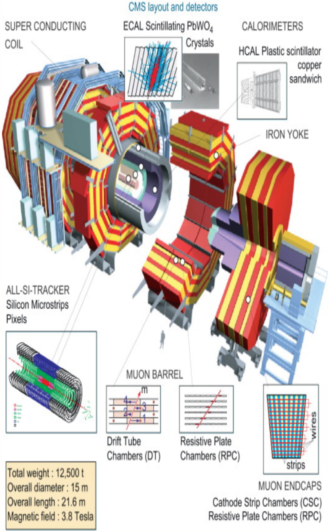
ECAL TIMING

LHC and CMS

LHC

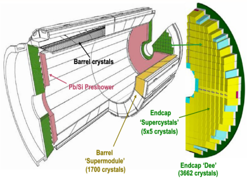


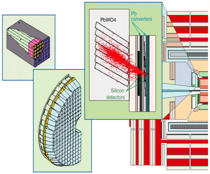
CMS Detector

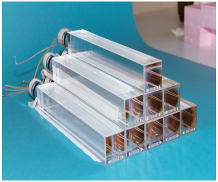


Electromagnetic Calorimeter

ECAL Subdetector





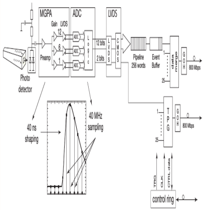


Barrel Detector (EB): $|\eta| < 1.475$.
Endcap Detectors (EE): $1.5 < \eta < 3.0$..

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.

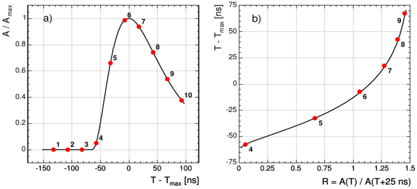
Readout Chain



ECAL Time Measurement

Time Reconstruction

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



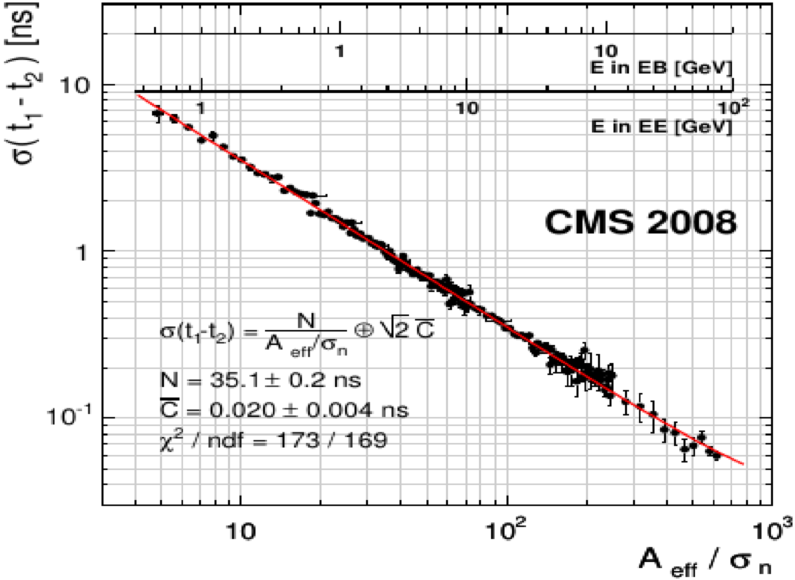
Time Measurement

▷∗ **Error Weighted**

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

Time Resolution Equation and parameter Definitions.

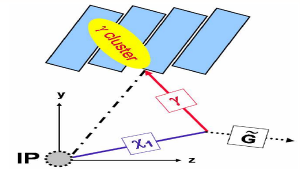
Test Beam Performance



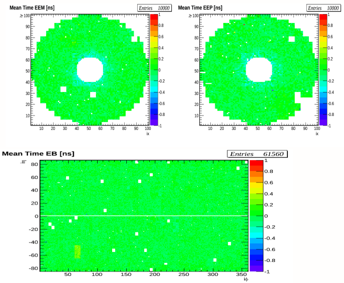
Timing Calibration

Calibration Procedure

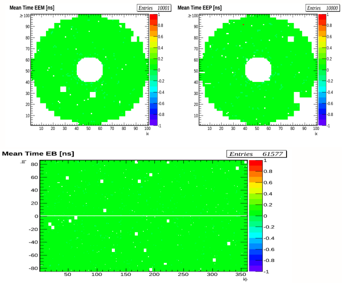
- Adjust Crystal time such that $\langle t^{\gamma}_{crys} \rangle \approx 0$
- Average is over events(*rechits*)/crystal.



Before Calibration



After Calibration

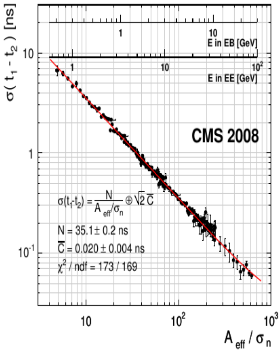


ECAL Timing Performance

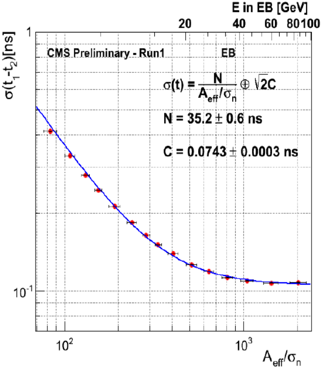
ECAL Timing Resolution

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

Test Beam



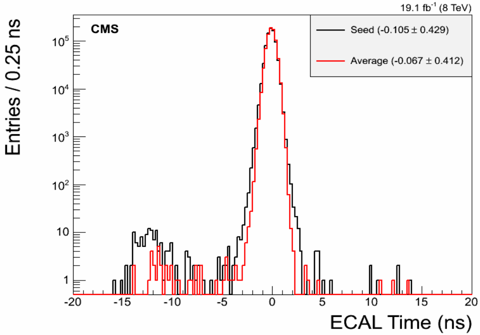
LHC RUN I



ECAL Photon Arrival Time

1. T_γ = Error weighted average time of crystals in photon.
2. T_γ = Seed (most energetic) crystal time.

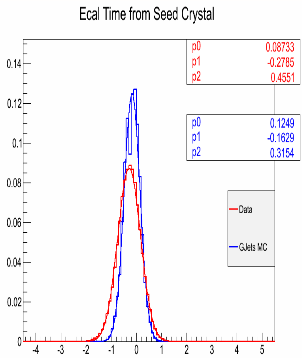
Photon Arrival Time



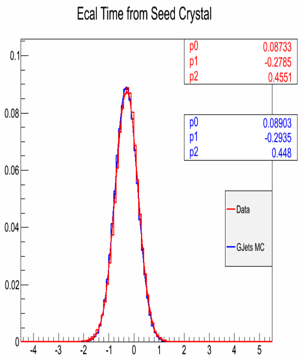
- ▷∗ Similar time in seed and average.
- ▷∗ Photon time = Seed crystal time.

MC Vs Data ECAL Timing

Before Correction



After Correction



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

SEARCH ANALYSIS

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

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

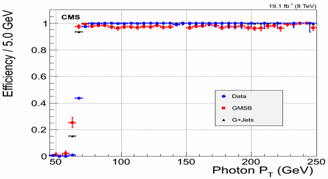
- **Signal MC [GMSB (SPS8)]**

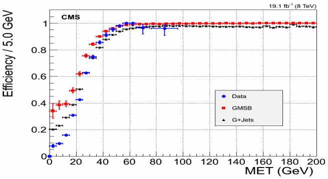
Λ [TeV]	100	120	140	160	180	300
$M_{\tilde{\chi}_1^0}$ $[GeV/c^2]$	140	169	198	227	256	430
$c\tau$	215	325	130	245	185	
(mm)	425	645	515	490	365	495
	1700	1290	1030	975	730	
	3400	1935	2060	1945	1100	995
	5100	2955	2920	2930	2195	2960
	6000	3870	3985	3910	3950	
	9300	5985	6000	5875	5980	6000
		9825	10450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

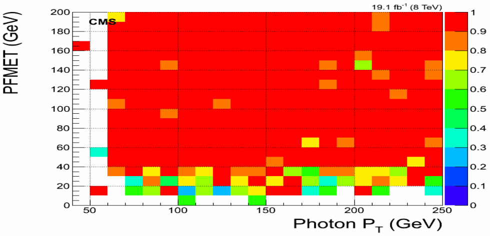
- **$\gamma+$ Jets MC**

$\hat{p}_T$ [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_DisplacedPhoton65_CaloIdVL_IsoL_PFMET25

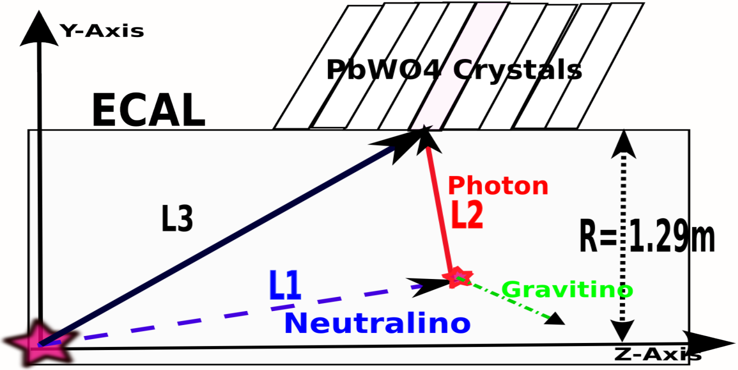






Source of Delayed Photons?

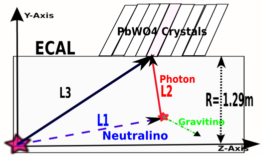
- Decay of slow moving particles; $\beta << 1$,
- Non-nominal photon flight path,
- Stopped particles in detector.

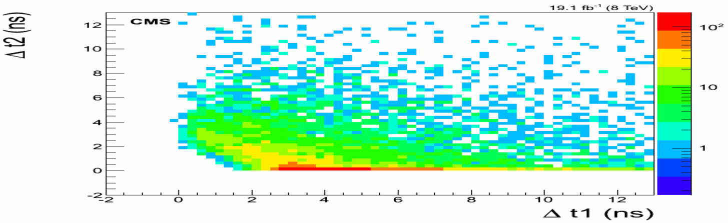


Photon Measured Time

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

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

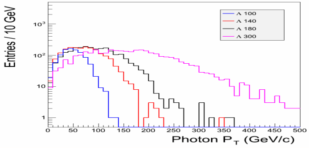




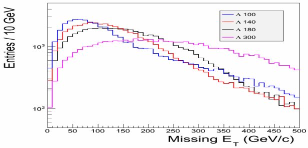
- Delayed photons mostly from slow moving decay.

Kinematic Distribution

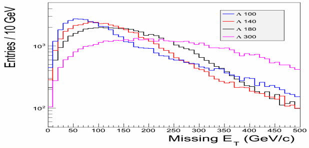
Photon p_T



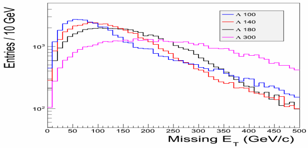
Neutralino $c\tau$



MET(E_T^{miss})



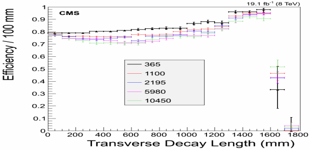
NJets



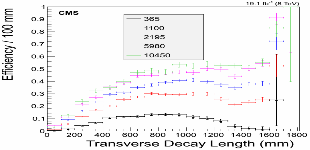
- Different Λ values with the same $c\tau$(10 m). Photon p_T is harder with higher values of Λ.

Signal Efficiency and Acceptance

Efficiency

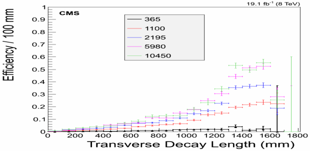


Acceptance

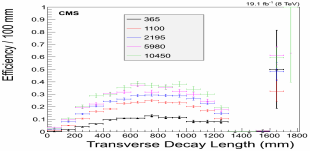


- Slow moving neutralino decay causes sudden efficiency drop.

Slow moving



Off-Pointing



- Peak Acceptance at transverse decay length= 800 mm.

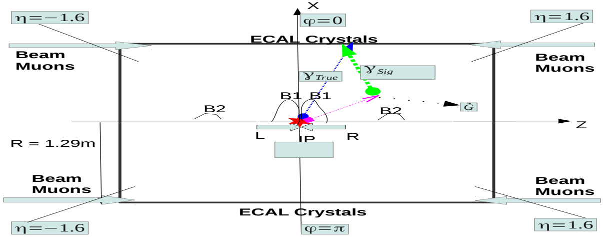
Signal and Background

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.

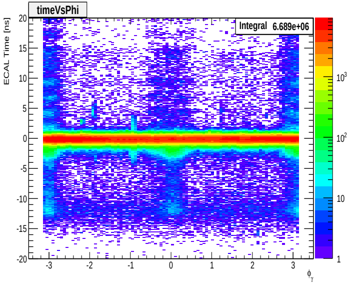
- **Background Sources**

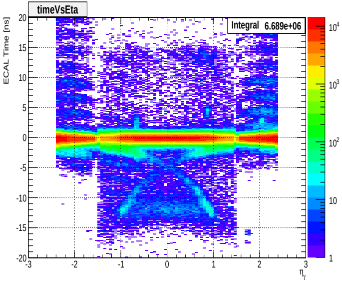


- **Strategy**
  - I Identify, tag and reject Non-Collision events.
  - II Perform ABCD background estimation technique on residual non-collision events.
  - III Perform ABCD background estimation technique on collision events.
  - IV Performed a combined ABCD background estimation technique.
- **Clusure 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.

Events Cleaning

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



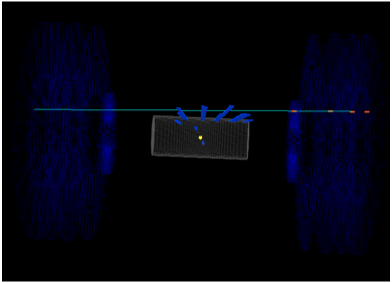


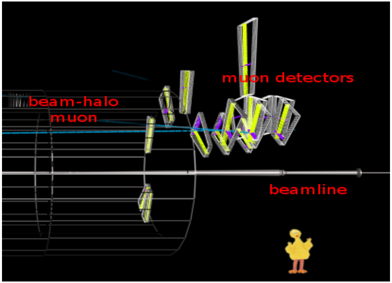
Features around $\phi = 0, \pm\pi$ and η-dependence shows that background sources originate from both collision and non-collision events.

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.

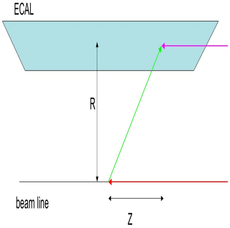
will produce energetic muons traveling parallel with main proton beam and showering in the Calorimeters.





Halo Photon (II)

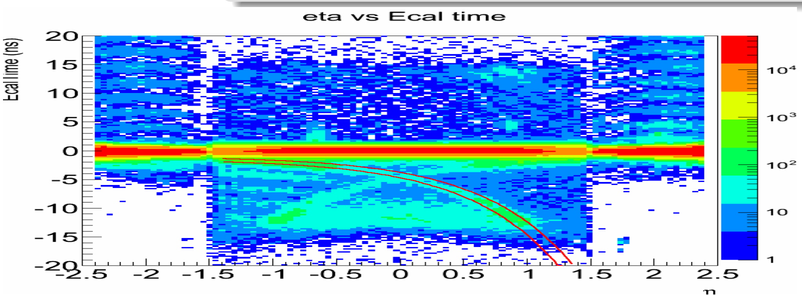
Using Halo kinematics, We can tag and estimate halo photons produced from halo muons showering in ECAL as follows:



Halo Expected ECAL Time

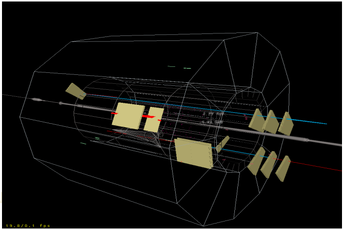
$$t_0 = \frac{\rho}{c} = \frac{R}{\sin\theta}\frac{1}{c}, \quad t_{halo} = \frac{Z}{c} = \frac{R}{\tan\theta}\frac{1}{c}$$

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



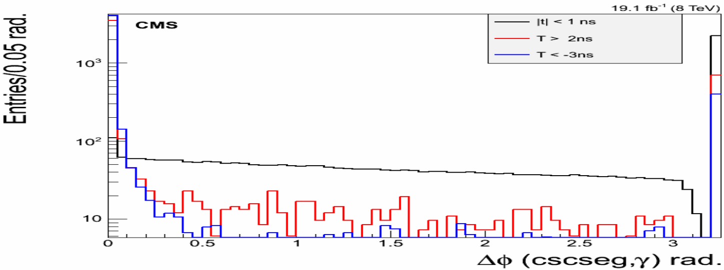
Halo Photon (III)

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

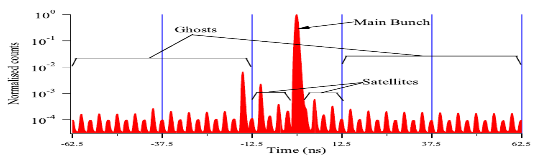
$$\Delta\phi(CSCSeg, \gamma) = |\phi_{CSCSeg} - \phi_{\gamma}|$$



Satellite/Ghost Beam Halos

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

LHC LDM Proton Beam Profile



Halo Photon (V)

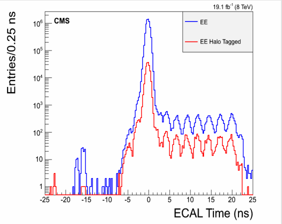
Halo Photon Event Properties

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

Halo Photon Tagging Criteria

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

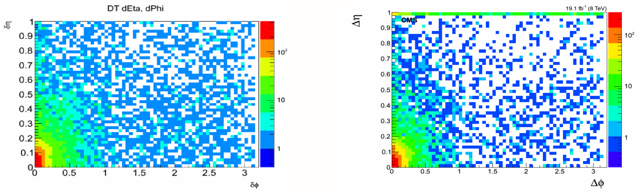
Ghost/Satellite EE



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)

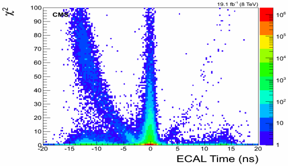


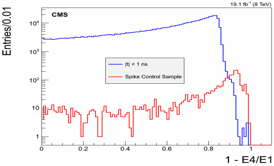
$DT(\delta\eta, \delta\phi)$ tagging of cosmic muons in data and a pure cosmic sample(without LHC proton beam) is comparable.

ECAL Spikes

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

Spike Identification and Rejection





PF-Missing Transverse Energy(PF-MET)

PF-Missing Transverse Energy($E_{\mathrm{T}}^{\text{miss}}$)

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

- $\mathbf{E}_{\mathrm{T}}^{\text{miss}}$: PF-MET.
- $\mathbf{E}_{\mathrm{T}}^{\text{miss}^{\gamma}}$: PF-MET with photon E_{T}.

Signal Selection Criteria

SIGNAL: $\geq 1\gamma + \geq 2Jets + E_{T}^{\text{miss}} > 60$ GeV, $E_{\mathrm{T}}^{\text{miss}^{\gamma}} > 60$ GeV

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
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 25 GeV

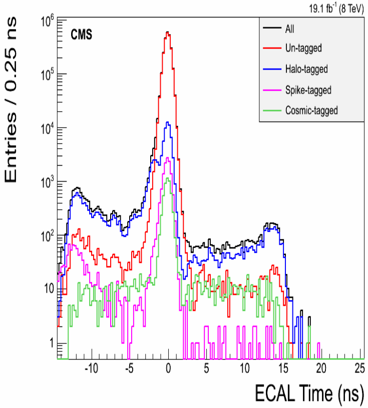
Mis-Tagging Rate

- Tagging reliable but not 100% efficient.

Mis-Tag Rates

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

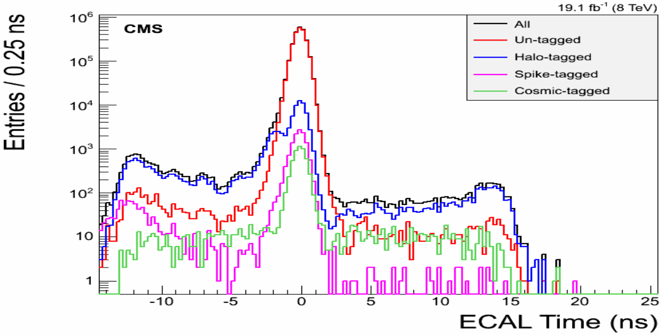
Tagging Performance



ABCD Background Estimation

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.

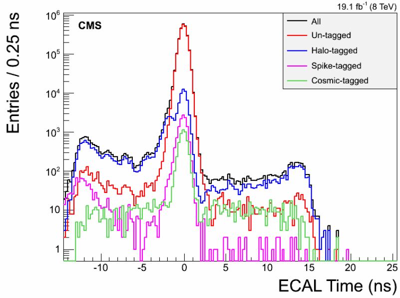
Event Tagging and Cleaning Performance



Non-Collision Events.

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

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



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

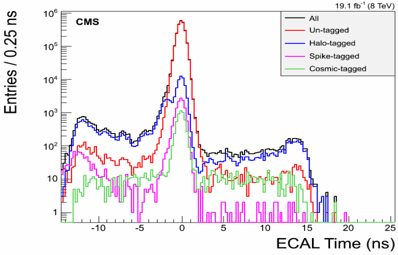
$$\mathbf{D} = \frac{\mathbf{B}}{\mathbf{A}} \cdot \mathbf{C}$$

ABCD Method: Collision Background

Collision Events.

$E_{\mathrm{T}}^{\text{miss}\,\gamma} < 60$ **GeV**

	$E_{\mathrm{T}}^{\text{miss}} < 60$	$E_{\mathrm{T}}^{\text{miss}} > 60$
$-10 < t < -3$ ns	B'	B
$\lvert t\rvert < 2$ ns	F'	F
$3 < t > 13$ ns	D'	D



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

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

$$\mathbf{Q_b} = \frac{\mathbf{F}}{\mathbf{F'}} \cdot \mathbf{B'}$$

ABCD Method:Combined Background

Combined Background Estimation.

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

Closure Test: < 2-Jets Events

$E_{\mathrm{T}}^{\text{miss}^{\gamma}} < 60$ **GeV**

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

Closure Test: < 2-Jets Events

$E_{\mathrm{T}}^{\textbf{miss}} > 60$ **GeV**

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

Control Sample $Z \rightarrow ee$ 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

- 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.

RESULTS

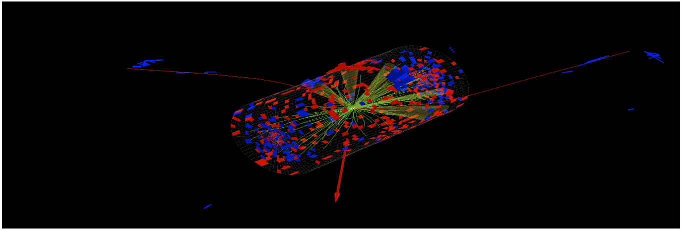
- Observed **1 Event**
- Expected **0.0886 Events**

Events Passing Final Selection

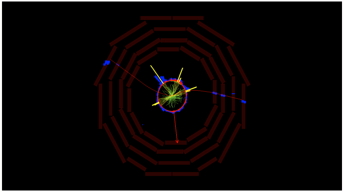
Sample	**Lifetime($c\tau$)[mm]**	**Number Of Events**
GMSB $\Lambda = 180$ TeV	10500	
GMSB $\Lambda = 180$ TeV	6000	
GMSB $\Lambda = 180$ TeV	4000	
GMSB $\Lambda = 180$ TeV	3000	
GMSB $\Lambda = 180$ TeV	2000	
GMSB $\Lambda = 180$ TeV	1000	
GMSB $\Lambda = 180$ TeV	500	
Data	1.00	
Background Total	0.0886	

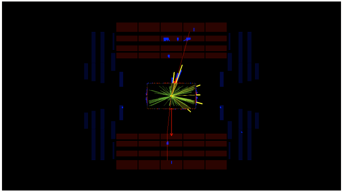
Observed Event

3-D View



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





Exclusion Limits

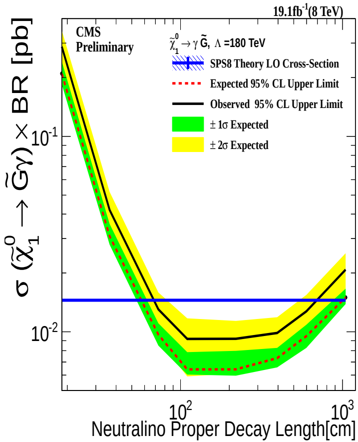


Figure : $c\tau$ Limits

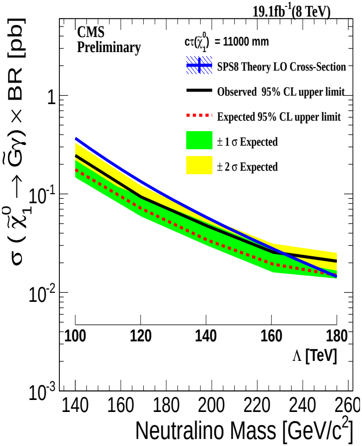
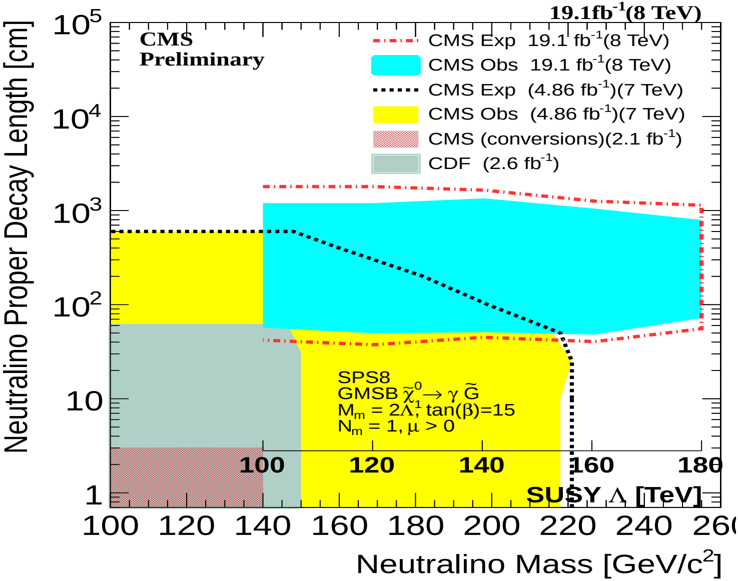
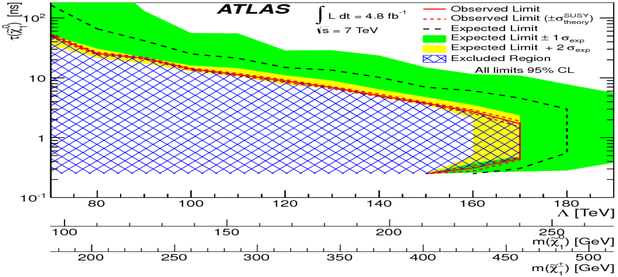


Figure : Mass Limit

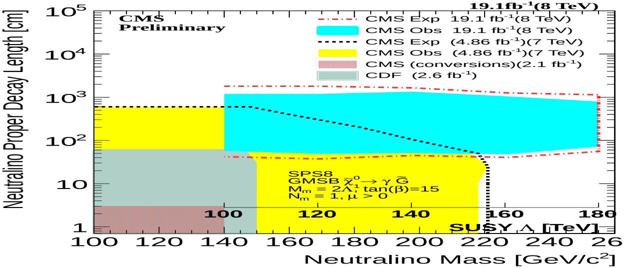
$c\tau$-mass Limits



▷∗ ATLAS



▷∗ CMS 8 TeV

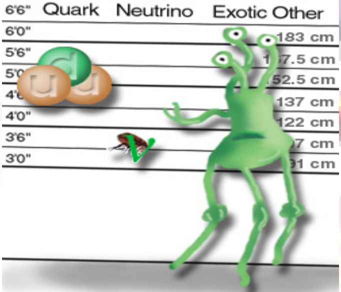


SUMMARY

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.

Merci Beaucoup!



"All right... which of you punks is responsible for dark matter?"

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

BACK UP

Funny Quarks

Signal Efficiency and Acceptance(III)

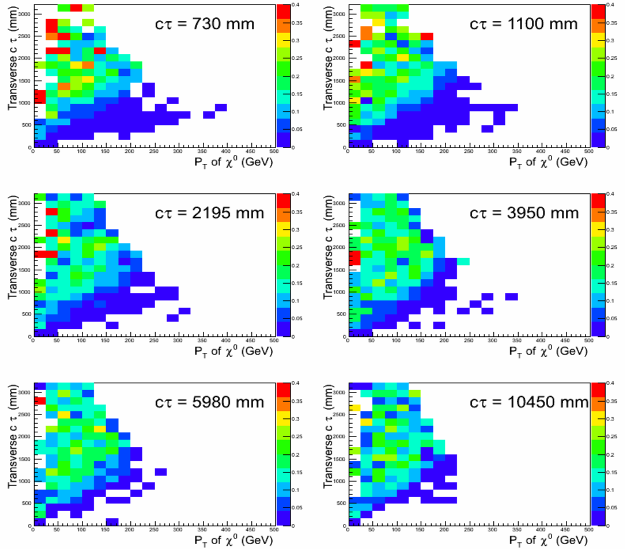


Figure : 2 Dim Efficiency

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.

HP Tagging Criteria

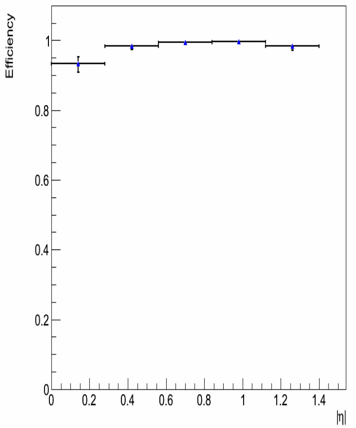
Halo Photon Tagging Efficiency

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

Halo Photon mis-Tag Rate

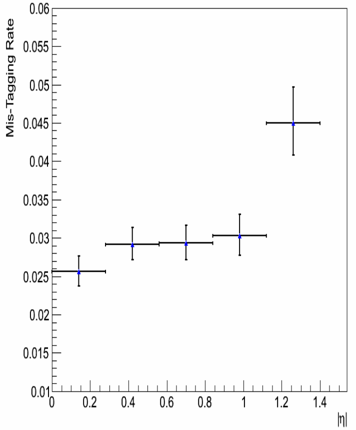
- Control Sample Selection:
  - $>=$ 2-jets events with $E_T^{miss} < 60$ GeV
  - ECAL time, $|t| < 1$ ns.
- mis-tag rate eveluated in 5η bins for S_{major} η dependence.

Tagging Efficiency



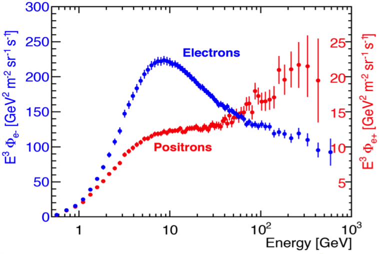
- Tagging Efficiency $\approx 98\%$

mis-Tag Rate

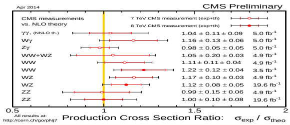


- mis-tag rate $\approx 3\%$

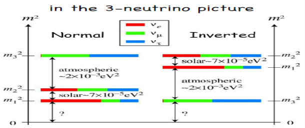
AMS Experiment on ISS



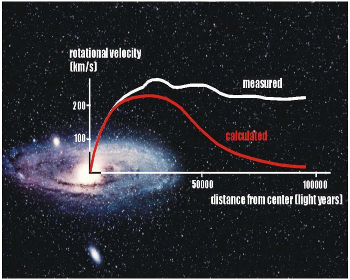
ZZ, WW Production

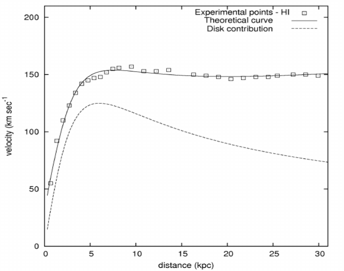


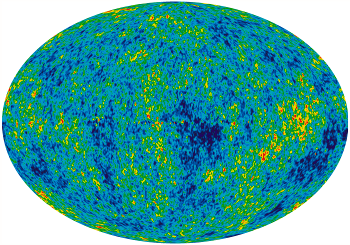
Neutrino Masses.

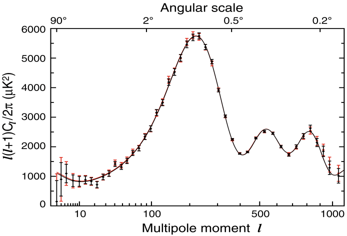


Dark Matter.

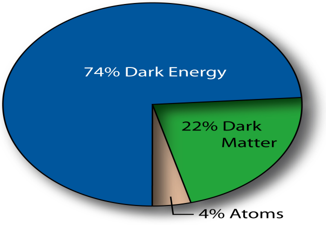

rotational velocity
(km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)


Experimental points - HI
Theoretical curve
Disk contribution
200
150
100
50
0
velocity (km sec^{-1})
0
5
10
15
20
25
30
distance (kpc)




Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
10
100
500
1000
Multipole moment l

Universe Matter Budget.



Dark Matter in our Galaxy?.