Search for Long-Lived Neutral Particles in Final States with Delayed Photons and Missing Transverse Energy in proton-proton collisions @ $\sqrt{s} = 8$ TeV

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Oral Exam

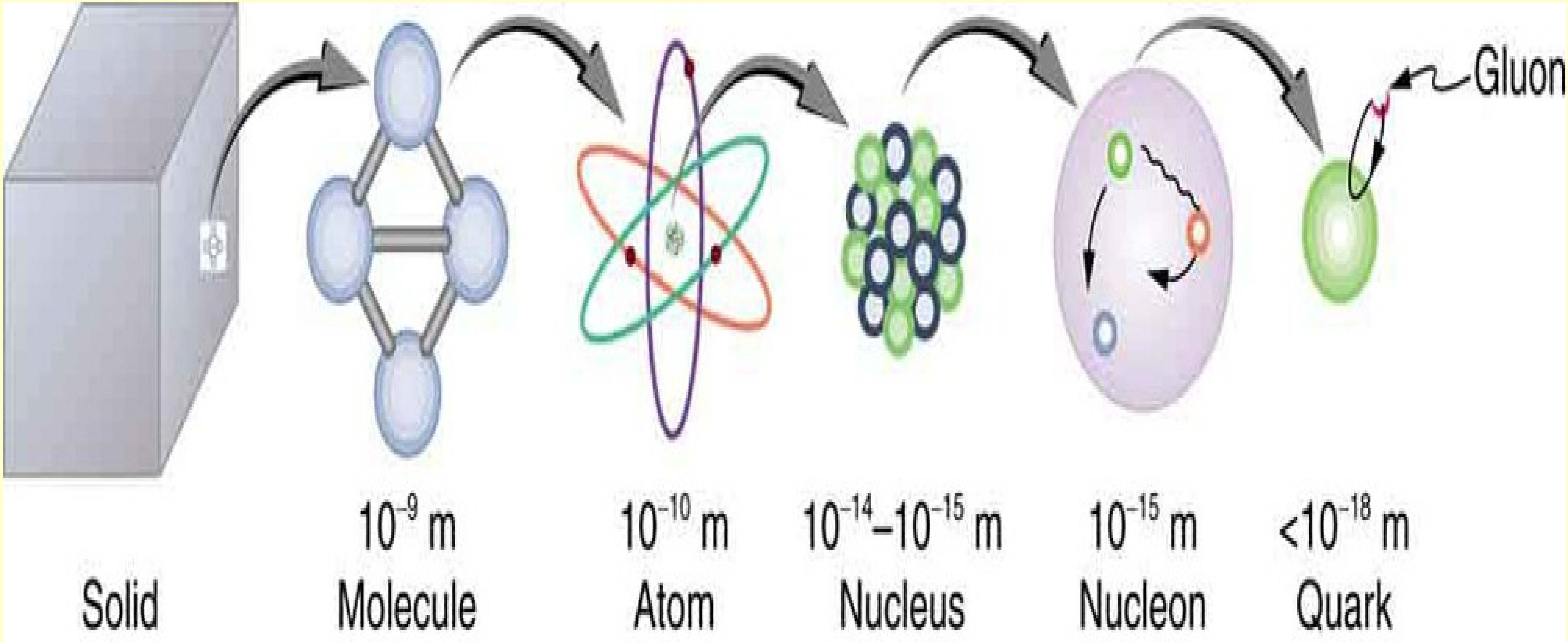
Nov 3, 2015

MENU

- Introduction
- ECAL Timing
- Search Analysis
- Result
- Summary

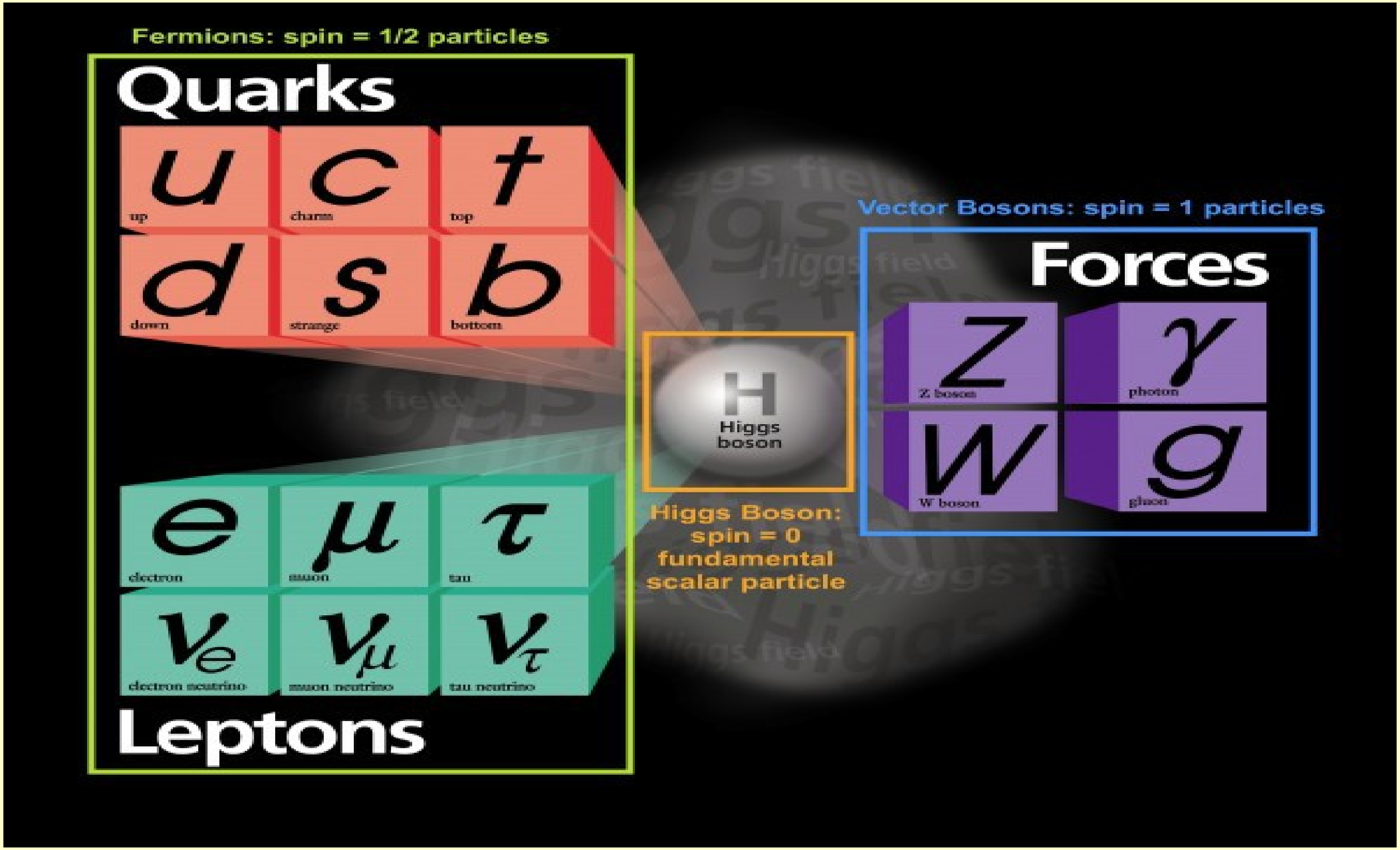
Introduction

Introduction



- Description of matter at lengths of about one billionth of a billionth of a meter.

The Standard Model



- Describes visible matter in the entire universe.

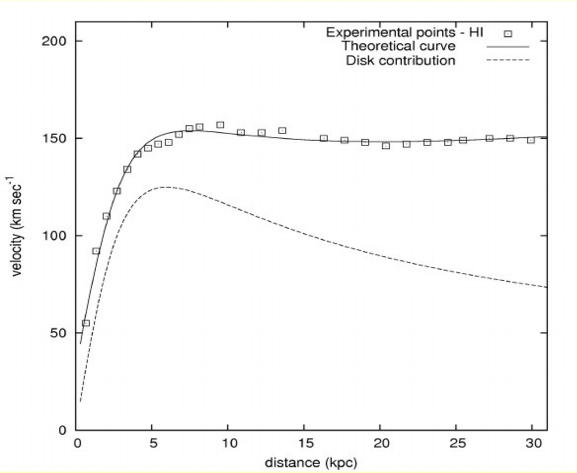
SM: Interactions & Lifetimes

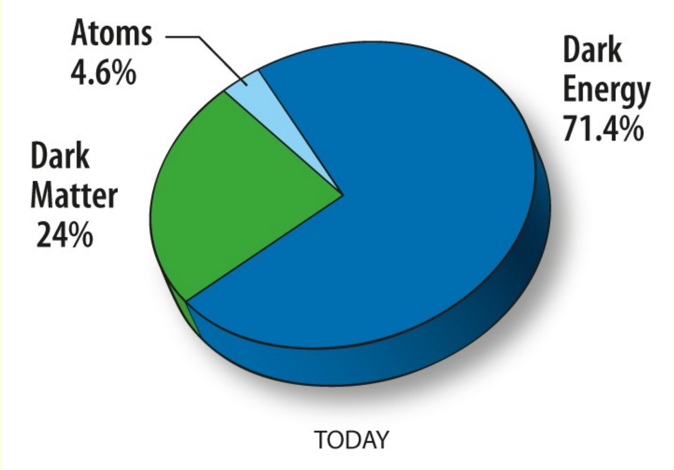
Boson	Interaction	Symmetry	Lifetime
W, Z	Weak	$SU(2)_L \otimes U(1)_Y$	10^{-8} to 10^{-13} s
Photon	Electromagnetic	$U(1)_Q$	10^{-14} to 10^{-20} s
Gluons	Strong	$SU(3)_C$	$< 10^{-22}$ s

- The SM does not describe gravity for which the typical lifetime is about the age of the universe(about 13.7 billion years).

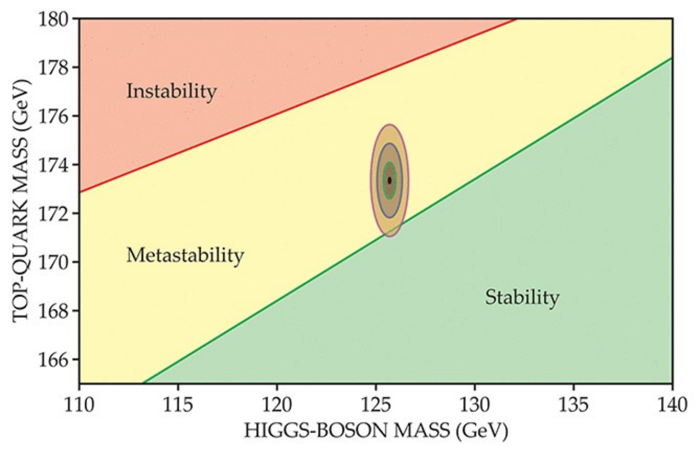
Exotic Forms of Matter

- Non-Visible or Dark Matter.





- Massive Long-Lived particles.
  - Mass > 1 GeV/cc,
  - Lifetimes from one billionth of a second to 13.7 billion years,
  - Neutral or charged.



Meta-stable universe: V.Branchina et al: http://dx.doi.org/10.1007/JHEP09(2014)182

Long-Lived Particle Models

- **Supersymmetry (SUSY):**

$$\boxed{\begin{bmatrix} \mathbf{Q}|fermion\rangle & = & |boson\rangle \\ \mathbf{Q}|boson\rangle & = & |fermion\rangle \end{bmatrix} \Rightarrow m_{\mathrm{f}}^2 = m_{\mathrm{b}}^2}$$

However, $m_f^2 \neq m_b^2$

$\Rightarrow$ **SUSY broken**

- **Gauge Mediated SUSY Breaking:**

$\langle F \rangle \sim \boldsymbol{F}$

$E \gtrsim 10^{18}\,GeV$

Breaking sector

U(1) Gauge

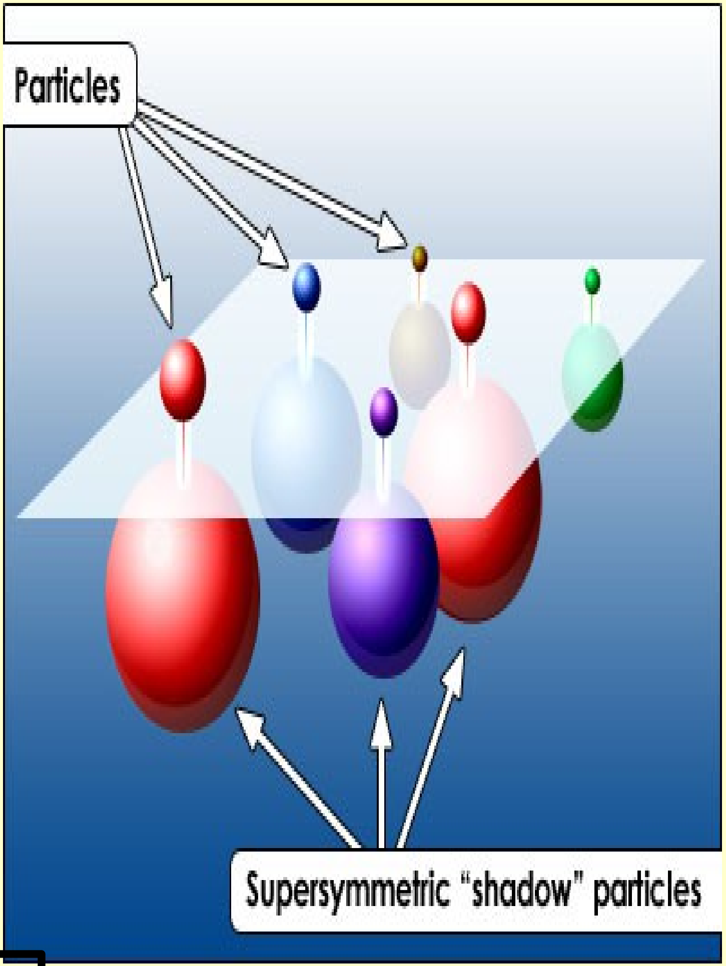
N msgr fields,

mass = **M**

Λ

$E \sim 1\,TeV$

Visible sector



GMSB Models: LL Particles

- Model parameters:
  - F : Fundamental SUSY breaking scale,
  - N : Number of the messenger fields,
  - M : Mass of Messenger particles.
  - $C_{\mathbf{grav}}$: Determines lifetime of the NLSP,
  - Λ : Determines the masses of SUSY particles.
- Typical lifetime of the NLSP with mass **m** is:

$$\boxed{\tau \approx C_{\mathrm{grav}}^{2} \frac{\left(\sqrt{F}\right)^{4}}{m^{5}}}$$

$$10^{-9}\,\mathrm{s} \leqslant \tau \leqslant \mathrm{years}$$

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SPS8 Benchmark GMSB Model

- Choice of parameters:

$$M = 2\Lambda,\ N = 1,\ \tan(\beta) = 15,\ sgn(\mu) > 0$$

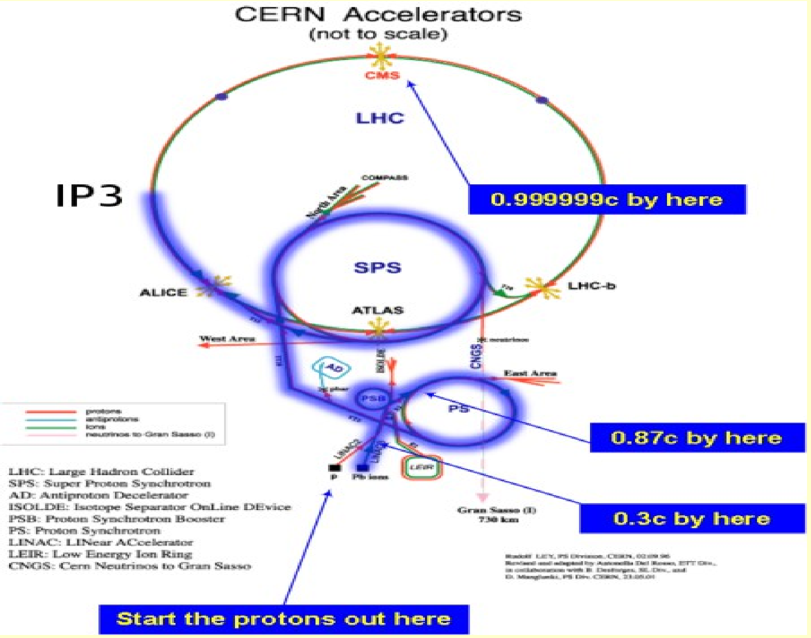
Λ and C_{grav} varies.

- Lightest Neutralino is the NLSP and decays to photon and gravitino 83 to 94 % of the time.
- Gravitino is the Lightest Supersymetric Particle(LSP).
- Lifetime of NLSP ranges from few **nanoseconds** to several **meters**.

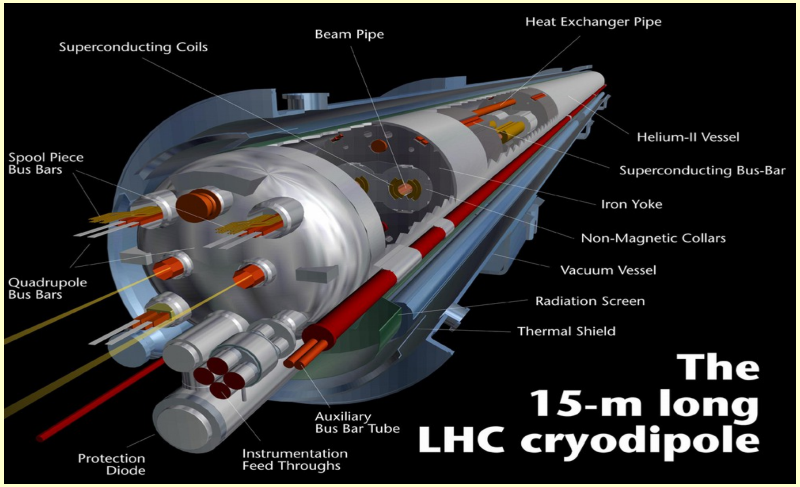
ECAL Timing

Large Hadron Collider

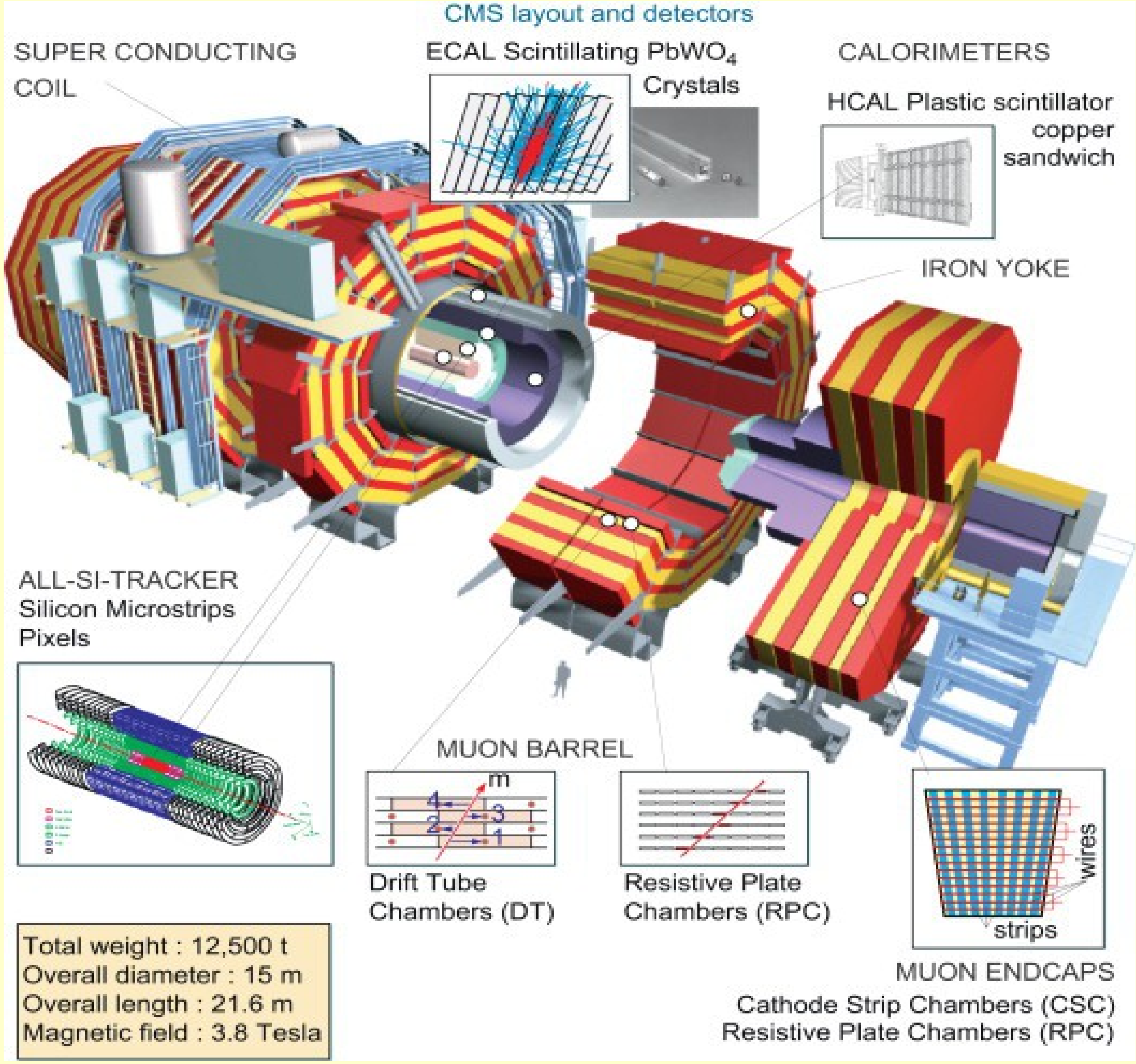
- **Search for Signatures of :**
  - The Higgs Boson,
  - Supersymmetry,
  - Dark matter.

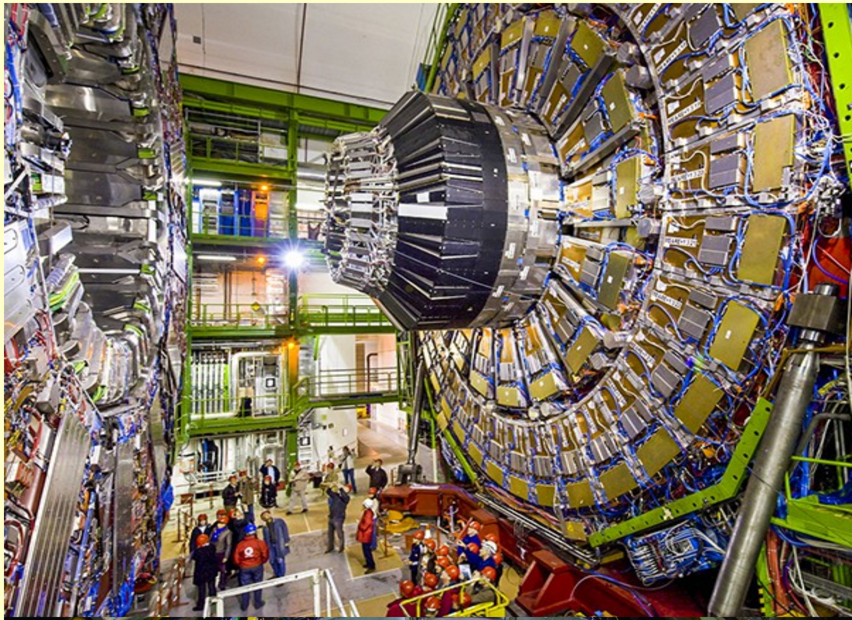


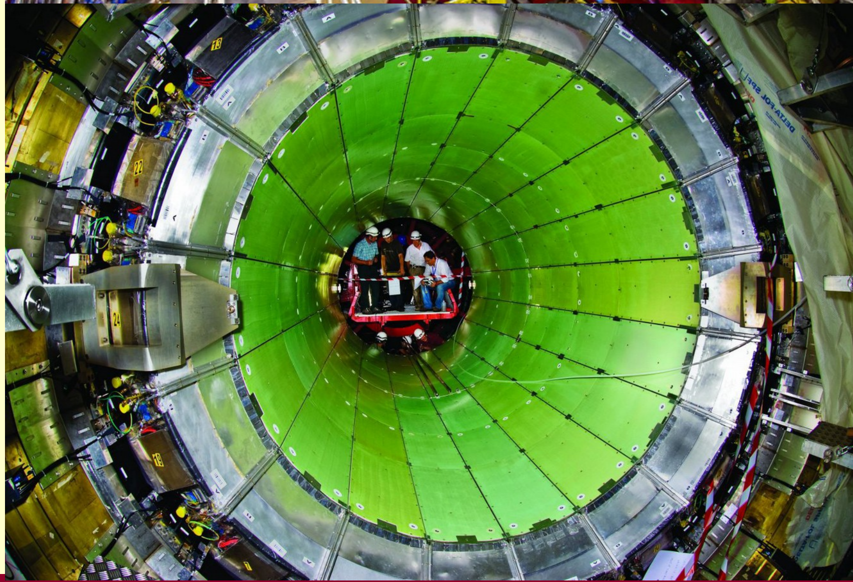
- **Designed Specifications :**
  - Proton-Proton bunch circulating in 26659m circumference synchrotron.
  - Accelerate protons up to 7 TeV.
  - 10^11 protons collide every 25ns.
  - Dipole and quadrupole magnets steer proton beams.



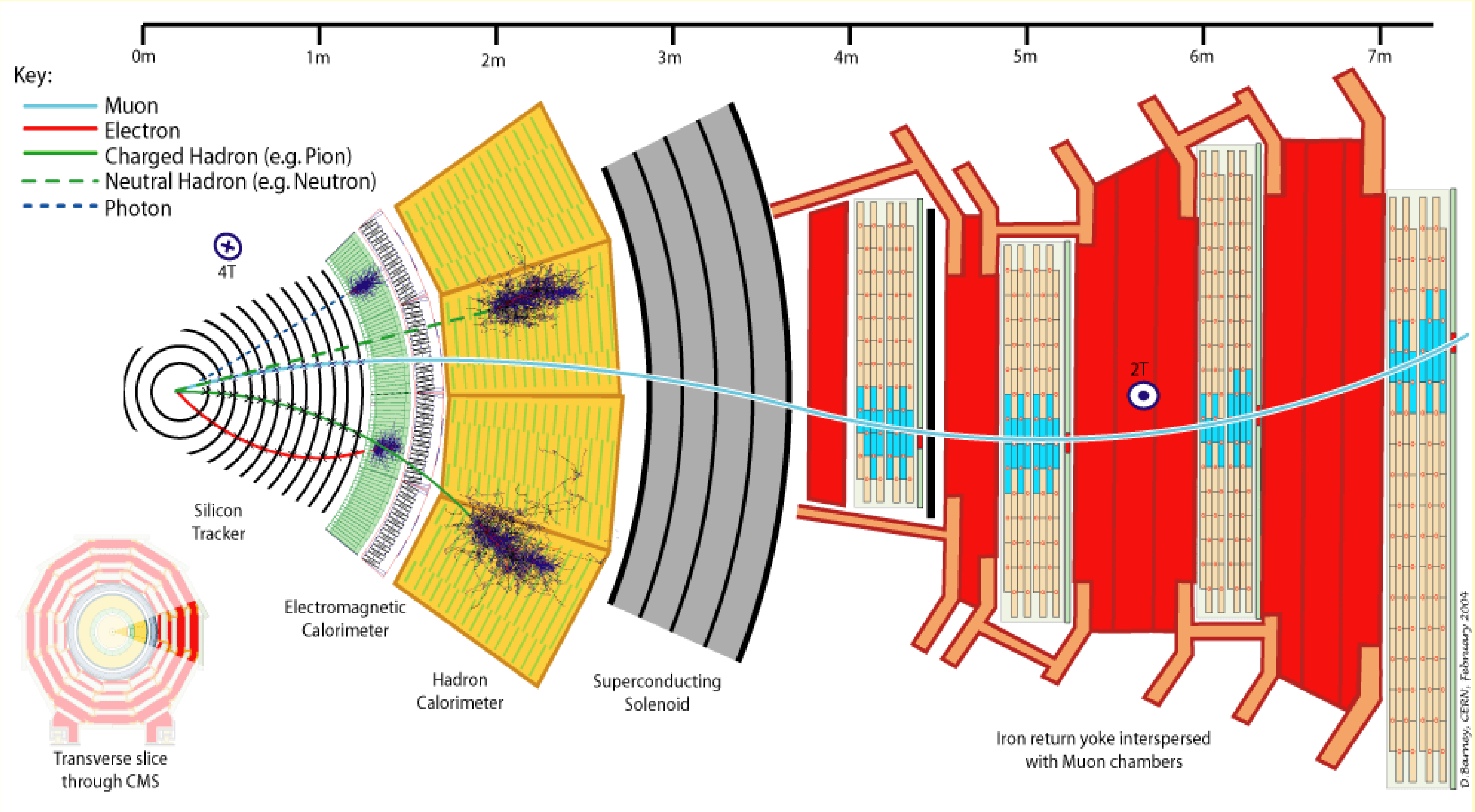
Compact Muon Solenoid





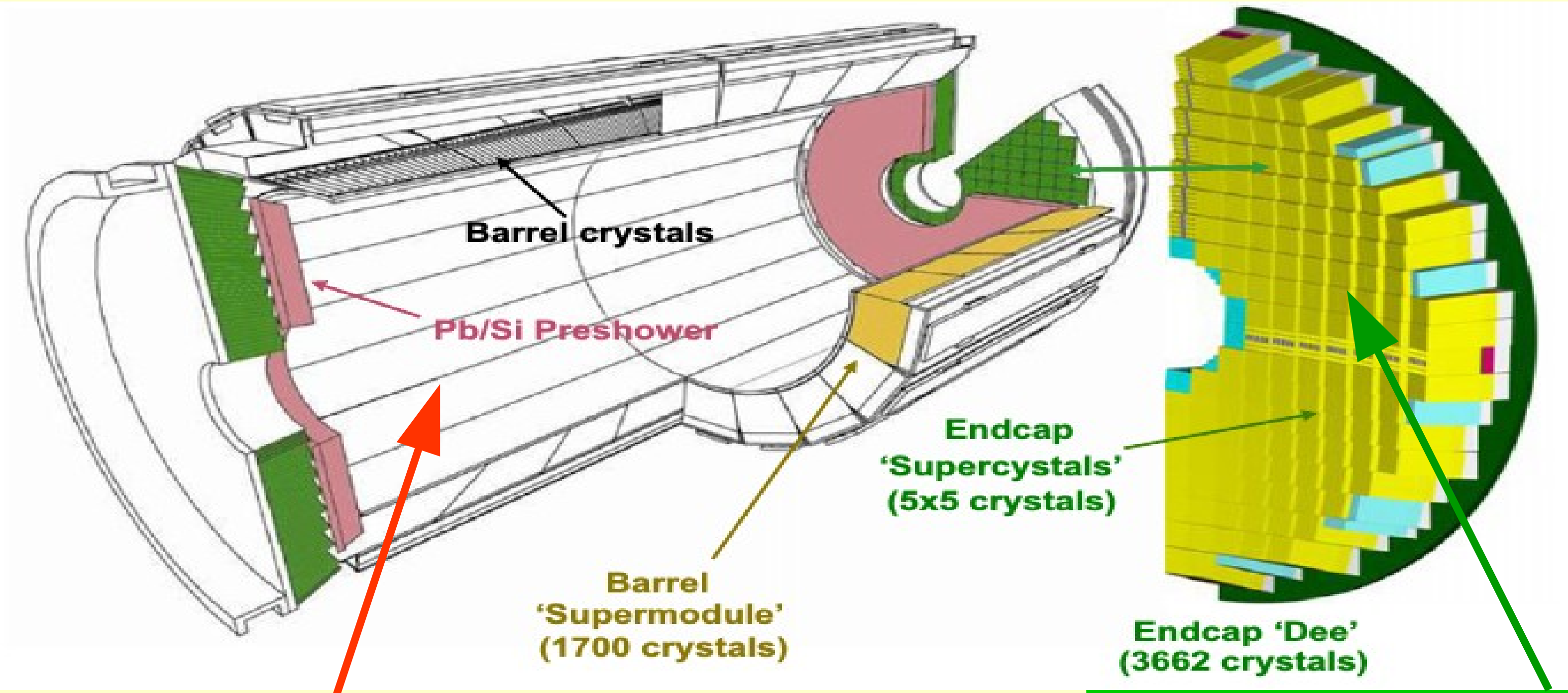


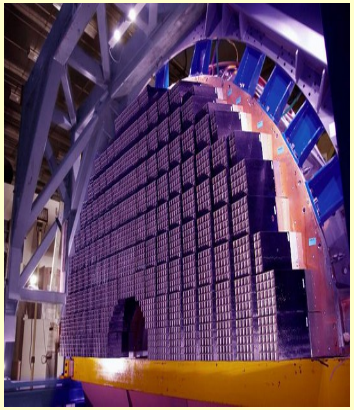
Particle Detection



Electromagnetic Calorimeter

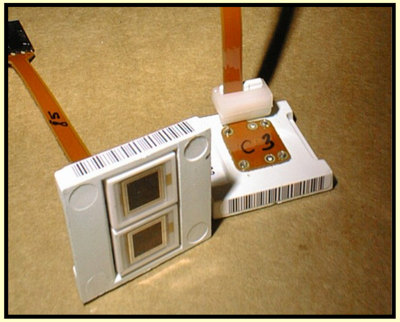
Lead Tungstate crystal Homogeneous calorimeter





Barrel(EB)

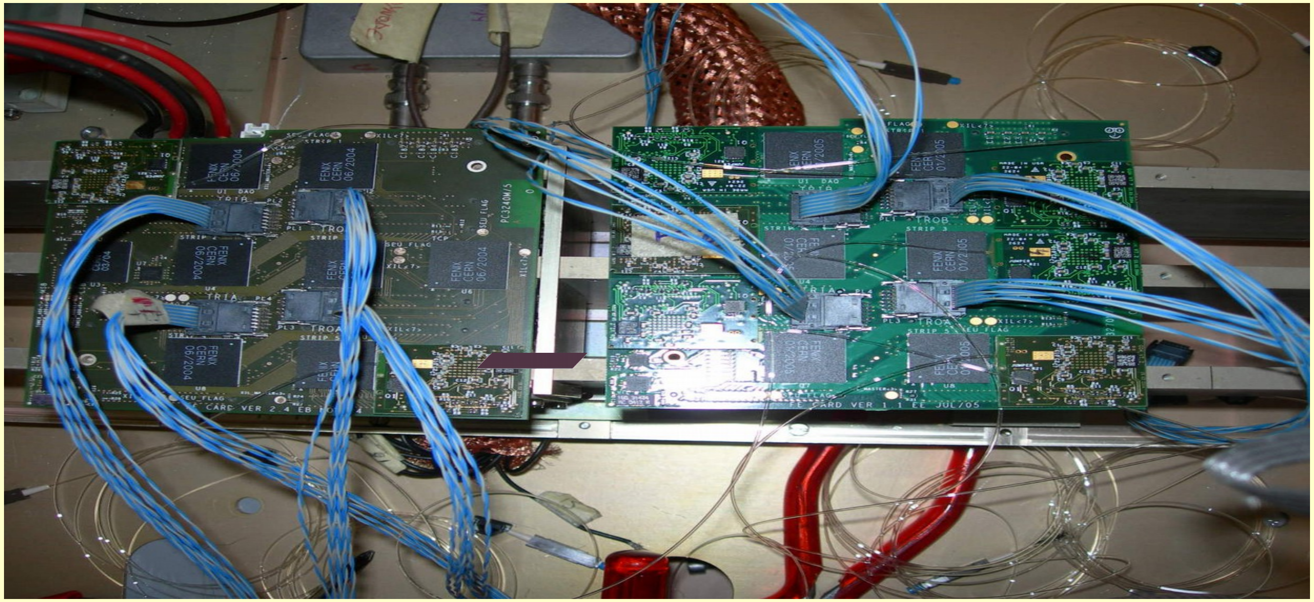
- 61200 crystals
- Covers |eta| < 1.48
- Uses APD photodetectors

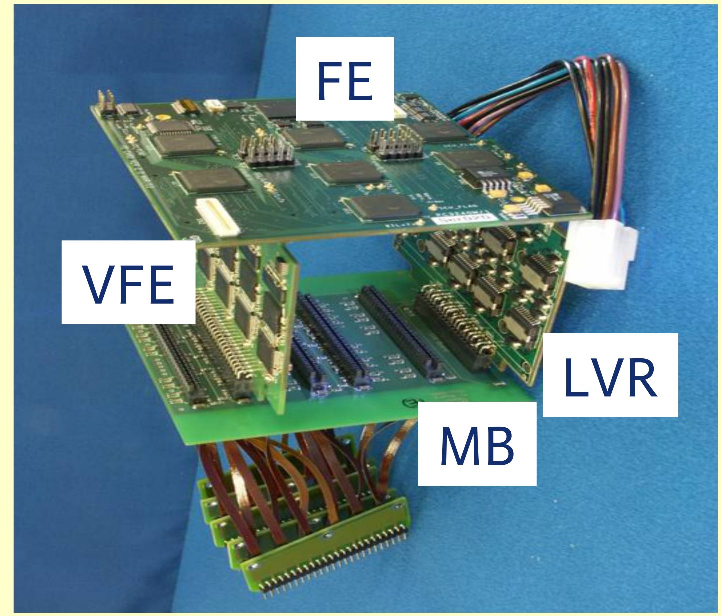


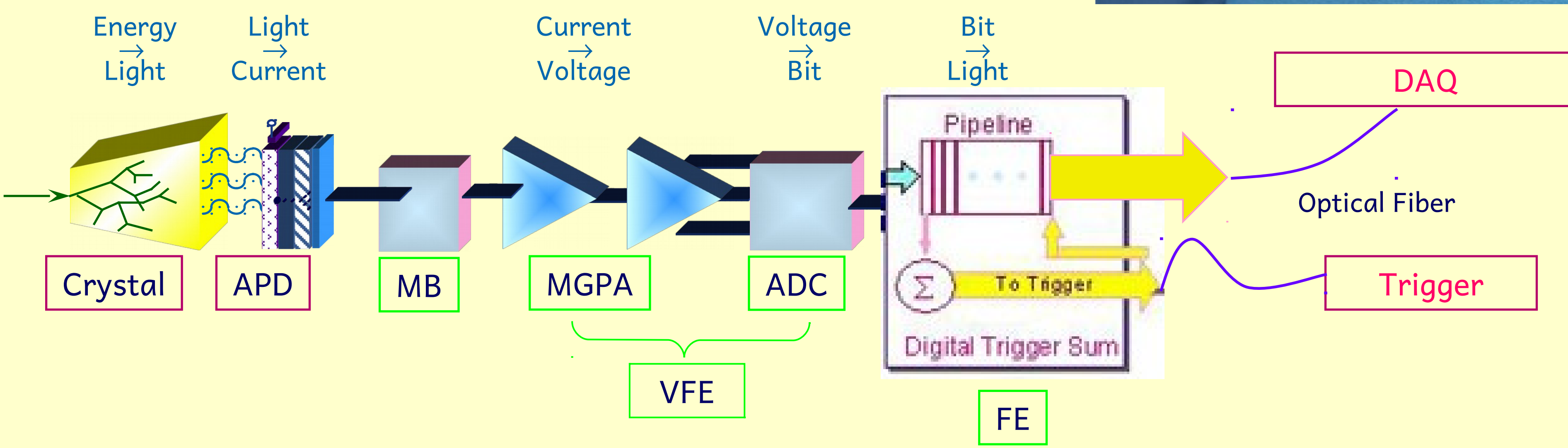
Endcap(EE)

- 2 Endcap sides each 7324 crystals
- Covers 1.48 < |eta| < 3.0
- Uses VPT photodetectors

ECAL ReadOut Electronics





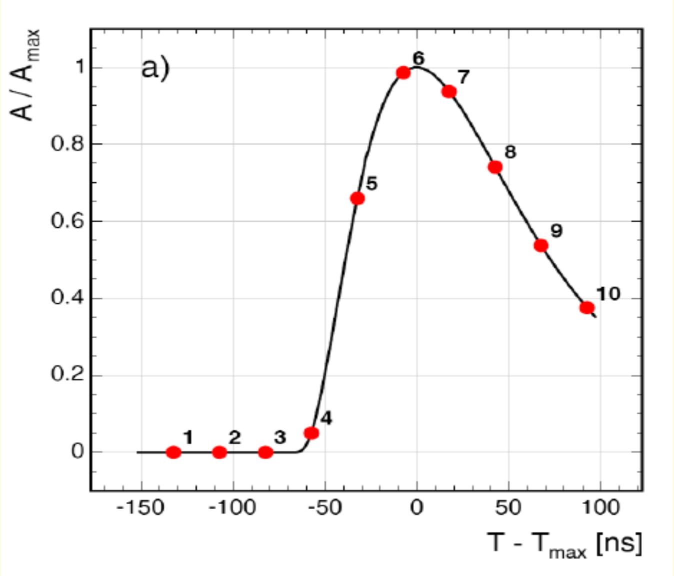


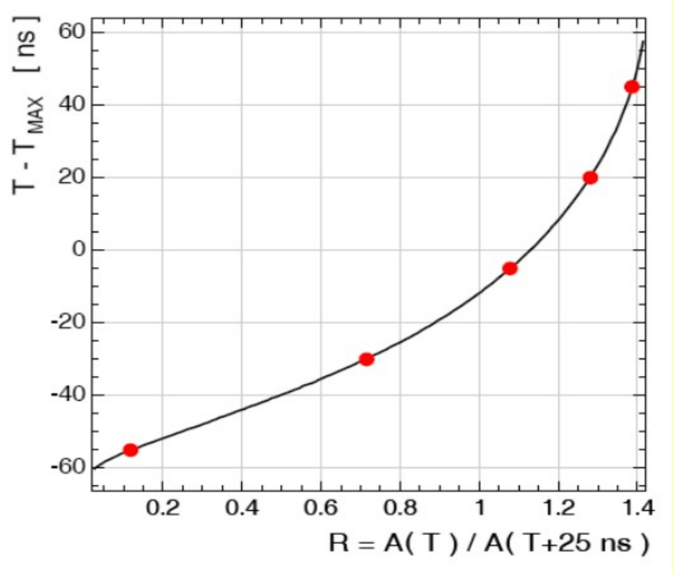
ECAL Time Measurement

- Each Crystal/Channel: Pulse
  - Digitize pulse amplitude into 10 samples,
  - **A_{Max}** for energy and **T_{Max}** for time,
  - Re-write pule height in ratios: $R_i = \frac{A_i}{A_{i+1}}$
  - Each R_i gives $(T_{\mathrm{Max},i}, \sigma_i)$: $T_{\mathrm{Max},i} = T_i - T(R_i)$
  - Precise value of **T_{Max}**:

$$T_{\mathrm{Max}} = \frac{\sum_{i=4}^{7} \frac{T_{\mathrm{Max},i}}{\sigma_i^2}}{\sum_{i=4}^{7} \frac{1}{\sigma_i^2}},$$

$$\sigma_T = \sum_{i=4}^{7} \frac{1}{\sigma_i^2}$$

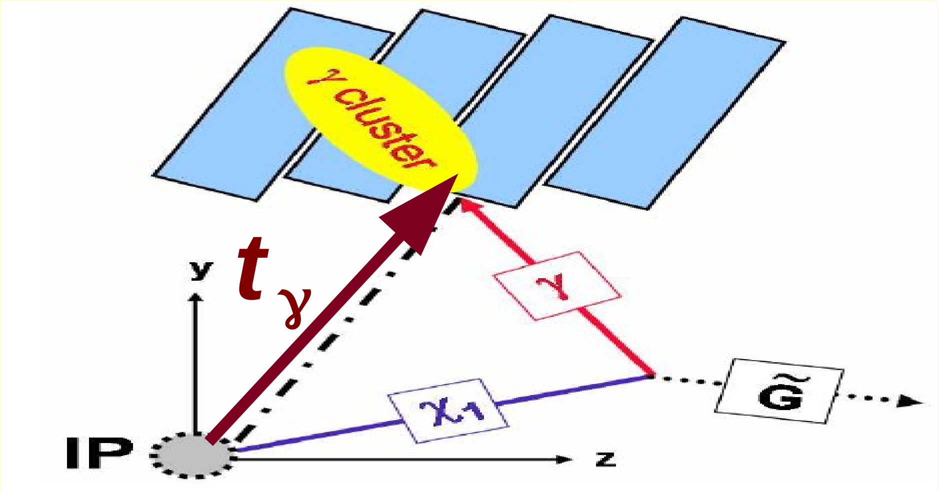




Crystal Time Alignment

- Time Alignment
  - Adjust crystal time such that:

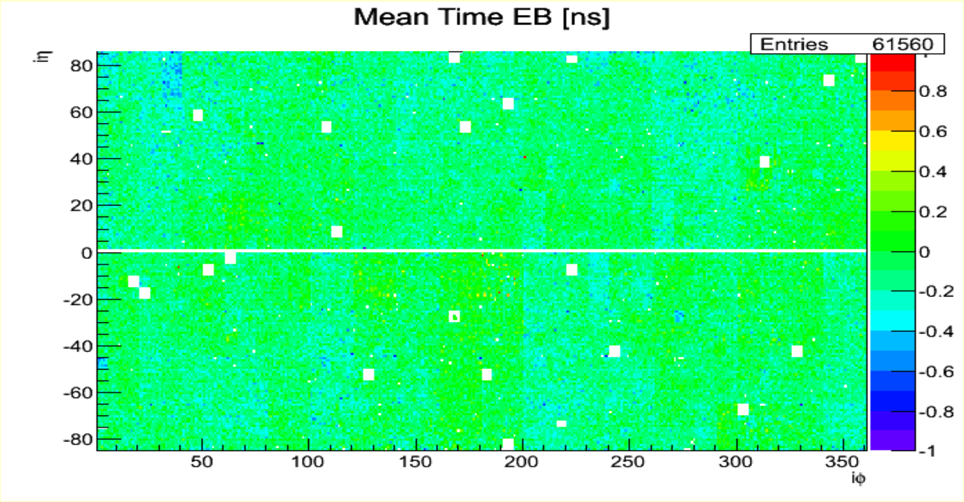
$$\langle t_{\gamma}^{\text{crys}} \rangle \approx 0$$

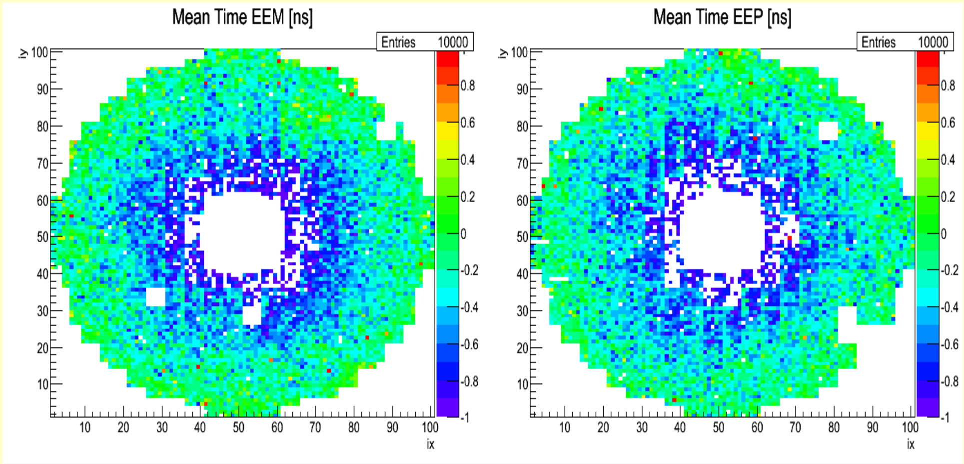


	Before Alignment		After Alignment	
	Avg. Mean Time[ns]	Sigma [ns]	Avg. Mean Time[ns]	Sigma[ns]
EB	-0.113	0.119	-0.014	0.021
EE-	-0.337	0.282	-0.003	0.002
EE+	-0.346	0.256	-0.004	0.021

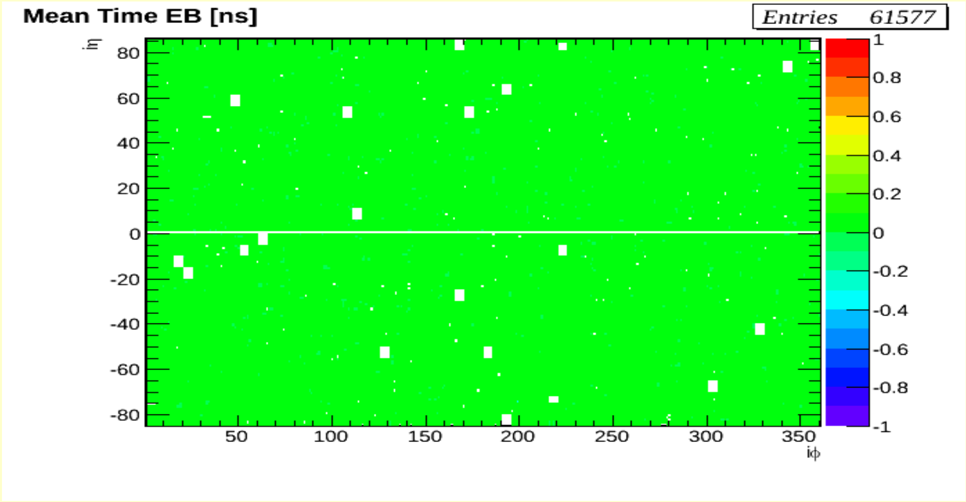
Crystal Time Alignment

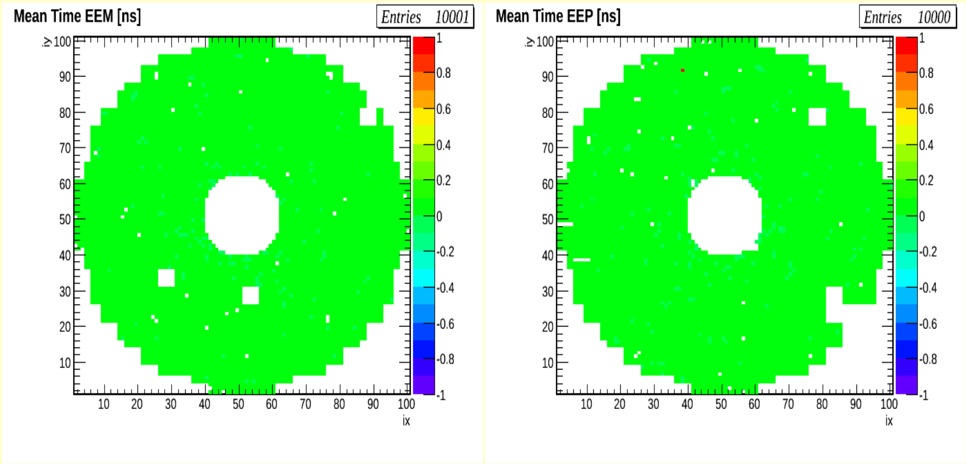
Before Time Alignment





After Time Alignment





Most crystals have average time of zero after alignment.

ECAL Timing Resolution

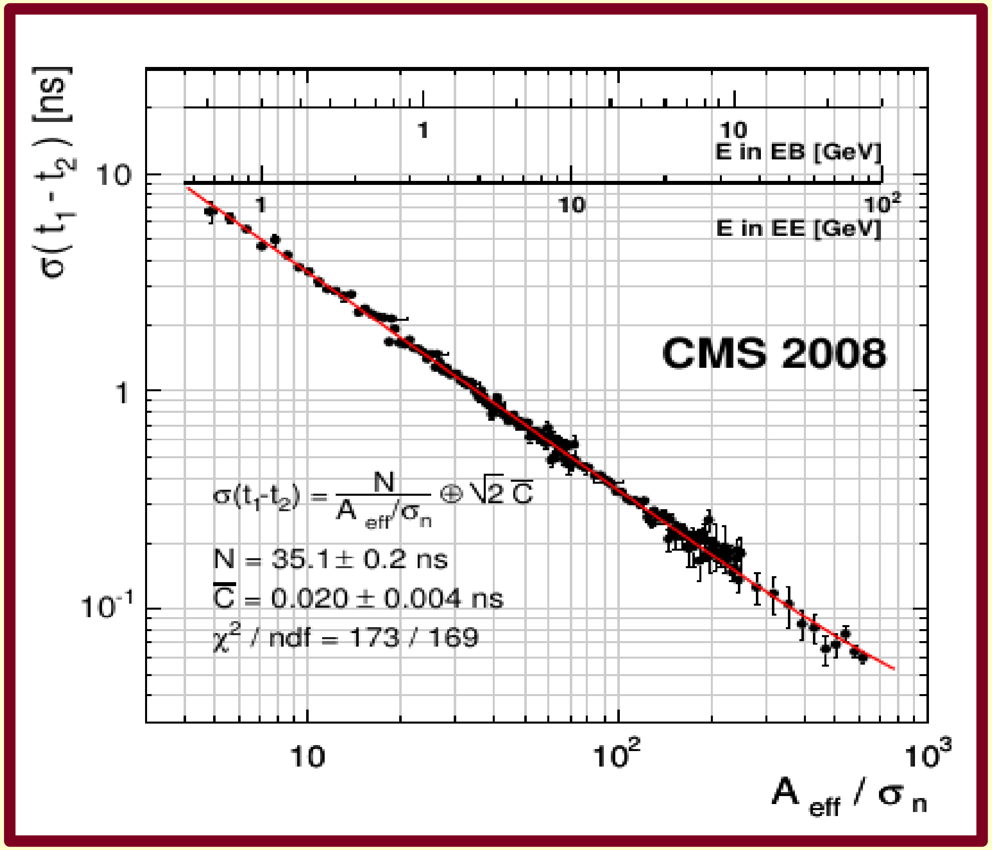
Parametrized as:

$$\boxed{\sigma^2(t_1 - t_2) = \left(\frac{N}{A_{\mathrm{eff}}/\sigma_n}\right)^2 + 2C^2,}$$

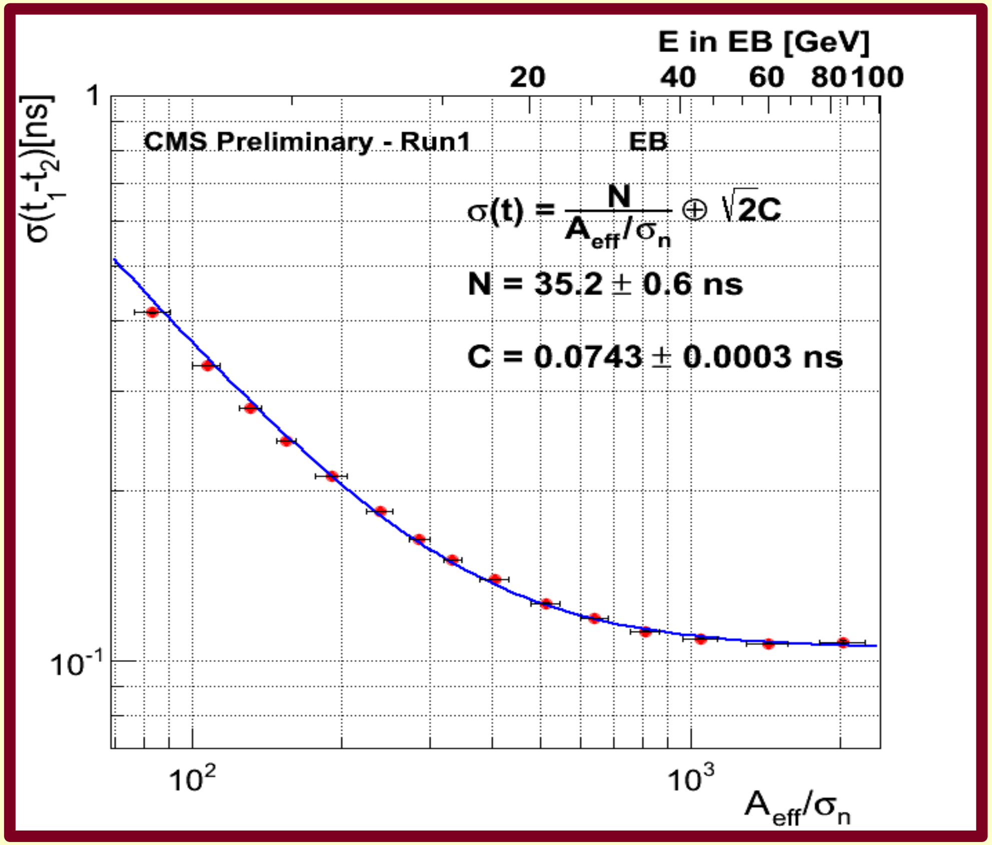
$$A_{\mathrm{eff}} = A_1 A_2 / \sqrt{A_1^2 + A_2^2}$$

- **N =** Noise term which depends on energy.
  - Electronic noise
- **C =** Constant term which is independent of energy.
  - Variations in pulse shape,
  - Systematics in time alignment.

ECAL Time Resolution



LHC Test Beam 2009



LHC Run 1 2012

ECAL timing resolution better than **400ps**.

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Search Analysis

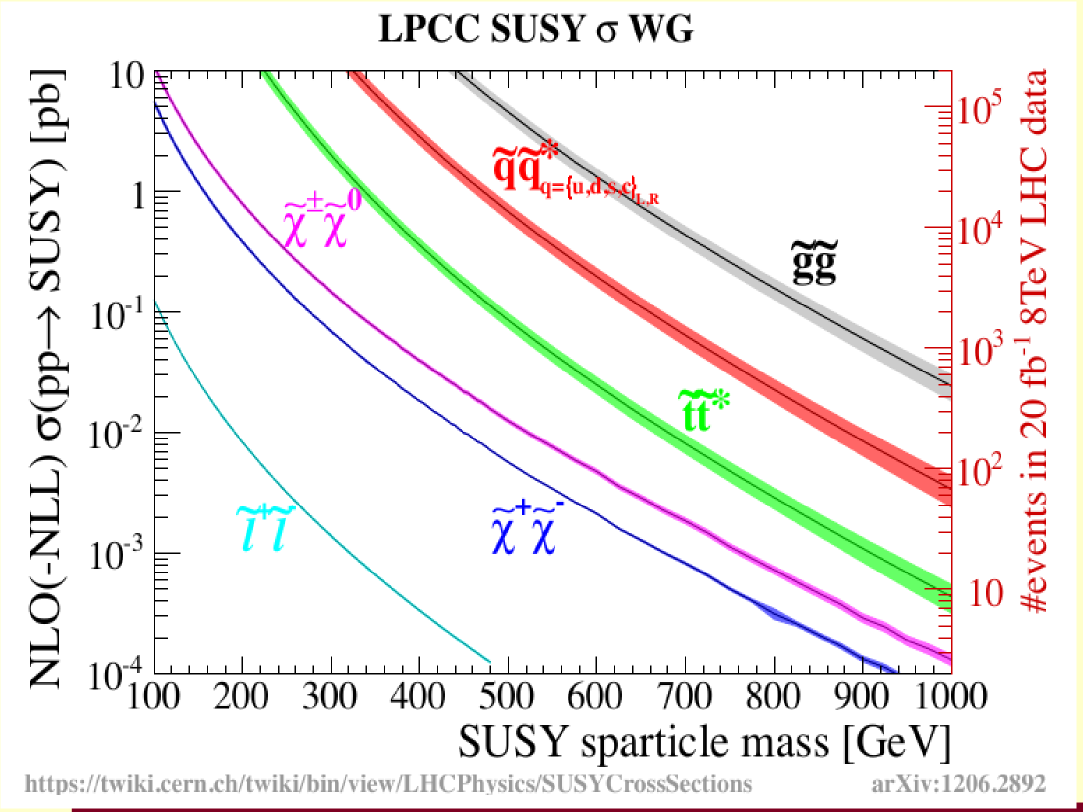
Search Analysis Method

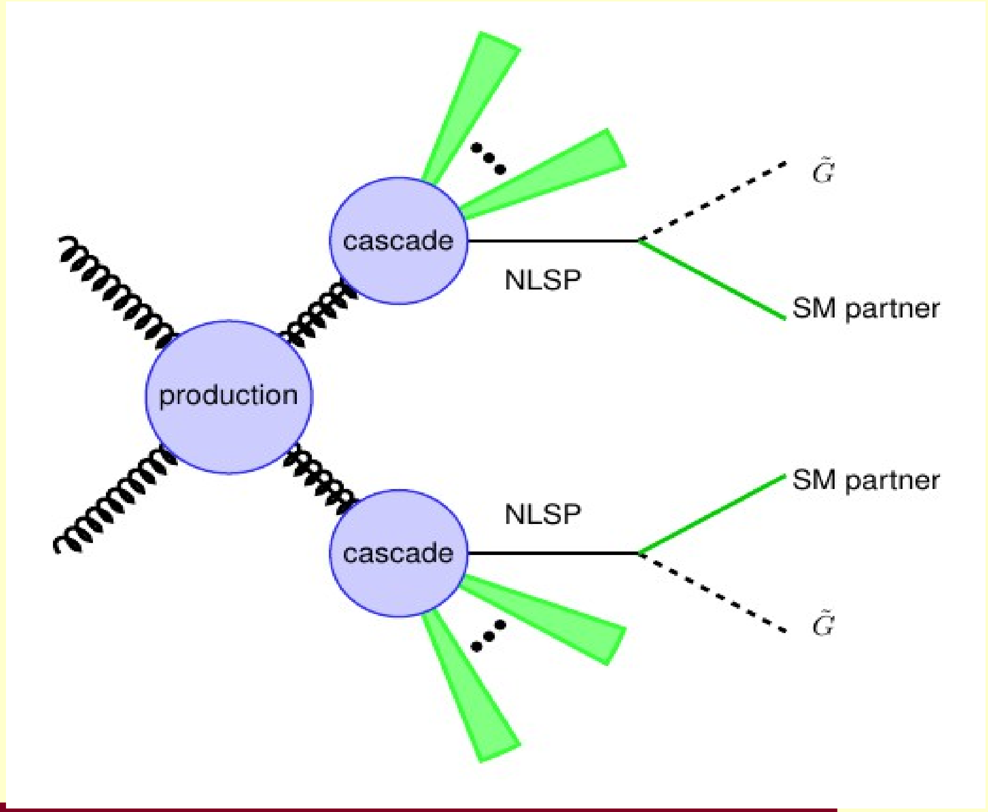
- Uses ECAL time to search for late photons,
- Count events with late photon(s) & compare with expectation from background events,
- Search is not restricted to any particular theory model, however, to understand signal we study the SPS8 benchmark GMSB model,
- Search is almost background free, veto events with late photons from proton beam activity & others and then estimate contribution from residual events using the **ABCD** background estimation method.

New Particles @ LHC

Event Rate = **Cross Section(E)[cm^2]*Luminosity[/s cm^2]*Efficiency**

- 1 barn[b] = 10^(-24)cm^2





Supersymmetry produced at LHC in strong interactions.

Signal & Background Events

Signal Events

- >= 1 late photon +
- >= 2 Jets +
- Large MET

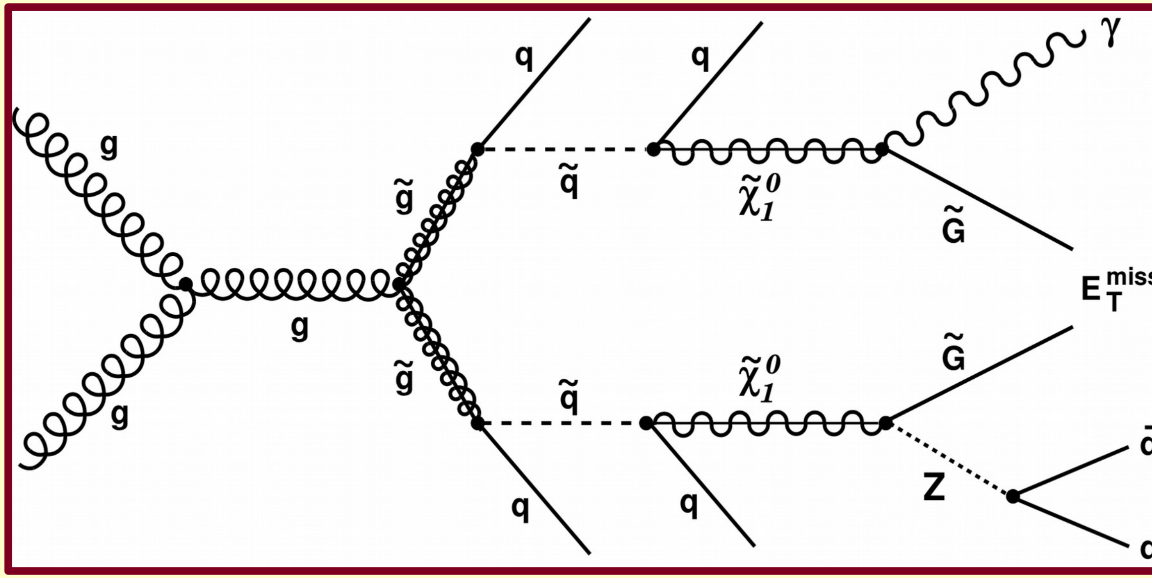
Background Events

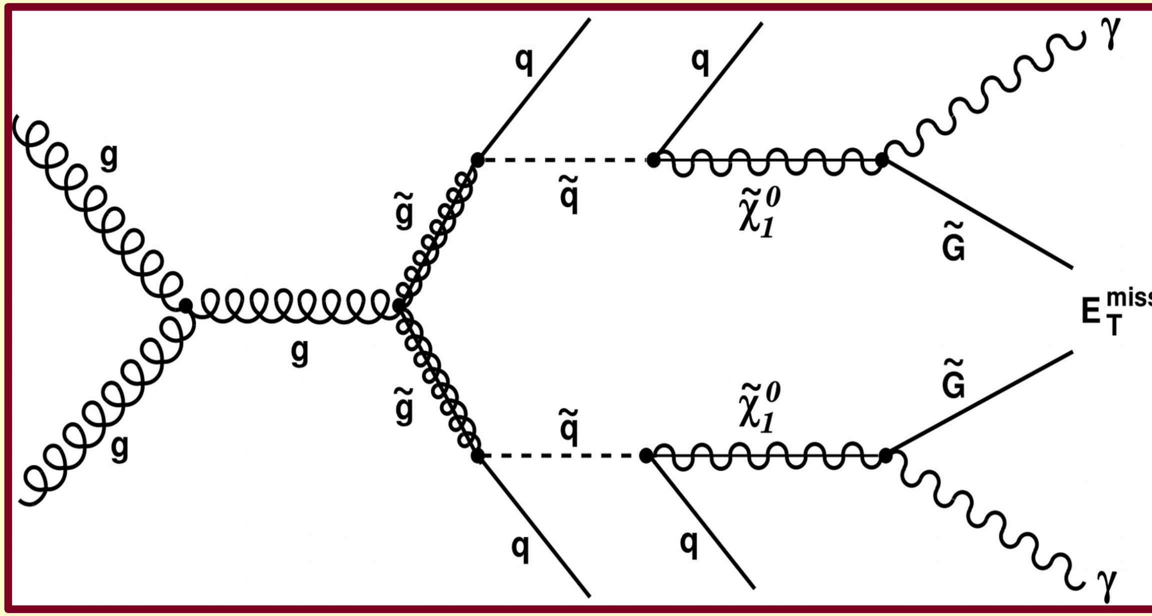
Collision Events

- - Mis-measured time collision events,
  - Satellite events.

Non-Collision Events

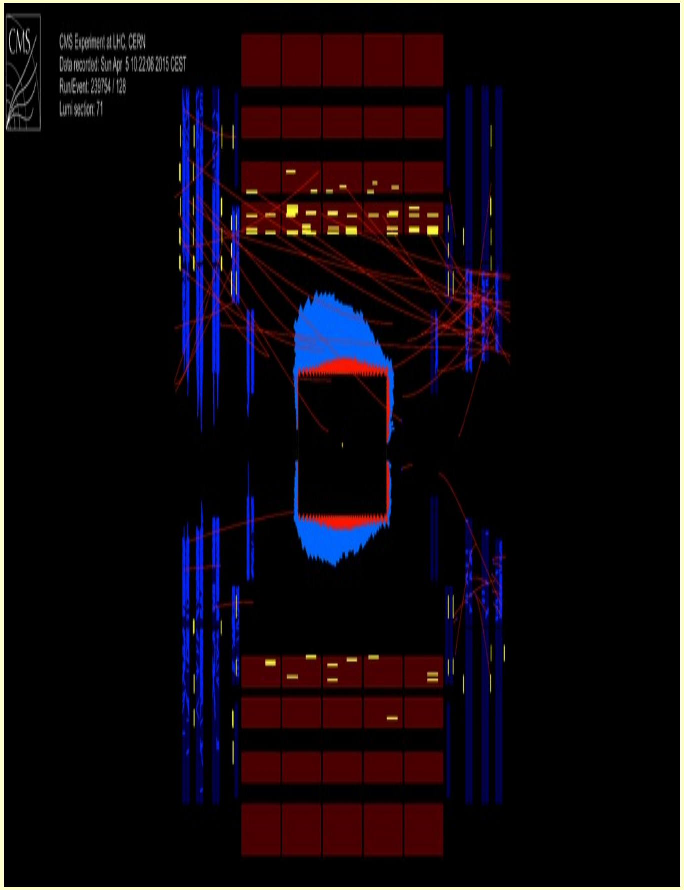
- - Beam halo muon events,
  - Cosmic muon events and spikes.



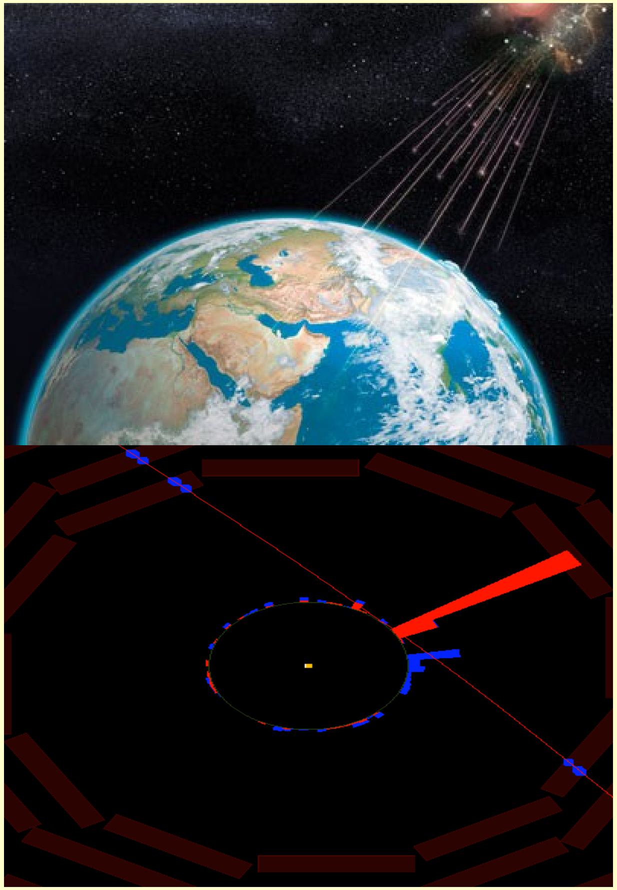


Non-Collision Bkgrnd Events

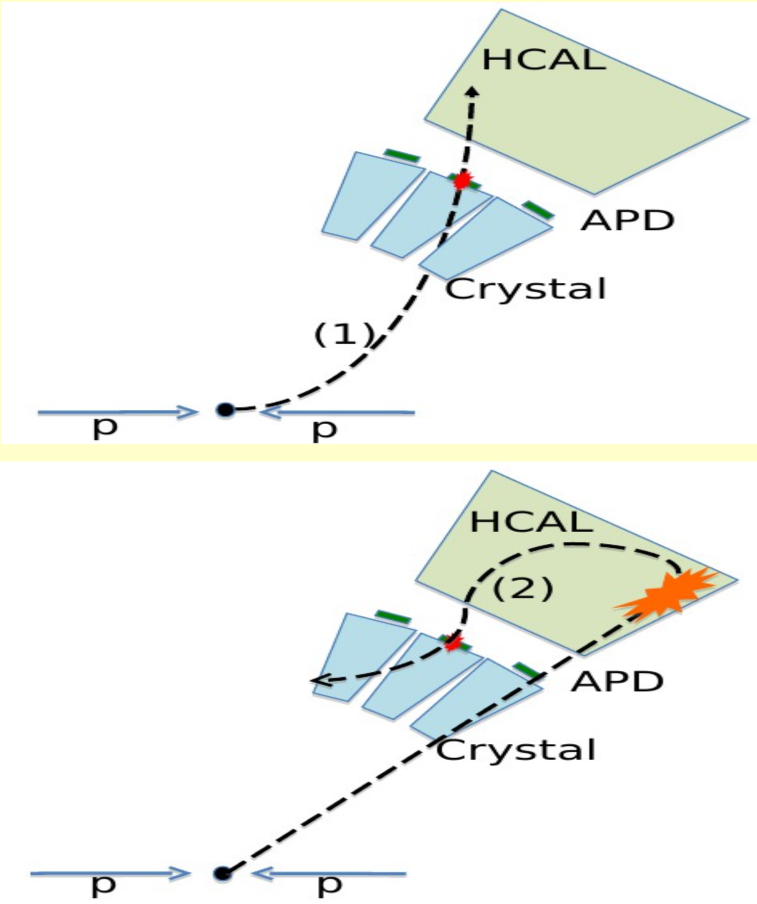
- Late photons from proton beam induced halo muons, Cosmic muons and anomalous photon events like spikes.



Beam Halo muon-induced photon



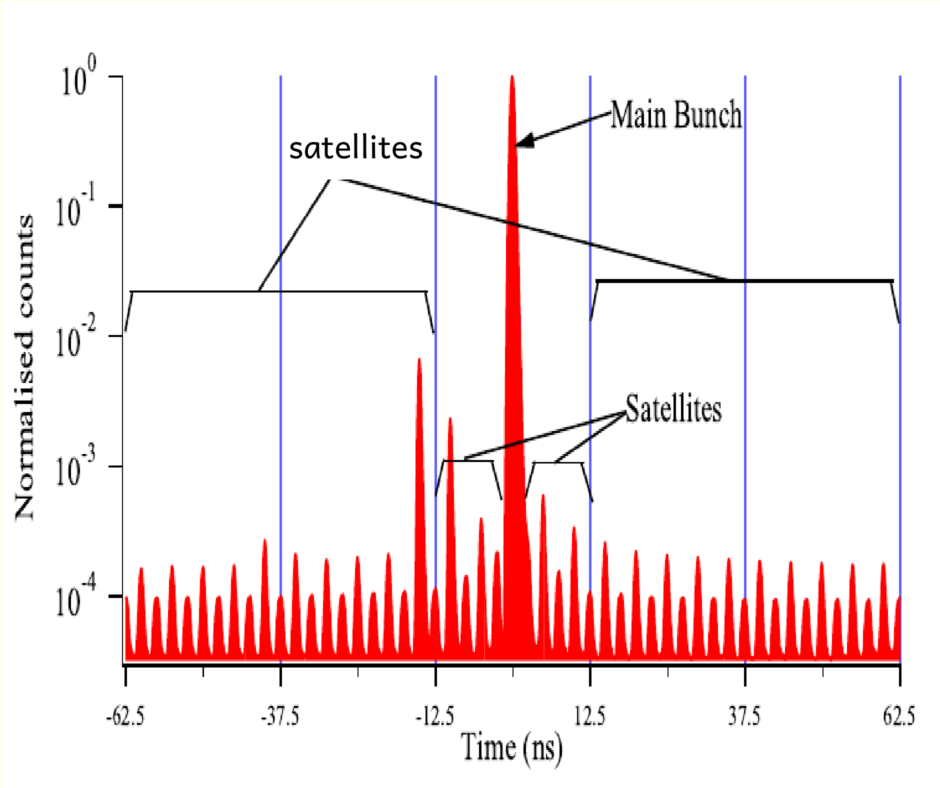
Cosmic Muon-Induced photon

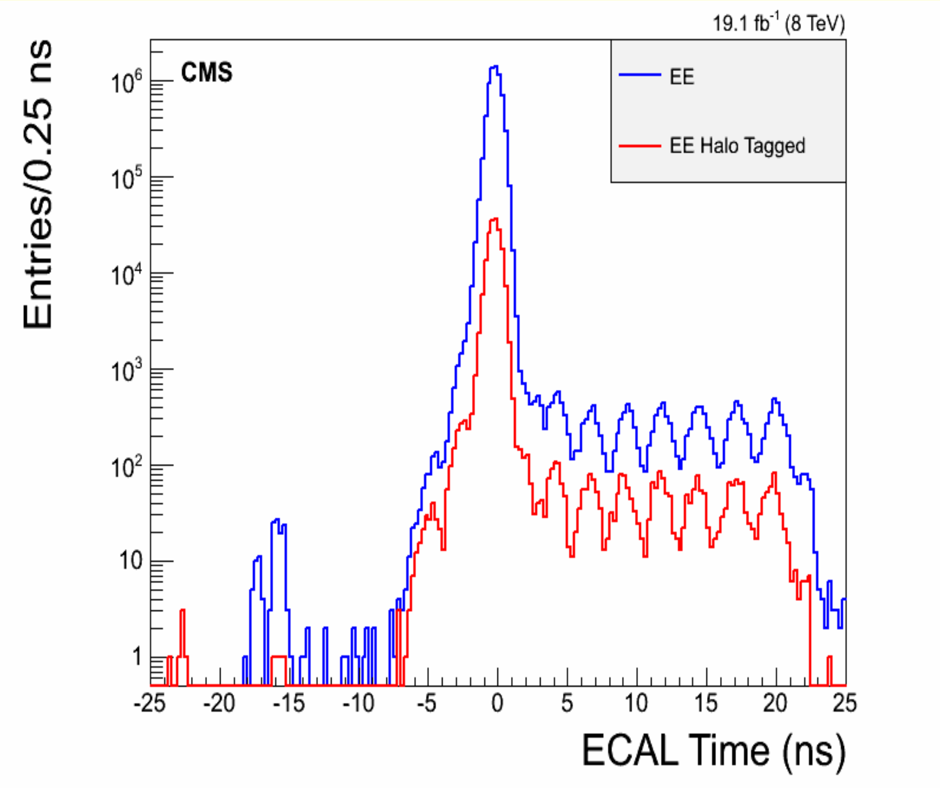


Spike-seeded photon

Collision Bkgrnd Events

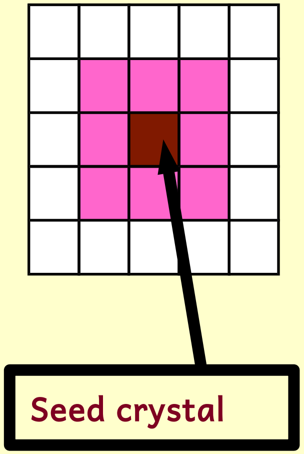
- Photons with mis-measured time from main proton bunch collision e.g QCD, W, top events.
- Photons from satellite proton bunches.
  - Satellite bunches lead or trail the main bunch by 2.5 ns.

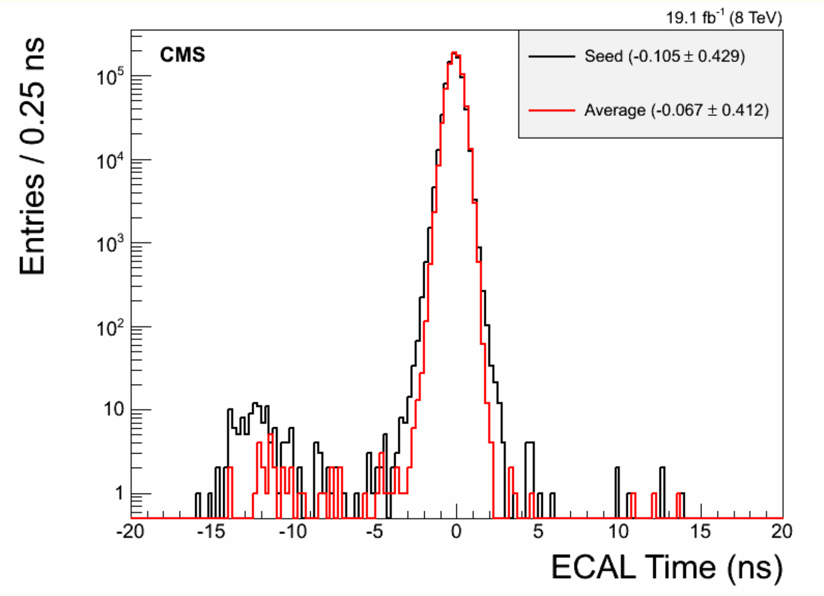




Photon ECAL Time

- Photon time = time of crystal with highest energy deposit.
- Late if photon time is within **3** to **13 ns.**
- Use *average* cluster time to define chi2.

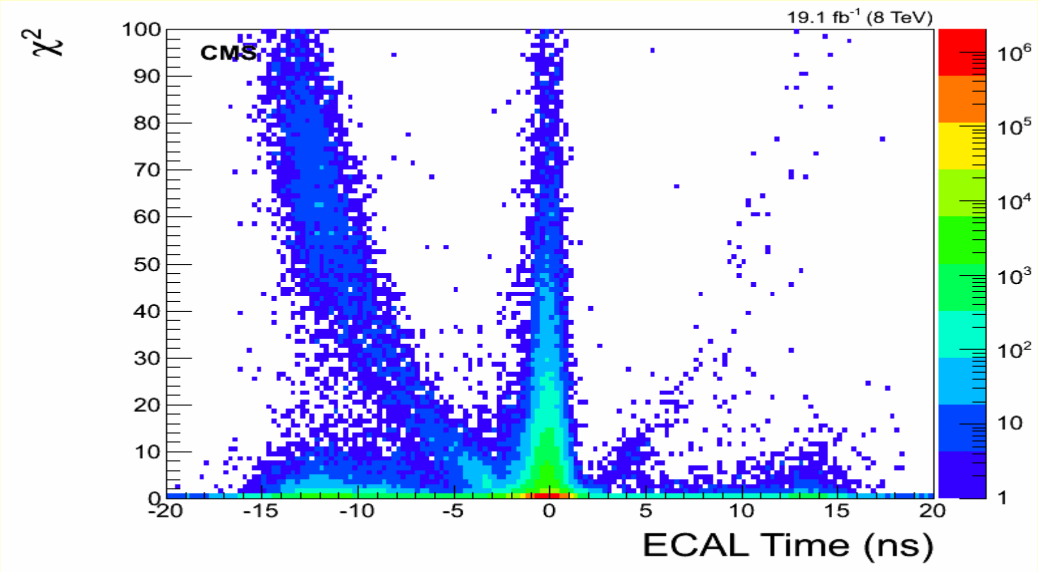




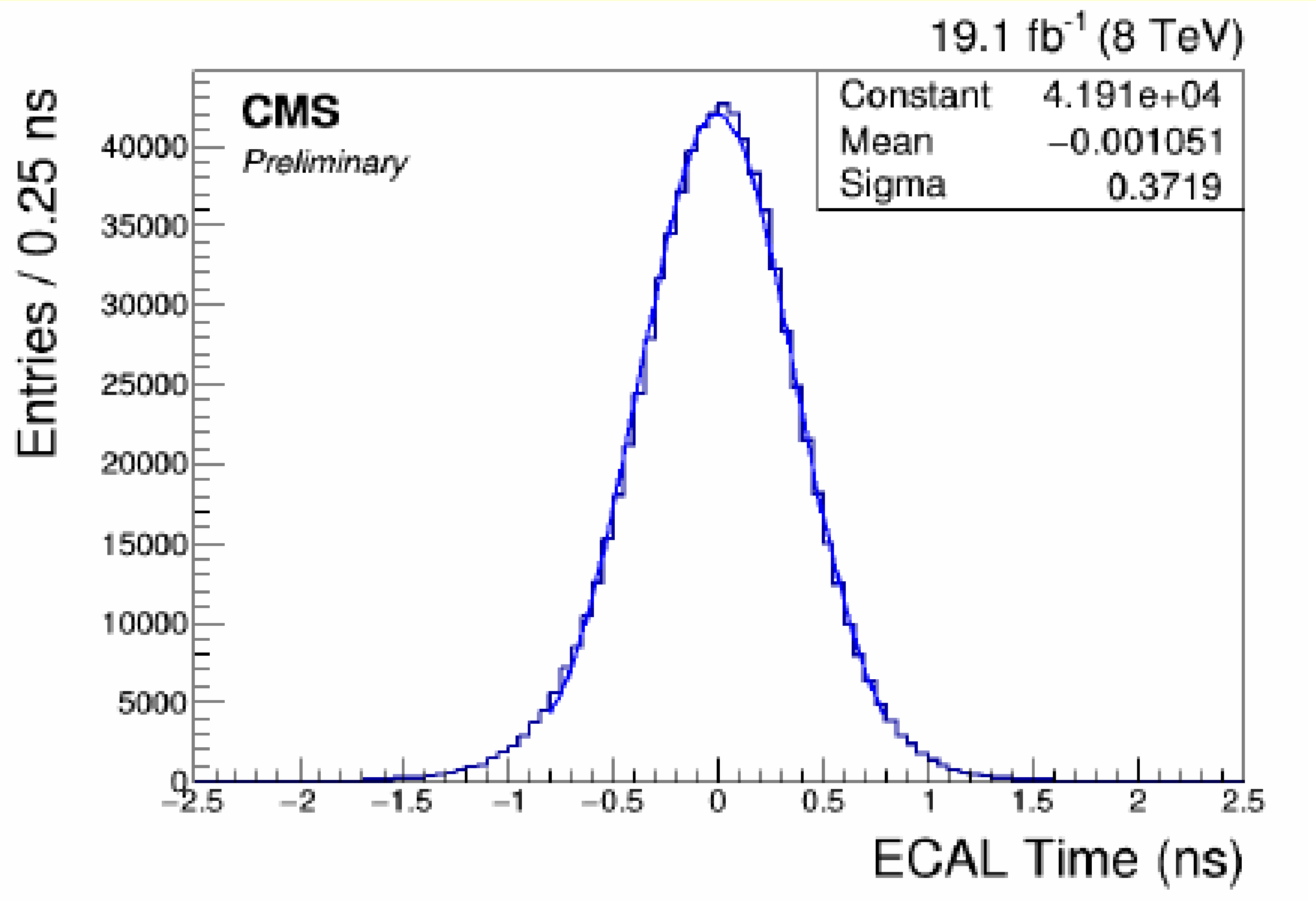
Photon time Chi2

- Chi2 > 4 populated by bad photon candidates.

$$\chi_t^2 = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{t_i - t_{avg}}{\sigma_i}\right)^2$$



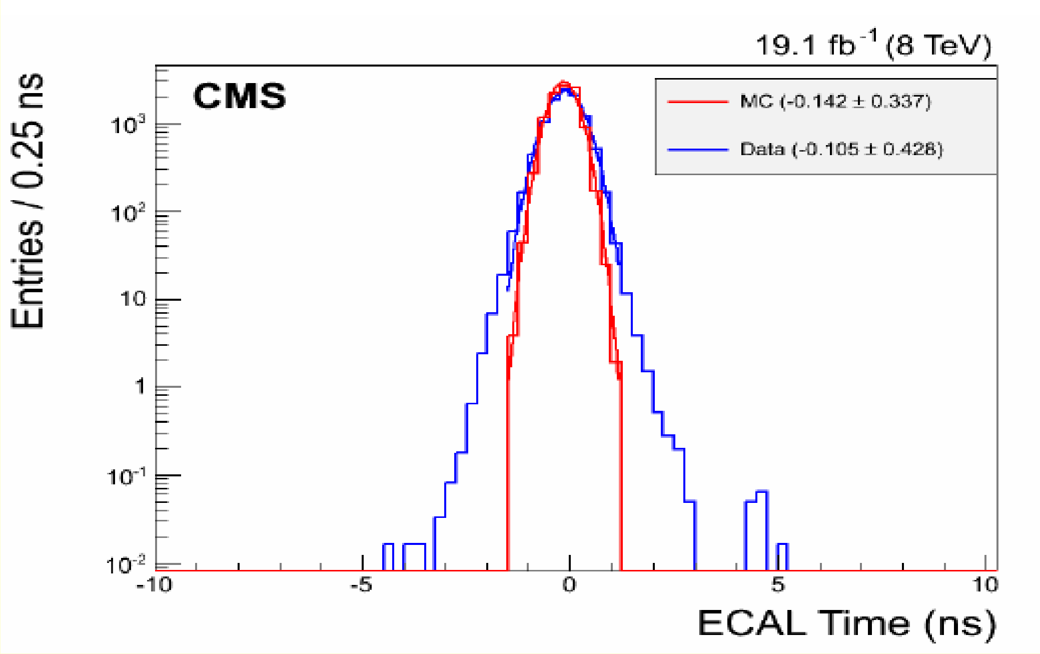
Single Photon Time Resolution

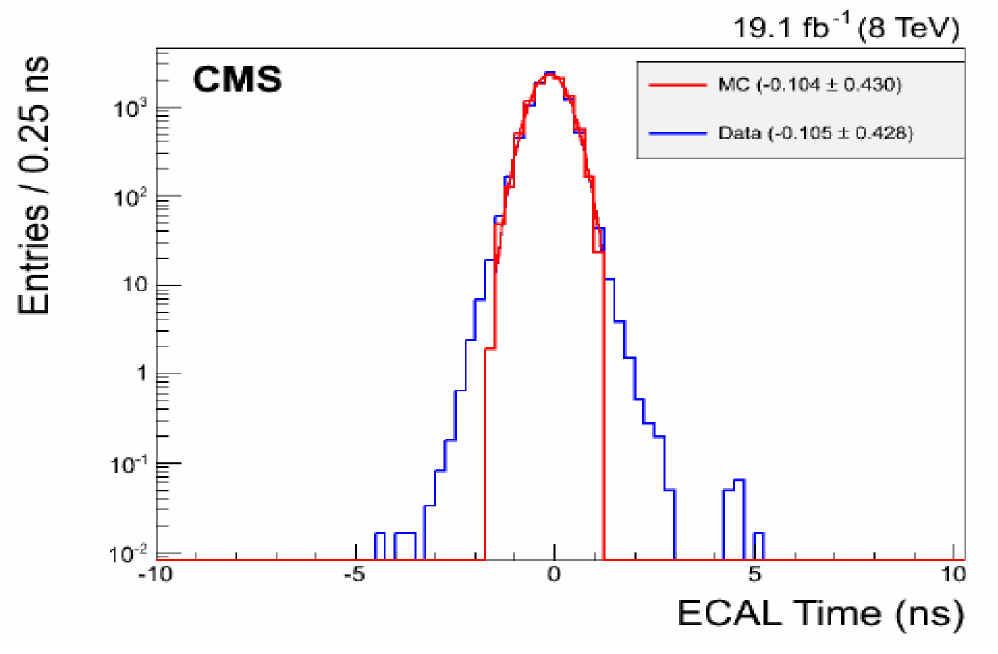


- Single photon timing resolution is about 372 ps.

ECAL Time: MC Vs Data

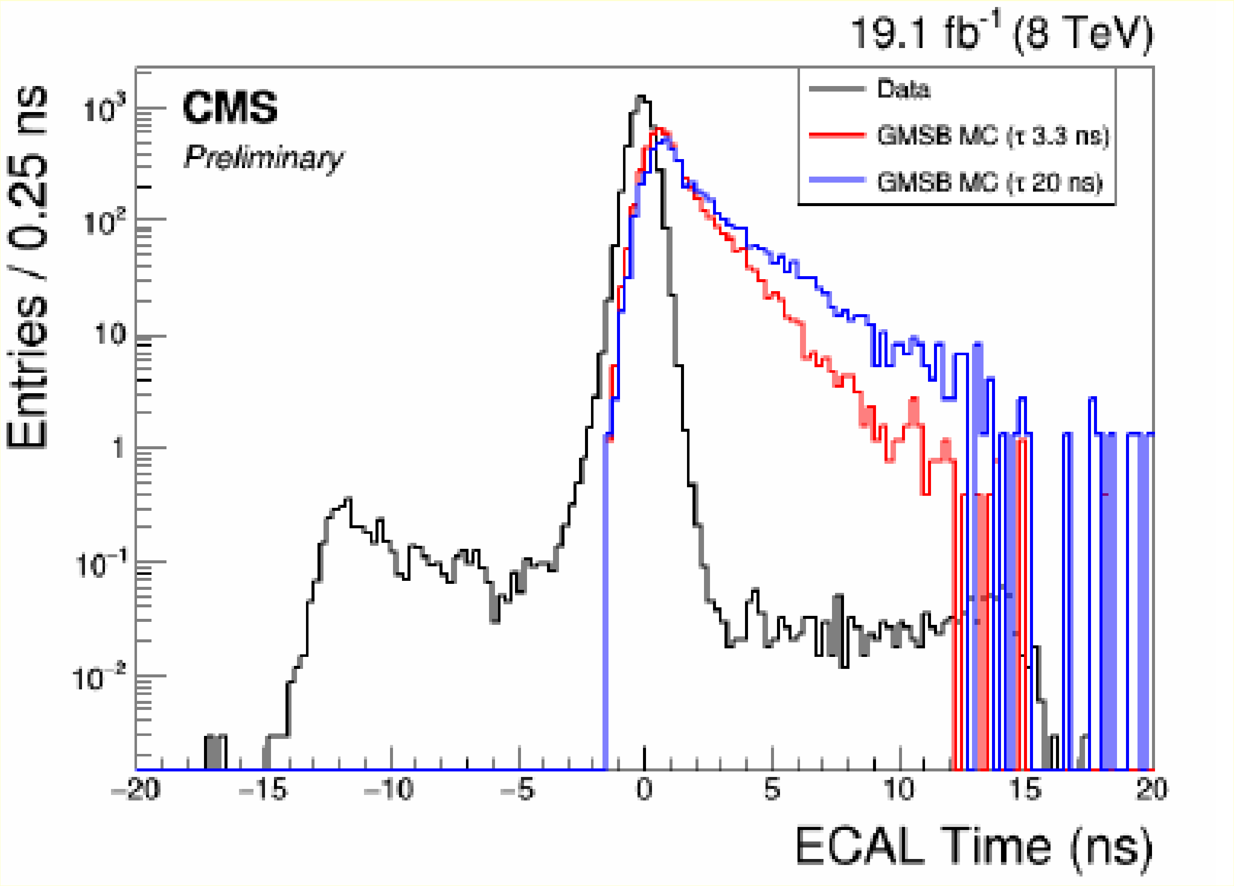
- Compare events passing selection requirement from photon + jet MC sample to data:
  - At least 1 or 2 jet in events,
  - PF-Isolated photon with pt > 80 GeV/c,
  - Event MET < 30 GeV
- Extract shift in mean time & resolution between MC and data and **adjust mean** & **smear sigma time** of photons from signal MC samples.





ECAL Time: MC Vs Data II

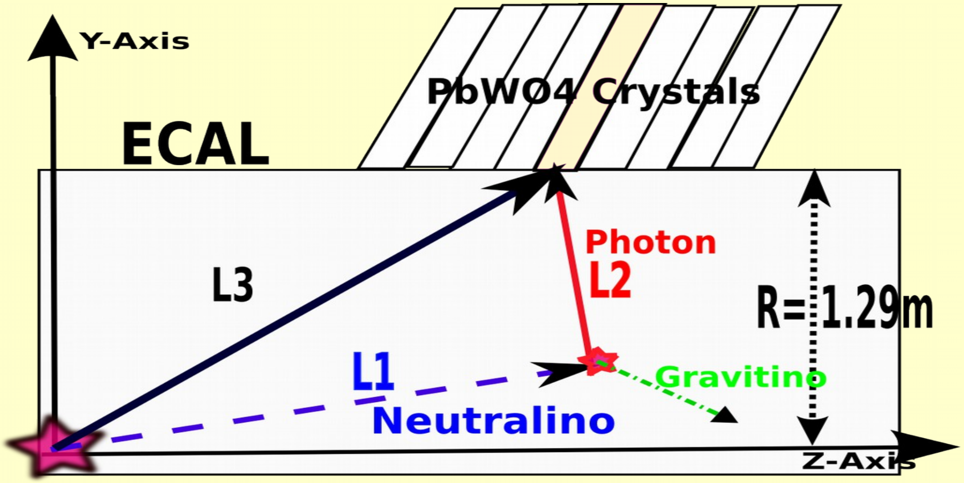
- Search Window is photon time between **3 ns to 13 ns,**
- Photons time between -10 ns to -3 ns use as control sample,
- Photons with time of about -12 ns are mostly “spikes”.



Photon Delay Mechanism

- Distance traveled by Neutralino before decay :

$$\boxed{L_1 = c\tau\left(\frac{p}{m}\right)}$$



- Photon time measured by ECAL:

$$t_{ECAL} = \Delta t1 + \Delta t2$$

  - For **slow moving** neutralino :

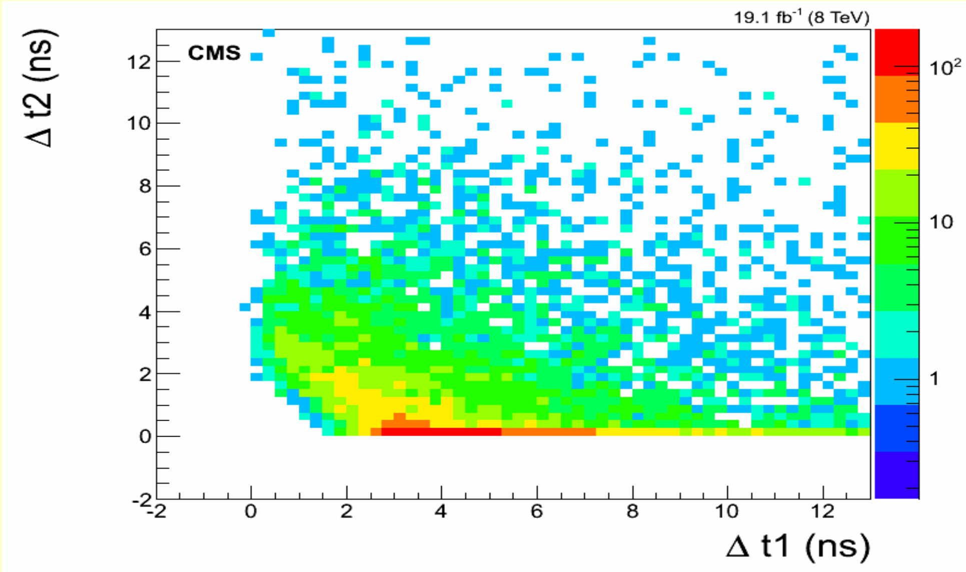
$$\Delta t1 = L1/c\beta - L1/c$$

  - For **Off-pointing** neutralino :

$$\Delta t2 = (L1 + L2 - L3)/c$$

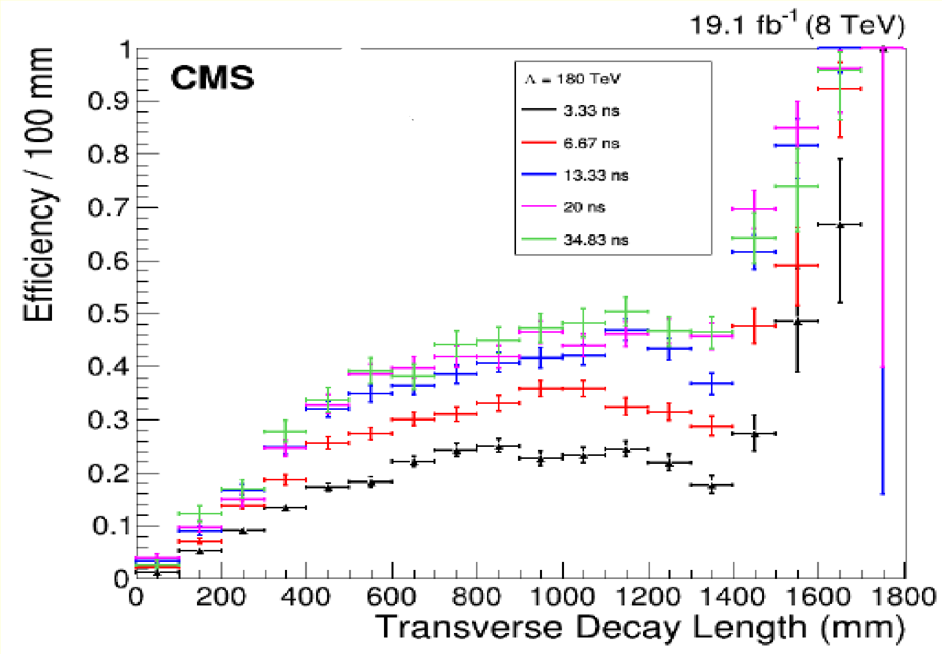
- Most late photons are from slow moving neutralinos.

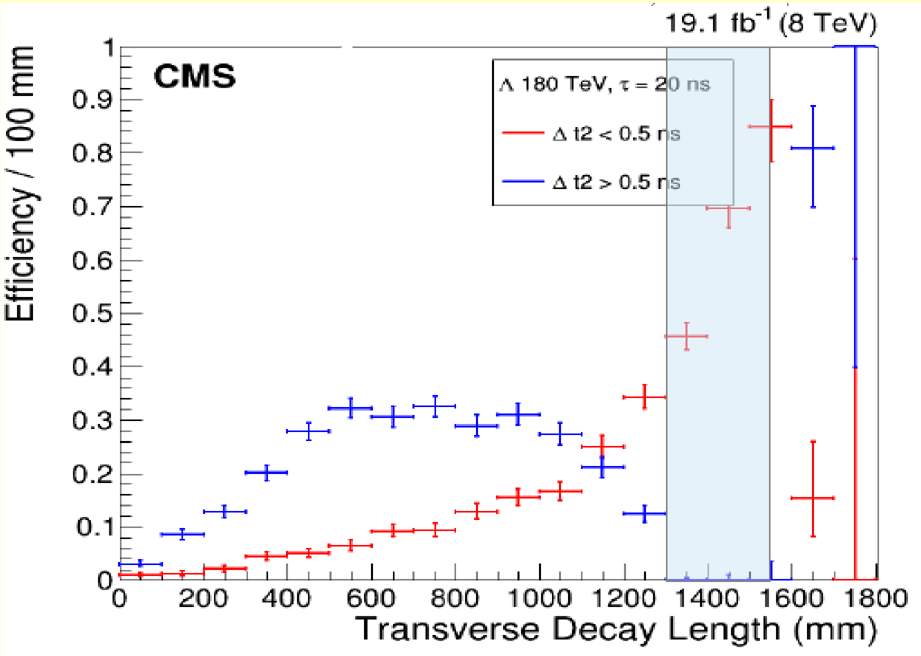
GMSB $\Lambda = 180$ TeV , $\tau = 20$ ns



Delayed Photon Efficiency

- Efficiency to detect photons with t > 3 ns, Vs Transverse decay length.
- No event selection applied yet,
- **Efficiency = Number of photons with t > 3 ns /Number of reconstructed photons** in EB.
- Using Delta t2 to separate the two types of delayed photons,

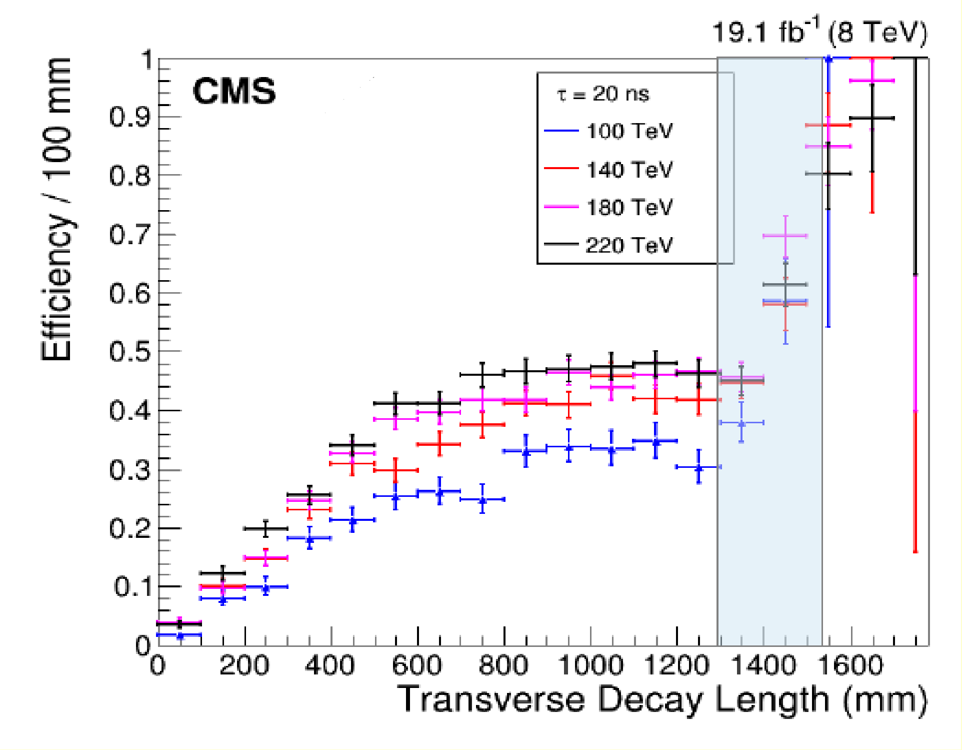


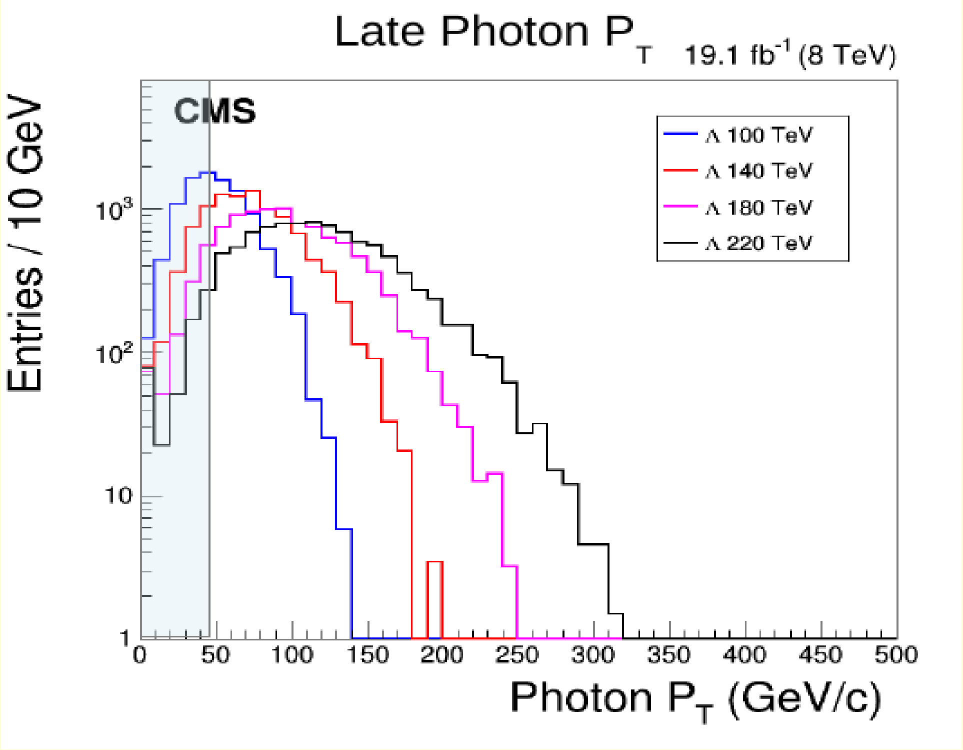


- Efficiency **increases with lifetime** provided **boost factor is not to large** since shorter lifetimes needs enough boost to reach the ECAL and overcome the 3 ns acceptance threshold.

Delayed Photon Efficiency II

- Efficiency of late photons, for different Neutralino Mass(Lambda) but fixed lifetime.
- No event selection applied yet,
- **Efficiency = Number of photons with t > 3 ns /Number of reconstructed photons** in EB.





- Efficiency **increases with lambda** due to increase with photon pt.

Missing Transverse Energy

- Event Missing Transverse Energy (MET) defined as:

$$\mathrm{MET} = \left| - \sum_{\text{All particles}} P_t \right|$$

- Define a new MET variable as: $\mathrm{MET}^{\gamma} = \mathrm{MET} + P_t^{\gamma}$

- **MET > 60 GeV & MET$^{\gamma}$ > 60 GeV** separates the different composition of background events.

Event Category	MET	MET$^{\gamma}$
Collision Bkg Events (QCD/Satellite)	< 60 GeV	> 60 GeV
Non-Collision Bkg Events(Halo, Cosmic,spike)	> 60 GeV	< 60 GeV
Signal Events	> 60 GeV	> 60 GeV

Event Samples: Data & MC

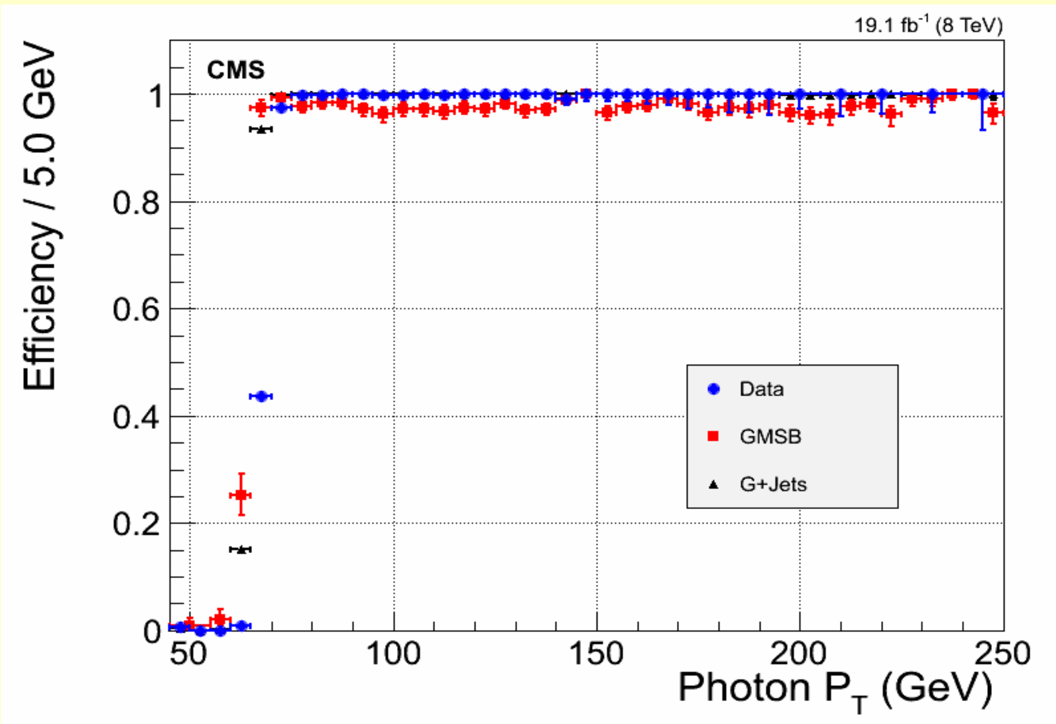
- **Data**
  - Events with at least one photon passing the HLT-trigger:

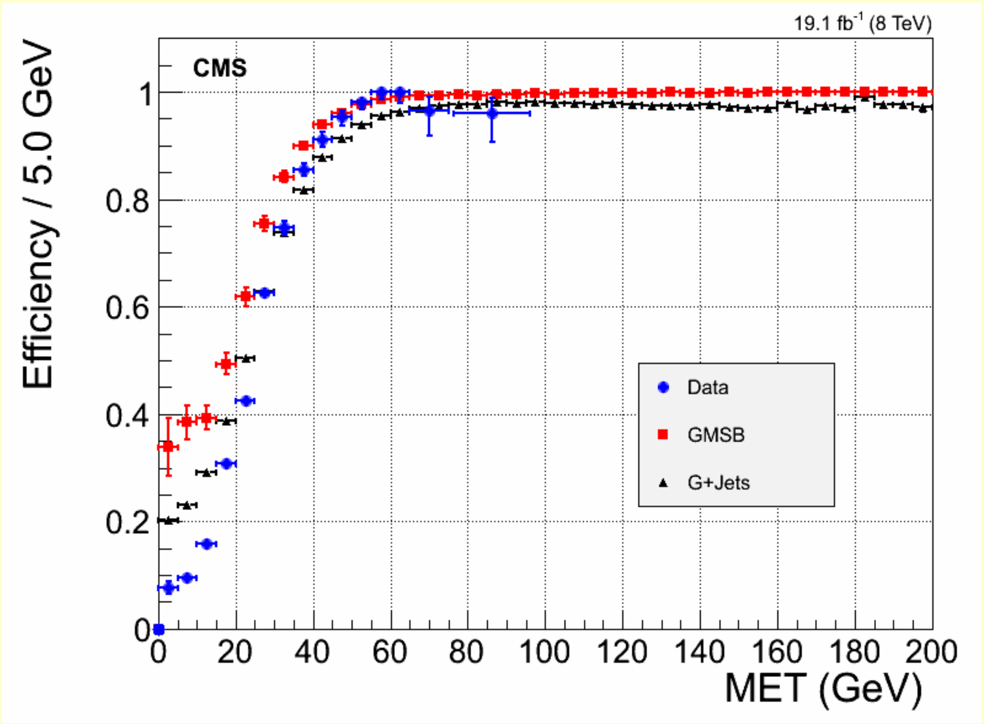
    HLT_DisplacedPhoton65_CaloIdVL_IsoL_PFMET25
  - Total luminosity of **19.1/fb**
- **SPS8 benchmark GMSB MC Samples**
  - Signal MC events: ~50k events for each lifetime and Lambda point,
  - Lambda ranging from **100 TeV** to **220 TeV**(6 points in total),
  - Lifetime(tau) ranging from **1.7 ns** to **33.3 ns** (7 points in total).
- **Data: SinglePhoton Events**
  - Single photon events passing the HLT-trigger:

    HLT_Photon50_CaloIIdVL_IsoL
  - For studying Displace photon HLT trigger efficiency.
- **Cosmic Data:** For studying cosmic tagging
- **MC Gamma + Jet:** For MC time study sanity check.

Online Event Selection

- HLT_DisplacedPhoton65_CaloIdVL_IsoL_PFMET25
  - Selects events: Isolated photon pt > 65 GeV/c + PFMET > 25 GeV
  - **Efficiency = Events passing online selection / Events passing offline selection and HLT_Photon50_CaloIdVL_IsoL HLT trigger.**
  - Offline selection: photon pt > 80 GeV/c, PFMET > 60 GeV.





Offline Event Selection

- **Photon:**
  - Lead photon pt > 80 GeV/c, other photons pt > 45 GeV/c, photon must belong in EB, simple cut-based photon Id selection, dR(photon, track) > 0.6.
- **Jets:**
  - PFJet of PFJet ID with pt > 35 GeV/c, must be within |eta| < 2.4 and dR(photon, Jet) > 0.3.
- **MET:**

  $\mathrm{MET(PFMET)} > 60\ \mathrm{GeV},\ \mathrm{MET}^{\gamma} = \mathrm{MET} + pt^{\gamma} > 60\ \mathrm{GeV}.$

- **Signal Events:** Final state with

  $\mathbf{\geq 1\ Photon + \geq 2\ Jets + MET > 60\ GeV + MET^{\gamma} > 60\ GeV}$

- **ABCD Method Test:** Events with final states

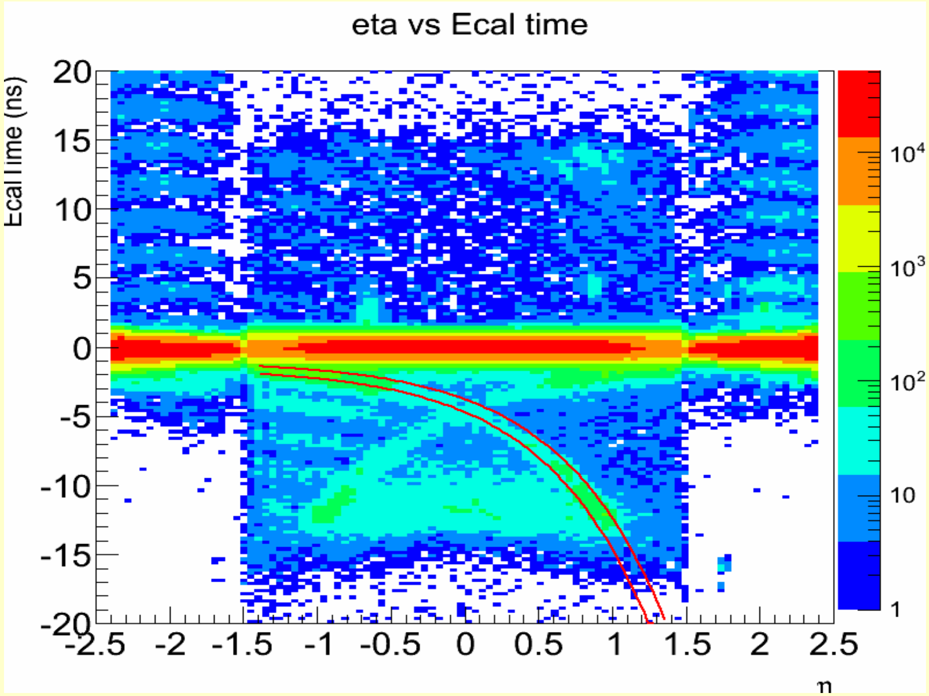
  $\mathbf{\geq 1\ Photon + 0\ \&\ 1\text{-}Jet + MET,\ MET^{\gamma} > 60\ GeV}$

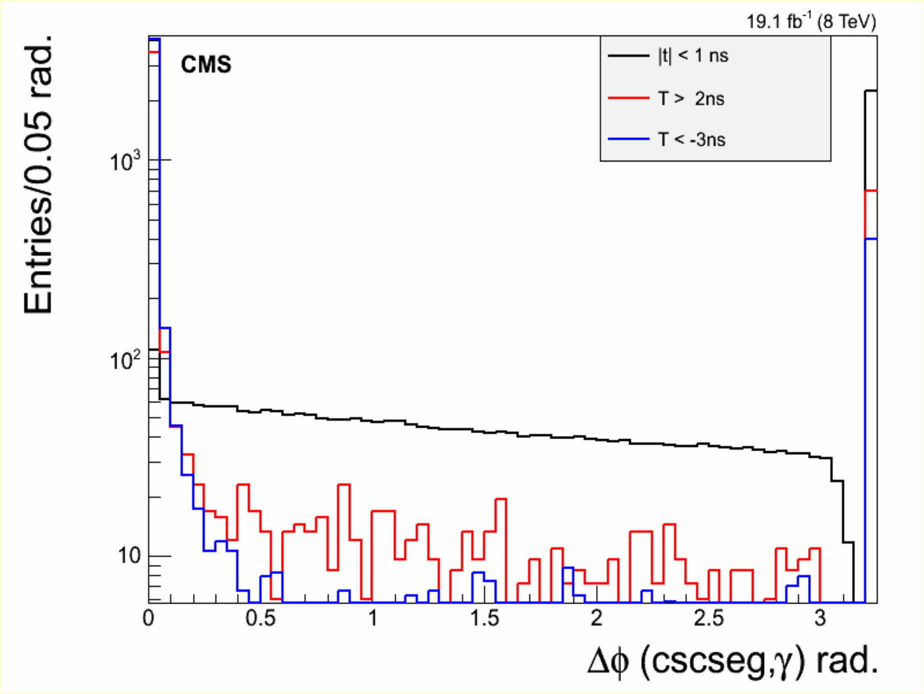
Background Reduction & Estimation

- Background estimation is data-driven,
- Compare in-time and out-of-time photon events:
  - Use 0- &1-jet events to study background events from non-proton-proton collision background sources,
  - Separate events into t < -3 ns & t > 2 ns and find a method to veto non-collision background photons like Beam Halo-induced photons, Cosmic-Induced photons and Spike-seeded photons.
- Using **ABCD** method we estimate the residual non-collision background events remaining after vetoing,
- Use a $Z \to ee$ event sample to estimated the non-Gaussian tail of the photon ECAL time.
  - Most representative sample of collision background events(e.g Collision, satellite proton bunch events),
  - Z mass constraint avoids contamination from non-collision background events.

Halo-Induced Photons

- Halo-induced photons from beam halo muons from main and satellite bunches are a major source of out-of-time photons.
  - Their ECAL arrival time depends on eta,
  - Studied using 0&1-jet events,
  - Can be tagged and veto using: $\Delta\,\phi(\text{CSCSegment},\gamma) < 0.05$

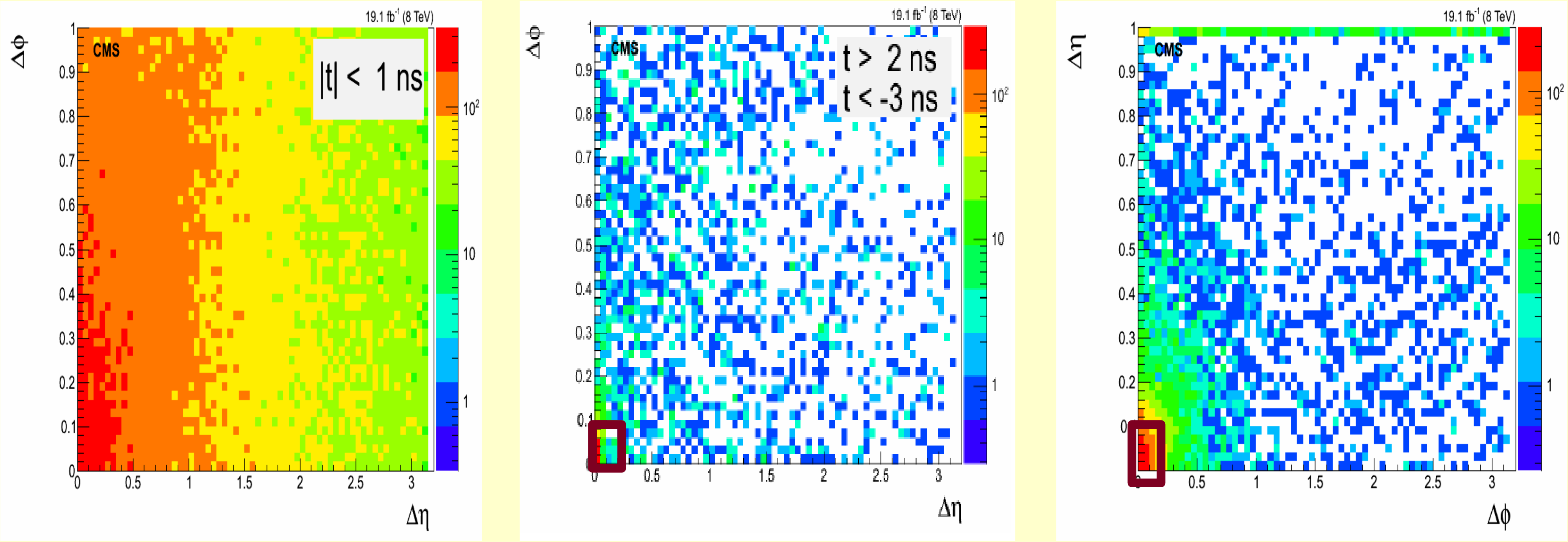




Cosmic-Induced Photons

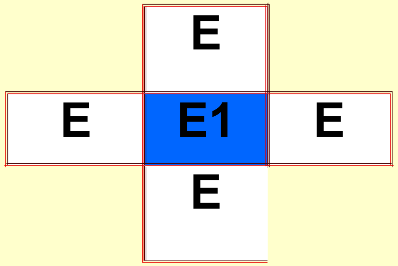
- Cosmic-induced photons from muons from cosmic rays is also a source of out-of-time(random) photons.
  - Their ECAL arrival time is random,
  - Can be tagged and veto using: $\Delta\eta(\gamma,\mathbf{DTSegment}) < 0.1$ & $\Delta\phi(\gamma,\mathbf{DTSegment}) < 0.1$
  - Studied using real cosmic data (data recorded by CMS in the absence of pp collisions),

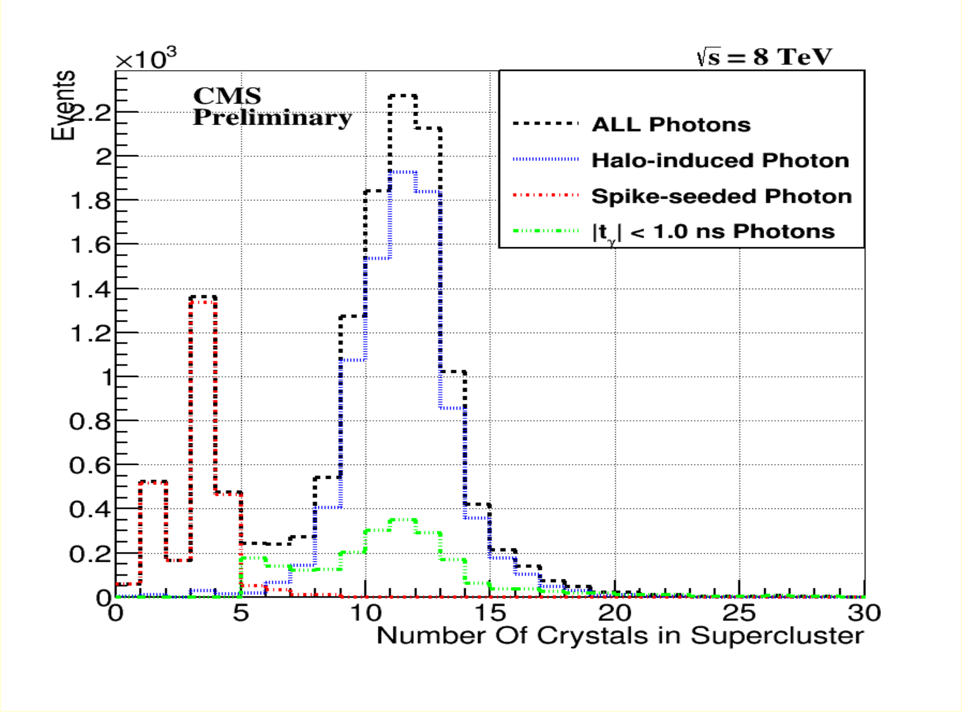
Real Cosmic data

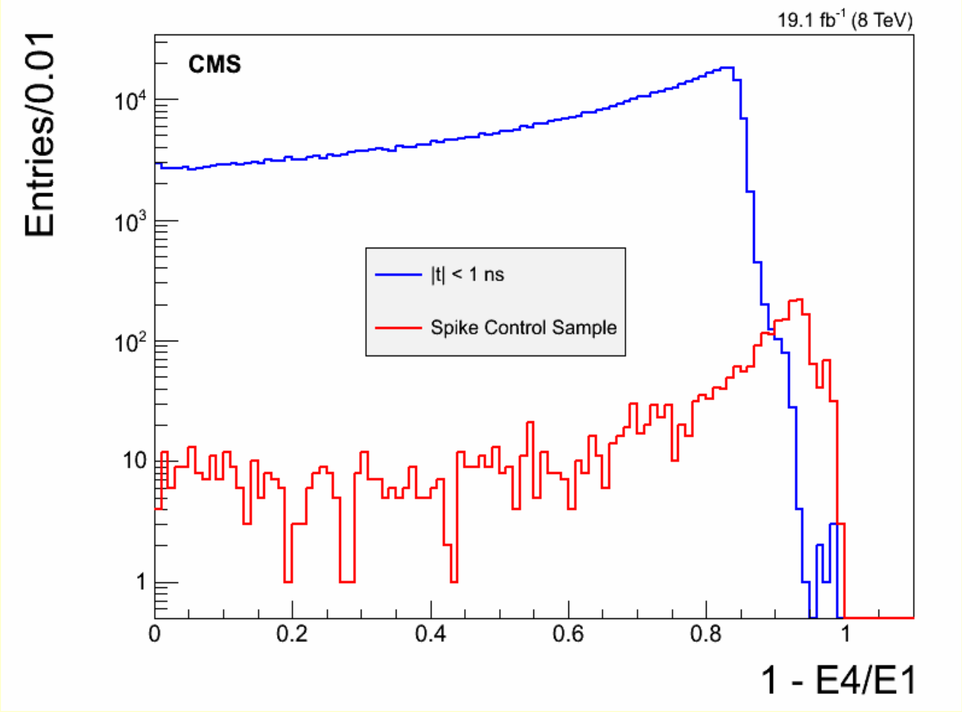


Spike-Seeded Photons

- Spike-seeded photons out-of-time signals produced as a result of neutrons hitting the APDs directly.
  - Populate mostly the negative time region,
  - Veto criteria: 1-E4/E1 > 0.9, Chi2 > 4, Ncrys < 7, SMinor < 0.17 & Smajor < 0.6

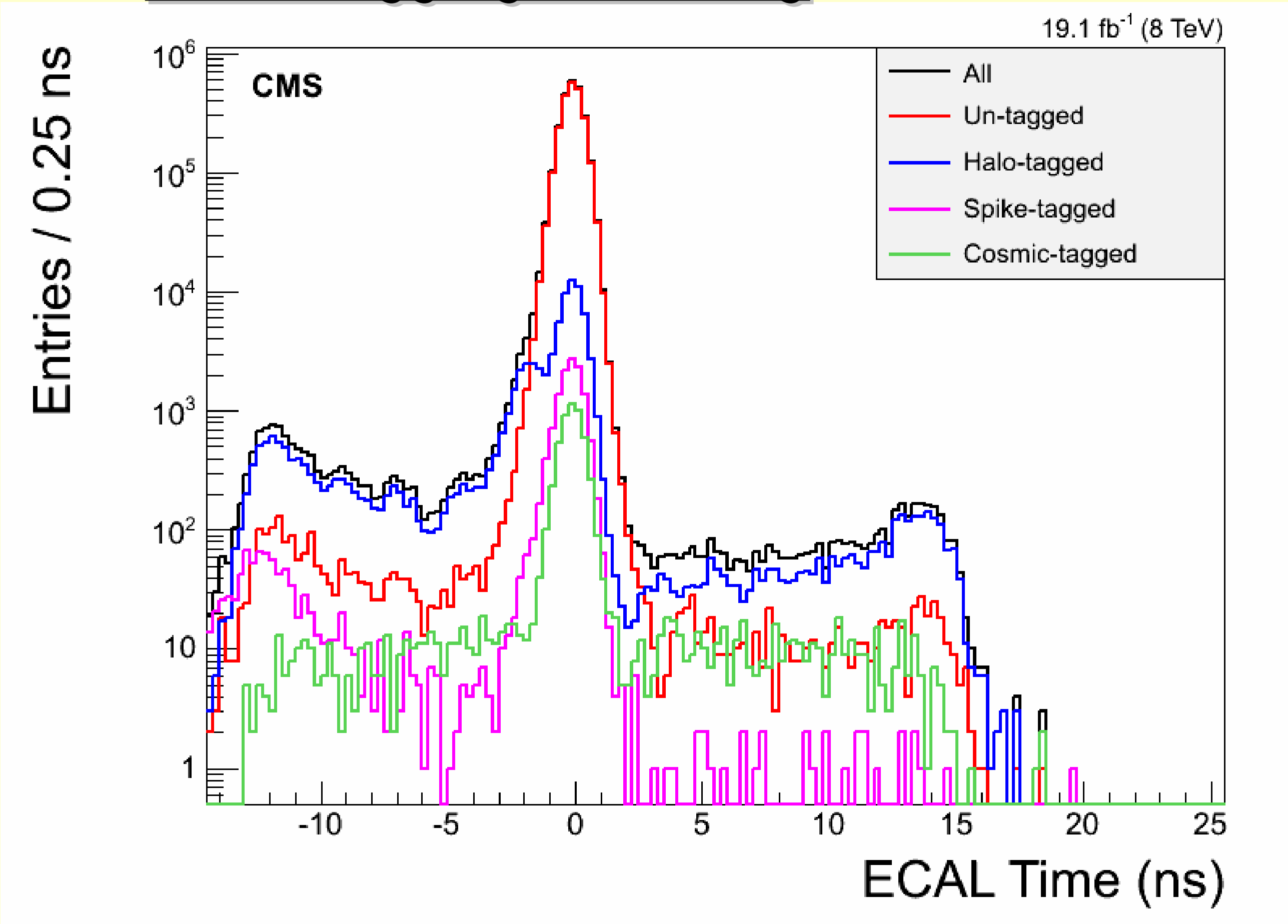






Photon Veto Performance

After Tagging & Vetoing



Untaggeable Events

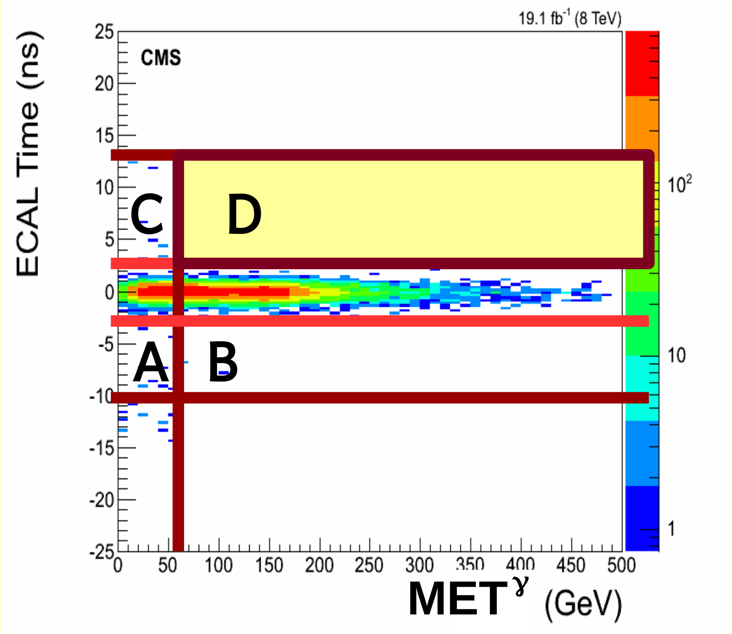
Event Class	Yield
Halo-induced photons	3 %
Cosmic-induced photons	1.4%
Spike-seeded photons.	0.4%

Non-collision event tagging and vetoing is not 100% efficient.

ABCD Background Estimation

- Estimate the residual halo-induced, cosmic-induced and spike-seeded photons in the signal sample **(D)** after the veto.

MET > 60 GeV		
	MET^{γ} < 60 GeV	MET^{γ} > 60 GeV
3 ns < t < 13 ns	C	D
-10 ns < t < -3 ns	A	B



- **MET > 60 GeV**
  - **Supresses** collision/satellite out-of-time events.
  - A & C have very negligible(**free**) collision/satellite events.

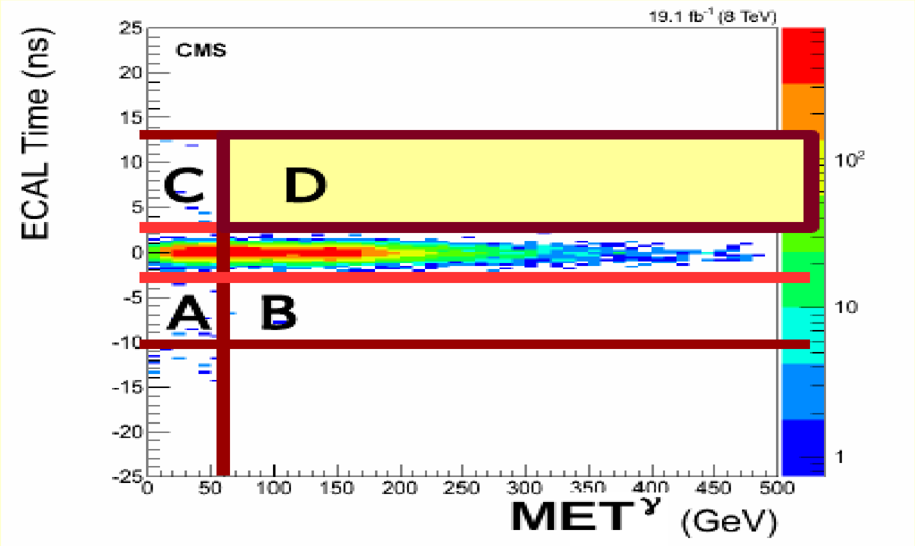
D = (B/A) *C

Collision Backgd Estimation

- Estimate the contributions from collision/satellite events with out-of-time photons in **B & D**.

Event Category	MET	MET$^{\gamma}$
Collision Bkg Events (QCD/Satellite)	< 60 GeV	> 60 GeV
Non-Collision Bkg Events (Halo, Cosmic,spike)	> 60 GeV	< 60 GeV
Signal Events	> 60 GeV	> 60 GeV

MET > 60 GeV



- Need a sample with highly suppressed non-collision background events to estimate collision/satellite events.
- Adjust the ABCD formula for background expectation to take into account the contributions from collision/satellite events into **B** & **D**.

$Z \rightarrow ee$ Method

- Most representative sample of collision events with out-of-time electromagnetic particles
- Use Z-mass constraint to highly suppressed non-collision events.
- **Find the Probability of an in-time($|t| < 2$ ns) photon becoming out-of-time($t < -3$ ns or $t > 3$ ns) because of time mis-measurement & Satellite out-of-time event Probability:**
  - Mass of Z candidate: **76 GeV/cc < M_{ee} < 104 GeV/cc**,
  - Seperate candidate events into 3 cathegories: $|t| < 2$ ns, $t < -3$ ns and $t > 3$ ns
  - Fit non-Z mass window (**50 GeV/cc < M_{ee} < 76 GeV/cc & 104 GeV/cc < M_{ee} < 130 GeV/cc** to extract polynomial function.
  - Use polynomial function to determine the background events of the true Z events in each of the candidate Z events cathegories.
  - Use **ratio** of out-of-time and in-time true Z events as probability.

Total Background Estimation

- Total background estimation:

$$\boxed{D = \left(\frac{B - B^{Col}}{A}\right) * C + D^{Col}}$$

- ## Closure Test: ABCD method validation
  - Using events with **0 & 1-jets only**.

	MET^{γ} < 60 GeV	MET^{γ} > 60 GeV
3 ns < t < 13 ns	C=359	D=10
| t | < 2 ns		(1p) 35097 + (2p) 174
-10 ns < t < -33 ns	A=851	B=38

- From Z→ee Method:

$$B^{Col} = 0.64^{+0.35}_{-0.33}$$

$$D^{Col} = 0.56^{+0.11}_{-0.09}$$

- Expected Events:

$$D = 16.41^{+3.00}_{-2.59}$$

- Observed Events:

$$D = 10$$

- Statistically closed

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Results

RESULTS

- Events with **2-jets & above**
  - **Expected Number of Background Events:**
    - From Z→ee Events: $B^{Col} = 0.51^{+0.28}_{-0.27}$, $D^{Col} = 0.37^{+0.09}_{-0.07}$
    - Predicted Number of Events: $D = 0.37^{+0.39}_{-0.07}$
  - **Observed Number of Events: 1**

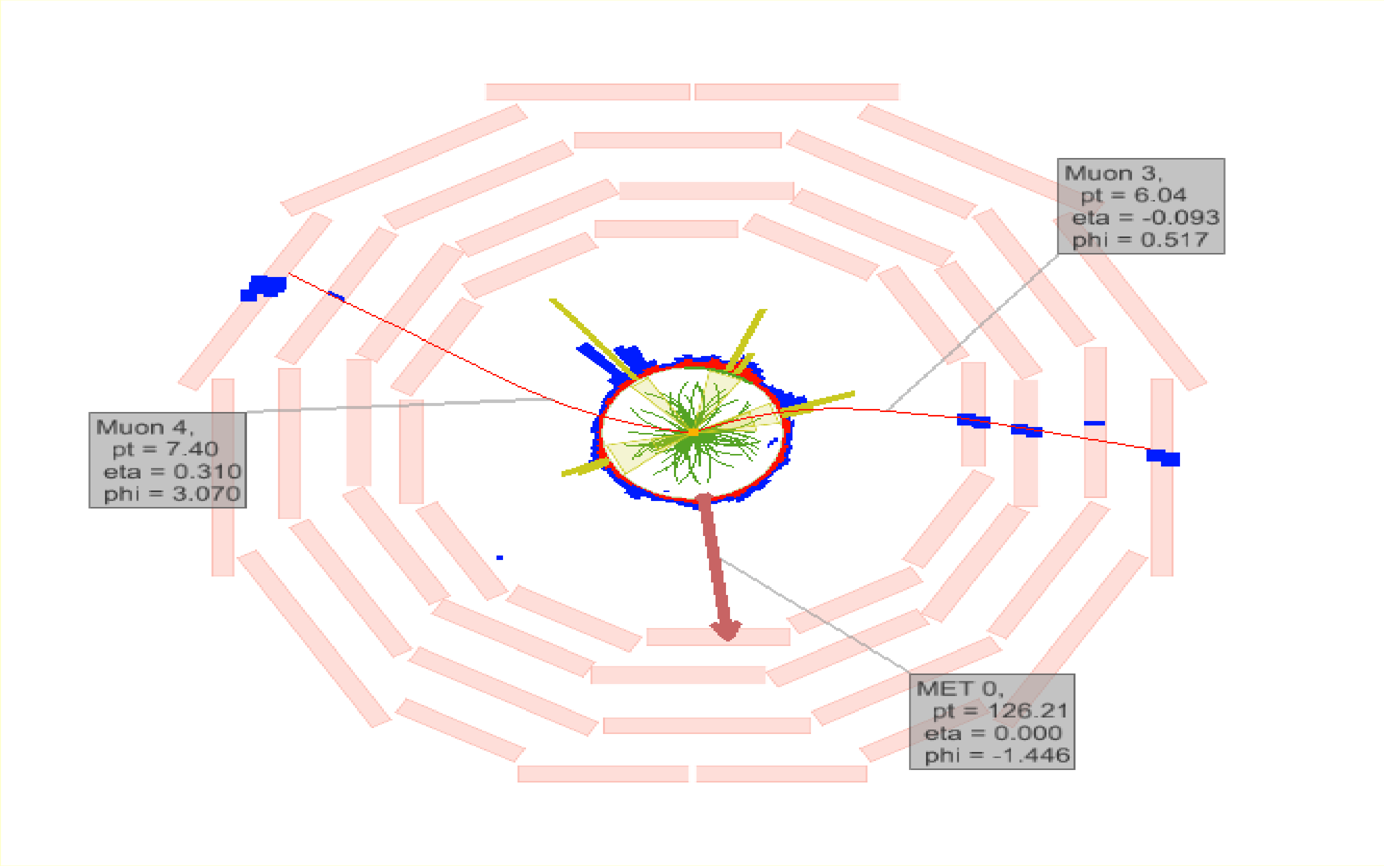
	MET^{γ} < 60 GeV	MET^{γ} > 60 GeV
3 ns < t < 13 ns	C=0	D=1
| t | < 2 ns		(1p) 35097 + (2p) 174
-10 ns < t < -33 ns	A=3	B=1

Observed Event

- Event's final state: Photon + 2 Jets + Large MET
  - **Photon:**
    - Pt = 225 GeV/c, ECAL Time = 12 ns, Eta = 0.32, Phi = 1.13
  - **MET:**
    - MET = 333 GeV, MET_{photon} = 125 GeV
  - **JET:**
    - 2 Jets (pt = 86 GeV/c, 36 GeV/c)
- The large MET and small MET_{photon} makes indicates this event is a good Beam Halo/Cosmic-Induced photon event.

Observed Event Display

CMS Detector Transverse View



Observed event is a cosmic muon candidate.

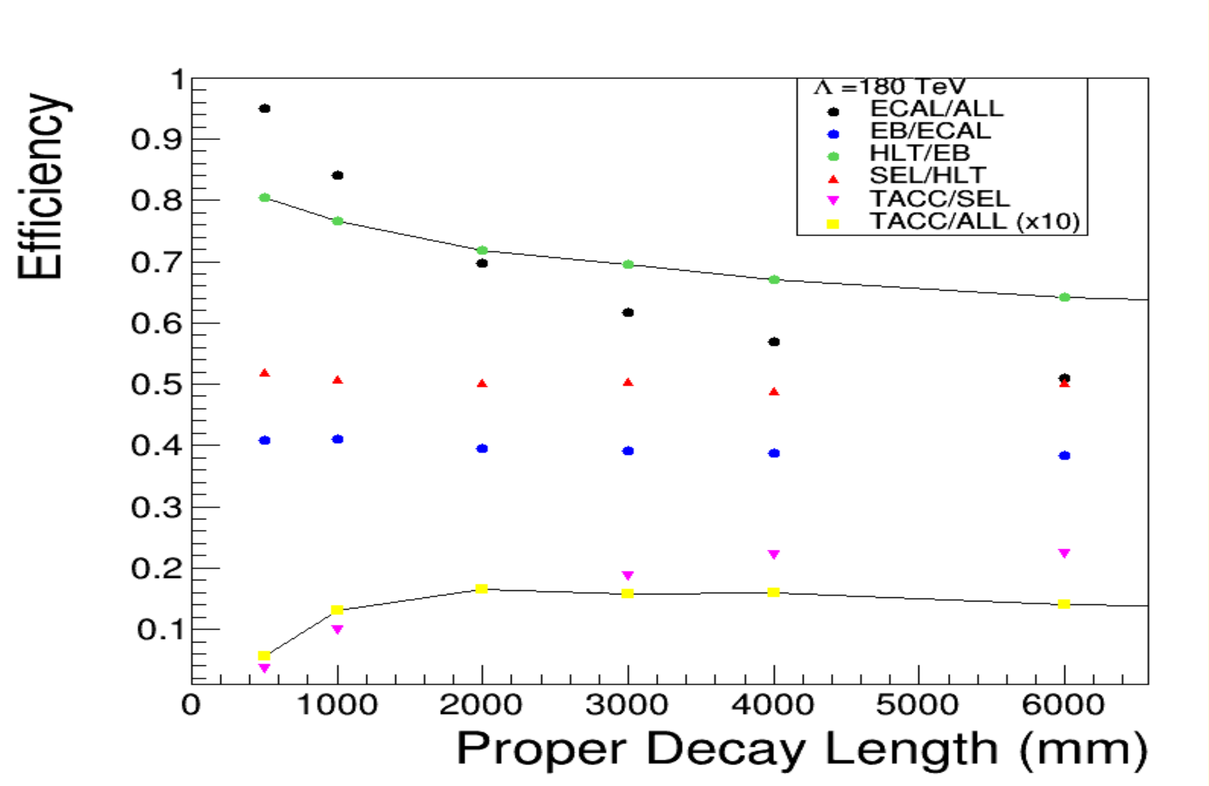
Uncertainties

- Main systematics are from Timing bias and unclustered energy for MET.
- Effect of systematics is measured by varying by 1-sigma upward and downward and measure the percentage of the event yield.
- Background uncertainty is given as statistical uncertainty on the predicted background.

Systematic Source	**Uncertainty(%)**
Absolute reference ECAL Time	6 to 10
Unclustered Energy for MET	4 to 10
Photon Energy Scale	2 to 4
ECAL Timing resolution	2 to 5
Jet Energy Scale	3 to 9
Jet Energy Resolution	2 to 9
Luminosity and Choice of PDF	2.6 & < 1

Signal Selection Efficiency

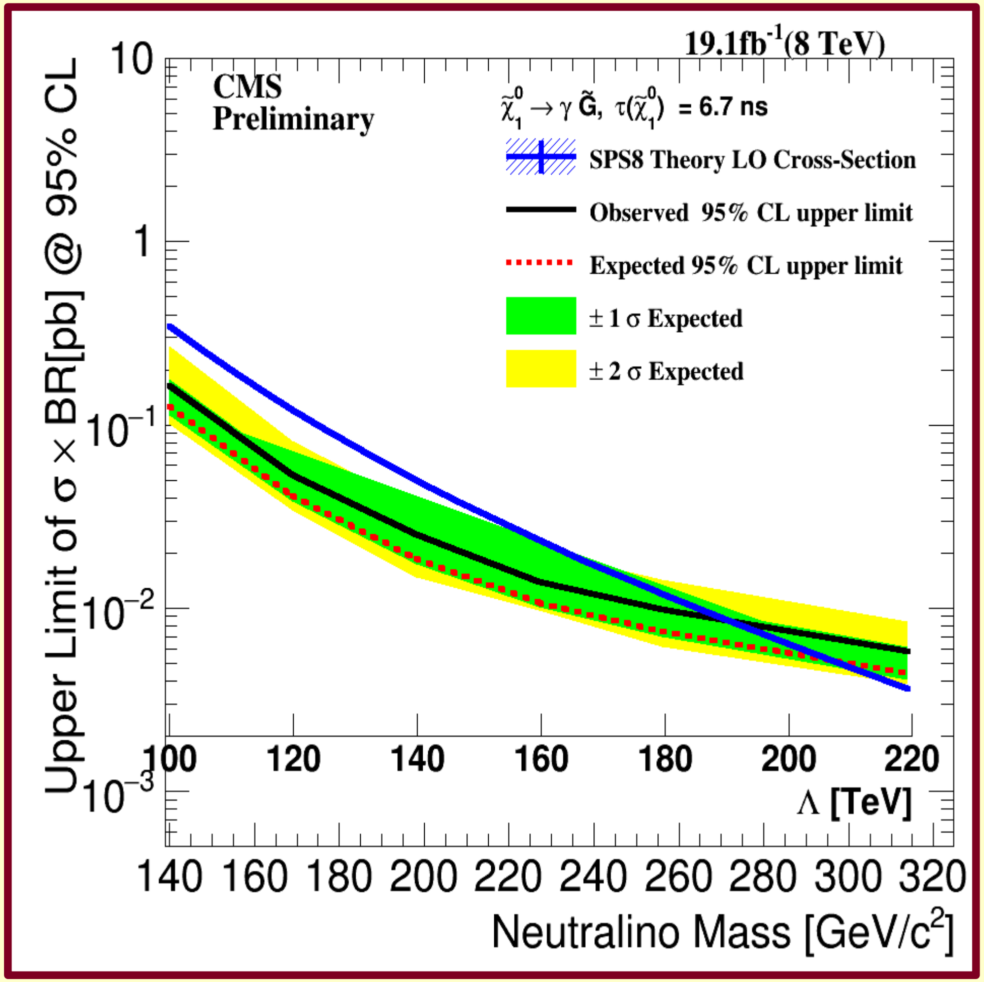
- Signal event selection efficiency times acceptance (TACC/ALL) peaks at 1.6% for lifetime = 6.7 ns.
- **Efficiency times acceptance is = Number of photons in EB passing event selection requirment with t > 3 ns / All photons from decay of neutralino including those not reconstructed.**
- Signal event selection efficiency is small for short lifetime since most of the photons cannot make it pass the t > 3 ns acceptance threshold and also small for long lifetimes because the neutralino decays out-side of ECAL.

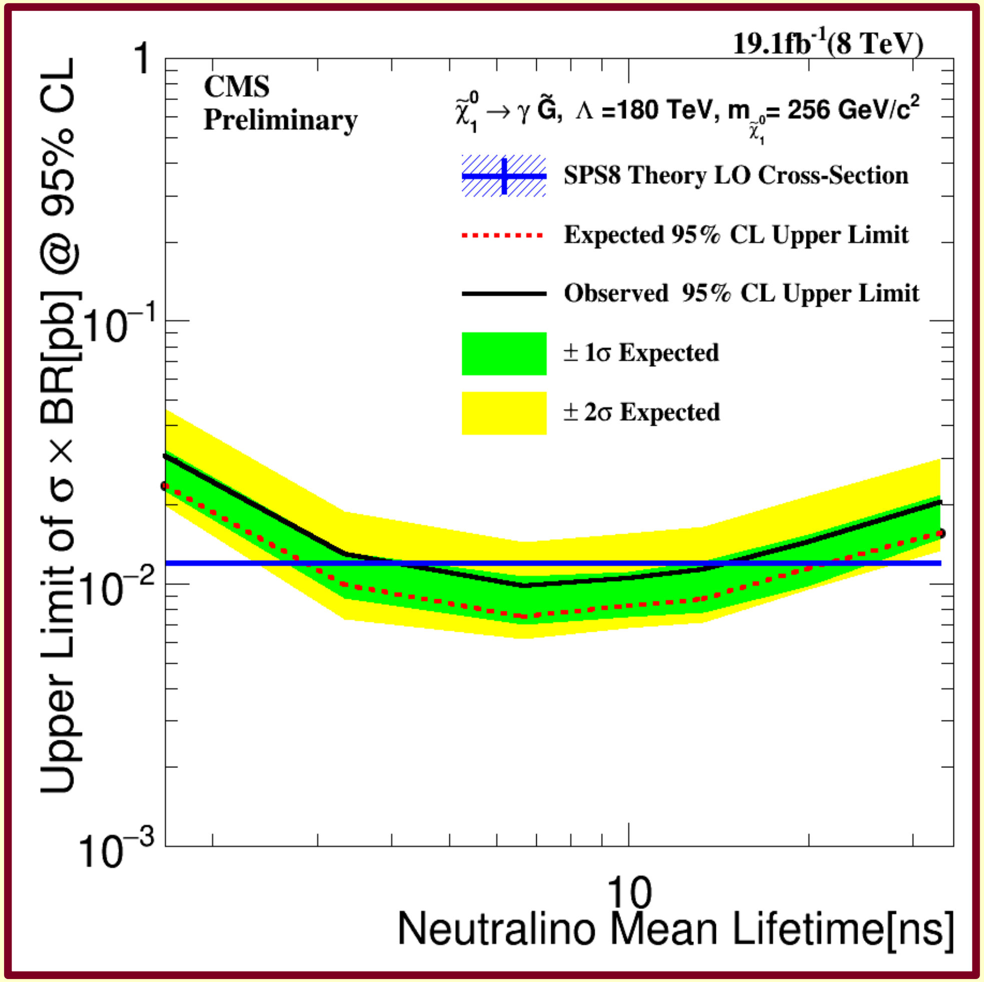


Cross-section Upper Limit

- Using the 1 observed event and the estimated number of background of 0.37 events, we set an upper limit of **4.37** on the number of Signal events.
- Using the maximum efficiency times acceptance at 1.6% for lifetime = 6.7 ns and Mass = 256 GeV/cc, we set an upper limit on the cross-section times branching ratio of **0.0143 pb.**
- Cross-section for other masses and lifetimes shown later.

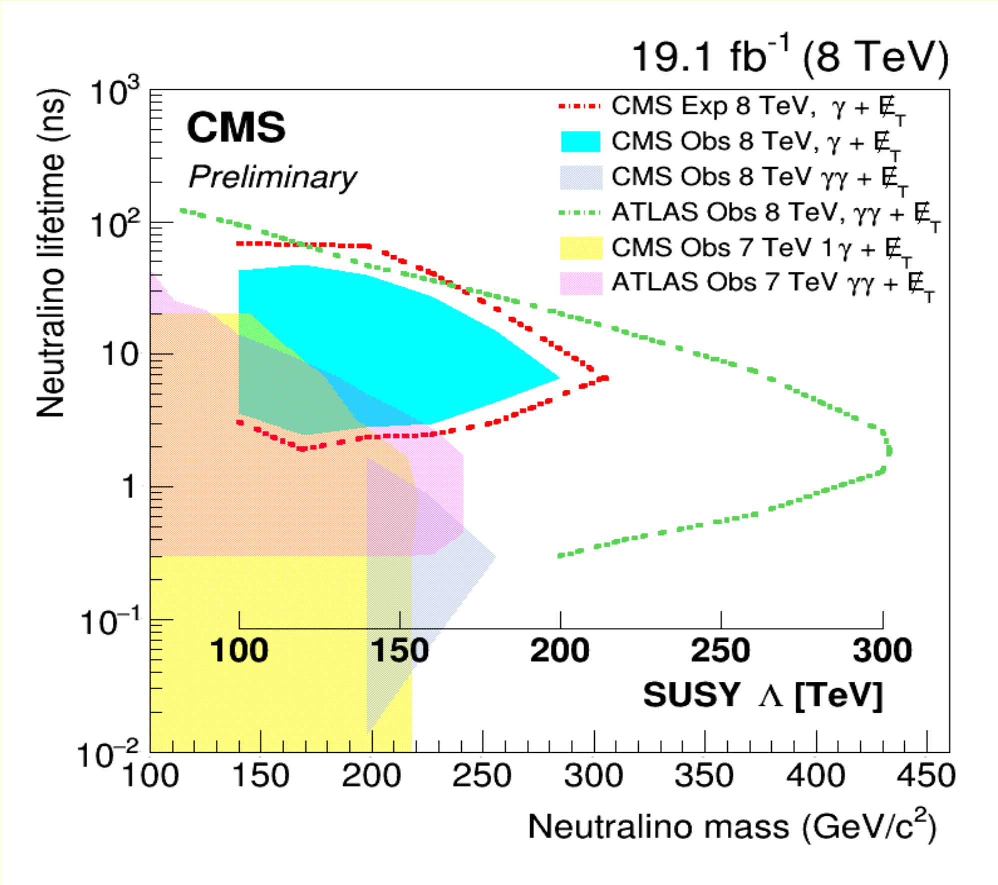
Mass & Lifetime Limits in SPS8

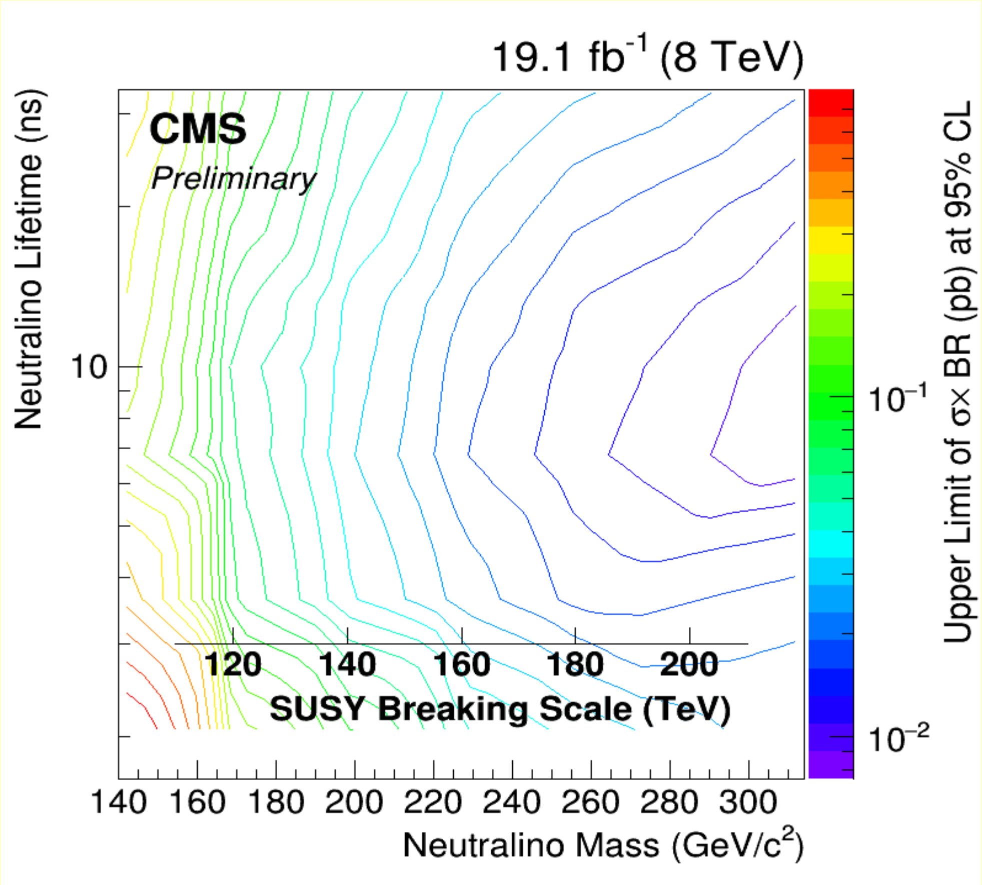




- Neutralinos with **Mass < 270 GeV/cc** and **Lifetime = 6.7 ns** excluded at 95% confidence level.
- Neutralinos with **3.2 ns < Lifetime < 19.87 ns** and **Mass = 256 GeV/cc** excluded at 95% confidence level.

Mass & Lifetime Limits in SPS8





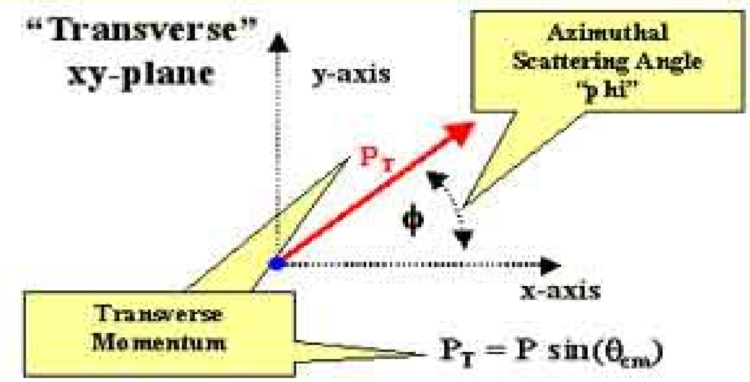
- Excluded neutralinos with **140 GeV/cc < Mass < 270 GeV/cc** and **3 ns < Lifetime < 35 ns** at 95% confidence level(CL).

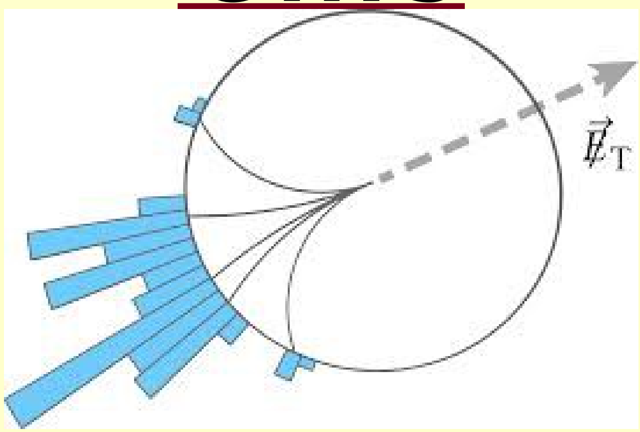
Summary

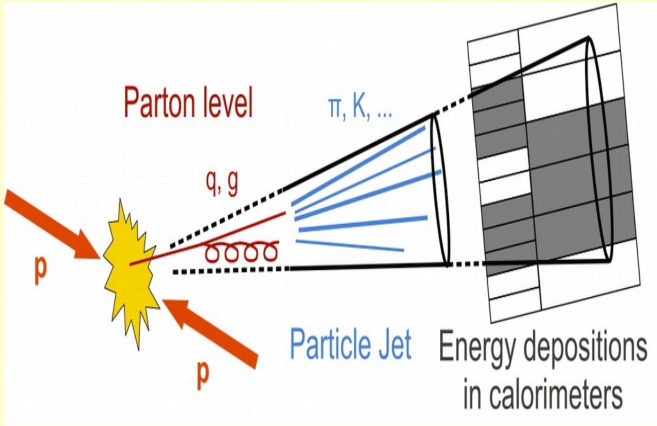
- We presented a search for neutral long-lived particles in final states with late photons and large missing transverse energy using the CMS detector. ECAL timing measurement of the photon arrival time is used for identifying the late photon.
- We set an upper limit of **4.37** on the number of signal events at 95% CL which can be translated into production cross-section times branching ratio of Neutralino **< 0.0143 pb** with **Mass = 256 GeV/cc** and **lifetime = 6.7ns** are excluded at 95% CL.
- Excluded neutralinos with **140 GeV/cc < Mass < 270 GeV/cc** and **3 ns < Lifetime < 35 ns** at 95% CL.

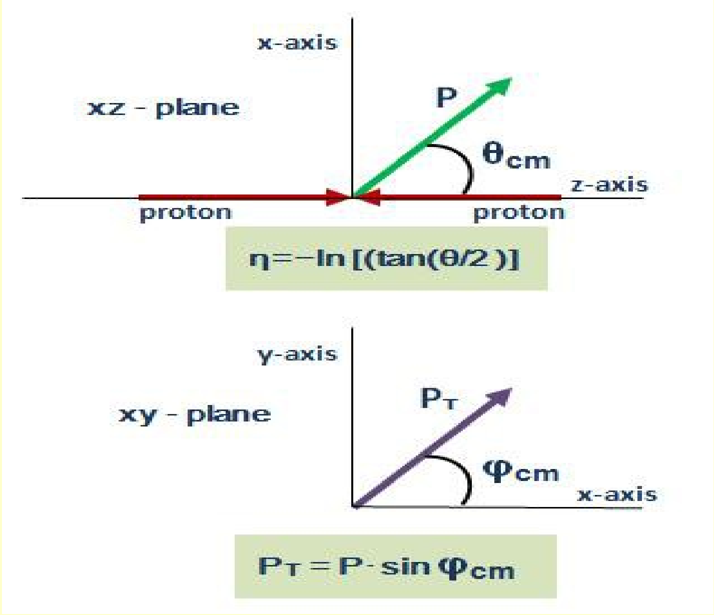
Thanks A LOT!

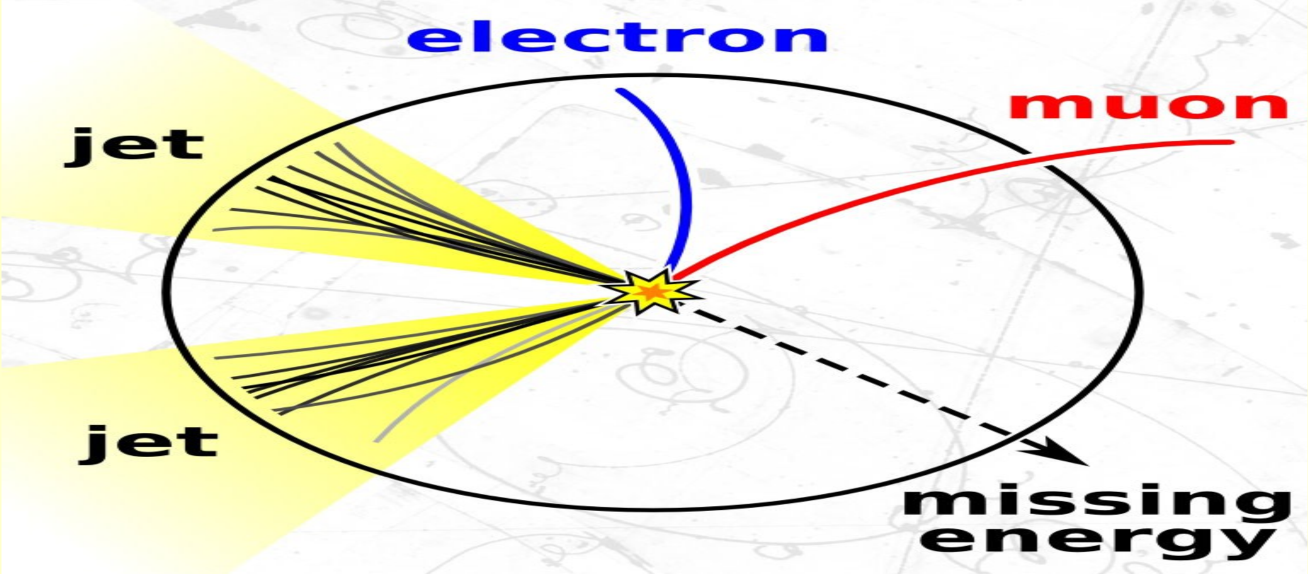
BackUp: Physics Objects in CMS





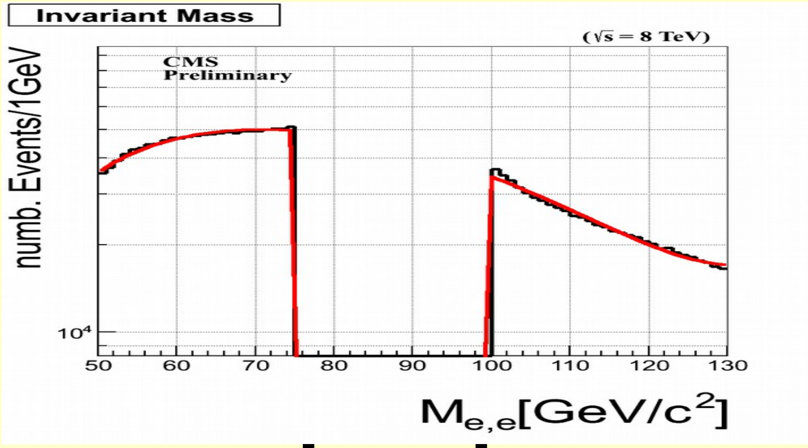




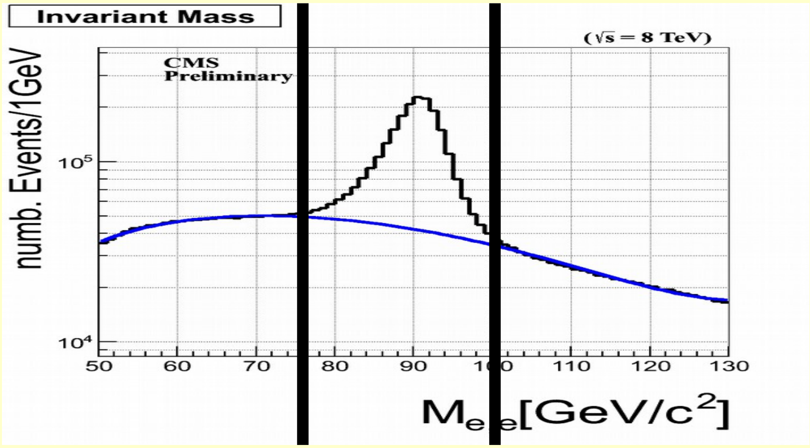


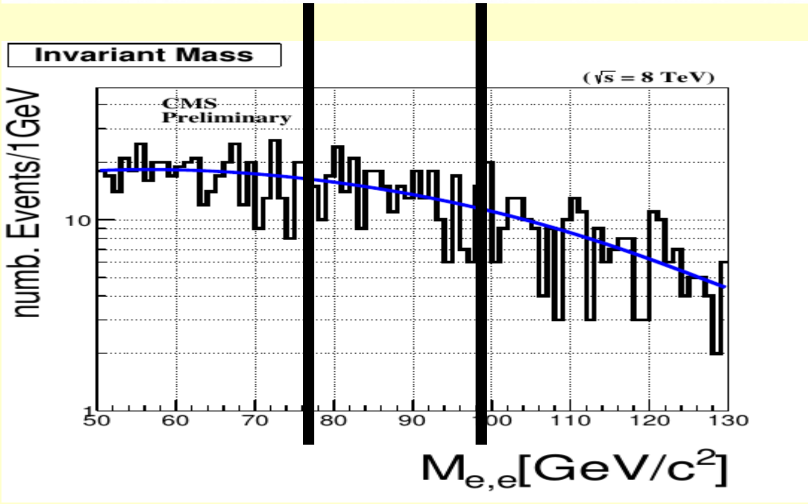
Z→ee Method

Sideband events.

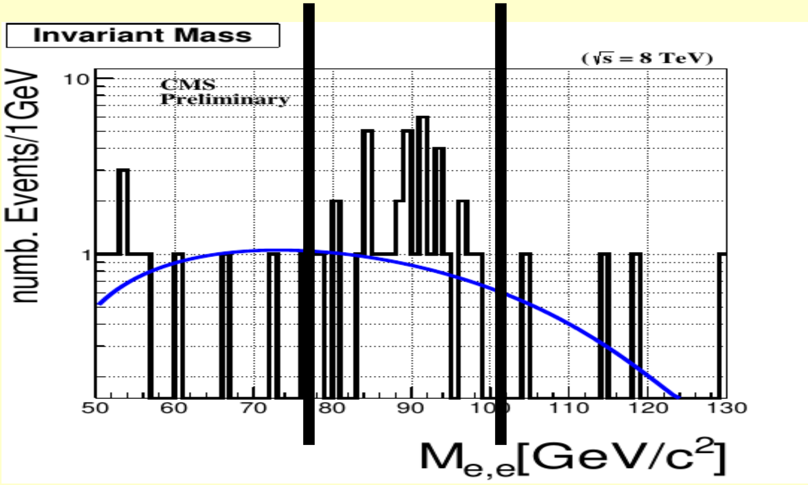


Early (|t| < 2 ns) Events





Early (t < -3 ns) Events



Late (t > 3 ns) Events

Z→ee Method

- Observed **3 candidate Z events** with both electron arrival **time > 3 ns**.
- Estimated number of Events in Seprate Cathegories:

	In Time (|t| < 2 ns)	Early Time(t < -3 ns)	Late Time(t > 3ns)
True Z Events	1352383.4	49	32.4
Background Events	996803.6	329	8.6
Total Events	2349187.0	378	41.0

- Thus the probability of Only One~(P1) electron candidates and both~(P2) to be out-of-time (Early or Late) is

	P1	P2
Early (t < -3 ns)	0.000018116	0
Late (t > 3 ns)	0.00001087	0.000021739

Collision Backgrd Estimation II

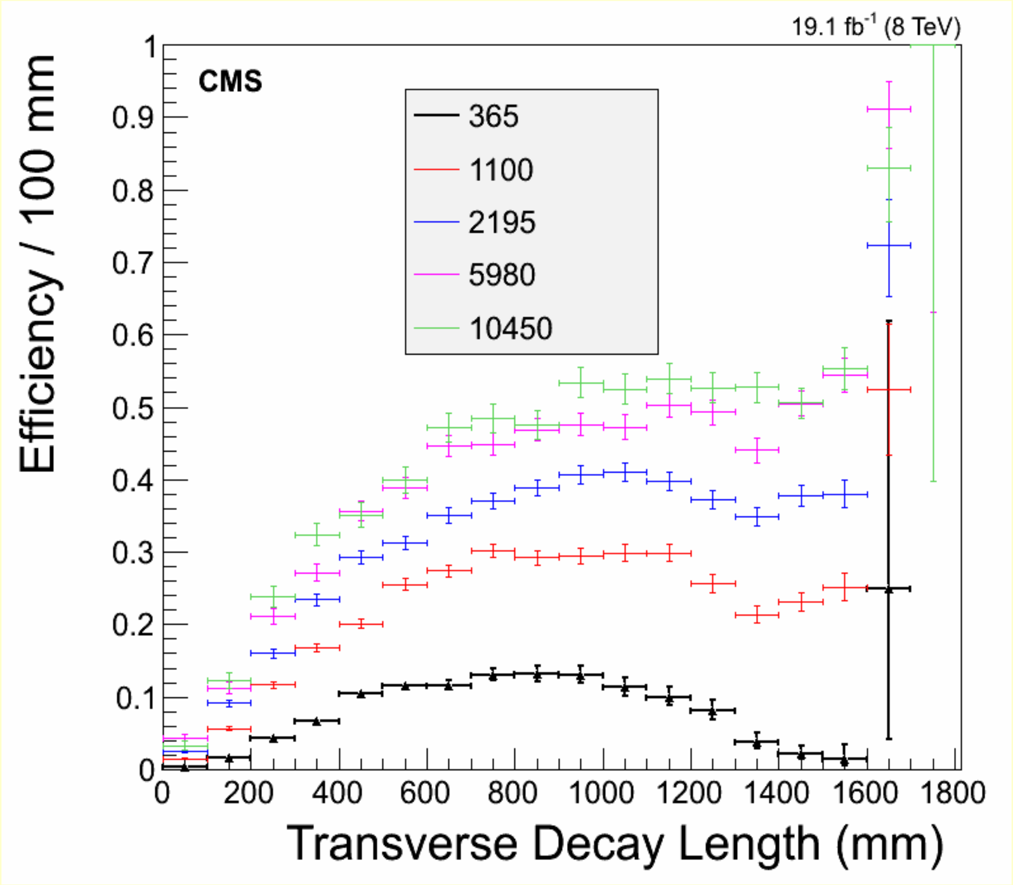
- Using the probabilities derived, we can estimate the collision background events in samples **B & D** as

$$N = n_1 * P_1 + n_2 * \left(2P_1\left(1 - P_1\right) + P_1^2\right) + n_1 * P_1 + n_2 * P_2$$

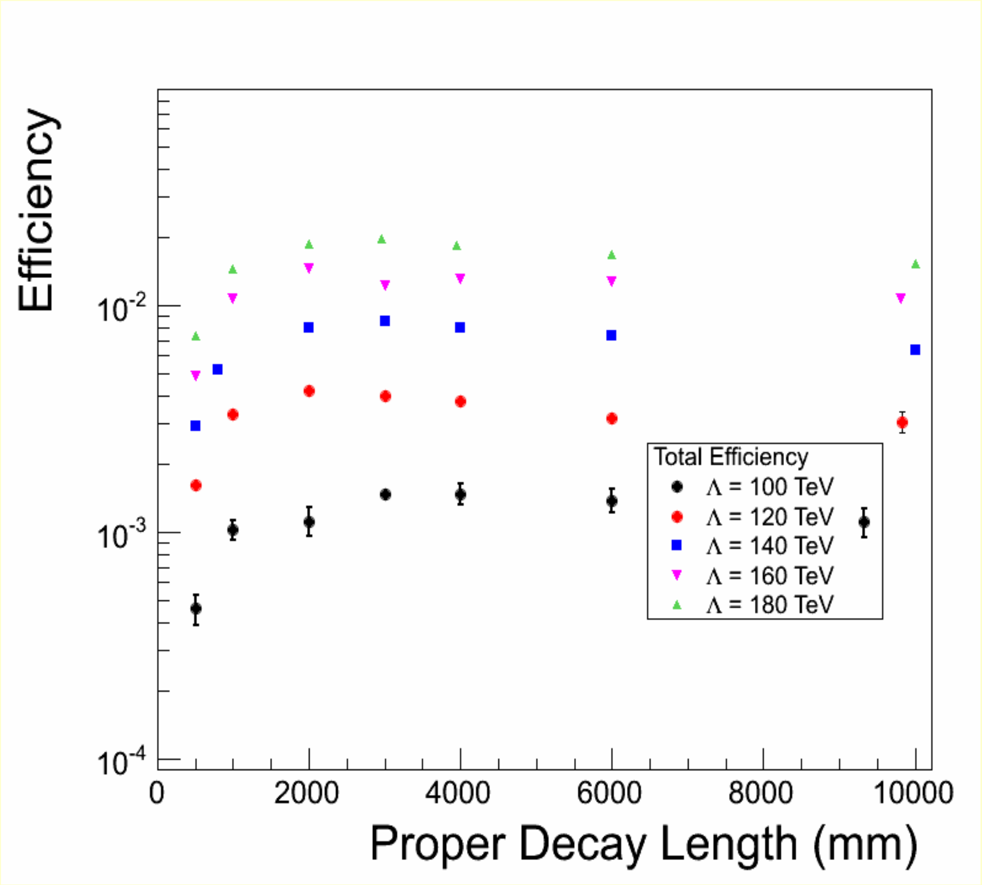
- With **n1** is the number of **in-time single photon** events & **n2** is the number of **in-time double photon** events.
- The probabilities P1 and P2 are interepreted as:
  - **P1**: is the probability of getting an in-time event identified as an out-of-time due to timing missmeasurement.
  - **P2**: is the to get a true out-of-time event from collision(mostly satellite collsiions).
  - The **3 out-of-time(late) Z candidates** events are assumed to come from **satellite collisions**.

Efficiency & Acceptance

Transverse Detector Decay Length



Particle Inherent Decay Length

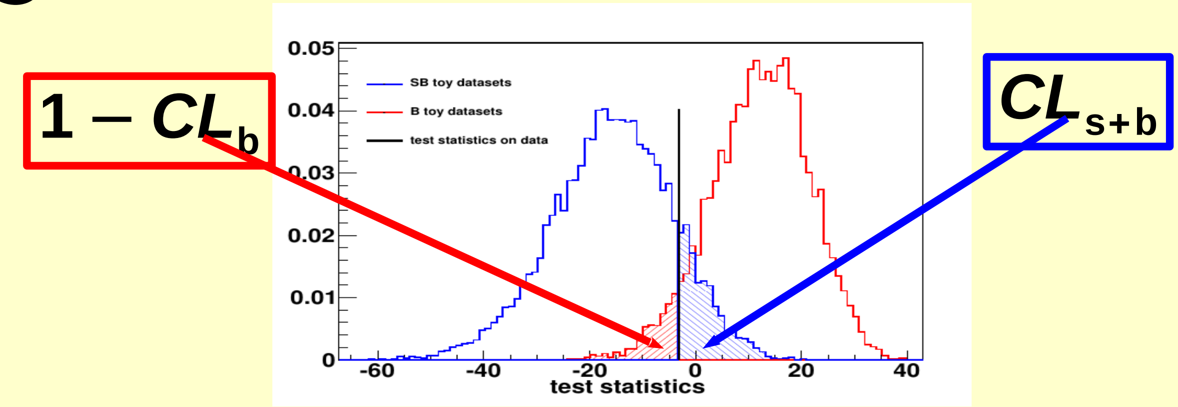


Efficiency and Acceptance determines our final Observed event rate.

Limit Setting

- Use the Cls method:

$$CL_s = \frac{CL^{\mu}_{s+b}}{CL_b}$$

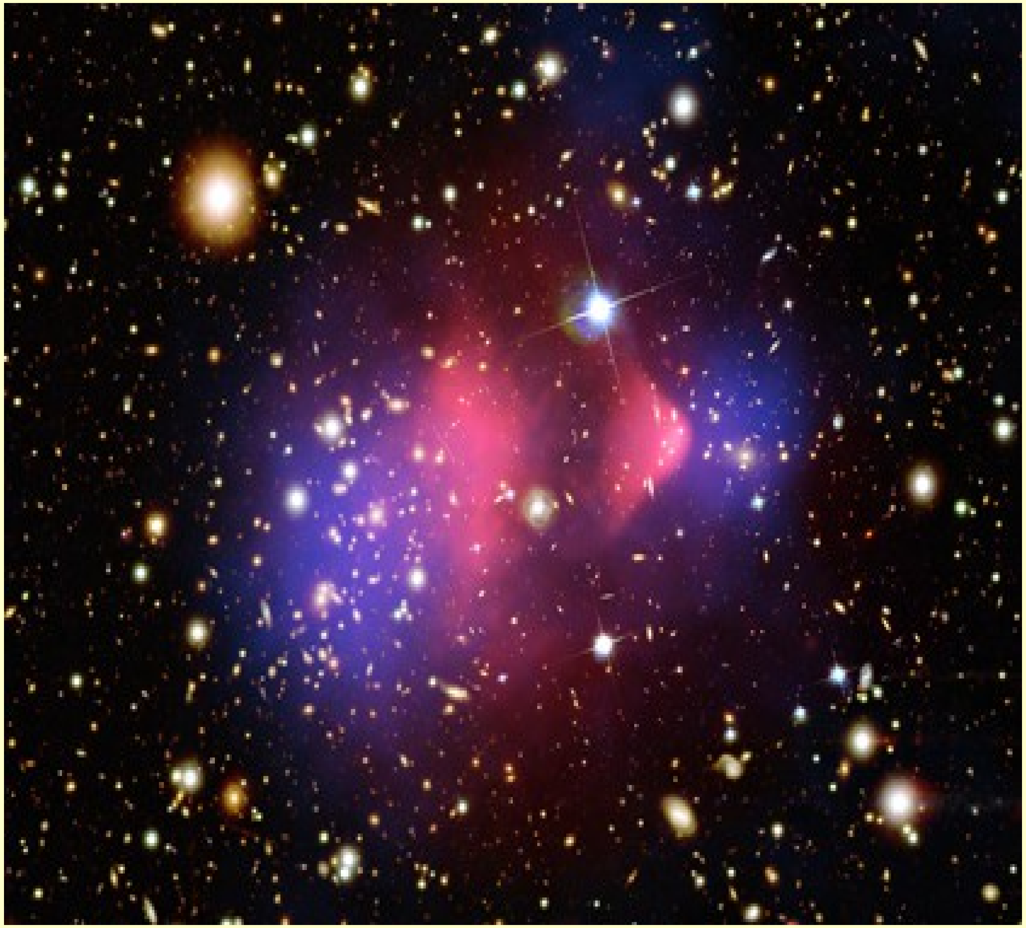


- CL{s+b} and CL{b} are probabilities for signal + background and background only hypotheis, respectively.
- Mu is signal strength modifier parameter.
- Excluded region in Mu or cross-section are values for Mu for which the probability CL{s} is less than **0.05% for 95%** confidence Limit(CL)
- Background Only hypothesis gives **expected or median limit**.
- **+/- 1-sigma** and **+/- 2-sigma** gives statistical uncertainty bands on the expected limit.
- **Observed limit** is obtained from fitting Signal + background model to data.

Dark Matter?

Properties

- Stable(long-lived).
- Neutral; does not interact with light.
- Light or massive?

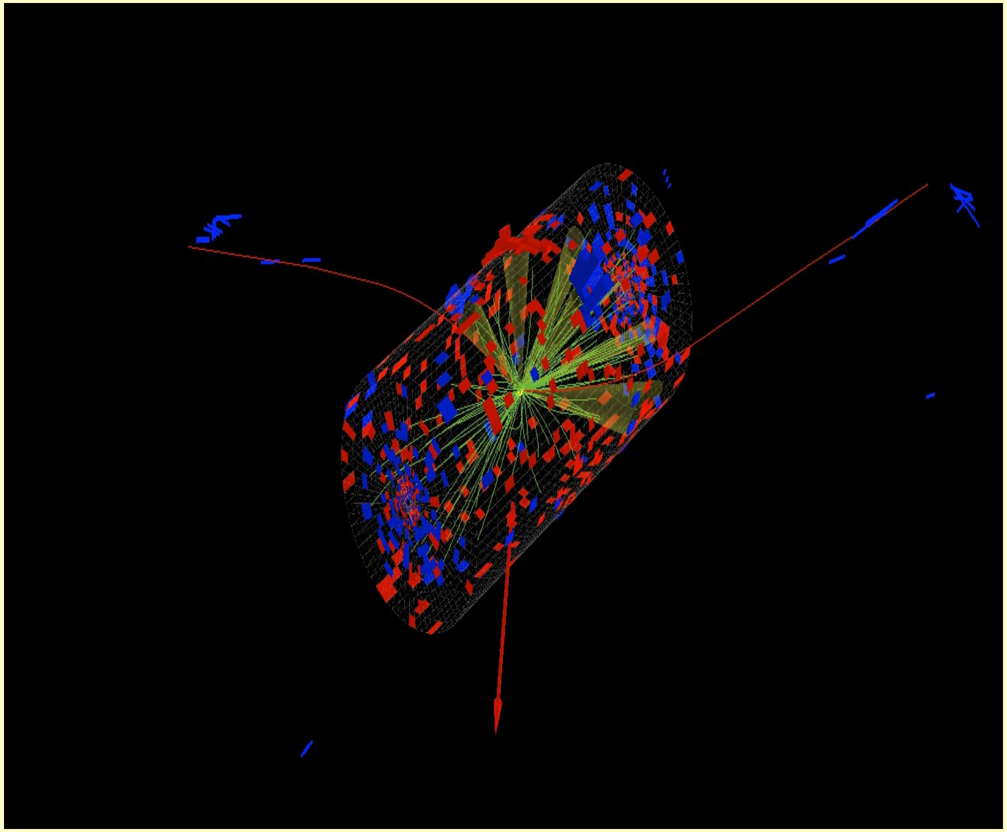


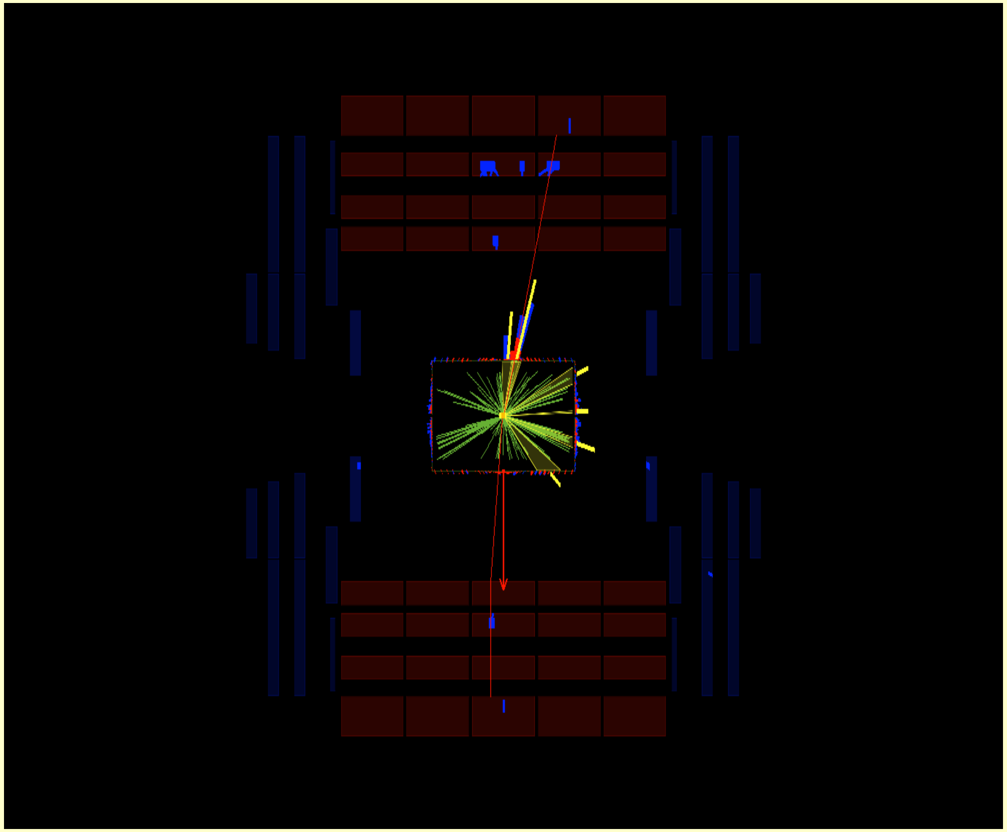
- **Where are Dark Matter particles?**

Observed Event Display

3D View

Rho – Z View





CMS event Display of observed Cosmic Muon event in CMS detector.

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