# 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

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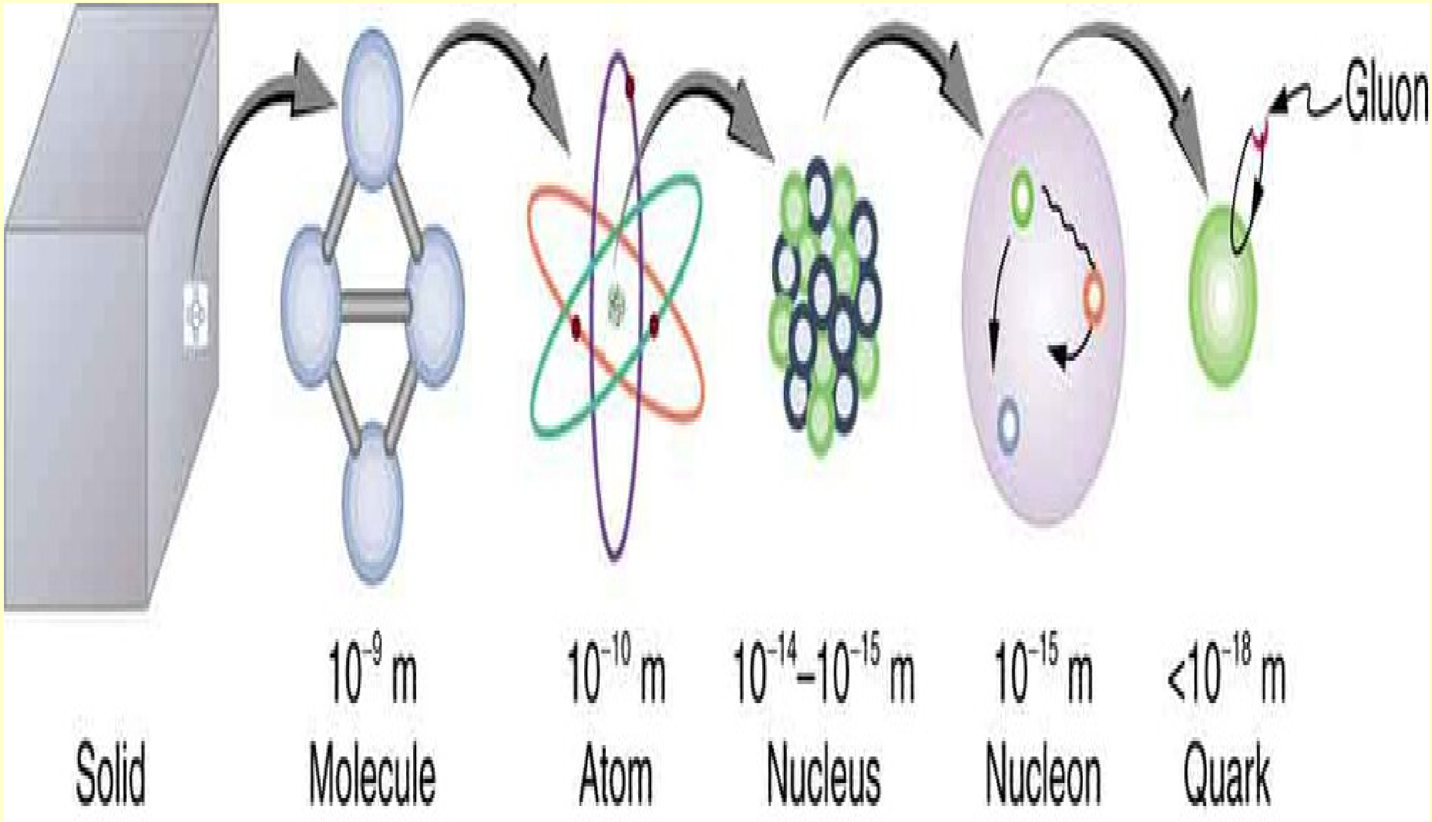
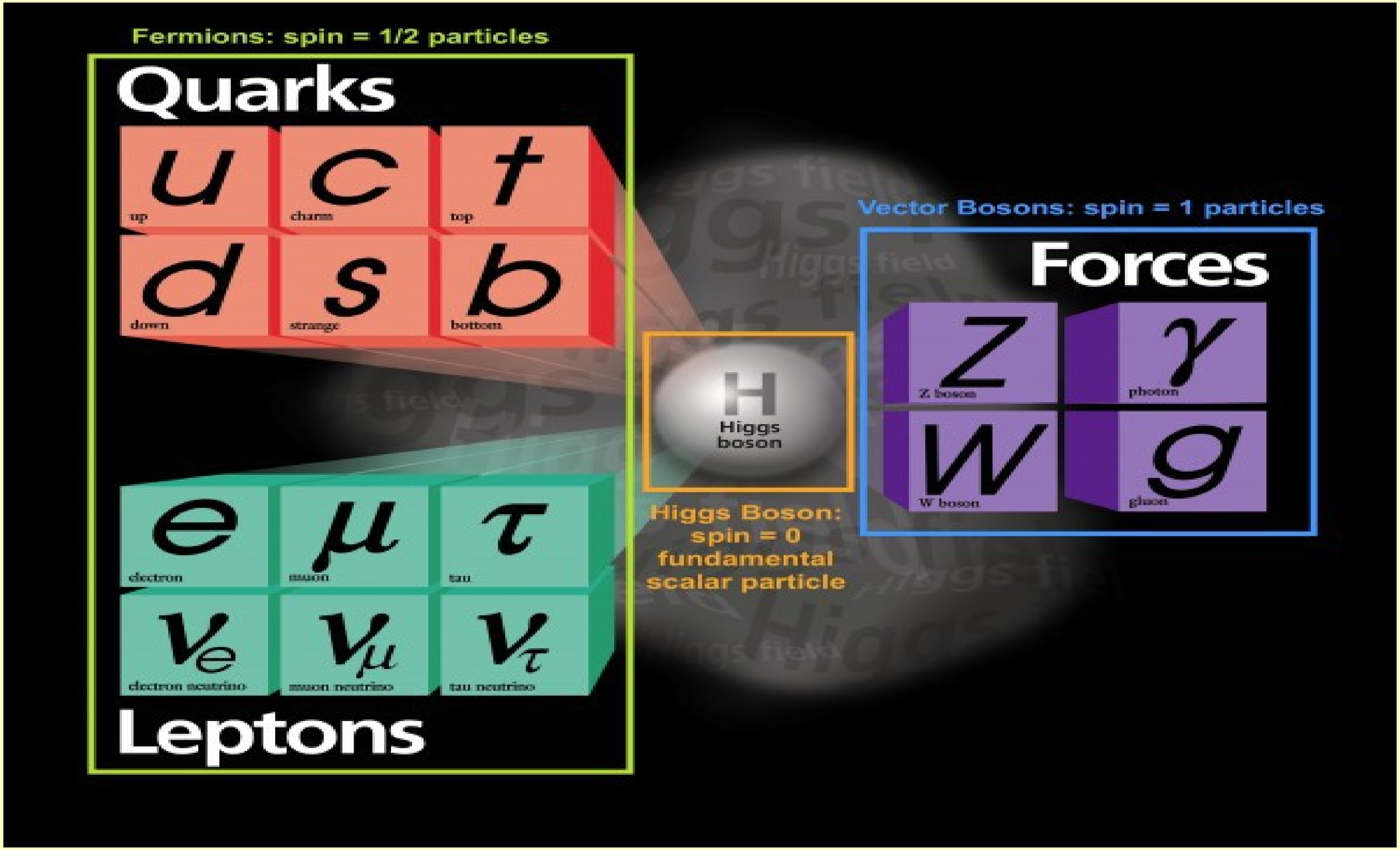
# Introduction

# 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.

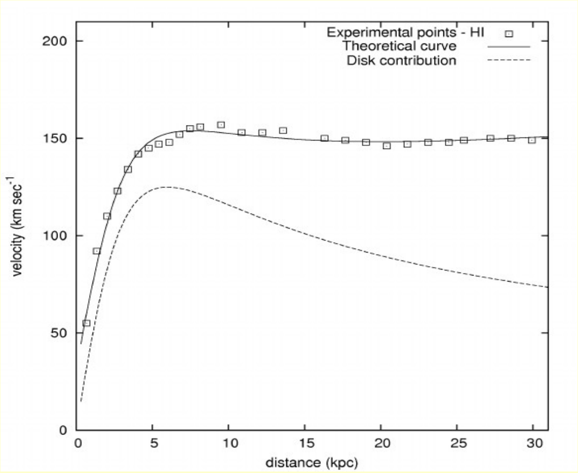
# SM: Interactions & Lifetimes

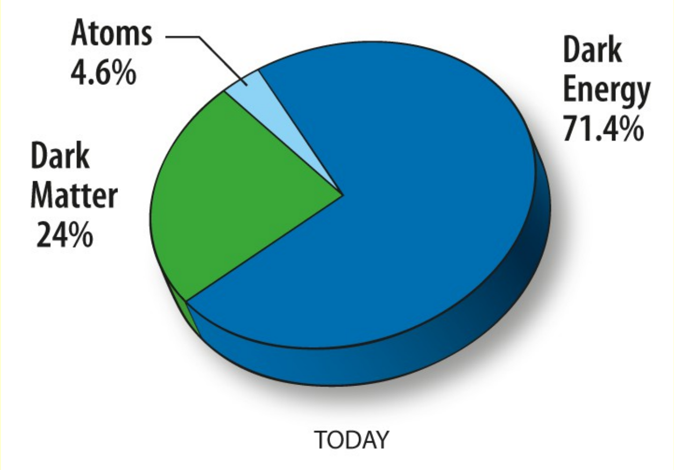
| Boson | Interaction | Symmetry | Lifetime |
|---|---|---|---|
| *Gluons* | Strong | $SU(3)_{\mathrm{C}}$ | $< 10^{-22}\,\mathrm{s}$ |
| *Photon* | Electromagnetic | $U(1)_{\mathrm{Q}}$ | $10^{-20}$ to $10^{-14}\,\mathrm{s}$ |
| *W, Z* | Weak | $SU(2)_{\mathrm{L}} \otimes U(1)_{\mathrm{Y}}$ | $10^{-13}$ to $10^{-8}\,\mathrm{s}$ |

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

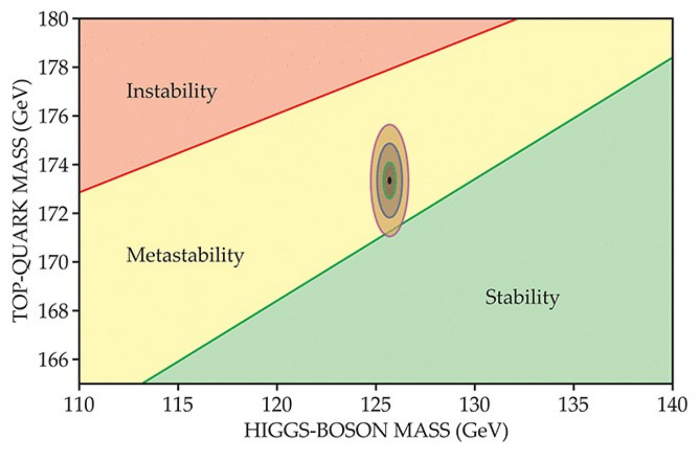
# Exotic Forms of Matter

- Non-Visible or Dark Matter.




- Massive Long-Lived particles.
  - Mass $> 1\,\mathrm{GeV}/c^2$
  - 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

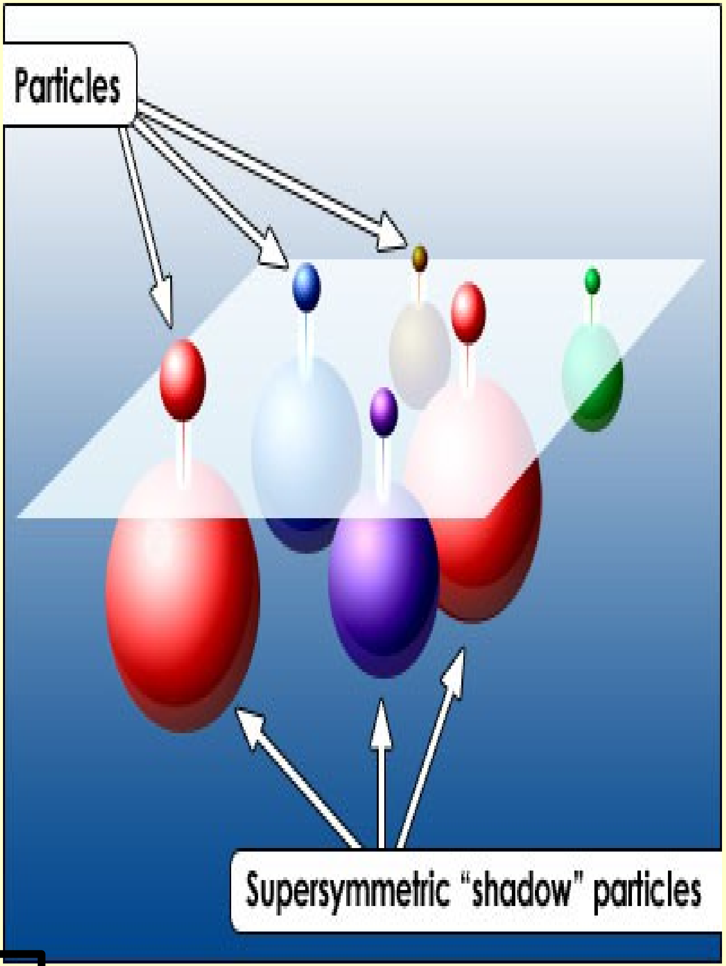
**N** msgr fields,

mass = **M**

$\Lambda$

$E \sim 1\,TeV$

Visible sector



# GMSB Models: LL Particles

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

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

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

# SPS8 Benchmark GMSB Model

- Choice of parameters:

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

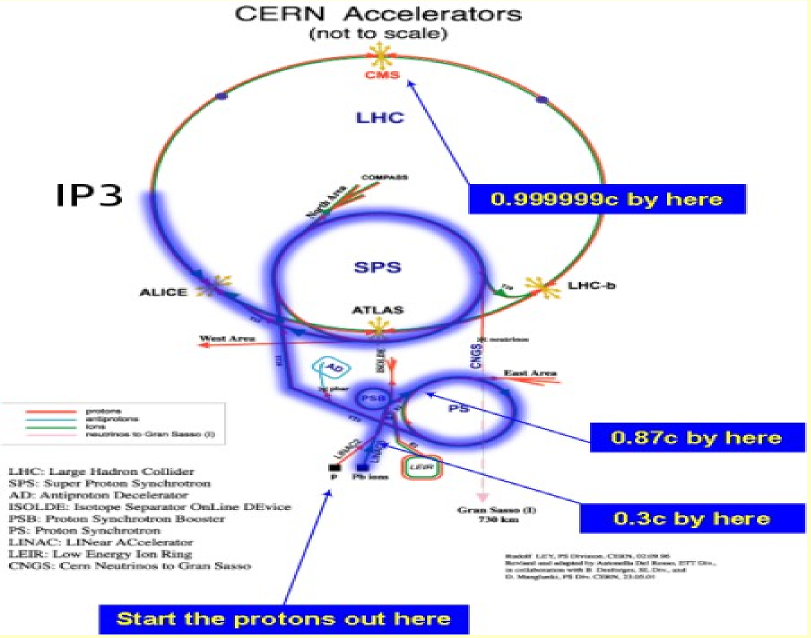
$\Lambda$ and $C_{grav}$ are free to vary.

- Lightest Neutralino is the Next-To-Lightest Supersymmetric Particle(NLSP) and decays 83 to 94 % of the time to a photon and gravitino.
- The Gravitino is the Lightest Supersymetric Particle(LSP).
- The Neutralino can be as short-lived or as long-lived as desired.

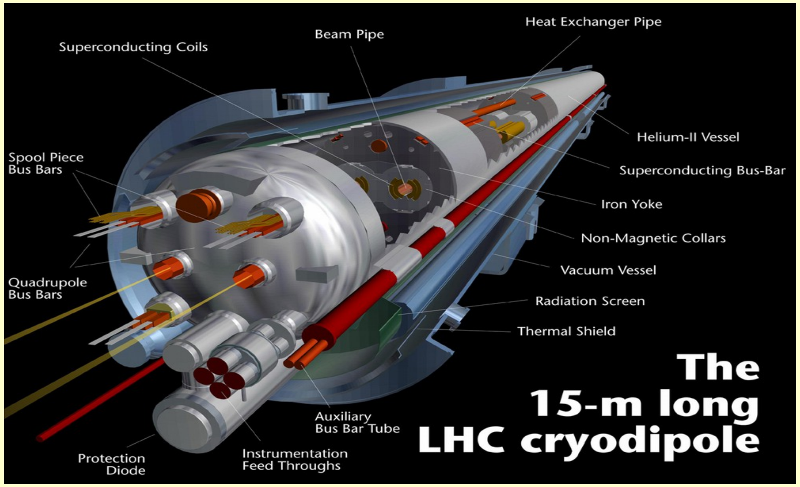
# Experimental Setup

# Large Hadron Collider

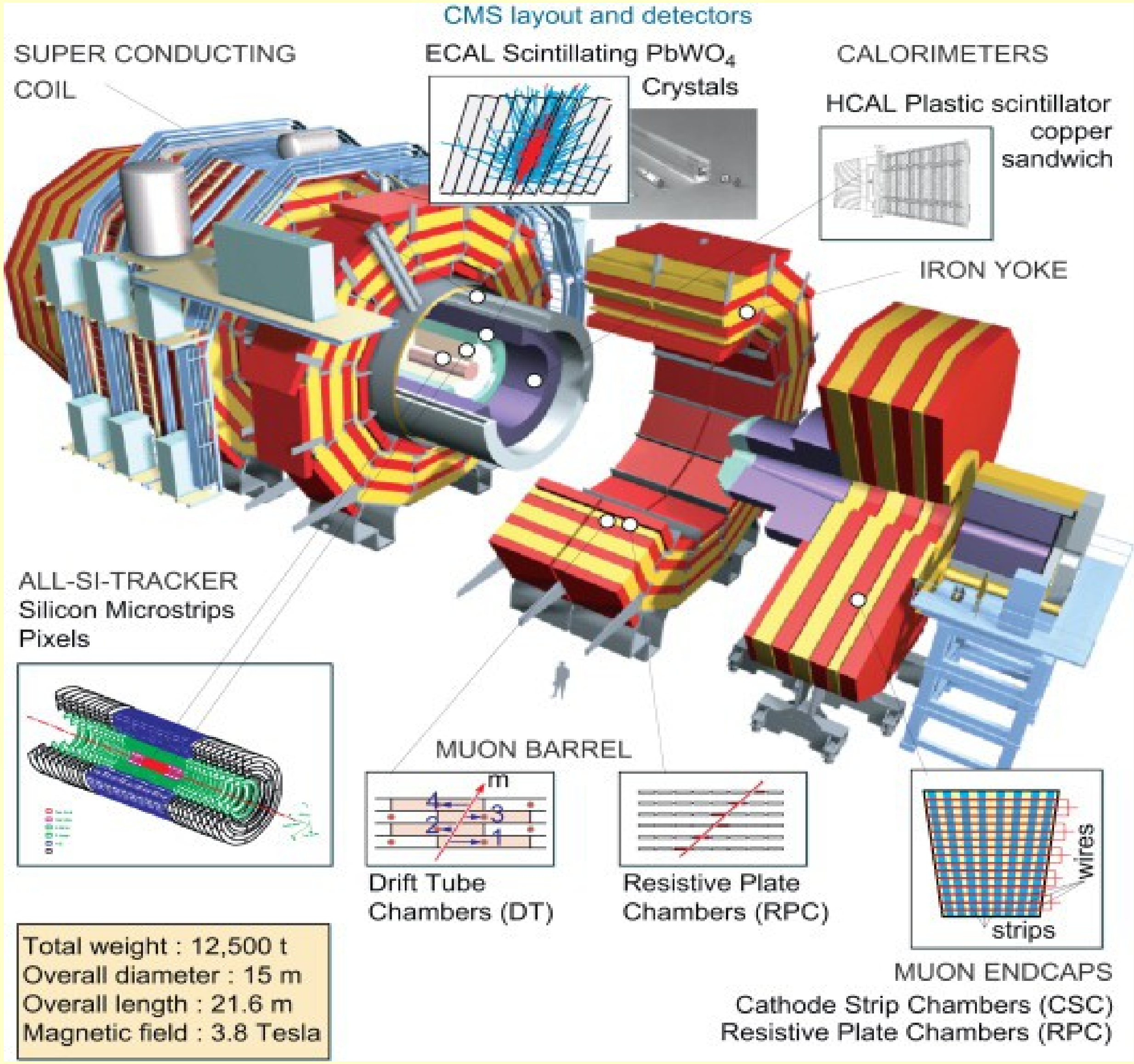
- **Designed Specifications :**
  - Proton-Proton bunches circulating in 26659m circumference  storage ring.
  - Accelerate protons up to 7 TeV.
  - Proton bunches collide every 25ns.
  - Dipole and quadrupole magnets steer proton beams.

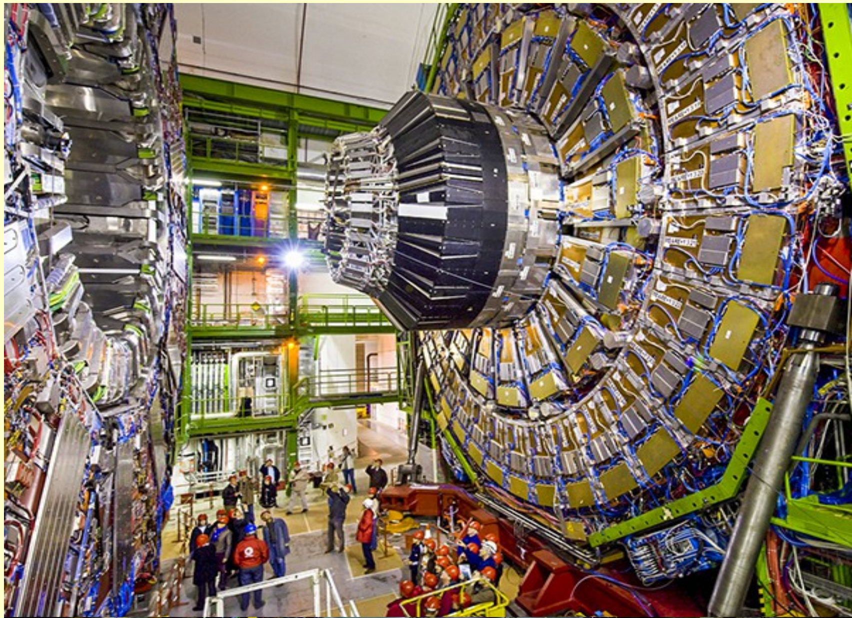


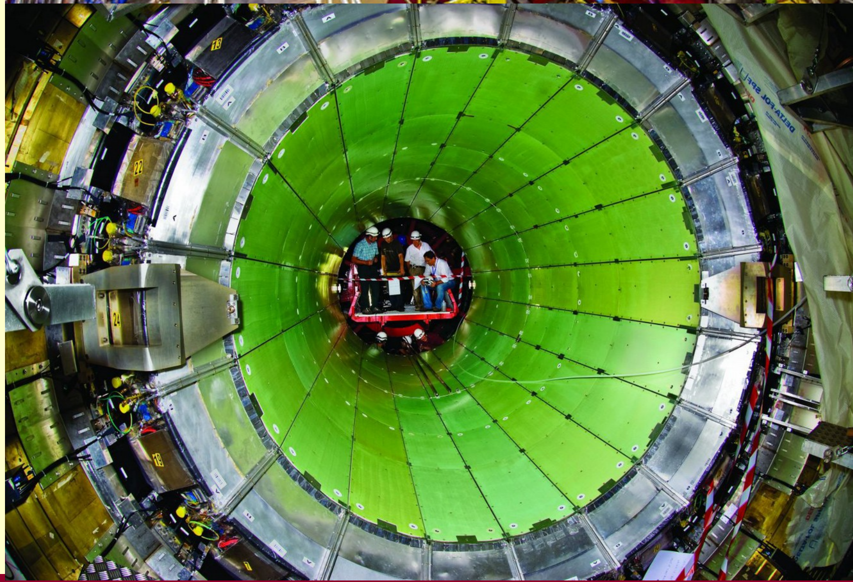

- **Search for Signatures of:**
  - ~~The Higgs Boson,~~
  - Supersymmetry,
  - Dark matter.



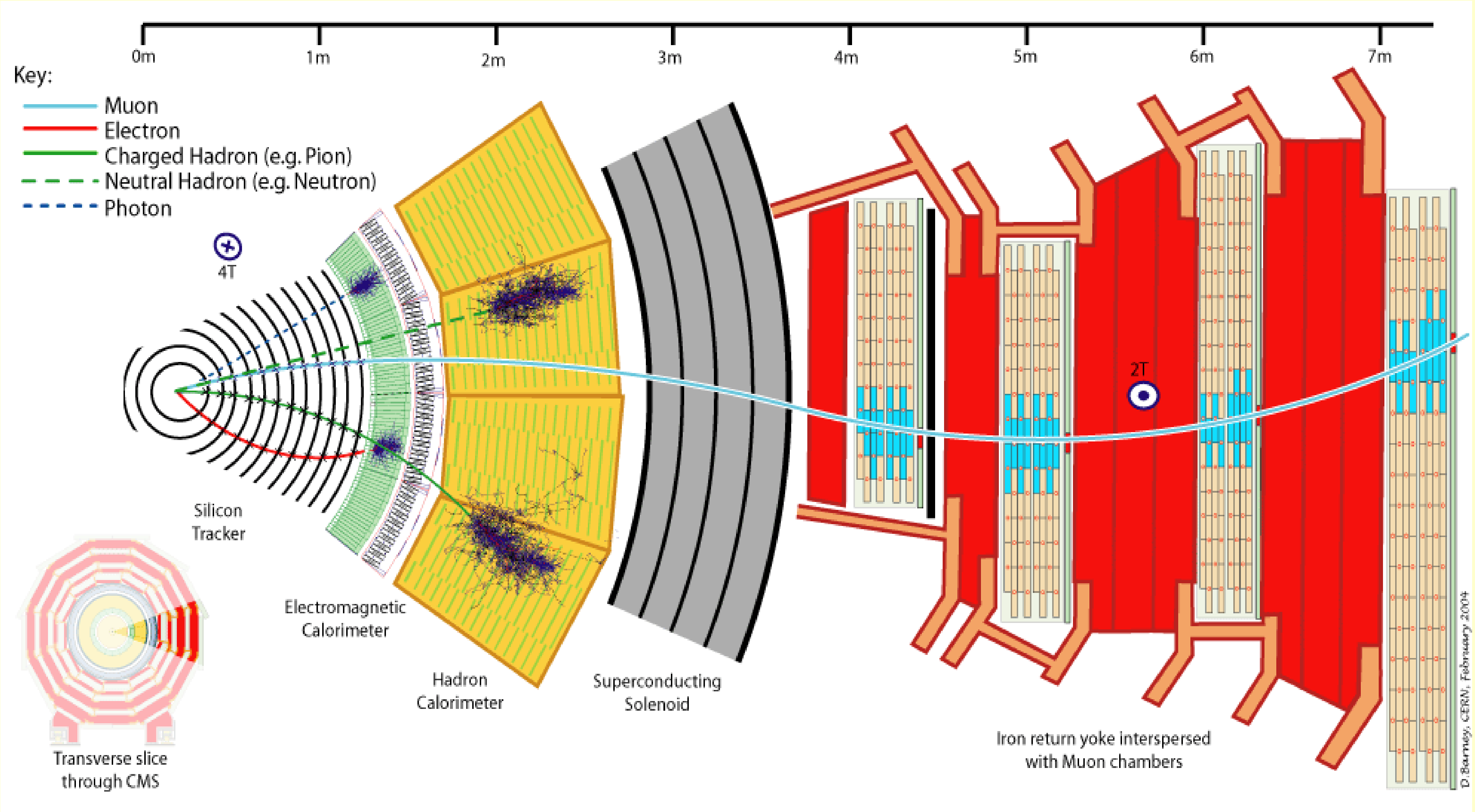
# Compact Muon Solenoid



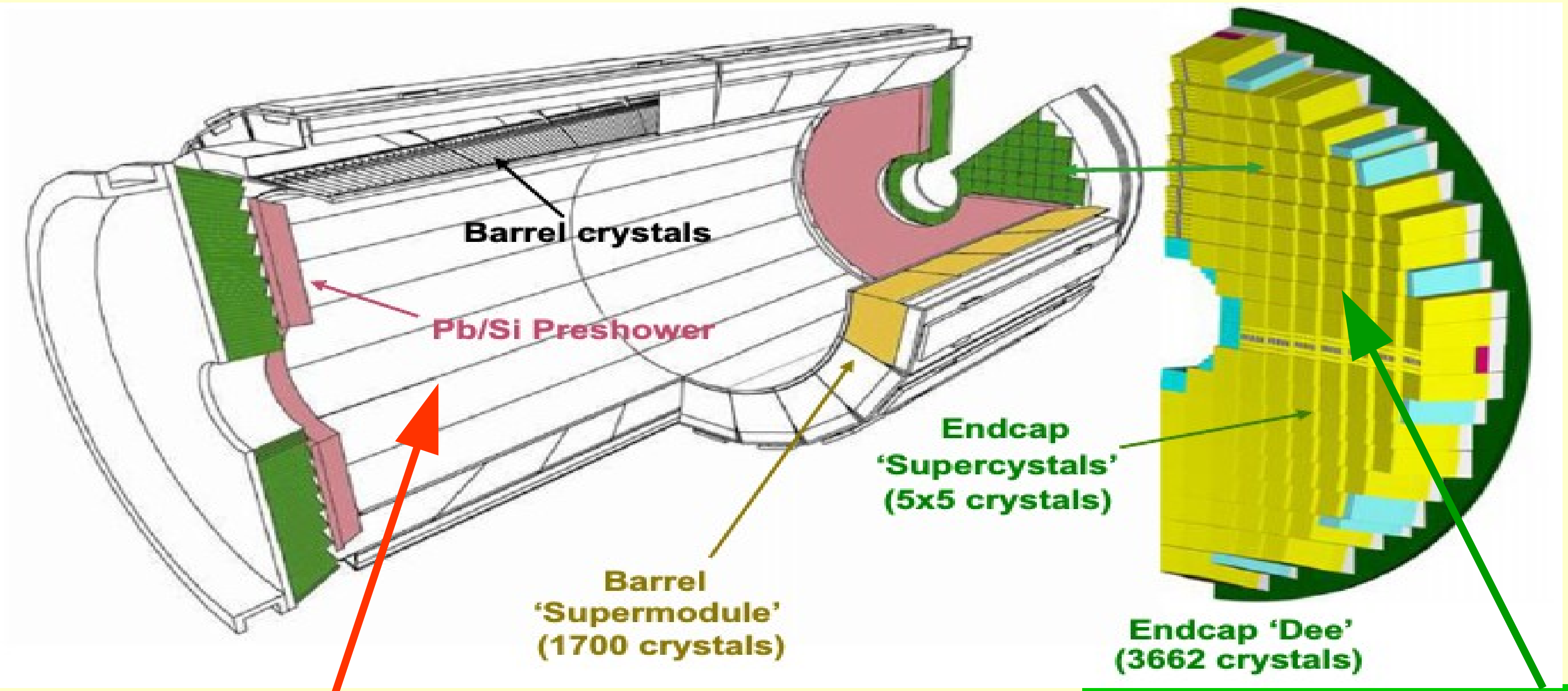


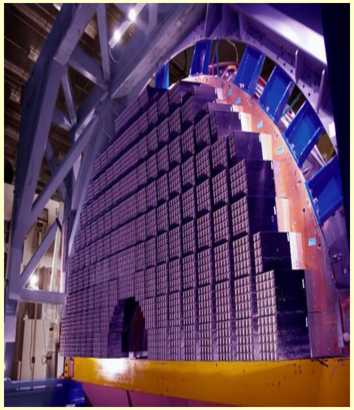
# Particle Detection



# Electromagnetic Calorimeter

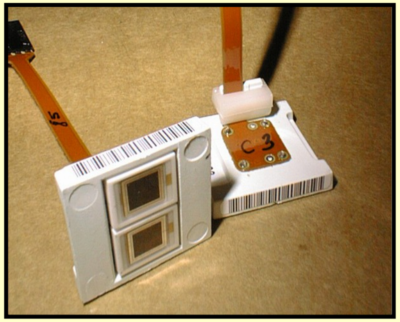
Lead Tungstate crystal Homogeneous calorimeter



## Barrel(EB)

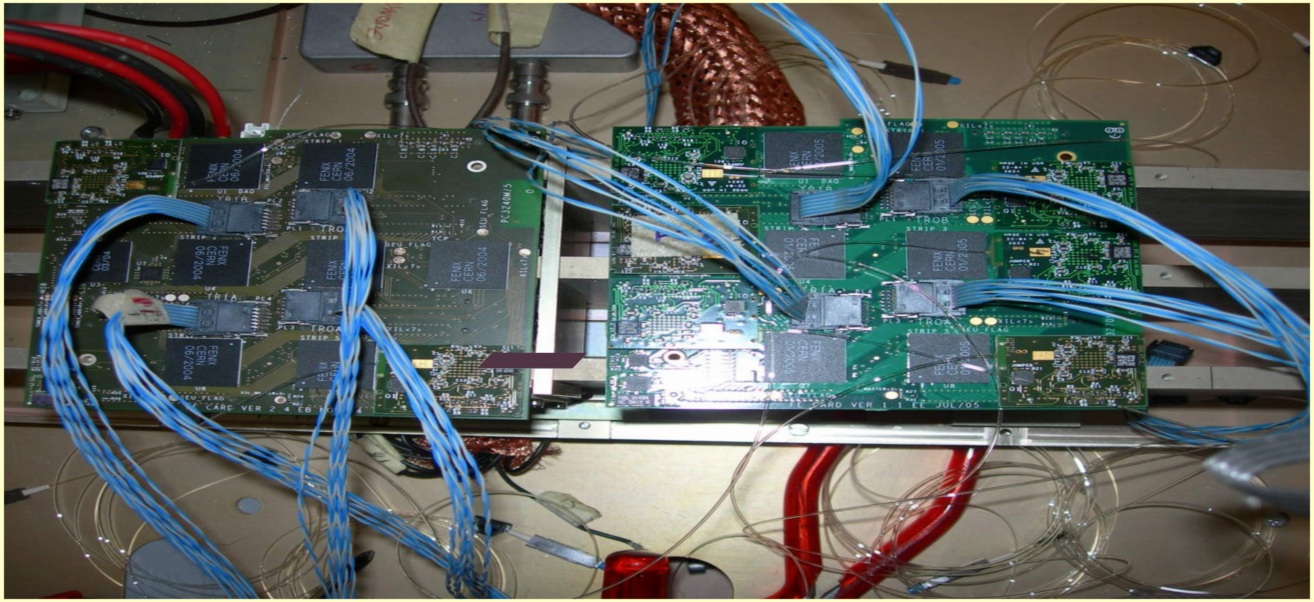
- 61200 crystals
- Covers |eta| < 1.48
- Uses APD photodetectors

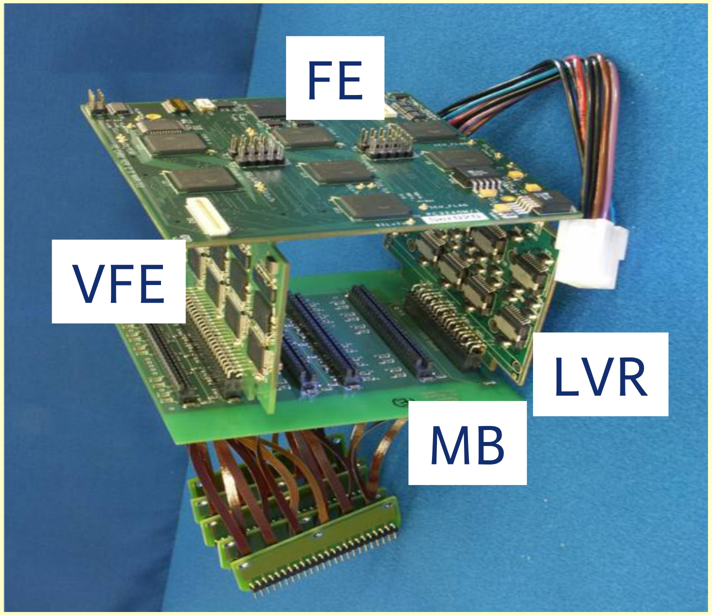


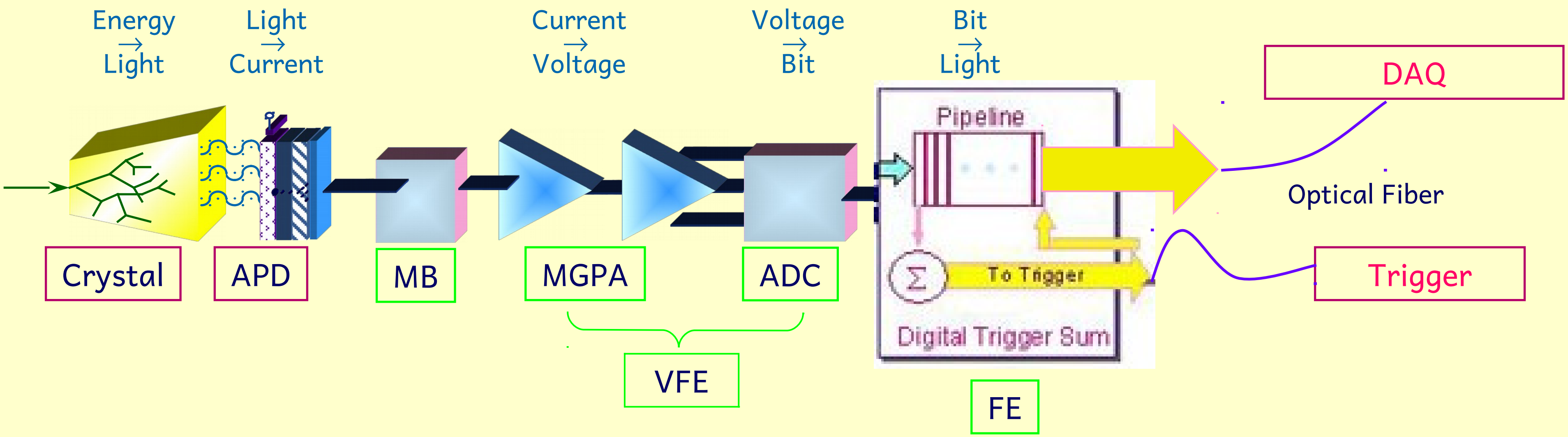
## Endcap(EE)

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

# ECAL ReadOut Electronics





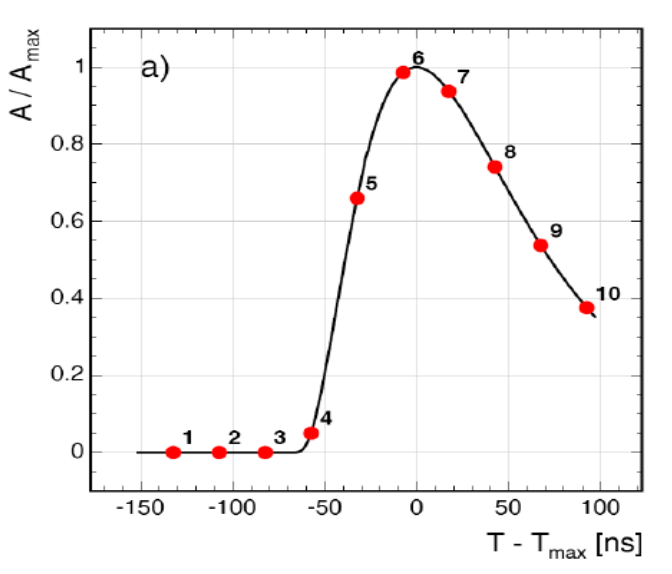



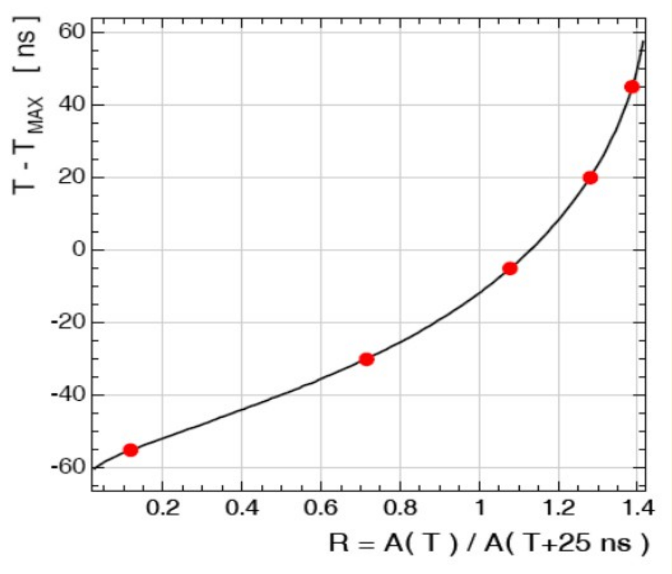
# ECAL Time Measurement

# 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: $R_i = \frac{A_i}{A_{i+1}}$
  - Fit with polynomial to extract function of T(R)
  - Each $R_i$ gives $(T_{\mathrm{Max},i}, \sigma_i)$: $T_{\mathrm{Max},i} = T_i - T(R_i)$
  - Precise value of **T_Max**:

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

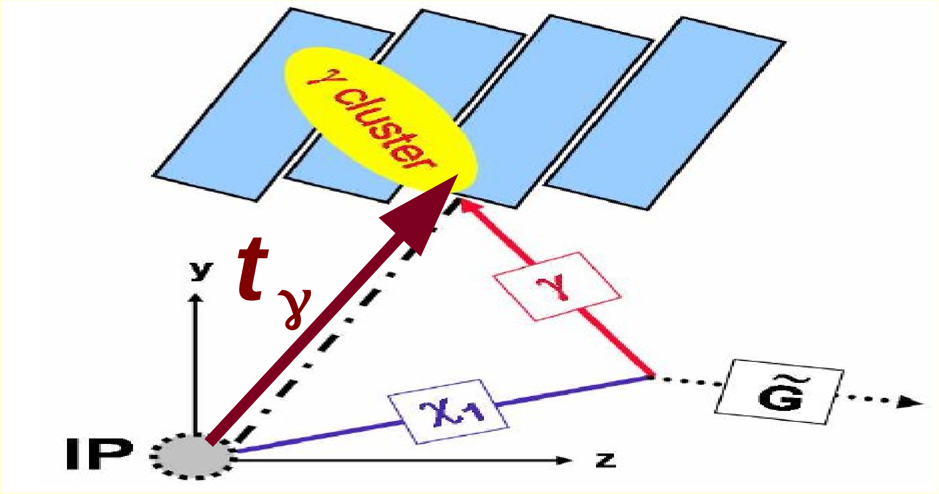


# Crystal Time Alignment

- Time Alignment
  - Adjust crystal time such that:

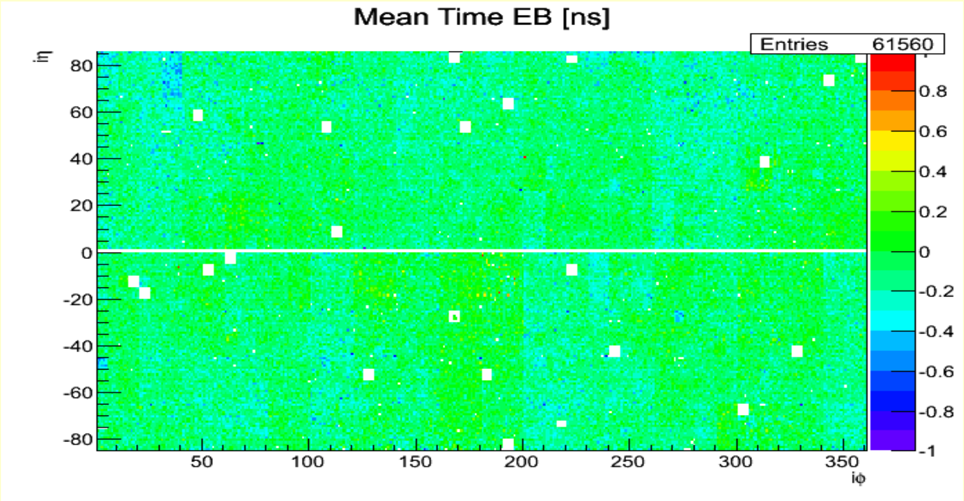
$$\langle t_{\gamma}^{\text{crys}} \rangle \approx 0$$

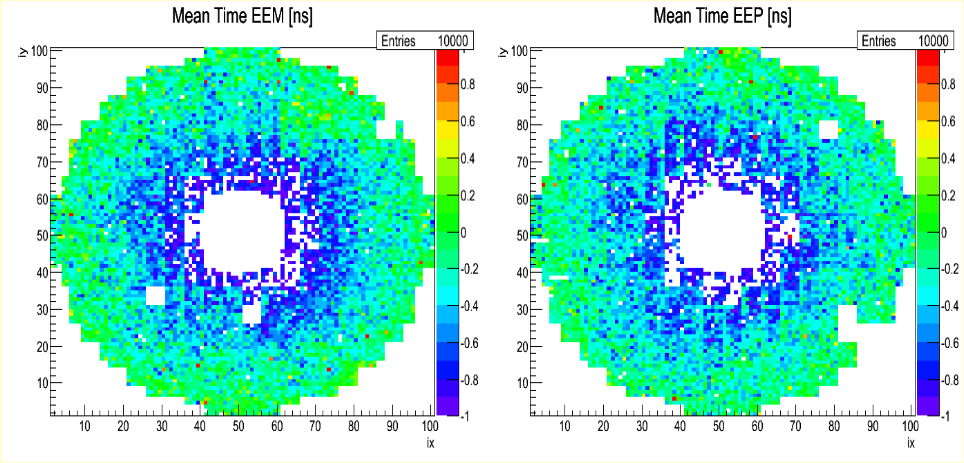



| | Before Alignment | | After Alignment | |
|---|---|---|---|---|
| | Avg. Mean Time[ns] | Sigma [ns] | Avg. Mean Time[ns] | Sigma[ns] |
| EB | -0.113 | 0.119 | -0.014 | 0.021 |
| EE- | -0.337 | 0.282 | -0.003 | 0.002 |
| EE+ | -0.346 | 0.256 | -0.004 | 0.021 |

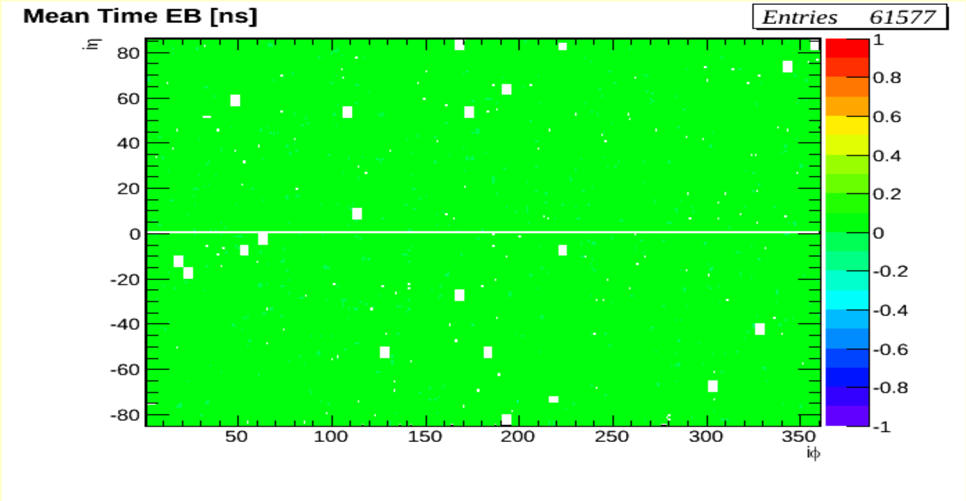
# Crystal Time Alignment

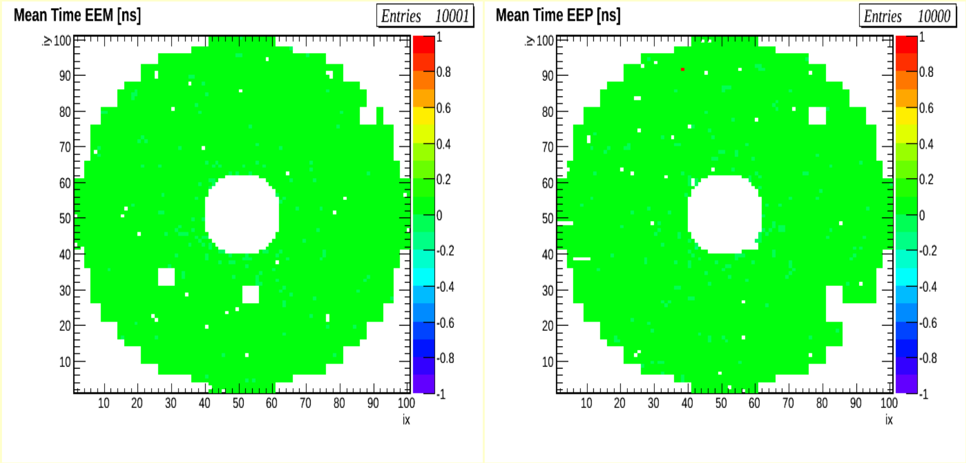
## Before Time Alignment




## After Time Alignment




Most crystals have average time of zero after alignment.



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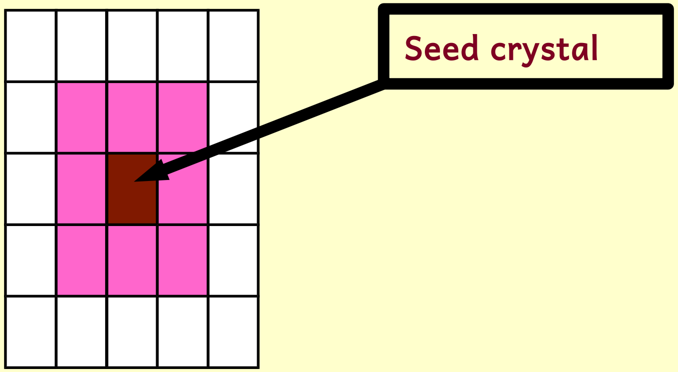
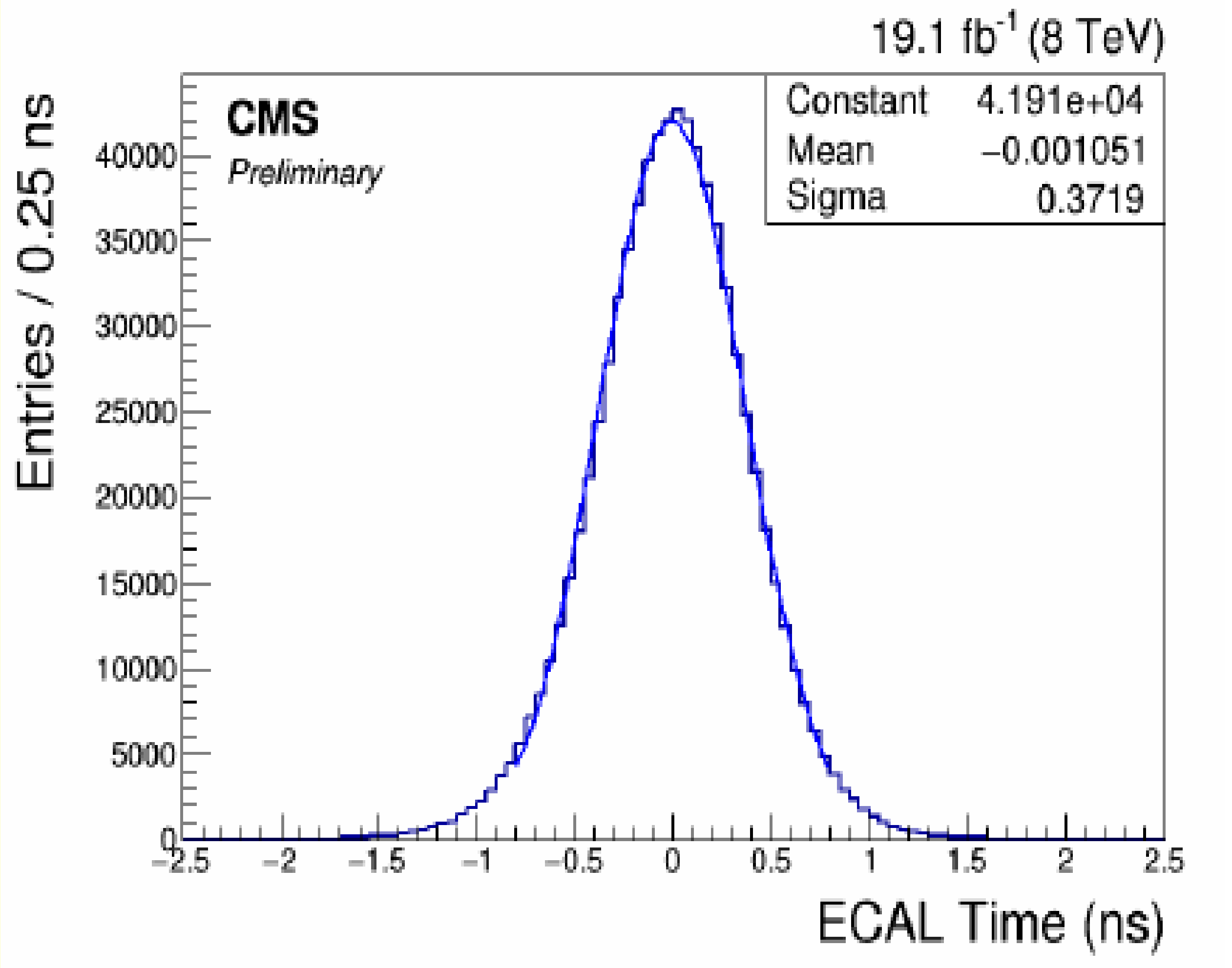
# Single Photon Time Resolution

- Photon time **= time of crystal with highest energy deposit.**



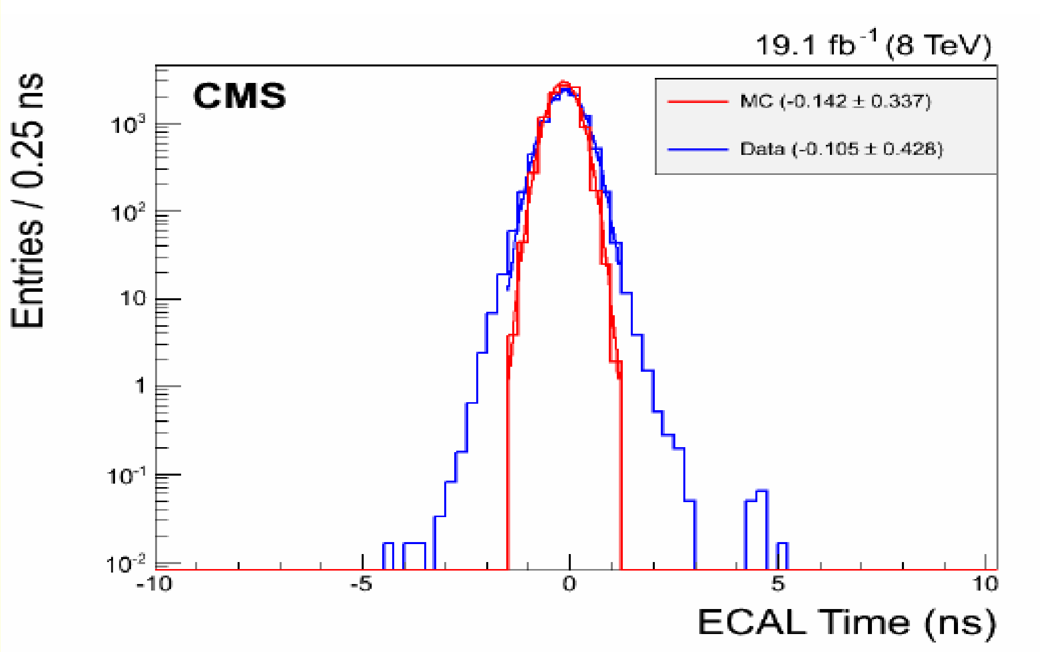

- Photon is late if time is within **3** to **13 ns.**

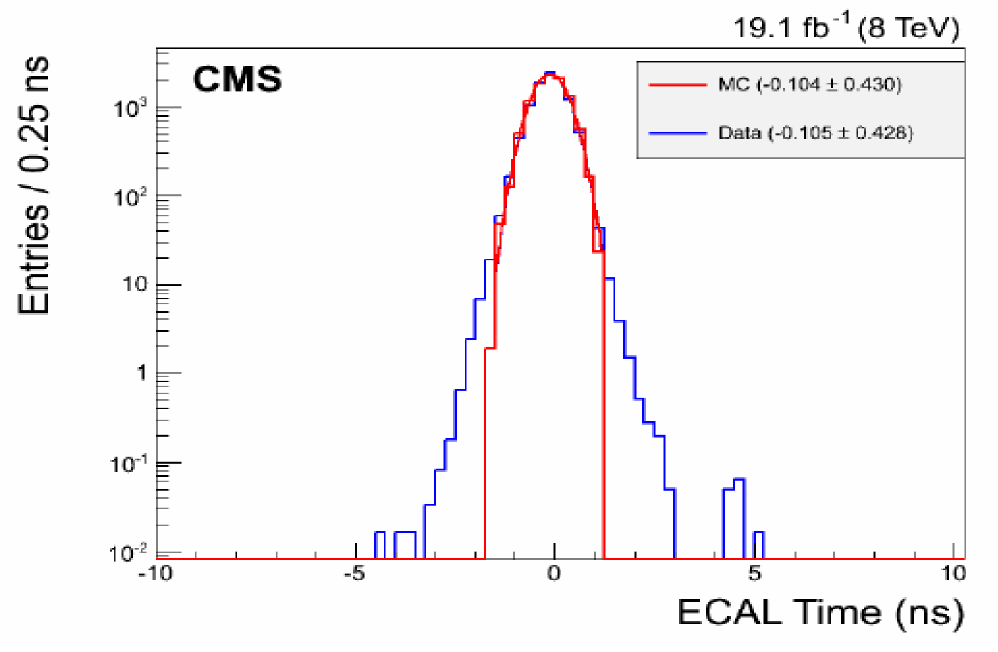



- Single photon timing resolution is about 372 ps.

# Photon Time: MC Vs Data

- Compare events passing selection requirement from photon + jet MC sample to data:
  - At least 1 or 2 jet in events,
  - 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.



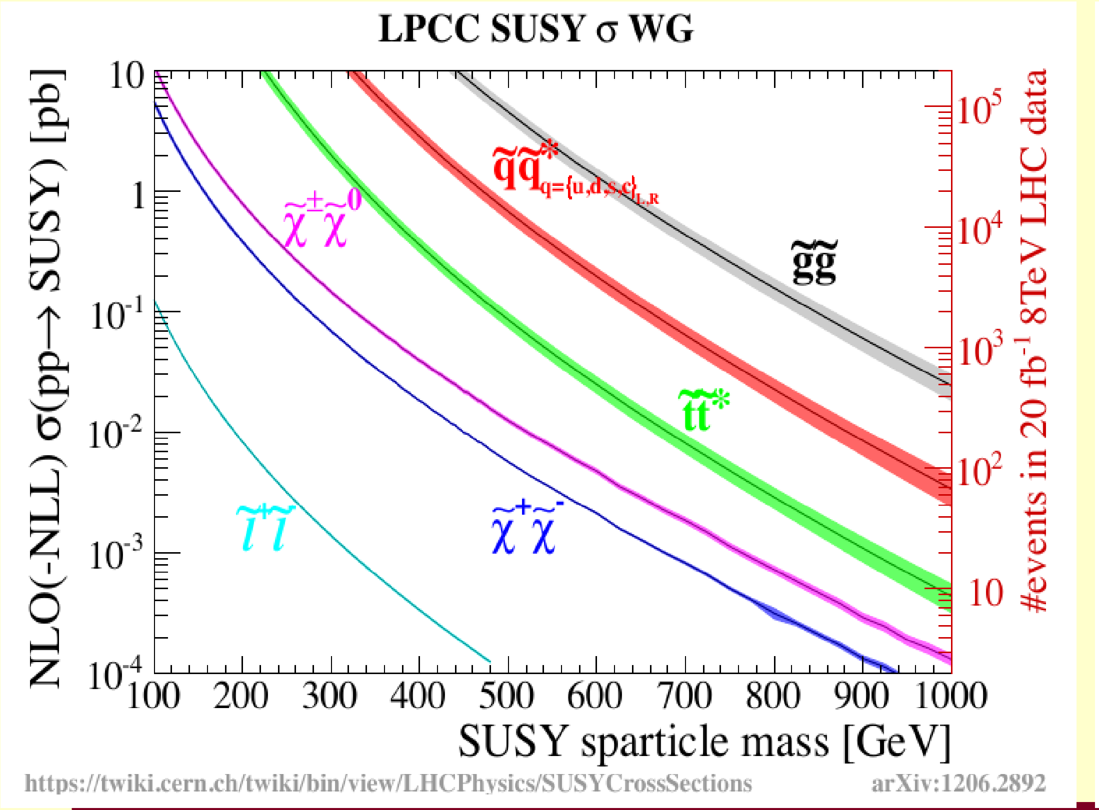



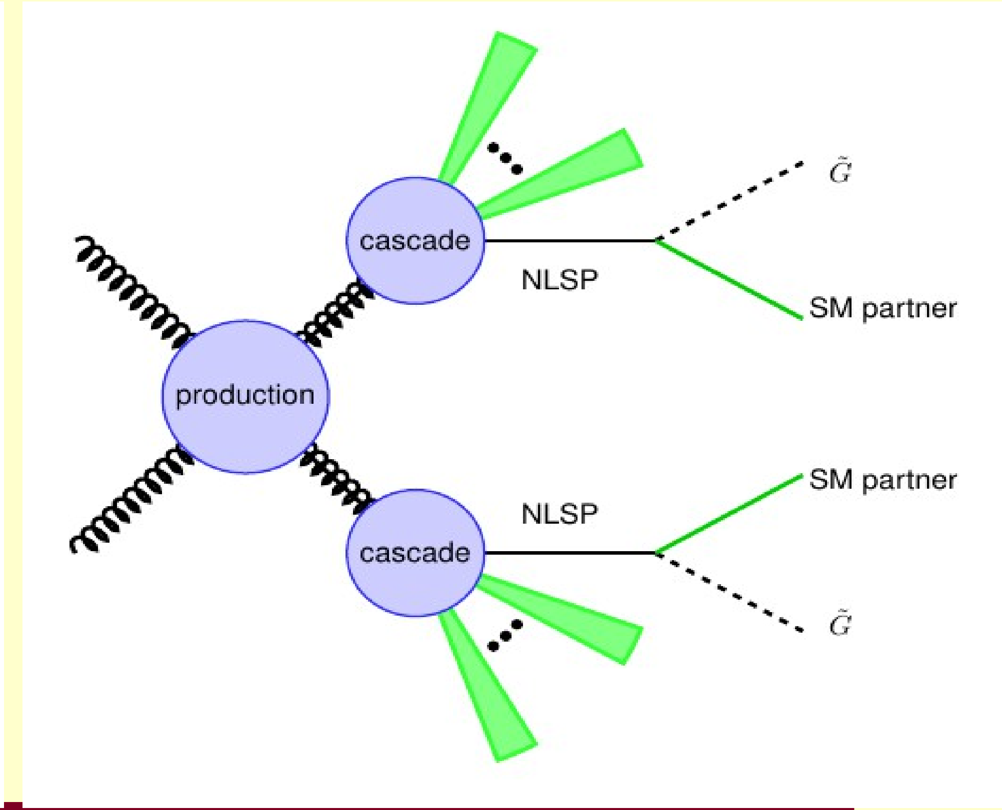
# Search Analysis

# 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 Events

## Signal Events

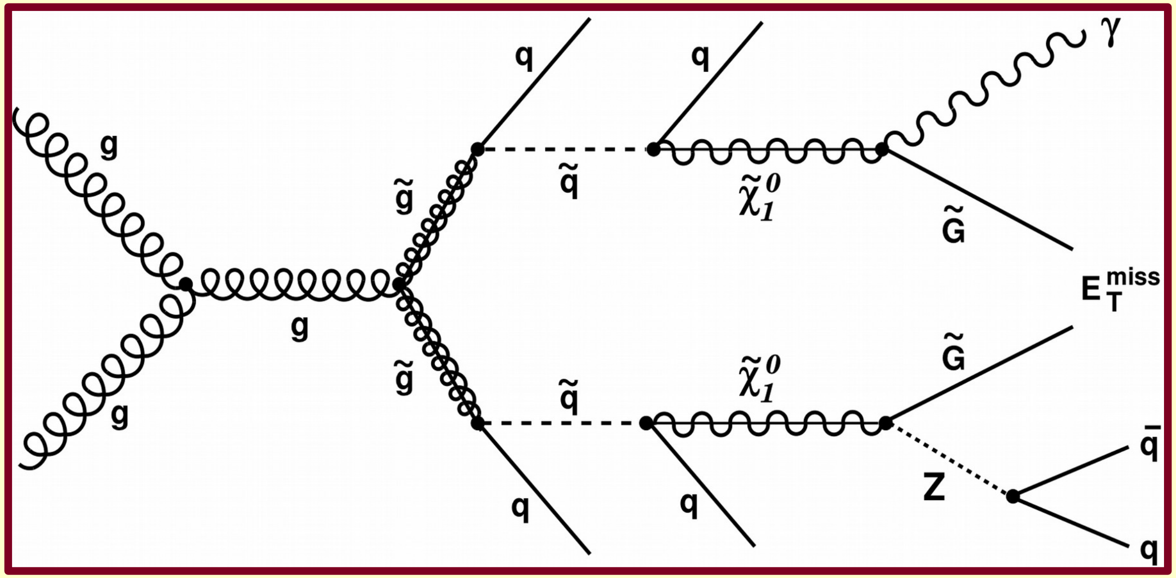
- >= 1 late Photon

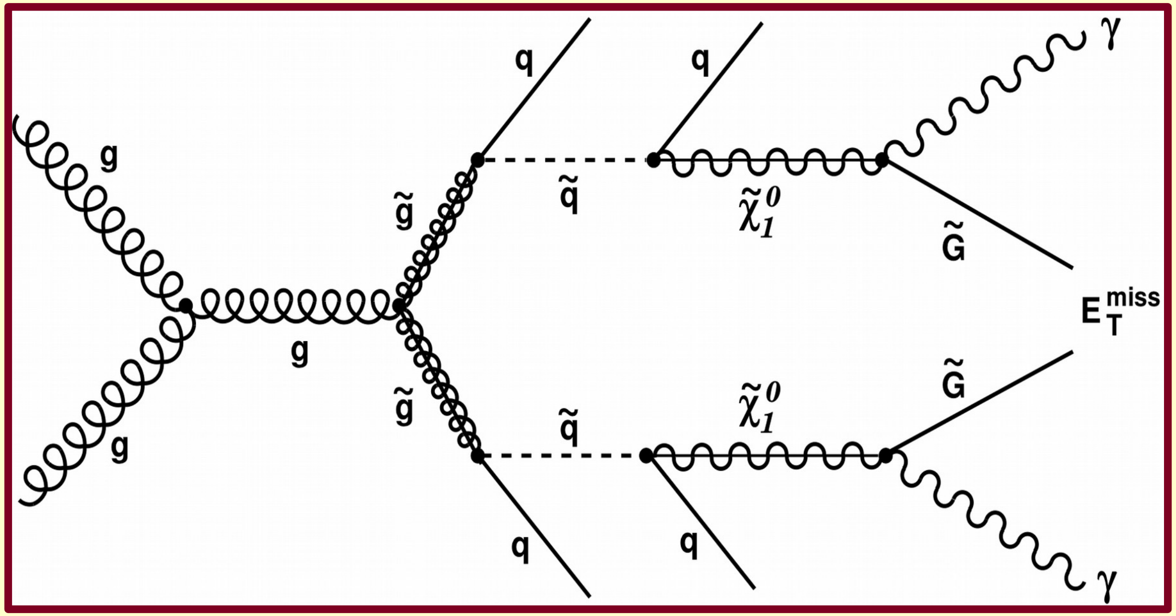
  +

  >= 2 Jets

  +

  Large MET

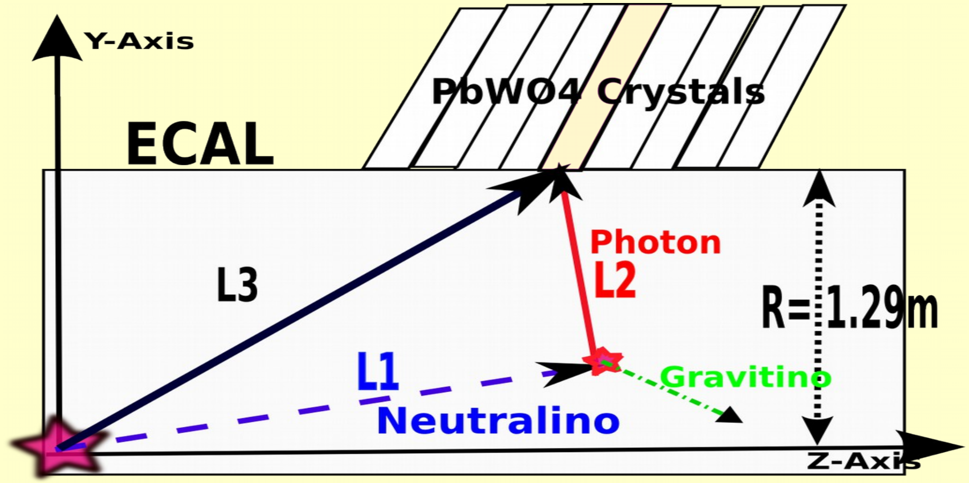


# Late Photon Mechanism

- Distance traveled by the neutralino before decay :

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




- Time measured by ECAL:

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

  - For **slow moving** neutralino :

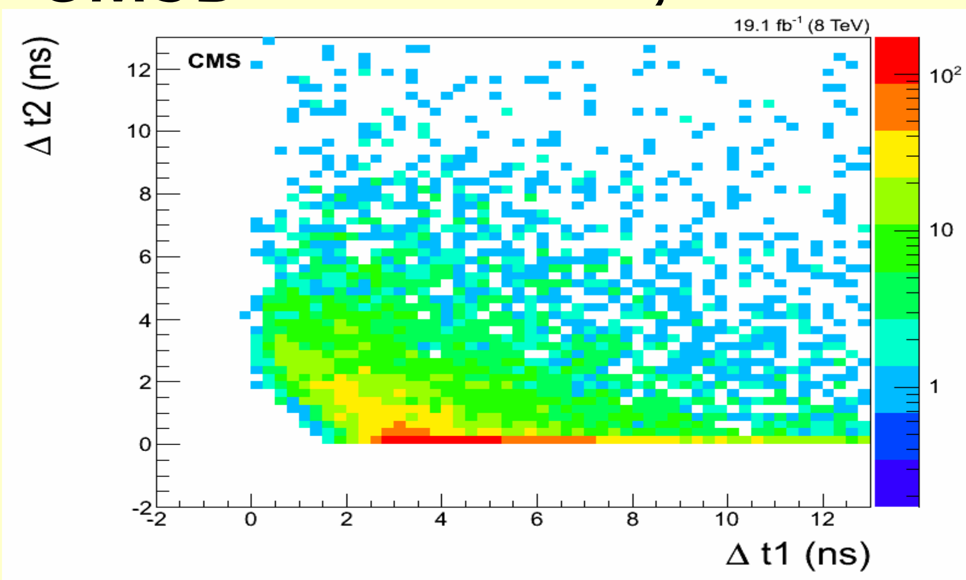
$$\Delta t1 = L1/c\beta - L1/c$$

  - For **Off-pointing** neutralino :

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

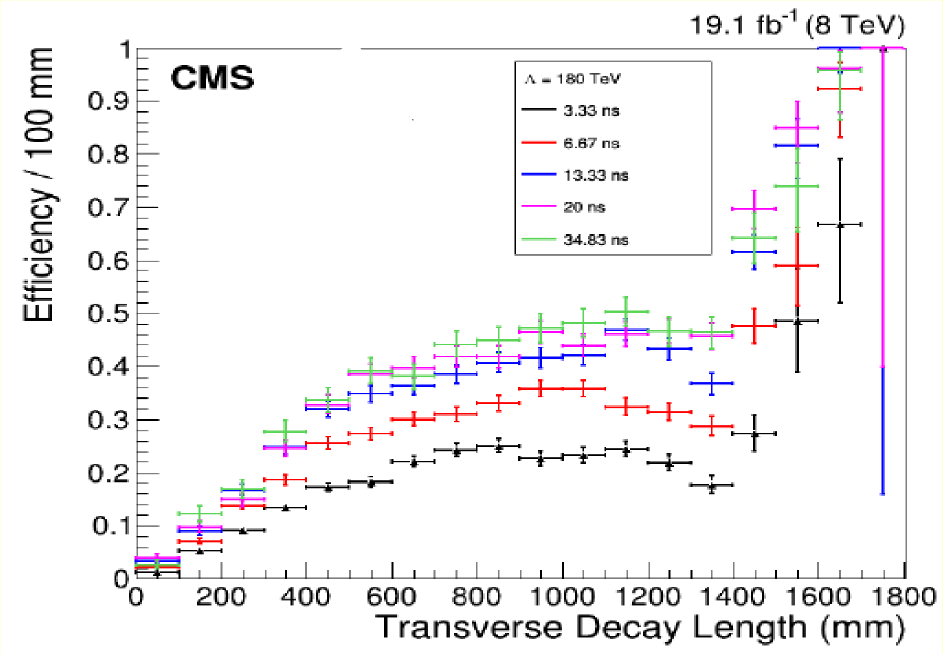
- Most late photons are from <u>slow moving</u> neutralinos.

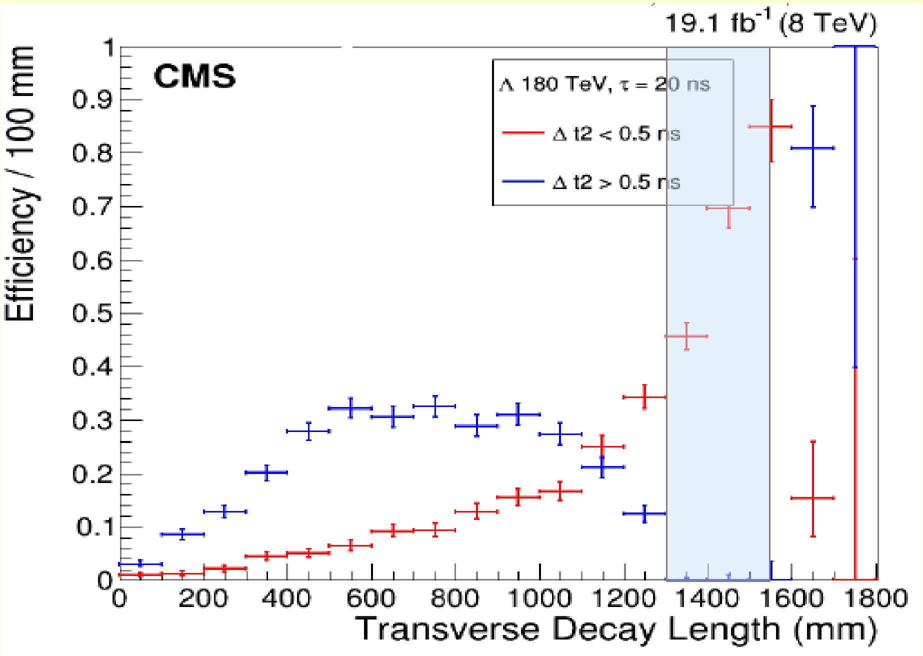
GMSB $\Lambda = 180$ TeV , $\tau = 20$ ns



# Late Photon Efficiency

- Efficiency to detect photons with t > 3 ns  Vs transverse decay length.
- **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.** Shorter lifetimes need enough boost to reach the ECAL and overcome the 3 ns acceptance threshold.

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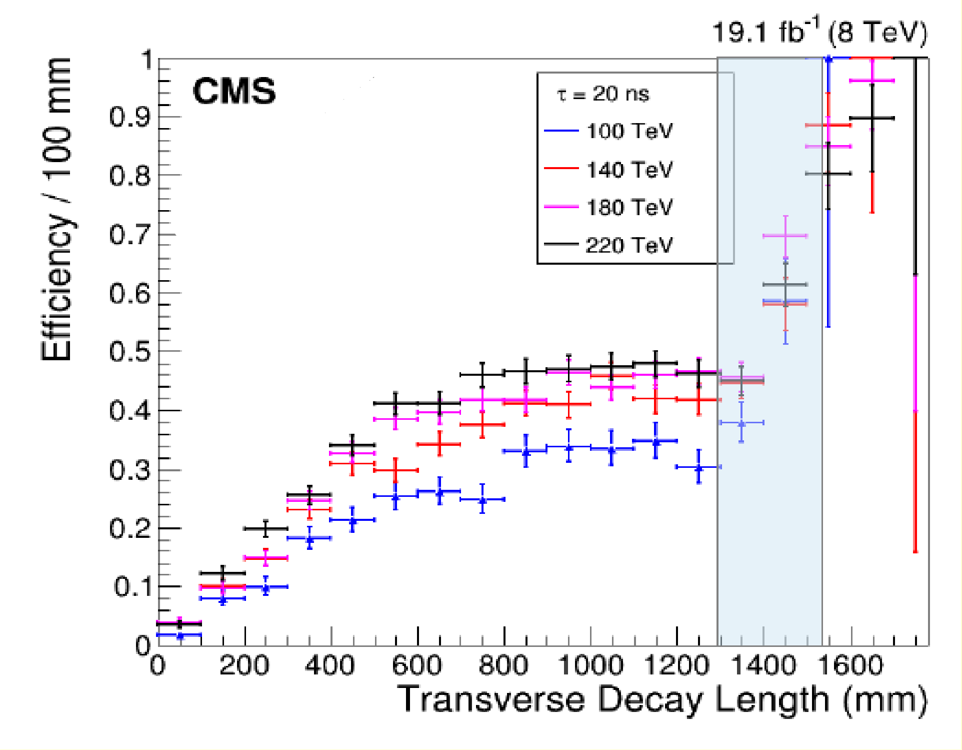
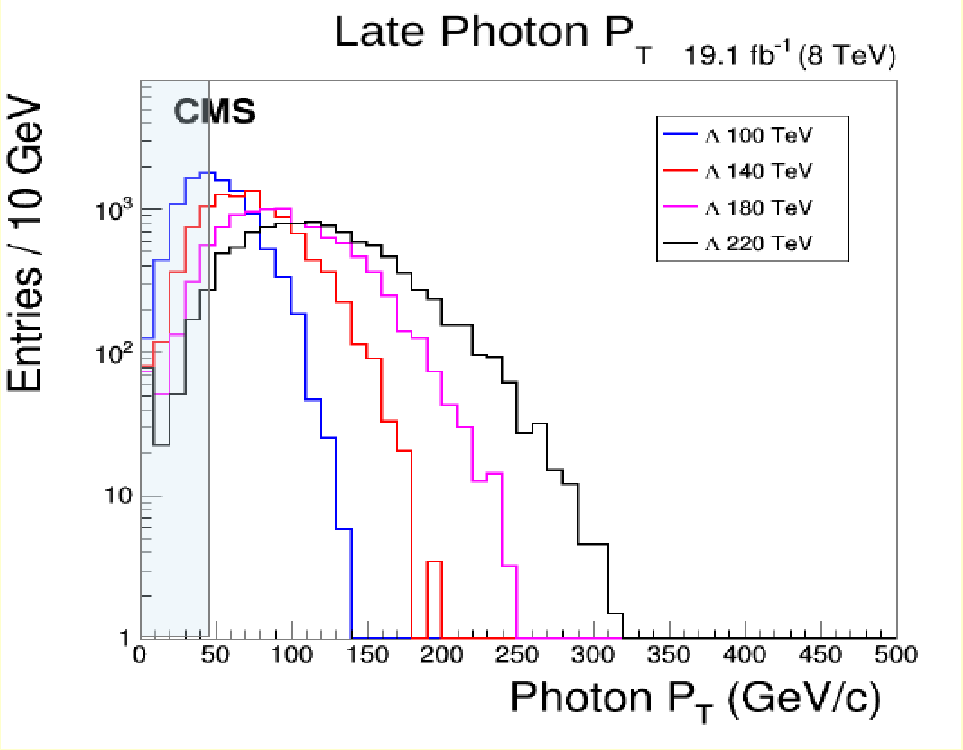
# Late Photon Efficiency II

- Efficiency for detecting late photons for different neutralino Mass (Lambda) with a fixed lifetime.
- **Efficiency = Number of photons with t > 3 ns /Number of reconstructed photons** in EB.




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

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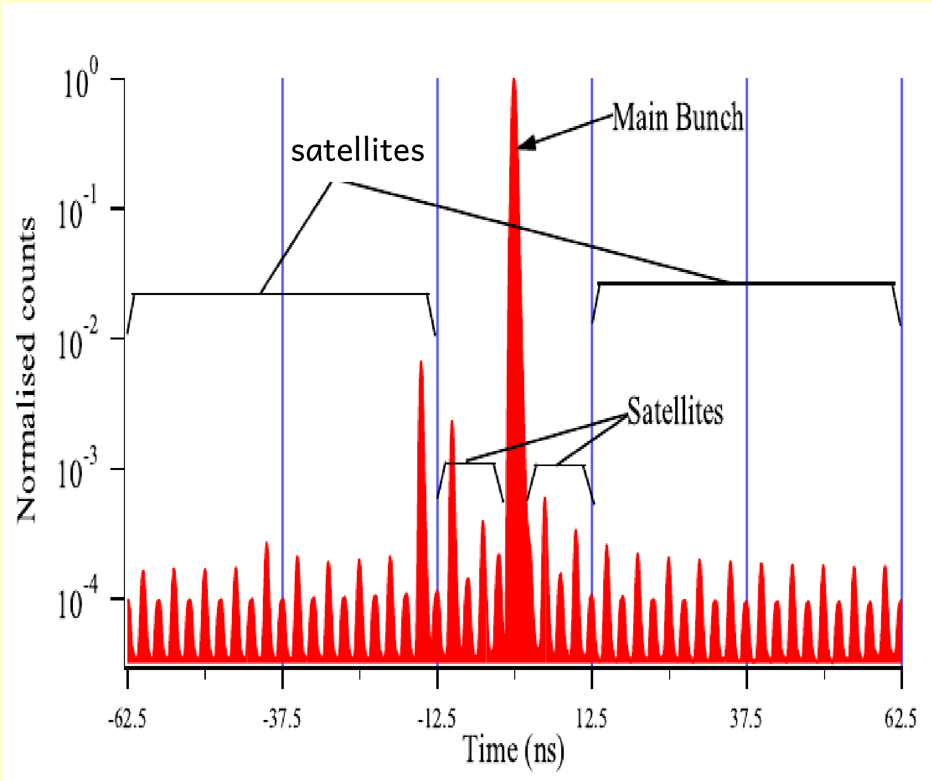
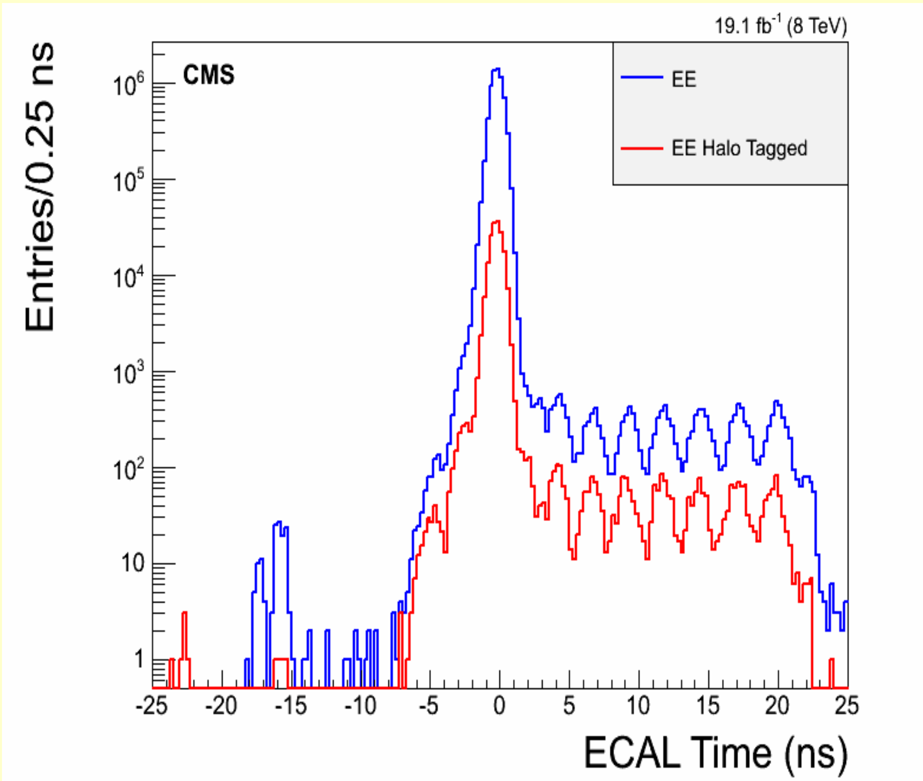
# Background Events

- Events with a late photon can arise from either:
  - **Collision Events**
    - Collision events with a photon with mis-measured time,
    - Events from Satellite proton bunches.
  - **Non-Collision Events**
    - Events with Beam Halo muon-induced photons,
    - Events with Cosmic Muon-induced photons,
    - Events with spike-seeded photons.

# Collision Events

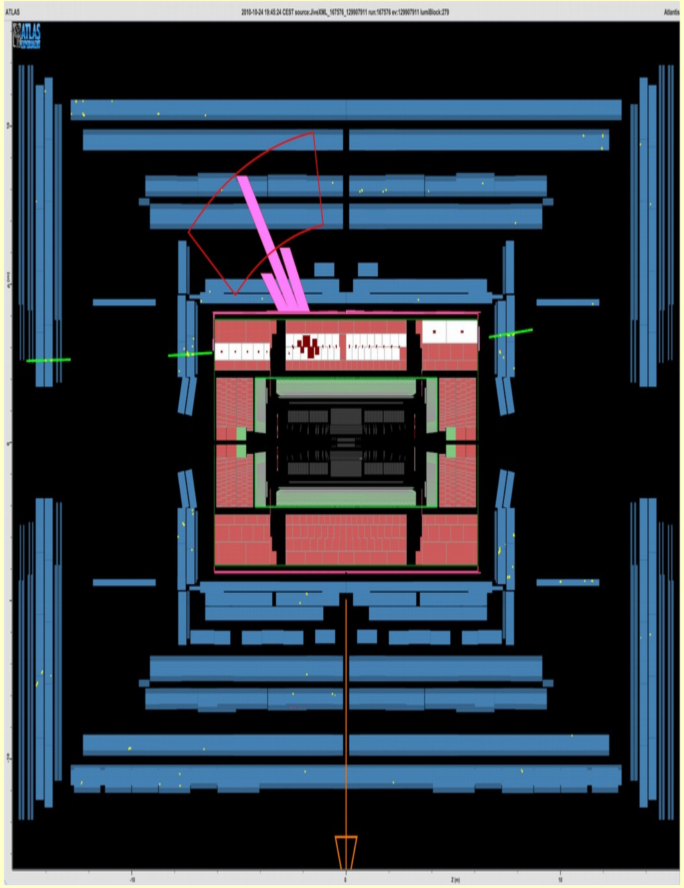
- Photons with mis-measured time from the main proton-proton bunch collisions e.g QCD, W, top events.
- Photons from satellite proton bunches.
  - Satellite proton bunches lead or trail the main bunch by 2.5 ns.



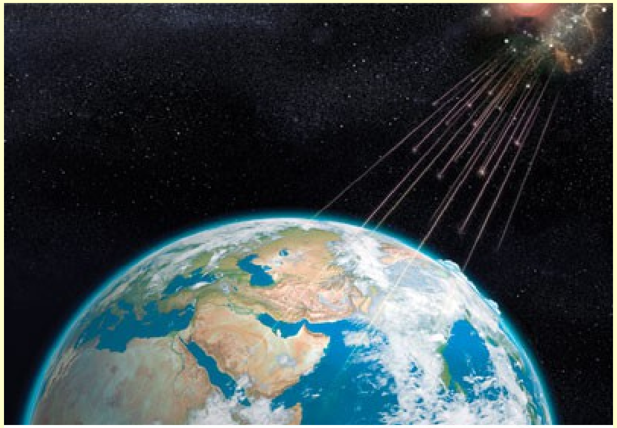



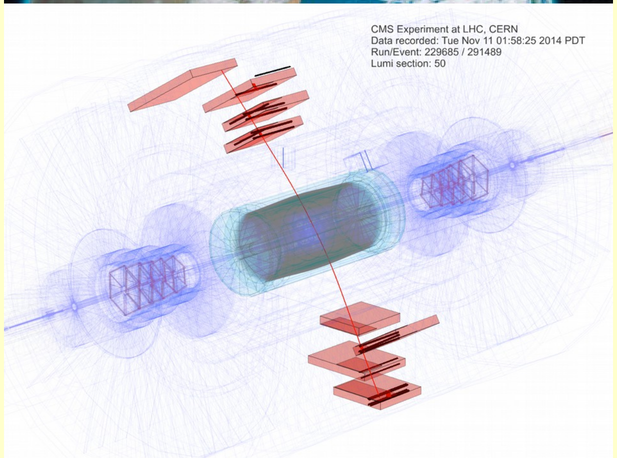
# Non-Collision Events

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

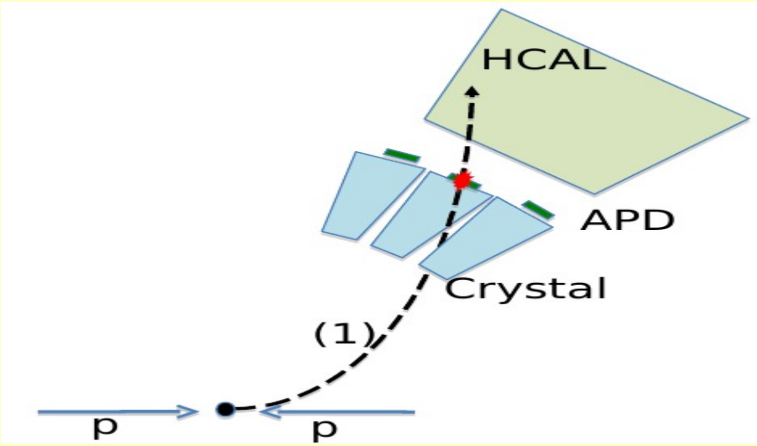


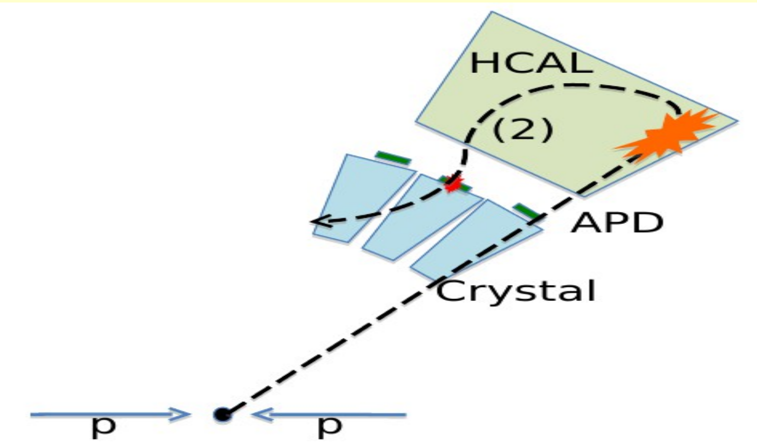
Beam Halo muon-induced photon






Cosmic Muon-Induced photon



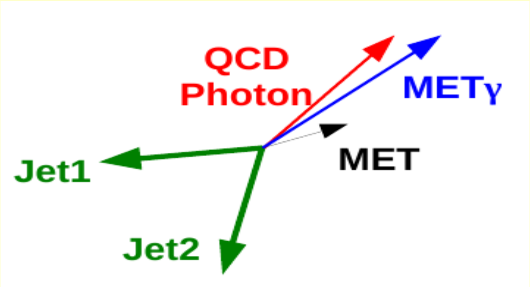




Spike-seeded photon

# Missing Transverse Energy

- Event Missing Transverse Energy (MET) defined as:

$$\vec{MET} = -\sum_{\text{All particles}} \vec{P}_t$$

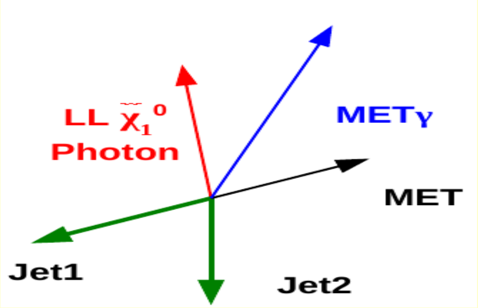


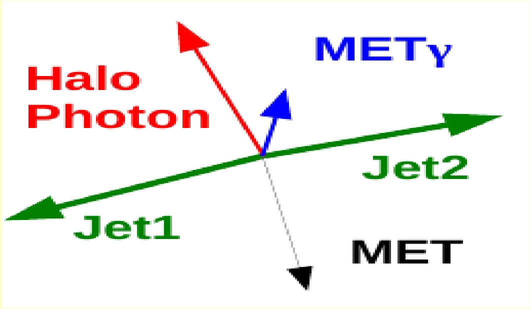

- Define a new MET variable as:

$$\vec{MET}^{\gamma} = \vec{MET} + \vec{P}_t^{\gamma}$$

- Identify signal events with:

MET > 60 GeV & $MET^{\gamma}$ > 60 GeV




| 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 |

# Search Analysis Method

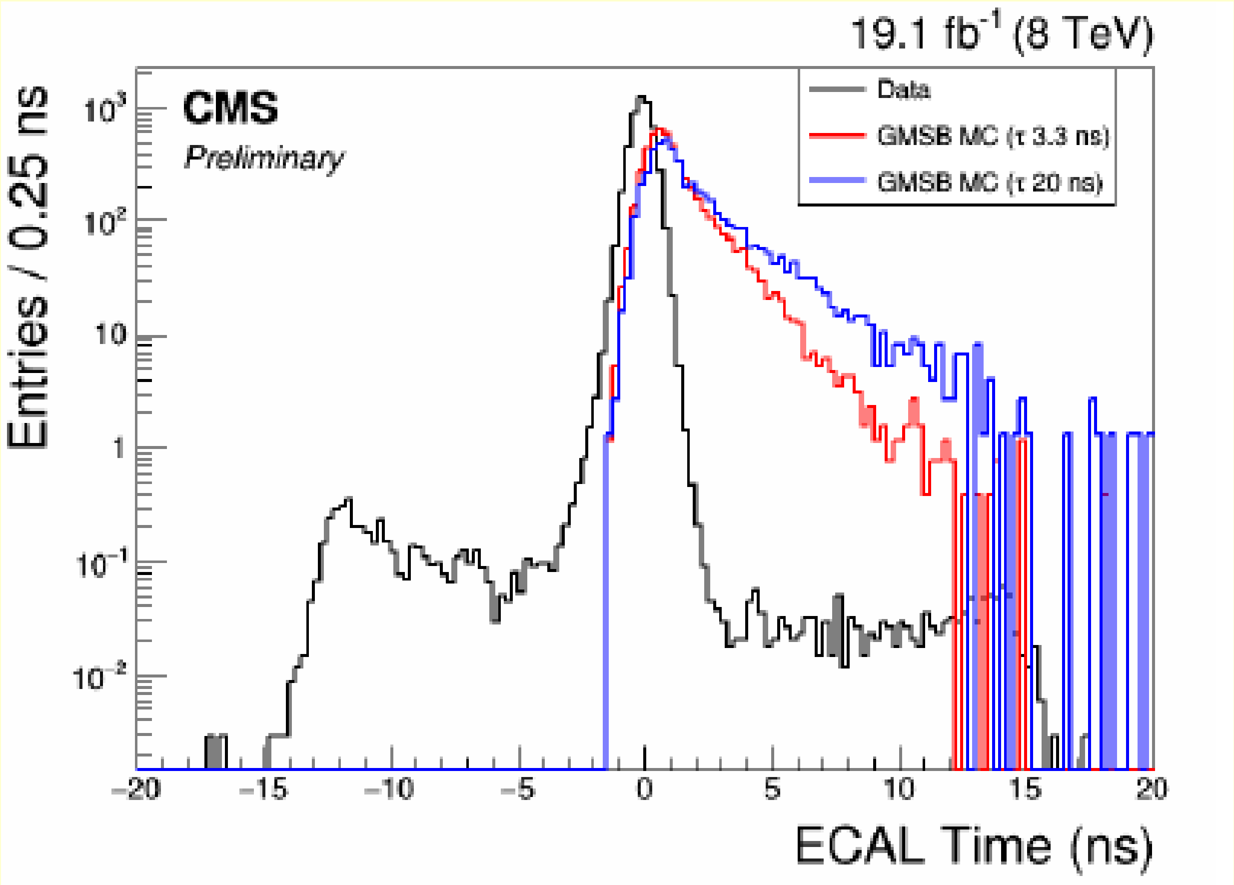
- Search uses an Event Counting Approach: We count the number of events with photon time above a photon acceptance threshold.
- First reject background events as much as possible,
- Estimate the remaining background events using an **ABCD** background estimation method.
- Test & validate **ABCD** background estimation method.
- Compare final estimated background events in signal sample with observation.

# Event Samples: Data & MC

- **Data**
  - Events with at least one photon selected by online trigger requiring **photon pt > 65 GeV/c + MET > 25 GeV**
  - 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**
  - Events with at least one photon selected by an online trigger requiring **photon pt > 50 GeV/c.**
  - For studying our late photon online trigger efficiency.
- **Cosmic Data:** For studying cosmic event tagging & rejection.
- **MC Gamma + Jet:** For MC time study sanity check.

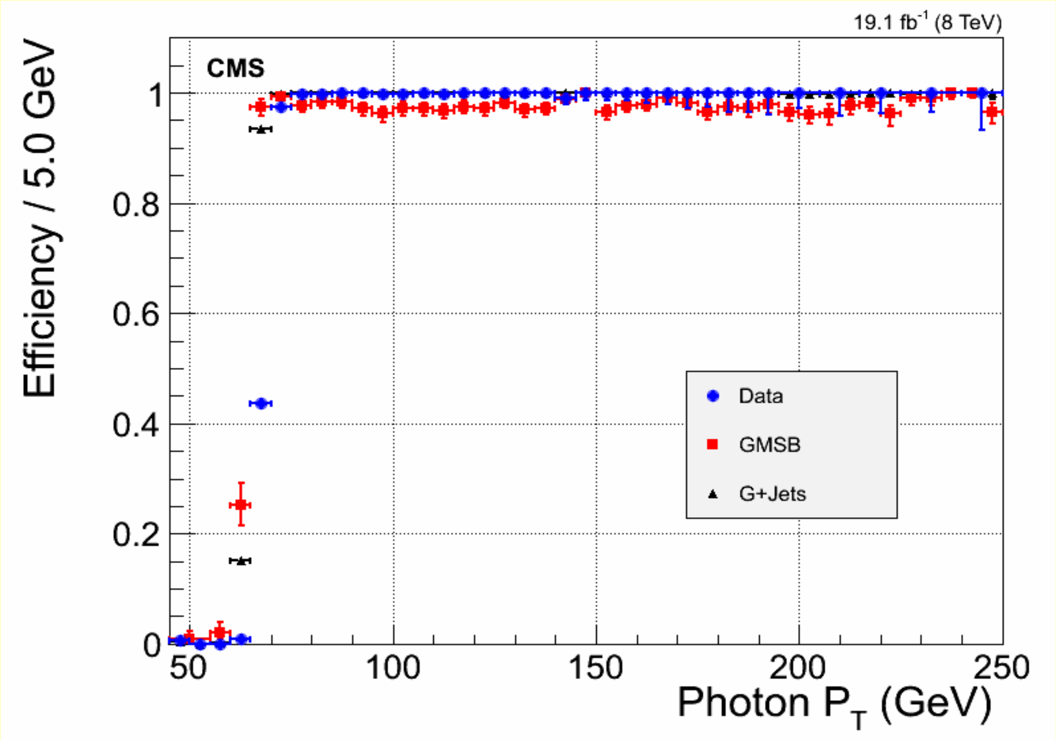
# ECAL Time Search Window

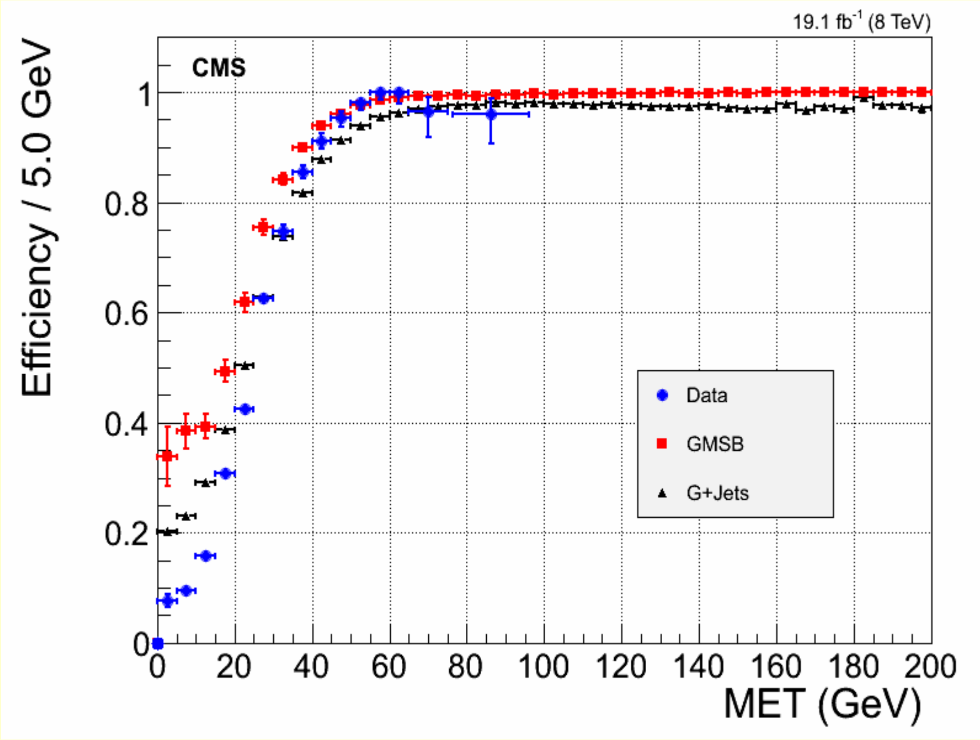
- Search window is for photon time between **3 ns to 13 ns,**
- Photons time between -10 ns to -3 ns used as a control sample,
- Photons with time of about -12 ns are mostly “spikes”.



# Online Event Selection

- **Online event selection trigger**
  - Selects events with Isolated photon pt > 65 GeV/c + MET > 25 GeV
  - **Trigger Efficiency = Events passing online selection / Events passing offline selection and trigger with photon pt > 50 GeV/c**
- **Offline selection:** Events with photon pt > 80 GeV/c, MET > 60 GeV



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# Offline Event Selection

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

  $MET > 60\ GeV,\ MET^{\gamma} > 60\ GeV.$
- **Signal Events:** Final state with

  $\geq 1$ **Photon + $\geq 2$ Jets + MET > 60 GeV + $MET^{\gamma}$ > 60 GeV**
- **ABCD Method Test:** Events with final state

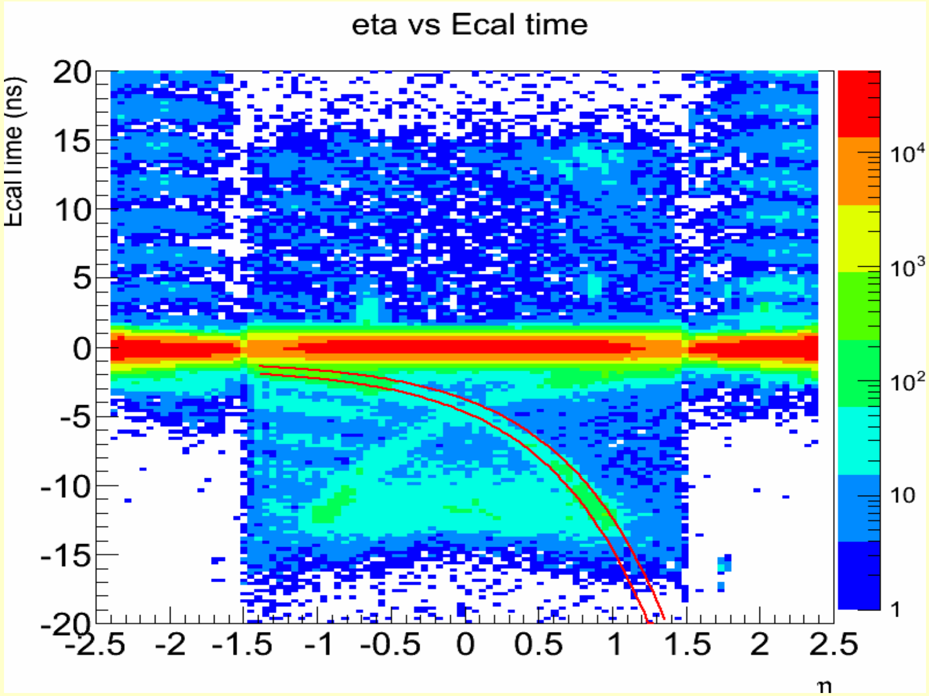
  $\geq 1$ **Photon + 0 & 1 -Jet + MET, $MET^{\gamma}$ > 60 GeV**

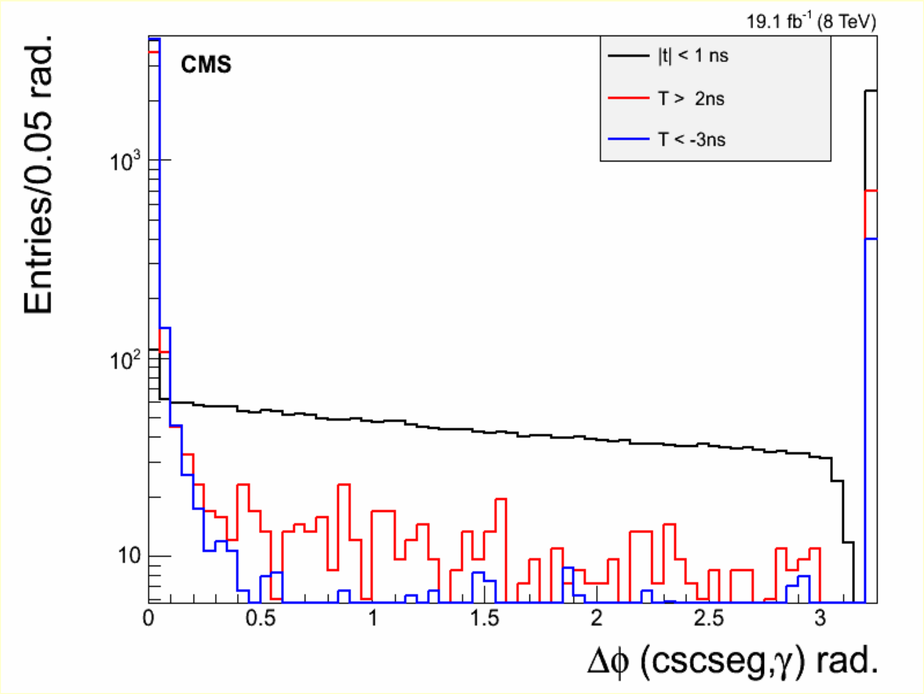
# Background Reduction & Estimation

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

# Halo-Induced Photons

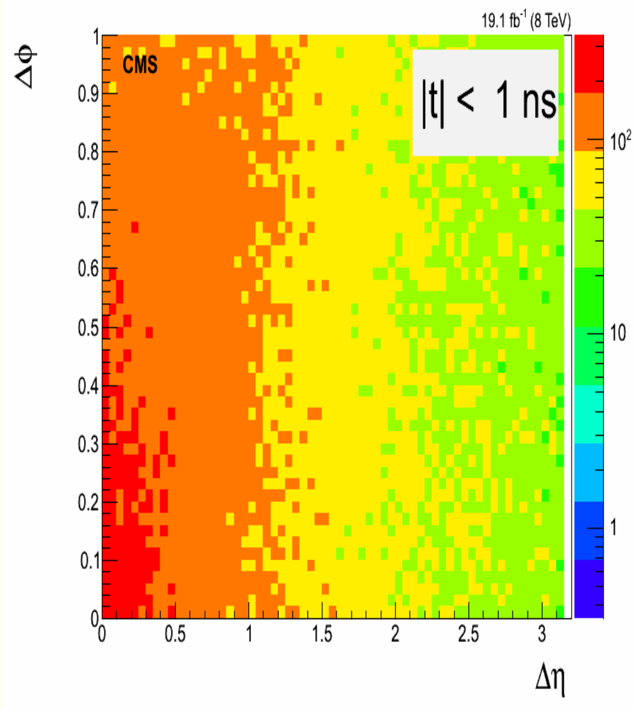
- Halo-induced photons from beam halo muons of main and satellite bunches are a major source of out-of-time photons.
  - Studied using 0&1-jet events,
  - Their arrival time in ECAL depends on eta,
  - Can be tagged and veto using: $\Delta\phi(\mathbf{CSCSegment},\gamma) < \mathbf{0.05}$

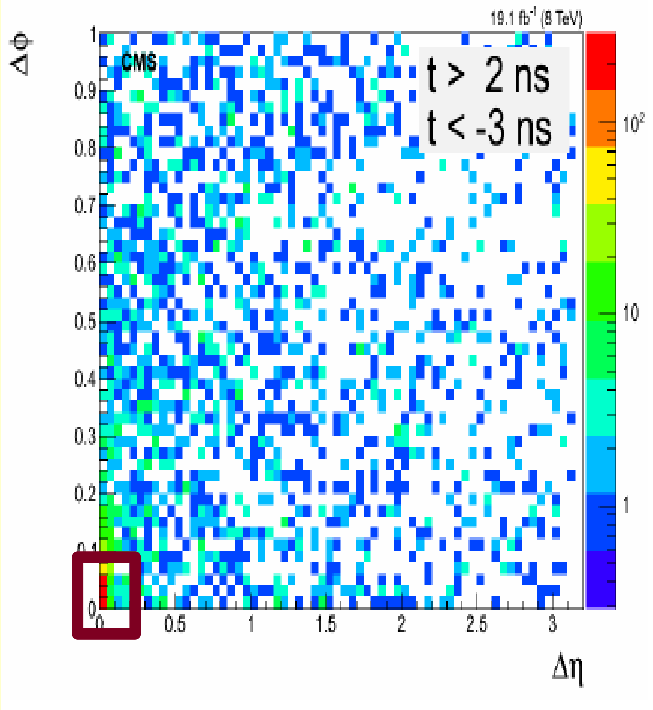


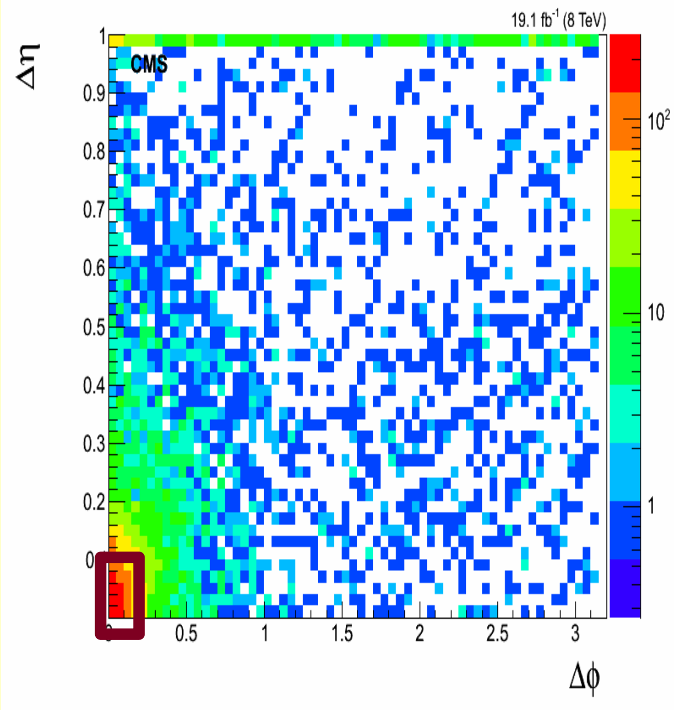
# Cosmic-Induced Photons

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



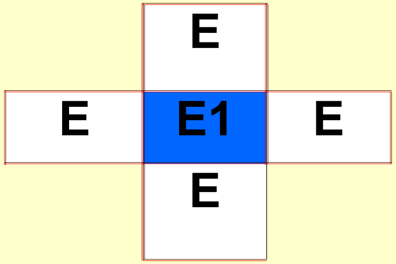



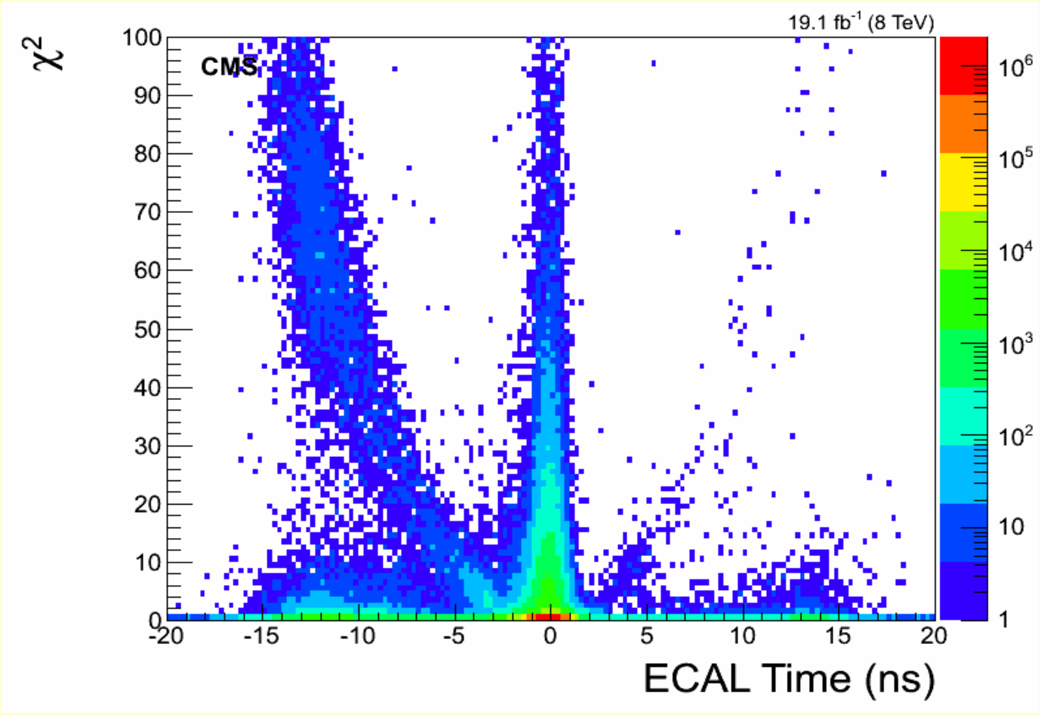

**Real Cosmic data**

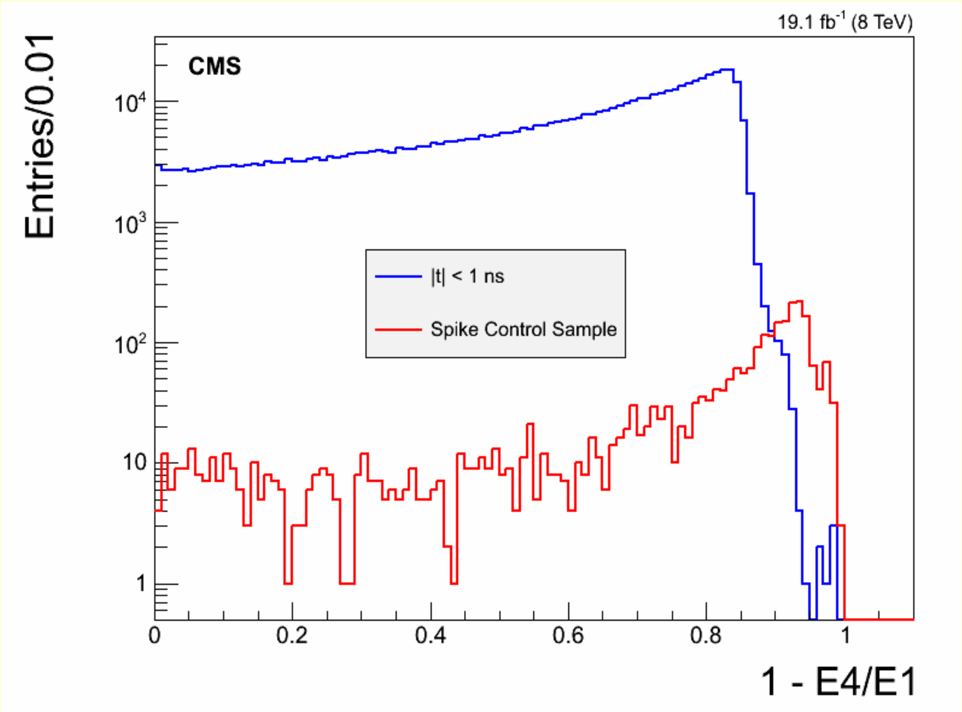


# Spike-seeded Photons

- 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, SMinor < 0.17 & Smajor < 0.6

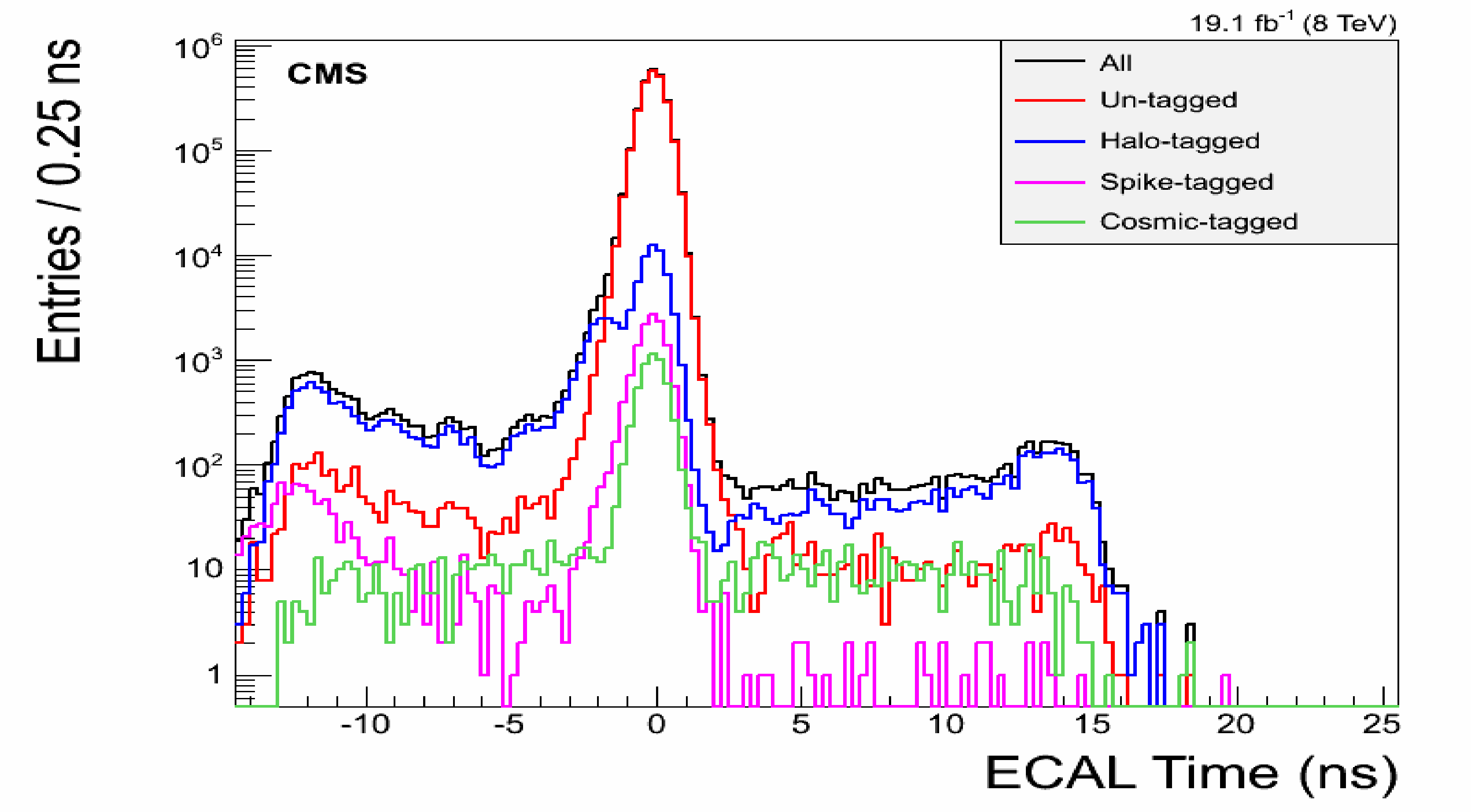


# Photon Veto Performance

## After Tagging & Vetoing

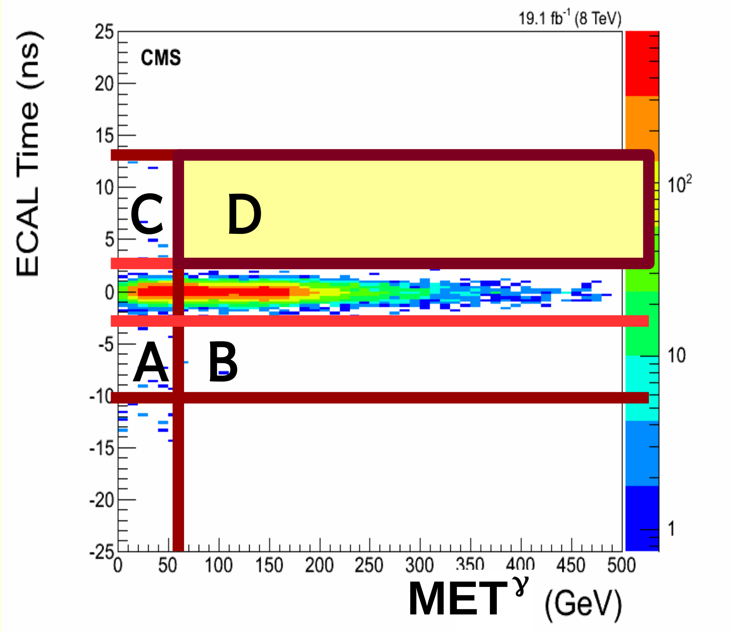



Non-collision event tagging and vetoing not 100% efficient.

# Non-Collision Bkg Estimation

- Use **ABCD** method to estimate the residual halo-induced, cosmic-induced and spike-seeded photons in the signal sample **(D)** after the veto.

| MET > 60 GeV | | |
|---|---|---|
| | $MET^{\gamma}$ < 60 GeV | $MET^{\gamma}$ > 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.

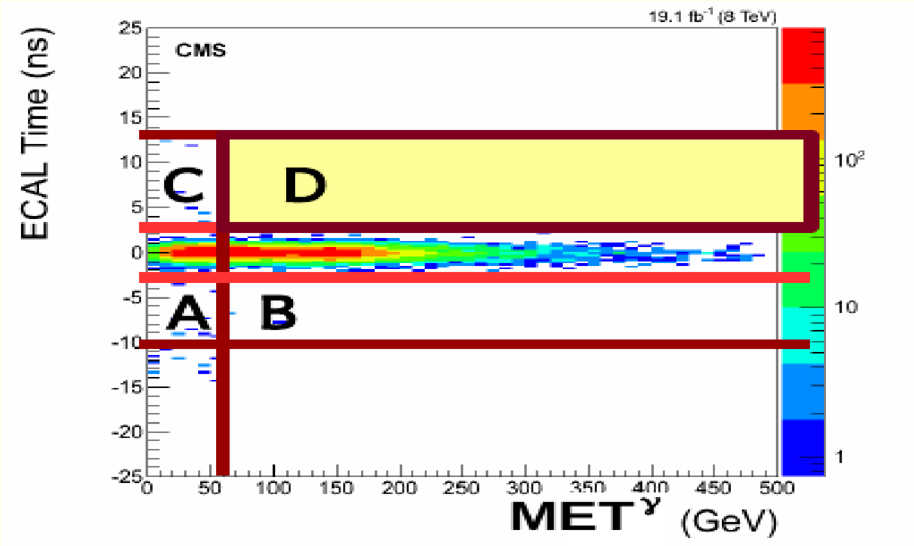
**D = (B/A) *C**

# Collision Bkg Estimation

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

**MET > 60 GeV**

| 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 |



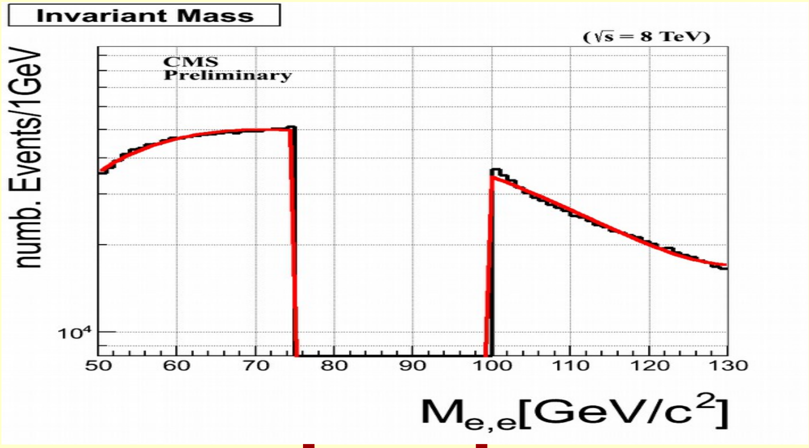

- Need a sample with highly suppressed non-collision background events to estimate collision/satellite events.
- Adjust the ABCD formula for background expectation to take into account the contributions from collision/satellite events into **B** & **D**.

# Z→ee Method

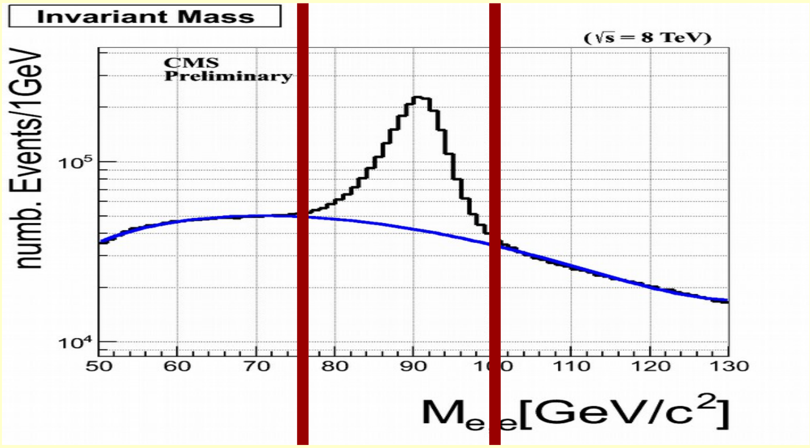
- Most representative sample of collision events with out-of-time electromagnetic particles
- Use Z-mass constraint to highly suppressed non-collision events.
- **Find the Probability of an in-time(|t| < 2 ns) photon becoming out-of-time(t < -3 ns or t > 3 ns) because of time mis-measurement & Satellite 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.

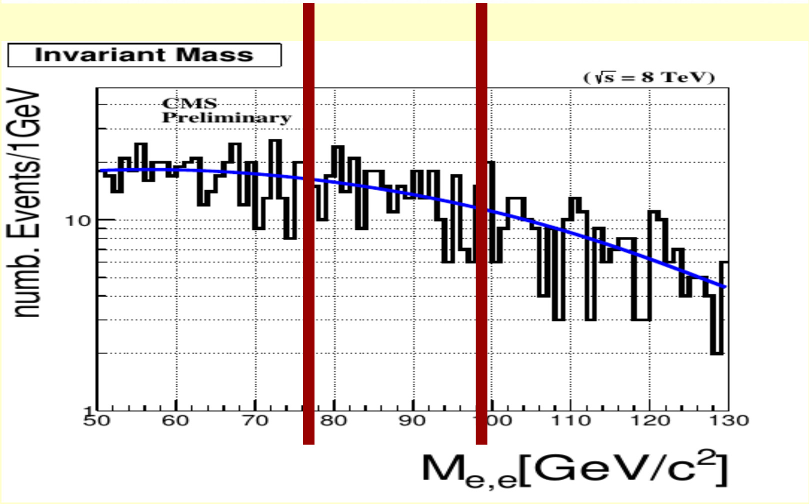
# Z→ee Method

Sideband events.

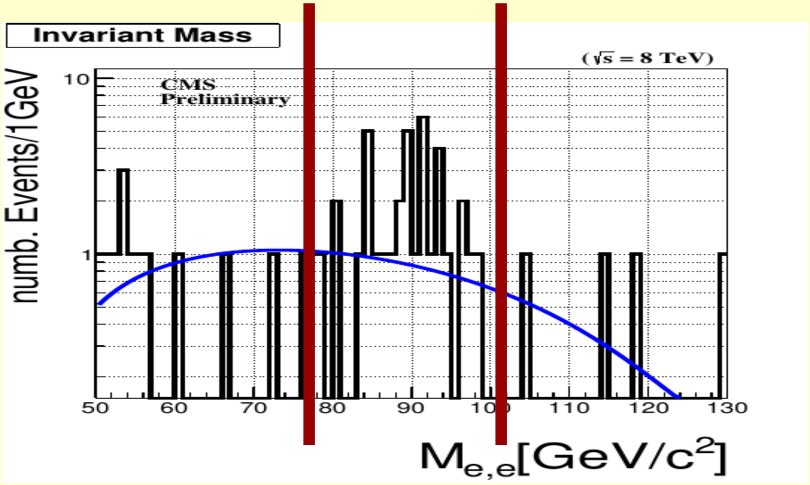



In-time (|t| < 2 ns) Events




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 Bkg Estimation II

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

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

- Where **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 mis-measurement.
  - **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 pronton bunch collisions**.

# 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**.

| | $MET^{\gamma} < 60$ GeV | $MET^{\gamma} > 60$ 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 |

- Statistically closed

- 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:

$$D = 10$$

# 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**

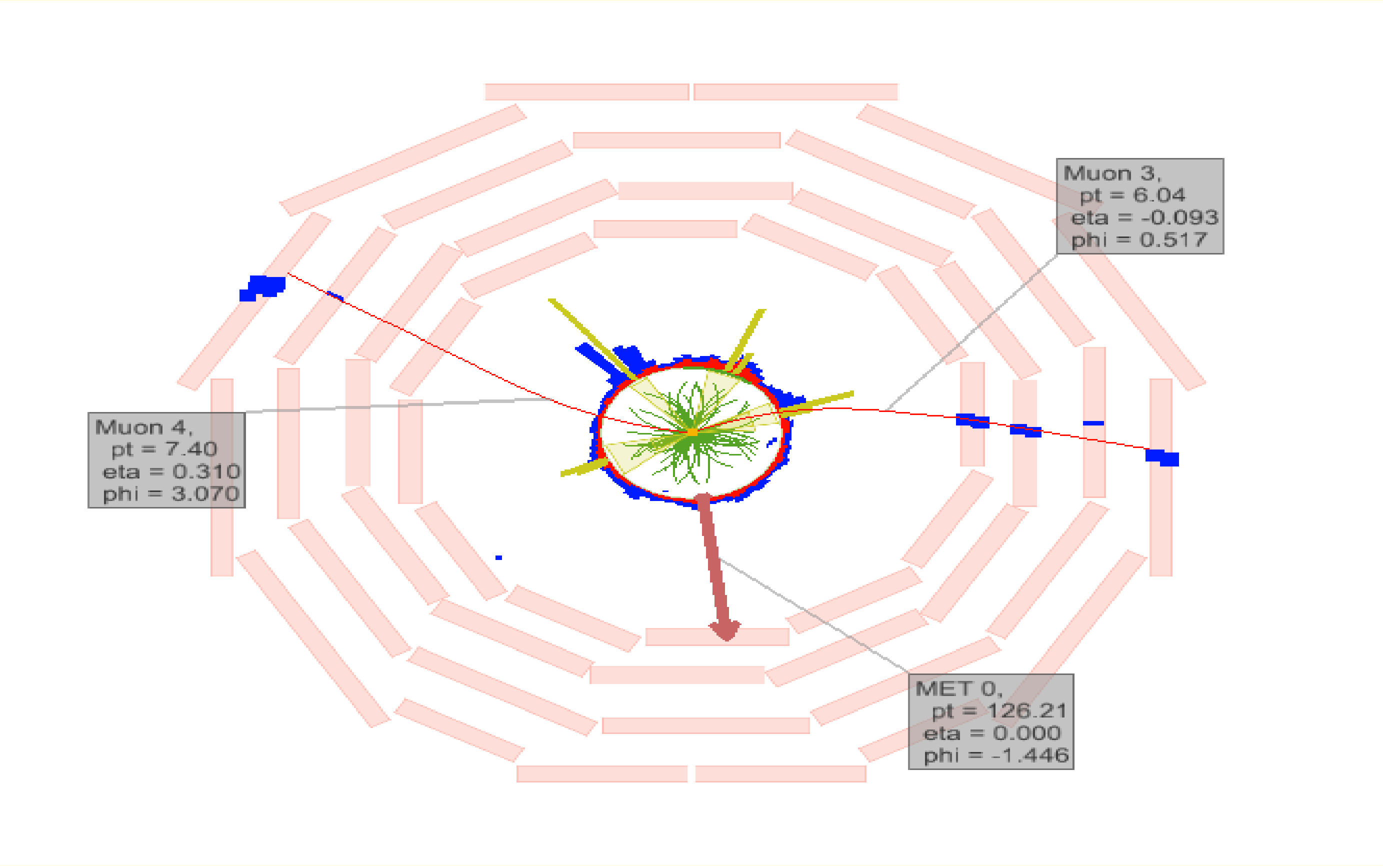
| | $MET^{\gamma}$ < 60 GeV | $MET^{\gamma}$ > 60 GeV |
|---|---|---|
| 3 ns < t < 13 ns | C=0 | D=1 |
| \| t \| < 2 ns | | (1p) 28208 + (2p) 38 |
| -10 ns < t < -33 ns | A=3 | B=1 |

# 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  seems like cosmic muon candidate.

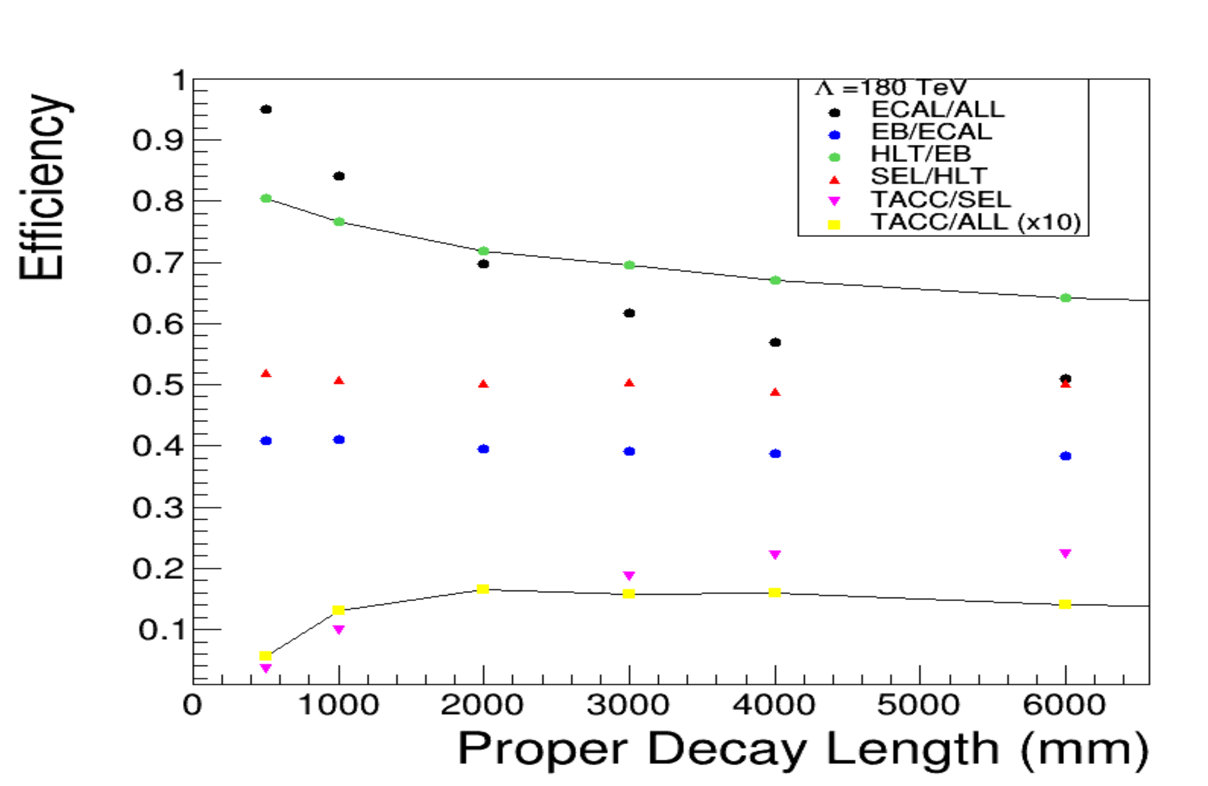
# Uncertainties

- 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.

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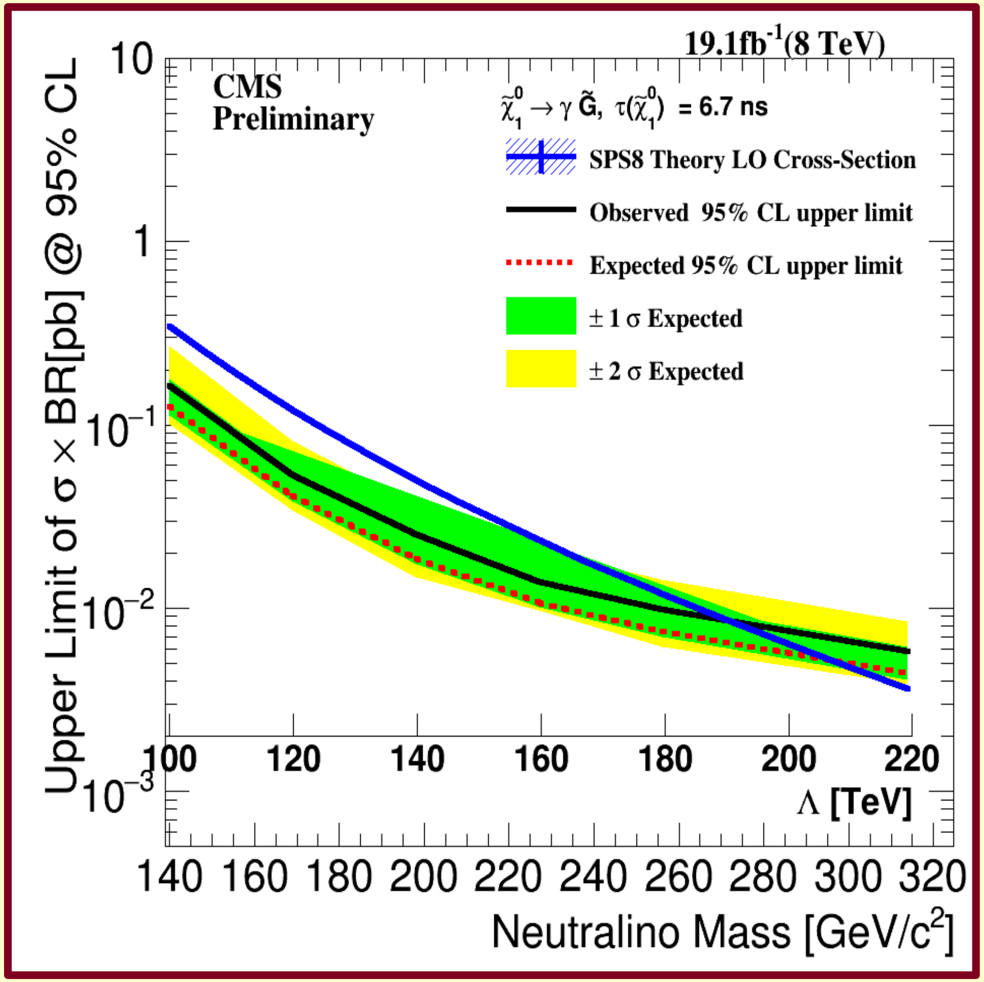
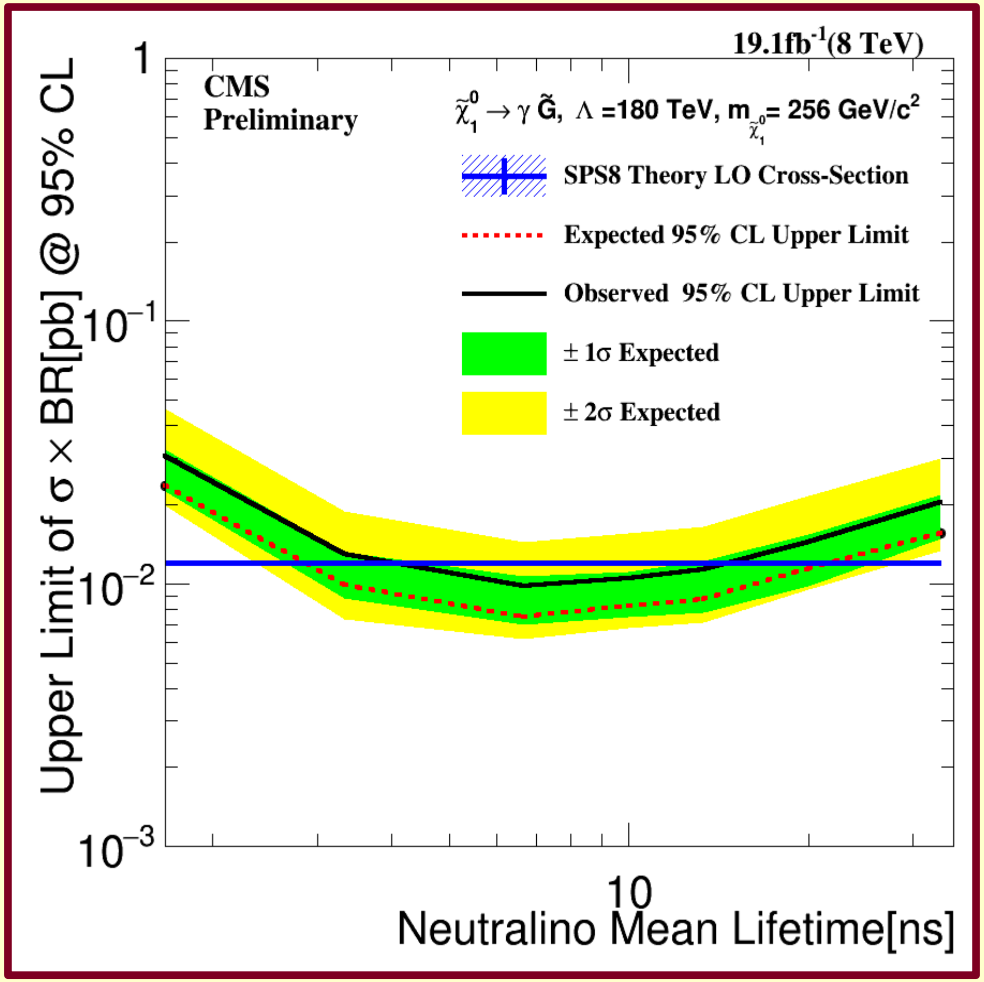
# Cross-section Upper Limit

- 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/c^2, 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.

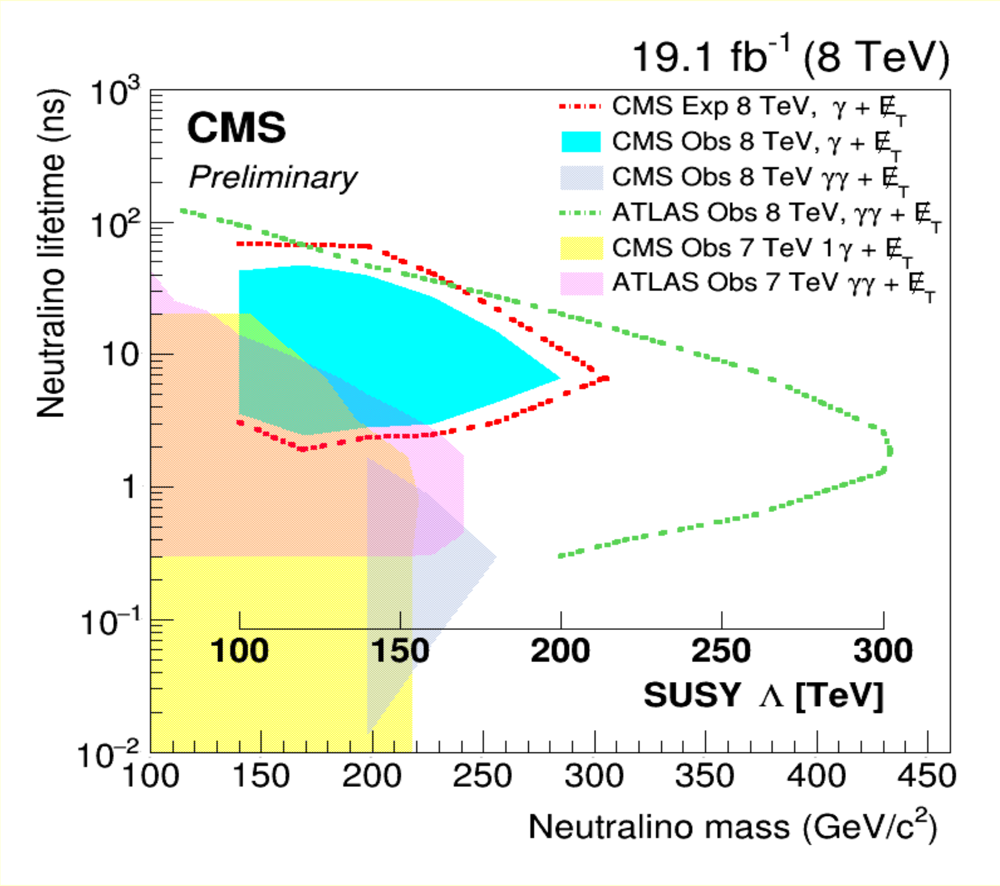
# Mass & Lifetime Limits in SPS8

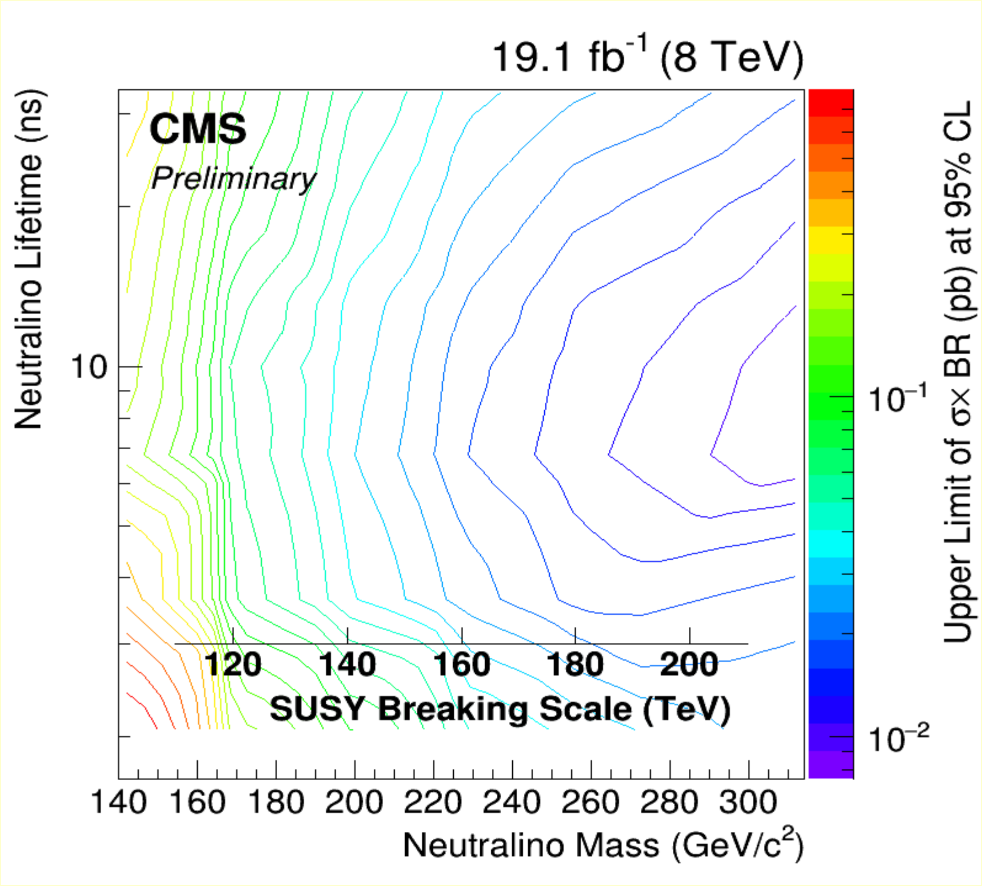



- Neutralinos with **Mass < 270 GeV/c^2** and **Lifetime = 6.7 ns** excluded at 95% CL.
- Neutralinos with **3.2 ns < Lifetime < 19.87 ns** and **Mass = 256 GeV/c^2** excluded at 95% CL.

# Mass & Lifetime Limits in SPS8




- Excluded neutralinos with **140 GeV/c^2 < Mass < 270 GeV/c^2** and **3 ns < Lifetime < 35 ns** at 95% confidence level(CL).

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# 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** at 95% CL.
- Excluded neutralinos with **140 GeV/c^2 < Mass < 270 GeV/c^2** and **3 ns < Lifetime < 35 ns** at 95% CL.

# Merci Beaucoup!!!

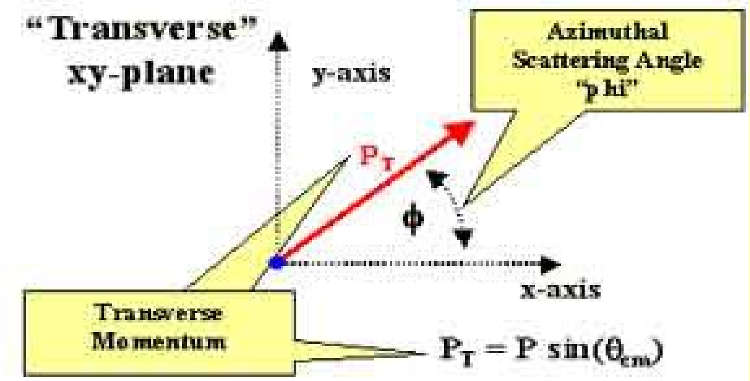
- Thank the graduate students past and present of the HEP and CMS group for keeping me sane and Jared in particular for always willing to help.
- Thank the postdocs past and present particularly Dr. Shih-Chuan Kao & his wife Olive for all the support and for working tirelessly to get this analysis approved for publication.
- Thank the Professors of CMS particularly Prof. Mans and my Co-Advisor Prof. Rusack for giving me the unique opportunity and all the help I needed to do experimental HEP.
- I thank my Advisor, Prof. Yuichi Kubota for accepting to be my advisor despite my numerous flaws as an experimentalist and for giving me uncountable opportunities to experience failure and improvment. I counldn't have had a better advisor.
- I thank the Graduate school for giving me the Desertation fellowship for 2013/2014.
- Thank you all for being here this morning and to some of you in particular for all the personal help I received throughout this incredible journey.

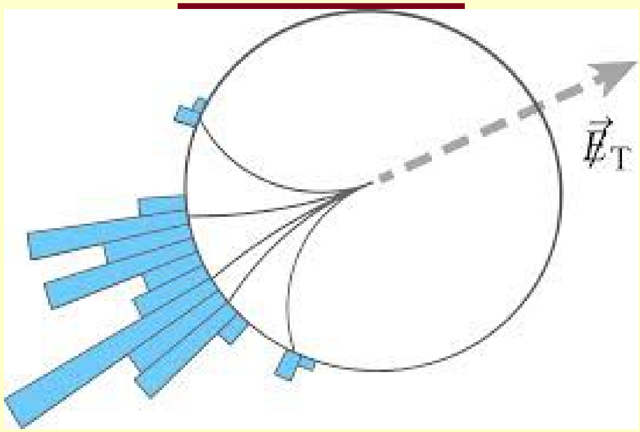
# Thanks A LOT!

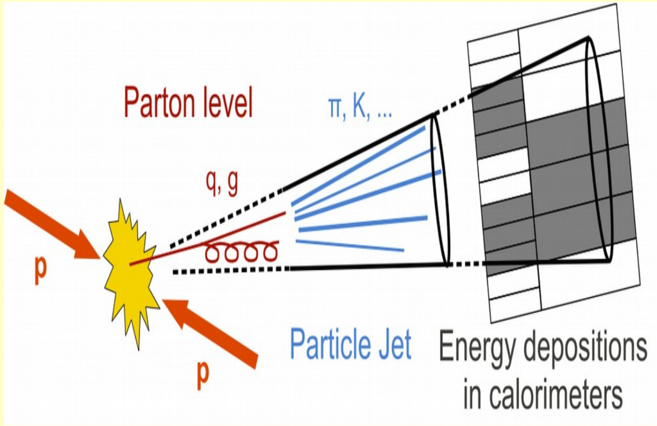
"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

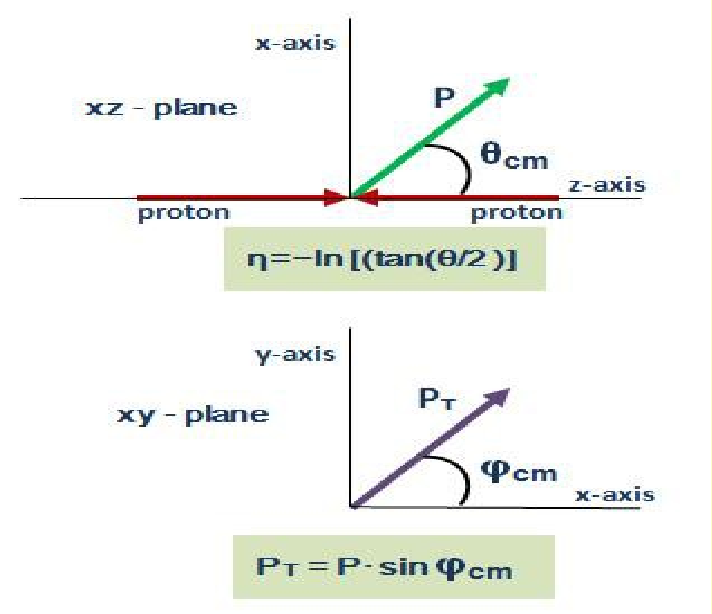
"Vacuums, black holes, antimatter - it's the elusive and intangible which appeals to me."

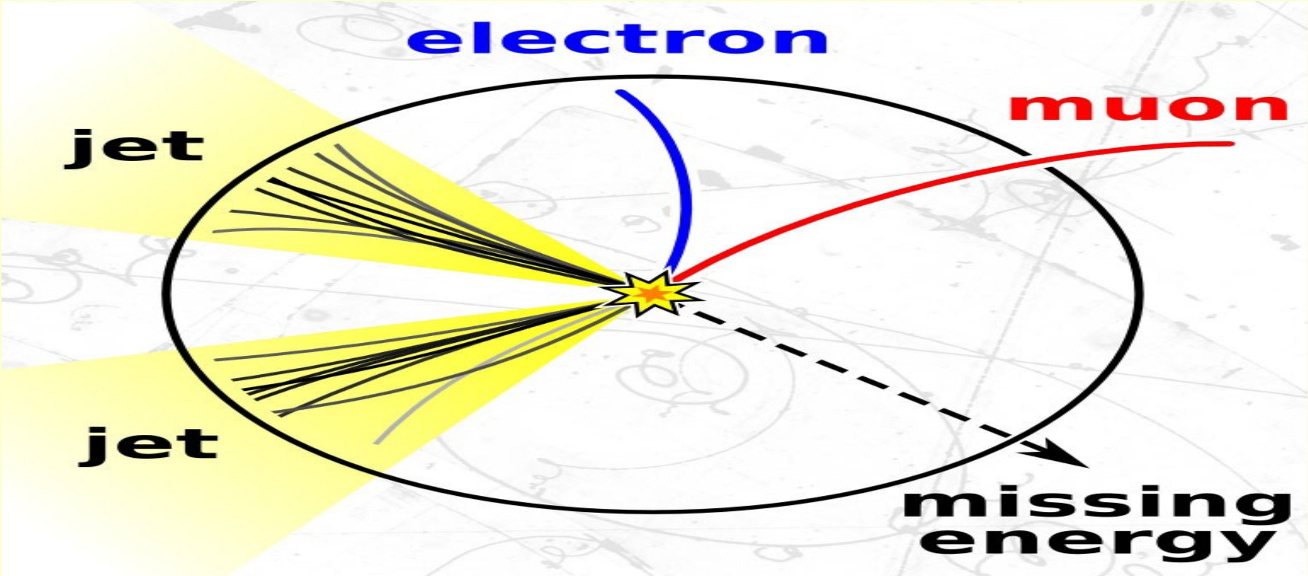
# BackUp: Physics Objects in CMS



# ECAL Timing Resolution

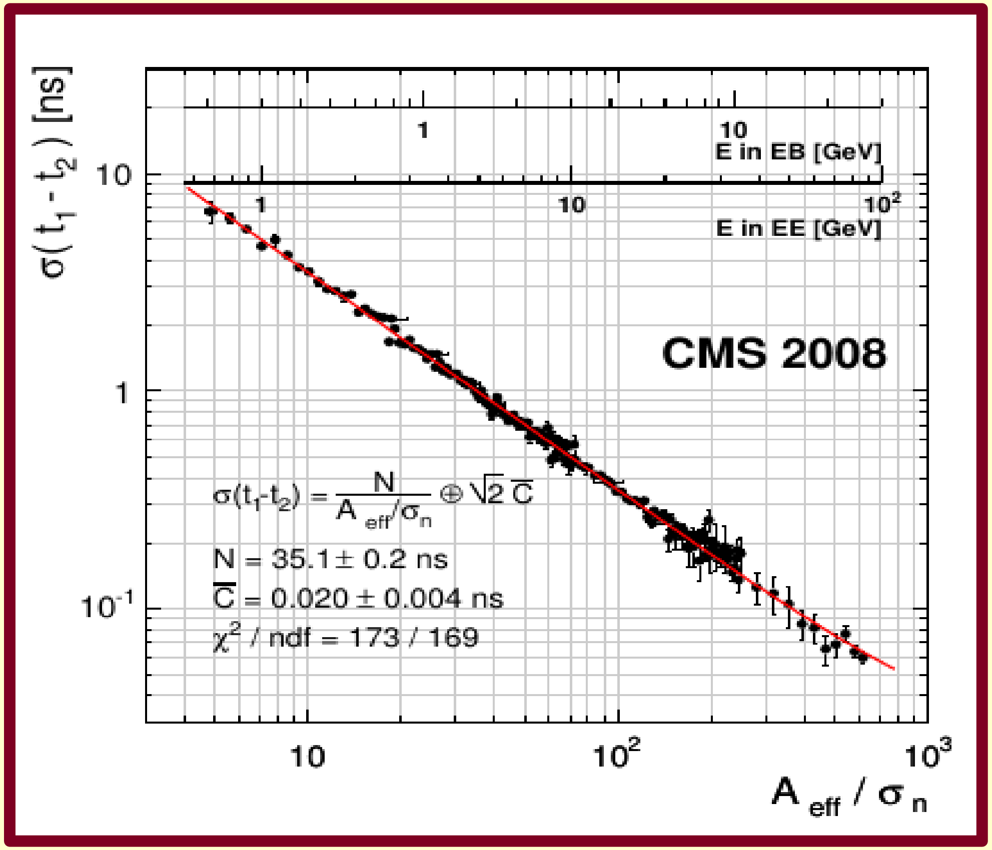
Parametrized as:

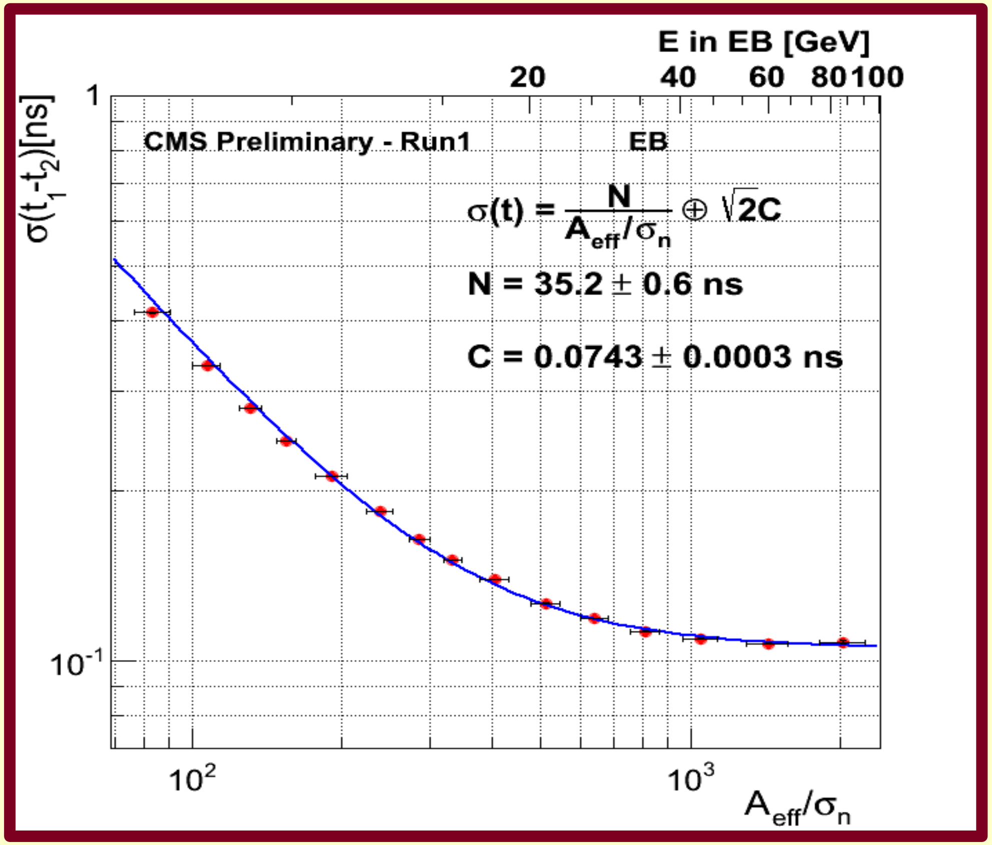
$$\boxed{\sigma^2(t_1 - t_2) = \left(\frac{N}{A_{\mathrm{eff}}/\sigma_n}\right)^2 + 2C^2,}$$

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

- **N** = Noise term depends on energy.
  - Electronic noise
- **C** = Constant term 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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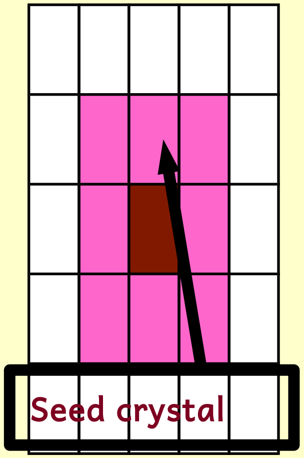
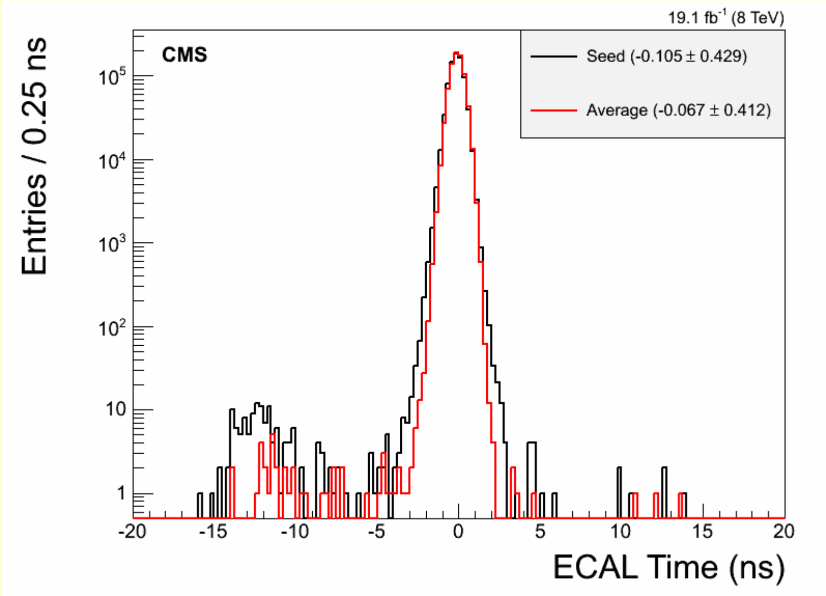
# Photon ECAL Time

- 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.

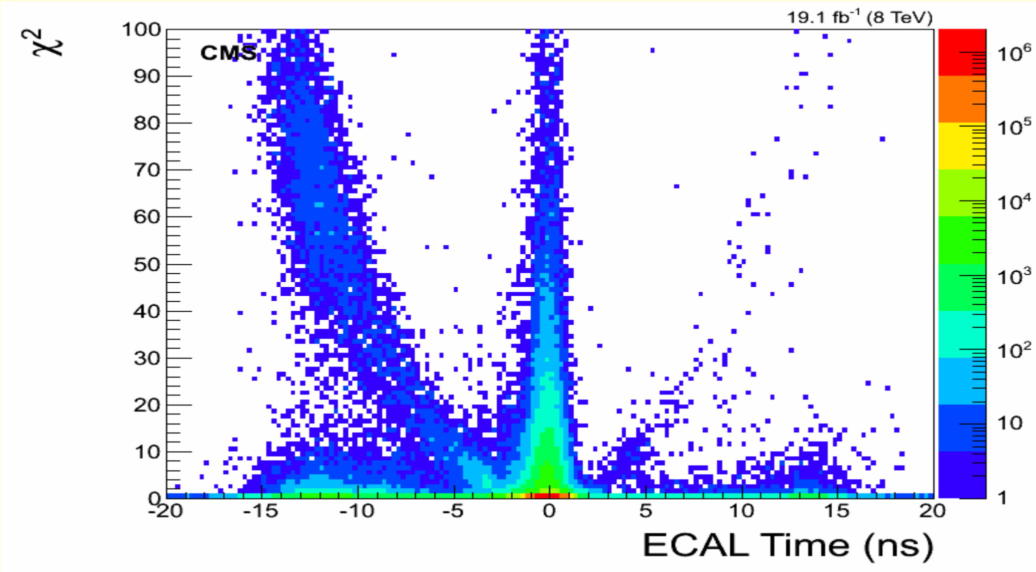



## Photon time Chi2

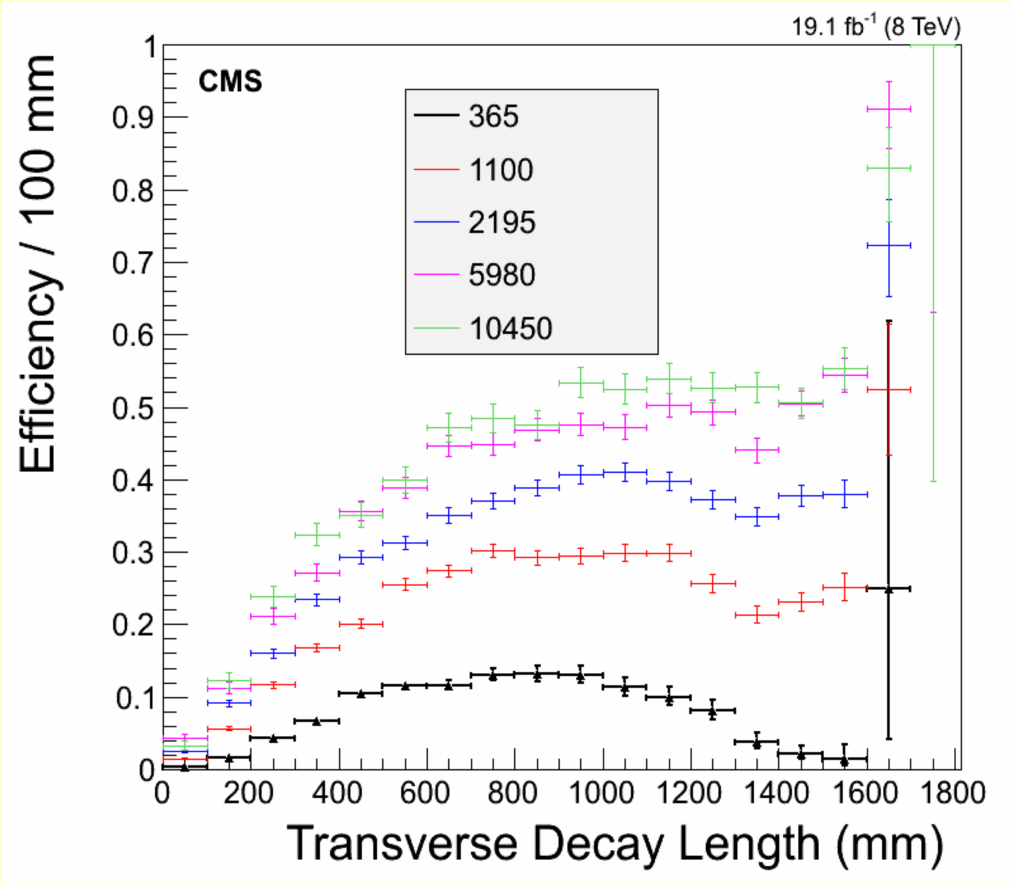
- Chi2 > 4 populated by bad photon candidates.

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

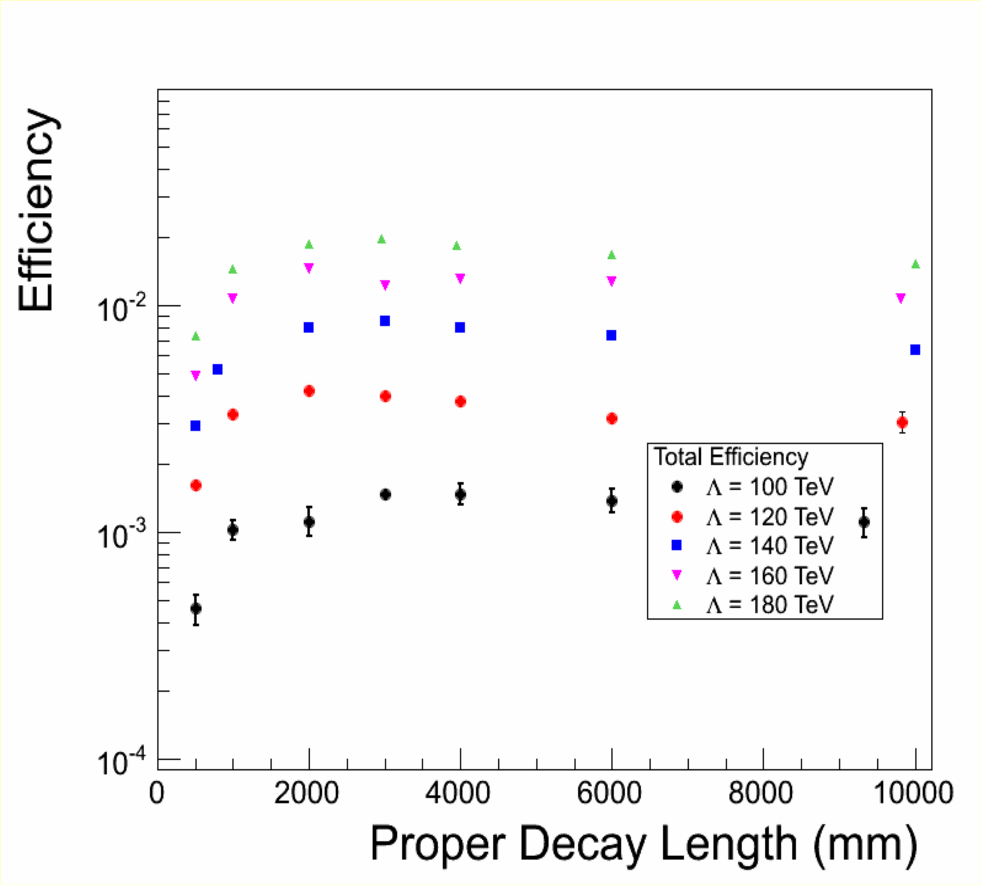


# Efficiency & Acceptance

## Transverse Detector Decay Length




## Particle Inherent Decay Length




Efficiency and Acceptance determines our final Observed event rate.

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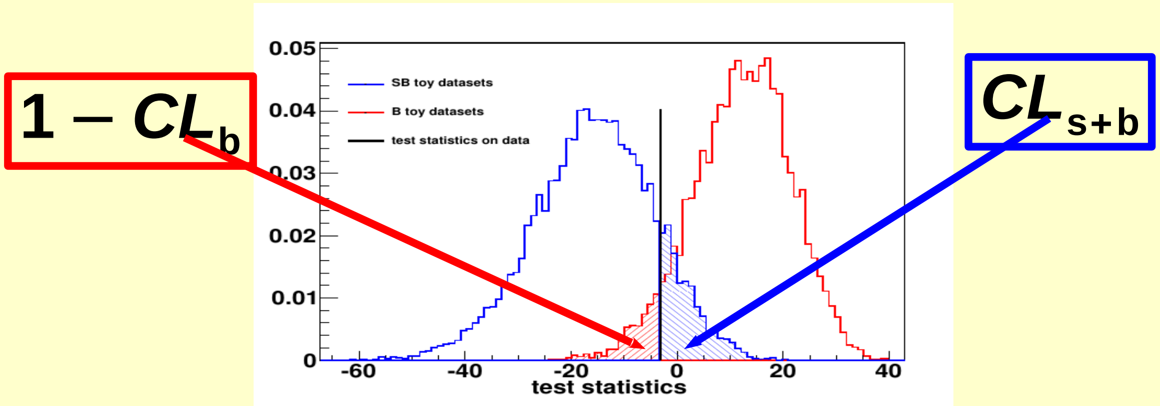
# Limit Setting

- Use the Cls method:

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

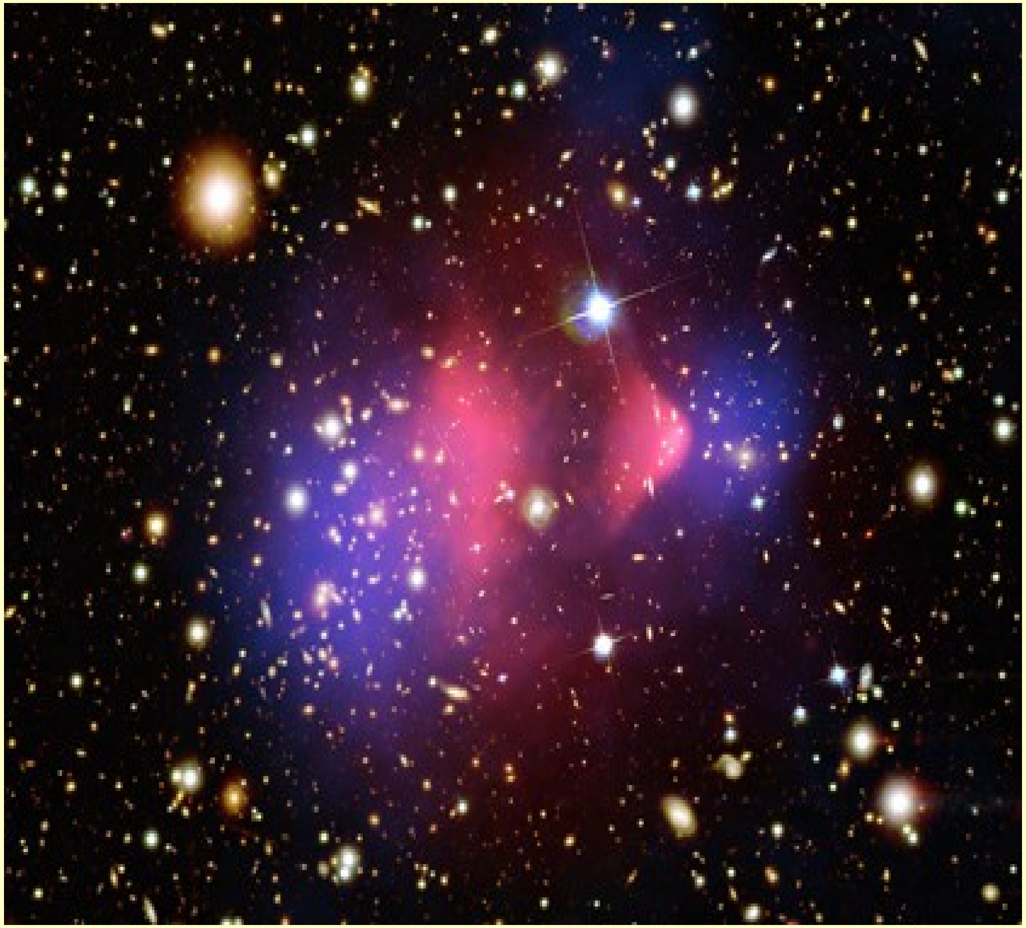



- CL{s+b} and CL{b} are probabilities for signal + background and background only hypotheis, respectively.
- Mu is signal strength modifier parameter.
- Excluded region in Mu or cross-section are values for Mu for which the probability CL{s} is less than **0.05% for 95%** confidence Limit(CL)
- Background 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

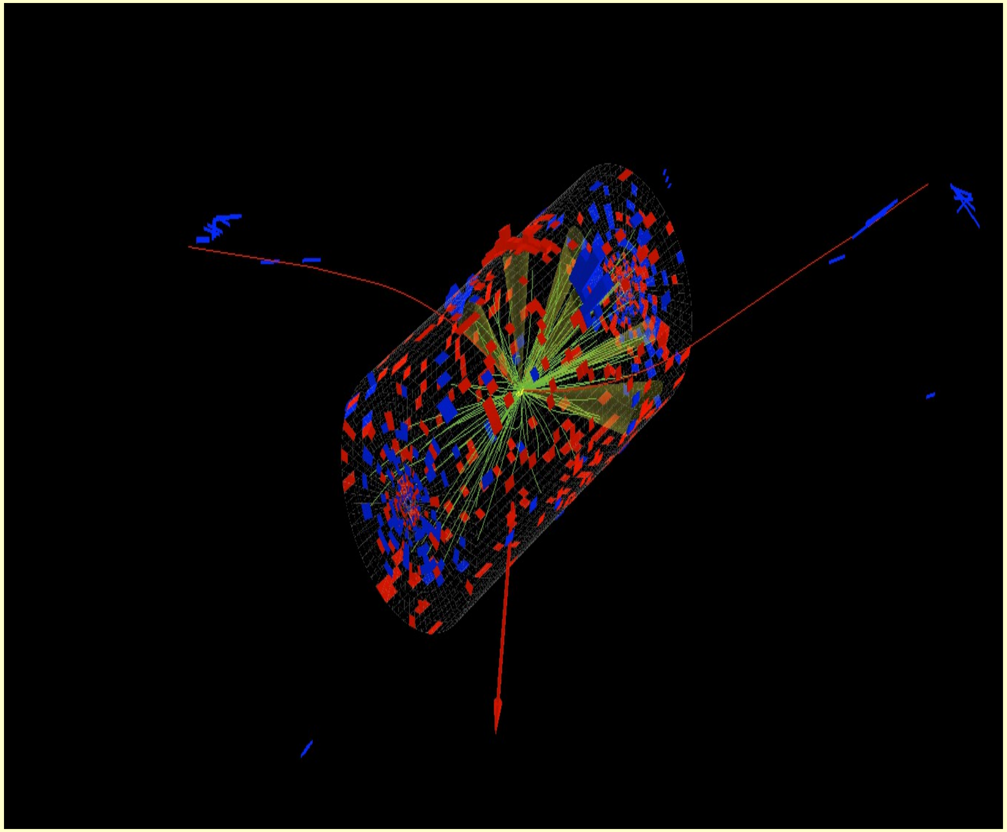
- Stable(long-lived).
- Neutral; does not interact with light.
- Light or massive?



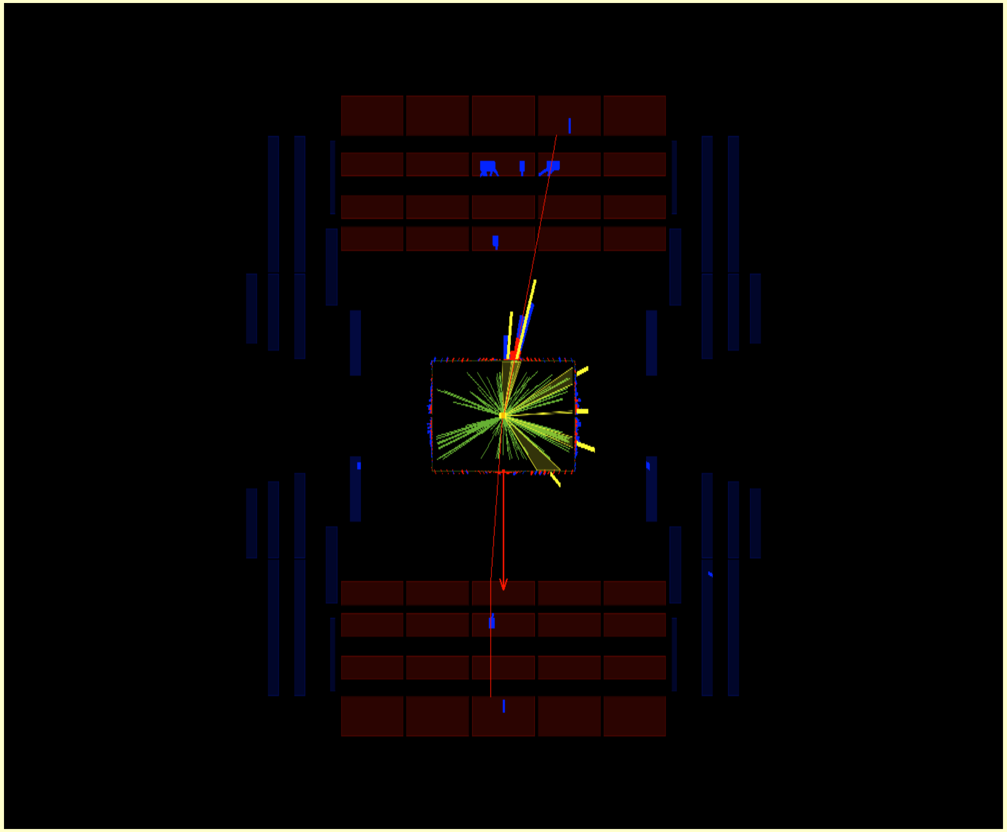
- **Where are Dark Matter particles?**

# Observed Event Display

**3D View**



**Rho – Z View**



CMS event display of observed cosmic muon event in CMS detector.



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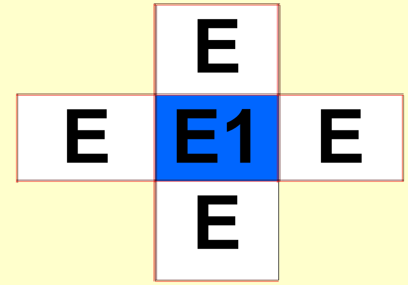
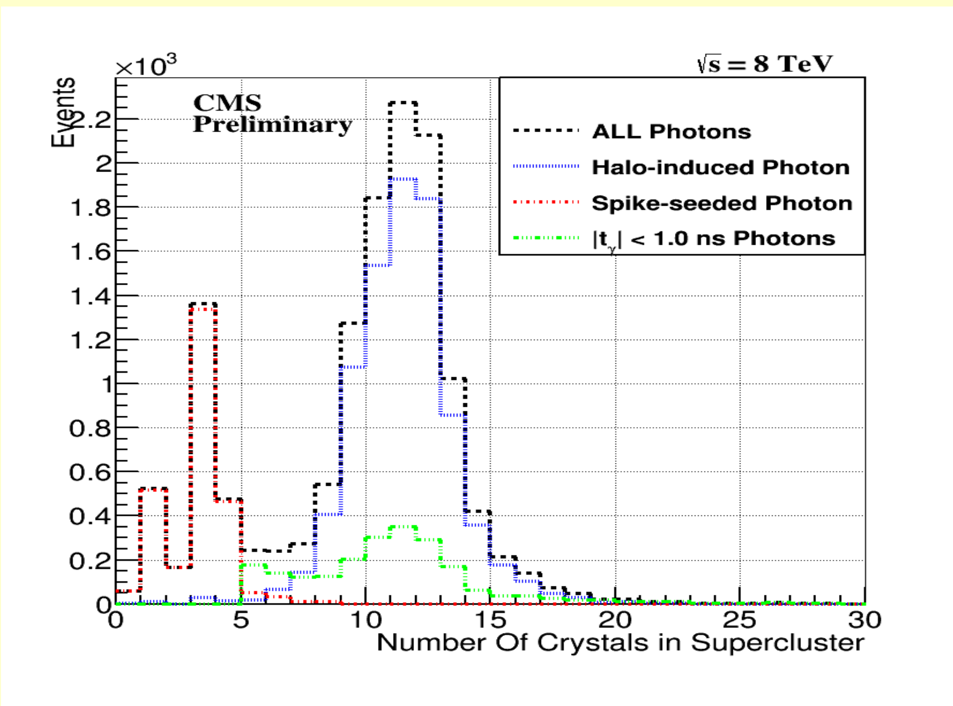
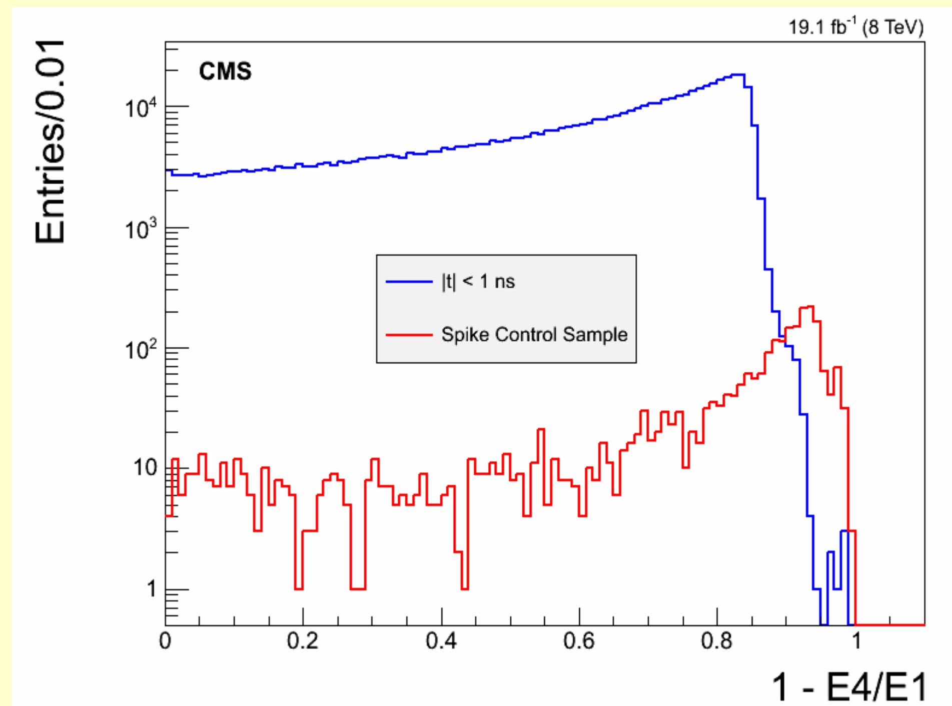
# Spike-Seeded Photons

- 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



# Non-Collision Bkg photon Mis-Tag Rate

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

## Beam-Halo-Induced Photon time estimation

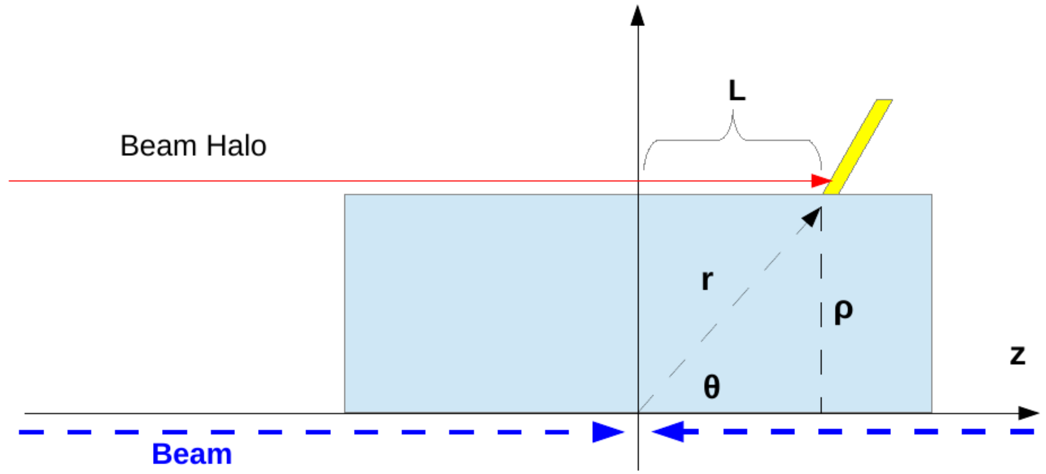
- Approximation of halo behavior :

→ $t\_0 = r/c = \rho / c \sin\theta$

$t\_halo = L / c = \rho / c \tan\theta$

$t\_ECAL = \rho/ c \tan\theta - \rho/ c \sin\theta = \rho/2c (\tan\theta/2) = - \rho/2c \exp(-\eta)$

→ Halo timing would be earlier than the normal collision.



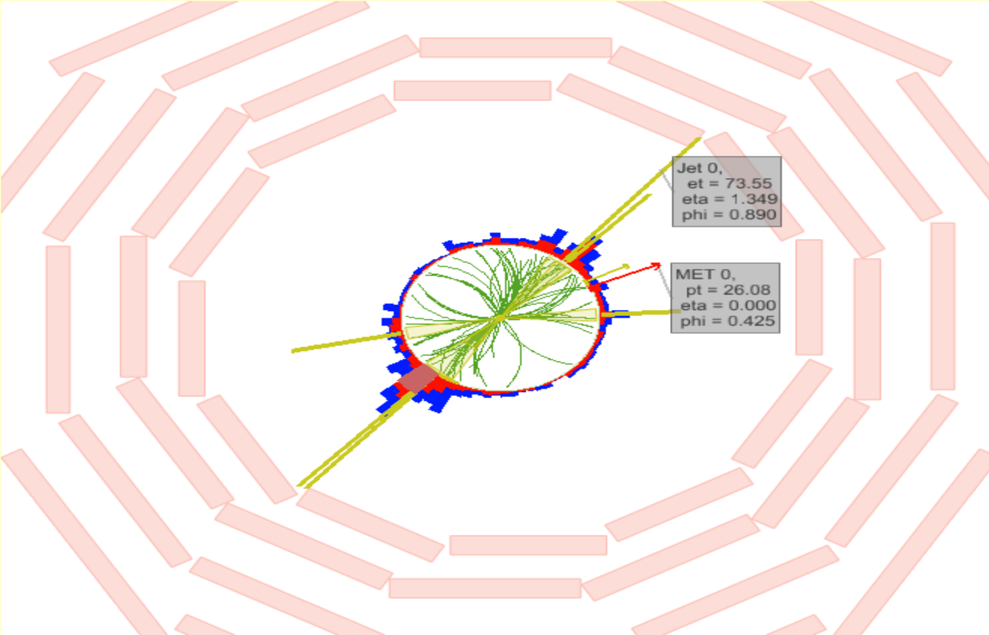
# ABCD Collision Bkg Estimation

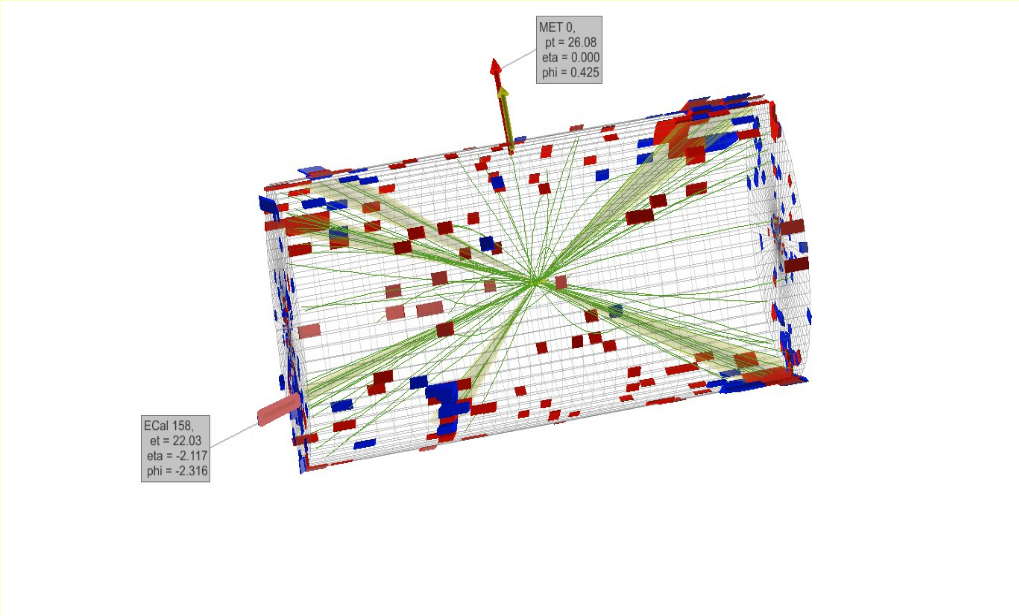
- **MET^Photon > 60 GeV**
  - Supresses Halo/Cosmic/Spike Background
- Samples **F' & F** *are* dominated by collision events.
- Collision events in **B** *and* **D** samples of Non-Collision background can be estimated *as*:

$$B^{Col} = B' * \left(\frac{F}{F'}\right) \qquad D^{Col} = D' * \left(\frac{F}{F'}\right)$$

| $MET^{\gamma} > 60$ GeV | MET < 60 GeV | MET > 60 GeV |
|---|---|---|
| 3 ns < t < 13 ns | D' | D |
| \| t \| < 2 ns | F' | F |
| -10 ns < t < -33 ns | B' | B |

# One of the Observed Z events




- M_ee = 98 GeV/c^2,
- t_e1 = 3.6 ns,  t_e2 = 4.3 ns

Out of time Z candiate event.