Search for long-lived neutral particles decaying to photons with missing energy using ECAL timing

Approval of EXO-12-035

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Documentation

- PAS :

  http://cms.cern.ch/iCMS/analysisadmin/versions?analysis=EXO-12-035
- NOTE :
  http://cms.cern.ch/iCMS/jsp/openfile.jsp?tp=draft&files=AN2013_001_v8.pdf
- TWIKI :

  https://twiki.cern.ch/twiki/bin/viewauth/CMS/DisplacedPhoton2012
- CADI :

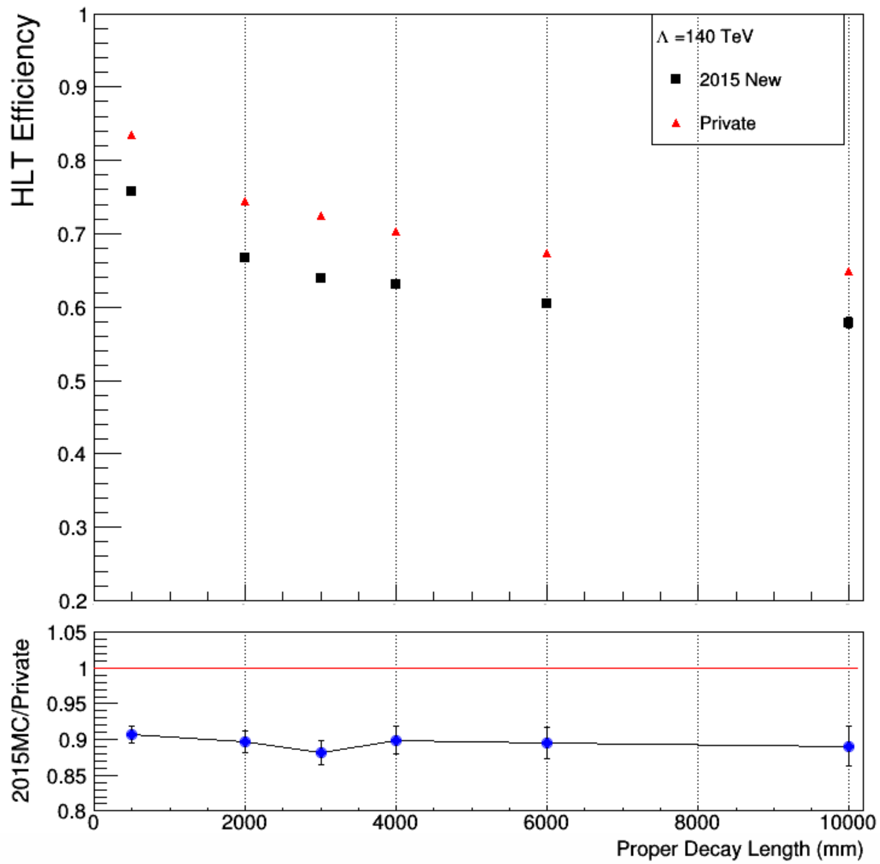
  http://cms.cern.ch/iCMS/analysisadmin/cadilines?line=EXO-12-035

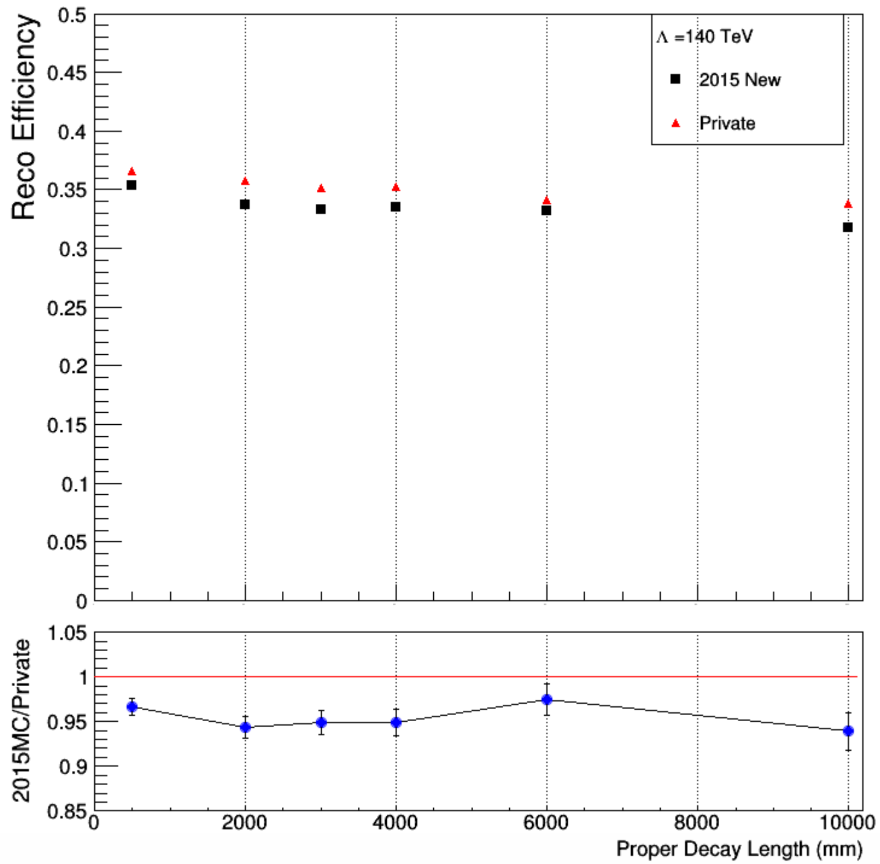
For Approval → Plots we would like to be approved for public use.

Outline

Updates since pre-approval

- Results are updated using new generated 8 TeV MC.
  - → New samples were produced centrally.
  - → Correct lifetime setup and official HLT simulation.
  - → 10% drop at HLT stage and 5% at RECO and event selection stage.
    - → Overall efficiency difference is about 15% ~ 20% lower.





Updates since pre-approval

- Change collision background estimation from an ABCD method to a Z→ ee method.

  → Non-Collision background estimation remain the same.

  → Two methods both suggest negligible contribution from collisions.

    → Choose Z→ ee method since it predicts larger background.

	Estimation in B Region	Estimation in D region
ABCD	$0.14^{+0.11}_{-0.06}$	$0.09^{+0.09}_{-0.05}$
Z→ ee	$0.51^{+0.28}_{-0.27}$	$0.37^{+0.09}_{-0.07}$
ABCD (closure test)	$0.19^{+0.08}_{-0.06}$	$0.05^{+0.05}_{-0.02}$
Z→ ee (closure test)	$0.64^{+0.35}_{-0.34}$	$0.46^{+0.11}_{-0.09}$

Introduction

- **Motivation** : Search for long-lived neutral particle decaying to photon with missing energy.

  → **Method** : Delayed ECAL timing

- **Benchmark model** : Snowmass Points and Slopes 8 (**SPS8**)

  → Neutralino ($\tilde{\chi}_1^0$) is NLSP, Gravitino ($\tilde{G}$) is LSP

  → 83 ~ 94 % BR for $\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma$

  → **97 ~ 99 % of events have at least one photon.**

  → SUSY breaking scale Λ changes the mass of $\tilde{\chi}_1^0$ and $\tilde{G}$.

- Lifetime is proportional to c_{grav}^2 .

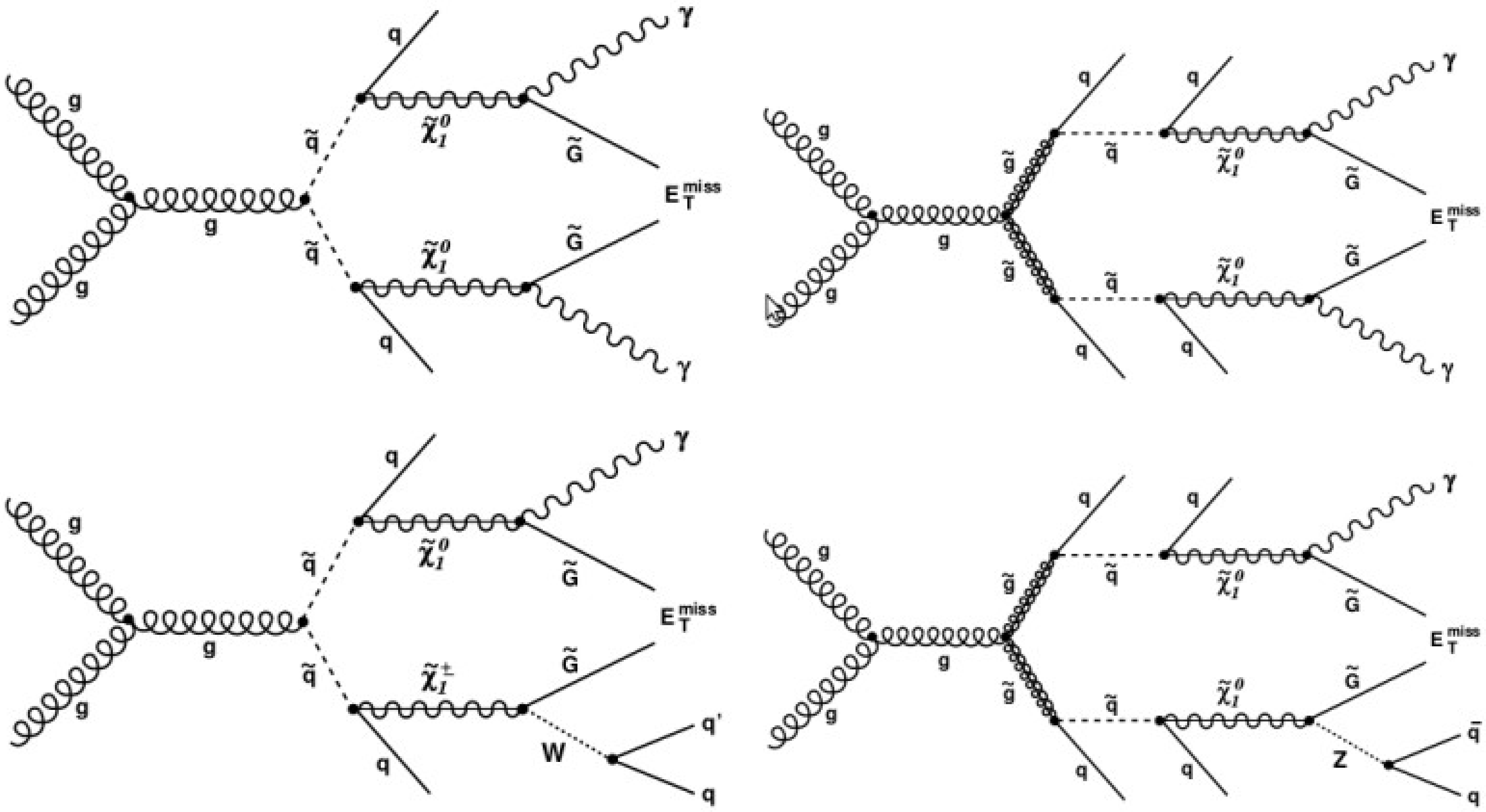
  → c_{grav} is Λ dependent. For each lifetime point of a particular Λ , c_{grav} needs to be adjusted accordingly.

- Lifetime of neutralino well constrained by theory, so we look for everywhere we can.

Production Mechanism

- Neutralinos are pair produced from the decay of squarks.

  → Signal signature : Photon, MET and Jets



Analysis Method

- Simple counting method.

→ Count number of event with at least one late photon (ECAL time > 3 ns).

→ Advantage : Negligible standard model/collision background.

→ Machine induced background and cosmic-rays become the main source.

→ Re-processed photon reconstruction in order to include out-of-time crystals in the reconstruction process.

- Use negative timing as background control region

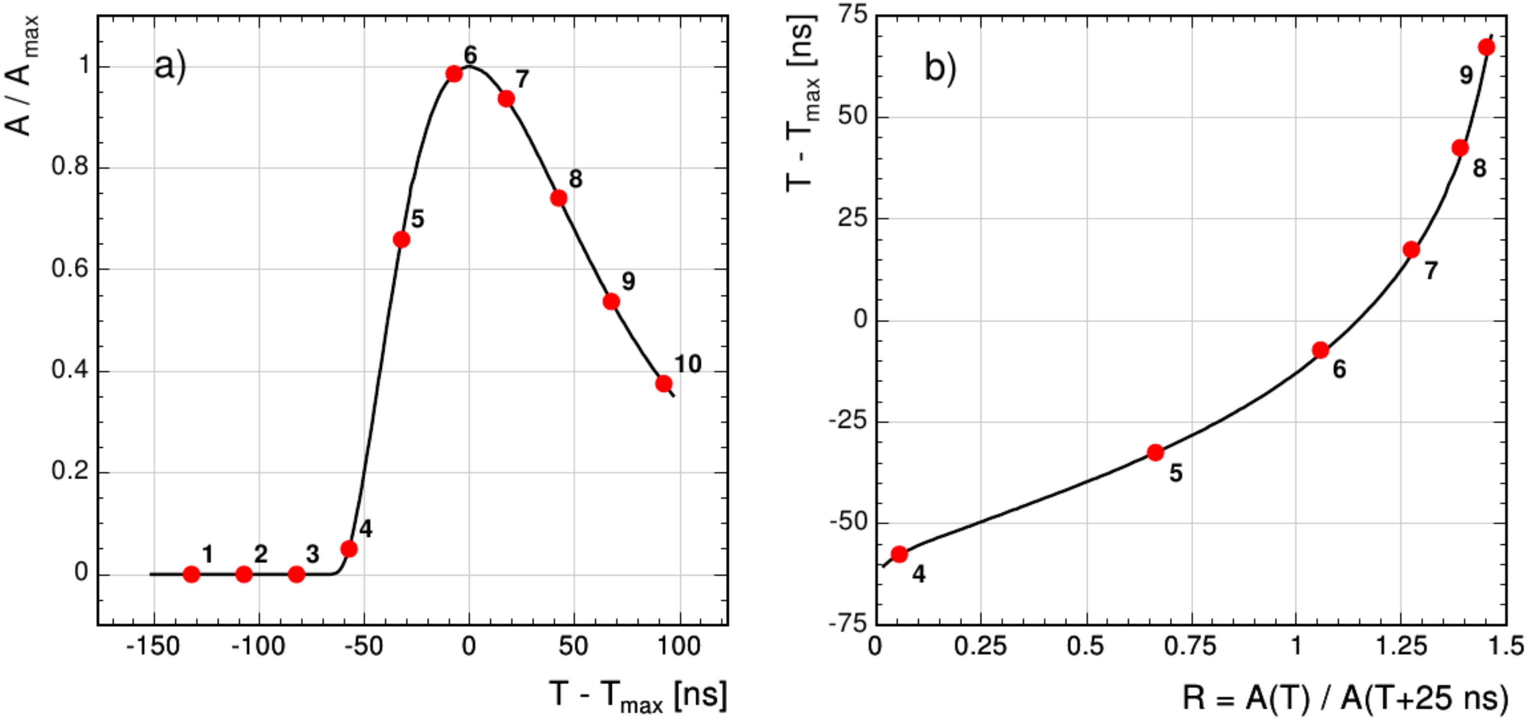
→ Study and develop background veto methods and background estimation.

ECAL Time (t)

- CMS ECAL Time is determined by 10 pulse sample measurement.

  → Determined by the sample time (Ti) and T(Ri) using the plot (b) and weighted average over samples (4~9).

$$T_{max} = \frac{\sum \frac{T_i - T(R_i)}{\sigma_i^2}}{\sum \frac{1}{\sigma_i^2}}$$



ECAL Time (t)

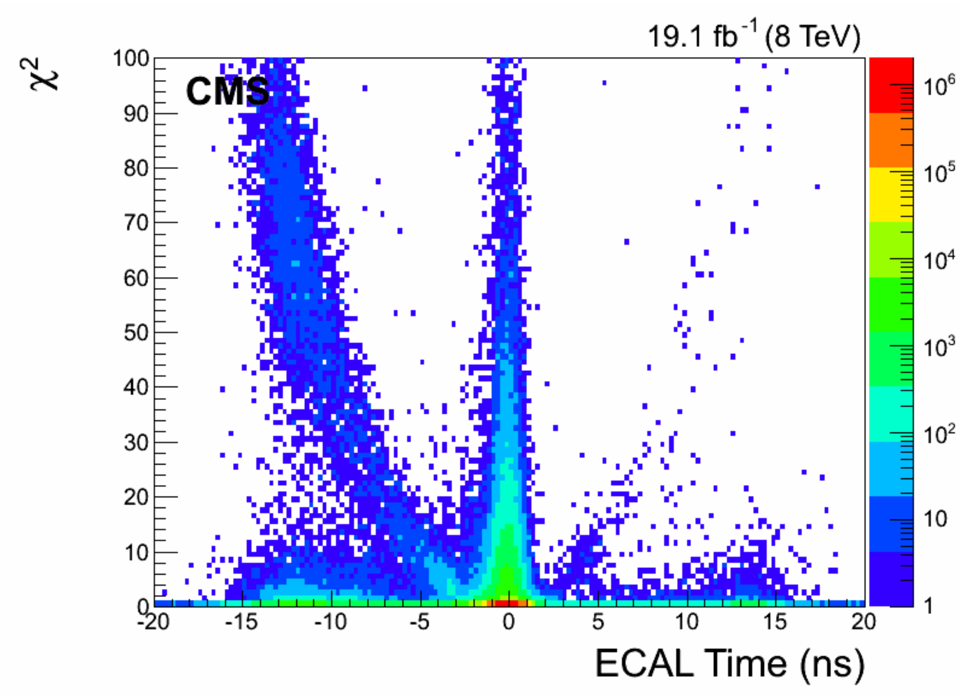
- Using time from seed crystal of the photon cluster.

→ Calculate χ2

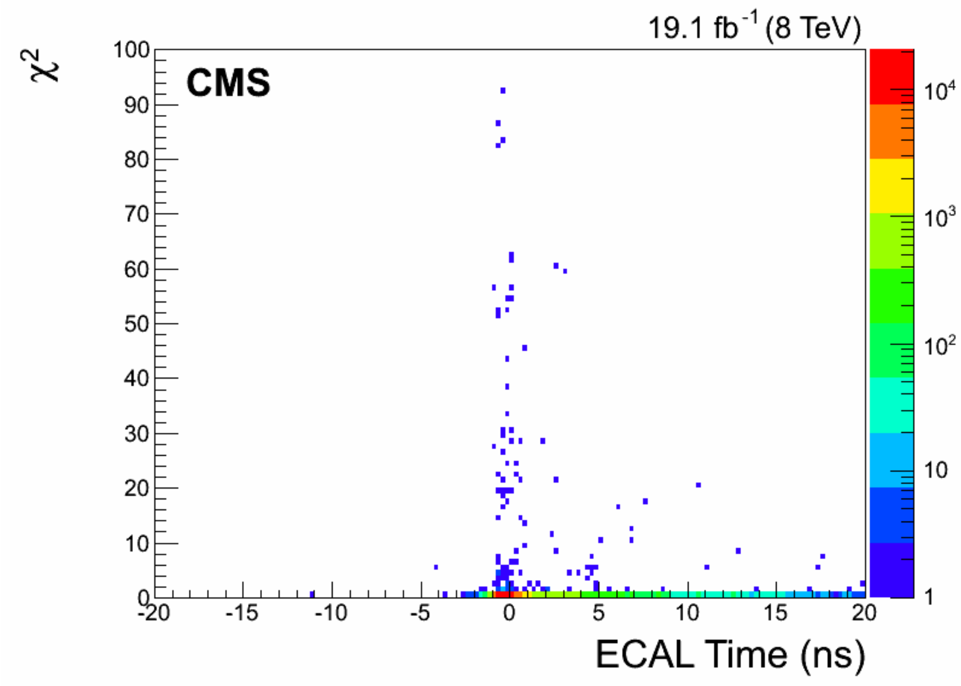
$$\chi^2 = \frac{1}{N-1} \sum \left(\frac{t_i - t_{cluster}}{\sigma_i} \right)^2$$

→ χ2 cut (χ2 < 4) reduces spike background.

→ Cluster time (t cluster) is the weighted average over the times obtained in all crystals in the seed cluster.



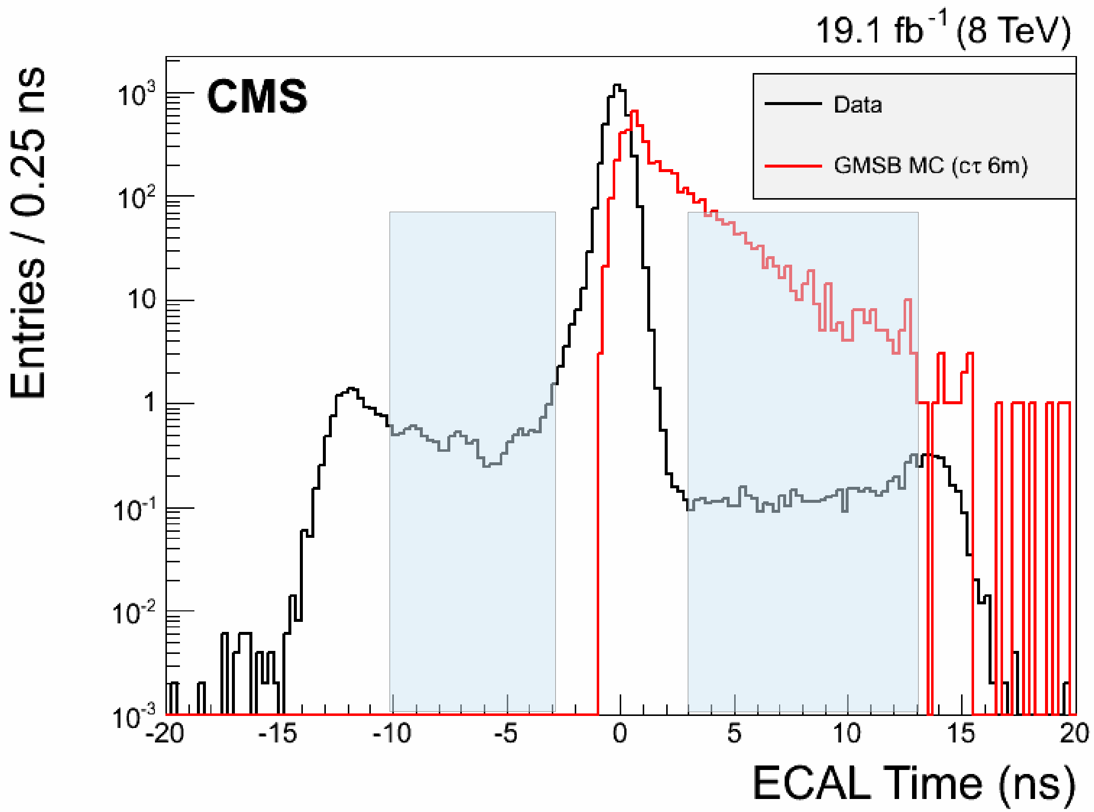
Displaced Photon Skim Dataset – No selection applied yet.

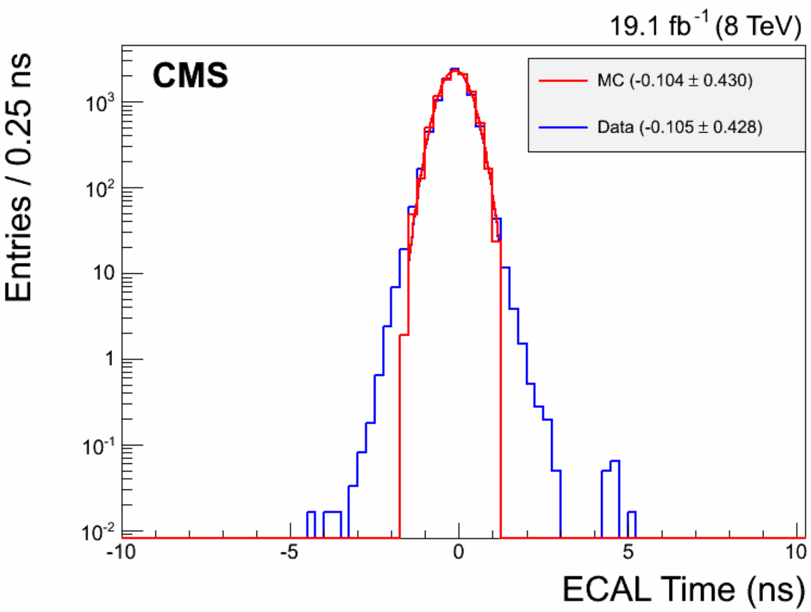


GMSB MC Sample – No selection applied yet.

ECAL Time (t)

- Resolution : ~ 500 ps
- Observation Scope : 3 ~ 13 ns
  → Linearity is verified up to 14 ns.
- Background control region : -10 ~ -3 ns
  → Avoid -12 ns peak from ECAL spike.

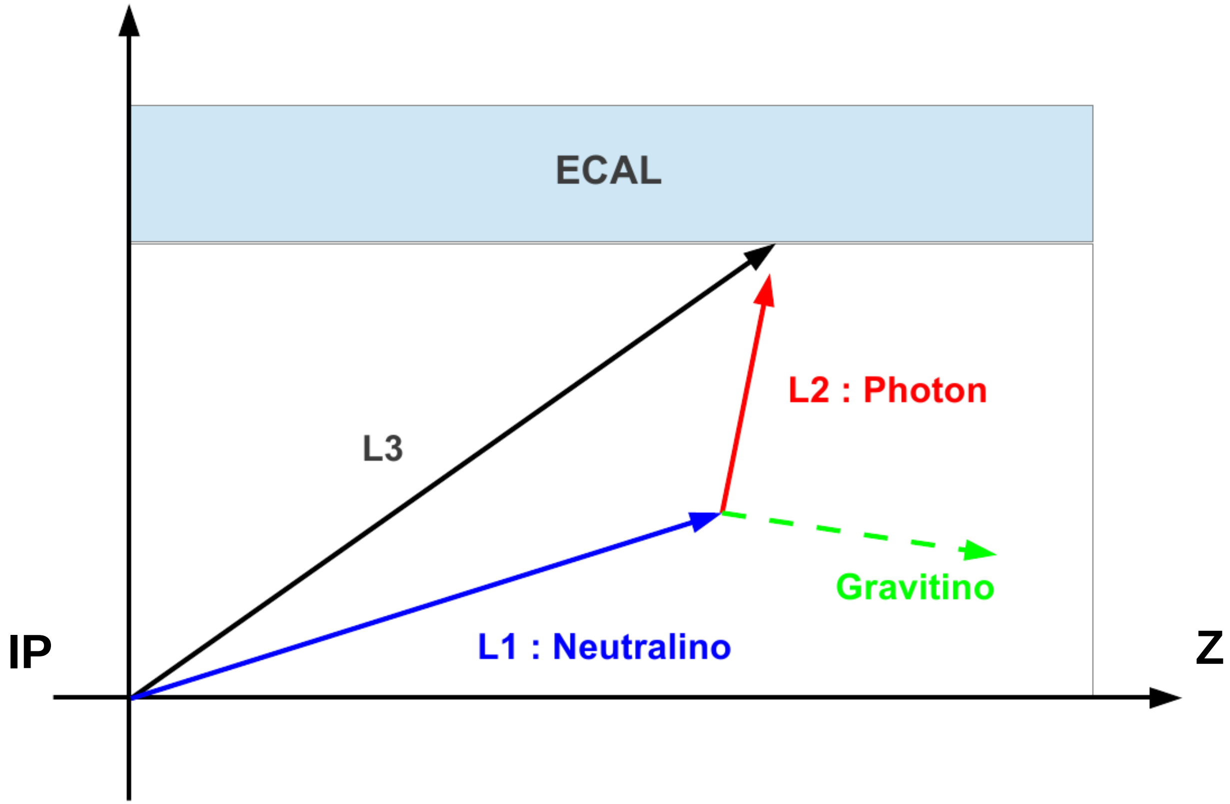




Adding extra smearing to MC samples to correct MC timing resolution.
(Detail in backup slide)

Delay Mechanism

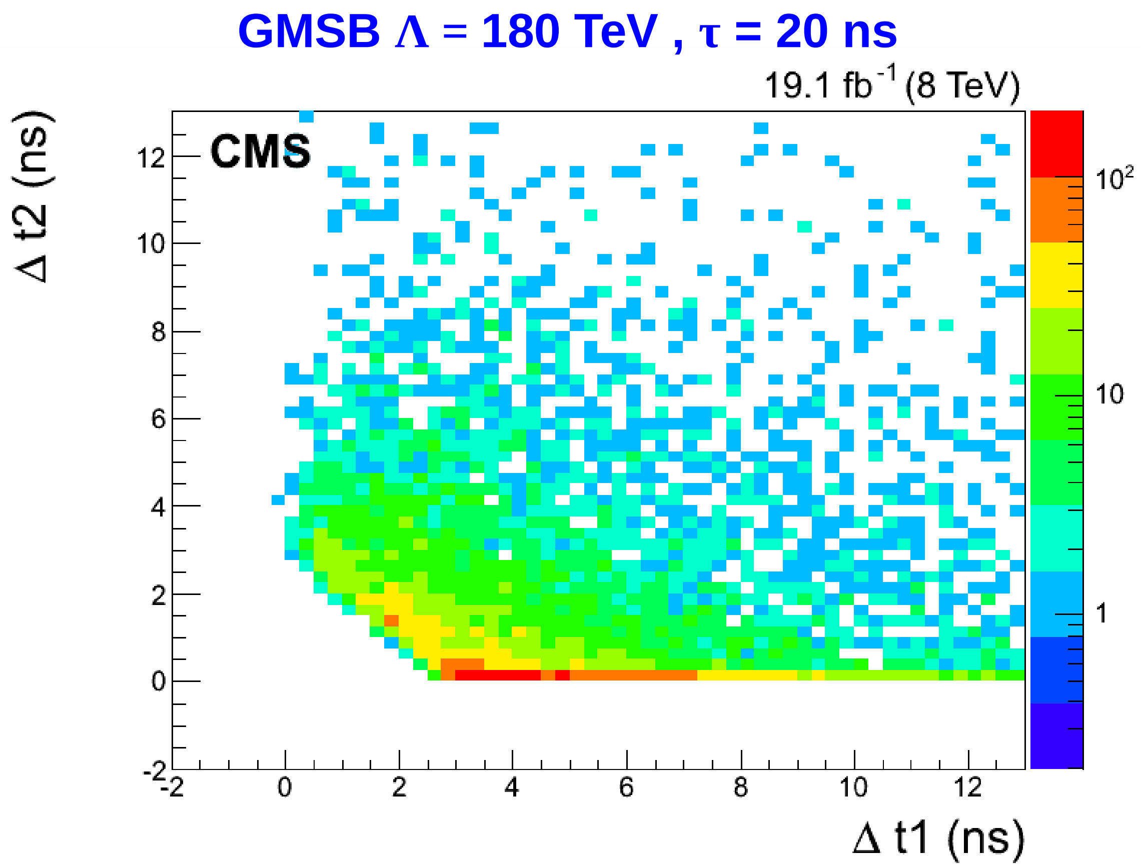
- Delay quantities (Δt1 and Δt2) :
  - → ECAL Time : L1/cβ + L2/c – L3/c
  - → Δt1 : L1/cβ – L1/c ; Delay from slow motion of neutralino.
  - → Δt2 : (L1 + L2 – L3)/c ; Delay from increase in path length.
  - → ECAL Time = Δt1+Δt2



Late Photons

- Check Δt1 and Δt2 for late photons (t > 3ns).
- Delay from slow motion is the main source for delayed signal.

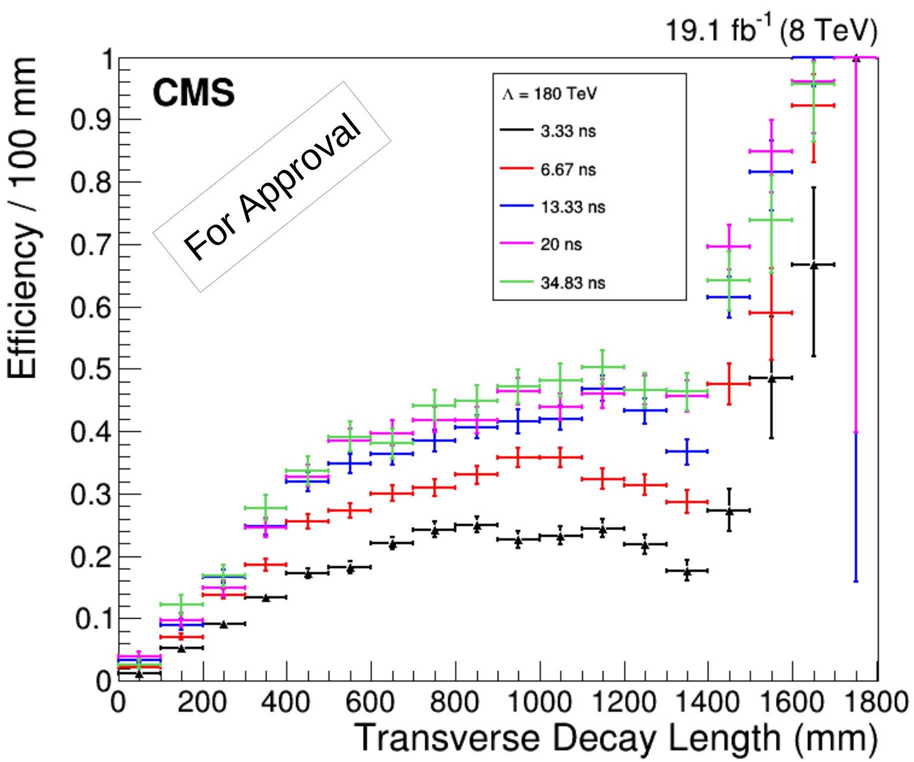
  → 37% of late photons have Δt2 < 0.5 ns.

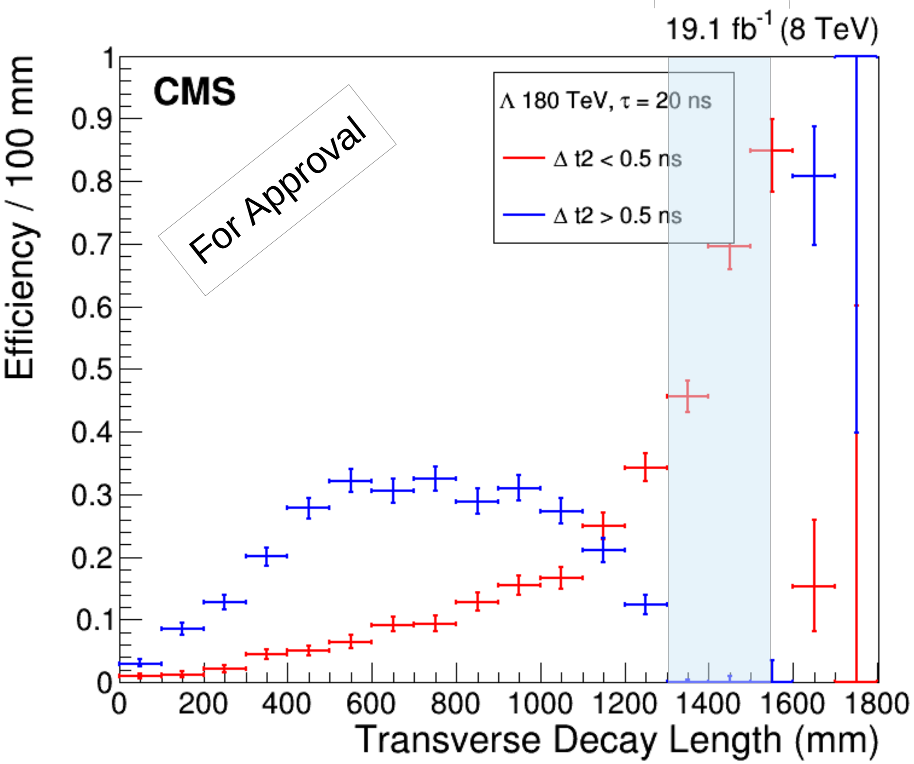


Late Photon Efficiency

- We evaluated photon efficiency w.r.t. transverse decay length of neutralino.
- The efficiency to detect a late photon (t > 3ns).
  - → Number of late photon / Number of reconstructed photon (EB only)
  - → No event selection cut applied yet.
- Separate two kinds of delayed photons using Δt2.
- The longer τ is, the higher efficiency (lower beta) would be.

Range of ECAL
1290 ~ 1550 mm

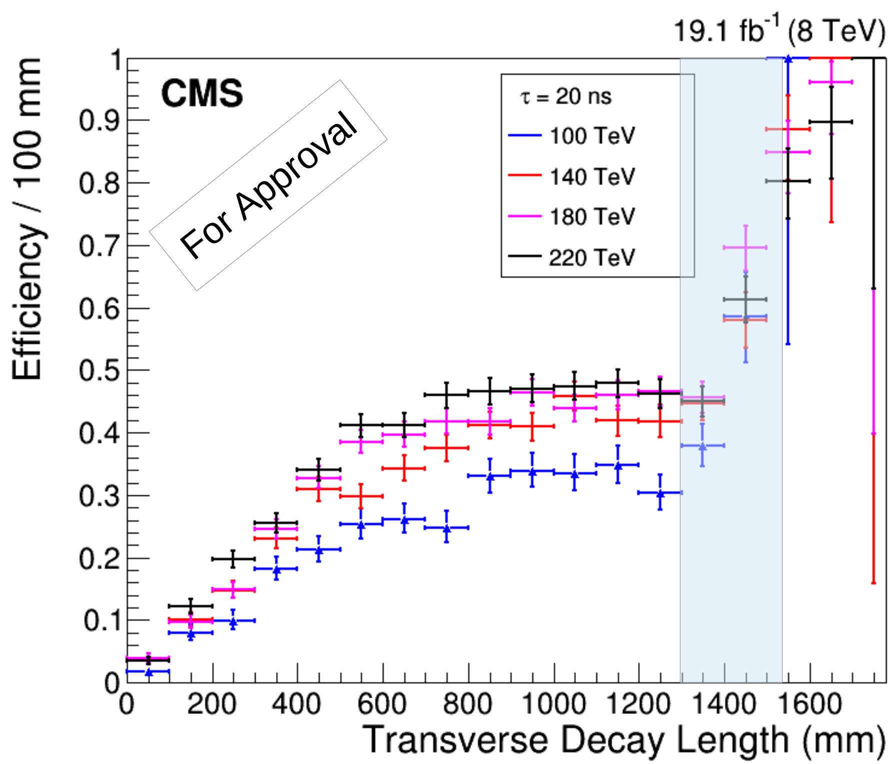


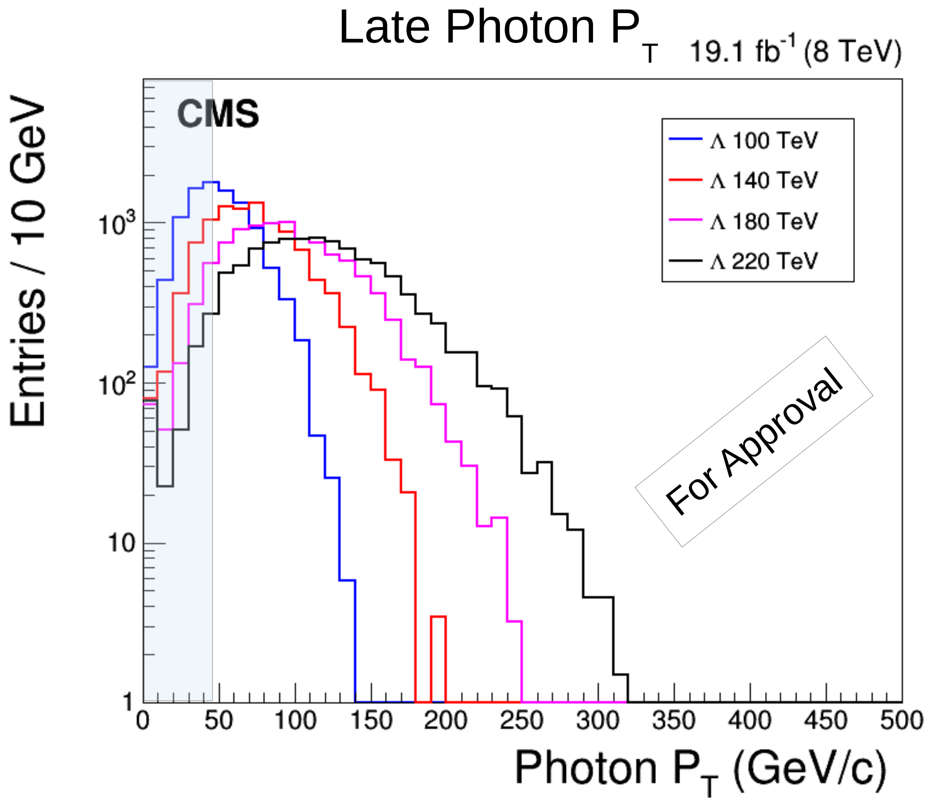


Late Photon Efficiency

- Efficiency among different Λ (with a fixed τ)

  $\rightarrow$ The larger Λ (heavier neutralino) is, the higher efficiency will be due to harder photon pT spectrum!

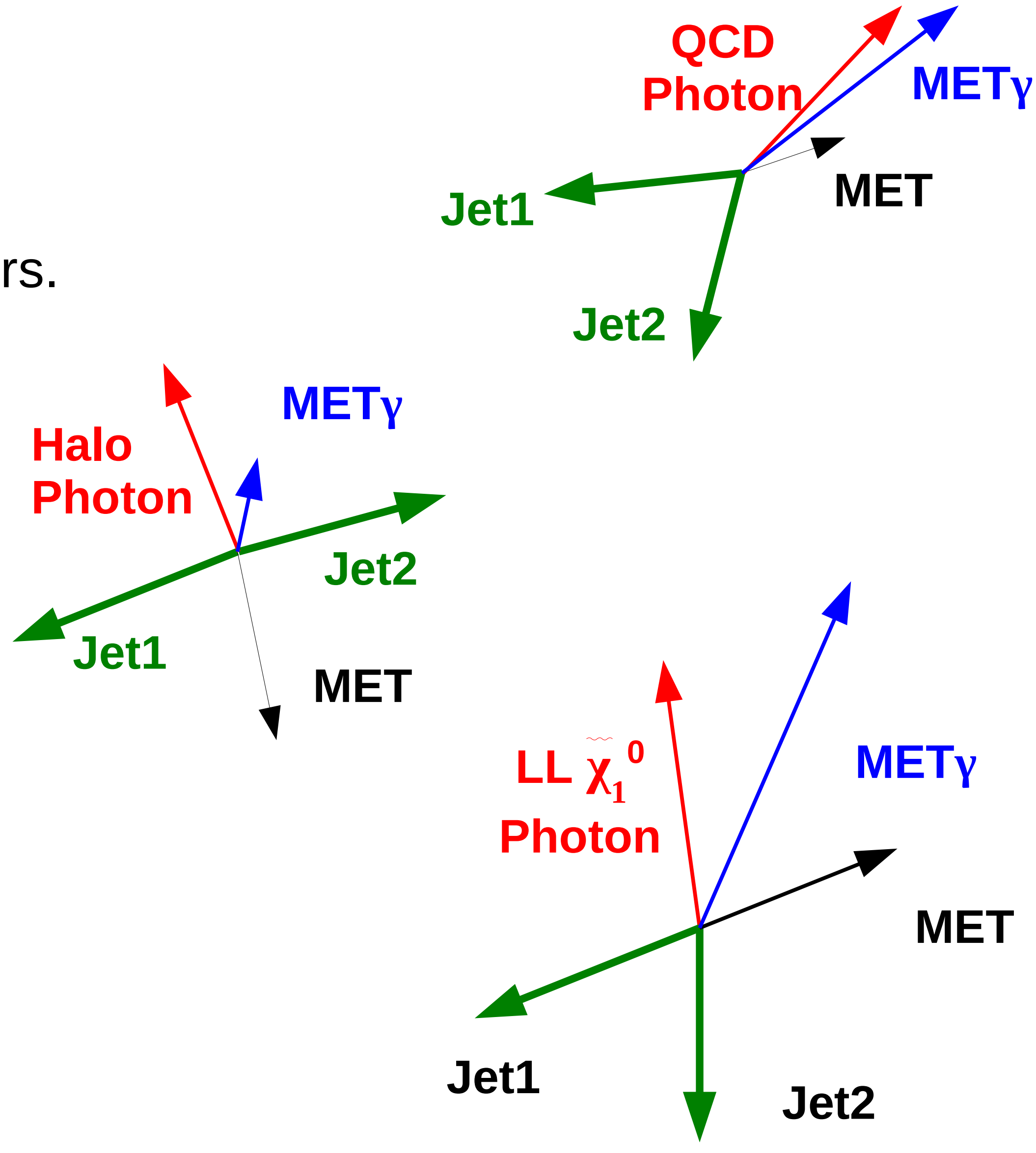




MET and METγ

- Define new variable - **METγ**
  → PFMET + photon Et (METγ)
- Set 60 GeV as threshold both MET quantities.
  → MET can separate QCD from others.
  → METγ separates Halo from others

	MET	METγ
QCD	Small	Large
Halo	Large	Small
LL $\tilde{\chi}_1^0$	Large	Large



Samples

- Data :

  → Displaced Photon Skim (Events fired DiplacedPhoton Trigger, HLT_DisplacedPhoton65_CaloIdVL_IsoL_PFMET25)

  → Total 19.1 /fb, 2012A is not included because the trigger was not available.

- Cosmic Dataset

  → For studying background

- IsoPhoton50 Data (HLT_Photon50_CaloIdVL_IsoL)

  → For trigger efficiency study

- GMSB MC

  → Signal MC (48000 events for each τ and Λ point)

    → (6 Λ values from 100 TeV to 220 TeV, 7 $c\tau$ points from ~0.2m to 10m)

- Gamma+Jets MC

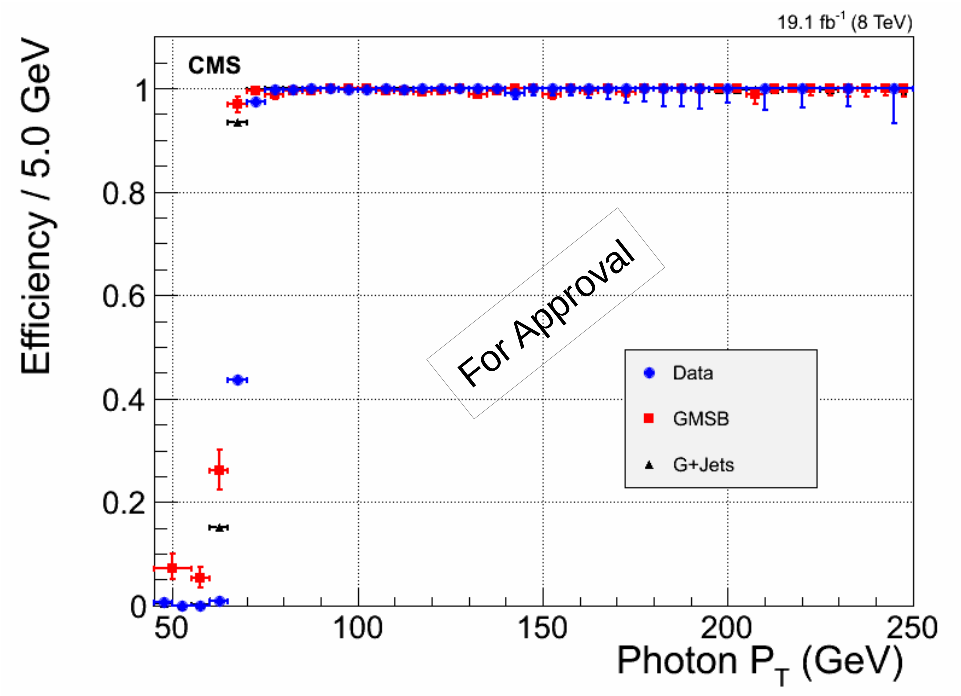
  → Background MC, only used for sanity check and timing resolution study

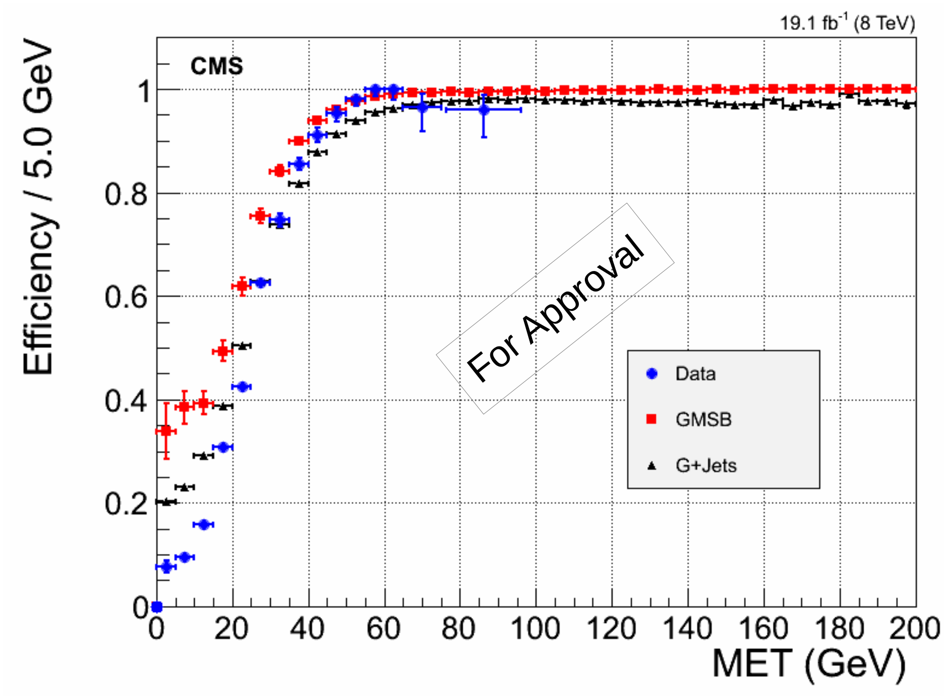
Trigger

- Displaced Photon Trigger

→ IsoPhoton(65 GeV) + Track rejection (dR > 0.5) + sMinor constrain(0.1 ~ 0.4) + PFMET(25 GeV)

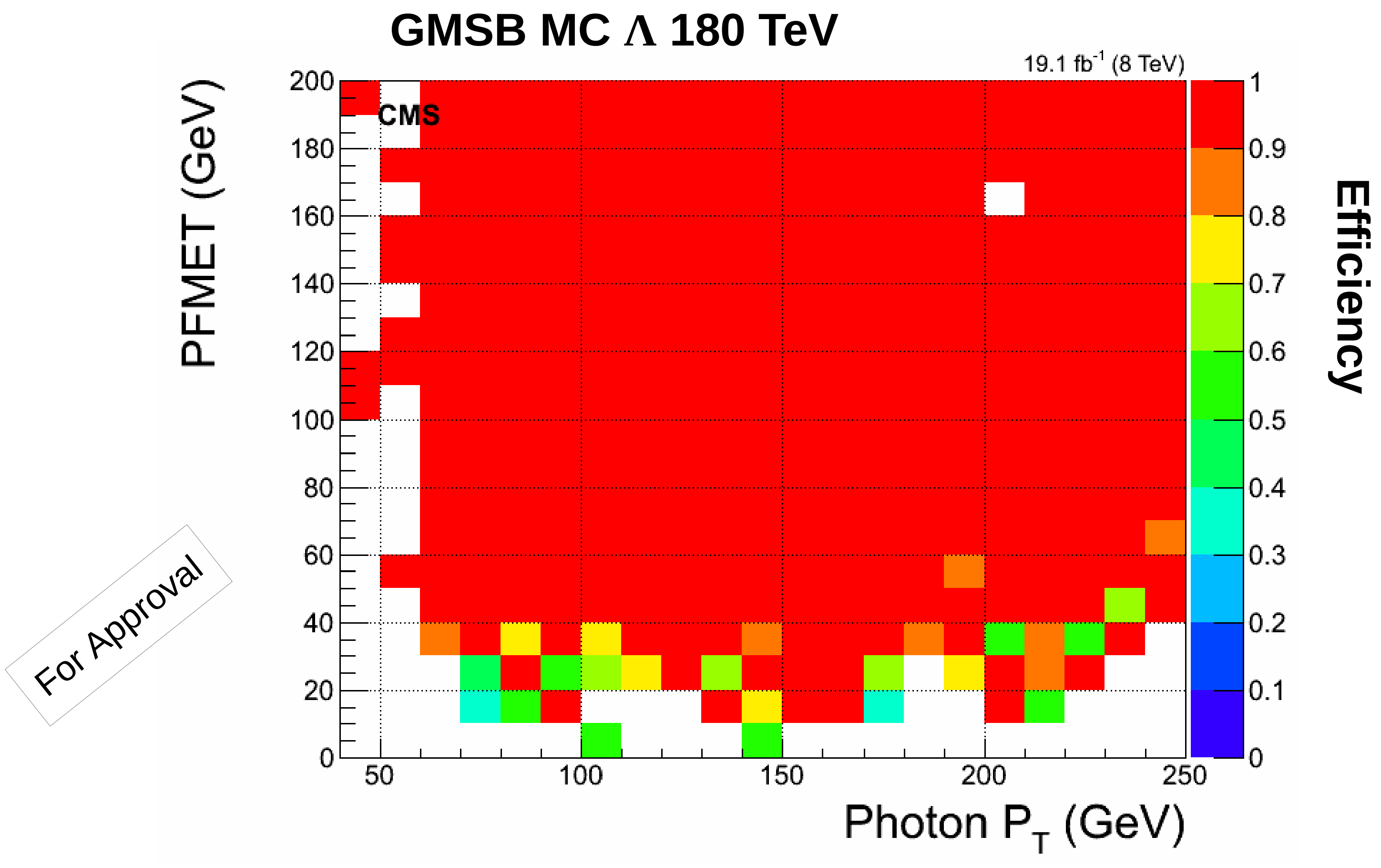
→ 100% efficiency for photon > 80 GeV/c and PFMET > 60 GeV. (used in off-line selection)





Trigger

- No correlation is found between photon object and PFMET.



Object and Event Selection

- Photon
  - → No PF isolation required , dR(γ,track) > 0.6, Standard Photon ID
  - → Leading photon Pt > 80 GeV/c, other photons Pt > 45 GeV/c, EB only
- Jet
  - → PFJet , pt > 35 GeV , $|\eta|$< 2.4 (Standard PFJet ID), dR(γ,jet) > 0.3
- MET
  - → PFMET (MET)
  - → PFMET + photon Et (METγ)
- Signal Selection :
  - → >= 1 photon, >= 2 jets , MET > 60 GeV, METγ > 60 GeV.
- Closure Test :
  - → >= 1 photon, 0 and 1-jet events, MET > 60 GeV, METγ > 60 GeV.

Background Estimation

- Comparing with in-time and off-time photon behavior.

  → Use 0 and 1-jet events as control region to study background particularly from non-collision sources.

  → $t < -3$ ns , $t > 2$ ns

  → Three non-collision sources : Halo, Cosmic-ray, Spikes

  → Find tagging criteria and veto the tagged photon objects.

- Residual non-collision backgrounds survived from veto

  → ABCD method.

- Collision background. (Non-Gaussian tail of ECAL time)

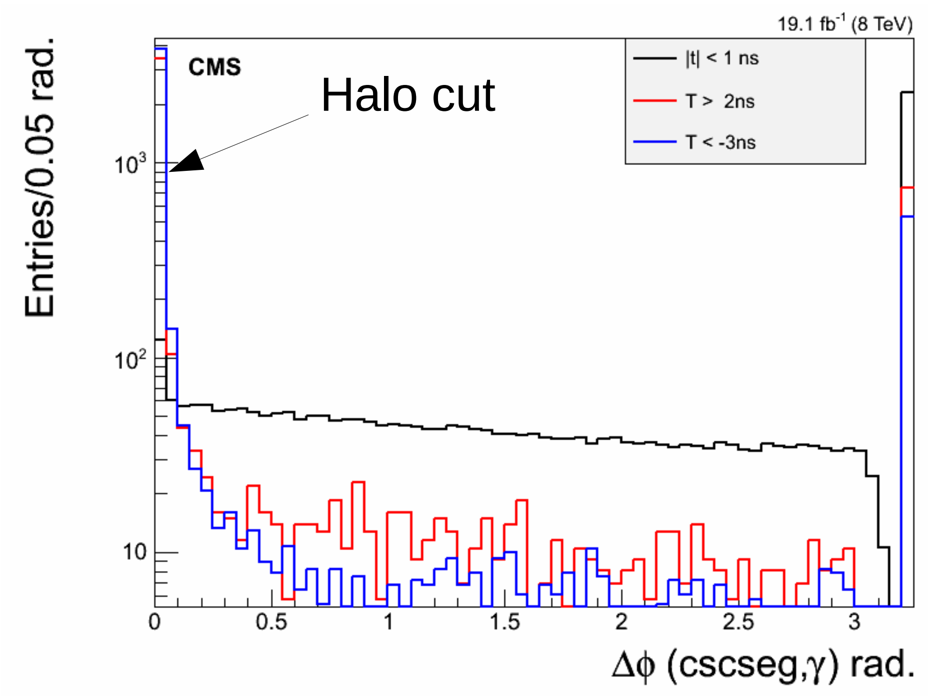
  → $Z \rightarrow e^{+}e^{-}$ method.

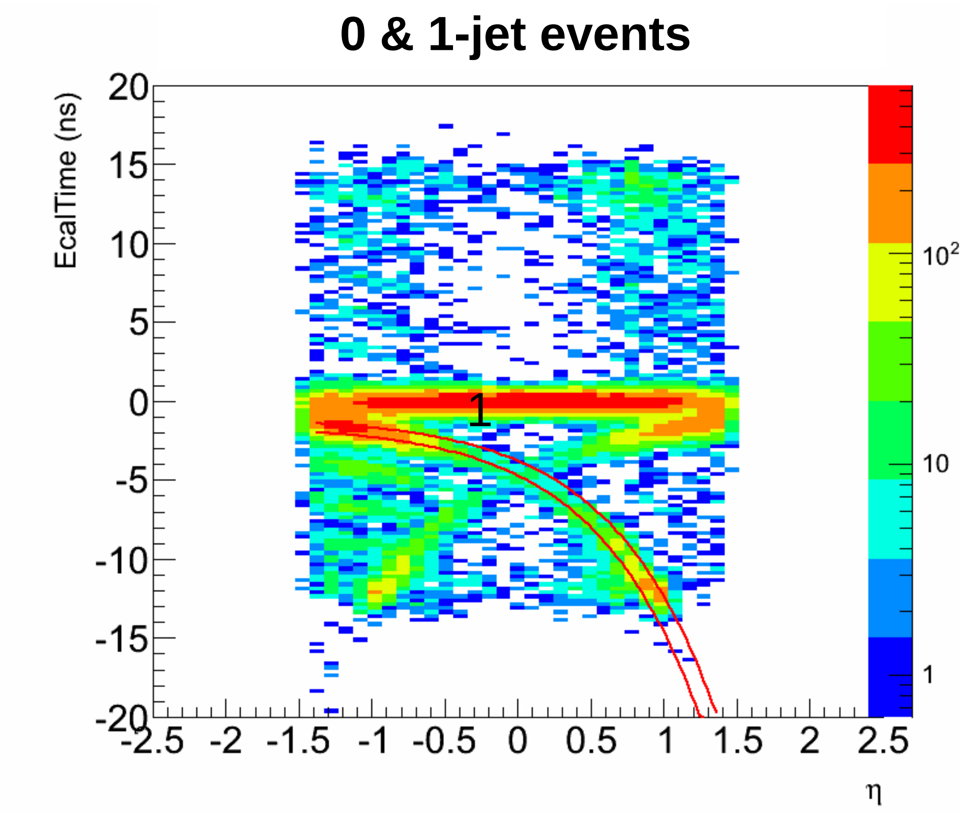
    → No discrimination to event type (e.g. QCD, W, Top ..).

    → Small contribution (cross-checked using an ABCD method)

Beam Halo

- The timing of beam halo is η dependent.
  - → Its timing is earlier than the associated beam crossing event.
  - → Beam halo from satellite bunches give possible late ECAL time.
  - → Veto photon objects if its $\Delta\Phi(\gamma, \mathrm{cscSegment}) < 0.05$.



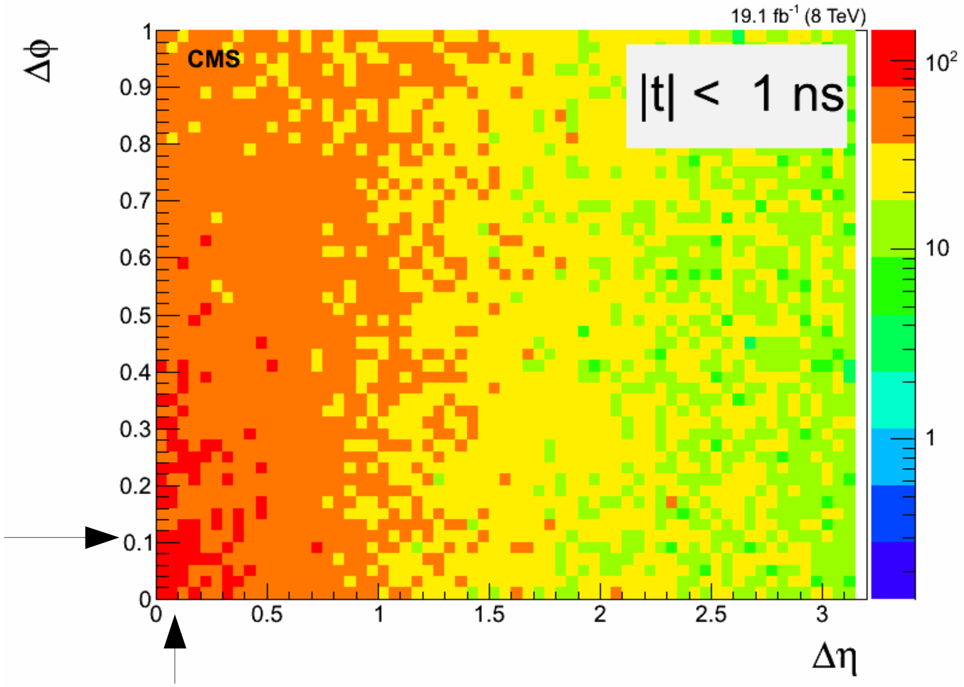


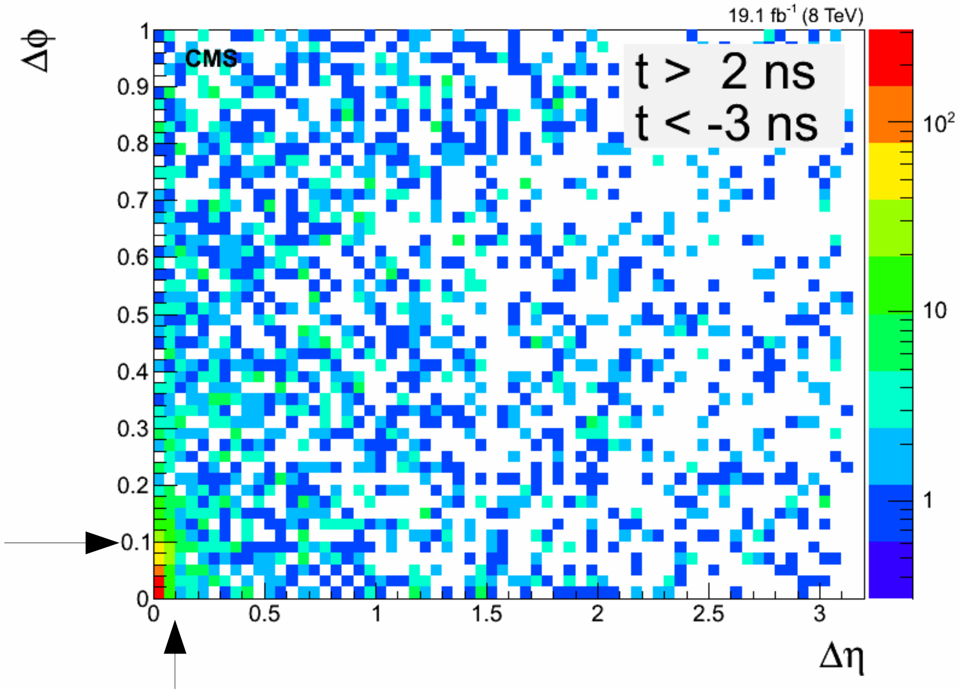
Cosmic-rays

- Cosmic-ray Rejection :

  → Δη(γ, DTCosmicRaySegment) < 0.1 & Φ(γ, DTCosmicRaySegment) < 0.1

  → Using cosmic-rays dataset to verify this method.

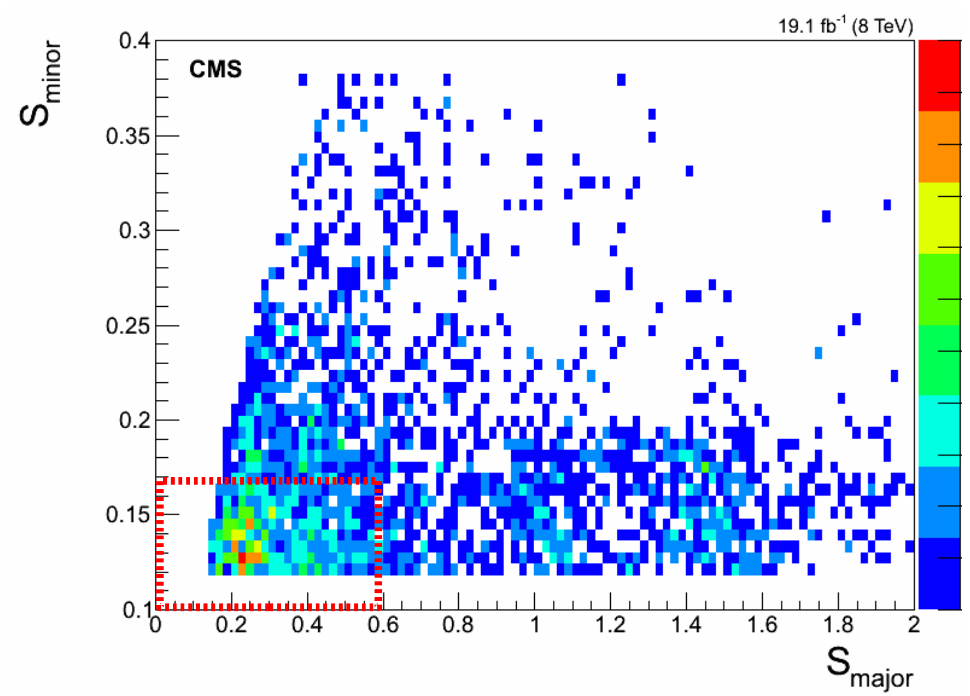


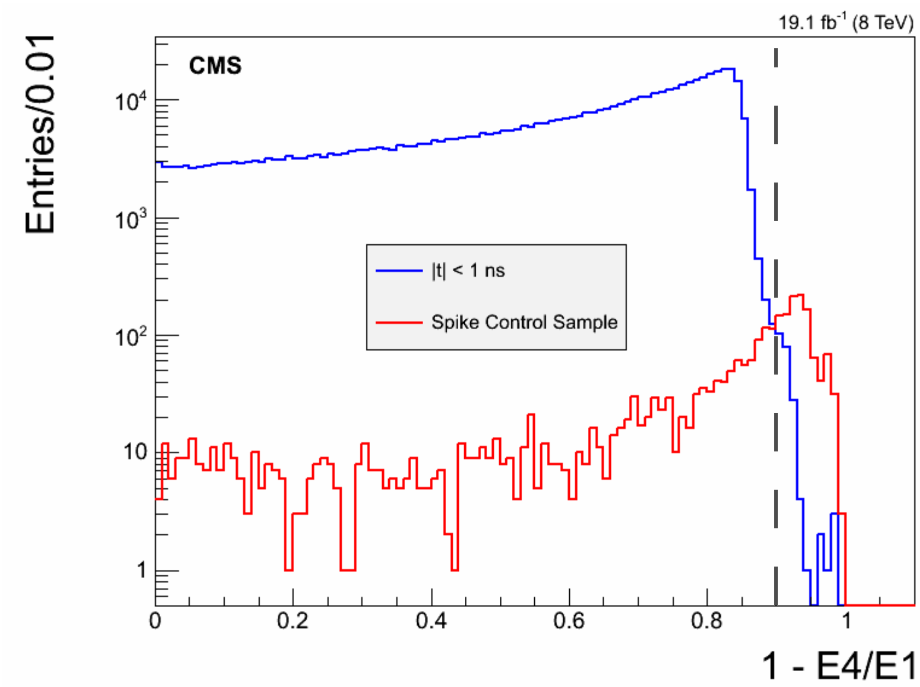


ECAL Spikes

- Direct energy deposit by particle in APD (Avalanche Photo-Diode)
- Most of them are negative timing.
- Remains from halo and cosmic-rays veto.
- Veto criteria : 1 – E4/E1 > 0.9 or sMajor < 0.6 & sMinor < 0.17

	E4	
E4	E1	E4
	E4	





Veto Performance and Fake Rate

- The efficiency for each veto method is difficult to estimate.

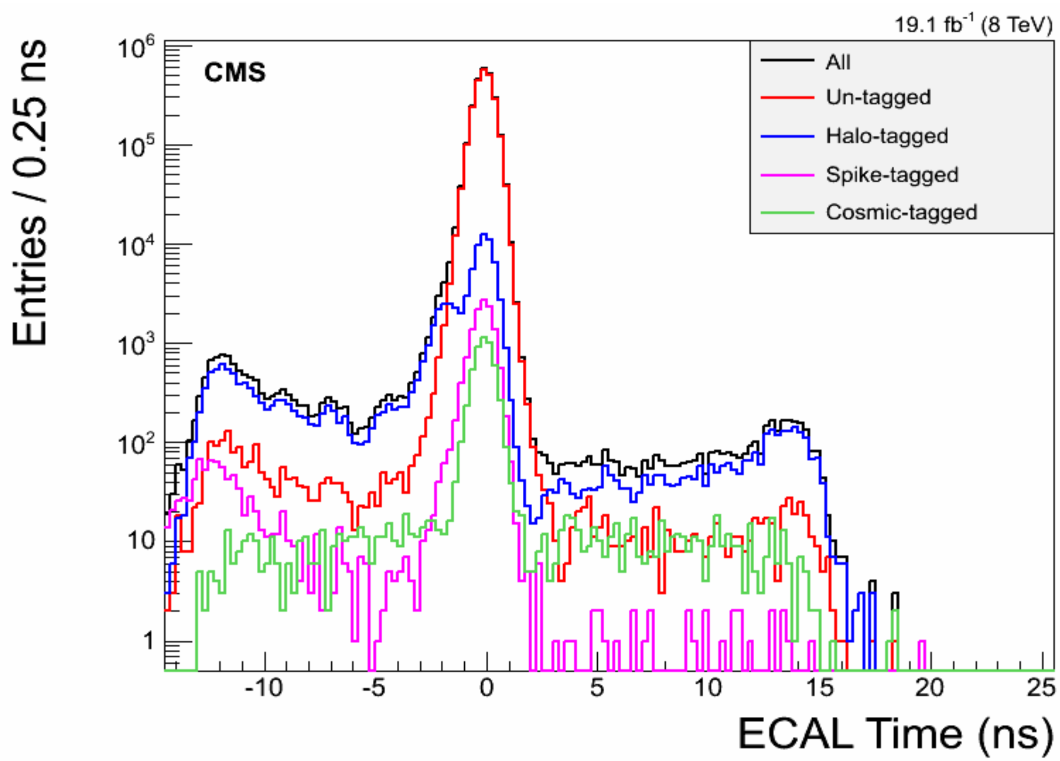
  → It's hard to define a pure control sample for each background source without contamination or bias.

- Fake rates of the veto are measured from in-time photon sample.

- Since the efficiency is not 100%, the residual non-collision background is not trivial.

  → Develop an ABCD method to estimate the leftover photons.

	Fake Rate
Halo	~3%
Cosmic-rays	1.4%
ECAL Spike	0.4%



ABCD – Non Collision Background

MET > 60 GeV	METγ < 60 GeV	METγ > 60 GeV
3 ns < t < 13 ns	C	D
-10 ns < t < -3 ns	A	B

- Estimate the residual from halo/cosmic-rays/spike veto
- MET > 60 GeV :

  → QCD is suppressed, Non-collision backgrounds has small METγ .

  → A and C are nearly QCD free.
- D = B/A x C

$Z \rightarrow e^+e^-$ Method

- Using Z events as a representative for collision background

→ Count Z events in three different time zone, in-time ($|t| < 2$ ns) , early ($t < -3$ns), late ($t > 3$ ns) , within Z mass window (76 ~ 104 GeV)

→ Polynomial fit sideband (50 ~ 76 GeV and 104 ~ 130 GeV) to determine background of Z events.

→ Take ratio of out-of-time and in-time electrons as the probability to get out-of-time measurement and apply it to our analysis selection.

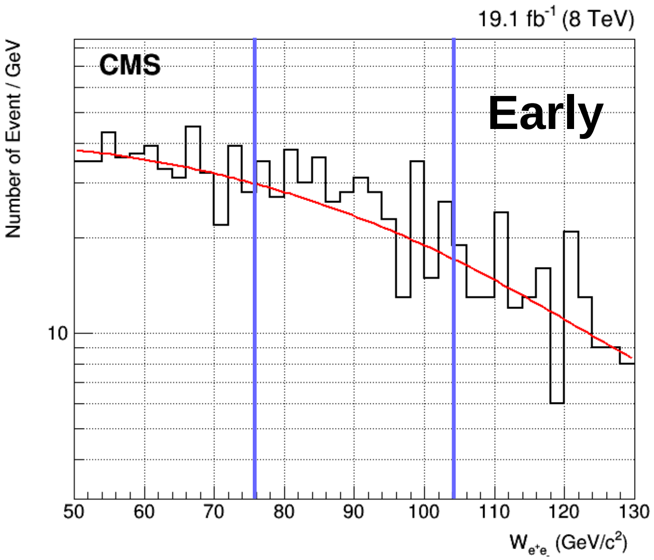
→ Observed 3 events with both electron late ($t > 3$ns).

→ Only one late electron : 1.09×10^{-5}

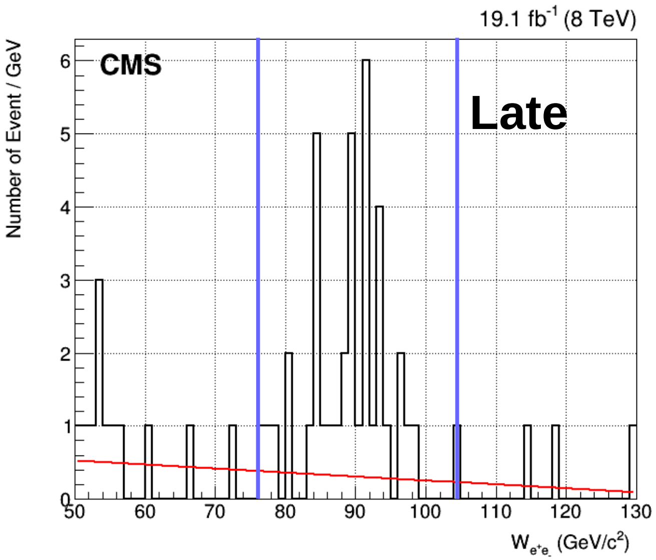
→ Two late electrons : 0.22×10^{-5}

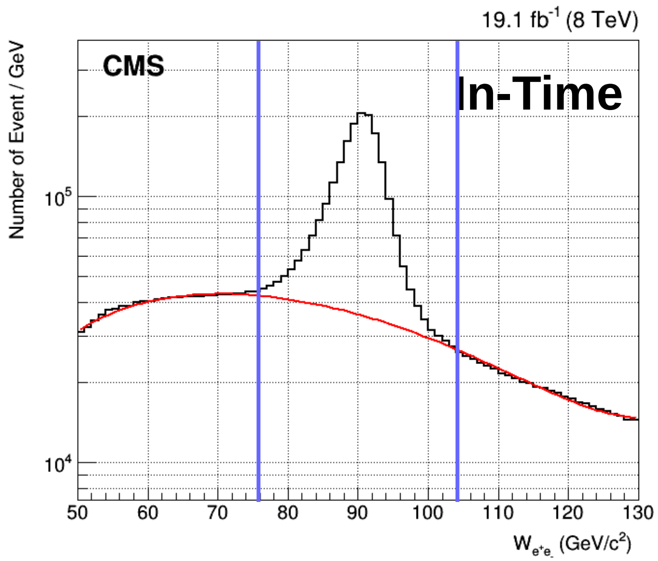
	T < -3 ns	| T | < 2ns	T > 3 ns
Total	378	2349187.0	41.0
DY Background	329	996803.6	8.6
Estimated Z	49	1352383.4	32.4

Z Mass Distribution



OR





$Z \rightarrow e^{+}e^{-}$ Method

- $\mathbf{N} = n_1 \times p_1 + n_2 \times (2\, p_1 (1 - p_1) + p_1^2) + n_1 \times p_2 + n_2 \times p_2$

  n_1 : in-time 1 photon events , n_2 : in-time 2 photon events.

  p_1 : Probability to get a late/early timing measurement.

  p_2 : Probability to get a late/early collision event (satellite bunch collisions).

  → **N = Estimated out-of-time background events.**

- Calculate p_1 and p_2 using values from previous table.

  → The observed 3 events (with two late electrons) are considered as events from satellite bunch collisions and are used for p_2 .

	p_1	p_2
Late	1.09×10^{-5}	0.22×10^{-5}
Early	1.81×10^{-5}	0

Combined Background Estimation and Closure Test

- Combined ABCD from non-collision and Z → ee collision background

  → D = (B – Qb) x C / A + Qd

- Using 0 and 1-jet events for closure test

  → Estimate : (38 -0.64)x359/851 + 0.46 = $\mathbf{16.41^{+3.00}_{-2.59}}$ ↔ Observed :**10**

  → $\mathbf{Q_d : 0.46^{+0.11}_{-0.09}}$, $\mathbf{Q_b : 0.64^{+0.35}_{-0.33}}$

For Approval

Non-Collision	METγ < 60 GeV	METγ > 60 GeV
3 ns < t < 13 ns	(C) 359	(D) 10 (16.41)
|t| < 2ns		35097 (1γ) + 174 (2γ)
-10 ns < t < -3 ns	(A) 851	(B) 38

Result

- Background estimation for signal sample :

→ Predict background : $((1 – 0.51) \times 0/3) + 0.37 = 0.37^{+0.39}_{-0.07}$

→ Observed 1

→ $\mathbf{Q_d : 0.37^{+0.09}_{-0.07}}$, $\mathbf{Q_b : 0.51^{+0.28}_{-0.27}}$

For Approval

Non-Collision	METγ < 60 GeV	METγ > 60 GeV
3 ns < t < 13 ns	(C) 0	(D) 1
|t| < 2ns		35097 (1γ) + 174 (2γ)
-10 ns < t < -3 ns	(A) 3	(B) 1

Uncertainties

- The main impact of the systematic is to signal efficiency.

  → Two factors, time bias (T0) and unclustered energy (MET), are the main sources of systematic uncertainty.

  → Reflect the method, ECAL time cut and MET cut.

  → Vary each systematic (1-sigma upward and downward) individually to get the percentage of the yield change.

For Approval

- Smaller Λ corresponds to larger systematic.
  → Efficiency is lower. Statistic uncertainty is dominated

- Uncertainty from background estimation is quoted from its statistical uncertainty
  → $0.37^{+0.39}_{-0.07}$.

Source	Uncertainty (%)
Time Bias (T0)	6 ~ 10
Unclustered Energy (MET)	4 ~ 10
ECAL Time Resolution	2 ~ 5
Jet Energy Scale	3 ~ 9
Jet Energy Resolution	2 ~ 9
Photon Energy Scale	2 ~ 4
Luminosity	2.6
PDF	< 1

One Observed Event

- Run Number: 206484 LumiSection : 620 Event Number: 871295869
- Photon :

  → Pt : 225 GeV, Ecaltime : 12 ns , η: 0.32, Φ: 1.13 , sMajor: 2.82, sMin: 0.16
- MET :

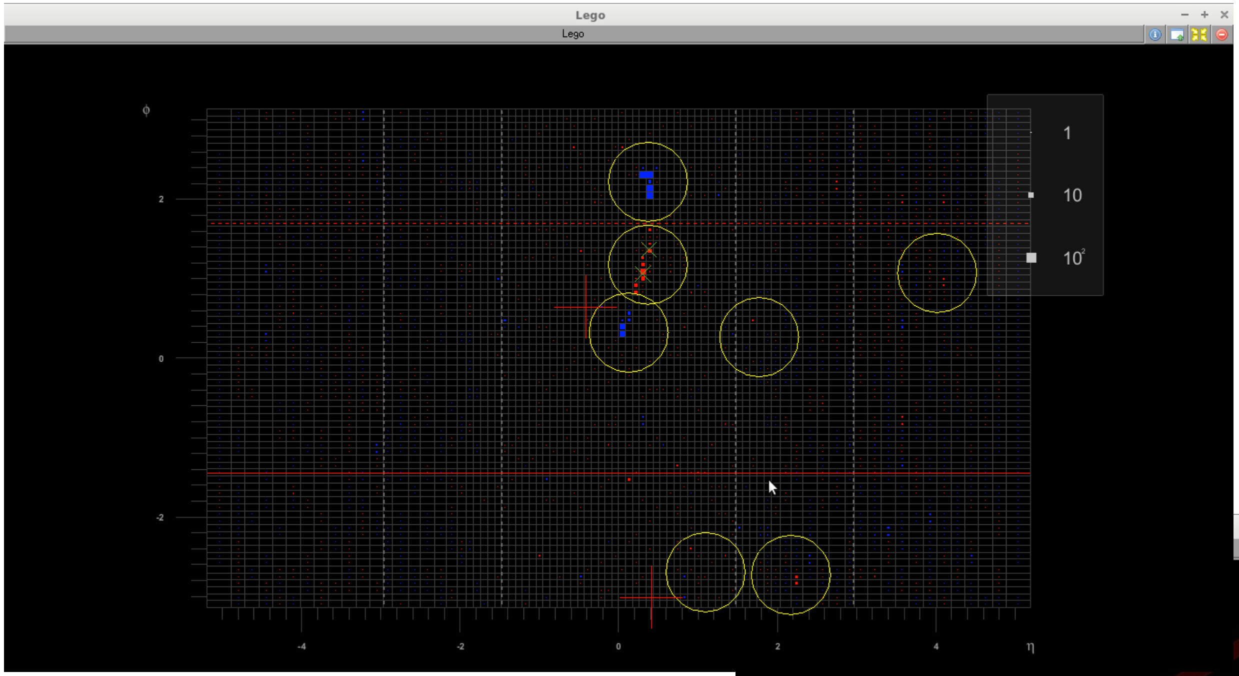
  → METγ : 125 GeV

  → MET   : 333 GeV

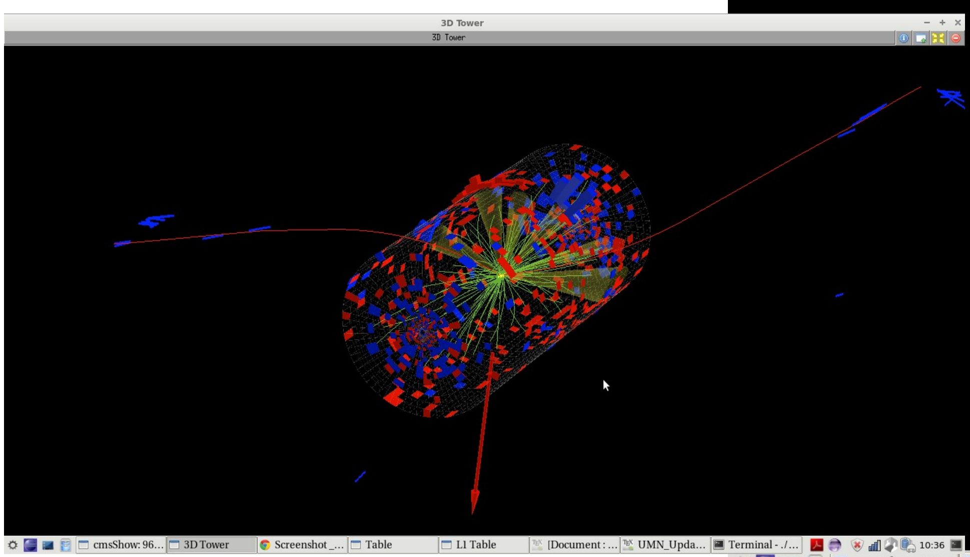
  → Larger MET and smaller METγ indicate Halo/Cosmic-rays like behavior.
- Jet :

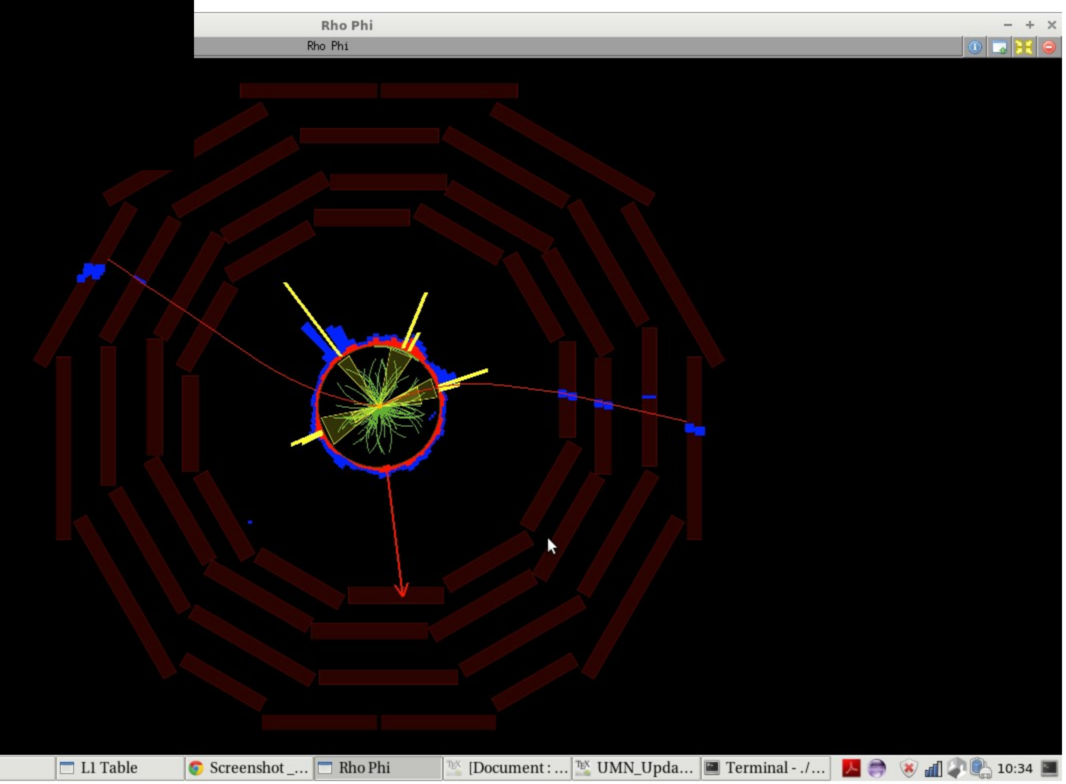
  → 2 jets (86 and 36 GeV)

Event Display



- Run Number: 206484
- LumiSection : 620
- Event Number: 871295869

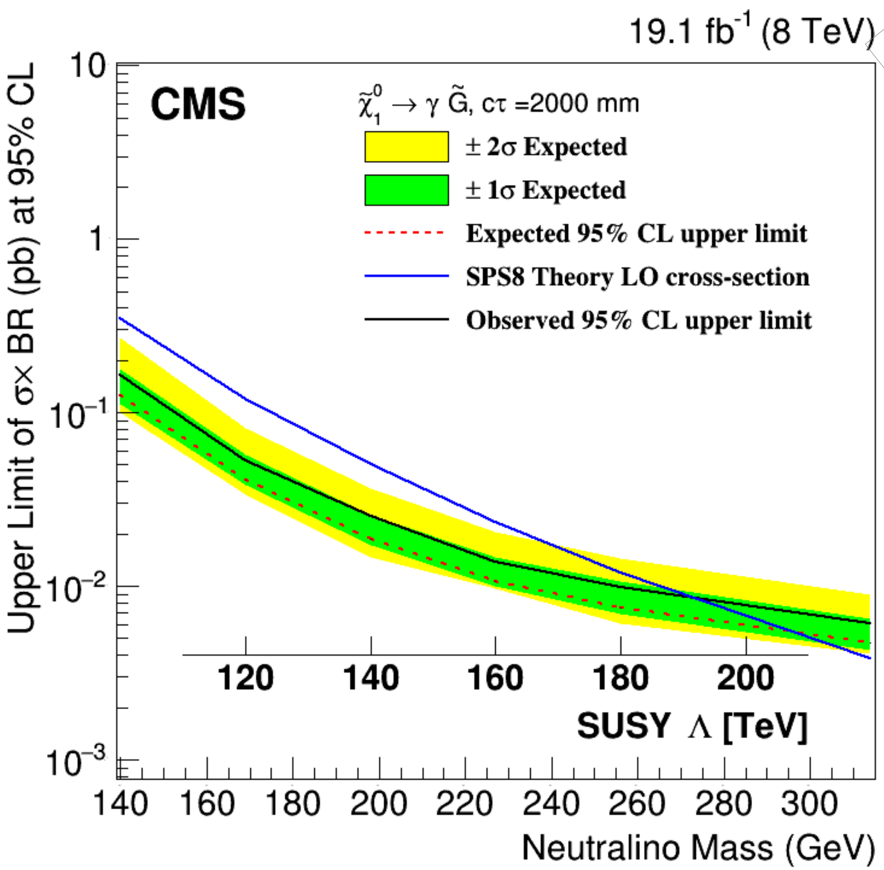


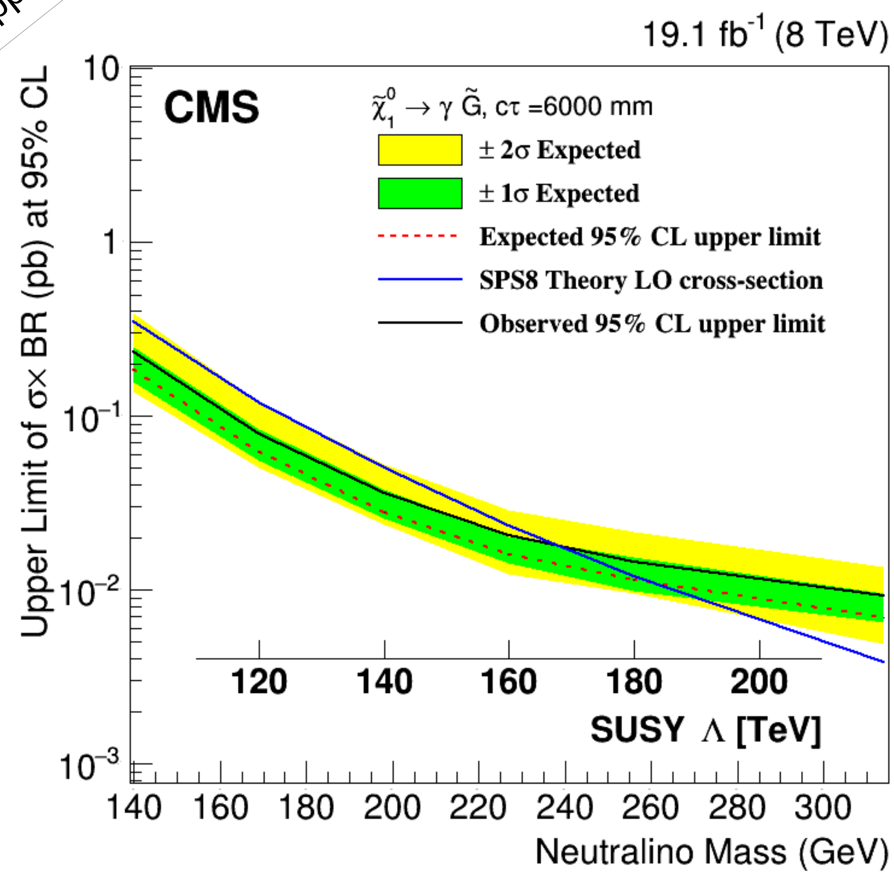


Limit – Neutralino Mass

- Set limits using CLs method.
- Under current background expectation (0.37) and observation (1), the upper limit of 4.07 events is set at 95% C.L.

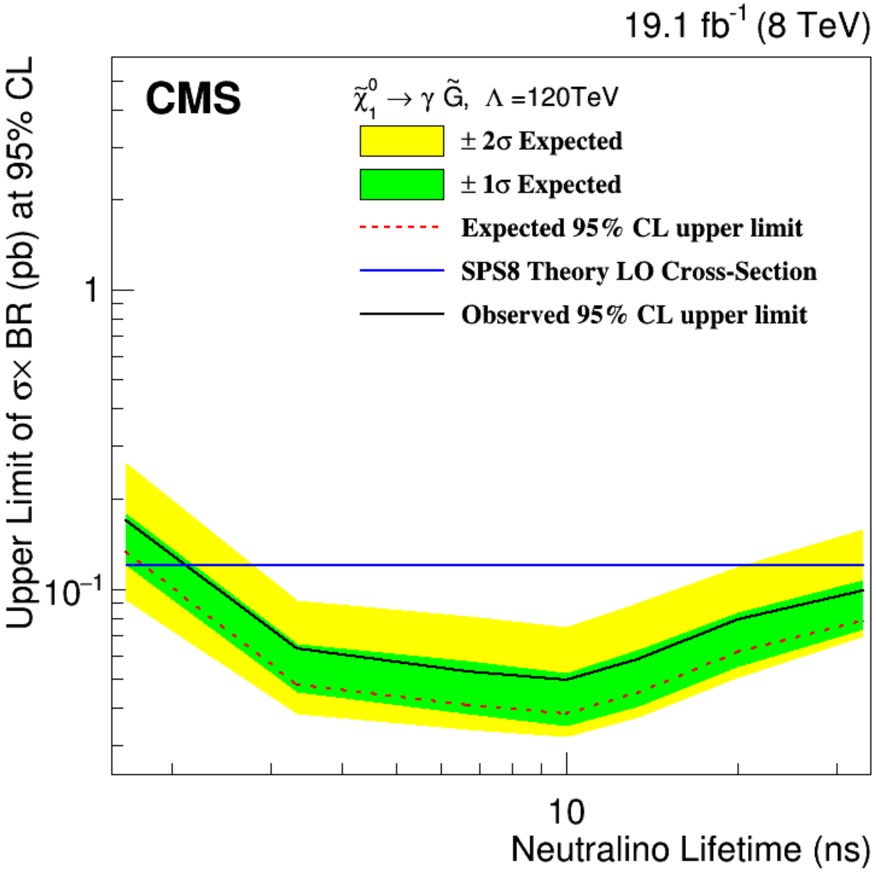
For Approval

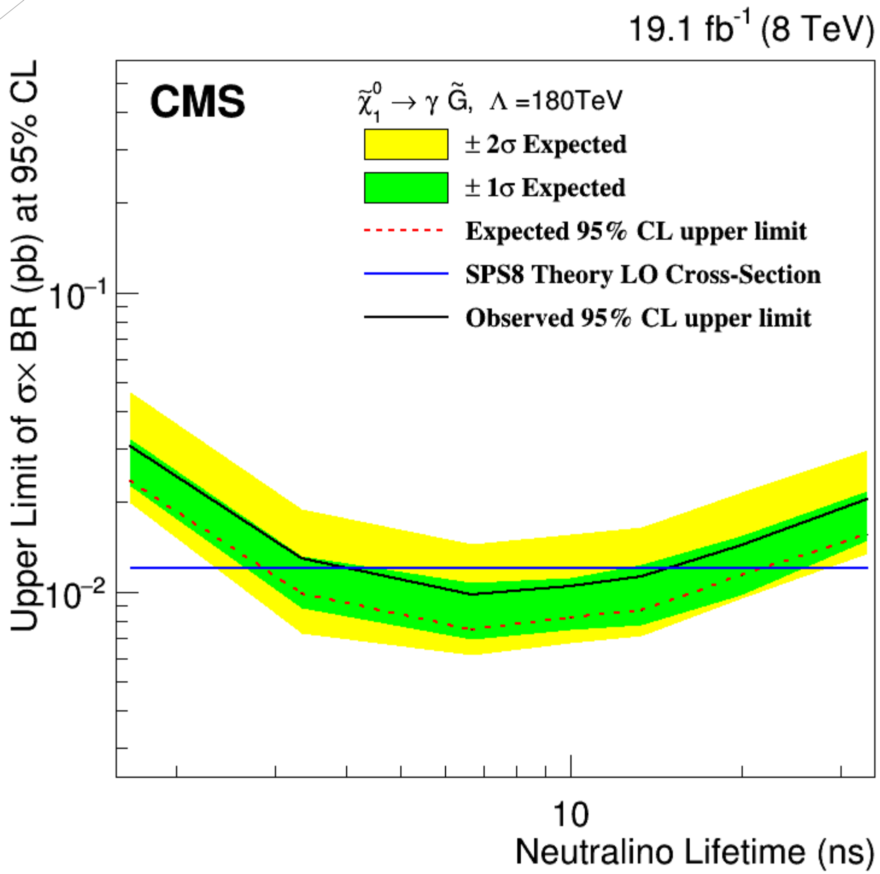




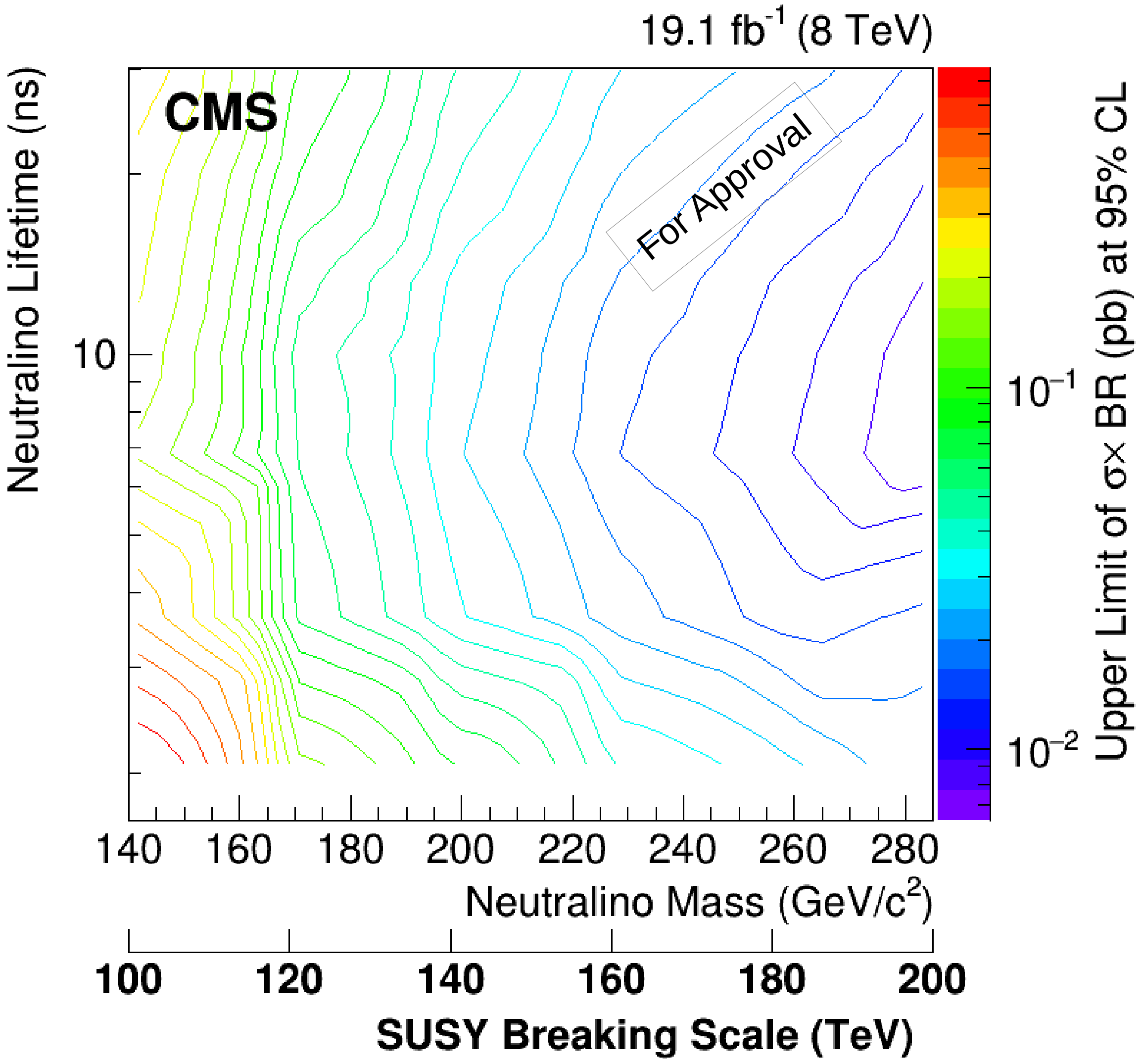
Limit - Lifetime

For Approval





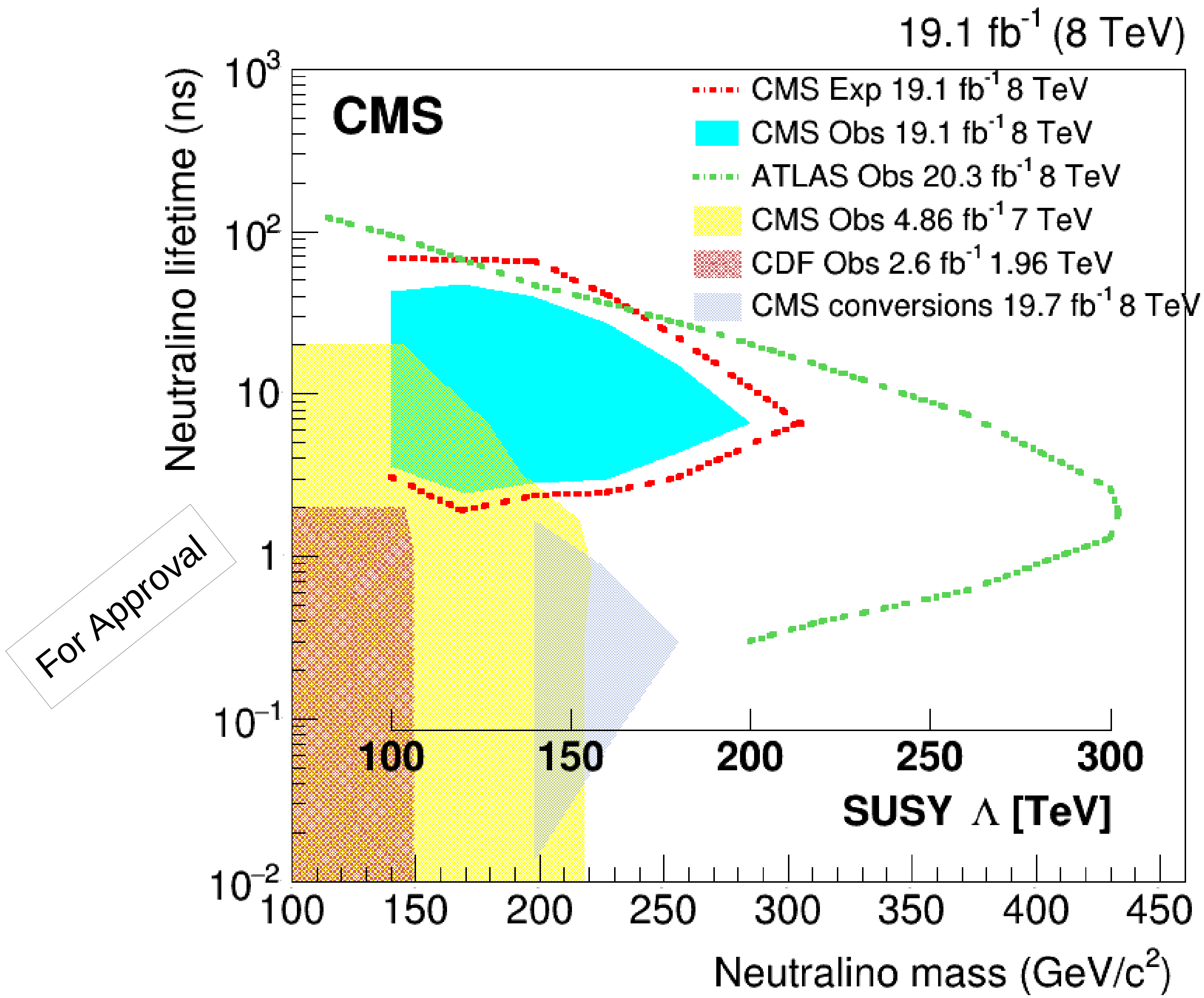
- An upper-limit of cross-section times branching ratio is provided in terms of neutralino's lifetime and mass.



Conclusion

- An exclusion region of neutralino mass and lifetime at 95% C.L. is set.

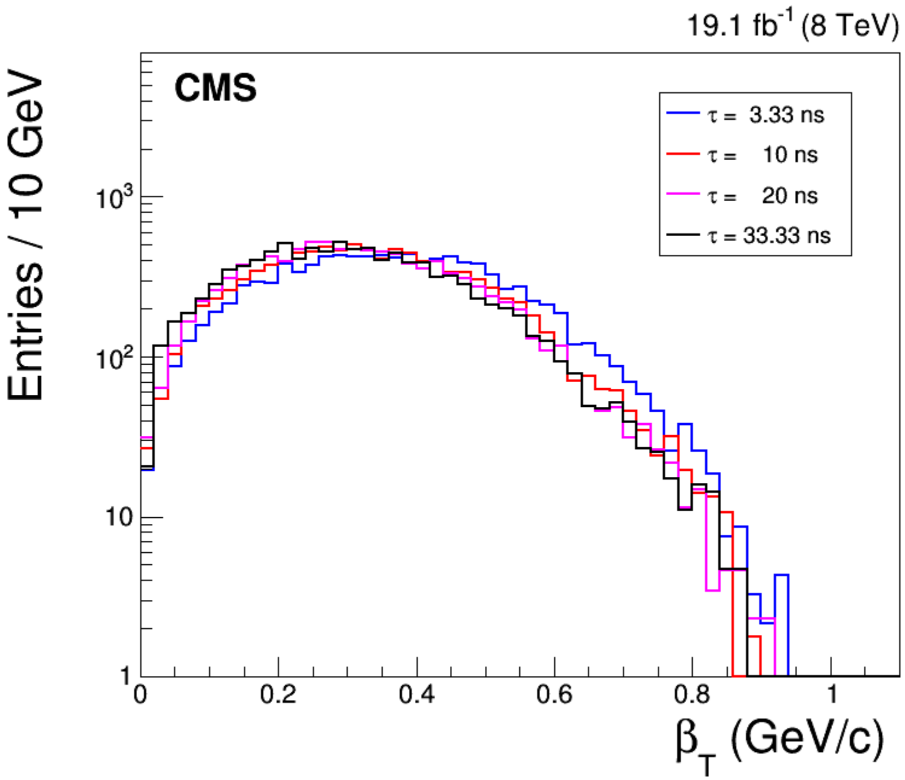
  → Lifetime : 3ns ~ 30 ns , mass: 140 ~ 260 GeV



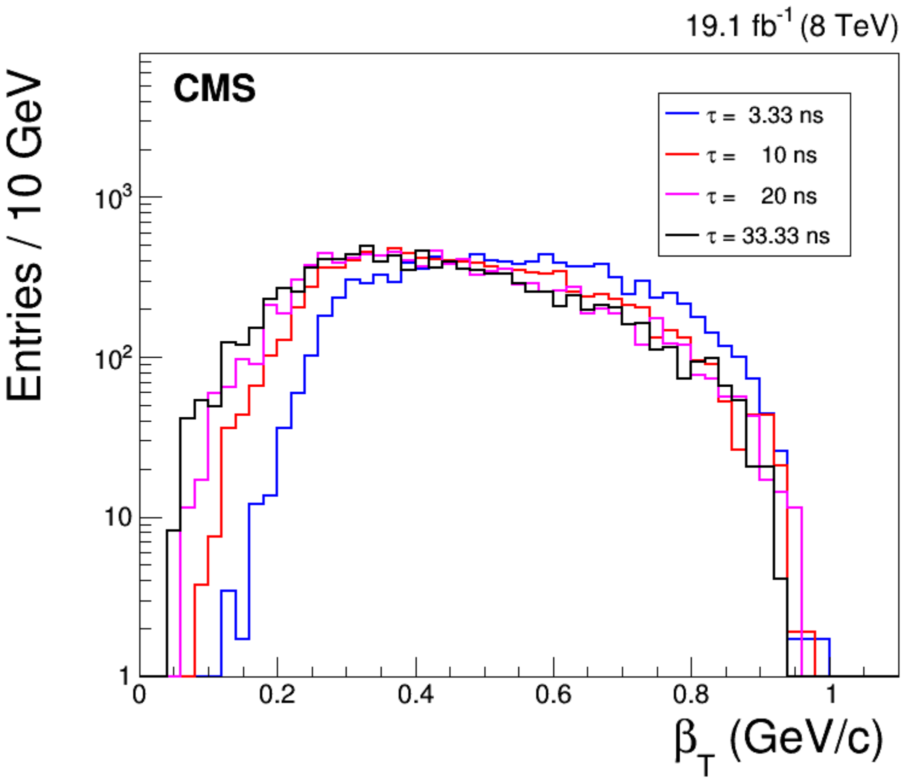
Back Up

Beta of Neutralino

- Delayed photons (T > 3ns) are mostly from slow neutralino.
- Shorter lifetime model need harder boost in order to reach the same transverse decay length (900 ~ 1200 mm),



β_T distribution of neutralino which produces a late photon.

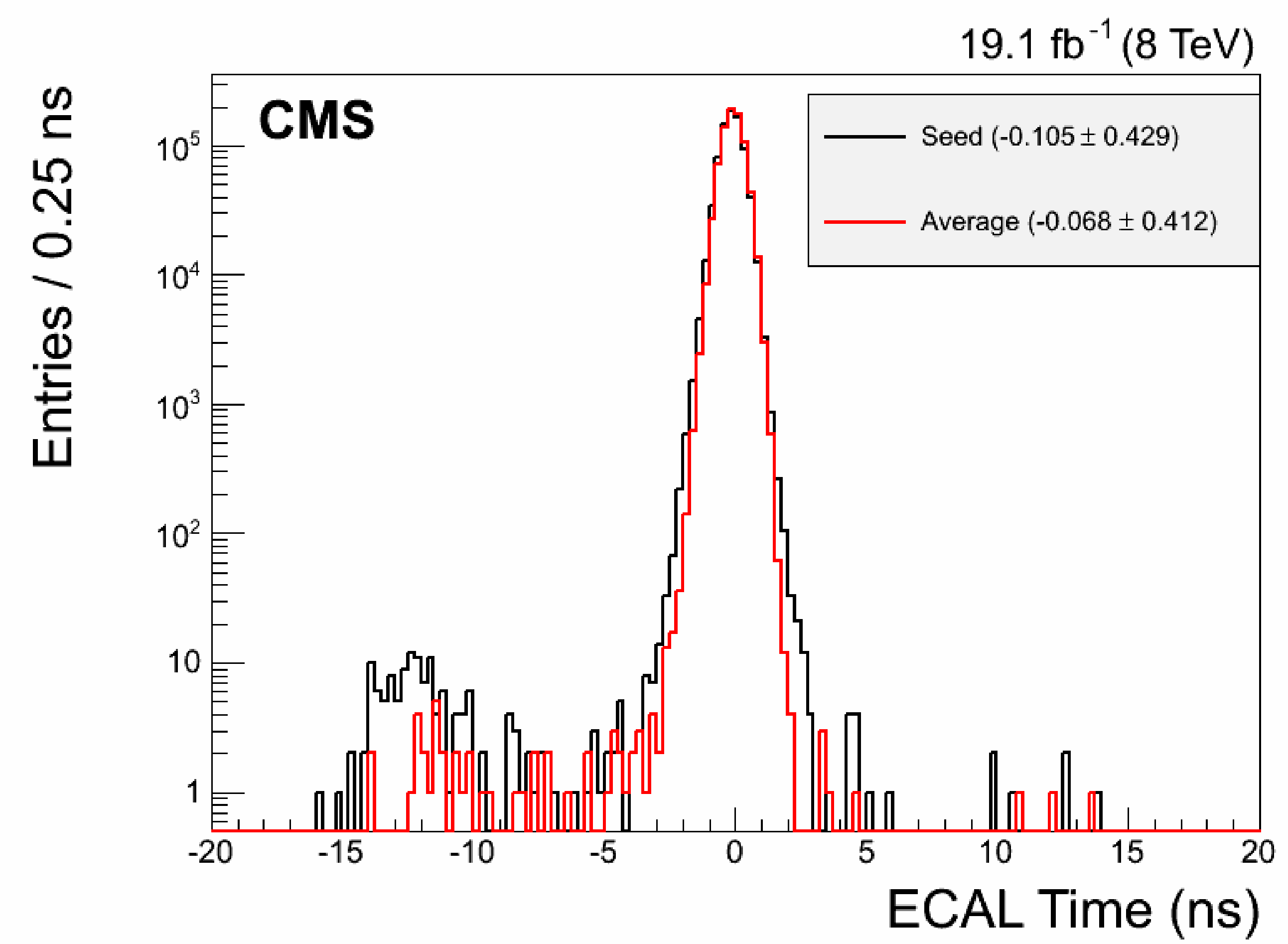


β_T distribution for neutralino with transverse decay length between 900 and 1200 mm.

Cluster Time and Seed Time

- Cluster time is weighted average over times from all crystals in seed cluster.
  → Both timing have similar performance.

$$t_{cluster} = \frac{\sum \frac{t_i}{\sigma_i^2}}{\sum \frac{1}{\sigma_i^2}}$$



Dataset

- Displaced Photon Skim

  /SinglePhoton/Run2012B-EXODisplacedPhoton-22Jan2013-v1/RECO

  /SinglePhoton/Run2012C-EXODisplacedPhoton-19Dec2012-v1/RECO

  /SinglePhoton/Run2012D-EXODisplacedPhoton-19Dec2012-v1/RECO

- IsoPhoton50

  /SinglePhoton/Run2012B-22Jan2013-v1/RECO

  /SinglePhoton/Run2012C-22Jan2013-v1/RECO

- GJets MC (Pt_hat : 50 ~ 800 GeV)

  /G_Pt-50to80_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/GEN-SIM-RECO

  /G_Pt-80to120_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/GEN-SIM-RECO

  /G_Pt-120to170_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/GEN-SIM-RECO

  /G_Pt-170to300_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/GEN-SIM-RECO

  /G_Pt-300to470_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/GEN-SIM-RECO

  /G_Pt-470to800_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/GEN-SIM-RECO

GMSB MC Samples

- /GMSB_Lambda-xxx_CTau-yyyy_TuneZ2star_8TeV-pythia6/Summer12DR53X-PU_S10_START53_V19-v2/GEN-SIM-RECO

  → xxx is the value of Λ and yyyy is the value of cτ (in mm).

- Range of SUSY breaking scale (Λ)

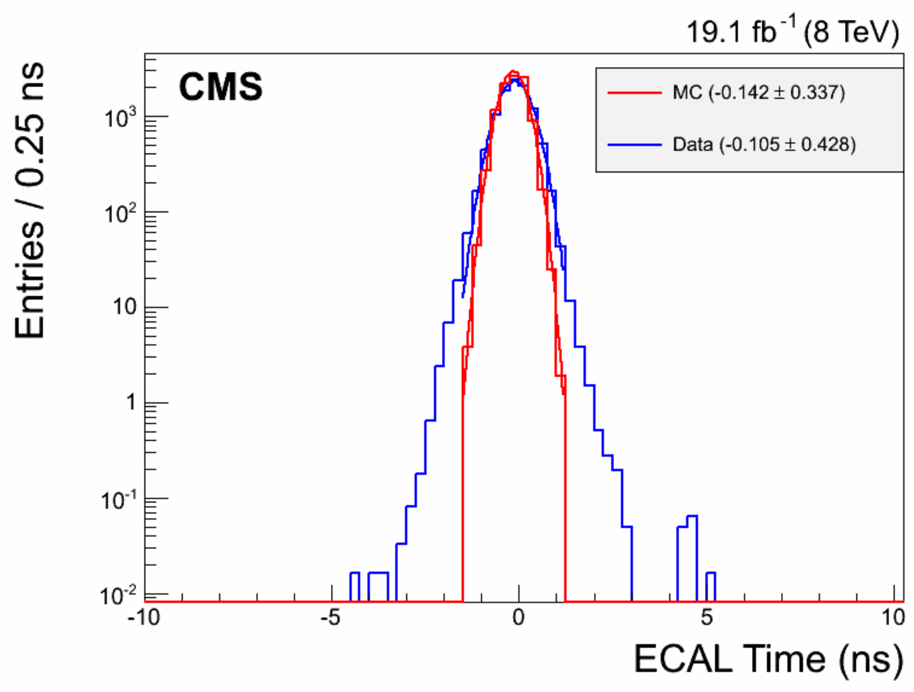
  → 100,120, 140, 160, 180, 220 TeV

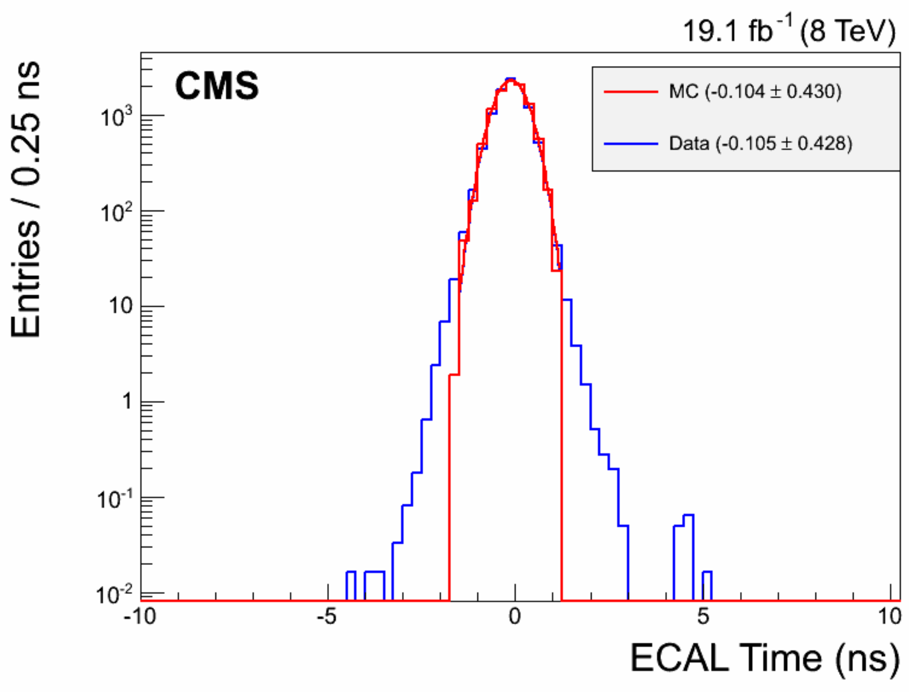
- Range of neutralino lifetime (cτ)

  → 500, 1000, 2000, 3000, 4000, 6000, 10000 mm

MC ECAL Time Calibration

- Events Pass signal selection.
  - → One PF-Isolated photon with Pt > 80 GeV , At least 1 or 2 jet in the evens, MET < 30 GeV.
  - → Comparing data and Gamma+Jets MC.
- Apply T0 shift and smear time resolution on each photon time to signal MC samples.





Halo Timing Approximation

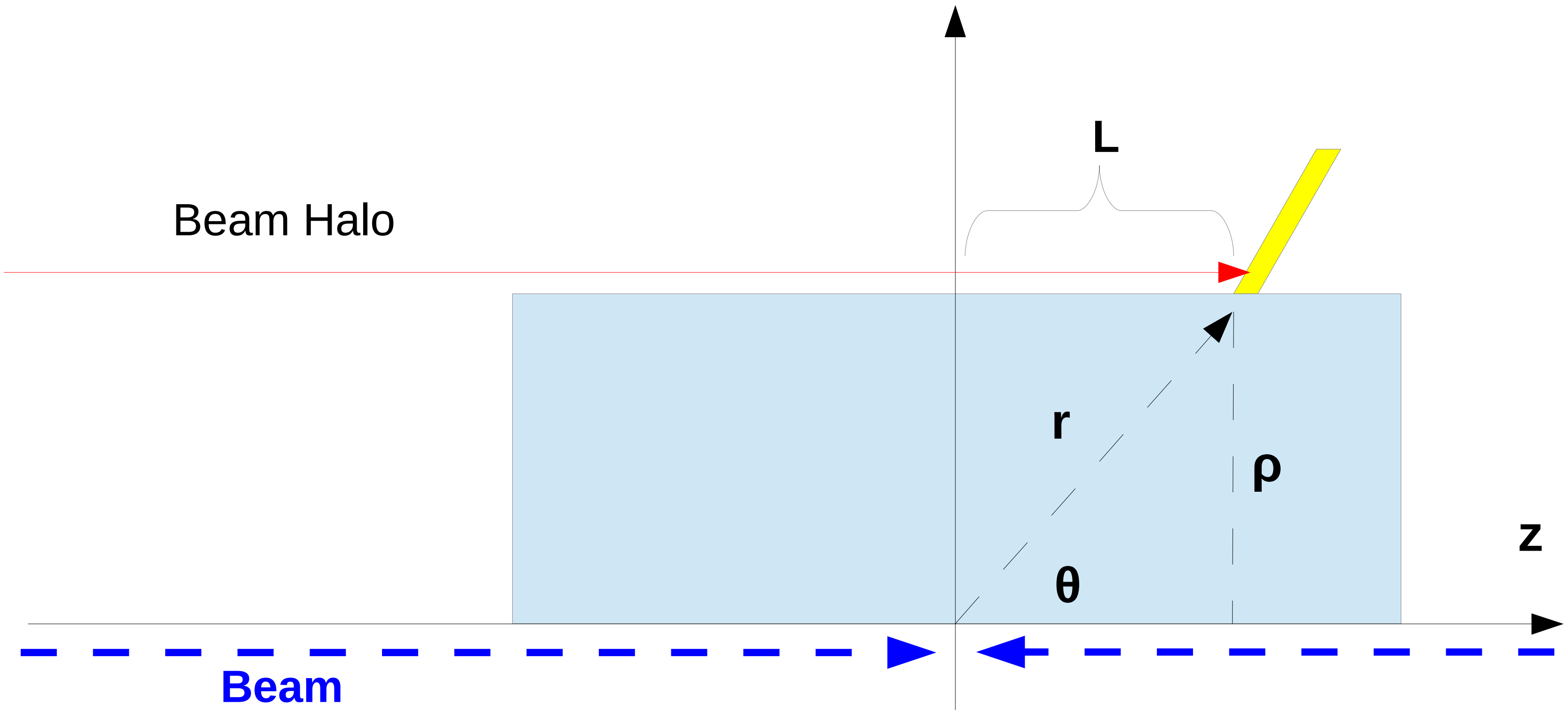
- Approximation of halo behavior :

  → $t\_0 = r/c = \rho / c \sin\theta$

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

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

  → Halo timing would be earlier than the normal collision.

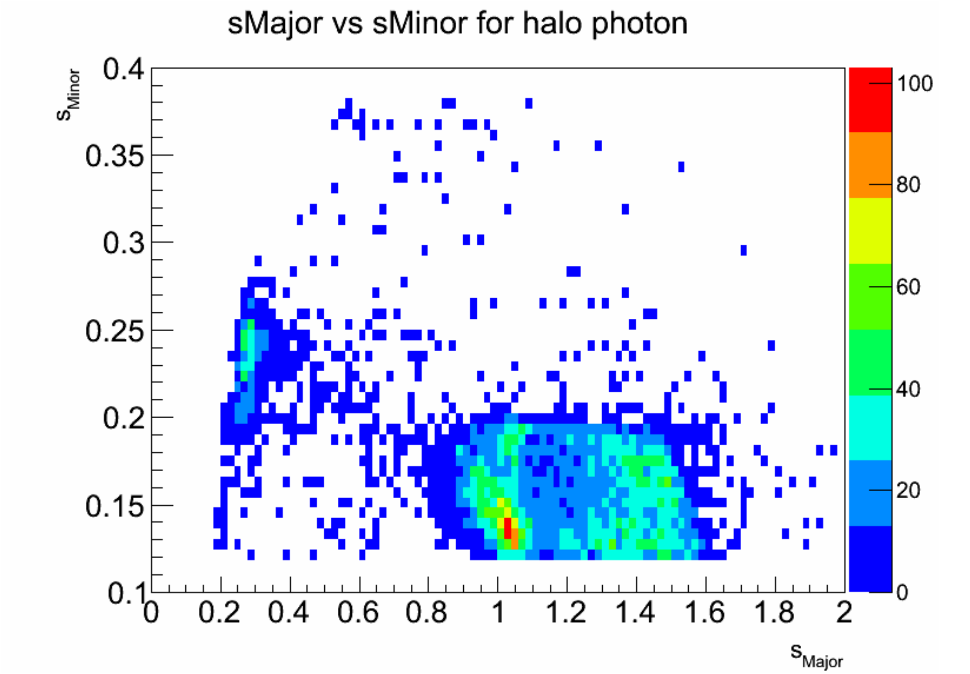


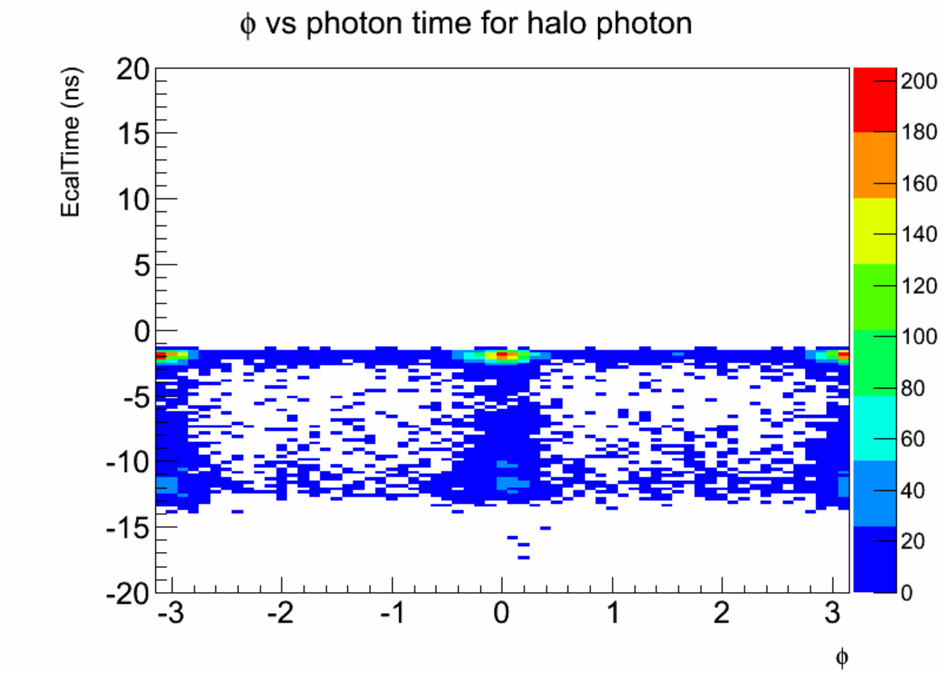
More Halo Signatures

- Halo sample can be extracted using the approximate formula. Other signature can be summarized

  → Mostly around 0 and π.

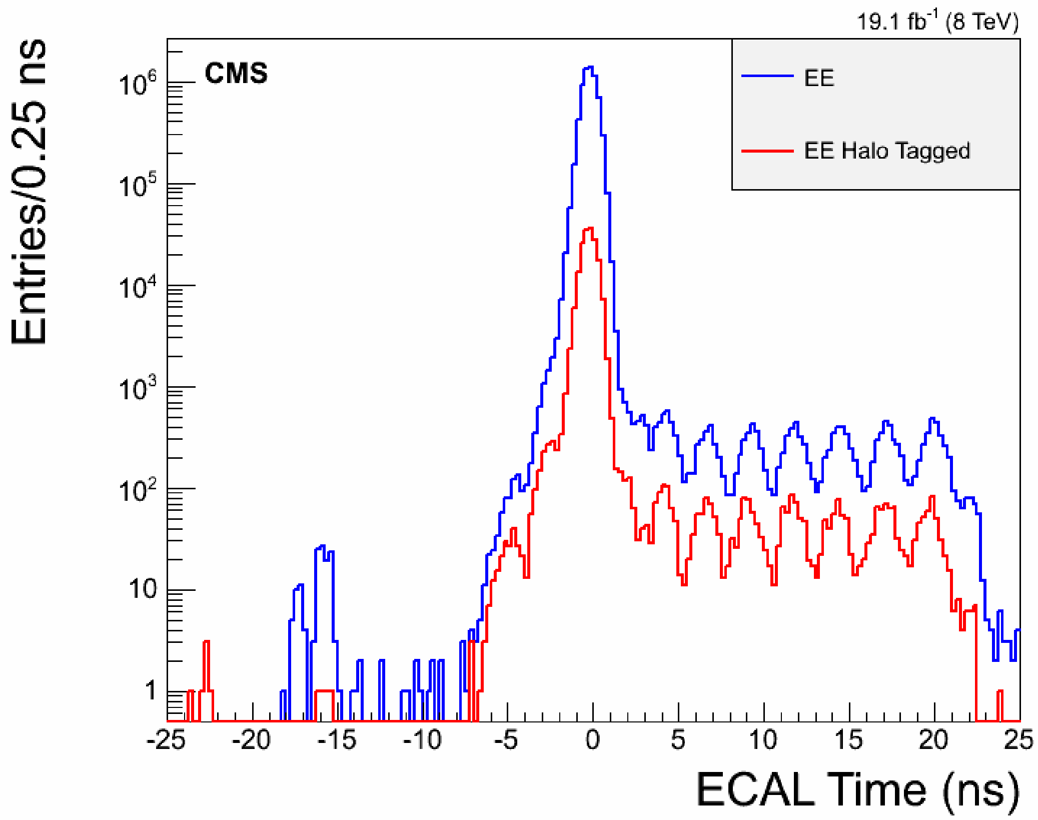
  → Large sMajor and small sMinor





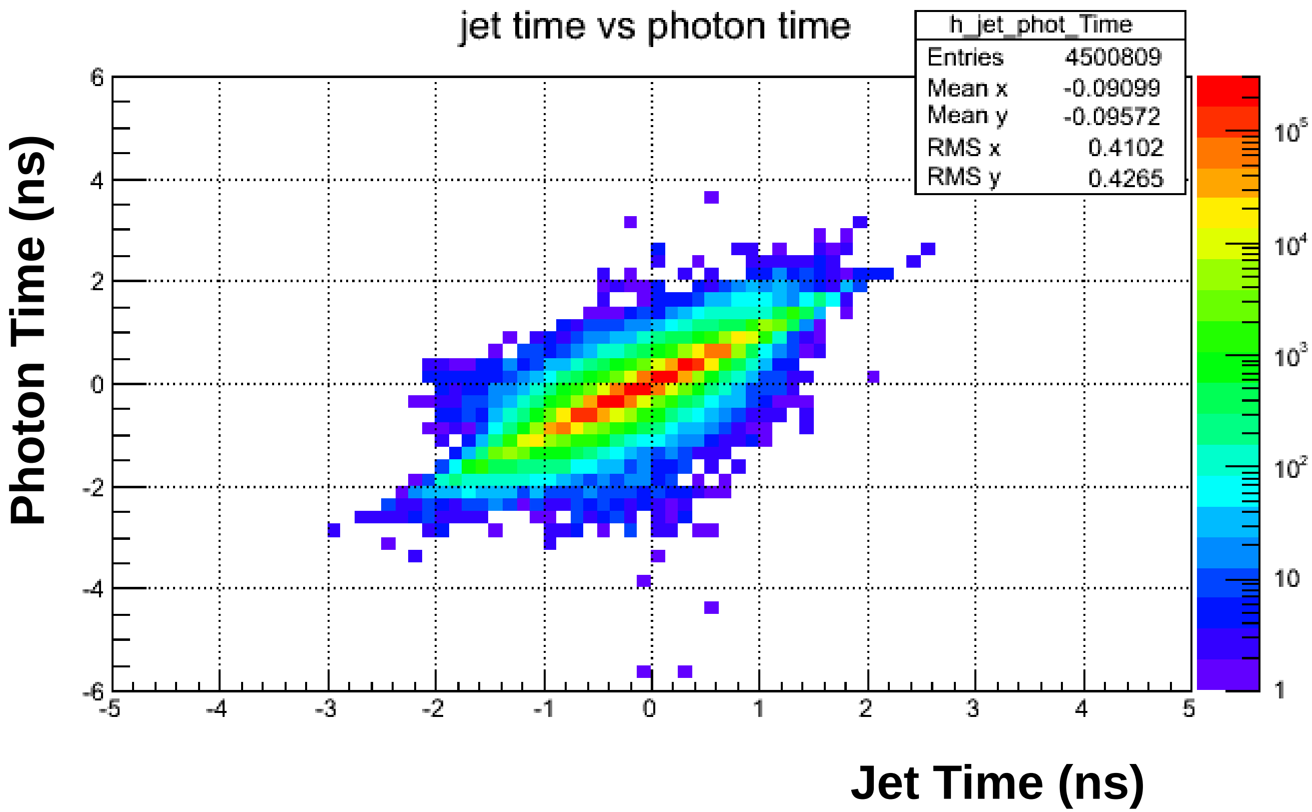
Satellite Bunches

- Satellite bunches can be found from EE time distribution.
- Halo from satellite bunches gives late photon signal.



Jet and Photon Time

- Events with at least 1 photon and at least 1 jet
- Use cluster time for jets and seed time for photon
- If a jet is mis-identified as a photon, its ECAL timing is still within normal time window (|t| < 3 ns)

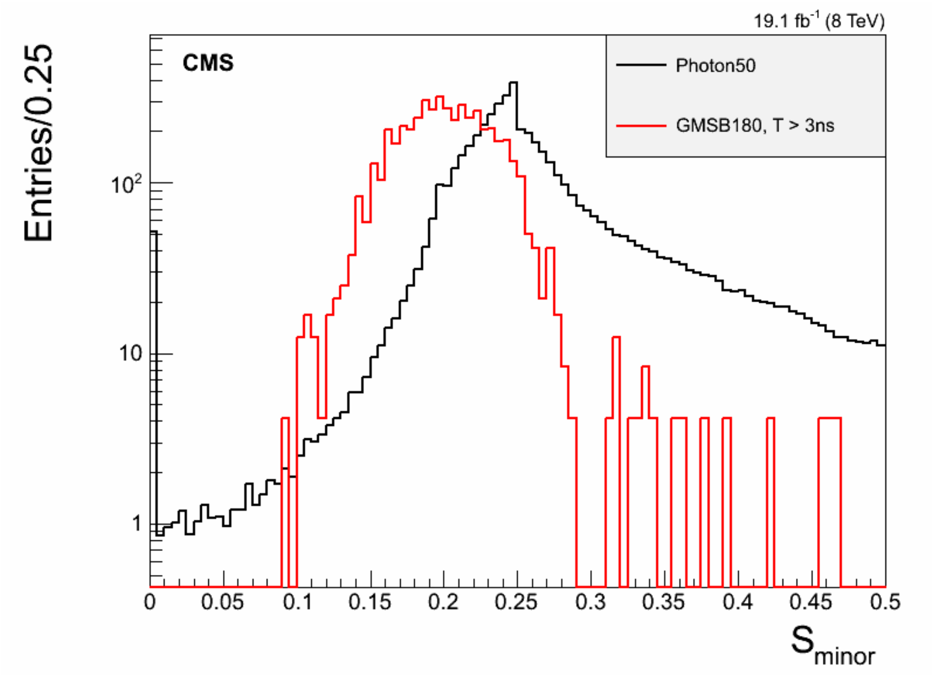


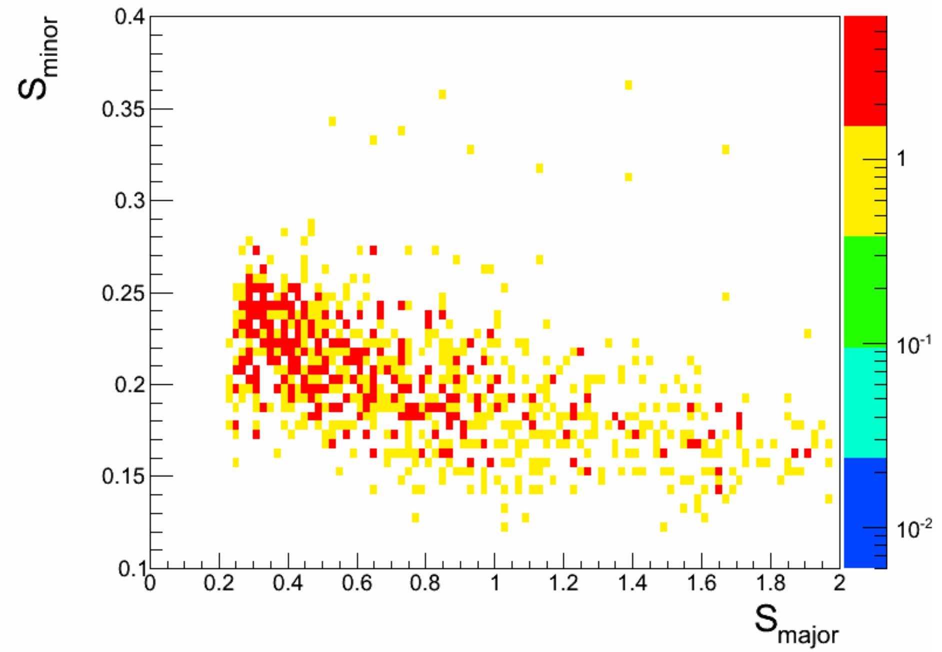
Sminor Constraint

- The variable, sMinor, can be used to enhance signal from late photons.

→ For late photon signal (for those off-pointing), the energy deposit produce elliptical cluster shape. Normal photons usually are round shape(with similar sMajor and sMinor value ~ 0.25)

→ ECAL Spikes usually have small or zero sMinor.

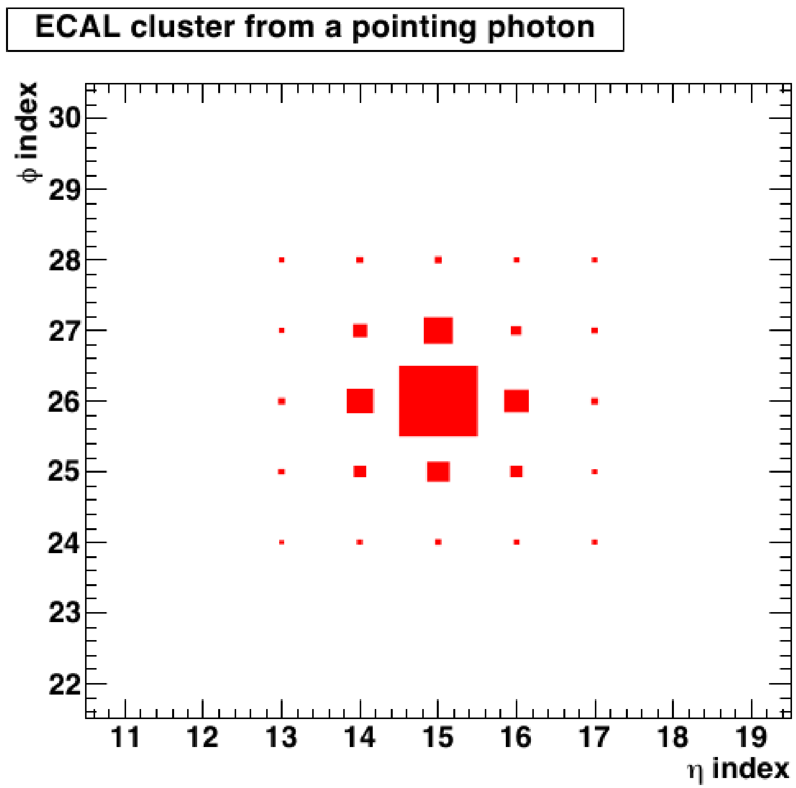


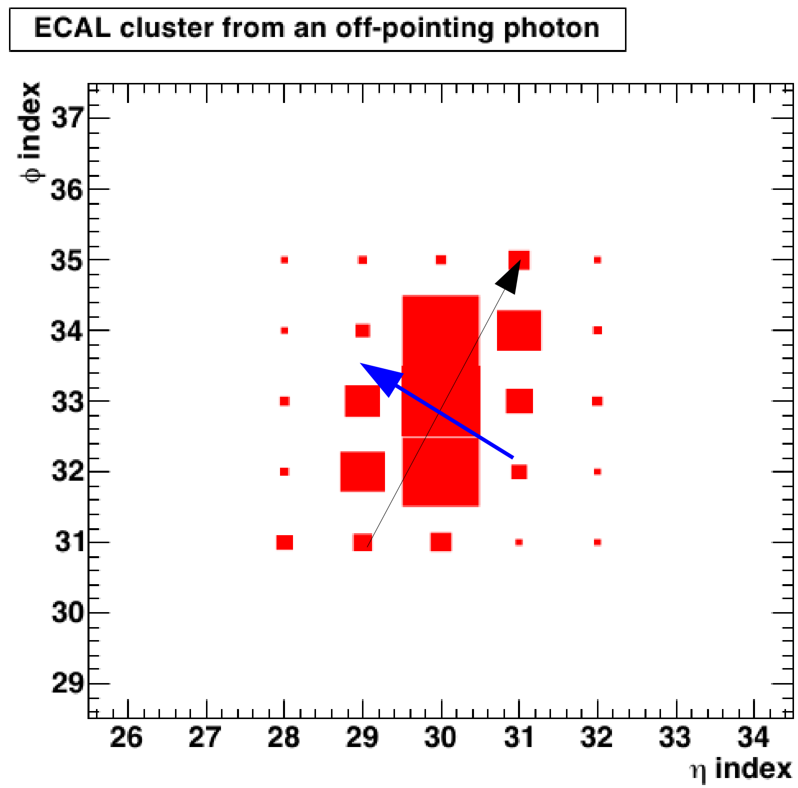


Smajor and Sminor

- Smajor and Sminor are the major and minor axes of the ellipse of ECAL cluster. They can be obtained by diagonalized the covariance matrix of

$$cov_{\eta\varphi} = \begin{bmatrix} \sigma_{\eta\eta} & \sigma_{\eta\varphi} \\ \sigma_{\varphi\eta} & \sigma_{\varphi\varphi} \end{bmatrix} \rightarrow \begin{bmatrix} S_{major} & 0 \\ 0 & S_{minor} \end{bmatrix}$$





Cosmic-Rays

- Use cosmic-rays dataset to verify cosmic-rays veto method.
- Dataset :

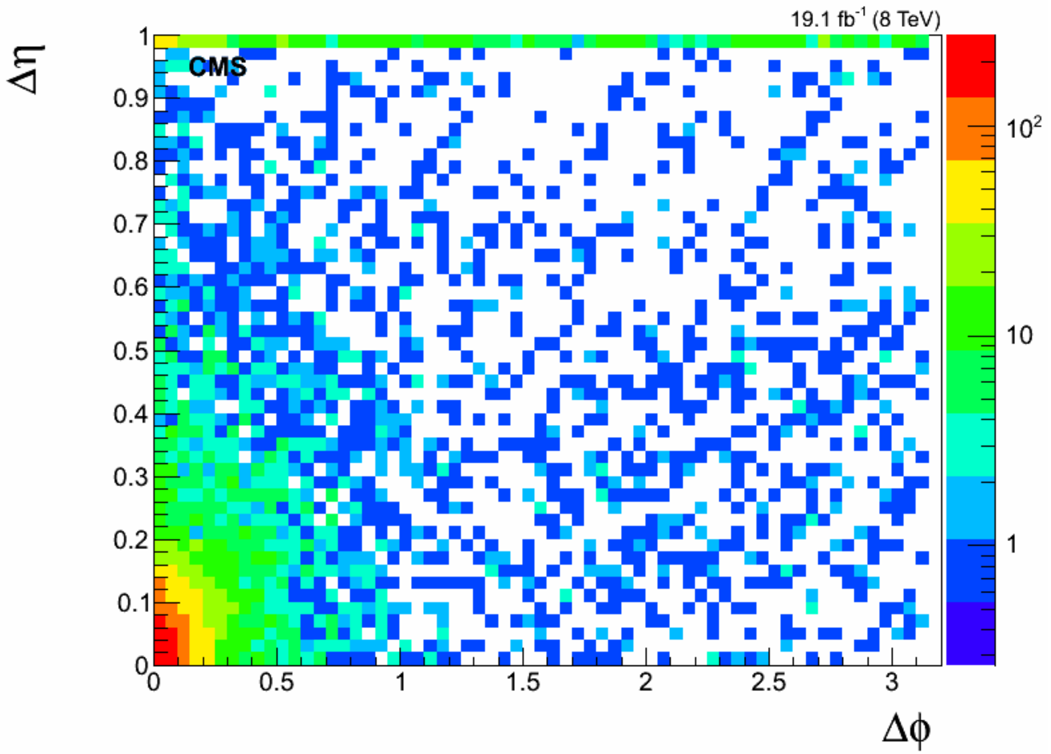
  /Cosmics/Run2012C-22Jan2013-v1/RECO

  /Cosmics/Run2012D-22Jan2013-v1/RECO

- No Photon object available in cosmic dataset.

  → Use supercluster (> 10 GeV) instead

  → Efficiecy : 75%



ABCD – Collision Background

METγ > 60 GeV	MET < 60 GeV	MET > 60 GeV
3 ns < t < 13 ns	D'	D
-2 ns < t < 2 ns	F'	F
-10 ns < t < -3 ns	B'	B

- METγ > 60 GeV :

  → Halo/Cosmic-rays/Spikes are suppressed.
- F' and F are dominated by collision events.
- Collision events in D and B region can be estimated by

  → Collision in D : Q_d = D' x F/F' , Collision in B : Q_b = B' x F/F'