Searches for long-lived particles at CMS

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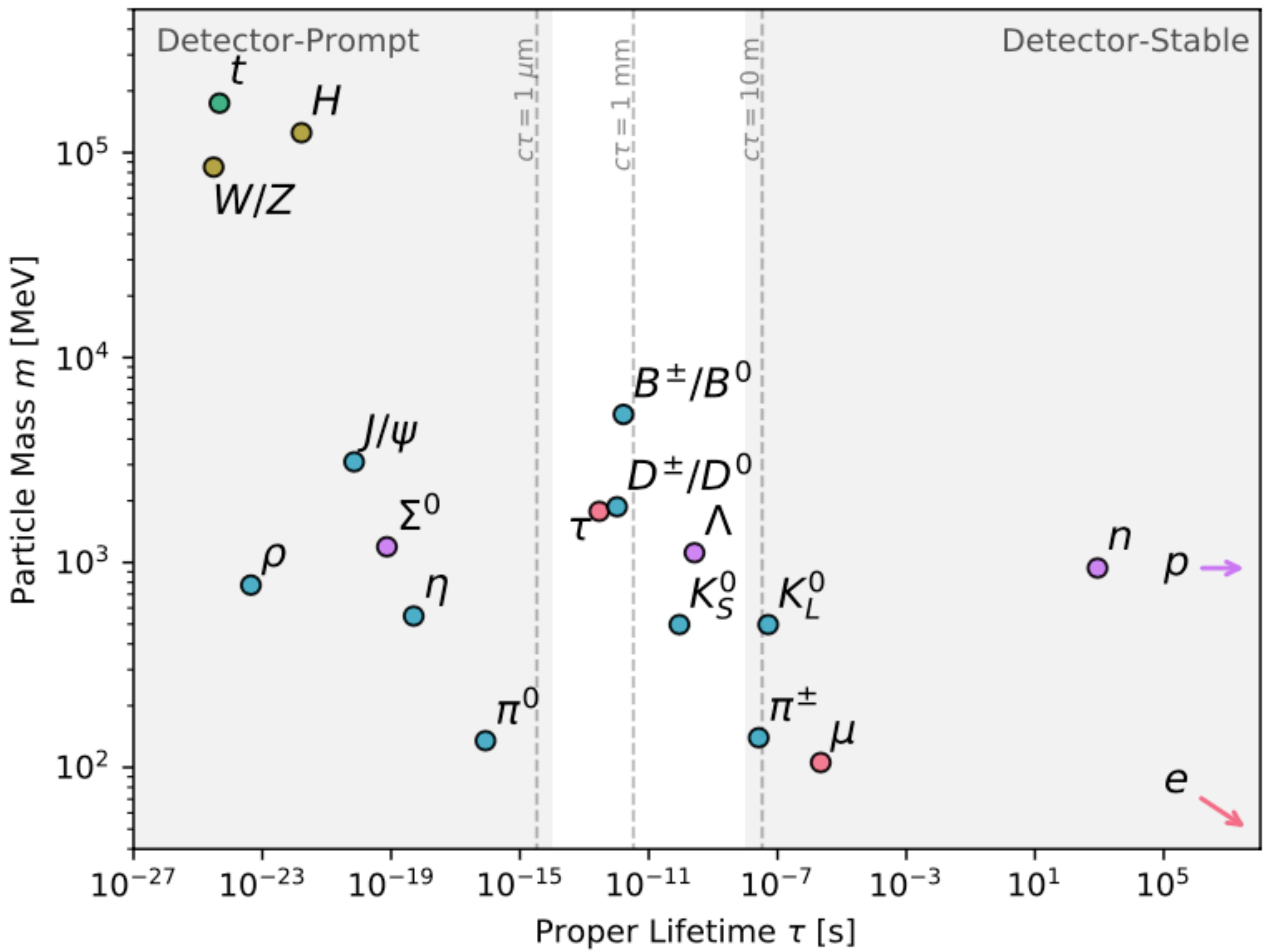
Long-lived Particles in the SM

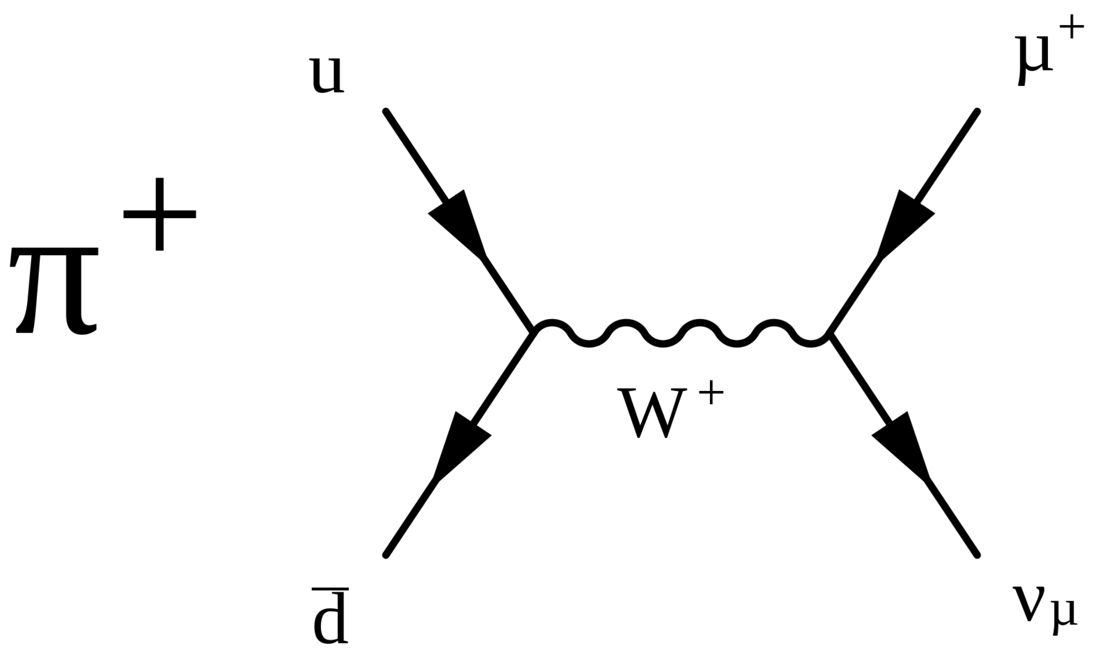
arXiv:1810.12602



- **Long-lived particles are everywhere in the SM**
- **Wide range of masses and lifetimes**

Long-lived Particles at the LHC

SM Long-lived Particle: $\pi^{\pm}$



e.g. $\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$ ($c\tau_0 \sim 7.8$m)

small coupling

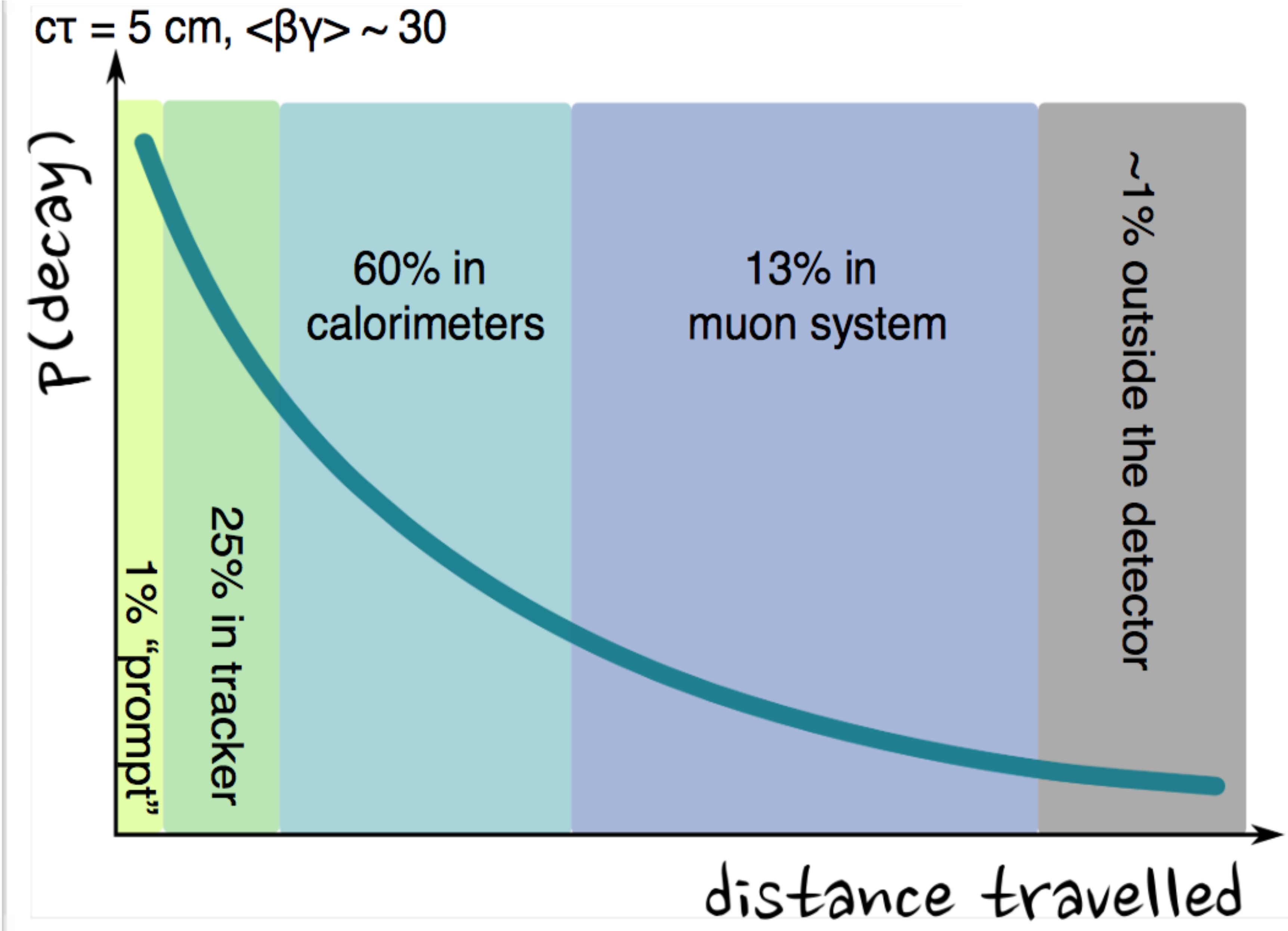
$$\frac{1}{\tau} = \frac{f_{\pi}^2 |V_{ud}|^2}{256\pi m_{\pi}} \left[\frac{g^2}{M_W^2} \frac{m_{\mu}}{m_{\pi}} (m_{\pi}^2 - m_{\mu}^2) \right]^2$$

heavy mediator

compressed spectra

- **Lifetime can be treated as a free parameter**
- **Same reasons apply for BSM particles**

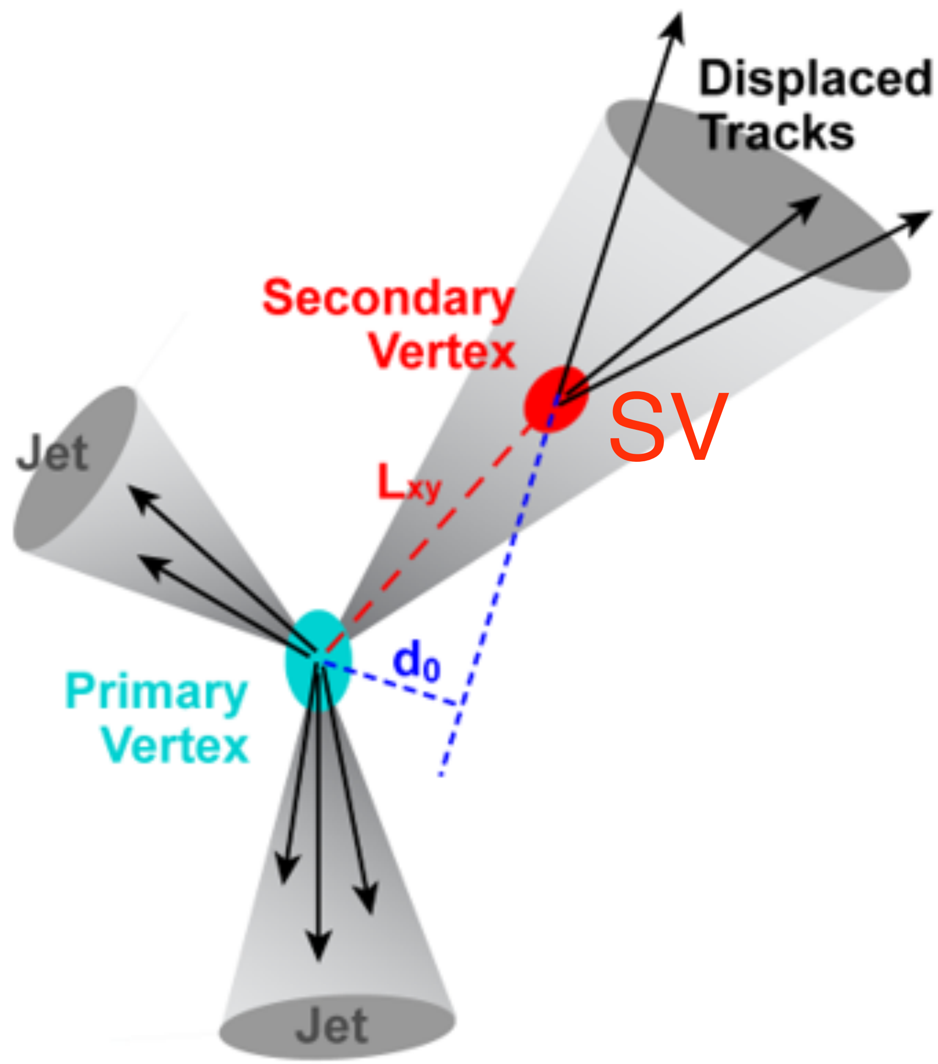
Long Lived Particles at the LHC

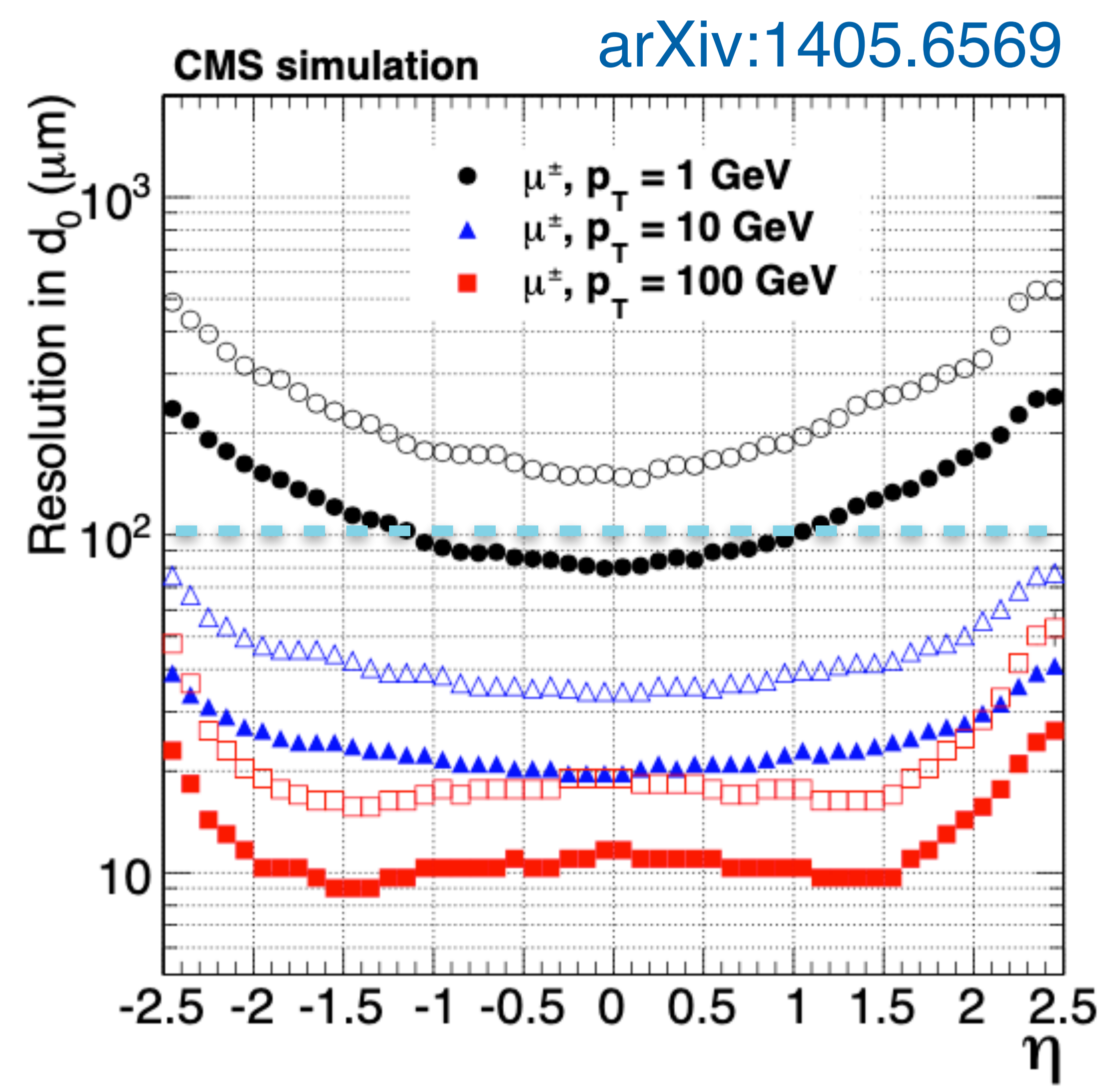


- LLPs follow an exponential decay
- **Important to use all sub-detectors**

Silicon Tracker

Outstanding impact parameter (d_0) resolution: below 100 μm



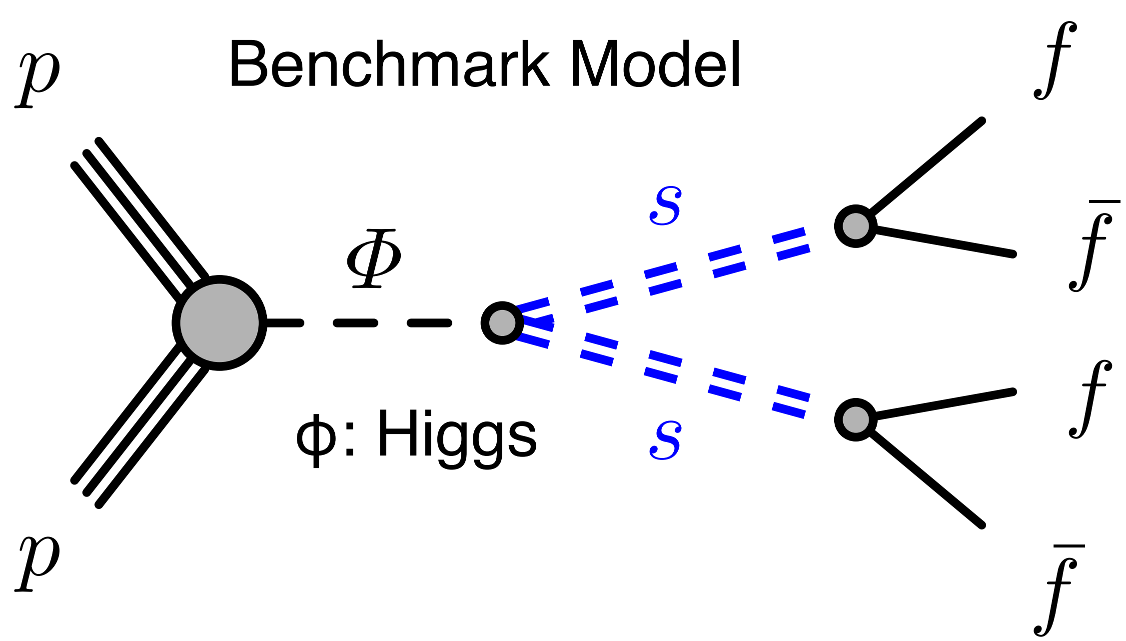


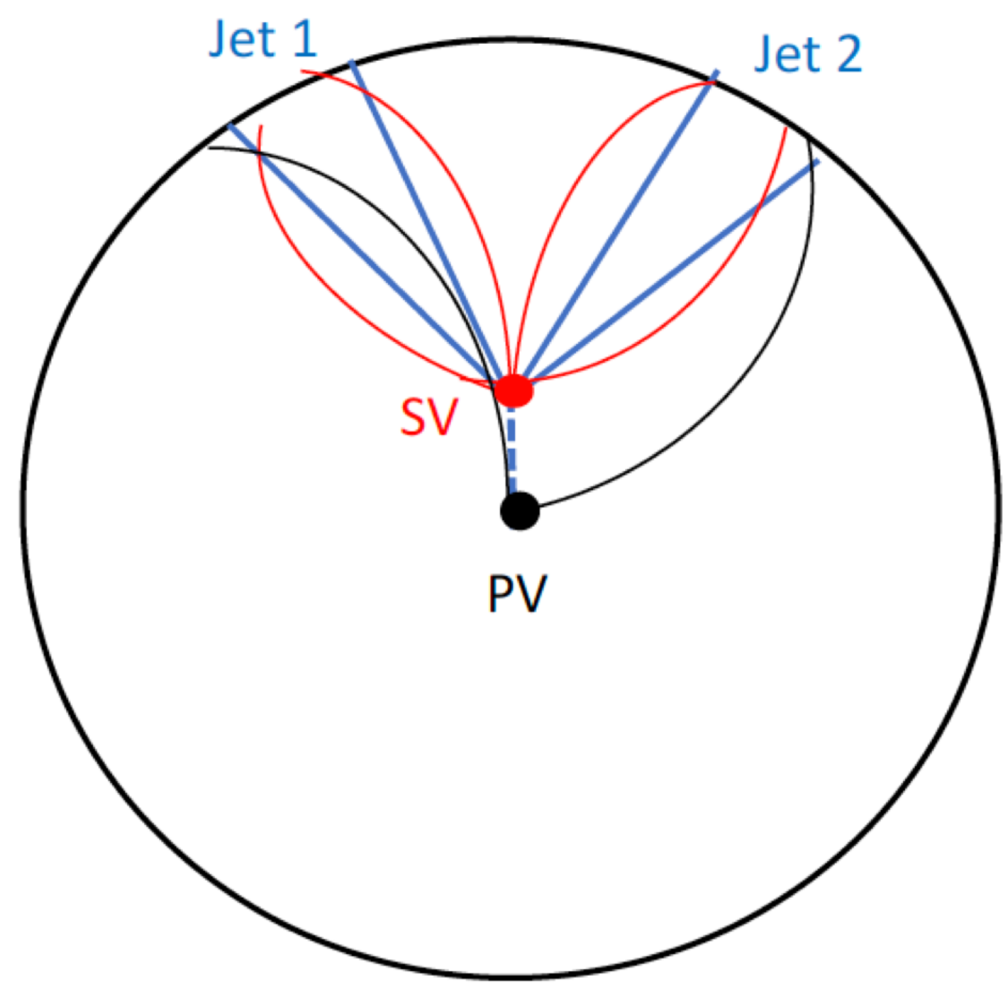
d_0 resolution critical for SV → enables LLP sensitivity

LLP to Displaced Dijets in the Tracker Volume

NEW: EXO-19-021

LLP decays in tracker volume → Secondary vertex





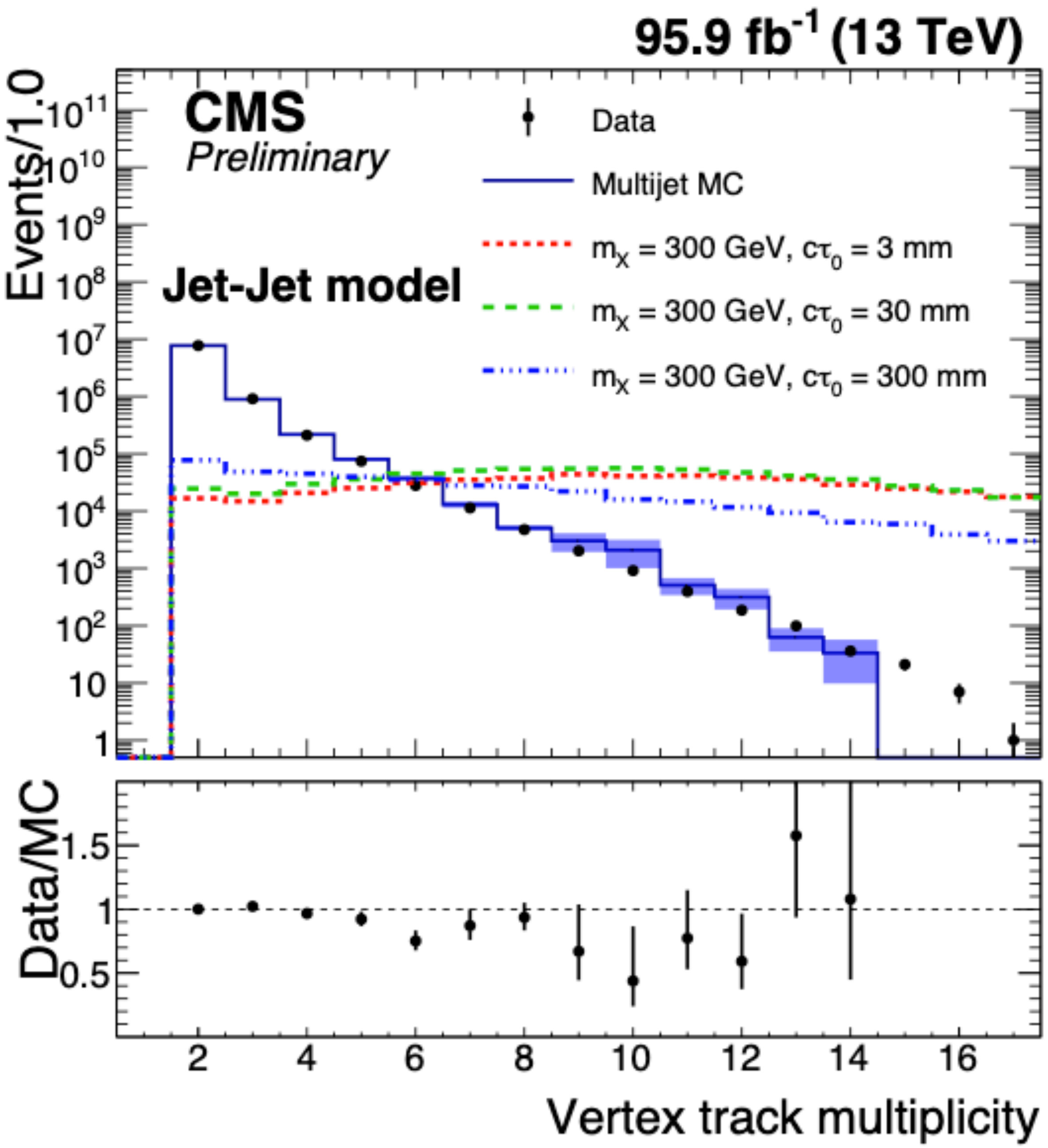
Use tracks with large d_0 to form a SV

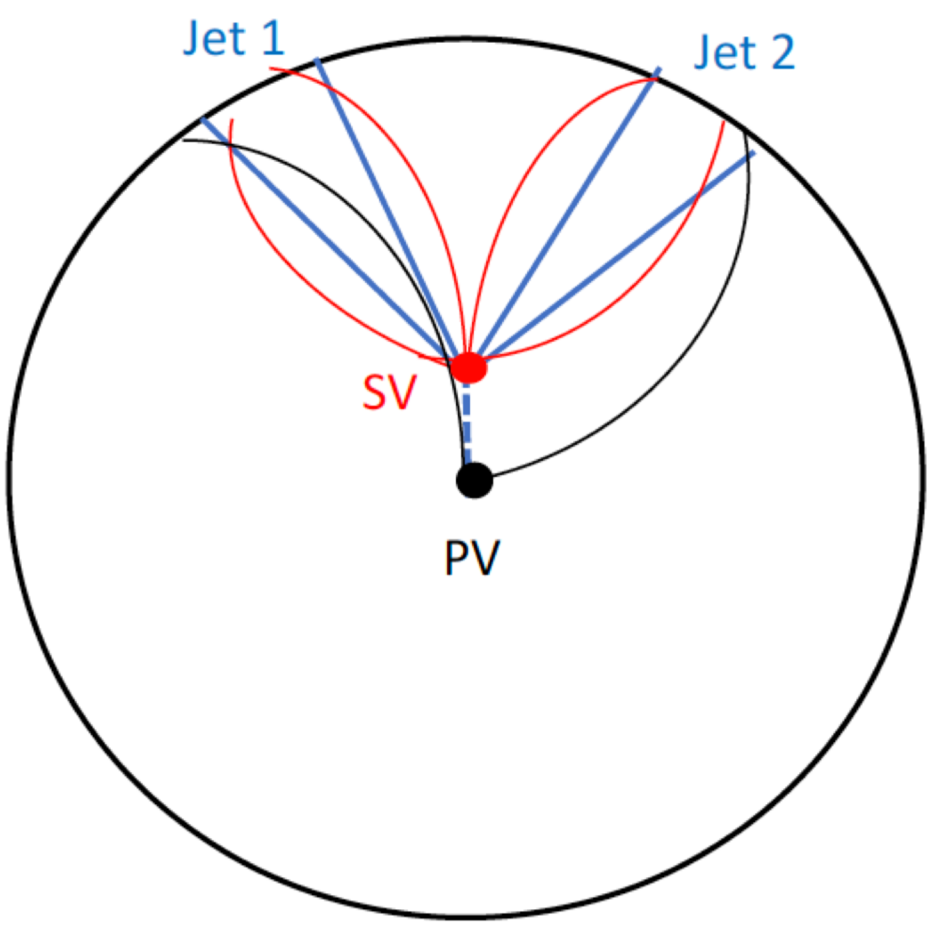
Use SV to suppress SM backgrounds

Displaced Dijets in the Tracker Volume

NEW: EXO-19-021

SV from LLP decays have higher track multiplicity





Other SV information:

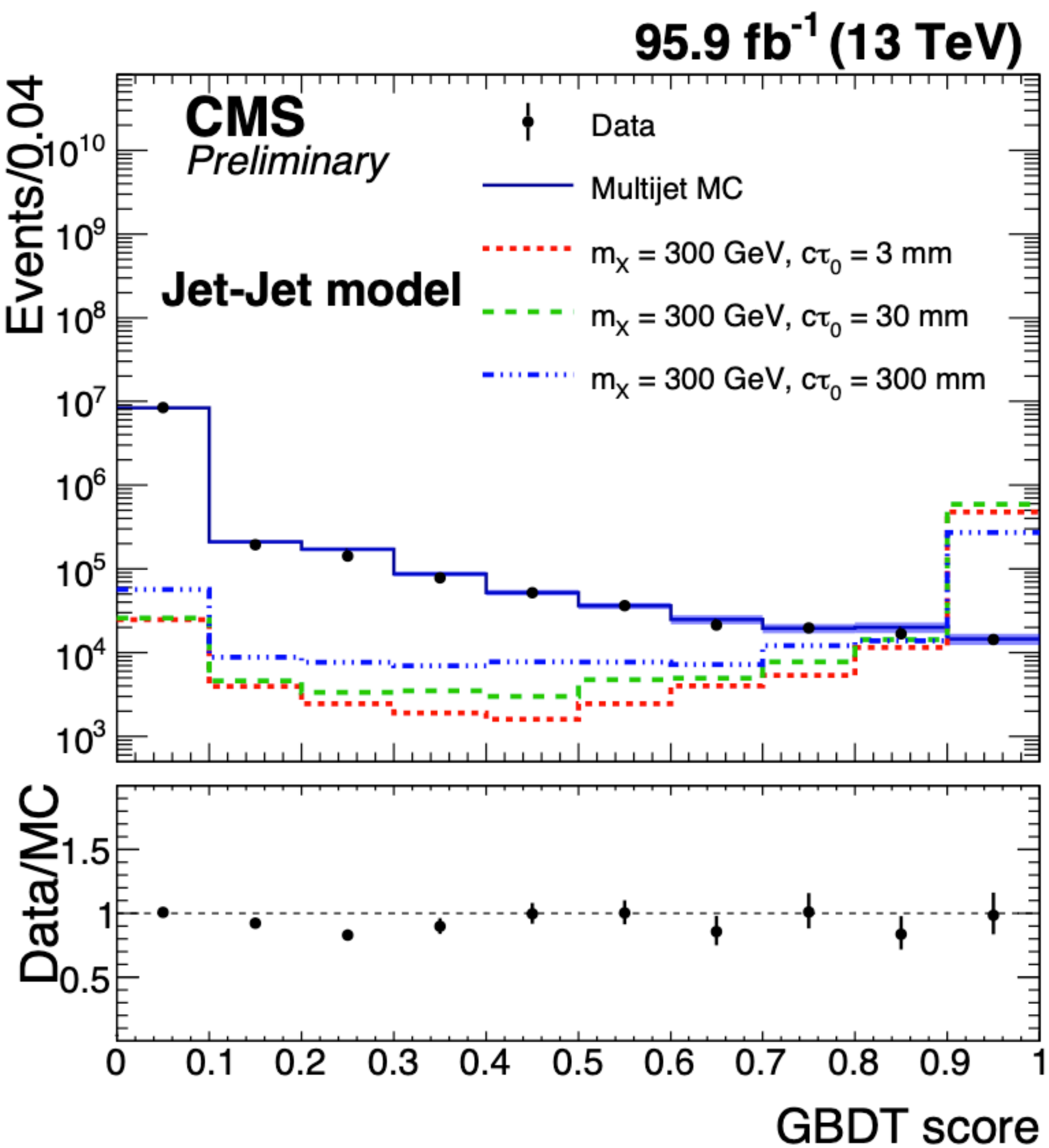
- Vertex track multiplicity;
- Vertex L_{xy} significance
- Cluster RMS

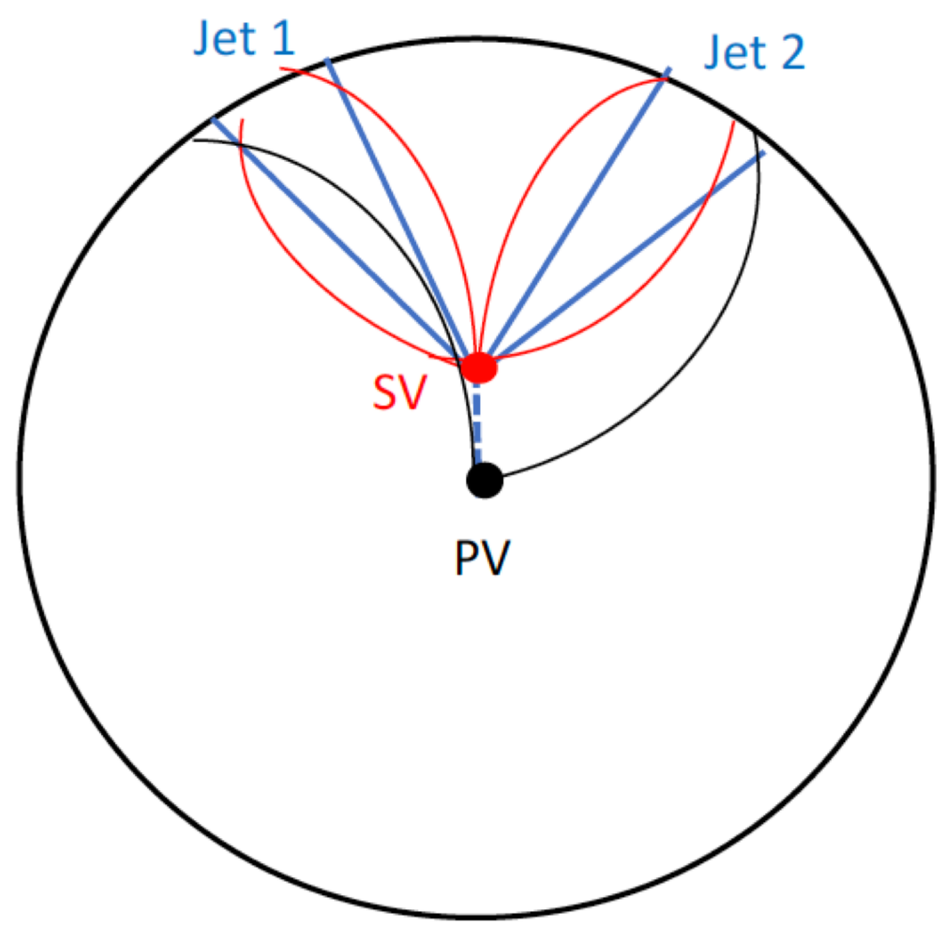
Fermilab

Displaced Dijets in the Tracker Volume

NEW: EXO-19-021

SV information is combined into a Gradient Boosted Decision Tree (GBDT)





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Fermilab

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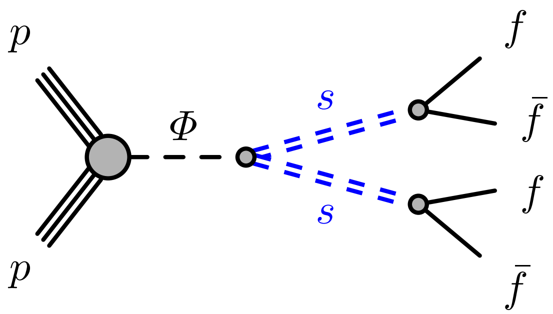
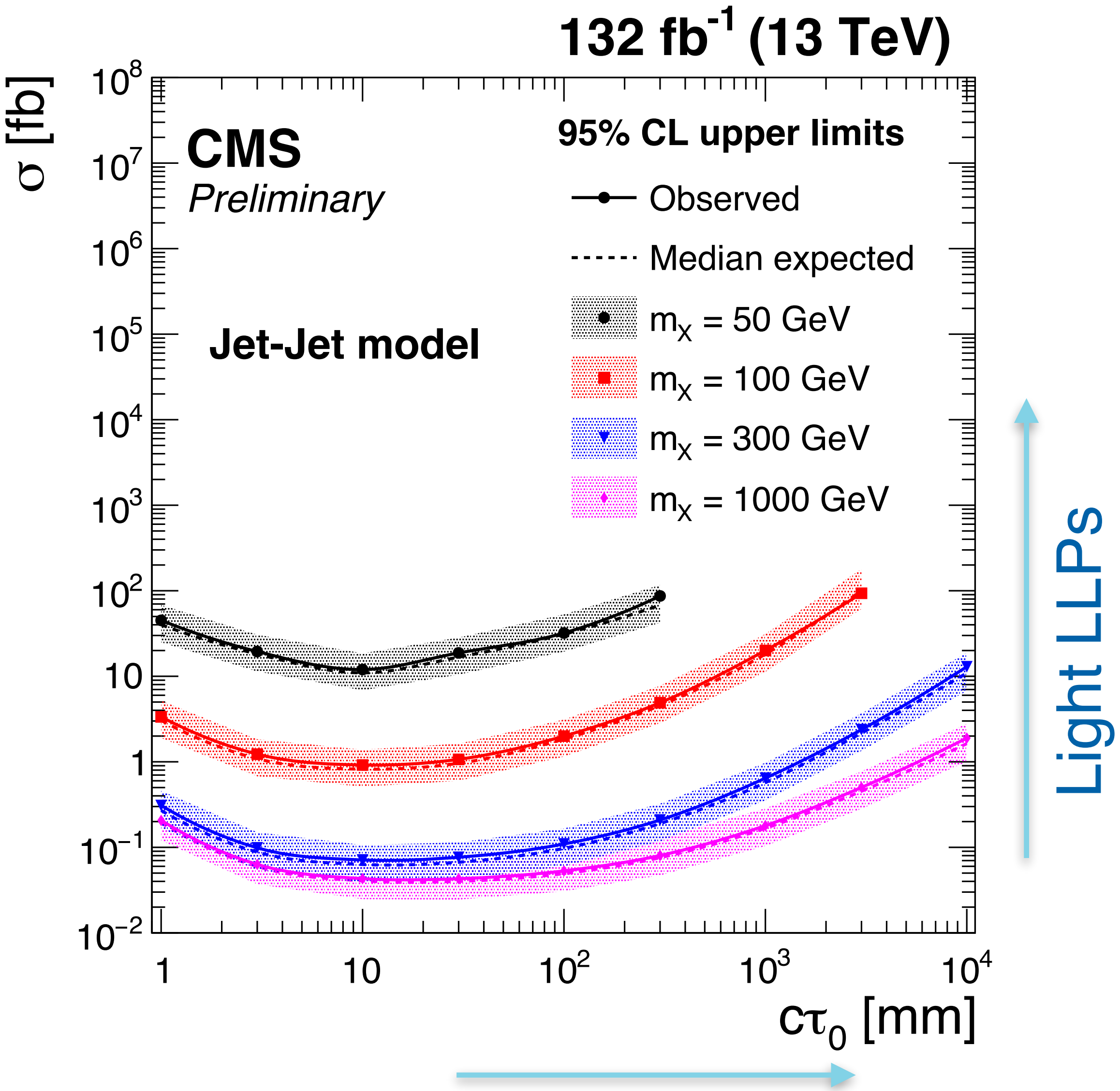


Inclusive approach — 1 Secondary Vertex

NEW: EXO-19-021

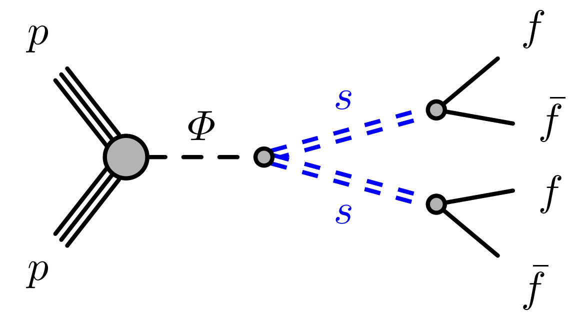


- Best sensitivity at ~10-100 mm
- Lost of sensitivity at 1m → acceptance
- Drop in sensitivity at low LLP masses

Drop in **acceptance × tracking efficiency**

Fermilab

Displaced Dijets in the Tracker Volume



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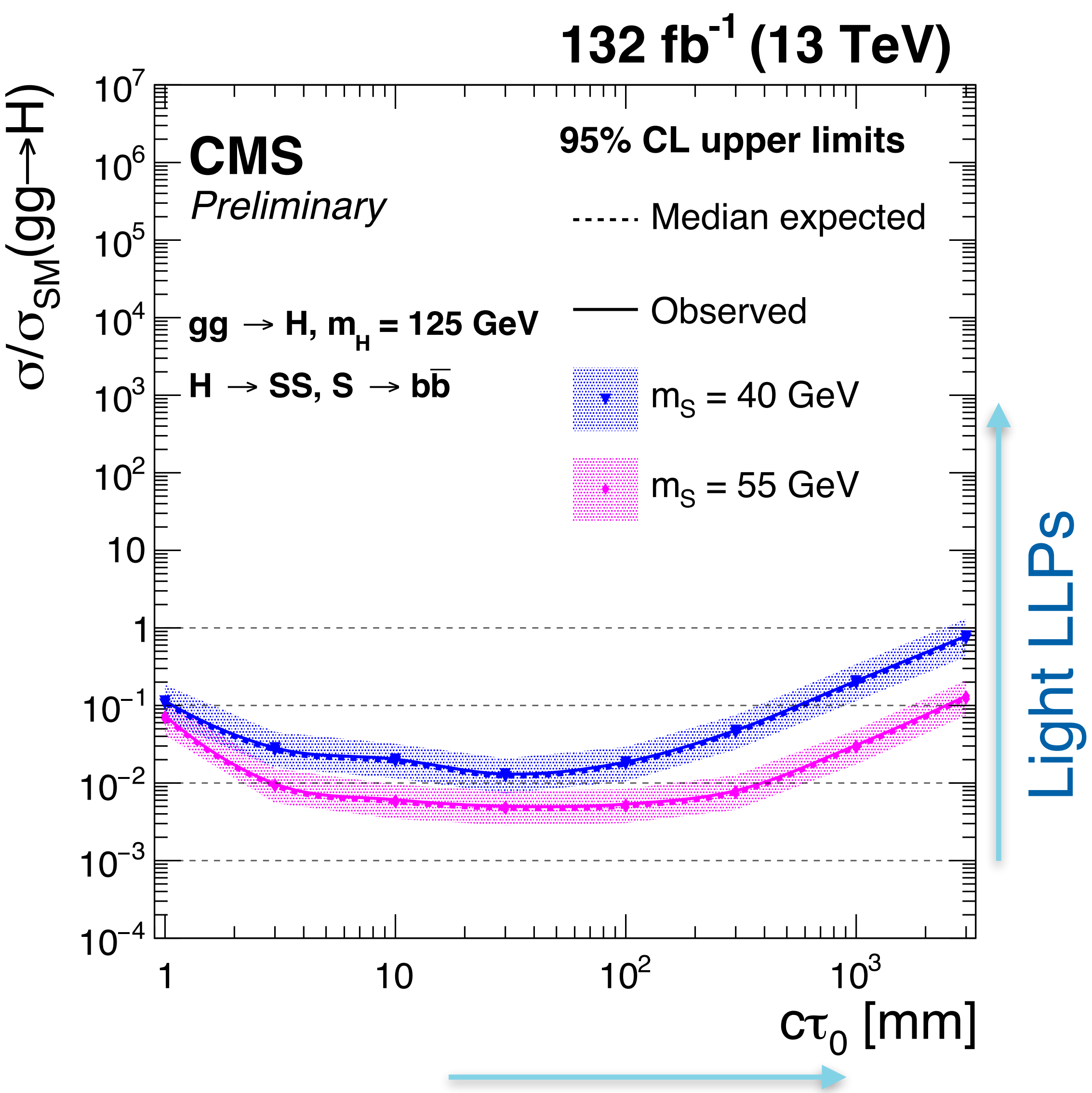
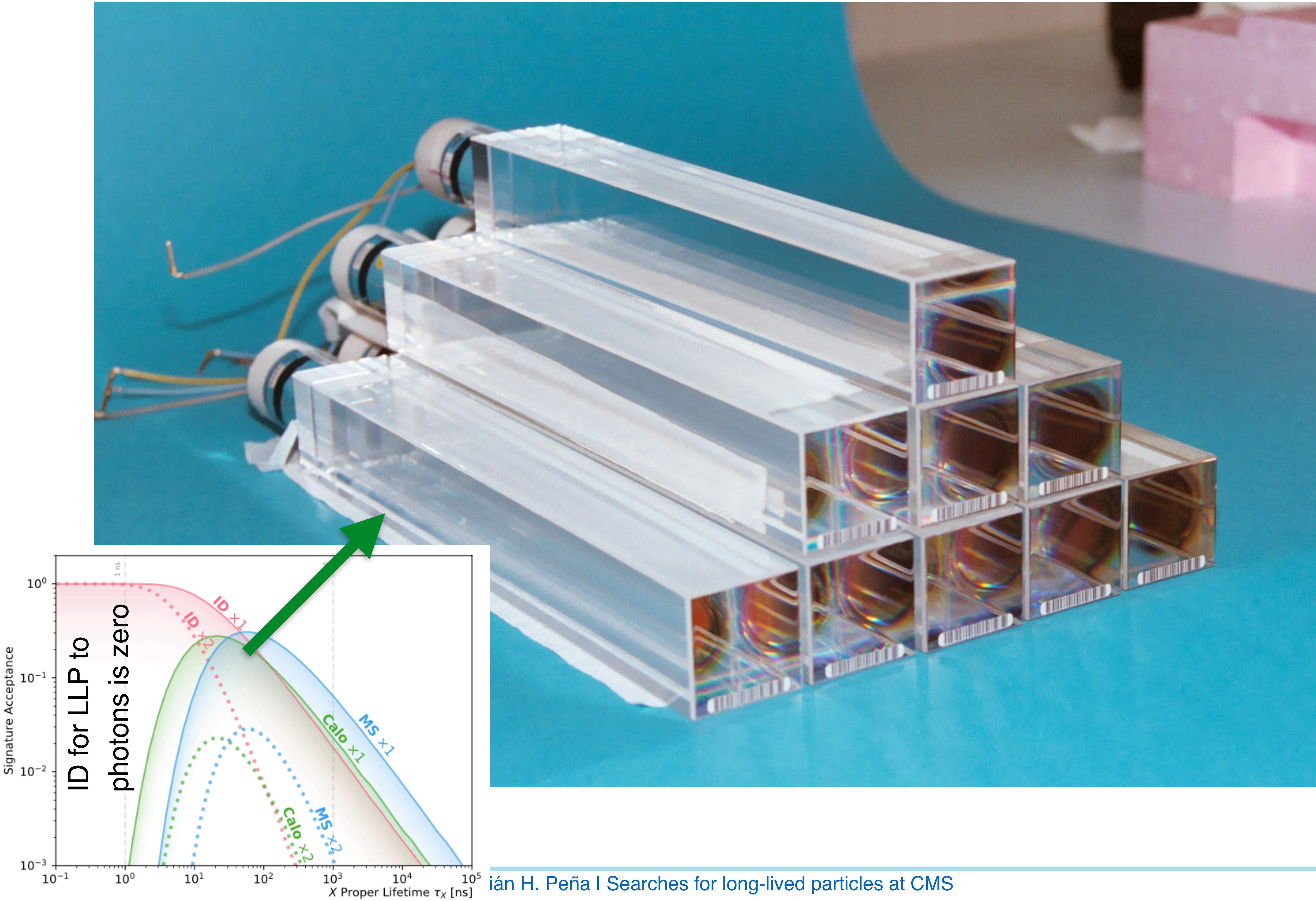


- **Best sensitivity for h → ss with:**
  - lifetimes ~1- 50 cm and masses 40-55 GeV
- LLP (s) → bb decreases sensitivity
- No sensitivity below ~20 GeV LLPs

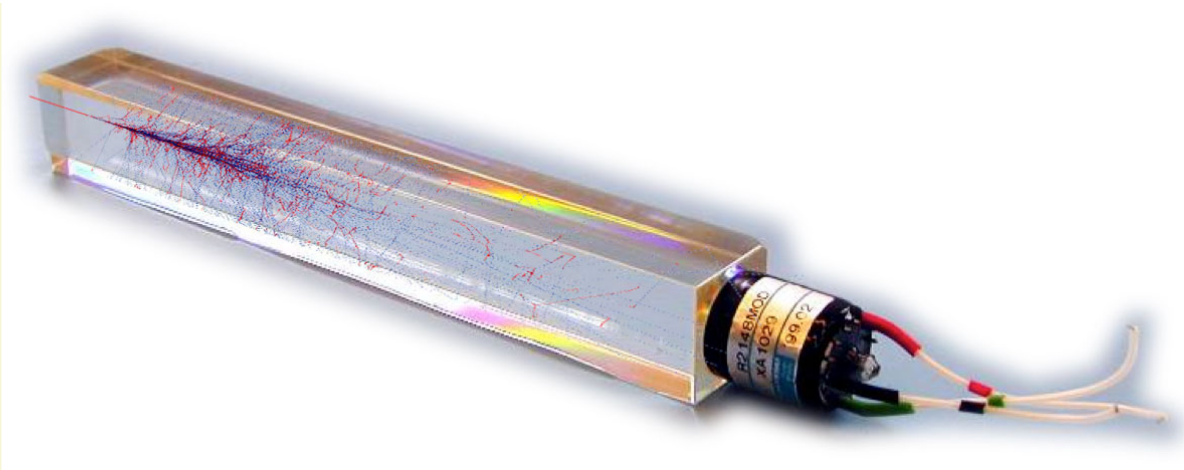
Drop in **acceptance × tracking efficiency**

ALSO NEW: EXO-19-011→DNN-based LLP tagger

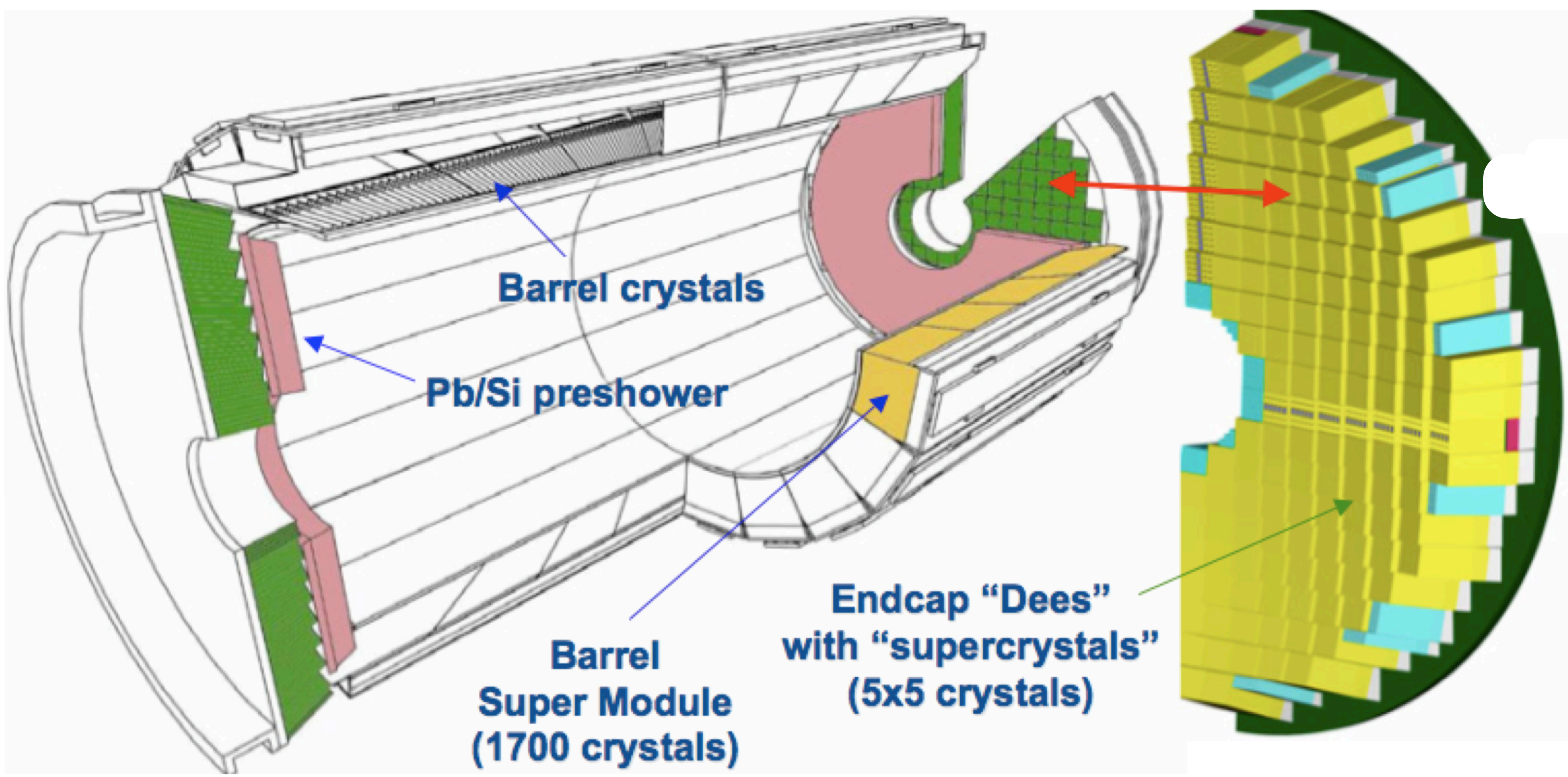
LLP Decays in the ECAL



Technology Legacy: Crystal Electromagnetic Calorimeter



- Designed for excellent energy resolution
- Crucial role in H→γγ observation
- Resulted in outstanding **time resolution**
  - **LLP enabler**



Delayed Photons in the Electromagnetic Calorimeter

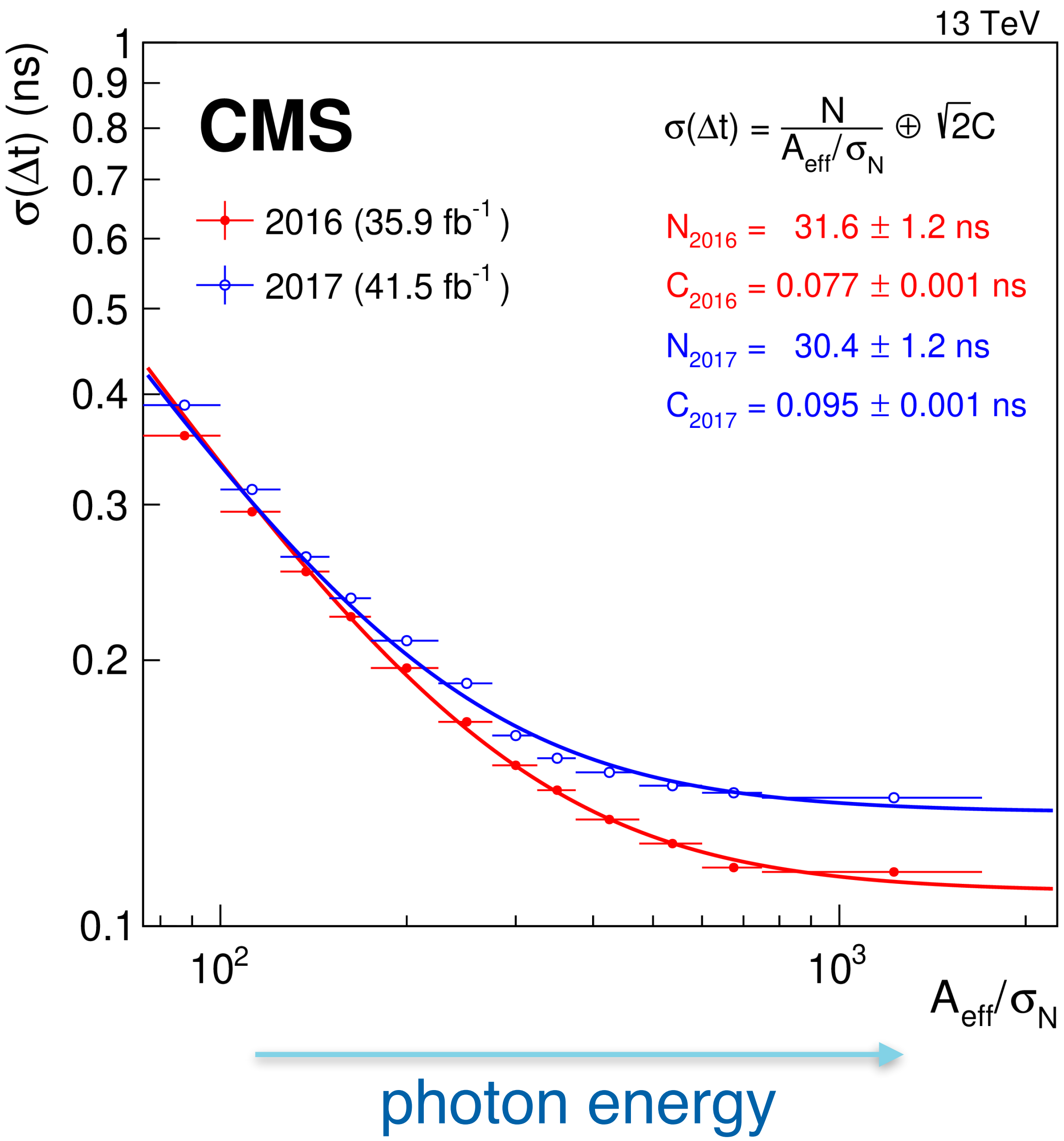
Lesson from tracker: LLP sensitivity drops at ~1m

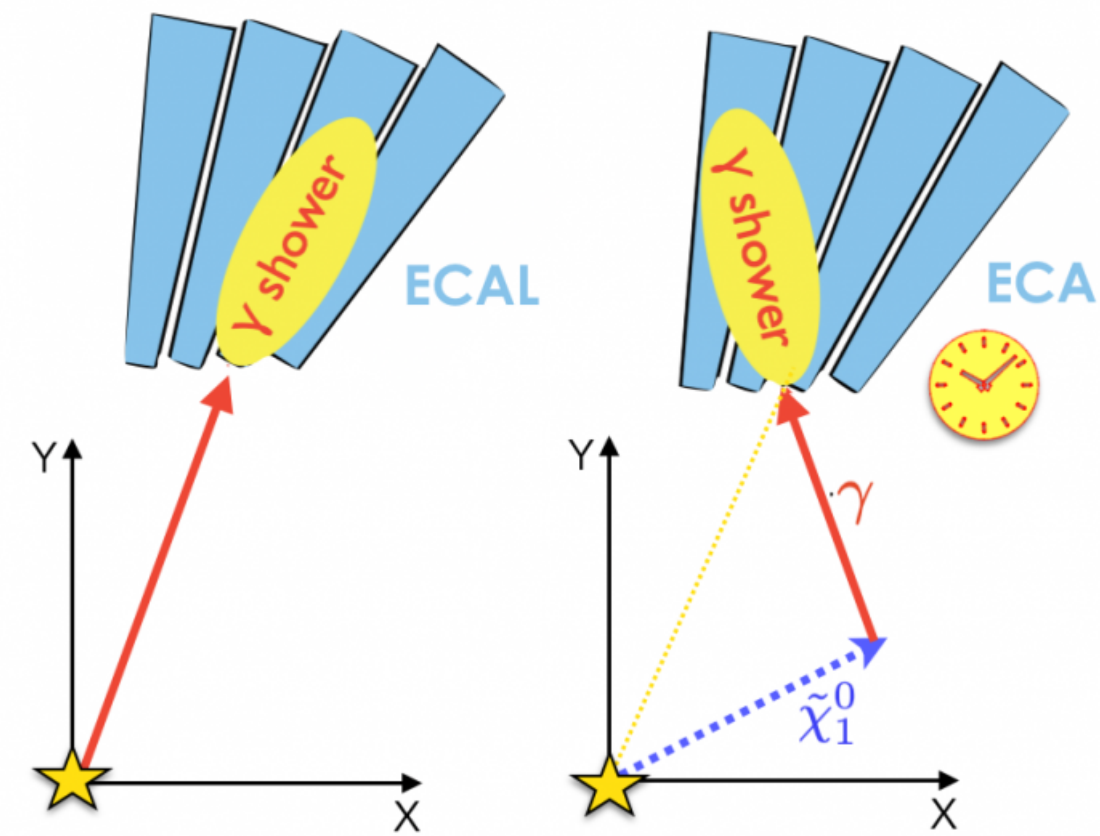
$\tilde{\chi}_0$: LLP — heavy: slow moving → delayed

EXO-19-005

10.1103/PhysRevD.100.112003

ECAL Timing enables this search





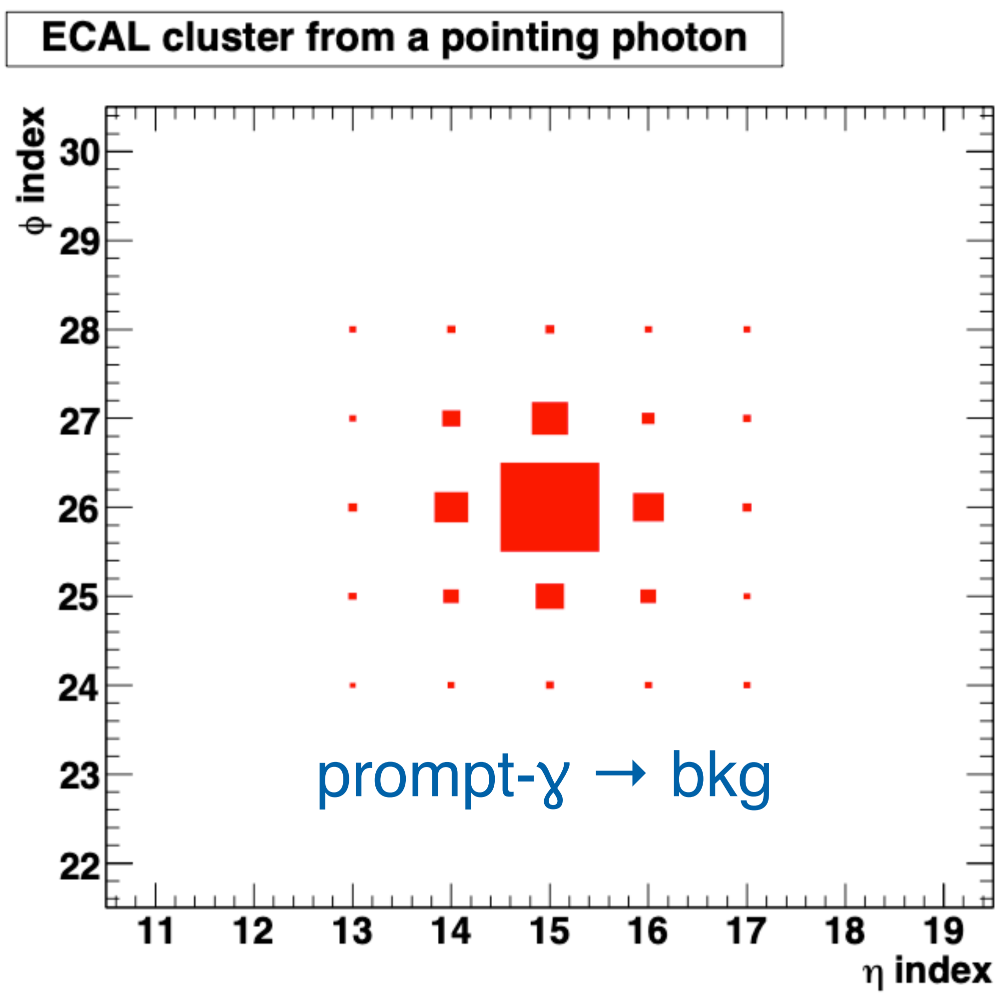
Signature

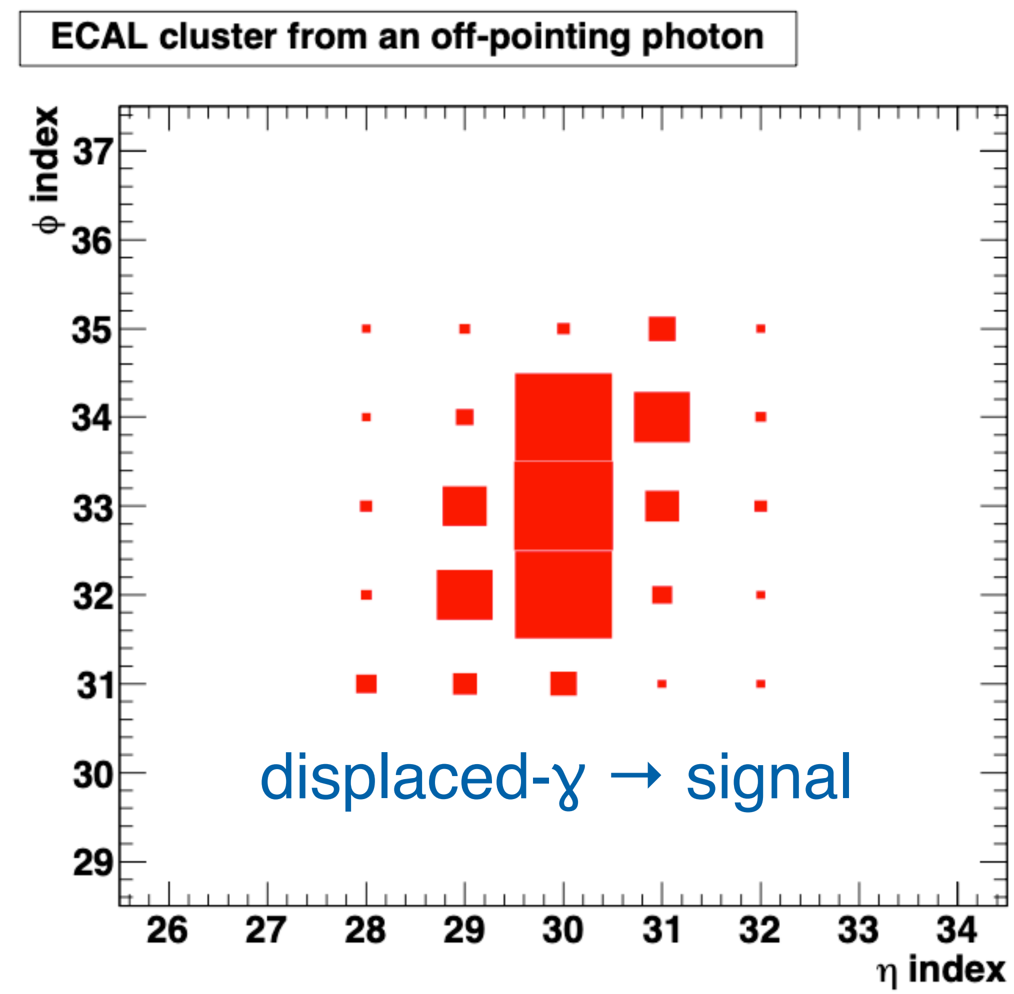
γ : **delayed and slanted at ECAL**

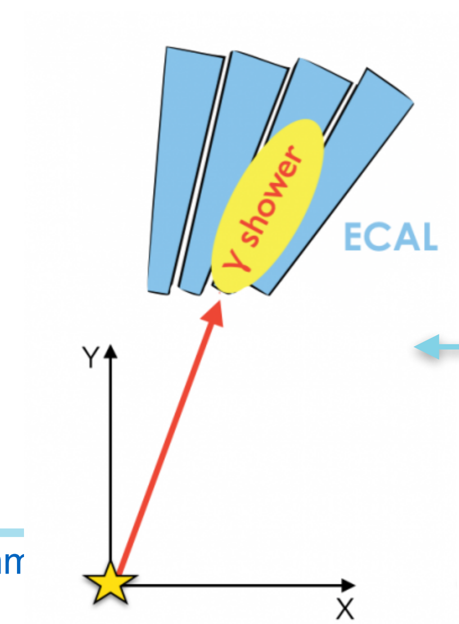
See also Justin's talk (here)

Use Cluster Shape to ID Photons from LLP Decays

http://www.roma1.infn.it/cms/tesiPHD/franci.pdf

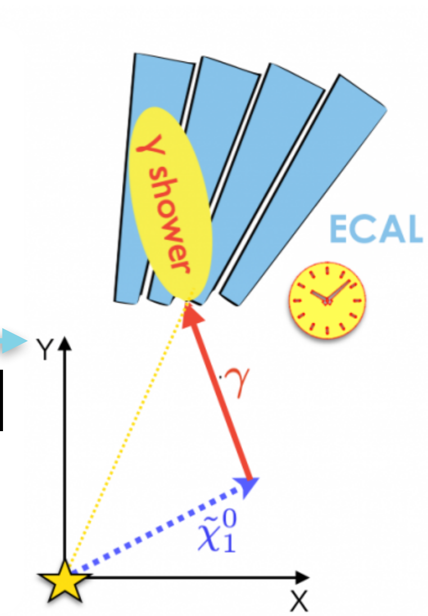






Pointing (PV) — Slanted

SM Bkg — LLP signal



Fermilab

Use Cluster Shape to ID Photons from LLP Decays

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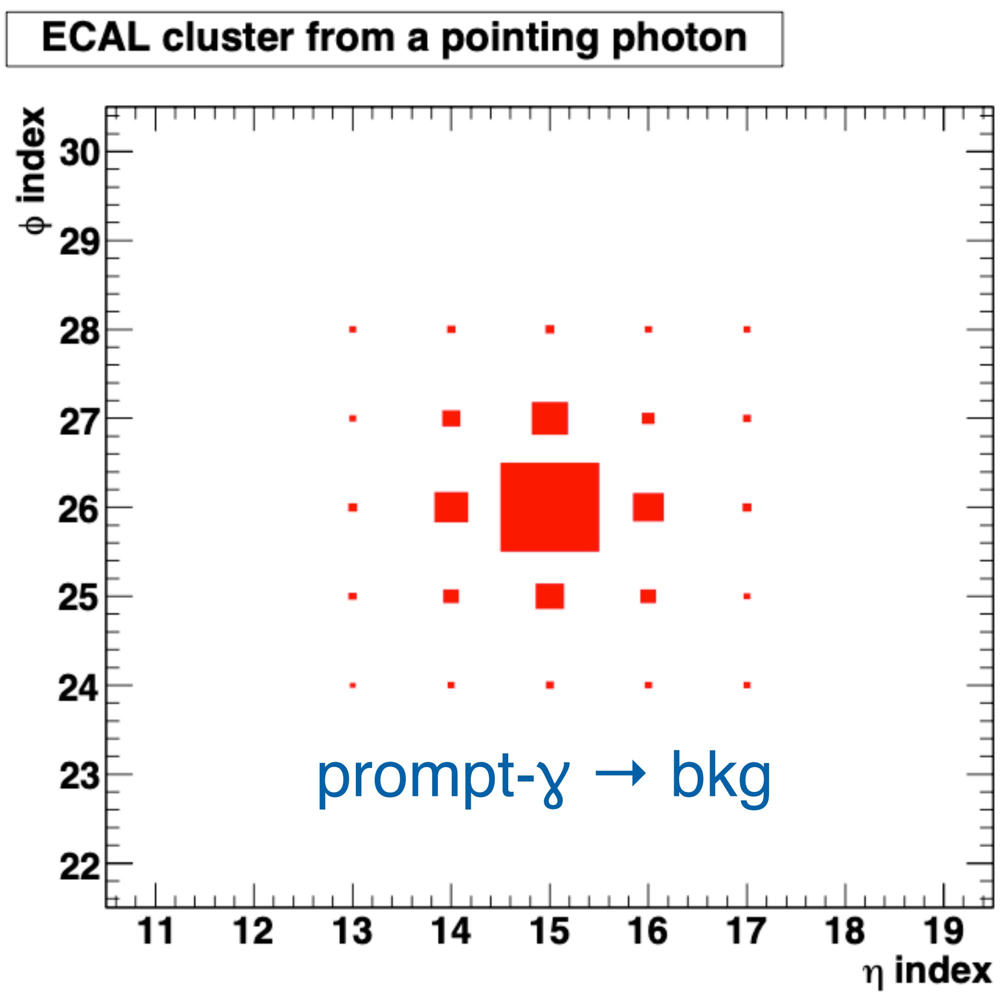

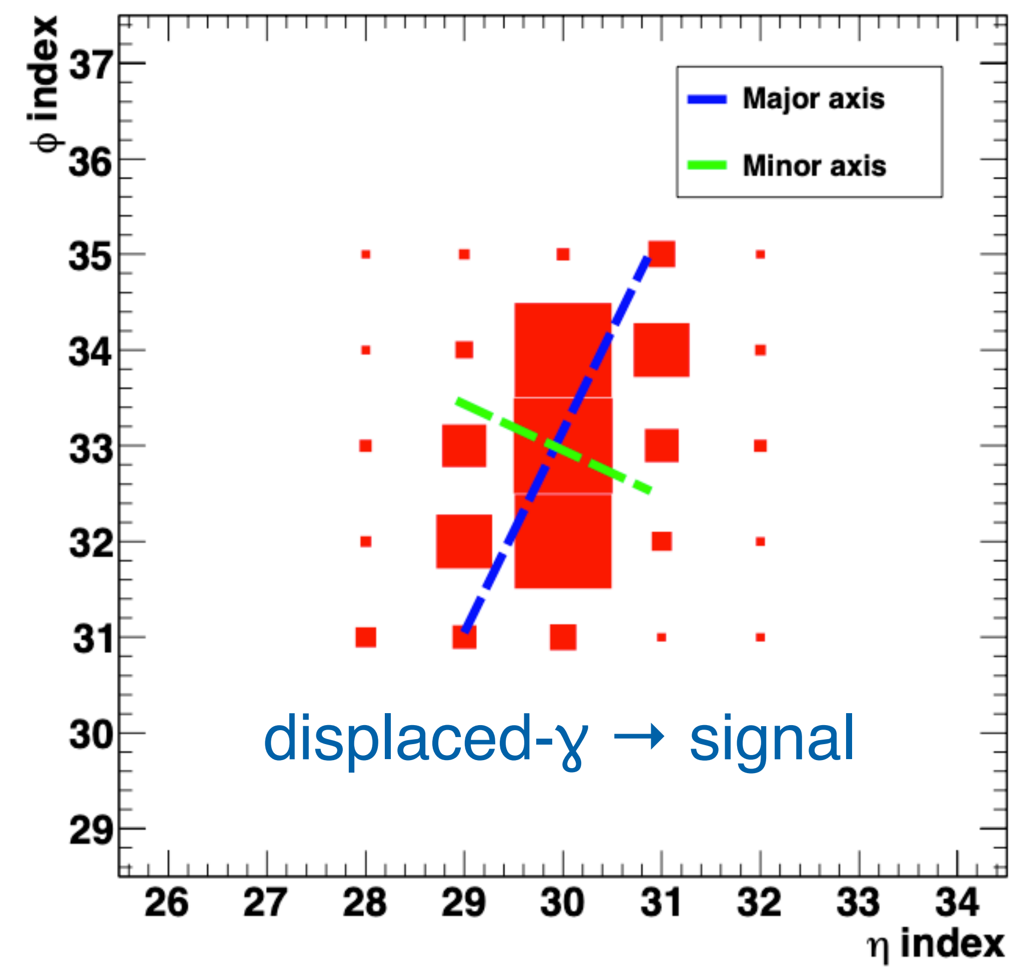

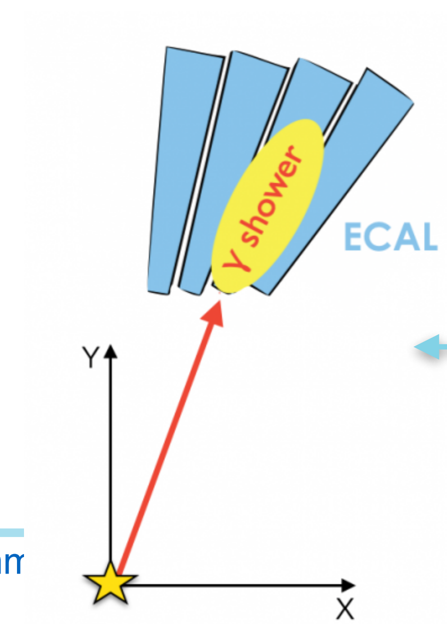

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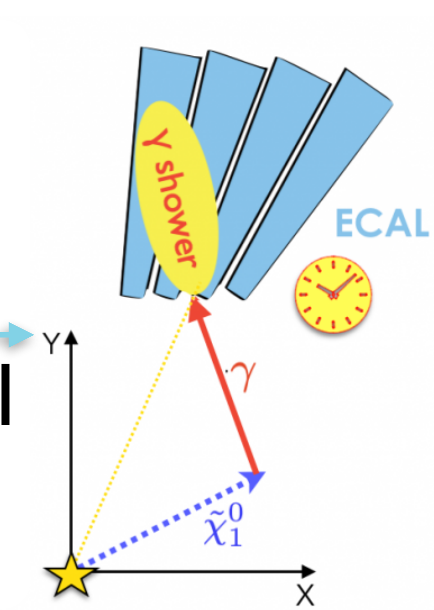
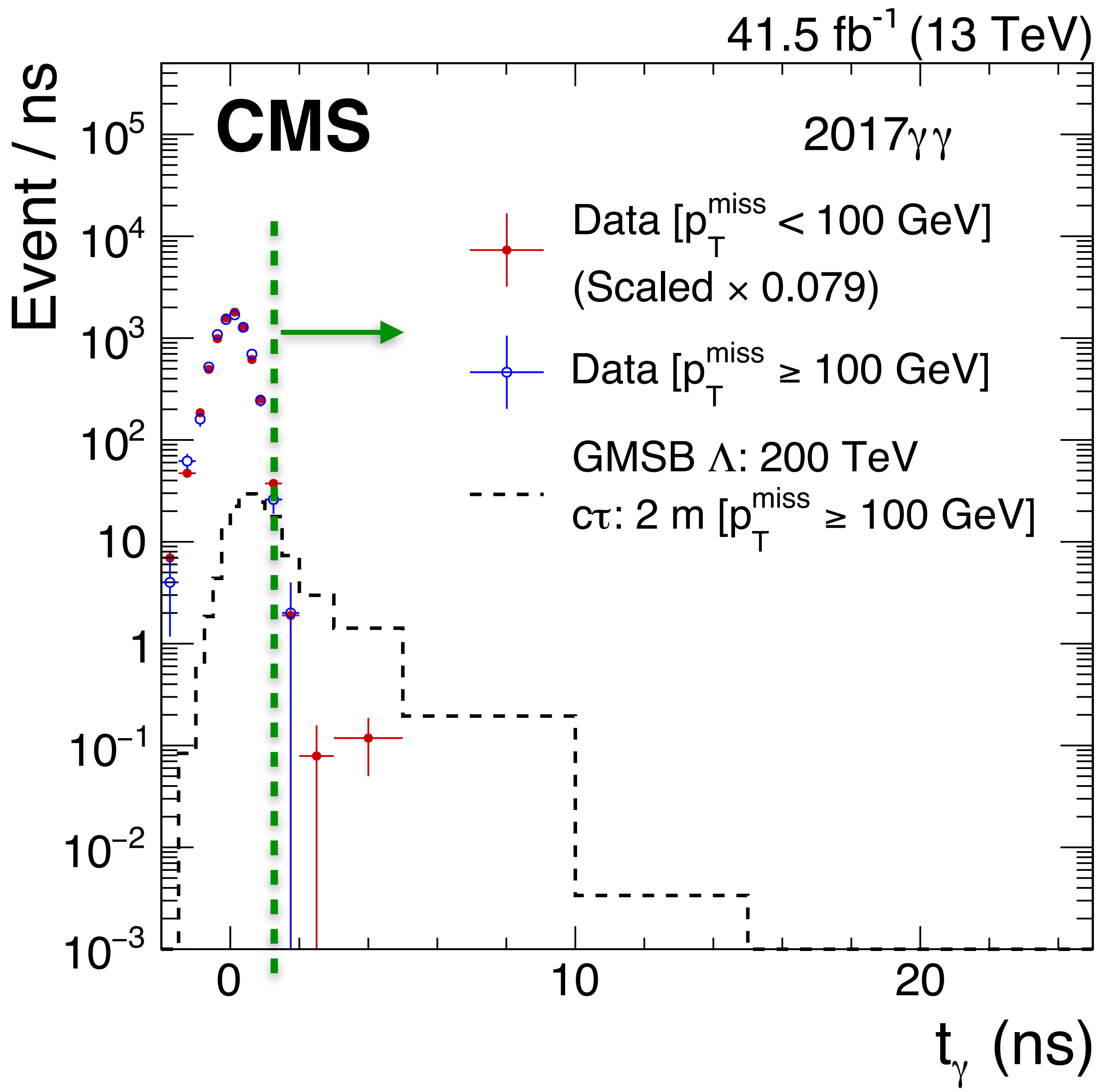
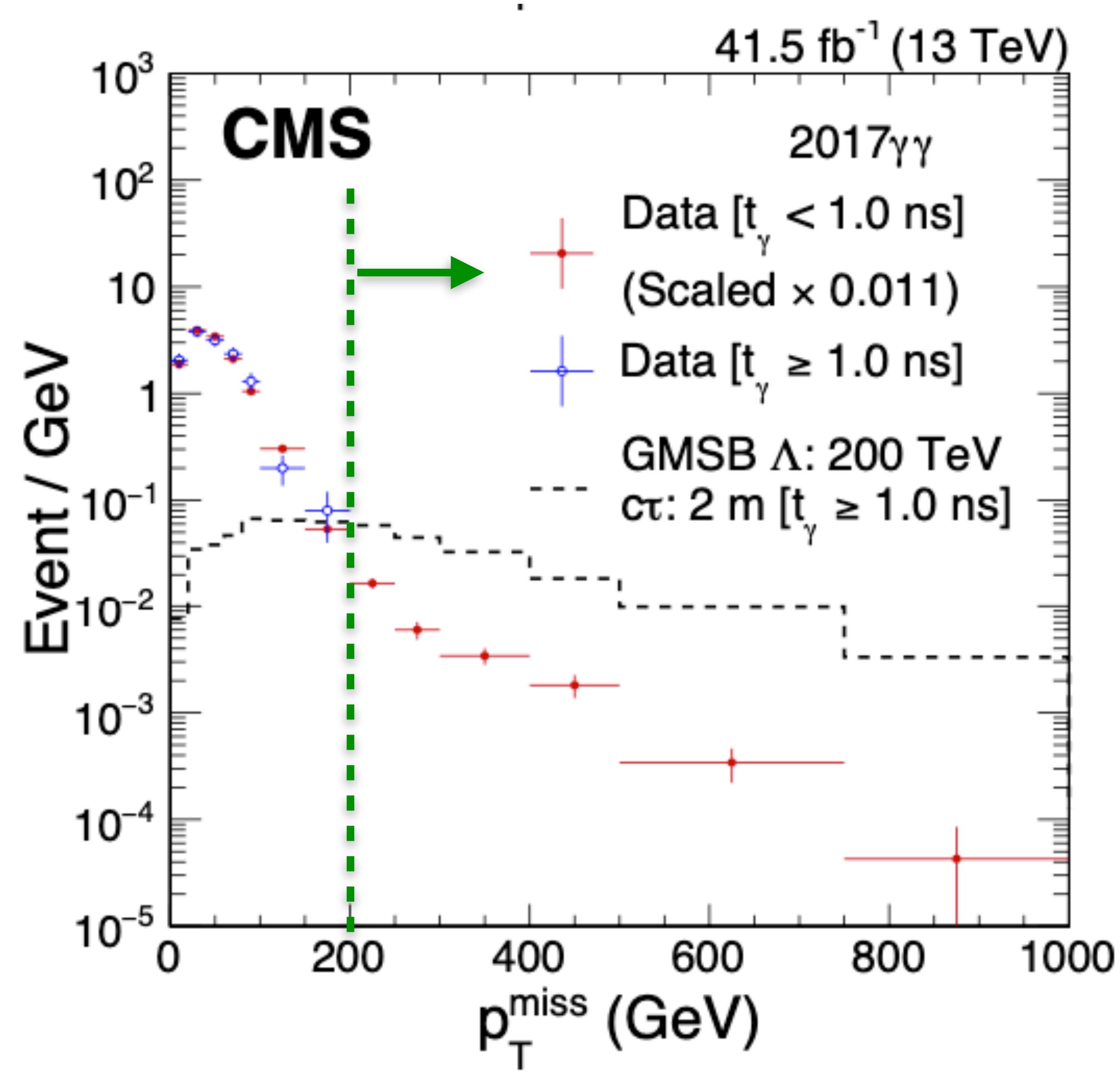


Fermilab

Delayed Photons in the Electromagnetic Calorimeter



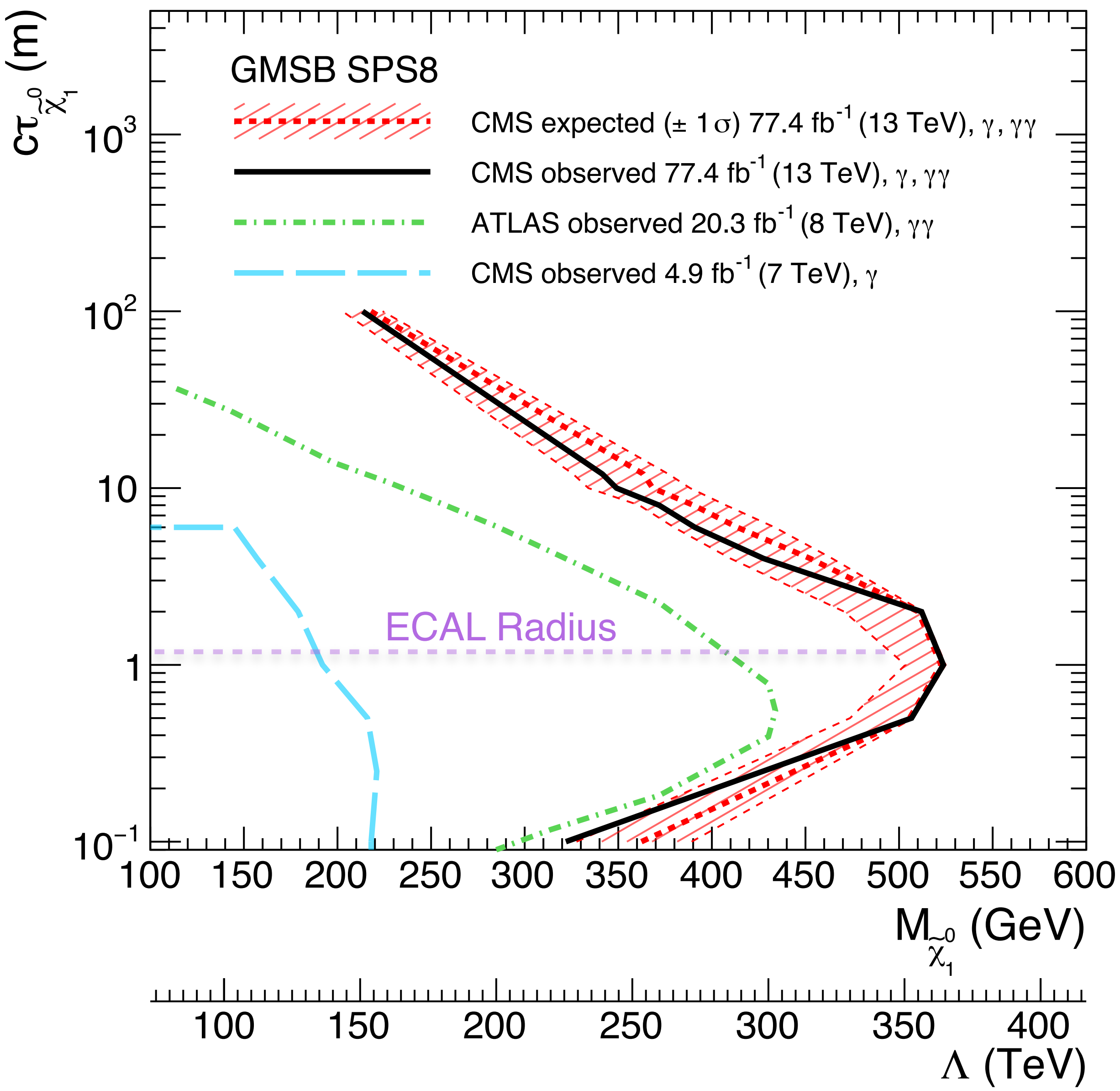


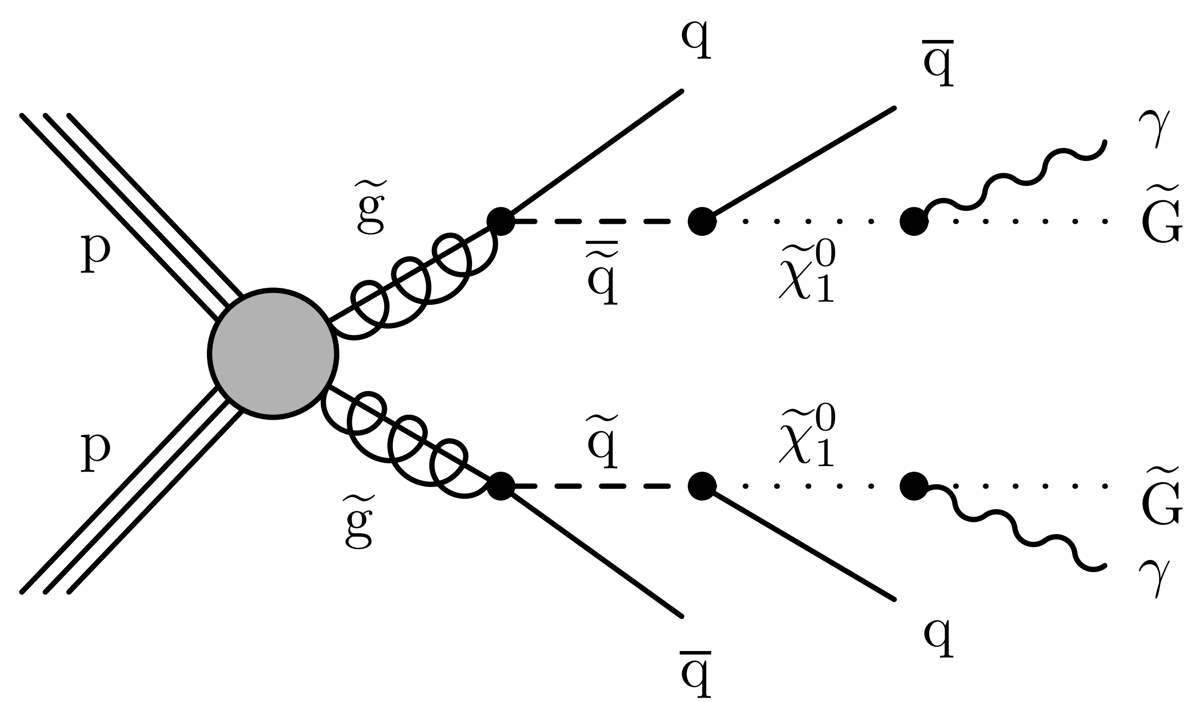
- Signal delayed (>1.5 ns) wrt SM backgrounds
- Final selection also uses pT^{miss} (200 GeV)

Delayed Photons in the Electromagnetic Calorimeter

EXO-19-005

Large extension in cτ and mass





~10-fold increase in cτ

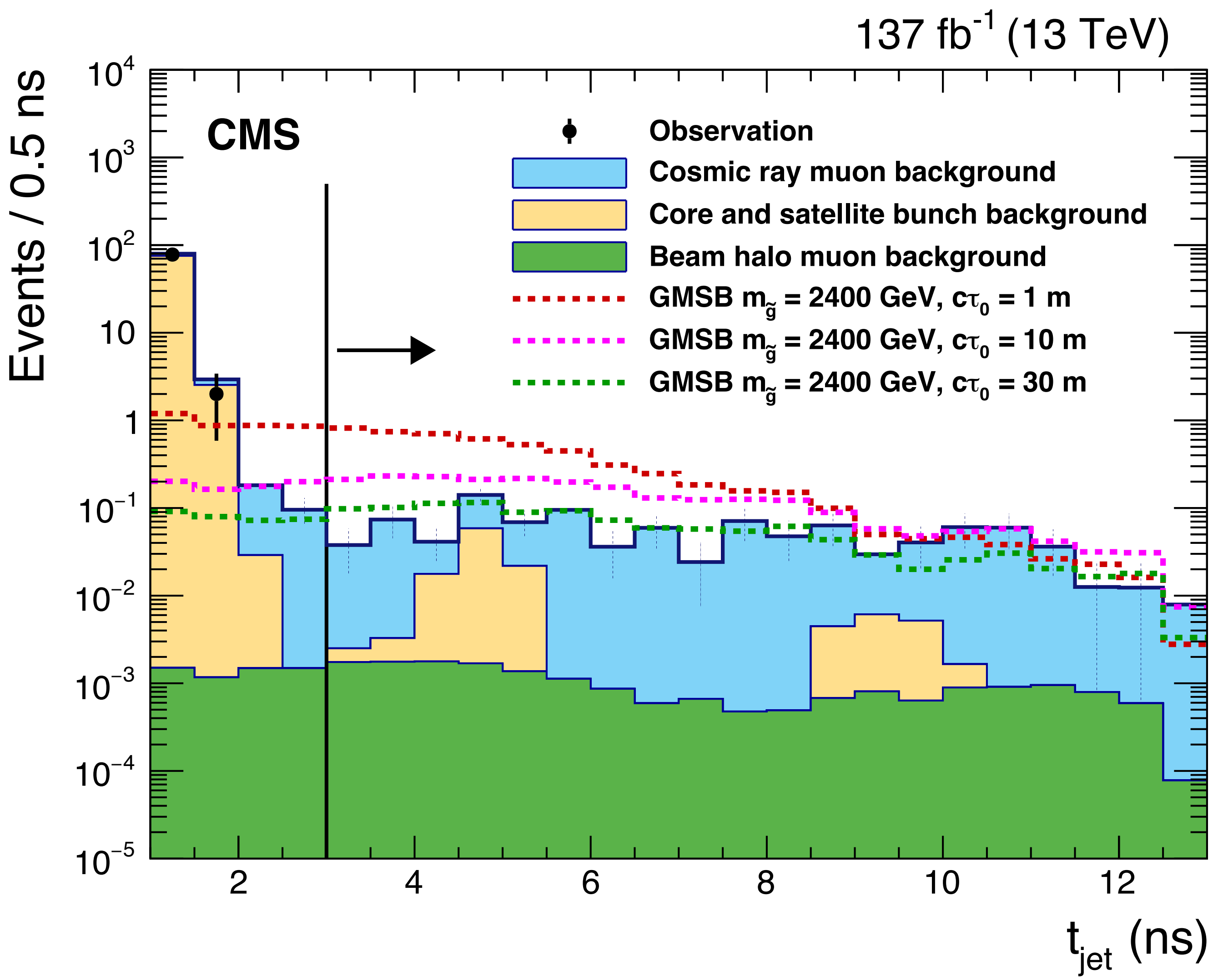
Peak sensitivity around ~few meters

LLP-HLT Trigger (2017) → 1 photon search → expanded cτ coverage

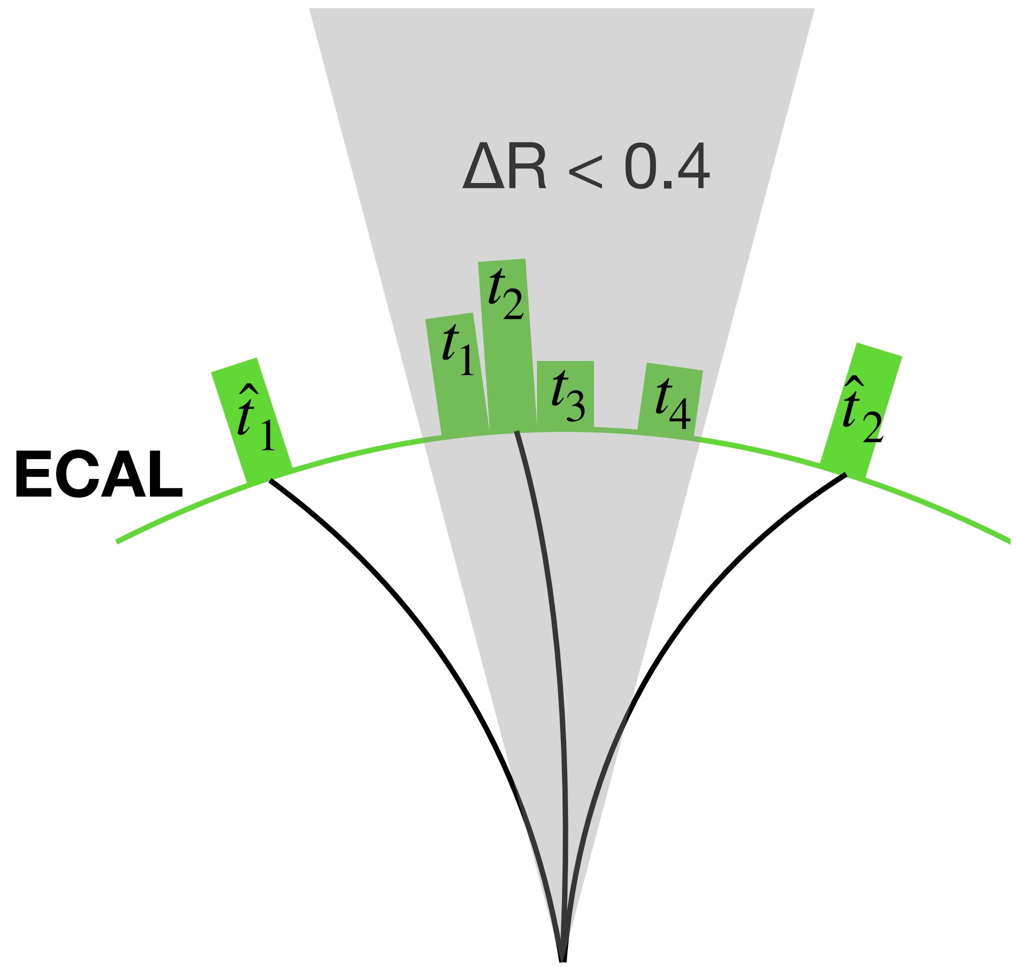
Delayed jets in the Electromagnetic Calorimeter

EXO-19-001

10.1016/j.physletb.2019.134876



Use ECAL deposits define a jet timestamp

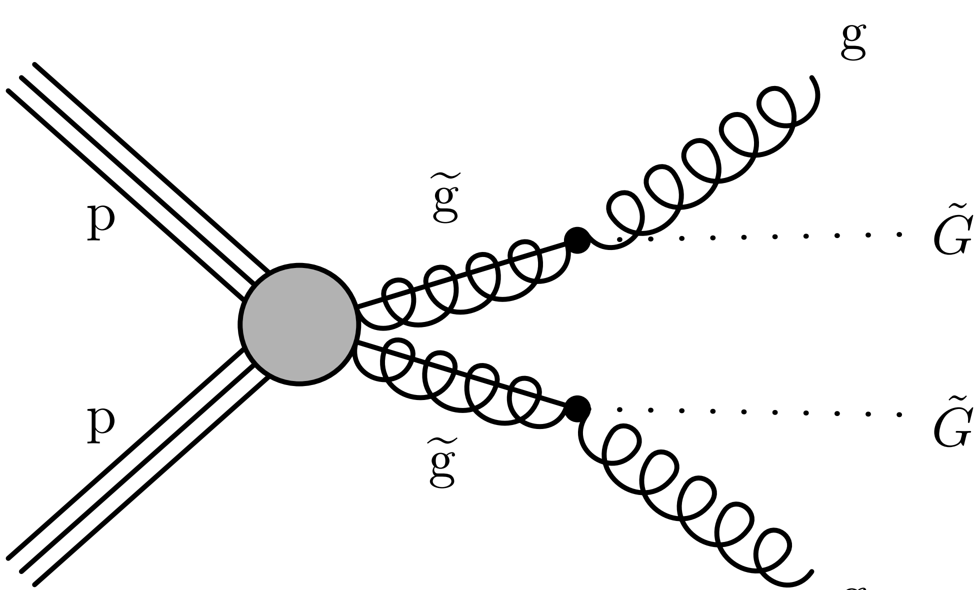


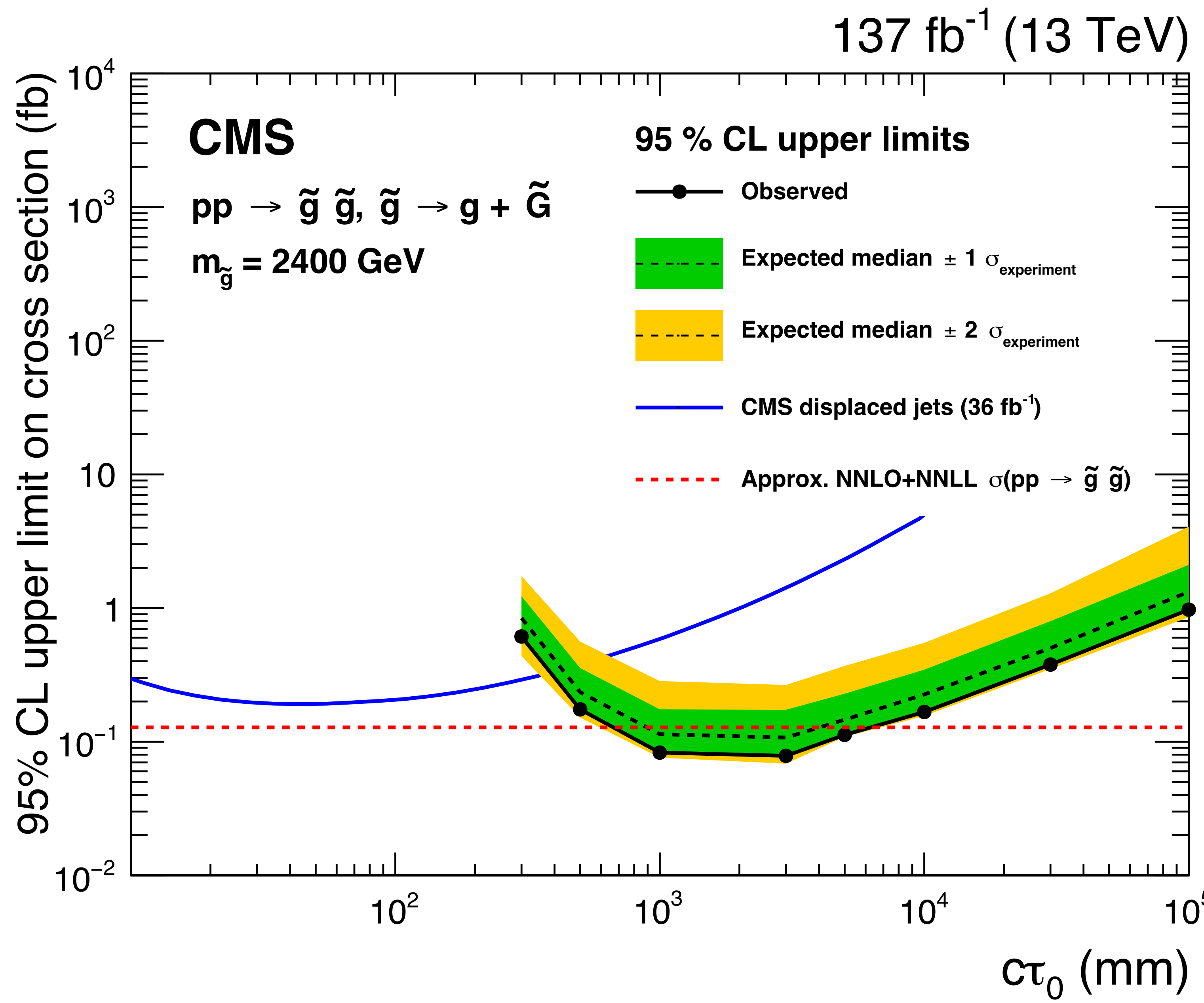
Delayed signals jets in calorimeter

Delayed jets in the Electromagnetic Calorimeter

EXO-19-001

10.1016/j.physletb.2019.134876





Expands lifetime for heavy LLPs

(increased acceptance for longer lifetimes)

Summary

- CMS tracker-based search provides outstanding sensitivity for lifetimes ~ 1- 50 cm.
- CMS ECAL-timing LLP searches extend lifetime coverage and access unique LLP photon decays
- Many opportunities for improvement remain for Run2, Run3 and Phase-II:
  - LLP aware triggers, innovative LLP reconstruction, precision timing

Backups

- **CMS Fundamentals**:
  - **4T magnet & ALL silicon tracker**
  - **Muons + Compact**
  - **Crystal EM Calorimeter**
- Precision timing & Track-Triggering

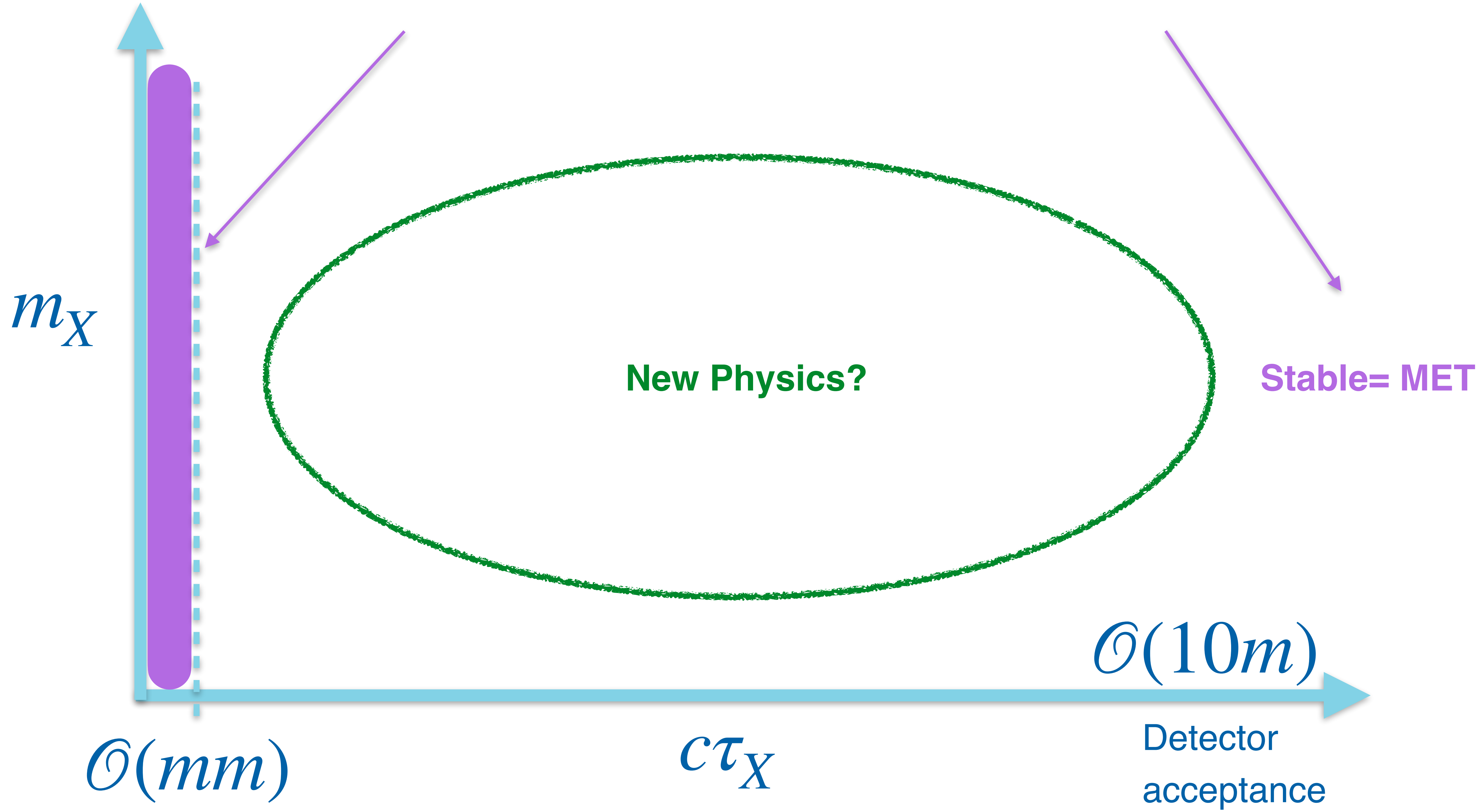
Physics Legacy

Technology Legacy

- Higgs and EWK Symmetry Breaking
- New Physics Probes
  - Dark Matter
  - SUSY (strong & EWK)
  - Exotics (new resonances…)
- **Probing Long-lived Particles**

New Physics at the LHC: long-lived particles

Up to now: large majority of experimental work



Long-lived Particles at the LHC (II)

Lifetime Mechanism

New Physic Model

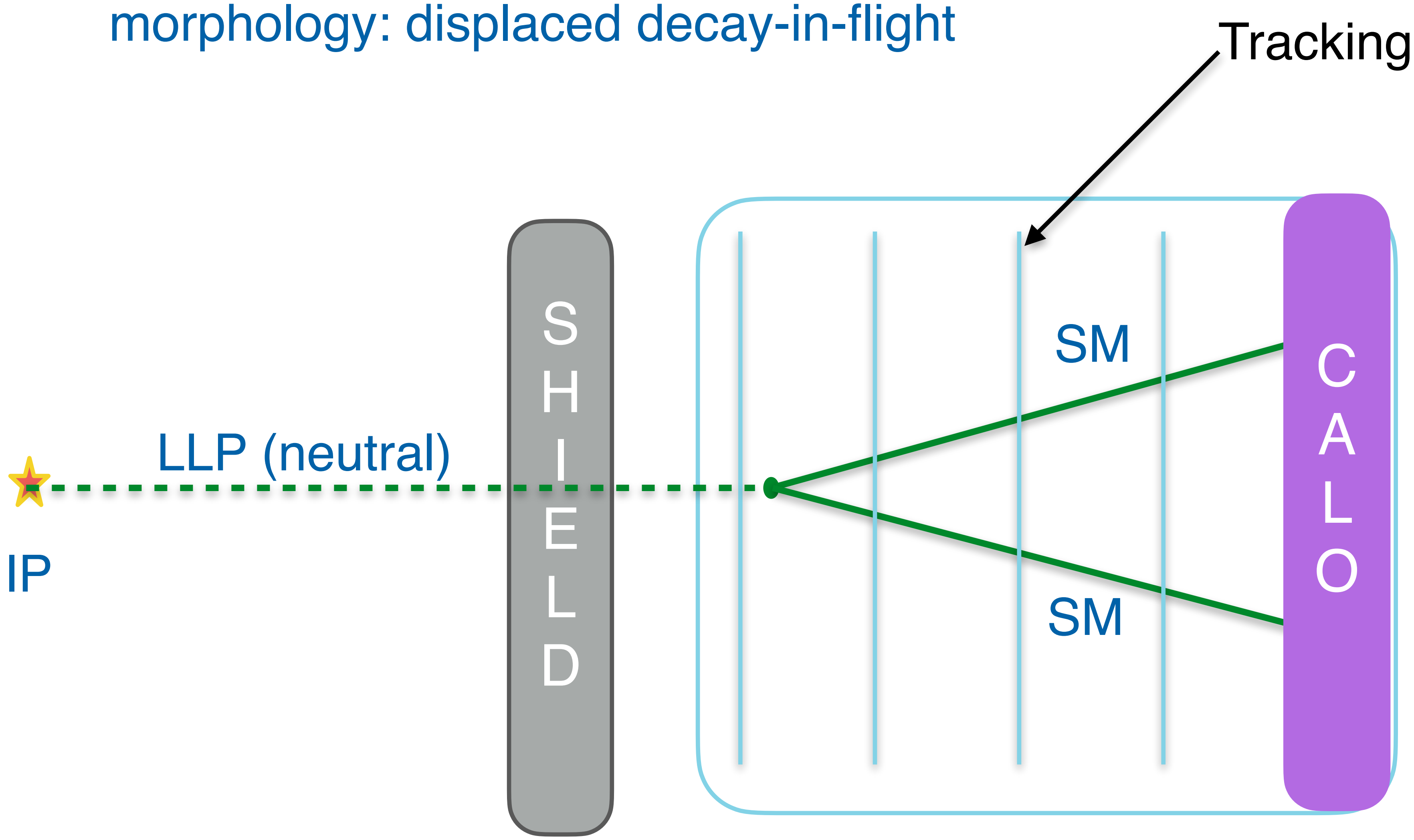
		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

- **Long-lived particles ubiquitous in BSM Physics**

Detecting Long-lived Particles

Generic LLP signature

morphology: displaced decay-in-flight



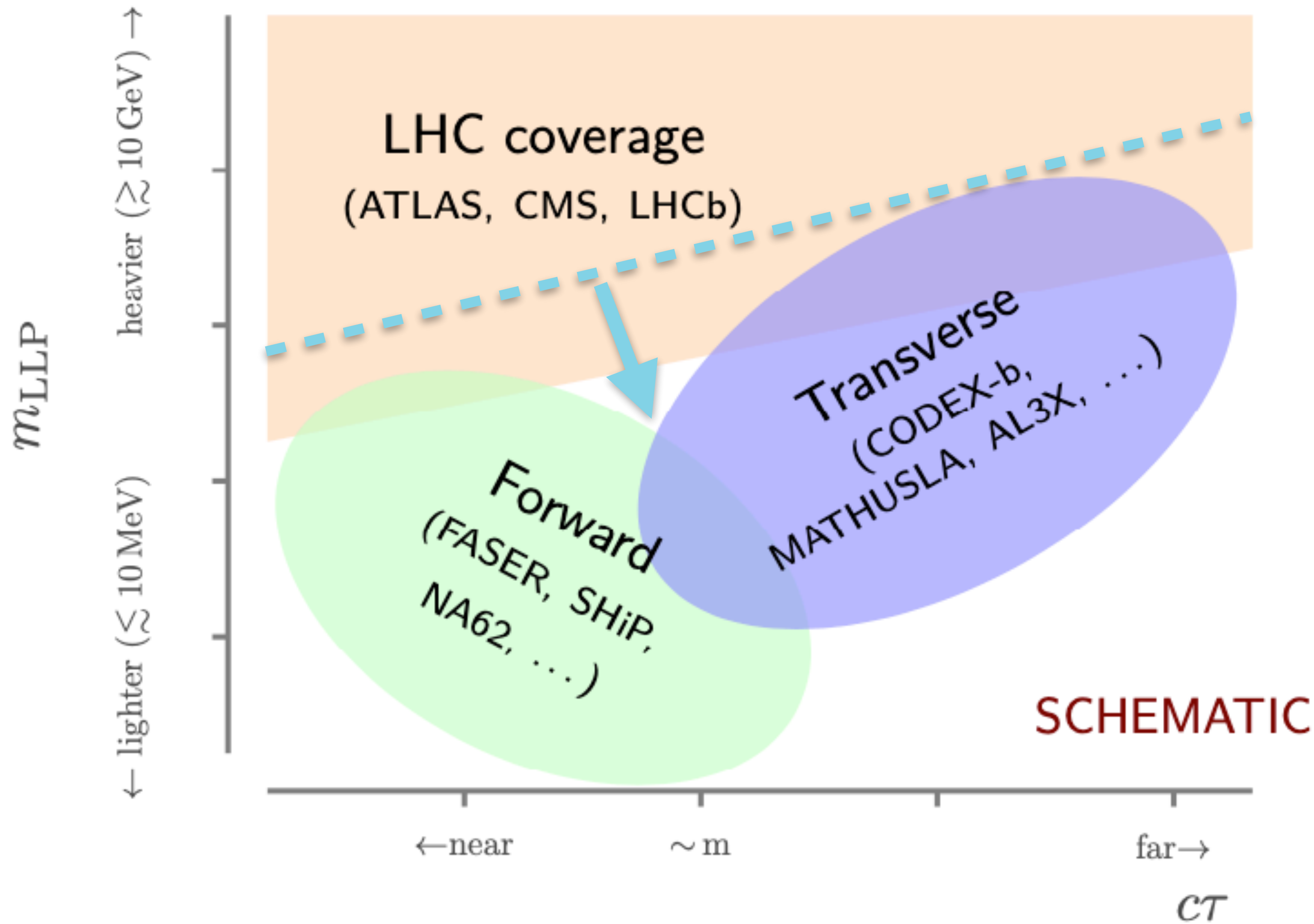
signature: displaced vertex

Experimental Considerations

- Center-of-mass energy
- Fiducial Volume
- Distance from IP
- Triggering
- Irreducible background

CMS: Critical Role on Long-lived Particles

arxiv:1911.00481 — CODEX-b

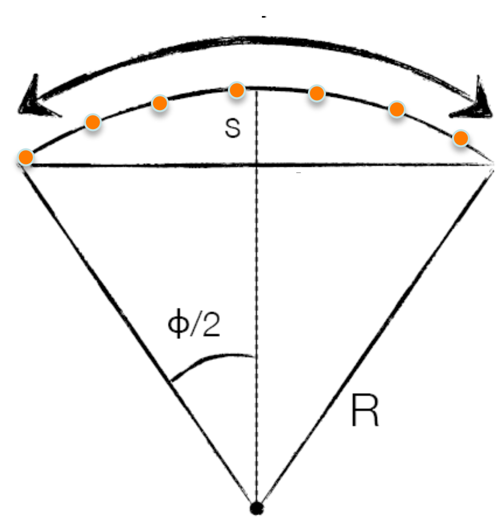


- **How to unlock CMS' full LLP potential?**
- **How far can we push mass and lifetime?**

Technology Legacy: Silicon Tracker

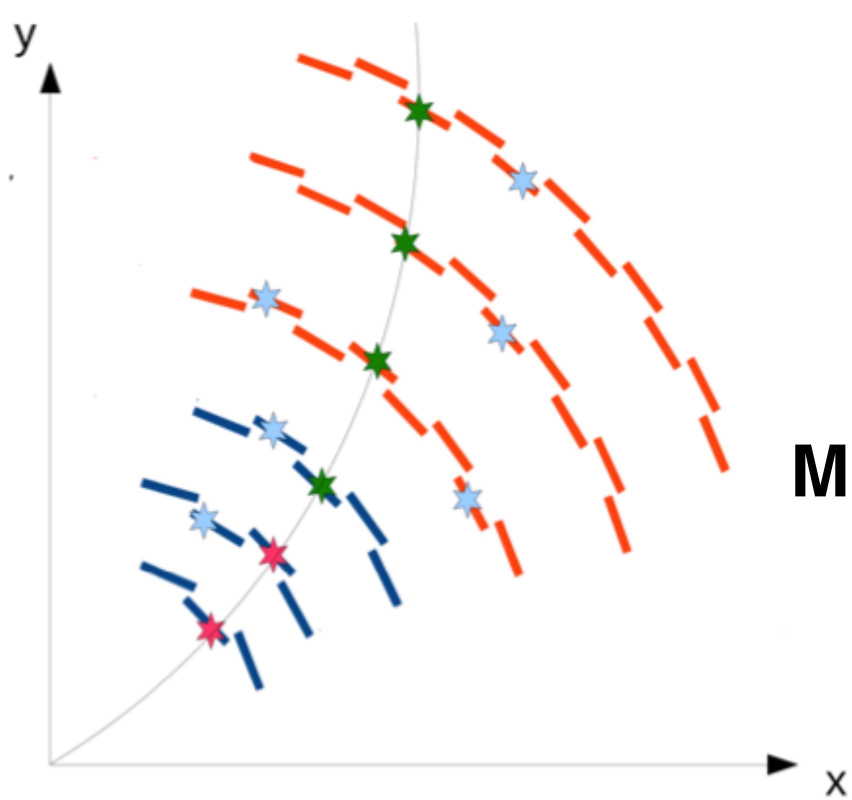
$$\frac{\sigma_p}{p} \sim p \frac{\sigma_s}{BL^2}$$

Long path-length



"s" means curvature

Example: 1 TeV → s ~250 μm ⇒ σ_s ~ 25 μm (10% uncertainty)



R.L. Gluckstern
NIM 24 (1963) 381

$$\sigma_s = \frac{\sigma_{r\phi}}{8}\sqrt{\frac{720}{N+5}}$$

Many layers (>10) with **outstanding intrinsic resolution**

This design WILL enable LLP searches in tracker

Fermilab

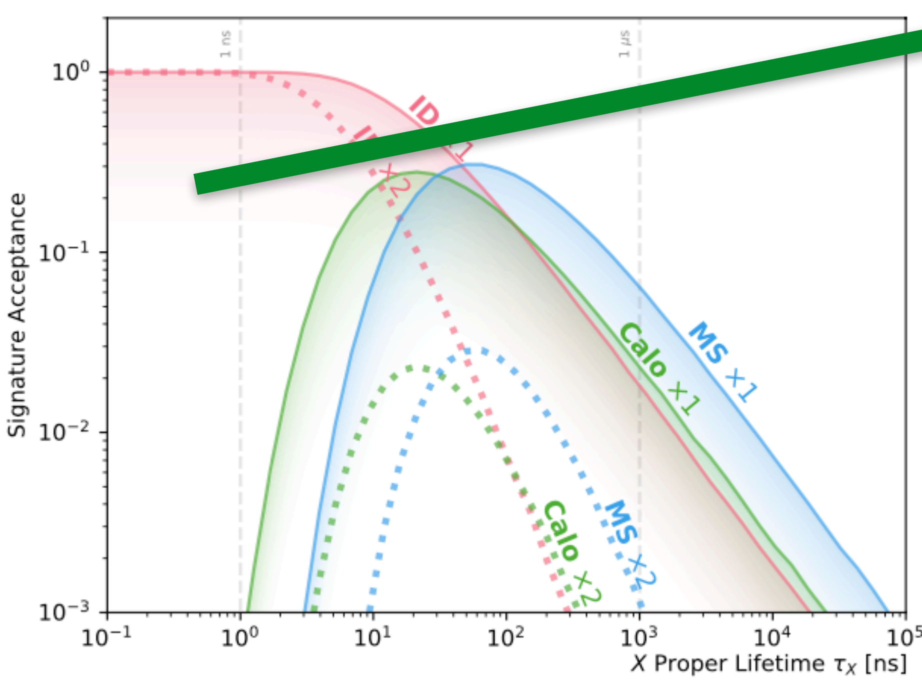
Technology Legacy: Silicon Tracker

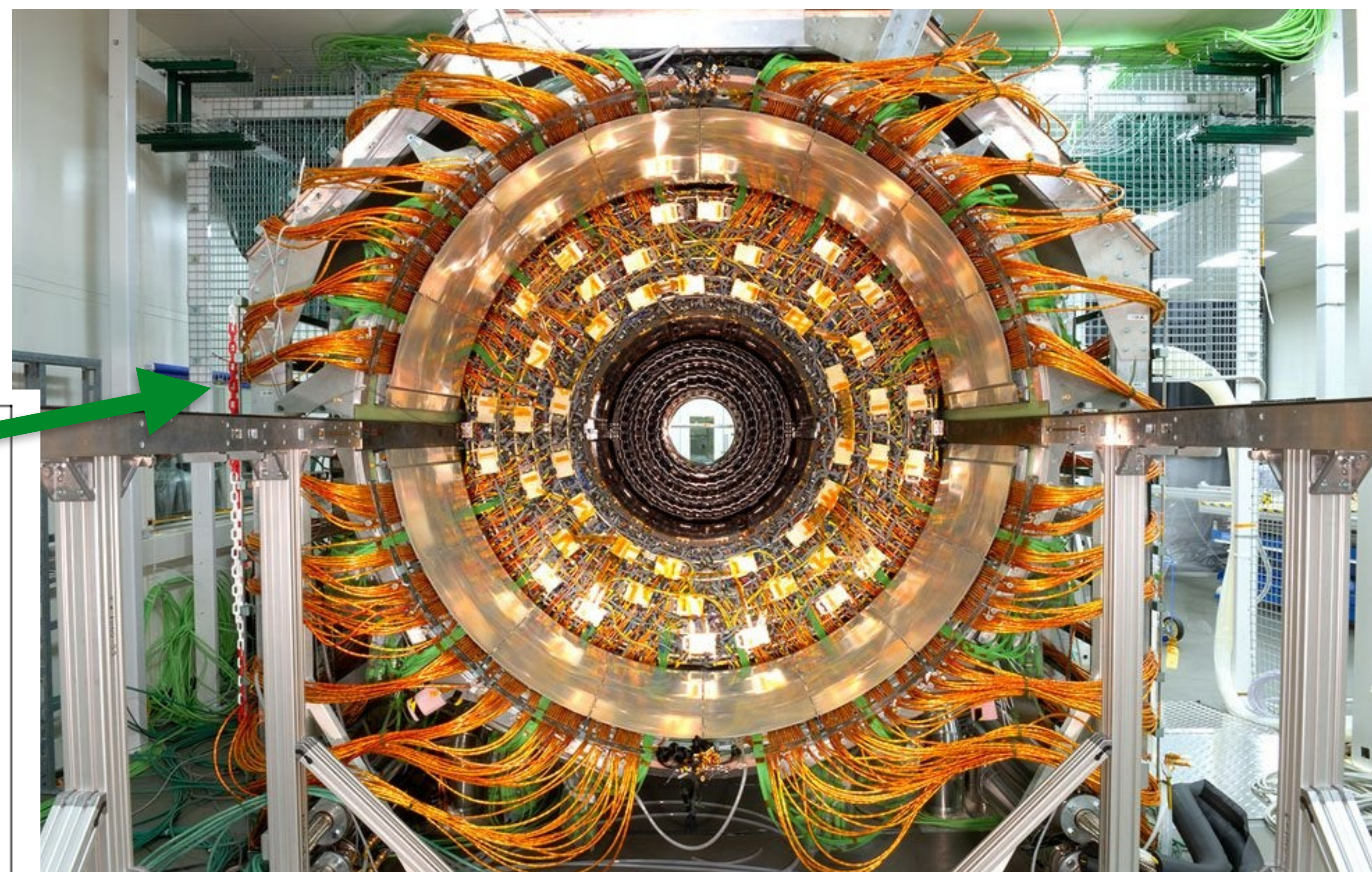
World's largest all-silicon tracker

Momentum resolution: 1-3% for 1-100 GeV

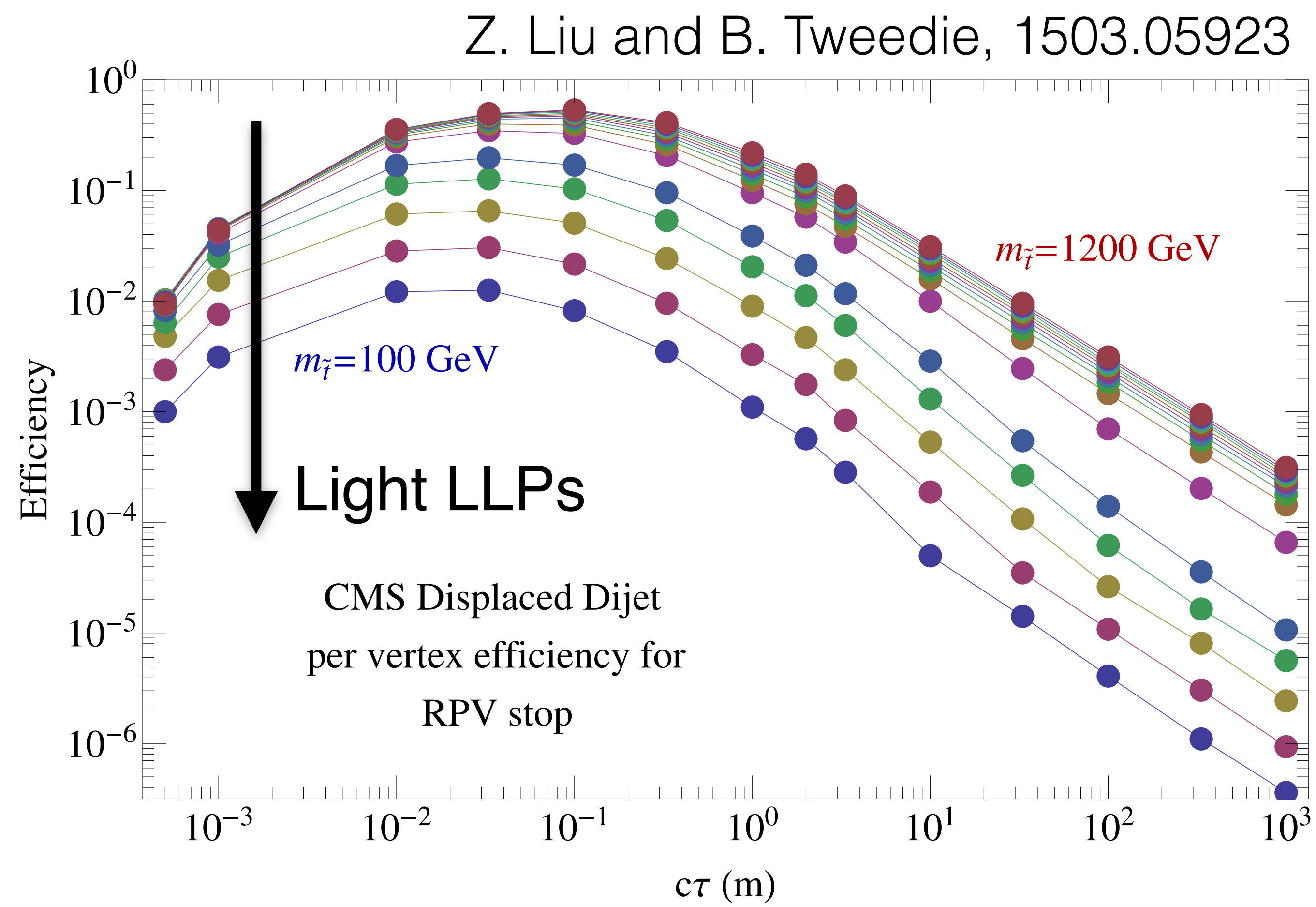
Impact parameter resolution: ~few 10μm

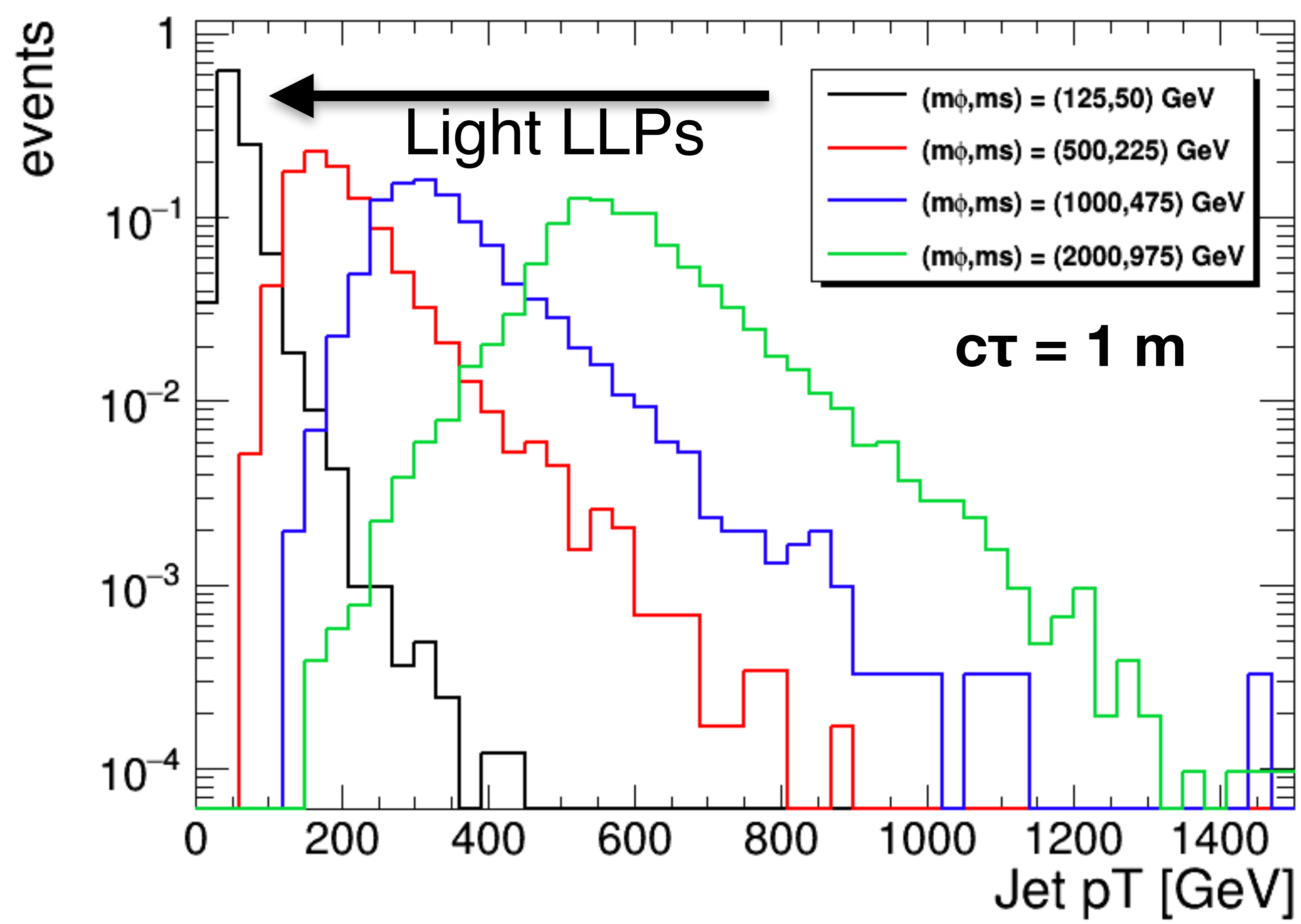
Ideal for displaced-vertex LLP signature





Triggering on Long-lived Particles

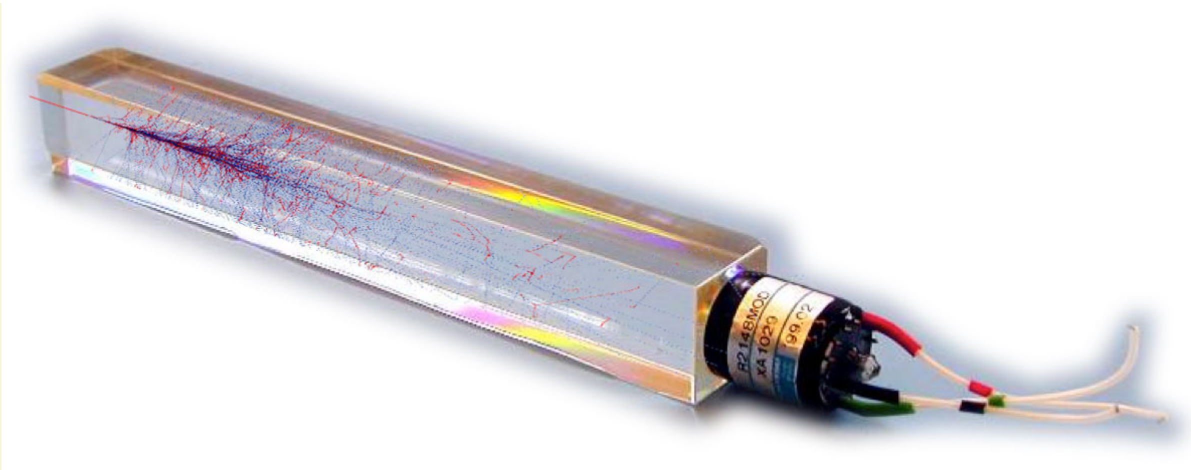




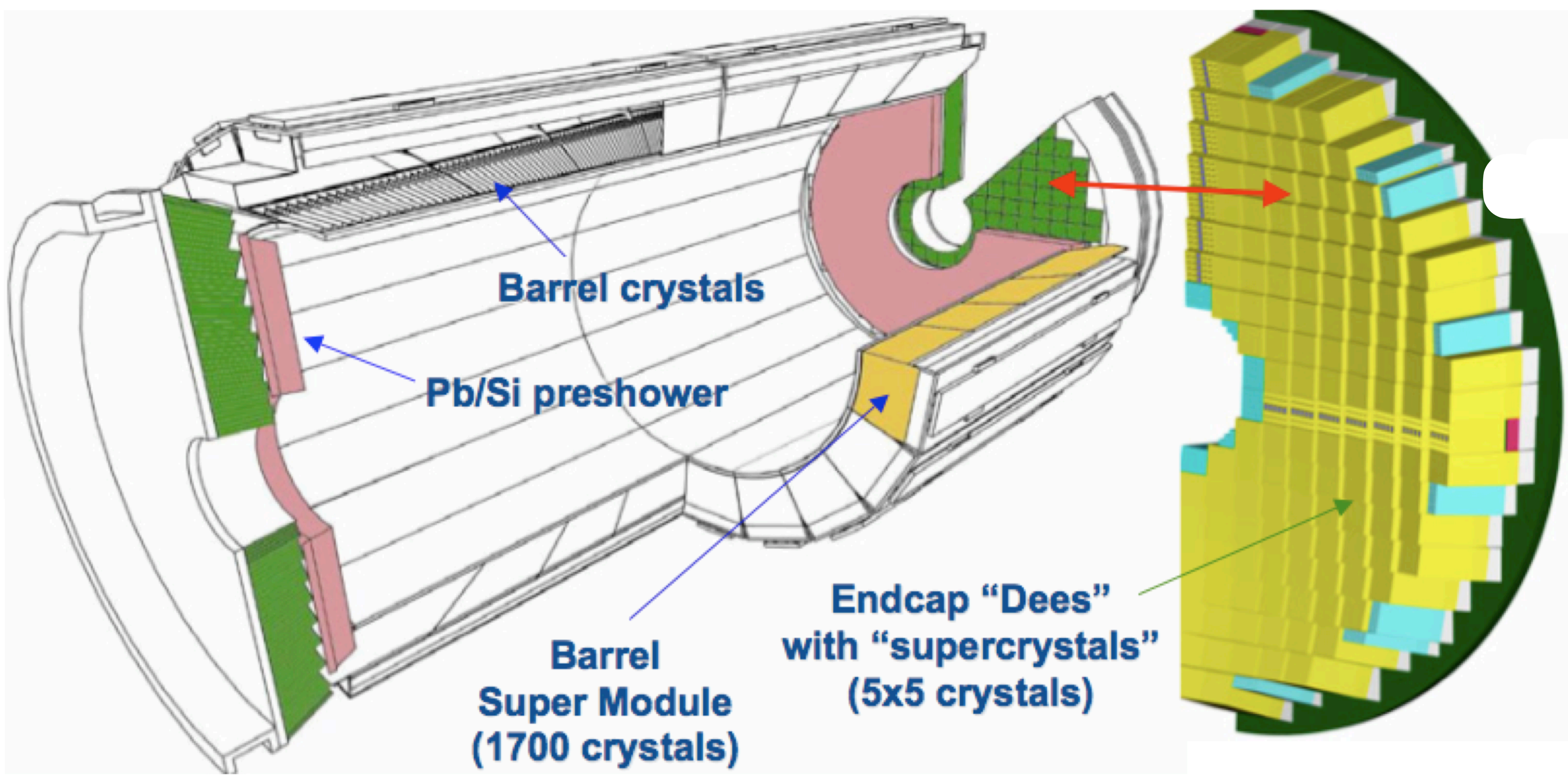
Large Efficiency drop for light LLPs

- Very soft (displaced) jets — well **below current thresholds**
- **Critical need** for dedicated triggers — **Run3 opportunity**

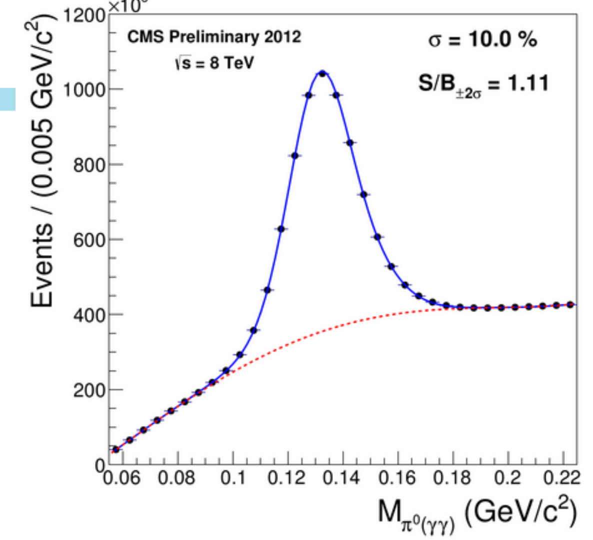
Technology Legacy: Crystal Electromagnetic Calorimeter



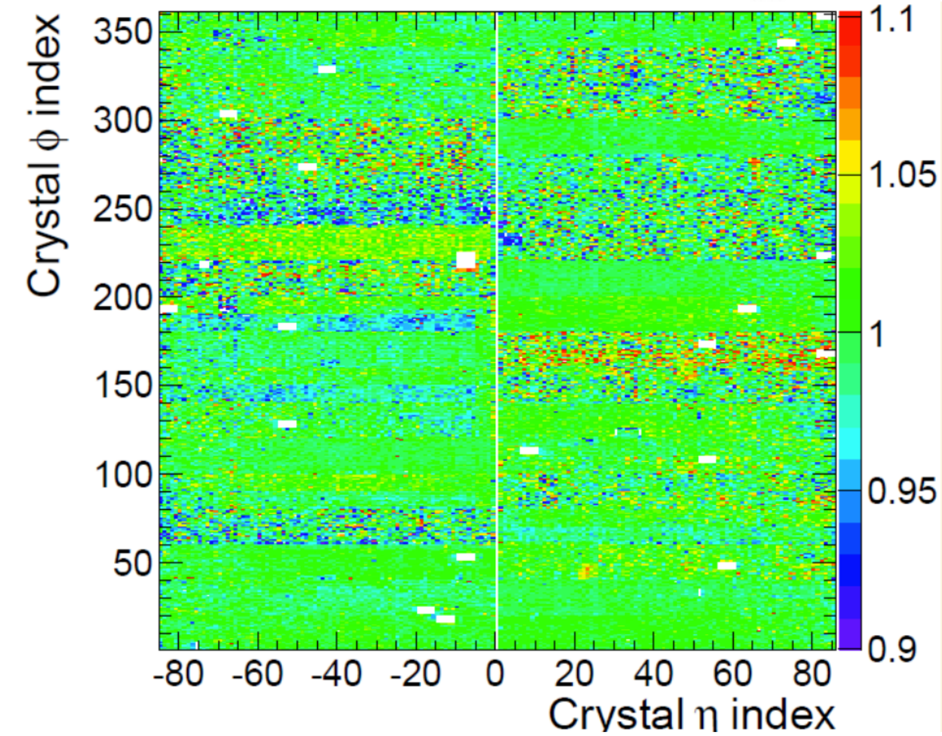
- Designed for excellent energy resolution
- Crucial role in H→γγ observation
- Resulted in outstanding **time resolution**
  - **LLP enabler**

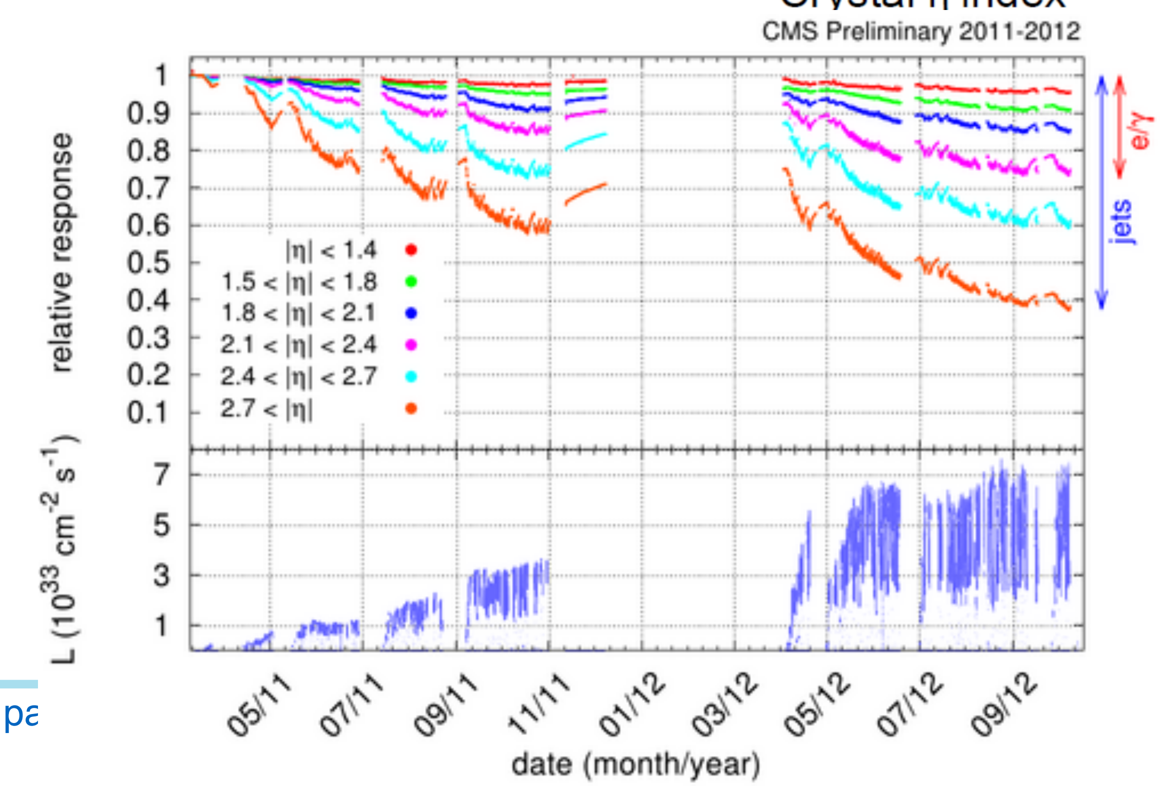


Technology Legacy: ECAL Calibrations



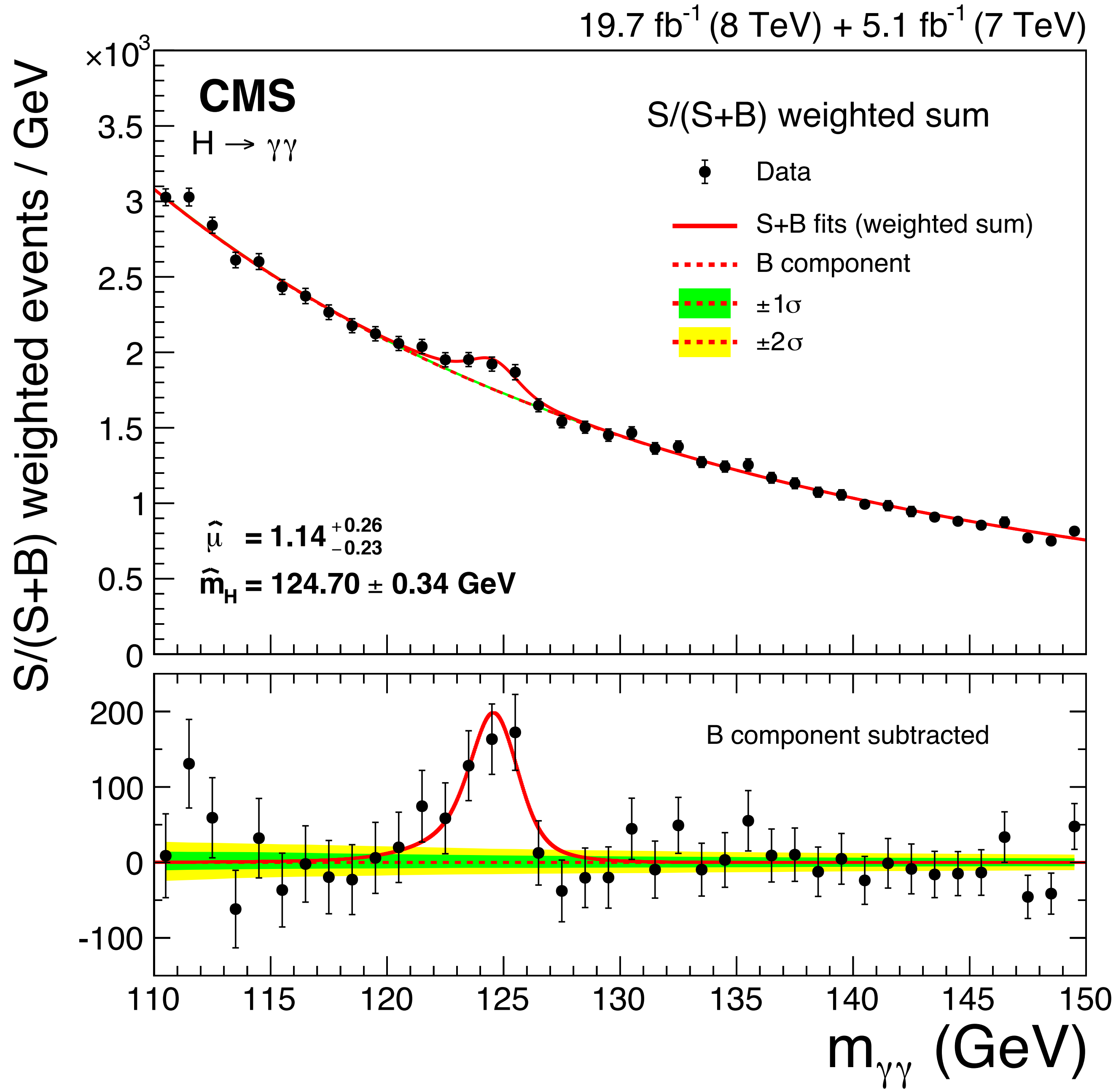
- In-situ inter-calibrations using resonances, geometric symmetries, electron E/p
  - **For each of 75,000 crystals to 0.5% precision**
- Live monitoring of crystal transparency with laser: **once every 40 min for each crystal**
- Corrections for local containment, module boundaries, shower shape, pileup, etc.





Each is a colossal task

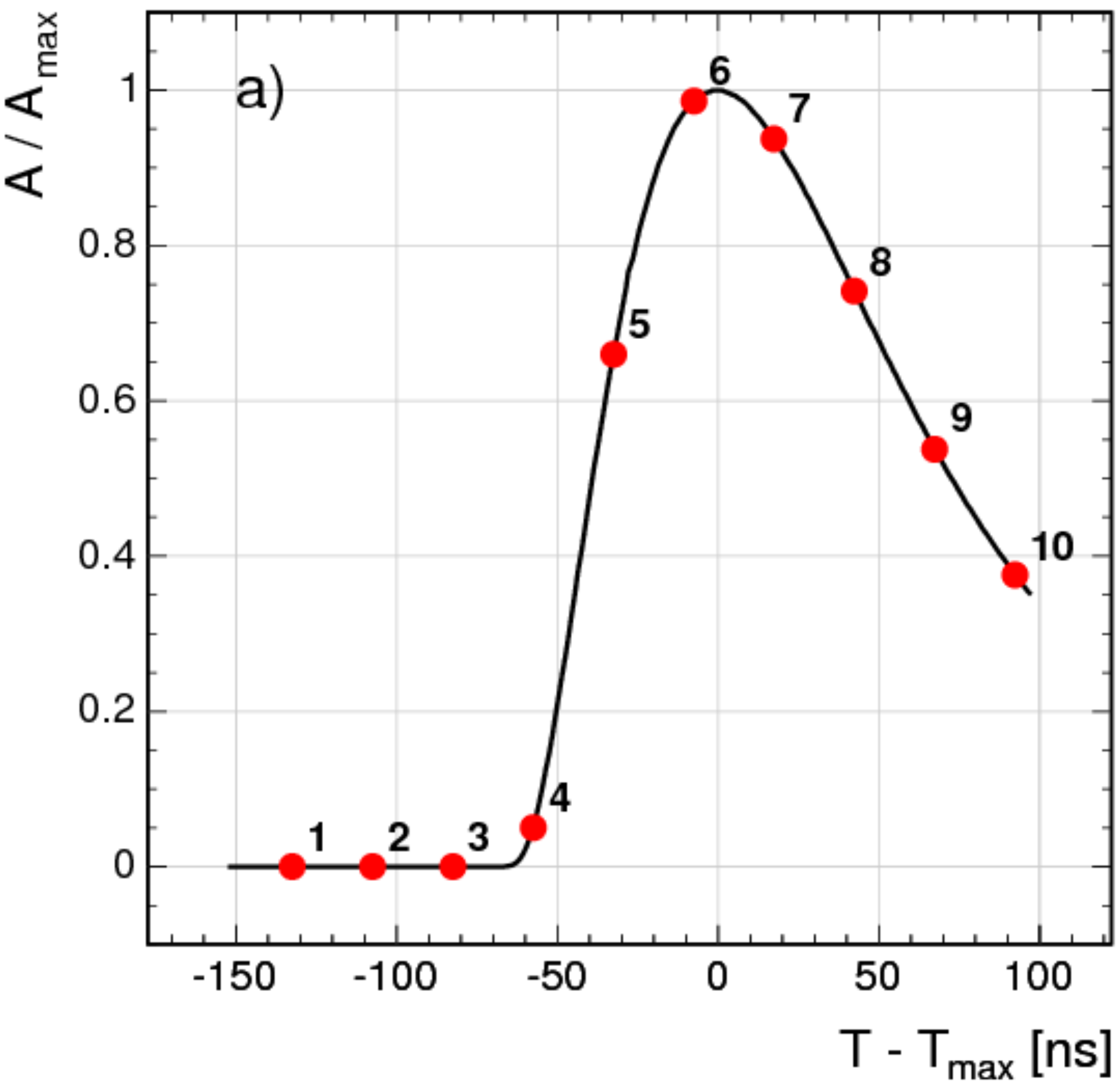
Physics Legacy: H→γγ



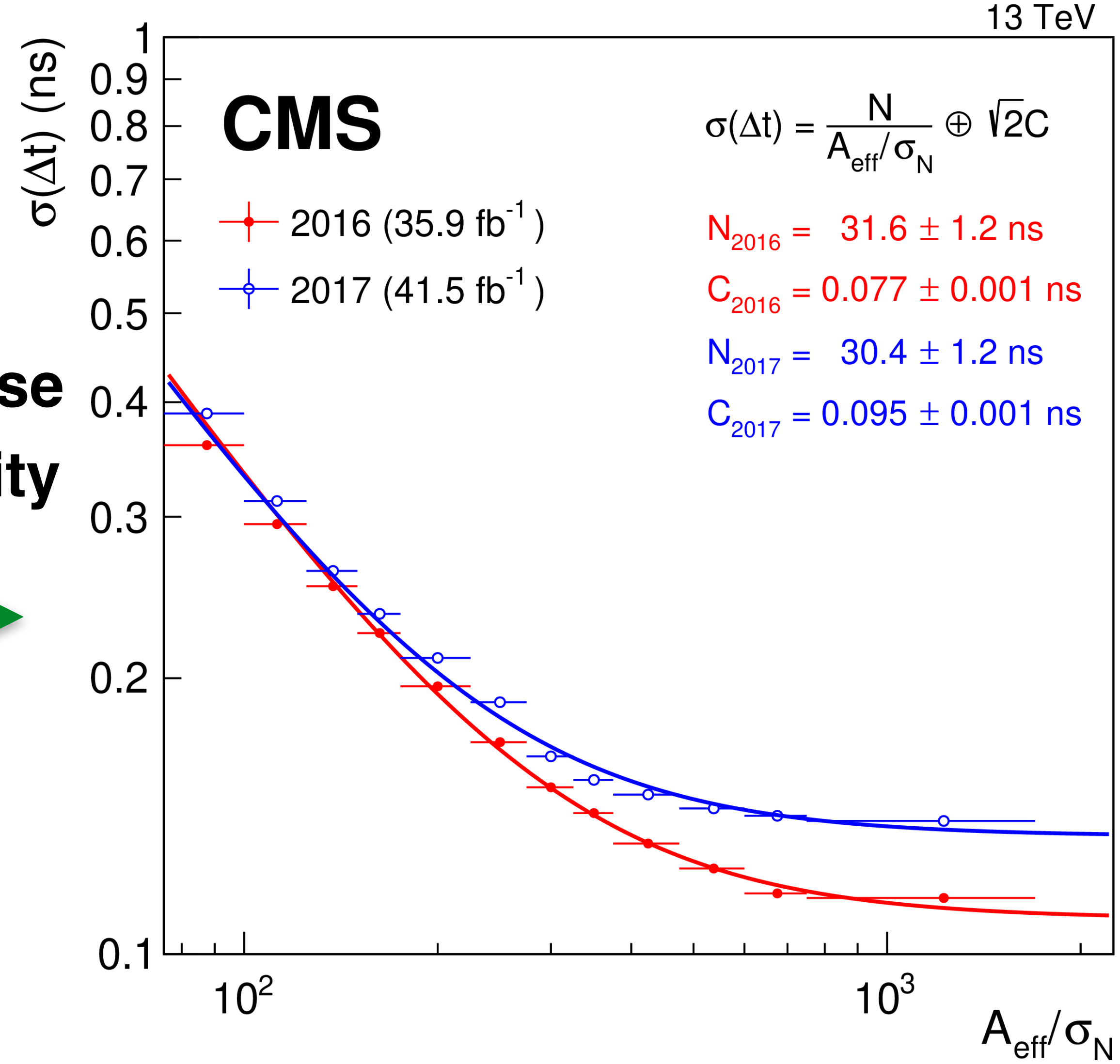
H→γγ observed @ 5.6σ significance

Physics Legacy (H→γγ) ⟹ Technology Legacy

Stringent H→γγ constraints required …



Excellent pulse shape stability

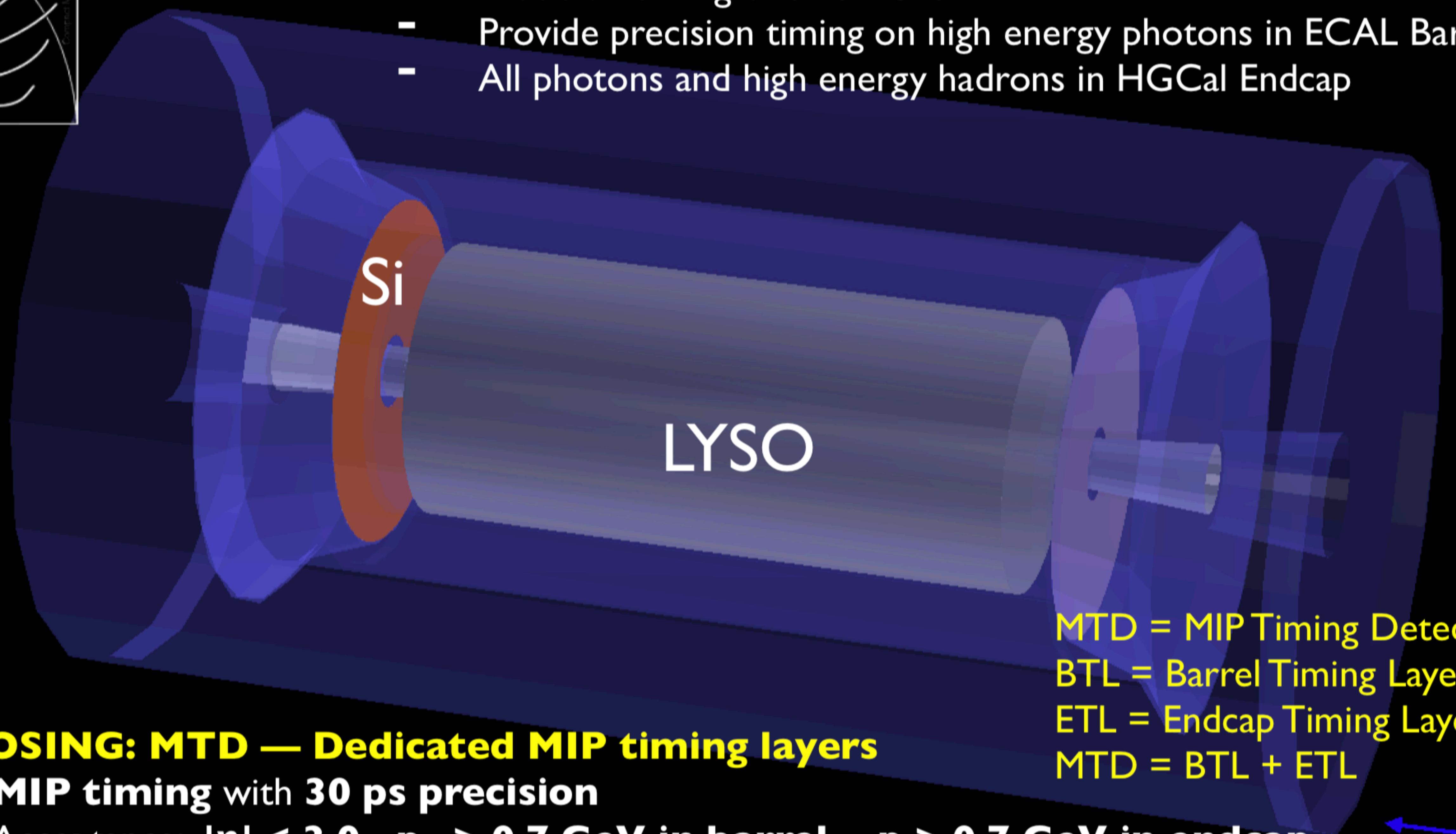


Time resolution of ~ 100 ps for energetic photons

Future Technology Legacy: Precision Timing

Calorimeter upgrades:

- Precision timing of **showers**
- Provide precision timing on high energy photons in ECAL Barrel
- All photons and high energy hadrons in HGCal Endcap



MTD = MIP Timing Detector
BTL = Barrel Timing Layer
ETL = Endcap Timing Layer
MTD = BTL + ETL

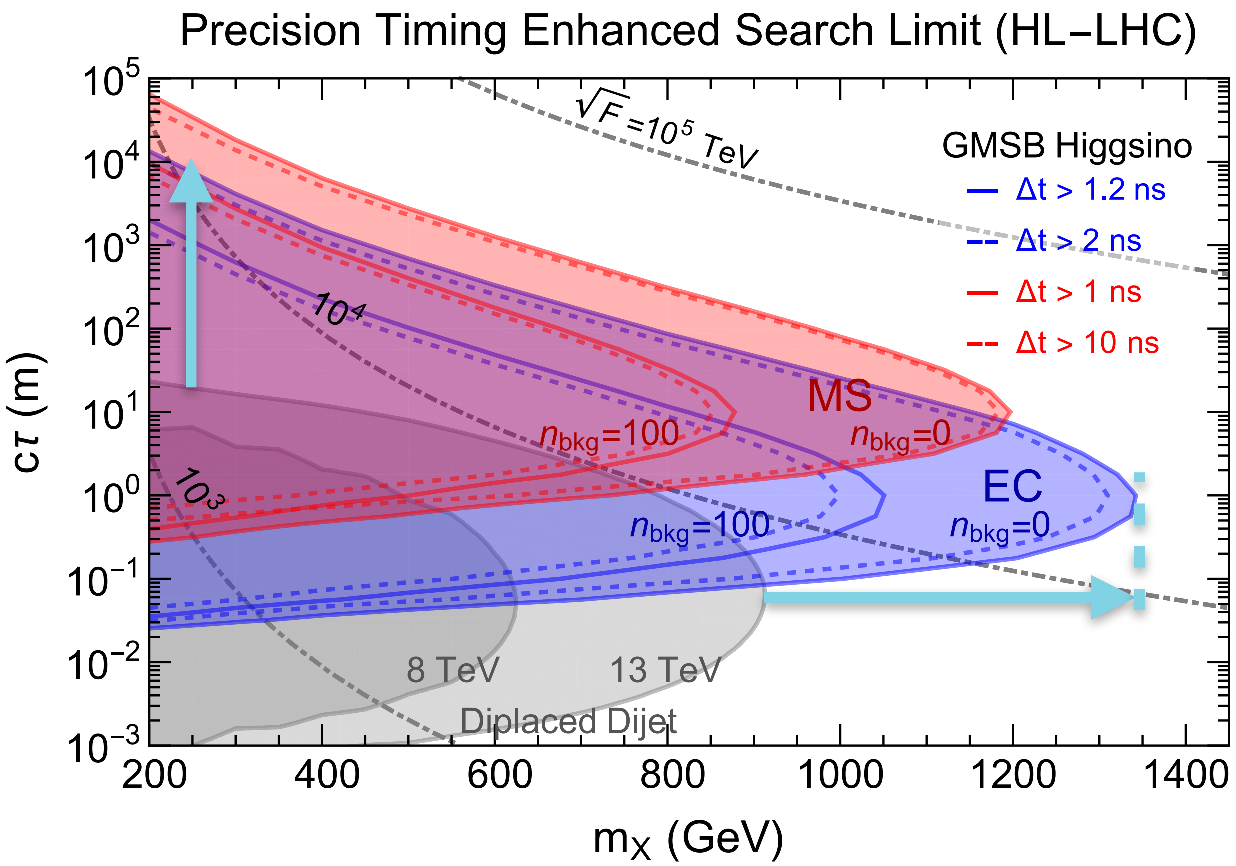
PROPOSING: MTD — Dedicated MIP timing layers

- **MIP timing** with **30 ps precision**
- Acceptance: **$|\eta| < 3.0$, $p_T > 0.7$ GeV in barrel, ~p > 0.7 GeV in endcap**
- Location: just outside the tracker

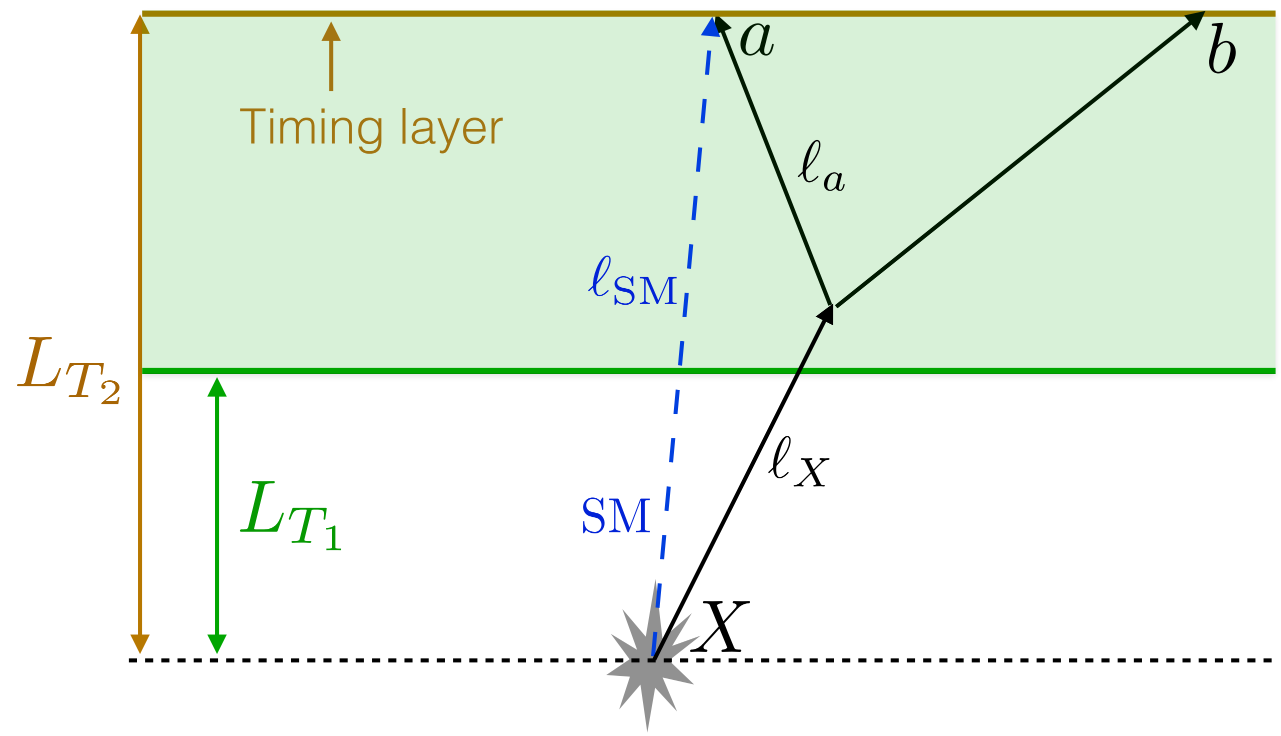
LLPs and Precision Timing

study by Zhen Liu et al.

https://arxiv.org/abs/1805.05957



$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{SM}}{\beta_{SM}}$$

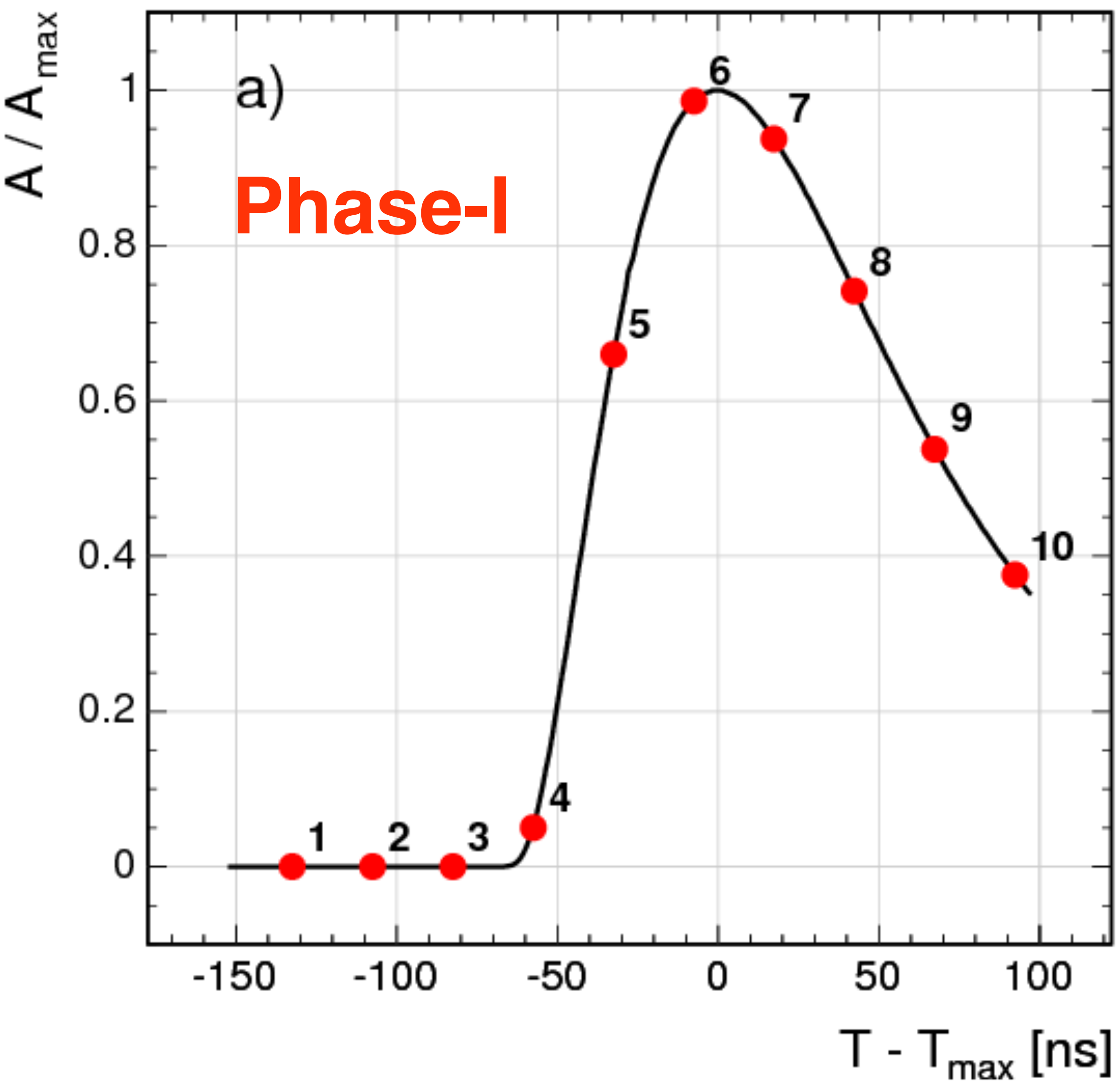


Timing results in large gains in $c\tau$ and mass reach

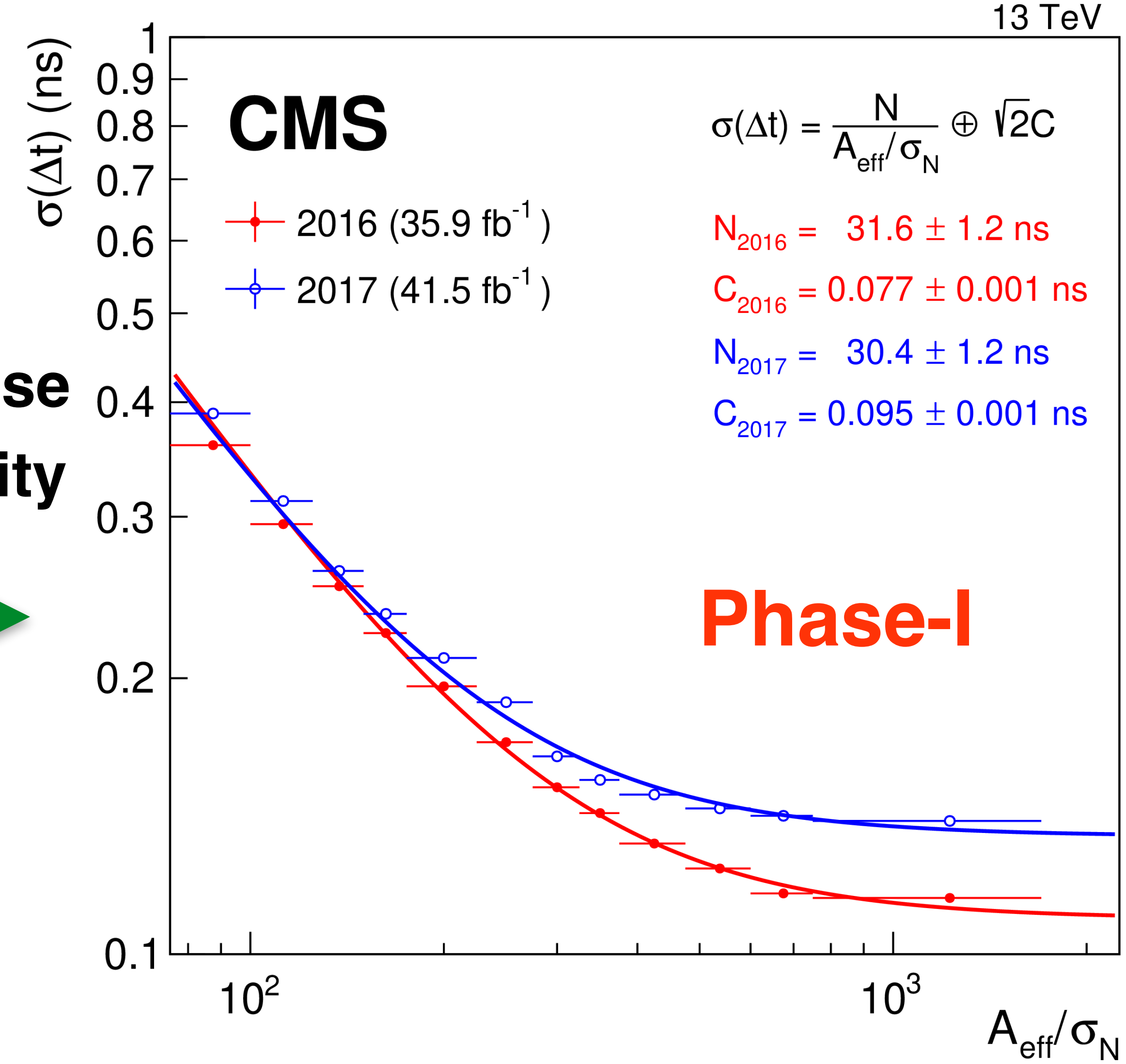
Needs L1-trigger to fully exploit LLP potential

Physics Legacy ($H \to \gamma\gamma$) $\Longrightarrow$ Technology Legacy

Stringent $H \to \gamma\gamma$ constraints required …



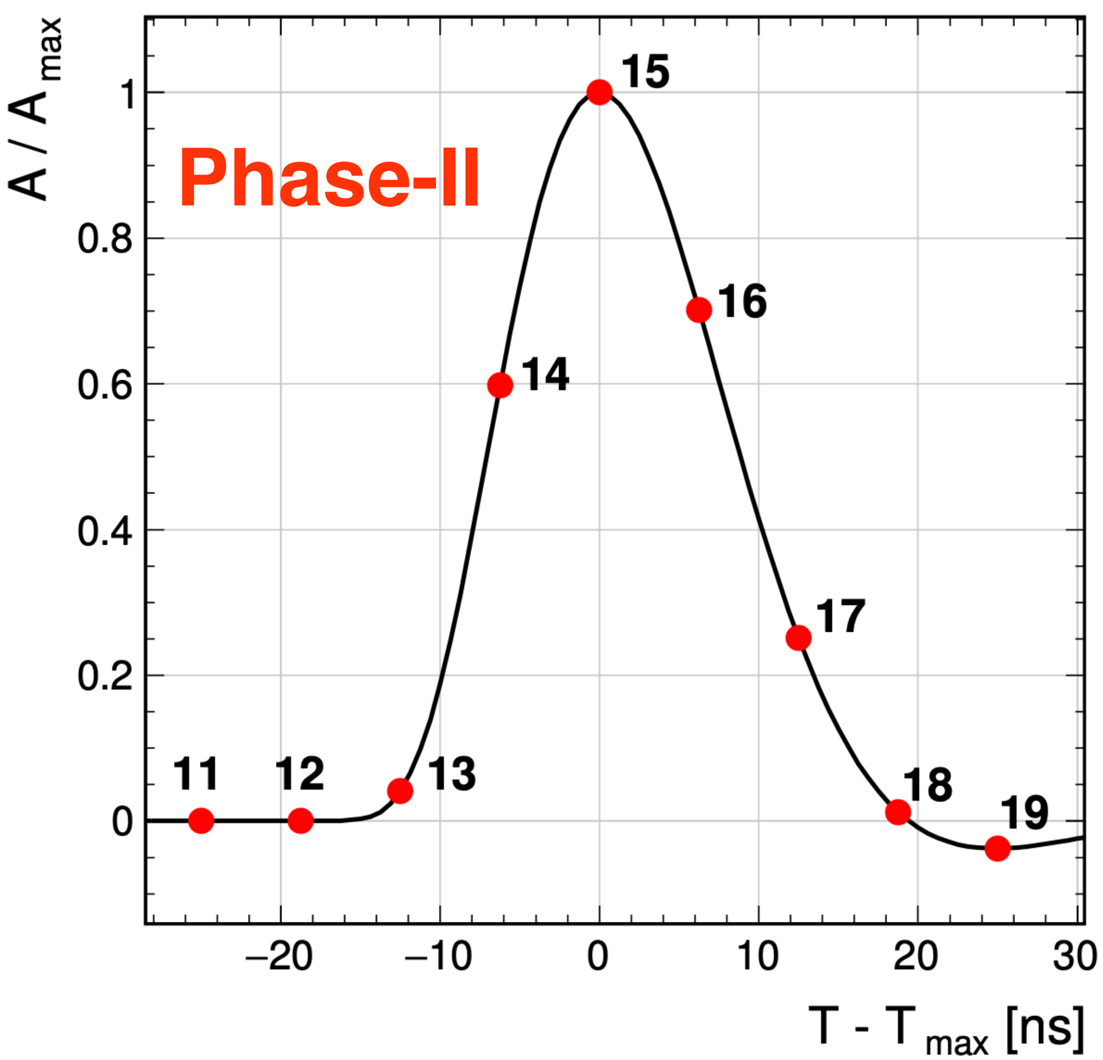
Excellent pulse shape stability



Time resolution of ~ 100 ps for energetic photons

Physics Legacy (H→γγ) ⟹ Technology Legacy

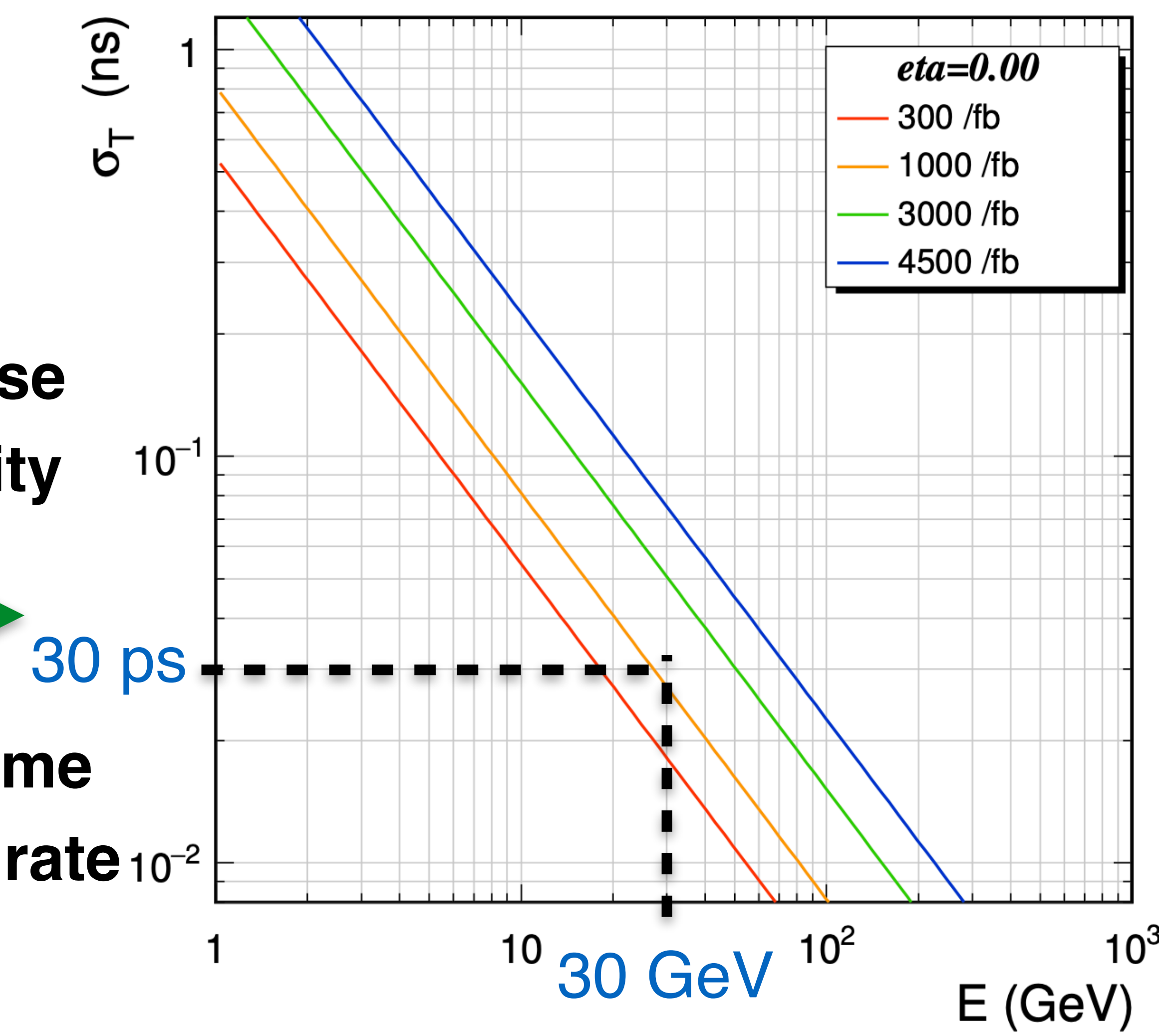
Stringent H→γγ constraints required …



Excellent pulse shape stability

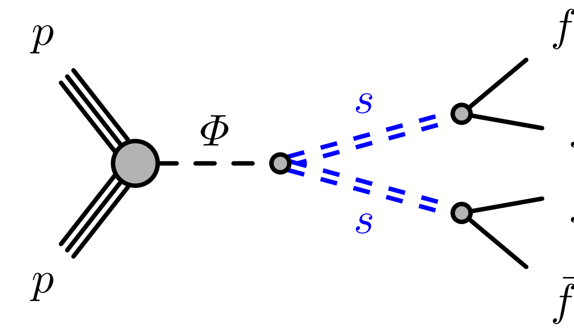
Fast-shaping time

High sampling rate



Time resolution of **~ 30 ps** for energetic photons

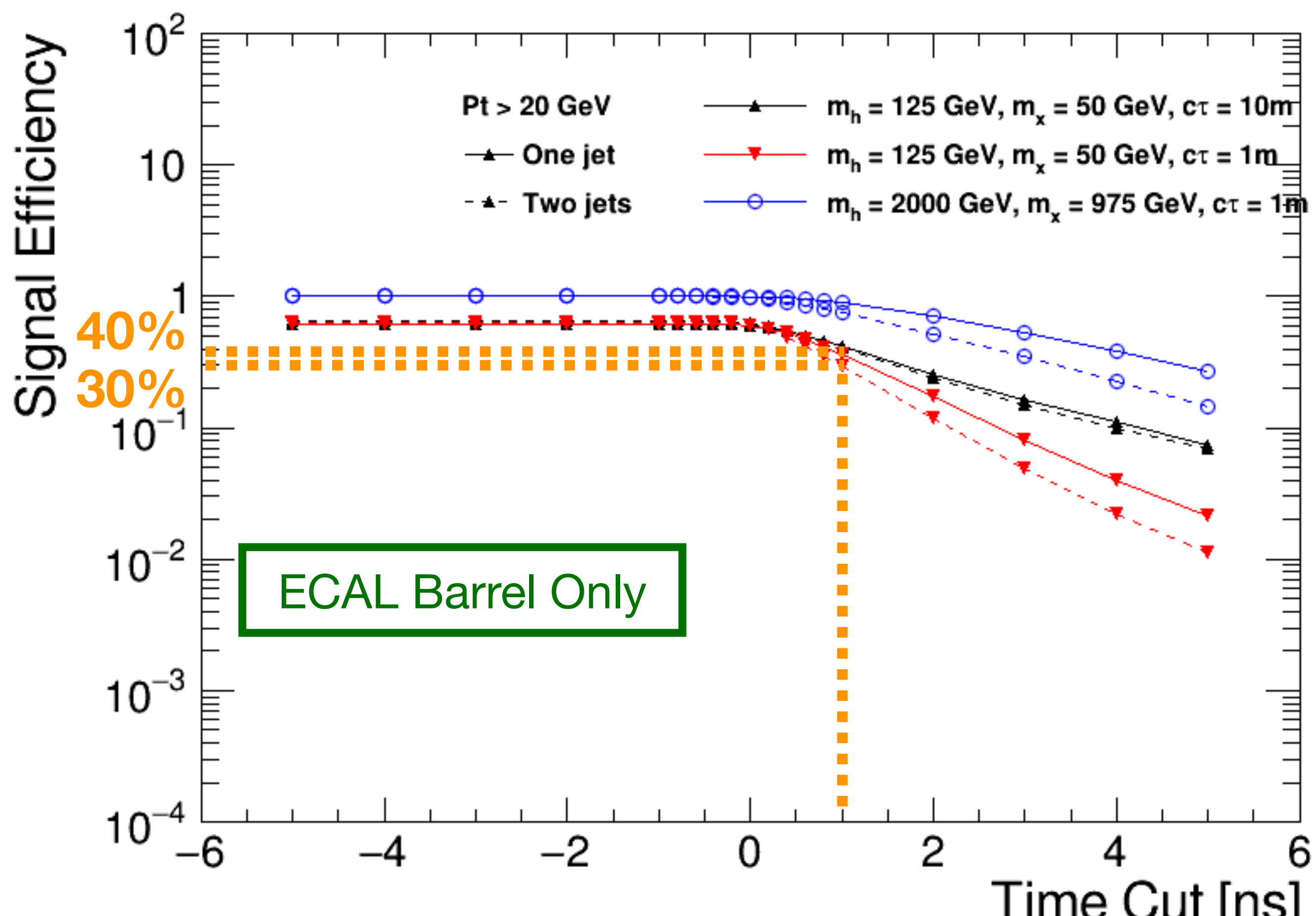
LLPs and Precision Timing



- Use **Timing** (MTD or ECAL) to tag Jets at L1
  - 30 ps for 20 GeV neutral energy deposits in ECAL
  - 30 ps for MIPS

M_h = 125 GeV

M_x = 50 GeV, $c\tau$ = 1m



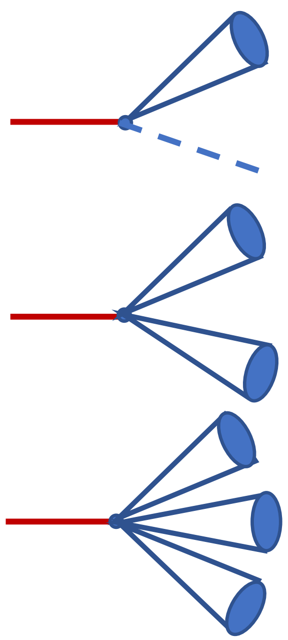
- Jet pT > 20 GeV and EB time > **1ns**
- One jet trigger → signal efficiency is around **40%**

Fermilab

LLP to Displaced Dijets in the Tracker Volume

EXO-18-007

LLP decays in tracker volume → Secondary vertex



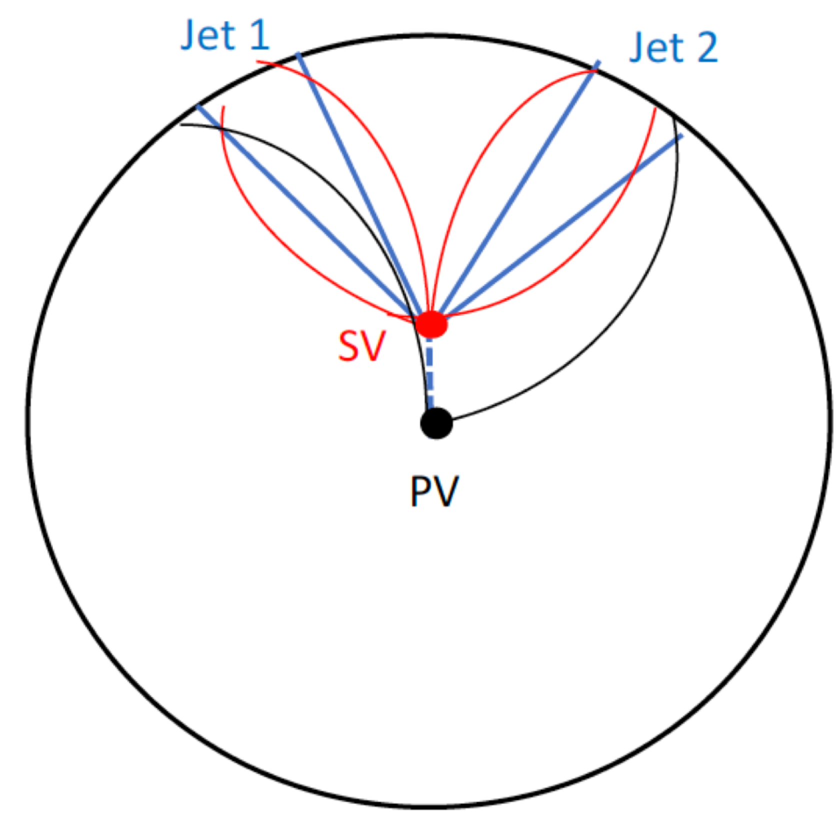
X→j+lepton/MET

X→jj+...

X→jjj+...

Utilize jet, track and SV information to discriminate displaced-jet signatures from backgrounds.

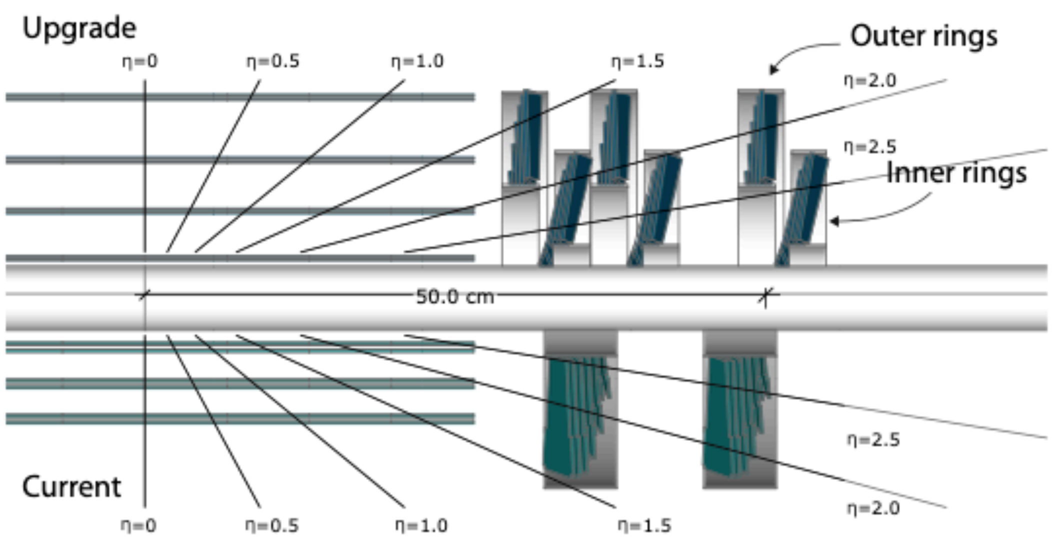
Doesn't require the existence of two displaced vertices, one vertex is enough



- **Offline Calo H_T and Jet Selection:**
  Calo H_T>400GeV, Calo jets p_T>50GeV, |eta|<2.0

- **Secondary vertex reconstruction**
  - Select the tracks associated with the dijet candidate, and not compatible with the primary vertex (IP2D>0.5mm, $IP2D_{sig}$>5.0);

CMS Technology Legacy: Phase1 Tracker Update



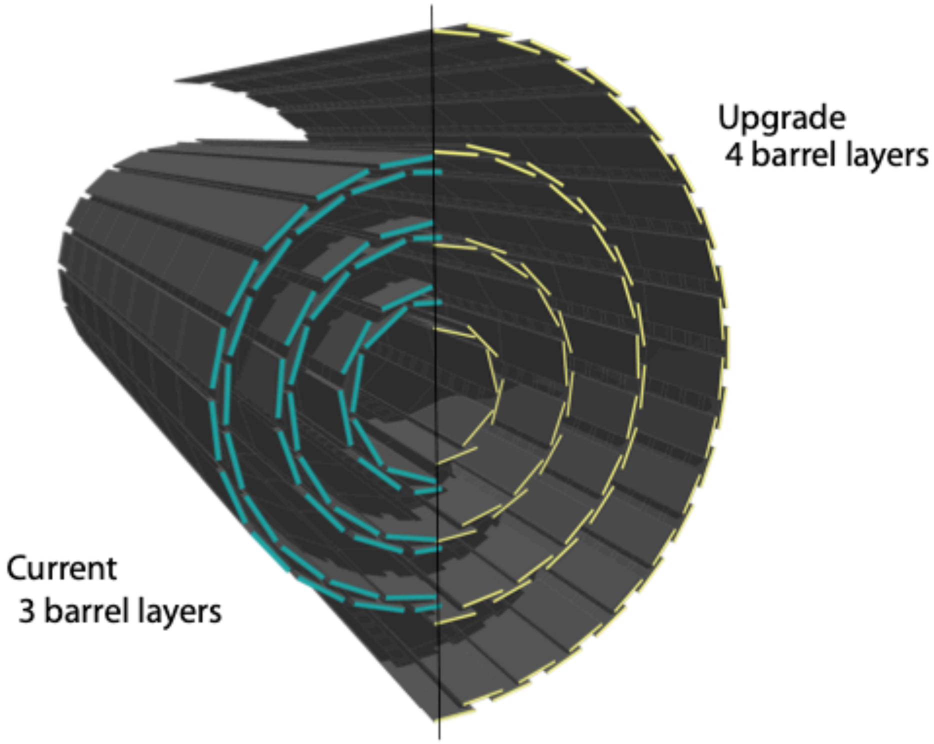
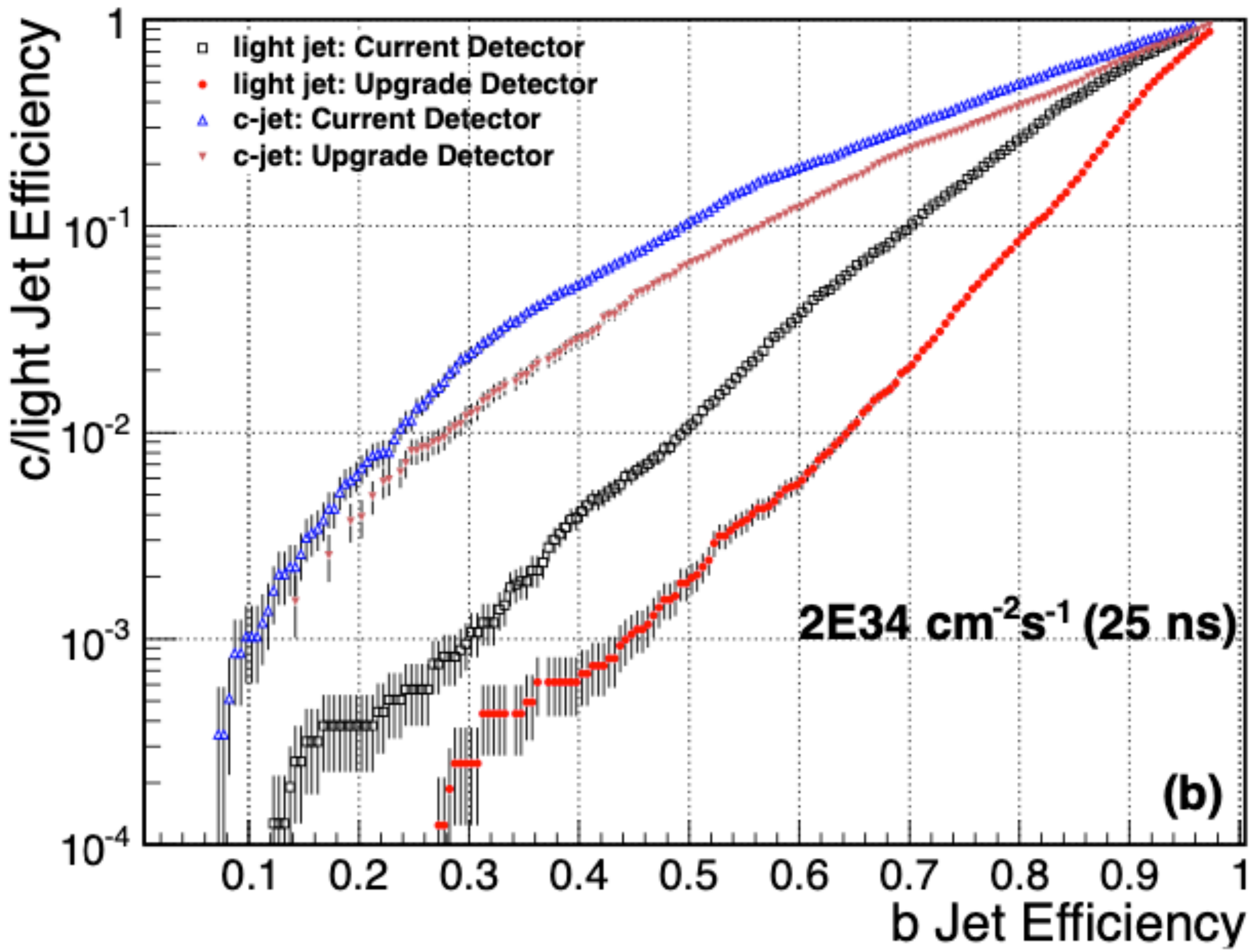


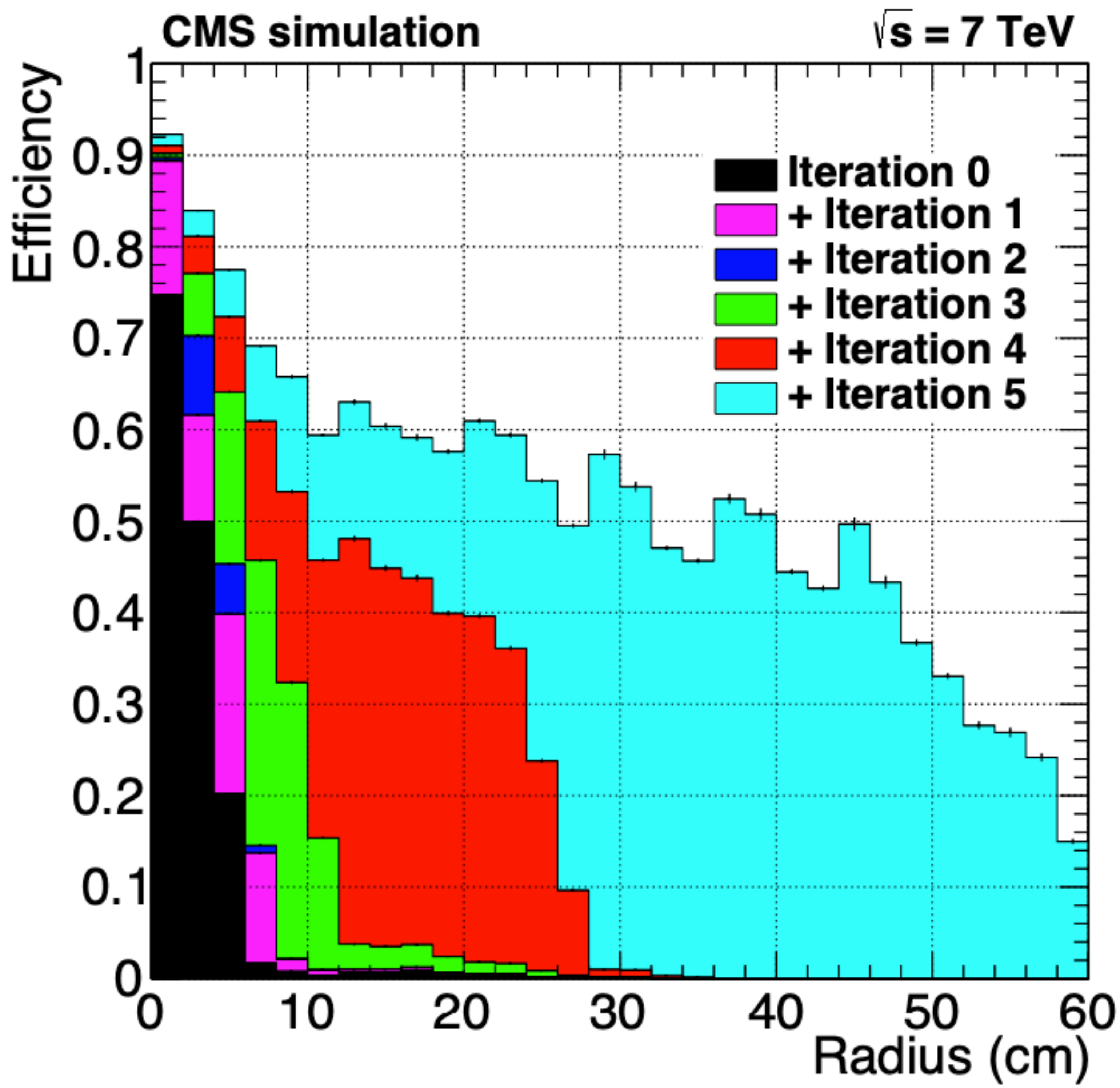
Figure 2. Left: Conceptual layout comparing the different layers and disks in the current and upgrade pixel detectors. The disks are placed in order to maximize the 4-hit η coverage. Right: Transverse-oblique view comparing the pixel barrel layers in the two detectors.

CMS Technology Legacy: Phase1 Tracker Update



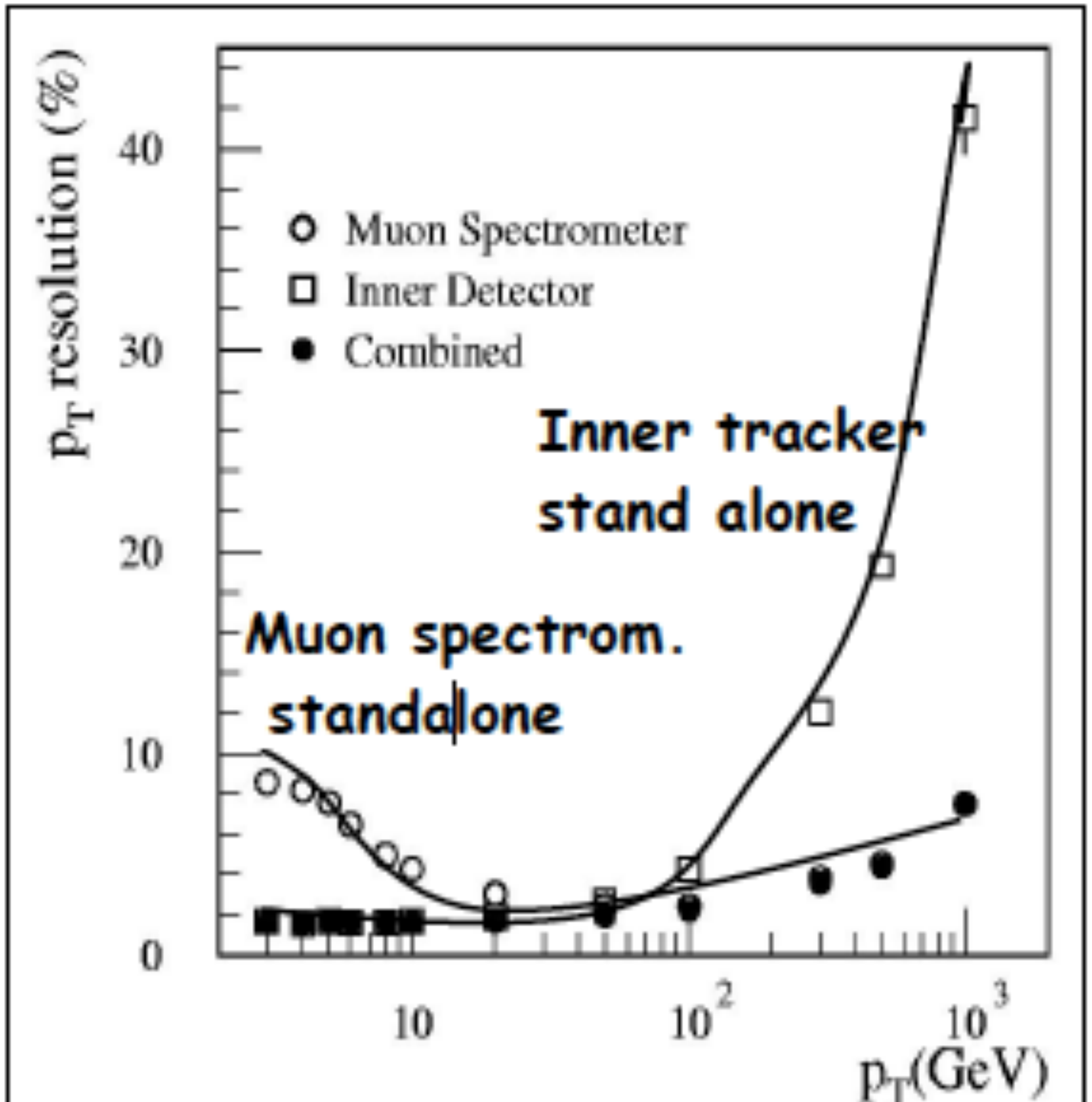
30% (rel) increase b-tagging efficiency @ 1e-2 light fake rate

CMS Technology Legacy: Iterative Tracking

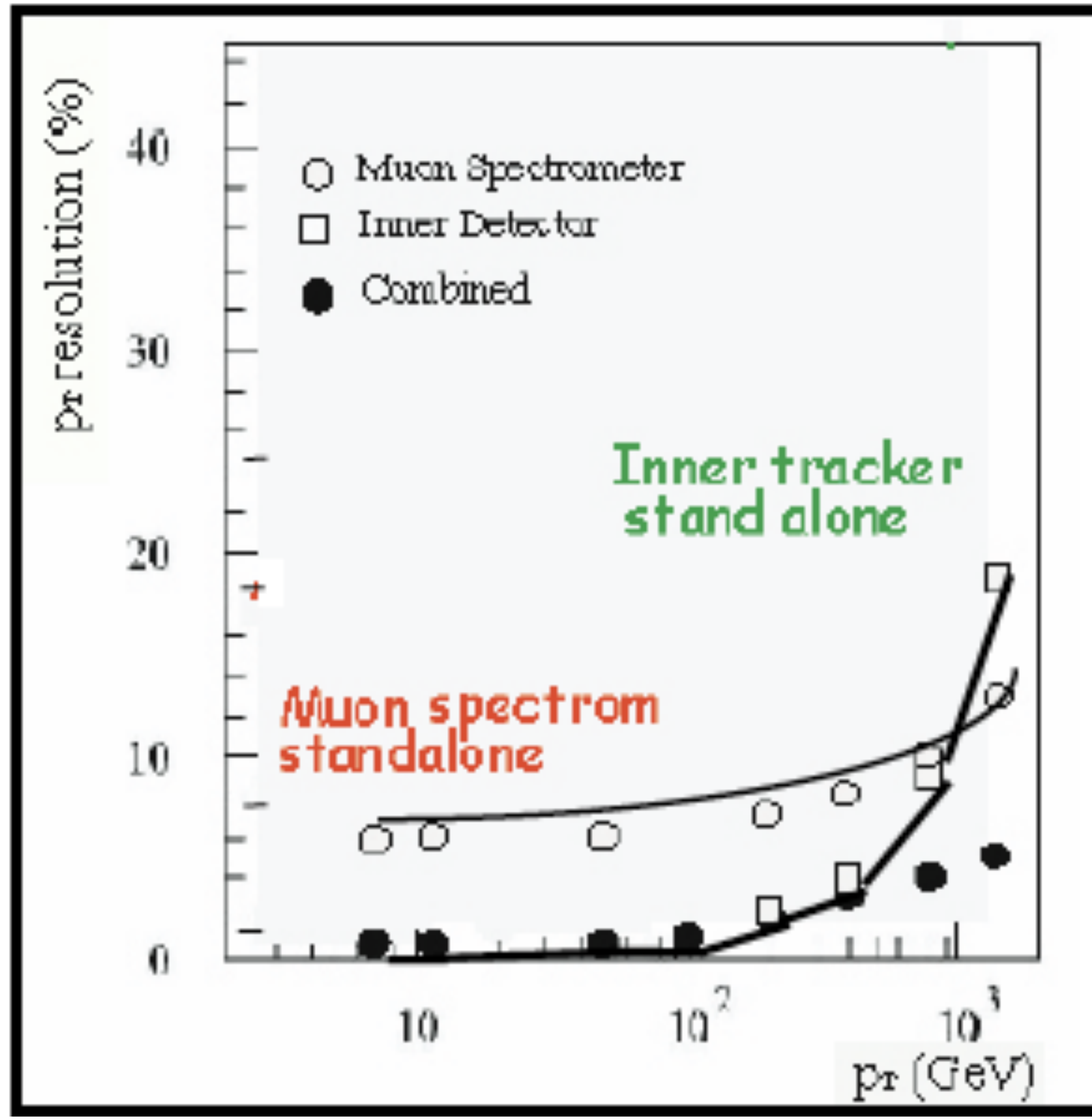


CMS Technology Legacy: Muon Momentum Resolution

ATLAS



CMS

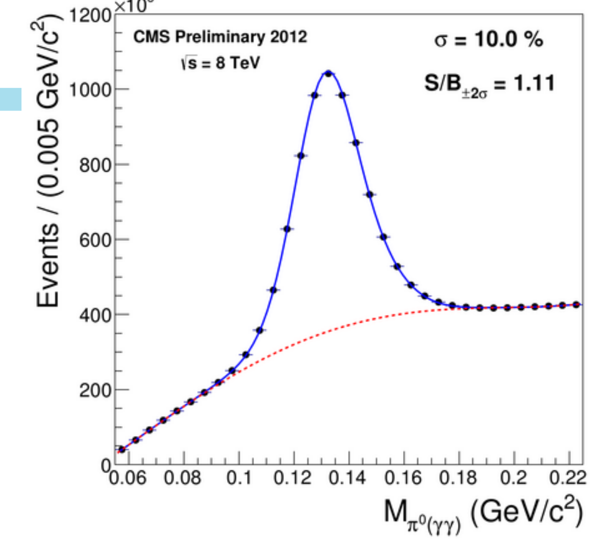


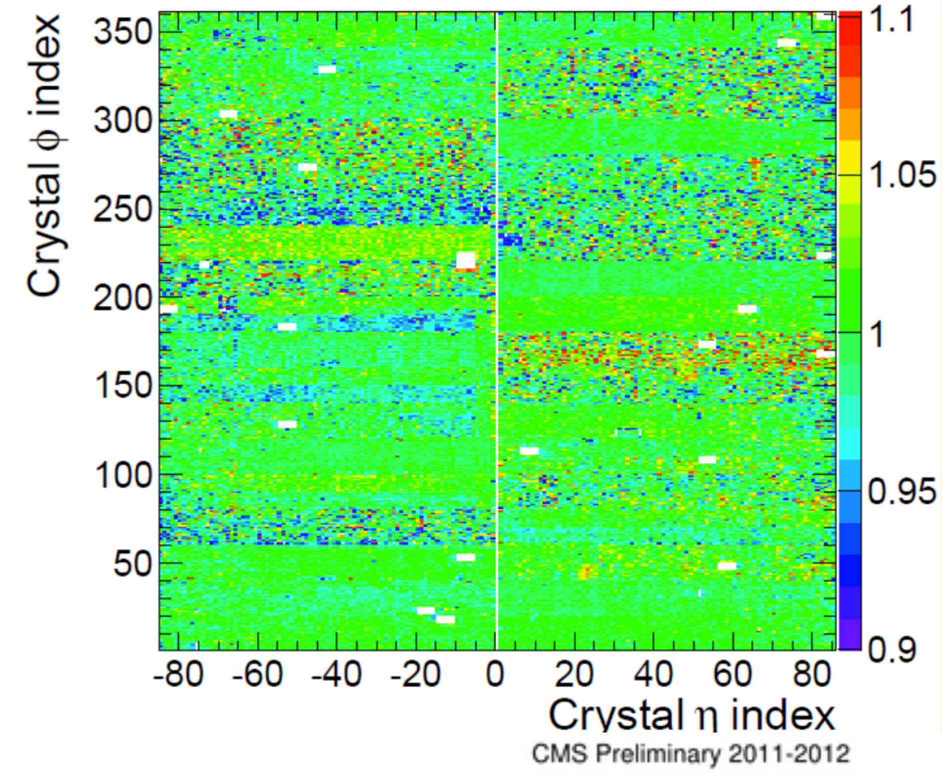
CMS: Tracker does a lot of the job

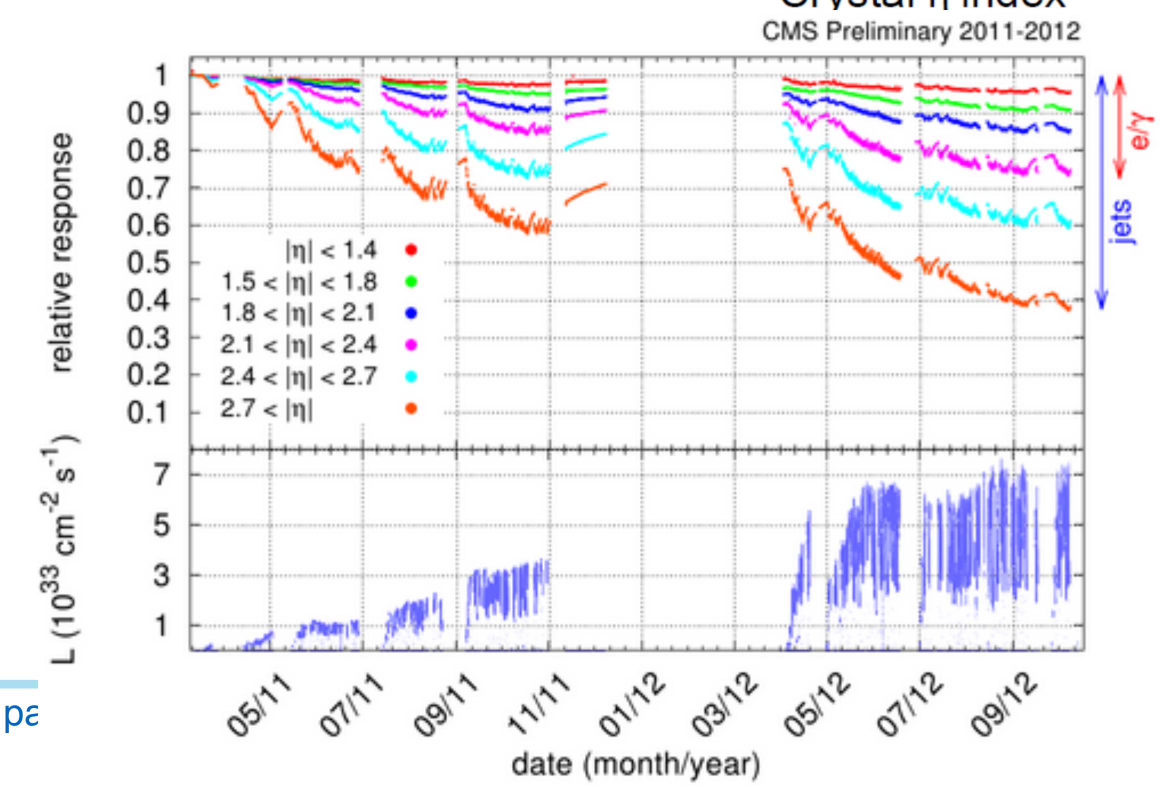
Technology Legacy: ECAL Calibrations

- In-situ inter-calibrations using resonances, geometric symmetries, electron E/p
  - **For each of 75,000 crystals to 0.5% precision**
- Live monitoring of crystal transparency with laser: **once every 40 min for each crystal**
- Corrections for local containment, module boundaries, shower shape, pileup, etc.

Each is a colossal task







HL-LHC Beamspot

- Beamspot has a width in time of ~180ps