Long-lived Particle Triggering with the CMS Hadron Calorimeter

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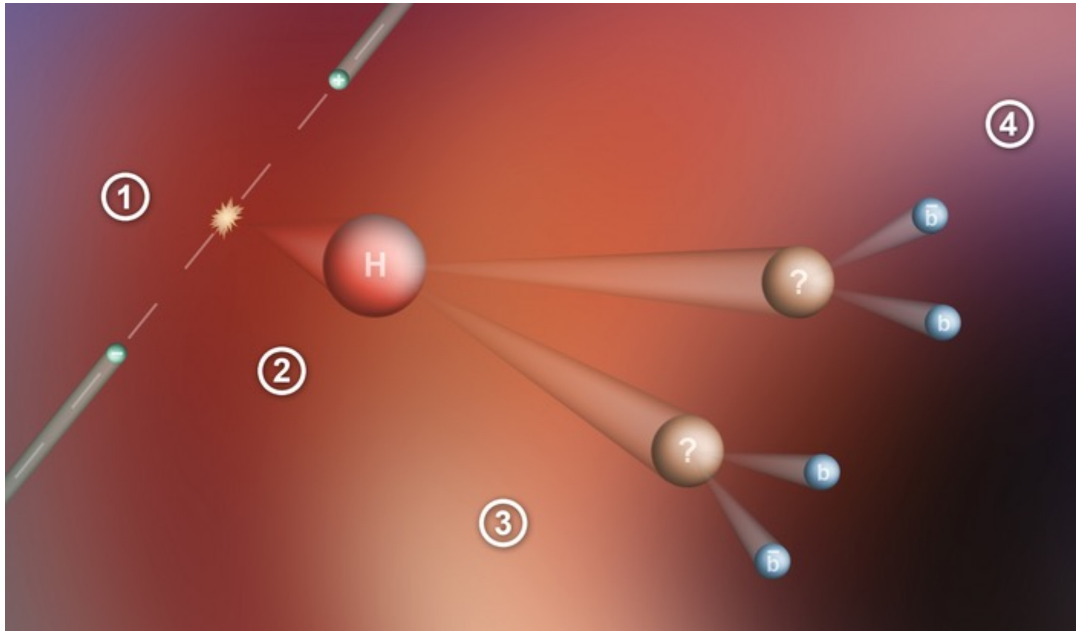
An Avenue to New Physics: Exotic Higgs Decays

- Compelling direction for new particle searches
- Probe exotic decays of the Higgs boson
  - Newest discovery in Standard Model
  - Higgs can couple to any massive particle – potential avenue to physics beyond the Standard Model
  - $\mathrm{BR}(H \to \mathrm{undetected}) \leq 16\%$ [1]

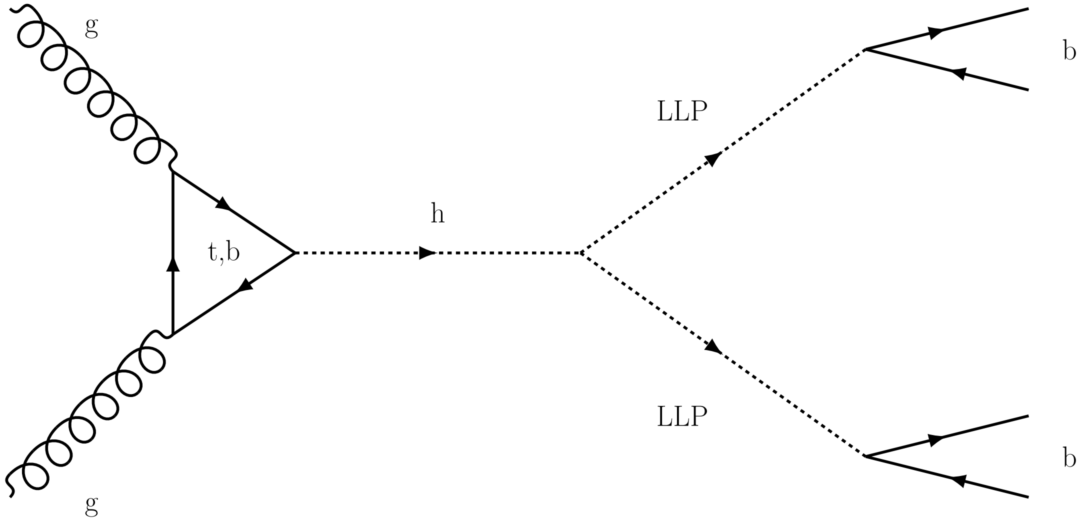


AAAS

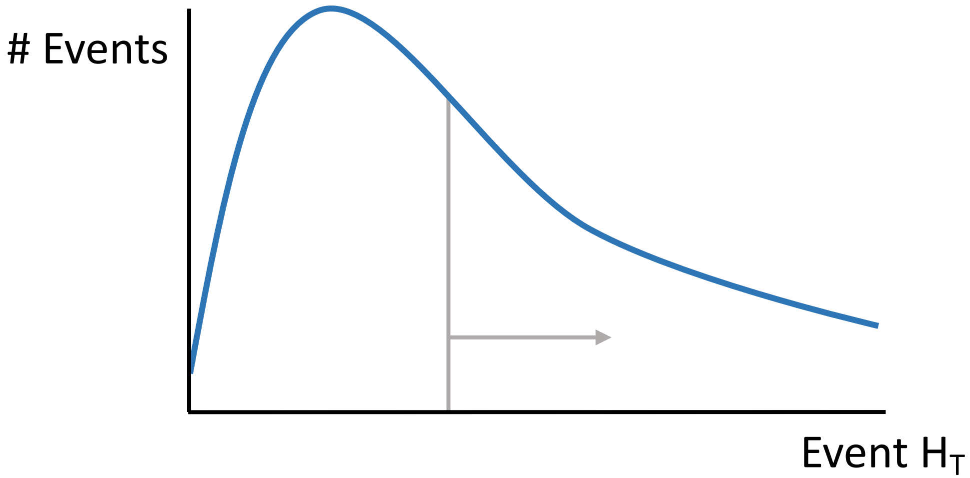
Long-Lived Particle (LLP) Searches at the LHC

Compelling model: $H \to SS \to b\bar{b}b\bar{b}$

- Exotic decay of the Higgs boson
- Less well covered when S is long-lived



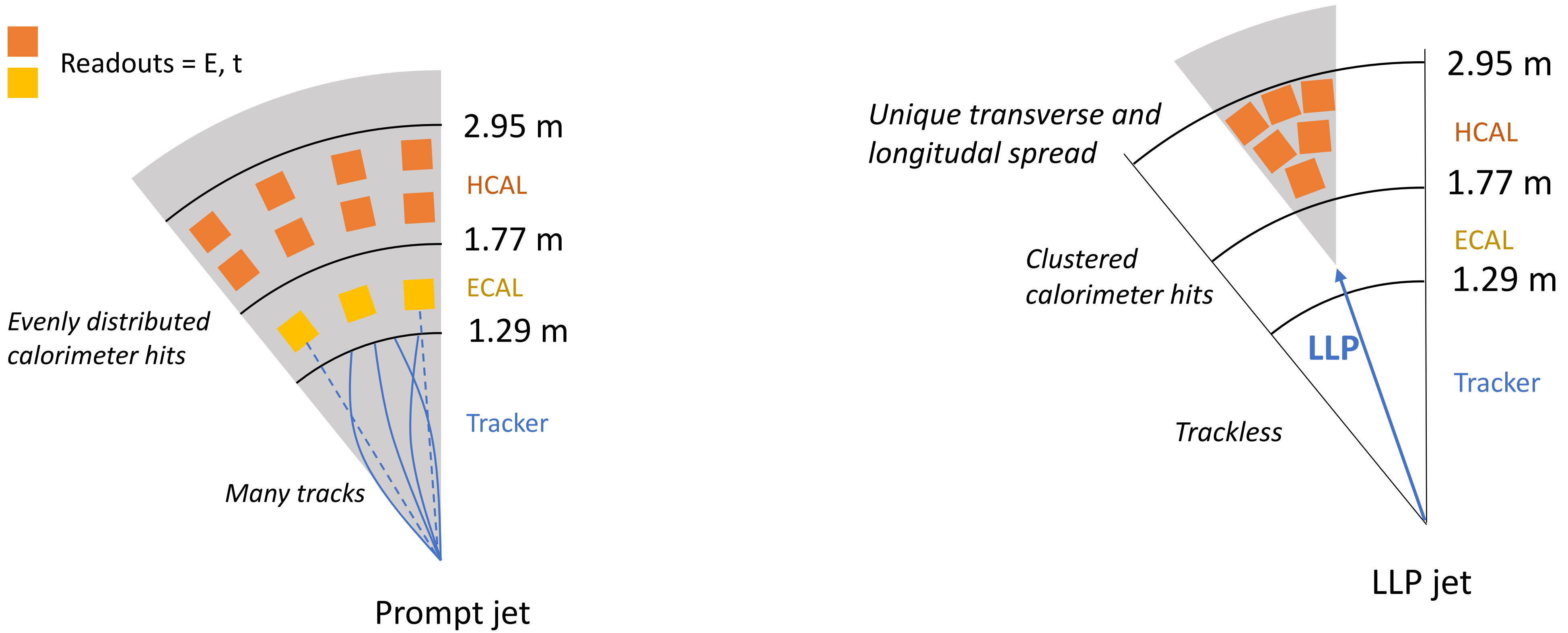
Benchmark model: $H \to SS \to \bar{b}b\bar{b}b$



Often leads to high **energy-based searches** to reduce backgrounds

Calorimeter Based LLP Reconstruction

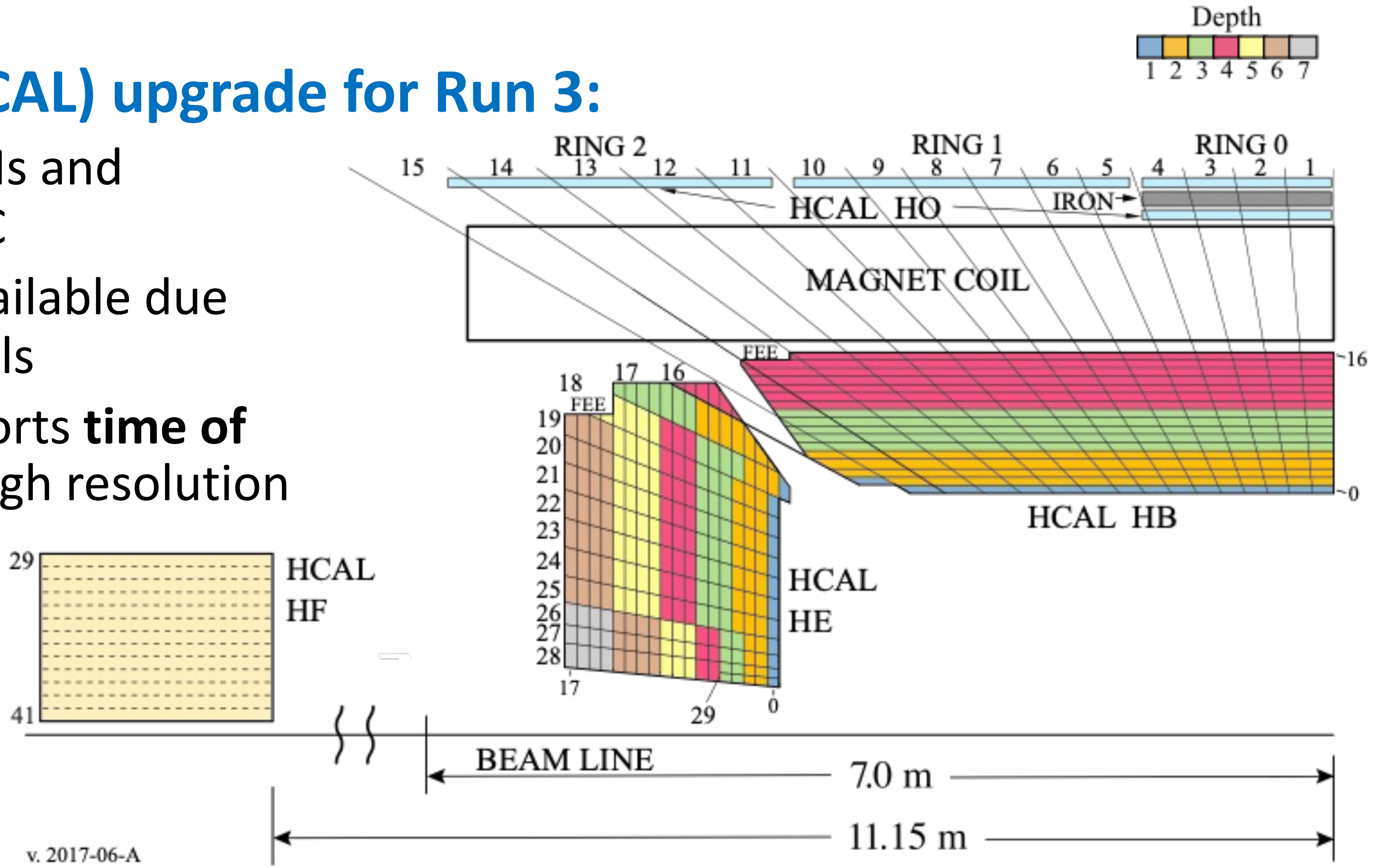
Segmented calorimeters are a powerful handle in LLP identification



Phase 1 HCAL upgrade segmentation + timing = **excellent opportunity for LLP triggering**

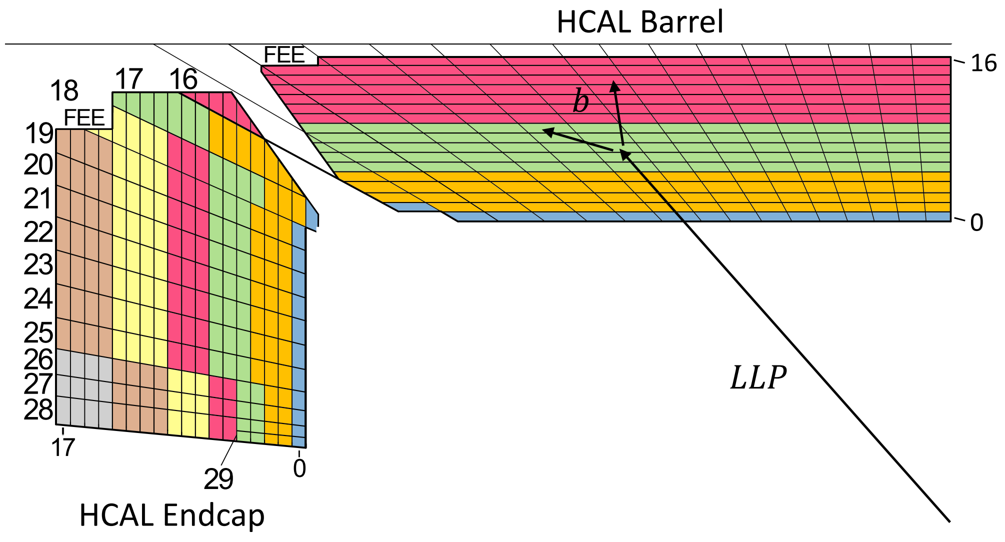
Phase-1 Upgrade of the Hadron Calorimeter

- **Hadron Calorimeter (HCAL) upgrade for Run 3:**
  - Replaced HPD with SiPMs and upgraded front-end ASIC
  - **Depth segmentation** available due to more readout channels
  - Custom QIE 11 ASIC reports **time of pulse** rising edge with high resolution



DocDB

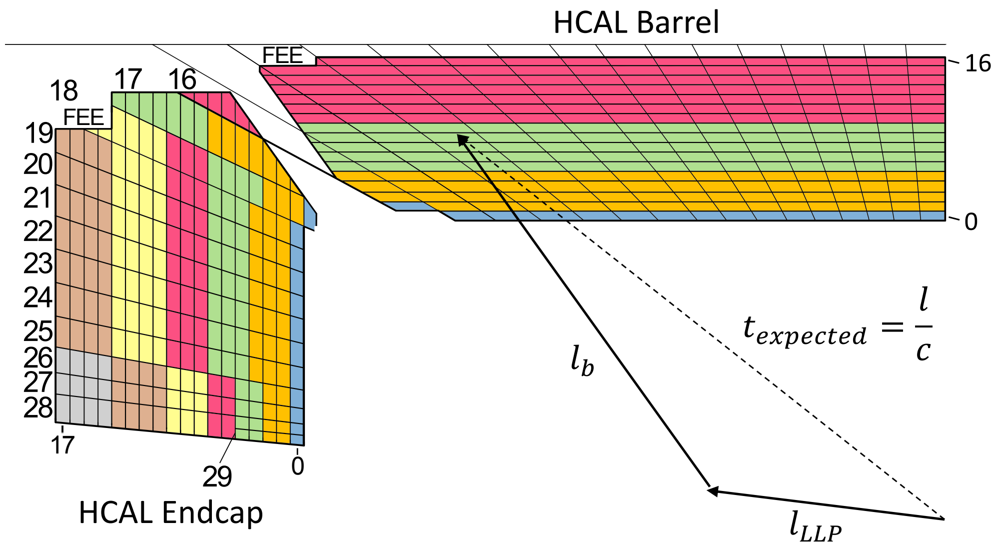
HCAL LLP Trigger for Run 3 (2022)



- Two handles for triggering on LLPs:
  - Depth segmentation – identify **displaced jets**, resulting from LLPs decaying inside the HCAL

Signatures: energy deposited in **deep calorimeter layers**

HCAL LLP Trigger for Run 3 (2022)

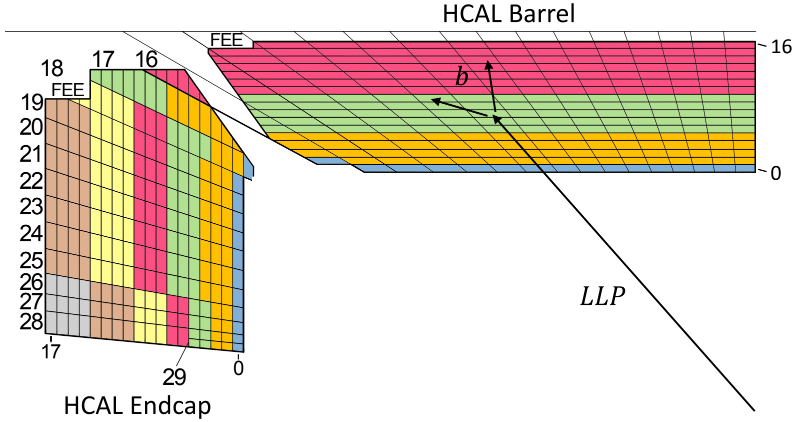


$$\Delta t = \frac{l_{LLP}}{v_{LLP}} + \frac{l_b}{c} - t_{expected}$$

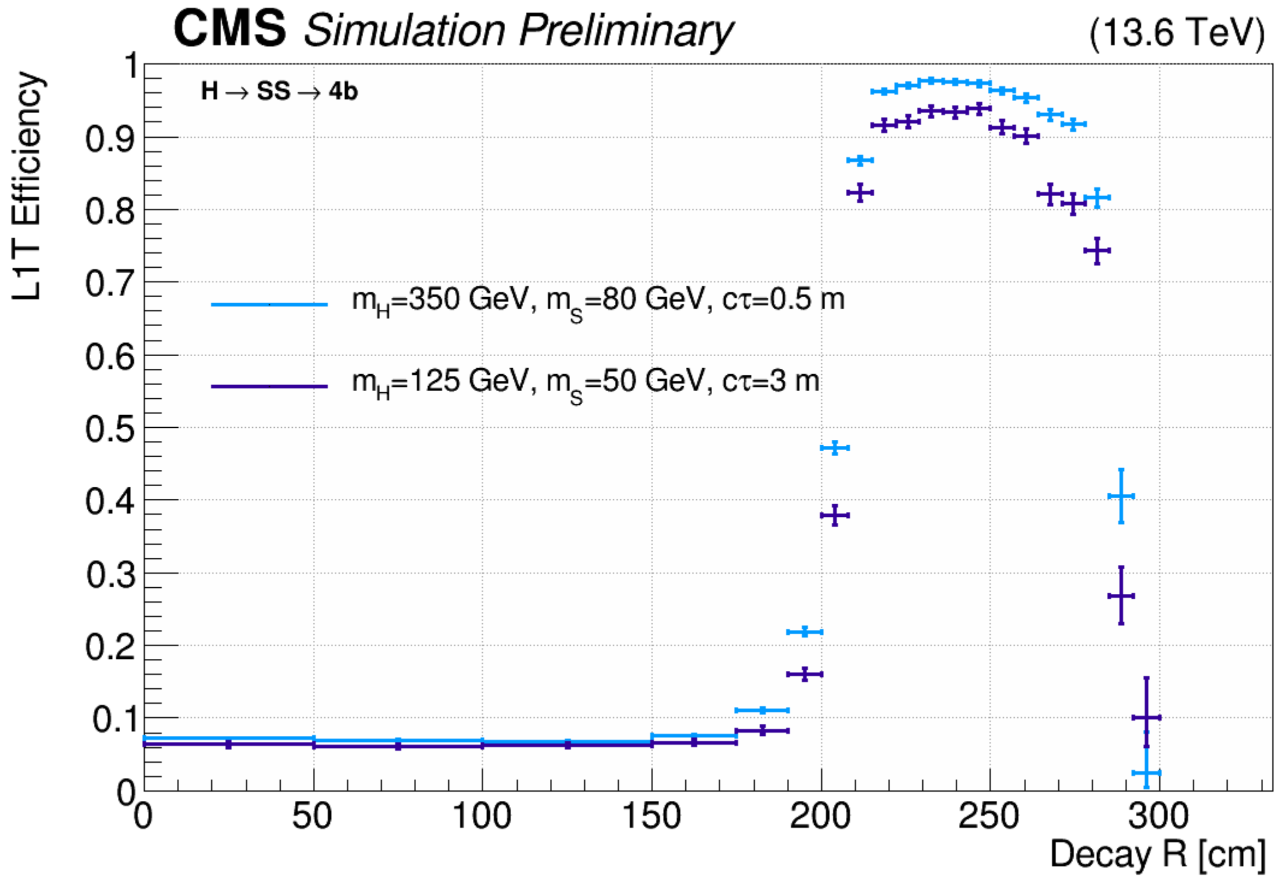
Signatures: energy deposited in **deep calorimeter layers**
delayed time of arrival of hits in calorimeter

- Two handles for triggering on LLPs:
  - Depth segmentation – identify **displaced jets**, resulting from LLPs decaying inside the HCAL
  - Timing information (TDC) – identify **delayed jets**, resulting from the decay of massive LLPs
- Define LLP-flagged L1 jets in a hardware-based LLP trigger [2, 3]

Displaced Decay Sensitivity



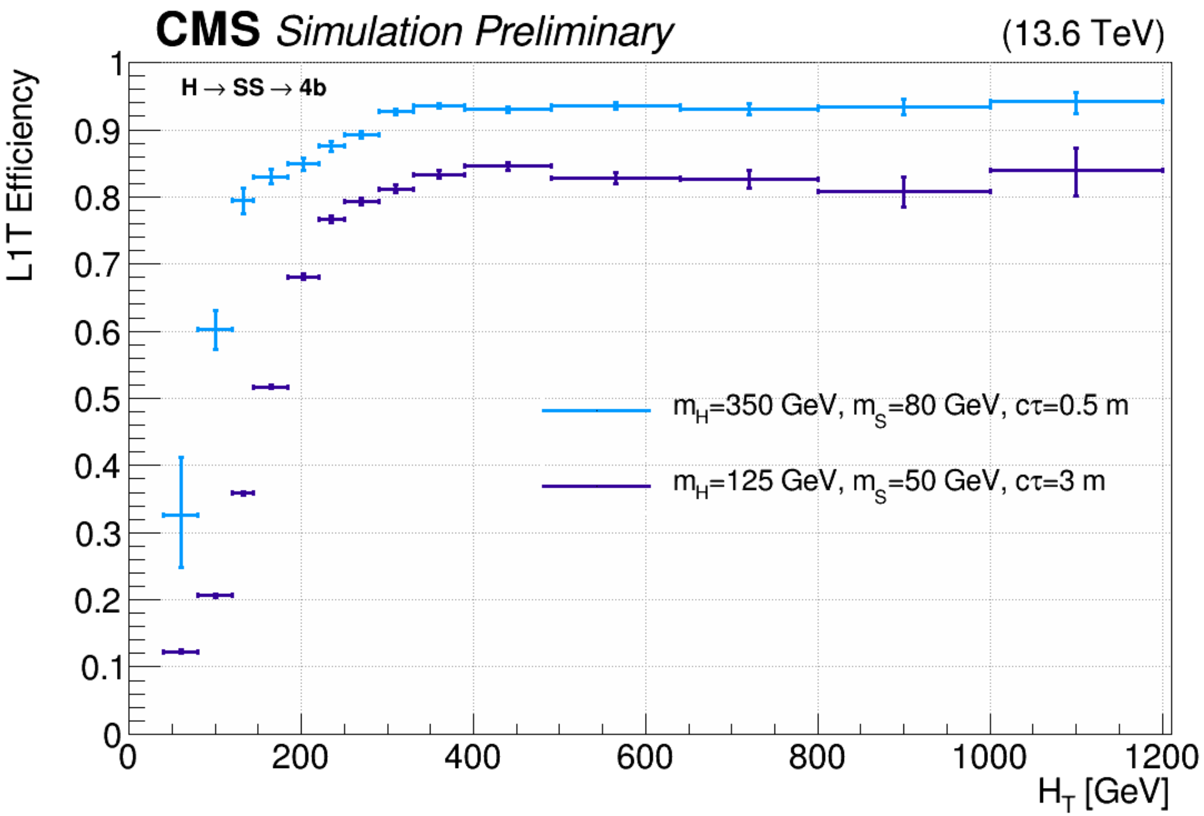
Depth 1: 177 cm
Depth 2: 190 cm
Depth 3: 214 cm
Depth 4: 245 cm



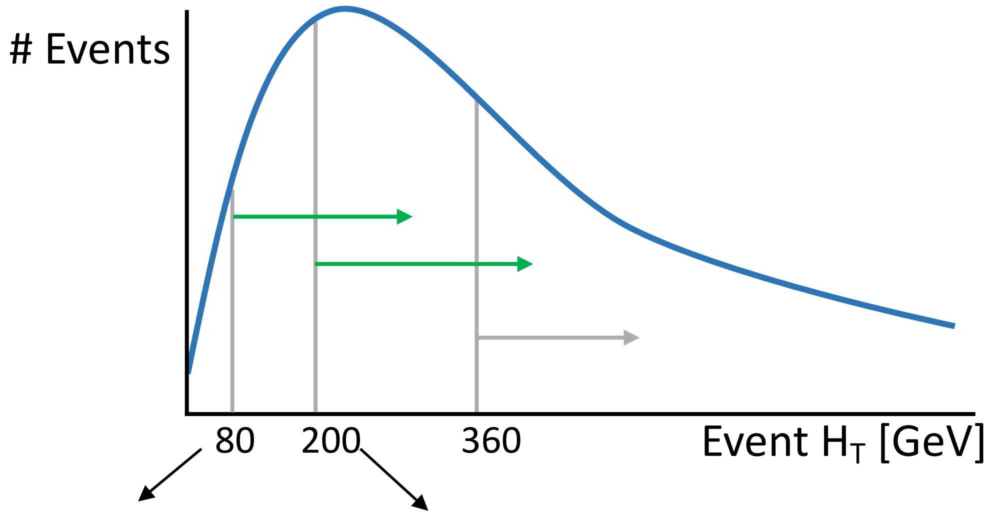
LLPs decaying in HCAL depths 3 and 4 are identified with high efficiency

[5] CMS DP-2024/058

Provides Sensitivity to Lower Energy Events



New triggers increase accessible phase space:

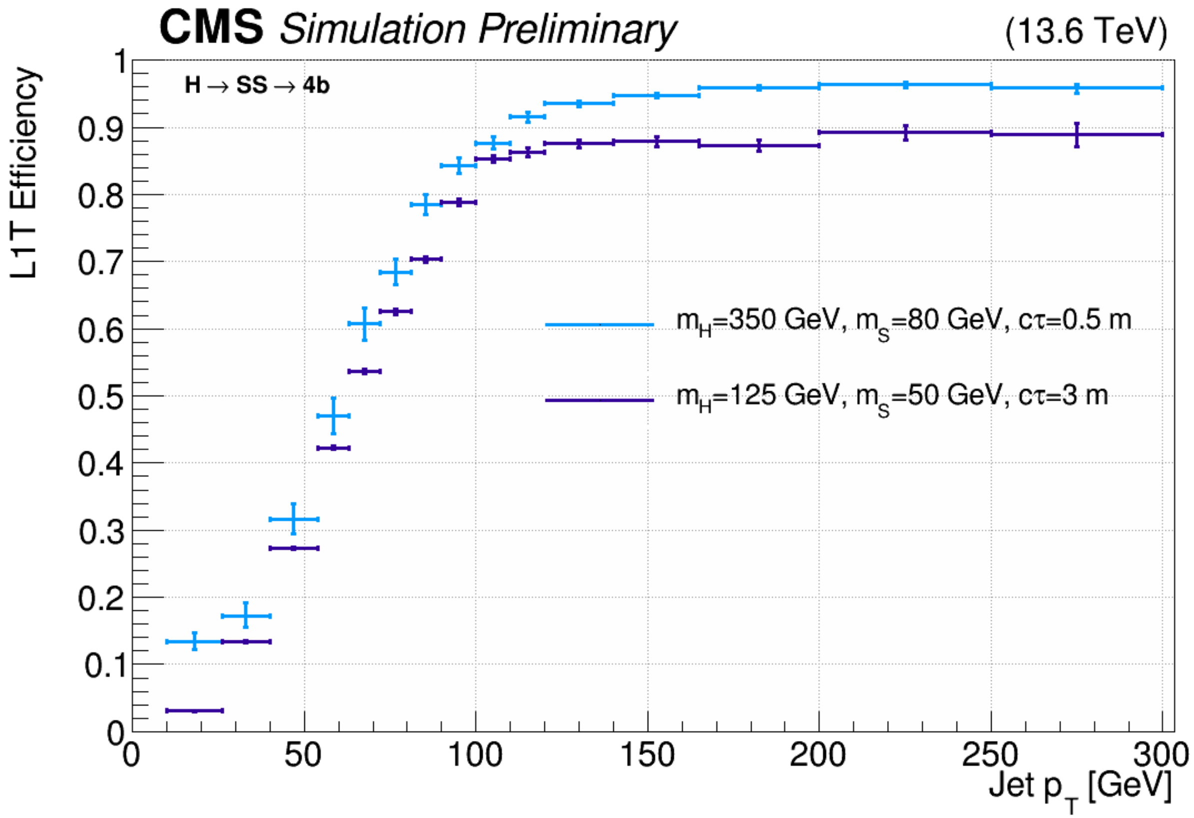


New hardware trigger saves **low energy events** that are often inaccessible with purely energy-based seeds! Previous choice for many displaced jet paths was L1 H_T 360 GeV seed, reaching 80% efficiency at H_T 400 GeV [4].

[5] CMS DP-2024/058

Provides Sensitivity to Lower Energy Jets

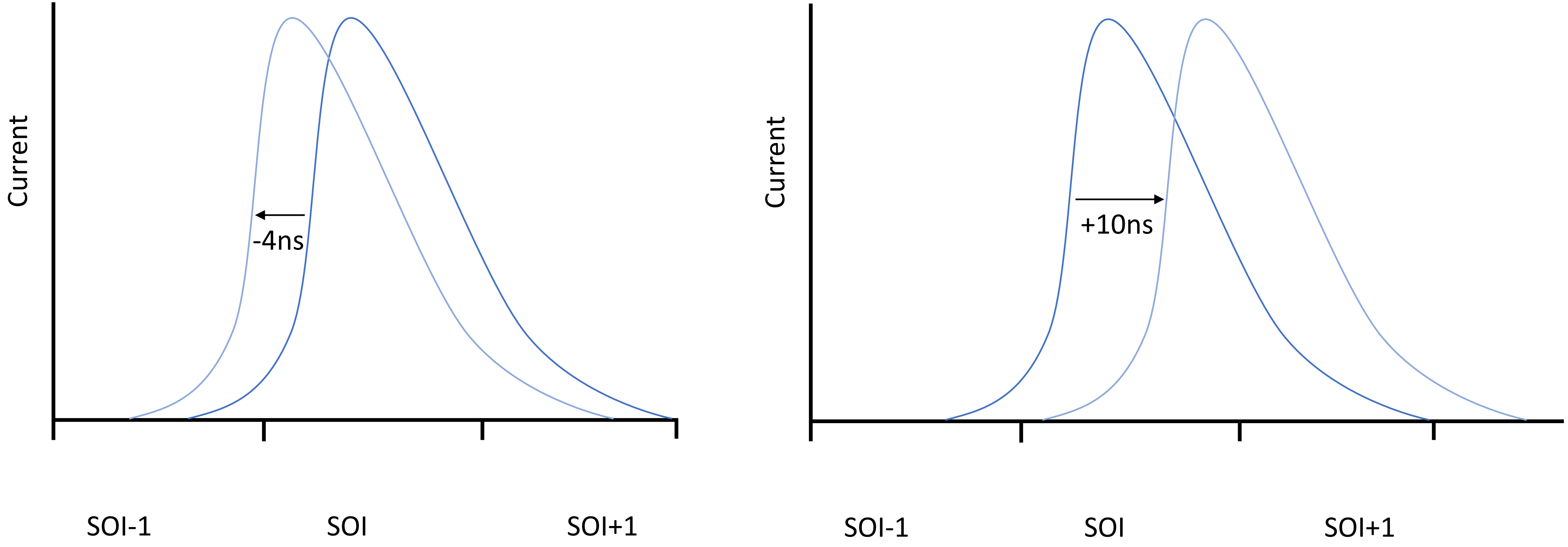
High sensitivity to displaced jets resulting from LLPs decaying within the calorimeter volume



Comparison: Lowest single jet energy-based trigger (180 GeV) reaches 80% efficiency at offline jet p_T of 200 GeV [4].

[5] CMS DP-2024/058

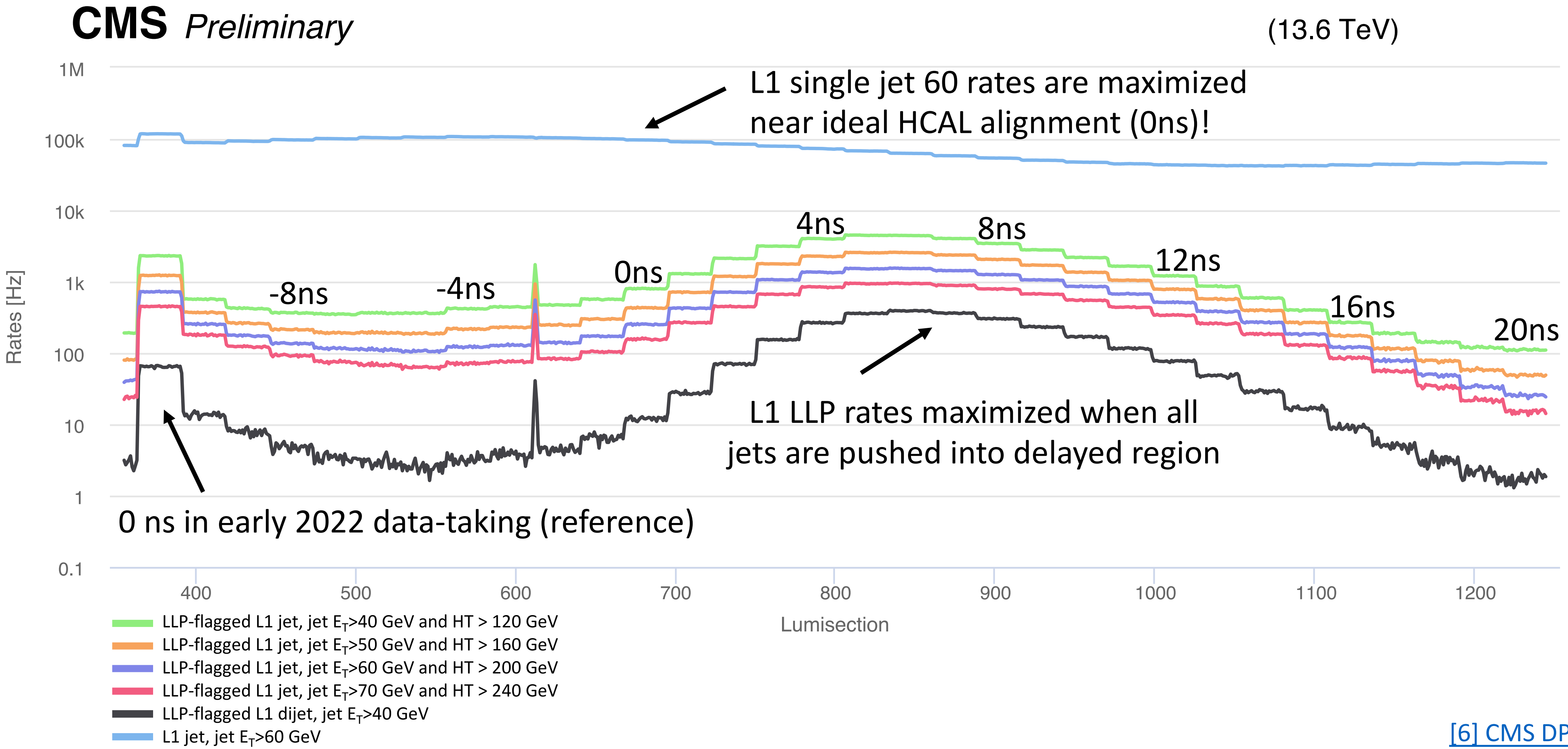
Phase Scan for Artificially “Delayed” Signals



During collisions, scan HCAL clock to **selectively adjust the timing of incoming jets**

Enables calibration and evaluation of LLP trigger in data

Trigger Rates Sensitive to Delayed Jets

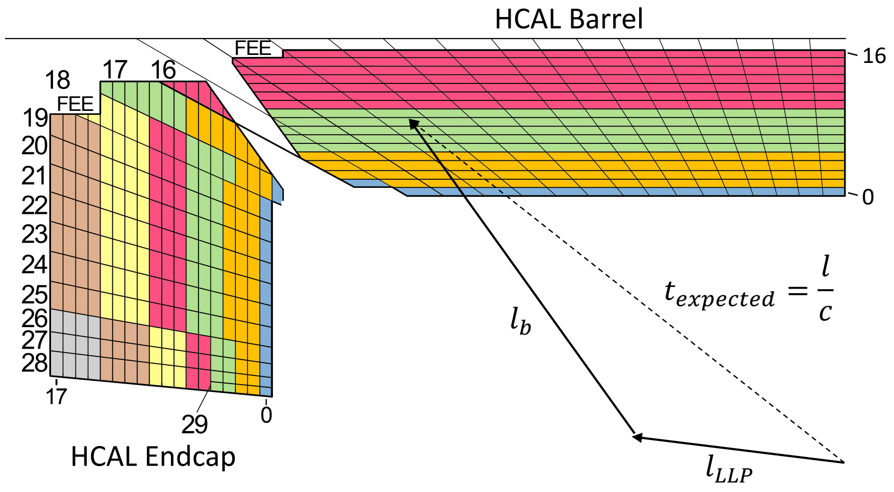


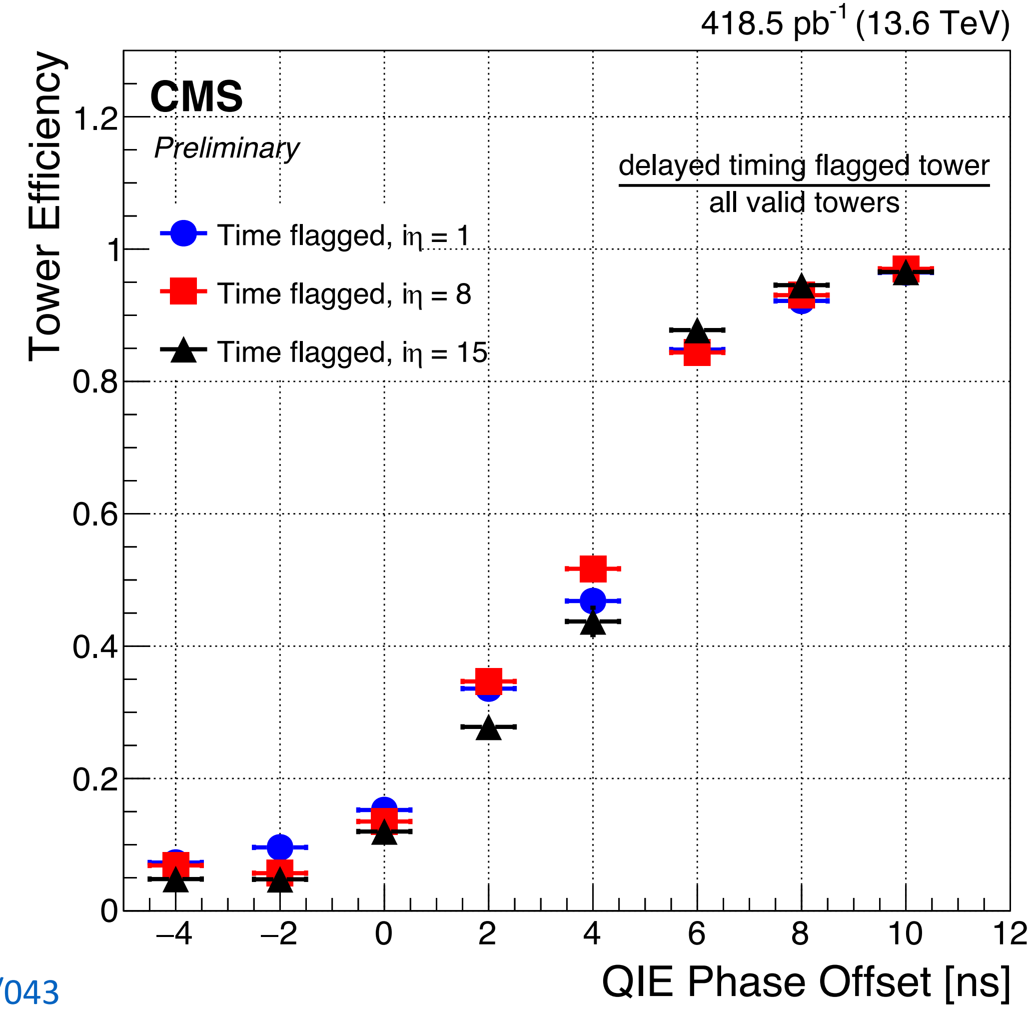
[6] CMS DP-2023/043

LLP Flagged TP Performance with Timing Scan

High sensitivity to pulse timing:

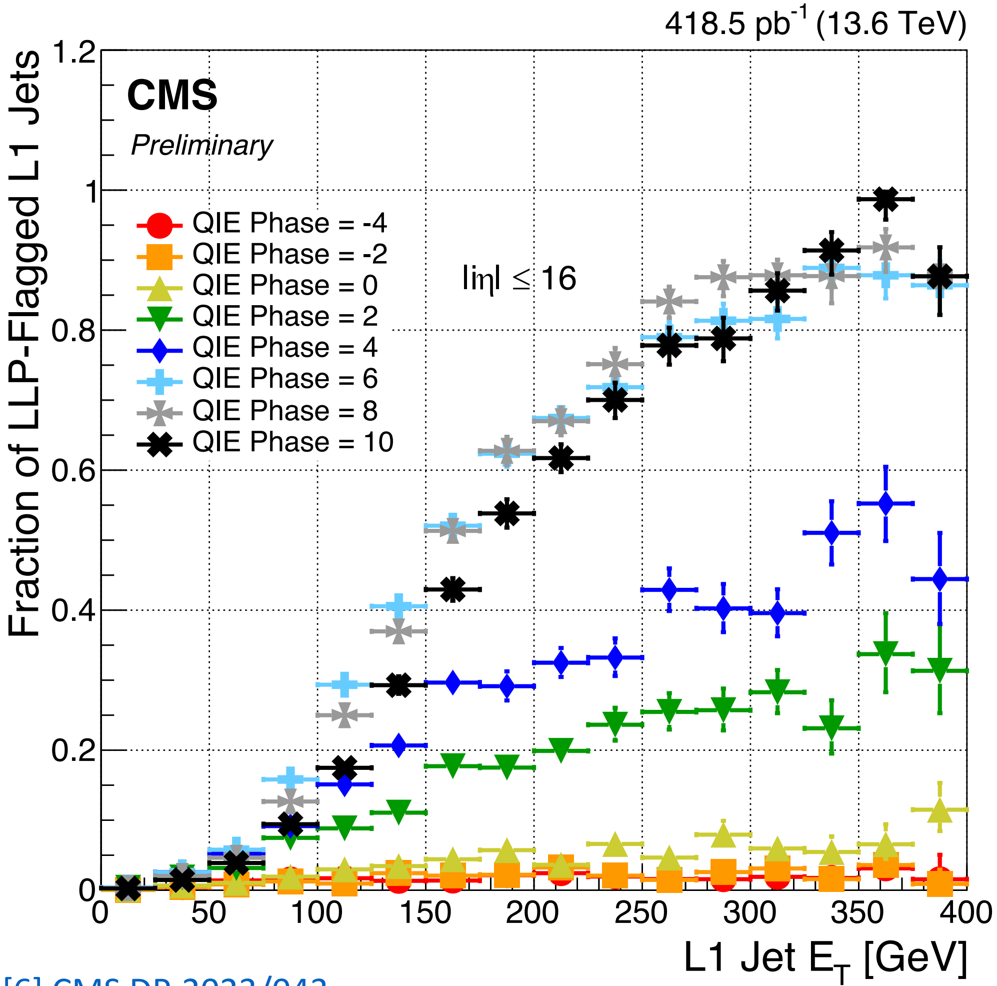
- Delayed towers (> 6 ns arrival time) are identified with high efficiency





[6] CMS DP-2023/043

LLP L1 Jet Performance with Timing Scan



[6] CMS DP-2023/043

Delayed **L1 LLP-flagged jets** are identified

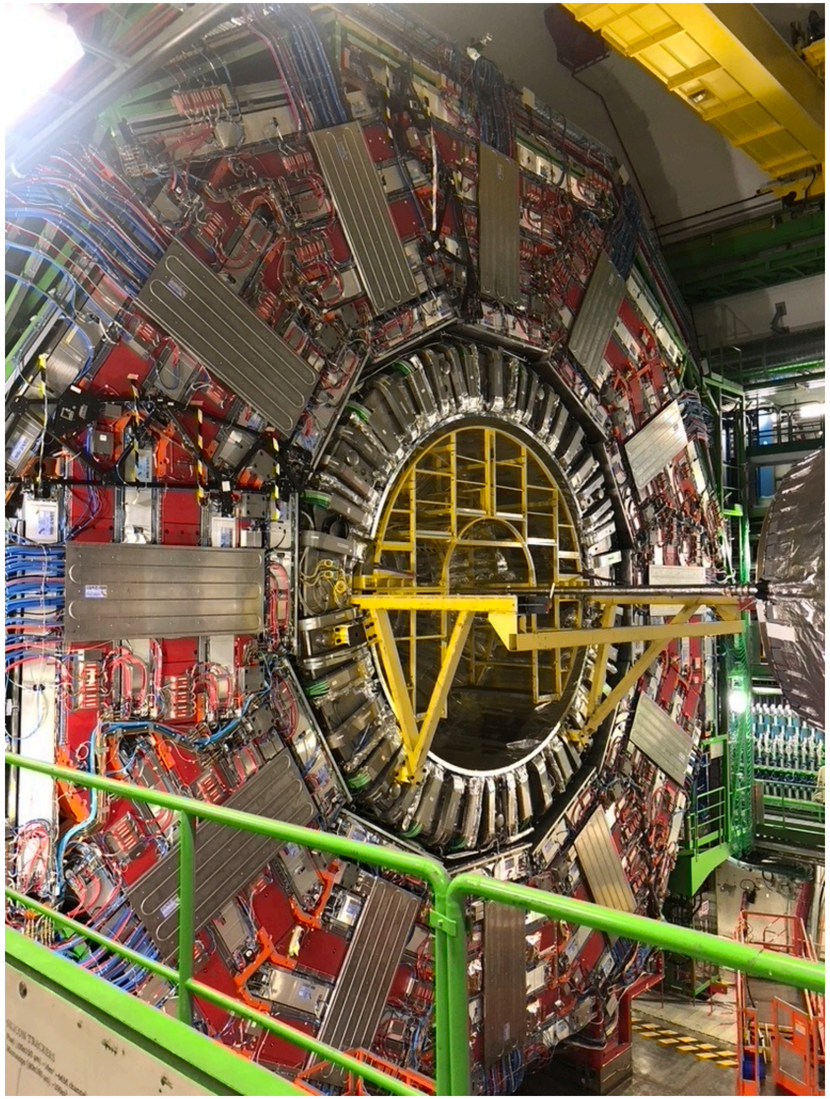
- Fraction reaches 1 as phase delay is increased
- Implicit requirement for a jet to have two cells with E_T > 4 GeV sculpts the distribution with respect to L1 jet E_T

Conclusions

- **Hardware (L1) trigger** uses both the new depth and timing capabilities of HCAL for LLP identification
  - Expands LLP phase space sensitivity into otherwise difficult regions
  - First L1 trigger use of the HCAL segmentation
- Triggers enable **increased LLP acceptance**
  - Up to a factor of 4 for $m_H = 125$ GeV, $m_S = 50$ GeV, $c\tau = 3$ m [6]
  - Triggers and calorimeter segmentation utilized in ongoing Run-3 LLP analysis!

Thank you!

Questions?



References

[1] CMS Collaboration, *A portrait of the Higgs boson by the CMS experiment ten years after the discovery*, Nature **607** (2022), no. 1, 60–68. https://www.nature.com/articles/s41586-022-04892-x

[2] Gillian Kopp, Christopher Tully, Kiley Elizabeth Kennedy, Wonyong Paul Chung, Svitlana Hoienko, Jeremiah Michael Mans, Michael David Krohn, Bryan James Crossman, Joshua Hiltbrand, Andris Skuja, and Long Wang, *A Novel Timing Trigger with the CMS Hadron Calorimeter*, CERN Document Server (2023). https://cds.cern.ch/record/2891496?ln=en.

[3] Gillian Kopp, Chris Tully, Owen Long, and Georgia Karapostoli, *Specifications for HCAL uHTR Firmware*, CMS Public DocDB, August 2021, Available at https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=12306&filename=LLPbits_uhtr_spec.pdf&version=22.

[4] CMS Collaboration, *Performance of L1 Jets and MET Trigger in early Run 3*, 19 August 2023. CMS DP-2023/054. https://cds.cern.ch/record/2868796/files/DP2023_054.pdf

[5] CMS Collaboration, *Level 1 Trigger Algorithm for Long-lived Particle Jets in Run 3,* July 2024. CMS DP-2024/058. https://cds.cern.ch/record/2904694?ln=en

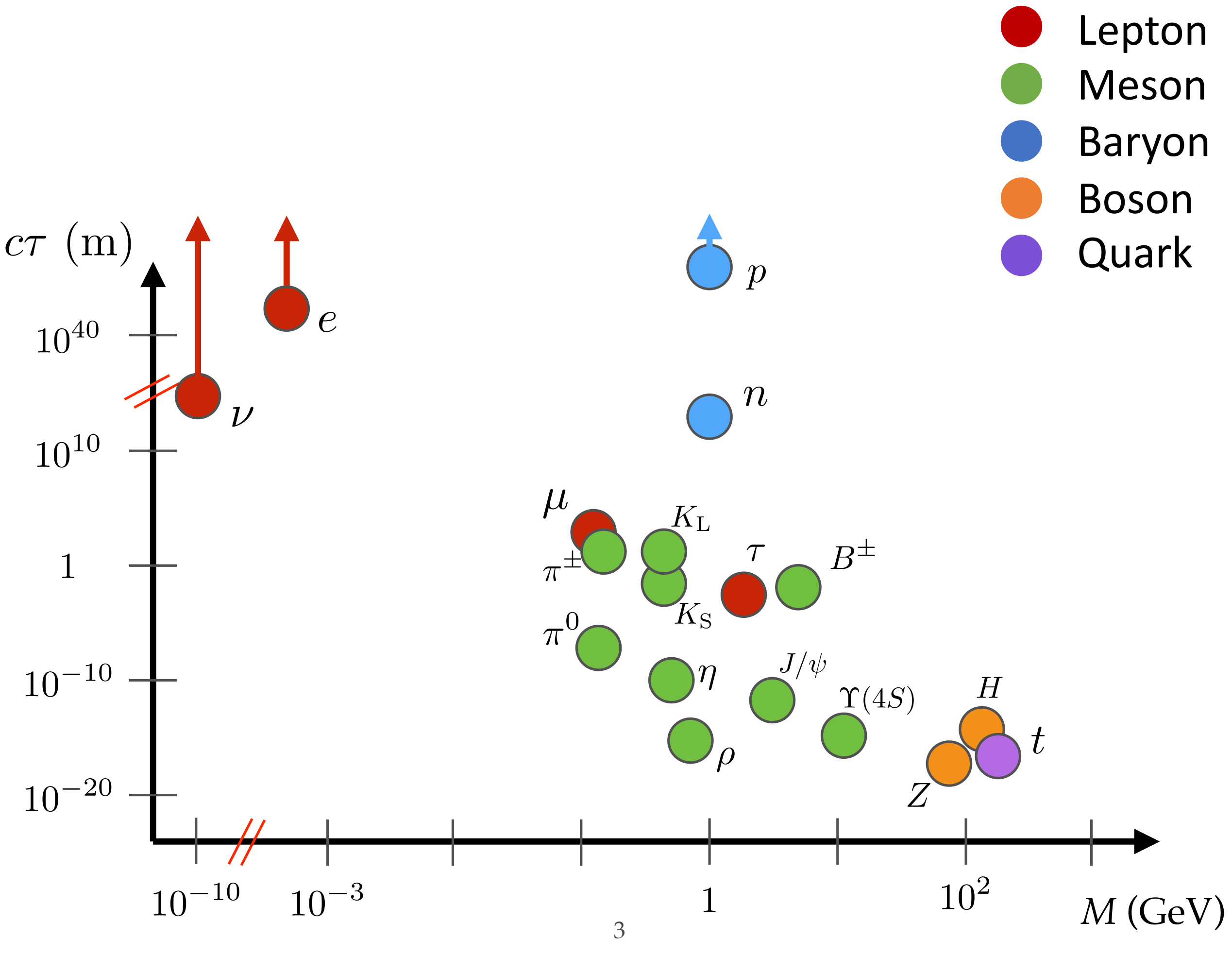
[6] CMS Collaboration, *Performance of long-lived particle triggers in Run 3,* July 2023. CMS DP-2023/043. https://cds.cern.ch/record/2865844?ln=en

[7] CMS Collaboration, *Search for low-mass long-lived particles decaying to displaced jets in proton-proton collisions at* $\sqrt{s} = 13.6\ TeV$. CMS-PAS-EXO-23-013. https://cds.cern.ch/record/2893044

Backup

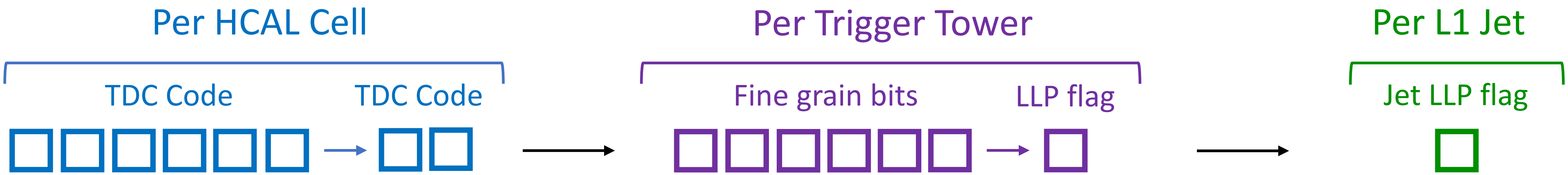
Long-lived Particle Motivations

- Small couplings
  - b quark
- Suppressed decay phase space
  - $n \rightarrow p^{+} + e^{-} + \bar{\nu}_e$
  - Limited decay phase space due to the small mass difference between *n* and *p*
- Scale suppression (heavy mediator)
  - $\pi^{\pm}$ have longer lifetimes than π^{0} due to weak interaction mediator contribution to small matrix element



[Searching for LLPs beyond the SM at the LHC](#)

LLP Trigger Pathway: HCAL through L1



HCAL TDC in 6:2 bits

HCAL IGLOO2 LUT defines 3 timing ranges
00 = Prompt
01 = Delay 1
10 = Delay 2
Set per $i\eta$, depth

HCAL uHTR sends 6 bits to L1 6:1

6 fine grain bits from uHTR are set based on TDC and energy measurements
Calo L1 applies 6:1 LUT, requiring either depth or timing flag set (with prompt veto) and forwards to Calo L2 jet algorithm

LLP jet flag set if jet contains ≥ 2 LLP towers in 9x9 jet region

L1 Accept after jet and HT energy requirements applied
5 L1 pathways (single, double jet)
15 HLTs seeded with L1 LLPs

```
Depth OR Timing = bit0 || (!bit1 && (bit2 || bit3))
```

HCAL Alignment with Phase Scan

Four TDC codes throughout timing scan:

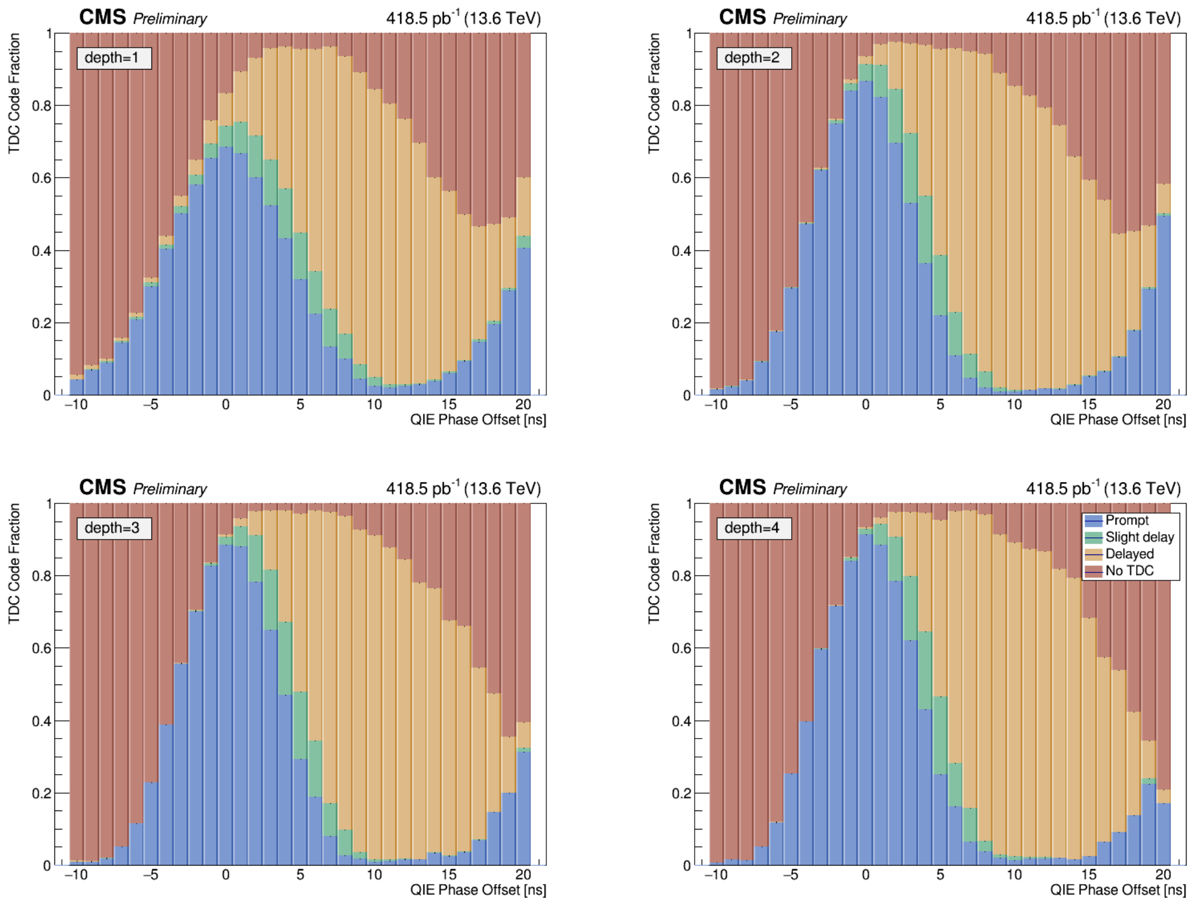
- 00: Prompt (TDC $\leq$ 6 ns)
- 01: Slight delay (6 < TDC $\leq$ 7 ns)
- 10: Delayed (TDC > 7 ns)
- 11: No valid TDC (set in another bunch crossing)

The prompt timing distribution (blue) is maximized at the optimal time alignment (0 ns)

As pulses are moved later (increasing phase offset), more delayed (green and orange) TDC codes are seen

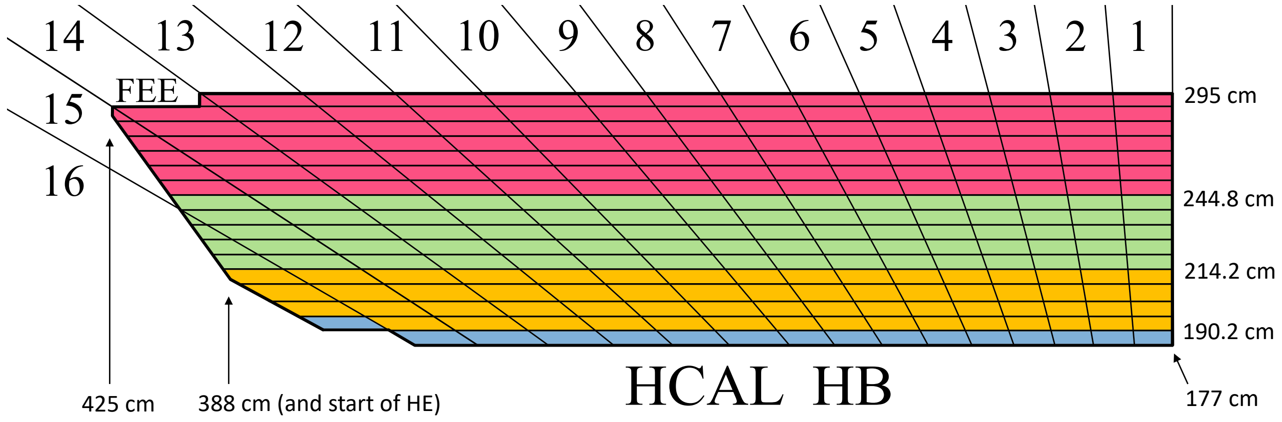
New TDC-based HCAL alignment improves over previous methods, which are biased by pulse shape differences across $i\eta$ and depths.

June 2023 TDC-based alignment
Consistent pulse arrival time across detector



[6] CMS DP-2023/043

HCAL Interaction Lengths



- Layer 0: 9 mm scintillator, 61mm stainless steel.

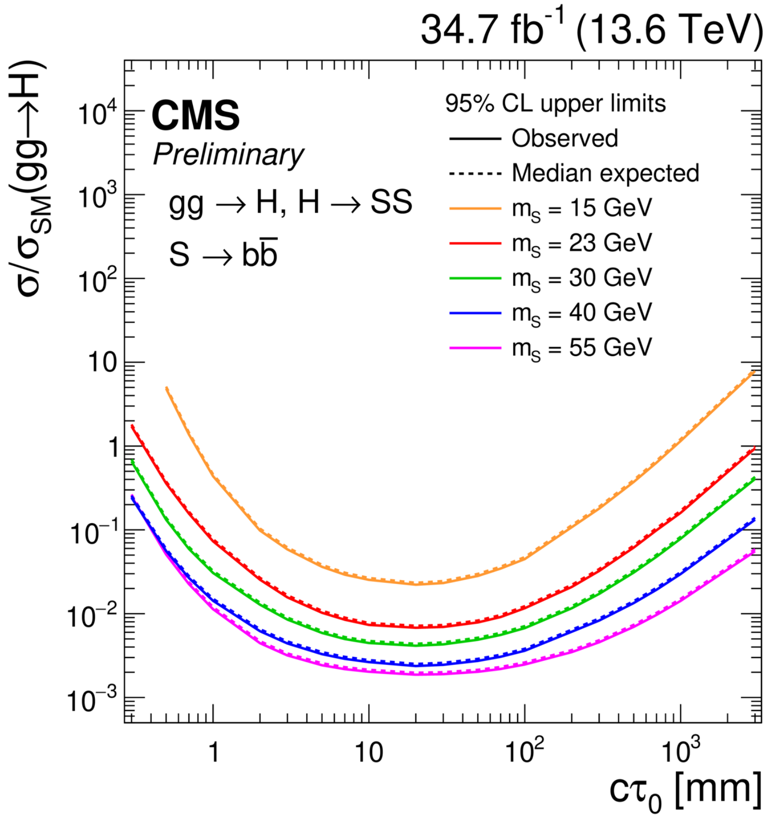
  Note that this layer has a larger scintillator directly behind ECAL to capture low energy showering particles from support material between HCAL and ECAL. In addition, there is no absorber before the scintillator (no dead material), but a significant shower can develop from the ≈ 1 interaction length provided by ECAL. HCAL depth 1 is unique because it also contains a neutral density filter.

- Layer 1-8: 3.7 mm scintillator, 50.5 mm brass
- Layer 9-14: 3.7 mm scintillator, 56.5 mm brass
- Layer 15+16: 3.7 mm scintillator, 75 mm stainless steel, 9mm scintillator

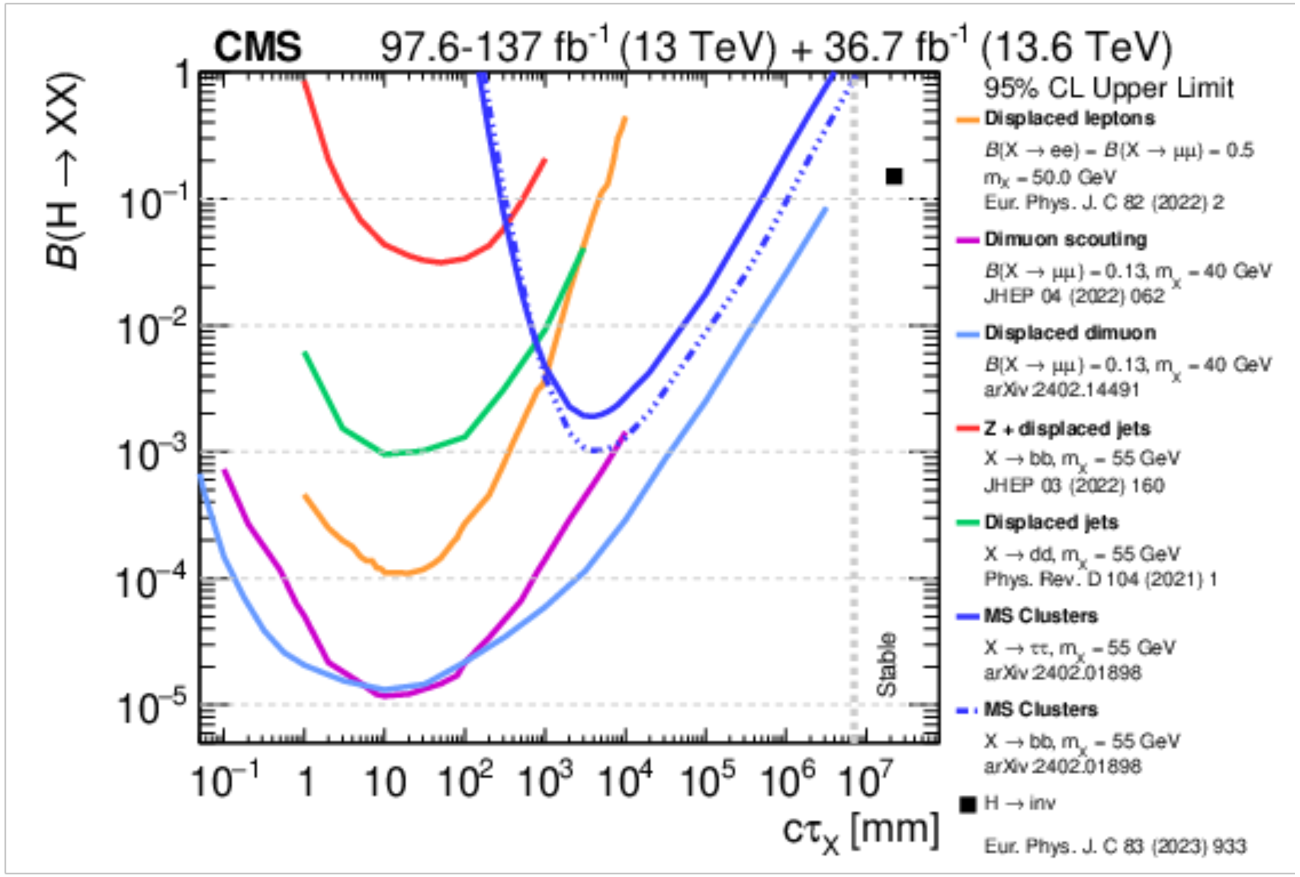
	Depth 1	**Depth 2**	**Depth 3**	**Depth 4**
λ_I (brass)	-	1.23	1.57	1.72
λ_I (steel)	0.58	-	-	0.72
λ_I (total)	0.58	1.23	1.57	2.44

Approximation of interaction lengths per depth, based on brass and steel absorbers.

Existing Limits on $H \to SS$



[7] CMS-PAS-EXO-23-013



CMS-EXO-23-005

Trigger Efficiency Selections (MC, Slides 8-10)

In all plots, an LLP is matched to an offline jet, with the following cuts:

- LLP with $|\eta| \leq 1.26$ must match with $\Delta R \leq 0.4$ to an offline AK4 jet in HB, satisfying jet $|\eta| \leq 1.26$
  - If the LLP decays within the HCAL, require that $\Delta R \leq 0.4$ between LLP and jet center
  - If the LLP decays before the HCAL, require that $\Delta R \leq 0.4$ between LLP decay product and jet center

To demonstrate the trigger performance on the efficiency plateau as a function of each variable, cuts are made on the LLP decay position, jet p_T, and event H_T:

- **LLP decay R** plot: additionally require event H_T > 250 GeV and matched jet p_T > 100 GeV
- **Event H_T** plot: additionally require that at least one of the leading 6 jets has jet p_T > 40 GeV and is matched to an LLP with a decay radius of $214.2 \leq R < 295$ cm (decay occurring in HCAL depth 3 or 4, motivated by sensitivity of the depth-based trigger)
- **Jet p_T** plot: additionally require that the jet is matched to an LLP with a decay radius of $214.2 \leq R < 295$ cm

The numerator requires the same LLP – offline jet matching, while also requiring that any of the HCAL-based L1 LLP triggers are passed.