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Time Alignment of the CMS Hadron Calorimeter for a Novel Timing Trigger

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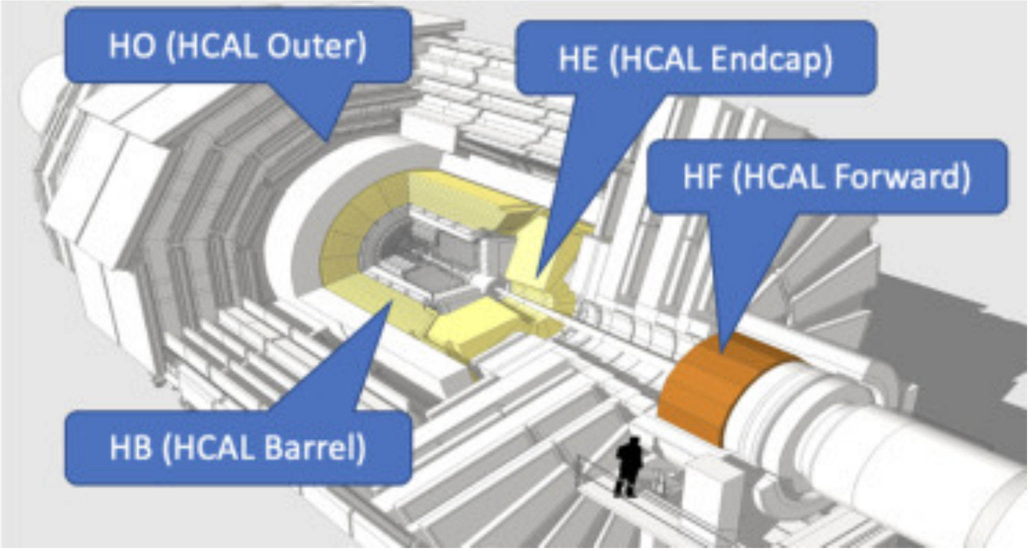
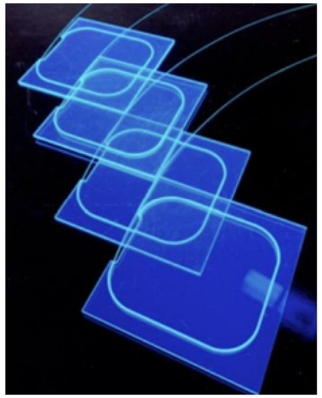
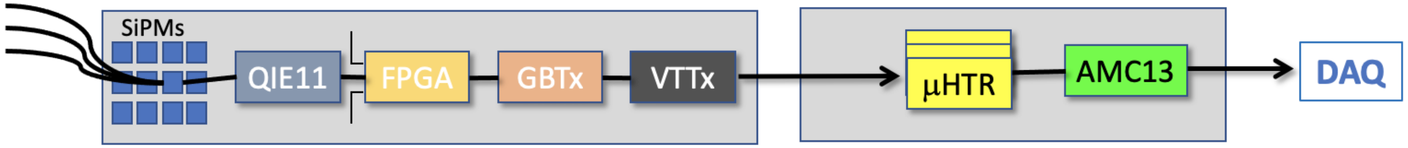
CMS Hadron Calorimeter (HCAL)

- HCAL measures charged and neutral hadrons with 4π coverage
  - Brass absorber interleaved with plastic scintillating tiles (HB and HE)
  - Wavelength shifting fibers → clear fibers → optically decoded on SiPMs
  - SiPMs recently replaced hybrid photodiodes
    - Higher photon detection efficiency
    - Increased energy resolution
    - Increased number of readout channels
  - Custom ASICS (QIE11) digitize signals
    - Measure energy and time, and send to back-end electronics



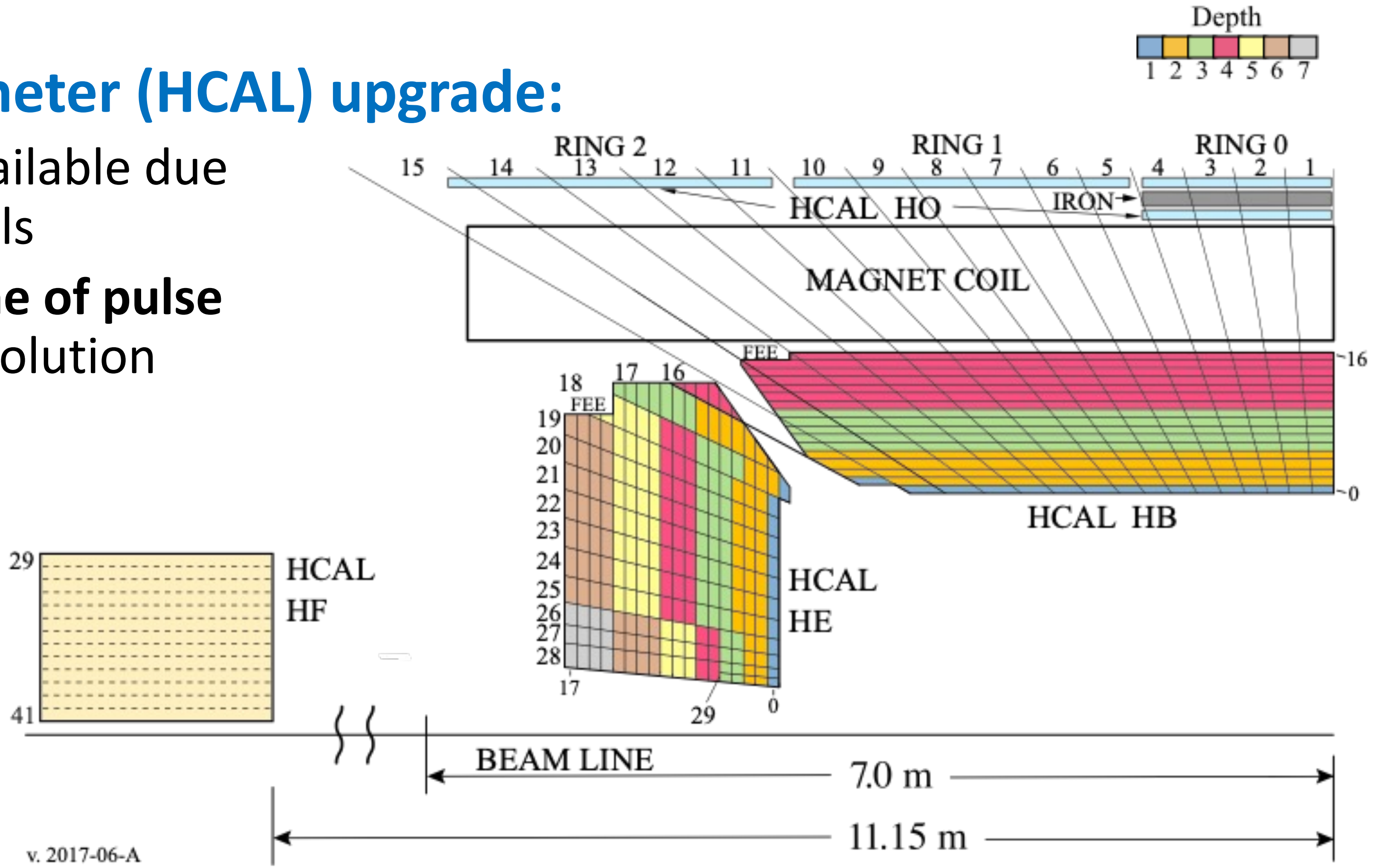


[1], [2]



Phase-1 Upgrade of the Hadron Calorimeter

- **Phase 1 Hadron Calorimeter (HCAL) upgrade:**
  - **Depth segmentation** available due to more readout channels
  - Custom ASIC reports **time of pulse** rising edge with high resolution



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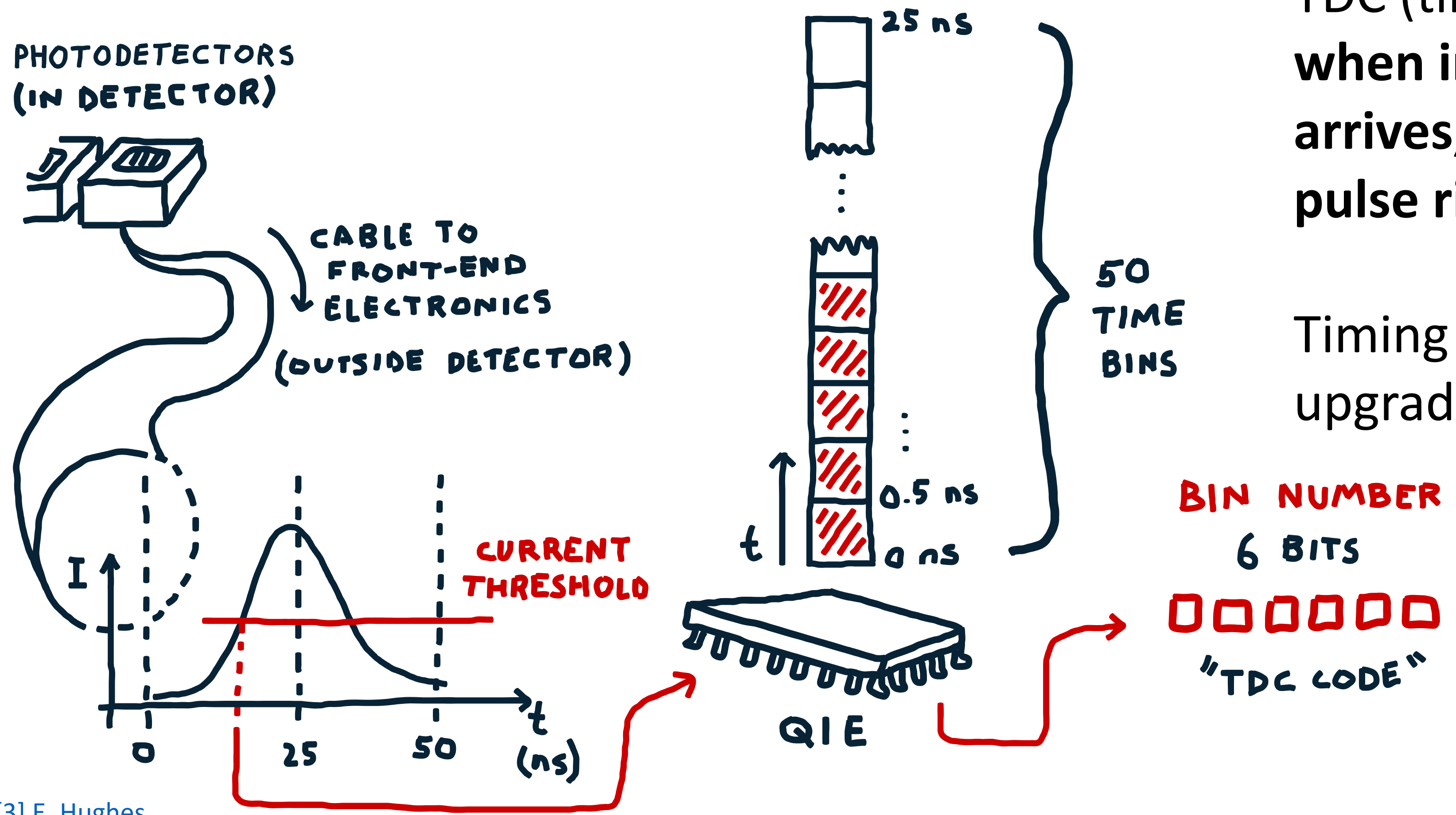
Timing at HCAL

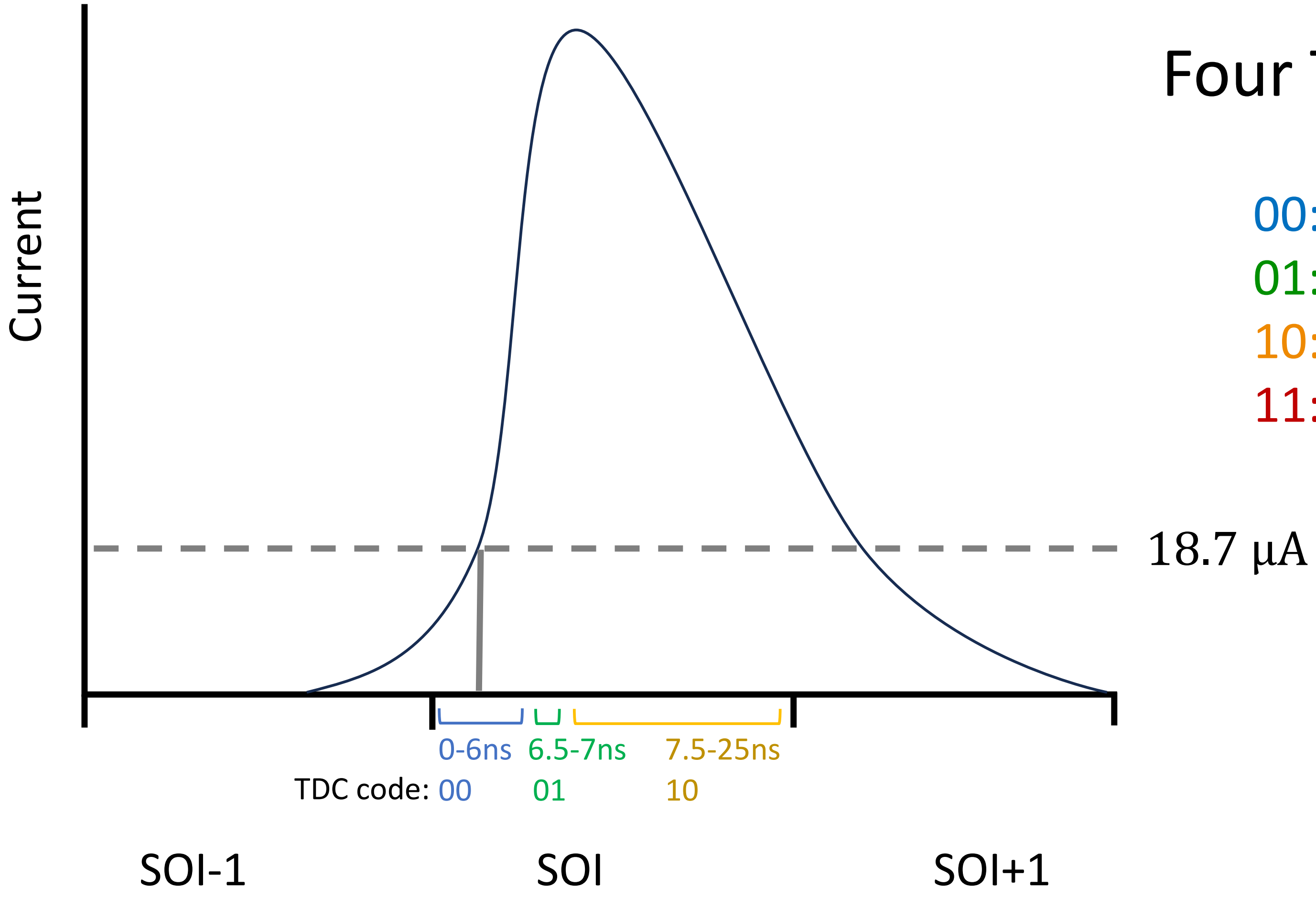


TDC (time to digital converter) **identifies when in a bunch crossing the pulse arrives, with high sensitivity to the pulse rising edge**

Timing readout added in Phase 1 upgrade with the QIE11 (ASIC)

[3] E. Hughes

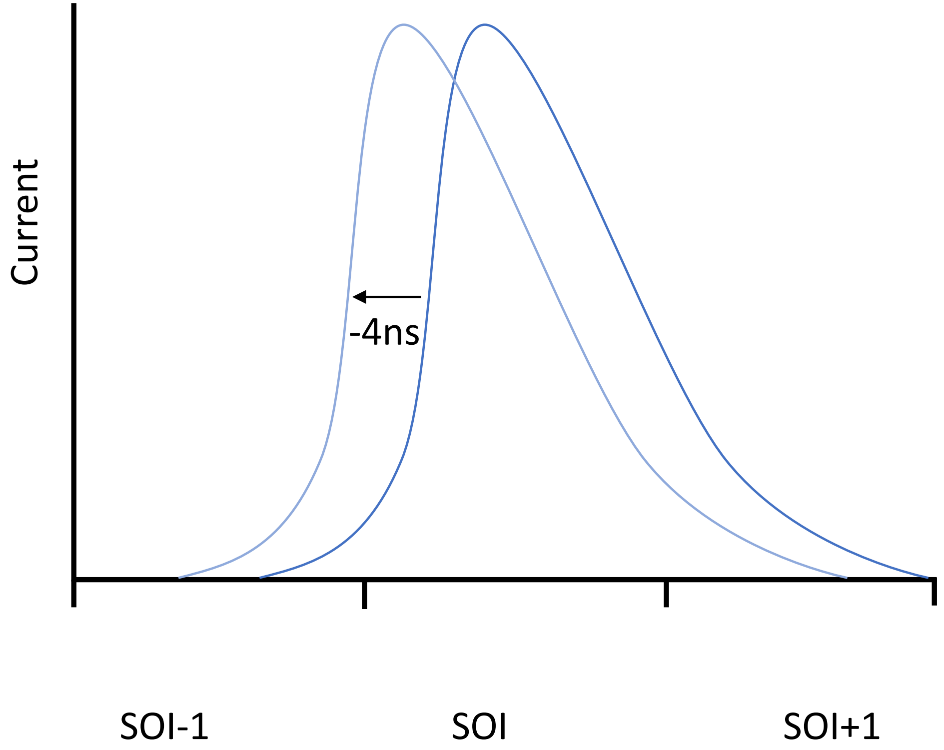
Diving into HCAL Timing

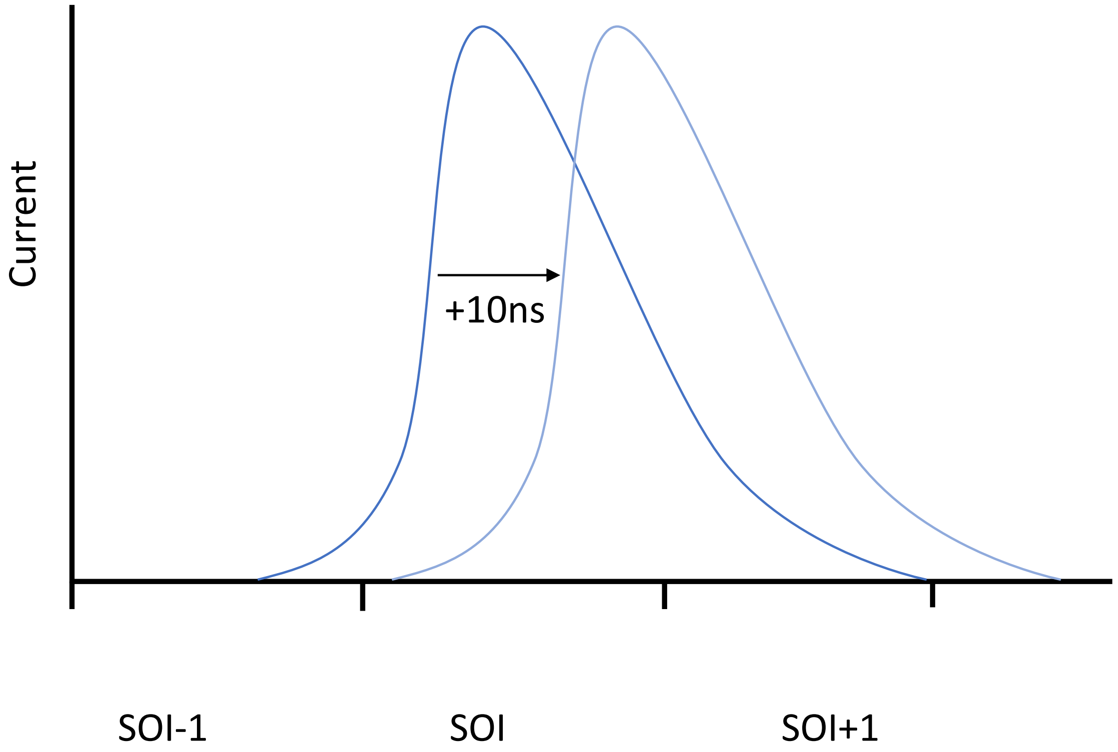


Four TDC codes available for HCAL:

- 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)

Phase Scan for Artificially "Delayed" Signals





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

HCAL Alignment with Phase Scan

Four TDC codes throughout timing scan:

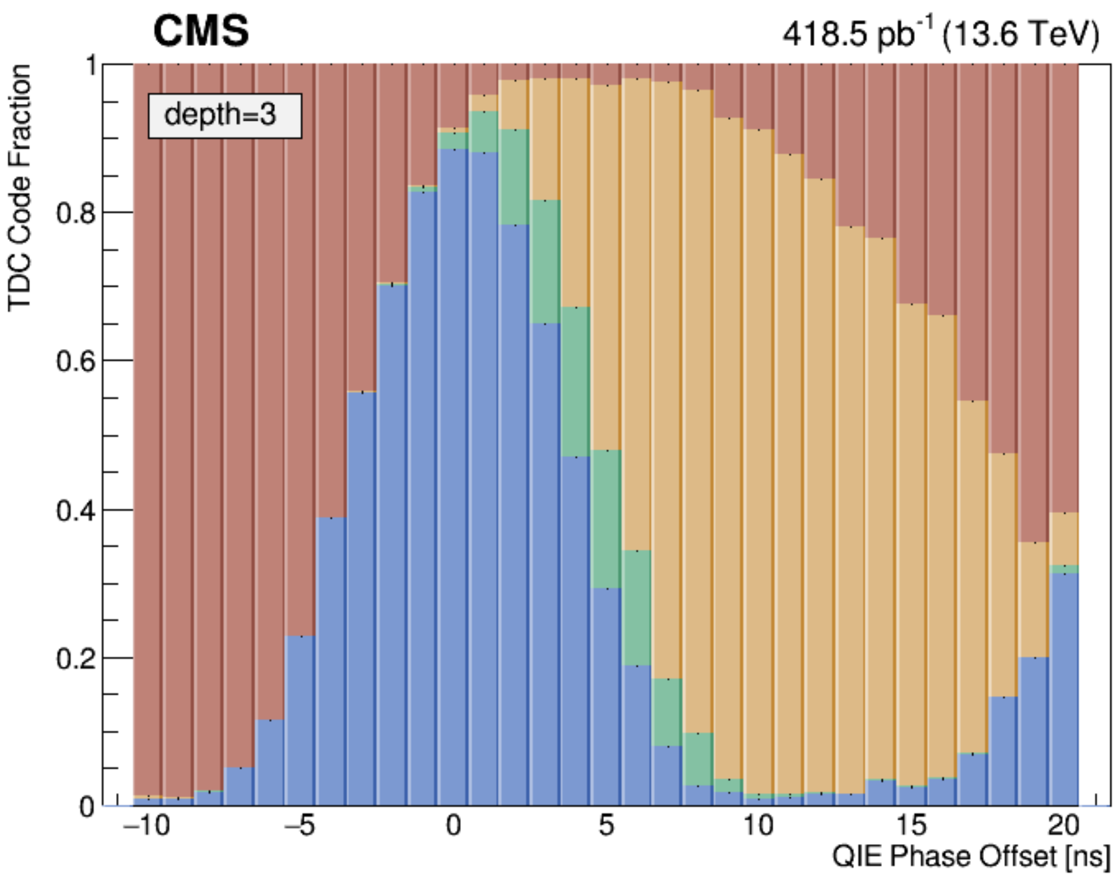
- 00: Prompt
- 01: Slight delay
- 10: Delayed
- 11: No valid TDC

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

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

Alignment achieved to within 0.5 ns

June 2023 TDC-based alignment



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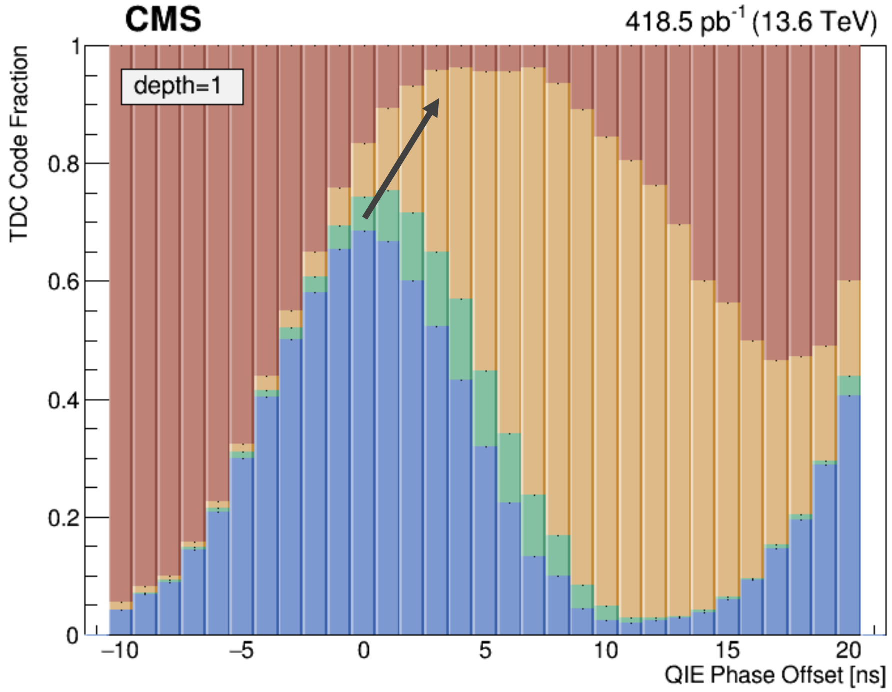
Depth 1 Behavior

- Depth 1 behaves differently than other depths
  - Lower prompt fraction that peaks before efficiency plateau
  - Prompt rising edge is broadened due to tail of high EM fraction showers
    - Thin layer, behind ECAL without HCAL absorber
    - Showers reduced in later depths due to absorber
- Solution implemented for 2024
  - Delay pulses by +3ns and widen prompt range



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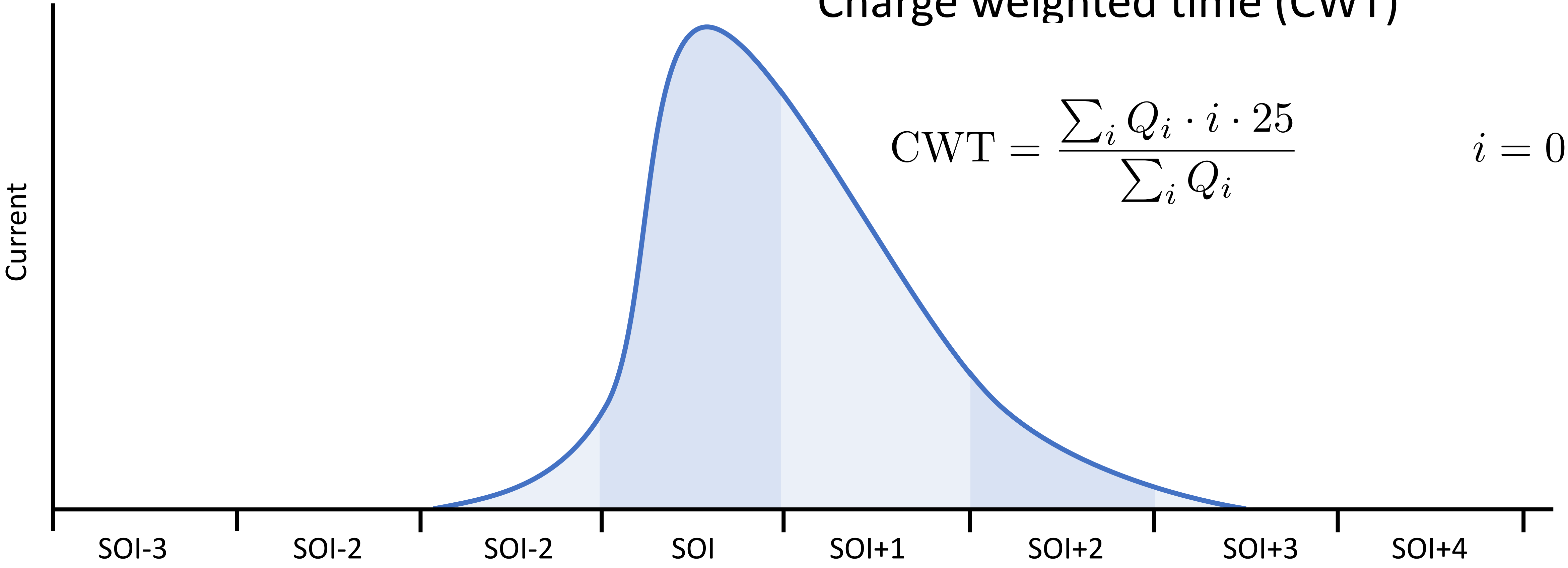
Comparison to Previous Time Alignment

Charge weighted time (CWT)

$$\mathrm{CWT} = \frac{\sum_i Q_i \cdot i \cdot 25}{\sum_i Q_i} \qquad i = 0...7$$



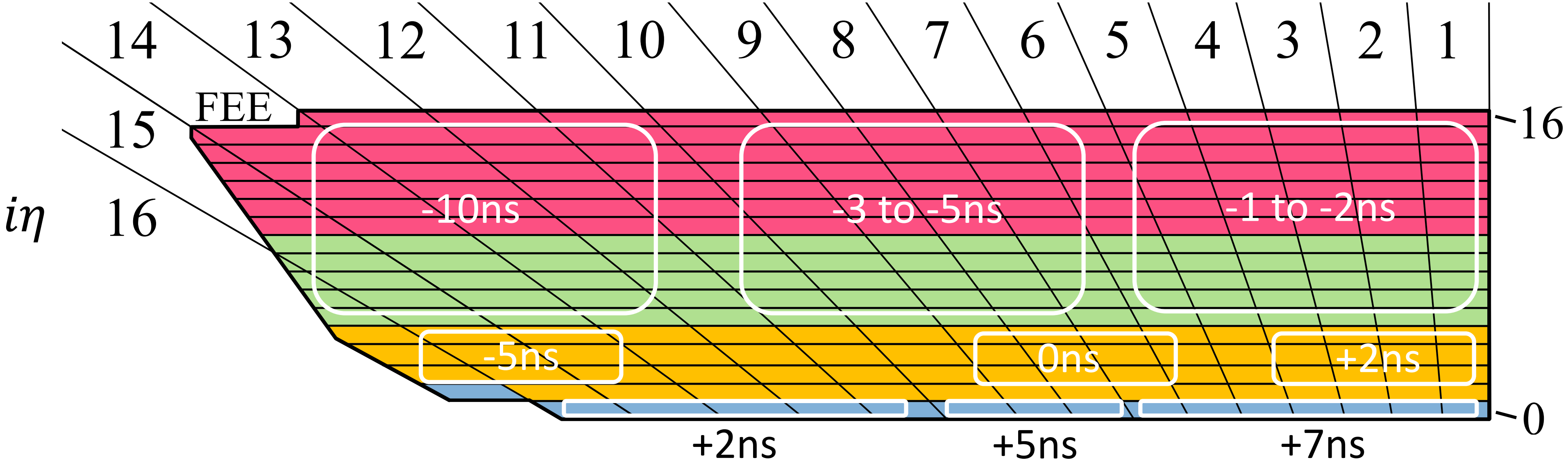
TDC vs. CWT

- TDC is sensitive to the leading-edge pulse timing
  - Very clean way of measuring pulse arrival time
  - Straightforward alignment method with newly available timing information

- CWT measures the mean of the pulse energy
  - Very sensitive to pulse shape variations with depth and shower propagation
  - 5.8 λ_I in the HCAL: depths 3 and 4 have more hadronic shower fluctuations
    - Depth dependent pulse shapes are being implemented

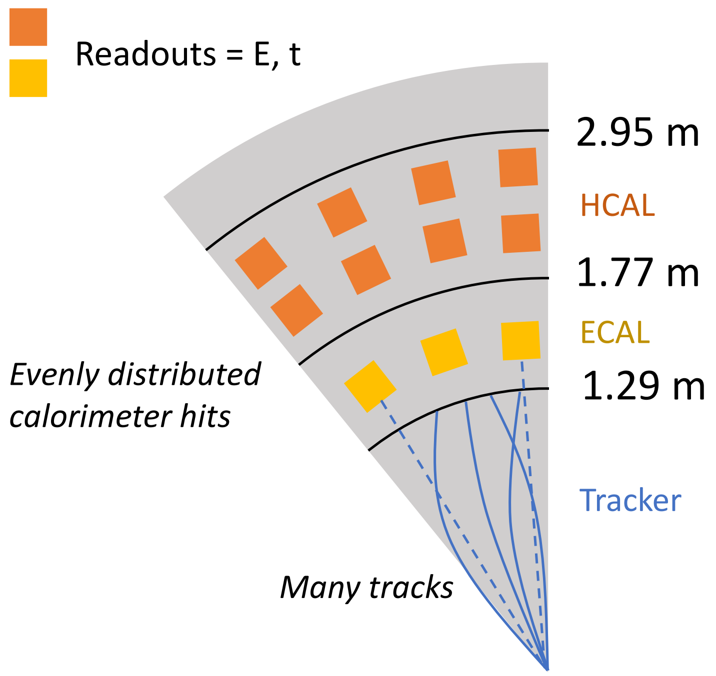
Far-Reaching Impacts of HCAL Time Alignment

- New HCAL timing alignment deployed in June 2023
  - Misaligned HCAL has pulses arriving up to 10 ns early at high depth, high $i\eta$
  - HCAL barrel energy resolution improved by 10% after alignment
  - Adjustments significantly reduced L1 pre-firing

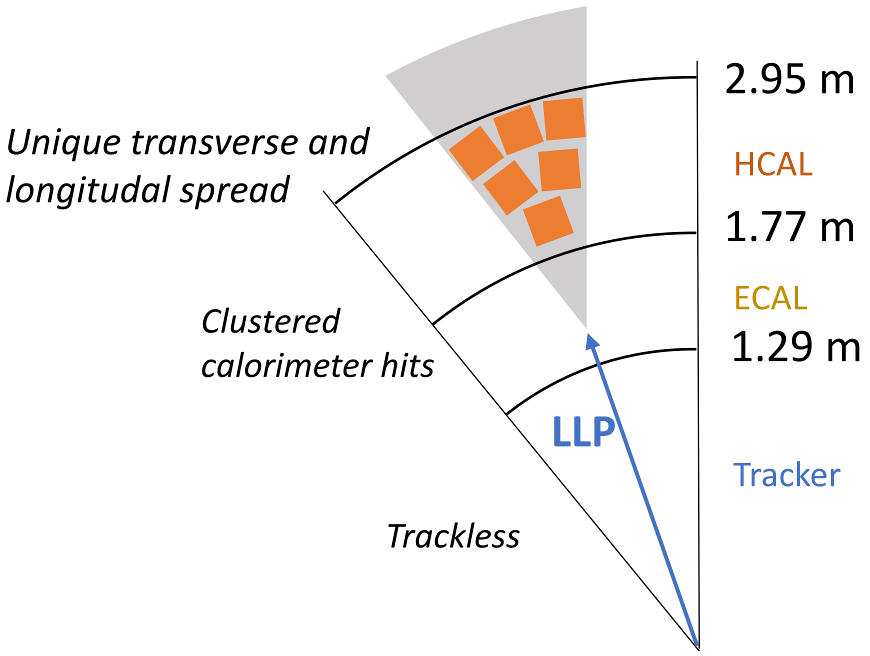


Calorimeter Based LLP Reconstruction

Segmented calorimeters are a powerful handle in LLP identification



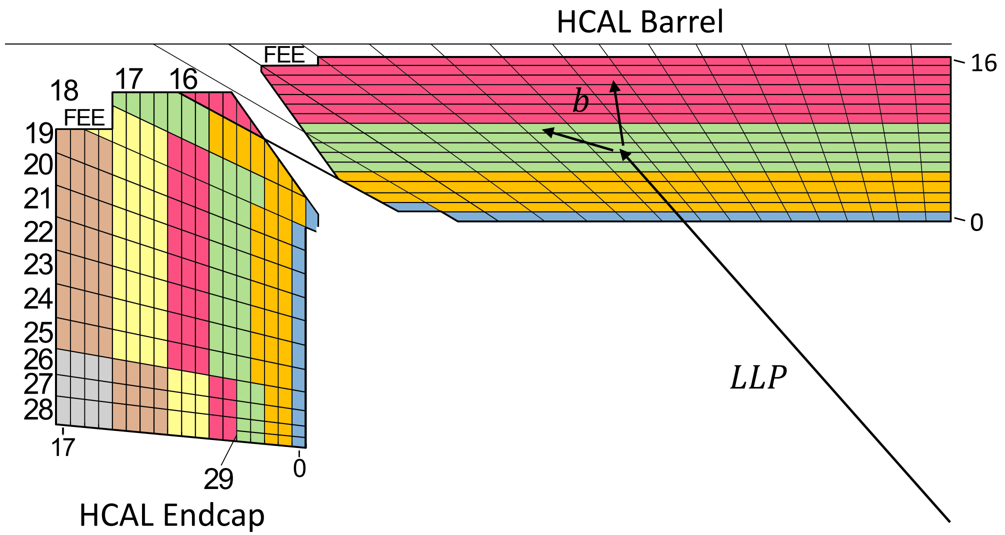
Prompt jet



LLP jet

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

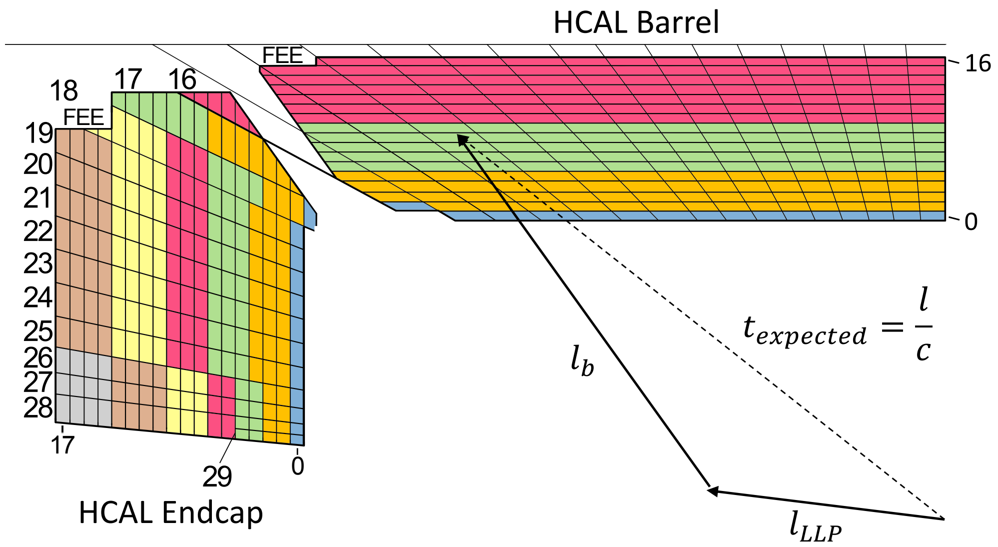
HCAL LLP Trigger



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

- Two handles for triggering on LLPs:
  - Depth segmentation – the trigger algorithm identifies **displaced jets**, resulting from LLPs that decay inside the HCAL

HCAL LLP Trigger

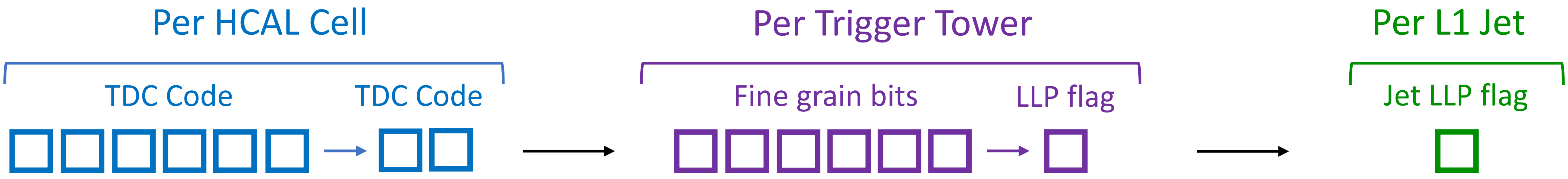


$$\Delta t = \frac{l_{LLP}}{v_{LLP}} + \frac{l_b}{c} - t_{expected}$$

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

- Two handles for triggering on LLPs:
  - Depth segmentation – the trigger algorithm identifies **displaced jets**, resulting from LLPs that decay inside the HCAL
  - Timing information (TDC) – identify **delayed jets**, resulting from the decay of massive LLPs
- Create LLP flagged L1 jets
  - Require a cluster of timing or depth flagged towers within the jet

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

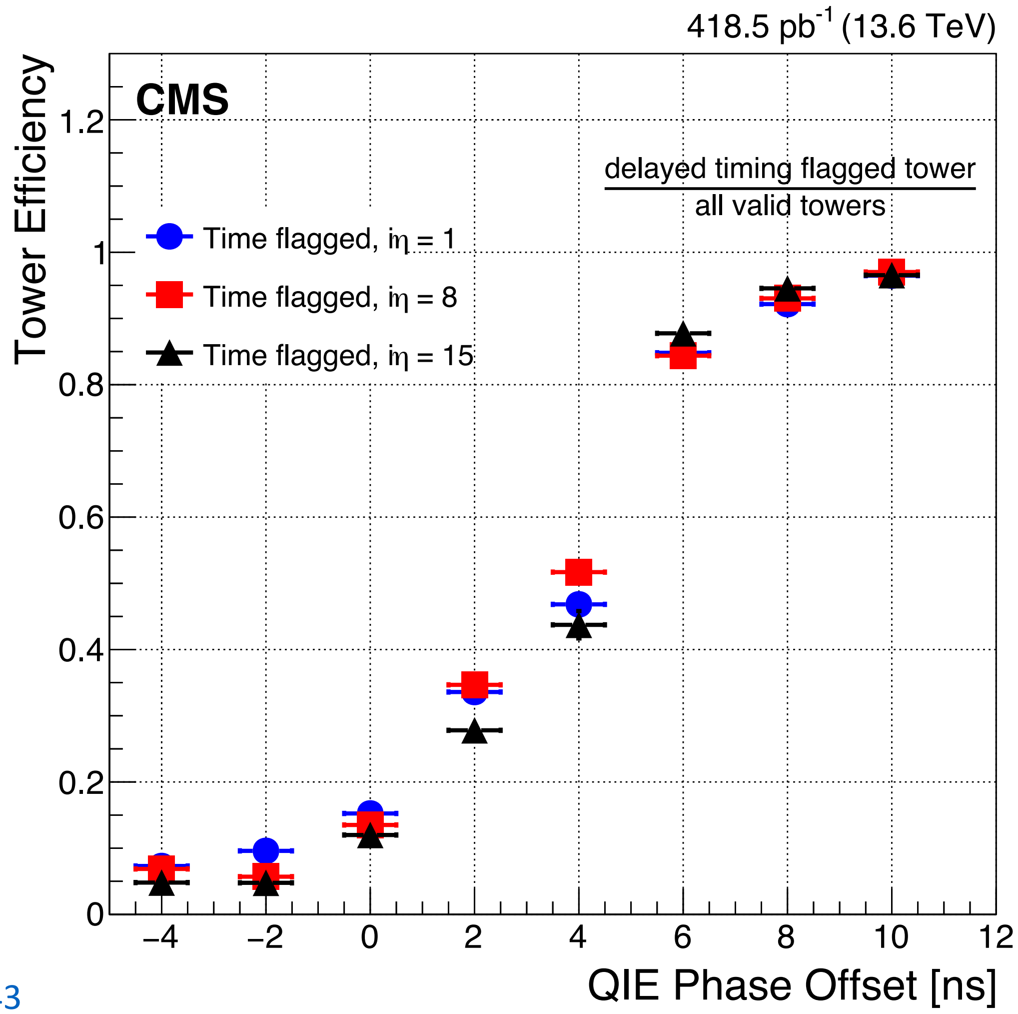
L1 Accept after jet and HT energy requirements applied
5 L1 pathways (single, double jet)
15 HLTs seeded with L1 LLPs

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

LLP Flagged TP Performance with Timing Scan

Delayed tower efficiency vs. phase offset

- **High sensitivity to pulse timing**: delayed timing tower efficiency greatly increases between 0-6 ns, as expected with prompt timing range set at 6 ns



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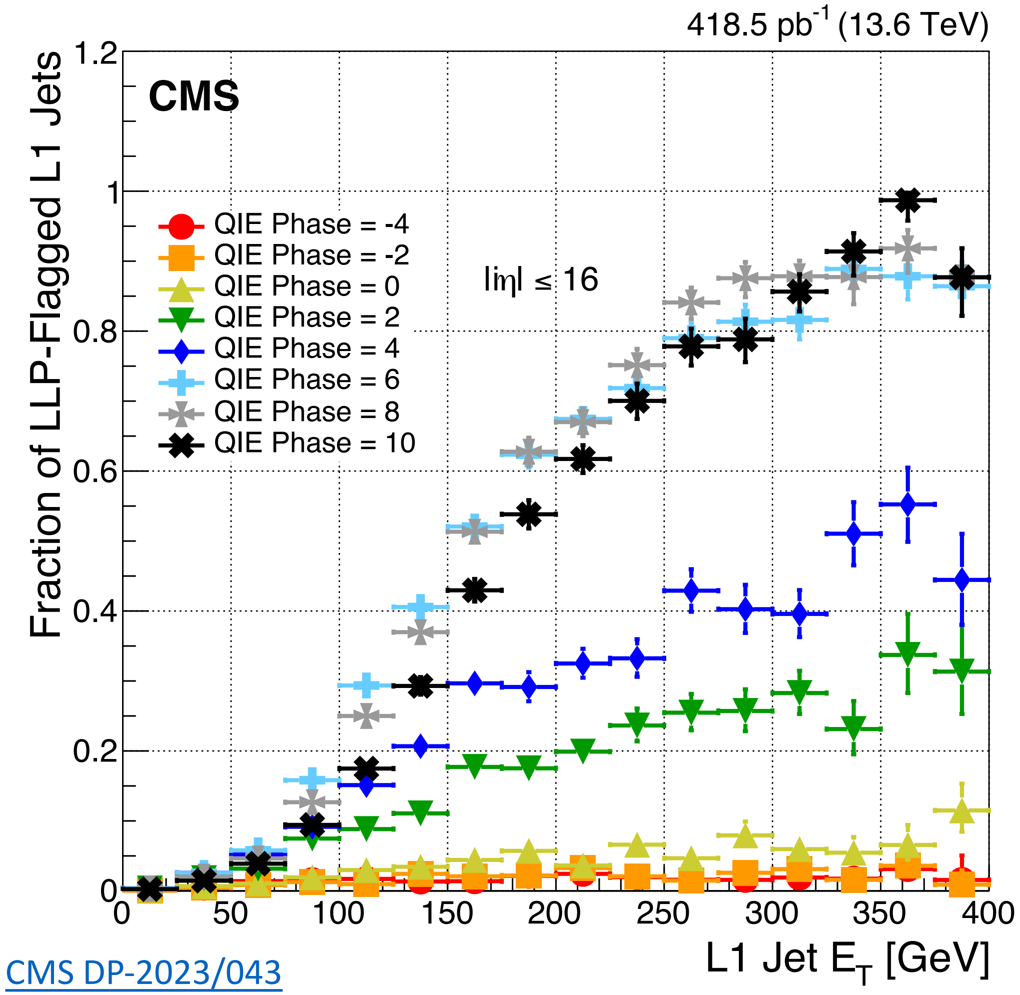
LLP L1 Jet Performance with Timing Scan



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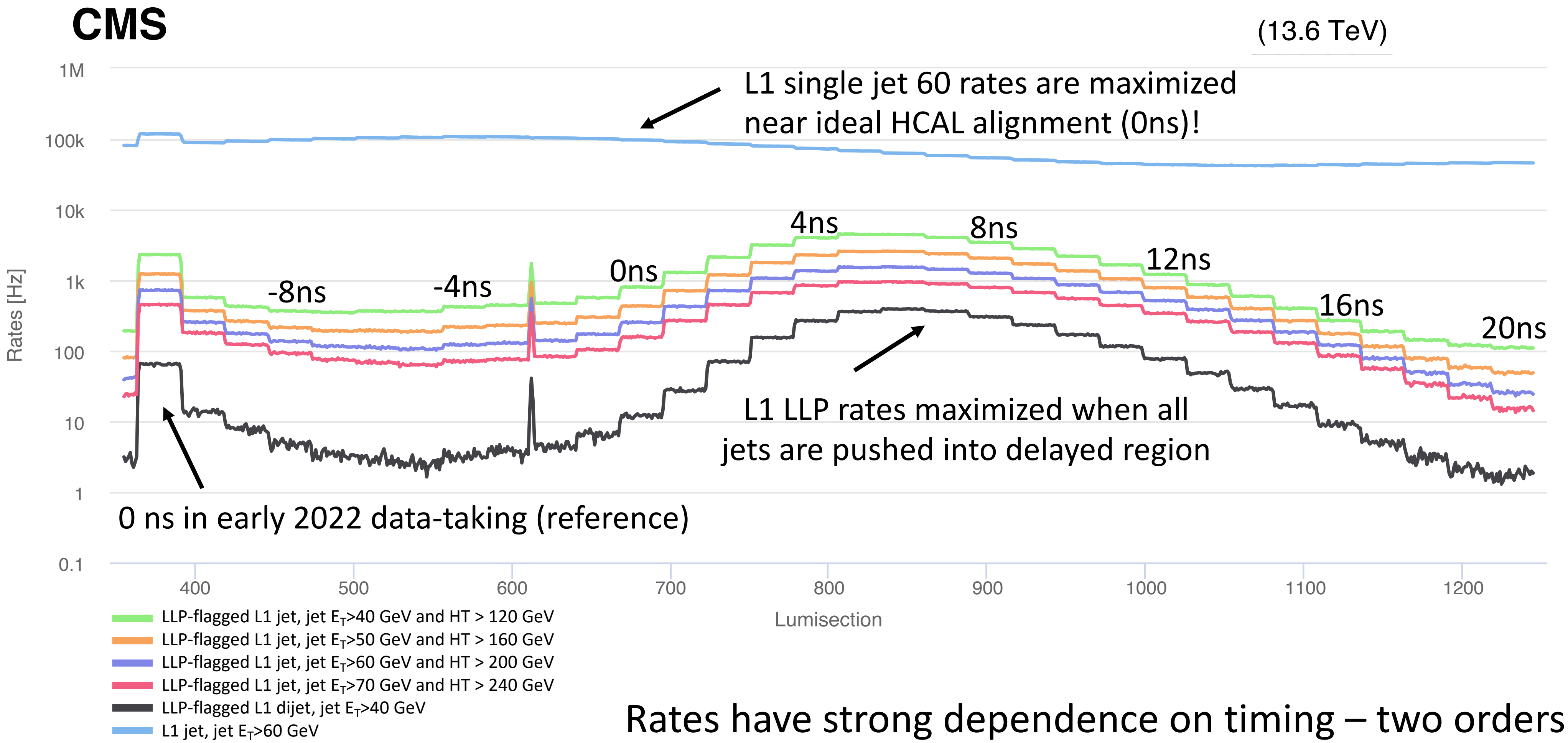
LLP-flagged L1 delayed jet fraction vs. jet E_T by phase offset

- 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

Sensitivity of Triggers to Time Offsets



Rates have strong dependence on timing – two orders of magnitude suppression for the double jet trigger! Total HCAL LLP L1 trigger rates are ~1 kHz.

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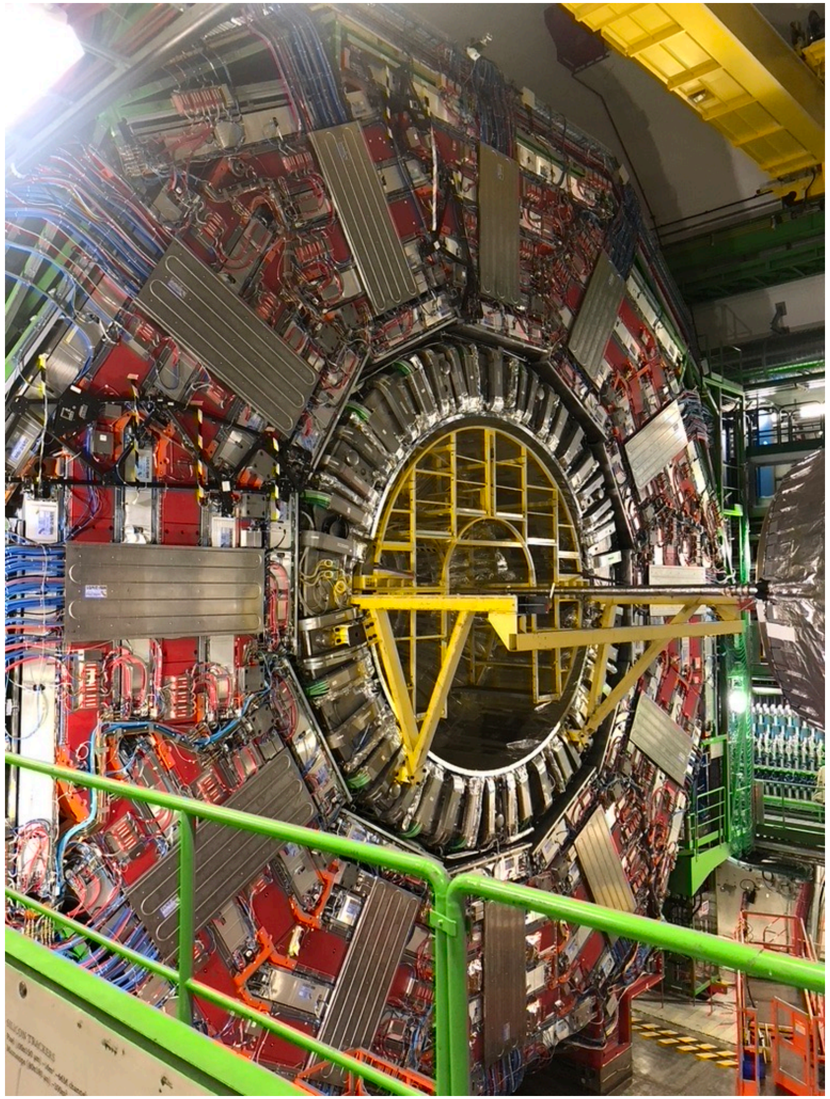
Conclusions

- **Calorimeter timing information (TDC)** used for new HCAL time alignment procedure
  - Alignment to within 1 ns achieved
  - Improved HCAL energy resolution
- **L1 LLP trigger** uses the new depth and timing capabilities of HCAL
  - Expands LLP phase space sensitivity into otherwise difficult regions
  - First L1 trigger use of the HCAL segmentation

Thank you!

Questions?



Backup

Published Material

Gillian Baron 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). http://cms.cern.ch:80/iCMS/jsp/db_notes/showNoteDetails.jsp?noteID=CMS%20DN-2023/022

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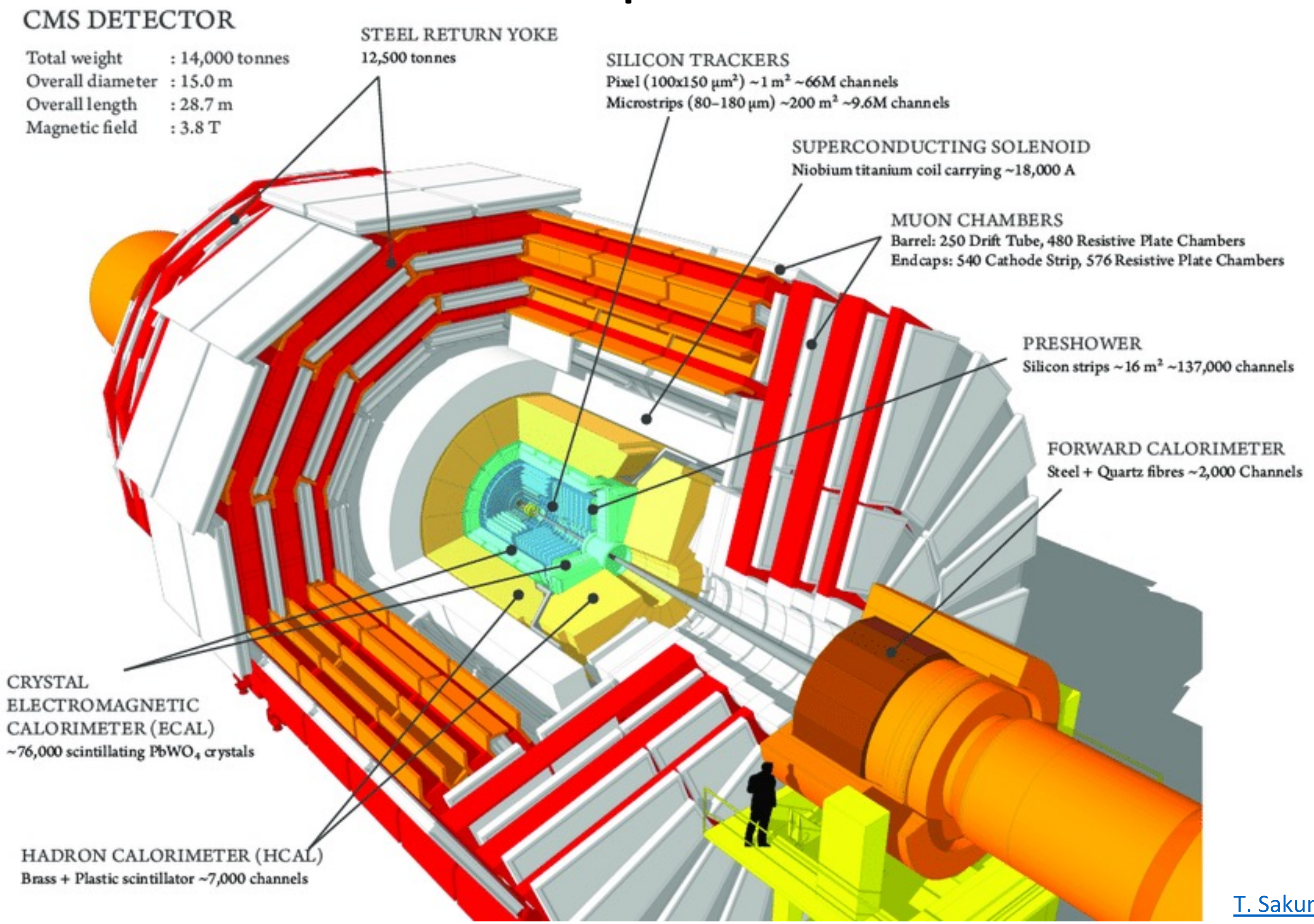
[1] *CMS BRIL, Muons, and HCAL upgrade for Run2/3 – operations and performance*. A. Shevelev on behalf of the CMS Collaboration. CERN Detector Seminar, 3 May 2024. CERN. https://indico.cern.ch/event/1409212/

[2] *Phase 1 Upgrade of the CMS Hadron Calorimeter*. Candan Isik for the CMS Collaboration. The CMS Experiment Conference Report, CMS CR-2022/049. 25 March 2022. https://cds.cern.ch/record/2810162/files/CR2022_049.pdf

[3] *A New Generation of Charge Integrating ADC for the CMS HCAL Upgrade: The QIE10/11*. Elliot Hughes. TIPP 2014. https://indico.cern.ch/event/192695/contributions/353256/attachments/277181/387778/Elliot-Hughes.pdf

The Compact Muon Solenoid Experiment

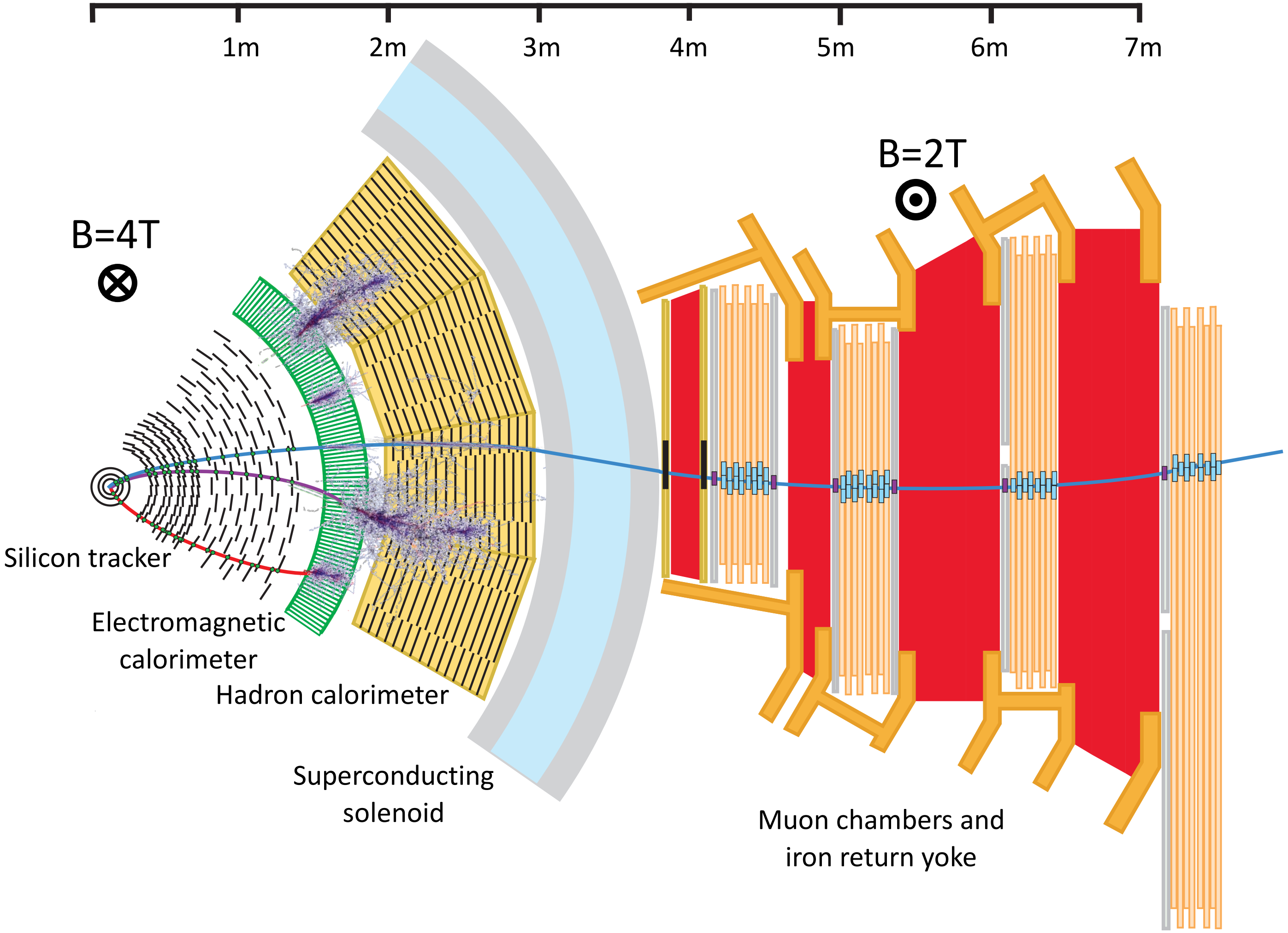


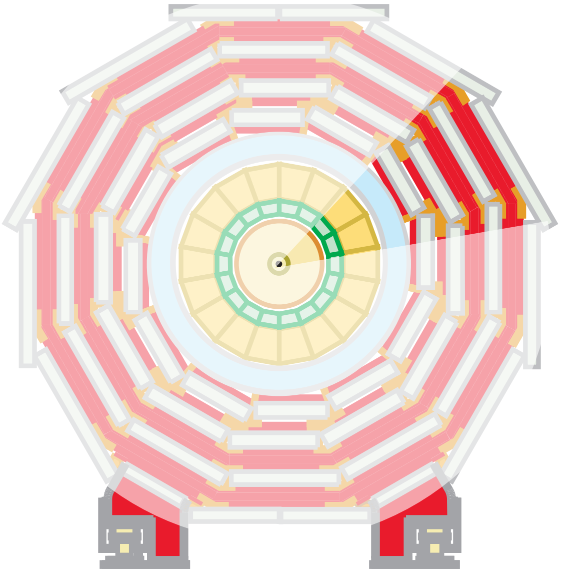
Layers of cylindrical detectors:

- Silicon tracker
- Electromagnetic calorimeter
- **Hadron calorimeter** (HCAL)
- Superconducting solenoid
- Muon chambers

T. Sakuma, T. McCauley

Particle Detection in CMS

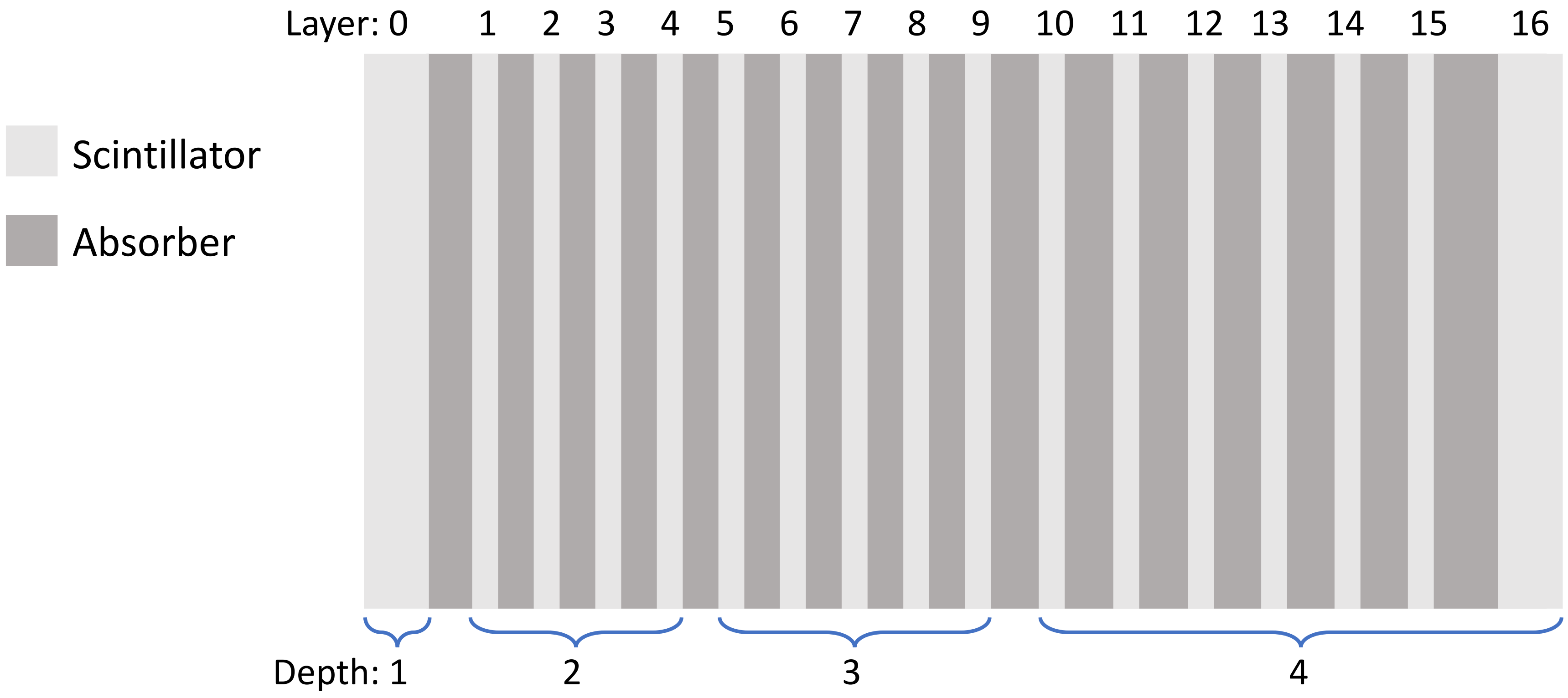




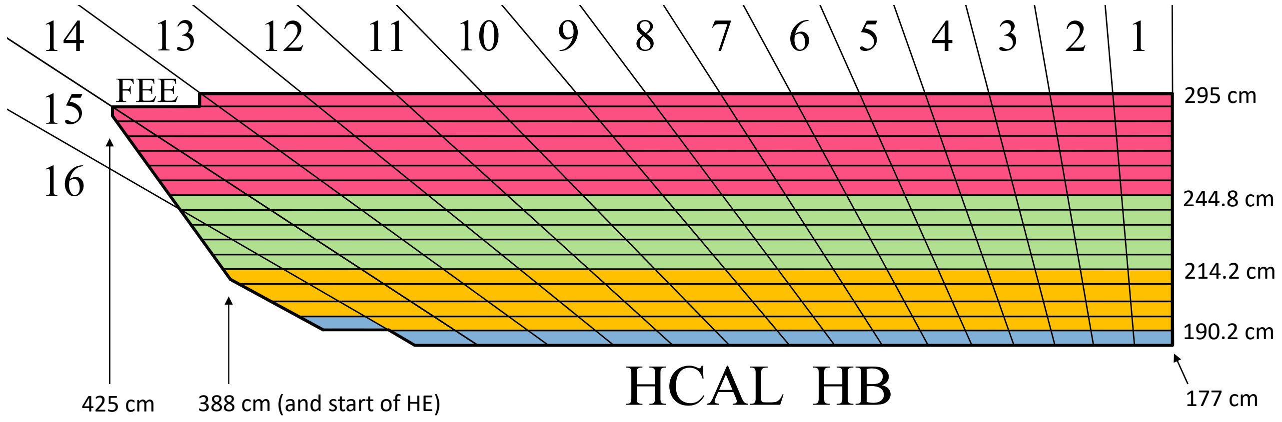
Transverse slice of CMS

CMS Twiki

HCAL Layers and Depths



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.

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)

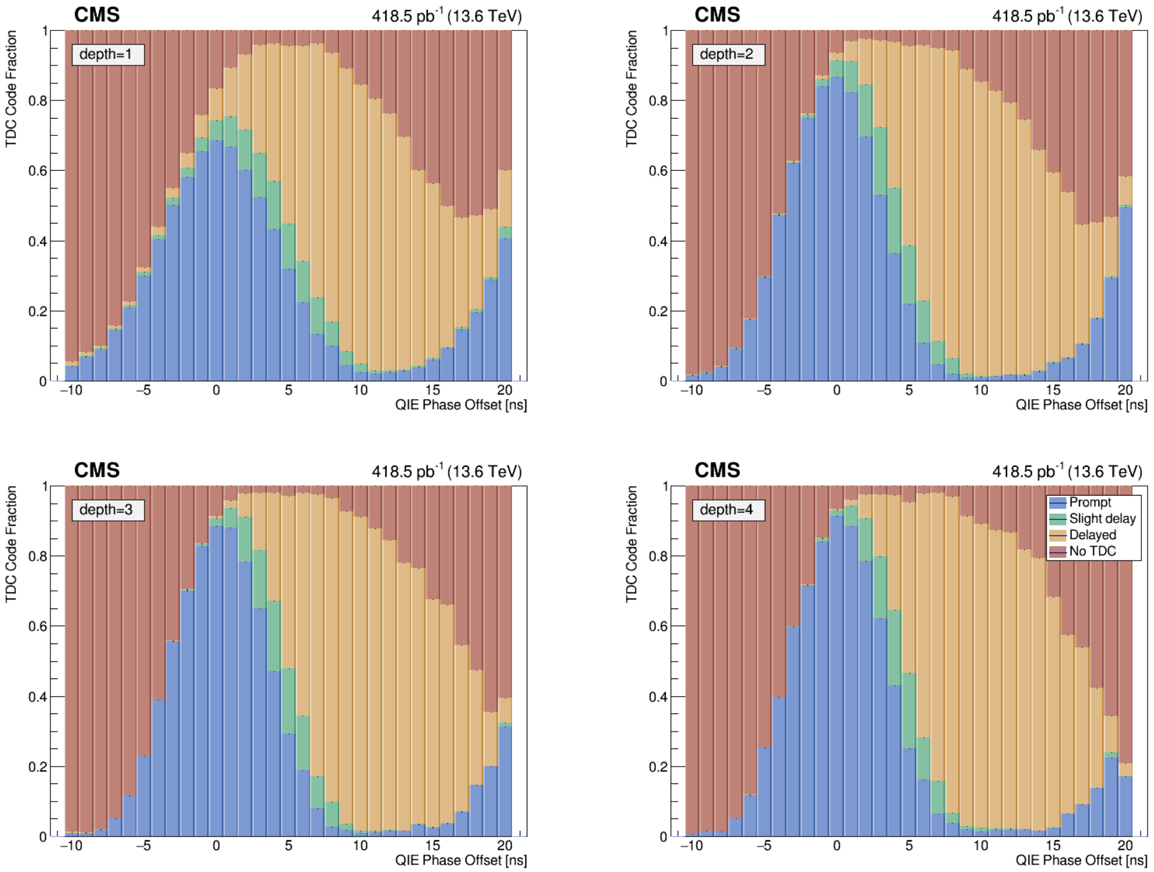
The prompt timing distribution (blue) is maximized at the optimal time alignment (0 ns)

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



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Charge Weighted Time

- CWT is re-weighted and linearized for optimal use as a timing estimator
  - Reweighting and calibration procedure relies on alignment known from TDC
  - TDC is a fundamentally accurate measurement of the time of the pulse leading edge and does not assume a uniform pulse shape spanning bunch crossings
- CWT assumes identical pulse shapes spanning multiple bunch crossings
  - **Reweighting** accounts for different pulse shapes in each depth
  - **Calibration** enforces 1-1 linearity between QIE phase and CWT

$$w_{i,depth} = [1, 1, w_{i=2,depth}, 1, w_{i=4,depth}, 1, 1, 1]$$

$$\mathrm{CWT_{depth}} = \frac{\sum_i Q_i \cdot i \cdot 25 \cdot w_{i,depth}}{\sum_i Q_i \cdot w_{i,depth}} \qquad i = 0...7$$

$$w_{i=2,depth} = \frac{\mathrm{ideal}(i=2)}{\frac{SOI-1}{SOI}}$$

$$w_{i=4,depth} = \frac{\mathrm{ideal}(i=4)}{\frac{SOI+1}{SOI}}$$

HCAL Timing Alignment

- TDC is a very clean way of measuring pulse arrival time
  - Accurate alignment is vital both for TDC and energy measurements, particularly with new HCAL PFA1’ scheme
  - Too early means TDC not set in SOI, too late means energy is under-reported
- Straightforward alignment method
  - TDC threshold is low, but does not fire from PU
  - Plot distribution of TDC times for each channel
  - Adjust delays so that arrival time distributions (given a minimum pulse height and low TDC threshold) are the same relative to clock edge
- TDC is linear in clock delay, and makes no pulse shape assumptions