Long Lived Particle Triggering at Level-1 with the CMS Hadron Calorimeter

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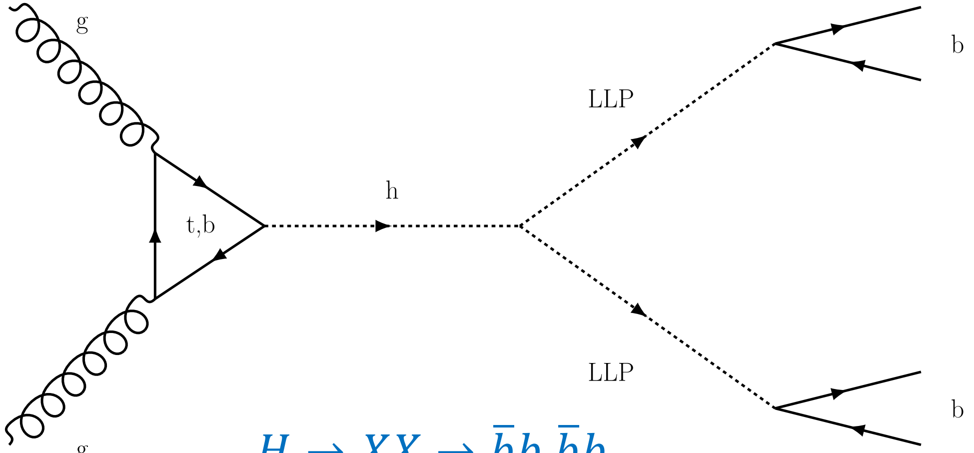
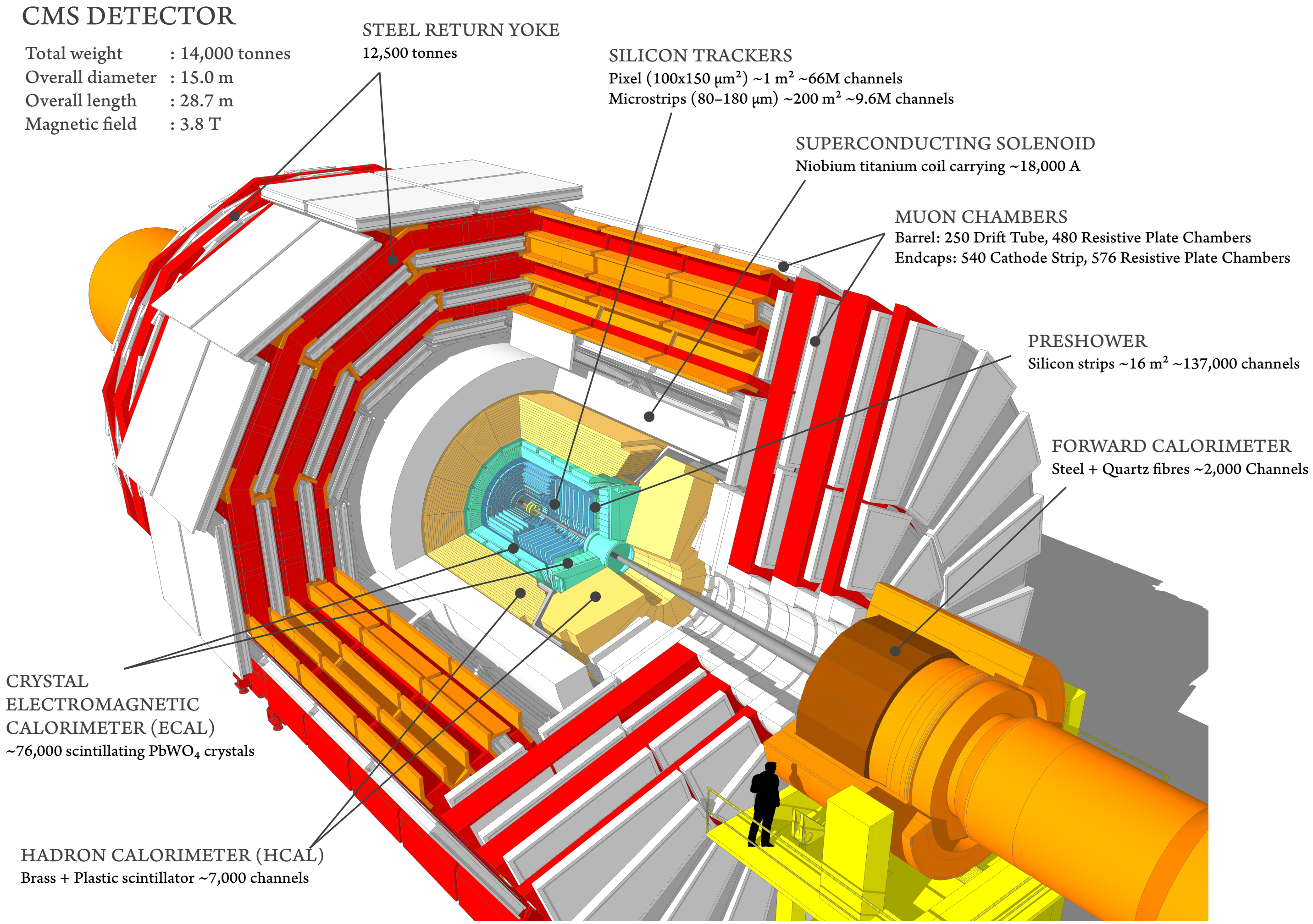
Long Lived Particles to Search for New Physics



$H \rightarrow XX \rightarrow \bar{b}b\,\bar{b}b$

- Long lived particles are in many BSM models, resulting from:
  - small couplings
  - suppressed phase space
  - approximate symmetries
- LLP signatures may be observable at the LHC!
  - Unique energy deposits, delayed time stamps, characteristic jet shape, and shower position are handles to search for LLPs
- Improving searches involves expanding our ability to trigger on LLPs
  - Highlight first **hardware-based** CMS calorimeter LLP trigger, in Run-3!

LLPs in CMS

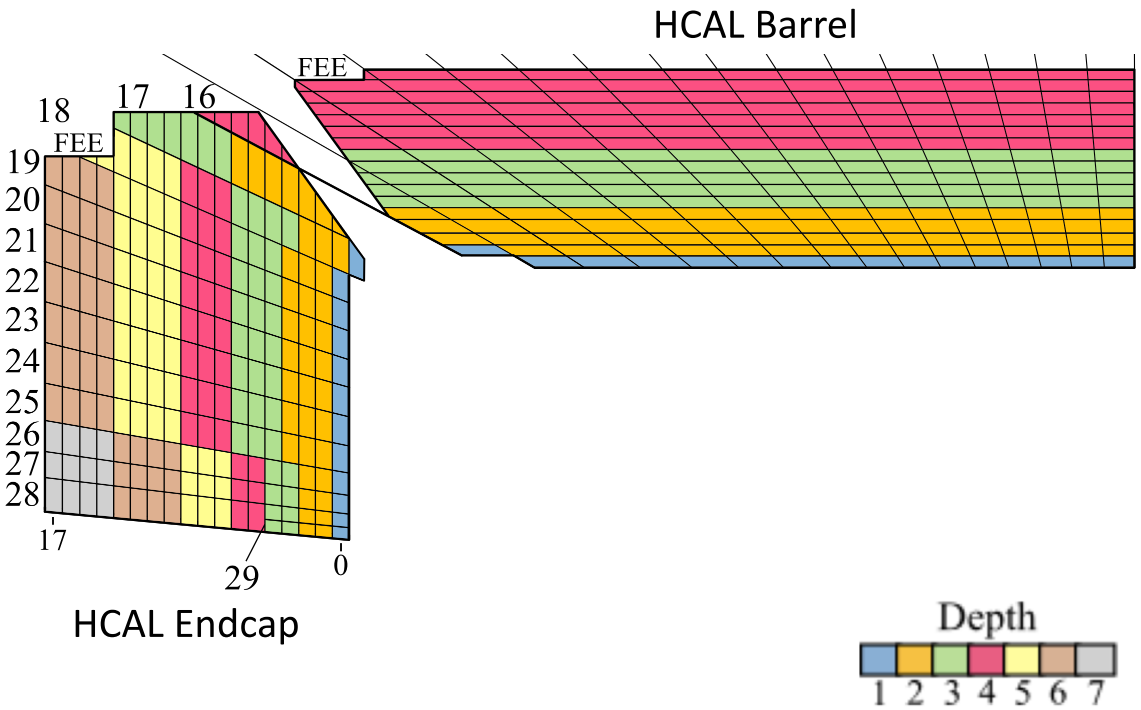


- CMS has utilized many handles to trigger on LLPs, including with the tracker, ECAL timing, and the muon system
- CMS LLP triggers have expanded for Run 3, both at software and hardware levels, making this an exciting run for LLP searches!

This talk's focus: utilizing the hadron calorimeter upgrade for **additional LLP trigger capabilities at Level 1 (hardware) that are implemented for Run 3.**

CMS HCAL Phase 1 Upgrade

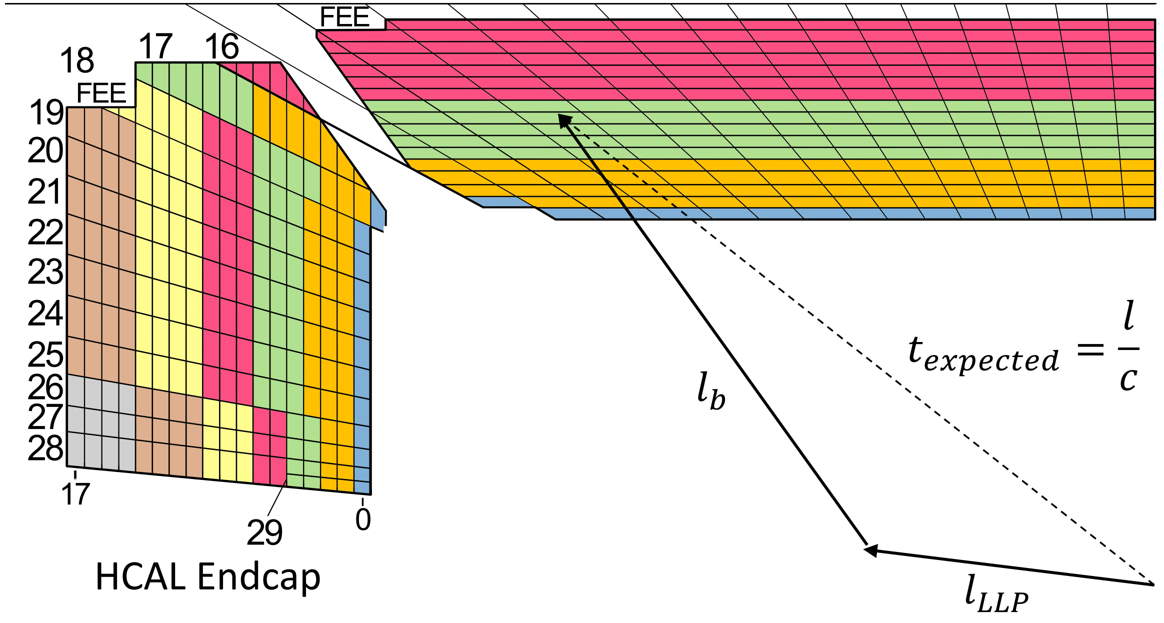
- HCAL Phase 1 upgrade replaced HPDs with SiPMs and updated the on-detector electronics (dedicated ASICs)
  - Major upgrade improved energy resolution by replacing HPDs with SiPMs
  - SiPMs allow for **increased number of readout channels** (depth segmentation) and new ASICs have **time-to-digital converter** (TDC) measurements
- In addition, these upgrades provide new ways to identify long lived particles!



CMS HCAL for LLP Triggering

- Two handles for triggering on long lived particles:
  - Timing information (TDC) – identify **delayed jets**, resulting from the decay of massive LLPs

Signatures: **delayed time of arrival** of hits in calorimeter

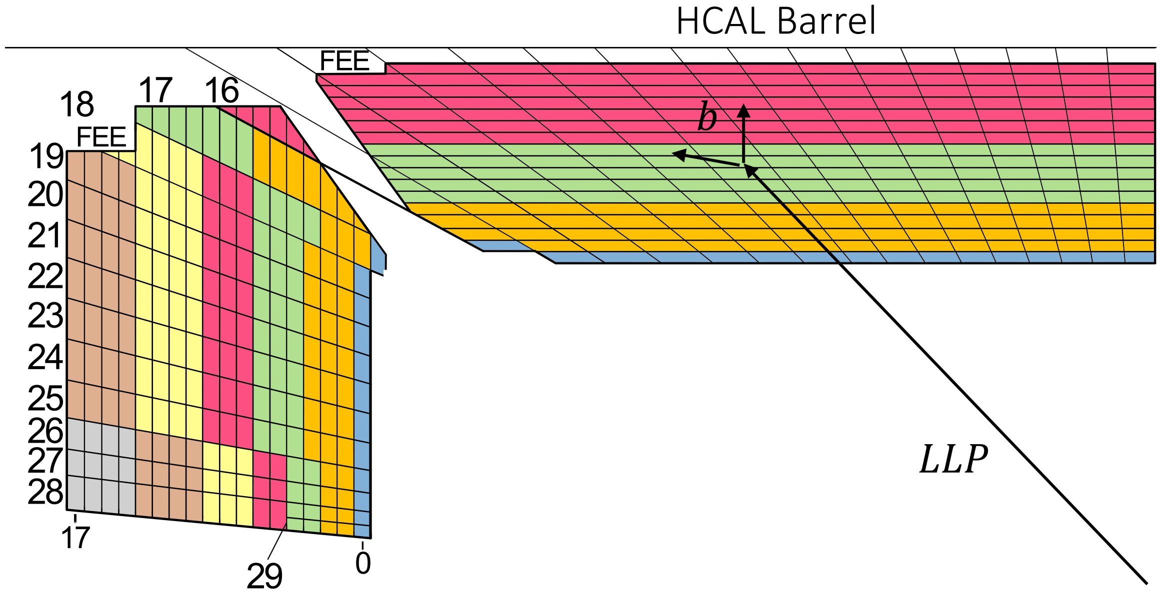


$$\Delta t = \frac{l_{LLP}}{v_{LLP}} + \frac{l_b}{c} - t_{expected}$$

CMS HCAL for LLP Triggering

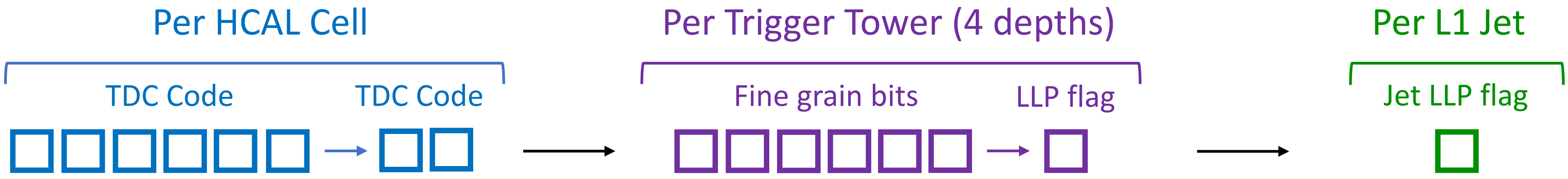
- Two handles for triggering on long lived particles:
  - Timing information (TDC) – identify **delayed jets**, resulting from the decay of massive LLPs
  - Depth segmentation – the trigger algorithm identifies **displaced jets**, resulting from LLPs that decay inside the HCAL
- Create LLP flagged L1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

Signatures: **delayed time of arrival** of hits in calorimeter
energy deposited in **deep calorimeter layers**
Identify LLP L1 jets based on a cluster of flagged towers



Significant energy in depths 3 and 4 and little energy in early depths 1 and 2

LLP Trigger Pathway: HCAL through HLT



HCAL TDC in 6:2 bits

HCAL TDC LUT defines 3 timing ranges:

- Prompt
- Slightly delayed
- Very delayed

HCAL uHTR sends 6 bits to L1 6:1

6 fine grain bits per tower are set based on time and energy measurements

Calo L1 LUT requires either depth or timing flag (with a prompt hit veto) and forwards to Calo L2 jet algorithm

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

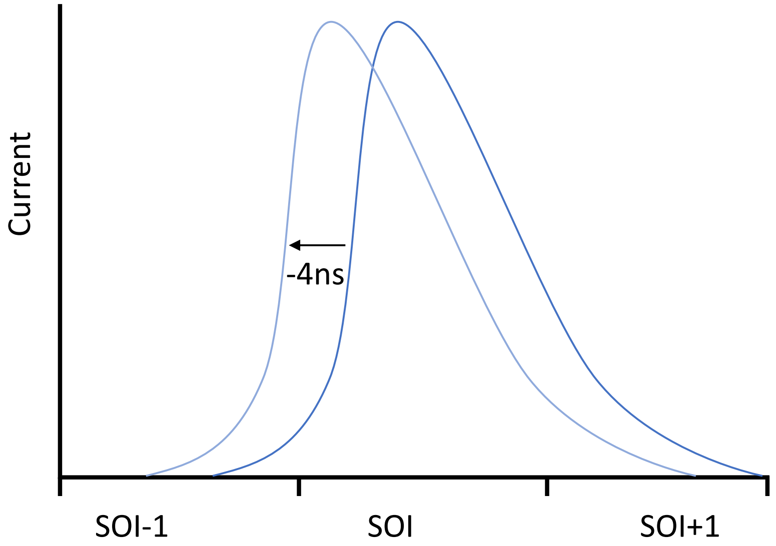
L1 Accept after jet and HT energy requirements applied

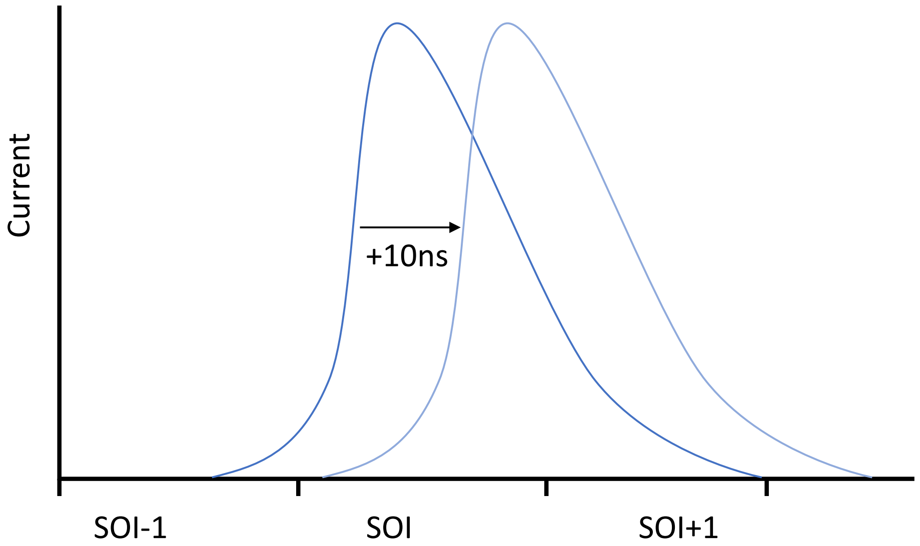
5 L1 pathways (single, double jet)
13 HLTs seeded with L1 LLPs

HCAL Timing Scan in Run 3

Scanning the HCAL clock artificially places prompt signals in the delayed range. Timing data from these scans allow to:

1) Align the calorimeter with high precision
2) Evaluate LLP trigger performance with delayed jets in collisions
3) Validate the new firmware and new trigger algorithm





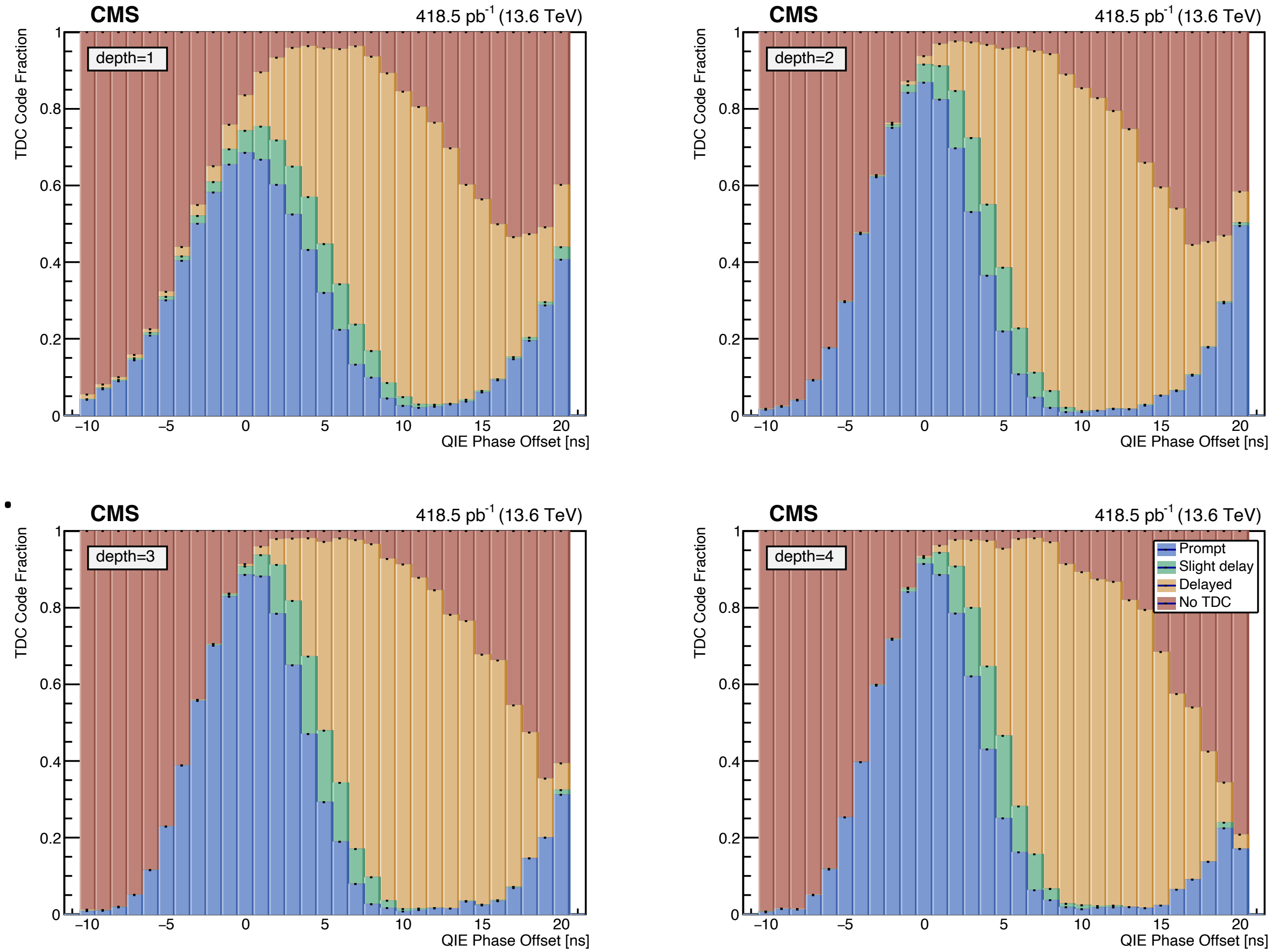
Large effort to use online timing to align HB to within 0.5ns: new alignment was deployed June 12, implementing shifts of several ns to achieve consistency across the detector

HCAL TDC Distributions

Four TDC codes throughout timing scan:

- Prompt (TDC ≤ 6 ns)
- Slight delay (6 < TDC ≤ 7 ns)
- Delayed (TDC > 7 ns)
- No valid TDC (set in another bunch crossing)

The prompt timing distribution (blue) is maximized at the optimal time alignment (0 ns). With increasing phase offset, more delayed (green and orange) TDC codes are seen, as pulses arrive in the delayed region.

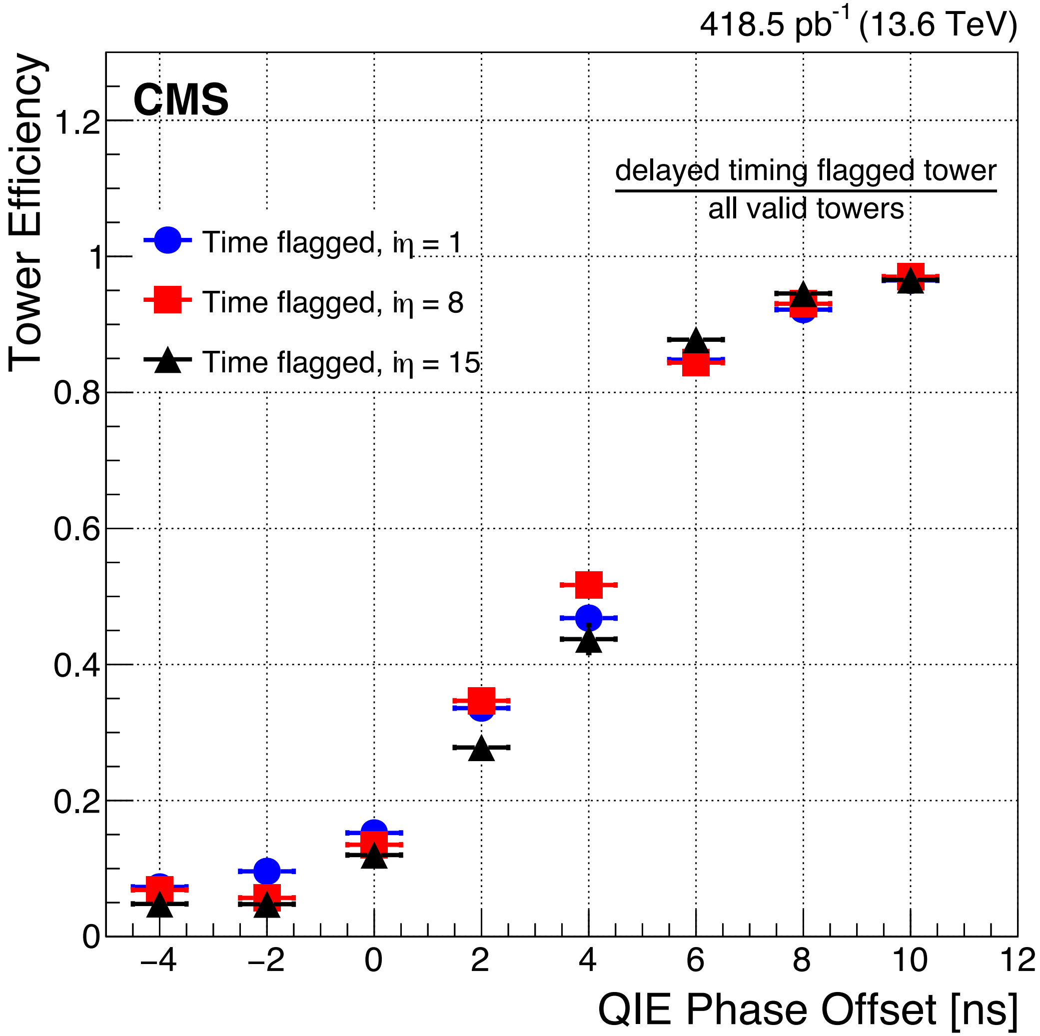


[2] CMS DP-2023/043

LLP Flagged Trigger Towers

HCAL delayed timing tower efficiency vs. phase offset

- Delayed timing tower requires at least one delayed cell and no prompt cells (in 4 depths contained in a trigger tower)
- Delayed timing tower efficiency greatly increases between 0-6 ns, as expected with prompt timing range set at 6 ns
- Demonstrates high sensitivity to pulse timing

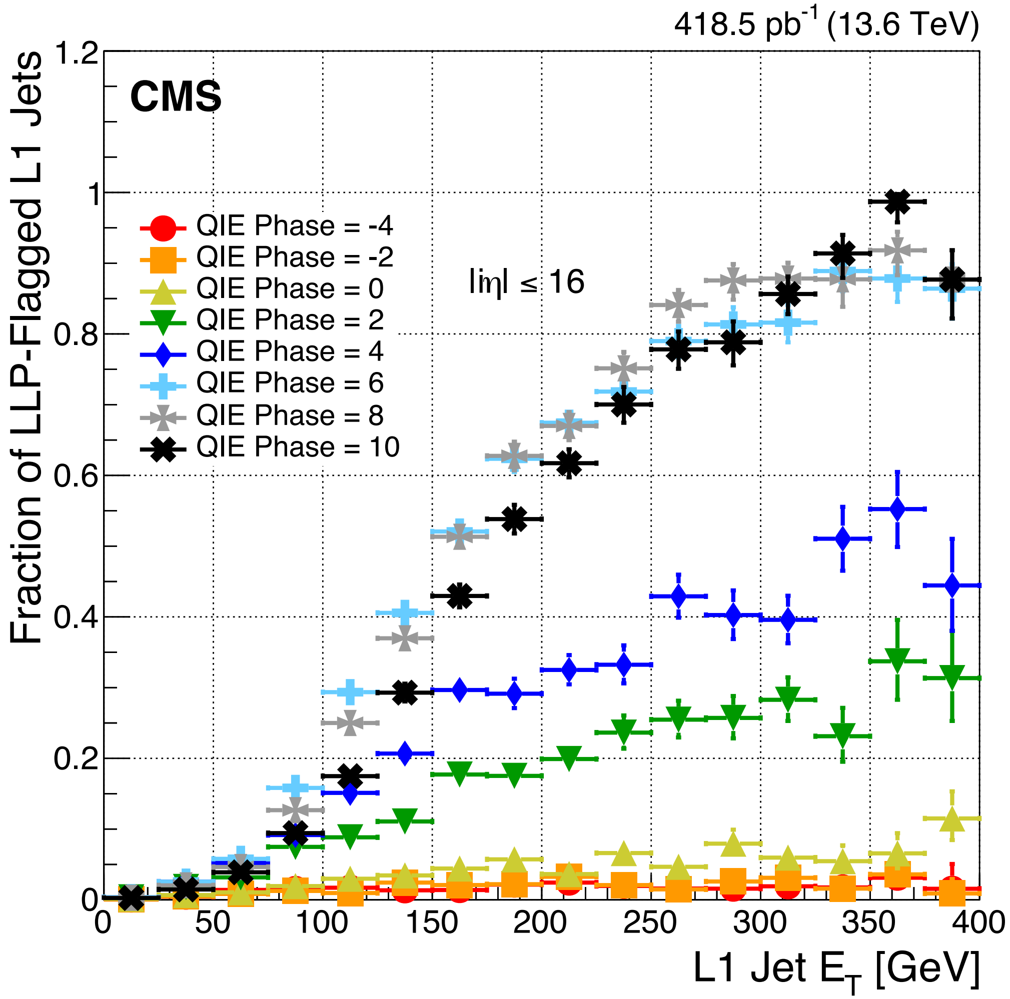


[2] CMS DP-2023/043

LLP Flagged L1 Jets

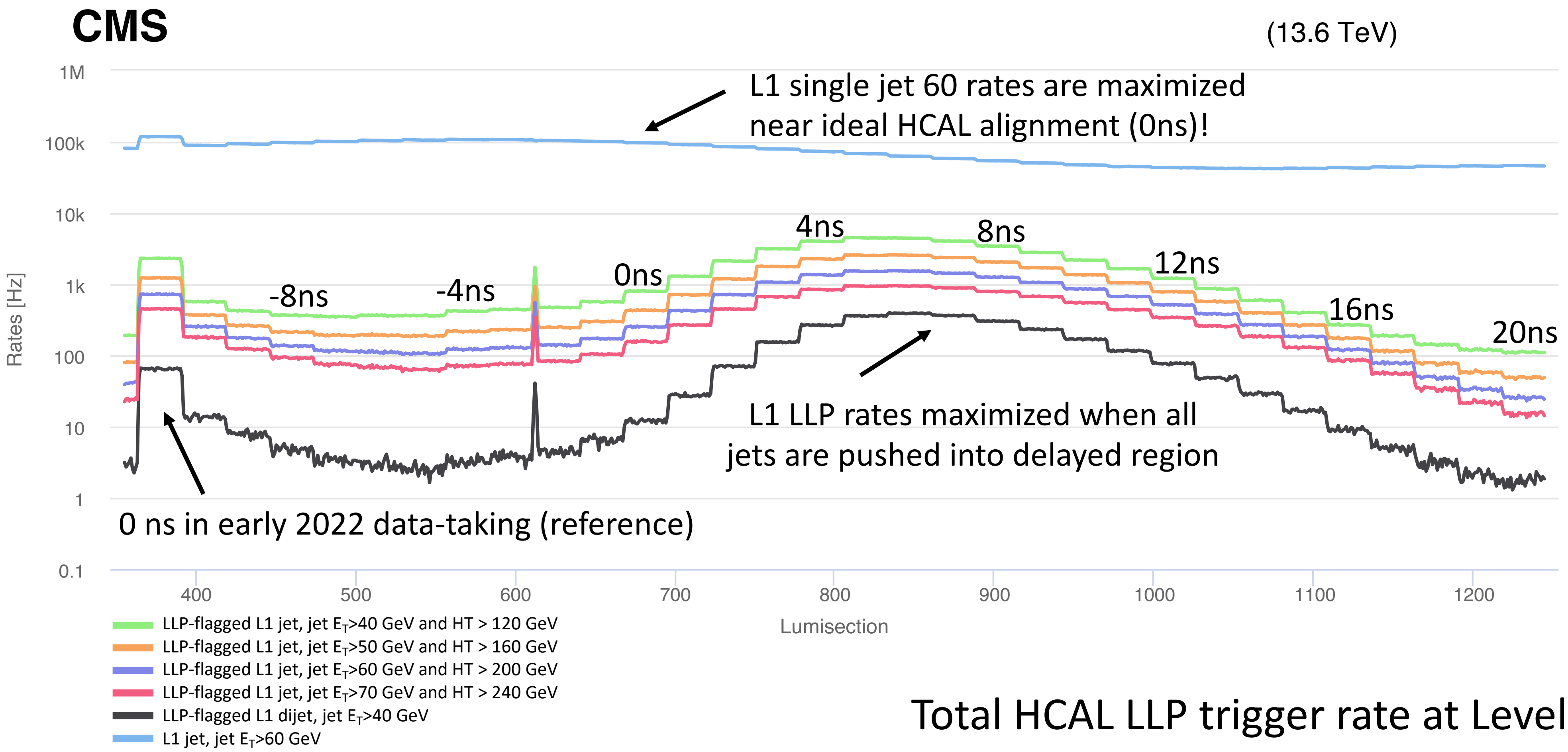
LLP-flagged delayed Level-1 jet fraction vs. jet E_T split by phase offset

- Require at least two LLP-flagged trigger towers
- LLP-flagged jet 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



[2] CMS DP-2023/043

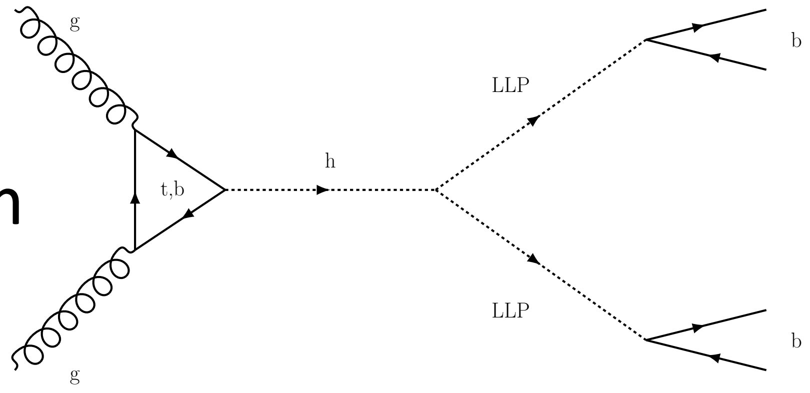
Sensitivity of Triggers to Time Offsets



Total HCAL LLP trigger rate at Level 1 is ~1 kHz

Future Directions

The dedicated L1 LLP triggers lead to a significant increase in LLP acceptance with respect to standard triggers due to their lower jet transverse momentum thresholds – up to a factor of 4 for signal with $m_H = 125 \text{ GeV}, m_{LLP} = 50 \text{ GeV}, c\tau = 3 \text{ m}$.



Dedicated triggers and increased readout granularity (used at analysis level!) are a powerful tool in LLP searches in Run-3. Many of these exciting approaches explored in Run-3 can be extended to HL-LHC.

Thank you!

Questions?

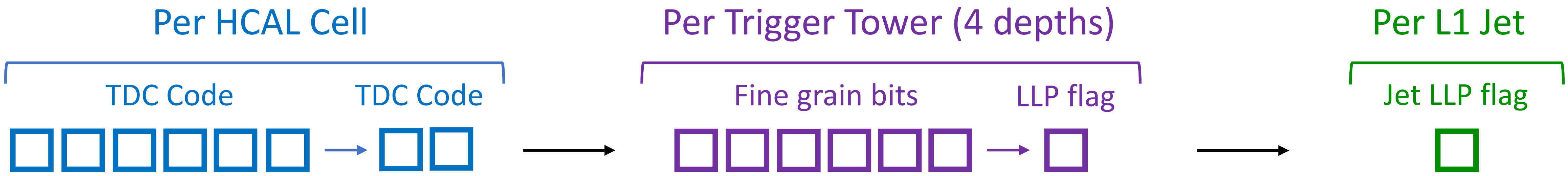
References

[1] Elliot Hughes, A New Generation Of Charge Integrating ADC For The CMS HCAL Upgrade: The QIE10/11, TIPP 2014:140604, 2014, Available at https://home.fnal.gov/~chlebana/CMS/Phase1/ Elliot-Hughes.pdf

[2] CMS Collaboration, Performance of long lived particle triggers in Run 3 (CMS DP-2023/043), Tech. report, CERN, cms-trigger-coordinator@cern.ch, July 2023, Available at https://twiki.cern.ch/twiki/bin/view/CMSPublic/Run3LLPHLT. Link to: DP Note

Backup Slides

LLP Trigger Pathway: HCAL through HLT



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

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

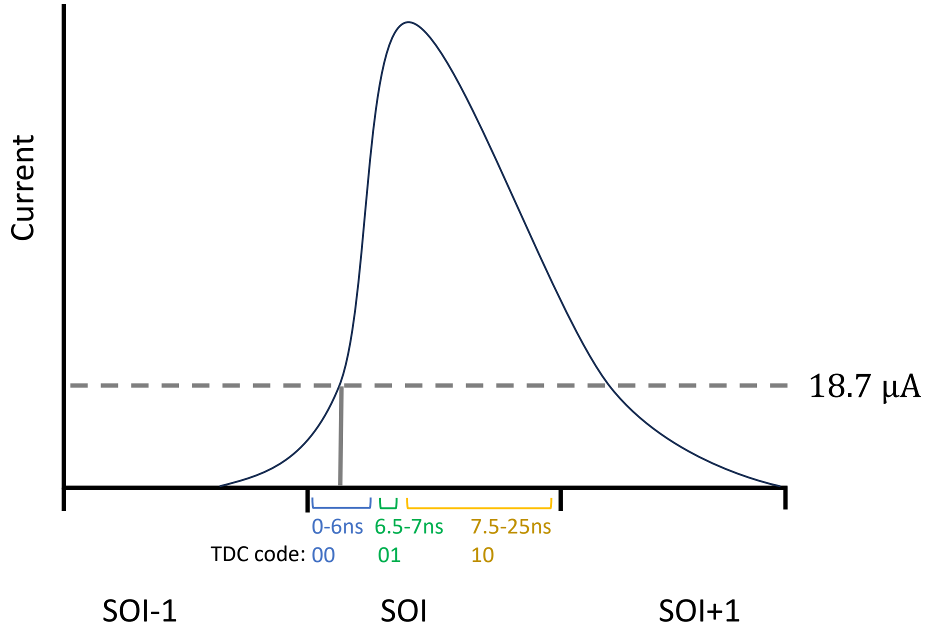
LLP jet flag set if jet contains ≥ 2 LLP towers in 9x9 jet region

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

HCAL Timing Measurements (TDC)

TDC is a very clean way of measuring pulse arrival time, and provides a straightforward alignment method

- 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

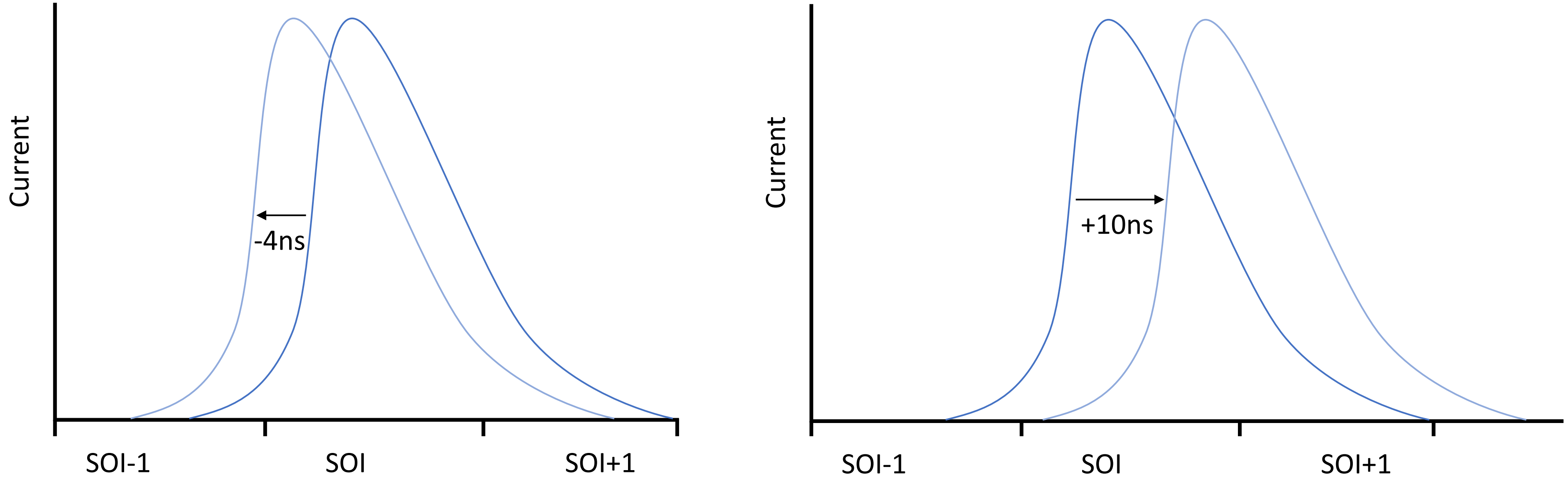


Useful for both LLP triggering and HCAL alignment!

- Large effort to use online timing to align HB to within 0.5 ns
- New alignment successfully deployed June 12, implementing several ns shifts to achieve consistency across detector

HCAL Timing Scan in Run 3

HCAL timing scans in 2022 and 2023 provide a valuable look at artificial delayed jets in collisions data and are crucial to understanding the detector and trigger performance. Timing scan is performed by shifting HCAL clock relative to LHC clock, over 30 ns.

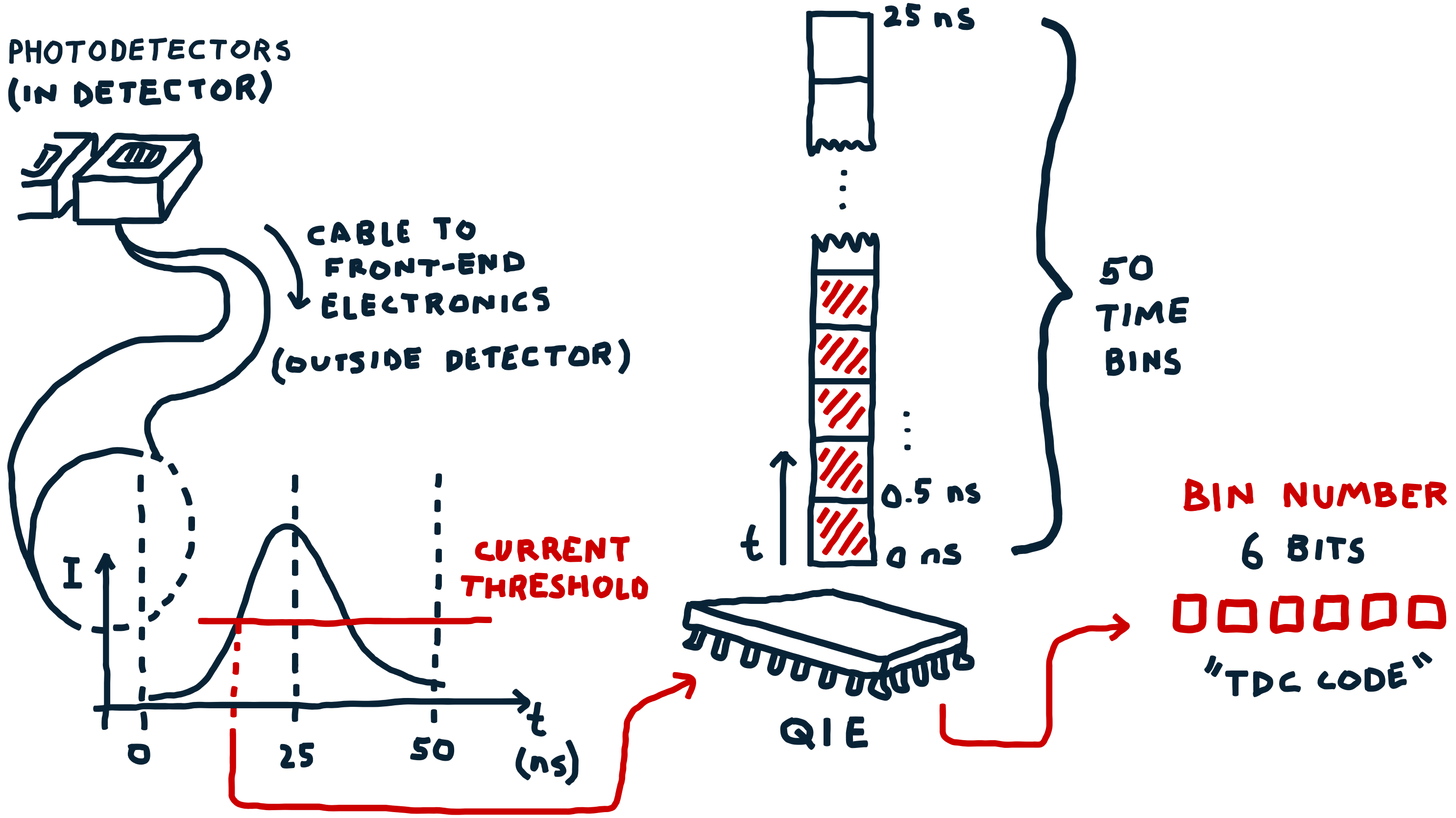


This approach is used for the time alignment of HCAL and to demonstrate LLP trigger performance. Final alignment places prompt arrival pulses close to the start of the bunch crossing, which is ideal for the accuracy of timing and energy measurements.

HCAL Alignment Procedures

- Previously, HB alignment was determined with charge weighted time, which was best timing measurement prior to Run 3. With upgraded calorimeter, can now utilize TDC readouts for improved alignment.
  - Learned that pulses were arriving early at high $i\eta$ and depth; and arriving late at central $i\eta$ and low depths.
  - After understanding arrival times of prompt jets, adjusted HCAL time alignment to have prompt pulses arrive at a uniform time across the detector
  - Requires a shift by a few ns, specific shifts determined per $i\eta$ and depth
  - Validated with HCAL phase scans in collisions and LED runs

Timing from HCAL



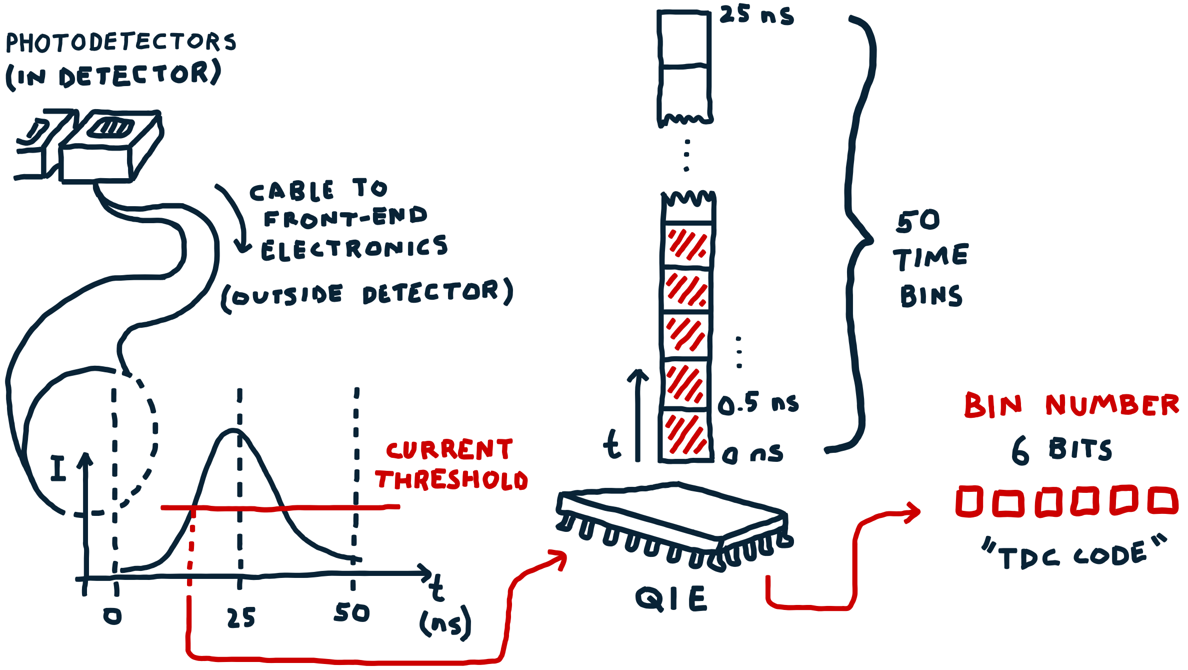
Timing readout added in Phase 1 upgrade with the QIE11 (ASIC).

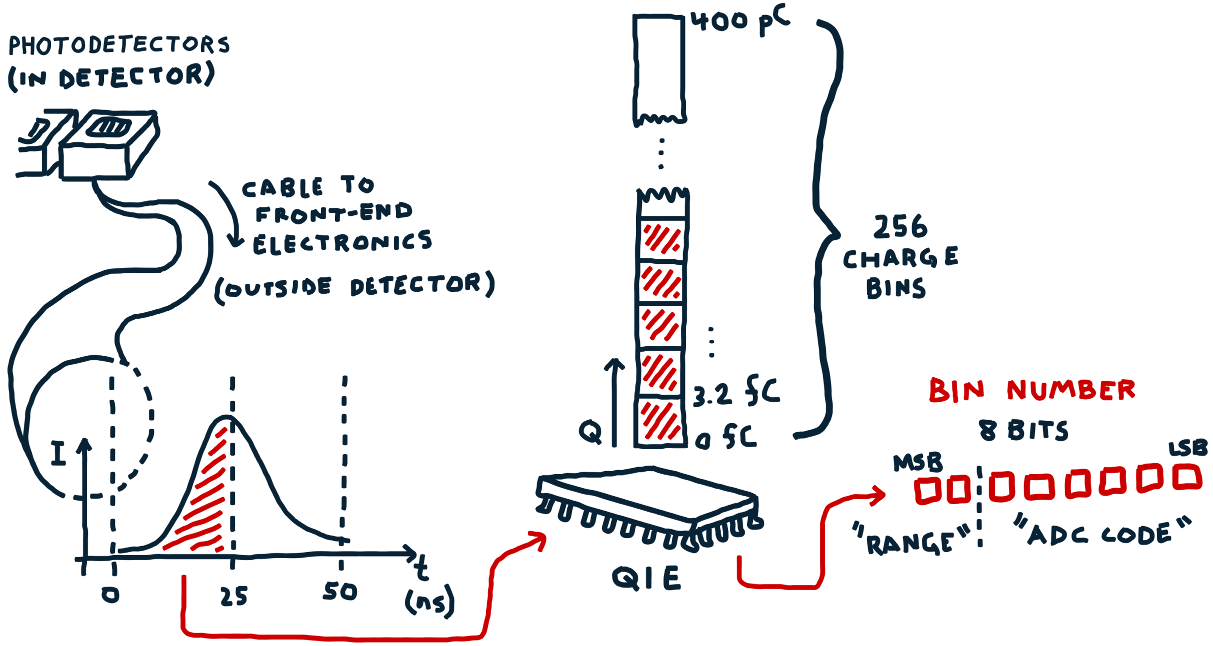
TDC (time to digital converter) value describes time at which pulse reaches a current threshold – high sensitivity to pulse rising edge.

Identifies when in a bunch crossing the pulse arrives.

[1] E. Hughes

TDC and ADC from HCAL





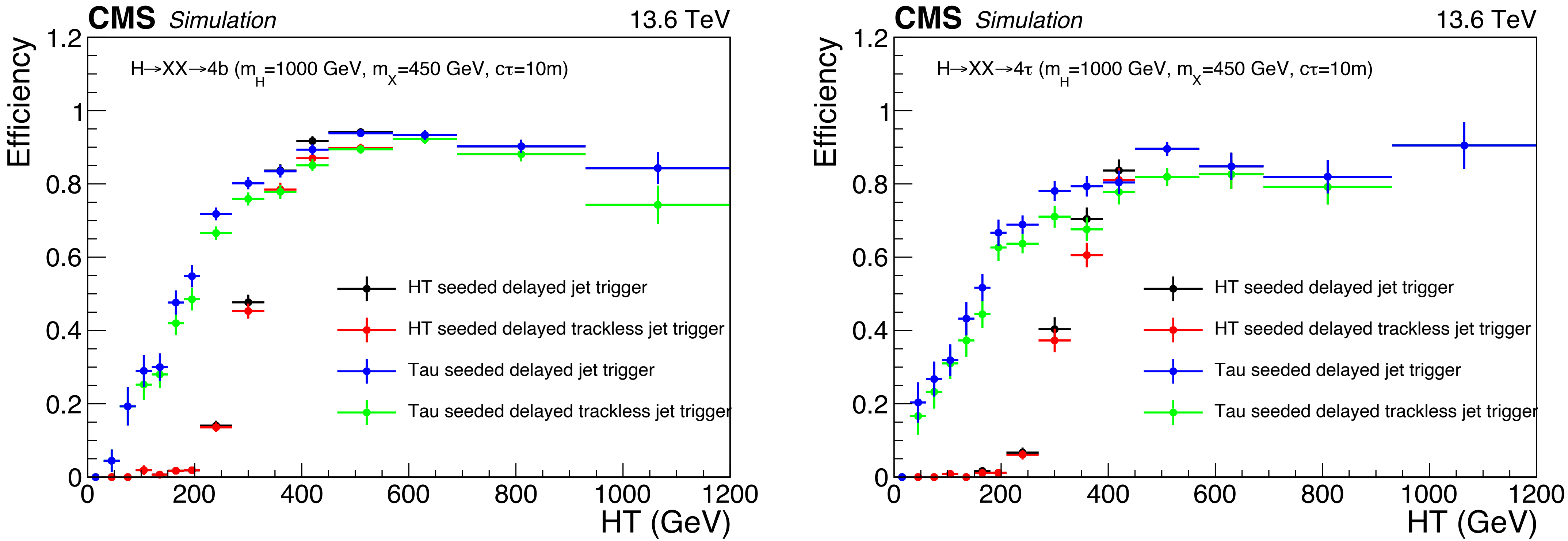
[1] E. Hughes

HCAL-based L1 and HLT Paths in Run 3

- L1_HTT120_SingleLLPJet40
- L1_HTT160_SingleLLPJet50
- L1_HTT200_SingleLLPJet60
- L1_HTT240_SingleLLPJet70
- L1_DoubleLLPJet40

- HLT_HT200_L1SingleLLPJet_DisplacedDijet35_Inclusive1PtrkShortSig5
- HLT_HT200_L1SingleLLPJet_DisplacedDijet40_Inclusive1PtrkShortSig5
- HLT_HT240_L1SingleLLPJet_DisplacedDijet40_Inclusive1PtrkShortSig5
- HLT_HT280_L1SingleLLPJet_DisplacedDijet40_Inclusive1PtrkShortSig5
- HLT_HT170_L1SingleLLPJet_DisplacedDijet40_DisplacedTrack
- HLT_HT200_L1SingleLLPJet_DisplacedDijet40_DisplacedTrack
- HLT_HT270_L1SingleLLPJet_DisplacedDijet40_DisplacedTrack
- HLT_HT200_L1SingleLLPJet_DisplacedDijet60_DisplacedTrack
- HLT_HT320_L1SingleLLPJet_DisplacedDijet60_Inclusive
- HLT_HT420_L1SingleLLPJet_DisplacedDijet60_Inclusive
- HLT_HT200_L1SingleLLPJet_DelayedJet40_DoubleDelay0p5nsTrackless
- HLT_HT200_L1SingleLLPJet_DelayedJet40_DoubleDelay1nsInclusive
- HLT_HT200_L1SingleLLPJet_DelayedJet40_SingleDelay1nsTrackless
- HLT_HT200_L1SingleLLPJet_DelayedJet40_SingleDelay2nsInclusive
- HLT_L1SingleLLPJet

Tau Seeded HLTs in Run 3



Suite of Run-3 triggers developed targeting LLPs using ECAL timing at HLT to identify delayed jets. A subset of these are seeded with L1 taus, requiring tau pT > 120 GeV. The tau seeded triggers have improved signal efficiency, as seen on $H \rightarrow XX \rightarrow 4b$ and $H \rightarrow XX \rightarrow 4\tau$ ($m_H = 1000$ GeV, $m_X = 450$ GeV, and $c\tau = 10$ m). The tau triggers (blue and green curves) show improvement in HT < 430 GeV region compared to the HT seeded triggers (black and red curves, with HT 360 GeV). Additional requirements are: jet pT > 40 GeV, jet timing > 2 ns, number of ECAL cells > 5, and $|\eta| < 1.48$.

[2] CMS DP-2023/043

LLP Models Targeted

- Particularly targeting models with 1-10+ m $c\tau$ LLP
  - $H \to XX \to \bar{b}b\bar{b}b$ with $m_H = 125, m_X = 50$ GeV performs well (3-4x integrated luminosity gains)
  - L1 efficiencies are carried through at HLT
  - New detector signature made possible by Phase 1 HCAL upgrade