Study of Electron/Photon Reconstruction Performance in the Level-1 Phase-2 Calorimeter Trigger at CMS

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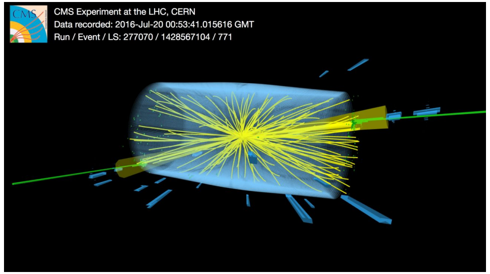
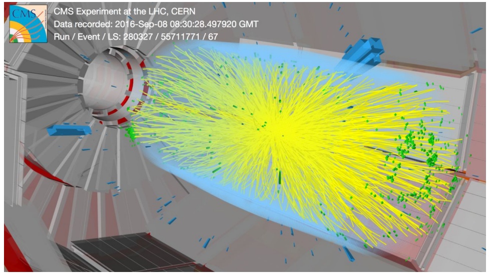
High-Luminosity LHC:

- Searches for rare events often statistics-limited
- Increasing luminosity increases the number of rare events in the detector

PU = 25:



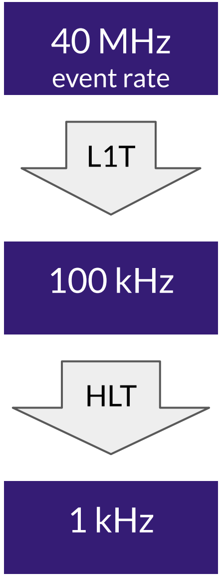
PU = 86:



[1]

→ PU = 200 in HL-LHC

CMS Trigger System in Phase 1



Level-1 Trigger (L1T)

- Custom processor boards
- Coarse-grain detector readout
- Calorimeter and muon chamber input
- Max output rate: 100 kHz

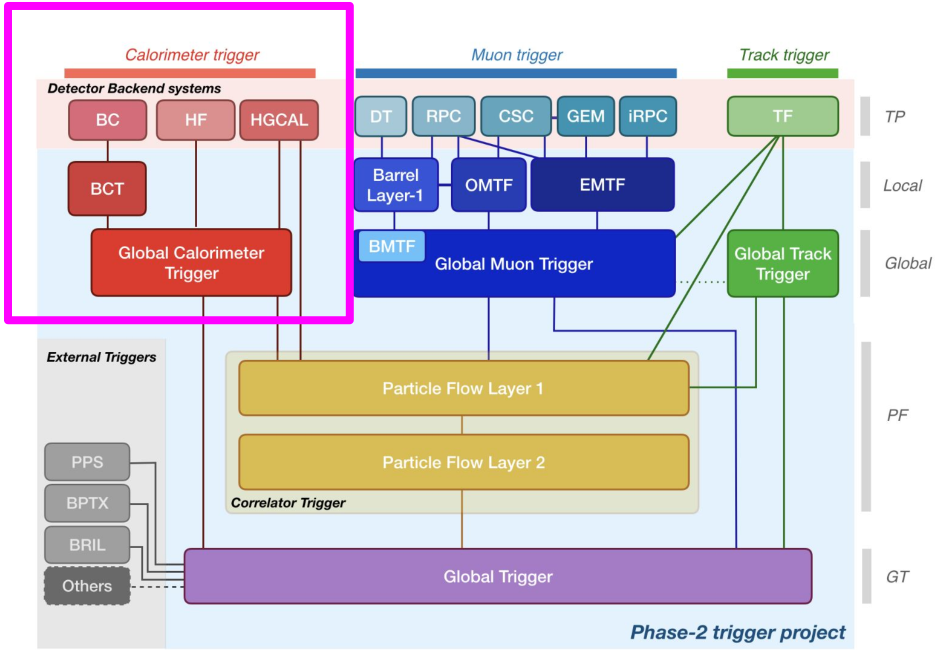
High-Level Trigger (HLT)

- Streamlined version of offline reconstruction software
- Commercial CPU & GPU cores
- Reads out entire event
- Average output rate: 1 kHz

Phase-2 Upgrade to the Level-1 Trigger:

Max rate increase from 100 kHz ➔ 750 kHz
Latency increase from 3.8 µs ➔ 12.5 µs

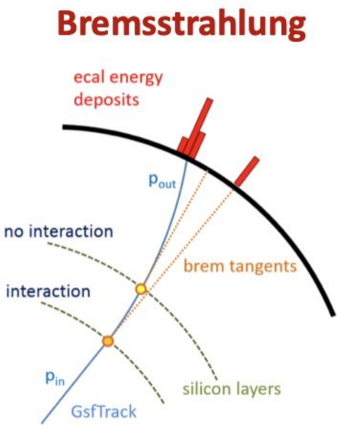
Level-1 Calorimeter Trigger will process **crystal-level information** from calorimeters for **first time: 25x increase in granularity**



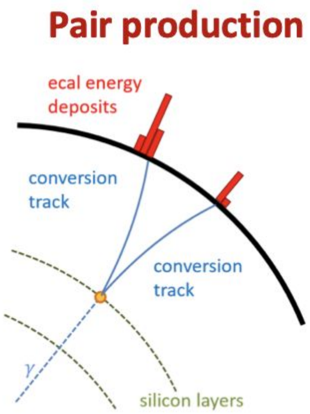
[2]

Electromagnetic Showers in the ECAL

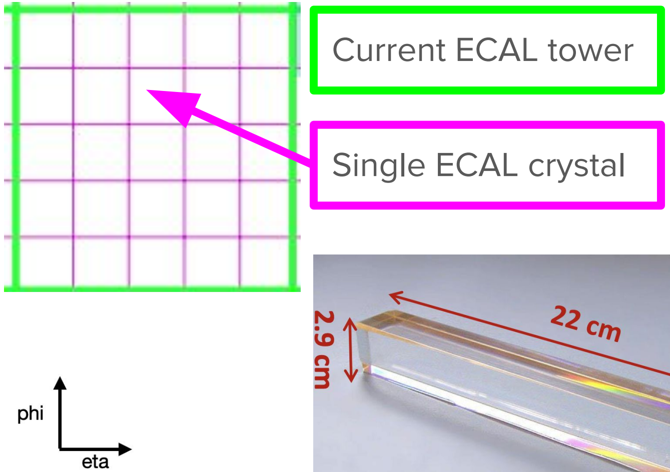
electrons (e):

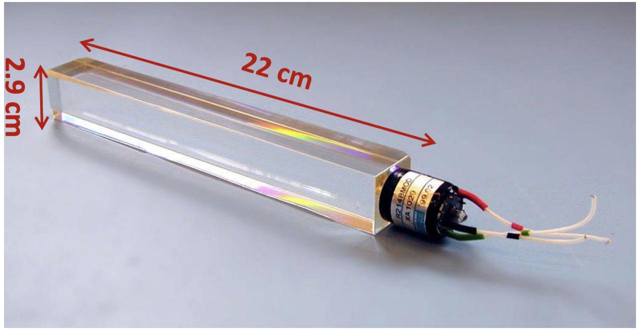


photons (γ):



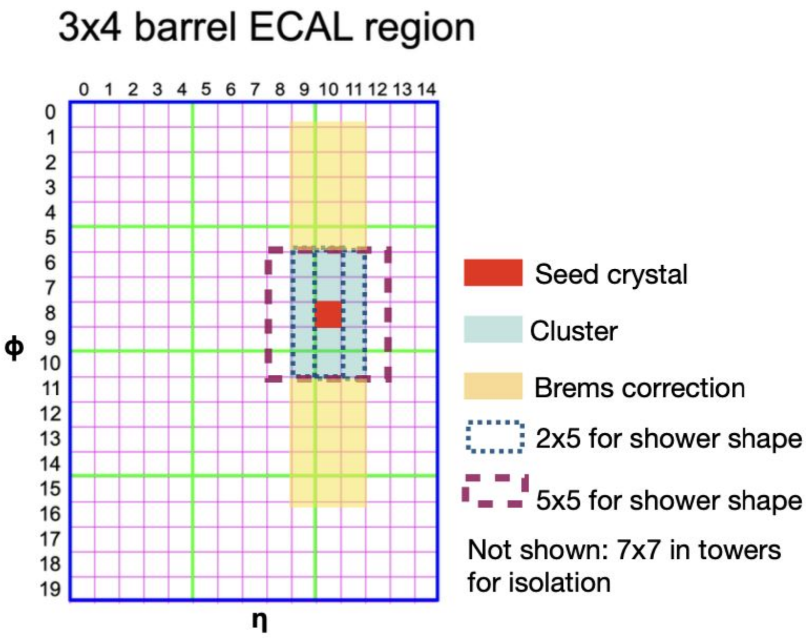
ECAL crystals designed to capture e/γ showers:





[3]

Barrel ECAL e/γ Reconstruction Algorithm



[4]

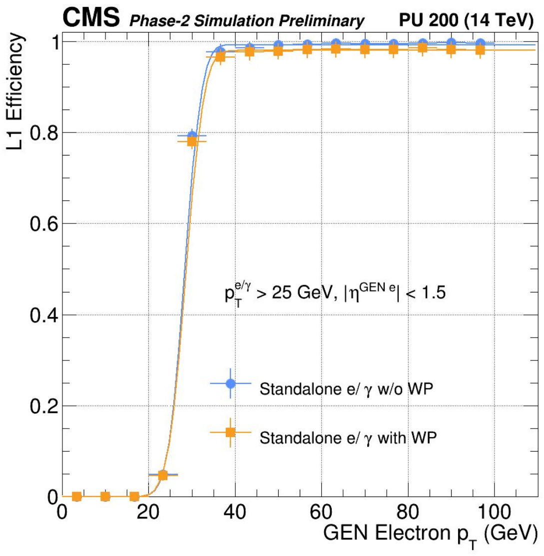
- Recover energy lost to bremsstrahlung (yellow spread in ϕ)
- Compute:

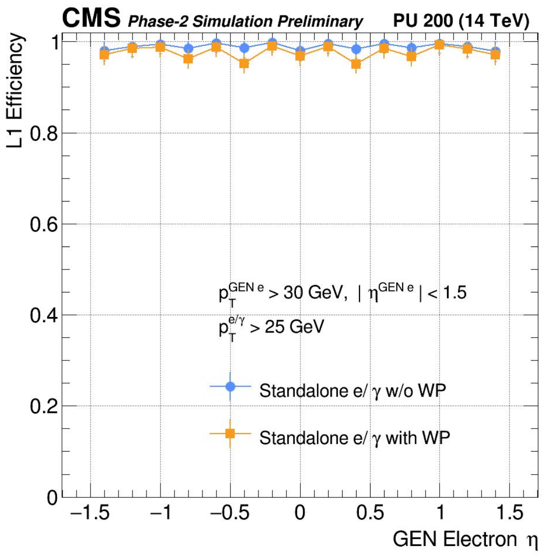
$$\text{Relative isolation} = \frac{\text{energy in 7x7 towers}}{\text{cluster energy}}$$

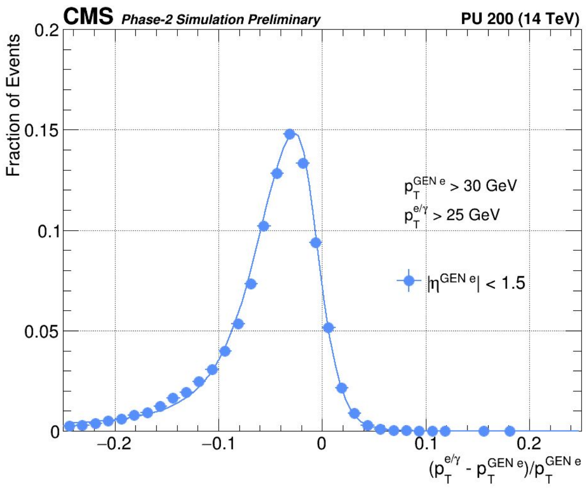
$$\text{Shower shape} = \frac{\text{energy in 2x5 crystals}}{\text{energy in 5x5 crystals}}$$

Performance in Phase 2: efficiencies and resolution (CMS-DP-2024-057 [5])

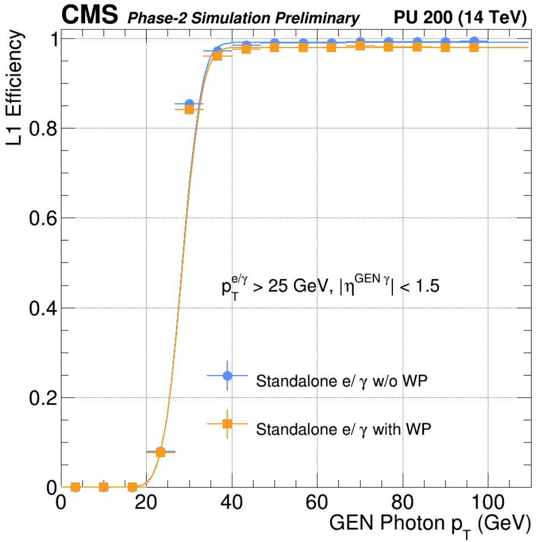
- Electron objects in MC sample have p_T between 0 and 100 GeV
- Working point is logical OR of shower/isolation requirements

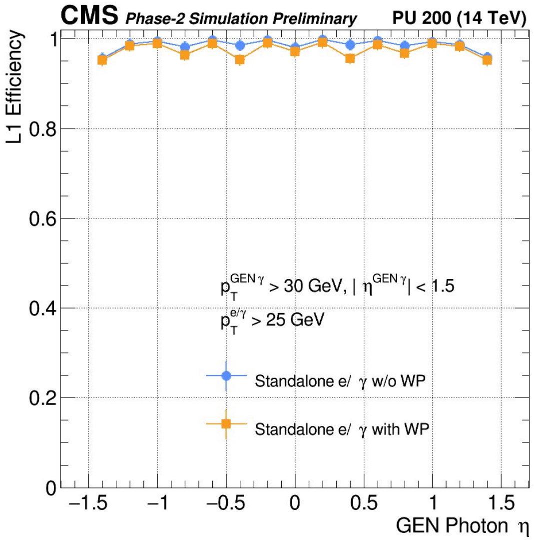


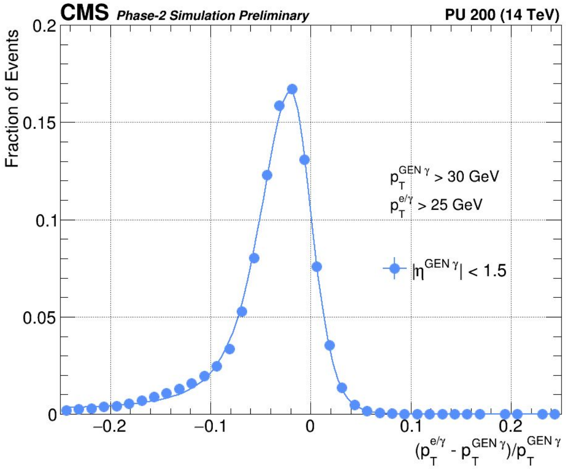




Photon Performance (CMS-DP-2024-057)

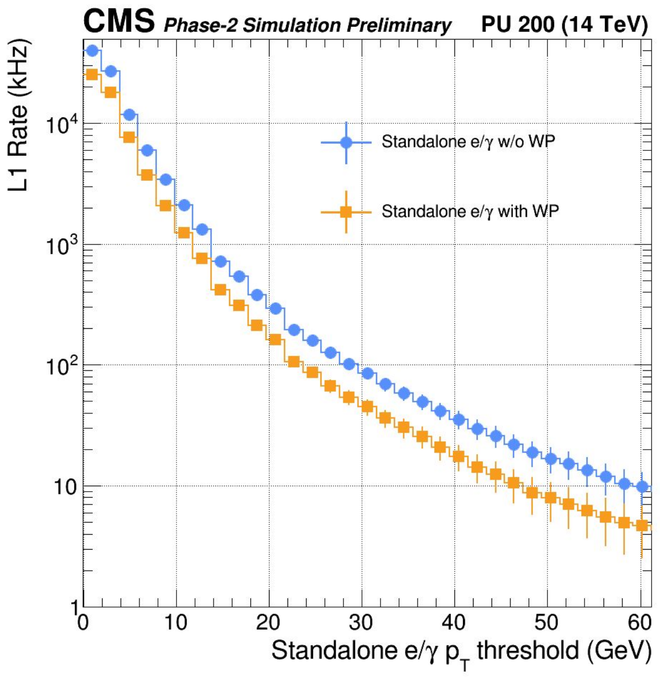


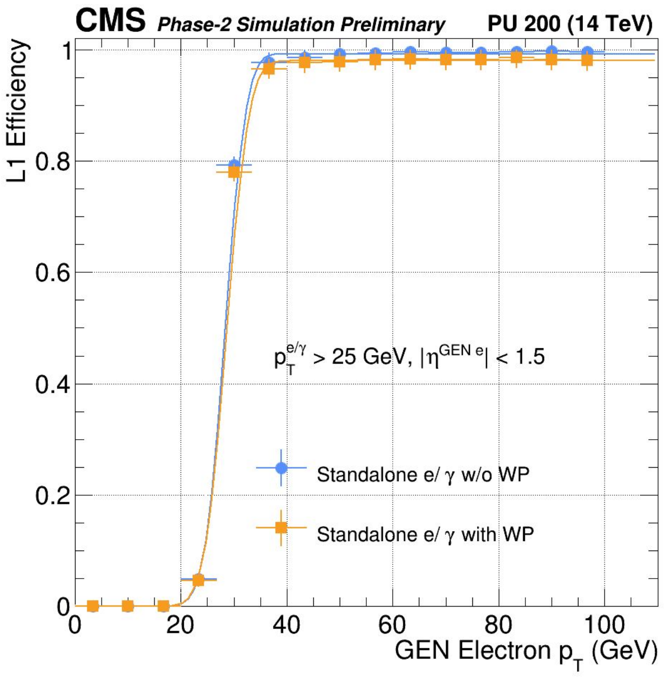




Performance in Phase 2: rate and resolution (CMS-DP-2024-057)

Working point (yellow) significantly reduces rate with a slight decrease in efficiency





Conclusion

- Standalone e/γ barrel algorithm for Phase-2 Level-1 Calorimeter trigger achieves **high efficiency and expected rates** in a scenario with 200 average pileup interactions.
- This algorithm has been included in the CMS Phase-2 emulation sequence and trigger menu
- The HL-LHC's larger data samples and upgraded detector capabilities will make a broader range of physics analyses possible

Thank you!

Image & Figure Sources

Slide 2: [1] Pileup event display

Slide 4: [2] Phase 2 L1T Functional Diagram

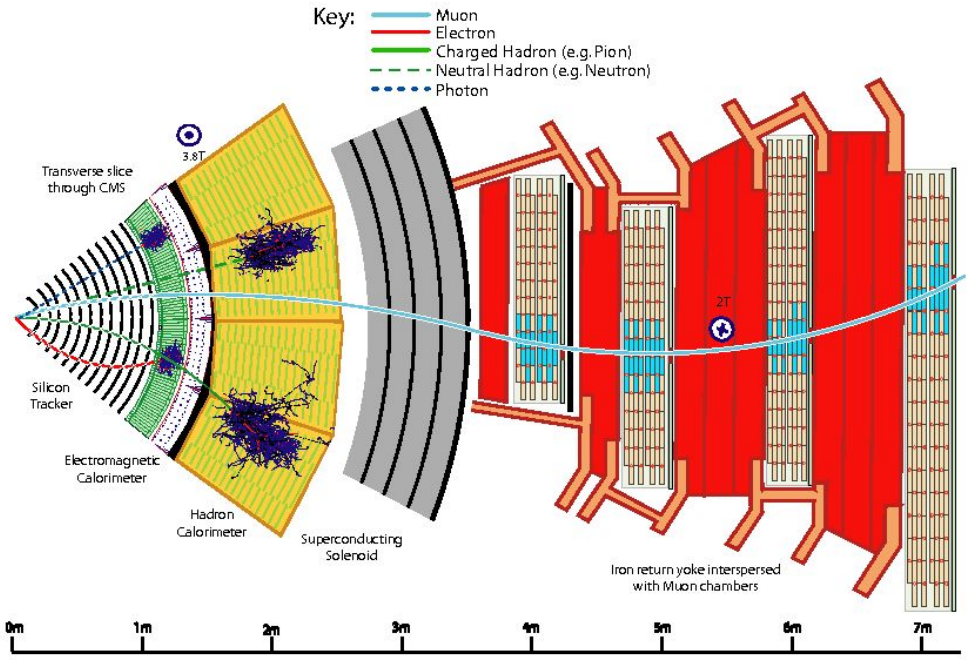
Slide 5: [3] Bremsstrahlung, Pair Production, crystal

Slide 6: [4] Barrel ECAL region

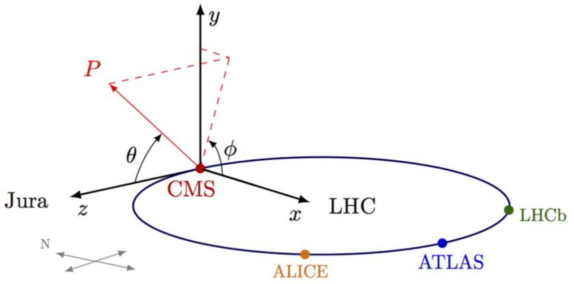
Slides 7-9: [5] All figures: The CMS Collaboration, "Standalone barrel e/gamma and calorimeter based jet and tau reconstruction in the Level-1 Phase-2 Calorimeter Trigger", CMS-DP-2024-057, 2024.

Backup

CMS Detector

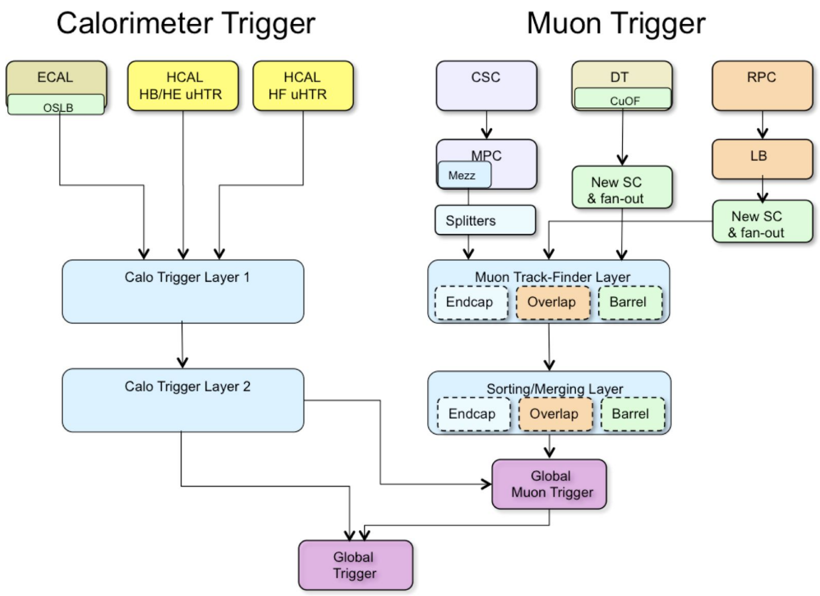


- Beams collide at the center of detector
- Layers of silicon strip and pixel trackers
- Electrons and photons absorbed by crystals in the electron calorimeter (ECAL)
- Hadronic showers measured in the hadronic calorimeter (HCAL).
- Muons detected in muon chambers



$$\eta \equiv \frac{1}{2} \ln \tan(\frac{\theta}{2})$$

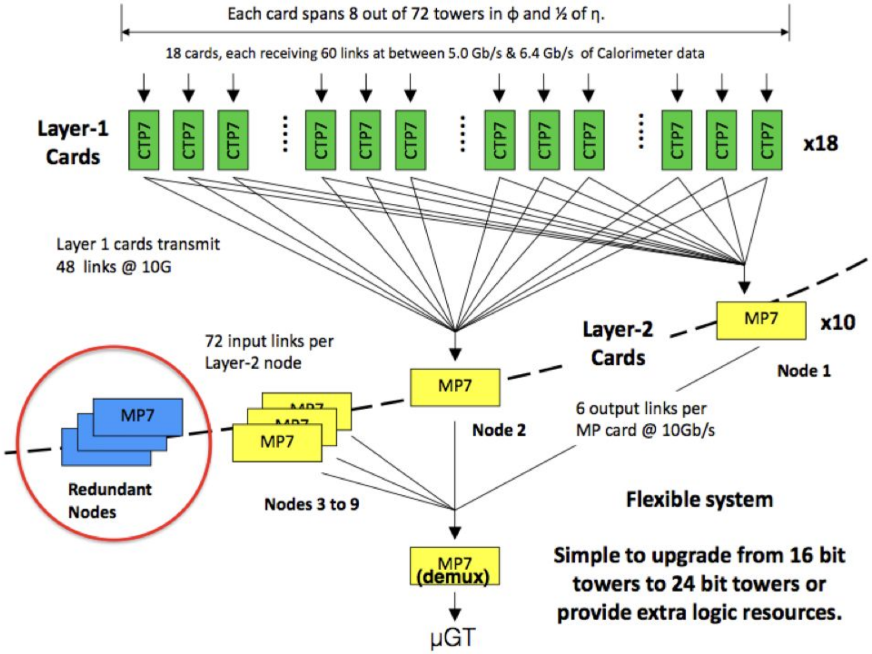
Closer look: Current L1T



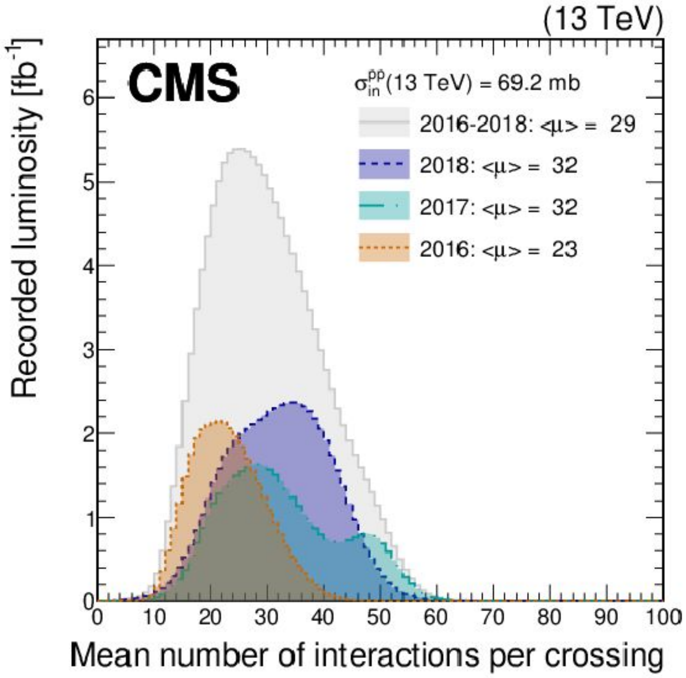
Phase 1 L1T Design Functional Diagram

- Muon trigger: 3 subdetector inputs
- Calorimeter Trigger
  - ECAL/HCAL input
  - Constructs candidates: electron/photon, jets
- Global Trigger
  - 512 algorithms
  - Issues ultimate Level- 1 Acceptance (L1A) decision

Level-1 Calorimeter Trigger: Phase 1

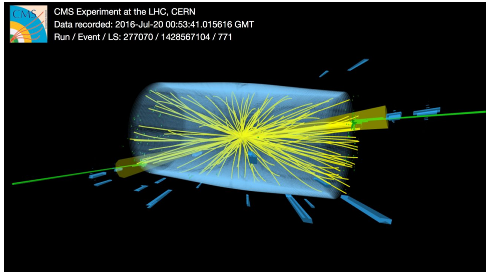


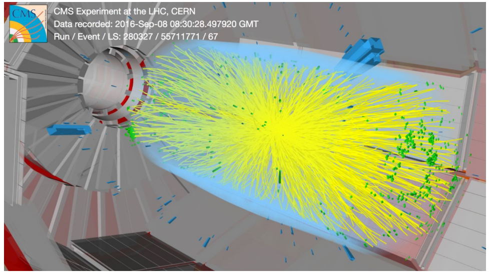
Effect of High Luminosity: Pileup



$$\text{Pile-up} = \frac{\mathcal{L} \cdot \sigma_{inelastic}}{n_{bunches} \cdot f}$$

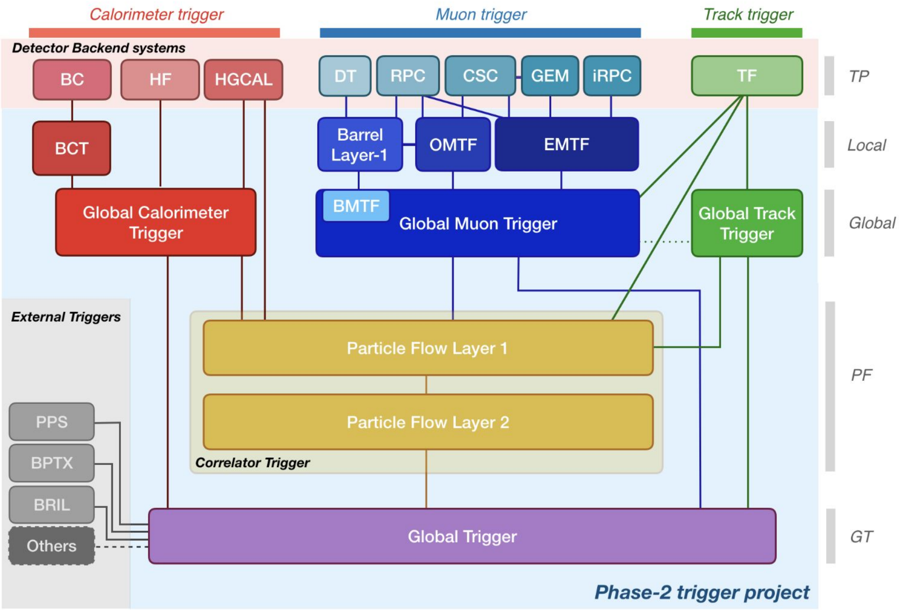
- Pileup: average number of proton-proton collisions per bunch crossing
- Pileup makes reconstruction difficult:
  - PU = 25: PU = 86:





- Instantaneous luminosity of 7.5×10^{34} cm^{-2}s^{-1} corresponds to average pileup of 200
- Our strategies to handle pileup in Phase 1, including the trigger system, need to meet increased pileup challenges during Phase 2

Phase-2 Upgrade

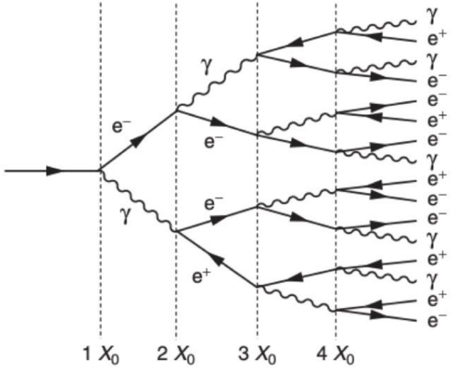


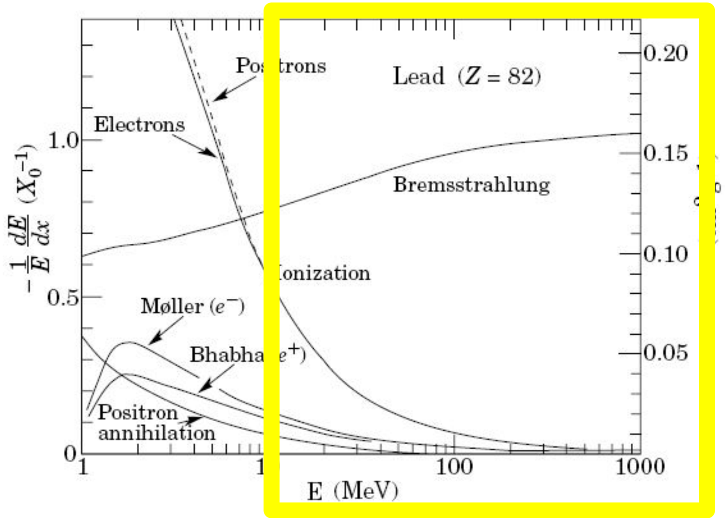
Max rate: 750 kHz
Latency: 12.5 microseconds

- Calorimeter Trigger: Barrel calorimeter trigger and HGCAL process **crystal-level information** from calorimeters to produce high-resolution clusters and identification variables
- **Track Trigger**: Tracks from Outer Tracker are reconstructed in track finder processors
- Muon Trigger: Muon track finder algorithms process trigger primitives (TPs) separated into barrel, overlap, and endcap regions.
- **Correlator Trigger**: Calorimeter clusters matched with tracks

Bremsstrahlung Recovery

- ECAL design driven by electron behavior
- Bremsstrahlung: a very high energy electron emits photon which carries a large fraction of its energy
- High η and ϕ granularity and ECAL crystal depth designed to capture bremsstrahlung shower (X_0)





Firmware development

- Xilinx UltraScale+ FPGAs are used in the main Advanced Processor (APx) boards. The firmware is designed to operate at 360 MHz clock, and target latency within 3 µs. The algorithms are spread across the super logic regions (SLR) of the FPGAs to meet the timing constraints.
- Total number of APx boards required:
  - XCVU9P FPGA (previous architecture from TDR): test configuration with 46 boards
    - RCT: 36 boards
    - GCT: 10 boards
  - XCVU13P FPGA (current architecture under development): 34 boards
    - RCT: 24 boards
    - GCT: 10 boards

Firmware implementation: GCT barrel

Division of functionalities across the VU9P board:

- SLR2:
    - Stitch e/ɣ clusters across RCT card boundaries, create GCT towers
    - PF clustering: 3x3 clustering of GCT towers, sent to Correlator Trigger for further processing
- SLR1:
    - Create GCT jets in barrel
- Output:
    - 48 links to Correlator Trigger
    - 6 links to GCT sum board
- Latency: 692 ns out of 3 µs budget
- Resource utilization:
    - Look-up Tables (LUTs): 22%
    - Flip-flops (FFs): 18%
    - Digital Signal Processor (DSP): 0%