



Triggering on Long-Lived Particles: Efficiency of a Dedicated Level-1 Trigger in the CMS Muon System

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Introduction

Searching for Long-Lived Particles (LLPs)

A long-lived particle (LLP) is defined by how far it travels before decaying ($\tau \gtrsim 1$ ns). These particles are of interest because many Beyond the Standard Model theories predict them. Multiple analyses have already been conducted at the Compact Muon Solenoid (CMS) detector to search for these exotic particles. Because LLPs travel so far before decaying, their signatures are difficult to identify. Detectors like CMS were not designed with these particles in mind, so finding them requires creativity: both in repurposing the existing hardware and developing clever new analysis strategies.

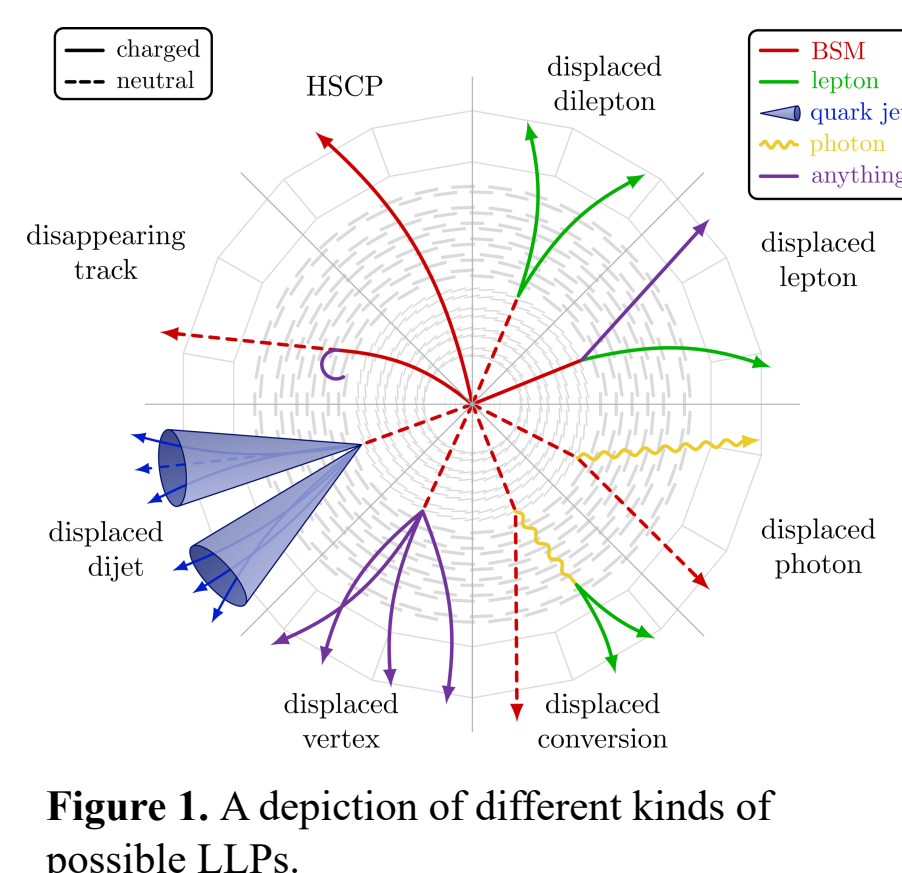


Figure 1. A depiction of different kinds of possible LLPs.

Using the CMS Muon System as a Sampling Calorimeter

The original design for the Muon System at CMS was to detect and track muons produced at the interaction point (IP). Its structure consists of a steel yoke with multiple kinds of detectors scattered about the barrel and endcaps of the apparatus. This special configuration makes the muon system an excellent choice for a sampling calorimeter, where the absorber is the steel yoke, and the active media are the detectors.

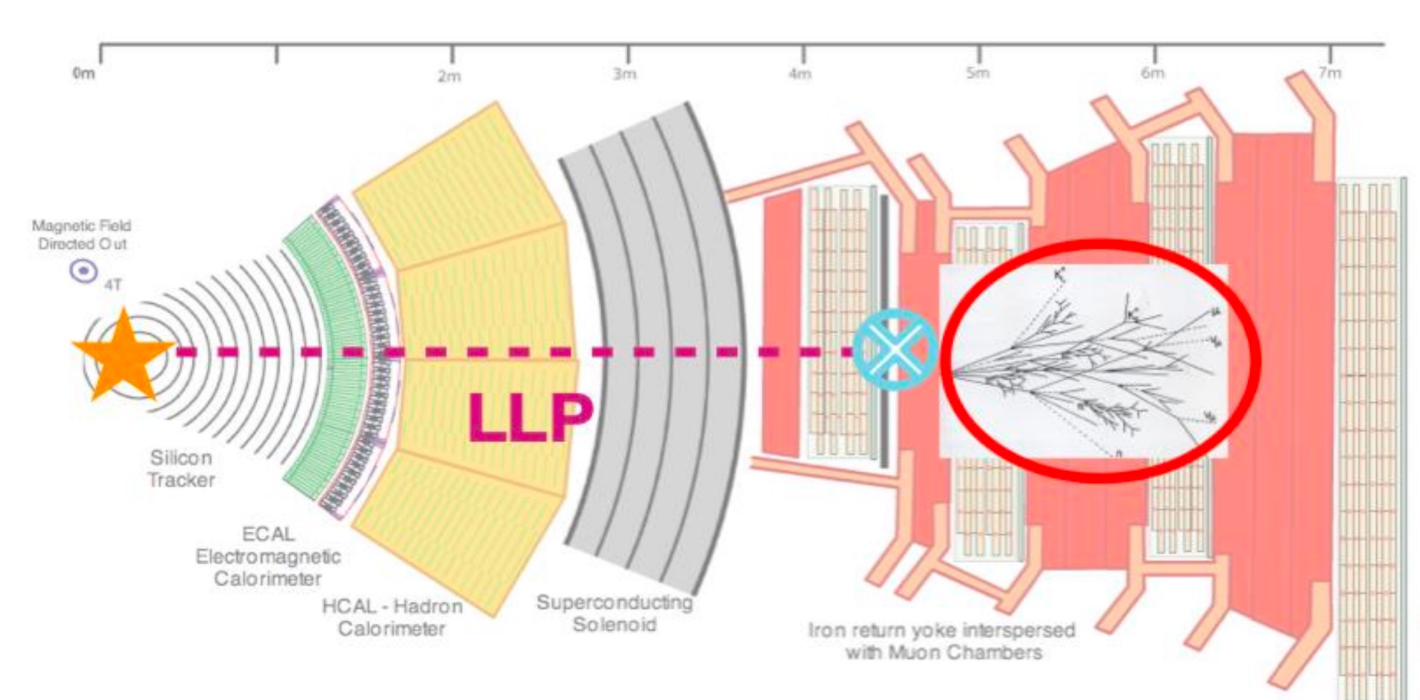


Figure 2. Slice of the CMS detector showing the expected path of an LLP showering in the muon system.

A **muon detector shower (MDS)** is a shower induced in the muon system by exotic LLPs or other known Standard Model phenomena. Reasons for using this signature include:

- Sensitivity to many decays
- Excellent background suppression
- Coverage of decays that are far from the IP.

Detector Structure of CMS

The Compact Muon Solenoid detector

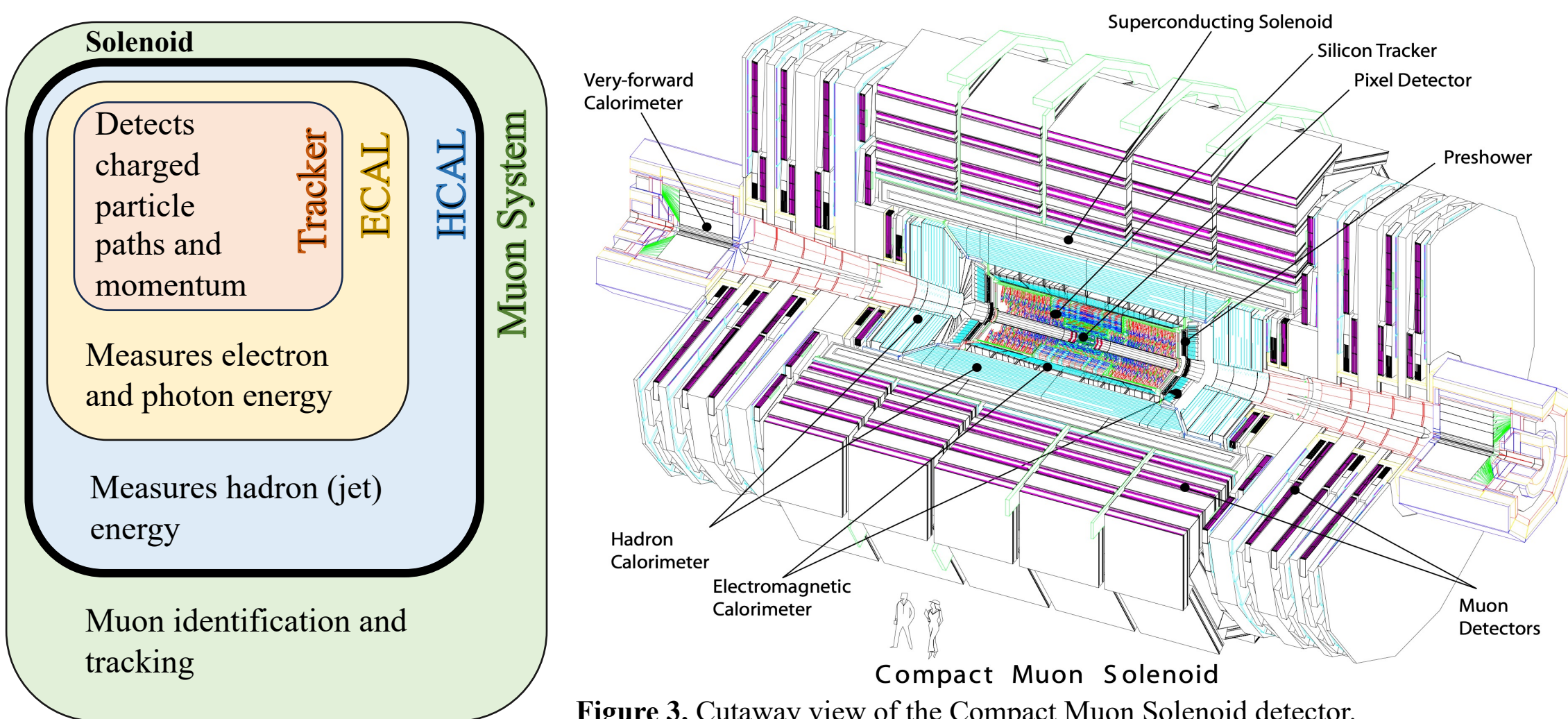


Figure 3. Cutaway view of the Compact Muon Solenoid detector.

The Muon System of the CMS detector

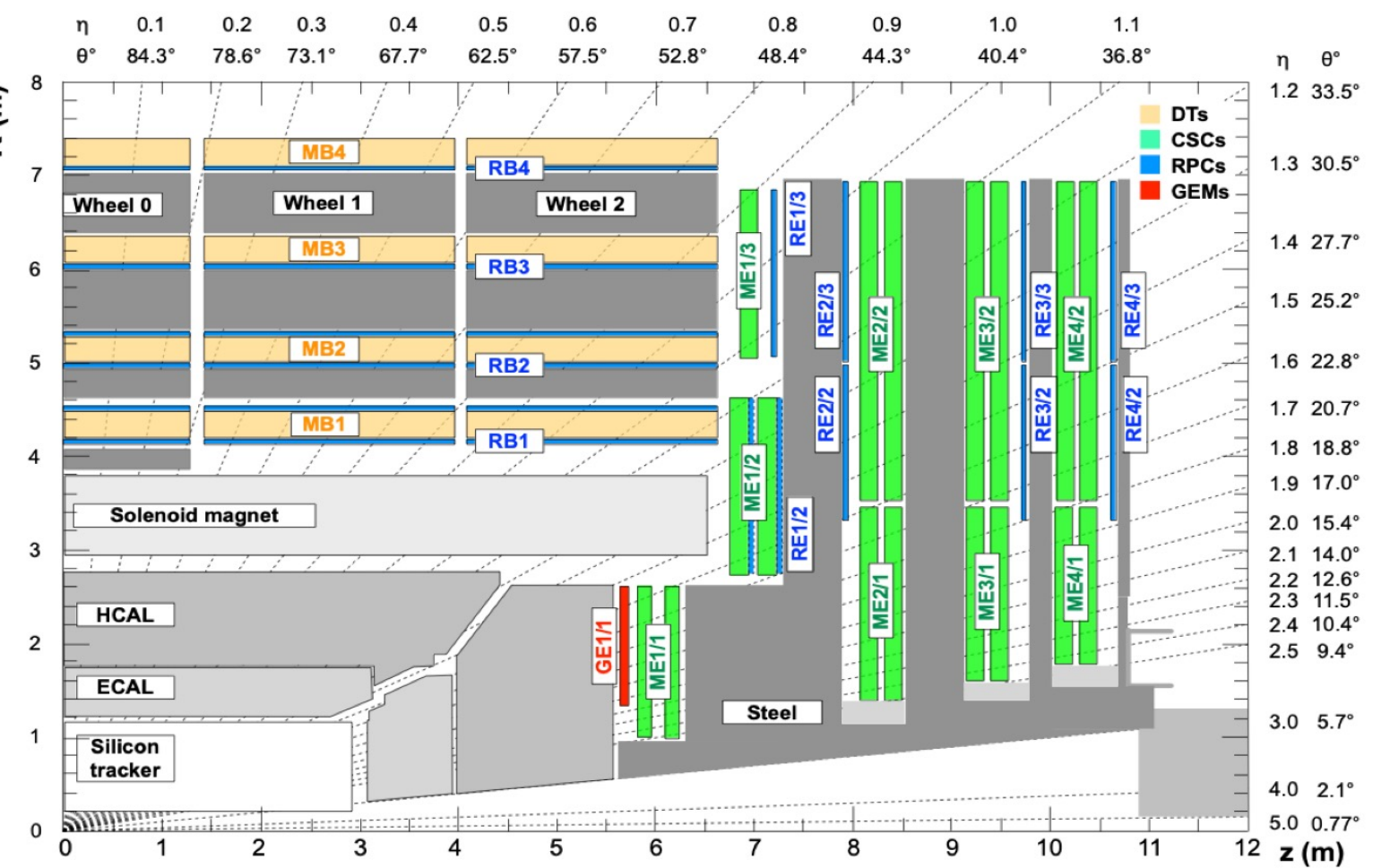


Figure 4. Longitudinal slice of the CMS detector highlighting the different sections of the muon chamber.

Gas detectors interleaved with the steel return yoke.

- Drift Tubes (DTs): barrel
- Cathode Strip Chambers (CSCs): endcaps
- Resistive Plate Chambers (RPCs): barrel & endcaps
- Gas Electron Multipliers (GEMs): forward endcap

Design of the Dedicated Level-1 and High Level Triggers

Level-1 Trigger (L1T) Implementation

Original Configuration of the L1T:

- Inner CSC station rings counted individual anode wire and cathode strip hits
- Outer CSC station rings counted **only** anode wire hits

Changes to L1T configuration for 2025:

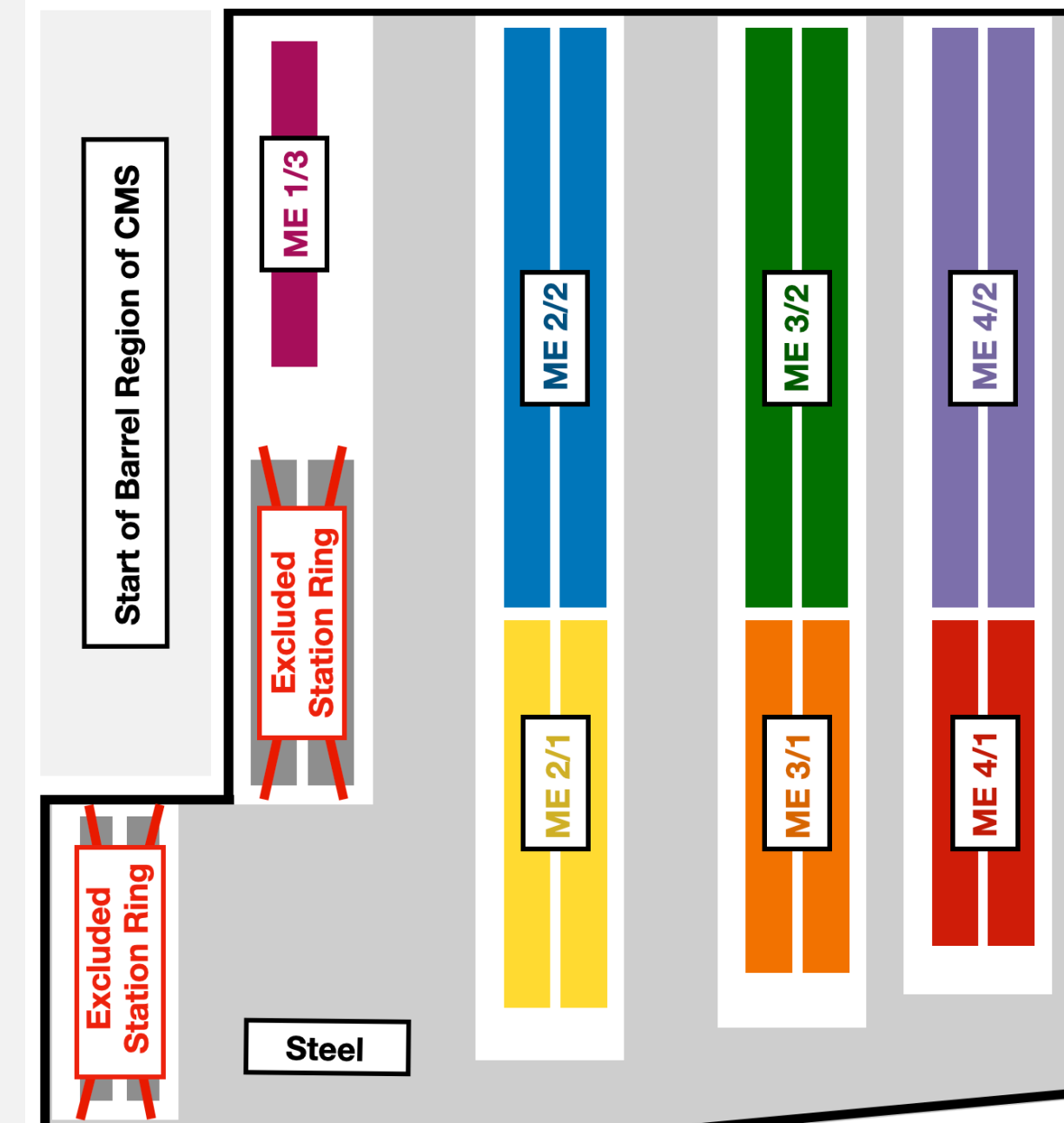
- Trigger thresholds were tuned twice during 2025 data taking to optimize trigger rate
- Inner CSC station ring counting logic was changed to only count anode wire hits

CSC Station Ring	Nominal Threshold		
	2024	pre-F	post-F
ME 1/3	14	14	15
ME 2/2	28	34	30
ME 3/2	26	21	25
ME 4/2	27	23	27
ME 2/1	56	76	50
ME 3/1	55	67	50
ME 4/1	62	80	40

Table 1. Table of the trigger threshold changes for the outer rings (ME 1/3, ME 2/2, ME 3/2, & ME 4/2) and the inner rings (ME 2/1, ME 3/1, & ME 4/1).

Station rings are grouped based on their position in the η -plane:

Inner rings: $|\eta| > 1.9$
Outer rings: $|\eta| < 1.9$



Cathode Strip Chamber

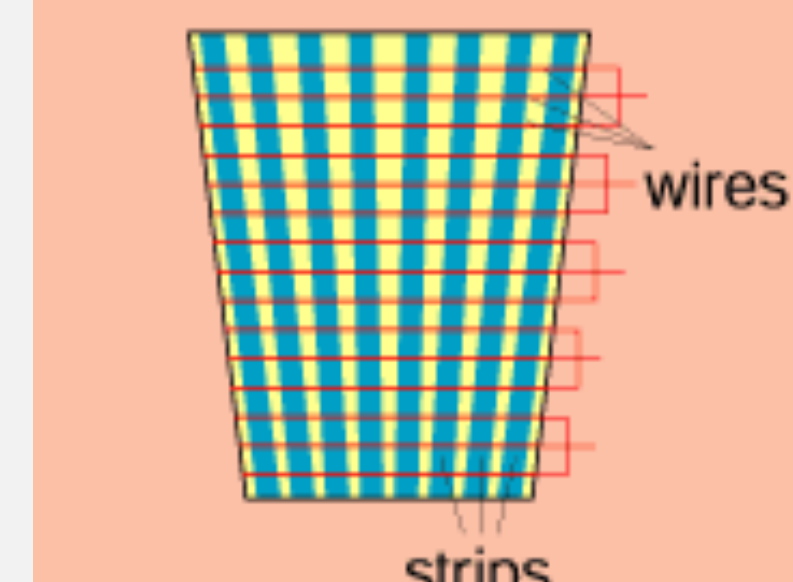


Figure 6 (above). Section of Muon System showing the chambers used in the study.

Figure 7 (left). Section of the Cathode Strip Chamber highlighting the structure of the anode wires and cathode strips.

High Level Trigger (HLT) Implementation

Reconstructed hits (rechits) are used to form clusters.

- Rechits are defined as the 2D intersection between CSC wires and strips.
- Clustered using Cambridge-Aachen in η - ϕ space with $\Delta R = 0.4$

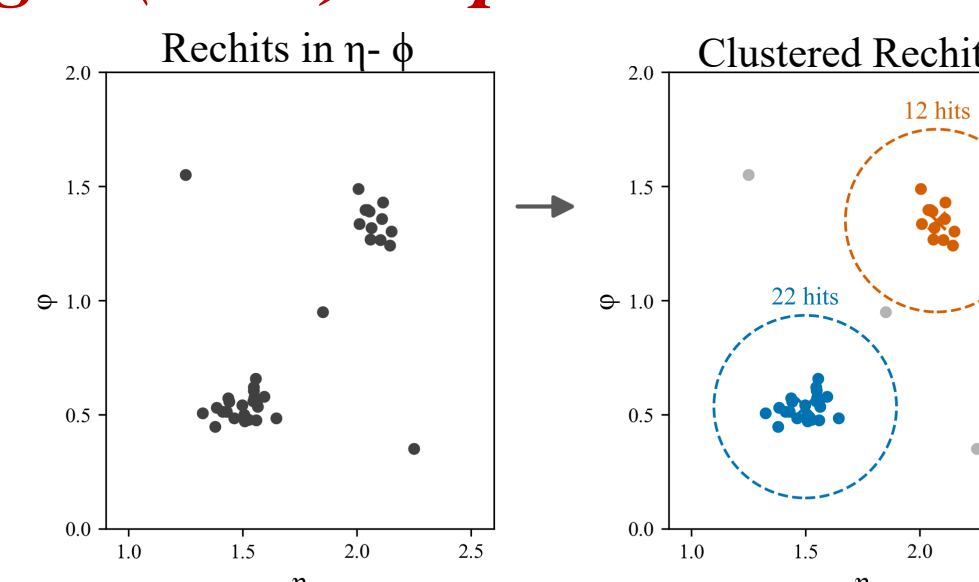


Figure 5. Groups of rechits formed into clusters with $\Delta R = 0.4$ based on their separation in the η - ϕ plane.

Level-1 Trigger Efficiency Measurement Strategy

For a given (offline) cluster of size X reconstructed hits in station ring Y , what is the likelihood of the L1T firing?

Measurement Sample

Goal: Construct an unbiased dataset that triggers on known physical phenomena to measure the efficiency of the L1T.

- Reconstruct clusters induced by **muon bremsstrahlung**.
- Select events using an uncorrelated isolated muon trigger (**HLT_IsoMu24**) to create an **orthogonal sample**.

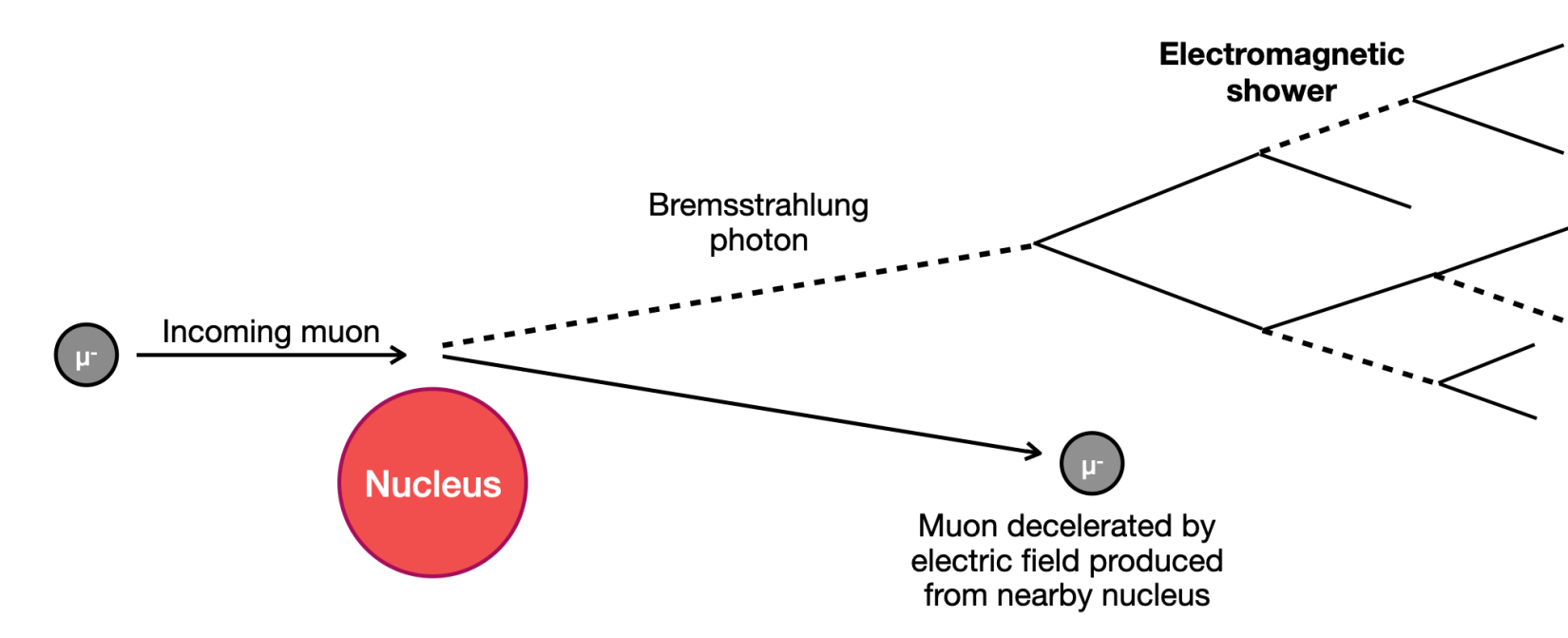


Figure 8. Deceleration of a muon as it passes by a nucleus forms bremsstrahlung radiation.

Measurement Selections

Event Selections

- Pass HLT_IsoMu24
- Exactly one offline CSC rechit cluster

Muon Selections

- Pass CMS loose ID criteria
- $p_T > 20$ GeV
- $|\eta| < 2.4$
- PF Isolation/ $p_T < 0.4$ for a cone of radius 0.4

Offline Cluster Selections

- No hits in ME1/1 & ME1/2
- At least 90% of rechits are in observed station ring
- Cluster is in time (-5 ns $< T_{cls} < 12.5$ ns)
- Cluster is matched ($\Delta R < 0.4$) to **any** selected offline muon
- Cluster position does not coincide with observed noisy chambers

$$\text{L1 Efficiency definition} \equiv \frac{\text{Events passing trigger AND offline selections AND L1 MDS Trigger}}{\text{Events passing reference trigger AND offline selections}}$$

Summary

- CMS searches for long-lived particles (LLPs) that decay in the muon system and produce electromagnetic or hadronic showers.
- A dedicated Level-1 seed and High Level Trigger path were developed to select these muon detector showers using the Cathode Strip Chambers (CSCs).
- In early 2025, the Level-1 trigger configuration was changed to improve efficiency in the inner-ring stations.
- Efficiencies measured in 2025 data show no conclusive improvement in the inner rings, while the outer rings remain consistent with expectations.

Results

Inner Ring Efficiencies

Expectation: Removing the cathode strip hits from L1T configuration will increase the efficiency of the inner station rings.

Why? This is the only difference between the inner and outer rings.

- Efficiency **did not improve** after removing cathode strip hit logic from L1T.
- Secondary threshold tuning in 2025 led to an increase in efficiency.
- Observed a universal dip in efficiency for clusters with many rechits.

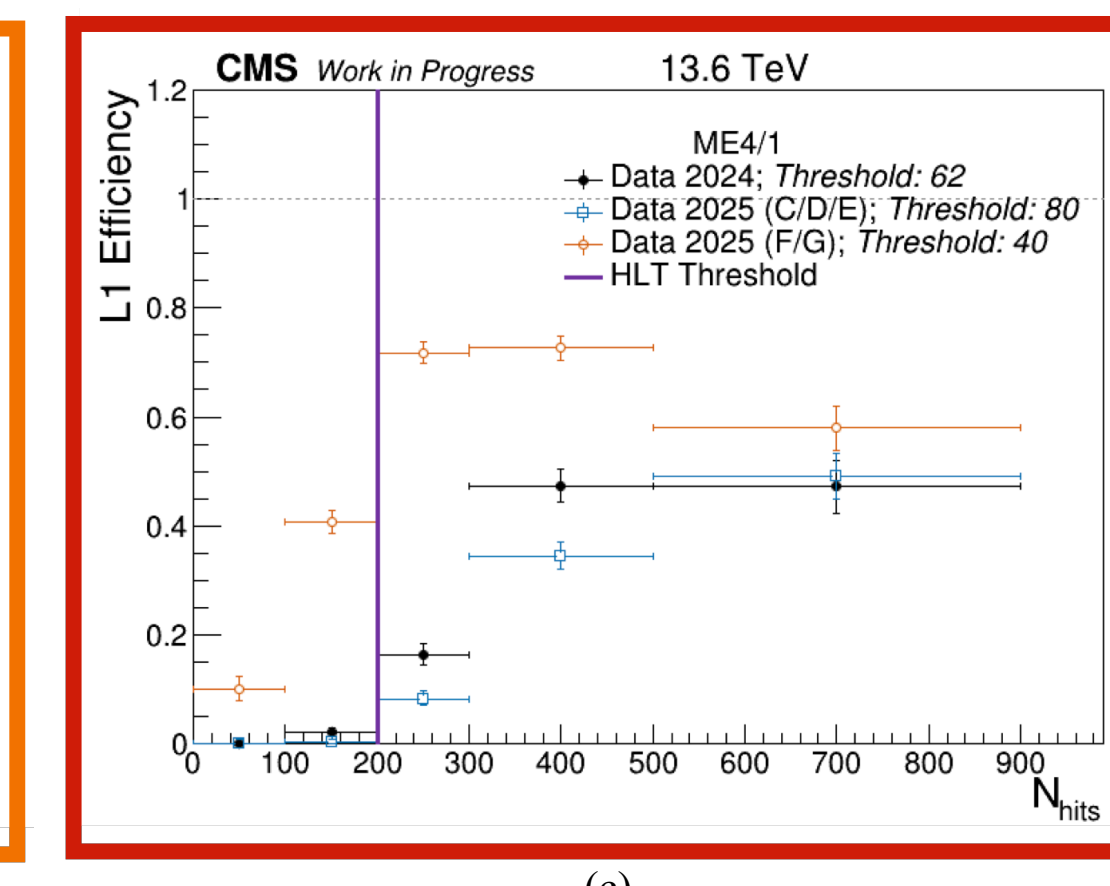
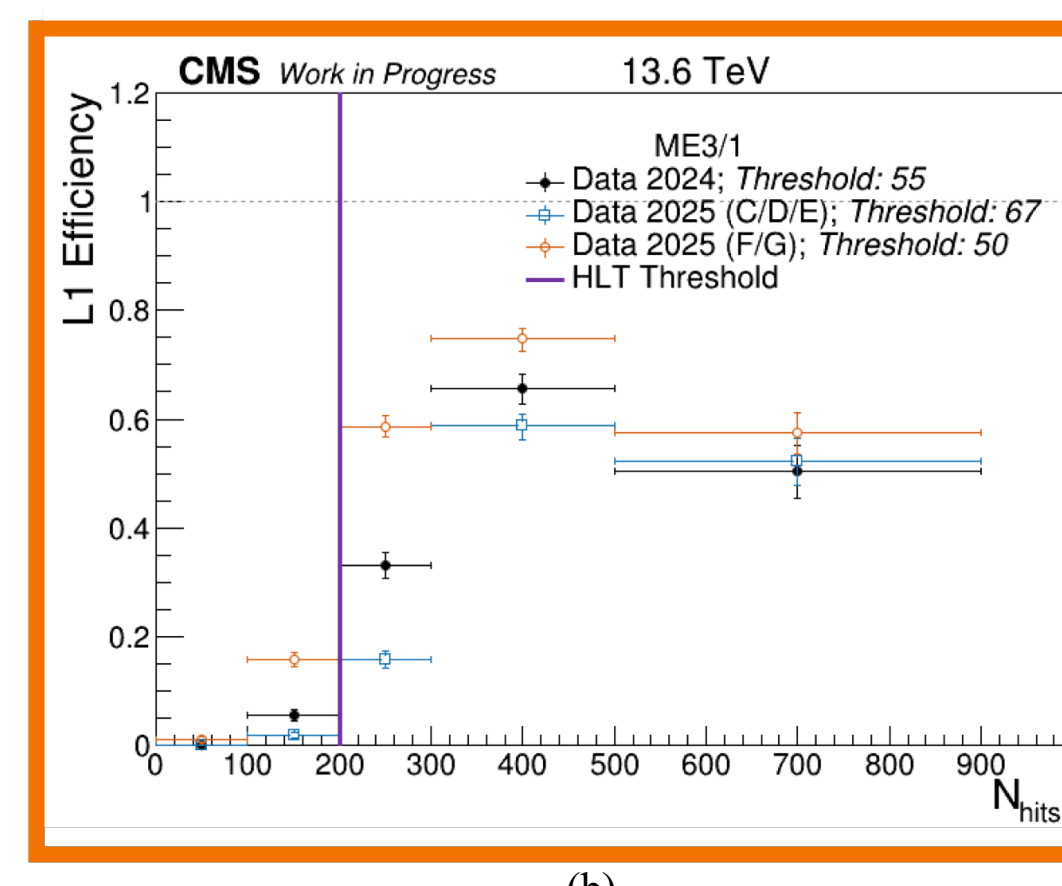
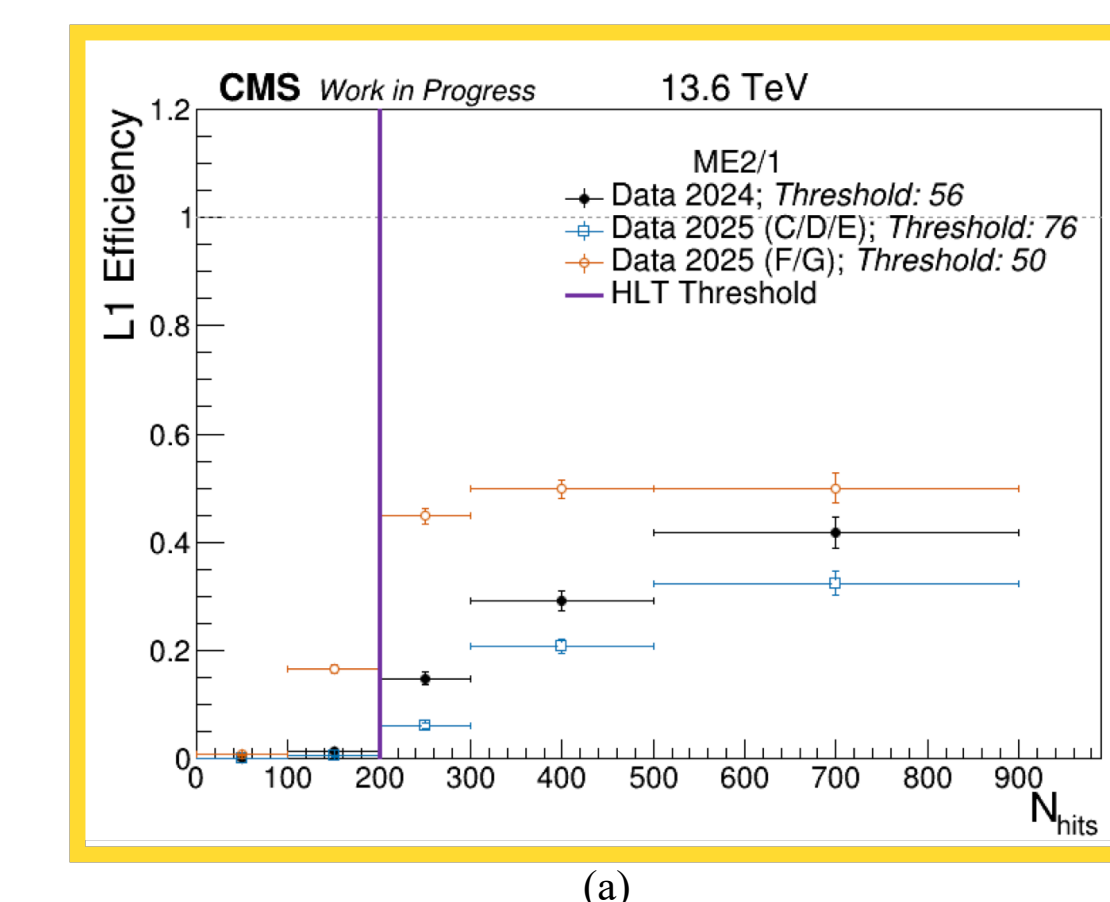


Figure 9. L1T Efficiency per threshold (2024 and 2025) for the inner ring stations: (a) ME2/1, (b) ME3/1, and (c) ME4/1. N_{hits} on the x-axis refers to the number of rechits in a given cluster.

Outer Ring Efficiencies

- Outer rings experienced negligible changes to L1T efficiency.
- Differences in efficiency in the “turn on” region of the curve come from changes in the trigger thresholds at the beginning and in the middle of data taking in 2025.

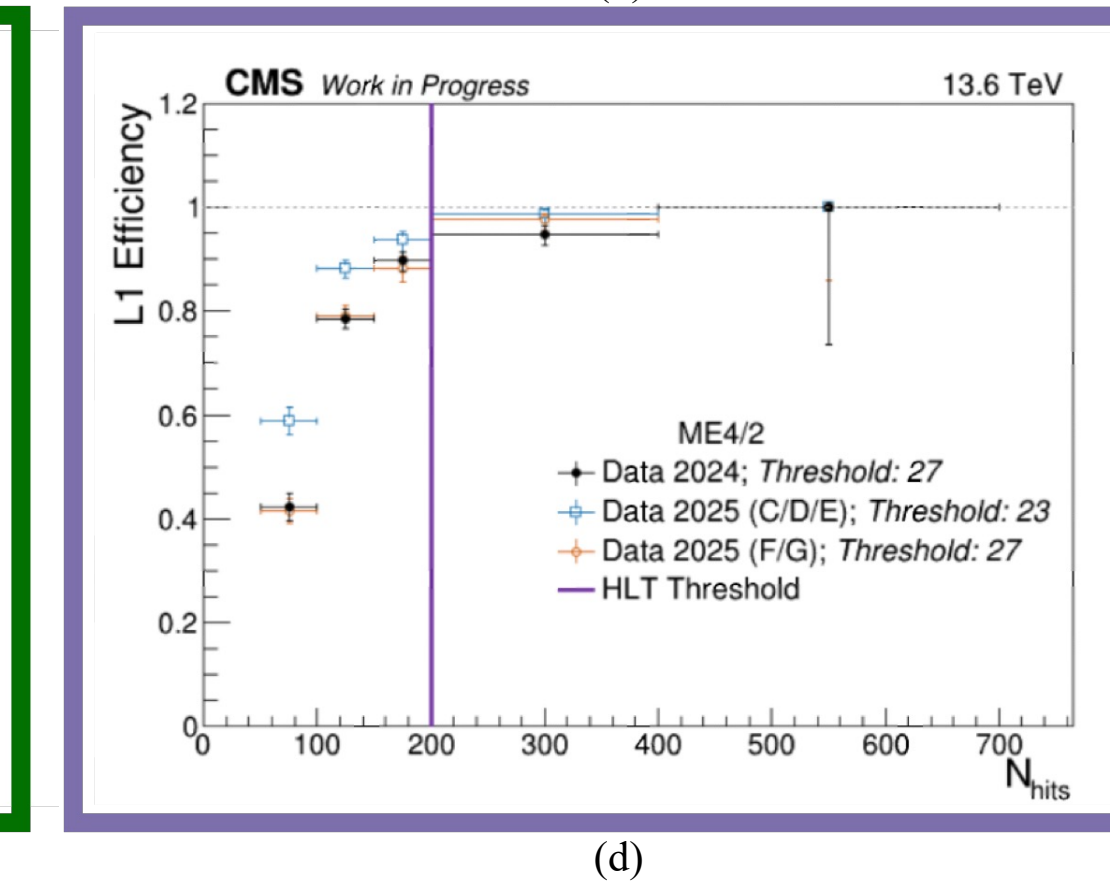
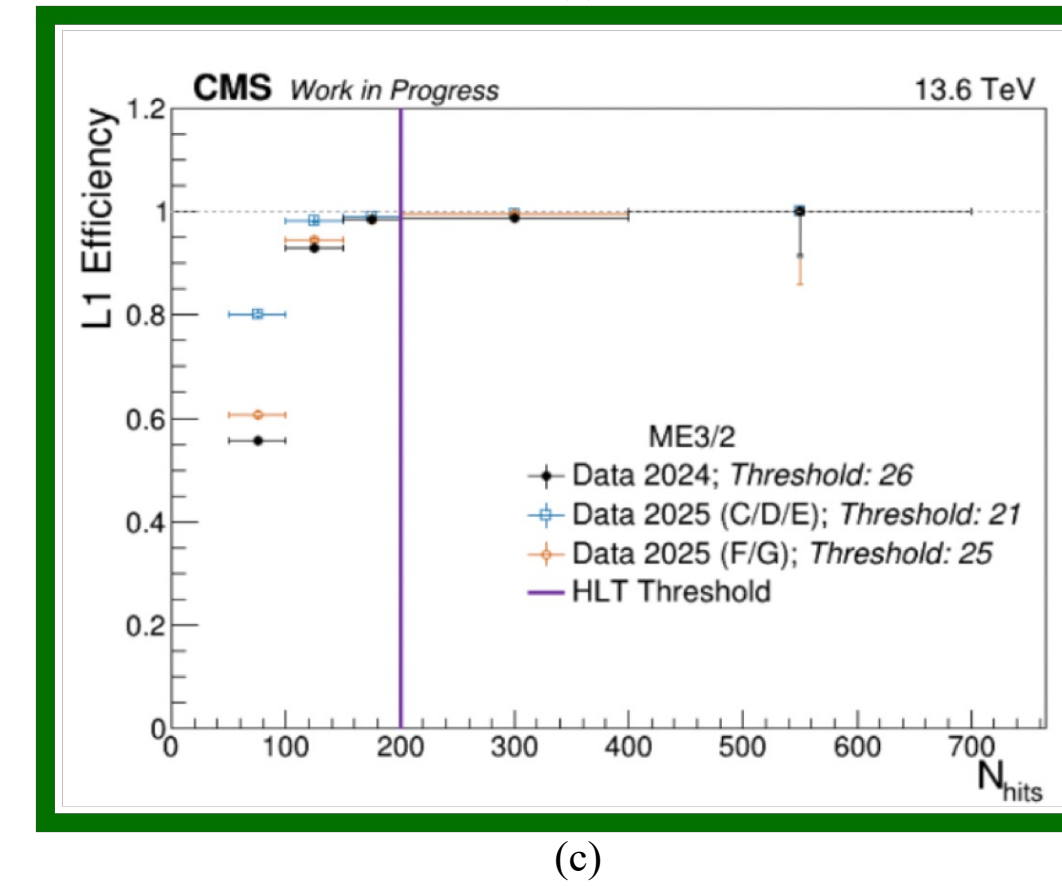
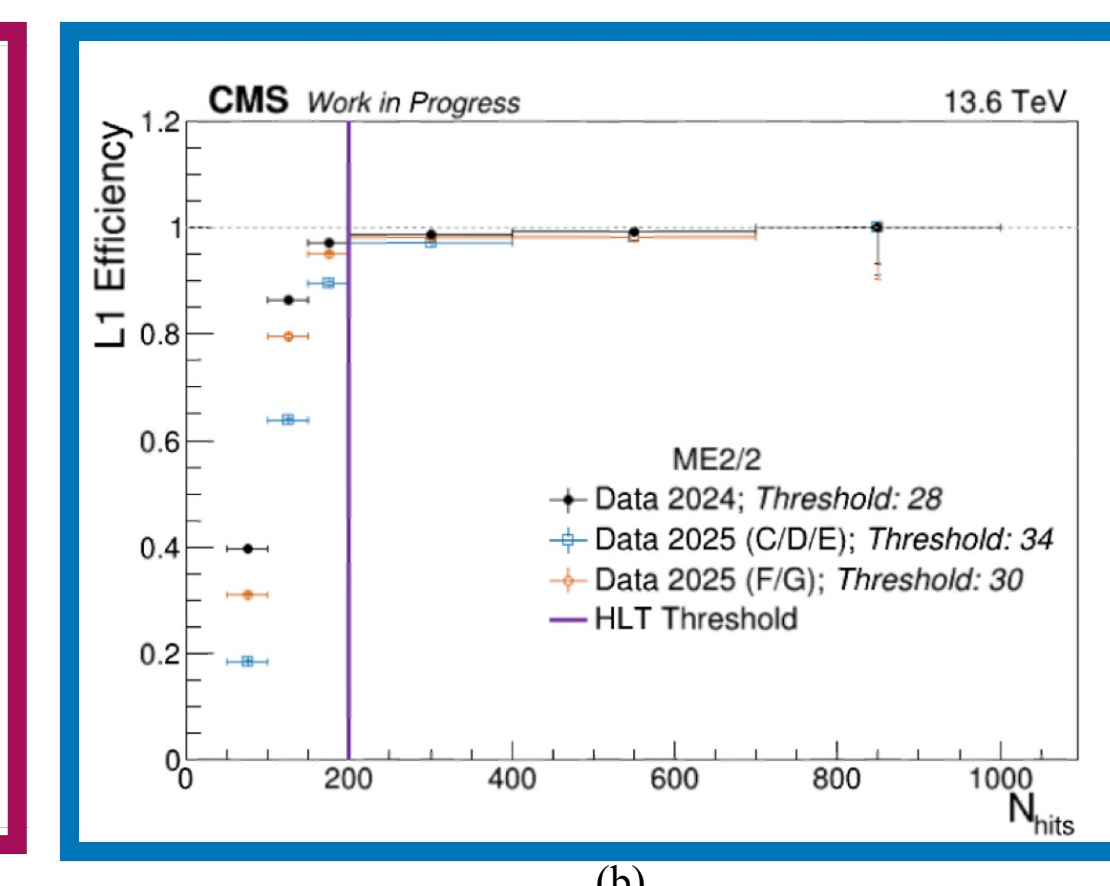
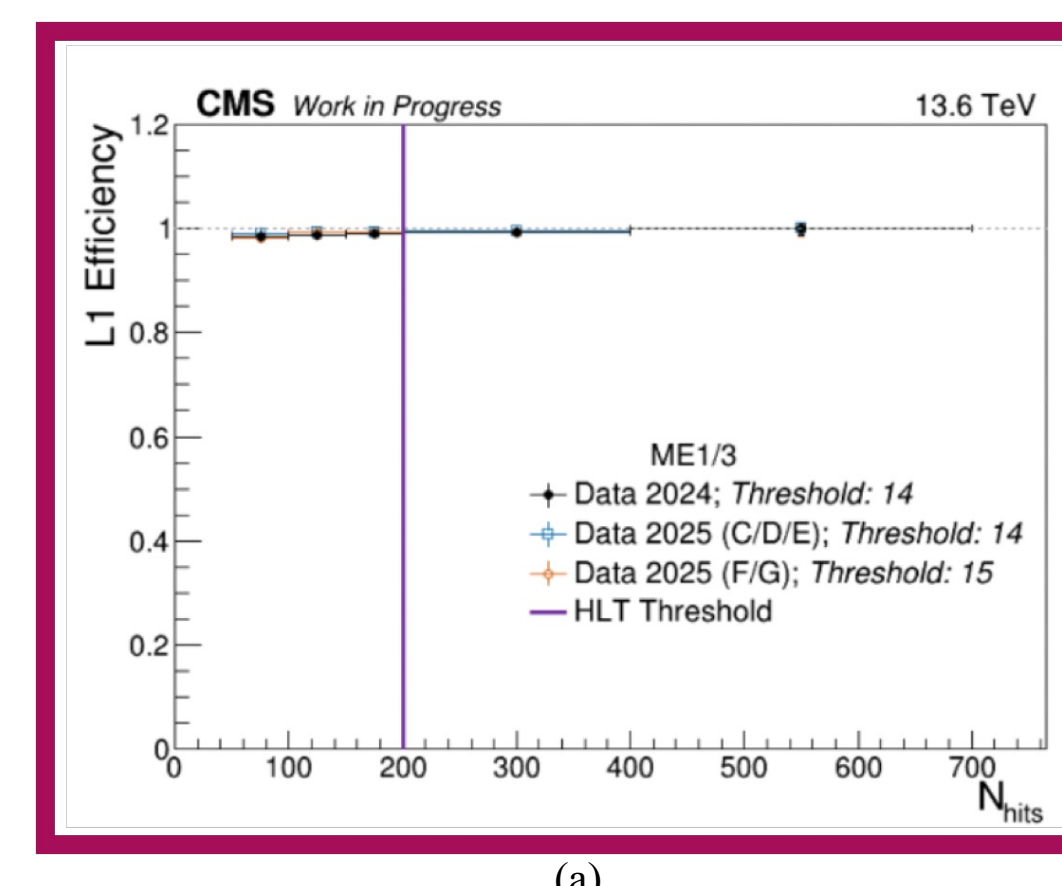


Figure 10. L1T Efficiency per threshold (2024 and 2025) for the outer ring stations: (a) ME1/3, (b) ME2/2, (c) ME3/2, and (d) ME4/2. N_{hits} on the x-axis refers to the number of rechits in a given cluster.

Works Cited

- CMS Collaboration, “Long-lived particles in light of the LHC Run 3 data,” CMS News (26 Oct 2023), <https://cms.cern/news/long-lived-particles-light-lhc-run-3-data>.
- CMS Collaboration, “Search for long-lived particles with a pair of muon detector showers in proton-proton collisions at $\sqrt{s} = 13.6$ TeV,” CMS-PAS-EXO-25-005 (2026).