# Long-Lived Particle Trigger Strategies with the CMS Detector

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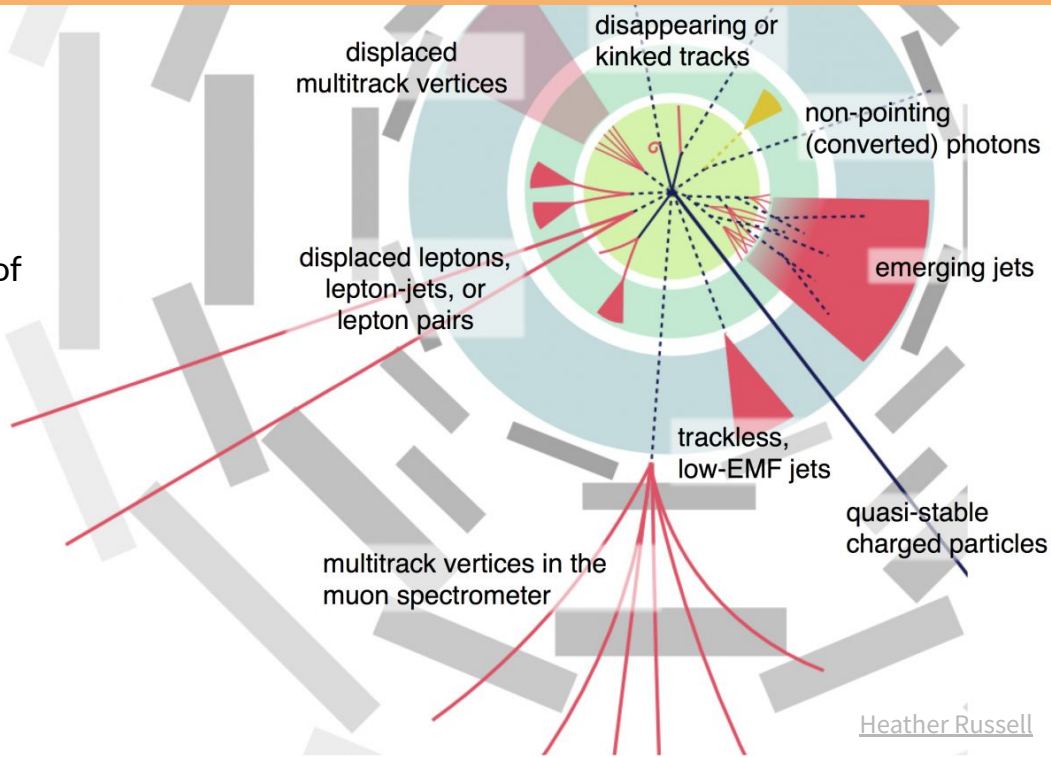
# Why LLPs? Triggers?

➔ A comprehensive and robust LLP search program should be sensitive to a broad range of LLP masses, lifetimes, and final states

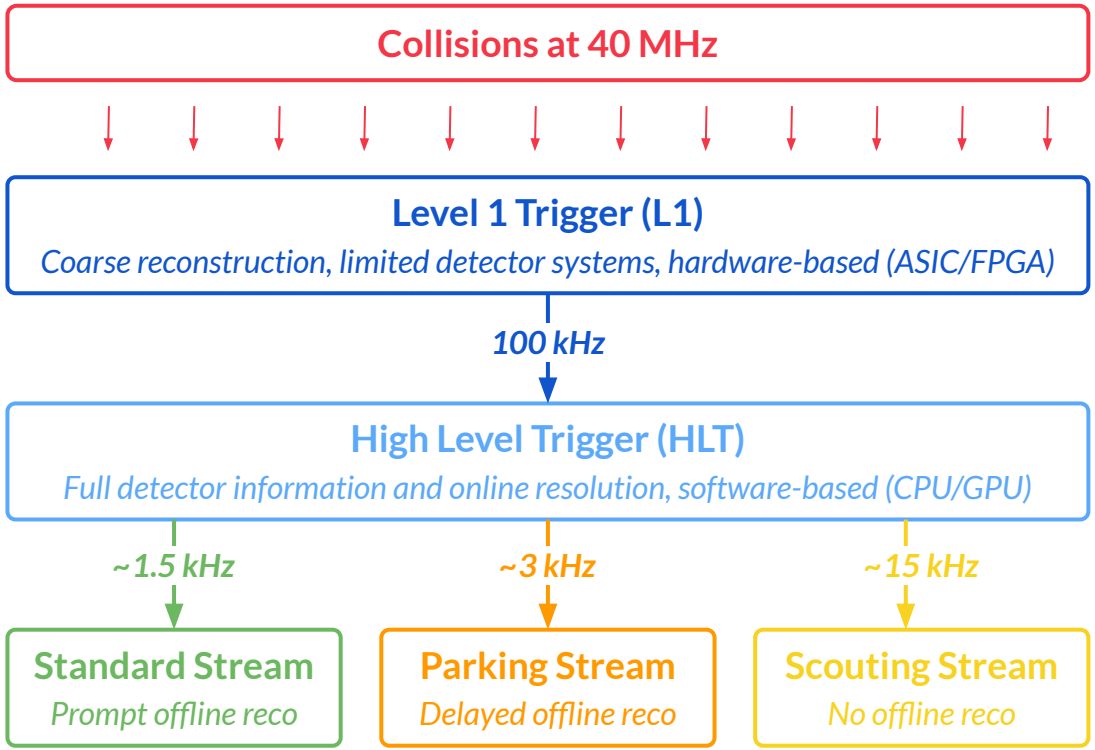
➔ Limited number of dedicated LLP triggers before Run 3 – most LLP analyses used "standard" prompt-based algorithms:

- ◆ Trigger directly on LLP decay products → *limited sensitivity to soft final states*
- ◆ Trigger on associated prompt objects → *reduced model dependence, cross sections*




***Sensitivity to many LLP signatures is trigger-limited, so it critical to develop dedicated triggers and leverage new triggering capabilities***

# The CMS Trigger System: *Simplified*




**Trigger Development: Key Challenges**

- ➔ Low (reasonable) rates at L1 and HLT
- ➔ Latency at L1 within budget
- ➔ CPU resource usage at HLT within budget
- ➔ Operational difficulties

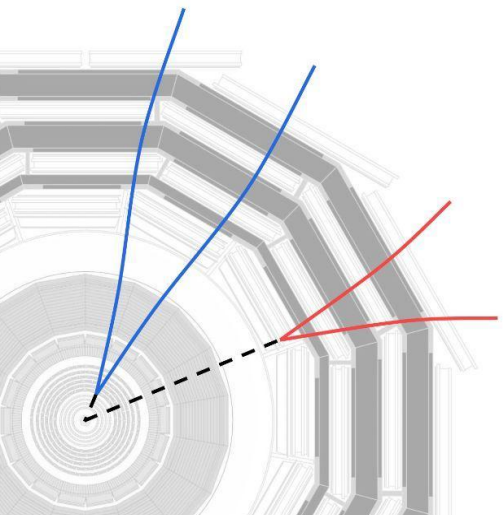
# Overview

- ~~Introduction + Motivation~~
- Case Study: Displaced Muon Triggers
- Case Study: Displaced and Delayed Jet Triggers
- Leveraging The Parking and Scouting Streams
- Common Themes Across LLP Trigger Strategies
- Conclusions + Outlook

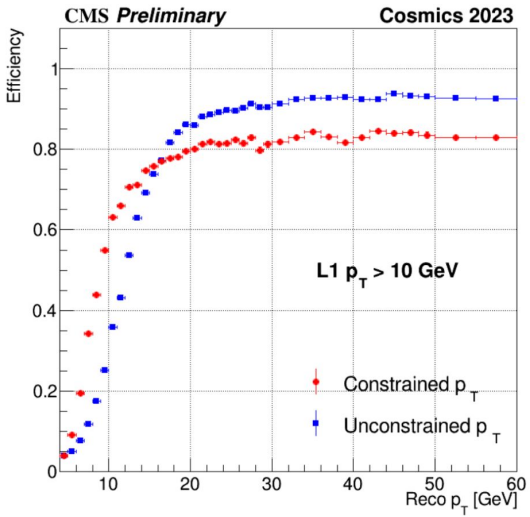
Title Image Credit:
Michael Hoch
"CMS-The Art of Science"

# Displaced Dimuon Triggers

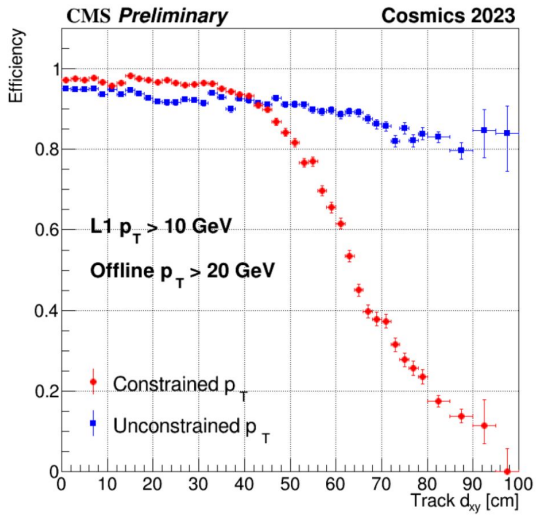
- ➔ **Target**: displaced muons reconstructed with the muon spectrometer and/or tracker subsystems
- ➔ **Custom L1**: Standard L1 muon reconstructions includes a beamspot (BS) constraint for $p_T$ calculation
  - ◆ In the barrel, implemented momentum assignment without the BS constraint → New in Run 3!
  - ◆ Significantly improved reconstruction efficiency of displaced muons



**L1 Efficiency vs. Momentum**

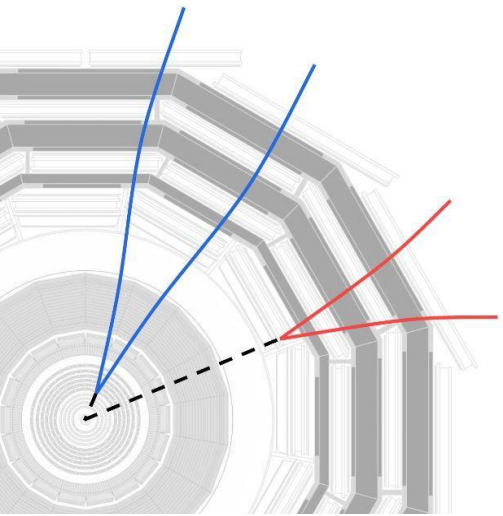



**L1 Efficiency vs. Displacement**

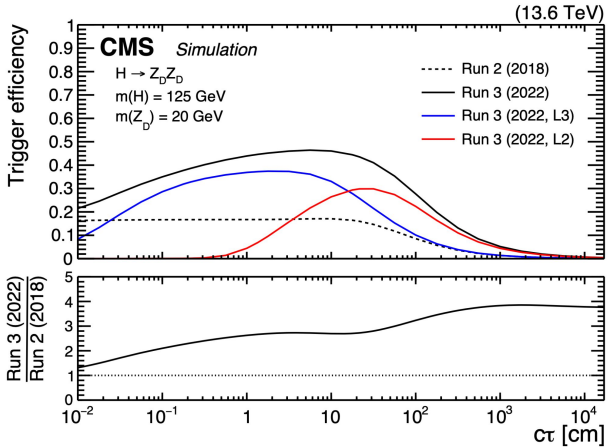


# Displaced Dimuon Triggers

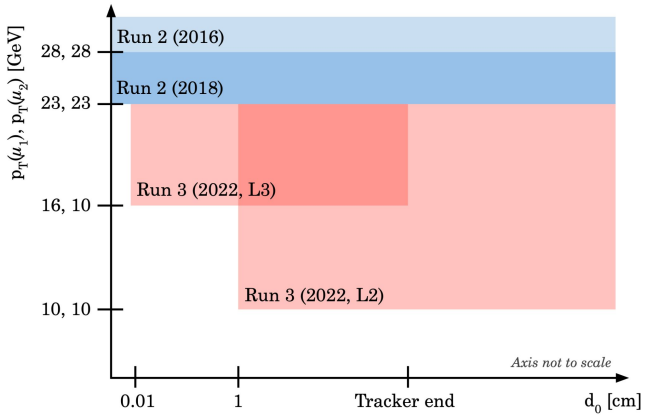
- **Target**: displaced muons reconstructed with the muon spectrometer and/or tracker subsystems
- **Dedicated HLT**: Use both tracking and muon spectrometer subsystems to enhance acceptance
  - L2 Muons: reconstruction with only the muon system
  - L3 Muons: reconstruction with both the tracker and muon system; veto on prompt



**HLT Efficiency vs. LLP Decay Length**




**Enhanced Phase Space Coverage from Run 2 to Run 3**




*New Results with 2022 Data! See arXiv:2402.14491 and Mangesh's talk this week*

# Displaced + Delayed Jet Triggers | *Overview*

CMS Performance Note

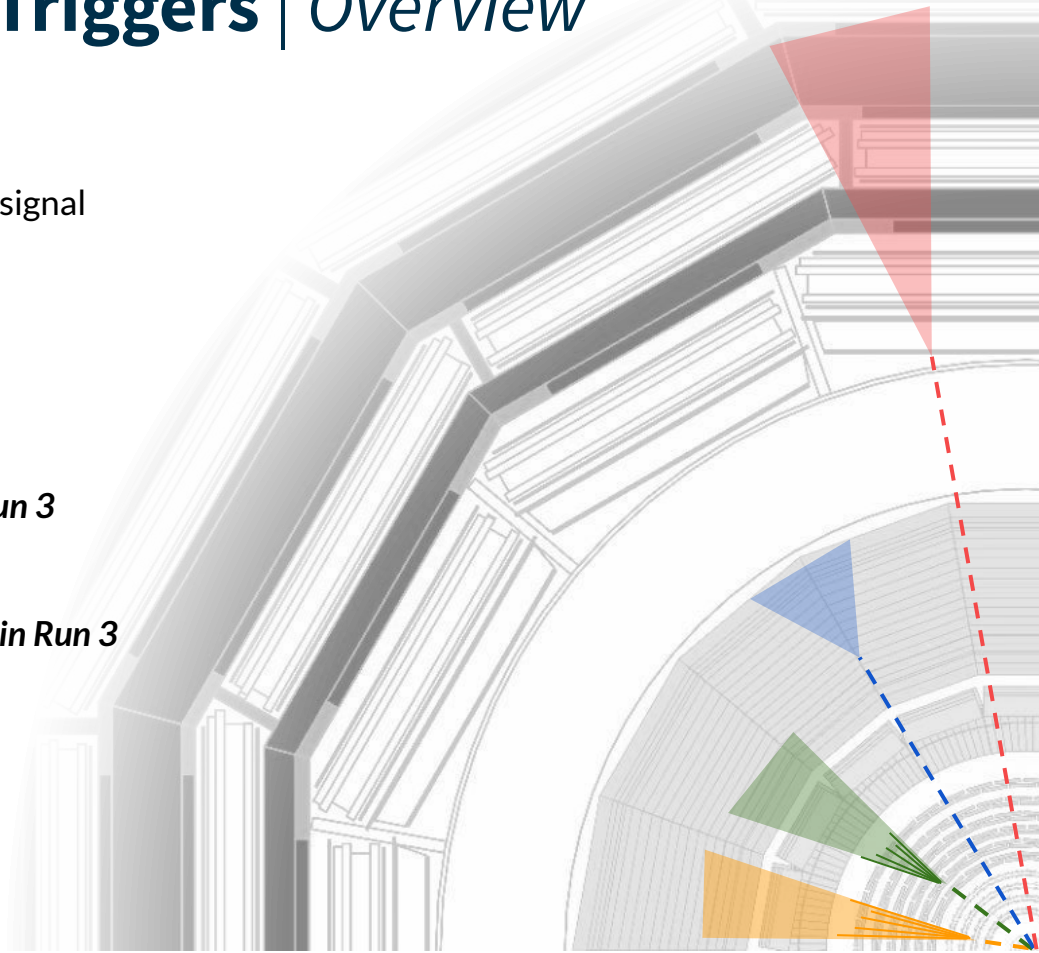
**Motivation:**

- ➔ Maximize trigger acceptance across a range of signal lifetimes for hadronically decaying LLPs
- ➔ Extend sensitivity to softer final states

**Triggers Discussed Today:**

- ➔ Tracking-based displaced jets→ *Updated!* ***in Run 3***
- ➔ ECAL-based delayed jets → *New!* ***in Run 3***
- ➔ HCAL-based displaced & delayed jets → *New!* ***in Run 3***
- ➔ MS-based displaced jets → *New!* ***in Run 3***

*Note that the results discussed today focus on the Standard Reconstruction Stream*

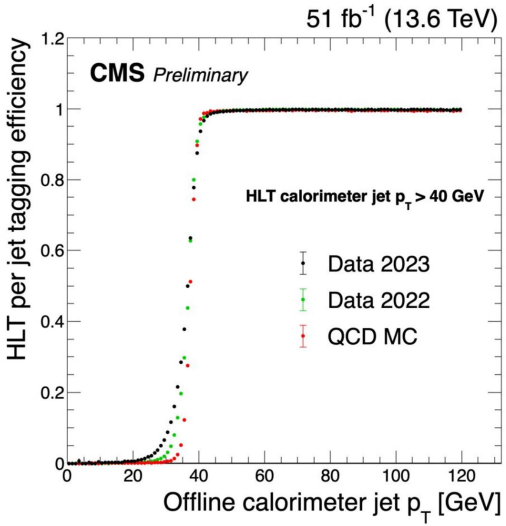


# Tracking-Based Displaced Jet Triggers

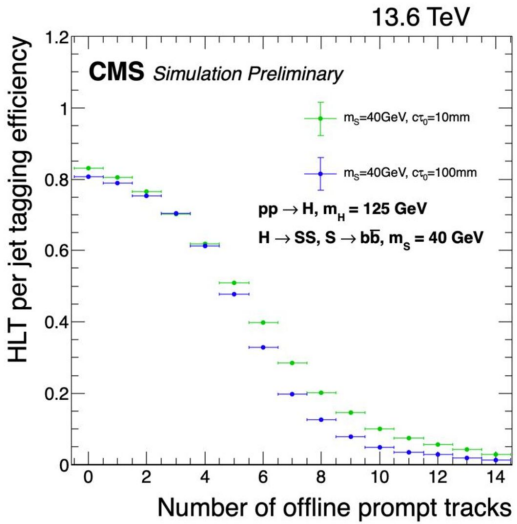
CMS Performance Note
CMS-PAS-EXO-23-013

- **Target**: displaced jets with displaced tracks and/or prompt track vetoes
- **L1 Strategy**: seeds with $H_T$ > 430 or with soft muons (muon $p_T$ > 6 GeV and $H_T$ > 240 GeV)
  - Soft muon triggers sensitive to signatures with b-jets in the final state
- **Dedicated HLT**:
  - Inclusive: jet has at ≤ 1 prompt track
  - Displaced: if there is 1 prompt track, there must also be ≥ displaced track

**HLT Efficiency vs. Jet $p_T$ in Data**




**Efficiency vs. Number of Prompt Tracks in Data**




*Implemented in both Standard and Parking Stream (Standard shown)*

*New Results with 2022 Data! See CMS-PAS-EXO-23-013 and Jingyu's talk this week*

# ECAL-Based Delayed Jet Triggers

➔ **Target**: delayed jet signatures using online ECAL timing at HLT

➔ **L1 Strategy**: seeds with $H_T$ > 430 or L1 Tau $p_T$ > 120 GeV

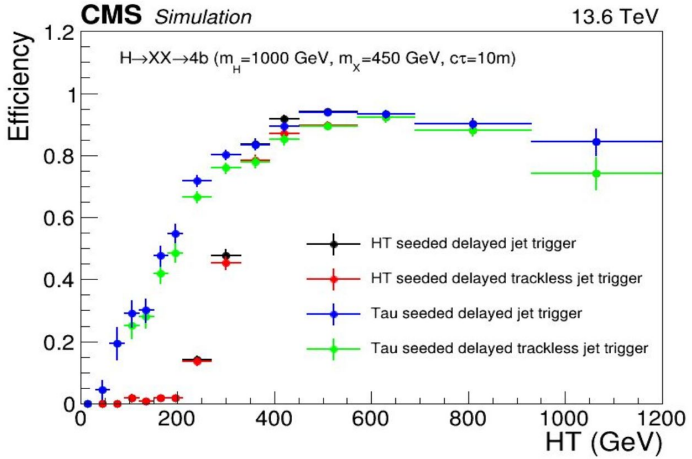
- Displaced jets from massive LLPs become collinear & can look like τ leptons

*Implemented in both Standard and Parking Stream (Standard shown)*

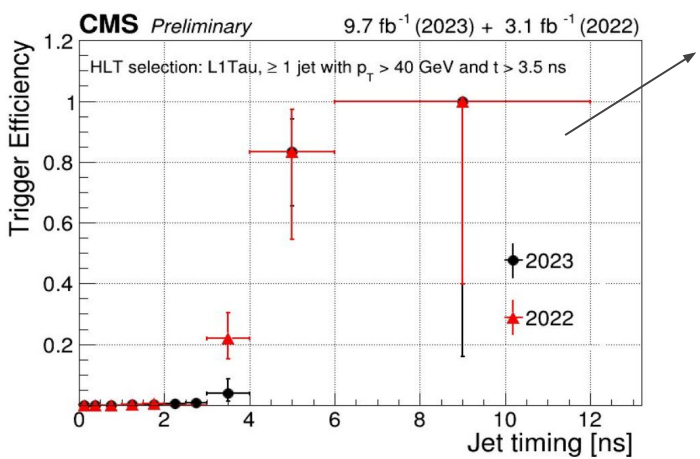
➔ **Dedicated HLT**: at least 1 or 2 jets with $p_T$ > 40 GeV and ECAL timing delay

- Key challenge: rates depend on ECAL crystal transparency – excellent work by team to ensure good data quality

**HLT Efficiency vs. HT in Signal**




**HLT Efficiency vs. Timing in Data**




*Trigger efficiencies reach ~80-100% for jets with ECAL times > 4 ns*

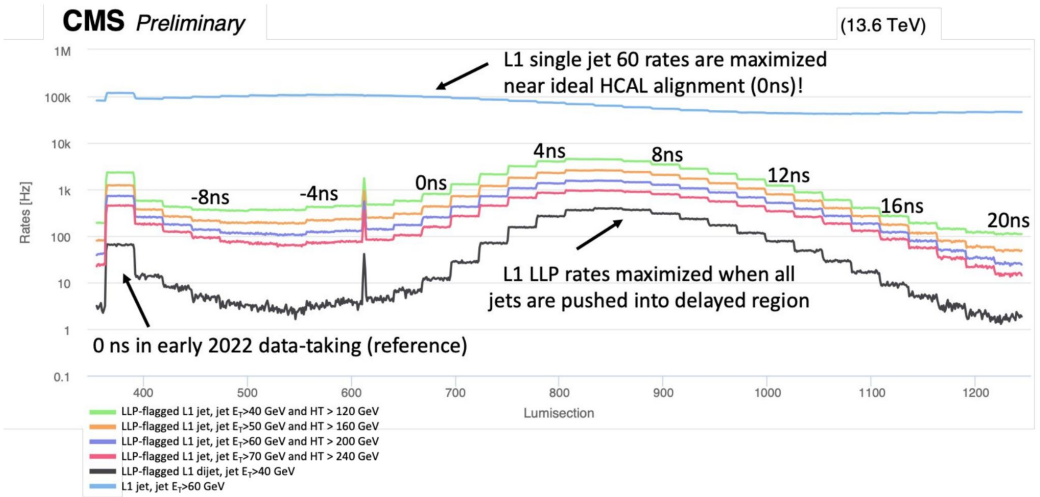
# HCAL-Based Displaced + Delayed Jet Triggers



- **Target**: displaced & delayed jets using HCAL measurements at L1
  - Phase I HCAL barrel upgrade added depth segmentation (1→4 layers) and precision timing ASIC (0.5 ns resolution)
- **Custom L1**: at least 1 or 2 jets with either:
  - Depth flag: Minimal energy deposits in the first two layers and high energy deposits in the second two layers
  - Time flag: Significant time delays
- **HLT Strategy**: tracking- and ECAL-based HLT paths with lower $H_T$ thresholds

**Timing Calibration Employed Special "Phase Scan" Runs**

*Shift HCAL clock w.r.t. the LHC clock to create artificially out-of-time jets in collisions*



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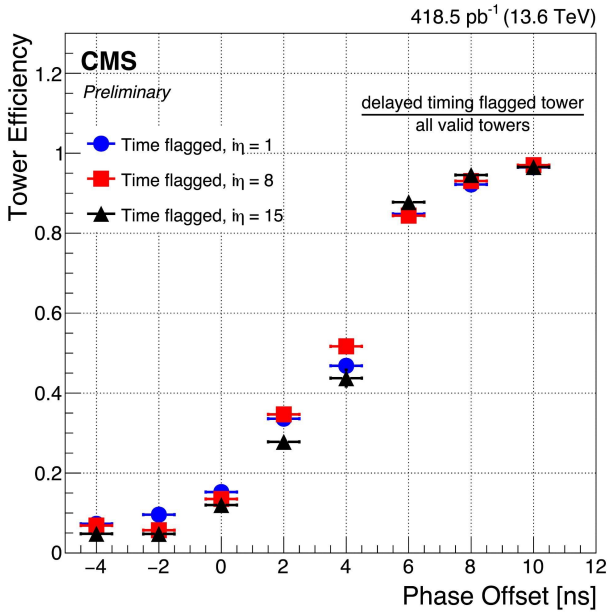
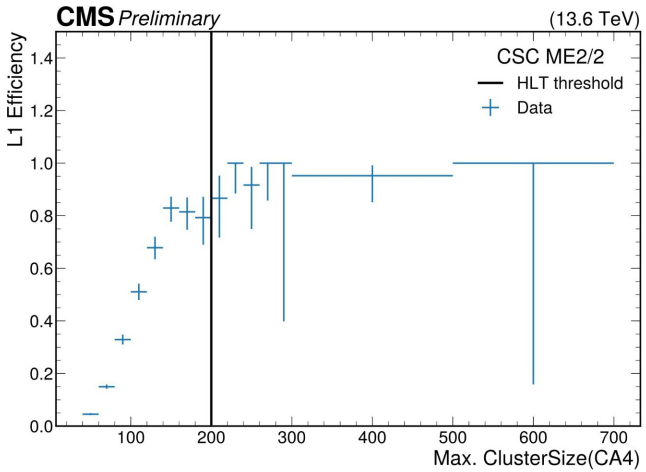
**L1 Tower Efficiency vs. Time Delay**



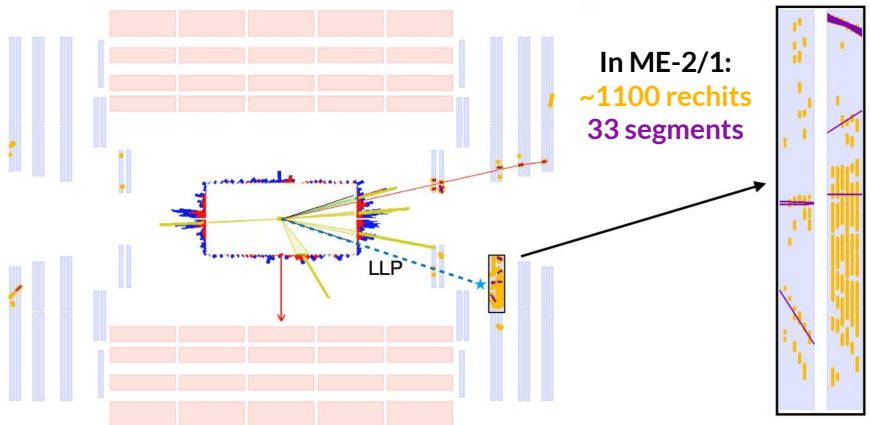
# Muon Spectrometer-Based Displaced Jet Triggers

- **Target**: hadronic showers in the cathode strip chambers (CSCs)
- **Custom L1**: cut on the number of CSC hits N in a chamber (N configurable, varies per ring)
- **Dedicated HLT**:
  - Clustering with Cambridge-Aachen algorithm R=0.4
  - Additional selections on cluster properties, including number of hits and number of rings with > 10 hits

**L1 Efficiency vs. Cluster Size**




**Example Signal Event Display**



# Leveraging the Parking + Scouting Streams

arXiv:2403.16134
arXiv:2403.04584
arXiv:2112.13769

## Parking at 3 kHz

*Delayed Offline Reconstruction*

➔ **Paradigm**: save only RAW event content uses less computational resources, enabling higher rates and thus lower kinematic thresholds

➔ Dedicated LLP Parking at 150 Hz
- ◆ Both tracking- and ECAL-based displaced and delayed jet triggers
- ◆ Lower thresholds (higher rates) compared to prompt

➔ Used to extend sensitivity to long-lived HNLs with the 2018 B-Parking dataset:
- ◆ Dataset: 41.6 $fb^{-1}$ (~12B BBbar enriched events)
- ◆ See arXiv:2403.04584 and Anne-Mazarine's talk this week

# Leveraging the Parking + Scouting Streams

arXiv:2403.16134
arXiv:2403.04584
arXiv:2112.13769

## Scouting at 15 kHz

*No Offline Reconstruction*

- ➔ **Paradigm**: only save limited number of online objects and variables (no RAW content available), enabling *much* higher rates and *much* lower thresholds

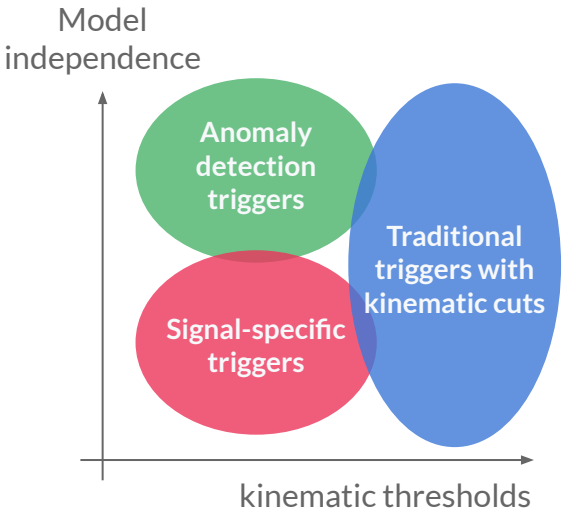
- ➔ Used to extend coverage to very low-mass displaced dimuon resonances (as low as 0.3 GeV)
  - ◆ See arXiv:2112.13769

## Electron and Photon Observables Available in the Run 3 Scouting Dataset

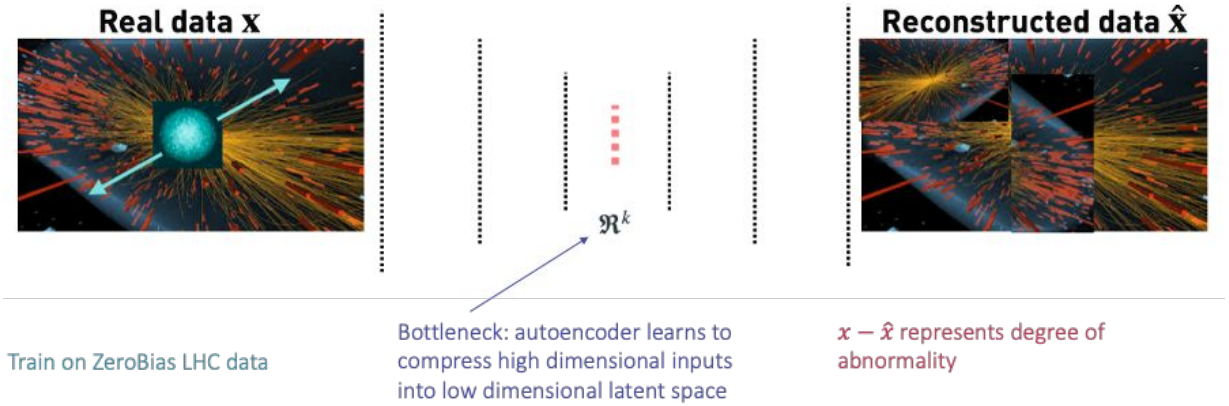
| Observable | Definition |
|---|---|
| *Electron/photon common quantities (calorimeter-based)* | |
| (E, $p_T$, $\eta$, $\phi$) | ECAL SC four-momentum |
| $\sigma_{i\eta i\eta}$ | Spread of the ECAL shower from the central crystal |
| $H/E$ | Ratio of energy deposit in HCAL to ECAL |
| $I_E$ | ECAL isolation |
| $I_H$ | HCAL isolation |
| $r_9$ | Relative energy deposit in 3x3 $\eta$-$\phi$ matrix |
| seed ID | Crystal number of the central crystal |
| energy matrix | Energy deposit in each crystal of the SC |
| detector ID | Crystal number of each crystal of the SC |
| time matrix | Time stamp of each crystal of the SC |
| $s_{minor}$ and $s_{major}$ | Second moments of the SC energy matrix |
| rechitZeroSuppression | Flag indicating events with nonzero reconstructed hits |
| *Electron quantities only (tracker-based)* | |
| track (E, $p_T$, $\eta$, $\phi$) | GSF track four-momentum |
| track $d_0$ | Track $d_0$ |
| track $d_z$ | Track $d_z$ |
| track $\chi^2$/dof | Reduced-$\chi^2$ of the track fit |
| track missing hits | Missing hits in the tracker inner pixel region |
| track $q$ | Track charge |
| $\Delta\eta_{in}^{seed}$ | Difference in $\eta$ between central ECAL crystal and inner track |
| $\Delta\phi_{in}$ | Difference in $\phi$ between SC and inner track |
| $1/E - 1/p$ | Difference between the inverse of SC $E$ and track $p$ |
| $I_{track}$ | Track isolation |

# New Opportunities with Anomaly Detection Triggers

- **Paradigm**: "What if we miss new physics because we did not design the right trigger?"
  - Anomaly detection triggers are sensitive to rare processes that we may not have triggers for – including LLPs!
- Two active efforts working on anomaly detection triggers with autoencoders at L1: CICADA & AXOL1TL




**Simplified Diagram of an Autoencoder:**



# Common Themes Across LLP Trigger Strategies

### Complementarity Across Subsystems

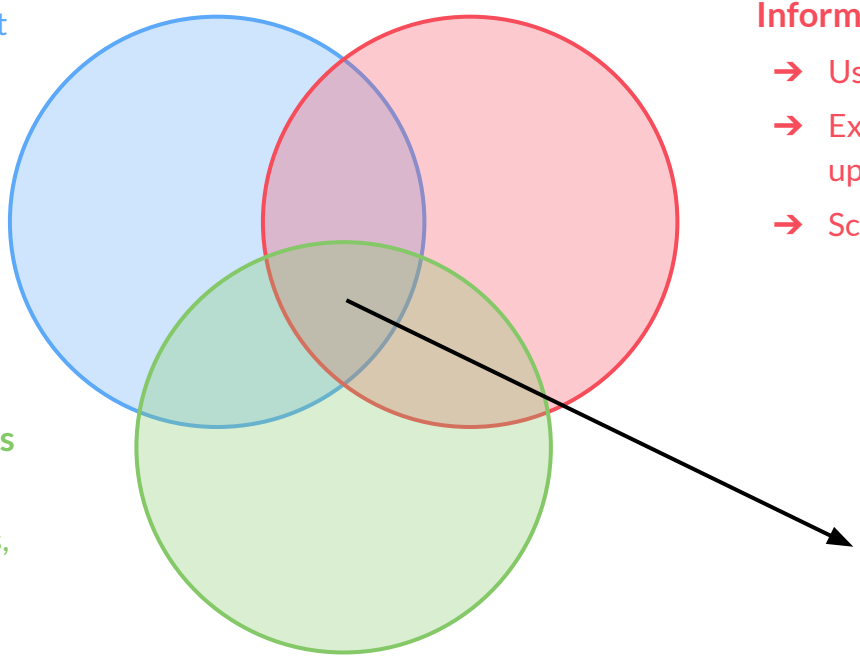
➔ Measurements from different sub-detectors increase acceptance and lead to improved $c\tau$ coverage

### Creative Use of Existing Information & Infrastructure

➔ Using muon and tau L1 seeds

➔ Exploiting capabilities of upgraded HCAL

➔ Scouting + parking streams



### Sensitivity to Softer Final States

➔ In addition to reconstructing displaced LLP decay products, ~all triggers discussed today focus on coverage of soft LLP decay products

**Robust and exciting LLP trigger program!**

# Looking Ahead to the HL-LHC

***What themes and strategies should we employ to improve LLP triggering at the HL-LHC?***

*Disclaimer: just some of my thoughts*

- ➔ Implement more dedicated LLP triggers at L1
  - ◆ Increased latencies at L1 enable more sophisticated algorithms
  - ◆ Advancements in putting ML on FPGAs – e.g. CMS L1 anomaly detection efforts
  - ◆ Further motivated by upgrades, e.g. tracking L1 in CMS, full LAr granularity at L1 in ATLAS

- ➔ Exploit detector timing capabilities
  - ◆ Upgrades to both CMS + ATLAS include dedicated precision timing detectors O(10 ps)

- ➔ Wealth of opportunities with the CMS Scouting and ATLAS Trigger-Level Analysis streams
  - ◆ Proposal for CMS Scouting at 40 MHz (Phase-2 Upgrade of the CMS Level-1 Trigger TDR)
  - ◆ May be possible to save variables relevant for LLP searches!

# Conclusions + Outlook

## Conclusions

- ➔ Active community of LLP enthusiasts at CMS have successfully implemented, commissioned, and analyzed a number of dedicated LLP triggers for Run 3
  - ◆ Displaced muon and displaced + delayed jet triggers shown today extend phase space to softer LLP final states
- ➔ Several LLP analyses have taken advantage of the lower kinematic thresholds afforded by the CMS parking and scouting streams

## Outlook

- ➔ Continue to ensure LLP triggers take high-quality data through the end of Run 3
- ➔ Extensive opportunities to develop dedicated LLP triggers at the HL-LHC!


Thank You!