Unconventional triggers for BSM searches in CMS

Frontiers in Particle Physics

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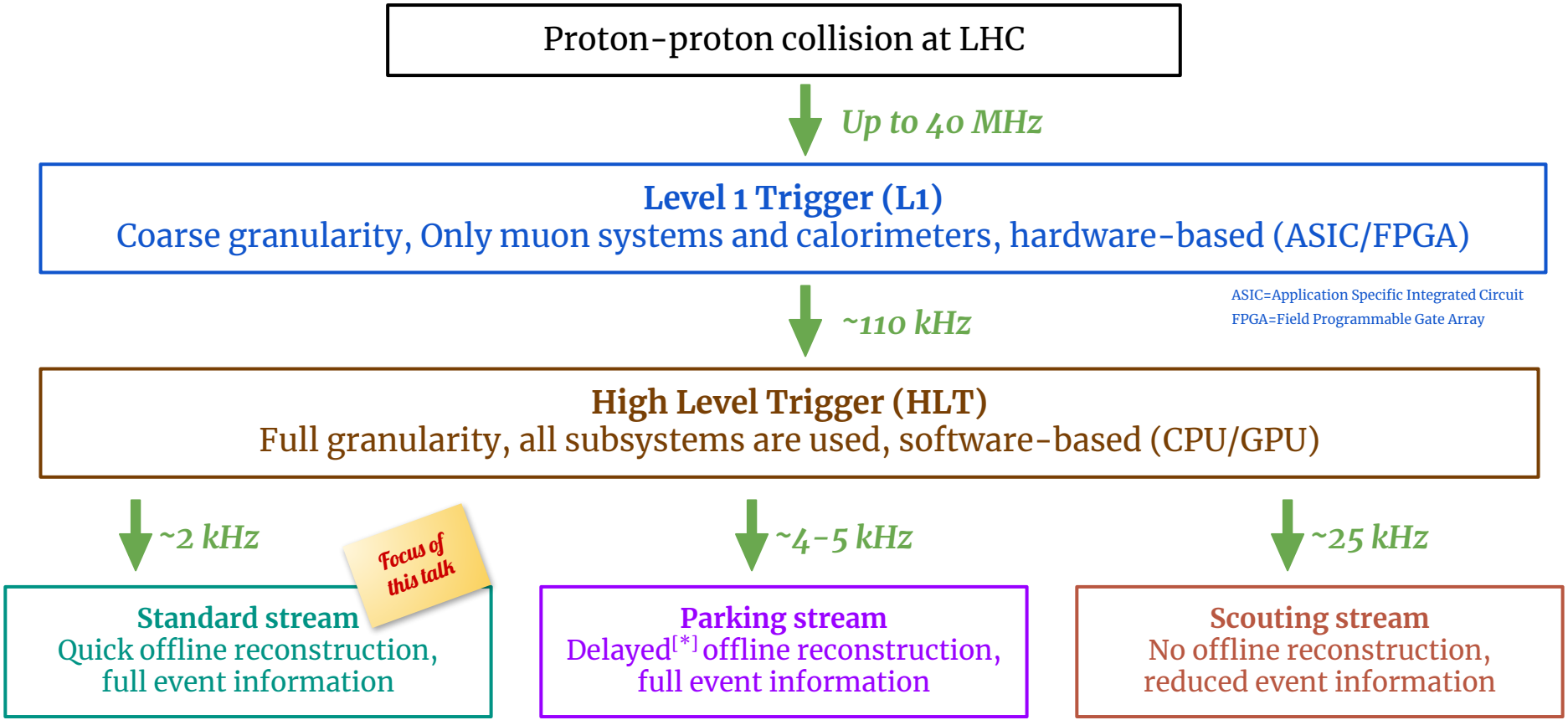
On behalf of the CMS collaboration

CMS trigger system (Run3)



[*] If resource is available, parking data is reconstructed as promptly as the standard data

CMS trigger system (Run3)

Standard stream
Quick offline reconstruction, full event information

Parking stream
Delayed [*] offline reconstruction, full event information

Scouting stream
No offline reconstruction, reduced event information

- Majority of high level triggers (often called HLT paths) belong to this category.
- Few hundred HLT paths collecting data for **varied purposes**
  - Alignment and calibration of detector components
  - Generic HLT paths used in various physics analysis (precision measurements, BSM searches)
  - Dedicated HLT paths for targeted physics analysis
    - Example: dedicated **HLT paths for LLP searches**
  - Dedicated HLT paths to catch any anomalous event which could be BSM (**anomaly finder**)

Focus of this talk

[*] If resource is available, parking data is reconstructed as promptly as the standard data

LLP=Long Lived Particle

CMS trigger system (Run3)

Standard stream
Quick offline reconstruction, full event information

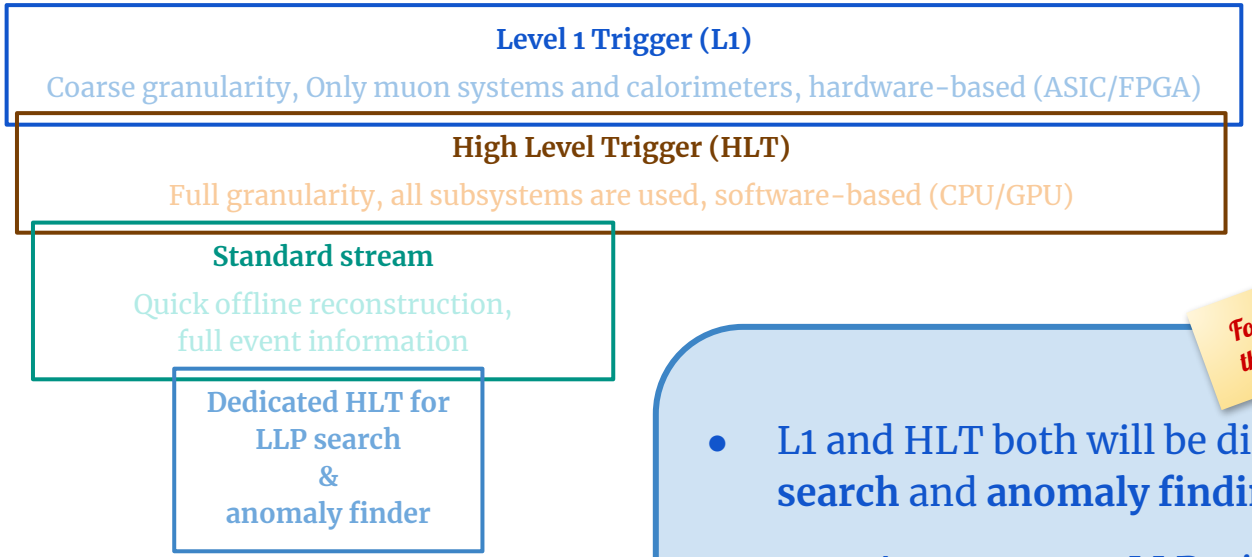
Parking stream
Delayed [*] offline reconstruction, full event information

Scouting stream
No offline reconstruction, reduced event information

- Parking and scouting triggers play major role in LLP searches as well.
- The parking strategy changes (~yearly) according to physics needs. Currently CMS has **dedicated parking triggers for LLP searches**.
- **Scouting data has been useful for LLP searches**.
  - Example: Longlived dark-photon search using muon scouting data https://arxiv.org/abs/2112.13769 (published in JHEP)
- I will barely discuss scouting / parking in this talk due to lack of time (bring it up in discussion session if you are interested)

[*] If resource is available, parking data is reconstructed as promptly as the standard data

Scope of the talk



Focus of this talk

- L1 and HLT both will be discussed in the context of **LLP search** and **anomaly finding**.
  - Among many LLP triggers, will discuss a few (the newest addition to trigger menu, and some personal bias).
- Will focus on Run3 (i.e the ongoing data-taking at LHC)

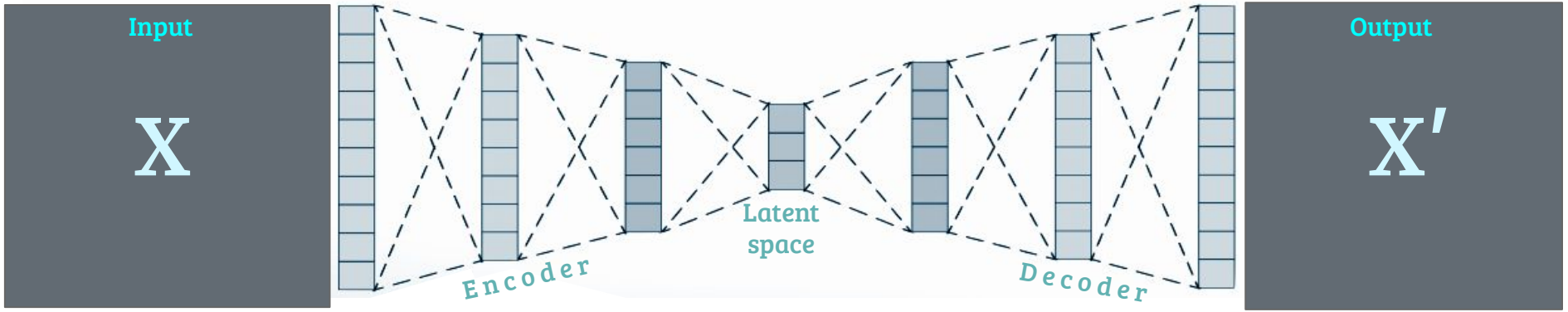
The need for anomaly detector @L1 trigger

- To find BSM in CMS experiment, we need a trigger.
- If we knew the exact signature we are looking for, we'd build a trigger for it!
- In absence of that, what else can we do?

Anomaly detector @L1 trigger: general idea

- To find BSM in CMS experiment, we need a trigger.
- If we knew the exact signature we are looking for, we'd build a trigger for it!
- In absence of that, what else can we do?

- Use of ML to learn the features of typical standard model events
- Then, pick events that are not typical, using **autoencoder** (AE)
- Train AE on typical events (ZeroBias data) and use reconstruction error (loss) as a metric for anomalous-ness



$$\mathcal{L} = || X - X' ||$$

Anomaly detector @L1 trigger in CMS

Two complementary approaches

AXOL1TL

Anomaly eXtraction Online Level-1 Trigger aLgorithm

Inputs: P_T, η, ϕ of Jets(x10) , e/γ (x4), μ (x4), and MET (from Calo layer-2 and Global Muon Trigger)

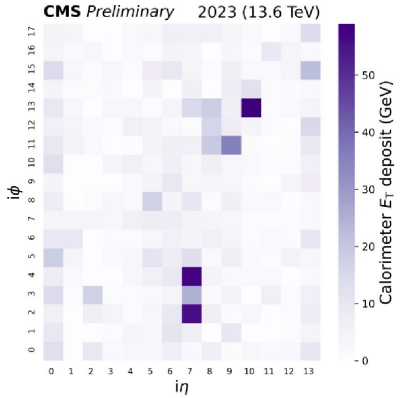
Ref: https://cds.cern.ch/record/2876546

CICADA

Calorimeter Image Convolutional Anomaly Detection Algorithm

Inputs: Low-level information (from Calo layer-1) in image format.

Ref: https://cds.cern.ch/record/2879816



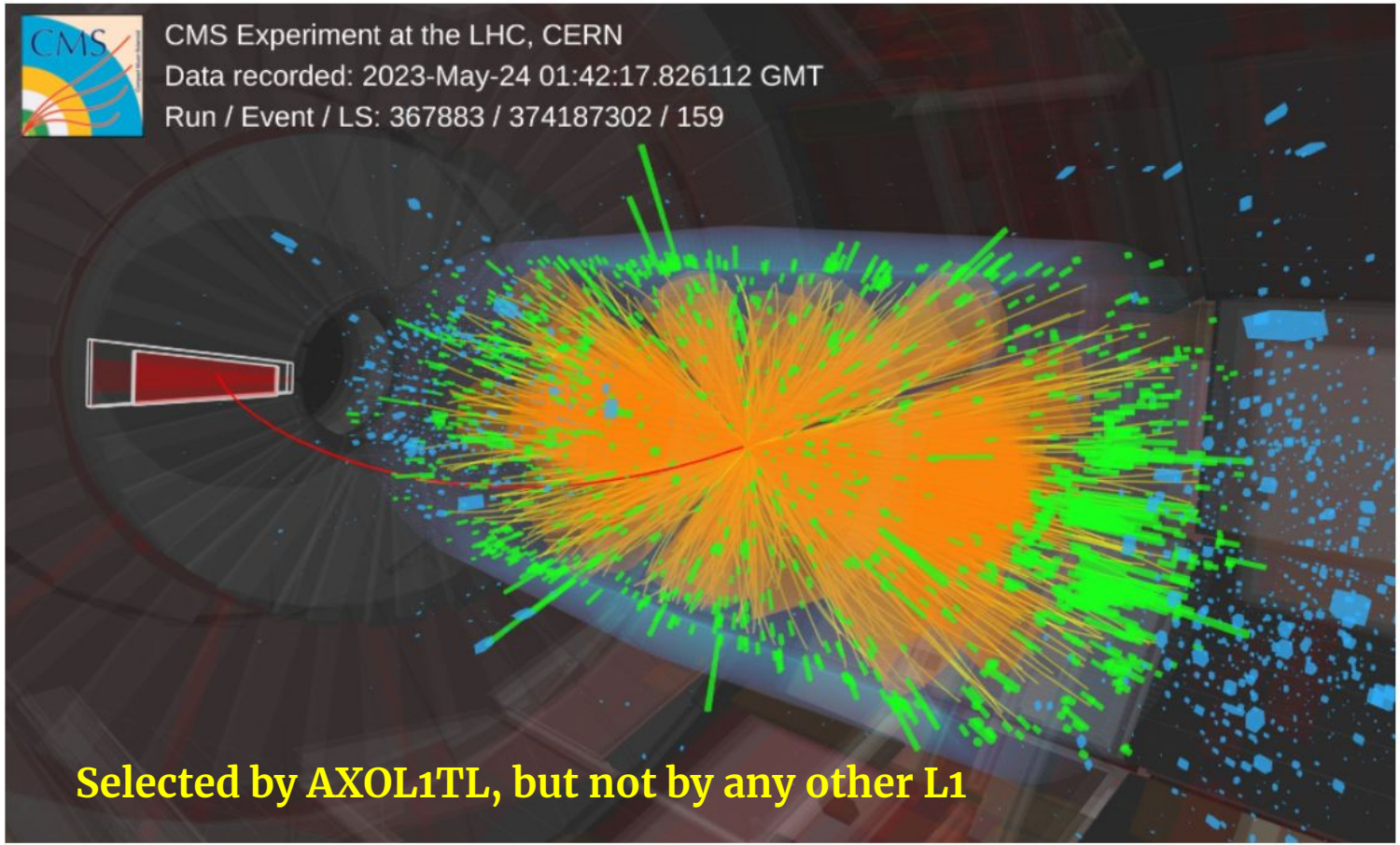
ML@L1 trigger becoming important. Tools for ML@FPGA developed.

- Neural Nets → HLS4ML (documentation)
- Boosted Decision Trees → Conifer (github, paper)

hls4ml

Conifer

An event selected by AXOL1TL



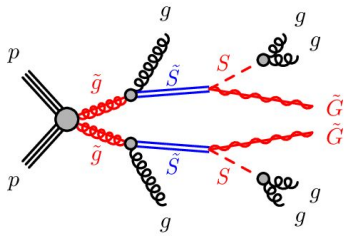
SUEP?

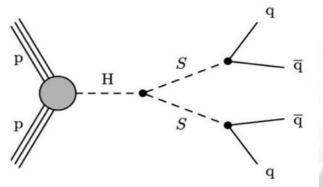
Emerging jet?

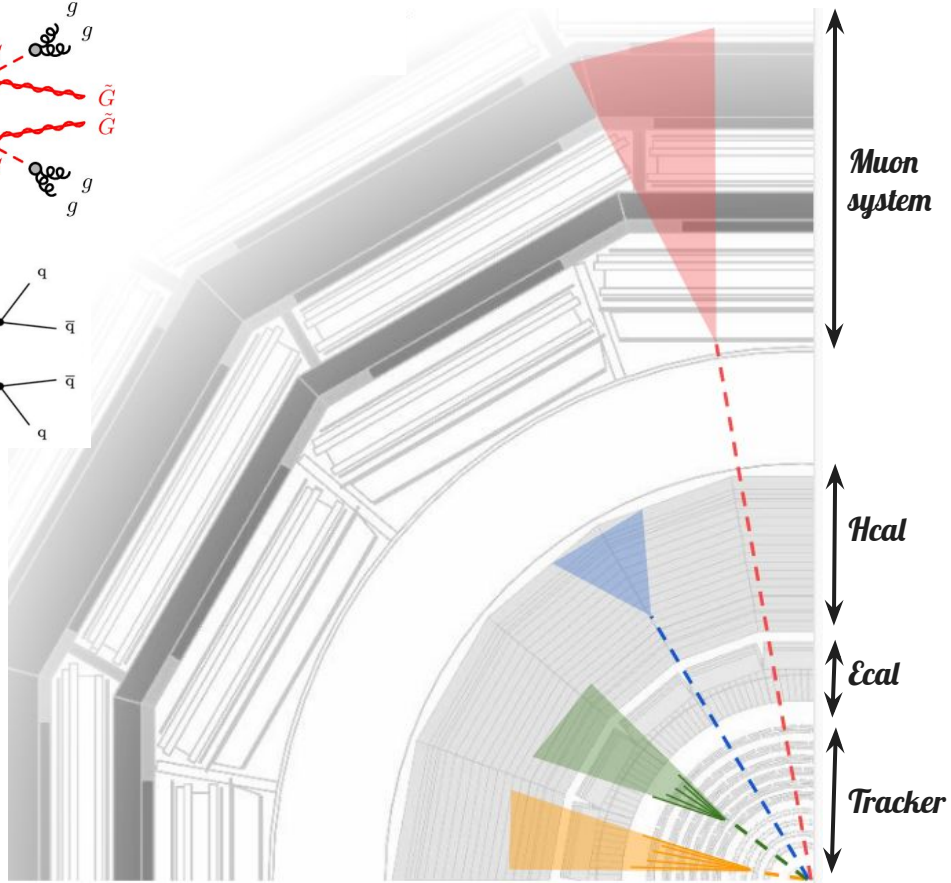
Or just normal QCD?

Displaced jet

- Hadronically decaying LLP is a viable BSM scenario.
- Several **displaced-jet triggers** to capture various detector signatures, depending of LLP's lifetime (decay length).
  - tracking-based
  - ECAL-based
  - HCAL-based
  - Muon system-based







Displaced jet trigger

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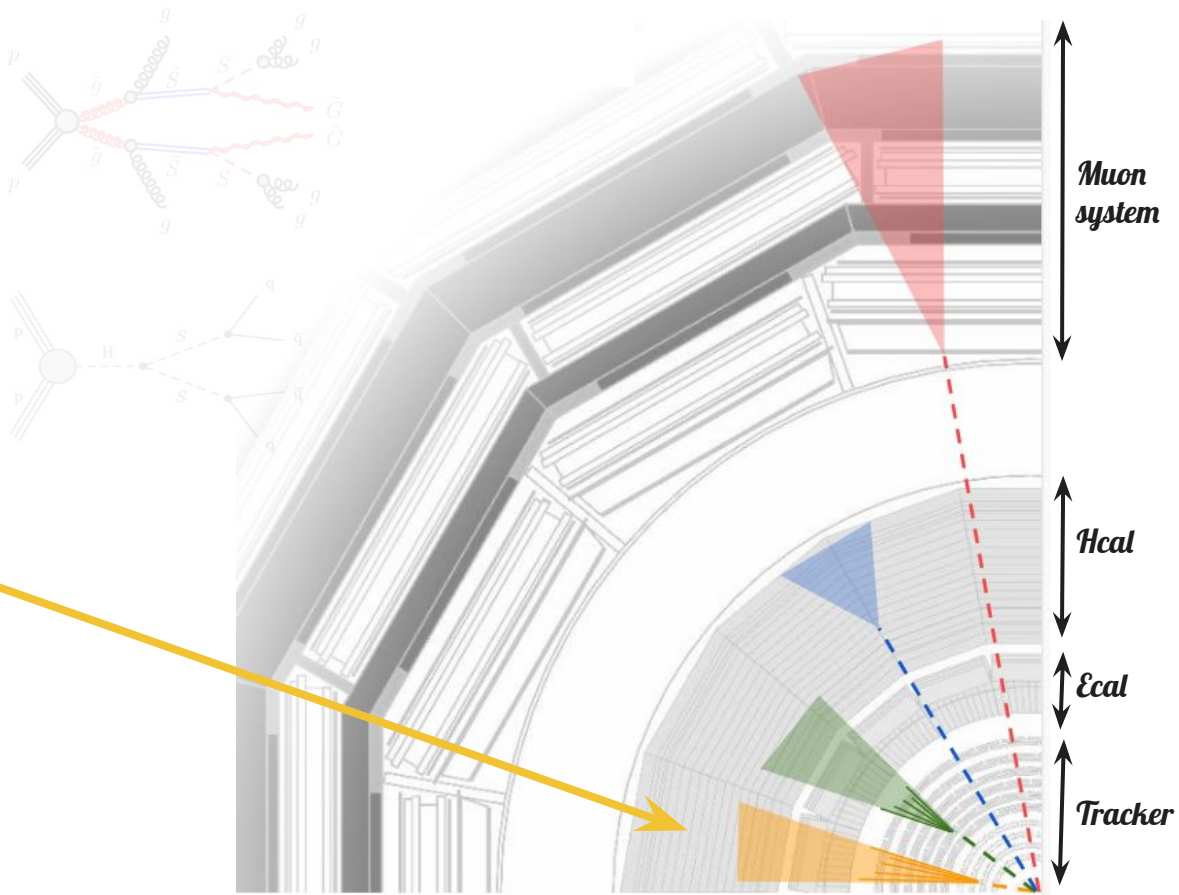
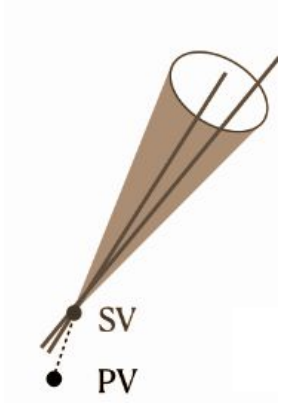


Tracking-based displaced jet trigger

- Trigger implemented in Run2.
  - Displaced-jets search with full Run2 data https://arxiv.org/abs/2012.01581 (Published in PRD)
  - Search is sensitive to a large variety of LLP models, for LLP masses from ~10 GeV to ~3 TeV.
- Run3 trigger improved. Better than Run2 by a factor of ~5-10
- L1 Strategy: HT>430 GeV or soft-muons (pT>6 GeV) and HT>240 GeV.
  - Triggering on soft muon enables lower HT thresholds and is sensitive to signatures with b-jets in the final state
- HLT strategy: Reconstruct displaced jets with displaced tracks. Prompt track veto
- Early Run3 result already public, CMS PAS EXO-23-013 (2022 data)



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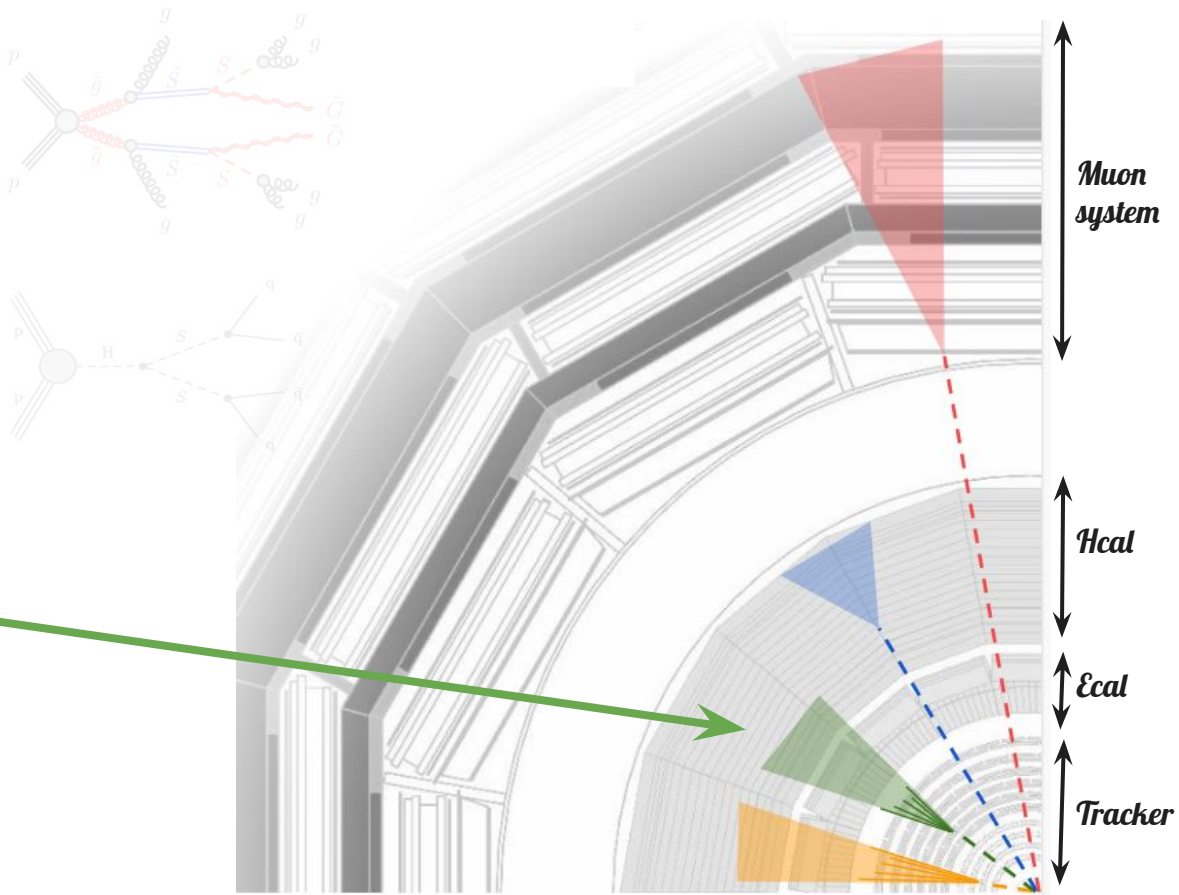
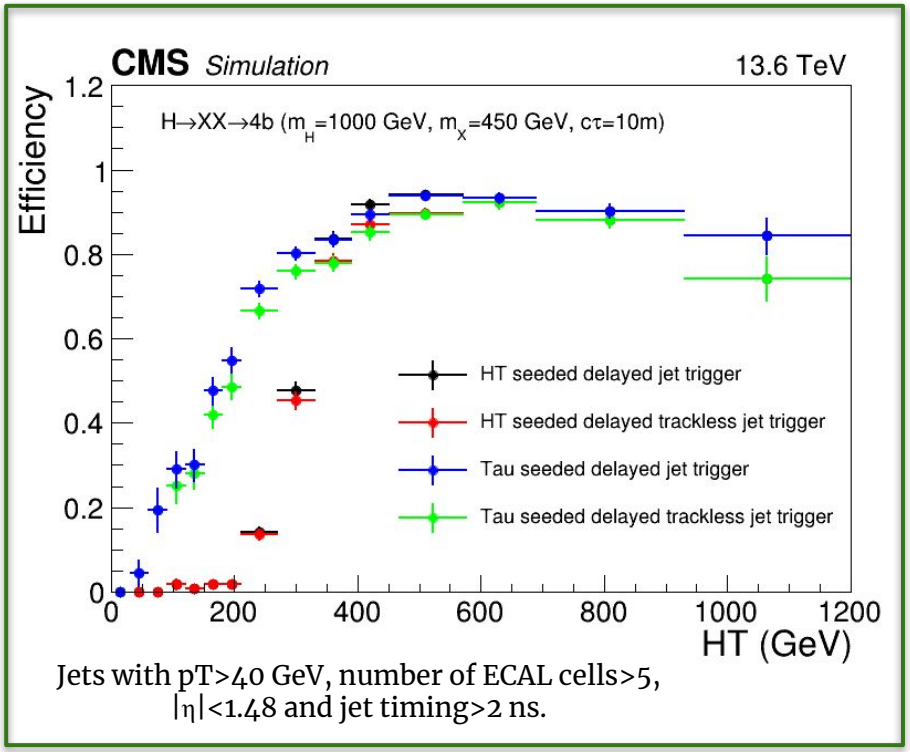


ECAL-based displaced jet trigger in CMS

ECAL timing is a powerful handle for LLP search.
ECAL measures arrival time of objects with precision of ~200 ps (for energy deposits >50 GeV)



Jets with pT>40 GeV, number of ECAL cells>5, $|\eta|<1.48$ and jet timing>2 ns.

- **L1 Strategy**: HT>430 GeV or L1 Tau pT>120 GeV and HT>360 GeV
  - L1 Tau seeds enable lower HT thresholds.
  - As LLPs become more massive and displaced, the resulting jets become collinear and can look like τ leptons
- **HLT strategy**:
  - Nominal jets (track matched to the jet) or trackless jets (no matched track).
  - Use ECAL timing information for jet timing.
- Key challenge: HLT rates depend on ECAL crystal transparency

Ref: https://cds.cern.ch/record/2865844

Exciting searches ongoing!

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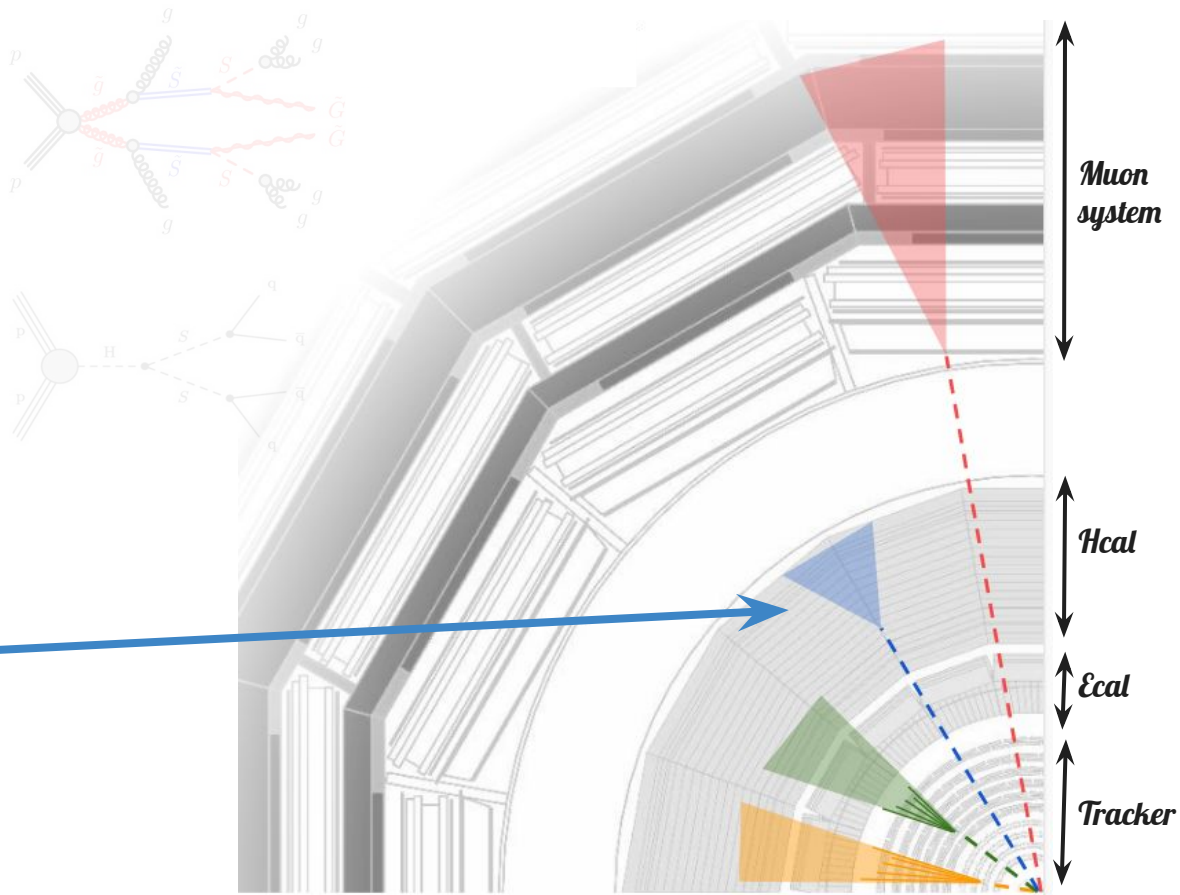
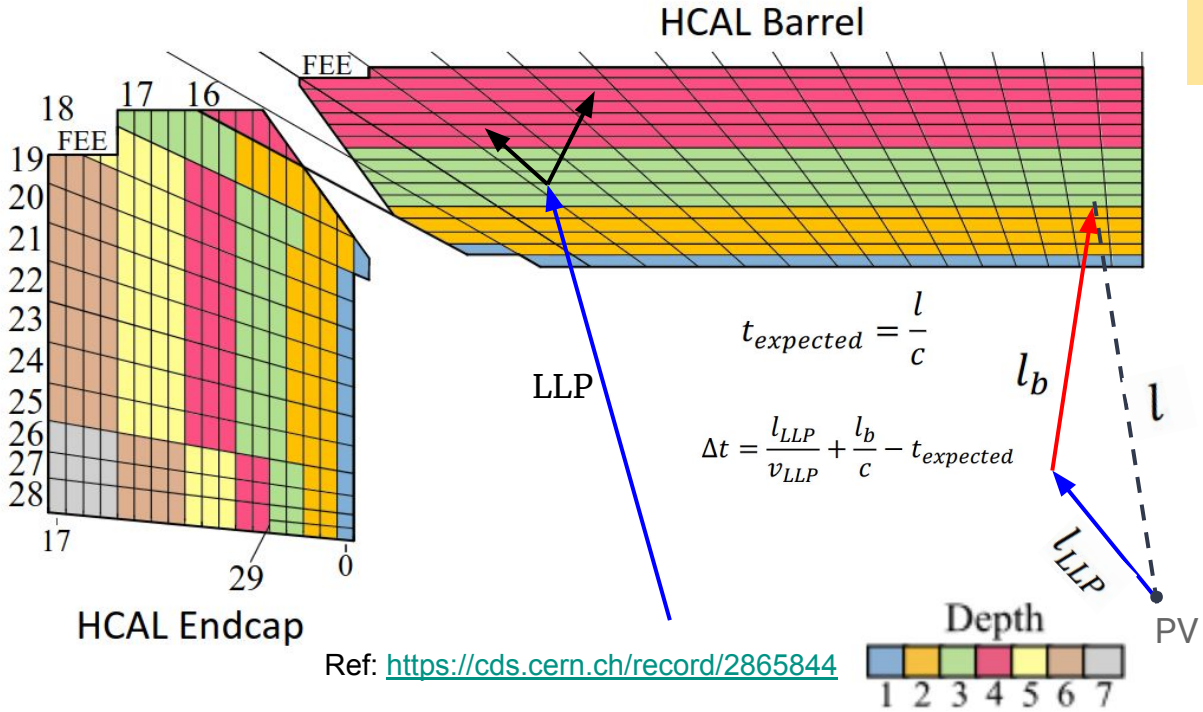


HCAL-based LLP triggers

HCAL depth segmentation + HCAL timing → excellent for LLP
Exploit these capabilities in L1 triggers (and subsequently in HLT)

2 scenarios considered @L1: Time-flagged & Depth flagged

1. **Use HCAL time information at the L1 trigger level to identify delayed jets (>6 ns). Prompt veto applied.**
2. **Trigger on minimal energy deposits in the first two layers and high energy deposits in the later layers**



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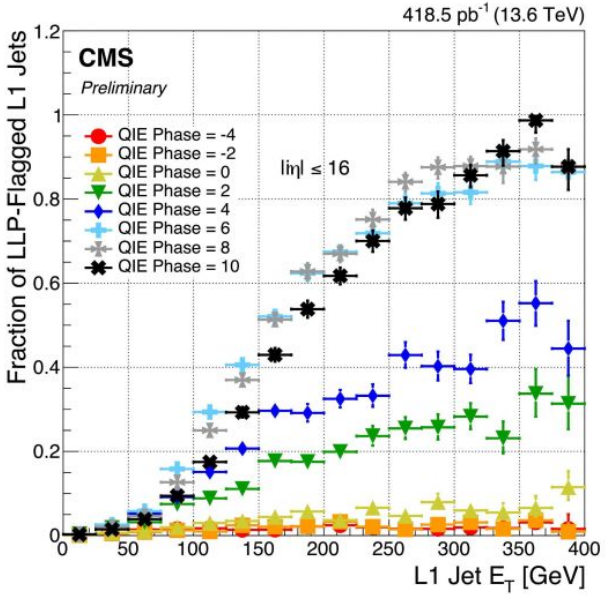

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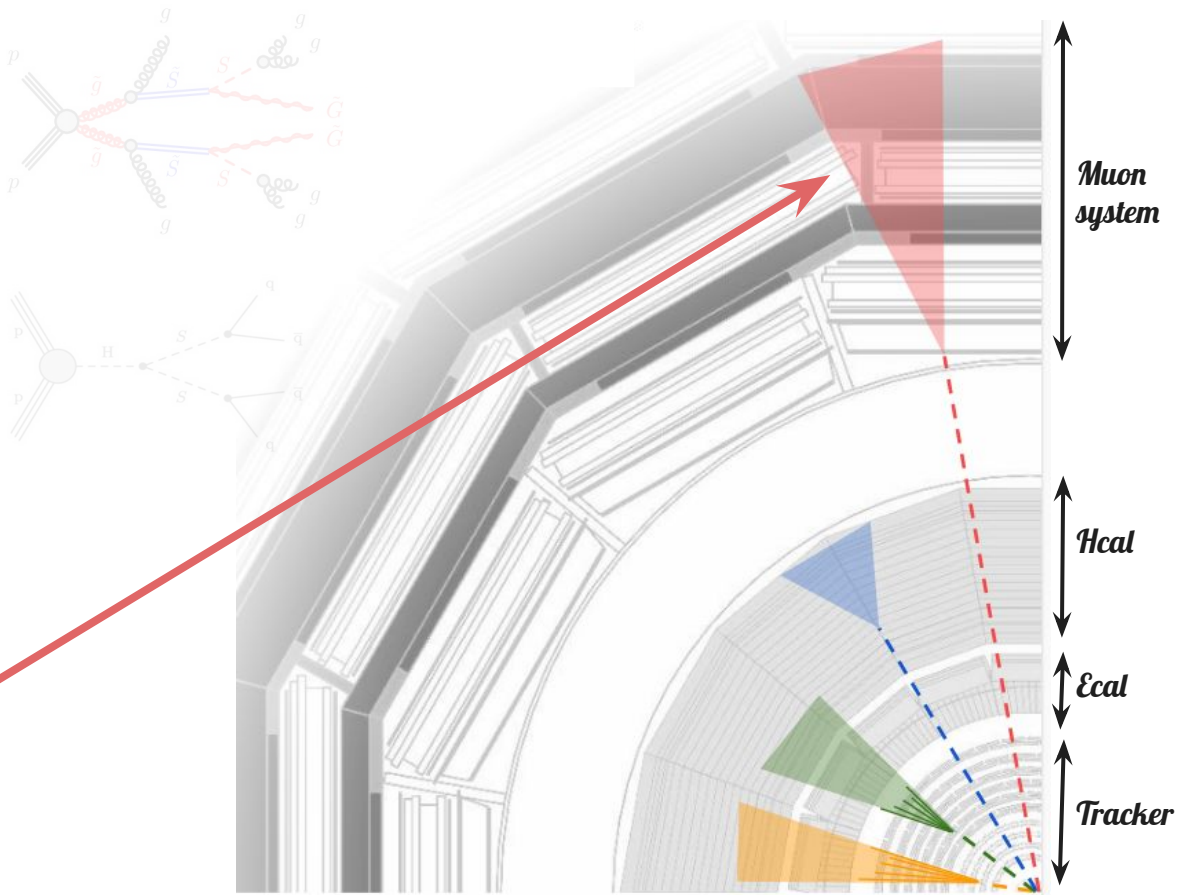
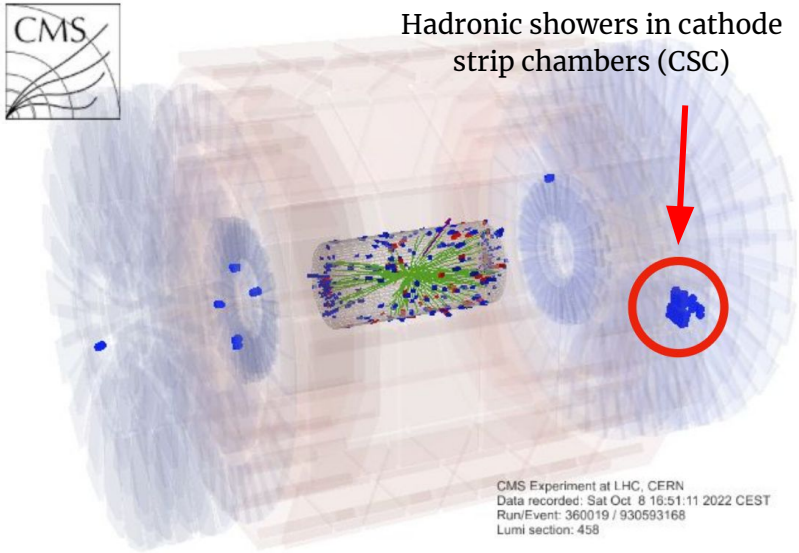


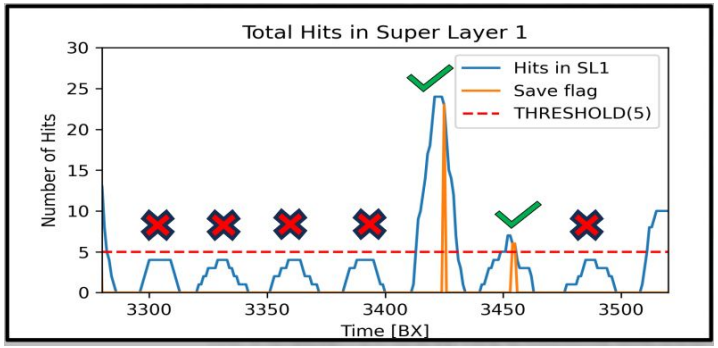
Muon system based displaced jet trigger

- Signature was studied in offline analysis already in Run2, but no dedicated trigger strategy.
- Analysis with full **Run2** data:
  - https://arxiv.org/abs/2107.04838 (endcap-only) (published in PRL)
  - https://arxiv.org/abs/2402.01898 (endcap+barrel) (submitted to PRD)
  - **Both triggered with MET.**
- In **Run3**, improved the trigger strategy (in endcaps).



L1 strategy: Count hits in a given muon chamber. Event accepted if hit multiplicity is greater than some threshold (configurable).

HLT strategy: Reconstructed hits clustered using Cambridge-Aachen (CA) algorithm. Some selections applied on cluster properties.



Ref: https://cds.cern.ch/record/2842376

Due to limited time, I could not discuss other triggers and analyses like this one:
https://cds.cern.ch/record/2868338/files/EXO-23-014-pas.pdf