CMS HIGH LEVEL TRIGGER

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ON BEHALF OF THE CMS COLLABORATION

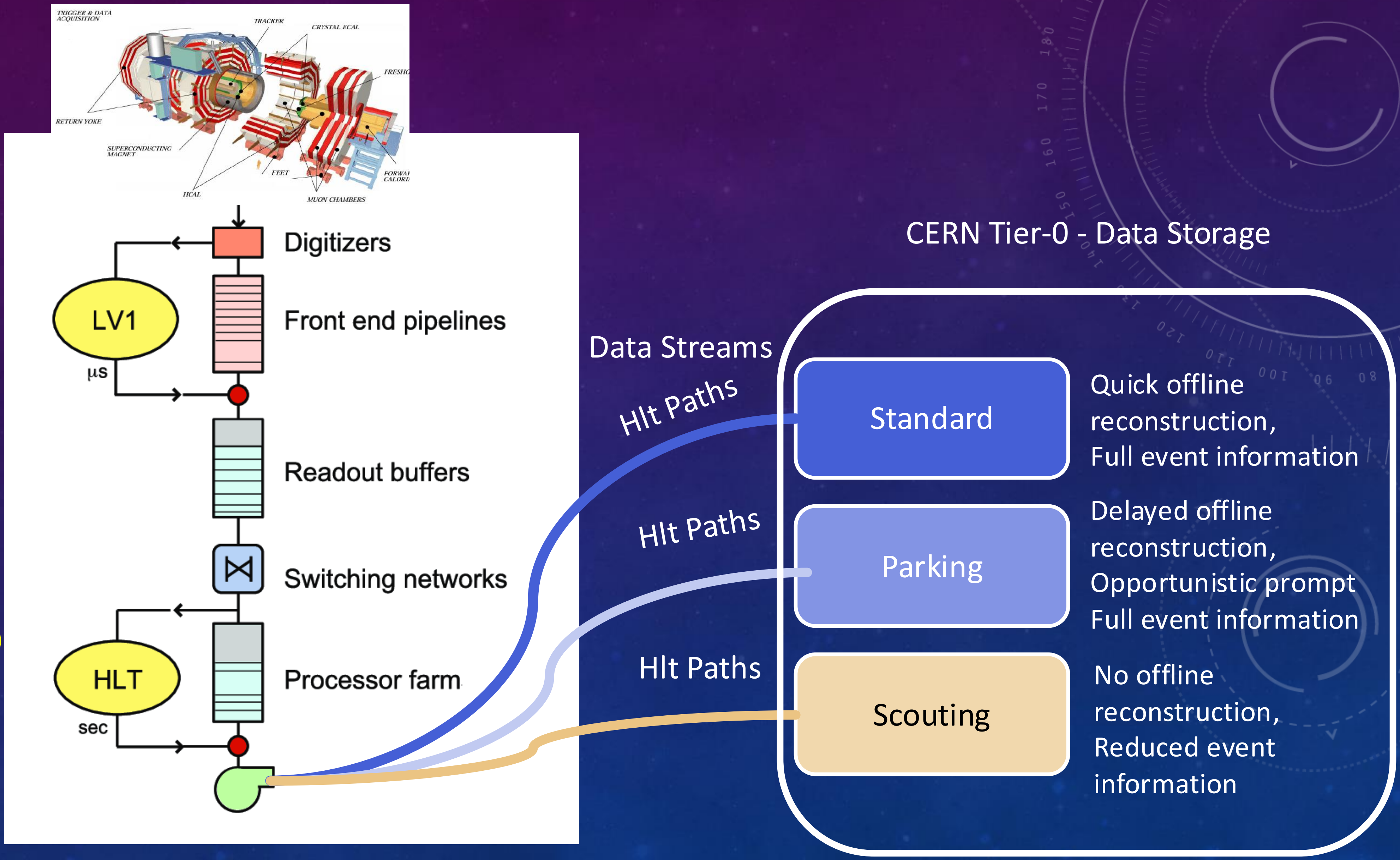
LHC DAYS IN SPLIT 2024

CMS – TWO LEVEL TRIGGERING SYSTEM

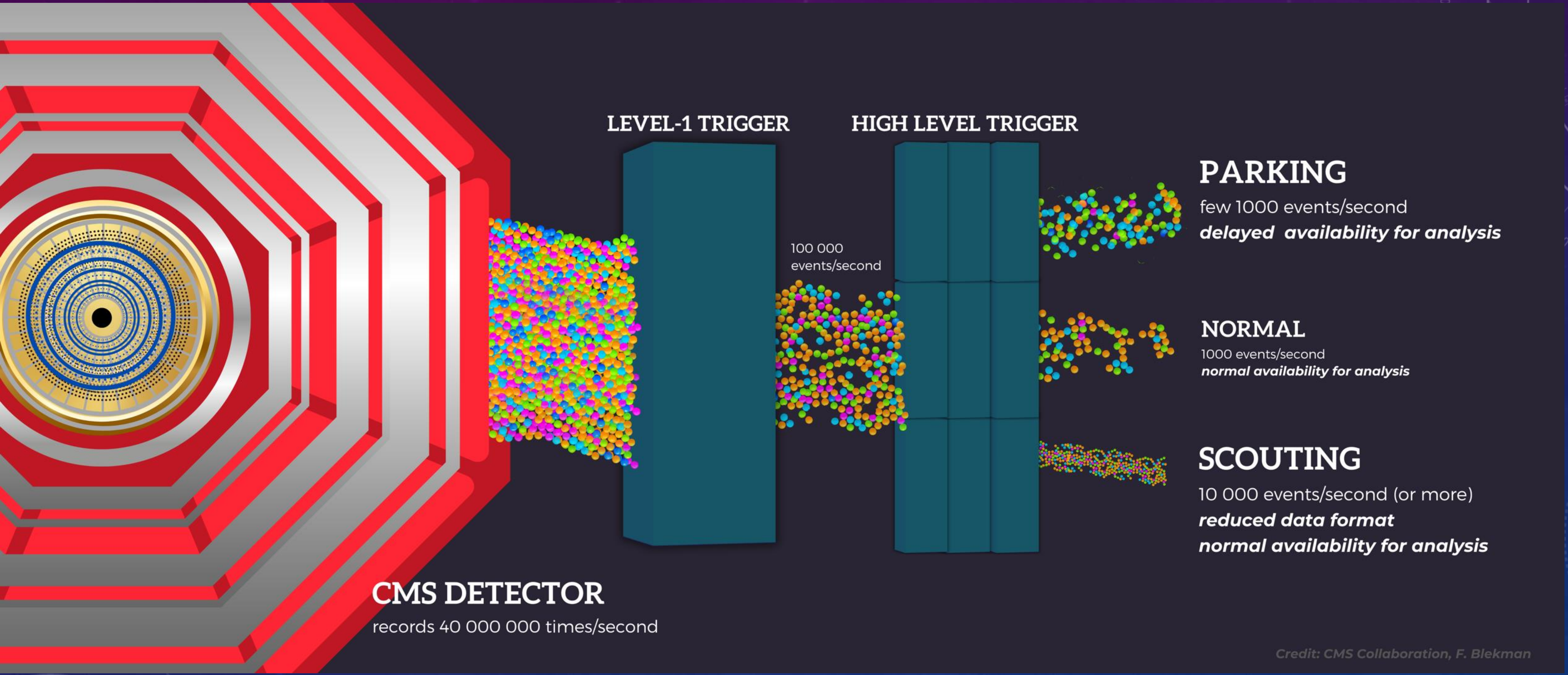
Real time event selection

<u>L1Trigger</u>
hardware-based
coarse granularity,
only muon systems
and calorimeters

<u>High Level Trigger</u>
software-based (CPU/GPU)
full granularity,
entire detector

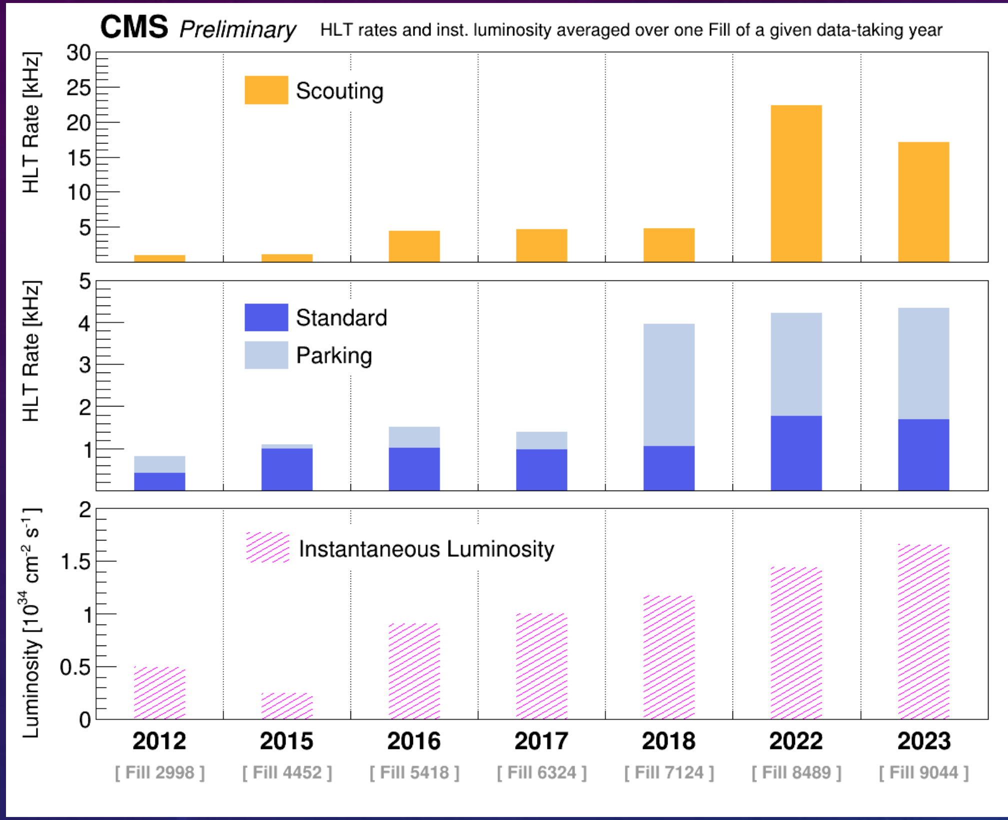


CMS TRIGGER STRATEGY – MORE PHYSICS WITH SAME DETECTOR

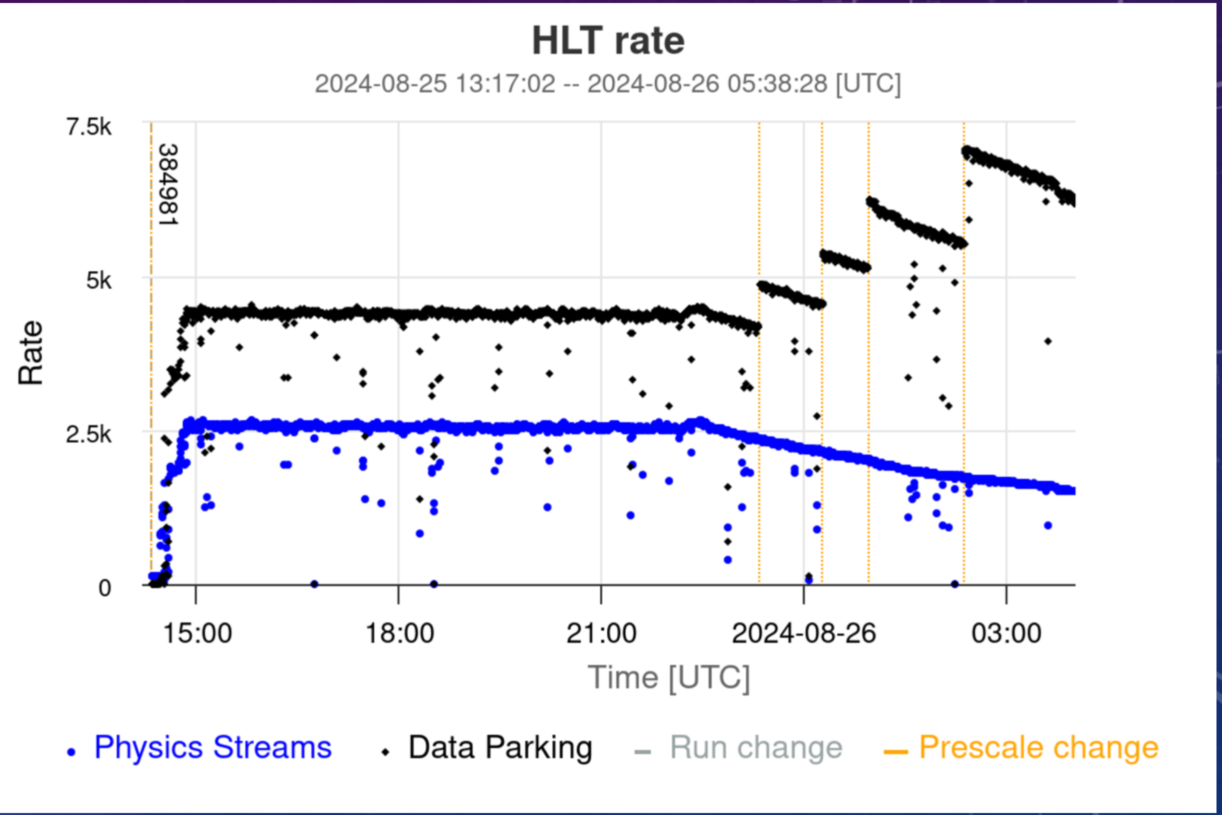


RATE OF HLT STREAMS OVER YEARS

2012-2023



2024



The standard streams follows the luminosity profile, while the parking one shows the strategy of optimizing the output bandwidth

HLT TECHNOLOGY – CPU AND GPU

- CMS HLT uses heterogeneous resources CPUs + GPUs to increase compute power
- GPUs require re-writing of HLT code and API (Alpaka)
  - Pixel, HCAL ECAL and Particle Flow reconstruction run on GPUs
- More compute power allowed CMS to:
- ○ develop more accurate object reconstruction in HLT
  - Better resolution -> lower rates and higher efficiency
- ○ Lower rates -> extend the physics program
  - Allows to running HLT scouting at much higher rate than Run 2.

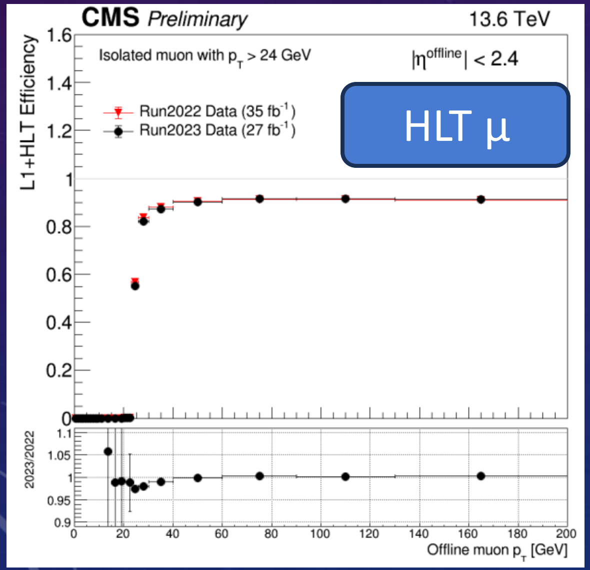
STREAM

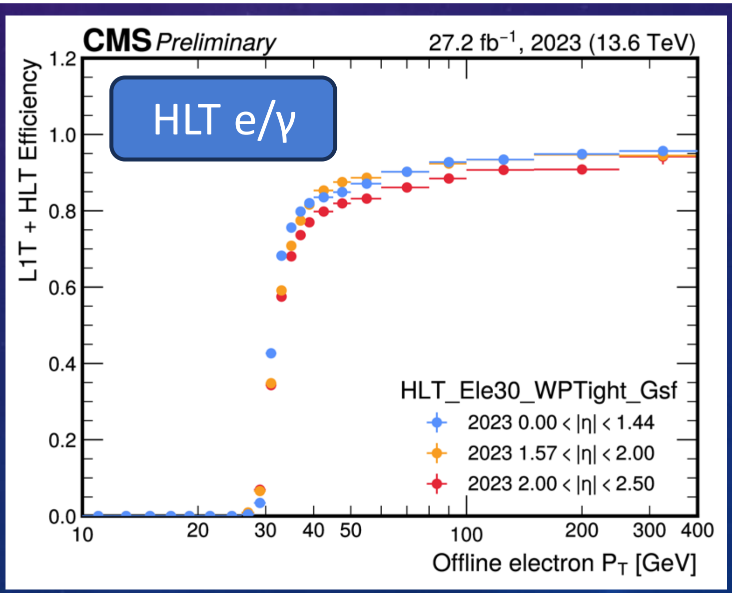
Standard

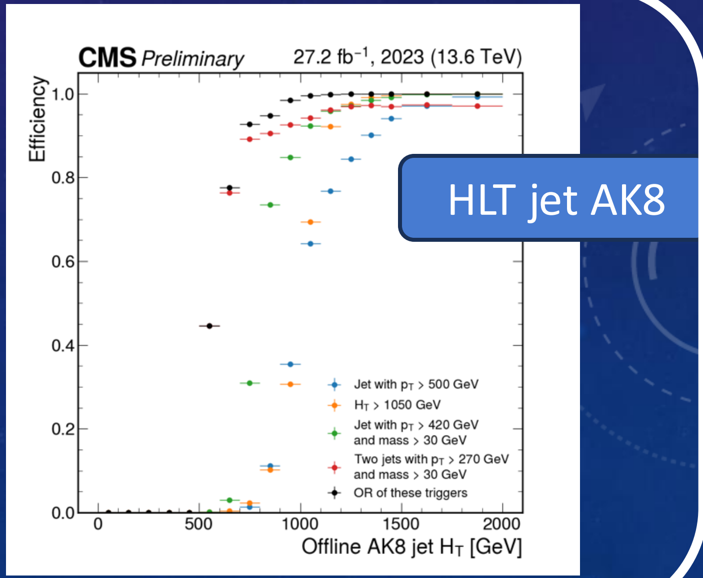
Quick offline reconstruction, full event information

- Most of HLT paths (hundreds)
- Collect data for a wide range of CMS needs (Physics program + Alignment and Calibration)
- Physics program
  - **Generic HLT paths** covering multiple physics analysis needs (broadly used, well studied, high efficiency)
  - Dedicated HLT paths for particular physics analysis that require special requirements for sufficient stats
  - Dedicated HTL paths to catch anomalies to the known physics signatures

Generic Pahts







STREAM

Parking

Delayed offline reconstruction (Opportunistically prompt)
Full event information…. no double copy of files

- For physics analysis that need special triggers with rates that don't fit in Standard stream bandwidth
- Stream content is flexible and adjusted to actual physics needs
- Current CMS priorities are signatures of LLP, di-Higgs, and VBF Higgs production, B-Physics
- Novel triggers for Run3 or standard triggers (Run2) but with lower thresholds
- Exceptionally rich B-Physics ptogram with low pT muon and electron triggers
  - Various searches for LFU violation are being considered: measuring R_{D*} , searching for LFV in tag-side

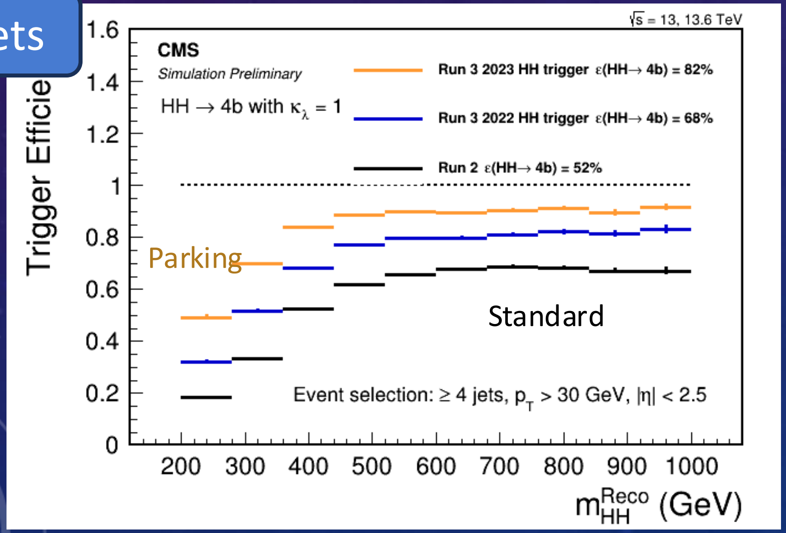
$D^0 \to \mu^+\mu^-$

$B_s^0 \to \mu^+\mu^-$

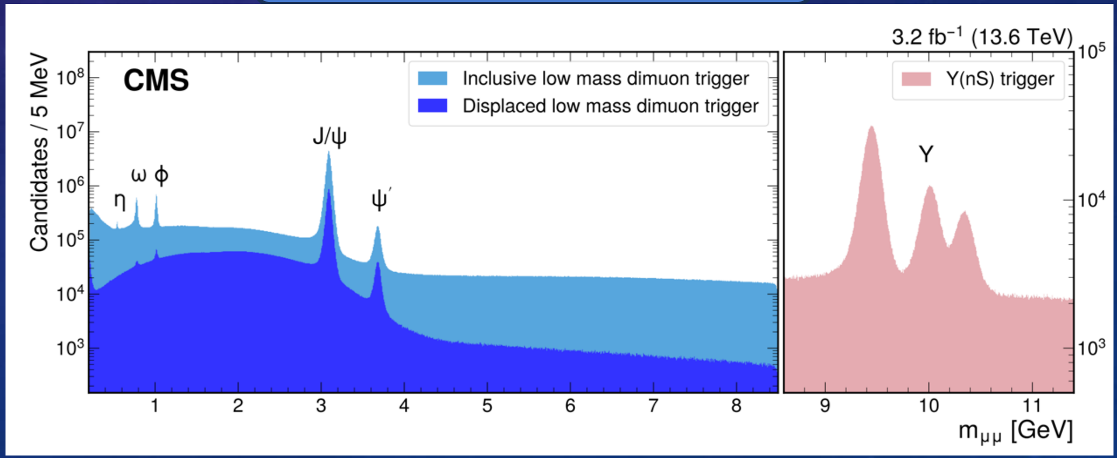
$B^0 \to J/\psi K_S^0$

$B^+ \to K^+e^+e^-$

HLT 4-jets



From B parking in 2022



mass distribution for pairs of μ's oppositely charged,
 originating from a common vertex (inclusive & displaced).
Imporoved L1 (Kalman) and HLT (GPUs)

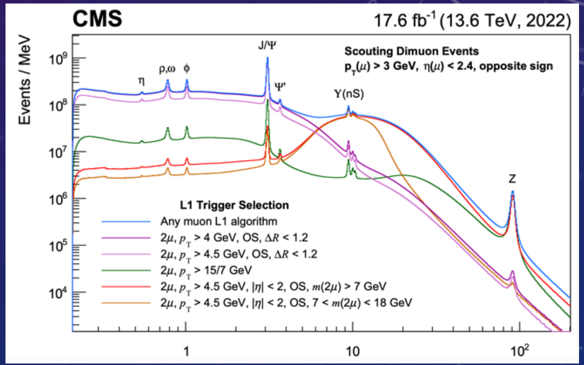
STREAM

Scouting

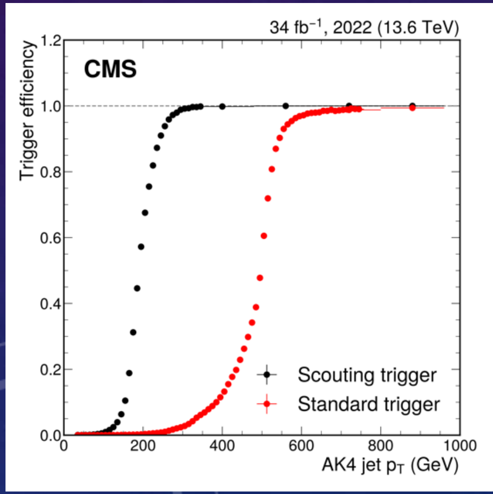
No offline reconstruction, Reduced event information

- Improvements in HLT reconstruction (use of GPUs) allowed for improved scouting strategy in Run3
  - PF algorithm w/ tracker tracks built solely with pixel hits
  - offloaded to GPUs) only slightly worse resolution for low-pT (Scouting)
  - Run 3 scouting rate > 20 kHz

Scouting path	CPU-only [ms]	CPU+GPU [ms]
1 electron/photon	76.0	49.5
≥2 electrons/photons	9.3	6.8
≥2 muons	69.0	41.6
Jets or MET	83.3	52.1
Full HLT menu	578.4	377.7



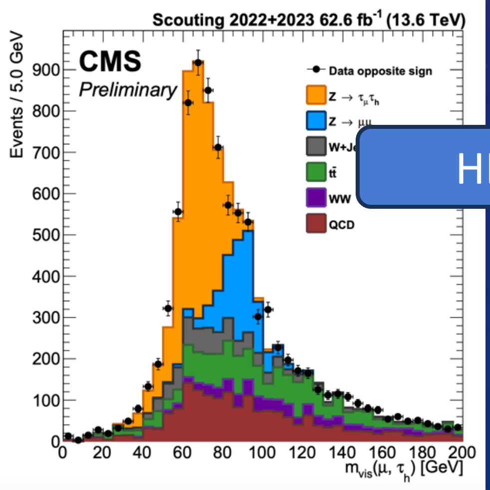
- Essential in searches for very low-mass resonaces.
  - also for LLP searches (with LLP decaying to muons, ex. Dark photon).
- B-physics analyses (first observation of η meson -> 4 μ)



HLT Jet AK-4

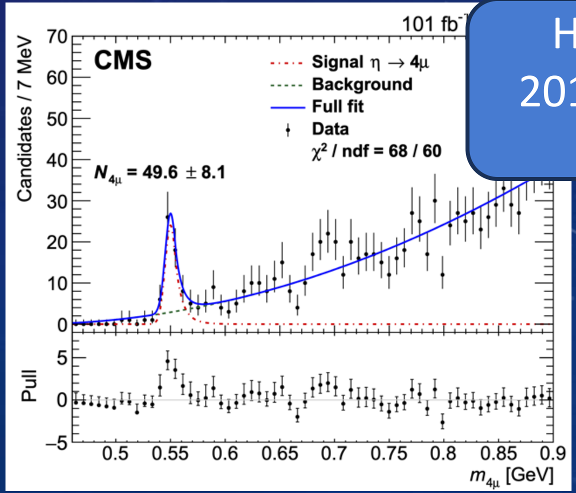
Much lower hadronic trigger thresholds than standard strategy relying on offline reconstructed data

Scouting HLT Jet p_T > **180 GeV**
Main stream HLT Jet p_T > **500 GeV**



HLT τ_h

$Z \to \tau_\mu \tau_h$ mass

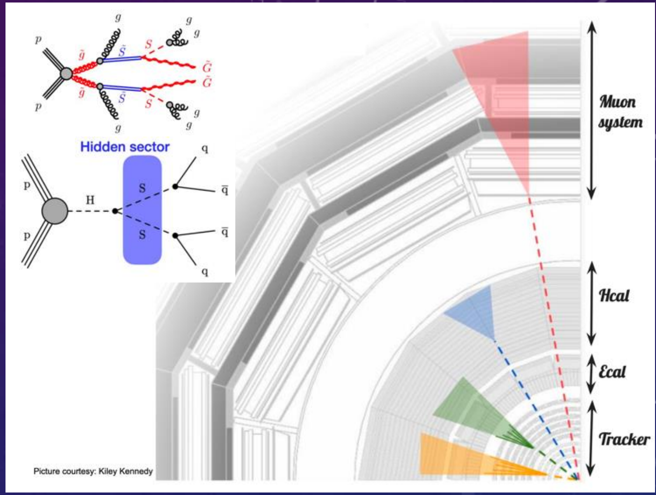


HLT 2 μ 2017-2018

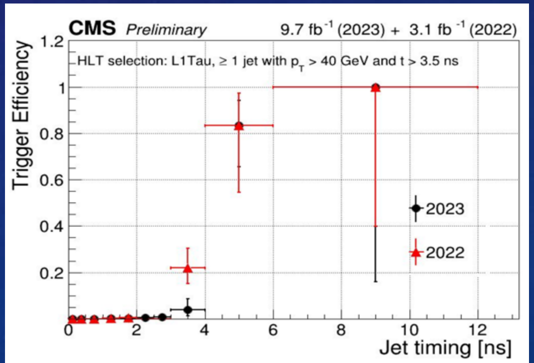
η-> 4 μ mass

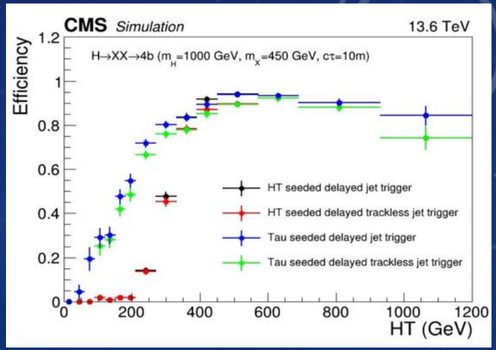
TRIGGERING ON LONG-LIVED-PARTICLES (LLP)

- Run 3 – look for new physics. Eg. LLP.
- Several **displaced-jet HLT triggers** to capture various detector signatures, depending of LLP's lifetime (decay length).

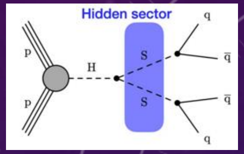


- Tracker-based – Reconstruct objects with **non-prompt tracker-tracks**
  seed L1 H_T > 450 GeV (or Use L1 H_T > 240 GeV + μ)
  HLT jets reconstructed with displaced tracks (prompt veto) Run3 result limits public EXO-23-013
- ECAL-based - Exploit timing of **ECAL that measures arrival within ~200 ps**
  seed L1 HT>430 GeV or (L1 Tau pT>120 GeV and HT>360 GeV)
  HLT jets (nominal track match to ECAL, or ECAL only) w/ timing > 2 ns
- HCAL-based
- Muon system-based



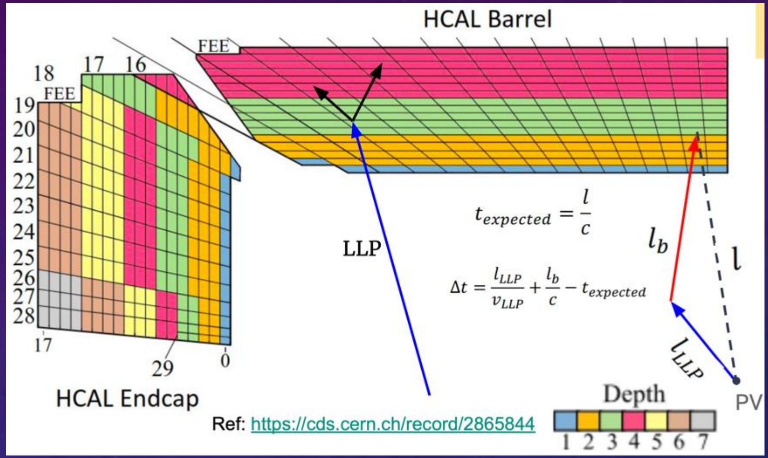


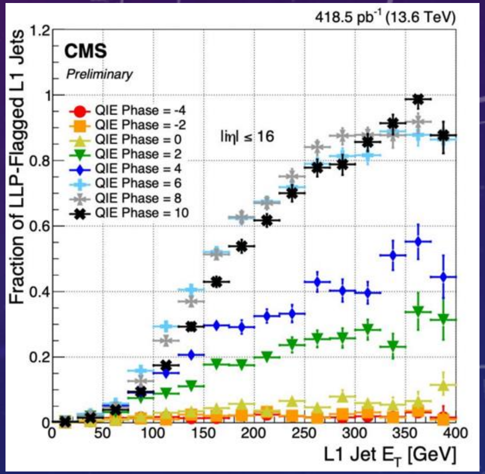
TRIGGERING ON LONG-LIVED-PARTICLES (LLP)



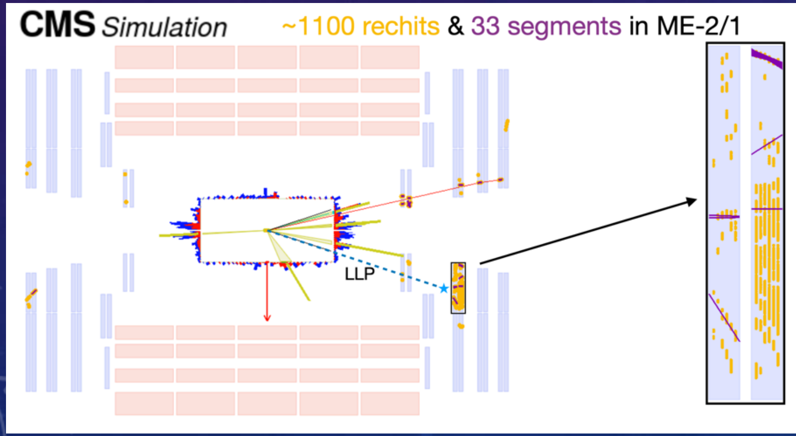
- Several **displaced-jet HLT triggers**

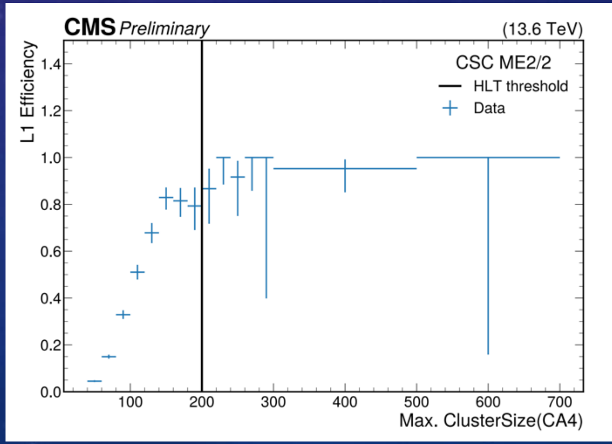
- HCAL-based exploit HCAL depth segmentation + timing
  seed L1 jets with HCAL depth or time – flagged (> 6 ns)
  HLT jets with minimal energy deposit in first 2 layers
  + high energy deposits in later layers





- Muon system-based exploit hit counting capability of muon chambers
  seed L1 a cluster of hits in a given muon chamber. Accept if multiplicity is greater than some threshold.
  HLT reconstructed hits clustered using Cambridge-Aachen (CA) algorithm. Ref: https://cds.cern.ch/record/2842376





OTHER LLP TRIGGERS

- Displaced Dimuons.
  - For SUSY particles can have signatures of decays to SM particles at macroscopic distances from the proton-proton interaction point.
  - Trigger Strategy

    Use L1 (Kalman filter) and HLT reconstruction algorithms for non-prompt muon tracks. Apply d0 veto.
    HLT trigger on pair displaced muon tracks, oppositely charged, from same secondary vertex.
    Public results available EXO-23-014

- Out of Time Objects
  - LLP objects could be stopped inside of CMS and decay at some later time.
  - Trigger strategy

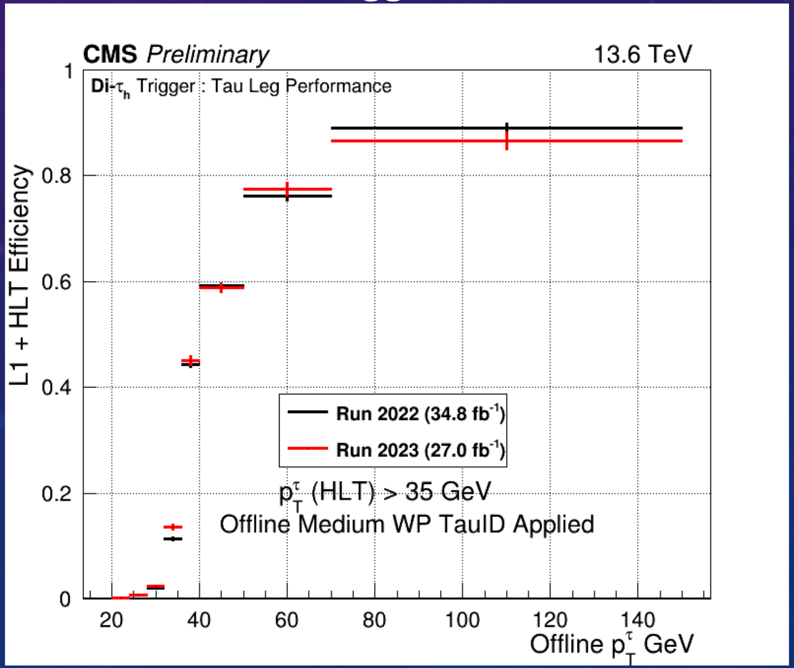
    Look for decay particles in **empty (non colliding) BX**

- Displaced Photons
  - Trigger strategy

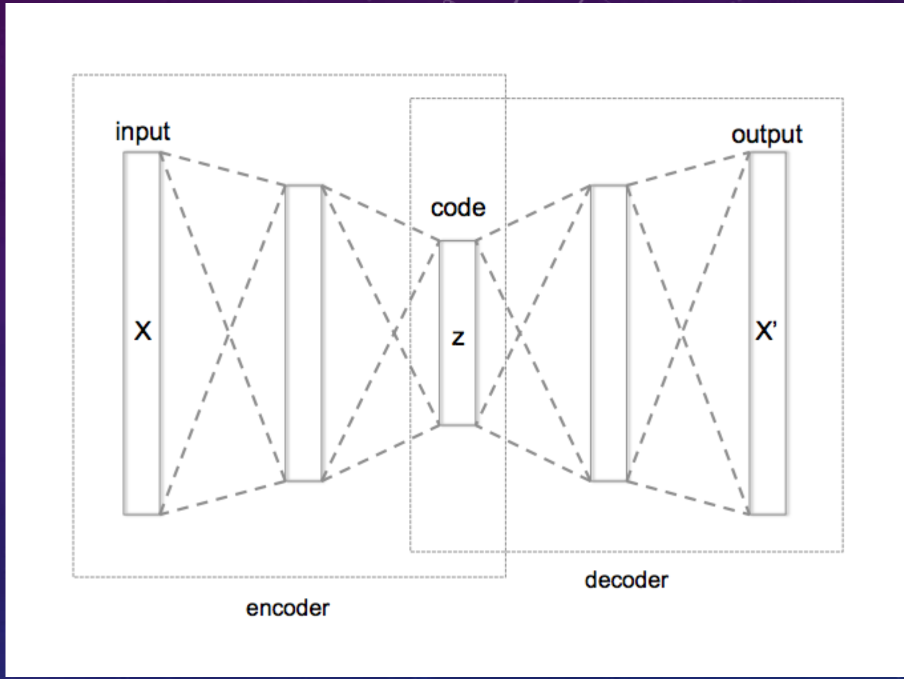
    Use objects with ECAL timing

MACHINE LEARNING IN HLT

- Machine Learning is heavily used in CMS HLT object reconstruction and Identification.
- Seed of L1T jet
- HLT Tau:
    - Reconstruction: Hadron plus strip
        - target hadronic decays of taus by aligning calo deposits in strips (from Π^0)
    - Identification with Neural Network :CNN + DNN based tagger



MACHINE LEARNING IN L1/HLT

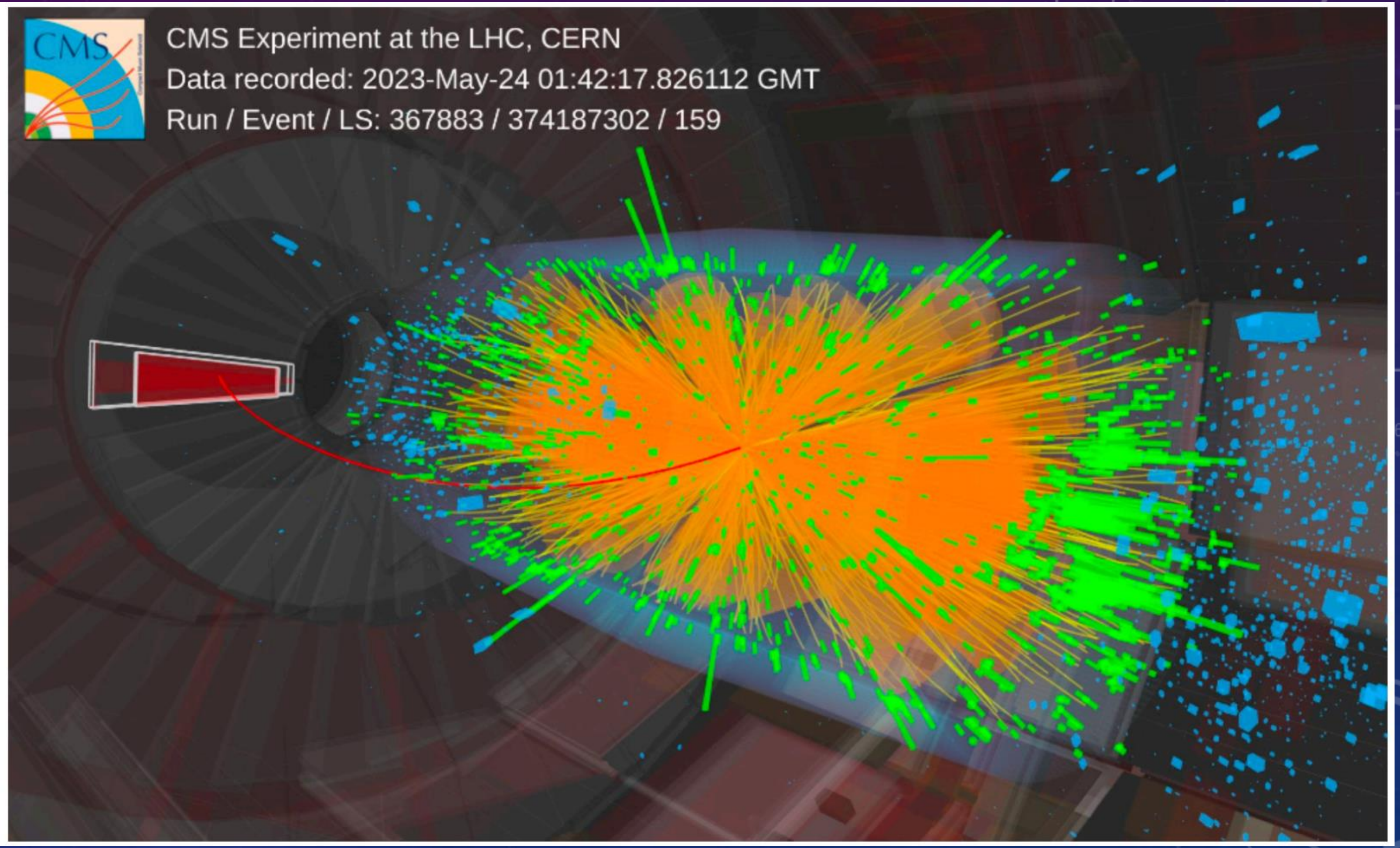


- Machine Learning is heavily used in CMS HLT object reconstruction

- Novel approaches for ML
  - Look for unknown, different from everything known, and detect anomaly
  - Make ML algo learn signatures of typical of SM processes
  - Identify events that are not typical, using Autoencoder (AE)
  - Measure the size of anomaly via Reconstruction Error (Loss)
  - Use this already at L1T
    - AXOL1TL – Anomaly eXtraction Online Level-1 Trigger Algorithm
      - Inputs: PT, η, ϕ of Jets(x10) , e/γ (x4), μ (x4), and MET (from Calo layer-2 and Global Muon Trigger)
    - CICADA – Calorimeter Image Convolutional Anomaly Detection
      - Input image of Calorimeter deposits of energy in η-ϕ plane

MACHINE LEARNING IN L1/HLT

- Example of CMS event selected by AXOL1TA not selected by any other CMS trigger
- Features at L1T
  - 12 jets, 11 w/ p_T >20 GeV
  - 1 μ, p_T > 3 GeV
  - Large number of primary vertices (75)



THANK YOU

THANK YOU

BACK-UP

CMS HLT FOR HL-LHC (RUN4-6)

CMS detector	LHC Run-2	HL-LHC Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size	2.0 MB [a]	5.7 MB [b]	7.4 MB
Event Network throughput	1.6 Tb/s	23 Tb/s	44 Tb/s
Event Network buffer (60 seconds)	12 TB	171 TB	333 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power [c]	0.5 MHS06	4.5 MHS06	9.2 MHS06
Storage throughput	2.5 GB/s	31 GB/s	61 GB/s
Storage capacity needed (1 day)	0.2 PB	2.7 PB	5.3 PB