Anomaly Detection in the CMS L1 Trigger with AXOL1TL

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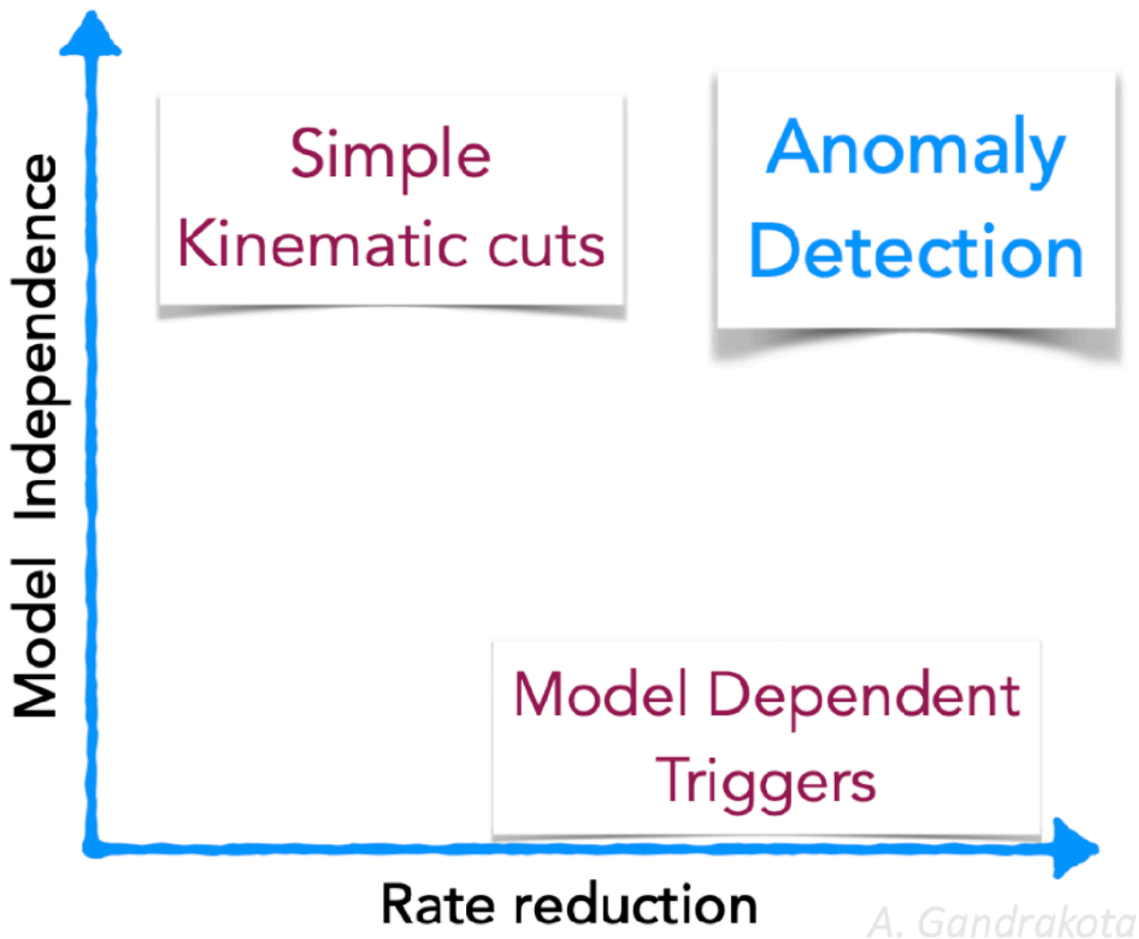
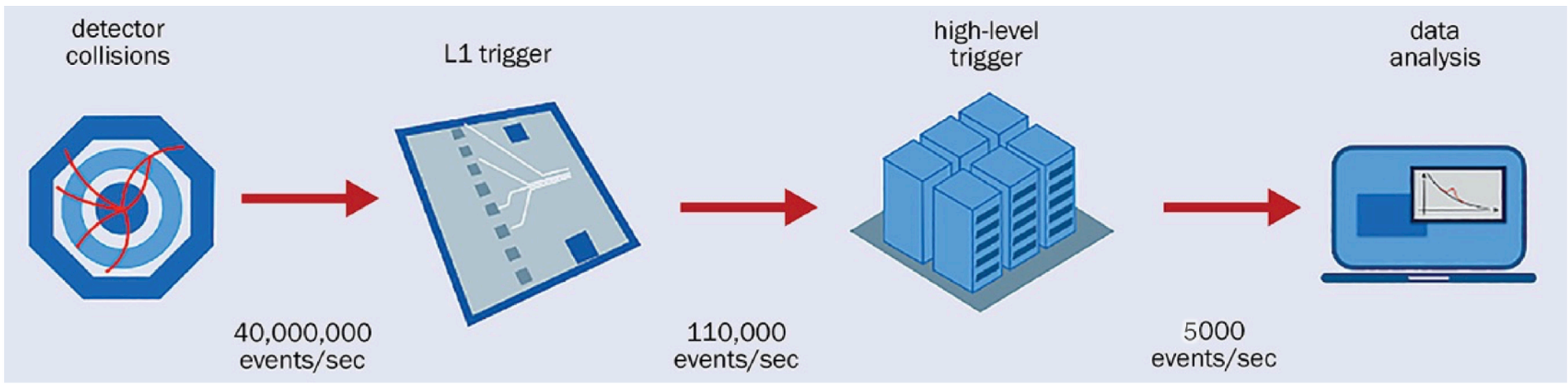
**UC San Diego*

CMS Level-1 Trigger

- L1 trigger rejects >99% of LHC events
  - Constrained by low latency of 4 μs and low resource utilization on FPGAs
- What if we are missing new physics because we did not design a suitable trigger?
- → Anomaly detection in L1





Autoencoders for Anomaly Detection

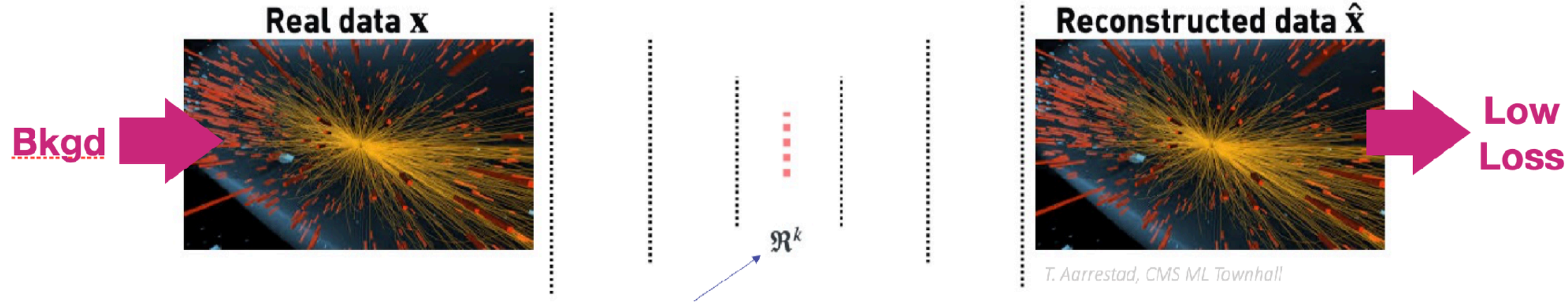
- Unsupervised ML learns efficient encodings of backgrounds

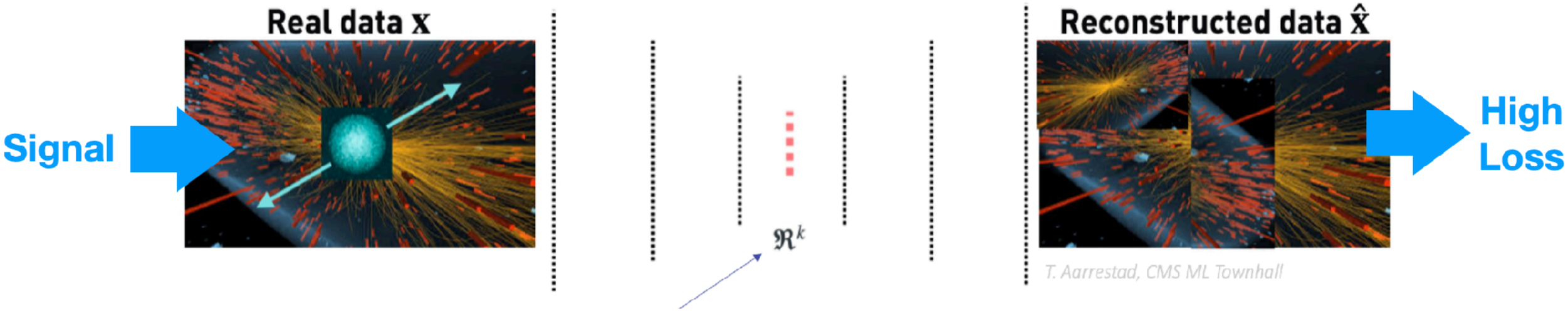
Train on ZeroBias LHC data

Bottleneck: autoencoder learns to compress high dimensional inputs into low dimensional latent space

$$\text{Loss} = ||x - \hat{x}||^2$$

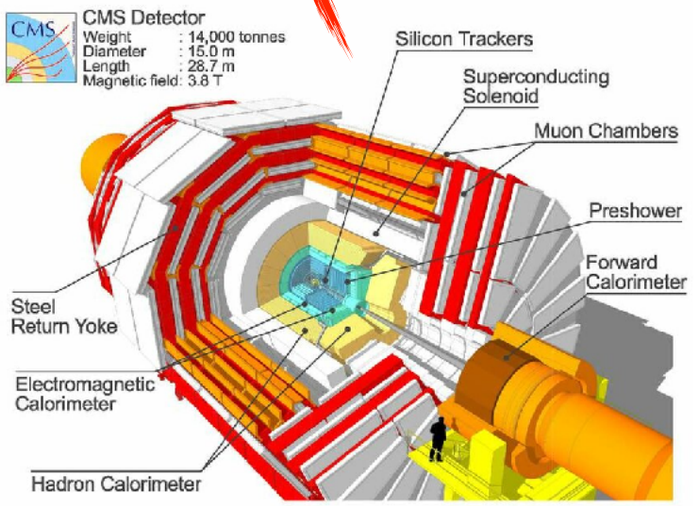
Reconstruction loss

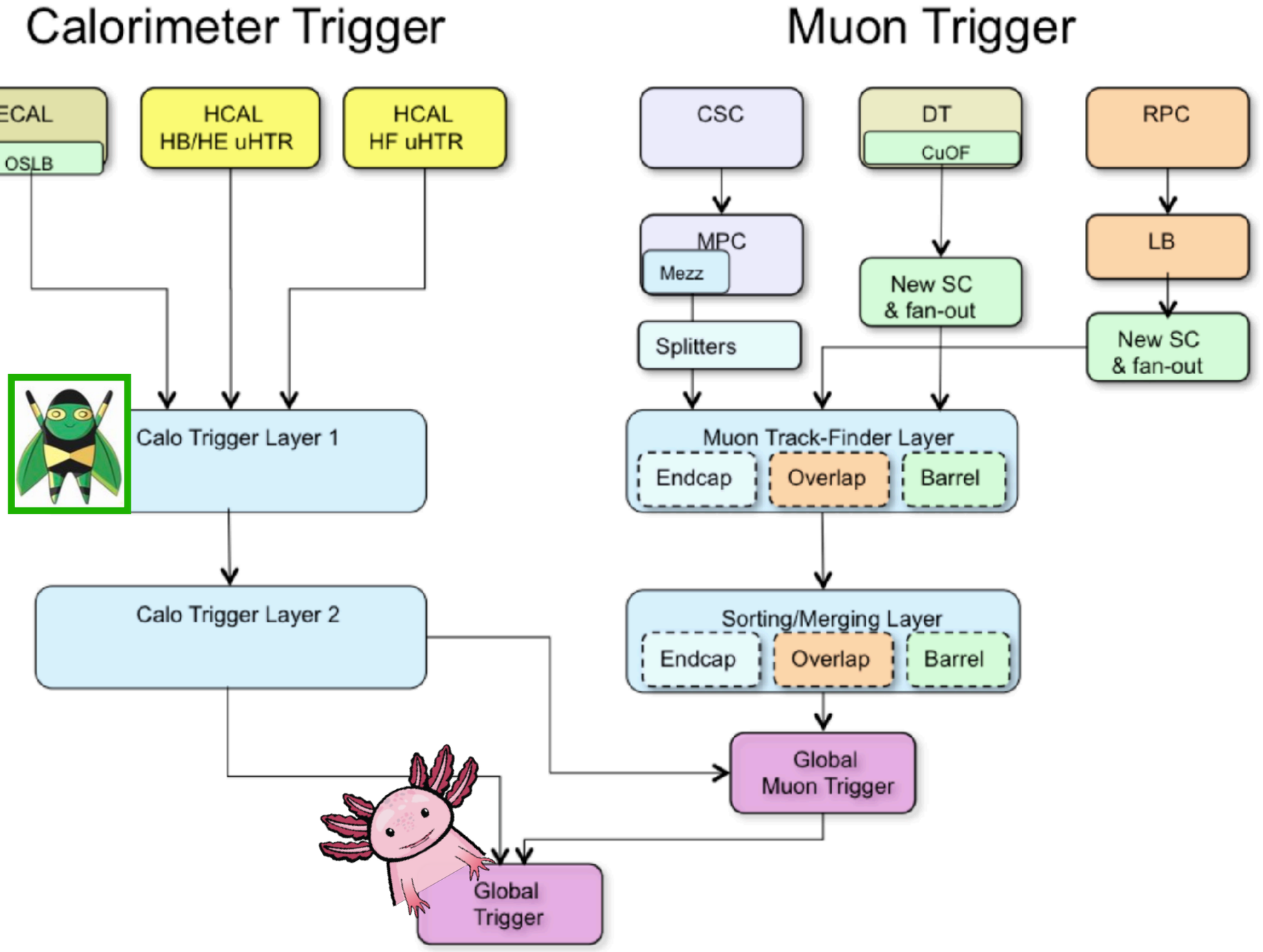




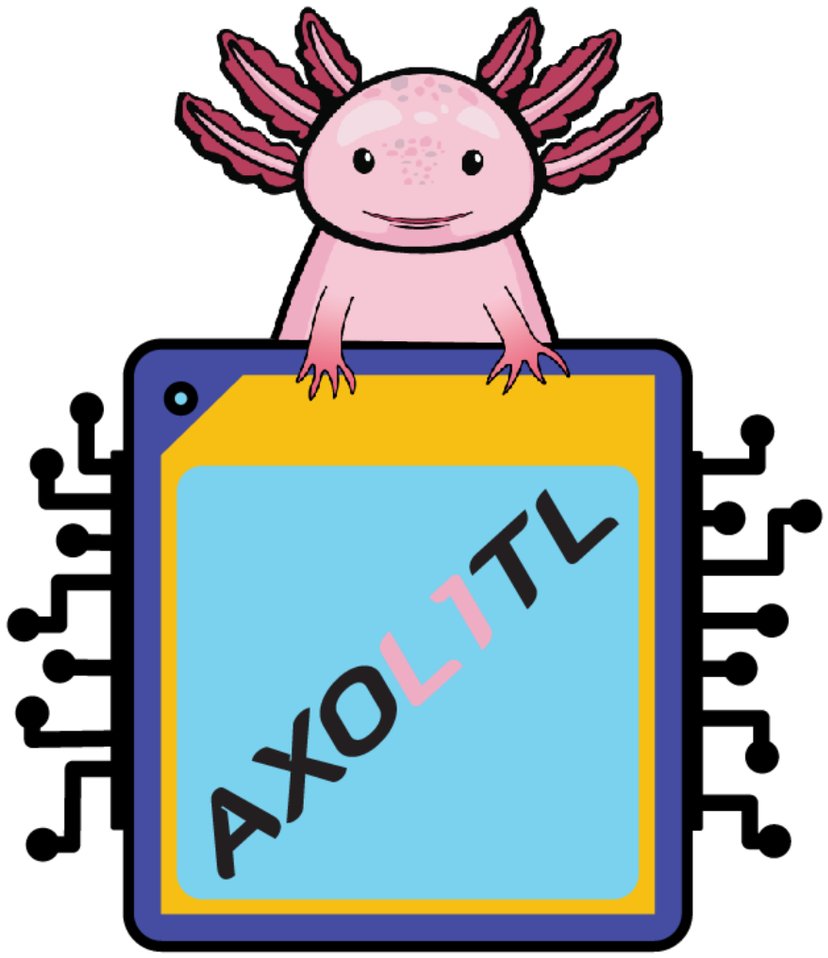
Current L1 Trigger Structure

- AXOL1TL+CICADA: autoencoder-based anomaly detection in L1 Trigger





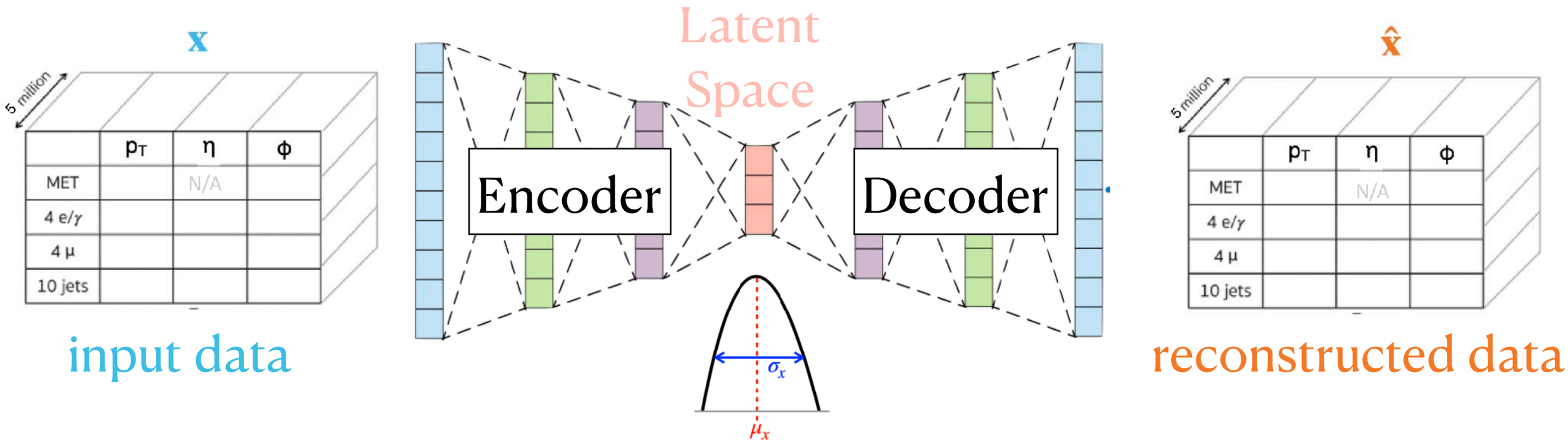
AXOL1TL



- "**A**nomaly e**X**traction **O**nline **L1** **T**rigger **L**ightweight" → Anomaly detection at CMS L1 Global Trigger
  - Unsupervised variational autoencoder trained on ZeroBias data
  - Trained using L1 global trigger input objects
  - Deployed for 2024 data taking
    - → focus of this talk

AXOL1TL Design

- **Inputs L1 trigger objects**: (pT, η, ϕ) of MET, 4 electron/photons, 4 muons, 10 jets
- **Train on ZeroBias data** collected by CMS in 2023/2024
- **Variational autoencoder**: Additional KL-divergence loss term regularizes latent space to be normal gaussian ($N(\mu_x, \sigma_x) \rightarrow N(0,1)$) to prevent overfitting



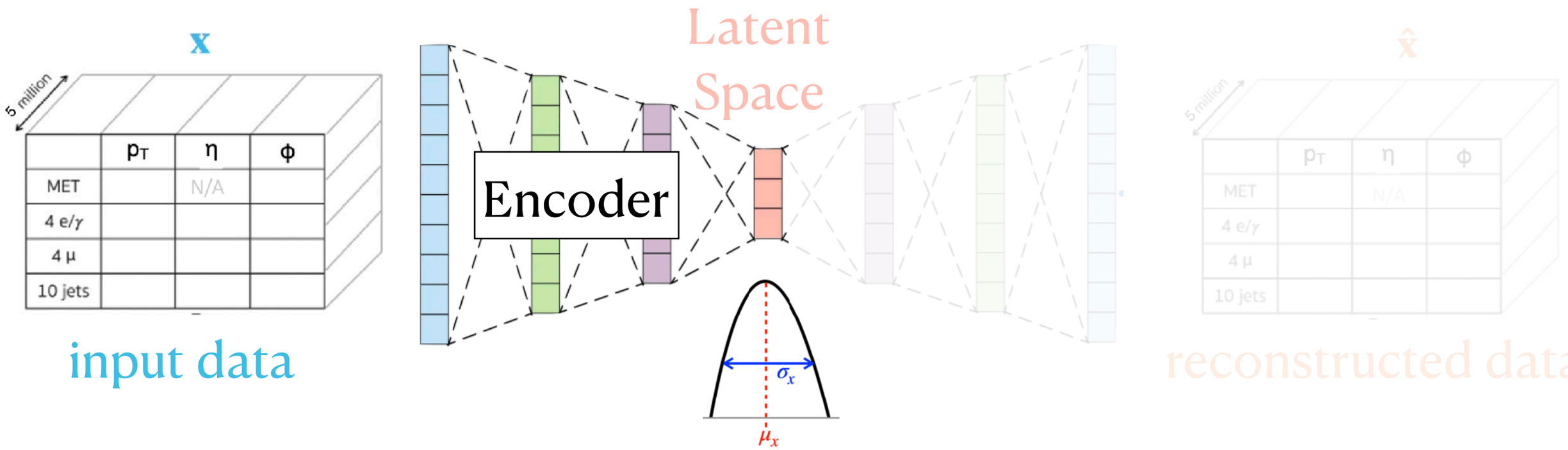
$$\text{Loss} = ||x - \hat{x}||^2 + \text{KL}[N(\mu_x, \sigma_x) \rightarrow N(0,1)]$$

Reconstruction loss

Full regularization term (Kullback–Leibler divergence)

AXOL1TL Design

- **Only deploy encoder half of the network**, compute degree of abnormality from latent space directly → **Halves the network size and latency!**
- Small, fully connected network architecture
  - **Satisfies strict μGT requirements**: latency of 4 μs, low resource utilization



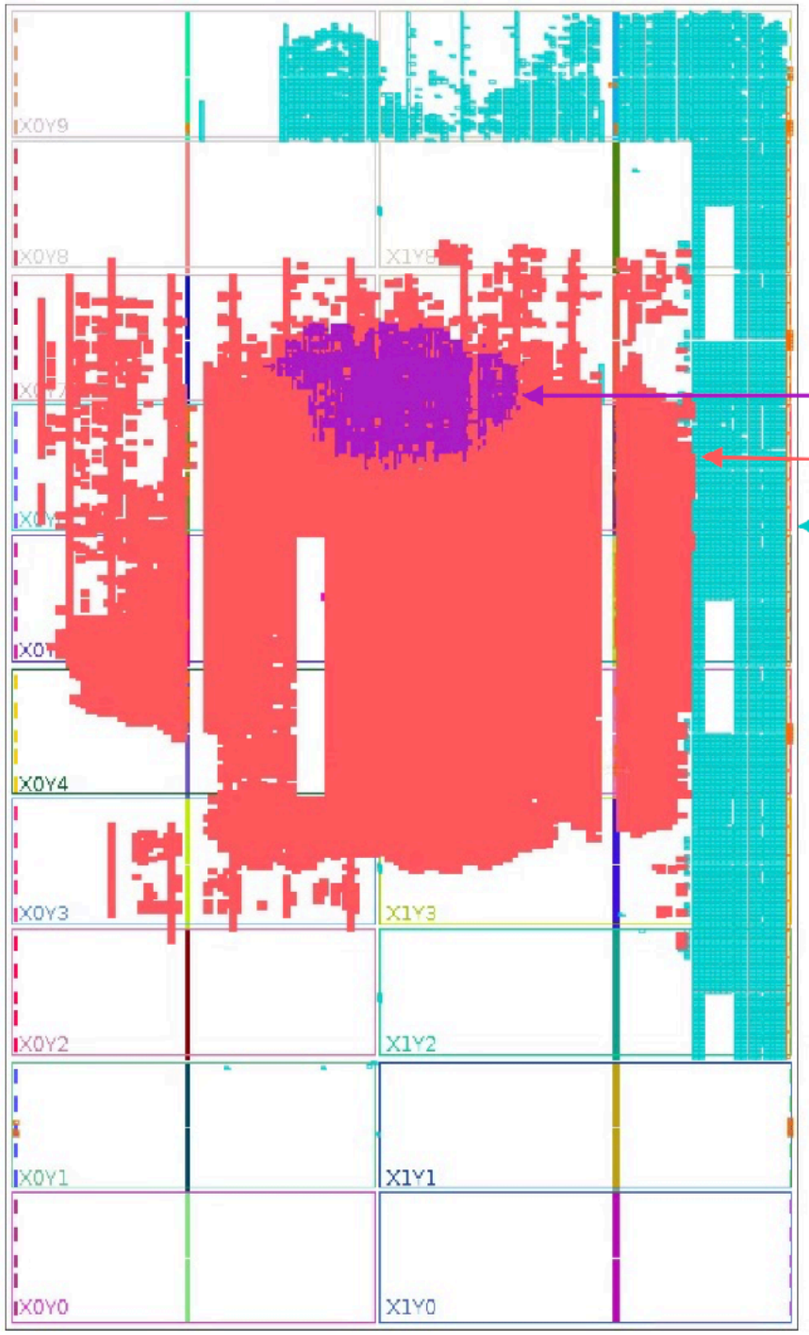
Loss = [... N(0,1)]

Anomaly Score ~ $\Sigma\mu_x^2$

Re... term

(Kullback–Leibler divergence)

AXOL1TL Implementation

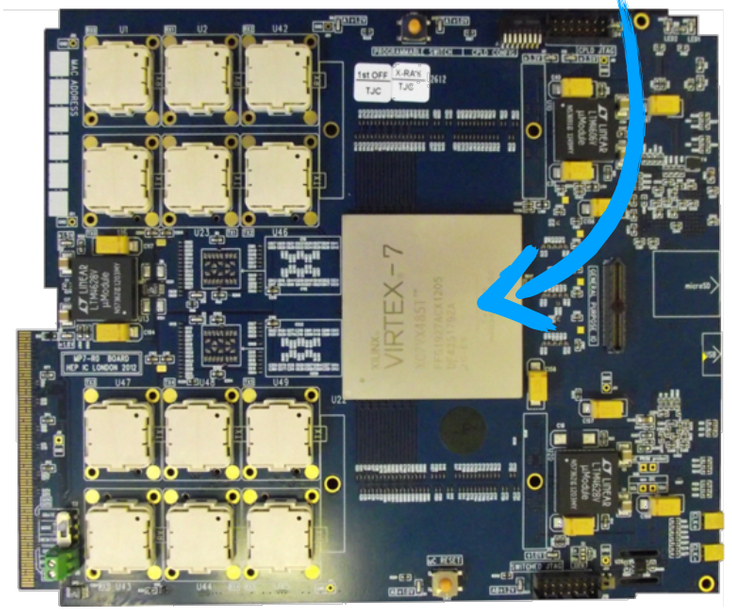


AXOL1TL

MP7 payload

MP7 infrastructure

Xilinx Virtex-7 FPGA on MP7 board used at Level-1 Global Trigger



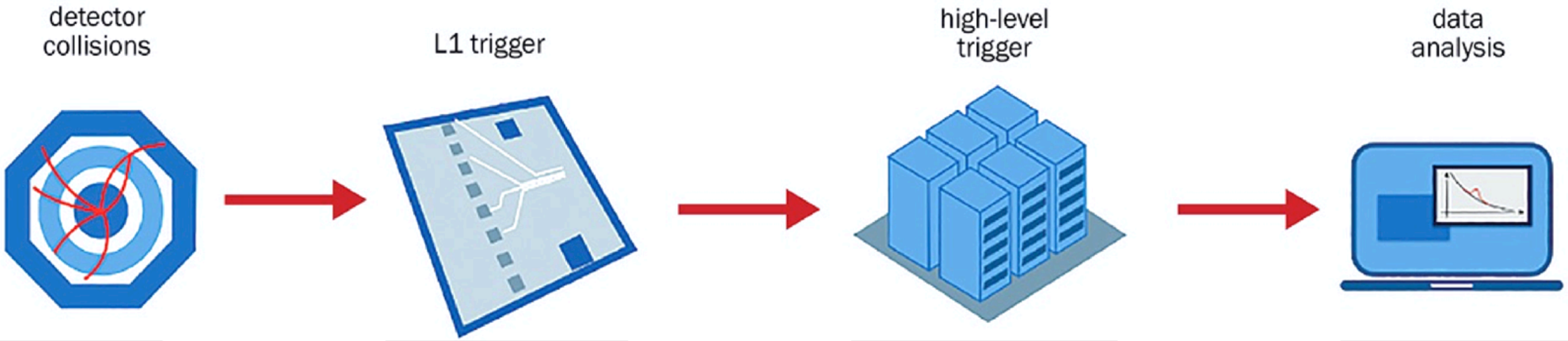
- Implemented on L1 FPGAs
- **Satisfies strict μGT requirements**: latency of 4 μs, low resource utilization on FPGAs

Resource utilization of Virtex-7 FPGA chip on Imperial College MP7 µGT board

	Latency	LUTs	FFs	DSPs	BRAMs
AXOL1TL	2 ticks 50 ns	2.1%	~0	0	0

hls 4 ml

AXOL1TL Trigger Strategy



L1_AXO_VLoose 1000 Hz → **Masked (monitoring)**

L1_AXO_Loose 400 Hz → **Masked (monitoring)**

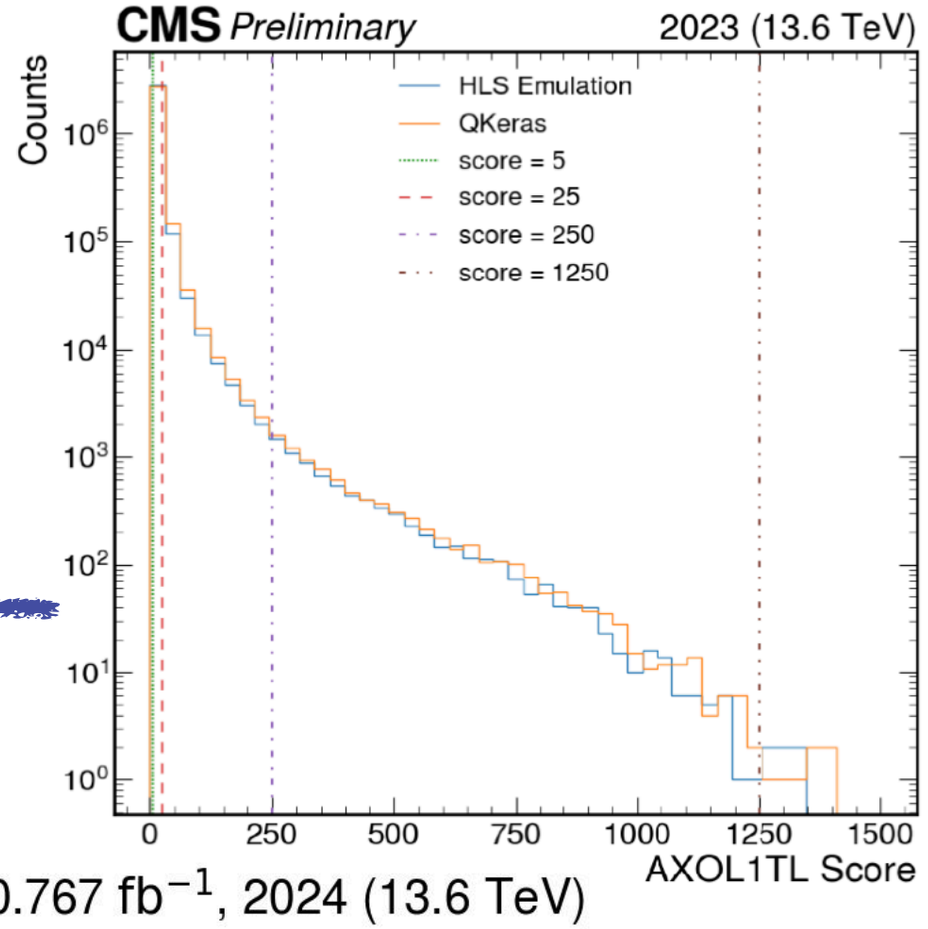
L1_AXO_Nominal 200 Hz → **Passthrough (scouting)** → **HLT Scouting (reduced event content)**

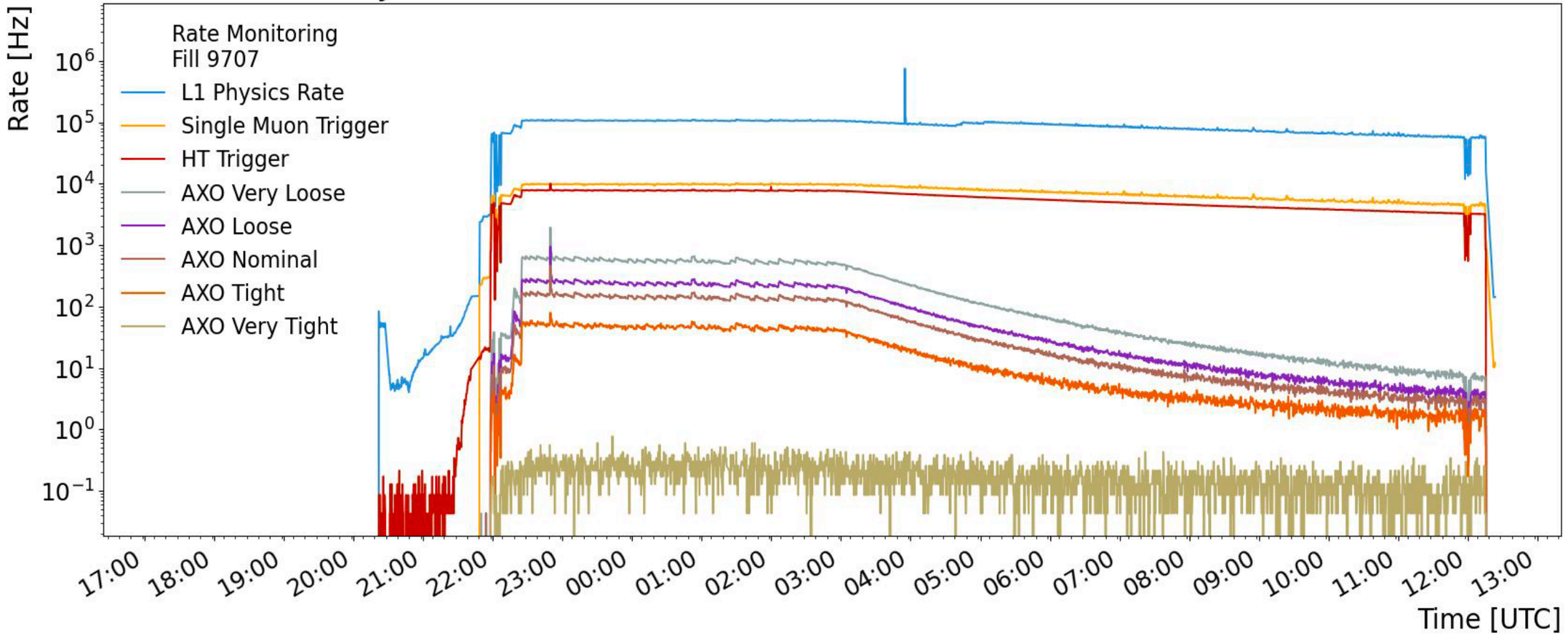
L1_AXO_Tight 100 Hz → **Passthrough (scouting)**

L1_AXO_VTight 10 Hz → **Passthrough (Prompt)** → **Offline reconstruction (full event content)**

AXOL1TL Implementation

- Score thresholds target different trigger rates
- Rates stable relative to other L1 triggers

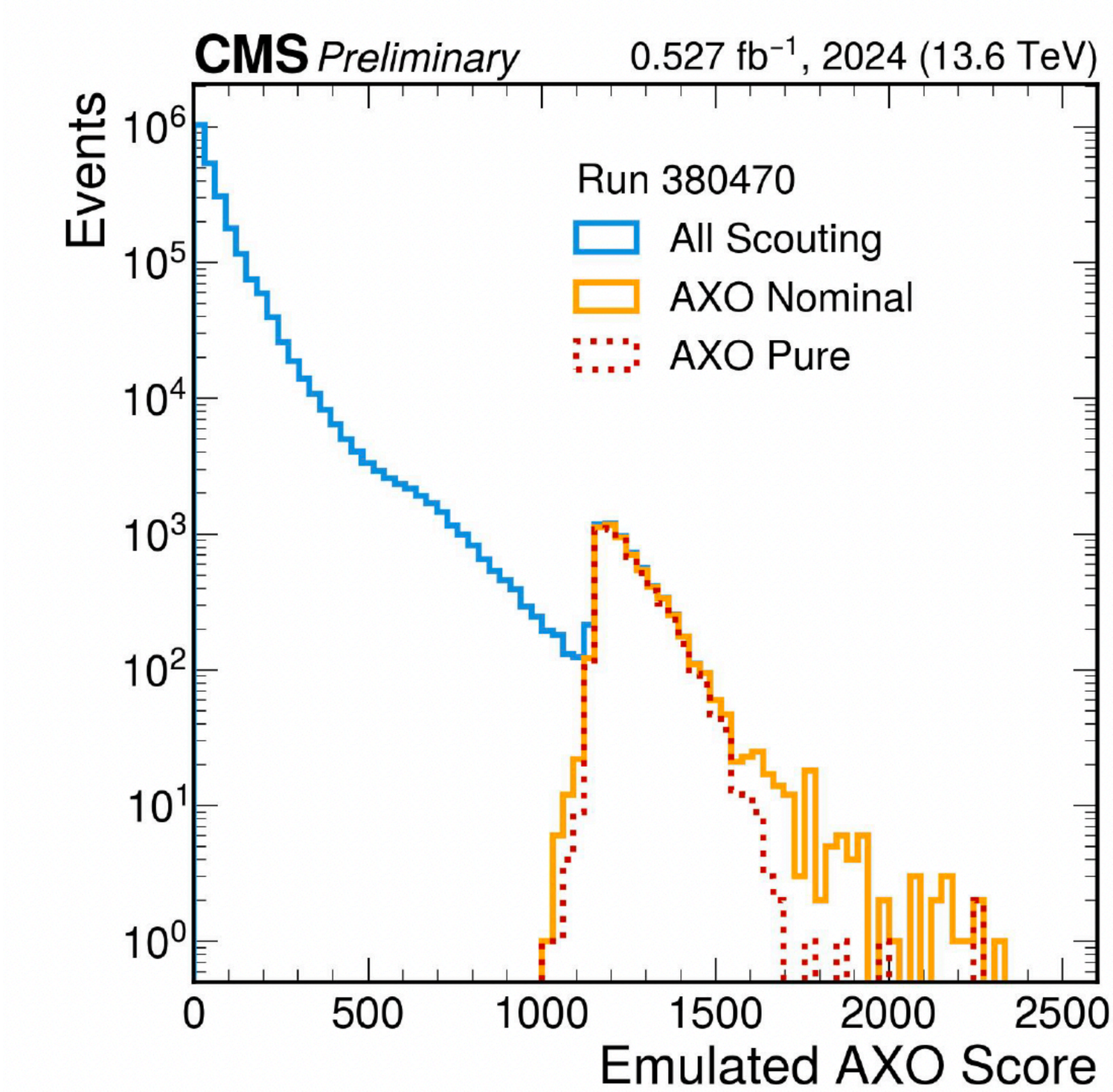




Preliminary Results

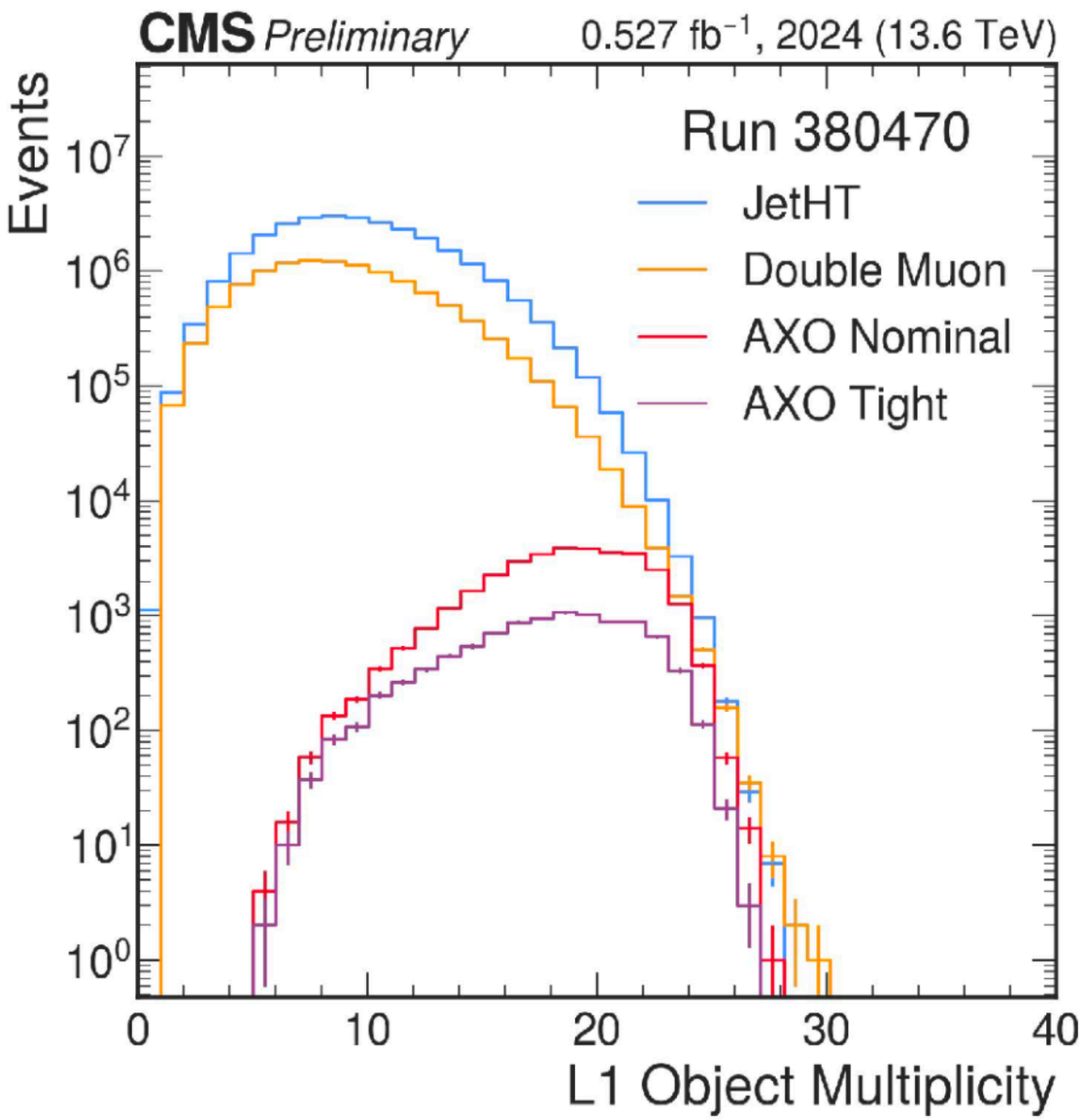
- Improved physics performance relative to existing L1 menu

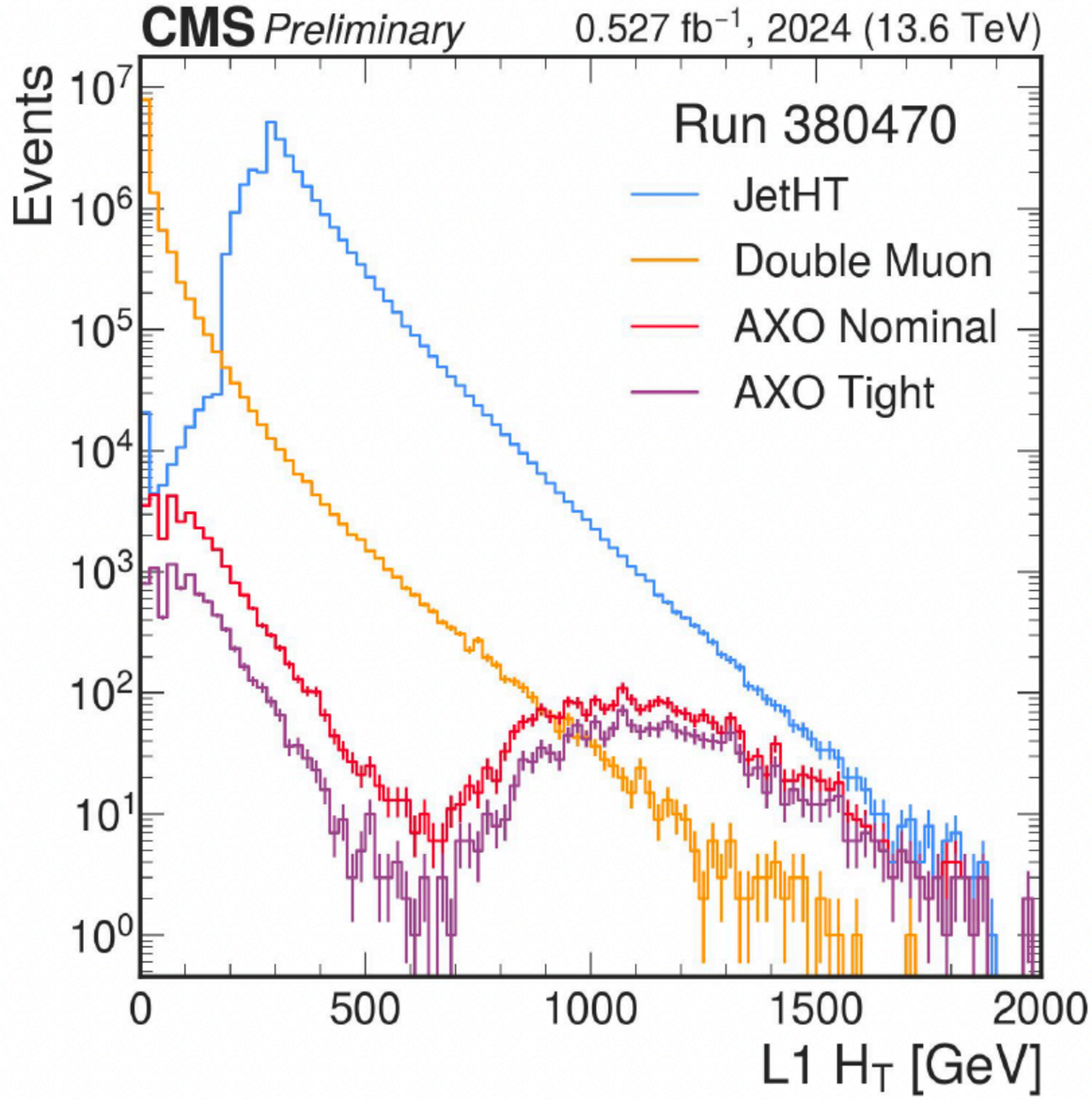
  → Events unique vs. existing triggers



Preliminary Results

- Preliminary distributions in partial scouting dataset (May 2024)





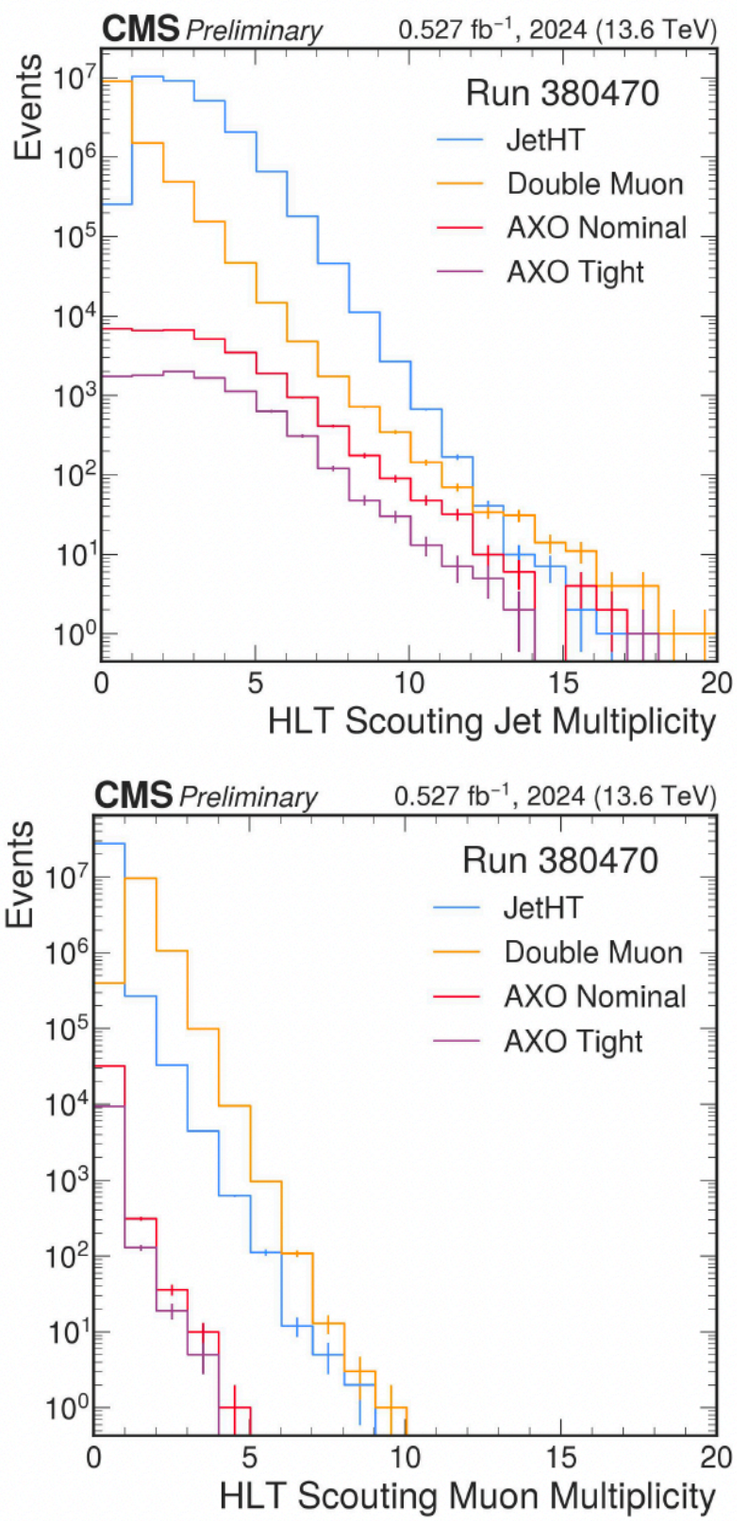
→ Preference for higher object multiplicity vs. existing triggers

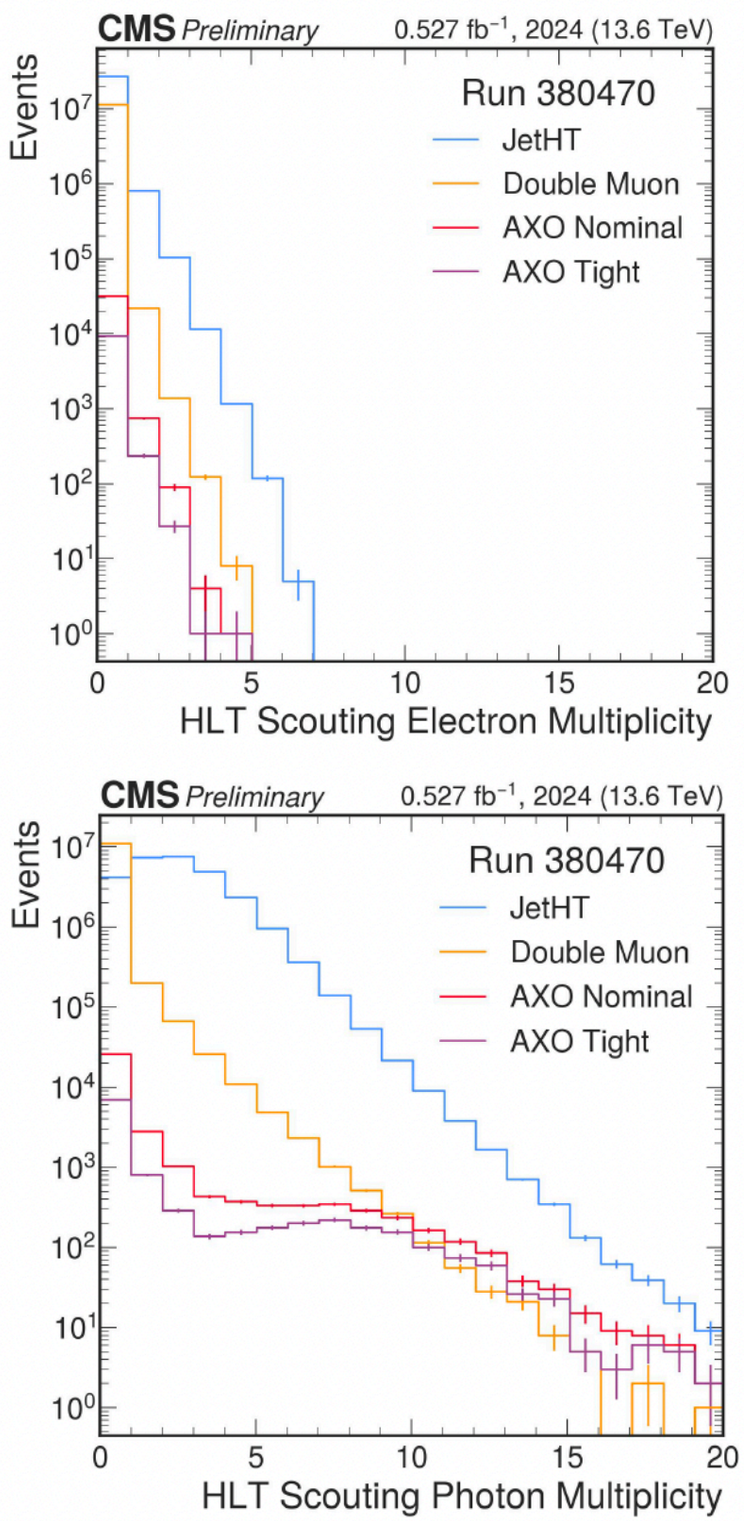
→ Preference for higher jet multiplicity & p_T

Preliminary Results

- Preliminary distributions in partial scouting dataset (May 2024)

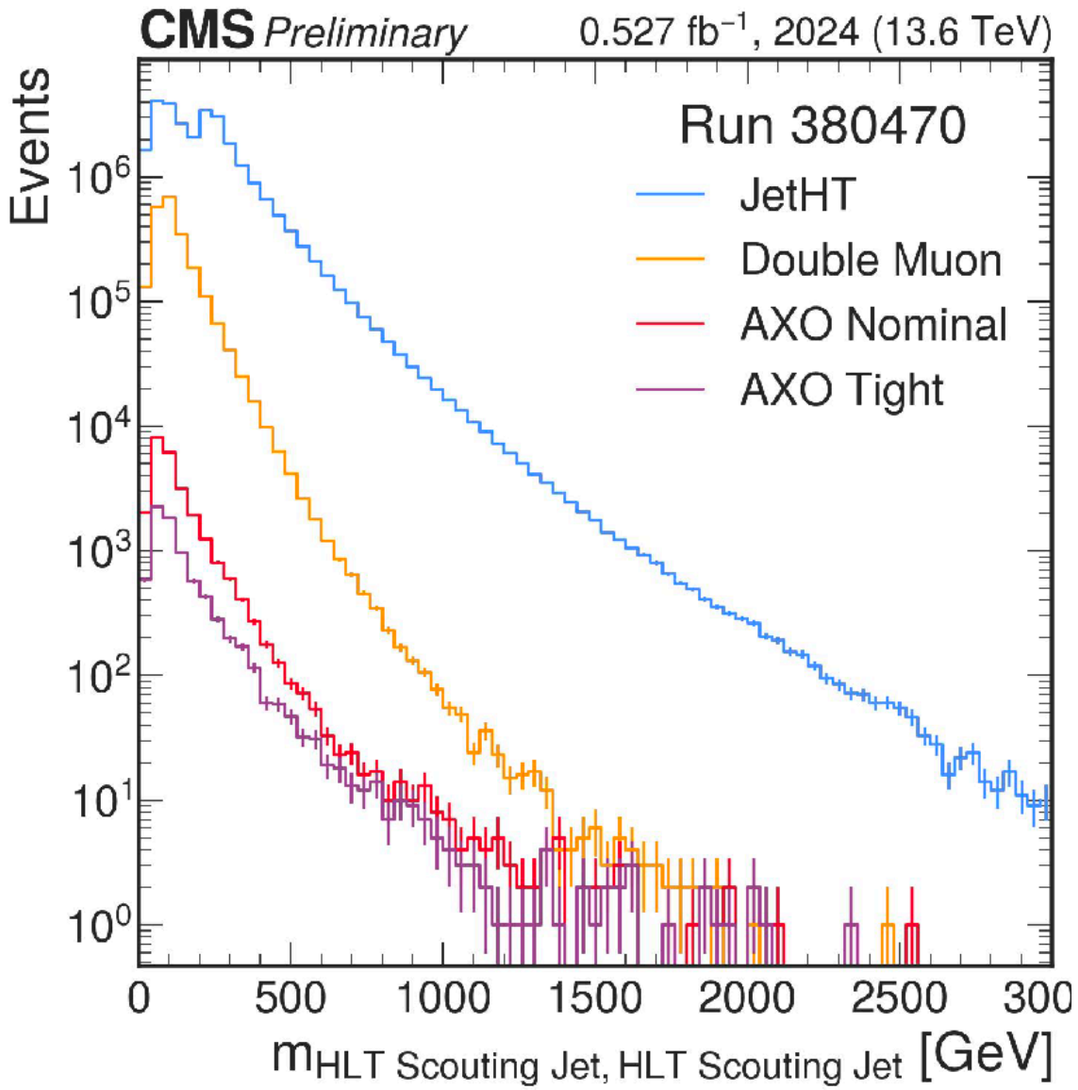
  → Preference for higher jet, photon, & electron multiplicity vs. existing triggers

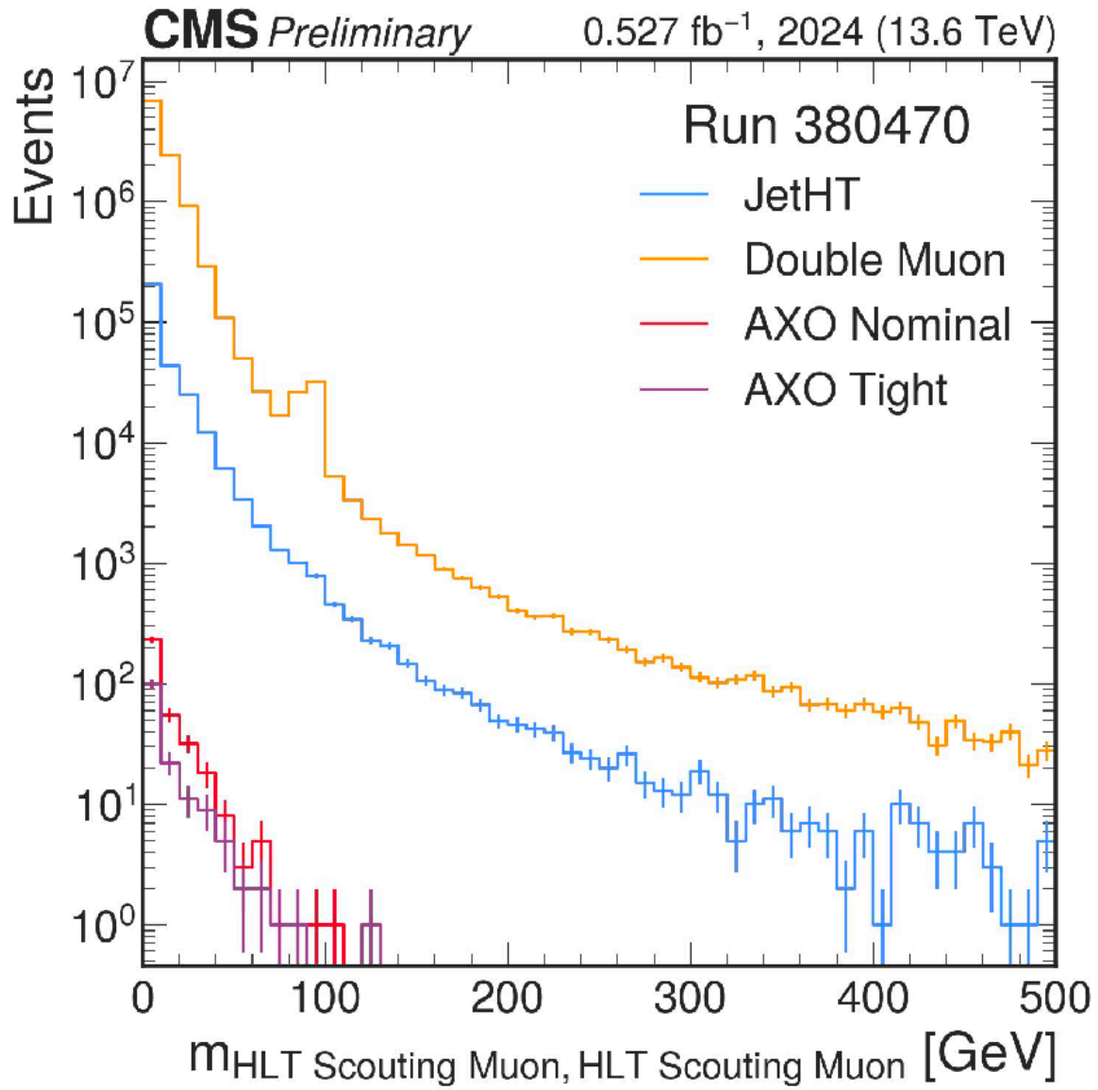




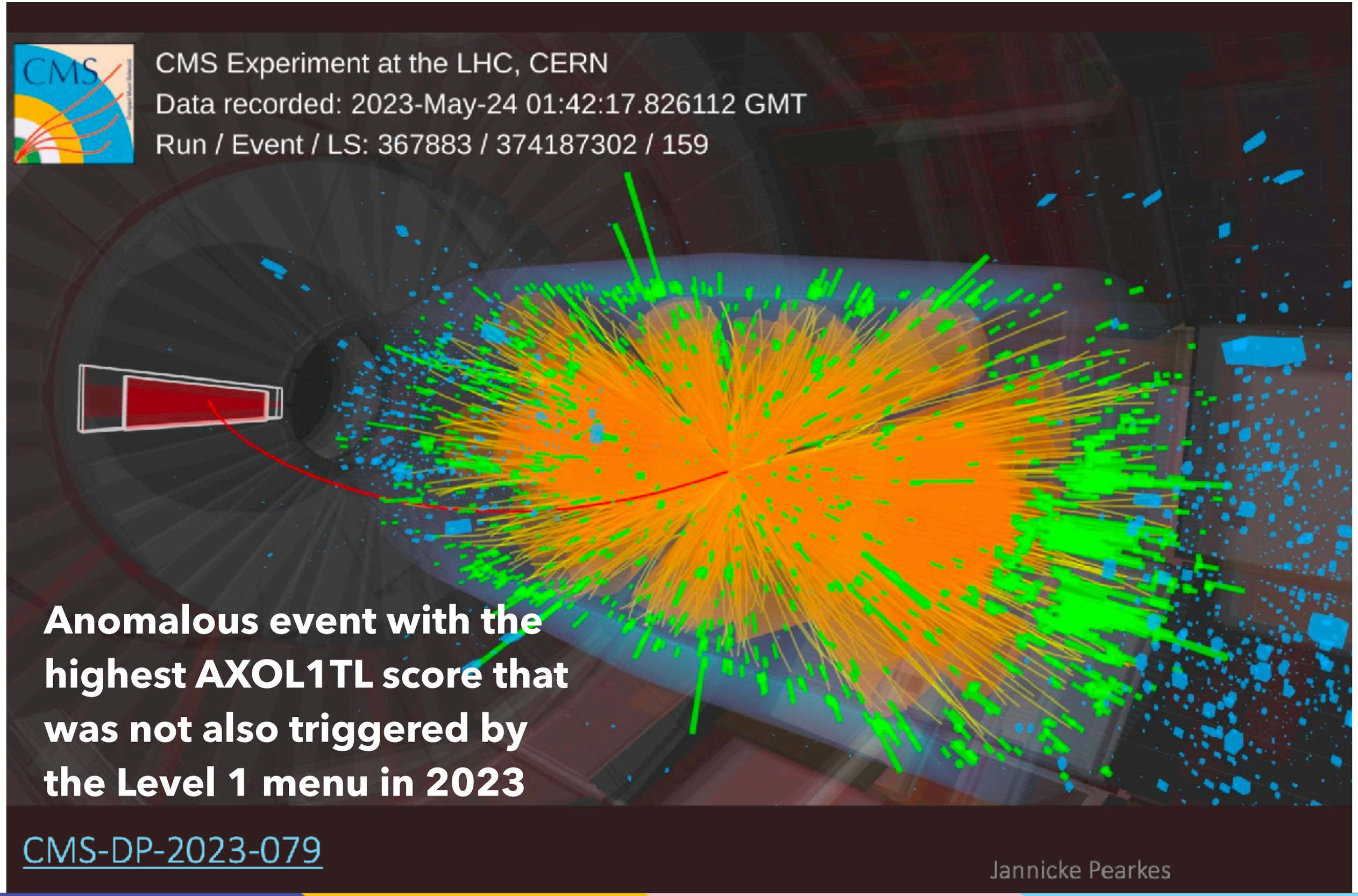
Preliminary Results

- Preliminary invariant mass distributions in partial scouting dataset (May 2024)
  - AXO triggers: Generally smoothly falling distributions, no sculpting
  - Ideal for BSM/SM searches

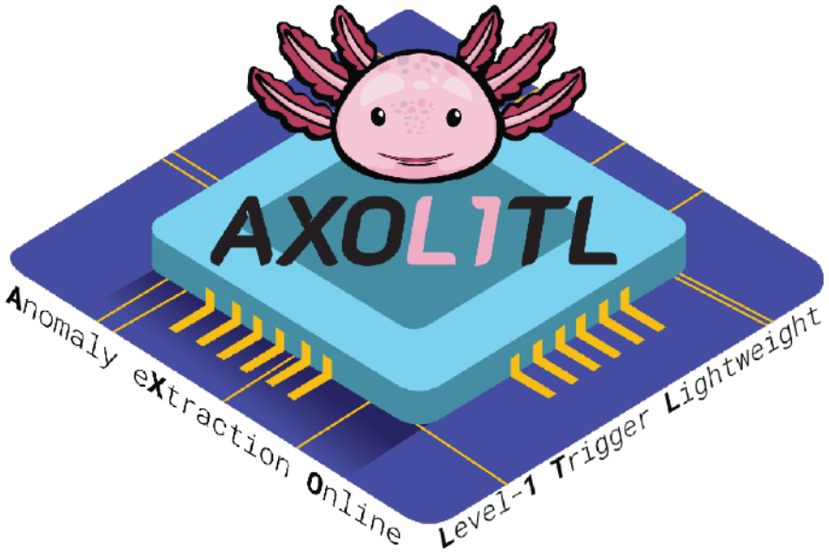


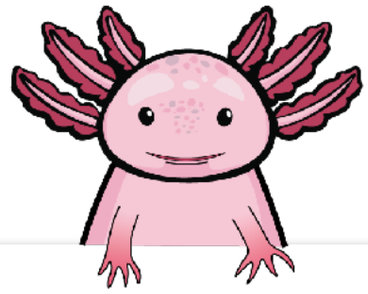


Anomalous Event Example



Conclusion





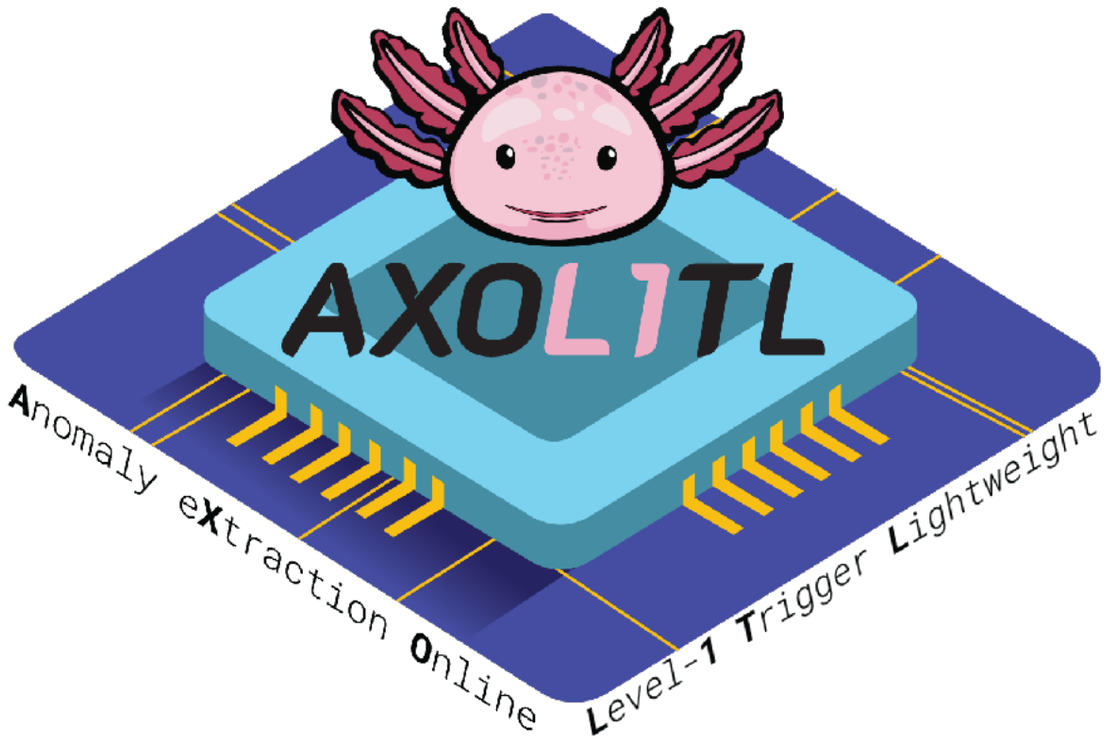
Publications/Presentations:

DP Note 1: 2023 Test Crate Implementation

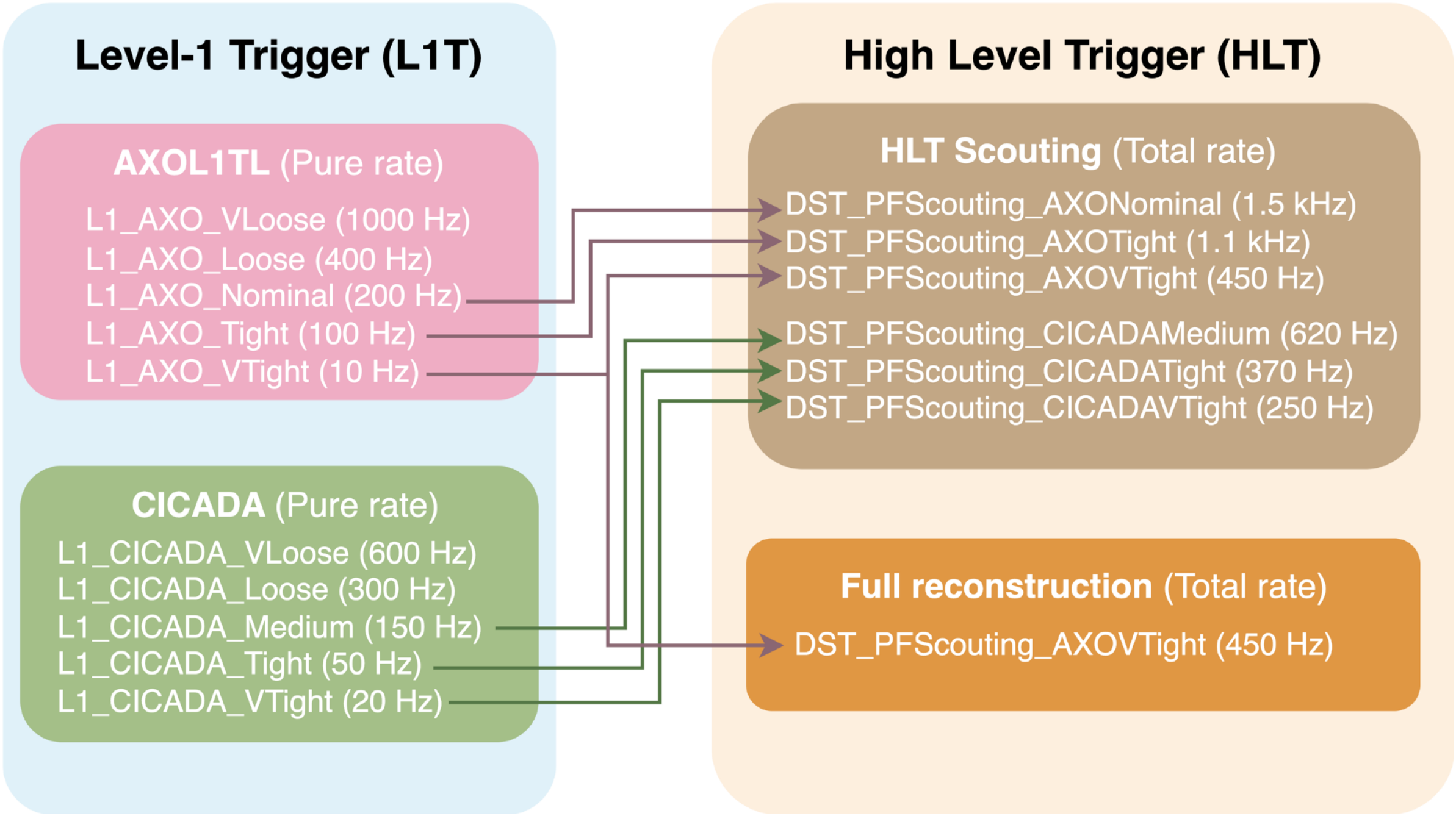
DP Note 2: 2024 Data Taking

ICHEP 2024 Presentation (A. Gandrakota)

- ML-based anomaly detection in CMS L1 Global Trigger
  - Sensitive to rare SM + potential new physics despite low rates!
- V4 deployed for 2024 data-taking
  - Updated V5 deployed in 2025 → coming soon!
  - Improving model for future runs + HL-LHC
  - Developing analysis strategy
- Possible due to support from CMS L1 Trigger community!

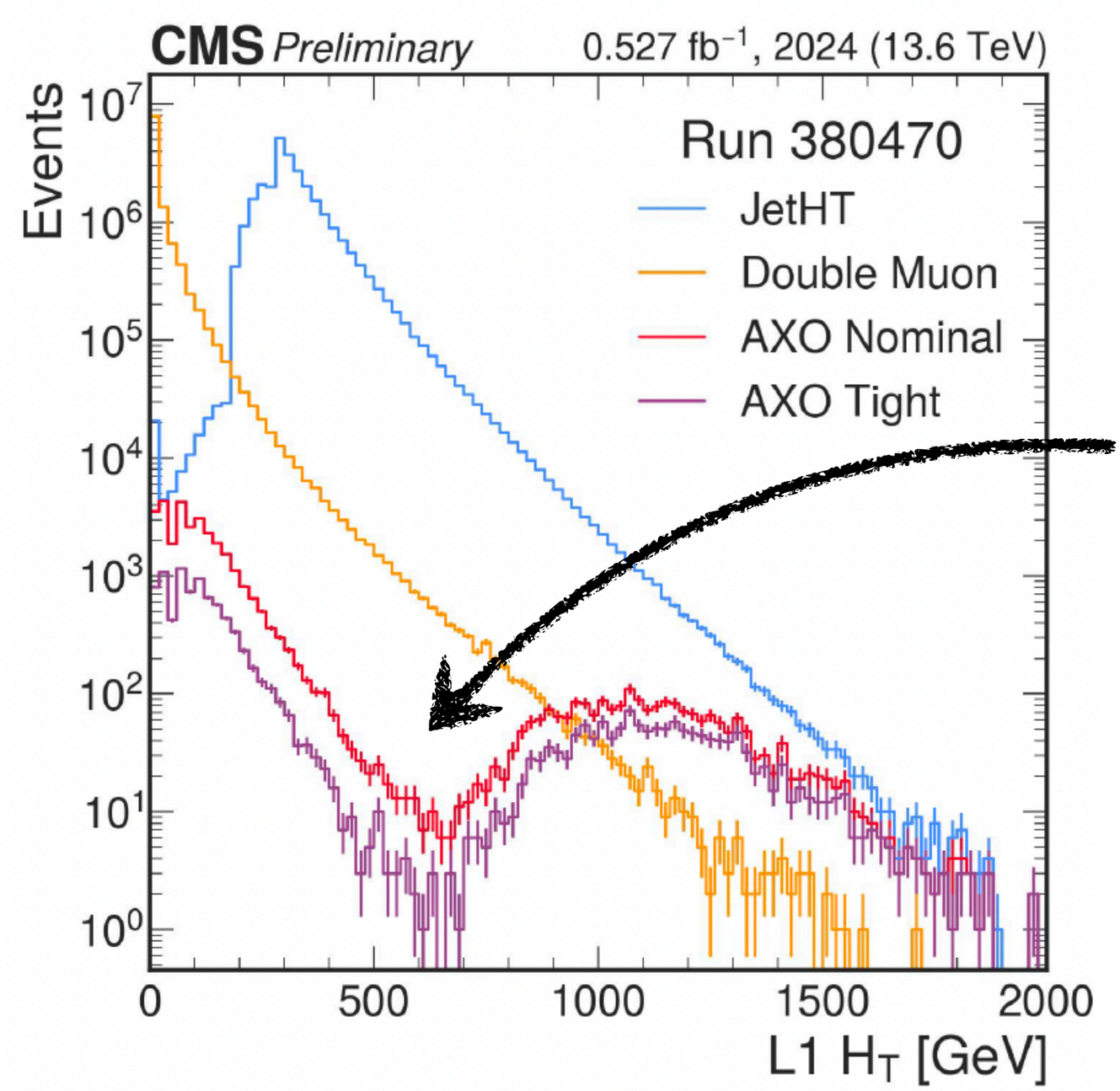

AXOLITL
Anomaly eXtraction Online
Level-1 Trigger Lightweight

Trigger Paths



AXOL1TL V4. Figure by Sabrina Giorgetti

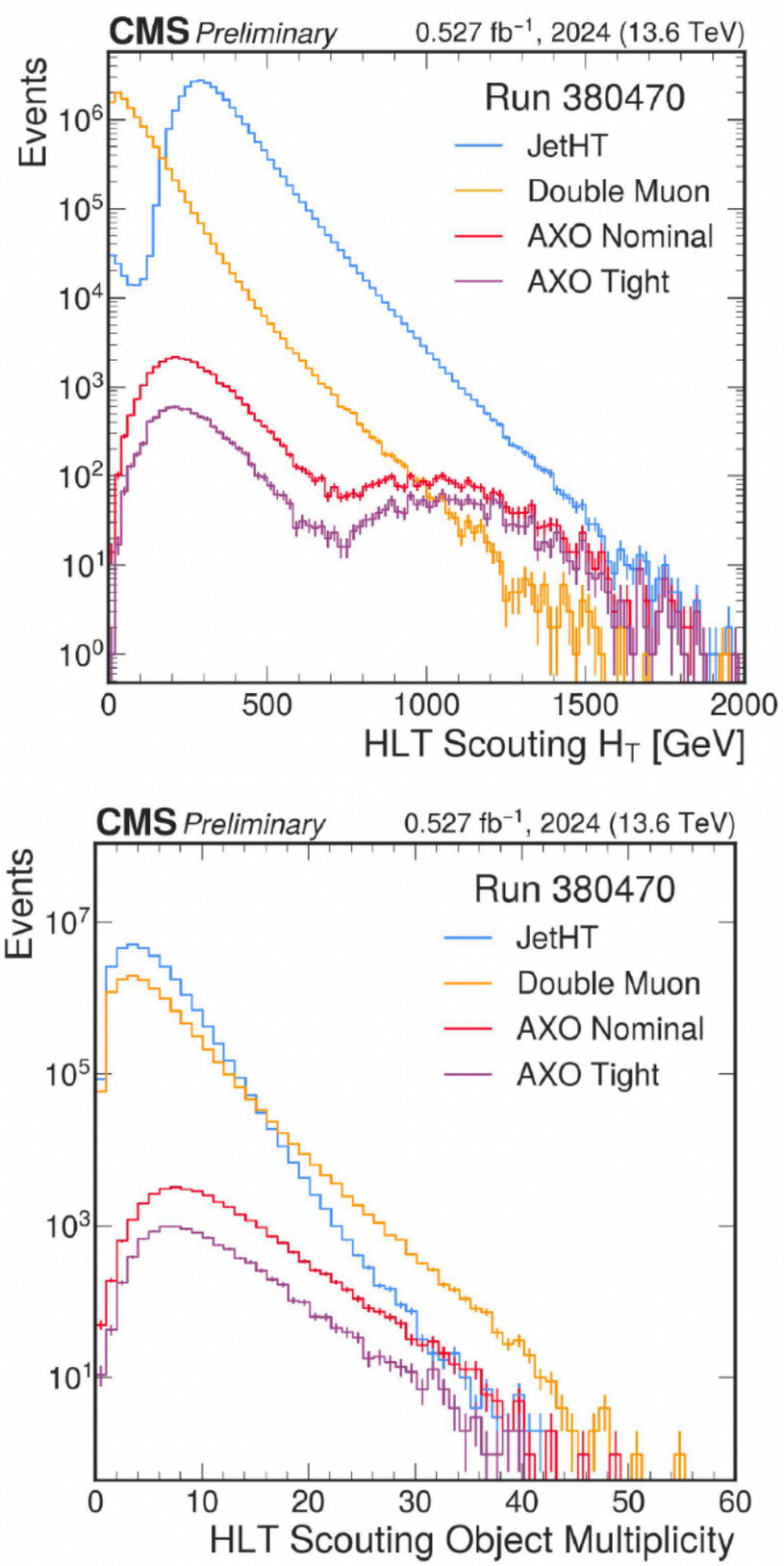
Preliminary Results

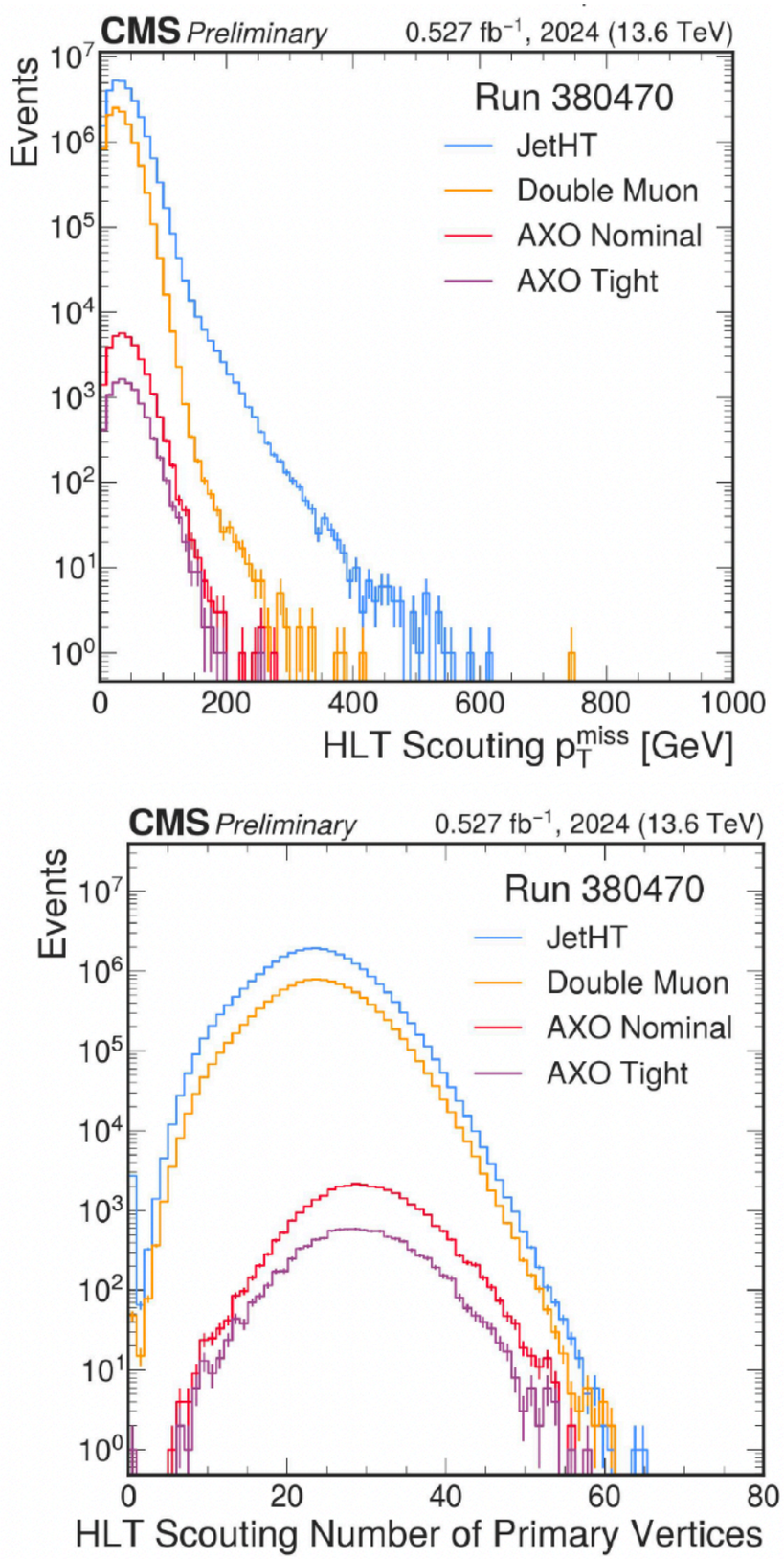


Dip in AXO-selected events due to the abundance of energetic dijet events seen by the L1T, making them less anomalous with respect to other features of interest

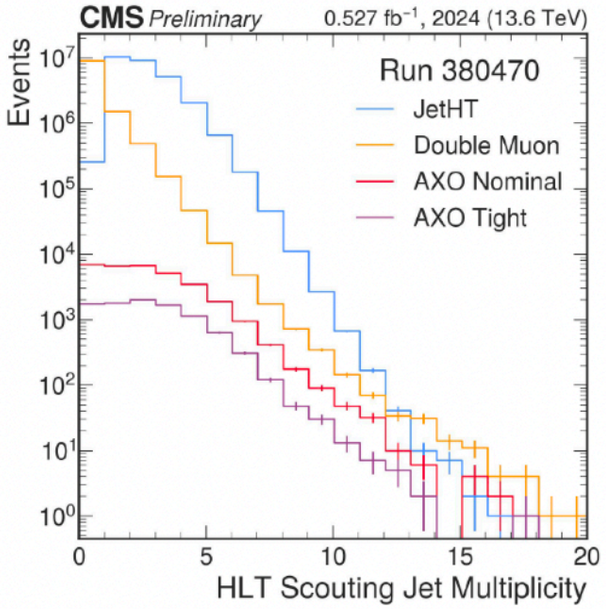
→ Preference for higher jet multiplicity & p_T

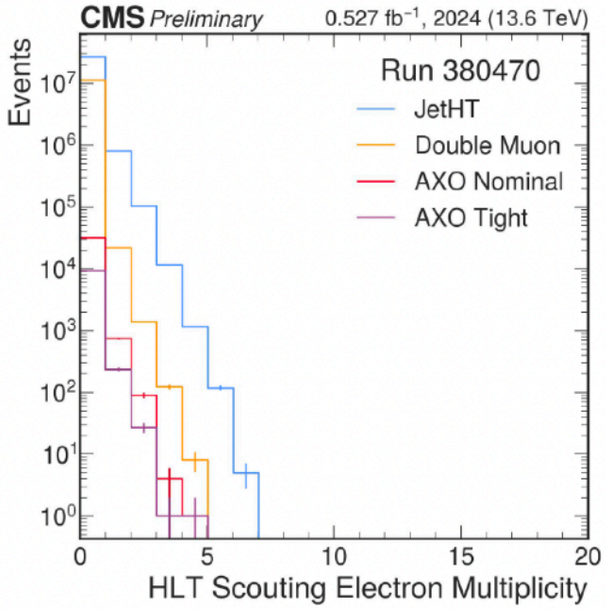
HLT Kinematics

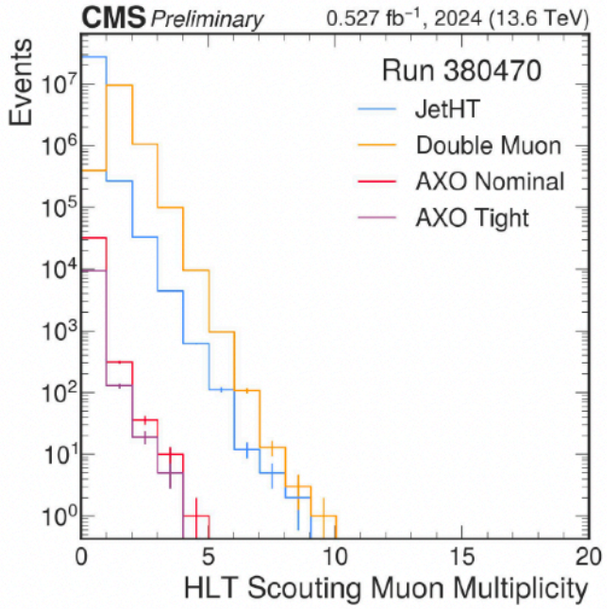


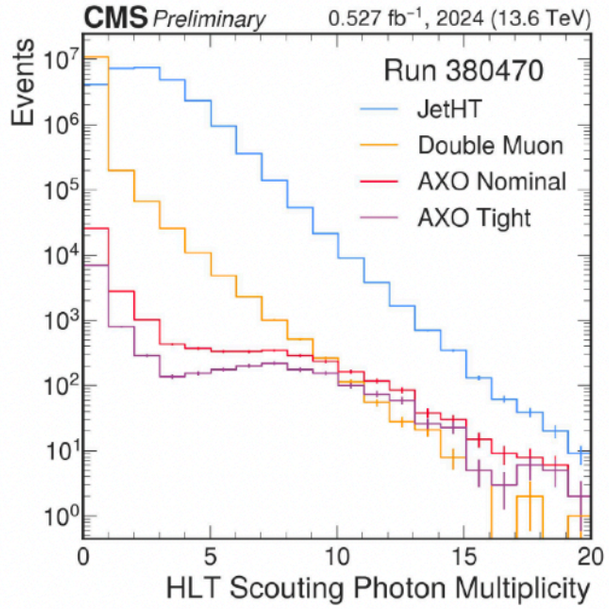


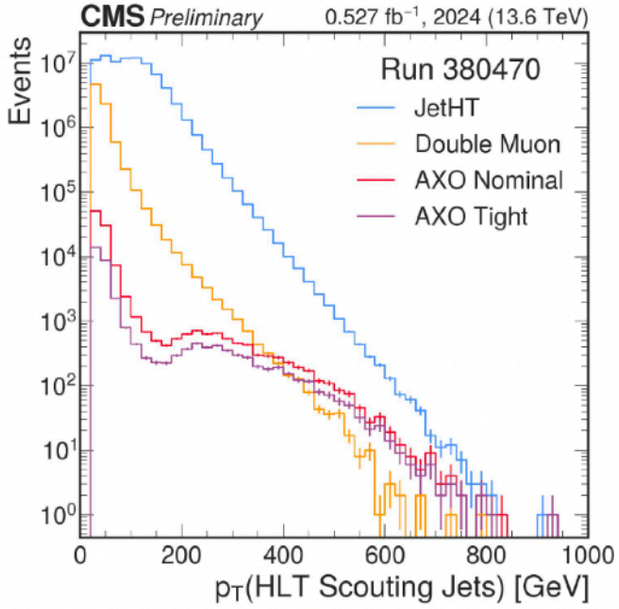
HLT Kinematics

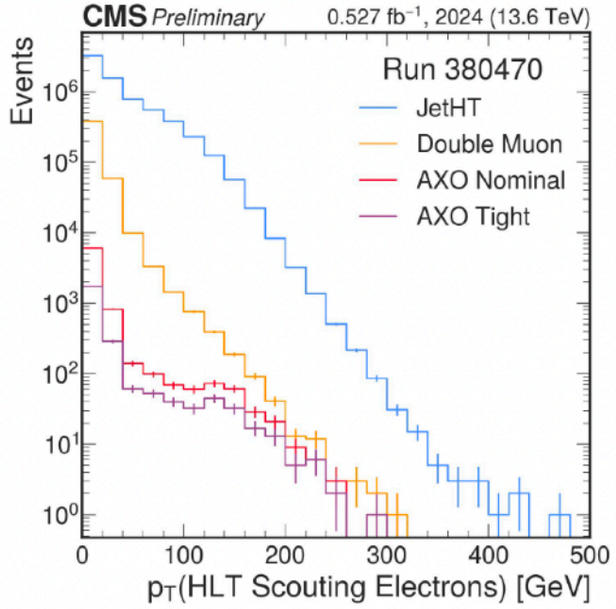


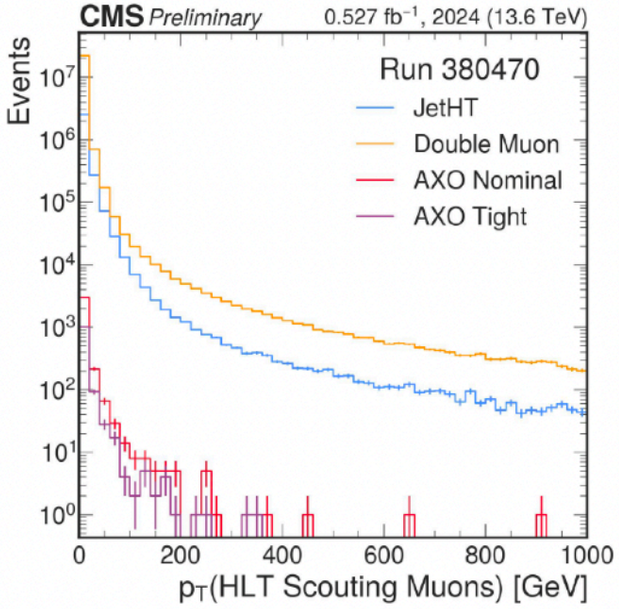


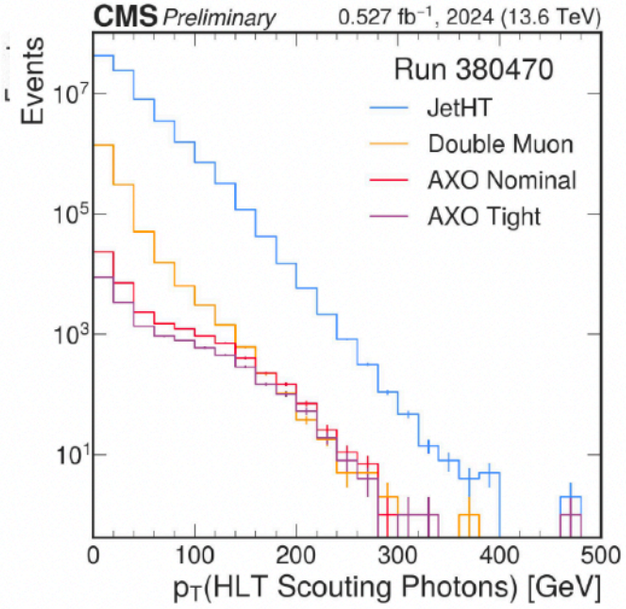






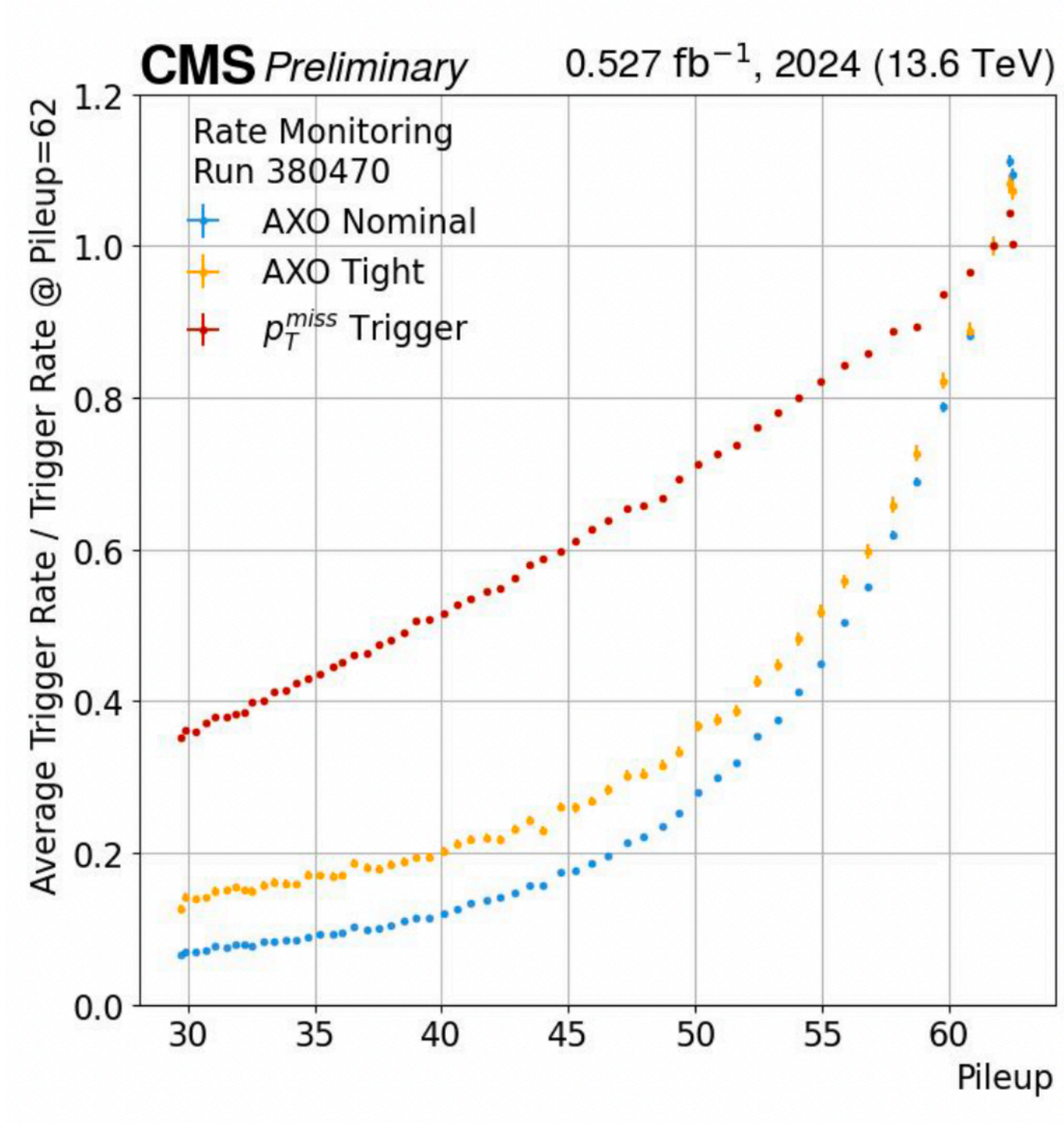




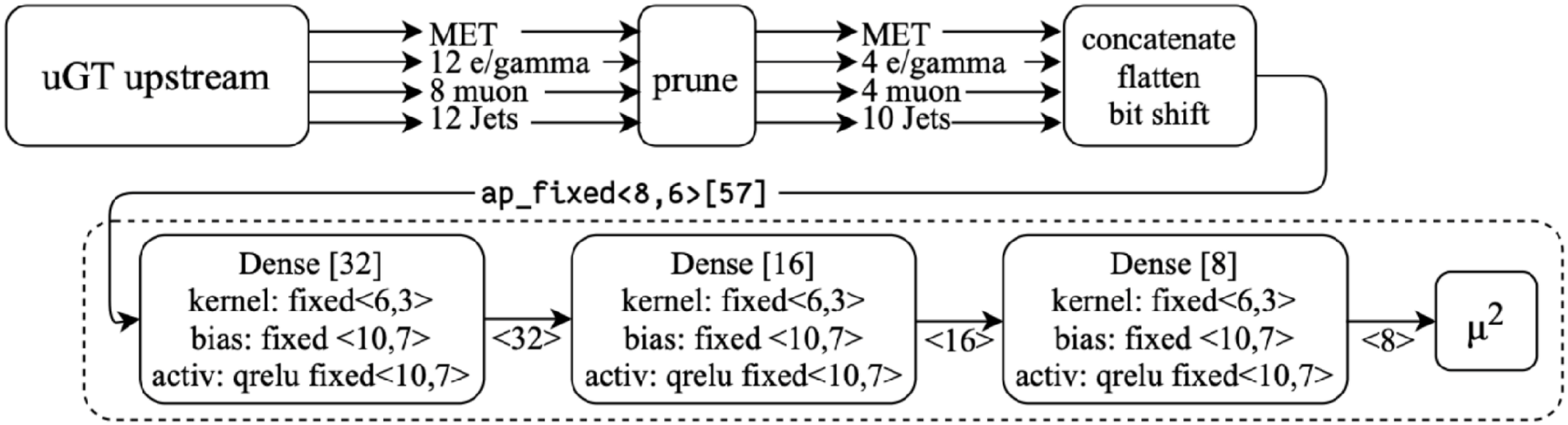


Pileup Dependence

- Strong pileup correlation due to correlation with high object multiplicity and high total energy, which increase at higher pileup.
- Pileup mitigation studies underway

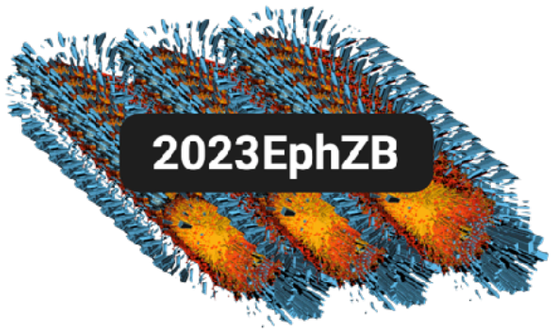


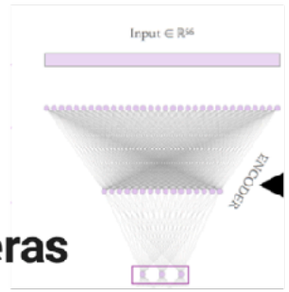
AD Encoder Implementation



AD Encoder

Implementation





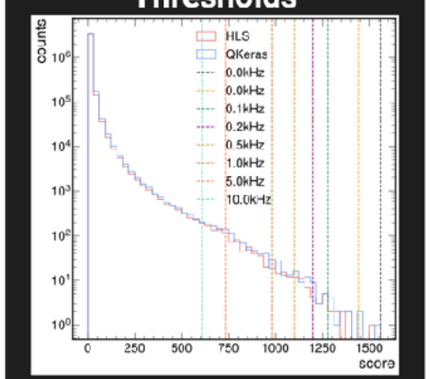
Train QKeras

Model .h5

Evaluate QKeras

hls 4 ml

Plots Thresholds



L1 menu xml (example)

uGT HLS fwk

uGT HLS (C++)

Model HLS (C++)

pybind11

Standalone Emulator (Py)

Vitis™ HLS

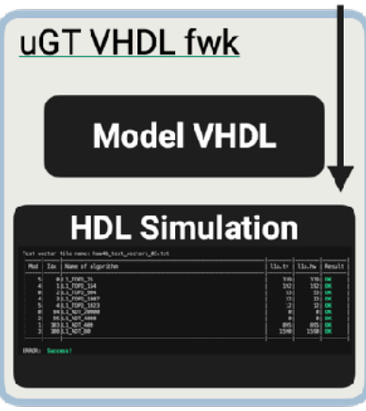
Model VHDL

Test Vectors

uGT VHDL fwk

Model VHDL

HDL Simulation

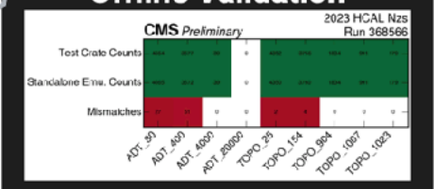


CMSSW Emulator

cms-hls4ml

Coming Soon

Offline Validation

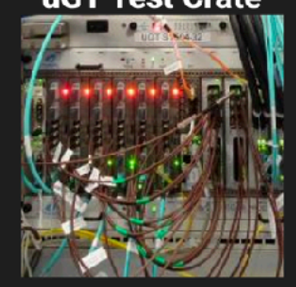


L1 NTuples (w/TC)

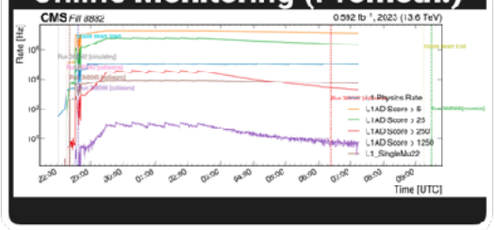
RAW

Collisions

uGT Test Crate



Online Monitoring (Prometh.)



L1 keys

uGT bitfiles