Available on CMS information server

CMS DP -2024/059

The Compact Muon Solenoid Experiment

CMS Performance Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

14 July 2024

2024 Data Collected with AXOL1TL Anomaly Detection at the CMS Level-1 Trigger

CMS Collaboration

Abstract

AXOL1TL (Anomaly eXtraction Online Level-1 Trigger aLgorithm) is an anomaly detection algorithm operating in the global trigger subsystem of the CMS Level-1 Trigger. The CMS experiment has been collecting data with this algorithm since May 2024. This note summarizes the features of the data collected by the AXOL1TL algorithm during the first months after its deployment.

2024 Data Collected with AXOL1TL Anomaly Detection at the CMS Level-1 Trigger

CMS Collaboration
cms-dpg-conveners-l1t@cern.ch, cms-trigger-coordinator@cern.ch, and cms-conveners-ml@cern.ch

Glossary

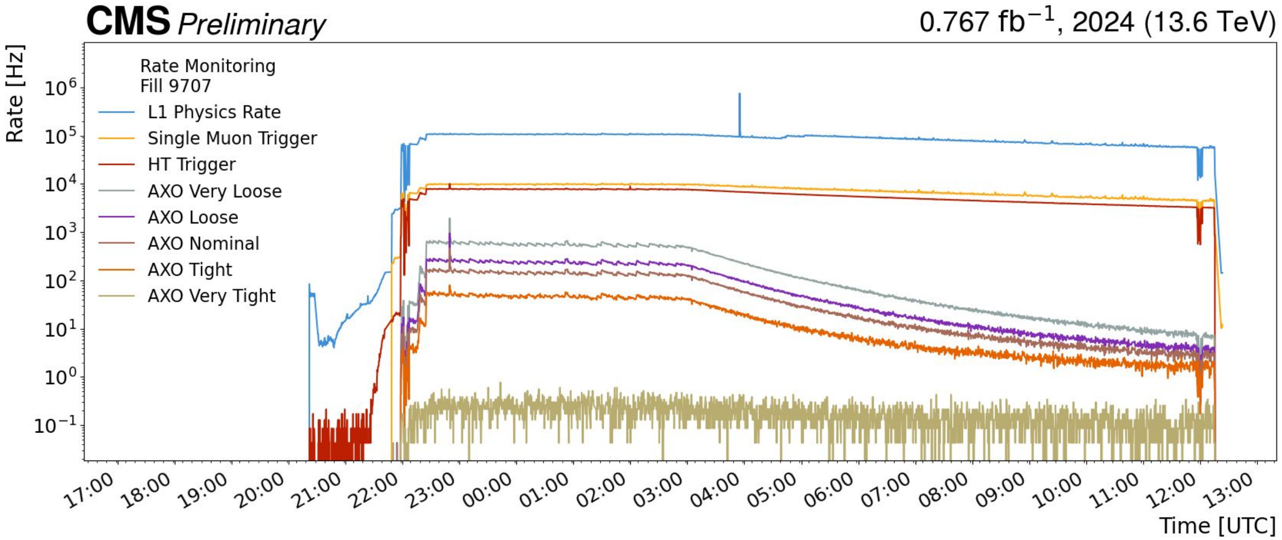
- **AXOL1TL (Anomaly eXtraction Online Level-1 Trigger aLgorithm)** – Acronym for anomaly detection at the global trigger level
- **HLT** - High Level Trigger
- **HLT Scouting** – Data-taking strategy that reduces event content on disk by only saving objects reconstructed online in order to allow for higher rates at the same bandwidth. [1]
- **Machine Learning (ML)** – The training of computer algorithms to recognize patterns and make decisions based on data
- **Latent space** – Low-dimensional space into which network inputs are encoded
- **L1T** - Level-1 Trigger
- **Passthrough trigger** - A trigger from a Level-1 seed with no filtering applied at the HLT
- **Pileup** – Proton-proton collisions in addition to the interaction of interest
- **Prescale** – A scale factor applied to the set of events passing a given trigger, allowing only a fraction of the total to be recorded
- **VAE (Variational Autoencoder)** – Neural Network architecture that encodes and decodes to/from a latent-space with probability distribution
- **ZeroBias** – Events recorded randomly during data-taking when there is a coincidence of two bunches crossing the detector at the same time
- **μGT** – Level-1 global trigger system

Introduction

- Previous DP Note (CMS-DP-2023-079) on test crate results [2]
- AXOL1TL is an machine learning-based trigger algorithm that selects anomalous events in real-time
- The unsupervised signal-agnostic approach gives sensitivity to a variety of signals
- A Variational Autoencoder (VAE) trained on ZeroBias data is used to detect data outliers
- The information bottleneck in the 8x1 Gaussian-distributed latent space enforces efficient information encoding ⇒ learning
- Calculated from standard μGT L1T objects
  - (p_T,η,ϕ) hardware inputs from p_T^{miss}, 4 e/γ, 4 μ, and 10 jet objects
- Version 3 (V3) of algorithm deployed in the CMS Level-1 Global Trigger (μGT) at the start of the 2024 pp run
  - Multiple triggers with different anomaly score thresholds calibrated for different L1T rates (Tight, Loose, etc.)
- Collecting data since May 2024 with three AXOL1TL triggers
  - AXO Very Tight
    - One passthrough trigger with a low rate, selecting events for which full offline reconstruction is performed and the full event content stored
  - AXO Nominal & AXO Tight
    - Two passthrough triggers selecting events for HLT Scouting, where reduced event content is stored

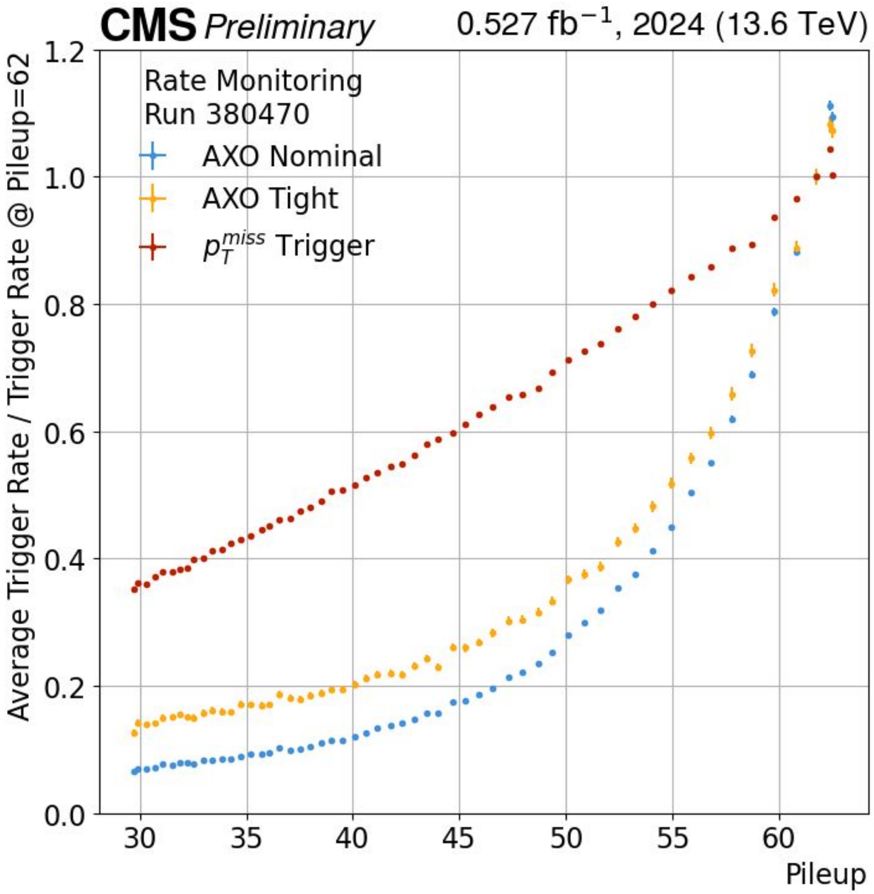
Rate Monitoring

Global trigger rate monitoring time series over the course of fill 9707 on June 3, 2024. L1T rates are shown for all 5 anomaly detection trigger seeds, using the same algorithm and various score cuts chosen to target specific L1T rates. Also shown for reference is the overall L1T physics rate, and rates for an un-prescaled single muon trigger (L1_SingleMu22) and H_T trigger (L1_HTT280er). Time-averaged pre-deadtime pre-prescale rates are read from monitoring software at a ~20s rate during good data-taking conditions in 2024. The AXOL1TL model is trained on 2023 Zero Bias data. Stable performance is shown over the course of the fill-cycle. The turn-on corresponds to the beginning of an LHC fill and the sawtooth pattern corresponds to luminosity levelling. Small spikes/dips in rate are not physical and due to transient detector effects.

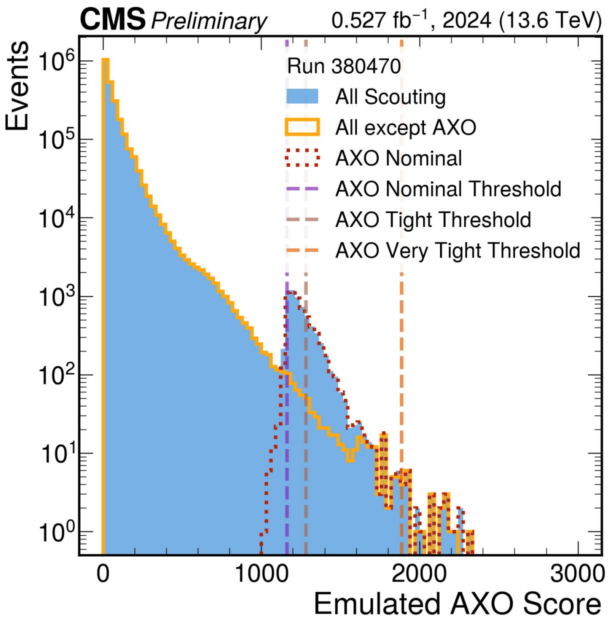


PU Dependence

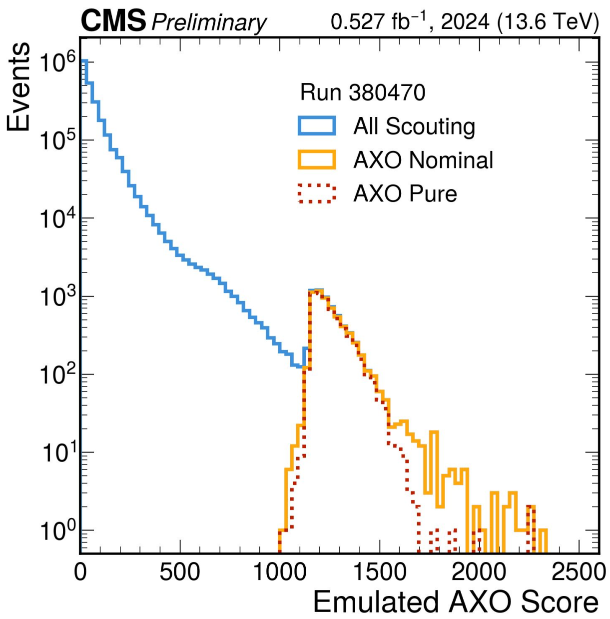
L1T rate vs. pileup plotted for CMS Run 380470 on May 7, 2024. It shows the AXOL1TL seeds included in the trigger menu as HLT Scouting passthrough triggers, AXO Nominal and AXO Tight. Pileup is calculated using the standard Beam Radiation, Instrumentation, and Luminosity (BRIL) toolkit. The distributions are normalized to the trigger rate at pileup of 62 for each trigger seed. A reference p_T^{miss} trigger (L1_ETMHF90) is included to show relative pileup dependence. Strong pileup correlation for the AXOL1TL seeds is observed due to the algorithm's correlation with high object multiplicity and high total energy, which increase at higher pileup.



AXOL1TL Scores in HLT Scouting



AXOL1TL score distributions for the HLT Scouting partial dataset (~6M events) for CMS Run 380470 on May 7, 2024. Scores are shown for all live AXOL1TL seeds as well as all the events triggered by non-AXO HLT Scouting seeds in the dataset to show where the AXOL1TL contribution lies. Score thresholds that were set in the trigger menu are observed at generally correct values. A small fraction (6.5%) of “mismatch” events are observed where the hardware score used to trigger an event diverges from the emulated score plotted on the x-axis.



AXOL1TL score distributions for the HLT Scouting partial dataset (~6M events) for CMS Run 380470 on May 7, 2024. Scores are shown for all events triggered by the AXO Nominal seed, and those only triggered by the AXOL1TL triggers and no other L1T triggers (AXO Pure). The shape of the pure contribution shows that the anomaly detection trigger is selecting unique events relative to the existing Level 1 triggers. At very high anomaly scores many of the events are already captured by the existing Level 1 triggers.

HLT Scouting Dataset

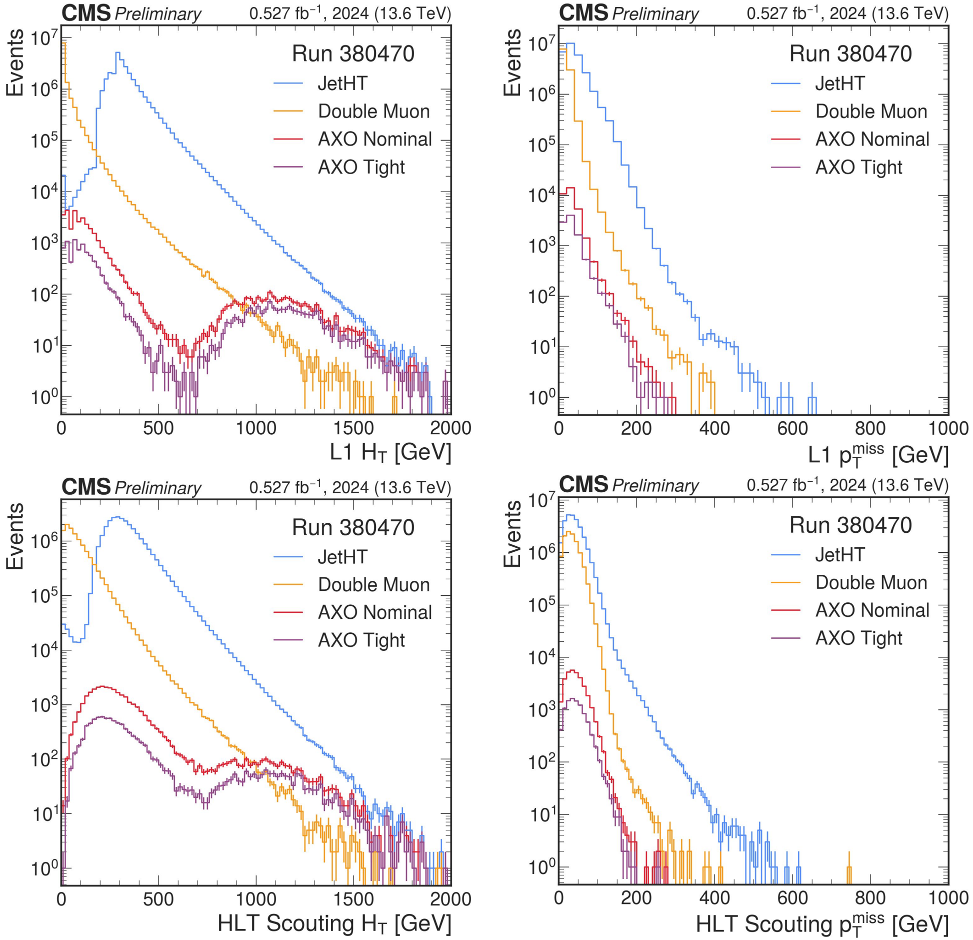
- Data from Run 380470
- Removing events with saturated energy values for L1 objects
  - These events are clearly anomalous, but these saturations are automatically triggered on by the existing L1T system and give little insight into the dataset uniquely recorded by AXO triggers
  - Cut on saturated L1T Jet p_T > 1000 GeV
  - Cut on saturated L1T p_T^{miss} > 1040 GeV

- Plotting
  - L1T Objects with p_T > 0.1 GeV
  - HLT Scouting Jets with p_T > 30 GeV, η < 3
  - HLT Scouting Electrons with p_T > 10 GeV, η < 2.65
  - HLT Scouting Photons with p_T > 10 GeV, η < 2.65
  - HLT Scouting Muons with p_T > 3 GeV, η < 2.4

All *following* plots have these selections applied

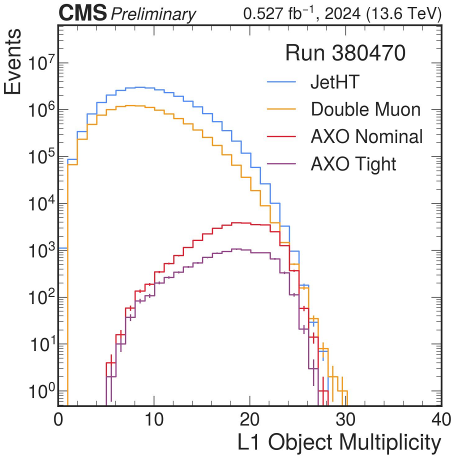
- Triggers plotted:
  - JetHT: Seeded by L1 single jet (p_T>180 GeV), double jet (p_T>30 GeV & m_{jj}>250 GeV) and H_T (> 280 GeV) triggers
  - Double Muon: Seeded by a variety of double muon triggers with p_T>0 GeV
  - AXO Nominal: Seeded by the AXOL1TL trigger with an anomaly score
  - AXO Tight: Seeded by the AXOL1TL trigger with an anomaly score

HLT Scouting Data : H_T and p_T^{miss}

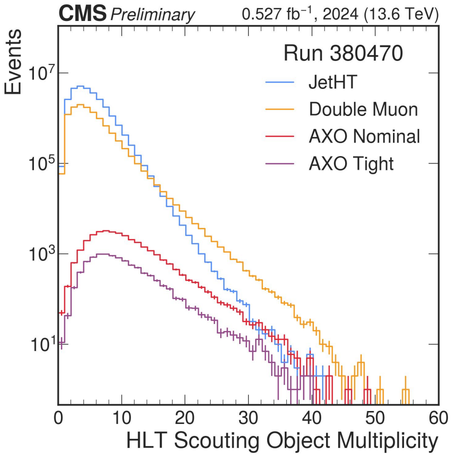


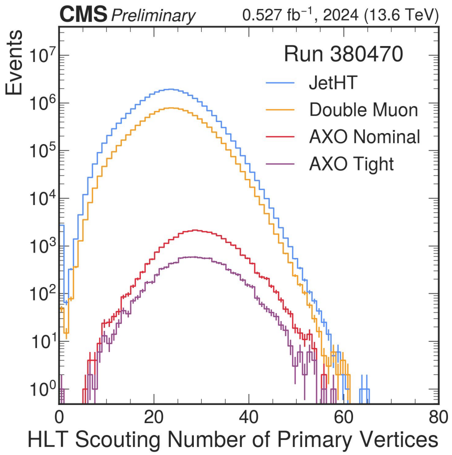
Energy sum distributions of events in CMS Run 380470 on May 7, 2024. Plots show L1T objects (top) and HLT Scouting reconstructed objects (bottom). Left plots show H_T, the scalar sum of jet p_T, and right plots show the missing transverse energy (p_T^{miss}). Plots compare conventional triggers (Jet H_T and Double Muon) with the AXO triggers of different thresholds. We observe a preference for higher H_T events, in accordance with the algorithm's correlation with high jet multiplicity and jet p_T. The dip in AXO-selected events near 600 GeV in the left plots can be explained due to the abundance of energetic dijet events seen by the L1T, making them less anomalous with respect to other features of interest. No features are observed in the p_T^{miss} plots. Better resolution and tighter quality cuts for the HLT Scouting objects smooth out the features observed in the L1T object plots.

HLT Scouting Data : Object Multiplicity

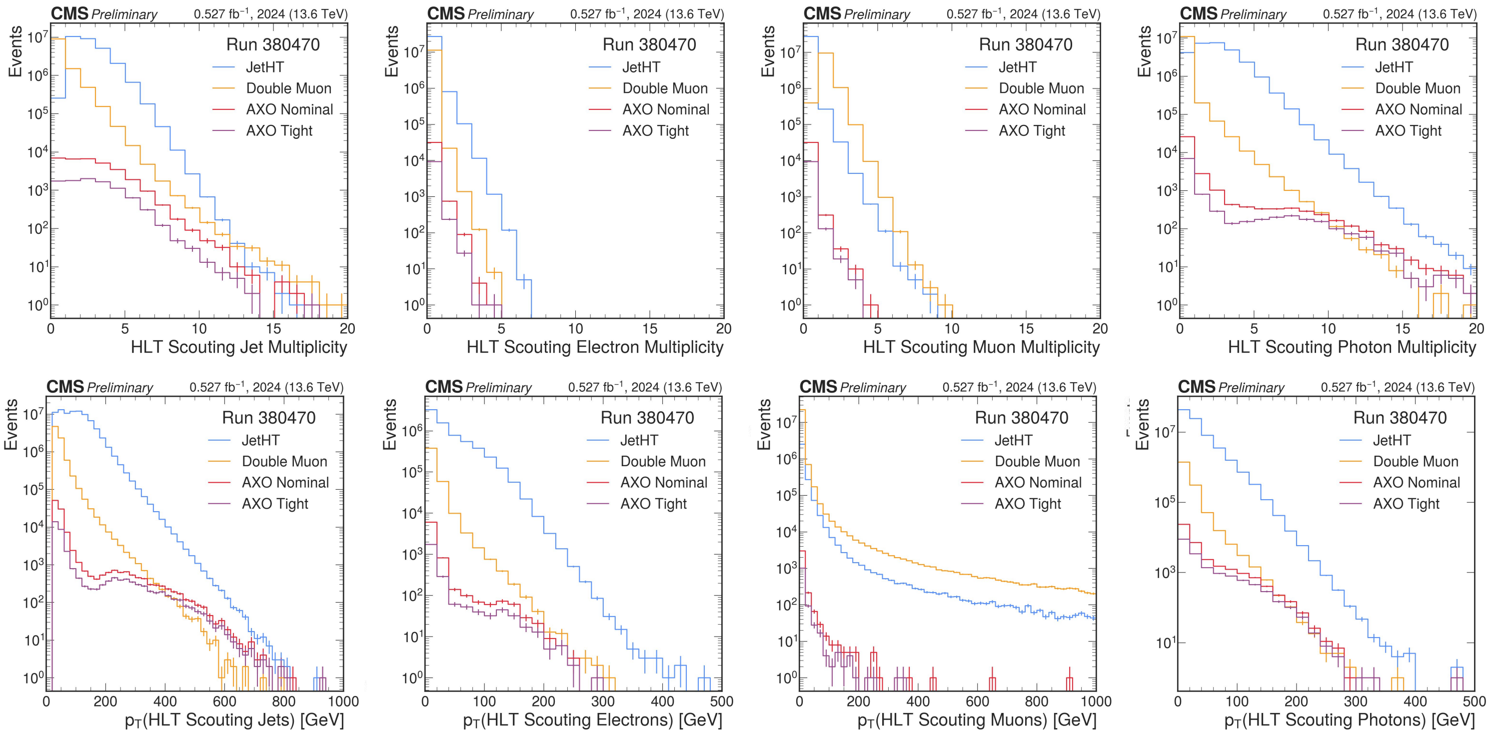


Object multiplicity distributions of events in CMS Run 380470 on May 7, 2024. Plots show L1T objects (top) and HLT Scouting reconstructed objects (bottom). The plots show the total object multiplicity (left) and the number of reconstructed primary vertices (bottom right). Plots compare conventional triggers (Jet H_T and Double Muon) with the AXO triggers at different thresholds. A preference for higher total object multiplicities and total primary vertices is observed in the AXO seeds, with respect to the reference triggers included.



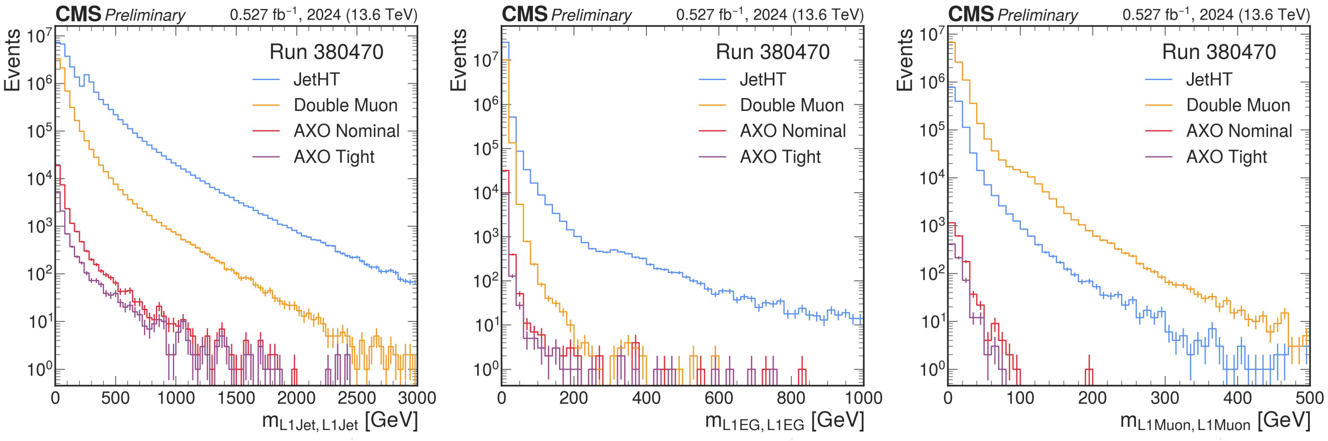


HLT Scouting Data : HLT Scouting Objects

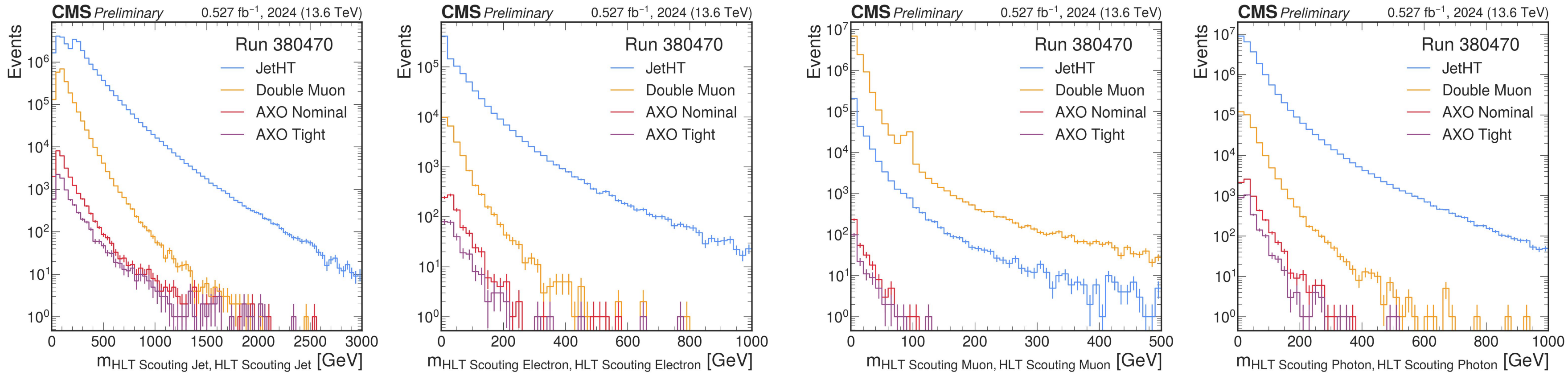


Kinematic distributions of events in CMS Run 380470 on May 7, 2024. Plots are shown for HLT Scouting reconstructed objects. Top row shows the multiplicities for jets, electrons, muons, and photons. Bottom row shows the p_T of jets, electrons, muons, and photons. A preference for higher multiplicities of jets, electrons, and photons is observed in AXO seeds, with respect to reference triggers.

HLT Scouting Data : Invariant Mass Distributions



Kinematic distributions of events in CMS Run 380470 on May 7, 2024. Plots show the invariant mass of L1T jets, e/γ candidates, and muons (top), as well as HLT Scouting reconstructed jets, electrons, muons, and photons. The invariant masses are computed from the highest and second highest p_T objects. Kinematic thresholds in the component triggers of the JetHT dataset generate structures that we observe in the blue curves, independent of the AXO triggers. The Z boson peak is visible in the dimuon invariant mass spectra. Generally smooth and falling distributions are observed in AXO-triggered events for all invariant mass combinations.



References

[1] CMS Collaboration. (2024). Enriching the physics program of the CMS experiment via data scouting and data parking. https://arxiv.org/abs/2403.16134

[2] CMS Collaboration. (2023). Anomaly Detection in the CMS Global Trigger Test Crate for Run 3. https://cds.cern.ch/record/2876546