New ML techniques for Anomaly Detection in the CMS Level-1 μGT System at CERN

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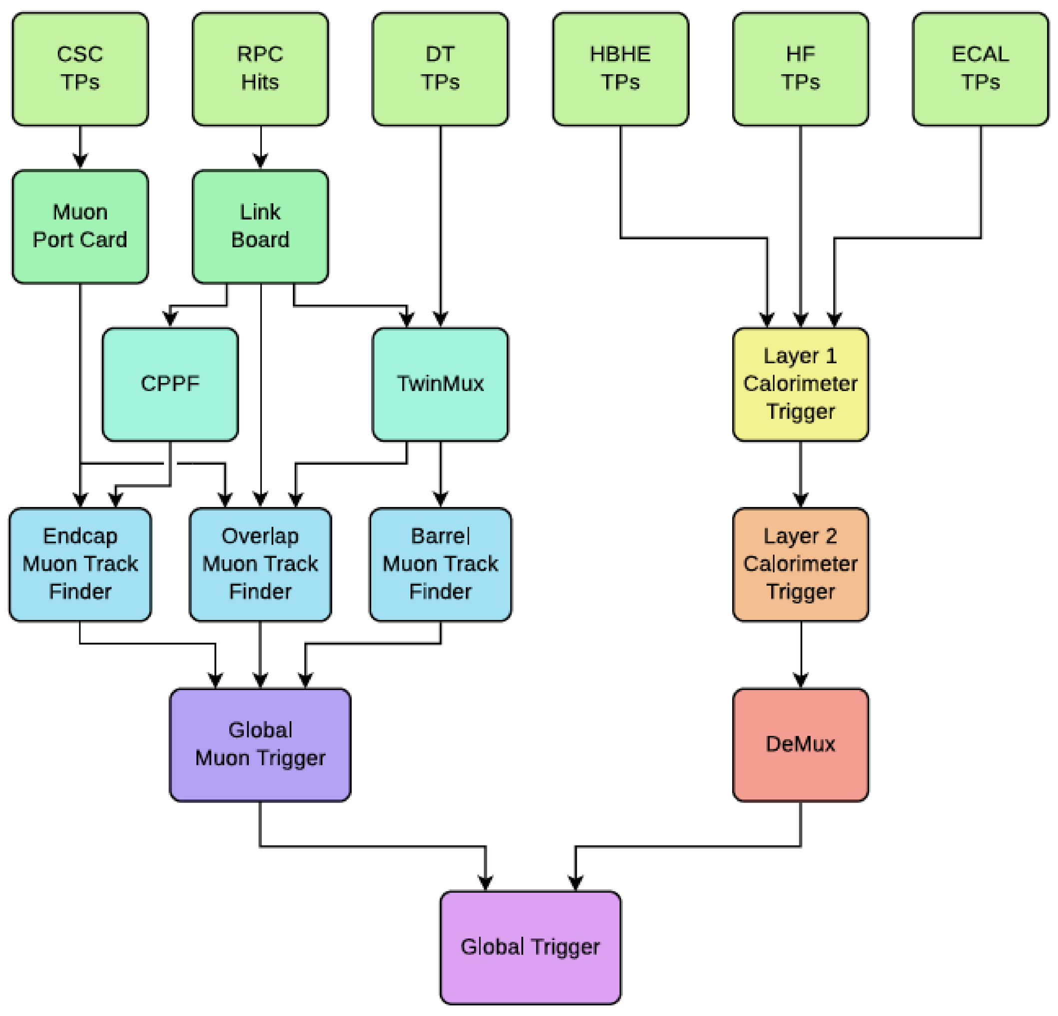
Poster ID

Motivation

- At LHC's CMS, supervised and theory-motivated ML algorithms have shown sensitivity to strong theoretical prior scenarios, such as the *Higgs boson*, but lack robustness against non-saturated BSM signals like *SUSY processes*. These algorithms utilize simple kinematic cuts on event-level observables, suppressing the SM background to identify anticipated new physics scenarios. However, this approach biases event selection analysis.
- A two-level system reduces the p-p collisions data throughput in the CMS detector by four magnitud orders. In the **Level-1 Trigger (L1T)**, where most non-bias rejections occur ($\sim 99.75\%$ of initial events), unsupervised and signal-model-agnostic, out-of-distribution based algorithms are being deployed to extract a rich spectrum of rare events as new physics signatures candidates. The primary challenge for these algorithms is to meet the extreme latency requirements at the LHC ($O(\mu s)$) and computational resource constraints while preserving high inference performance.

The Level-1 Trigger

Ultra-fast on-detector electronics for physics objects reconstruction!



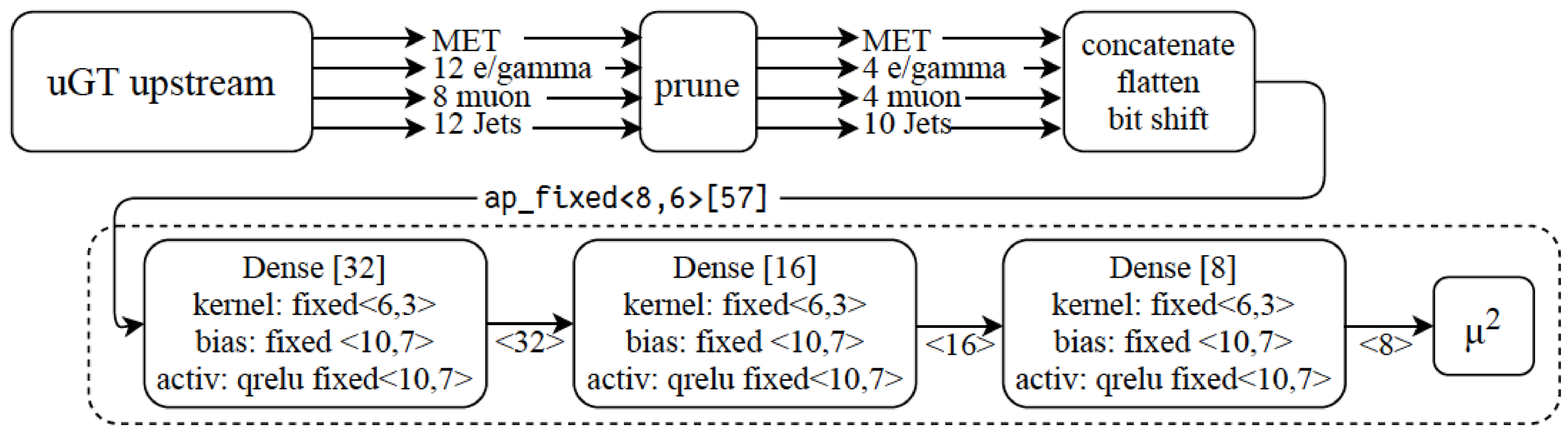
- The L1 reconstruction starts from a reduced-size objects readout in the calorimeter (HCAL, ECAL, HF) and muon chambers (CSC, DT, RPC), called *Trigger Primitives* (TP), by the (2-layers e/γ, *jets*, τ and E^T finder) **Calorimeter** and (3-subdetectors μ finder) **Muon Trigger** systems.
- The **Global Trigger (μGT)** combines μGMT (Muon Trigger last stage) and Calorimeter Trigger Layer-2 information, making a trigger decision based on the L1 algorithms menu for event tranfer to the *High-Level Trigger* (HLT).

Datasets

- Reconstructed L1 physical objects, such as E_T^{miss}, H^T, E^T, and the reconstructed particles (p_T, η, ϕ) momenta, are available in the μGT, corresponding with maximum of 12 e/γ's, 8 μ's, 12 τ's, and 12 jets particle inputs. E_T^{miss} has been considered as an extra input.
- For **A**nomaly **D**etection (AD) algorithms *training and testing*, unfiltered **background data** (named *Zero Bias*) collected by a CMS at LHC's Run 3 ($\sqrt{s} = 13.6$ TeV) p-p collision data events are used. The most recent algorithms are undergoing training with the *Run 381148/9* Ephemeral Zero Bias 2024 dataset, subject to the *menuv100* trigger menu selection criteria.
- For AD trigger algorithms *inference and performance evaluation*, benchmark Monte Carlo-simulated BSM scenarios are used. The most recent datasets (Run 3 Winter 2024 Campaign 133X) have been generated using `PYTHIA8` and `POWHEG`, and correspond to BSM **signal data** that may include VBF's, LLP's and SUSY samples. $H\,[125\text{GeV}] \rightarrow 2LLP\,[50\text{GeV}] \rightarrow 4b$ and $VV \rightarrow H \rightarrow 2\tau$ are signal examples.

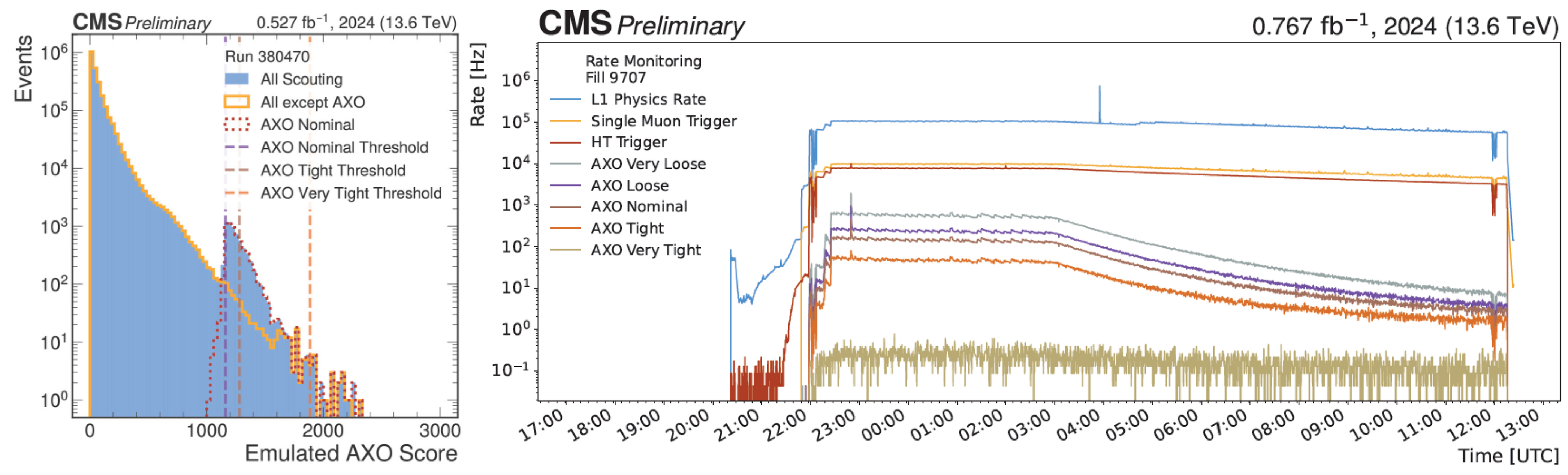
Trigger Algorithms

- **CICADA** (on-Calorimeter Layer-1) and **AXOL1TL** (on-μGT board), based on CNN and DNN autoencoders, are the leading AD trigger algorithms in CMS. AXOL1TL is taking data since May 2024, and CICADA was deployed in October. Let's focus on AXOL1TL:



AD Encoder

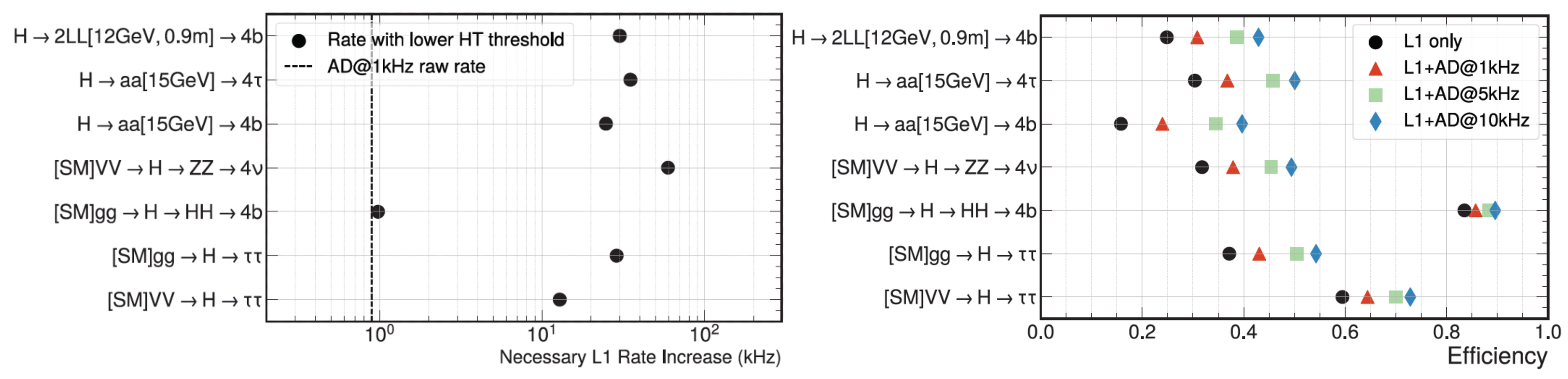
- AXOL1TL is asymmetric and unsupervised DNN ***V**ariational **A**uto**E**ncoder* (VAE) with a `Qkeras`-based quantized encoder trained on unsaturated, reshaped, bit-quantized, normalized, and pruned ***background data***, that inputs reconstructed L1 objects as (p_T,η, ϕ) hardware vectors. AXO's VAE is truncated to meet μGT resource and latency requirements (50 ns) in its FPGA L1 menu deployment via `hls4ml`.



- AXOL1TL calculates the abnormality degree in its latent space, distinguishing between ***background*** and ***signal***, and is regularized by a Gaussian *Kullback-Leibler divergence* ($D_{KL}\left[N(\mu,\sigma^2)||N(0,1)\right] \sim \mu^2$) , defined as an *Anomaly Score*, which sets a trigger threshold rate in the μGT logic. An increase in *pure* events (selected exclusively by AXOL1TL) was observed, improving physics performance relative to the L1 menu. A correlation with other triggers at high scores was also identified, along with a significant increase in signal efficiency for low trigger rate increments. It also was tested on MP7 boards in the GT test crate (μGT replica), showing a significant gain in efficiency for Higgs-to-scalar-to-quark BSM signals.

AXOL1TL Rate	1kHz	5kHz	10kHz
$H \rightarrow aa \rightarrow 4b$ Signal Efficiency Gain	46 %	100 %	133 %

- In general, AXOL1TL has shown a significant performance increase across various benchmark BSM signals when added to the top of the current L1 menu, exceeding 100% for some at a raw rate of 5 kHz. This has suggested that achieving the same signal efficiency improvement by lowering thresholds in traditional L1 paths leads to an unsustainable increase in background rate, with a worse purity than with AXOL1TL.



Future Work

The AXO+CICADA paper is now in progress, and the AXO's pipeline is being expanded to include τ leptons, boosting the model's robustness!

KEY REFERENCES

[1] Sun, C. (2023). AXOL1TL: Real-time Anomaly Detection in the CMS Hardware Trigger.
[2] Govorkova et al. (2021). LHC Physics Dataset for Unsupervised New Physics Detection at 40 MHz.
[3] Belis et al. (2024). Machine learning for anomaly detection in particle physics. Reviews in Physics, 100091.

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MORE INFORMATION

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https://gitlab.cern.ch/cms-l1-ad/l1_anomaly_ae/