REAL-TIME UNSUPERVISED ANOMALY DETECTION IN THE CMS LEVEL-1 TRIGGER

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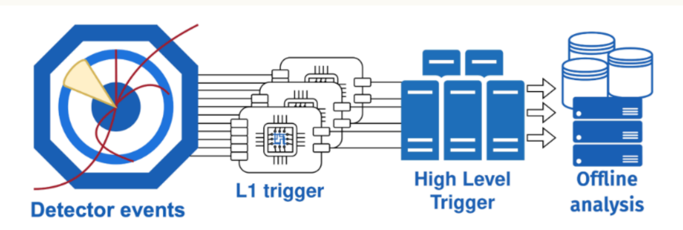
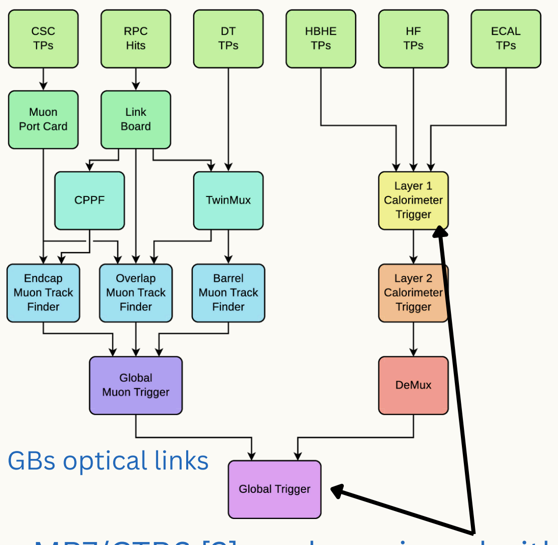
Level 1 Trigger

The CMS experiment at the LHC deploys a two-step trigger system to filter a 40 MHz proton-proton collision rates down to ~2 KHz for offline analysis.

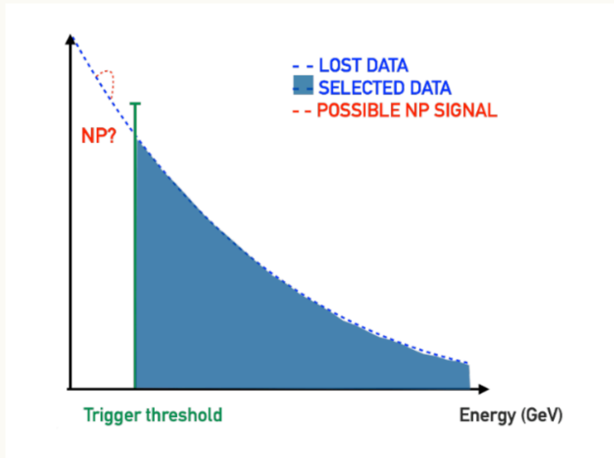


The L1 Trigger [1] reconstructs physics objects from detector subsystems, combining them in the Global Trigger (GT) to define a menu of conditions for the final accept/reject decision.



MP7/CTP6 [2] cards equipped with Xilinx Virtex-7 FPGA

Anomaly Detection



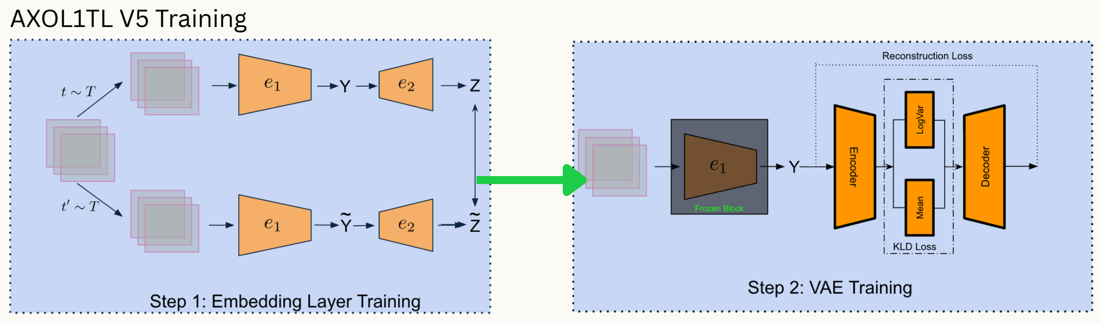
Although the trigger menu performs effectively, new physics may fall outside its acceptance. Anomaly detection triggers, such as AXOL1TL [3], and CICADA [4] are designed to identify new physics without bias toward specific signatures.

Anomalies can appear at any trigger and data representation level: the GT can detect anomalies in object correlations, while the calorimeter trigger can detect anomalous energy depostits.

AXOL1TL

AXOL1TL is deployed in the GT as Variational Autoencoder (VAE), and takes as input all available reconstructed objects: (pT, η, ϕ) of 4 e/γ, 4 μ, 10 jets, and P_T(miss).

AXOL1TL V5 Training

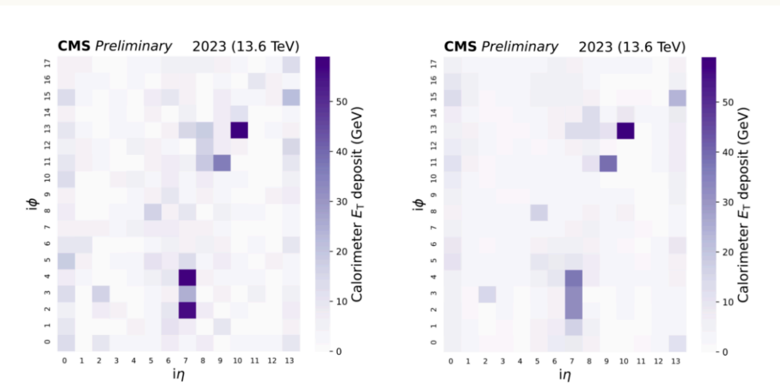


Step 1: Pre-training of encoder block using augmented views of the same event and the VICREG [5] loss.

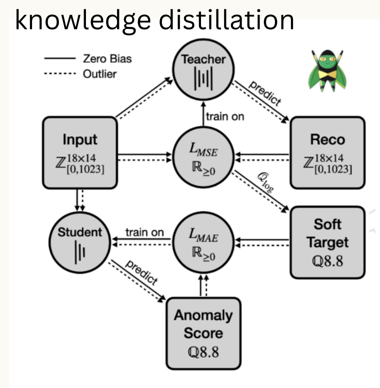
Step 2: Train VAE on encoder output: $S_{\text{Anomaly}} = \text{MSE}(X, \tilde{X}) = \frac{1}{n}\sum_{i=1}^{n}(x_i - \tilde{x}_i)^2$

CICADA

CICADA is deployed in the Calorimeter Layer 1 Trigger and takes as input a 18 x 14 φ x η grid of energy deposits. Then uses a Convolutional autoencoder (AE) to reconstruct its input.



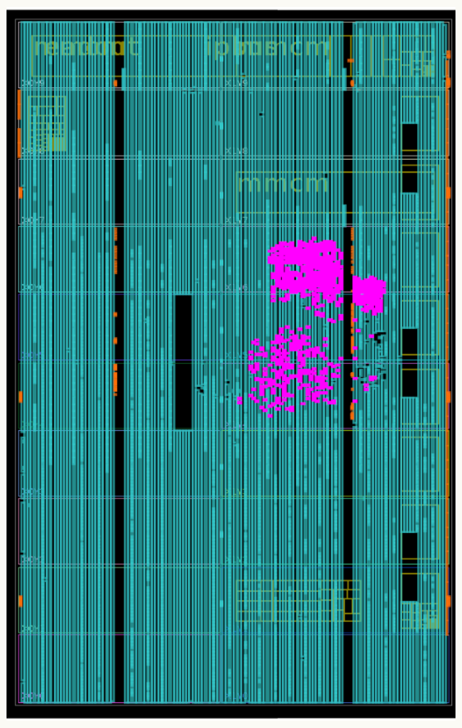
knowledge distillation



Step 1: Train a large teacher model to perform encoding and decoding.

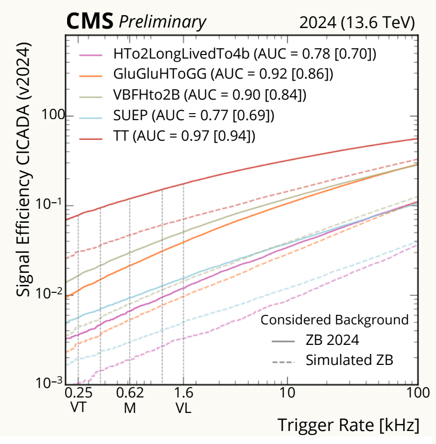
Step 2: Compact student model is trained to direct predict the anomaly score from the tracher. The student model is deployed.

Deployment

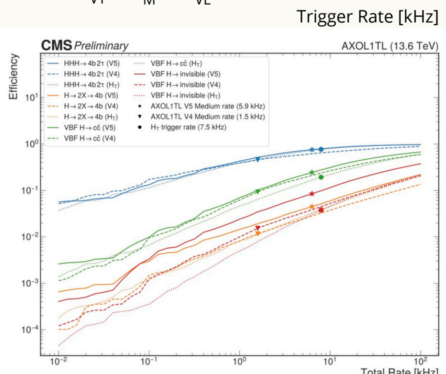


AXOL1TL and CICADA employ Quantization-Aware Training (QAT) [6] and are converted to firmware via High-Level Synthesis (HLS) using the HLS4ML tool [7]. Additionally, AXOL1TL uses the distributed arithmetic DA4ML [8] package to reduce latency, achieving a 50 ns target. AXOL1TL consumes ~1% of the chip's look-up-table (LUT) and digital-signal-processing (DSP) resources. The floorplan displays one GT module with AXOL1TL highlighted in pink. CICADA achieves timing closure in 81.25 ns, using 20% of resources on chip.

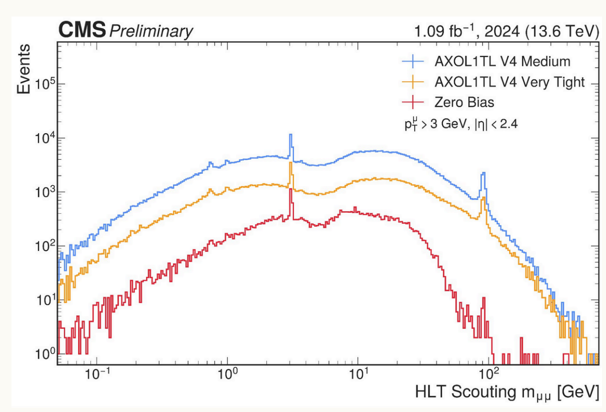
Results



Signal efficiency for multiple signals versus total CICADA rate, with M representing CICADA's total operation rate [4].



Signal efficiency for multiple signals versus total AXOL1TL rate. Points mark AXOL1TL V4 and V5 at their operating rate and H_T trigger for comparison [3].



Di-mass spectrum of HLT scouting [11] muons for AXOL1TL collected events shows the peak structure of J/ψ meson (3.1 GeV) and Z boson (91 GeV) [3].

References:
[1] CMS Collaboration, "CMS Technical Design Report for the Level-1 Trigger Upgrade," CERN-LHCC-2013-011, CMS-TDR-12, 2013
[2] K. Compton et al., "The MP7 and CTP-6: multi-hundred Gbps processing boards for calorimeter trigger upgrades at CMS," JINST, vol. 7, no. 12, 2012
[3] CMS Collaboration, Public Results, https://twiki.cern.ch/twiki/bin/view/CMSPublic/L1TriggerDPGResults
[4] CMS Collaboration, "Level-1 Trigger Calorimeter Image Convolutional Anomaly Detection Algorithm," CMS-DP-2023-086, 2023, https://cds.cern.ch/record/2879816
[5] A. Bardes, J. Ponce, and Y. LeCun, "VICReg: Variance-Invariance-Covariance Regularization for Self-Supervised Learning" 2022. Available: https://arxiv.org/abs/2105.04906
[6] Coelho, C.N. et al., "Automatic heterogeneous quantization of deep neural networks for low-latency inference on the edge for particle detectors." Nat Mach Intell 3, 675–686, 2021
[7] J. Duarte et al., "Fast inference of deep neural networks in FPGAs for particle physics," JINST, vol. 13, no. 07, 2018
[8] https://github.com/calad0i/da4ml
[9] CMS Collaboration, "HLT Scouting performance in 2024: muon triggers and objects," 2025, Available: https://cds.cern.ch/record/2935659

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