

GELATO: A Generic Event-Level Anomalous Trigger Option for ATLAS in LHC Run 3



Kenny Jia on behalf of the ATLAS Collaboration
SLAC National Accelerator Laboratory, Stanford University

Fast Machine Learning for Science 2025

Sep 3rd, 2025



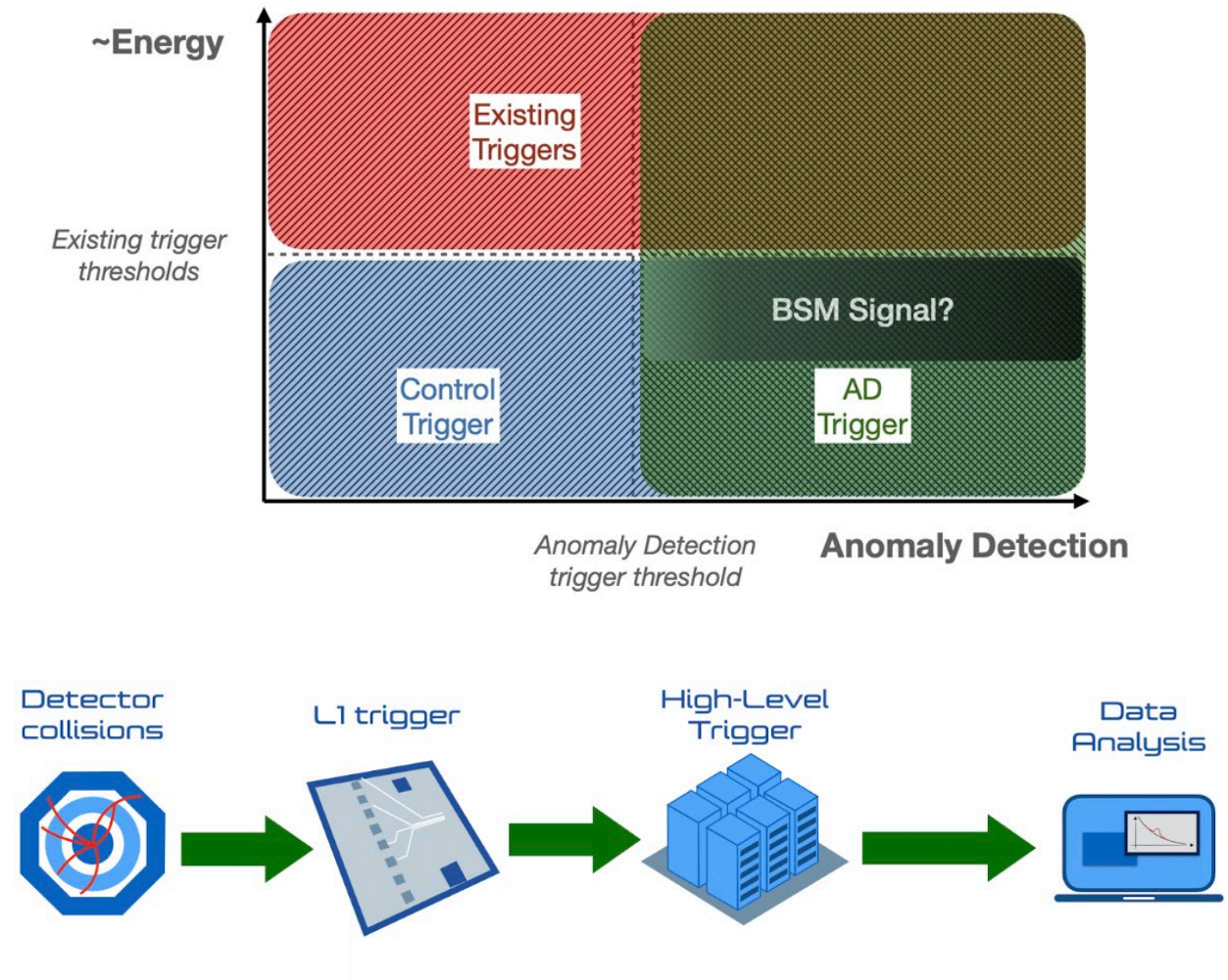
Introduction

Anomaly detection (AD) is generating growing interest in high energy physics, offering a **model-agnostic** approach to new physics with possible access to unknown features.

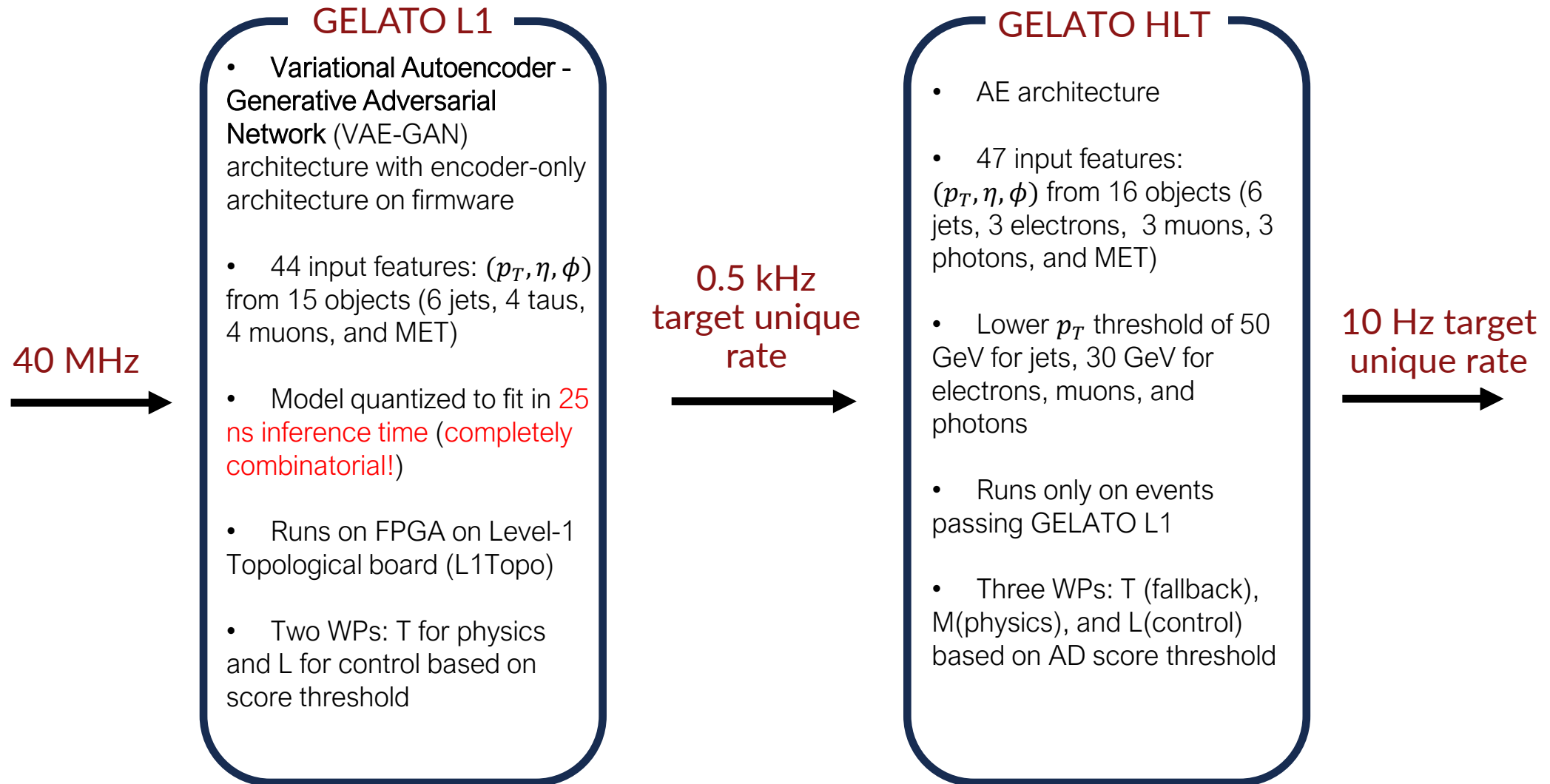
New physics can be rejected by standard set of triggers defined with simple heuristics.

CMS developed AXOL1TL [1], a L1 AD trigger. We introduce **GELATO**, an AD trigger system in both L1 and HLT level, providing unique opportunity to enhance detection efficiency for unknown signatures.

[1] <https://cds.cern.ch/record/2876546>



GELATO pipeline



GELATO in L1Topo

The L1 AD model is a VAE-GAN

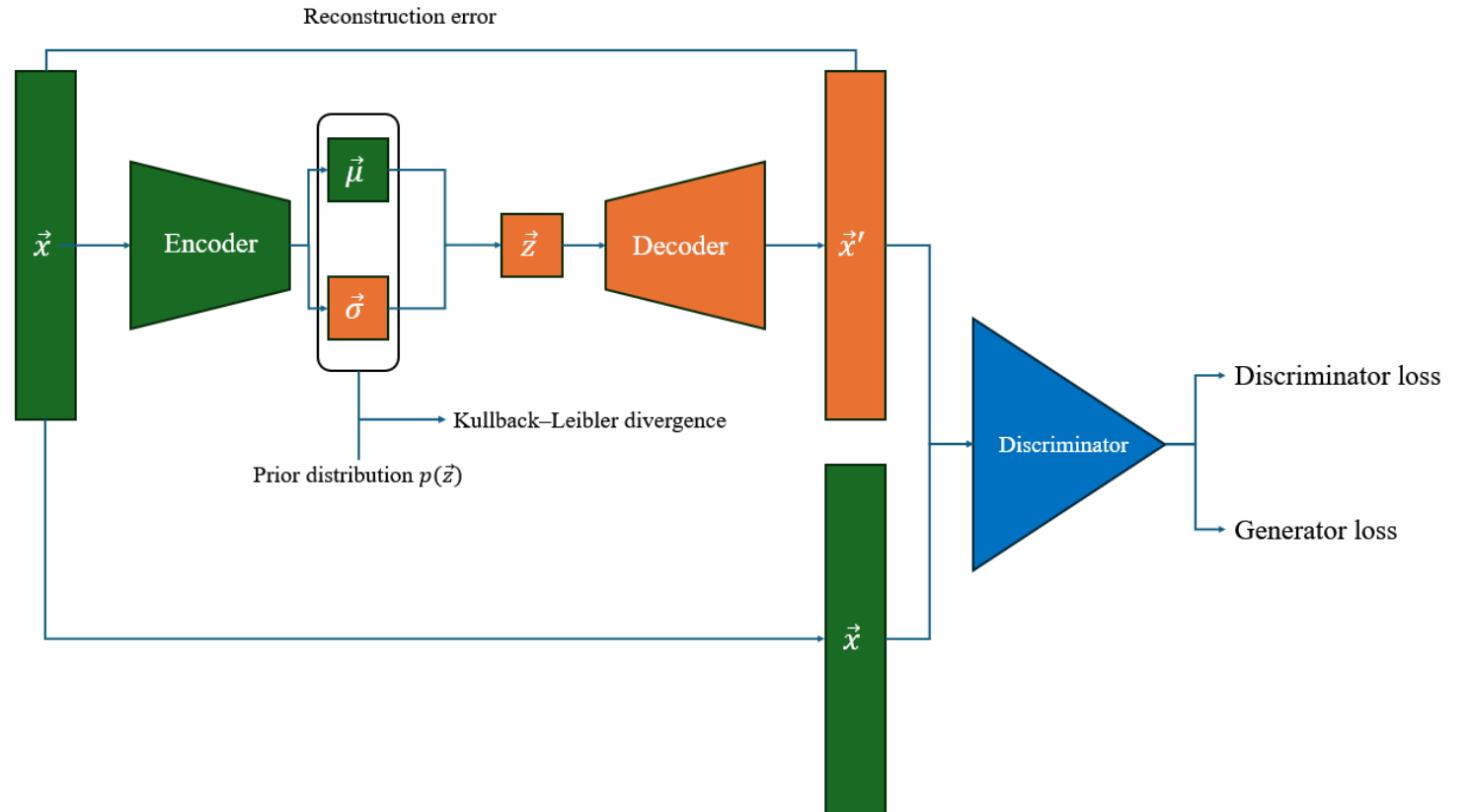
Where: VAE tries to encode input into latent representation and decode without recognize by discriminator. Discriminator attempts to distinguish inputs and outputs.

$$\mathcal{L}_{total} = MSE + \beta \times \mathcal{L}_{KL} + \gamma \times \mathcal{L}_{GAN}$$

AD score defined as the approximation of KL divergence

$$\mathcal{L}_{KL} = \sum \mu^2 + \sigma^2 - \log(\sigma^2) - 1$$

Online part sizes: 44 → 32 → 16 → 3



GELATO in L1Topo

The L1 AD model is a **Variational Autoencoder-Generative Adversarial Network(VAE-GAN)**

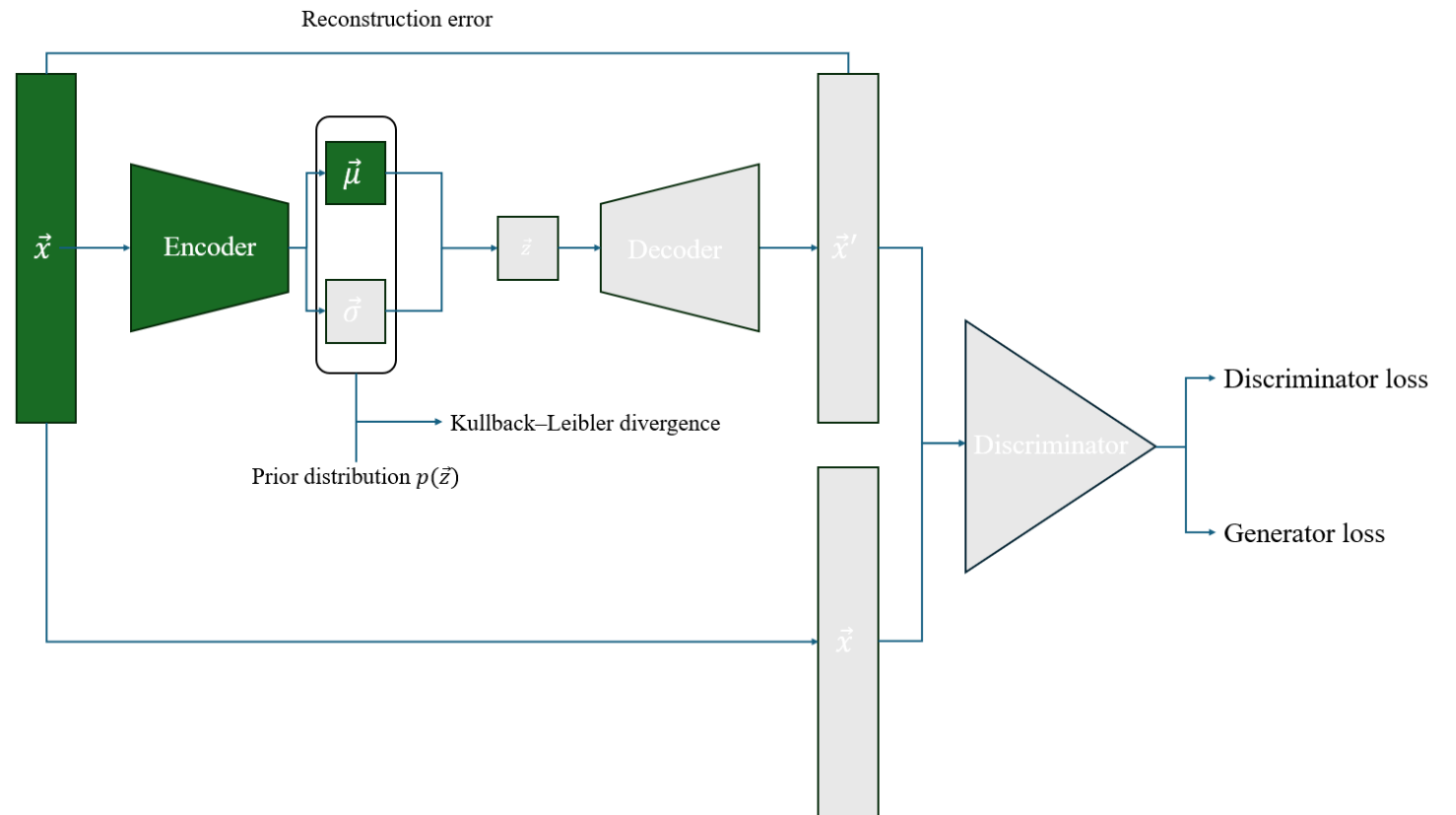
Where: VAE tries to encode input into latent representation and decode without recognize by discriminator. Discriminator attempts to distinguish inputs and outputs.

$$\mathcal{L}_{total} = MSE + \beta \times \mathcal{L}_{KL} + \gamma \times \mathcal{L}_{GAN}$$

AD score defined as the approximation of KL divergence

$$\mathcal{L}_{KL} = \sum \mu^2 + \sigma^2 - \log(\sigma^2) - 1$$

Online part sizes: 44 → 32 → 16 → 3



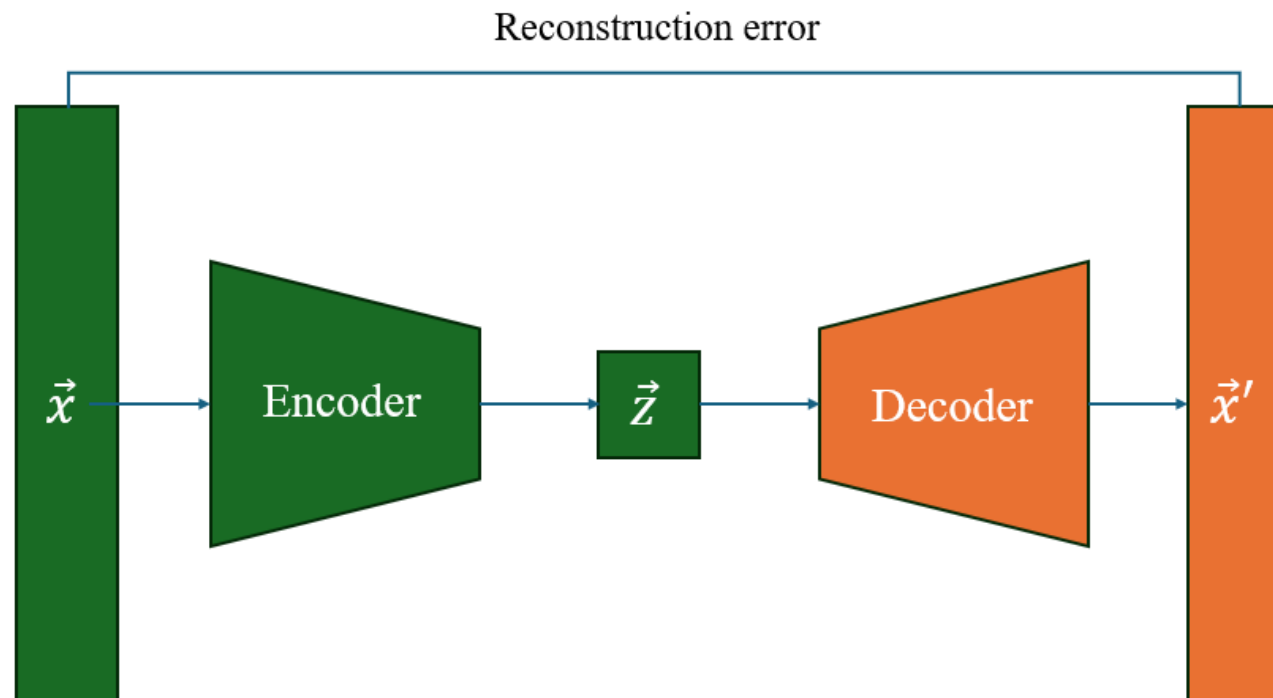
GELATO in HLT

The HLT AD model is an Autoencoder(AE) trained with masked mean squared error(MSE) loss: masked zero values from standard MSE.

AD score defined with the same loss used in training.

Network sizes:

$47 \rightarrow 100 \rightarrow 100 \rightarrow 64 \rightarrow 32 \rightarrow 4$



Datasets for training and testing

Both the L1 and HLT AD models are trained and tested with Enhanced Bias dataset (EB) and ZeroBias (ZB) dataset taken in 2024 (closest detector conditions to what we expect for 2025)

EB data are taken with an invertible trigger menu such that a single weight is calculable per event which corrects for the prescales applied during data taking and restores an effective ZB spectrum

Evaluation Signal Monte Carlo:

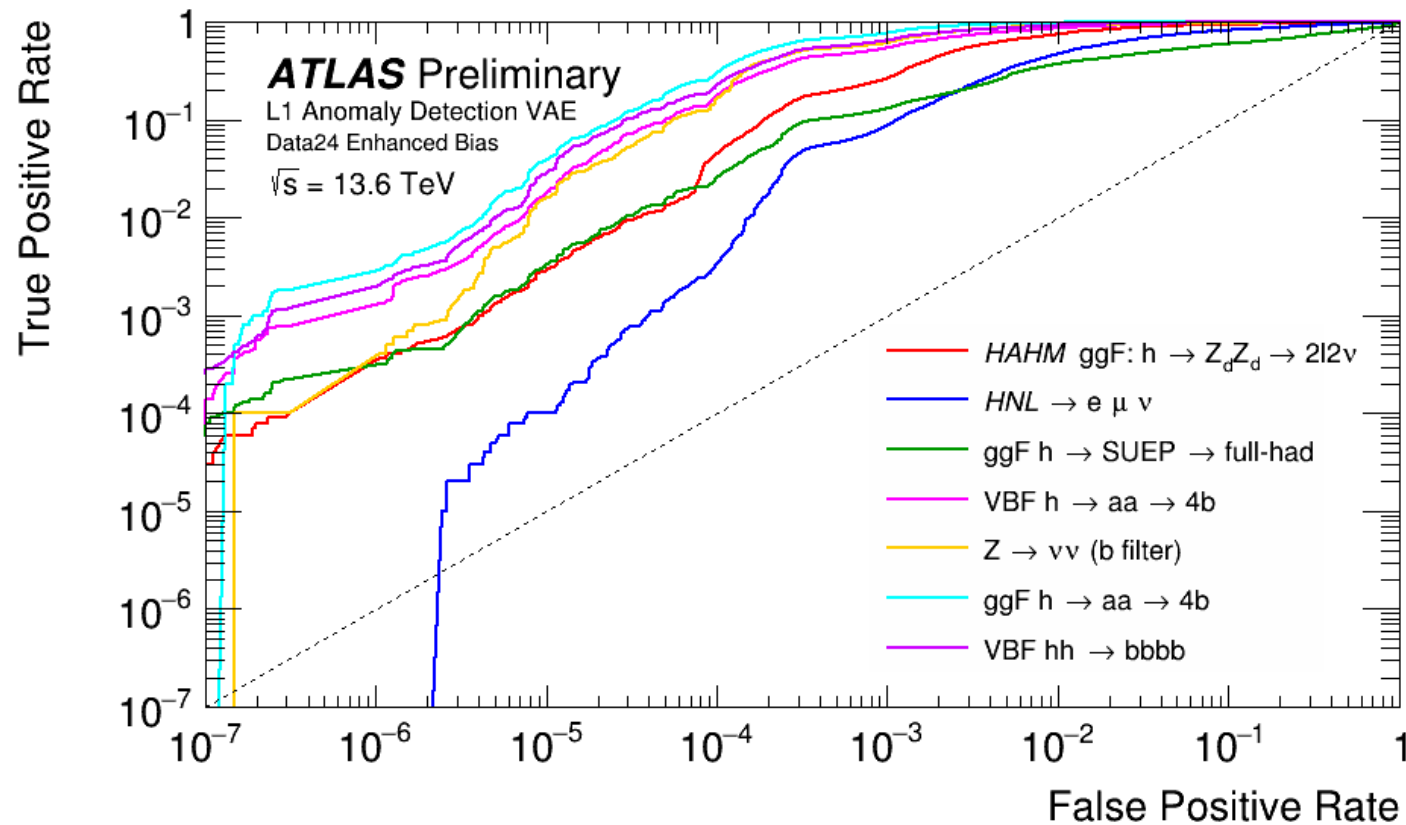
We test models with a broad selection of signal process to exhibit the model-independence. Selected cases where standard ATLAS triggers struggle:

1. $\text{HNL} \rightarrow e^\pm \mu^\pm \nu, m = 7.5 \text{ GeV}, c\tau = 1 \text{ mm}$
2. $\text{HAHM (ggF): } h \rightarrow Z_d Z_d \rightarrow 2\ell 2\nu, m_{Z_d} = 28 \text{ GeV}$
3. $\text{ggF: } h \rightarrow \text{SUEP} \rightarrow \text{full-hadronic}$
4. $\text{VBF } h \rightarrow aa \rightarrow 4b, m_a = 55 \text{ GeV}, \tau_a = 1 \text{ ns}$
5. $Z \rightarrow \nu\bar{\nu}$ (b filter)
6. $\text{ggF } h \rightarrow aa \rightarrow 4b, m_a = 16 \text{ GeV}, \tau_a = 10 \text{ ns}$
7. $\text{VBF } h \rightarrow 4b$



Performance evaluation: L1

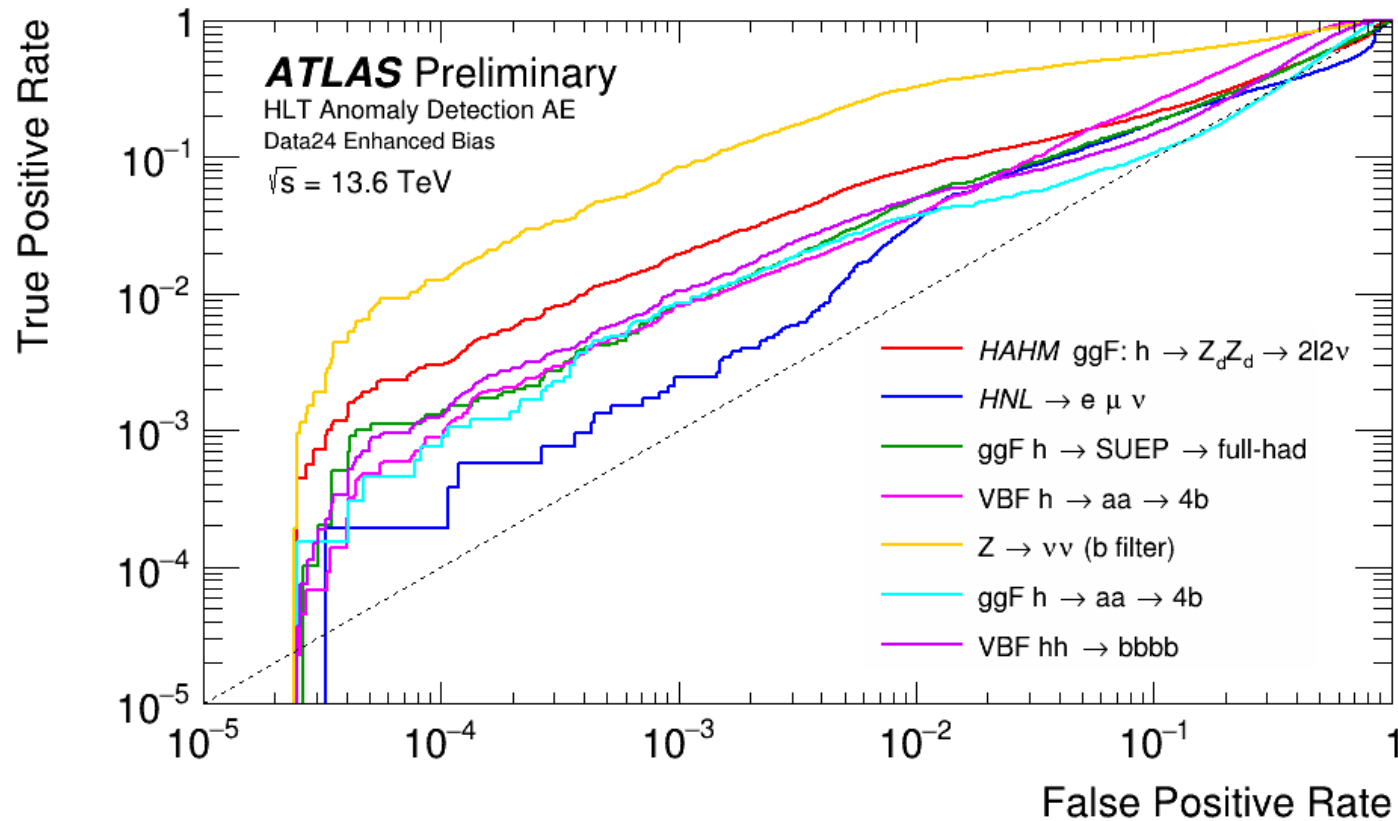
ROC curves for the L1 AD model, across wide variety of selected signatures. Performance evaluated at unique rate of 1 kHz, correspondent to FPR of 3.7×10^{-4}



<https://cds.cern.ch/record/2933255/>

Performance evaluation: HLT

ROC curves for GELATO system at HLT level, across wide variety of selected signatures. Performance evaluated at unique rate of 10 Hz, correspondent to FPR of 9.5×10^{-3}



<https://cds.cern.ch/record/2933255/>

Implementation and Validation

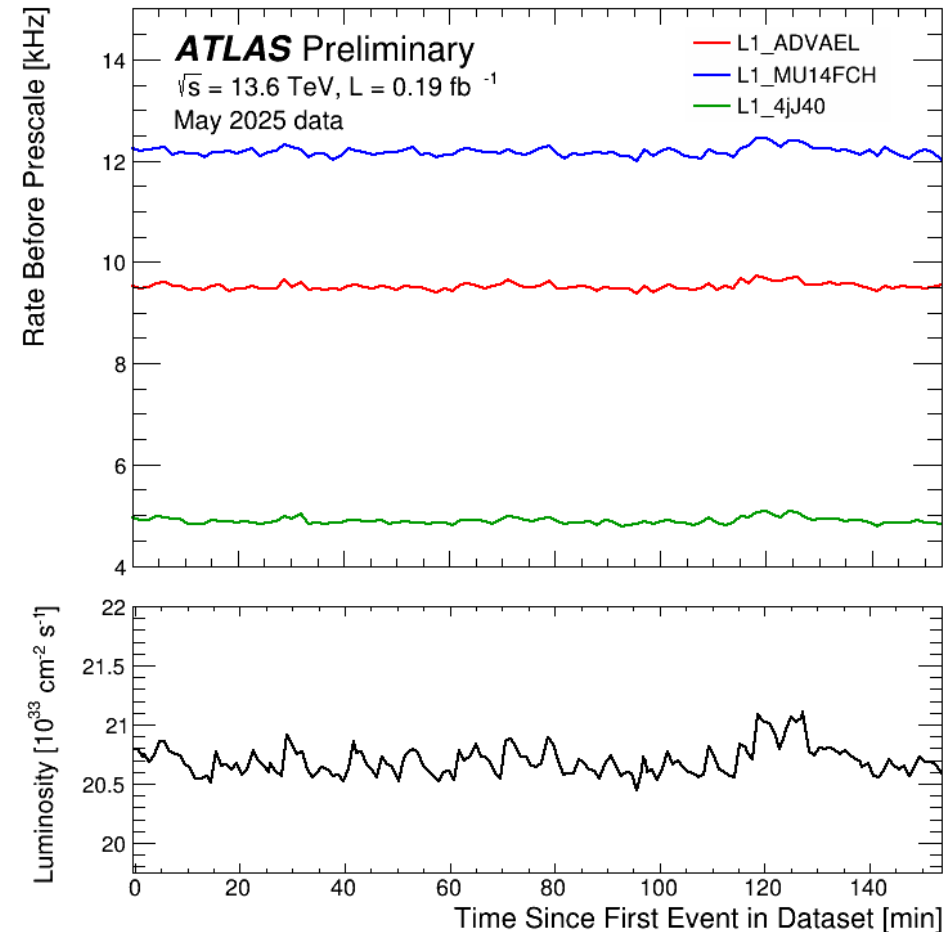
- Implementation:
 - High Level Synthesis for the L1 model done using [hls4ml](#). Model synthesized with AMD Vitis™
 - The HLT model converted to ONNX model for implementation in Athena running in HLT CPUs

- Validation:
 - L1: **Agreement** between firmware simulation, C simulation, and Athena simulation, up to sorting ambiguities in objects with equal p_T
 - HLT: **Agreement** between offline score computation and Athena implementation successfully verified

Trigger Rate Monitoring

Observed **L1_ADVAEL (GELATO L1)** stable trigger rate at ATLAS Central Trigger.





- Rates of **L1_ADVAEL (GELATO L1)** consistent with LHC luminosity and that of **L1_MU14FCH (14 GeV single muon trigger)** and **L1_4jJ40 (40 GeV 4-jet trigger)**.
- Total rate of 9.5 kHz consistent with calculations for 1 kHz unique rate



<https://cds.cern.ch/record/2933255/>

2025 Commissioning strategy

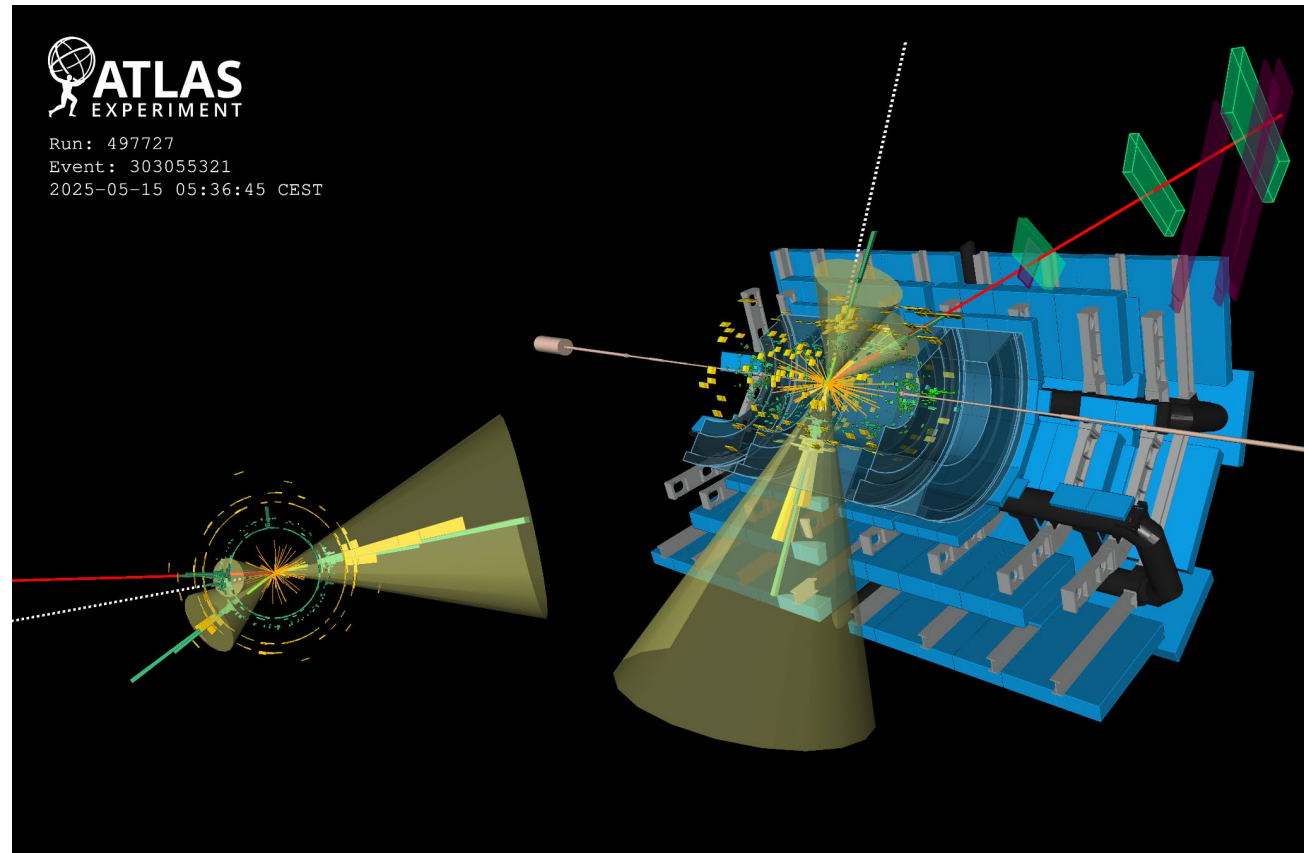
Gradual commissioning strategy in progress to ensure safe deployment 

- Early LHC ramp-up (April – Early May): 
 - GELATO L1 rate monitoring at ATLAS Central Trigger for stability checks. Not used for actual trigger decision
- First stable beams (Mid-May): 
 - GELATO L1 enabled for trigger decisions with pass-through HLT chain in 1 Hz prescaled rate
 - GELATO HLT not activated
- With stable detector/trigger conditions (Mid-June): 
 - GELATO HLT activated at ~0.1 Hz prescaled rate for checking events triggered by complete GELATO and CPU cost evaluation (0.5-1% of full harm)
- Next step: 
 - Enable complete GELATO chain with full capacity once everything is fully examined.

First Look at 2025 Data!



Event display of a GELATO L1 fired event with the highest GELATO HLT AD score during May 2025 with 13.6 TeV

Four jets with $p_T > 50$ GeV, three electrons and one muon with $p_T > 30$ GeV, and $E_T^{miss} = 215$ GeV.



<https://cds.cern.ch/record/2933255/>

Summary

- **First Anomaly Detection Trigger in ATLAS is now running!**
 - GELATO: two autoencoder-based AD algorithms at L1 and HLT
 - Sensitive to wide variety of physics signatures
 - Various studies and validations for successful deployment 
- Next steps
 - In process of ramping up operations to full capacity 
 - Strategies for calibration and physics analysis

Bon Appétit!



Backup



Firmware Resource Usage

```
=== Post-Implementation Resource usage ===  
SLICE:          0  
LUT:           23917  
FF:            0  
DSP:           0  
BRAM:          0  
URAM:          0  
LATCH:         0  
SRL:           0  
CLB:           4543
```

