GELATO: A Generic Event-Level Anomalous Trigger Option for ATLAS

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SLAC NATIONAL ACCELERATOR LABORATORY

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ATLAS EXPERIMENT

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U.S. DEPARTMENT OF ENERGY

Introduction

- The ATLAS trigger system is designed to control the data collection rates while maintaining an *unbiased* efficiency for many physics processes

- The trigger algorithms are tuned to have either baseline energy thresholds, or use a specific event topology to make a decision, limiting the potential to unusual and unanticipated BSM signatures
- Anomaly detection (AD) techniques provide a model agnostic approach to look for such signs of new physics

- We introduce **GELATO**, a topological AD-based trigger chain deployed in the ATLAS experiment

GELATO Pipeline

Level-1 (L1):
Hardware Based

High Level
Trigger (HLT):
Software Based

GELATO L1

Event-topology based anomaly detection algorithm running on an FPGA

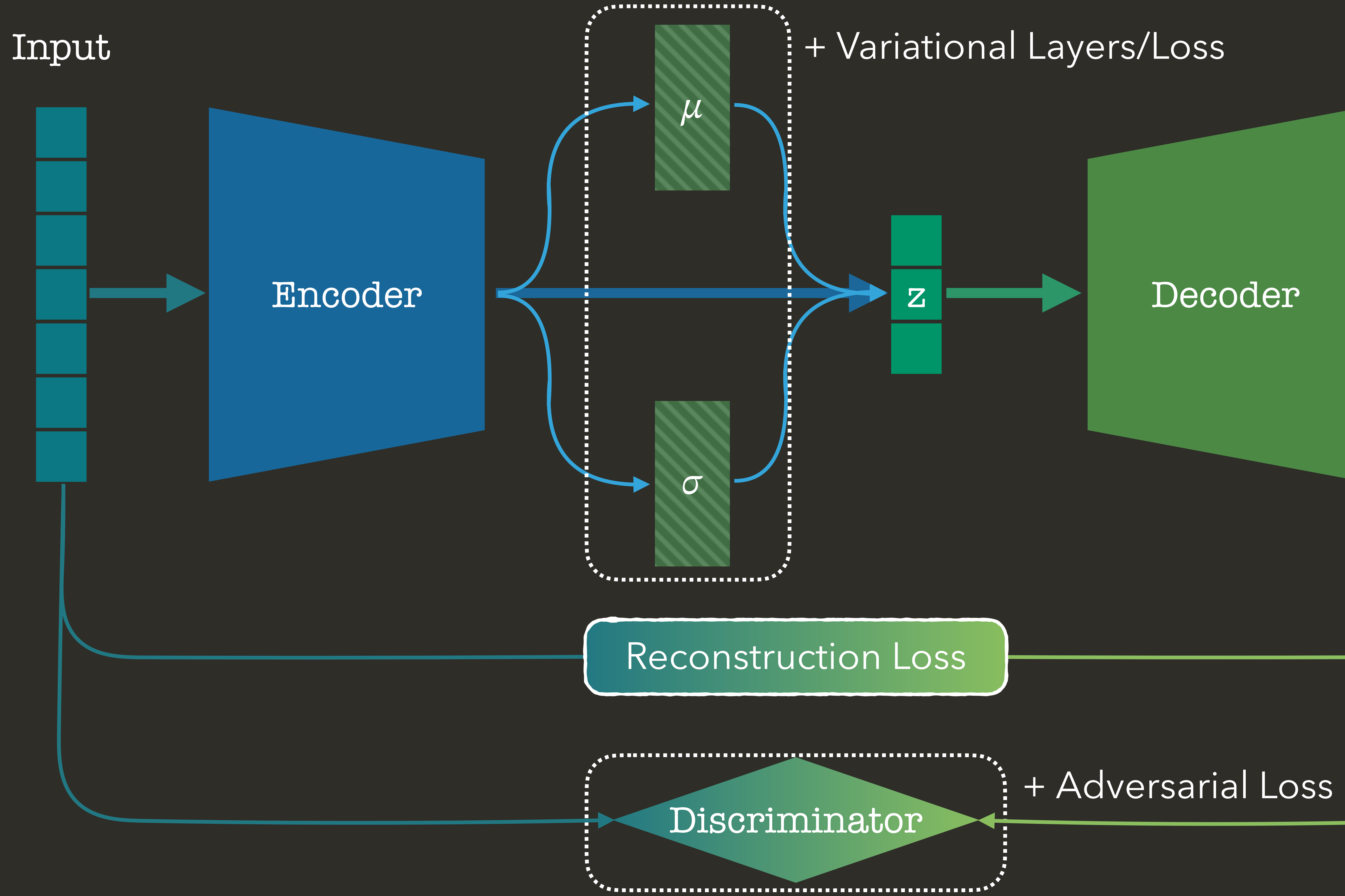
GELATO HLT

Event-topology based anomaly detection algorithm running on a CPU

Both models trained unsupervised

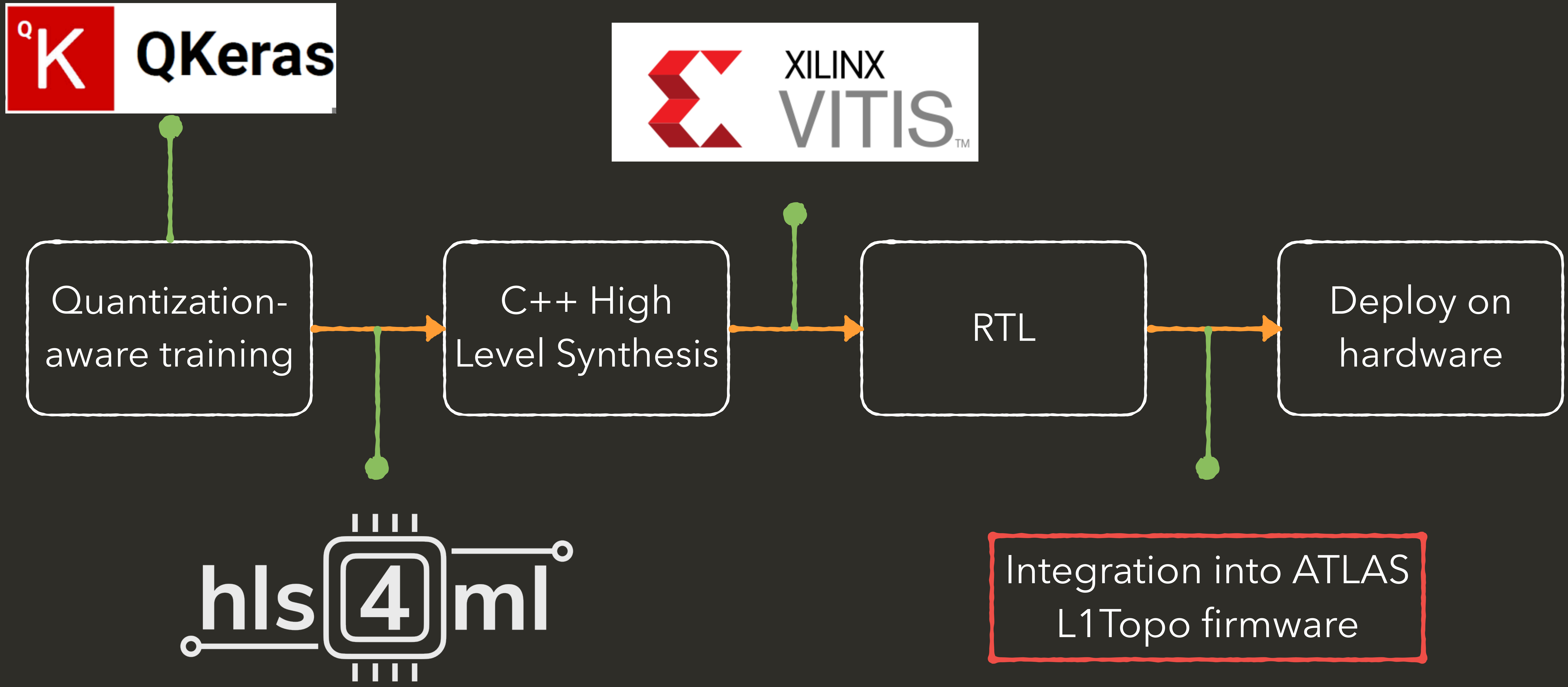
GELATO L1 Model

Quantization-aware training using Level-1 object reconstruction precision of a Variational Autoencoder - Generative Adversarial Network (VAE-GAN)



$$\mathscr{L} = \text{Mean Squared Error} + \beta \cdot \mathscr{L}_{\text{KL-Divergence}} + \gamma \cdot \mathscr{L}_{\text{GAN}}$$

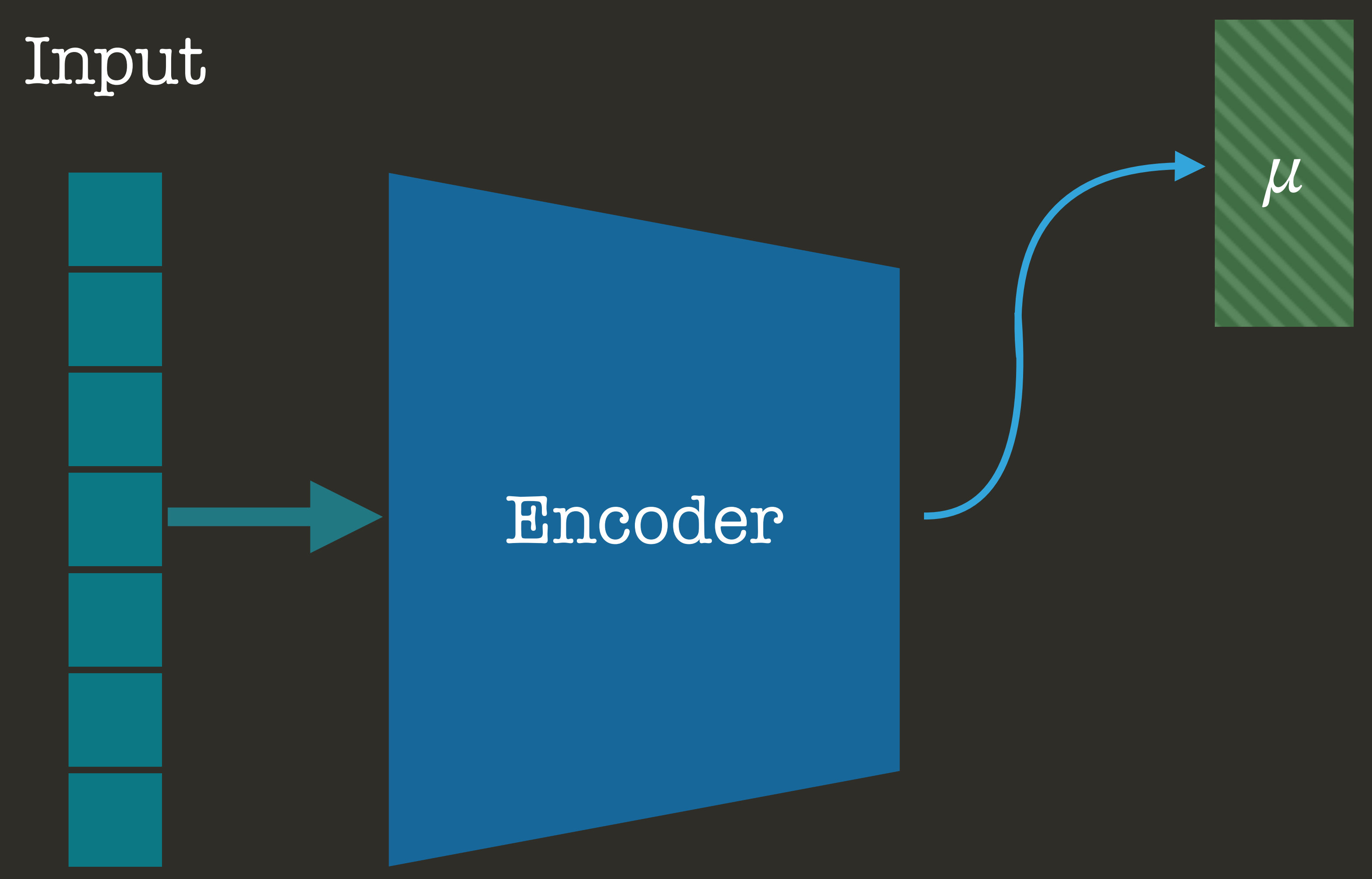
Synthesis


QKeras
XILINX VITIS
Quantization-aware training
C++ High Level Synthesis
RTL
Deploy on hardware
hls4ml
Integration into ATLAS L1Topo firmware

Inference

- The ATLAS Level-1 latency is limited at 2.5 μs
- However, most of it is taken up by signal transmission and formation of Level-1 objects
- At the stage of topological decision, further latency is consumed by object sorting and selection

- The GELATO L1 algorithm has no more than **25 ns** (time for 1 LHC bunch-crossing) to run inference! Needs a lot of creativity to fit a large model in the targeted latency requirements



The *clipped* KL-divergence is used as the anomaly score at inference

Anomaly score = $\Sigma \mu_i^2$

GELATO Pipeline

GELATO L1

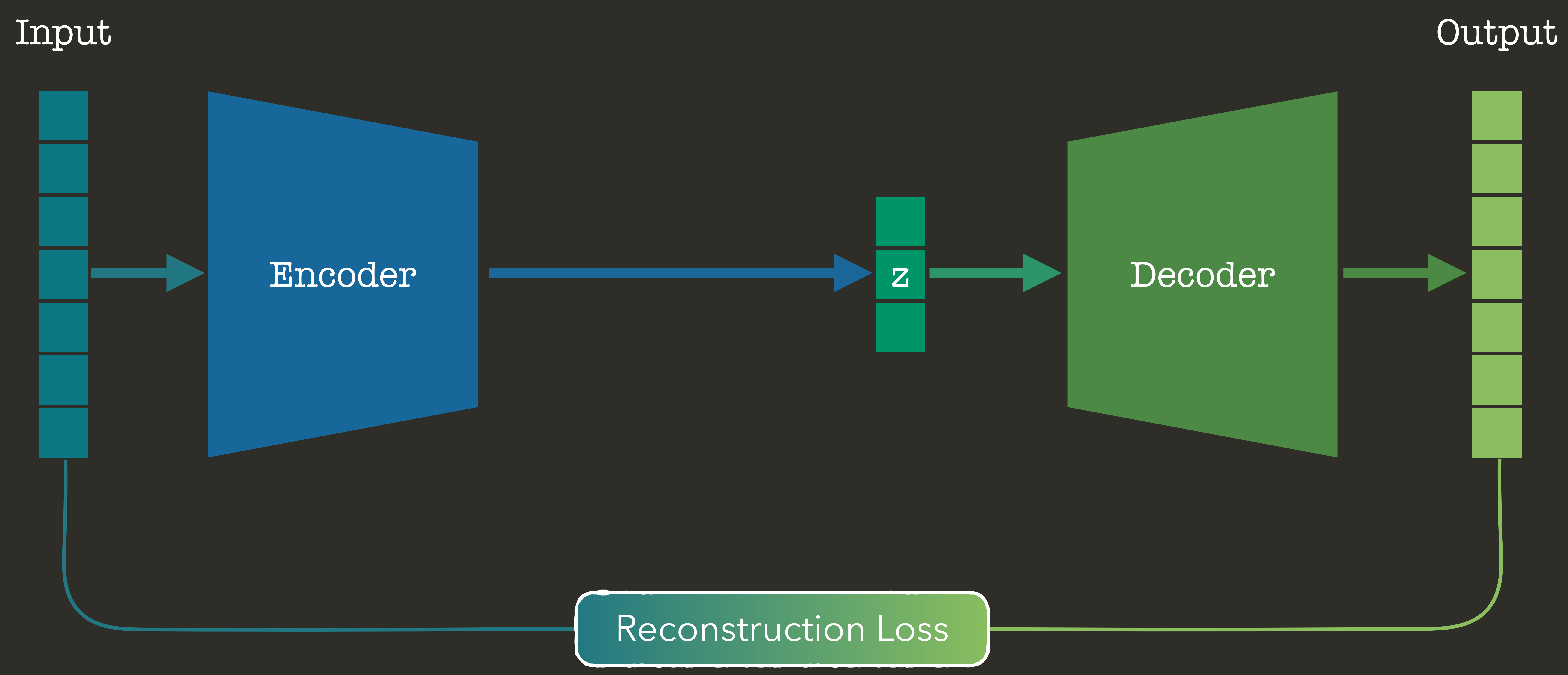
40 MHz

- Reconstruction loss + variational layers + adversarial loss
- **44 input features** (p_T, η, φ) from **15 objects** (6 jJets, 4 eTaus, 4 μ, MET)
- Commissioned to run on **L1Topo**
- Two streams: **T** (physics; 500 Hz) and **L** (control; 1 kHz) based on anomaly score threshold

added 500 Hz

GELATO HLT Model

Floating point training at HLT object reconstruction precision of an Autoencoder



$\mathscr{L}$ = Mean Squared Error

GELATO Pipeline

40 MHz

GELATO L1

- Reconstruction loss + variational layers + adversarial loss
- **44 input features** (p_T, η, φ) from **15 objects** (6 jJets, 4 eTaus, 4 μ, MET)
- Commissioned to run on **L1Topo**
- Two streams: **T** (physics; 500 Hz) and **L** (control; 1 kHz) based on anomaly score threshold

added 500 Hz

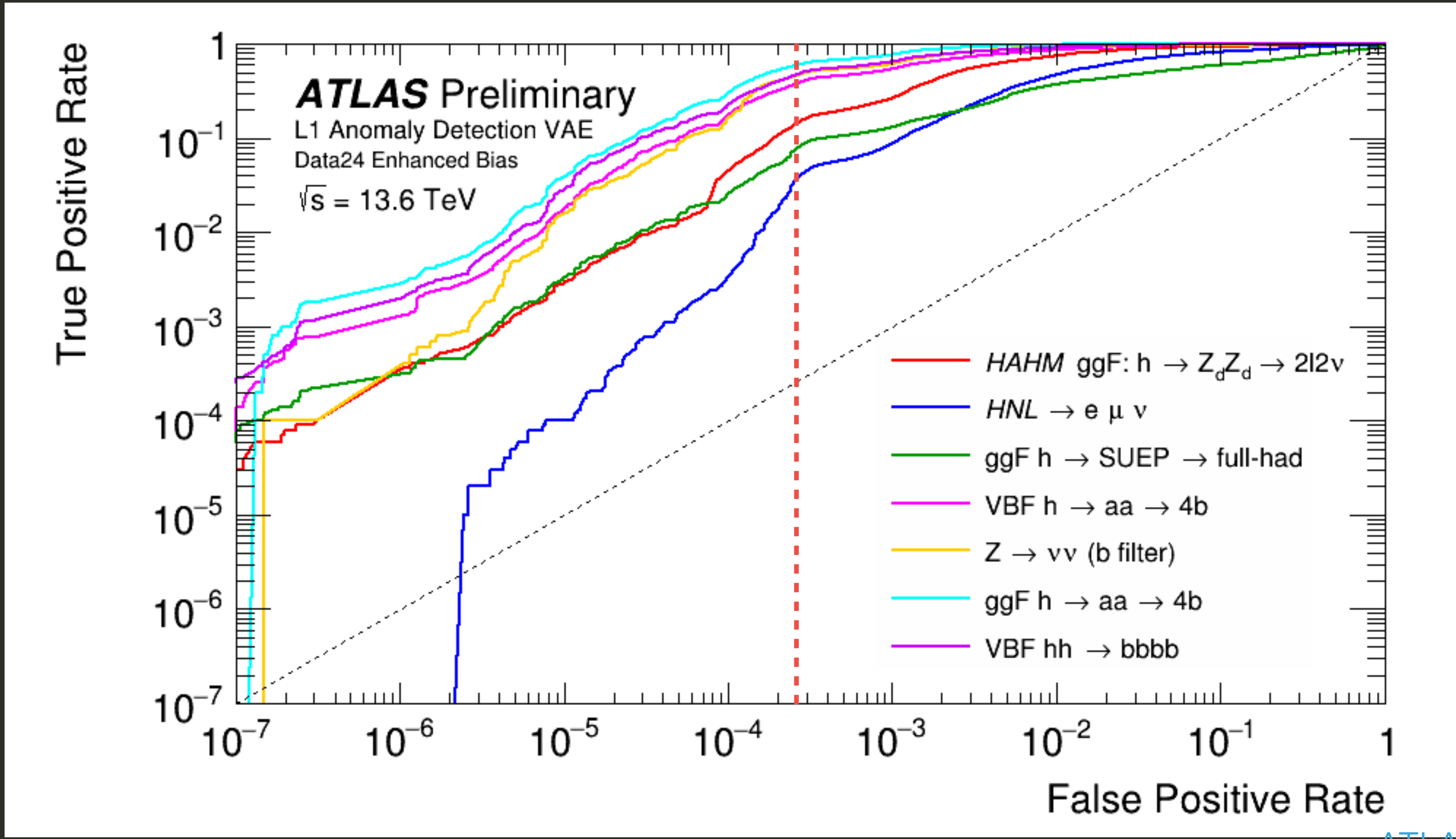
GELATO HLT

- Only reconstruction loss (p_T=0 inputs masked)
- **47 input features** (p_T, η, φ) from **16 objects** (6 jets, 3 μ, 3 e, 3 γ, MET)
- Seeded by **GELATO L1 pass** events
- Three WPs: **T** (fallback; 5 Hz), **M** (physics; 10 Hz), **L** (control; 20 Hz) based on anomaly score threshold

added 10 Hz

GELATO L1 Performance

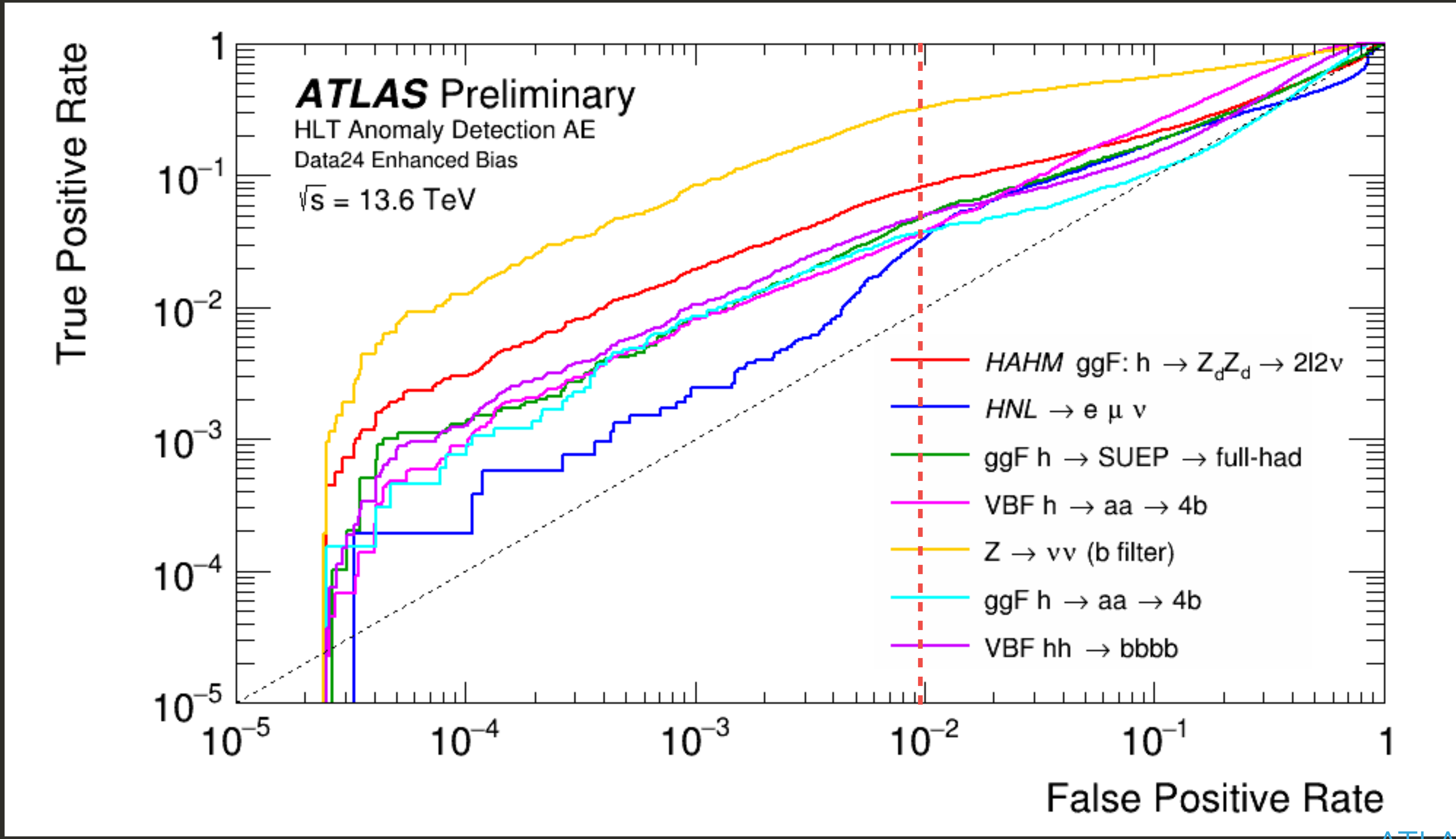
A 500 Hz added rate corresponds to an FPR of 2.6×10^{-4} which leads to 3-60% efficiencies for various processes



[ATLAS Trigger Public Plots]

GELATO HLT Performance

A 10 Hz added rate* corresponds to an FPR of 9.5×10^{-3} which leads to 3-30% efficiencies for various processes

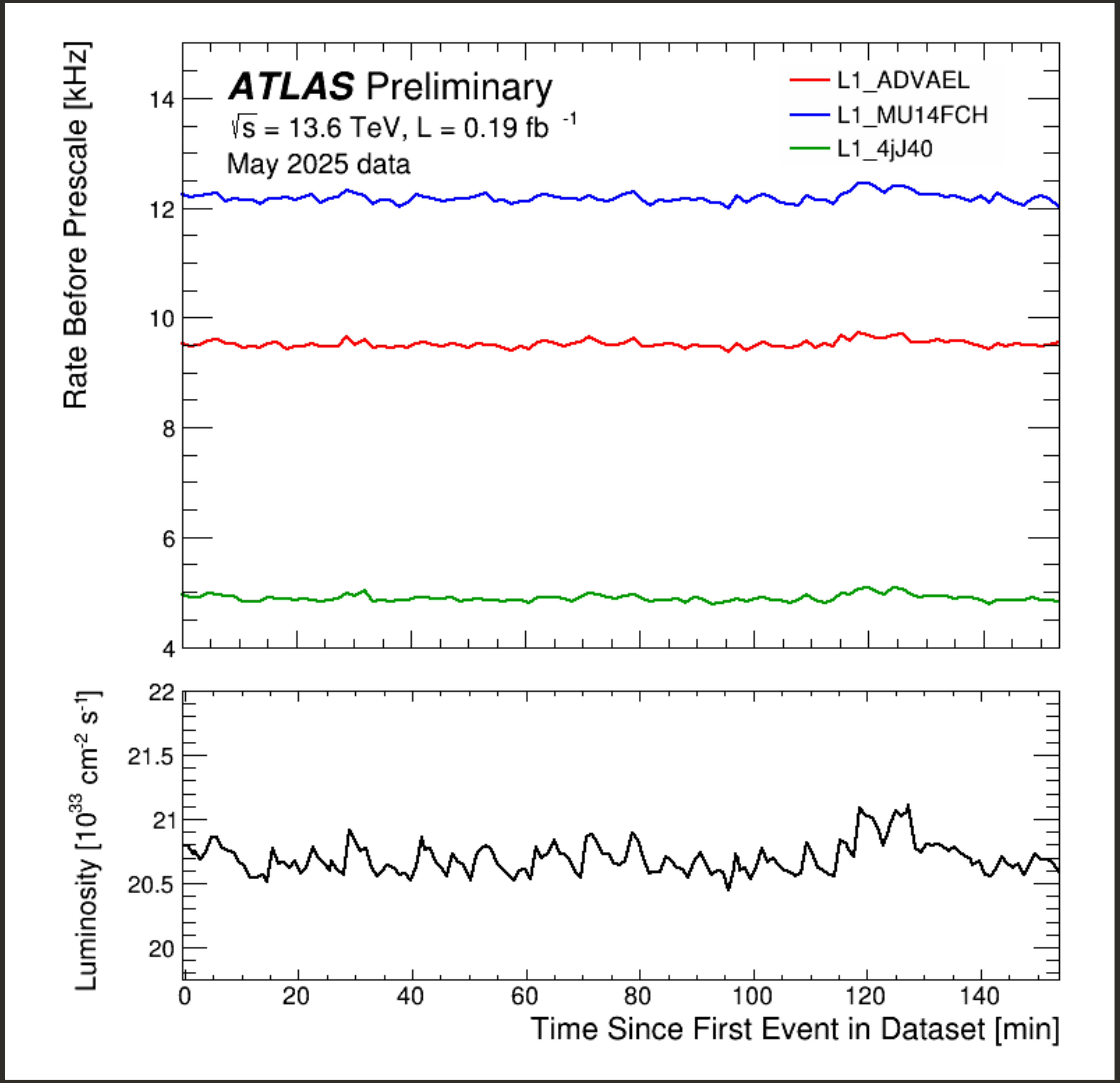


*Performance shown for events passed by GELATO L1 @ **1 kHz**

ATLAS Trigger Public Plots

GELATO L1 Rate Monitoring

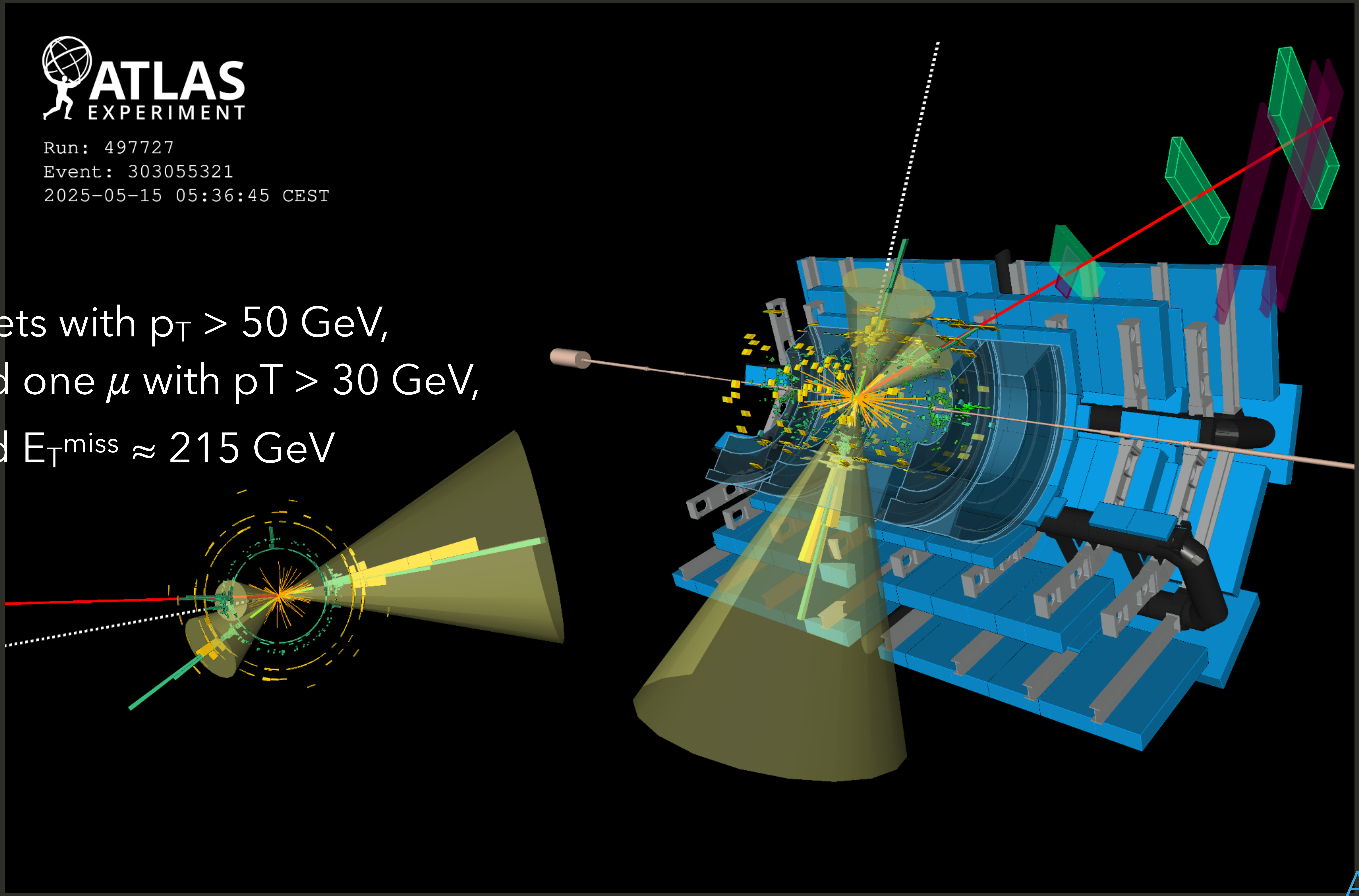
- Stability of the GELATO L1 chain is critical for stable data-taking operations
- Rate changes consistent with LHC luminosity fluctuations and at par with other standard triggers, such as the 14 GeV p_T muon trigger, and the 40 GeV p_T 4-jet trigger
- A *total* rate of 9.5 kHz is consistent with predictions for the corresponding anomaly score threshold
- The rate seen to be sane in abnormal detector conditions, such as local calorimeter hotspots



ATLAS Trigger Public Plots

First look at 2025 data

One of the first (from May) unique events triggered by GELATO L1 with the highest GELATO HLT AD score



Four jets with $p_T > 50$ GeV,
three e and one μ with $pT > 30$ GeV,
and $E_T^{miss} \approx 215$ GeV

ATLAS Trigger Public Plots

Summary and Next Steps

- First anomaly detection triggers are now running in ATLAS
- The models are trained **unsupervised** designed to add sensitivity to a range of physics models and final states
- Ongoing validation looking good – rate stability, physics performance, model response
  - Expect to enable GELATO at the full desired rates soon
- Added suitable support chains based on loosened score thresholds for trigger efficiency calibrations
- Currently studying physics analysis strategies using the collected dataset

ADDITIONAL MATERIAL

Training Dataset

- Both, the L1 and HLT models are trained unsupervised using the ***enhanced bias*** dataset collected in **2024**

- The enhanced bias dataset represents what the L1 sees, sculpted using dedicated event weights
- Originally designed for HLT rate predictions and its dependency on pileup and LHC beam conditions

- L1 model trained using (weighted) enhanced bias events which are not triggered by the 2024 L1 triggers

- HLT model trained with all of 2024 enhanced bias to maintain statistical power
- Looking into adding GELATO L1 to the enhanced bias trigger list for higher training statistics

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Commissioning Strategy

- A gradual commissioning sequence was decided to ensure a safe deployment
- Early ramp-up (April - May): ✅
  - Monitor GELATO L1 rates at ATLAS Central Trigger for stability without enabling the chain
  - GELATO HLT disabled
- First stable beams (May): ✅
  - GELATO L1 enabled at 1 Hz prescaled to check the collected dataset
  - GELATO HLT disabled
- With stable detector conditions (June): ✅
  - GELATO L1 enabled at 500 Hz
  - GELATO HLT enabled at 0.1 Hz prescaled to study trigger rate and CPU cost
- Next: 🕛
  - Enable the full GELATO chain at the desired rates