Real time Auto Encoder based Anomaly Detection Algorithm to Search for New Physics

CICADA

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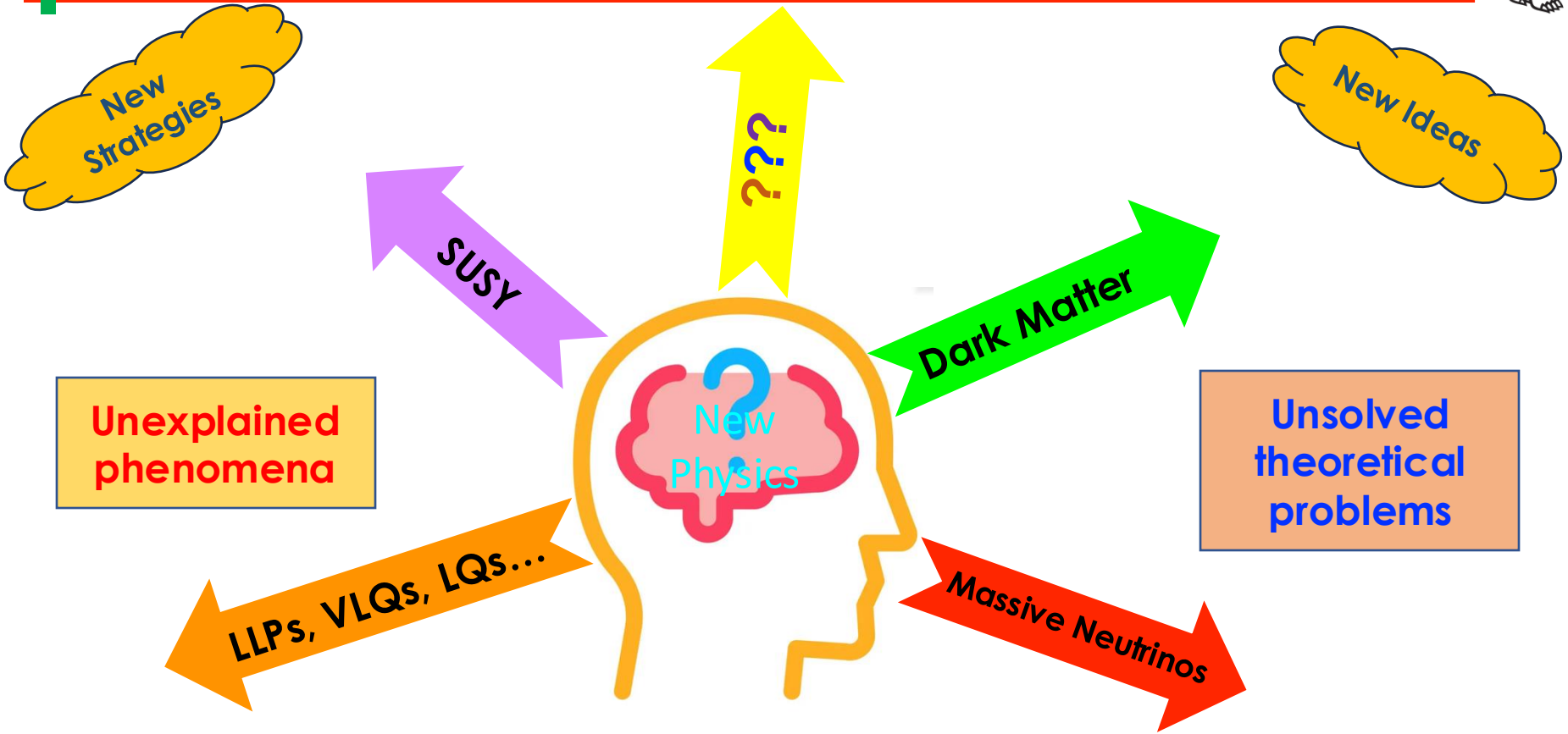
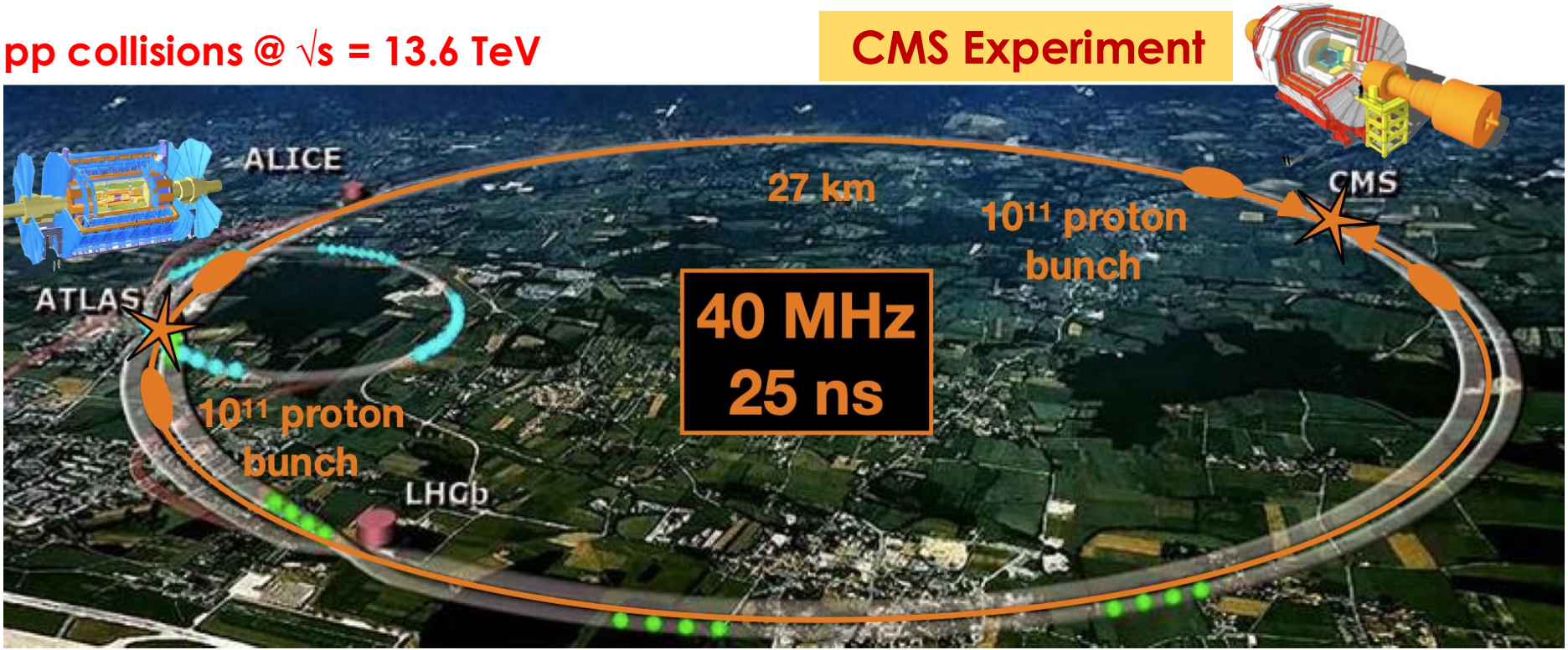
Searches in all direction & topologies



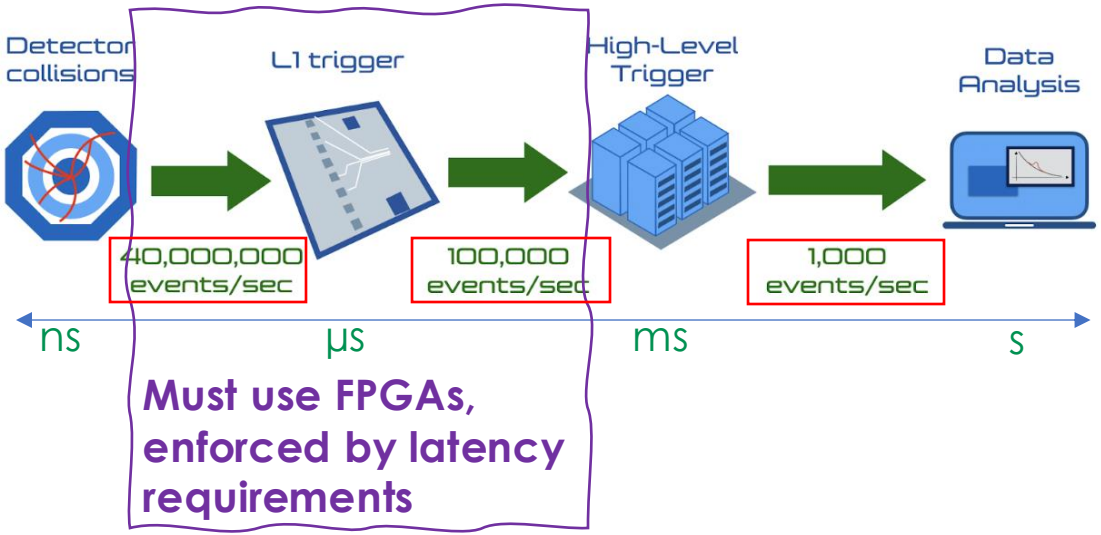
Large Hadron Collider (LHC)

pp collisions @ $\sqrt{s}$ = 13.6 TeV

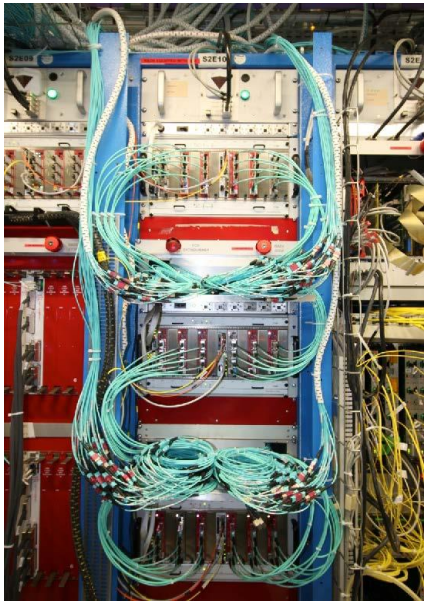
CMS Experiment



CMS Data Processing/Readout



Need to make fast decision or physics suffers!

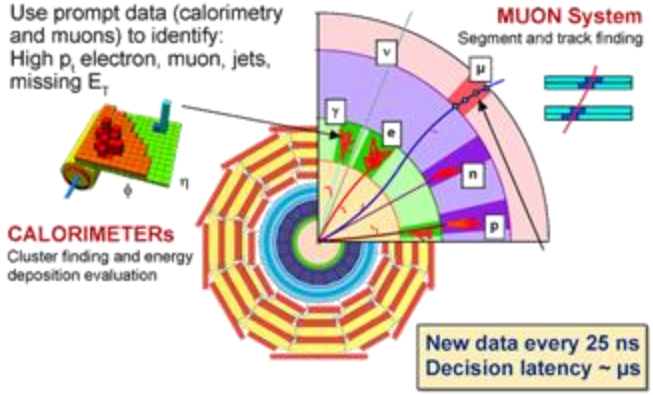


Xilinx's Virtex7 based
CMS L1 Calorimeter Trigger

No BSM discovery at the LHC (yet!)

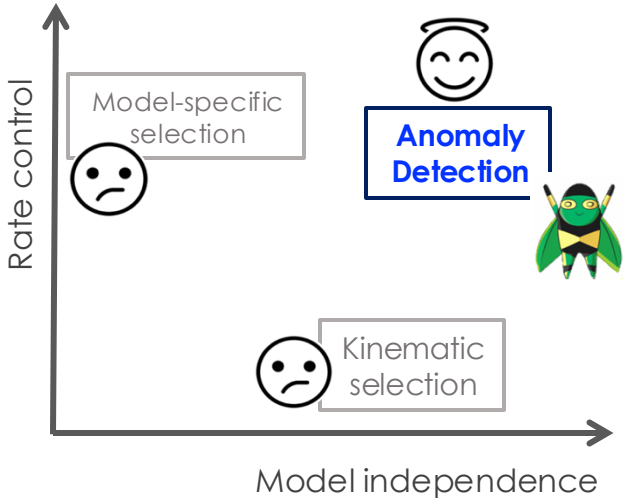
- ? New physics not possible at the current LHC scale
- ? Not enough data
- ? **Maybe we are not looking in correct direction**

Machine Learning at Level-1 Trigger



Traditional event selection at L1 based on object thresholds

- High-level and Data analysis selections limited to use those objects



ML decisions based on level-1 inputs themselves

- **Minimize human bias, completely data-driven**
- **ML can unearth unknown and complex correlation**
- **New physics searches in model-independent way**

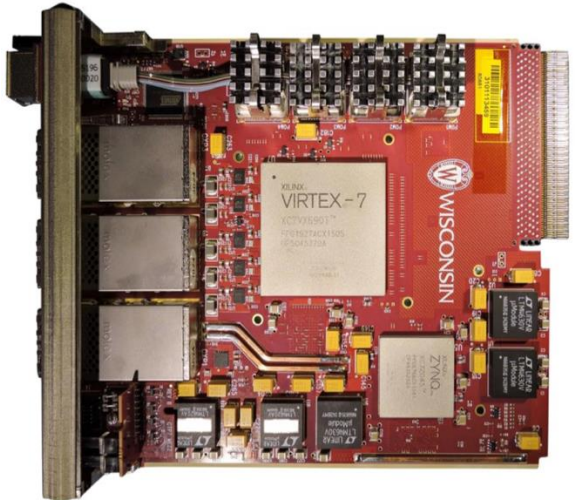
CICADA

Calorimeter **I**mage **C**onvolutional **A**nomaly **D**etection **A**lgorithm

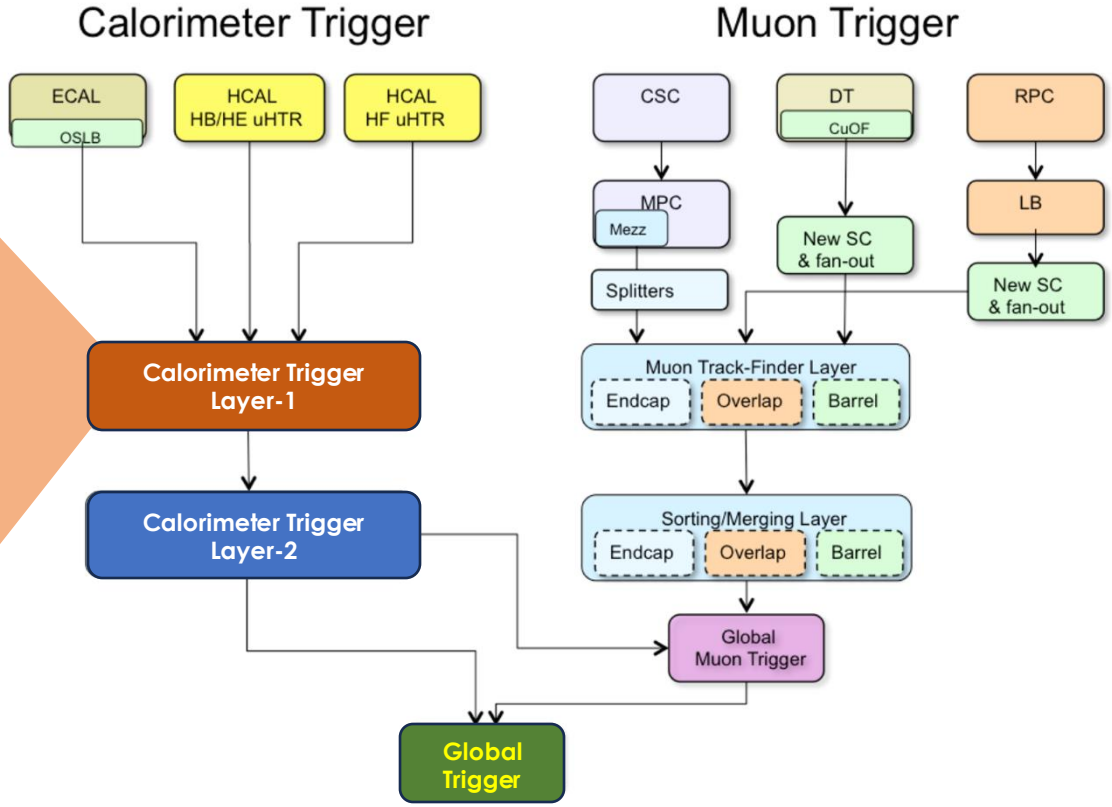
https://cicada.web.cern.ch/

CMS-DP-2023-086

CMS Level-1 Trigger



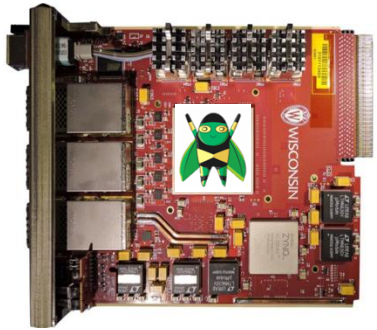
Wisconsin CTP7 Board
Xilinx's Virtex7 FPGA

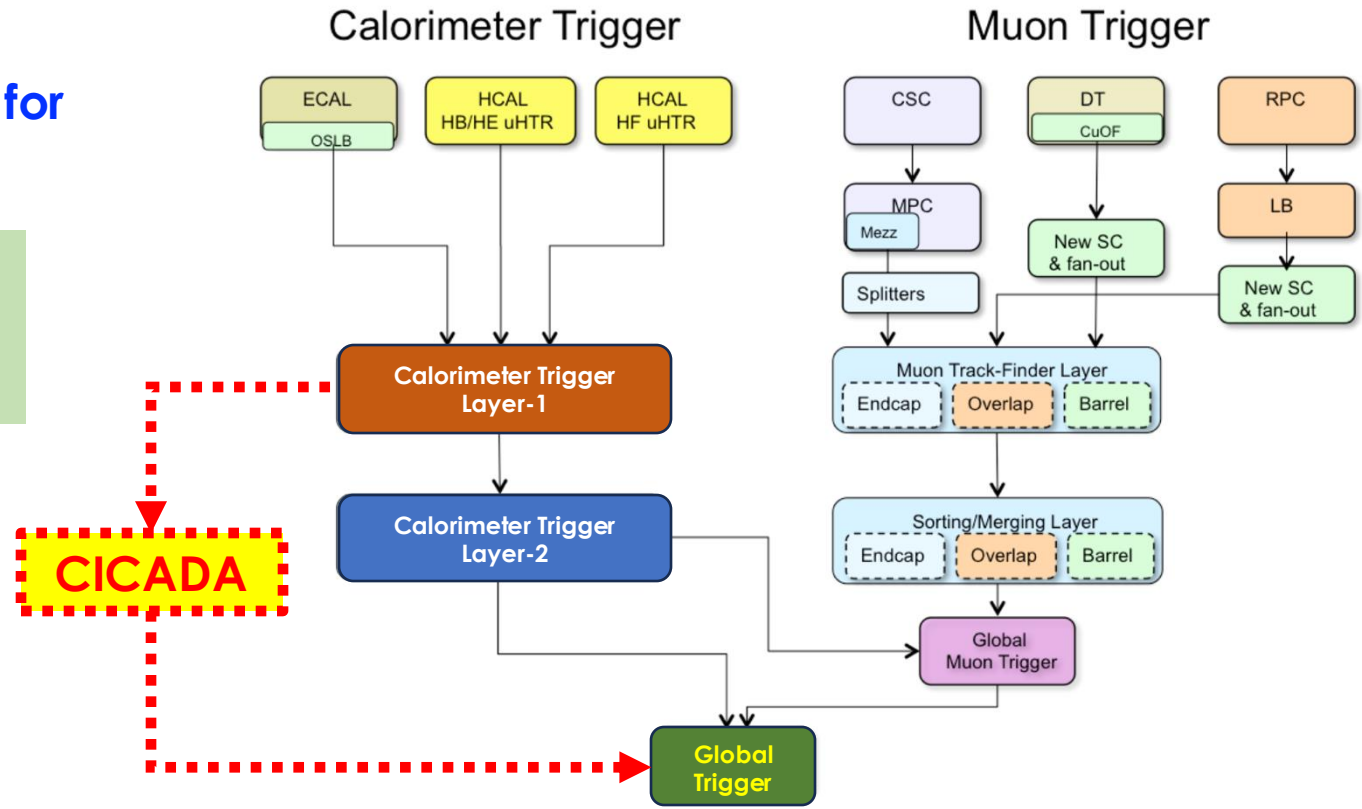


CICADA: New Addition in Run-3

ML-Based Improvements for Run-3

Currently taking Physics data @ CMS





CICADA: Inputs

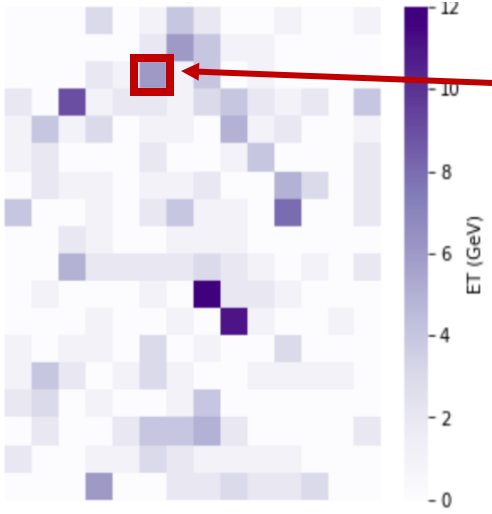
Anomaly Detection Algorithm to Select ~un-biased events for new physics searches

CICADA Inputs from CALO Layer-1

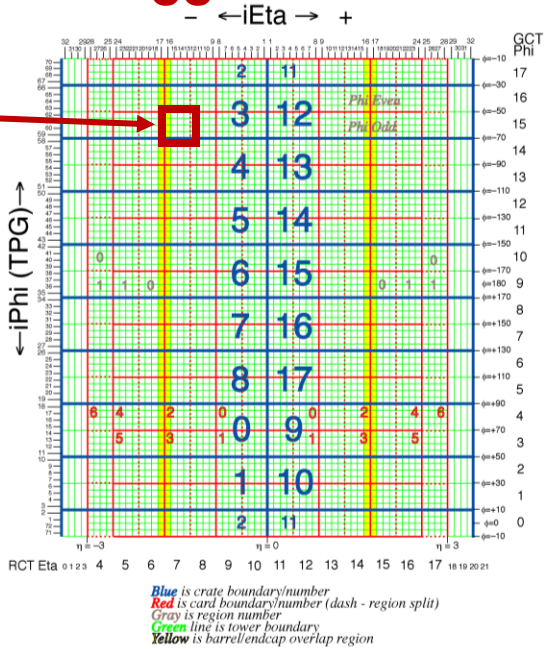
- 18 ϕ x 14 η regions, 252 regions in total
- Each region contains energy deposits from both ECAL and HCAL
- Summary of the energy distribution profile within the region

- Low level information not dependent on object reconstructions

One region = 4x4 trigger towers

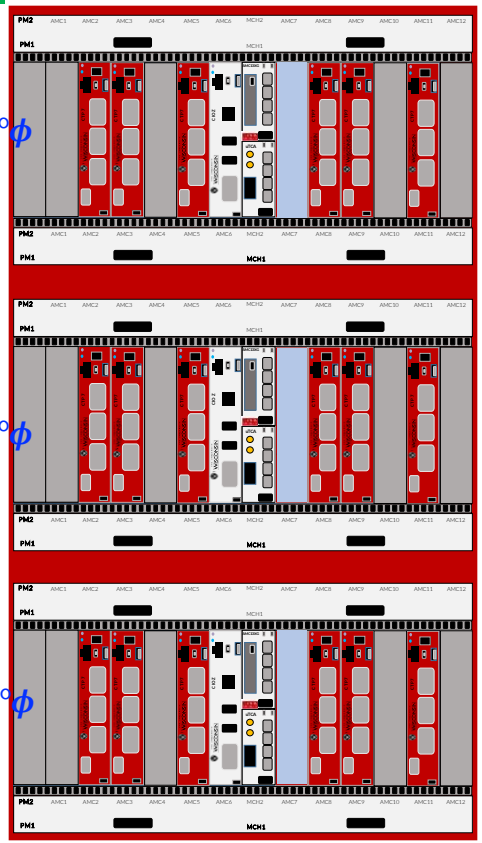


Calorimeter E_T deposit from One ZeroBias event



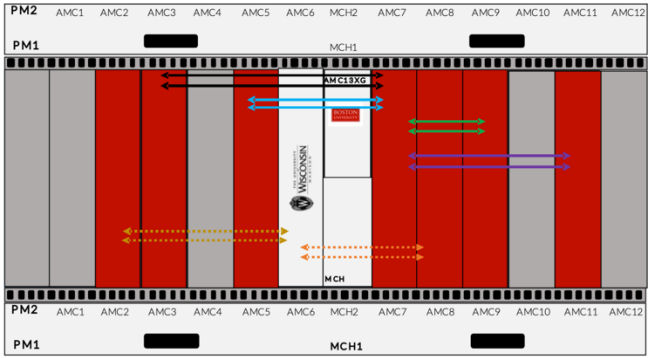
Calo tower region map

CaloL1 Setup



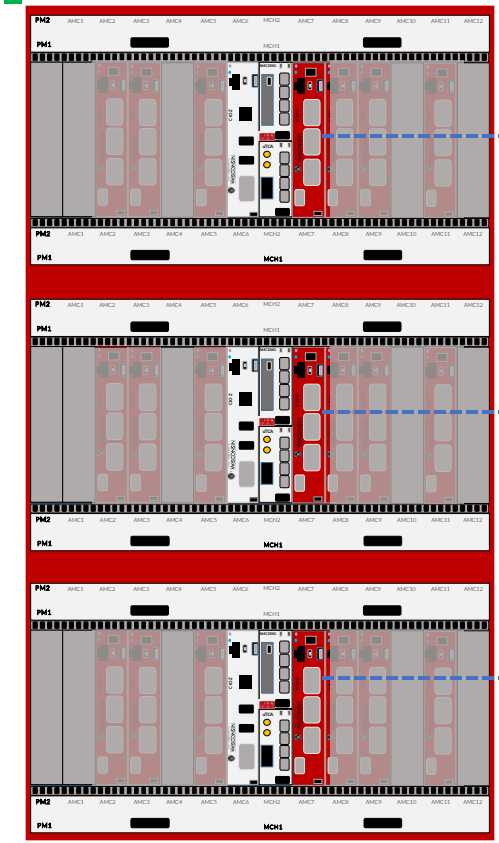
- Calo-Layer 1 Trigger consists of **3-μTCA crates** each equipped with **6-CTP7 cards**

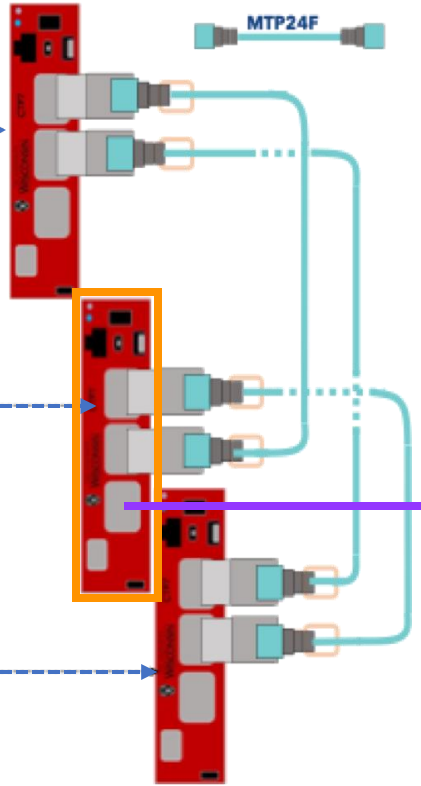
- Each CTP7 cards receive information from the calorimeters (HCAL, ECAL, HF) and send calibrated E+H & E/H to next lyare

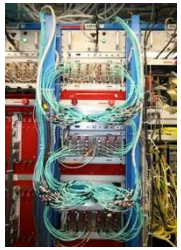


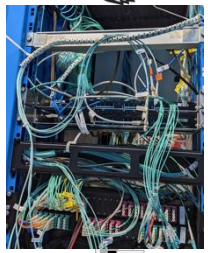
Backplane links

CICADA: Layer-1 to uGT

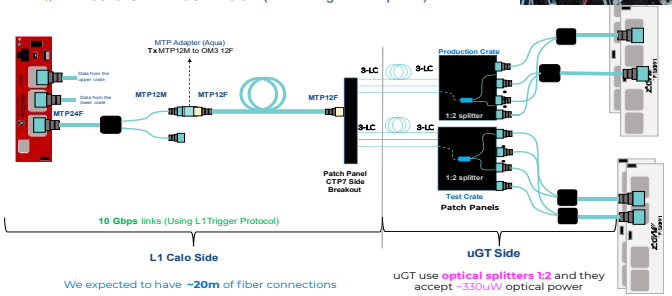








CICADA to uGT Fiber Path (Block Diagram Simplified)



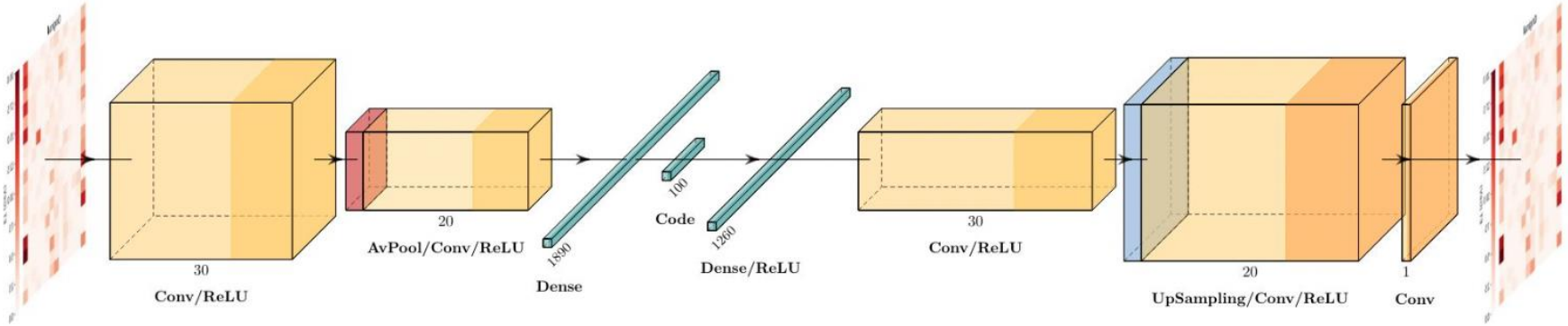
All data is collected in one card '**Summary Card**'

LC fibres

Global Trigger

CICADA: Auto-encoder Model

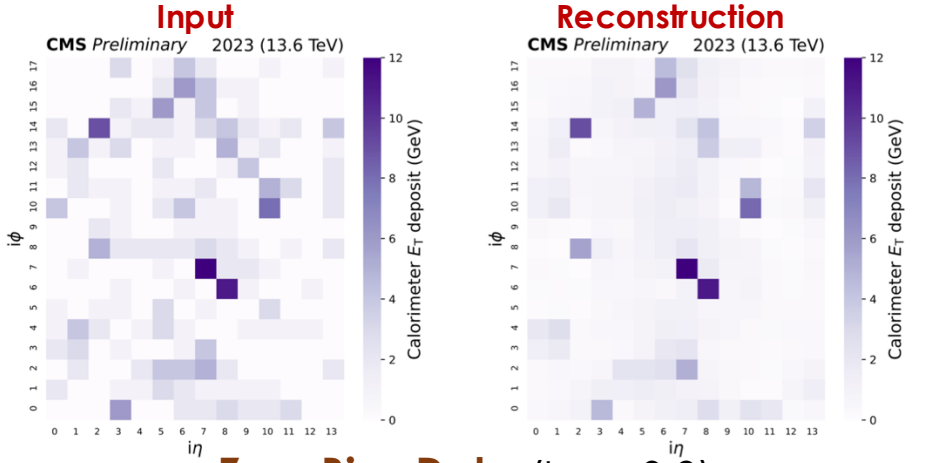
Model architecture: calo input → encoder → latent space → decoder → reconstructed input



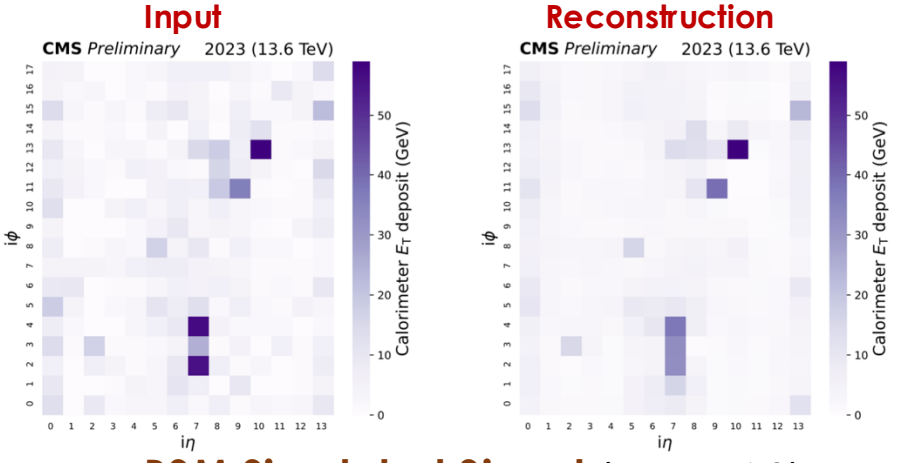
Autoencoder-based ***anomaly*** detection

- Input is a 2D tensor from the Calo region energy information
- Encoder and decoder are Convolutional Neural Networks
- ***Unsupervised*** learning : train only on ZeroBias data to learn input reconstruction

CICADA: Event Reconstruction



Zero Bias Data (Loss: 0.8)



BSM Simulated Signal (Loss: 14.2)

Expectation:

- *Good reconstruction* on **normal events** (ZeroBias used for training)
- *Bad reconstruction* on anything else such as **BSM signals** (never seen during training)

Goal:

- **Anomaly Score:** Mean Squared Error, **MSE(input, output)**

CICADA: Naive Auto-encoder Model

Layer (type)	Output Shape	Param #
input (InputLayer)	[(None, 18, 14, 1)]	0
conv2d_1 (Conv2D)	(None, 18, 14, 20)	200
relu_1 (Activation)	(None, 18, 14, 20)	0
pool_1 (AveragePooling2D)	(None, 9, 7, 20)	0
conv2d_2 (Conv2D)	(None, 9, 7, 30)	5430
relu_2 (Activation)	(None, 9, 7, 30)	0
flatten (Flatten)	(None, 1890)	0
latent (Dense)	(None, 80)	151280
dense (Dense)	(None, 1890)	153090
reshape2 (Reshape)	(None, 9, 7, 30)	0
relu_3 (Activation)	(None, 9, 7, 30)	0
conv2d_3 (Conv2D)	(None, 9, 7, 30)	8130
relu_4 (Activation)	(None, 9, 7, 30)	0
upsampling (UpSampling2D)	(None, 18, 14, 30)	0
conv2d_4 (Conv2D)	(None, 18, 14, 20)	5420
relu_5 (Activation)	(None, 18, 14, 20)	0
output (Conv2D)	(None, 18, 14, 1)	181

Total params: 323,731
Trainable params: 323,731
Non-trainable params: 0

Encoder(compressor)

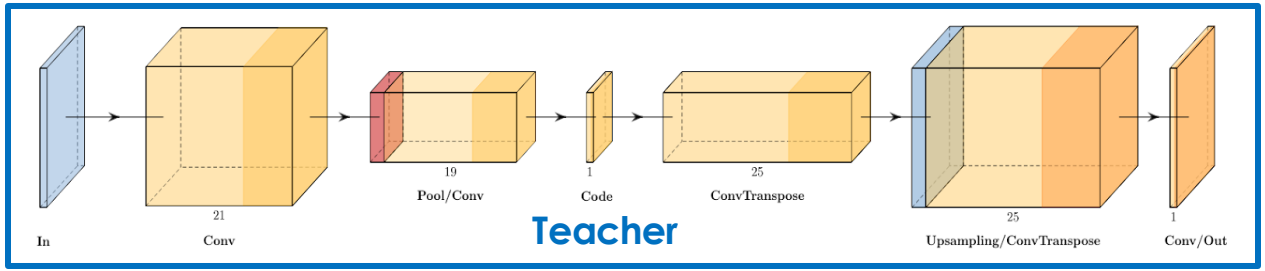
Latent space (compressed input)

Decoder (decompressor)

Challenges!

324 K parameters model size can't fit L1 constraints…

Knowledge Distillation + Quantization

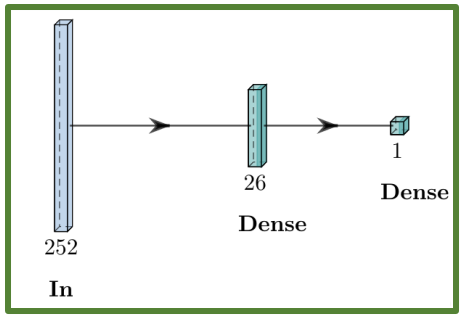


Compute score (e.g. MSE)

Anomaly score

Compare with teacher's score

Score regression



hls4ml

Knowledge Distillation

- Train a **smaller model (student)** under the guidance of a **bigger model (teacher)**
- The **student** learns to regress MSE from **teacher** outputs

Quantization-aware training (QKeras)

- Model weights quantized to fixed precision (e.g., 2 bits for integer, 4 bits for fraction)
- *Train a quantized model rather than quantize a trained model*

→ x10 reduction in resources/latency

CICADA: Teacher → Student Model

Layer (type)	Output Shape	Param #
input (InputLayer)	[(None, 18, 14, 1)]	0
conv2d_1 (Conv2D)	(None, 18, 14, 20)	200
relu_1 (Activation)	(None, 18, 14, 20)	0
pool_1 (AveragePooling2D)	(None, 9, 7, 20)	0
conv2d_2 (Conv2D)	(None, 9, 7, 30)	5430
relu_2 (Activation)	(None, 9, 7, 30)	0
flatten (Flatten)	(None, 1890)	0
latent (Dense)	(None, 80)	151280
dense (Dense)	(None, 1890)	153090
reshape2 (Reshape)	(None, 9, 7, 30)	0
relu_3 (Activation)	(None, 9, 7, 30)	0
conv2d_3 (Conv2D)	(None, 9, 7, 30)	8130
relu_4 (Activation)	(None, 9, 7, 30)	0
upsampling (UpSampling2D)	(None, 18, 14, 30)	0
conv2d_4 (Conv2D)	(None, 18, 14, 20)	5420
relu_5 (Activation)	(None, 18, 14, 20)	0
output (Conv2D)	(None, 18, 14, 1)	181

Total params: 323,731
Trainable params: 323,731
Non-trainable params: 0

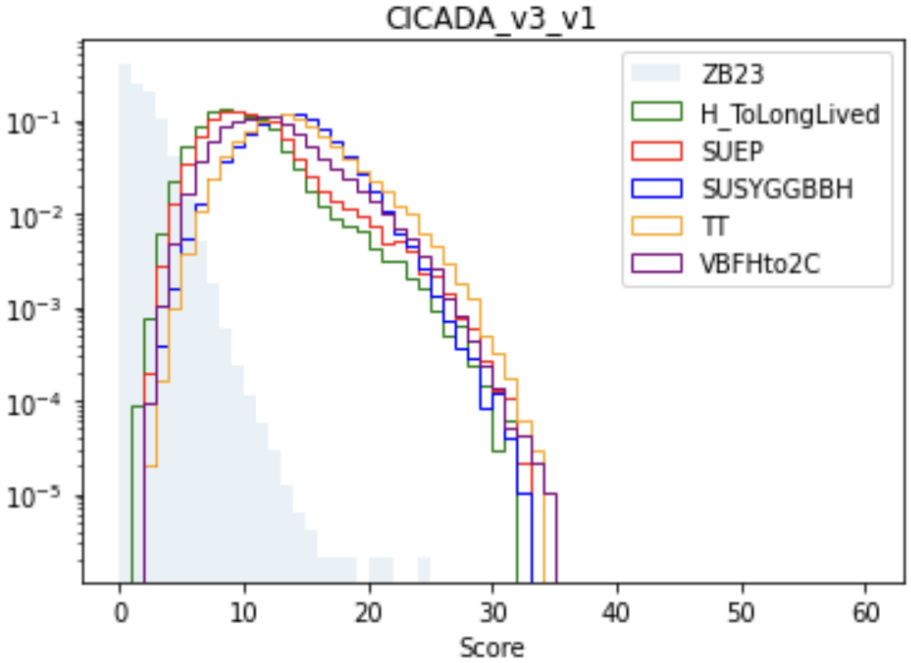
Student

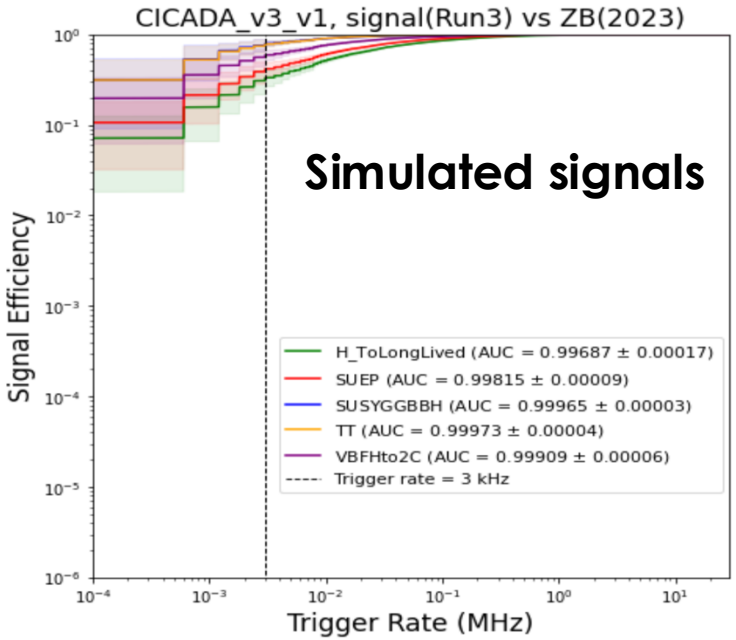
Layer (type)	Output Shape	Param #
In (InputLayer)	[(None, 252)]	0
dense1 (QDense)	(None, 15)	3780
QBN1 (QBatchNormalization)	(None, 15)	60
relu1 (QActivation)	(None, 15)	0
output (QDense)	(None, 1)	15

Total params: 3,855
Trainable params: 3,825
Non-trainable params: 30

324K parameters go down to 3.8K parameters

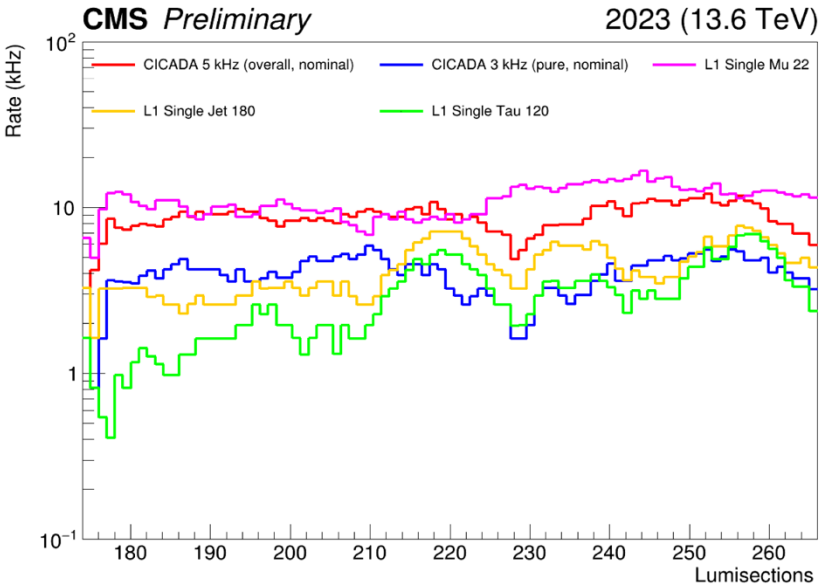
CICADA: Physics Performance

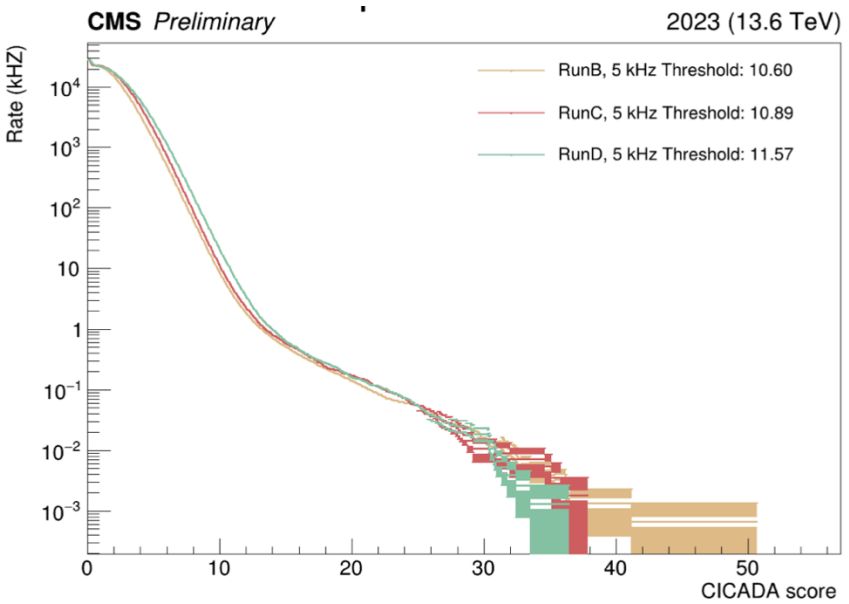




- **Model trained on 2023 ZB, evaluated on 2023 Simulated signals**
- **Able to pick up a wide range of BSM signals**

CICADA: Rate Stability

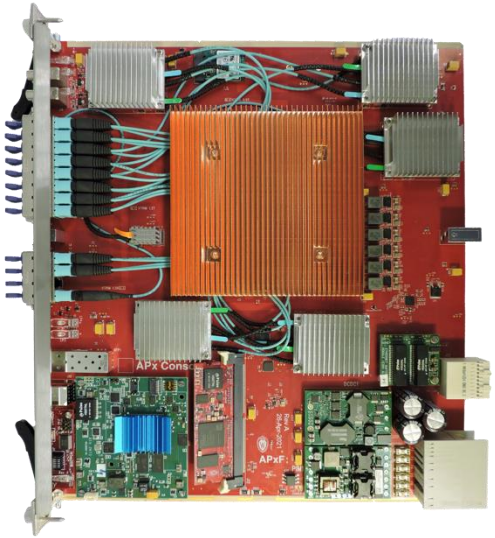




A Flexible trigger: tunable threshold for different rates, stable over the run

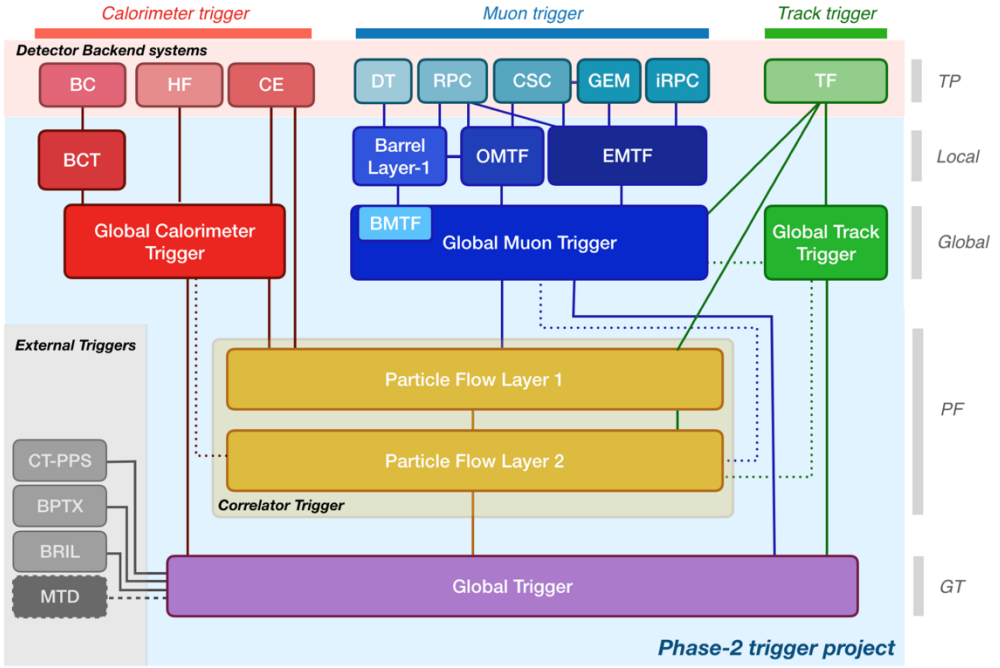
HL-LHC: Can be more adventurous

Wisconsin APxF Board



- Xilinx VU13P FPGA
- 25G Samtec Firefly optics (124 25 Gbps links)

CMS Upgrade to Level-1 Trigger



More resources available to implement ML based triggers

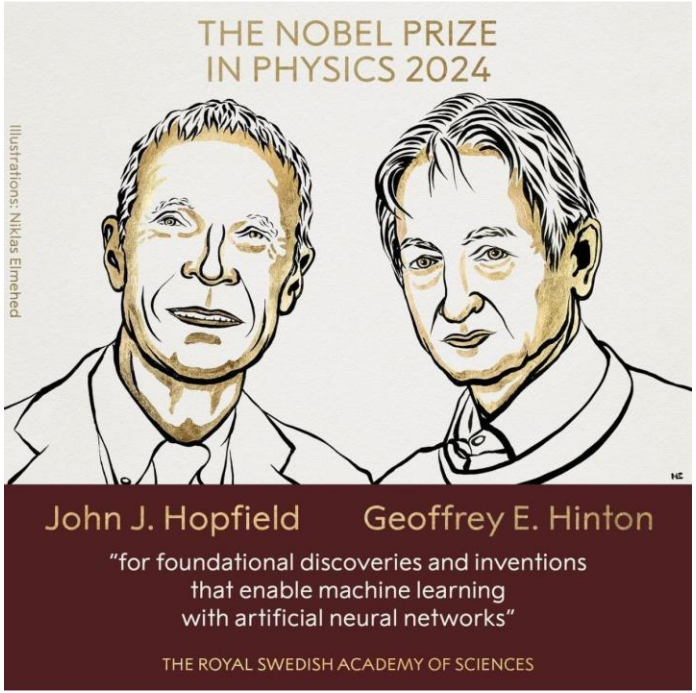
CICADA: Summary

- ✓ **CICADA: Calorimeter Image Convolutional Anomaly Detection Algorithm**
  - **New addition to CMS Level-1 Trigger system for Run-3**
  - **Unsupervised, Auto-encoder** based, **tunable algorithm** for a **model independent** search for new physics as close to the **"raw data stream"** as possible
  - **Taking Physics Data: 2024 – 2026* (Rate ~100Hz)**

- ✓ **Potential to catch more signals that are otherwise rejected by the current triggers**

- ✓ **HL-LHC: CMS Upgrade of Level-1 trigger**
  - Bigger/Faster FPGAs to provide more resources
  - More complex ML based algorithms being developed

Machine Learning is Everywhere



What is CICADA ☺

A **"CICADA"** is an insect of the family "Cicadoidea"

- Cicadas are known for their loud vocalizations (typically during summer)

- Much of a cicada's life cycle is actually spent underground, with a few famous American species (the "periodical cicada") only emerging every 13 (*magicicada tredecim*) or 17 (*magicicada septendecim*) years

Source: https://kids.nationalgeographic.com/animals/invertebrates/facts/cicada

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धन्यवाद

Thank you