# Introduction to the CMS Trigger System: Architecture, Strategies, and Outlook

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# About Me

**Research Experience**

- BA, Physics, Wesleyan University
  - Research: Computational Biophysics
  - REU at Columbia between junior and senior years
- PhD, Physics, Columbia University
  - ATLAS Experiment – hardware, operations, analysis
- Postdoc, CMS Group, Princeton University, 2022–present

**Research Interests and Activities**

- Long-lived particles
- Trigger strategies
- Machine learning
- Outer tracker upgrade
- Muon collider

# Overview

Part I – Introduction + Motivation

Part II – Overview of Trigger System

Part III – Trigger Performance: Key Metrics and Issues to Consider

Part IV – New Triggers in Run 3: Three Examples

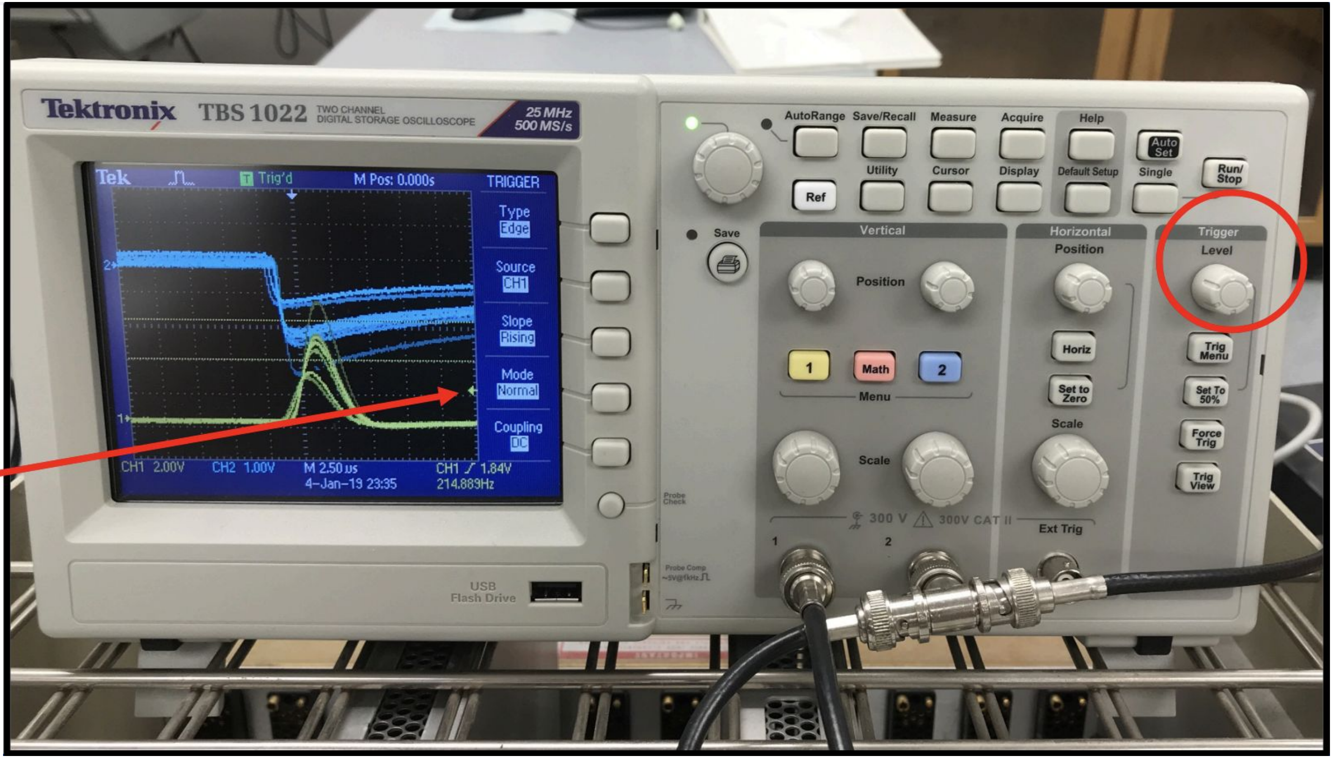
Part V – Outlook

# Part I: Introduction + Motivation

# What is a Trigger?

Slide credit: D. Acosta

Pulse threshold for triggering readout



# The Large Hadron Collider

**Largest & highest energy particle collider in the world**

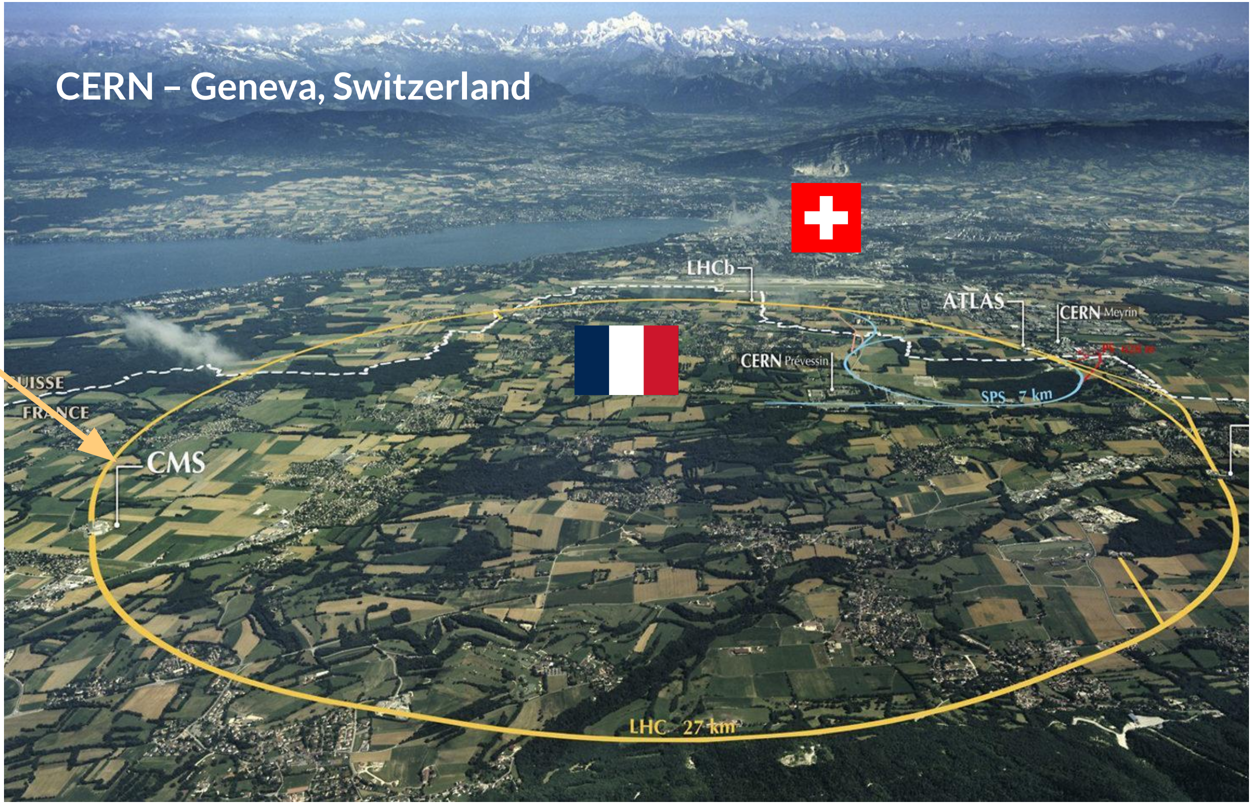
<u>CMS</u> is one of the two general-purpose LHC experiments

<u>Run 3</u>: Data-taking from 2022–

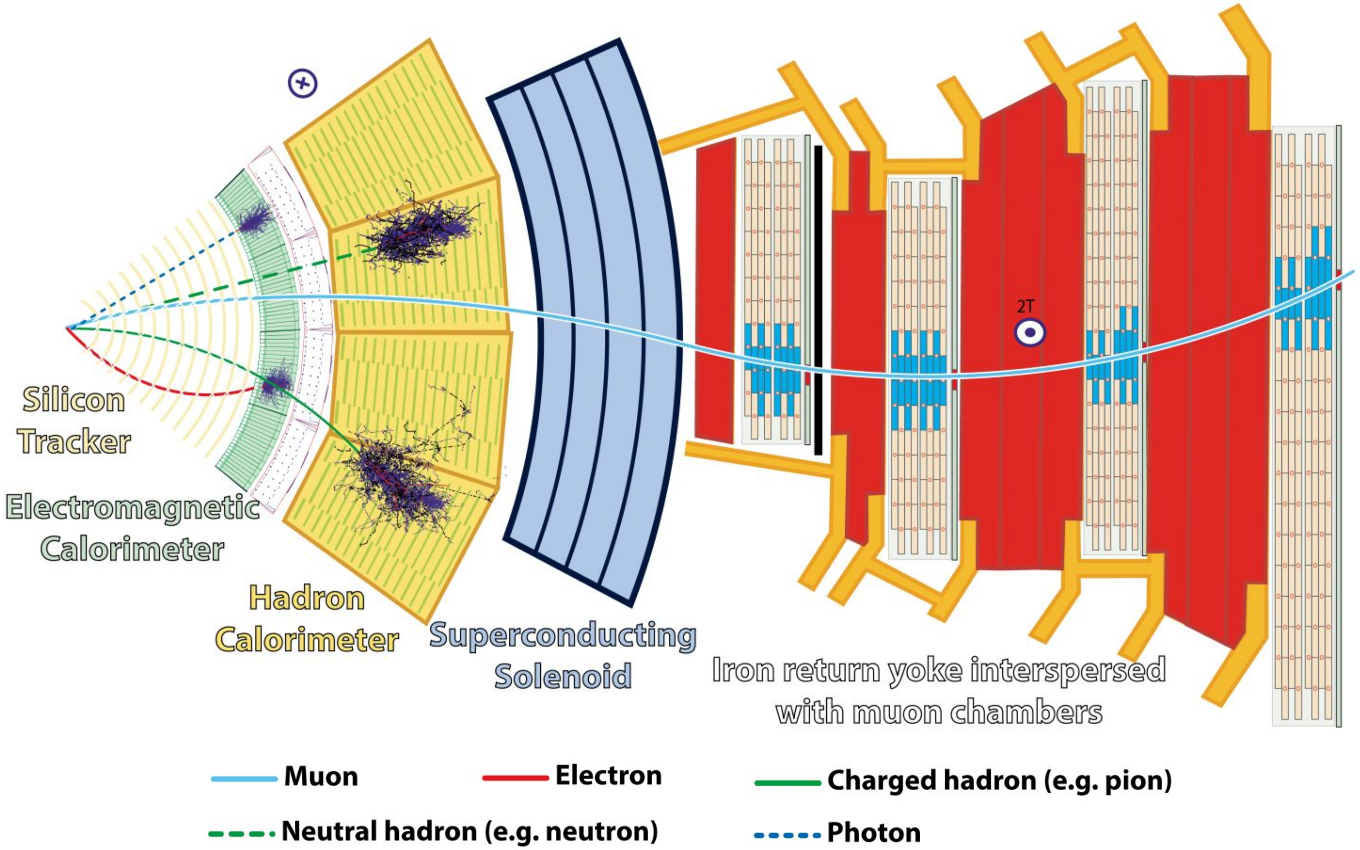
- *pp* collisions at 13.6 TeV
- Bunch crossings at 40 MHz
- $10^{11}$ protons per bunch

<u>Pileup</u>: Number of collisions per bunch crossing

- Typically 60-65 in Run 3



# The CMS Detector: Overview



# Why Do We Need a Trigger?

**Number of readout channels**:

- Inner Detector (silicon tracker): > 135M
- Electromagnetic Calorimeter (ECAL): > 75k
- Hadron Calorimeter (HCAL): ~20k
- Muon Spectrometer (MS): > 200k

**Event Size:** ~2 MB

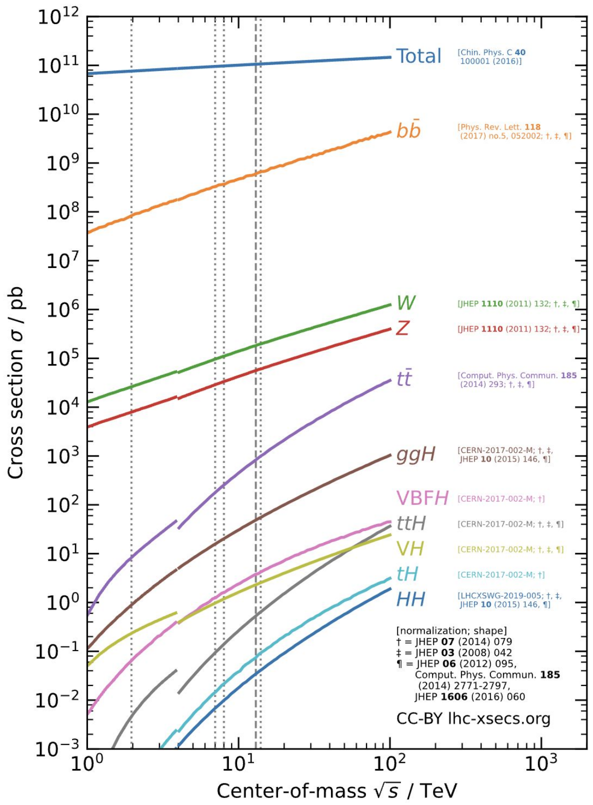
**Bunch Crossing Rate**: 40 MHz

**The CMS detector produces ~ 100 TB/s**

**This is impossible to save given current technological limitations**

**We must devise a “clever” way to filter events!**

# What Do We Want to Trigger On?




Total Collision Rate: ~2.5 GHz (= 40 MHz * 60 PU)

B-Quark Rate: ~10 MHz

W Boson Rate: ~4 kHz

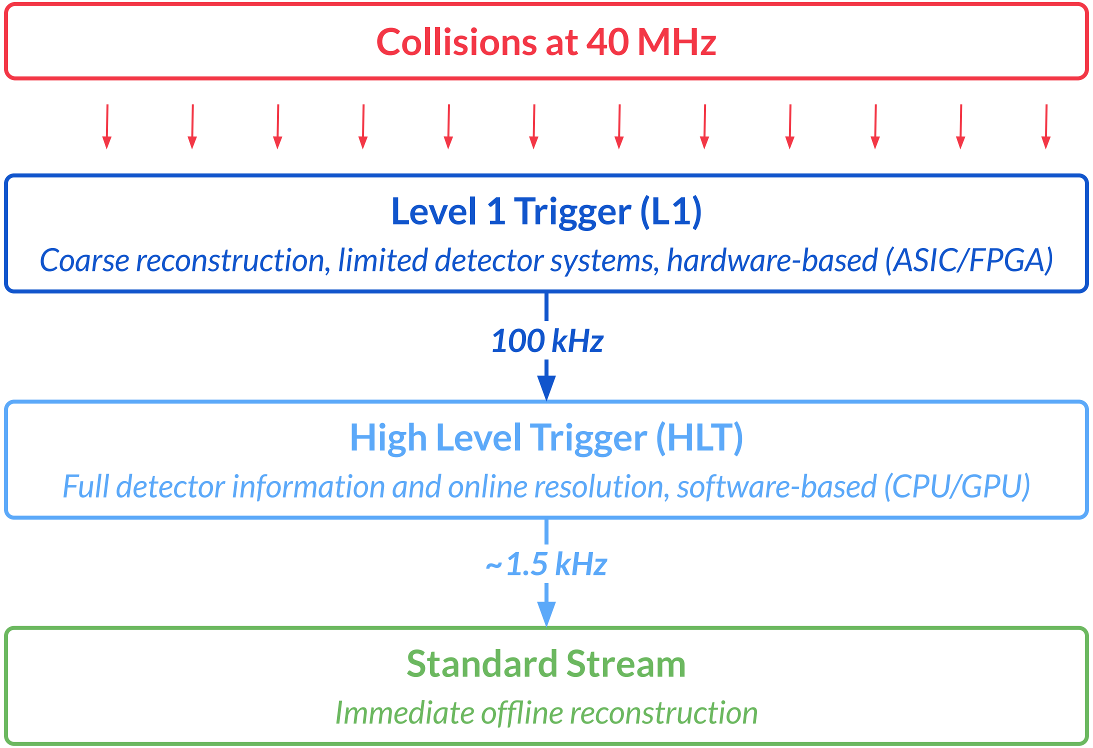
Higgs Boson Rate: ~1 Hz

**Goal**: Develop triggers to select for rare processes

- Typically by cutting out soft (low-$p_T$) background

# Part II – Overview of Trigger System

# Overview of CMS Trigger System




**Level-1:** 40 MHz → 100 kHz

- Latency of < 10 μs
- Implemented in hardware / firmware
- Calorimeter and muon spectrometer information only, and at a reduced level

**HLT:** 100 kHz → 1.5 kHz

- Ideally, timing within a few ms
- Streamlined version of the CMS offline reconstruction software
- Exploits the full detector information by including the track information

# Level 1 Trigger: Architecture

### The L1 Calorimeter Trigger:

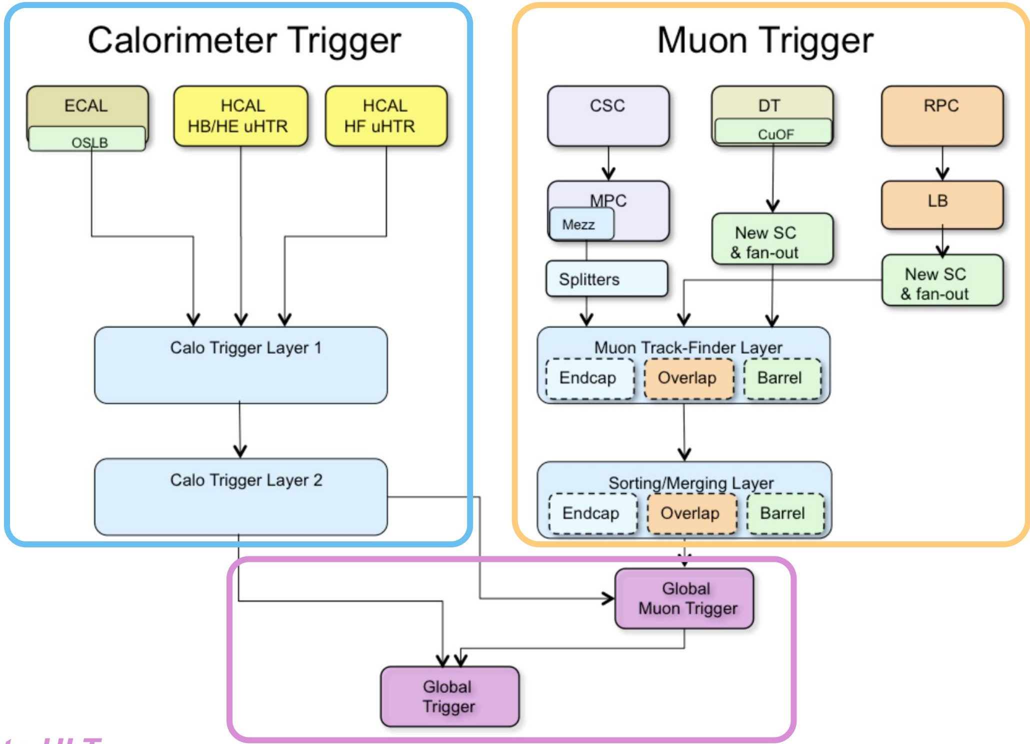
- Layer 1 receives information from the calorimeters and runs calibrations
- Layer 2 reconstructs physics objects (e/γ/τ/jet)

### The L1 Muon Trigger:

- Three muon track finders to reconstruct muon candidates in different detector regions
- Reconstructed muons are sent to
- Global Muon Trigger for final muon selection

### L1 Global Trigger:

- Collects Muon and Calorimeter objects
- Runs every L1 algorithm
- If any algorithm passes → ***Trigger accept, sent to HLT***



# Level 1 Trigger: Algorithms

Most of the ~400 L1 algorithms consist of kinematic selections on various standard objects. For example:

- Single object triggers and approximate rates:
  - **Muon**: `L1_SingleMu22` ~4 kHz
  - **e/γ**: `L1_SingleEG36er2p5` ~5 kHz
  - **Tau**: `L1_SingleTau120er2p1` ~1 kHz
  - **Jet**: `L1_SingleJet180` ~1 kHz
- Multi-object triggers and approximate rates:
  - **Di-e/γ**: `L1_DoubleEG_25_12_er2p5` ~2 kHz
  - **Tri-jet**: `L1_TripleJet_95_75_65_DoubleJet_75_65_er2p5` ~1 kHz
- Cross-triggers:
  - **Muon + 2 e/γ**: L1_Mu6_DoubleEG12er2p5 ~250 Hz

***Thresholds are chosen to select the events of physics interest while keeping the total rate of the menu below 100 kHz***

# High Level Trigger (HLT): Structure

**Reconstruction**: The HLT employs software reconstruction algorithms much closer to what is used offline

- Run on computing farm using commercially available hardware

**Menu Structure:** The HLT contains 600+ different paths (collection of paths = "Menu")

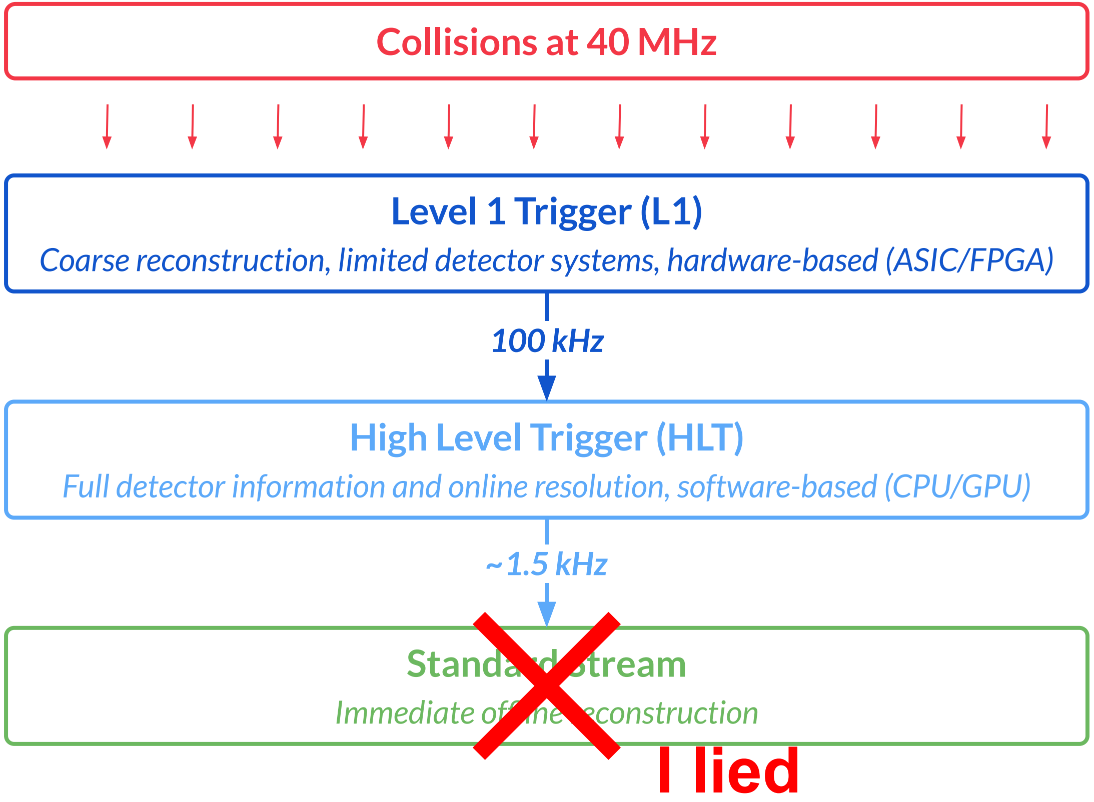
- Paths are seeded by one or more L1 triggers
- Each path is a sequence of reconstruction and filtering modules:
  - Looks like: *calculation* → *selection* → *calculation* → *selection* ... etc
  - Perform the most computationally "expensive" steps last, if possible
  - If a filter or selection fails, the rest of the path is skipped
- To reduce the CPU time consumption at HLT:
  - Some reconstruction stages restricted to the regions of interest around the L1 inputs
  - Simplified track reconstruction

# High Level Trigger: Algorithms

The 600+ HLT algorithms consist of kinematic selections on various standard objects as well as more sophisticated algorithms. For example:

- Standard single object triggers and approximate rates:
  - **Muon**: `HLT_IsoMu24` ~100 Hz
  - **Electron**: `HLT_Ele30_WPTight_Gsf` ~100 Hz
- Object ID using machine learning algorithms:
  - **Di-tau**: `HLT_DoubleMediumDeepTauPFTauHPS35_L2NN_eta2p1` ~13 Hz
  - **B-tagging**: `HLT_QuadPFJet70_50_45_35_PFBTagParticleNet_2BTagSum0p65` ~20 kHz
- Mass selections on multi-object systems:
  - **J/Psi**: `HLT_DoubleMu4_3_Jpsi_v16` ~21 Hz
- ...And many more!

# Overview of CMS Trigger System: Revisited



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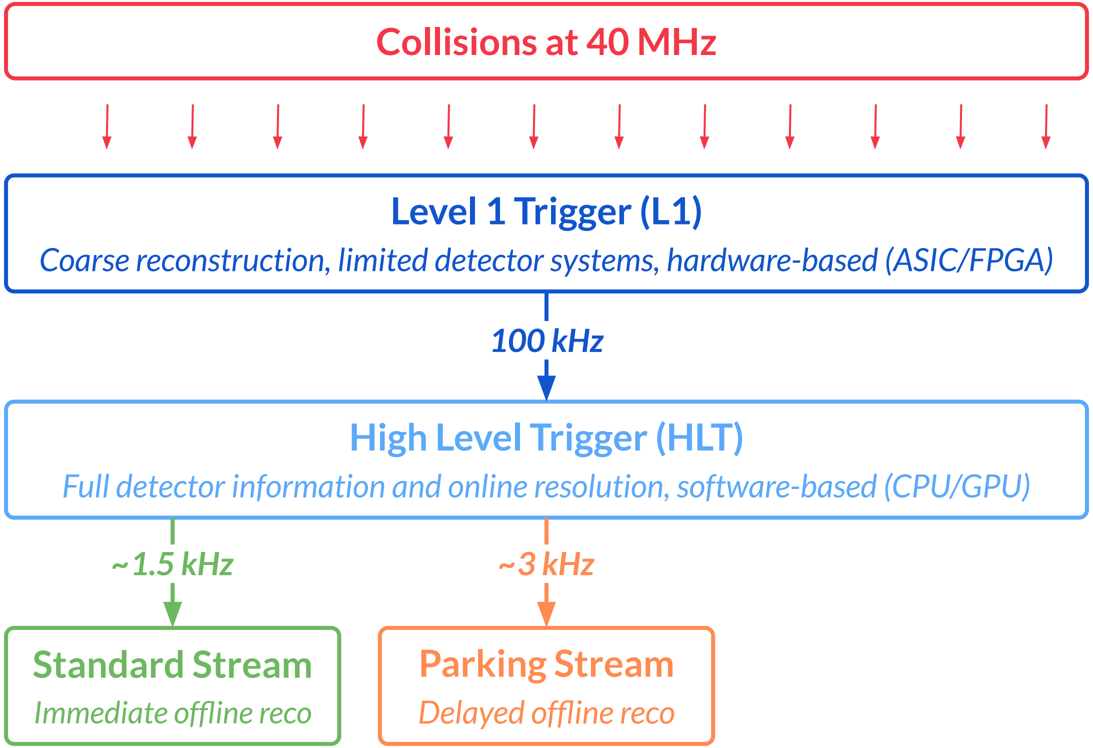
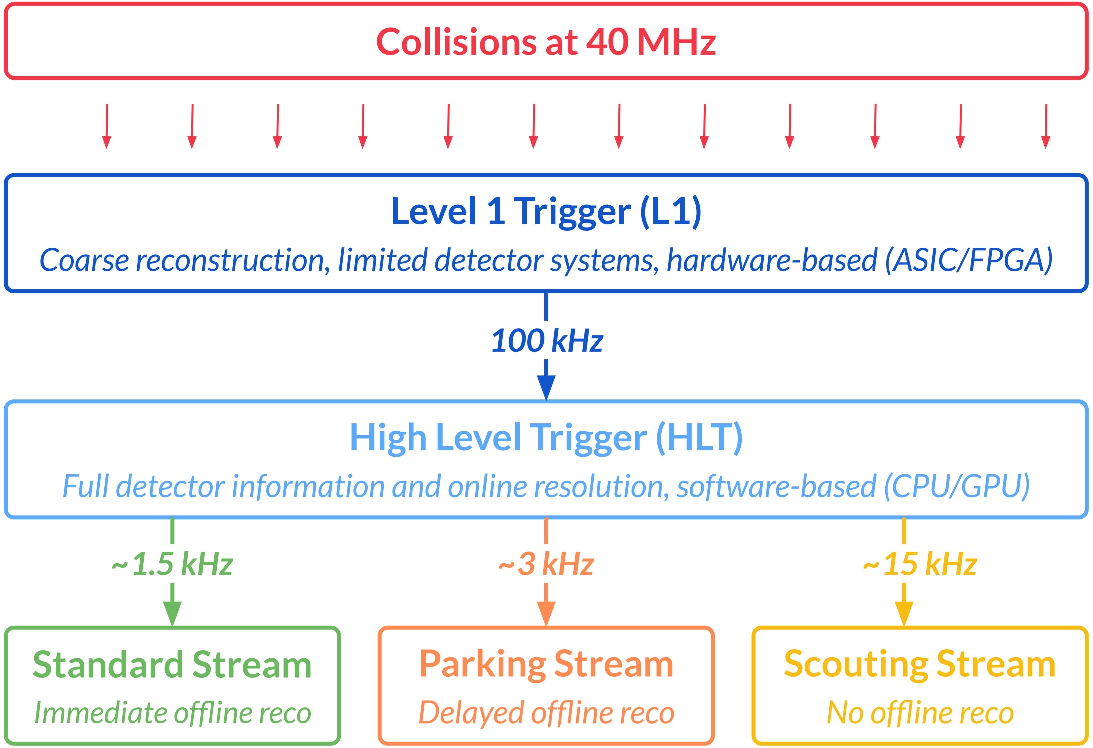



## Parking Stream: Delayed Offline Reconstruction

- **Paradigm**: save only RAW event content to be reconstructed later
- RAW contains complete detector information, but no object or event reconstruction
- Uses less computational resources, enabling higher rates and thus lower kinematic thresholds

# Overview of CMS Trigger System: Revisited




## Scouting Stream: No Offline Reconstruction

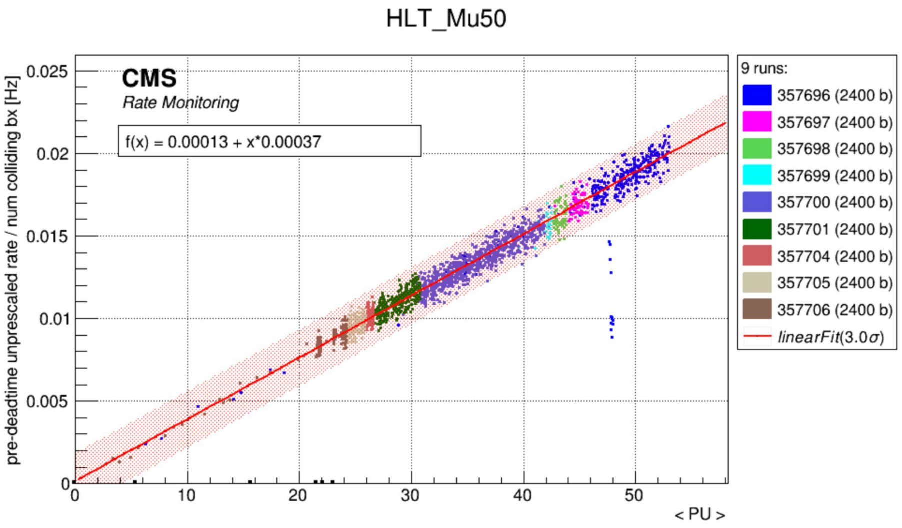
- **Paradigm**: save only limited objects and variables that can be calculated online
- No RAW content available (info is lost)
- Enables much higher rates and much lower thresholds

# Part III – Trigger Performance: Key Metrics and Issues to Consider

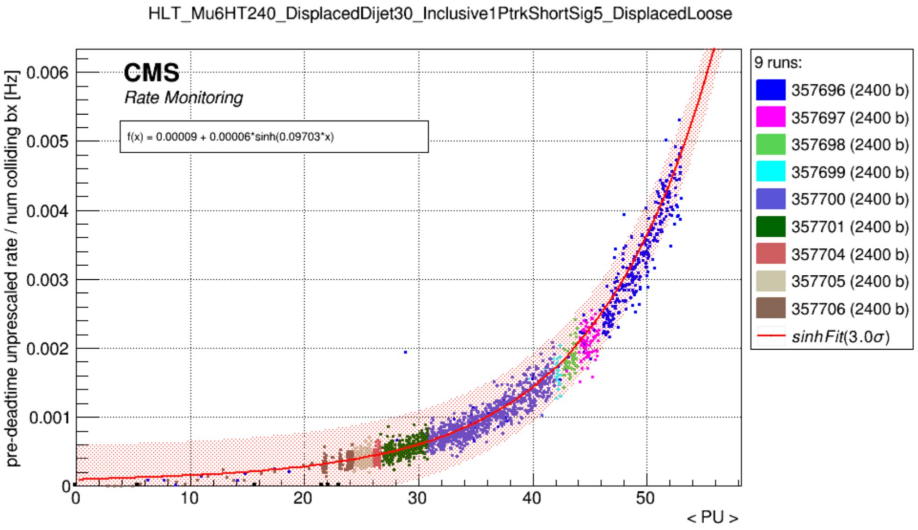
# Rates and Pileup Dependence

- We expect trigger rates to be ~linear with **pileup** (=the number of collisions per bunch crossing)

### The Good – Linear




### The "Bad" – Exponential



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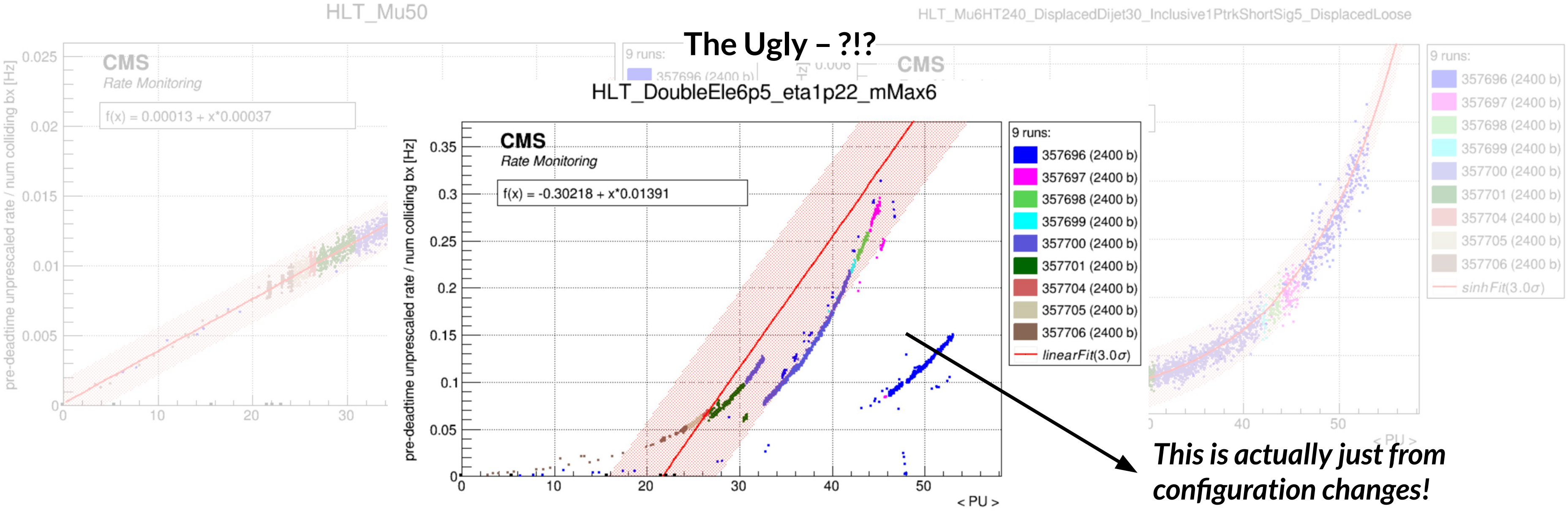
The “Bad” – Exponential




***This is actually just from configuration changes!***

# Rates and Prescales

**What if your trigger rate is higher than expected?**

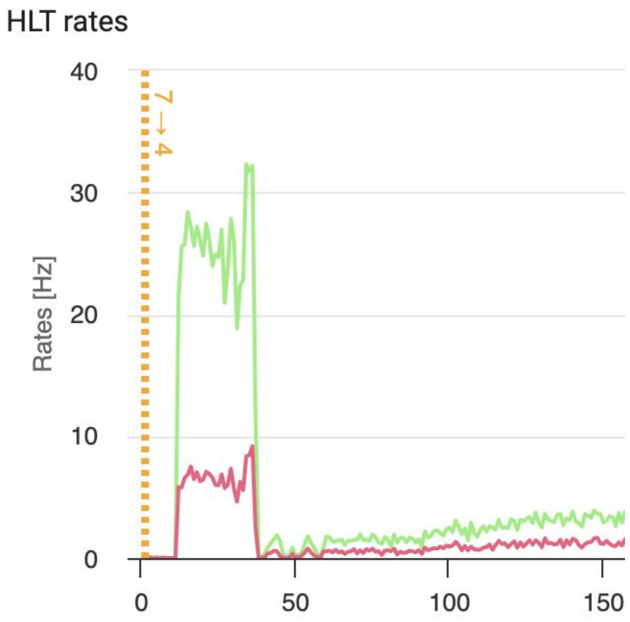
- Many causes: unexpected PU dependence, operational issues, etc

**Solution: “Prescales”**

- All L1 and HLT paths have associated prescales (PS)
- PS = 1 – keep every event that passed your algorithm
- PS = N – keep every Nth event that passed your algorithm
- PS = 0 – no events pass; trigger is fully disabled

**Benefits of Prescales**

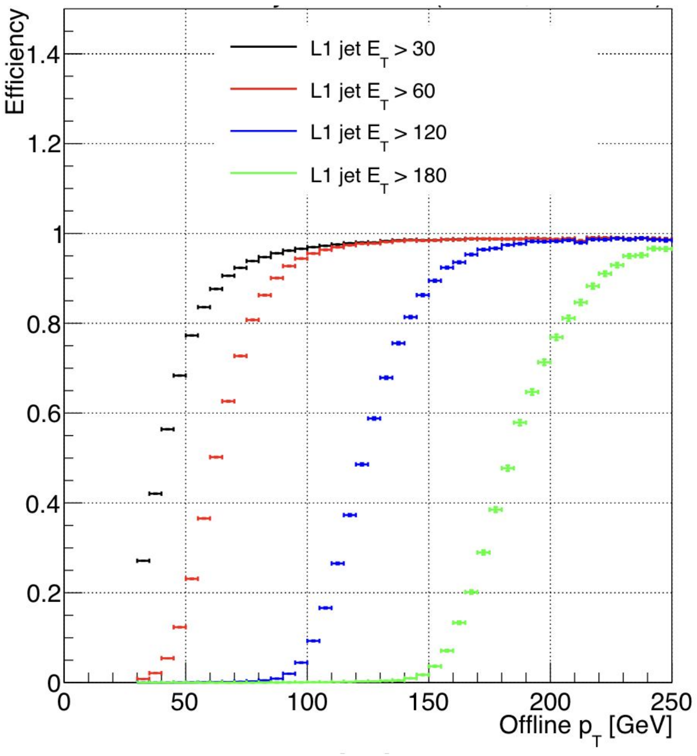
- Difficult (impossible) to change trigger algorithm during data-taking
- Include paths with different (tighter) thresholds → in case rates become too high, can move to paths with lower rates
  - E.g. HLT_Mu22 → HLT_Mu26



# Trigger Efficiencies

**“Turn-On” Curve**

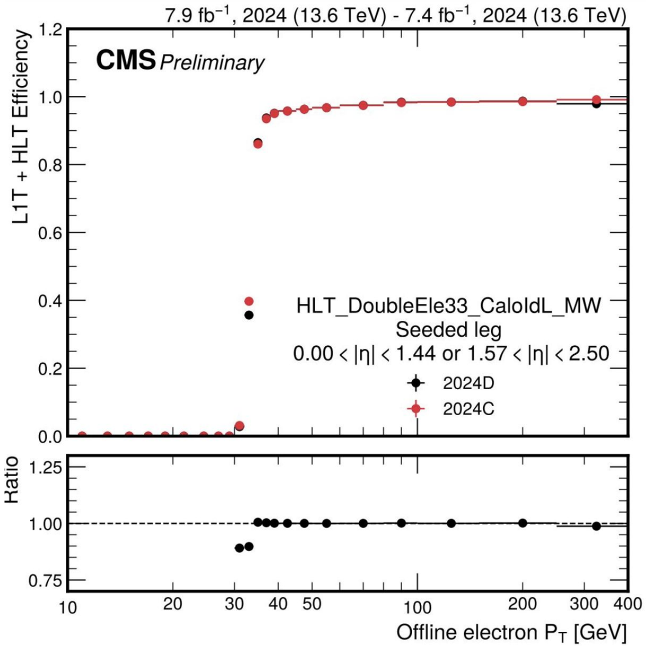
- <u>Sharper turn-on</u>: less rate from mismeasured low-$p_T$ objects
- <u>High, flat plateau</u>: high event yield, less uncertainty
- <u>Ideal Case</u>: step function



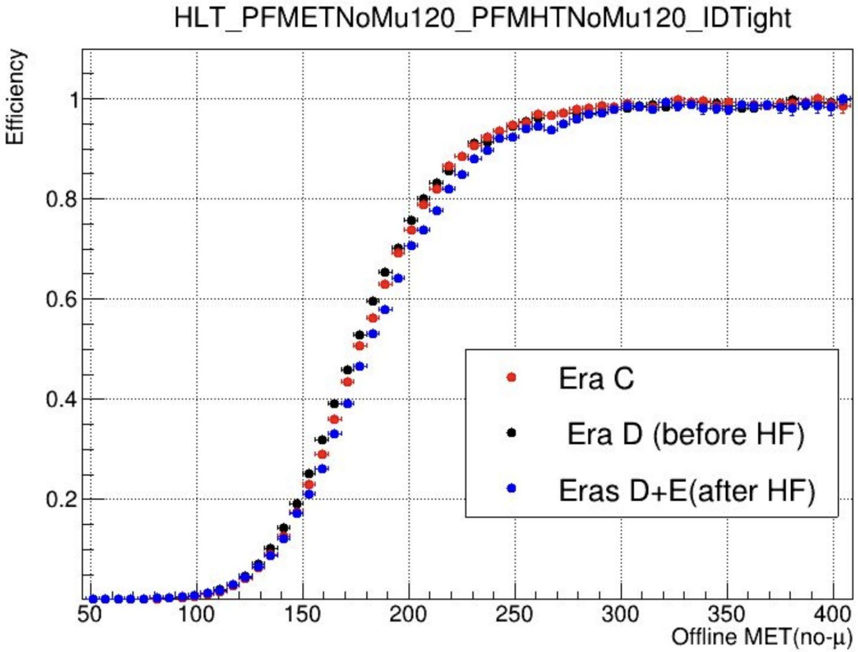
# Trigger Turn-On Curves

- The shape of turn-on curves depends on the type of object you are interested in

**Electrons: Clean Object, Sharp Turn-On**




**MET: Messy, less-sharp turn-on**

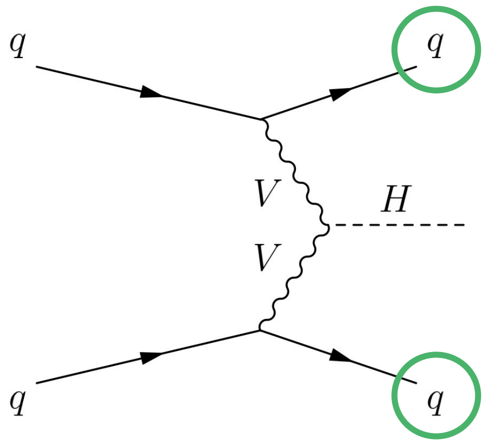


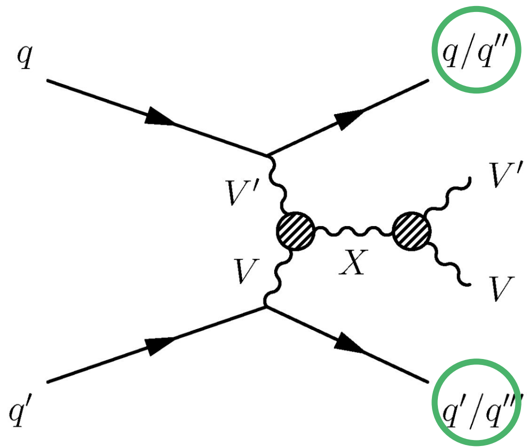
# Part IV – New Triggers in Run 3: Three Examples

# Case Study 1: Vector Boson Fusion Triggers

**Vector Boson Fusion (VBF)**: A quark from each incoming proton radiates off a heavy vector boson (**W/Z**), which interact ("fuse") to produce a particle

- Higgs Boson: VBF is the second largest production channel
- Beyond the Standard Model: VBF is a general production mechanism → use as a handle for hard-to-trigger events




*This trigger identifies very high-eta (forward) jets*

# Case Study 1: Vector Boson Fusion Triggers

Deployed in the Parking Stream during Run 3 – Total HLT Rate: 1 kHz

| Path | Target Signal(s) |
|---|---|
| VBF + μ | EXO: soft / displaced muons, light muon pairs; SUS: soft / displaced muons |
| VBF + γ | EXO: dark photon, ISR/FSR tagging; HIG: Hbb+$\gamma$, Hcc+$\gamma$, H$\rightarrow$meson+$\gamma$; SMP: EWK $\gamma$, Z$\gamma$, W$\gamma$ |
| VBF + e | HIG: H$\rightarrow$ττ |
| VBF + τ | HIG: H$\rightarrow$ττ |
| VBF + 2 central jets | EXO: displaced tracks (with dedicated path); HIG: Hbb, Hcc; SMP: VBS fully hadronic;<br>SUS: compressed spectrum in hadronic mode |
| VBF + MET | EXO: dark photon, track kinks, stopping tracks; HIG: H$\rightarrow$invisible;<br>SMP: VBS fully hadronic (ZV$\rightarrow\nu\nu$+jets) |
| Inclusive VBF | EXO: SUEP, soft displaced electrons, light non-mu lepton pairs |

# Case Study 2: Long-Lived Particle Triggers

**Long-Lived Particles (LLPs)**: Particles beyond the Standard Model that have relatively *long lifetimes*

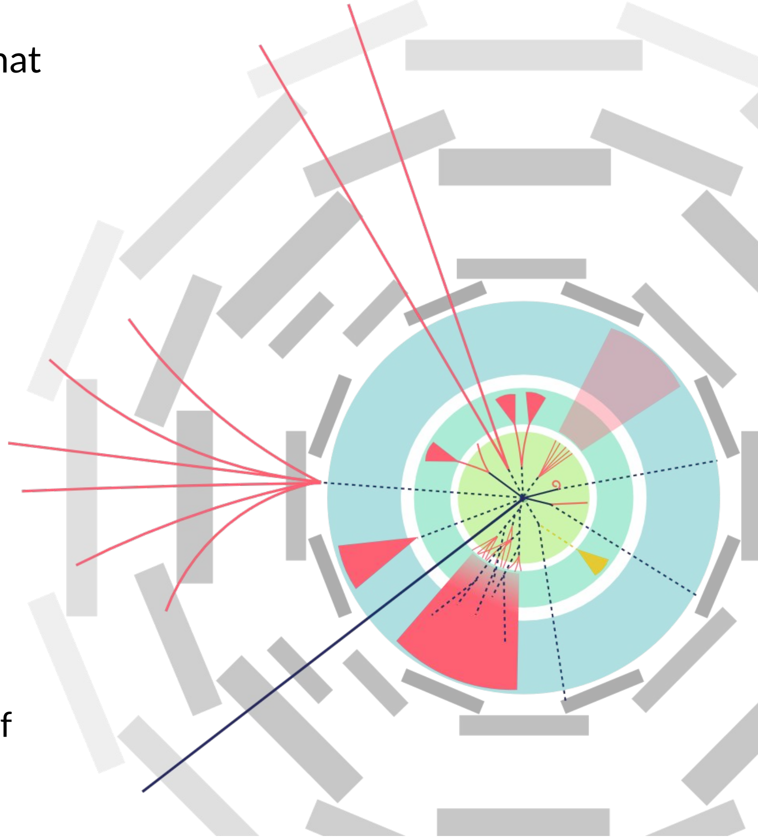
- Produced with momenta → *displaced decay products*
- Massive LLPs → Slow + "kinked" path → *delayed decay products*

**Challenging Reconstruction**

- LLP signatures often evade "standard" object reconstruction, requiring custom algorithms
- This applies to triggers as well!

**Expanding LLP Triggering in Run 3**

- Only a handful of dedicated LLP triggers were online before Run 3
- Since 2022, have many more LLP triggers covering a wide variety of final states and signatures!



# Case Study 2: Long-Lived Particle Triggers

**Recall – Key features of LLPs:**

- Displaced decay products
- Delayed decay products

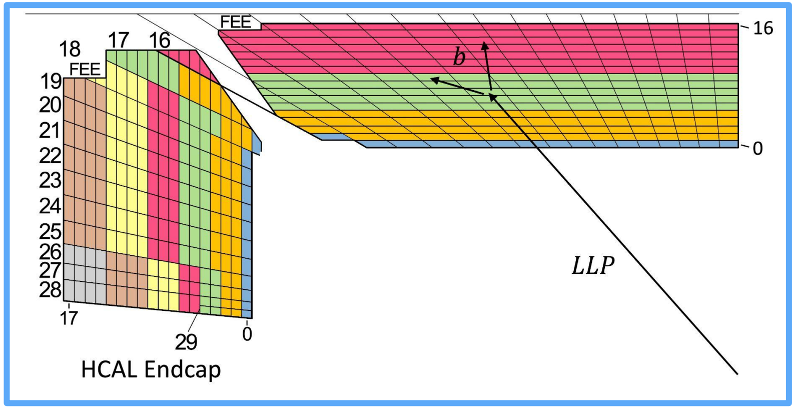
**Recent Hadron Calorimeter Upgrade:**

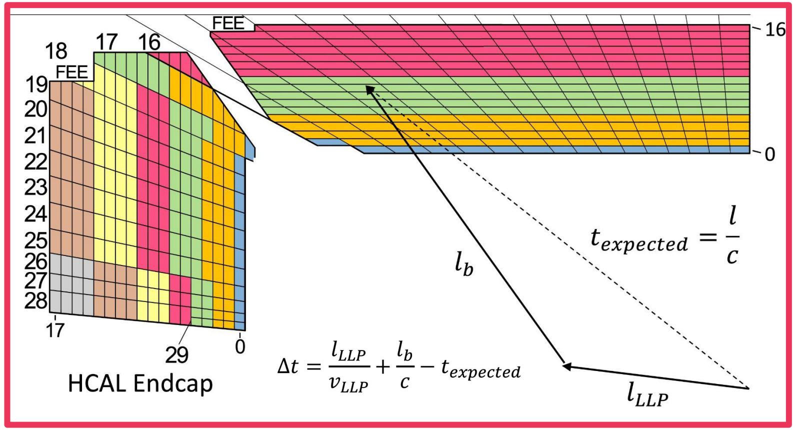
- Depth segmentation
- Precision timing

**HCAL LLP Jet Trigger Selects for:**

- Jets possibly produced inside the HCAL
- Jets with large time delays

**Deployed in the Prompt Stream in Run 3**
**Total HLT Rate: ~25 Hz**

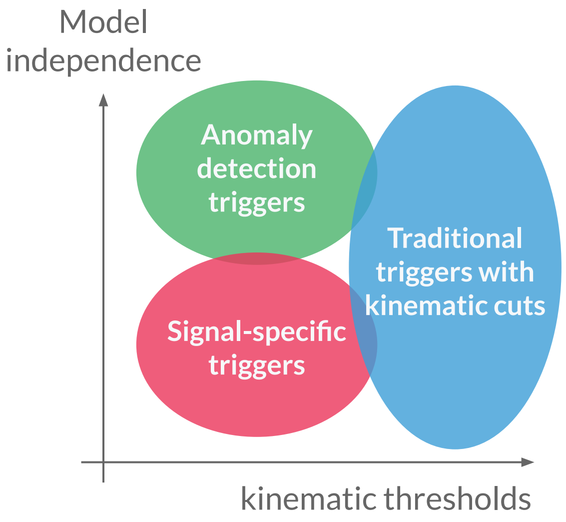


# Case Study 3: Anomaly Detection Triggers

**Paradigm**: “What if we miss new physics because we did not design the right trigger?”

- Anomaly detection triggers are sensitive to rare processes that we may not have triggers for



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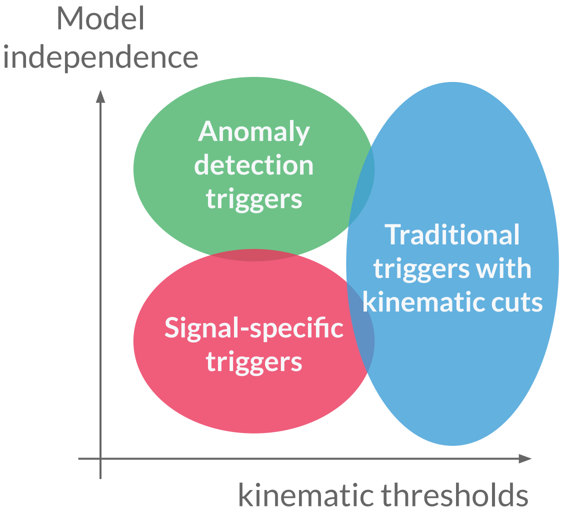
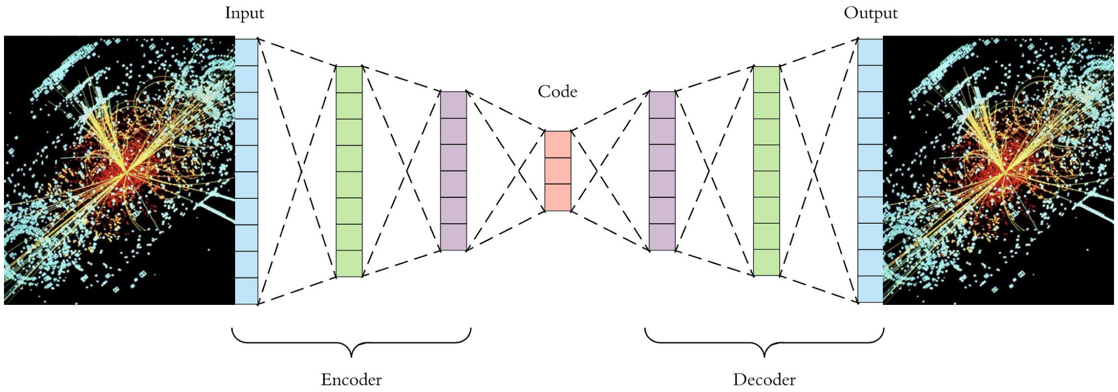
**Two triggers at L1**: CICADA & AXOL1TL → implemented as *autoencoders*




**Autoencoder:**

Train on background → network reconstructs background well (low anomaly score)



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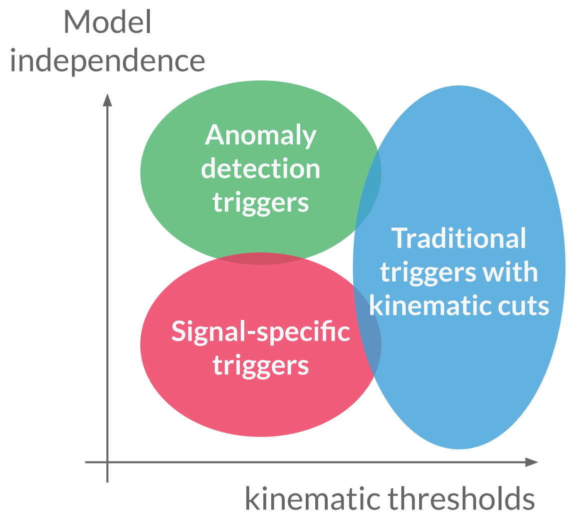
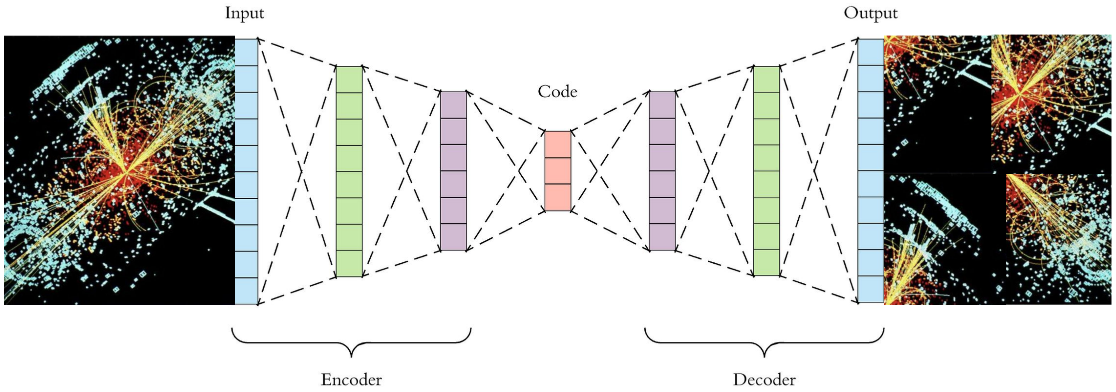



**Autoencoder:**

Run on signal → network reconstructs signal poorly (high anomaly score)



# Case Study 3: Anomaly Detection Triggers

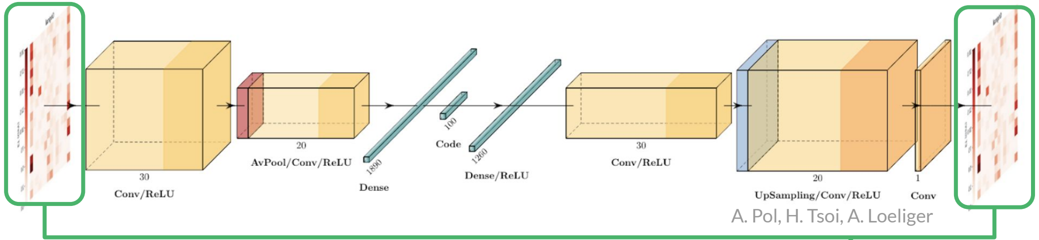
CICADA

Targeting Scouting Stream in Run 3
Total HLT Rate: ~500 Hz

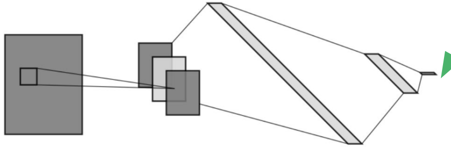
**Key challenge**: full model too large and slow for L1

**Solution**: knowledge distillation – train smaller model to predict the score of the larger network

<u>Model Developed in Software (Offline)</u>

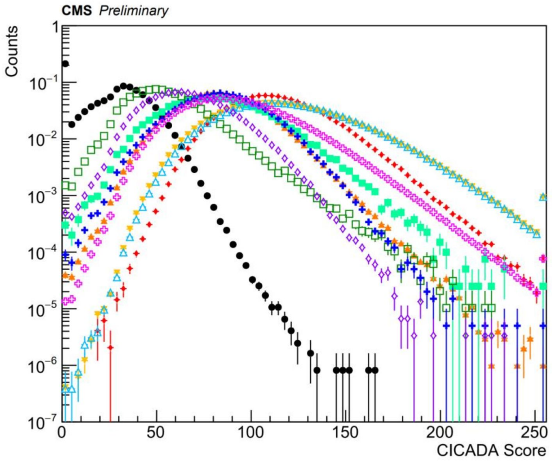



<u>Model Implemented in Firmware (at L1)</u>



<u>Performance in Background vs. Signals</u>

*Signals (color) have higher scores than background (black)!*



# Part V – Outlook

# HL-LHC Upgrade: Overview

- Upgrade enables collisions at a *higher instantaneous luminosity*, with more collisions per bunch crossing (~60→200+)
- The increased pileup creates more challenging experimental conditions → upgrade the CMS detector needed

# HL-LHC Upgrade to the CMS Detector *(Selected)*

## Tracker Upgrade:

- Increased granularity
- Tracking available for the first time at Level-1

## ECAL Upgrade:

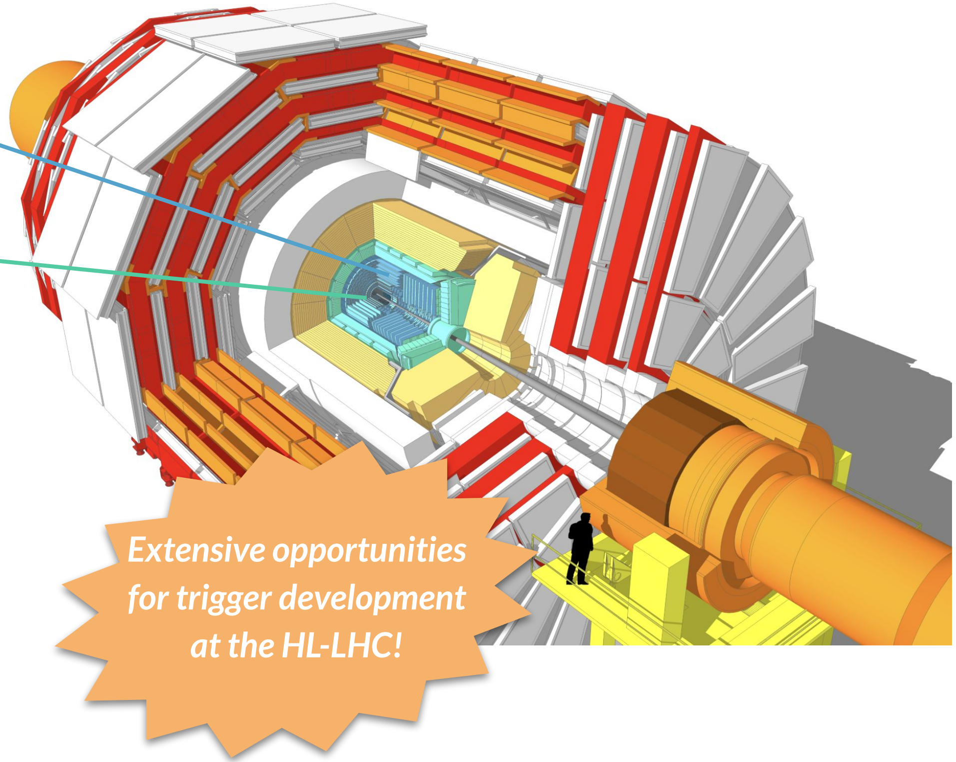
- Increased granularity at Level-1

## MIP Timing Detector:

- Timing precision on the ~10 ps level

## Trigger (L1+HLT):

- Level-1: Tracking and particle flow
- Level-1: 100 → 750 kHz
- Standard HLT: 1.5 → 7.5 kHz
- Scouting HLT: ~10 kHz → 40 MHz



# Summary + Outlook

**Summary**

- CMS trigger architecture has two main stages (L1+HLT) and with three output streams (Standard, Parking, Scouting) to maximize physics reach given heavy constraints on computational resources
- Key trigger metrics include rate and pileup dependence, prescales, and efficiencies
- There are many exciting trigger developments at CMS in LHC Run 3!

**Outlook**

- We are continuing to think about how improvements or additions to the trigger menu can enhance the CMS physics program
- The HL-LHC upgrade to the CMS detector provides exciting opportunities for new triggering capabilities!


Thank You!
Questions?