# INTRODUCTION TO TRIGGER AND DAQ SYSTEMS

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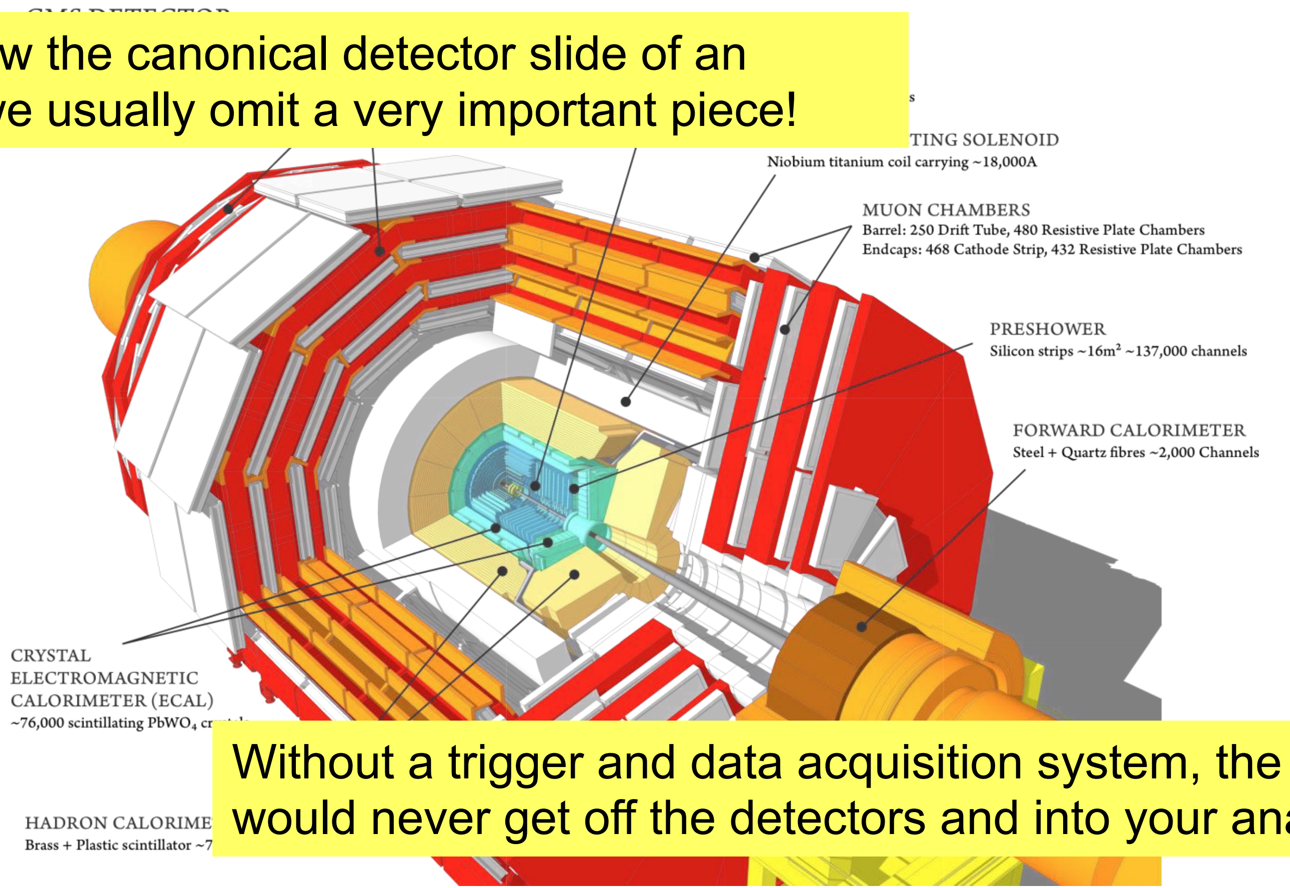
# Outline – Trigger

- What is a trigger and DAQ system, and why needed?
- Level-1 Trigger
- High Level Triggers
- Rate and efficiency curves
- Trigger Menus
- Parked data, data scouting
- Future Outlook
  - HL LHC trigger upgrade
  - AI in triggers
  - Triggerless?
  - FCC

# The "Compact" Muon Solenoid (CMS)

When we show the canonical detector slide of an experiment, we usually omit a very important piece!

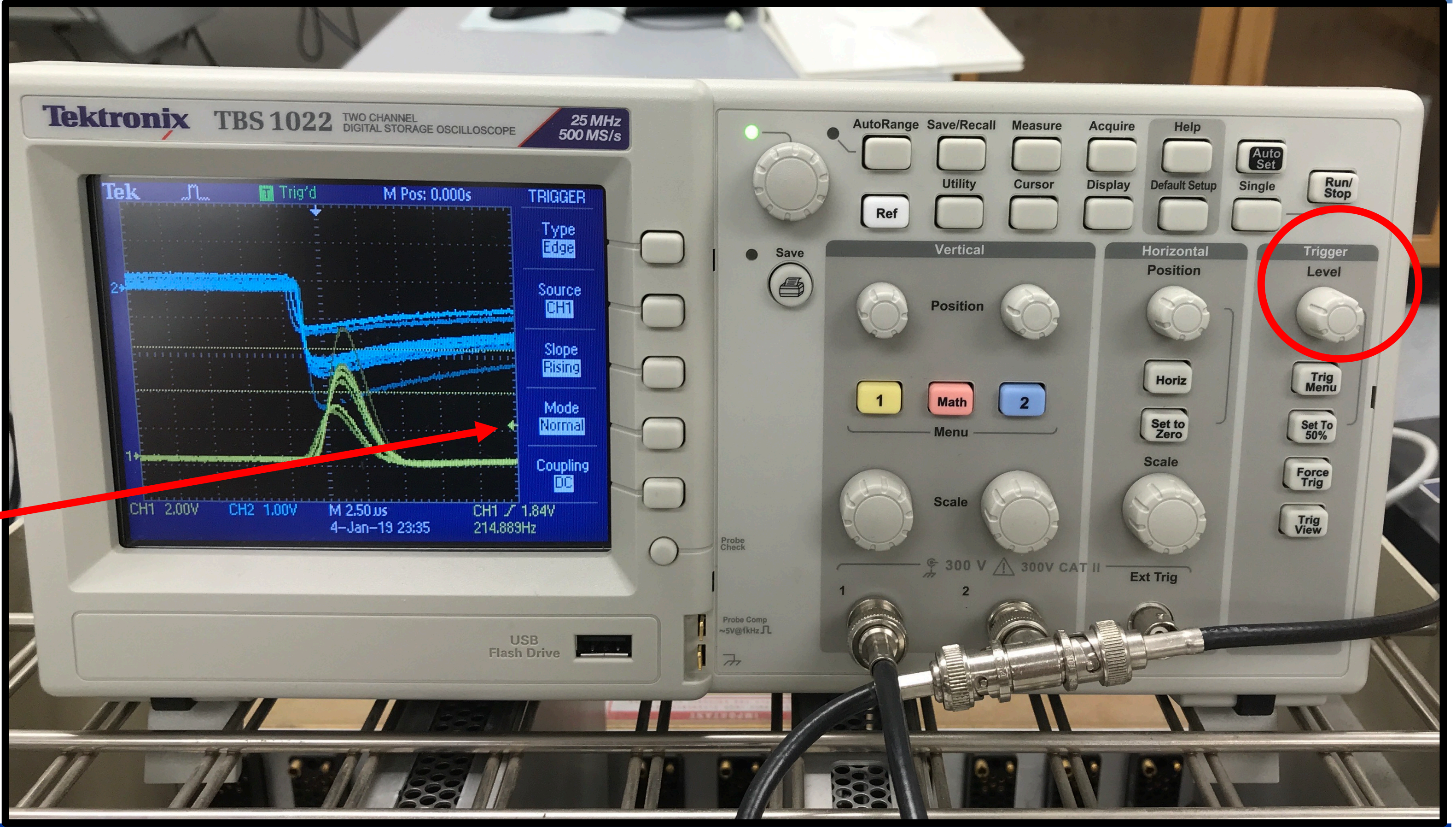



Without a trigger and data acquisition system, the data would never get off the detectors and into your analysis!

# Data Acquisition for HEP Experiments

- "Data acquisition" is the collection and storage of data recorded by a set of detectors comprising an experiment
- Often needs a "trigger", a set of conditions (a "menu") by which to initiate the sequence to digitize data from analog sensors (or read out from local buffers) and record to memory/disk/tape storage
  - Particle beam entering an experiment, or a collision taking place inside the experiment
- This trigger can be:
  - as simple as a single signal pulse indicating the presence of a particle passing or interacting in an experiment
  - or as complicated as partial reconstruction of a collision from detector data, and a long list of criteria to decide whether to store

# Example: Trigger on Oscilloscope



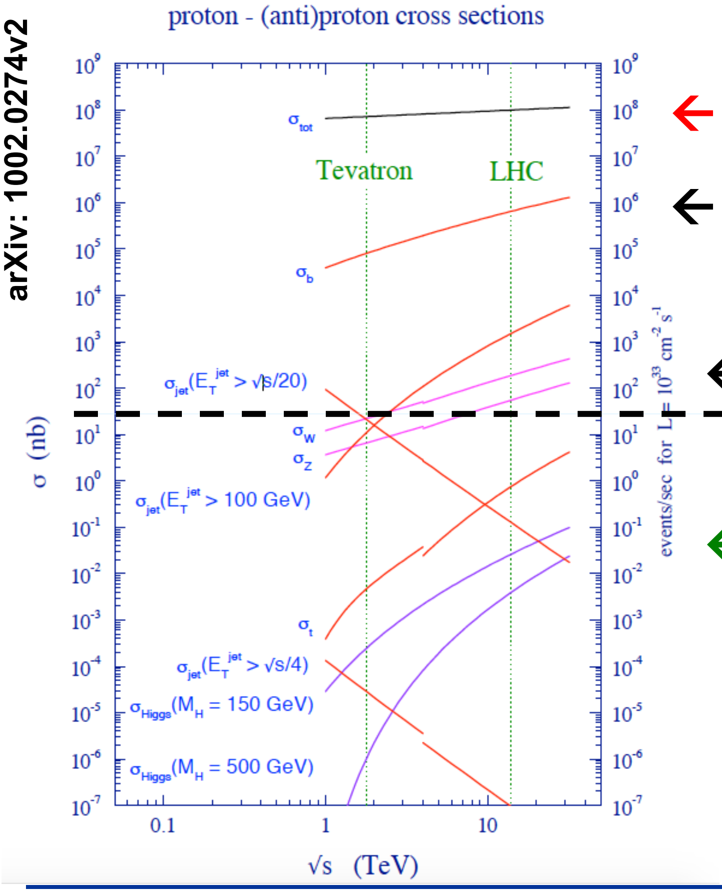

Pulse threshold for triggering readout

# Trigger for Particle Physics

- Why is a trigger needed?
  - Too much data to continuously stream to disk for storage and/or computer processing reasons
    - For example , an LHC experiment could generate ~100 terabytes of data per second!
  - Electronics data digitization may induce "dead time"
    - A period of time when further data cannot be recorded because of processing, and thus the experiment is insensitive to new incoming data. This wastes collider luminosity.
- It is really the first step of a data analysis
  - An online data filtering system
  - But irreversible – can't go back to data you did not record
    - e.g. Throw away 99.998% of all LHC crossings… (keep ~1000 Hz)
    - But, don't throw out the baby (Higgs) with the bath water!

# LHC Cross Sections and Rates

arXiv: 1002.0274v2




**for L =2 x $10^{34}$ Hz/cm$^2$**

← **Total collision rate: 2 GHz**

**Billions of collisions per sec but at a beam crossing rate of 40 MHz**

← **b quark rate: 10 MHz**

← **W boson rate: 4 kHz**

Keep

← **Higgs boson rate: 1 Hz**

We cannot keep all physics processes in order to collect enough data on interesting rare processes

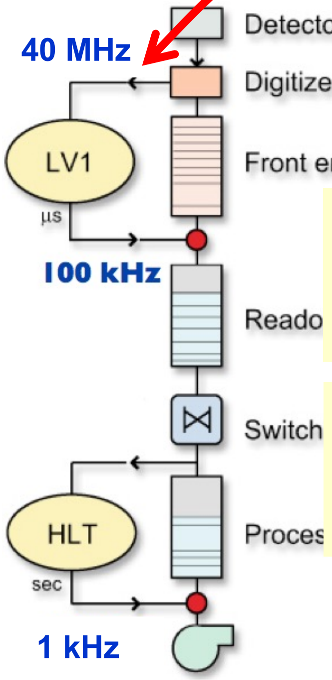
# Trigger Systems at Collider Experiments

- Typically segmented into multiple levels, with decreasing input rates and longer processing times (latencies)
- Level-1:
  - Custom electronic designs for maximum throughput (TB/s) and shortest latencies (microseconds). i.e. specialized computing
    - Custom chips (ASICs) and programmable logic (FPGAs)
  - Processing logic done in a maximally parallel way for shortest latency
  - Processing is pipelined, meaning processing is segmented into steps of a certain clock period (beam crossing), and intermediate results are registered after each step
- Level-2: (if needed…)
  - Combination of custom electronics and commercial computing equipment
- Level-3:
  - Commercial computing clusters of up to $O(10^4)$ CPUs with up to ~second per event processing time
    - i.e. Parallelized with different collision events processed with different CPUs, but mostly sequential within a CPU core

# More Cost Effective with Multiple Stages

# Example: CMS Trigger Architecture

- Only two levels*:
  - Level-1: custom electronics to reduce the data from a collision rate of 40 MHz to no more than 100 kHz for the detector readout electronics, with only a 4 μs latency (buffer depth)
  - High Level Trigger (HLT): event filter farm comprised of commercial CPUs running software to further reduce event rate to storage to an average of ~1 kHz (for LHC Run 2)



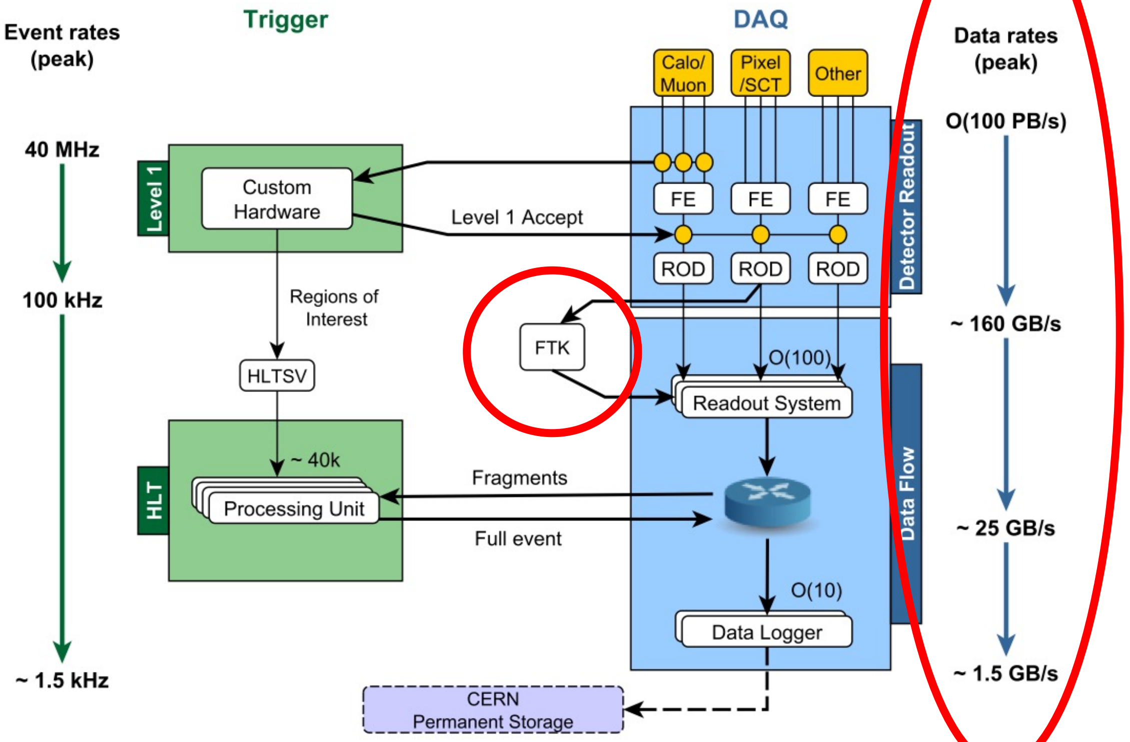

Note that data path is split @ L1

Data are sitting in buffers waiting for L1 decision

The L1 latency sets the depth of the buffers (and $)

*Historically, and for the ATLAS experiment initially, three levels were used. CMS was an adopter of a powerful HLT.

# ATLAS 2-Level Trigger Architecture

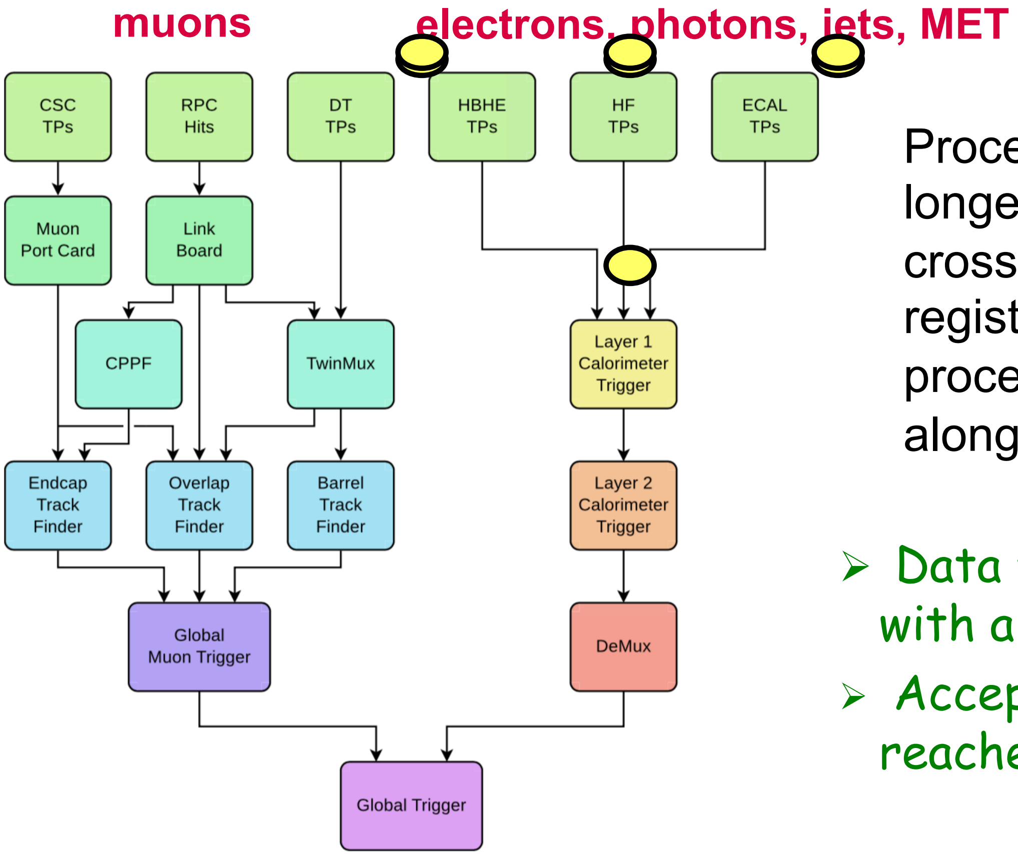



- Note the data rates (bandwidth) also gets reduced along with the event rate
- ATLAS also envisioned a custom accelerator for tracking at HLT

# Collider Trigger Comparisons

| | Tevatron / CDF (2004) | LHC / CMS (2018) |
|---|---|---|
| Beam Energy | 1 TeV | 6.5 TeV |
| Inst. Lumi. ($cm^{-2}s^{-1}$) | $10^{32}$ | 200X $2x10^{34}$ |
| Bunch xing freq / Time spacing | 2.5 MHz / 400 ns | 16X 40 MHz / 25 ns |
| L1 pipelined ? | No, initially | Yes |
| L1 output rate | 25 kHz | 4X 100 kHz |
| L2 output / HLT input | 400 Hz | 250X 100 kHz |
| L3 output rate | 90 Hz | 10X 1000 Hz |
| Event size | 0.2 MB | 5X 1 MB |
| Filter Farm | 250 CPUs | 40X O(10 000) CPUs |

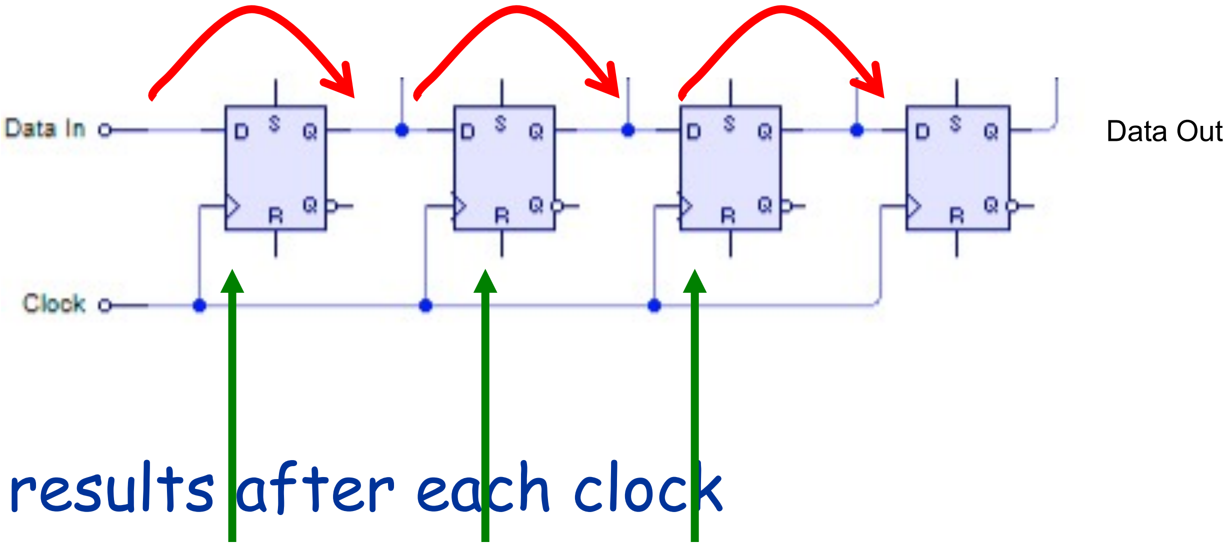
# "Pipelined" L1 architecture (CMS)




Processing takes longer than one beam crossing, so must register intermediate processing results along the way

- Data flows in a pipeline with a 40 MHz heartbeat
- Accept/reject decision reached in 4 μs

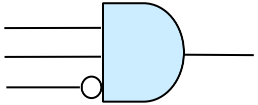
# Pipeline is Essentially a Shift Register



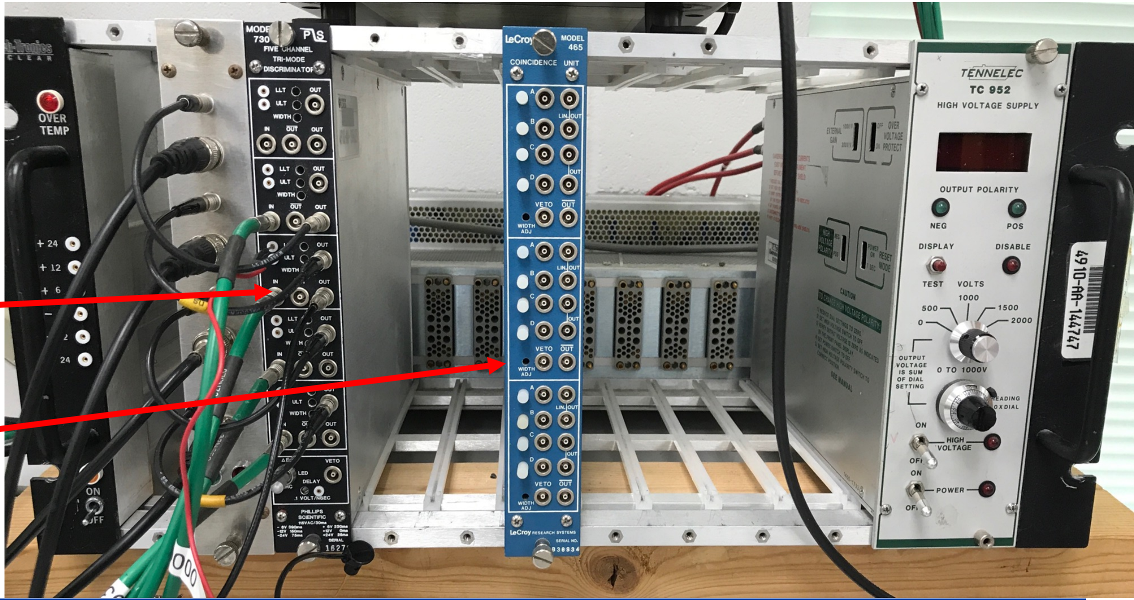

* Latch results after each clock
  * Processing step 1, step 2, step 3, …
* Implies your algorithm must be factorized into steps short enough to fit into 1 clock period

# Earliest Days for Trigger Implementation

- Simple logic coincidences
  - e.g. A and B and (not C)
  - Where, A, B, and C are digital signals coming from threshold discriminators on some detector signals (like scintillator paddles)



- NIM* modules could implement basic logical operations, including majority logic like 3 out of 4



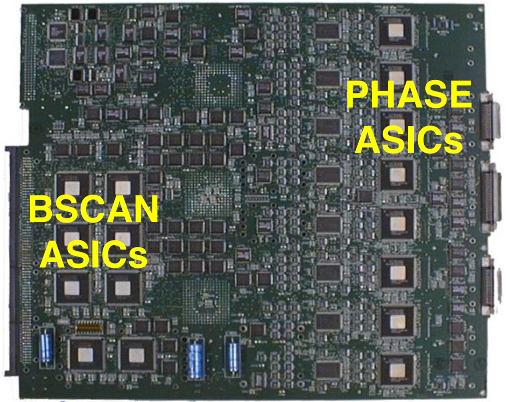

Threshold discriminator, to convert analog to logic pulse

Coincidence unit

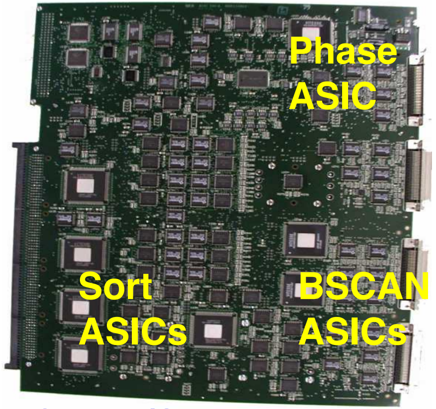
*Nuclear Instrumentation Module

# More recently: CMS Level-1 Trigger System

# Some Level-1 Hardware (circa 2004)



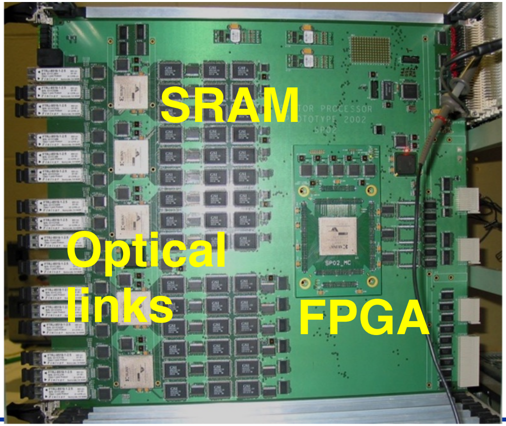

RCT Receiver card




RCT Jet/Summary card


RCT Electron isolation card

Muon Track-Finder




- Custom chips (ASICs) – adders, sorters...
- Programmable logic (FPGAs)
- Memory (RAM)
- Copper and Optical links, ~Gbit/s
- VME chassis (early computer hw format)

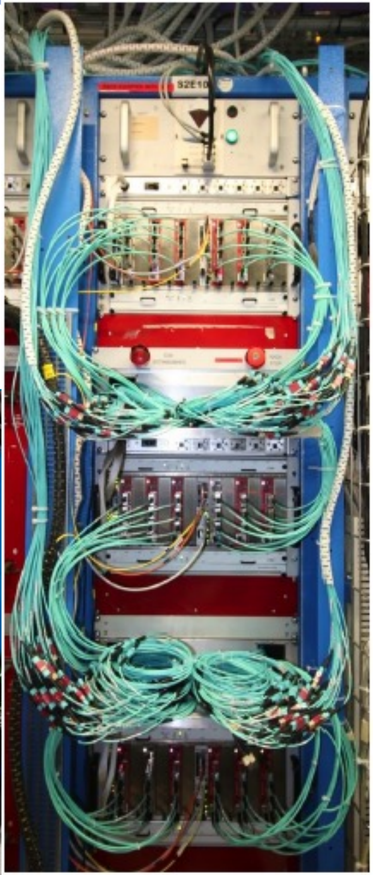
# Some Level-1 Hardware (circa 2016)

- ➢ Up to 10 Gbit/s optical links
- ➢ Large Field Programmable Gate Arrays (FPGAs)
  - Extensive logic and multiplier resources
- ➢ uTCA telecommunications infrastructure

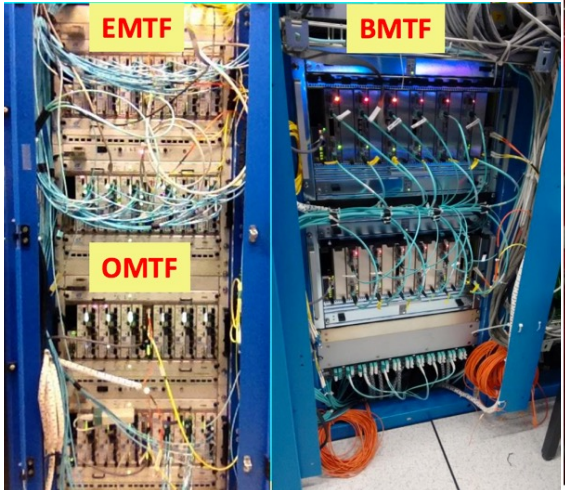
✸ Flexibility:

- ➢ Modest revisions to data formats between boards is possible
  - Send extra data if useful
- ➢ FPGA firmware can be updated, with generally room for new trigger ideas
  - e.g. Kalman Filter algorithm, neural networks
  - Can be written in high level languages (e.g. Vivado HLS)

Calo trigger rack

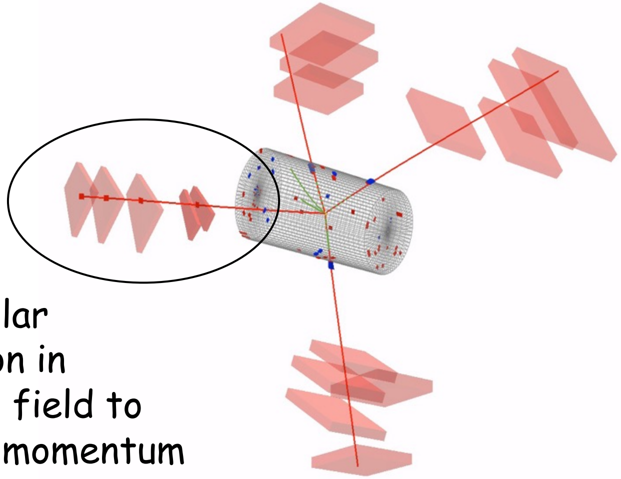


Muon trigger racks



# Example Algorithm: Level-1 Muon "Track-Finding"

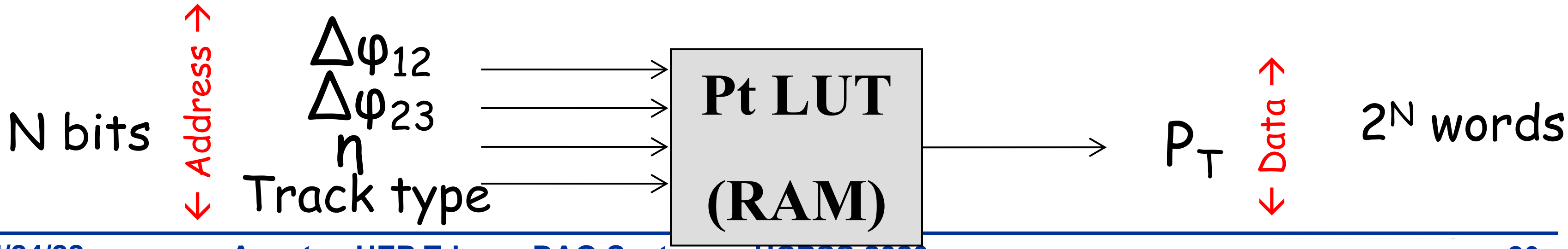
- Track-Finder links receive track segments and FPGA builds into distinct tracks through pattern recognition logic in firmware
  - 2-D tracks for barrel region, 3-D tracks for endcaps
  - Algorithm implemented in a programmable FPGA
- Performs a momentum measurement using the deflection of muon in the magnetic field
  - Using a memory look-up table
- Transmit highest quality candidates to Global Trigger for selection



Use angular deflection in magnetic field to measure momentum

# Aside: Triggers must be fast! Calculation by Look-up

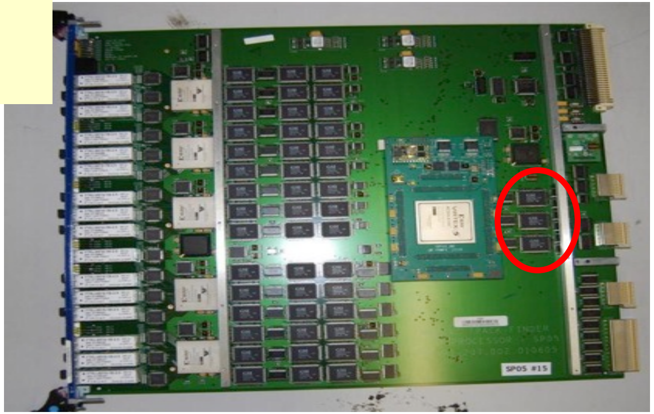
- The muon $P_T$ for previous is calculated from a memory look-up table
  - A "cheat" to do the calculation quickly (~50ns) in the L1 trigger.
    - Also must be fast for random addressing…
  - Don't really calculate it online at all (no CPU involved real-time)
  - Instead, pre-calculate offline the muon momentum using whatever algorithm you want and with however much computing resources you have!
    - But you must do this for every possible input to the memory
- The challenge:
  - You must squeeze all the data for your track fit into the memory address
    - N bits of of data requires a memory of $2^N$ addresses

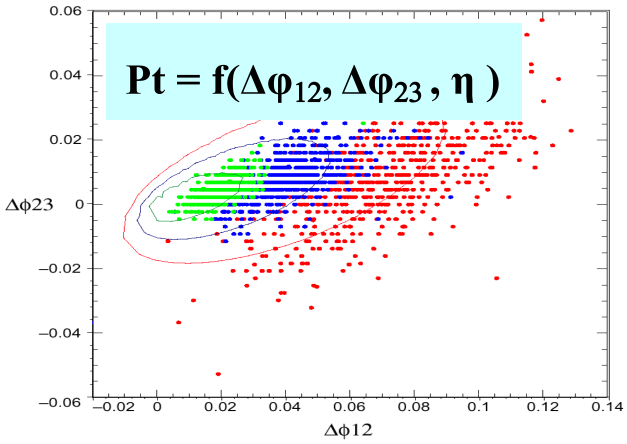


# Version 1: CSC Track-Finder, 2005-2015

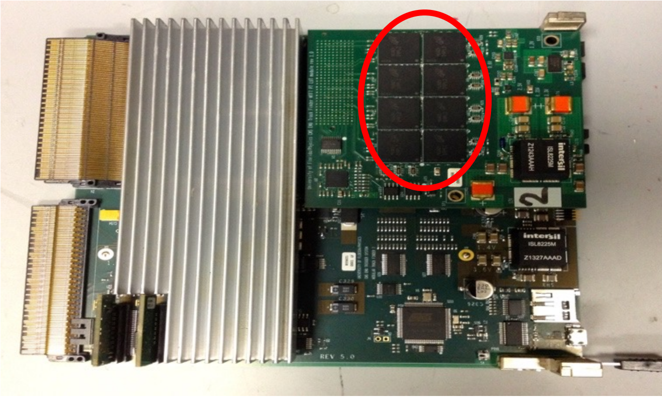
- 12 VME processors
  - Xilinx Virtex-5 FPGAs and memory
- $P_T$ calculated from an external SRAM memory look-up table
  - Largest available at time to do the job: 4MB → 22 bit address space
- Algorithm
  - Likelihood-based fit using $\Delta\varphi$ bending between at most 3 detector stations to assign $p_T$
  - Multiple scattering in iron carries momentum information in addition to magnetic bending
- Data compression
  - Introduced nonlinear scales to "shoe-horn" in as much data as possible

Too large for FPGA logic



# Version 2: Endcap Muon Track-Finder, 2016+




- 12 μTCA double-module processors
  - Xilinx Virtex-7 FPGA and memory
- $P_T$ calculated from Reduced Latency DRAM
  - 1 GB → 30 bit address space
  - +8 address bits (only) over previous CSCTF
- Algorithm
  - Machine Learning: Boosted Decision Trees (BDTs) used for regression to assign $P_T$
  - More data: Can use Δφ bending between 4 detector stations, and Δη, and bend angle in first station
  - But note, as before, algorithm is run offline and stored in memory

ACAT17, CMS-CR-2017-35

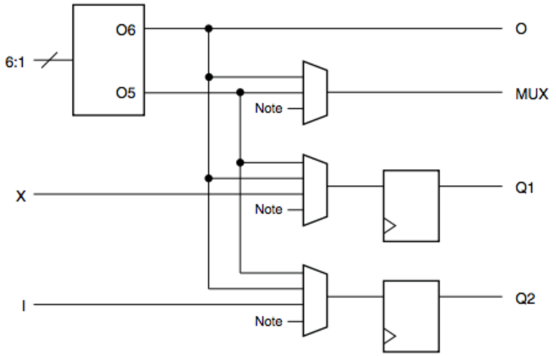
# An Aside on FPGAs: Reprogrammable Silicon

- Field Programmable Gate Arrays (FPGAs)
  - Off the shelf component, not custom
  - A silicon "breadboard" of configurable logic gates, memories, transceivers, Digital Signal Processors (DSPs), registers
- Fast digital logic at a lower level than a CPU because the logic is not pre-specified
  - Although you could program an FPGA to become a CPU in principle…
- State of the art (Xilinx Ultrascale+, 16 nm technology):
  - Up to 1.7M Configurable Logic Blocks (CLBs) - 6 bit LUTs
  - Up to 12K DSP slices
  - Up to 128 transceivers at up to 32 Gbit/s
  - Up to ~500Mbit of RAM
- But there is also the Intel/Altera family of FPGAs

Millions of logic gates!

Terabits per second!

# Xilinx Configurable Logic Block and DSP slice




- The Look-Up Table (LUT) can provide a 1 bit output for any collection of logic operations from 6 input bits
  - Like what a NIM module did
  - Millions of CLBs within large FPGA

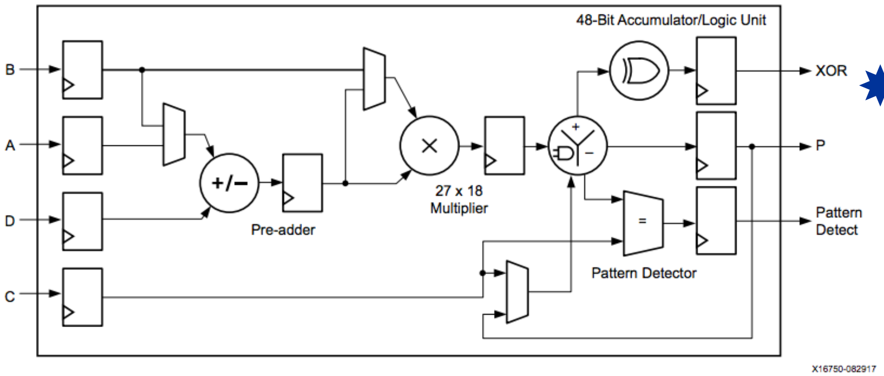


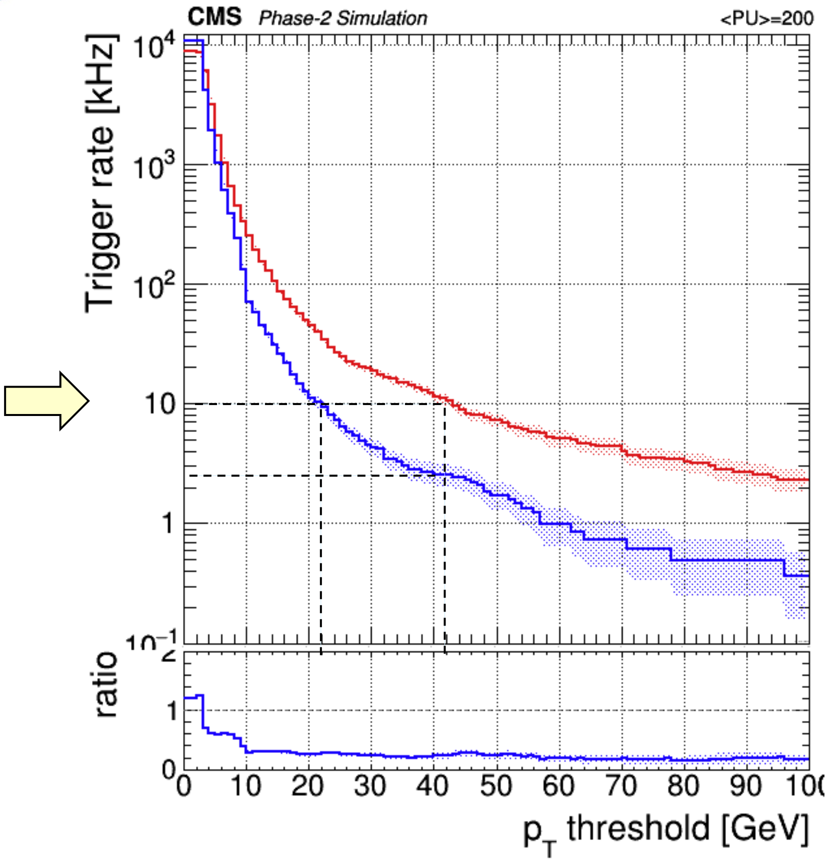

*Figure 1-1:* **Basic DSP48E2 Functionality**

- The DSP slice can specialize as a
  - 48 bit accumulator
  - 27 x 18 bit multiplier
  - 48 bit logic unit
    - Thousands within large FPGA

# FPGA Programming Possibilities

- These basic elements allow one to implement quite complex algorithms for a L1 trigger, such as
  - Massively parallel logic operations (remember, the L1 Trigger has only microseconds…)
    - pattern recognition for tracking
  - Matrix multiplication
    - Kalman filter track fitting
    - Artificial Intelligence: neural network implementation
- Programming an FPGA requires **firmware** to be written and synthesized into a "bit file" to load into the chip
  - But there are high-level languages to write the logic implementation, some very much like C/C++
    - VHDL, Verilog, Vivado HLS, OpenCL, …

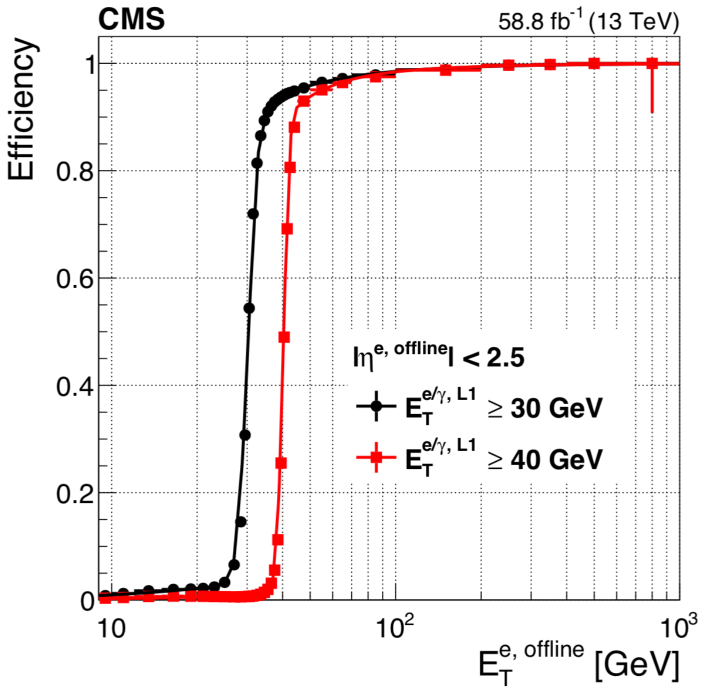
# Trigger Rate Curves (The cost of a trigger)




- Adjust a **threshold** for the rate you can afford to store
- These are simulated rate curves for a Level-1 single muon trigger at HL LHC
  - Current
  - Some improved algorithm
- Want a "knob" to be able to control the rate, albeit by raising the $P_T$ threshold here
  - Thus need good $P_T$ resolution

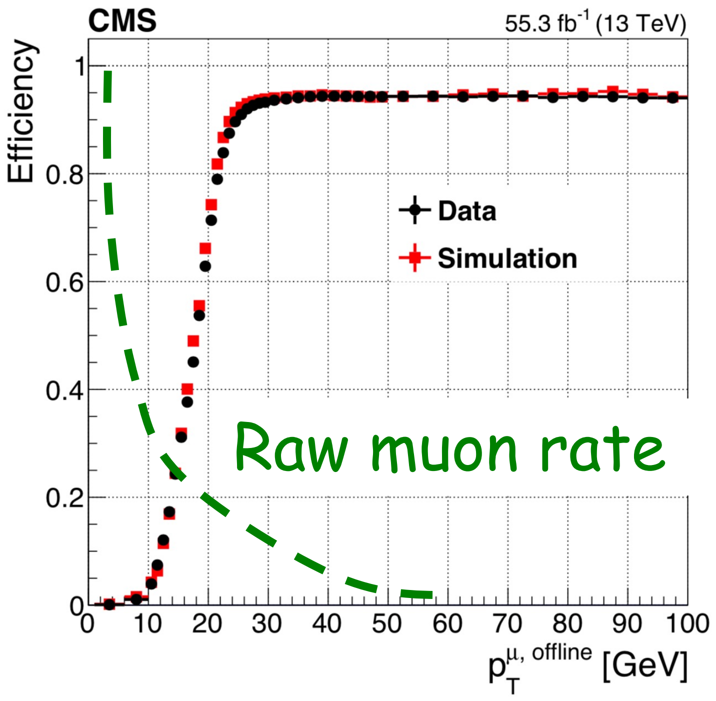
# L1 Trigger Efficiency Curves (above a threshold)

electron/photon trigger




$P_T$>30 or 40 GeV

Muon trigger




$P_T$>22 GeV

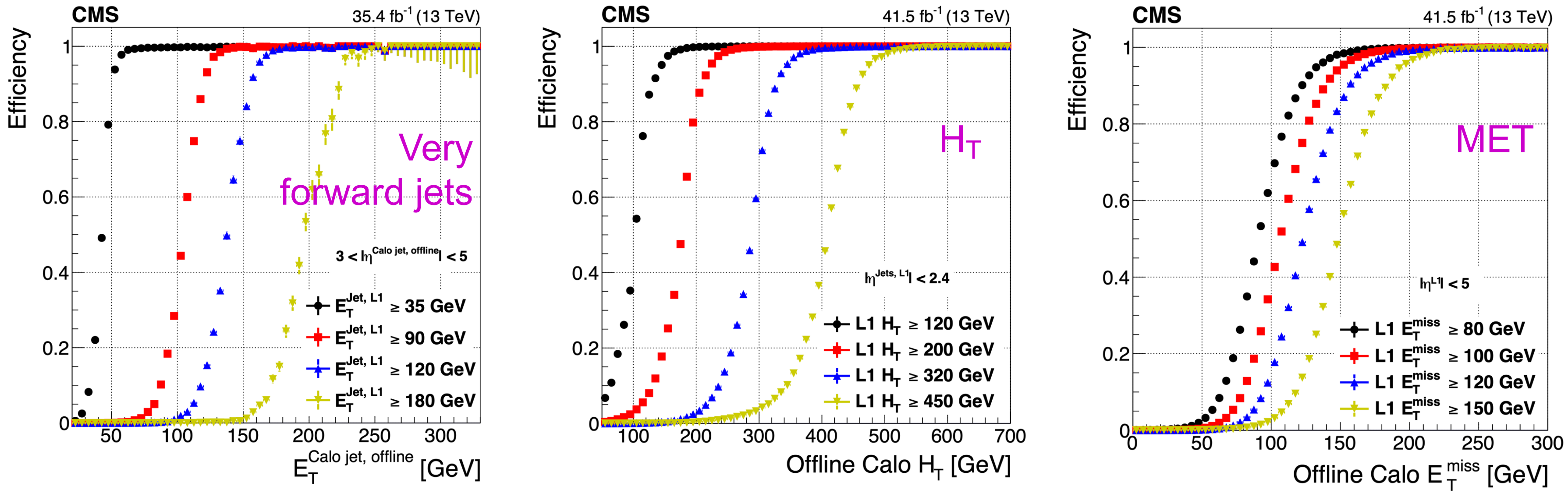
- Want sharp turn-on curves, and high efficiency plateaus that are flat
  - Why?

Sharper turn-on: less rate from mismeasured tracks at low PT

Flat, high efficiency plateau for event yield, less uncertainty

# Level-1 Jet, $H_T$, and MET Performance

JINST 15, P10017 (2020)

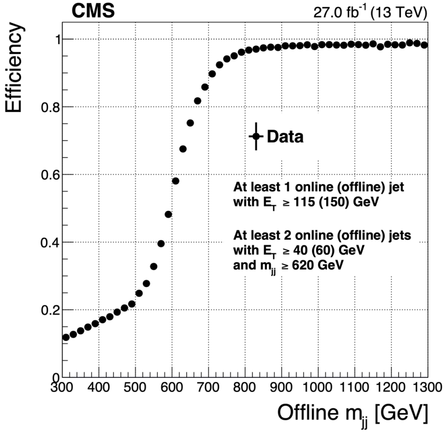


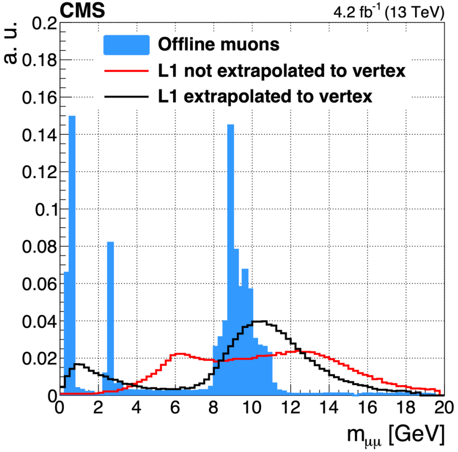

* Pileup mitigation applied

# Dedicated Level-1 Triggers for Analyses

[JINST 15, P10017 (2020)](#)

- Possibilities with Global Trigger:
- VBF dijet trigger with <u>invariant mass cut</u>
  - At least two jets with $E_T$ > 115 and $E_T$ > 35GeV and at least one pair of jets with $E_T$ > 35 GeV each, and an invariant mass greater than 620 GeV
- Low mass dimuon triggers with <u>invariant mass</u> cut (e.g. B trigger)
  - Apply lower $P_T$ thresholds with dimuon invariant mass cut
  - Muon momenta extrapolated to vertex for mass calc. from standalone muon measurement



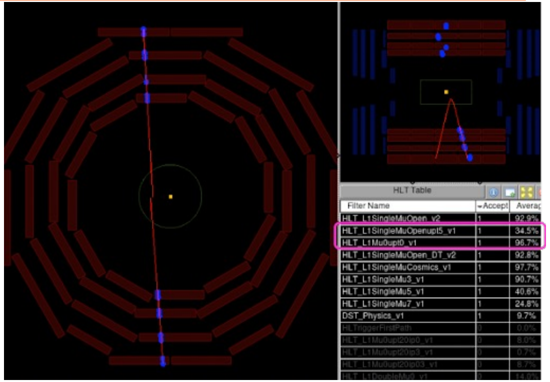

Other ideas are possible as well

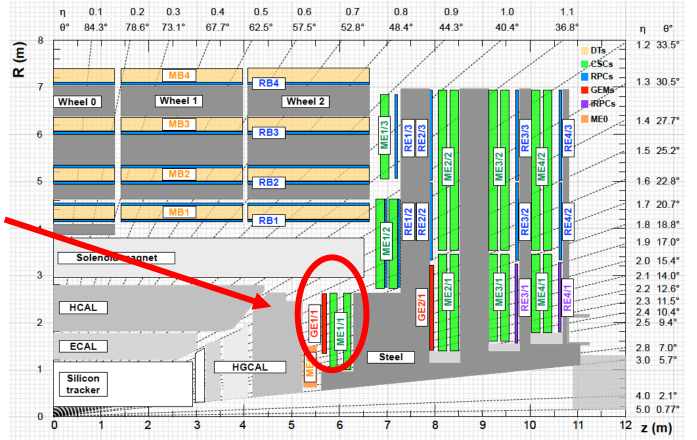
# Run 3 Enhancements for Level-1 Muon Trigger

PoS Vol. 343 (2019) 139

https://indico.cern.ch/event/998052/

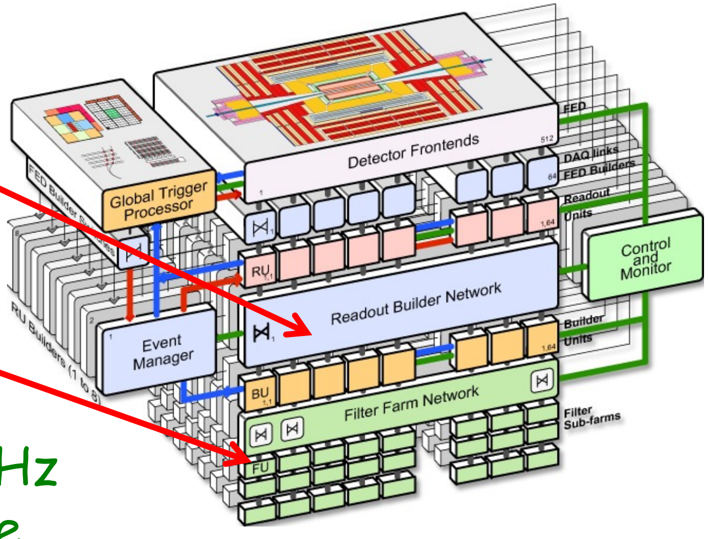
- **Barrel:**
  - Kalman filter for muon tracking has been incorporated into the FPGA logic of barrel muon trigger
    - Allows the possibility of triggering on LLPs with transverse displacements up to ~1m
    - Tested in recent cosmic muon data-taking
- **Endcap:**
  - Neural network for measuring displaced muons in endcap being ported to the FPGA logic of endcap muon trigger
    - Extends trigger on LLPs to endcaps
  - Innermost disk of Phase-2 GEM detectors being added to muon trigger
    - Should improve efficiency in the forward region: 1.6<|η|<2.1
    - Under commissioning
- **Potential to trigger on a single LLP leg**





# CMS Data Acquisition & High Level Trigger

- System accepts up to 100 kHz event rate (100 GB/s bandwidth) from detector electronics ("FEDs")
- Event builder
  - Run 1: Myrinet network switch
  - Run 2: Infiniband network switches
- High Level Trigger
  - ~26 000 CPU cores
  - Software-based algorithms
  - Output bandwidth ~GB/s
  - Average selection rate ~1000 Hz
  - ~300 ms/event processing time available for 100 kHz input rate

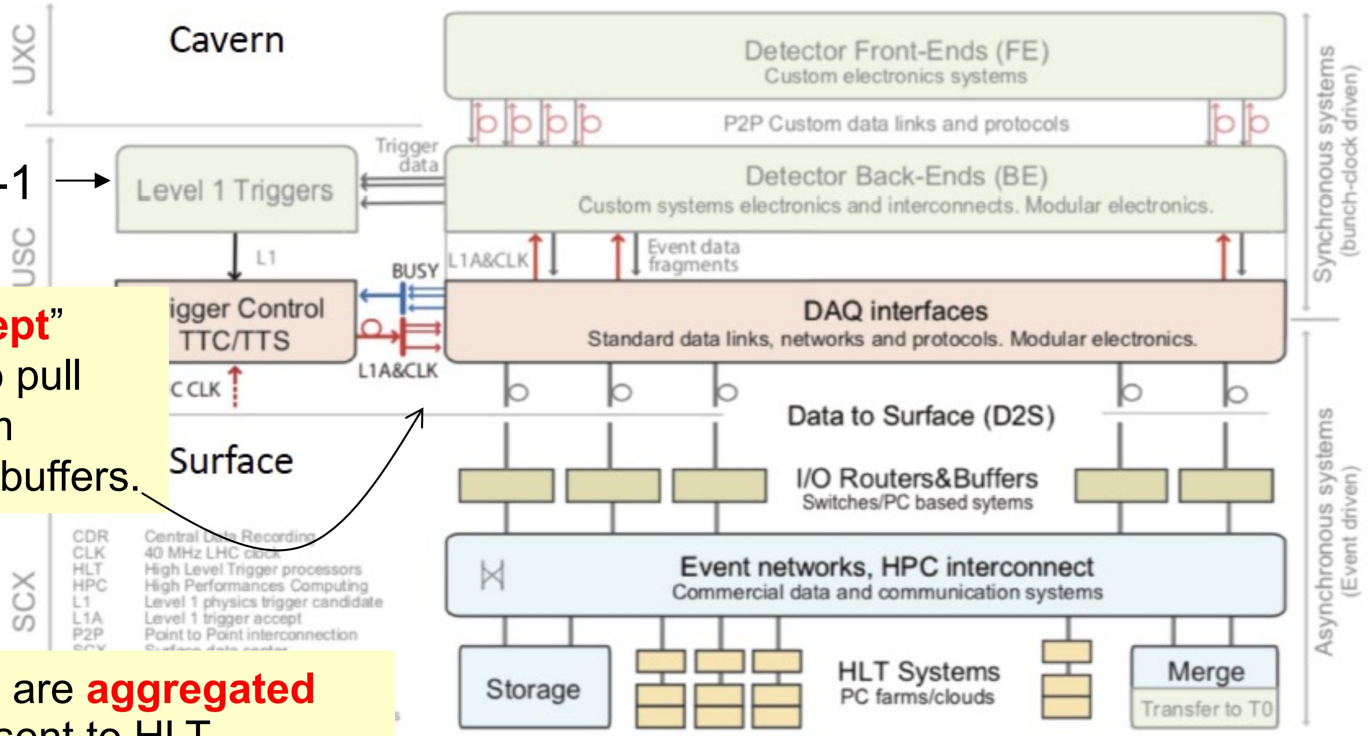


# HLT Implemented in a Local Computer Center

Computers get the best seat in the (CMS) house!

# CMS DAQ Architecture

Level-1




Detector data

Event Builder

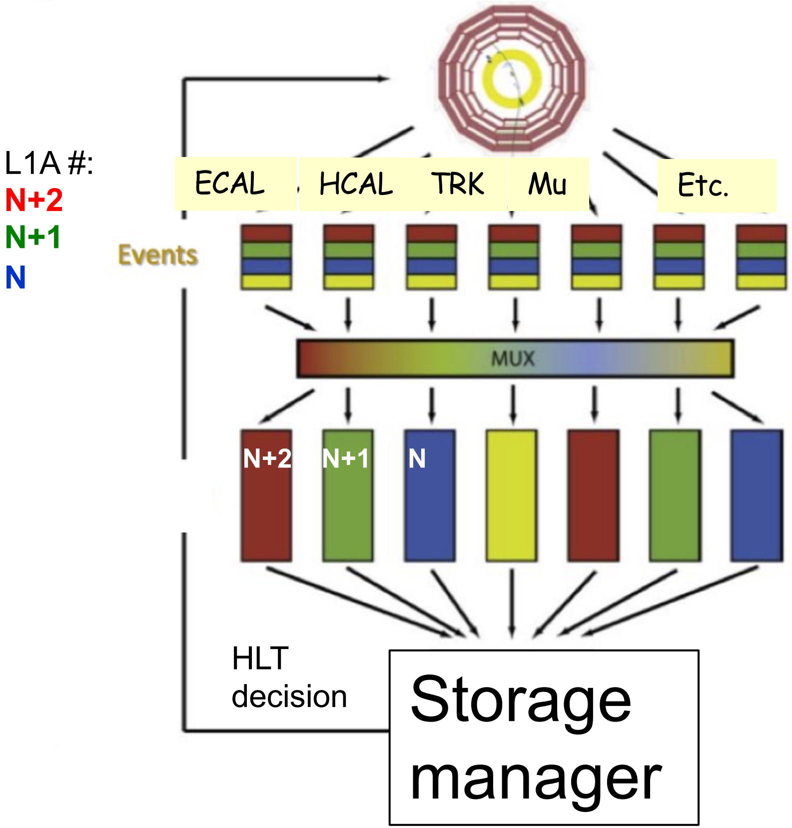
HLT

"**L1 Accept**" issued to pull data from detector buffers.

Data are **aggregated** and sent to HLT

When selected by an HLT node, event data sent to a **storage system**

# DAQ Event Building (aggregation)




- Fragments of events from different detectors and regions received at front-end
- Must aggregate data sent from different detector readouts from a specific L1 triggered bunch crossing:
  - "event building"
- Send full event data to a target processor destination in a round-robin fashion
- This is an asynchronous process (unlike Level-1, which is synchronous).

# The High-Level Trigger

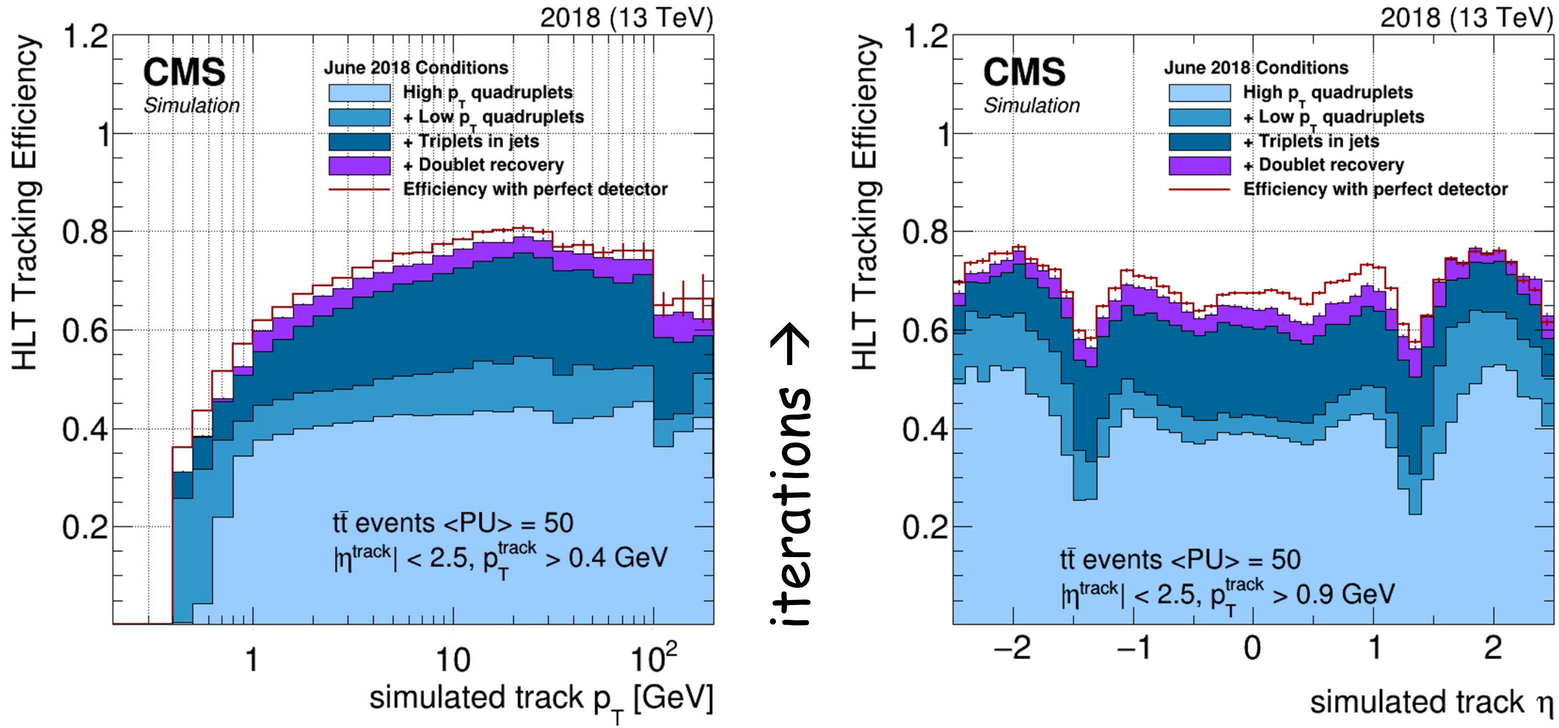
- Must reduce event rate from 100 kHz to ~1 kHz (LHC Run 2)
  - The output rate is set by offline computing data processing constraints and data storage limits
- But HLT starts with a data sample already enriched in physics!
  - Level-1 already applied a factor 400 background rejection, and still need to find another factor 100 reduction
- What else can HLT do?
  - Work with higher precision data than that used by Level-1
    - Uses same raw data as offline analyses
  - Include new detectors not used by L1
    - Silicon strip and pixel tracking
  - Employ more sophisticated algorithms
    - Particle flow, b-tagging
  - Use software very similar to that used offline

# HLT Tracking

- Tracking in the HLT is performed in 3 (+1) iterations
  - Start with tight requirements for the track seeds, and loosen for each subsequent iteration
    - Hits in the tracking detectors already used in a track are removed at beginning of the next iteration
  - The first two iterations require the maximum of four consecutive hits in the pixel detector to seed the tracking (first high $P_T$, then low)
  - The third iteration relaxes the number of hits in the track seeds to three, restricted to the vicinity of jets identified from calorimeter information and the tracks from the two previous iterations
  - An additional iteration was added using pixel doublets for $p_T > 1.2$ GeV as protection against DC/DC failures as observed in 2017

# HLT Tracking Efficiency

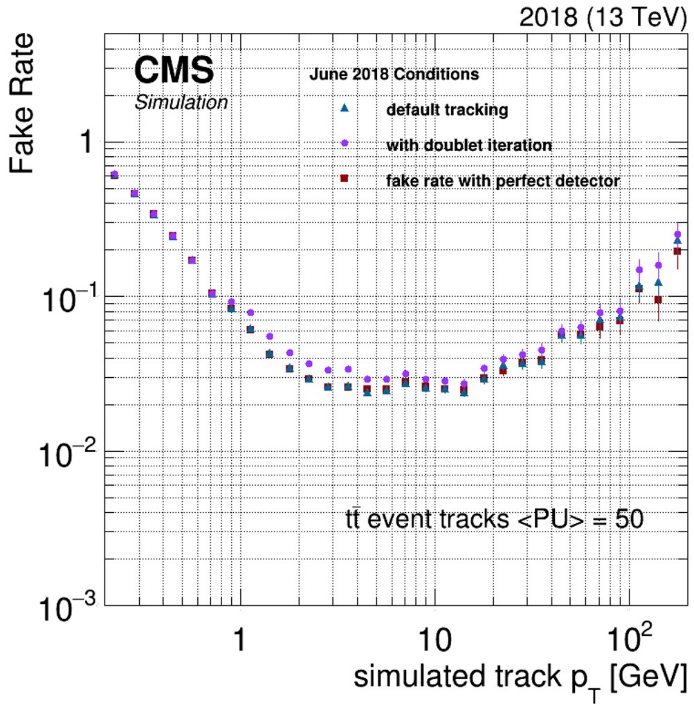
CMS-DP-2018-038

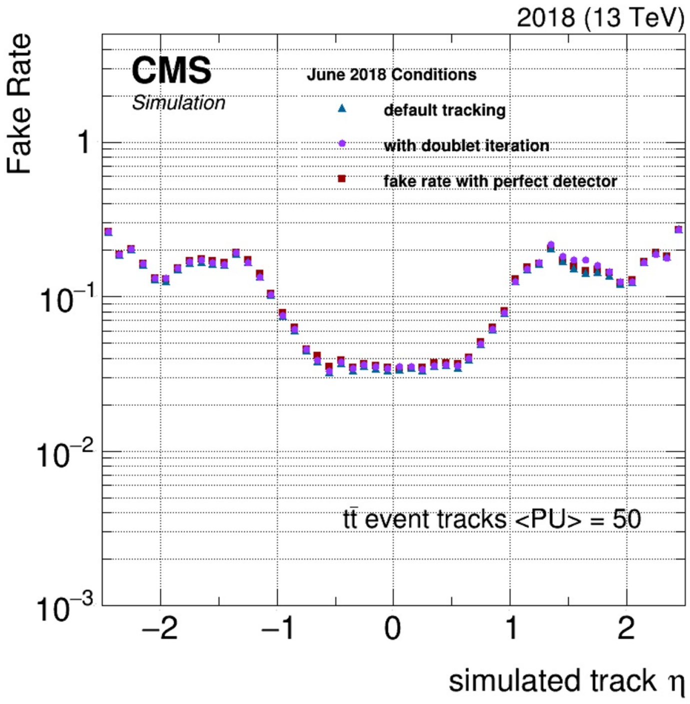



- After all iterations, efficiency is close to that expected for perfect detector
- Efficient for tracks as low as $p_T$ = 0.4 GeV

# HLT Tracking Fake Rate

CMS-DP-2018-038

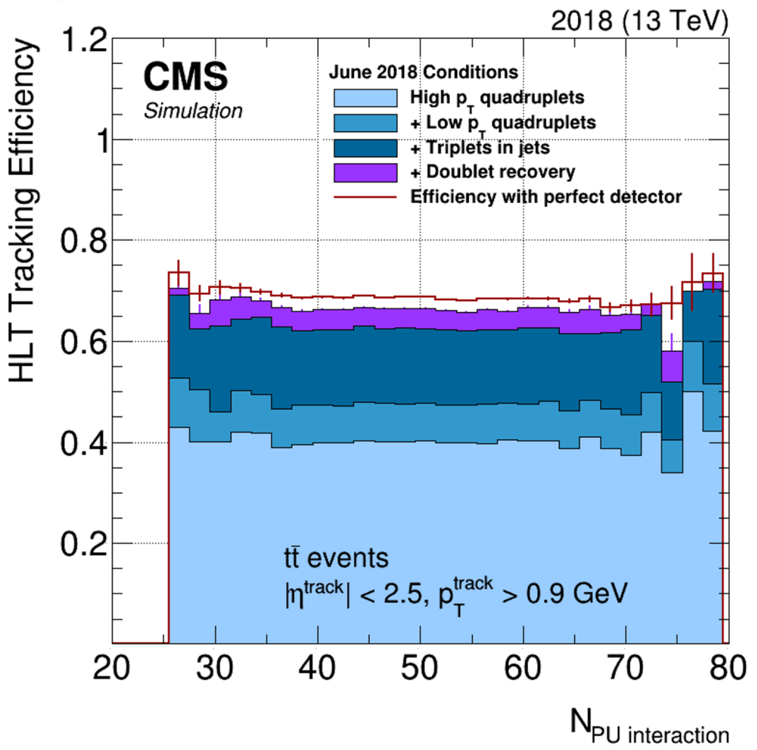


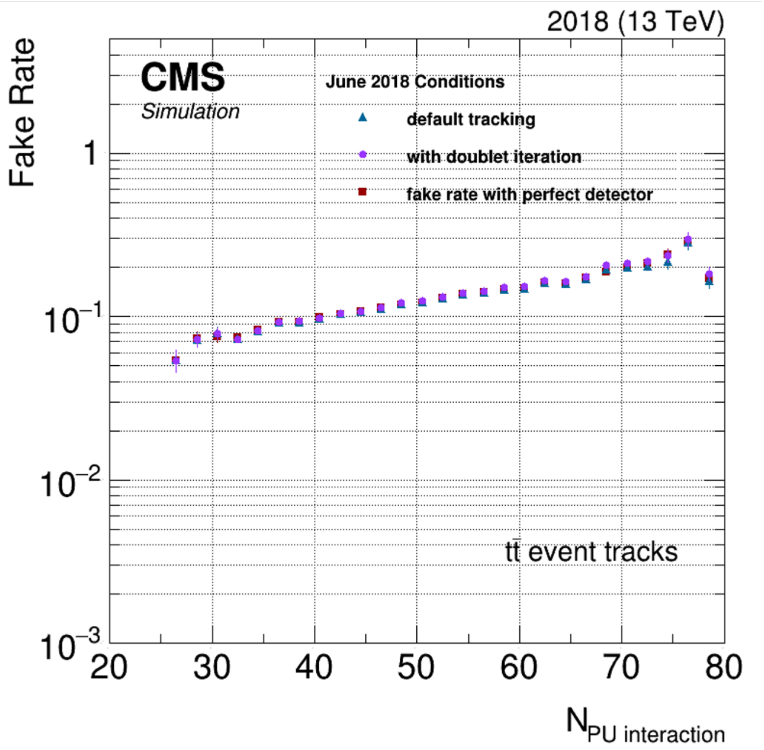




- Fake rate largest in forward regions, grows at low and high $P_T$

# HLT Tracking Pileup Dependence

CMS-DP-2018-038



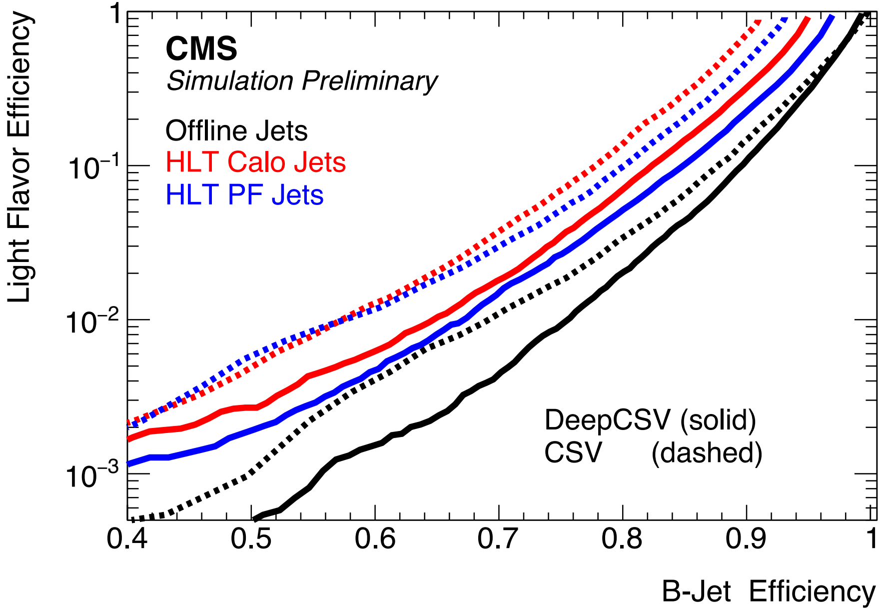




➢ Efficiency is stable with pileup, though fake rate grows slightly

# B-Tagging

CMS-DP-2019-042

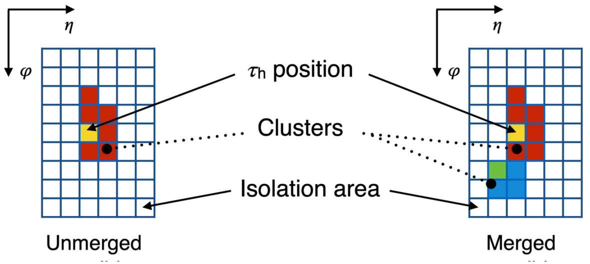
- Since 2017 a neural network classifier, DeepCSV, was used to identify b-jets (AK-4 jets)
- Improves b efficiency over previous CSV algorithm by 5-15% for fixed light flavor efficiency

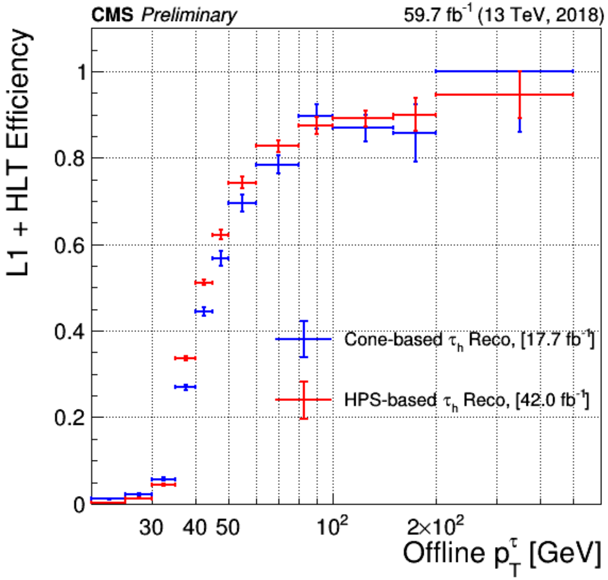


# Di-Tau Trigger, Hadronic Leg

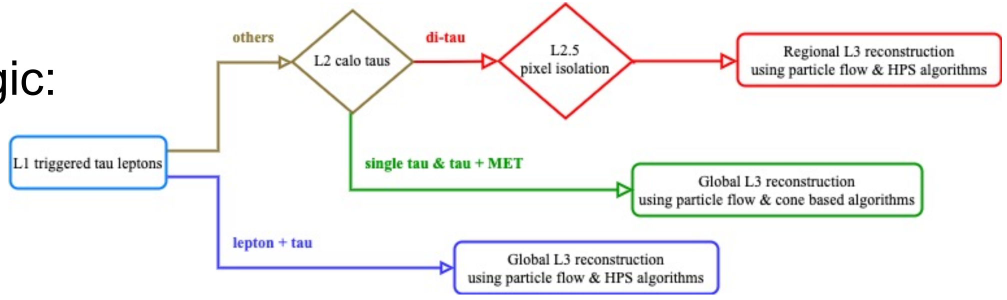
CMS-DP-2019-012

- Level-1 uses topological clustering of calorimeter deposits
- HLT reconstruction
  - Cone based reconstruction prior to mid-2018
  - "Hadron Plus Strips" reconstruction of exclusive decay modes used afterward (as offline)
- Used in combination with e, μ or another τ



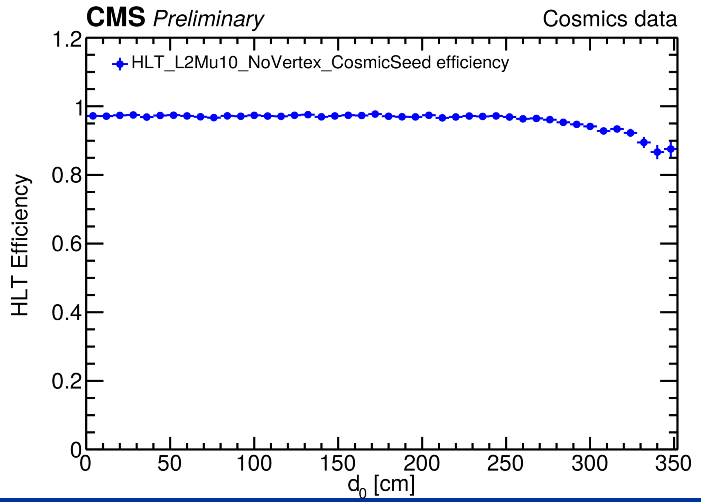

HLT Logic:

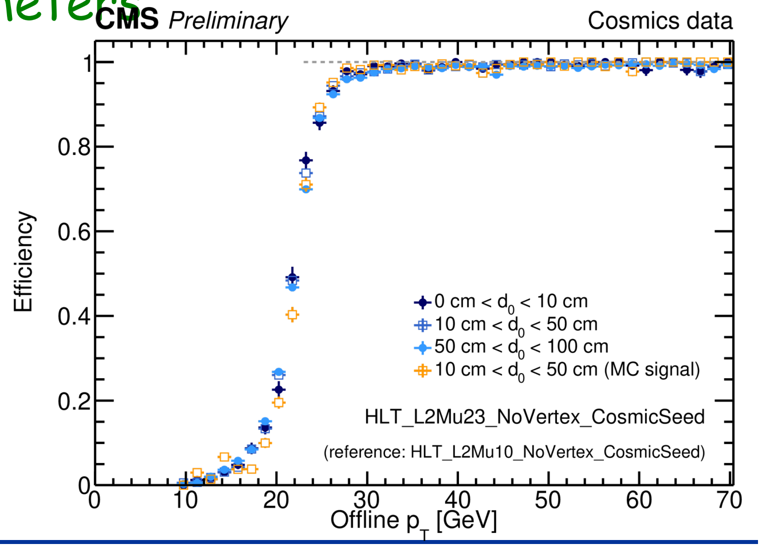


# Displaced Di-Muon Trigger

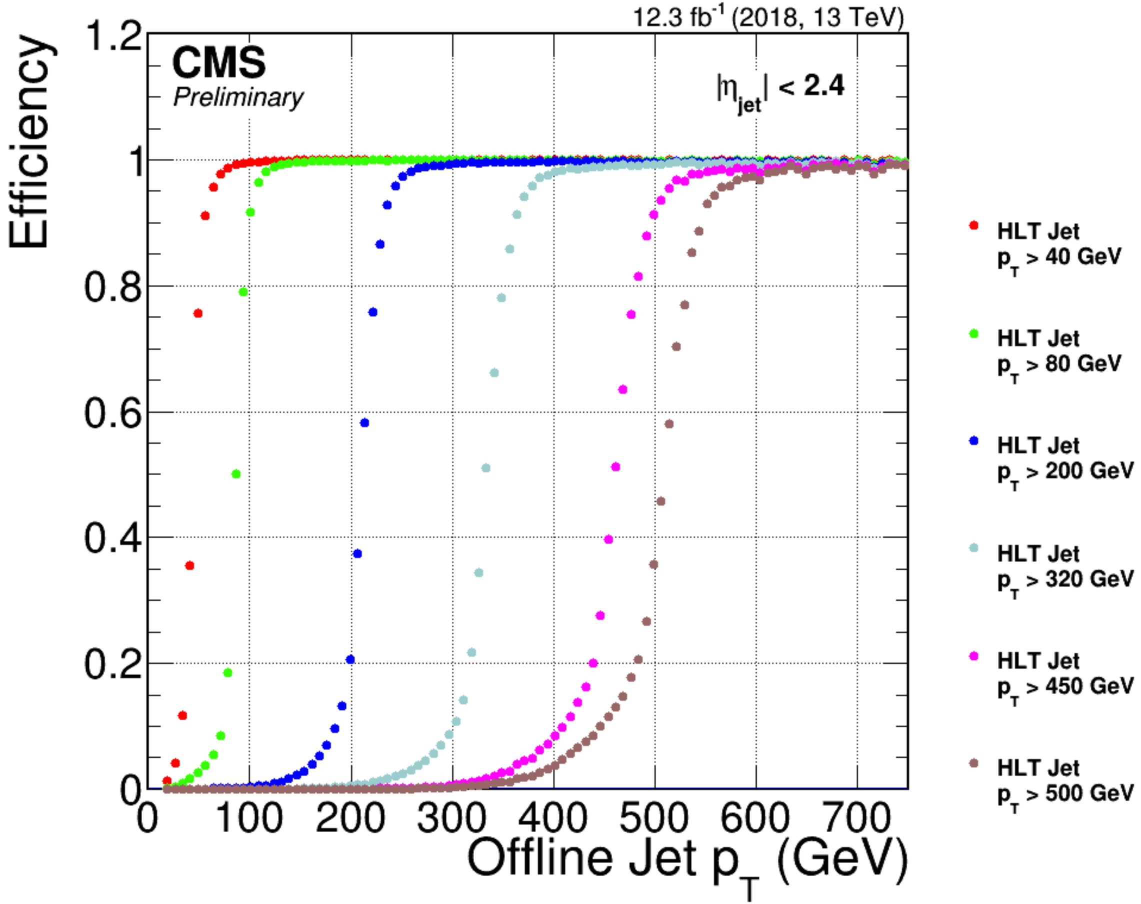
CMS-DP-2019-028

- Double muon trigger using only muon system (without tracker) and without a vertex constraint, for LLP searches
  - $p_T$ > 23 GeV each leg
- Performance measured using cosmic rays and compared with BSM signal MC:
  - Efficient for very large impact parameters

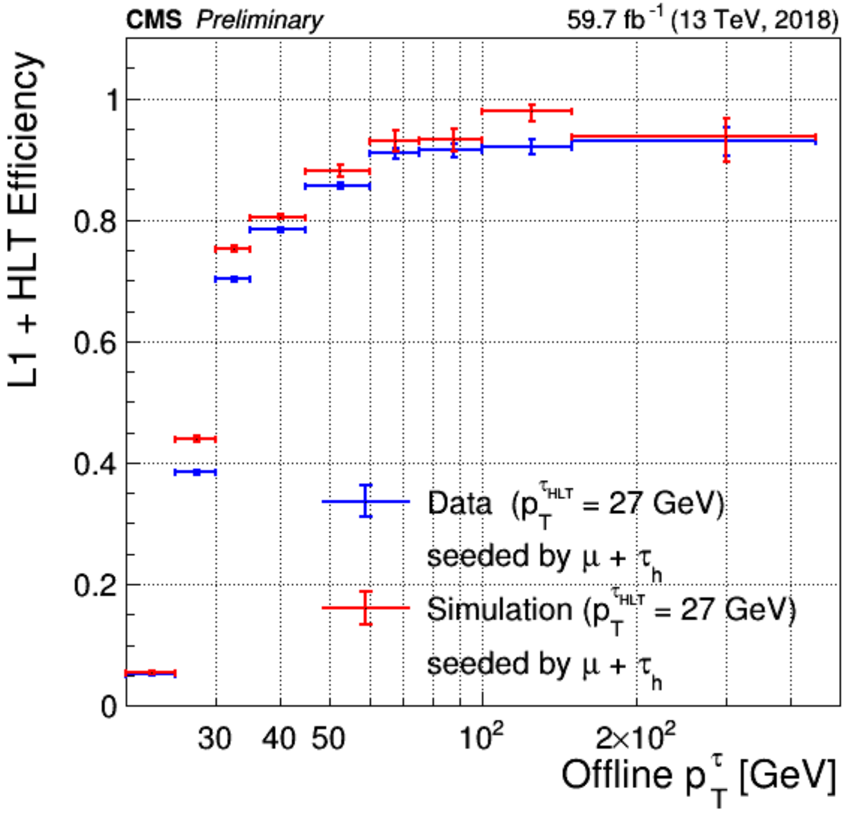


# HLT Trigger Efficiency Curves (Jets)



# L1+HLT Trigger Efficiency Curve (Taus)

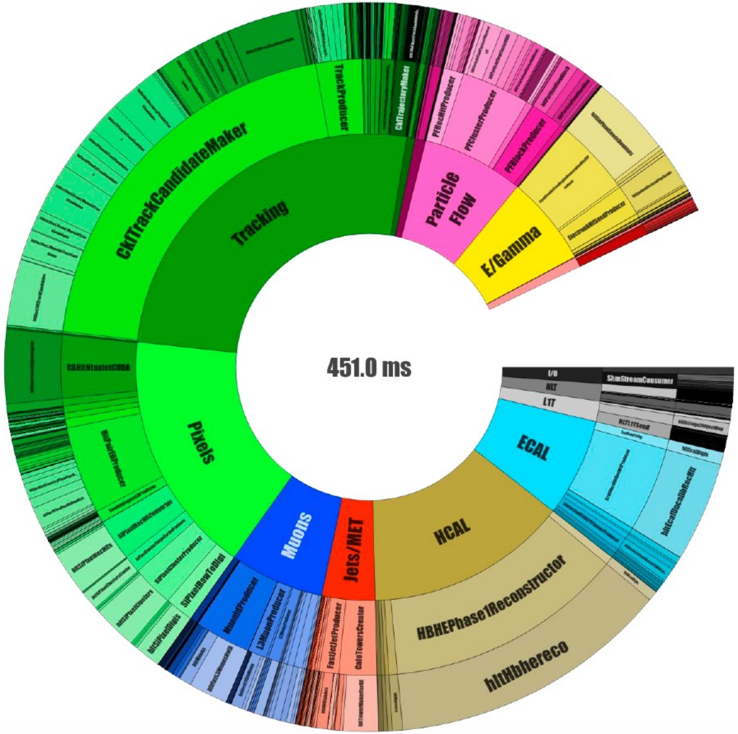



$P_T > 27$ on the tau leg, of a μ+tau trigger

# HLT CPU Time (Another cost of triggers)

## Timing of Run-3 HLT menu - CPU-only

Limits what can be done at HLT, so algorithms also must be fast




The pie-chart shows the distribution of CPU time in different instances of CMSSW modules (outermost ring), their corresponding C++ class (one level inner), grouped by physics object or detector (innermost ring). The empty slice indicates the time spent outside of the individual algorithms.

The HLT configuration is based on the 2018 definition, with minimal updates to the local reconstruction to reflect the ongoing developments foreseen for Run 3. Further updates and improvements are expected before the start of Run 3.

The timing is measured on pileup 50 events from Run2018D on a full HLT node (2x Intel Skylake Gold 6130) with HT enabled, running 16 jobs in parallel, with 4 threads each.

Tracking algorithms dominate

# Some Fun with Trigger Efficiencies

- Exercise : Suppose the efficiency for the trigger system to identify a lepton is 90%

  A) What is the efficiency of a trigger requiring 2 leptons given 2 leptons in the event?

  -

  B) What is the efficiency of a trigger requiring 1 lepton given 2 leptons in the event?

  -

  C) What is the efficiency of a trigger requiring 2 leptons given 3 leptons in the event?

  -

# COVID Mask Efficiency

- "Efficiency" also can be applied to the effectiveness of preventing the spread of the coronavirus between two people each wearing a mask.
  - Suppose that a mask stops 65% of virus transmission, which is an efficiency for passing viruses of 35% (i.e. 3X less than without a mask)
  - If both people wear masks, that transmission efficiency through both masks is reduced to $(0.35)^2 = 12\%$ (8X reduction)
  - Or in other words, the combined effectiveness of both people wearing masks to remove viruses is:
    - $1 - (\varepsilon_{mask})^2 = 1 - (0.35)^2 = 88\%$

# Measuring Trigger Efficiency

- Use events selected by an orthogonal trigger to measure performance of your trigger
  - e.g. select events satisfying requirements of a multijet trigger to measure the efficiency of a missing transverse momentum trigger
- "Tag and probe" is often used to measure trigger efficiencies of leptons
  - e.g. select one lepton in a Z→ll decay to satisfy a trigger, measure efficiency of other lepton to fire a trigger
- Can also use looser, "prescaled" triggers, to measure efficiency of a more complex trigger
  - Prescaling means only 1 in N events satisfying such a trigger are actually recorded (reduces rate by 1/N)
  - e.g. single lepton trigger to measure efficiency of leptons+jets
  - Disadvantage is collecting enough statistics, since effective luminosity is reduced

# Trigger Menus

- A trigger "menu" represents a (large) set of selection criteria for the broad physics program of the experiment, e.g.
  - Entrée 1: 2 muons of opposite charge, one with $P_T$>17 GeV and one with $P_T$>8 GeV
  - Entrée 2: "jets" with a total scalar jet $H_T$ > 500 GeV
    - These entrées are often referred to as "trigger lines", or trigger "paths" at HLT
- Crudely speaking, O(1) trigger per analysis topic
  - Some triggers are very general and serve many analyses (preference)
  - But often many "backup" triggers are required for the control regions of specific analyses, which increases the total count
- Separate L1 and HLT menus
  - L1 menu has ~300 items for CMS, ~500 for ATLAS
  - HLT menu has ~600 menu items for CMS, ~1500 for ATLAS
    - Each trigger item has prerequisite L1 "seeds"

# ATLAS Menu

| Trigger | Typical offline selection | Trigger Selection L1 [GeV] | Trigger Selection HLT [GeV] | L1 Peak Rate [kHz] | HLT Peak Rate [Hz] |
|---|---|---|---|---|---|
| | | | | L=2.0×$10^{34}$ cm$^{-2}$s$^{-1}$ | |
| Single leptons | Single isolated $\mu$, $p_T > 27$ GeV | 20 | 26 (i) | 16 | 218 |
| | Single isolated tight $e$, $p_T > 27$ GeV | 22 (i) | 26 (i) | 31 | 195 |
| | Single $\mu$, $p_T > 52$ GeV | 20 | 50 | 16 | 70 |
| | Single $e$, $p_T > 61$ GeV | 22 (i) | 60 | 28 | 20 |
| | Single $\tau$, $p_T > 170$ GeV | 100 | 160 | 1.4 | 42 |
| Two leptons | Two $\mu$, each $p_T > 15$ GeV | $2\times10$ | $2\times14$ | [illegible] | [illegible] |
| | Two $\mu$, $p_T > 23, 9$ GeV | 20 | 22, 8 | [illegible] | [illegible] |
| | Two very loose $e$, each $p_T > 18$ GeV | $2\times15$ (i) | [illegible] | [illegible] | [illegible] |
| | One $e$ & one $\mu$, $p_T > 8, 25$ GeV | 20 ($\mu$) | [illegible] | [illegible] | [illegible] |
| | One loose $e$ & one $\mu$, $p_T > 18, 15$ GeV | 15, 10 | [illegible] | [illegible] | [illegible] |
| | One $e$ & one $\mu$, $p_T > 27, 9$ GeV | [illegible] | [illegible] | [illegible] | [illegible] |
| | Two $\tau$, $p_T > 40, 30$ GeV | [illegible] | [illegible] | [illegible] | [illegible] |
| | One $\tau$ & one isolated $\mu$, $p_T > 30, 15$ GeV | [illegible] | [illegible] | [illegible] | [illegible] |
| | One $\tau$ & one isolated $e$, $p_T > 30$, [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Three leptons | Three very loose $e$, $p_T >$ [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Three $\mu$, each $p_T >$ [illegible] | [illegible] | [illegible] | [illegible] | 7 |
| | Three $\mu$, [illegible] | [illegible] | [illegible] | [illegible] | 9 |
| | Two [illegible] | [illegible] | [illegible] | 2.2 | 0.5 |
| | [illegible] | [illegible] | [illegible] | 2.3 | 0.1 |
| [illegible] | [illegible] | [illegible] | 140 | 24 | 47 |
| [illegible] | [illegible] | [illegible] | $2\times50$ | 3.0 | 7 |
| | [illegible] | [illegible] | 35, 25 | 3.0 | 21 |
| | [illegible] | $2\times15$ (i) | $2\times20$ (i) | 2.0 | 15 |
| [illegible] | [illegible] | 100 | 420 | 3.7 | 35 |
| | [illegible] | 111 (topo: $R = 1.0$) | 460 | 2.6 | 42 |
| | [illegible] $m_{jet} > 45$ GeV | 111 (topo: $R = 1.0$) | 420, $m_{jet} > 35$ | 2.6 | 36 |
| $b$-jets | [illegible] 285 GeV | 100 | 275 | 3.6 | 15 |
| | [illegible], $p_T > 185, 70$ GeV | 100 | 175, 60 | 3.6 | 11 |
| | [illegible] ($\epsilon = 40\%$) & three jets, each $p_T > 85$ GeV | $4\times15$ | $4\times75$ | 1.5 | 14 |
| | Two $b$ ($\epsilon = 70\%$) & one jet, $p_T > 65, 65, 160$ GeV | $2\times30$, 85 | $2\times55$, 150 | 1.3 | 17 |
| | Two $b$ ($\epsilon = 60\%$) & two jets, each $p_T > 65$ GeV | $4\times15$, $\lvert\eta\rvert < 2.5$ | $4\times55$ | 3.2 | 15 |
| Multijets | Four jets, each $p_T > 125$ GeV | $3\times50$ | $4\times115$ | 0.5 | 16 |
| | Five jets, each $p_T > 95$ GeV | $4\times15$ | $5\times85$ | 4.8 | 10 |
| | Six jets, each $p_T > 80$ GeV | $4\times15$ | $6\times70$ | 4.8 | 4 |
| | Six jets, each $p_T > 60$ GeV, $\lvert\eta\rvert < 2.0$ | $4\times15$ | $6\times55$, $\lvert\eta\rvert < 2.4$ | 4.8 | 15 |
| $E_T^{miss}$ | $E_T^{miss} > 200$ GeV | 50 | 110 | 5.1 | 94 |
| $B$-physics | Two $\mu$, $p_T > 11, 6$ GeV, $0.1 < m(\mu,\mu) < 14$ GeV | 11, 6 | 11, 6 (di-$\mu$) | 2.9 | 55 |
| | Two $\mu$, $p_T > 6, 6$ GeV, $2.5 < m(\mu,\mu) < 4.0$ GeV | $2\times6$ ($J/\psi$, topo) | $2\times6$ ($J/\psi$) | 1.4 | 55 |
| | Two $\mu$, $p_T > 6, 6$ GeV, $4.7 < m(\mu,\mu) < 5.9$ GeV | $2\times6$ ($B$, topo) | $2\times6$ ($B$) | 1.4 | 6 |
| | Two $\mu$, $p_T > 6, 6$ GeV, $7 < m(\mu,\mu) < 12$ GeV | $2\times6$ ($\Upsilon$, topo) | $2\times6$ ($\Upsilon$) | 1.2 | 12 |
| Main Rate | | | | 86 | 1750 |
| B-physics and Light States Rate | | | | | 200 |

**512 L1 items + O(1500) HLT chains to maximize the reach of ATLAS physics program**

Emma Torró, "The ATLAS trigger menu: from Run 2 to Run 3", LHCP2020 poster

# CMS HLT Menu Snippet

| | stream | dataset | path | group |
|---|---|---|---|---|
| 2 | | | | |
| 490 | PhysicsMuons | MuOnia | HLT_Mu7p5_Track7_Upsilon_v10 | BPH |
| 491 | PhysicsMuons | MuOnia | HLT_Trimuon5_3p5_2_Upsilon_Muon_v4 | BPH |
| 492 | PhysicsMuons | MuOnia | HLT_TrimuonOpen_5_3p5_2_Upsilon_Muon_v2 | BPH |
| 493 | PhysicsMuons | MuonEG | HLT_DiMu9_Ele9_CaloIdL_TrackIdL_DZ_v15 | SUS,HIG,SMP,EXO |
| 494 | PhysicsMuons | MuonEG | HLT_DiMu9_Ele9_CaloIdL_TrackIdL_v15 | SUS,HIG,SMP |
| 495 | PhysicsMuons | MuonEG | HLT_DoubleMu20_7_Mass0to30_L1_DM4EG_v6 | SMP,BPH |
| 496 | PhysicsMuons | MuonEG | HLT_DoubleMu20_7_Mass0to30_L1_DM4_v6 | SMP,BPH |
| 497 | PhysicsMuons | MuonEG | HLT_DoubleMu20_7_Mass0to30_Photon23_v6 | SMP,BPH |
| 498 | PhysicsMuons | MuonEG | HLT_Mu12_DoublePhoton20_v3 | SMP |
| 499 | PhysicsMuons | MuonEG | HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v13 | TOP,SUS,SMP,EXO |
| 500 | PhysicsMuons | MuonEG | HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v5 | TOP,SUS,SMP,EXO |
| 501 | PhysicsMuons | MuonEG | HLT_Mu17_Photon30_IsoCaloId_v4 | SUS |
| 502 | PhysicsMuons | MuonEG | HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v13 | TOP,SUS,SMP,B2G,EXO |
| 503 | PhysicsMuons | MuonEG | HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v5 | TOP,SUS,SMP,B2G,EXO |
| 504 | PhysicsMuons | MuonEG | HLT_Mu27_Ele37_CaloIdL_MW_v3 | B2G |
| 505 | PhysicsMuons | MuonEG | HLT_Mu37_Ele27_CaloIdL_MW_v3 | B2G |
| 506 | PhysicsMuons | MuonEG | HLT_Mu43NoFiltersNoVtx_Photon43_CaloIdL_v4 | EXO |
| 507 | PhysicsMuons | MuonEG | HLT_Mu48NoFiltersNoVtx_Photon48_CaloIdL_v4 | EXO |
| 508 | PhysicsMuons | MuonEG | HLT_Mu8_DiEle12_CaloIdL_TrackIdL_DZ_v16 | HIG,SUS,SMP,EXO |
| 509 | PhysicsMuons | MuonEG | HLT_Mu8_DiEle12_CaloIdL_TrackIdL_v16 | HIG,SUS,SMP |
| 510 | PhysicsMuons | MuonEG | HLT_Mu8_Ele8_CaloIdM_TrackIdM_Mass8_PFHT350_DZ_v17 | SUS |
| 511 | PhysicsMuons | MuonEG | HLT_Mu8_Ele8_CaloIdM_TrackIdM_Mass8_PFHT350_v17 | SUS |
| 512 | PhysicsMuons | MuonEG | HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v11 | HIG,SUS,SMP,B2G,TOP,EXO |
| 513 | PhysicsMuons | MuonEG | HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v9 | HIG,SUS,SMP,B2G,TOP,EXO |
| 514 | PhysicsMuons | SingleMuon | HLT_IsoMu20_eta2p1_LooseChargedIsoPFTau27_eta2p1_CrossL1_v10 | TAU,HIG,SUS |
| 515 | PhysicsMuons | SingleMuon | HLT_IsoMu20_eta2p1_LooseChargedIsoPFTau27_eta2p1_TightID_CrossL1_ | TAU,HIG,SUS |
| 516 | PhysicsMuons | SingleMuon | HLT_IsoMu20_eta2p1_MediumChargedIsoPFTau27_eta2p1_CrossL1_v10 | TAU,HIG,SUS |
| 517 | PhysicsMuons | SingleMuon | HLT_IsoMu20_eta2p1_MediumChargedIsoPFTau27_eta2p1_TightID_CrossL | TAU,HIG,SUS |

# Some Specific Examples from CMS

- Muons
  - Single isolated muon: $P_T > 24$ GeV
  - Double muon: $P_T > 17$, $P_T > 8$ GeV
  - Triple muon: $P_T > 12$, $P_T > 10$, $P_T > 8$ GeV
- Electrons
  - Single isolated electron: $P_T > 35$ GeV
  - Double electron: $P_T > 23$, $P_T > 12$ GeV
  - Triple electron: $P_T > 16$, $P_T > 12$, $P_T > 8$ GeV
- Jets
  - Single jet: $E_T > 200$ GeV
  - Quadjet: $E_T > 110$, $E_T > 90$, $E_T > 80$, $E_T > 15$ GeV
  - Sum of jet $E_T$ : $H_T > 500$ GeV
- MET
  - Missing $E_T > 250$ GeV

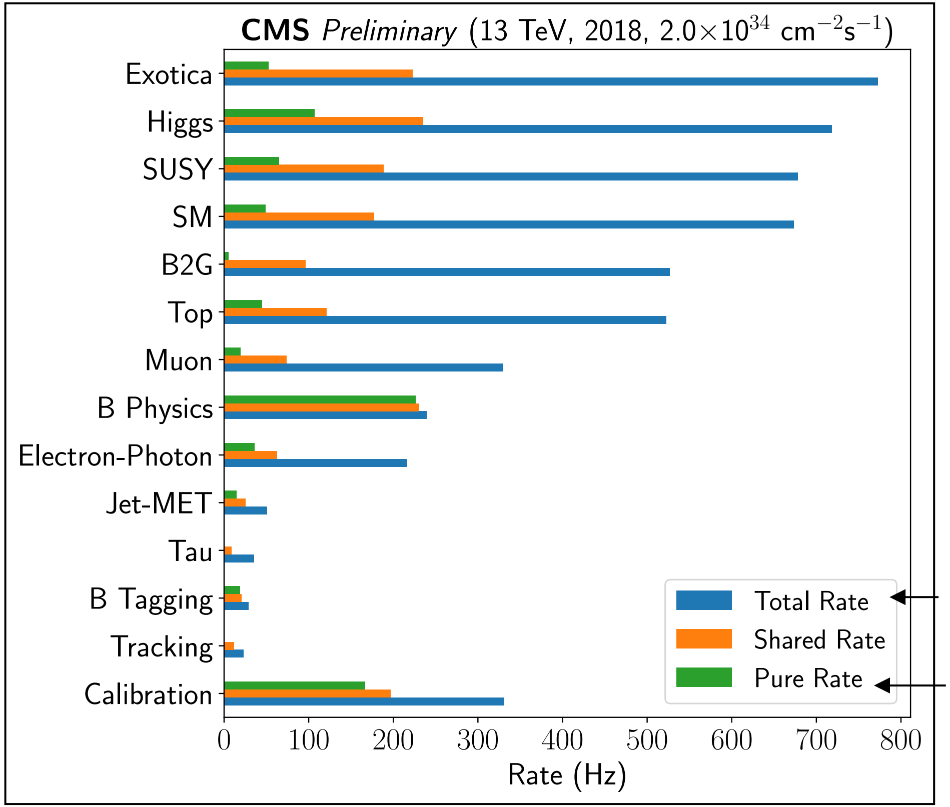
Why multi-object triggers?

# Trigger Menu Design Considerations

- **Goal**: Highest efficiency for your overall physics program at a recording rate that fits your budget
- Simple inclusive triggers could catch the most range of physics topics (e.g. single lepton trigger), but might have large rates for reasonably low thresholds
- Complex triggers (e.g. two leptons and two jets) will have lower rates from lower thresholds, but also lower efficiency. Also it may be difficult to measure their efficiency
  - e.g. efficiency = $\varepsilon^2_{lep} * \varepsilon^2_{jet}$
  - Simulations are not perfect, so it's important to validate in data the efficiency of your trigger
- Menu composition is often an art more than an exact science, with multiple ways to successfully construct. Also can evolve with time and priorities

# CMS Run 2 HLT Menu Physics Allocation

CMS-DP-2018-057




inclusive

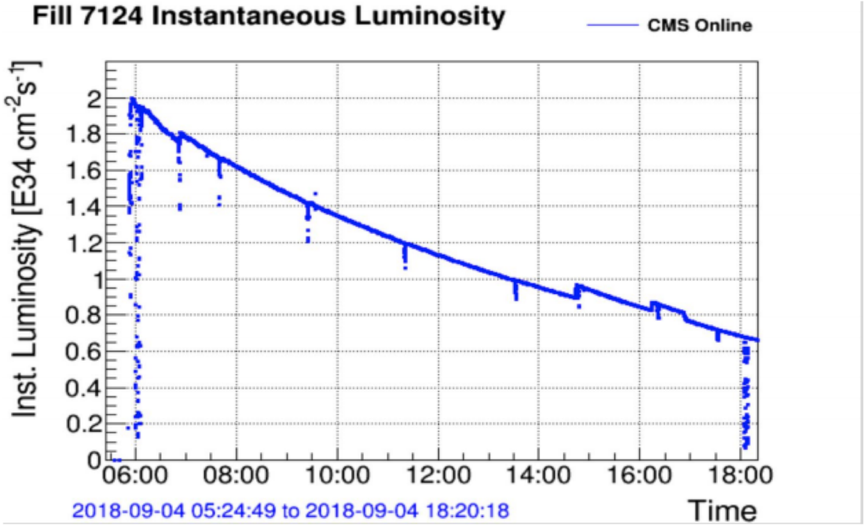
exclusive

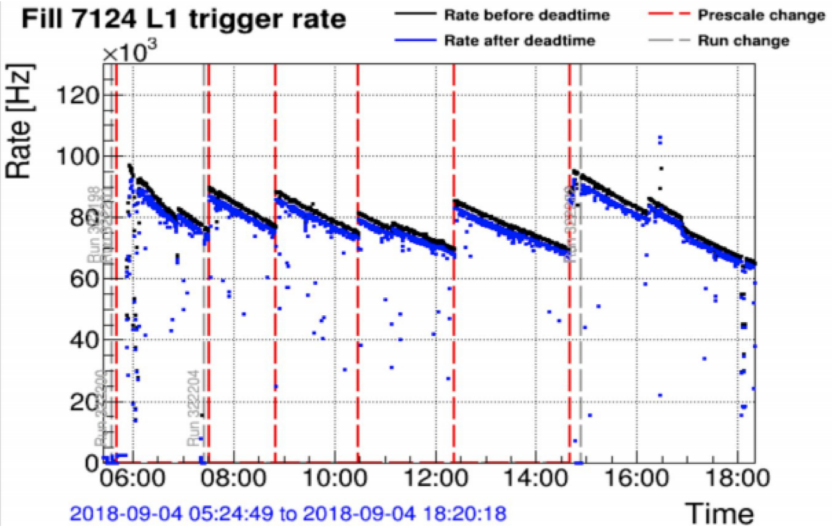
- Measured at $\mathcal{L}$=1.2E34 but scaled to $\mathcal{L}$=2.0E34
  - 510 Hz (~1/3) to searches
  - 530 Hz (~1/3) to Standard Model
  - 230 Hz to B-physics
  - 200 Hz to objects
  - 200 Hz to calibration
    - Note that calibration events are of reduced size

# Prescaling

- One solution to reduce the trigger rate is to just not accept every even that satisfies a trigger condition
- A "prescale" factor N means that only 1 of every N events selected by an algorithm is actually recorded
- What is the downside? Well, the collected luminosity is only $L_{int}/N$. You don't get full delivered luminosity.
- But sometimes that is okay!
  - Maybe you take what you can get if there is no other way to reduce the rate and keep all your events
  - e.g. B physics triggers at a hadron collider

# Prescaled Triggers




- As luminosity drops, one can afford to loosen triggers by reducing/removing prescale factors on some trigger lines
  - Increase trigger rate back to DAQ limit

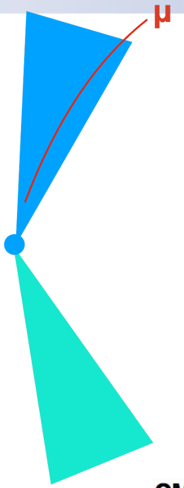
# How to Increase Data Storage Rate? Parking

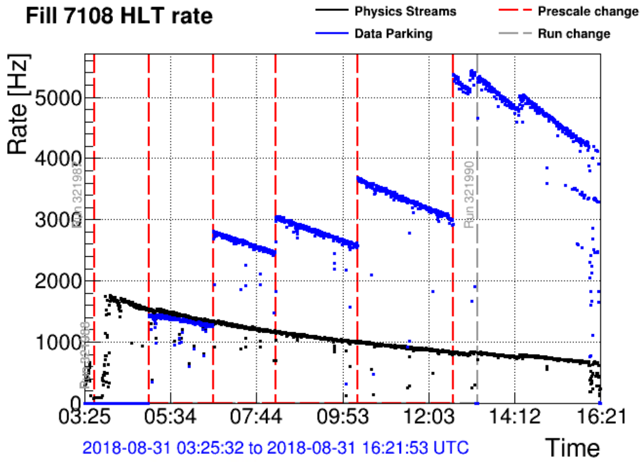
- Recall why a trigger is needed
  - Too much data to continuously stream to disk for storage and/or computer processing reasons
- If we can at least handle the storage rate, we can record data at an even higher rate to disk, but postpone processing that data until experiment is no longer running
- This is known as "data parking"
  - CMS does this to record more data for B physics studies, etc.
    - 10 billion events from Run 2
  - Plan to continue this for Run 3
- Can take advantage of year-end or long shutdown periods
  - For example, LHC has been in a 3-year long shutdown for upgrades

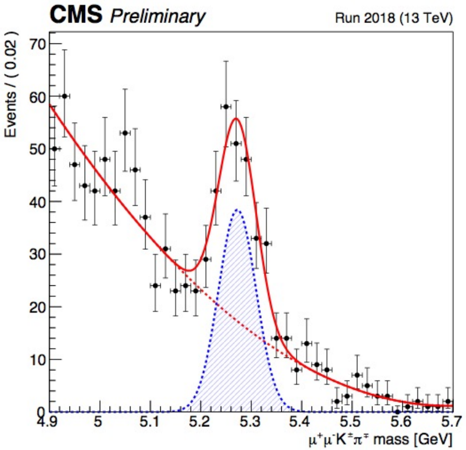
# B Data Parking

CMS-DP-2019-043

- Tag on muon from one side of event, other side unbiased
- The rate for the CMS physics streams (black curve) falls from ~2 kHz during this LHC fill in 2018
- The rate for the B Parking stream (blue curve) increases in steps at changes in the prescale column (loosening of trigger thresholds) during a CMS run, reaching as high as ~5 kHz.




$B \to J/\psi(\mu\mu)K^{*}(\pi K)$

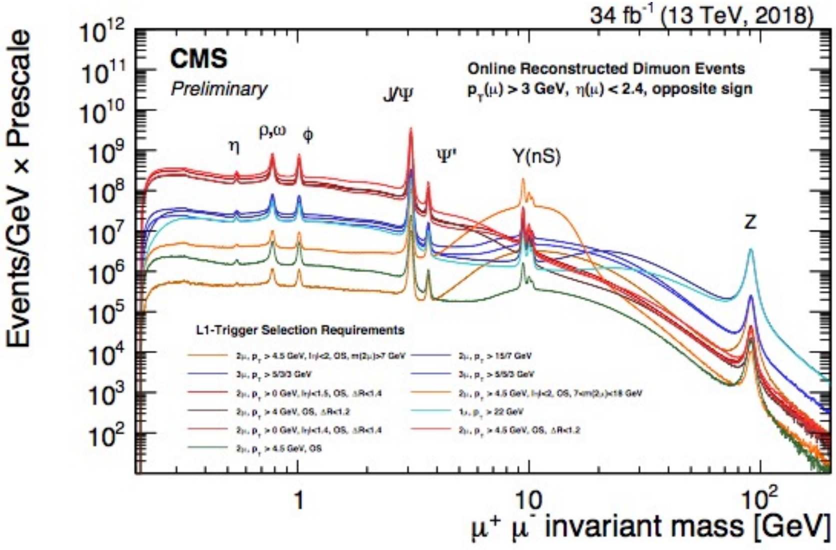
# Another Approach: Data Scouting

- The limit on DAQ is the bandwidth of the data to record to disk (few GB/s), not really the event rate per se
- If the amount of data to store per event is small enough, you could store in principle all events that occur, or at least a very high rate of them
  - e.g. ~10 kB vs. ~1 MB per event
  - CMS does this for calibration data, for example
- "Data scouting" (aka Trigger Level Analysis, or Turbo Stream) is a recent invention by the LHC experiments to store only a small summary of reconstructed event quantities, and not all the raw data, in order to record a higher rate of events
  - Allows much lower trigger thresholds, and thus a higher acceptance of a physics process
  - Generally does not allow reprocessing data afterward (from new calibrations or alignments)
    - Therefore only reliable for a mature experiment
  - Can induce additional HLT processing time from a higher input rate

# Run 2 Di-Muon Scouting Trigger

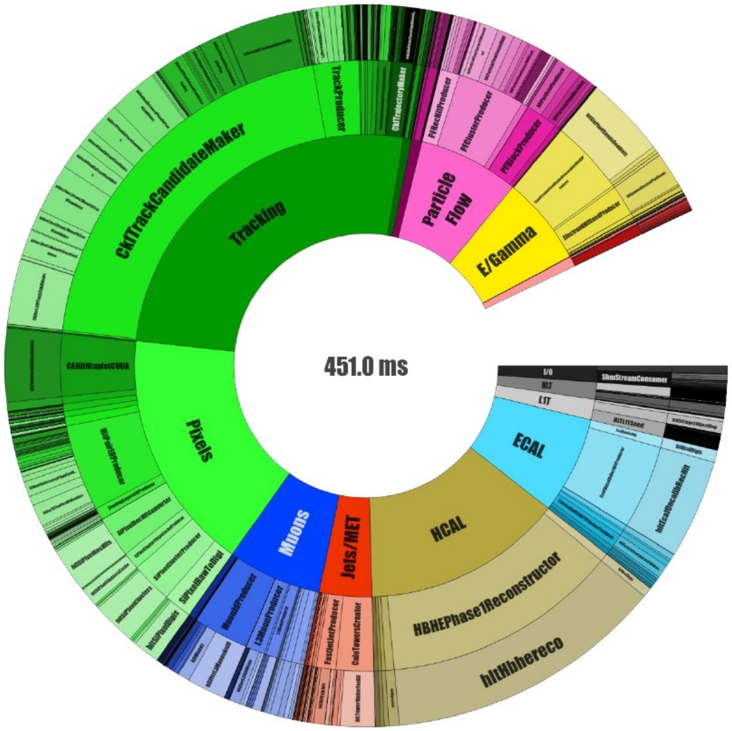
CMS-DP-2018-055

- Events required to have two muons with $p_T > 3$ GeV and $|\eta| < 2.4$
- HLT is seeded by various L1 triggers
- Events able to be recorded at a rate of up to 3 kHz for instantaneous luminosities of $L = 2\times10^{34}$ Hz/cm$^2$
- Sensitive to low invariant masses
  - Target dark photon searches



# HLT CPU Processing Time per Event

The computing cost of running the menu; limits what processing can be done online




- Distribution of CPU time in different instances of CMSSW modules (outermost ring), and grouped by physics object or detector (innermost ring).
- The HLT configuration is based on the 2018 definition, with minimal updates to the local reconstruction to reflect preparation for Run 3
  - Full HLT node (2x Intel Skylake Gold 6130) with HT enabled, running 16 jobs in parallel with 4 threads each

Tracking algorithms dominate

# Run 3 Preparation: GPU Acceleration

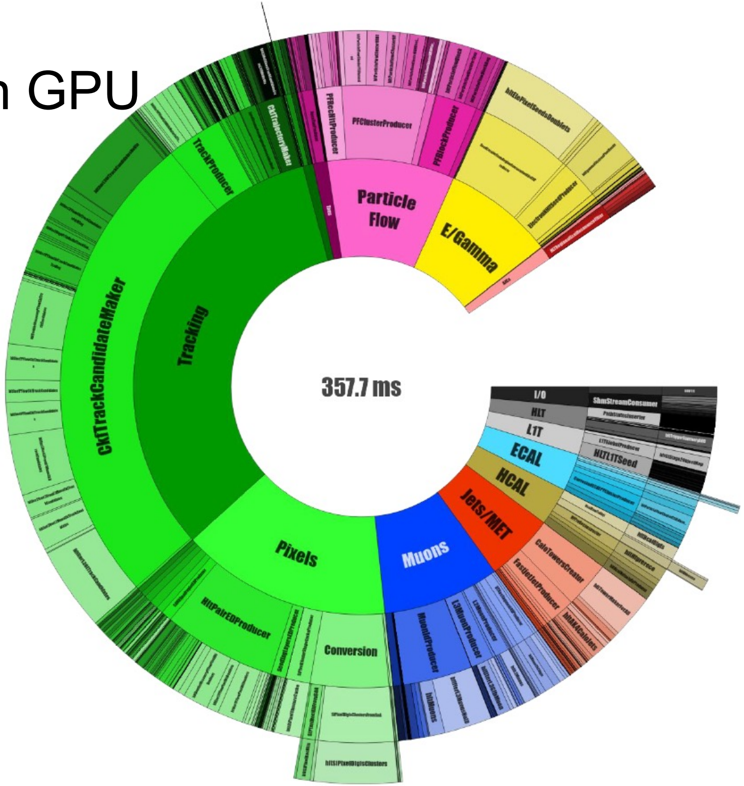
- One constraint on the HLT is the processing time per event
  - More computing time allows for tracking to be run on a larger fraction of events (e.g. for data scouting) and for more sophisticated algorithms
- Effort launched several years ago to port CMS algorithms to GPUs to accelerate the computations
  - Pixel-based tracking and vertexing ("Patatrack")
  - ECAL and HCAL local reconstruction
    - Written in NVidia CUDA language

Frontiers in Big Data 3 (2020), no. 10, 49

- For Run 3, CMS plans to equip the HLT farm with GPUs
  - Configuration to be determined later this year
  - Heterogeneous computing is essentially a must for HL LHC, so will need the experience to port even more algorithms

# HLT Processing Time with GPU Acceleration

with GPU

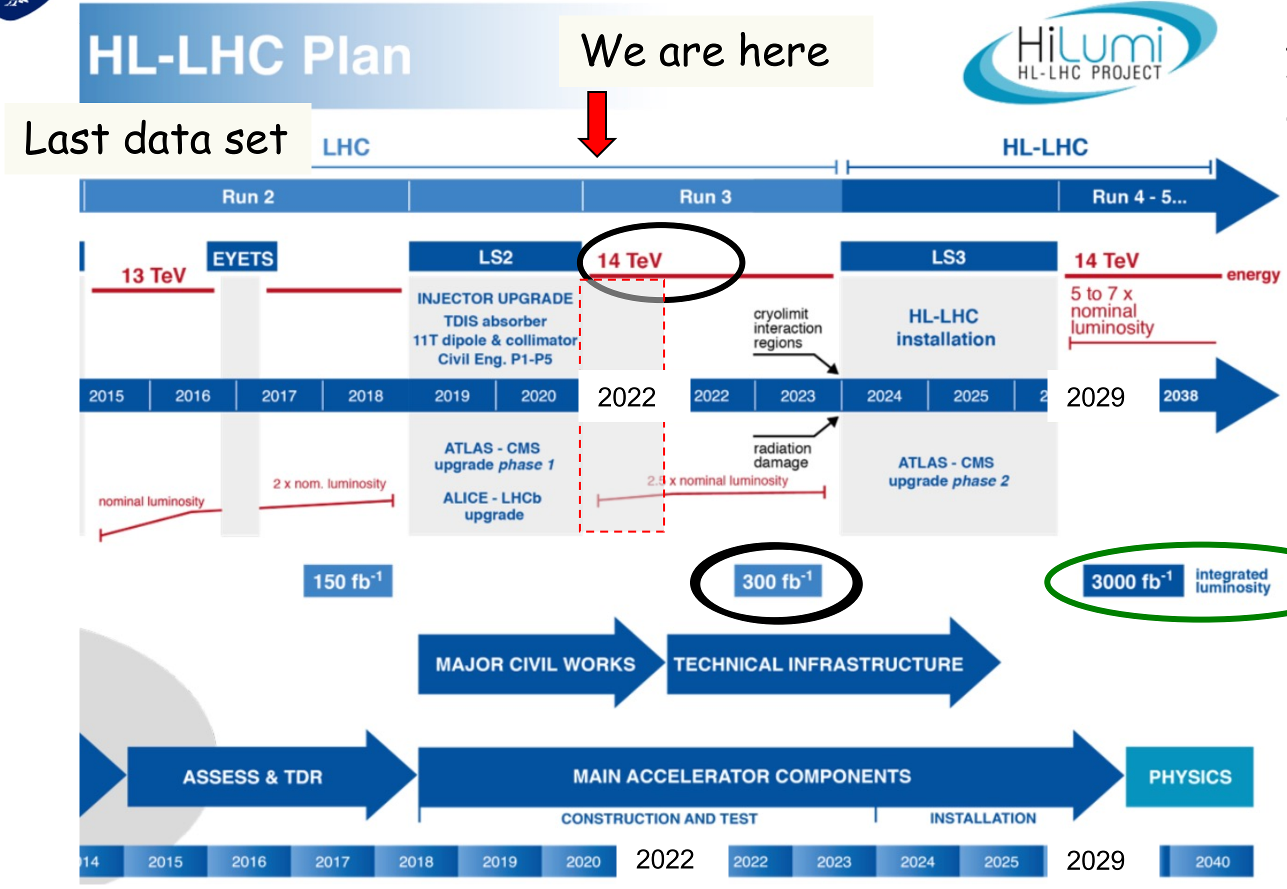



- Distribution of CPU time with GPU offloading in different instances of CMSSW modules (outermost ring), and grouped by physics object or detector (innermost ring).
- Offloaded pixel-based tracking (Patatrack) and vertex reconstruction ECAL and HCAL local reconstruction
  - Full HLT node + NVIDIA Tesla T4 GPU

21% offloaded

# FUTURE OF TRIGGER-DAQ

# LHC Run 3 and the HL LHC Upgrade Schedule




Initially, doubling of data set in next 4 years

Longer term, HL LHC luminosity and detector upgrades to start in 2029

20X more collected data than today with 4X busier collisions in detector by end

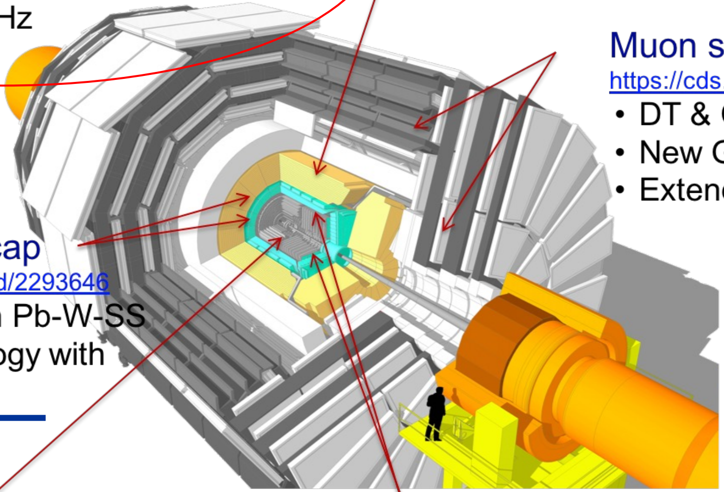
HL LHC starts in 2029

# CMS HL LHC Detector Upgrades

## L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

## Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

## Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



## Calorimeter Endcap
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

## Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

## Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

## MIP Timing Detector
https://cds.cern.ch/record/2296612
- $\simeq$ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

New detector systems with higher granularity to handle unprecedented pileup and radiation

Endcap calorimeter, Triggerable silicon tracker, Timing detector, more muon coverage, electronics

# HL LHC Trigger Challenge

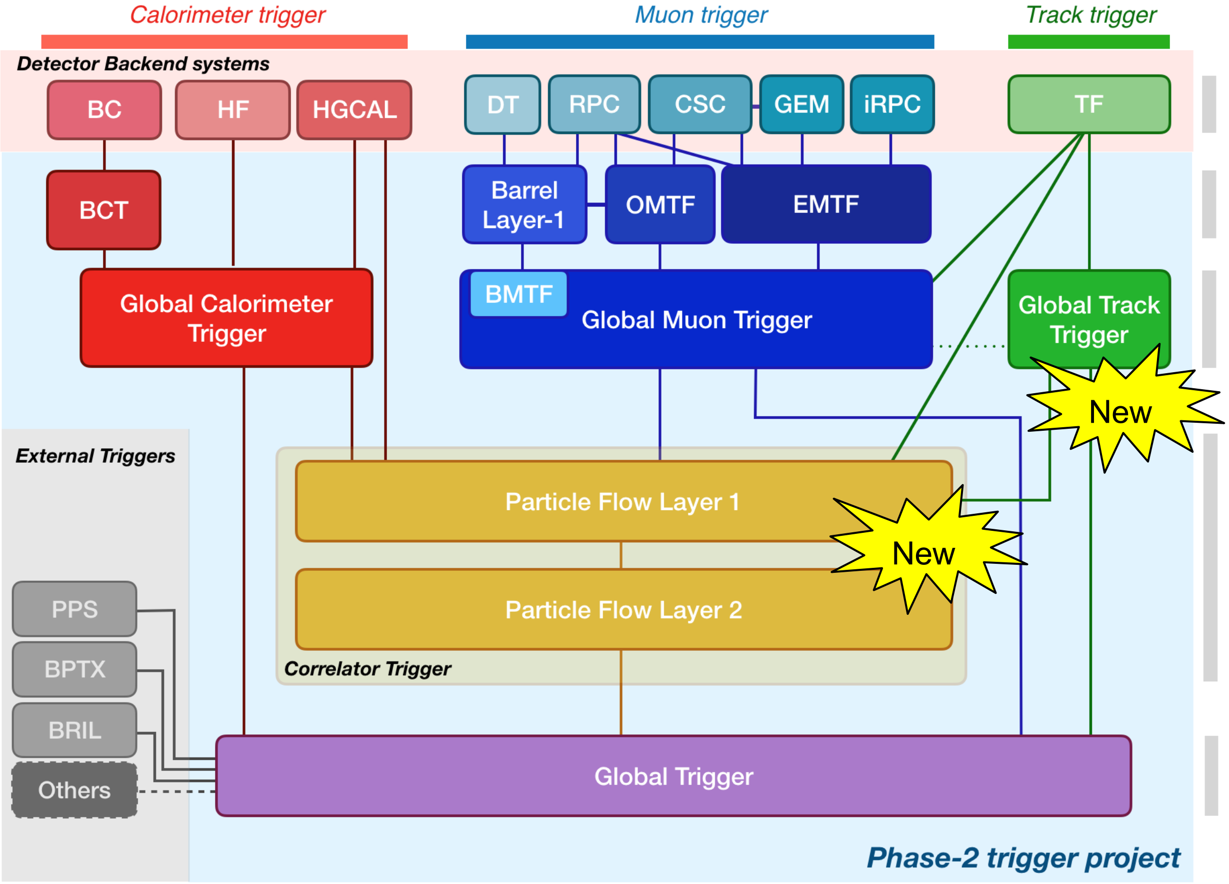
- Cope with higher collision rate and particle densities, yet maintain thresholds in trigger menu similar to LHC in order to retain sensitivity to electroweak scale physics
  - Want to benefit from the increased luminosity
  - Must improve rate reduction at no cost to efficiency
    - Need better trigger algorithms
- Add sensitivity to new physics scenarios, such as from long-lived heavy particles
  - Displaced "muons" from new particle decays
    - Particles displaced from the nominal collision vertex
  - Heavy stable charged particles
    - Muon-like particles traveling with $\beta < c$ and highly ionizing

# CMS HL LHC Trigger Requirements

- Increase Level-1 Trigger output rate: 0.1 → 0.75 MHz
  - Better sharing of rate reduction between Level-1 and HLT
- Increase Level-1 decision latency: 4μs → 12.5μs
  - More processing time for more complex algorithms
    - Both requirements imply changes to detector front-end electronics (deeper data buffers, higher bandwidth)
- Adding inner detector tracking (silicon strips) to Level-1
  - Better performing Level-1 Trigger
  - Recovers capability that Tevatron experiments had a generation ago (albeit with much less data throughput demands)
  - Major new change to make silicon detector systems fast enough for trigger purposes, and yet still able to power and cool
- Increase HLT DAQ storage rate to disk: 1 → 7.5 kHz

# CMS Proposed Level-1 Trigger Architecture

Dataflow

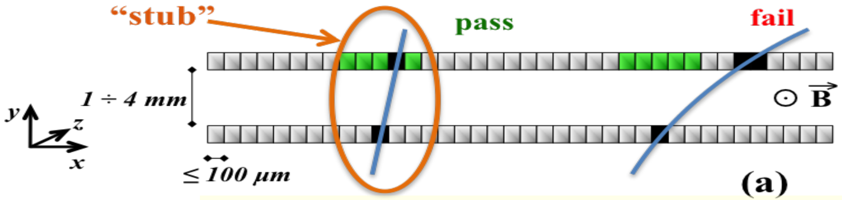


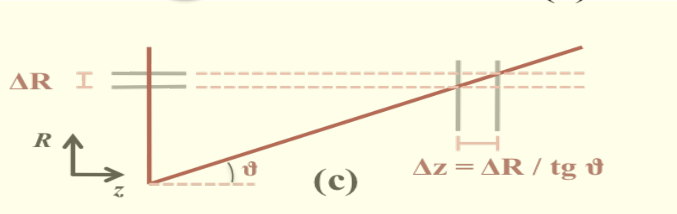

← Detector upgrades

**Match tracks with calorimeter clusters and muons**

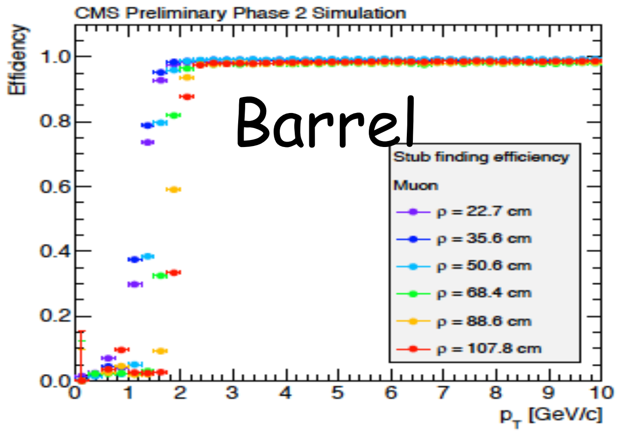
# Track Stub Finding in new CMS Tracker

- Coincidence of hits in a double layer of silicon helps reduce data bandwidth from detector
- Require a coincidence within a pattern, limits $P_T > 2$ GeV
  - < 3% of tracks
- "Push" design: all found stubs forwarded
  - 3-4 stubs/module/BX for Barrel layer 1
  - ~10K stubs/BX
  - O(50) Tbps




Stub efficiency vs. $P_T$ for various layers and disks →



# Silicon Track-Finding @ Level-1

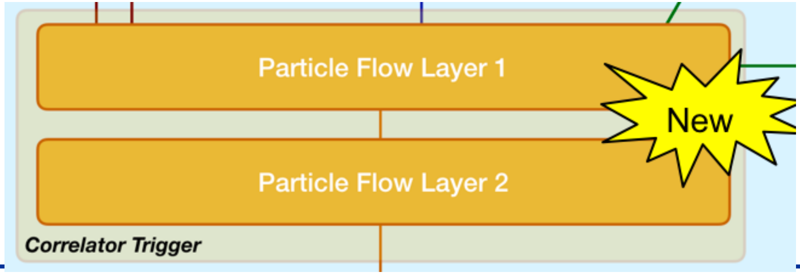
- Tracking at Level-1 is a feature that Tevatron experiments had...
- For CMS it is a "push" design – all stubs taken every beam crossing, whereas ATLAS experiment has a region of interest seeded design
- Latency: ~5 μs allocated for CMS design
- Multiple approaches under consideration to find tracks:
  - Pattern-based: Track patterns stored in Associative Memory chips
    - Target implementation in custom ASICs to store large number of patterns (~1 G overall)
  - "Tracklet" approach: Track building from stubs with pair-wise layer extrapolations
  - Hough transform: transformation of track patterns to clusters in transformed space
    - Target implementation in FPGAs
- Generally implemented with time-multiplexing of the input data (round-robin of event data to processors)
- All followed by a track-fitting stage to extract track parameters

ATLAS design (R.I.P.)

CMS options

# Particle Flow in Level-1 Trigger

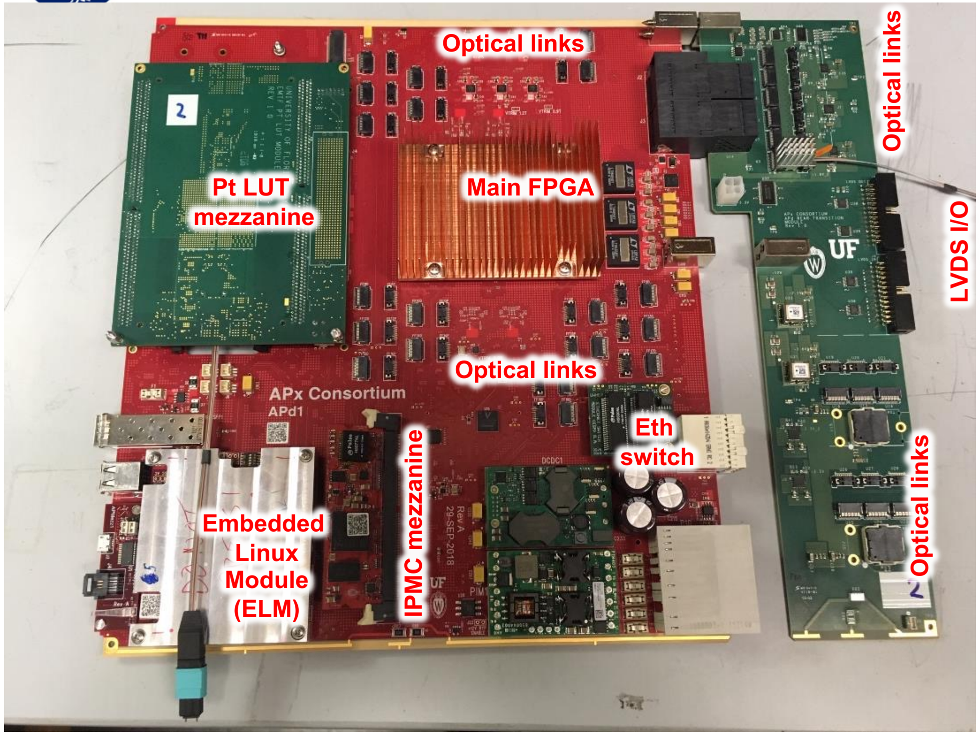
- "Particle Flow" is the optimum combination of tracking momentum and calorimeter energy measurements
  - Used successfully in CMS HLT and offline analyses
- Full exploitation of tracking at Level-1 for HL LHC proposed
  - Requires matching all calorimeter clusters to all tracks, removing clusters not attached to the primary vertex, and replacing cluster energy with track parameters for rest
  - Significantly improves the jet and hadronic energy flow measurements at CMS. Also reduces pile-up dependence.



# Technologies for the HL LHC Trigger

- Optical data links @ bandwidths up to 28 Gbit/s, and possibly 56 Gbit/s (from 10 Gbit/s currently)
  - Much more data to ship around
- Ultrascale+ FPGAs
  - O(100) data link receivers and transceivers
  - Factor 4 or more logic resources per chip than currently, to tackle more complex algorithms
- Large Memory banks (DDR4) – 128 GB
- Advanced Telecommunication Computing Architecture (ATCA)
  - Standardized shelf technology
    - Current CMS trigger uses μTCA, a daughter card of ATCA

# Next Generation Trigger R&D Prototype




APx: Xilinx VU9P FPGA, and 100+100 Tx+RX optical links at 28 Gbit/s, 128 GB RAM

# HLT @ HL LHC

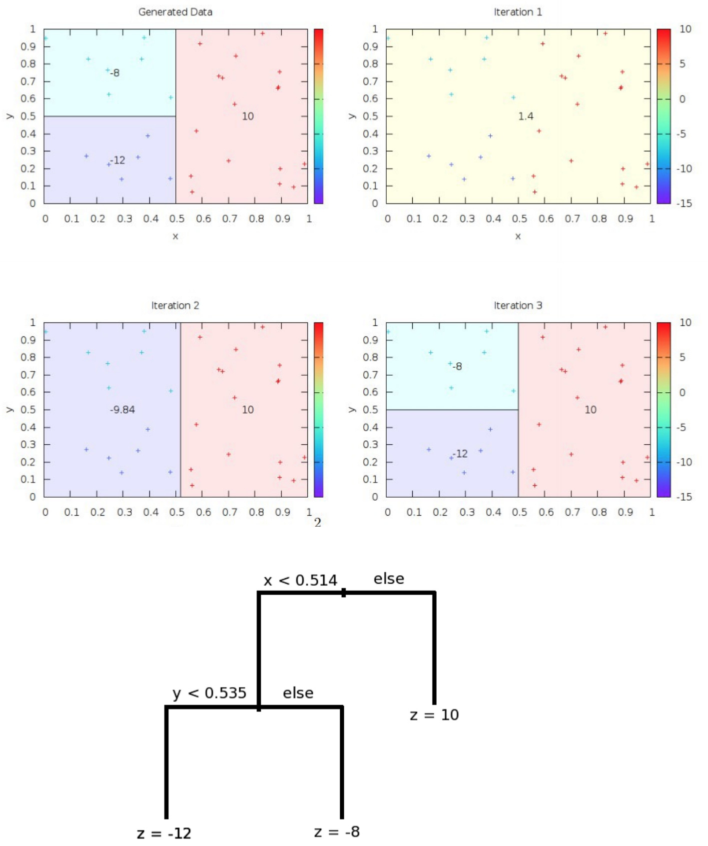
- If we have full tracking at Level-1, what is left for HLT to achieve another factor 100 reduction in rate reduction?
- Tracking
  - Has access to pixel hits in addition to strips → b jet tagging
  - HLT so far has not had the resources to perform global tracking for the entire Level-1 bandwidth
  - But with the Track-Trigger, the full collection of tracks can be accessed by HLT for every event and used even if Level-1 did not need to for all triggers to achieve rate reduction
    - This is what ATLAS experiment planned with its Fast Tracker (a custom "accelerator" for it computing processors)

# AI in Trigger Systems

- Machine learning algorithms (aka Artificial Intelligence) have been used in HEP analyses for decades
  - First in a limited capacity, but now extensively! Most Higgs boson measurements make extensive use of machine learning.
- Starting to be incorporated into the Level-1 Trigger
  - For example, a Boosted Decision Tree algorithm was used to train the muon momentum regression in the CMS endcap muon Level-1 trigger.
    - Results were precalculated offline and stored in a memory look-up table. (Logic not implemented directly)
  - But with current technology, neural networks (and BDTs) are possible to implement directly into the FPGA logic fabric, opening many possibilities!

# Boosted Decision Trees

- A decision tree repeatedly splits a dataset into smaller subregions based on features in that dataset
  - Similar to what particle physicists were doing already by hand ("cuts" on the data set)
- The Boosting takes an ensemble of decision trees, where each subsequent tree tries to improve upon the error from the previous one
  - Each tree gets a weight, and the ensemble gets the weighted sum



# Machine Learning for Regression

- Our trigger application is somewhere between a classification problem and a regression
  - We want to know the particle momentum above or below a specific threshold, but for multiple thresholds (just not an infinite set)
- We use a transformation + loss function to focus on low momentum events (whose mismeasurement to high momentum drives the rate)
  - Target= $1/p_T$ makes differences in low $p_T$ count more in loss
  - Loss = $|1/p_{T,meas} - 1/p_{T,true}|^2$, but studied other loss functions
    - Focus on low $p_T$ more → lower rate (good), lower effic. (bad)
    - Focus on low $p_T$ less → higher rate (bad), higher effic. (good)
- With redundant measurements (4 detector stations), ML can identify outliers (e.g. high momentum muon showering) and reject them to keep efficiency high
  - We used to have to introduce ad hoc "human" algorithms to recover effic.

# Encoding and Training the Result

ACAT2017

- Next pack (compress!) your input data in an optimal way if using a LUT
  - This is a data science in itself!
  - Here are muon track variables for the CMS trigger, for example:

*Many variables, but few bits each*

Appendix B - Schematic of 2017 PT LUT address bits

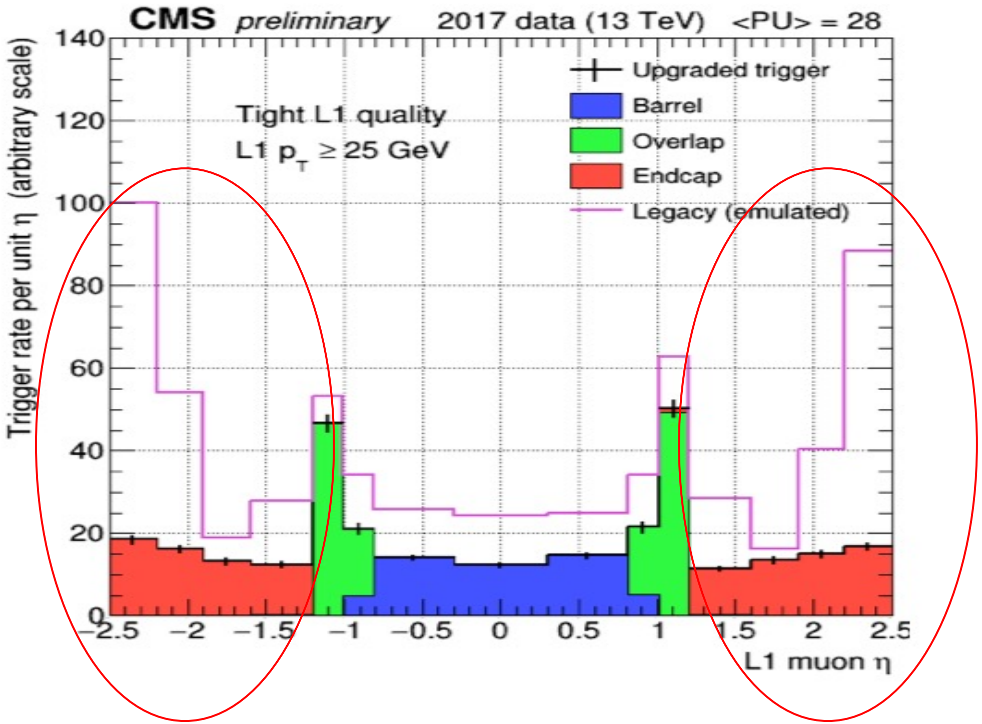
| PT LUT address bits | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 4 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Two-station tracks** | 0 | 0 | 0 | 0 | mode2 | | | 5b_theta | | | | | 3b_clctB | | | 3b_clctA | | | frB/A | | 3b_dThAB | | | 7b_dPhAB | | | | | | |
| **Station 2-3-4 tracks** | 0 | 0 | 0 | 1 | 5b_theta | | | | | 2b_rpc | | clct2 | | fr | 3b_dTh24 | | | s | 5b_dPh34 | | | | | 7b_dPh23 | | | | | | |
| **Three-station tracks** | 0 | mod3 | | 5b_theta | | | | | 2b_rpc | | clctA | | frB/A | | 3b_dThAC | | | s | 5b_dPhBC | | | | | 7b_dPhAB | | | | | | |
| **Four-station tracks** | 1 | 8b_theta_rpc_clct1 | | | | | | | | fr | dTh14 | | s34-23 | | 4b_dPh34 | | | | 5b_dPh23 | | | | | 7b_dPh12 | | | | | | |

*** Some names truncated for space. **Two-station:** [frB/A] = [frB][frA]. **Station 2-3-4:** [fr] = [fr2], [s] = [sph34]. **Three-station:** [mod3] = [mode3], [frB/A] = [frB][frA], [s] = [sphBC]. **Four-station:** [fr] = [fr1], [s34-23] = [sph34][sph23], [dTh14] = [2b_dTh14].

- Train the AI algorithm
  - For this example, used a Boosted Decision Tree for a regression on the momentum of the track
    - TMVA package of root.cern.ch
  - Trained on simulated track trajectories in the experiment
  - Care taken on choice of a loss function (penalty) so that performance is optimized for application (efficiency, rate)
- Apply trained algo to all $2^{30}$ input combinations and store in file

# How did it do?

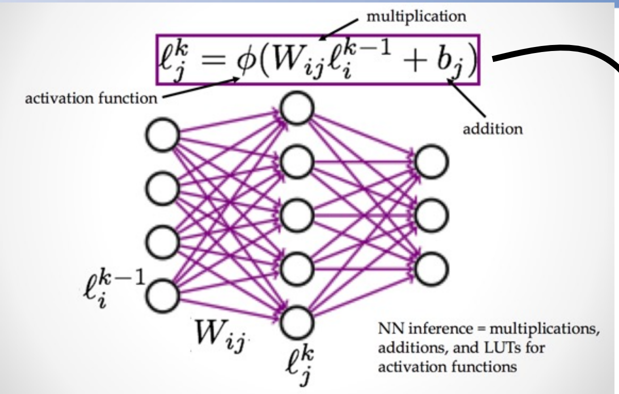
- Trigger rate versus regions of the detector:



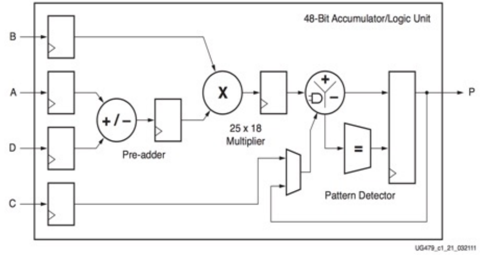

Endcap regions significantly improved with AI algorithm over previous algorithm

# Neural Networks in FPGAs

- The hls4ml toolkit
  - Implementation of fast neural network <u>inferences</u> into FPGAs:
    - arXiv:1804.06913v2
  - Converts results of a trained NN into Xilinx Vivado HLS firmware
  - The Xilinx DSP slice offers a 27 x 18 bit multiplier
  - Some Xilinx devices →
  - HLS4ML optimizes use of DSP slices
    - #bits, sequential re-use of slice, etc.



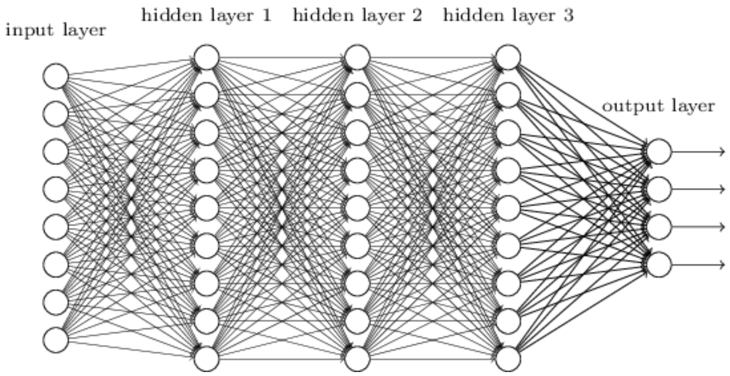

**Basic DSP slice**



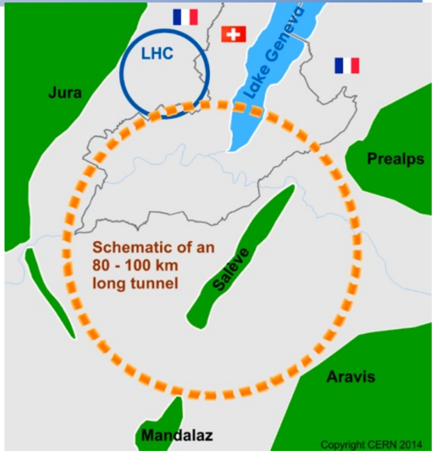

| Device | # of DSPs |
| --- | --- |
| Kintex-7 325T | 840 |
| Virtex-7 690T | 3600 |
| Kintex UltraScale KU115 | 5500 |
| Virtex UltraScale+ VU9P | 6800 |

# Neural Networks for Momentum Regression

- The Level-1 trigger needs fast inferences
- A neural network implemented within an FPGA alleviates the bottleneck of the memory look-up table approach
  - No loss of input variable precision
  - Can achieve better performance, and still fit into target FPGA
- Prototyped one for CMS muon trigger
  - 3 hidden layer, not too deep
  - Momentum regression output
- Aim to use to assign $P_T$ to displaced LLPs for Run 3



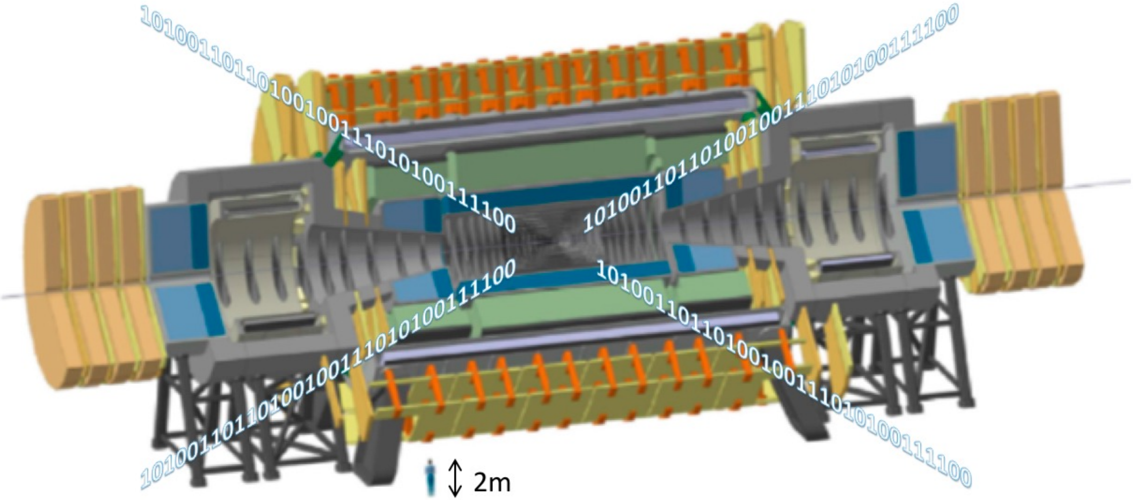
# Future Circular Collider (Hadron)




- Goals:
  - Higher energy: ~100 TeV
    - Explore high energy frontier
  - Higher luminosity: 5-30 x $10^{34}$ Hz/cm$^2$
    - High precision, e.g. Higgs boson couplings
- Trigger Challenges:
  - Pileup: O(1000) pp collisions per beam crossing (20X more than LHC)
  - Higher detector channel count from increased granularity
  - Radiation levels in tracking volume

# Data Collider!

- Exabytes per second before zero suppression and data reduction!




- Requires new ideas and new technologies to tackle next order of magnitude!
  - And you!

# Future Thrusts in Trigger/DAQ (?)

# Further Reading


- CMS Collaboration, "Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s}$ = 13 TeV", arXiv:2006.10165
- D. Acosta, C. Foudas and D. Newbold, "CMS gears up for the LHC data deluge", CERN Courier, Volume 56, Number 7, September 2016
- CMS Collaboration, "The CMS trigger system", Journal of Instrumentation 12 (2017) no.01, P01020
- CMS Collaboration, "The Phase-2 Upgrade of the CMS L1 Trigger Interim Technical Design Report", CERN-LHCC-2017-013; CMS-TDR-017
- CMS Collaboration, "The Phase-2 Upgrade of the CMS DAQ Interim Technical Design Report", CERN-LHCC-2017-014; CMS-TDR-018
- N.P. Ghanathe et al., "Software and firmware co-development using high-level synthesis", JINST 12 (2017) C01083.
- CMS Collaboration, "CMS Technical Design Report for the Level-1 Trigger Upgrade", CERN-LHCC-2013-011; CMS-TDR-012
- ATLAS Collaboration, "Performance of the ATLAS Trigger System in 2010", Eur. Phys. J. C 72 (2012) 1849