Trigger (CMS)

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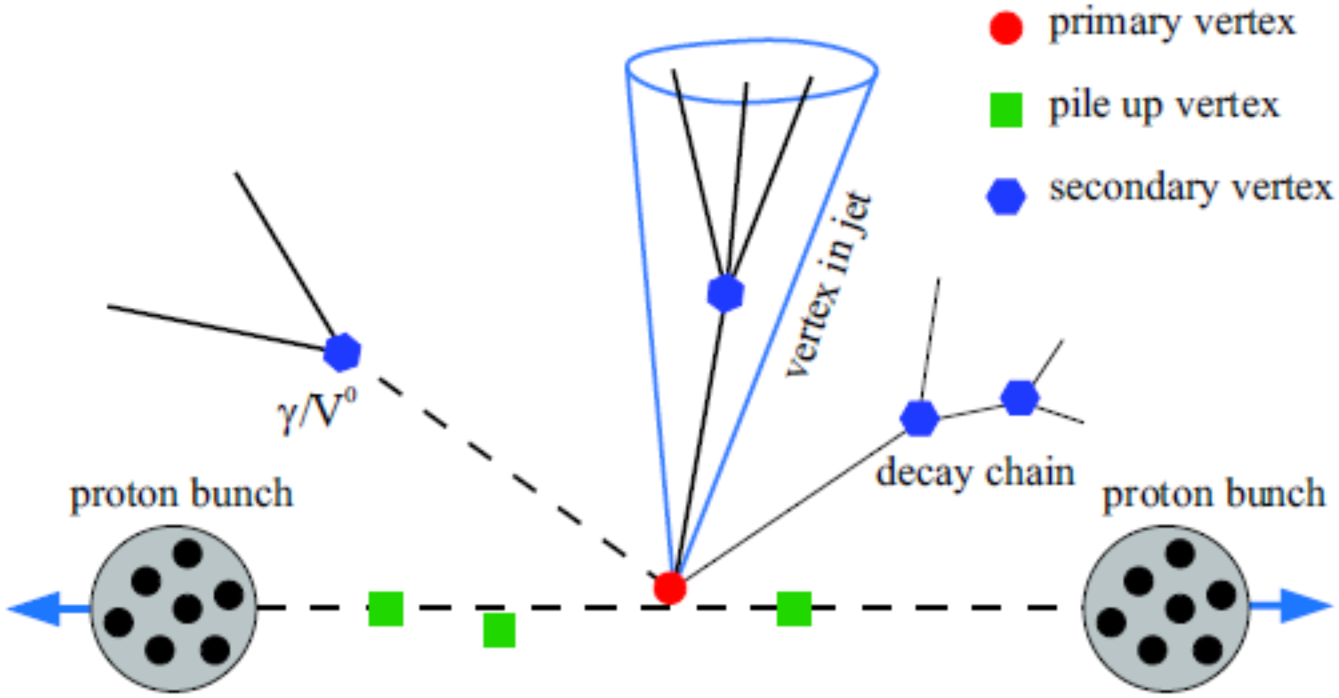
Introduction

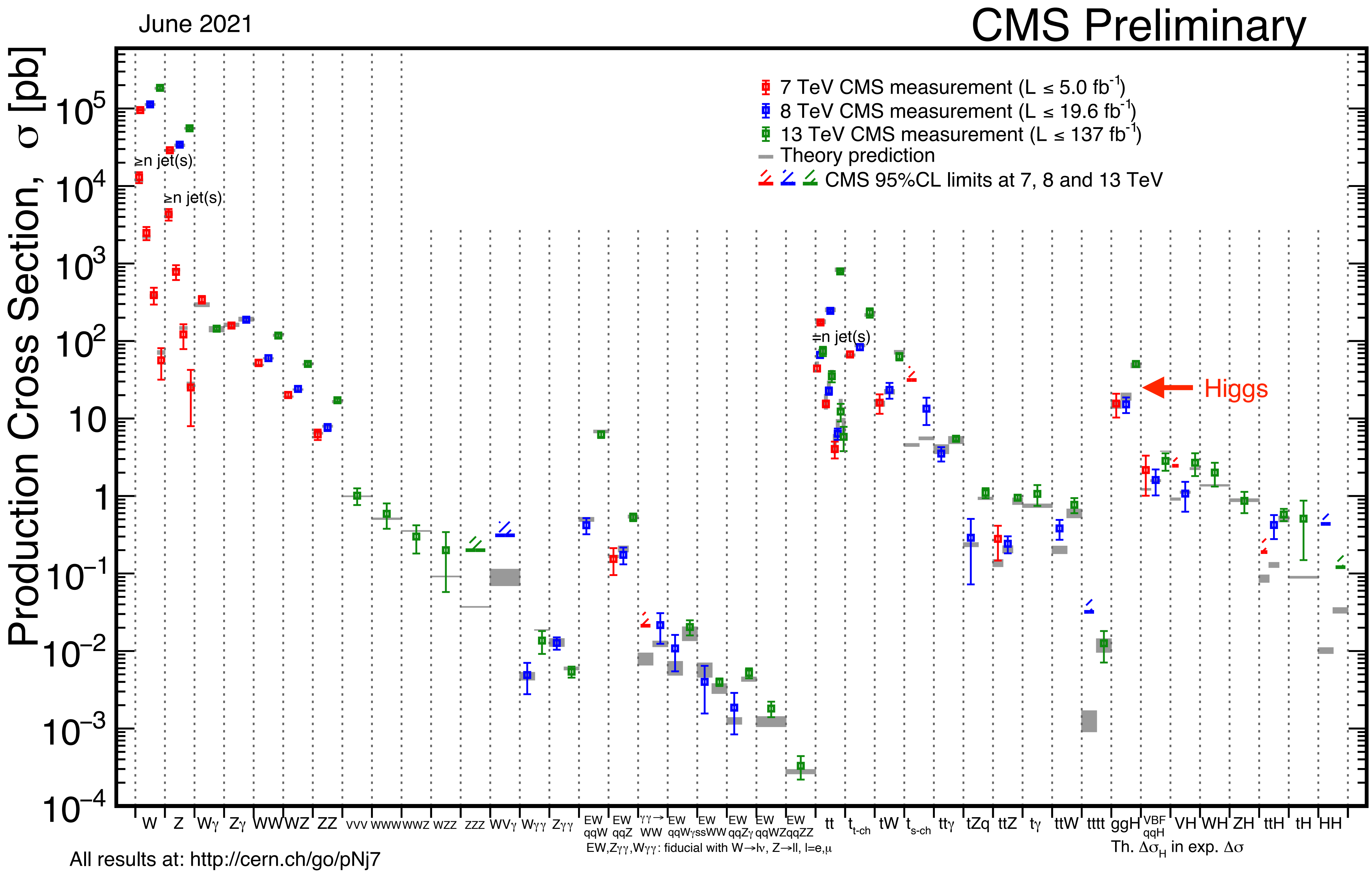
- The LHC is world's largest and most powerful particle collider in discovery mode
- Main physics goals:
  - Discover the Higgs boson to establish its role in EWSB
  - Search for beyond SM phenomena at TeV energy scale



One in a million millions!

- During Run-2:
  - 2556 bunches, ~2.5×10^{11} protons per bunch
  - Instantaneous luminosity reached 2.5×10^{34} cm^{-2} s^{-1}
  - A total of ~10^{16} proton-proton collision events out of which ~10^{4} produce the Higgs boson

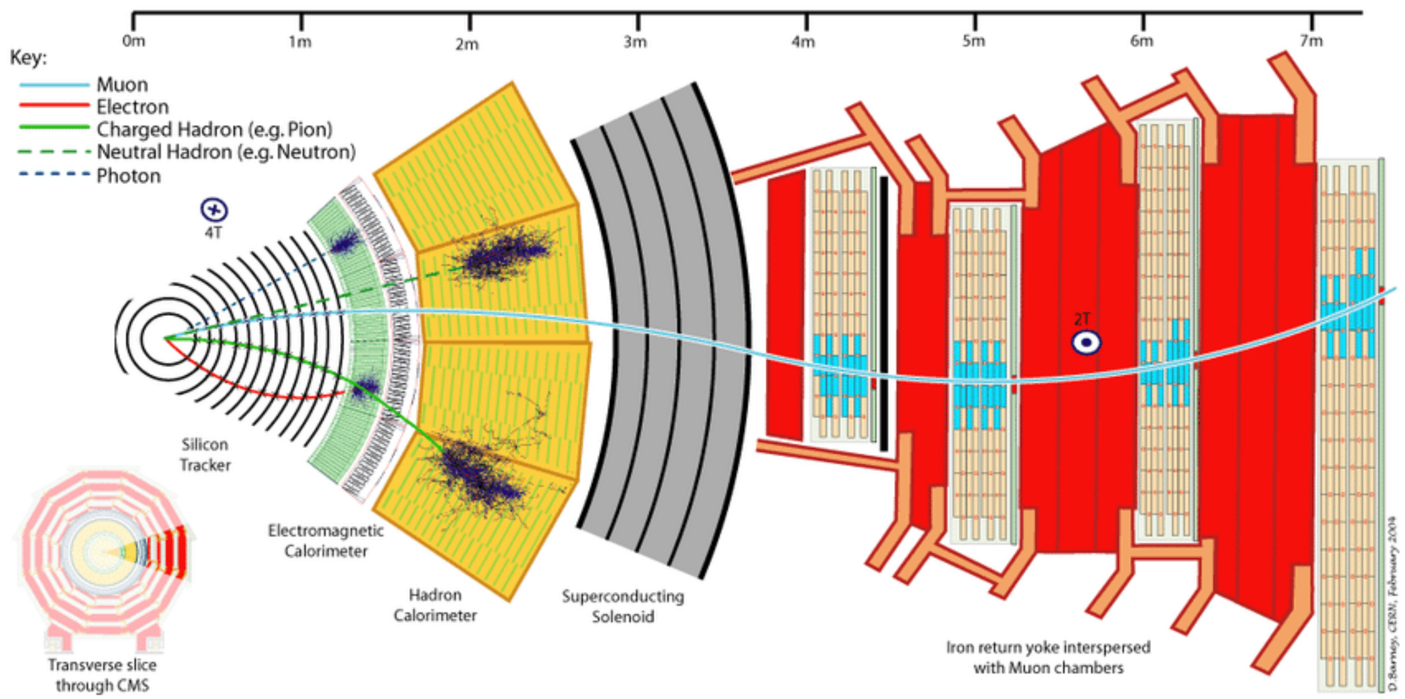
Rates of Physics Processes



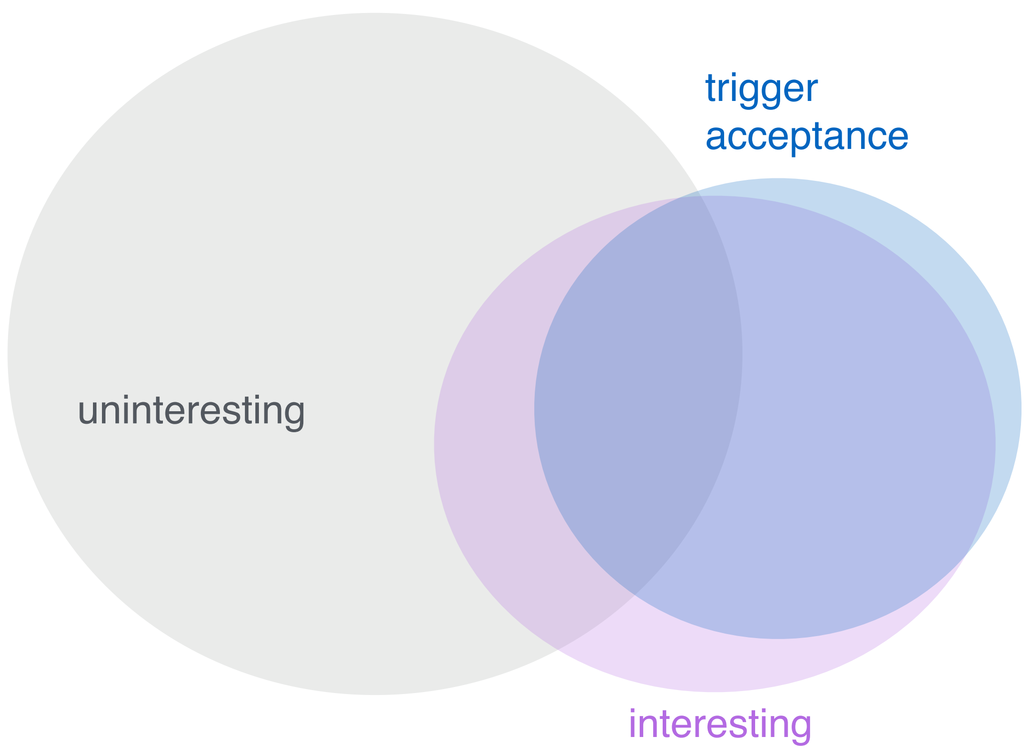
- New physics processes like Supersymmetry, dark matter etc predicted to have even lower cross sections
- Benefit-cost analysis between keeping large amount of data and storage capacity

The CMS Trigger System

- CMS is one of the two general purpose detectors at the LHC, built around a superconducting solenoid
- Dedicated sub-detectors to identify different particles, combined information to reconstruct collision event
- Decision to store interesting events taken by the online Trigger system at real time



Trigger system provides first decision to accept/reject events based on the topology

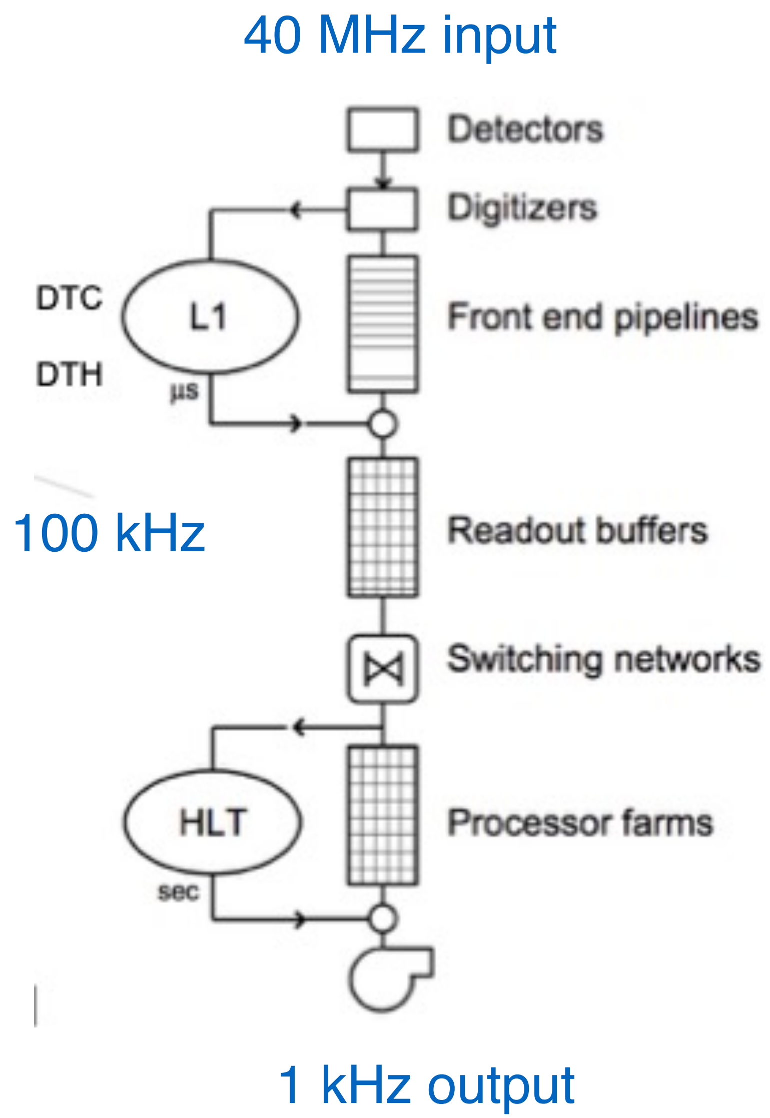


- Selection performed in stages:
  - Level-1 (L1): hardware driven, based on fast detector readout, custom electronics, limited granularity
  - High Level Trigger (HLT): software based, commercial PCs, improved object reconstruction comparable to offline
- Once rejected by trigger, event is lost forever

Trigger Design

- Challenges of hadron collider machine: high rejection of physics events
- Reconstruct physics objects and event variables online with available granularity
- At L1 each sub-detector provides a sub-trigger, logical OR of which is the global trigger (exploit trigger redundancy)
- At HLT sophisticated algorithms (*paths)* look for specific event signatures
- As a complement, also select minimum bias events to study unknown event signatures

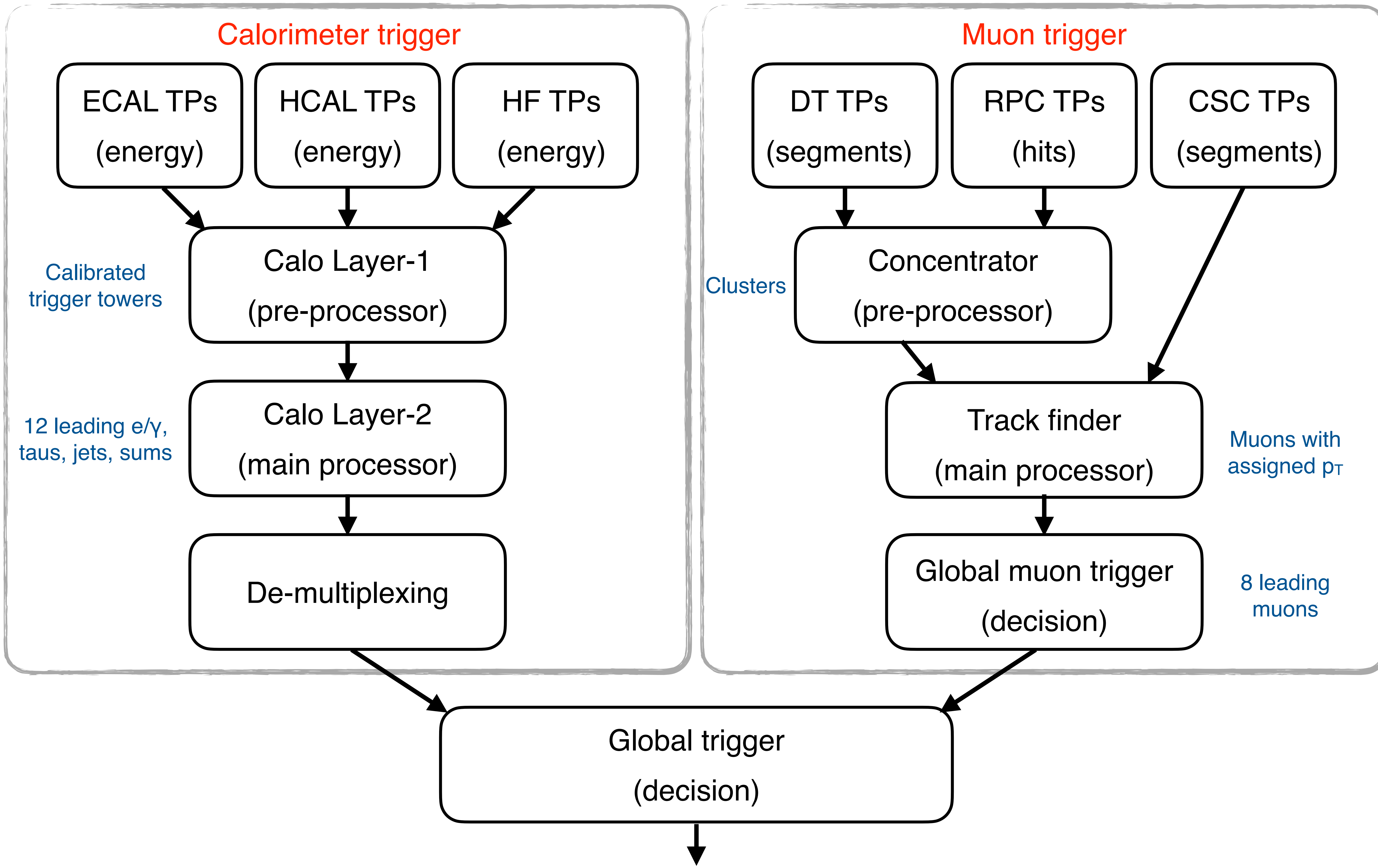
→1 out of 10^6 events selected



- Each reconstructed event takes ~1 MB of storage space
- Data acquisition constraint of ~1000 events per second
- Event prescaling: one event picked at random from several similar events to save storage

→still producing up to ~1 PB data per day

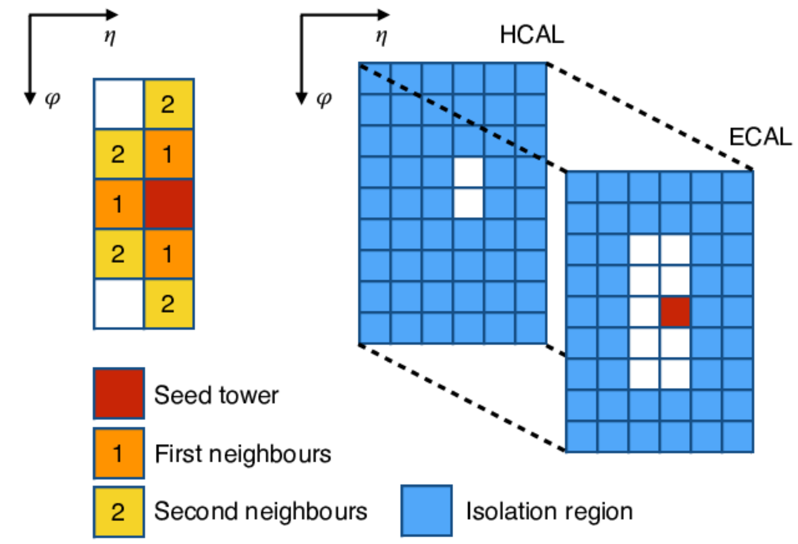
Level-1 Trigger Implementation



Level-1 Accept

Decision takes typically ~1 μs, coupled with propagation delay the latency is ~4 μs

Level-1 Trigger Algorithms



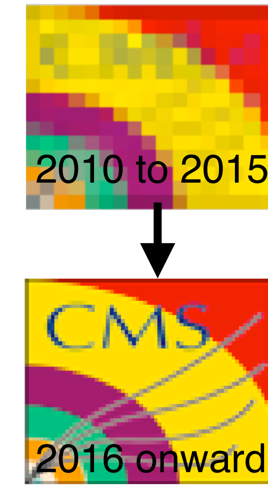
CERN-EP-2020-065

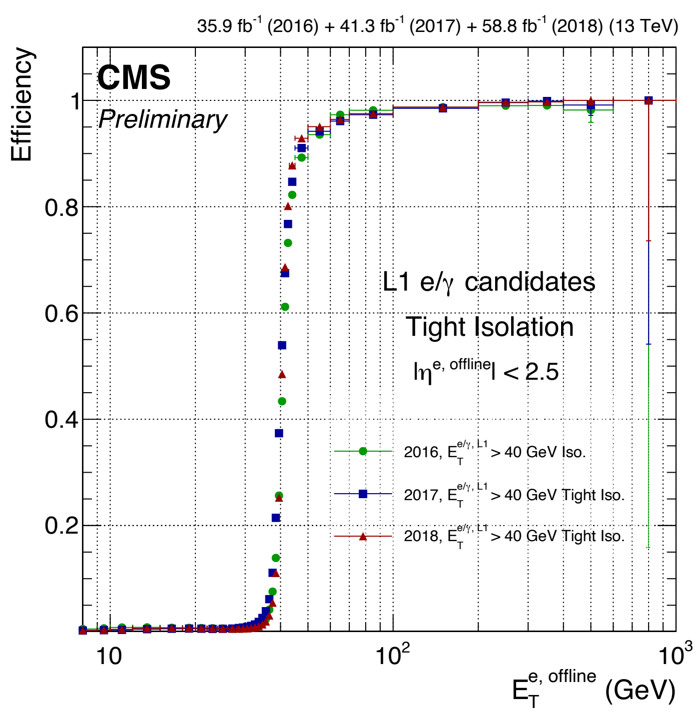
- Electrons/photons:
  - Cluster shape and electromagnetic energy fractions to discriminate against jets
  - Use of energy weighted position measurement, cluster energy calibration and isolation measurement
- Taus:
  - Similar to electrons/photons, shape discrimination optimised separately
- Jets:
  - Sliding window algorithm looking for trigger tower seeds over a given energy threshold
  - Sum of 9x9 trigger towers to match jet radius of 0.4 at offline
  - Pileup subtraction and calibration
- Energy sums:
  - Sum of jet energies with a restriction in energy and pseudorapidity
- Muons:
  - Extrapolation based track finding in barrel, pattern based in overlap and endcap regions
  - p_T assignment based on $\Delta\phi$ in barrel, patterns in overlap, BDT regression in endcap

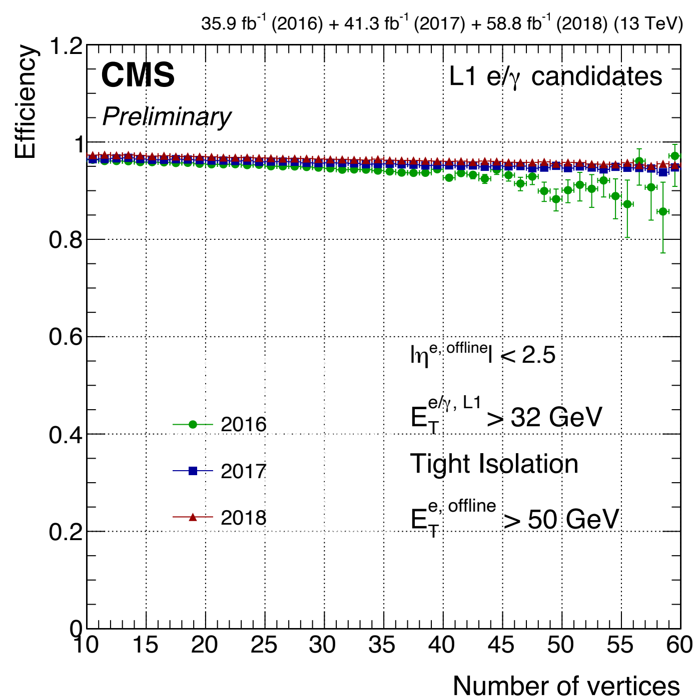
Level-1 Trigger Performance

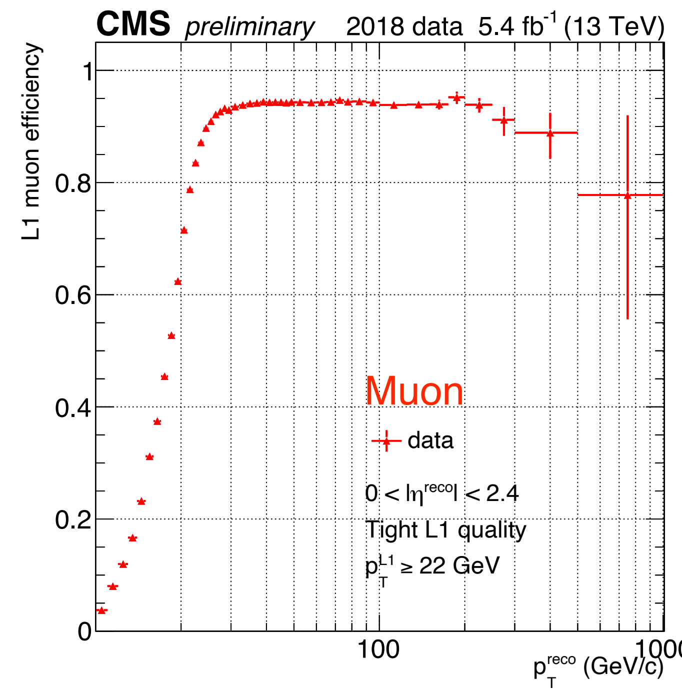
CMS-TDR-012

- Phase-1 upgrade of the L1 system in 2016 exploited full calorimeter granularity to give better energy and position resolutions while remaining within rate constraints
- Run-2 performance of L1 triggers also benefitted from pileup subtraction





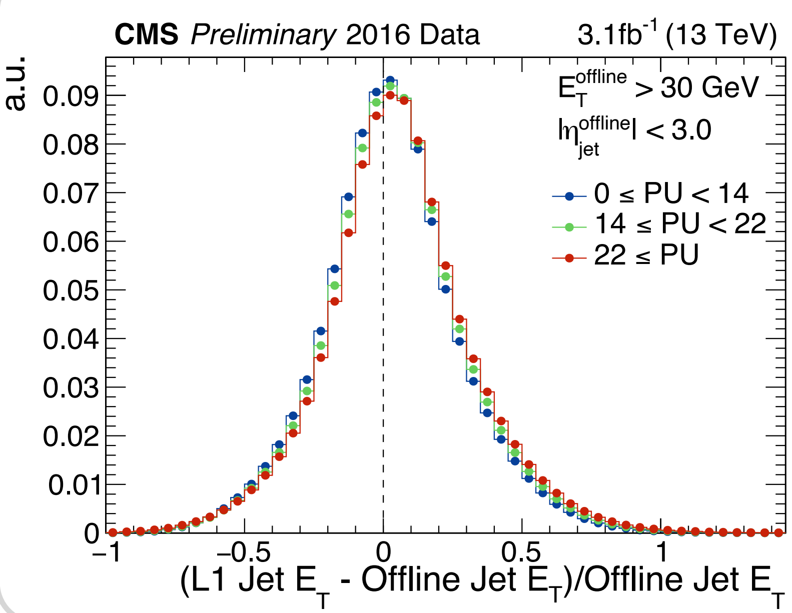


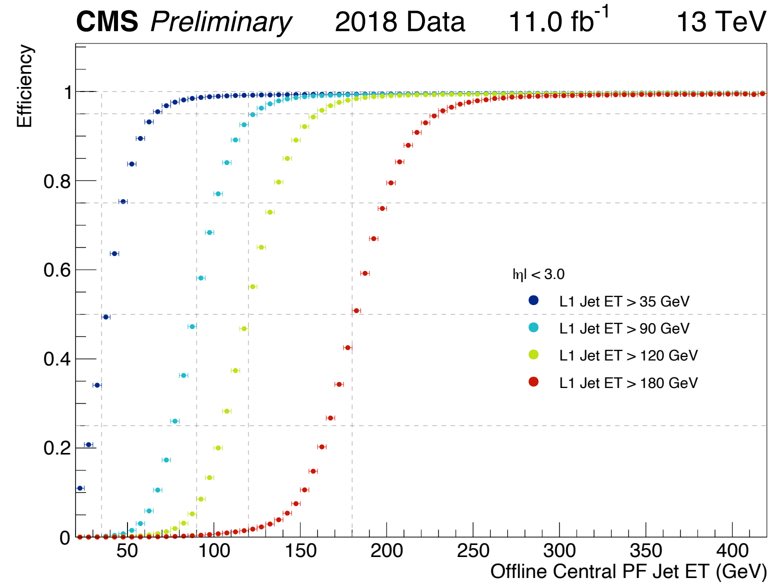


Electron/photon

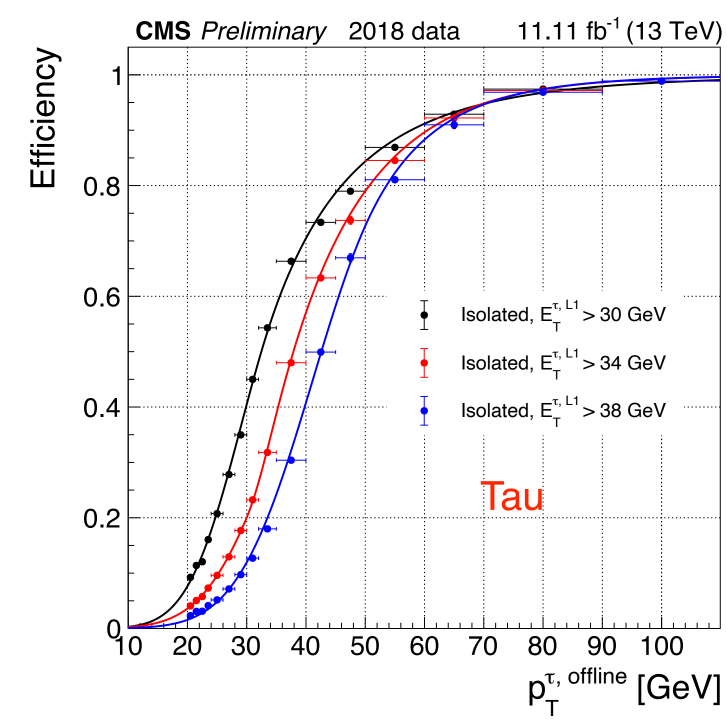
All reconstruction performances greatly independent of pileup

CMS DP-2019/020
CMS DP-2018/044
CMS DP-2018/040





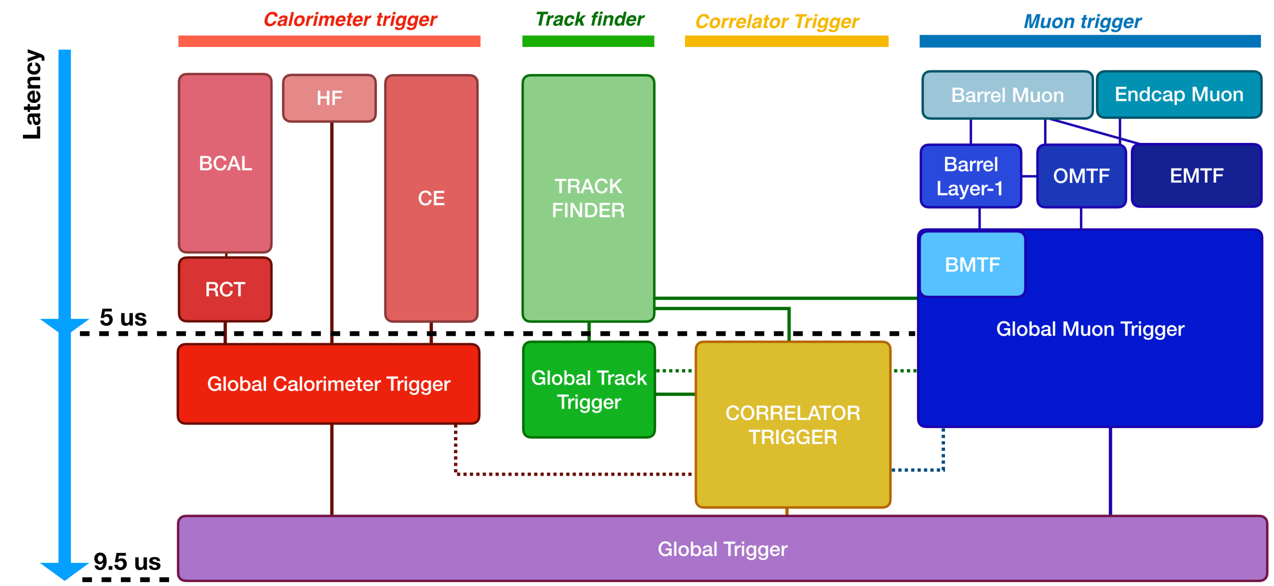
Jet



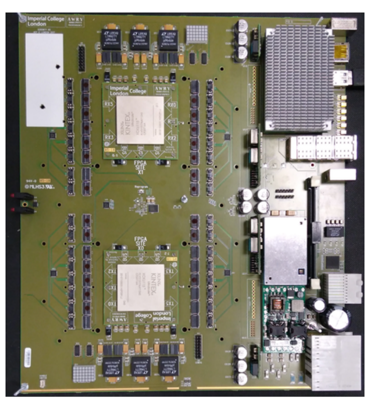
Level-1 Trigger HL-LHC Upgrade

CERN-2020-010

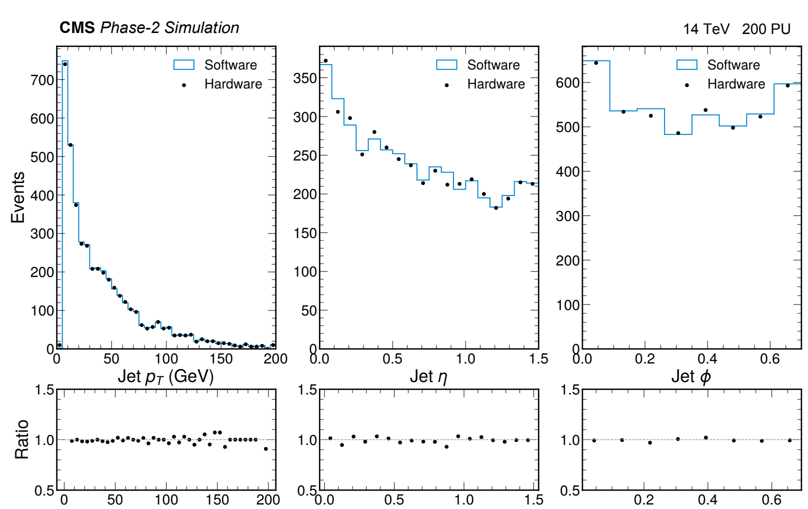
- The impending Phase-2 upgrade for the high luminosity phase or HL-LHC will see upgraded detectors, adding to efficiency gains at L1
  - Inclusion of tracking, PF algorithm
  - Increased granularity in calorimeter trigger, increased muon system pseudorapidity coverage
  - Use of state-of-the-art processing boards running more complex algorithms at 12.5 μs latency, optical links to send data at 28 GB/s, 750 kHz output bandwidth

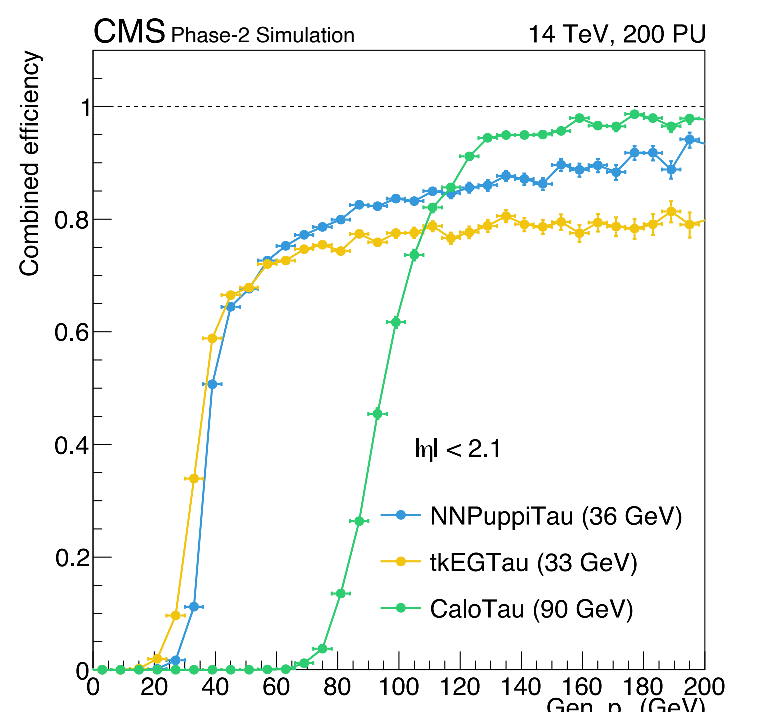


CMS-TDR-021

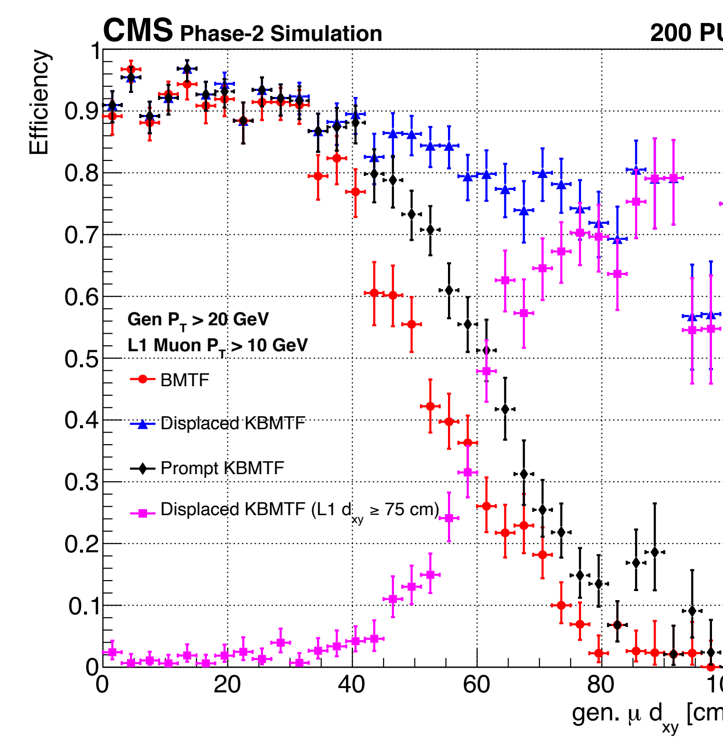


Serenity boards running PF-jet algorithm, 98% events have perfect agreement with software





NN based algorithms for tau reconstruction

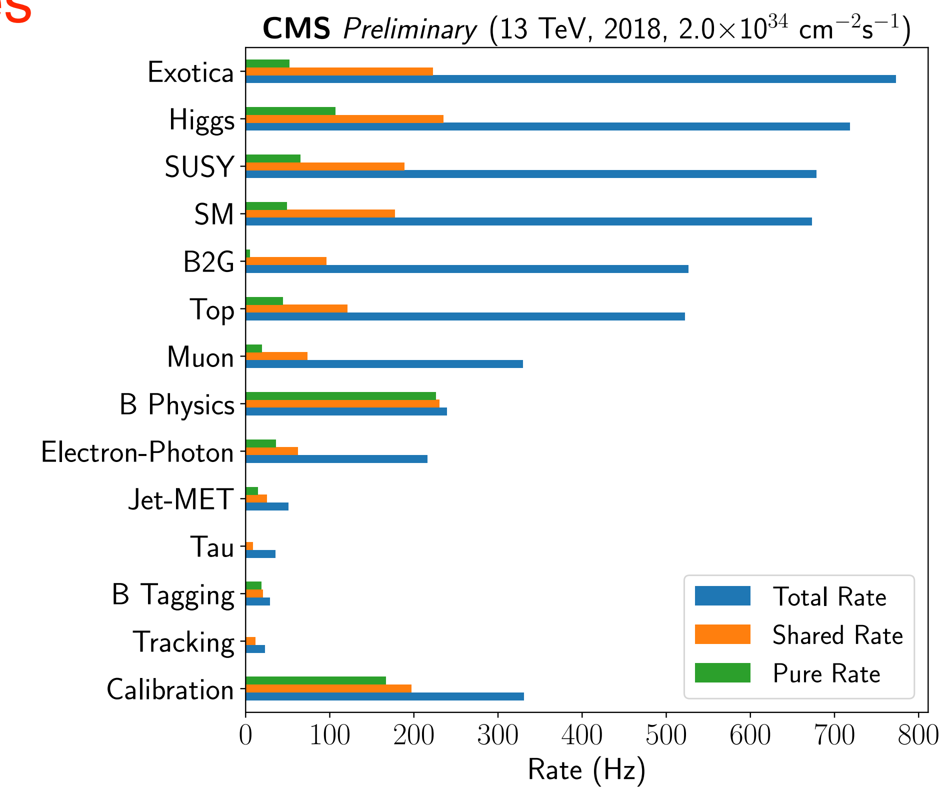


New displaced muon triggers using Kalman filter

High Level Trigger

- Software algorithms running asynchronously on commercial computing hardware
  - Same code and similar algorithms used for offline reconstruction but very optimized
  - 100 times faster than offline reconstruction
  - 30,000 CPU cores at the end of Run-2
- Make use of full detector data to select events for offline storage and analysis
- Modular approach to speed up online reconstruction
  - Alternate event builder and event filter steps
  - Starts with the fastest step, regional reconstruction around L1 seeds
  - Run time-consuming tracking and particle-flow only for interesting events after filtering
- Hundreds of HLT paths targeting broad event topologies
- Aim to select one out of every 100 events
- Output bandwidth ~2 GB/s
- In Run-2 HLT included improvements resulting from Phase-1 upgrades of Pixel and HCAL sub-systems
  CMS-TDR-010

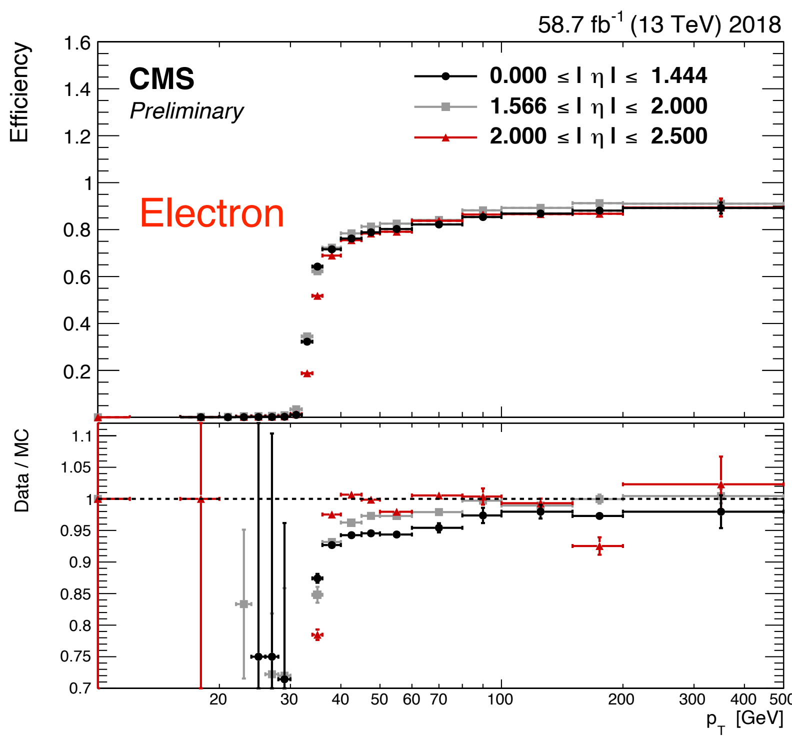
CMS DP-2018/057

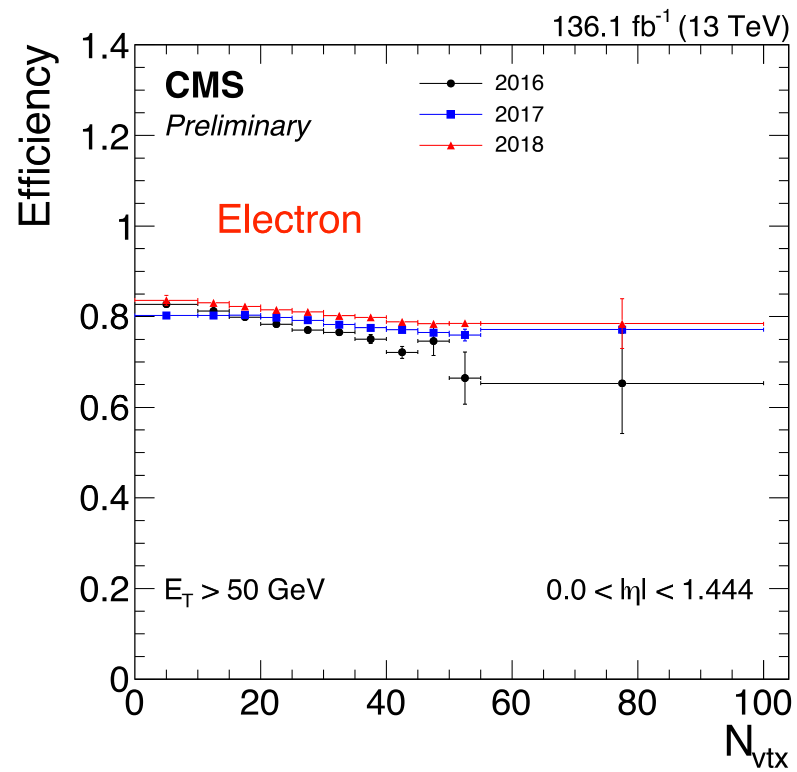


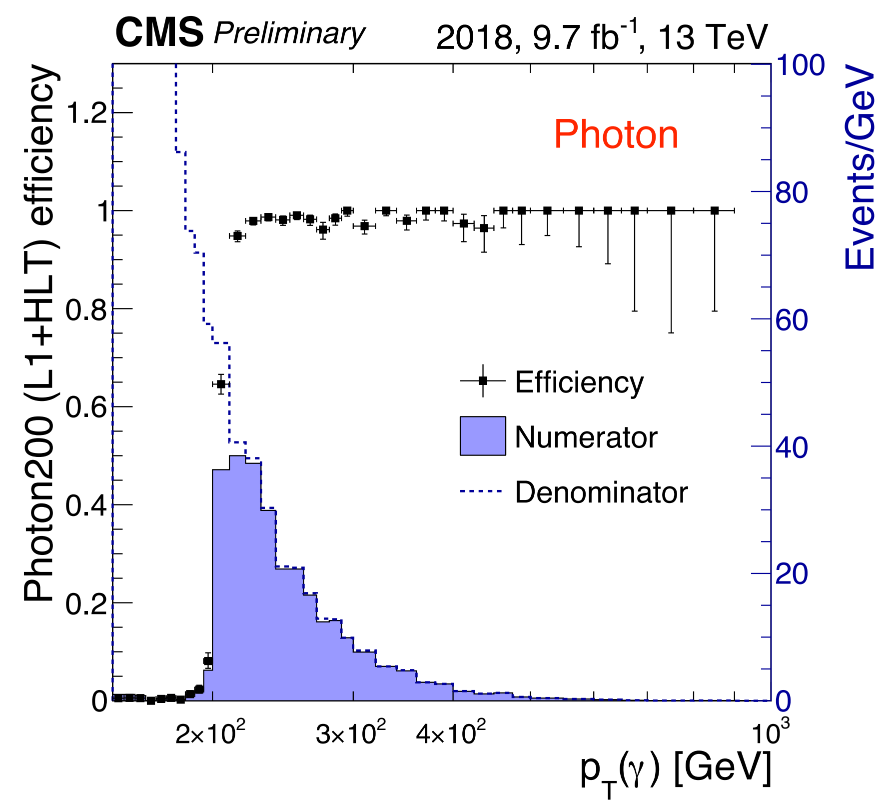
Decision takes typically ~300 ms

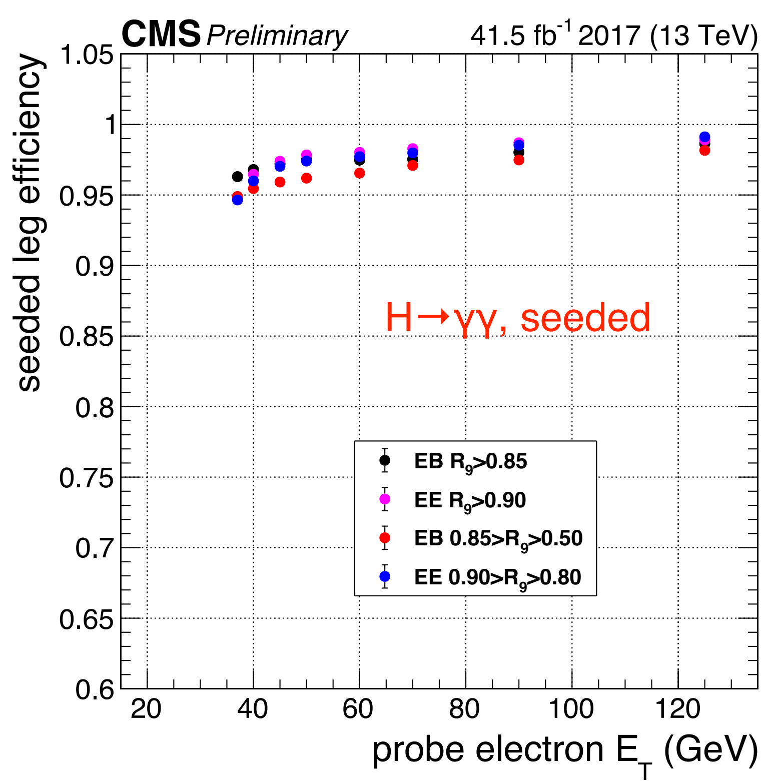
High Level Trigger Performance (I)

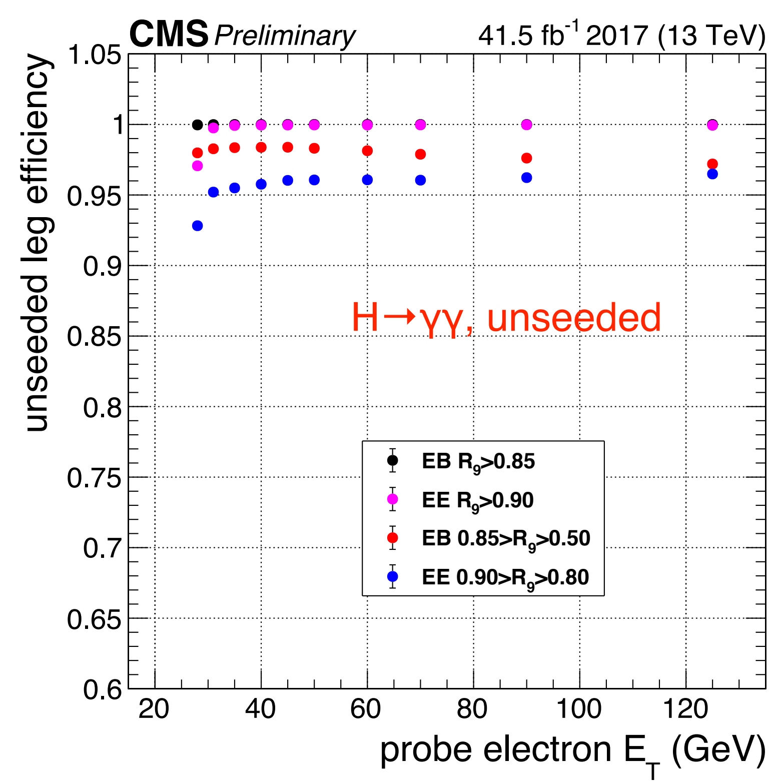
- In addition to HLT objects, many physics analysis oriented trigger paths defined at HLT, performance depends on specific requirements







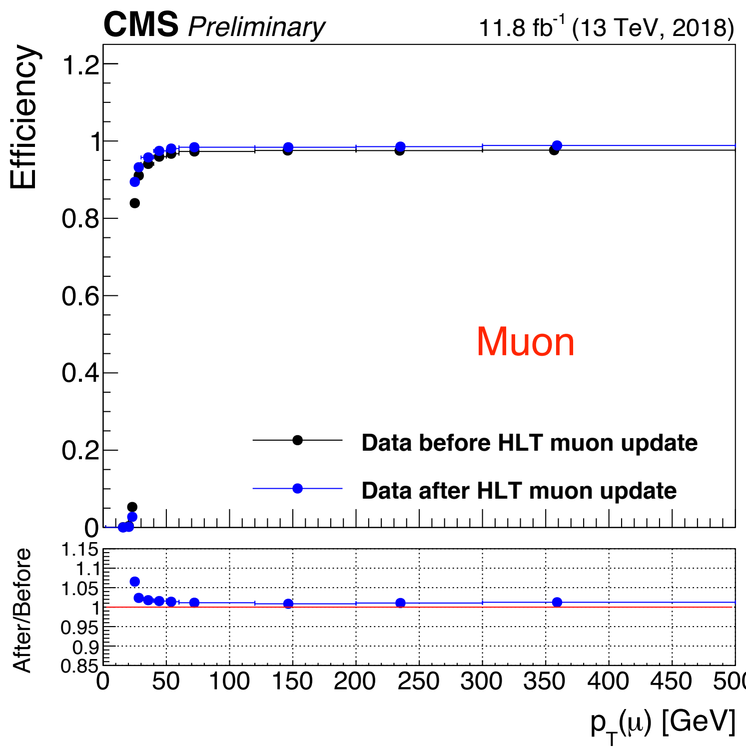


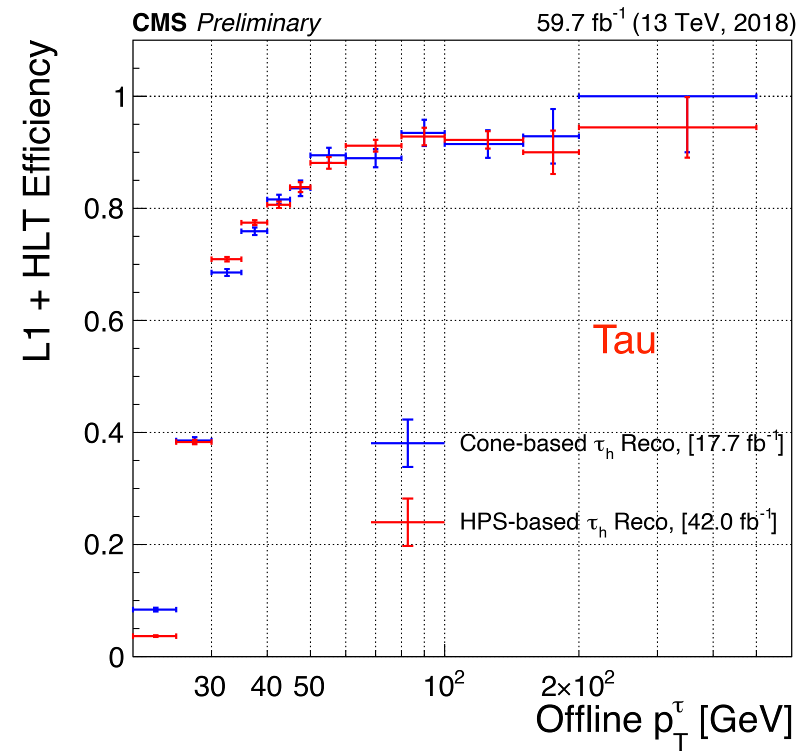


CMS DP-2020/016
CMS DP-2018/049
CMS DP-2018/039

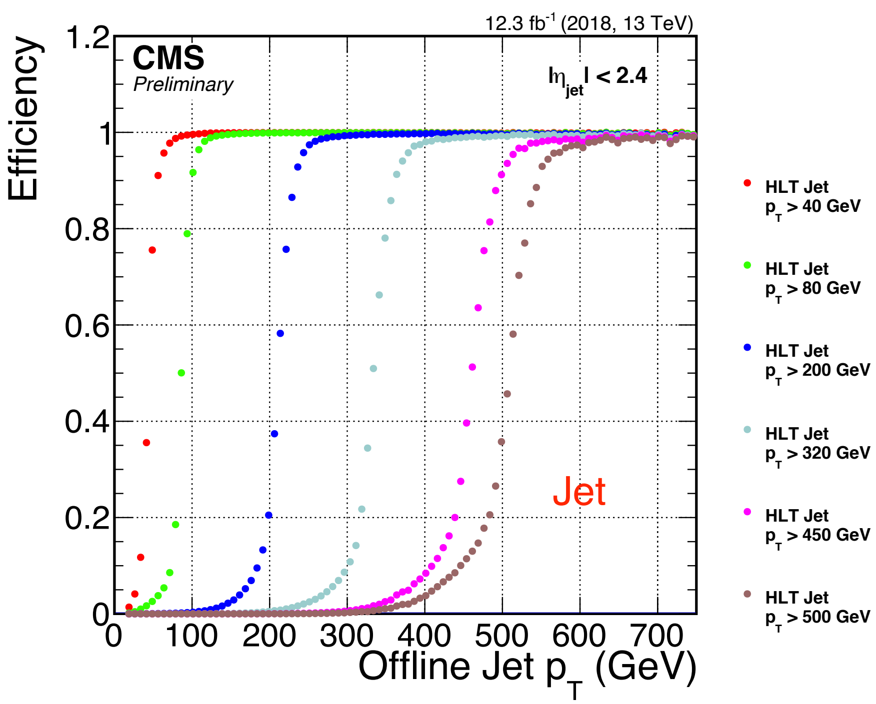
High Level Trigger Performance (II)

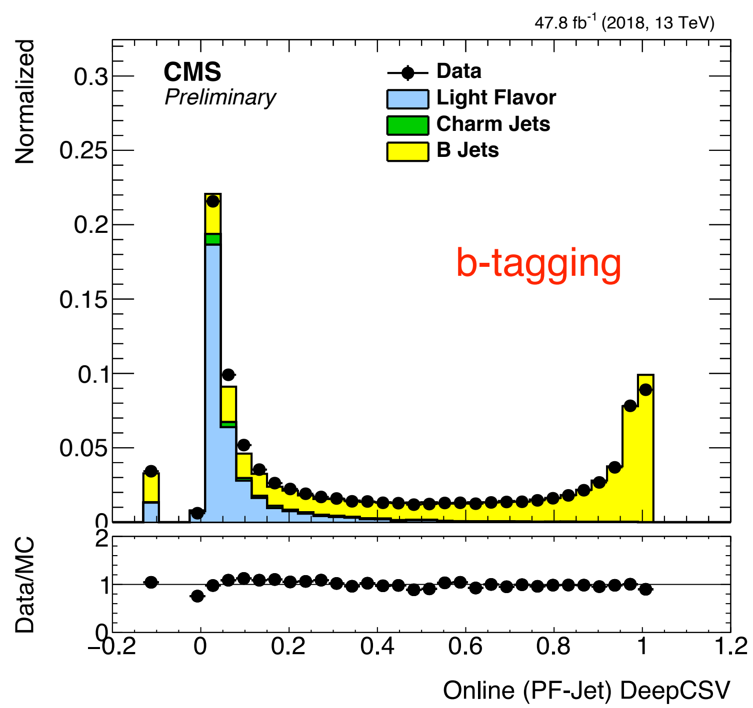
- In addition to HLT objects, many physics analysis oriented trigger paths defined at HLT, performance depends on specific requirements

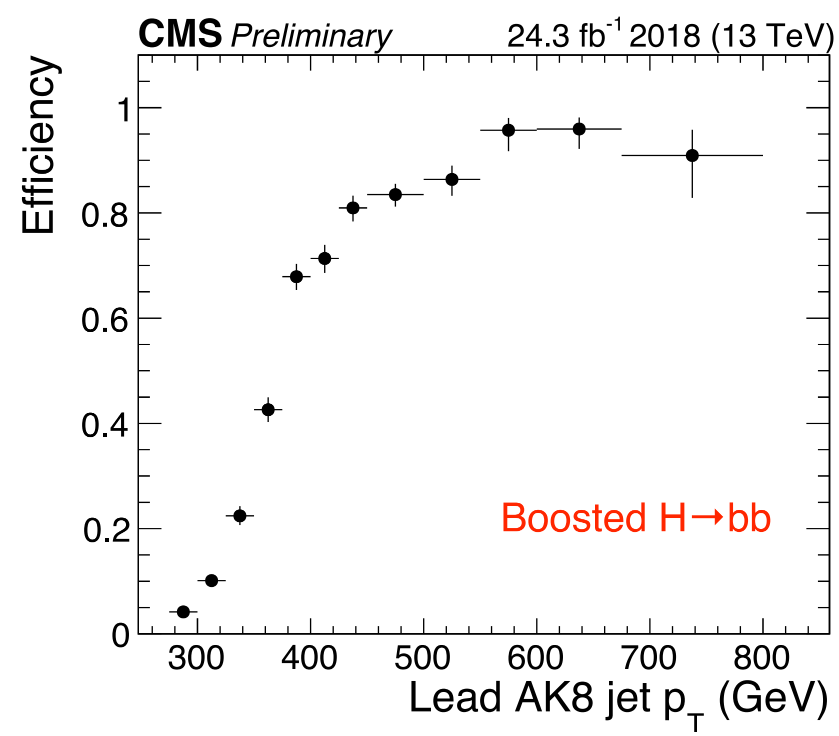




CMS DP-2018/034
CMS DP-2019/012
CMS DP-2018/037
CMS DP-2019/042
CMS DP-2018/053



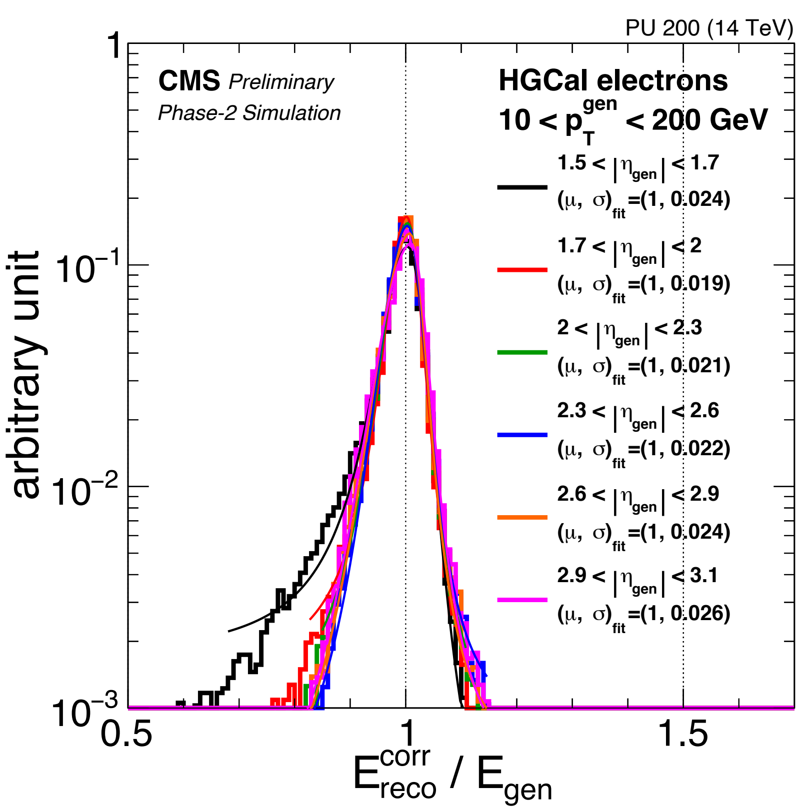




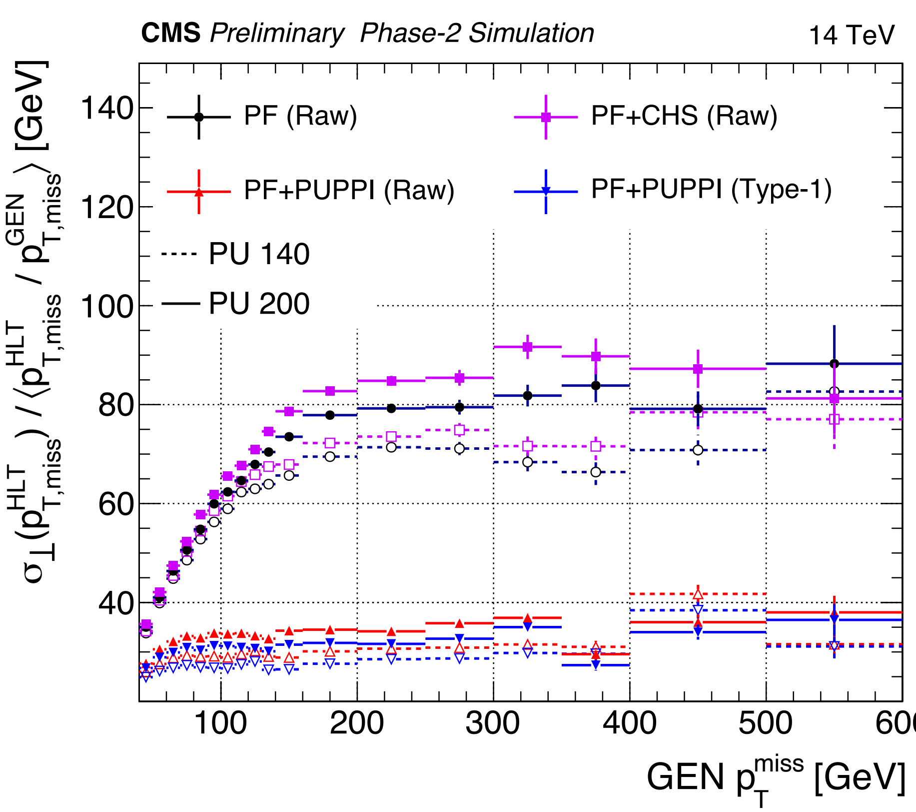
High Level Trigger HL-LHC Upgrade

- Manyfold increase in detector readouts during HL-LHC, CPUs unable to cope with demand in performance
- Adoption of heterogeneous architecture: using GPUs as a strategy for providing the necessary computing power at an affordable price
- Main features in algorithm improvement: 3D shower reconstruction, pixel tracks and vertex reconstruction, more pileup suppression…
- Output bandwidth increase to ~61 GB/s, with rate at 7.5 kHz

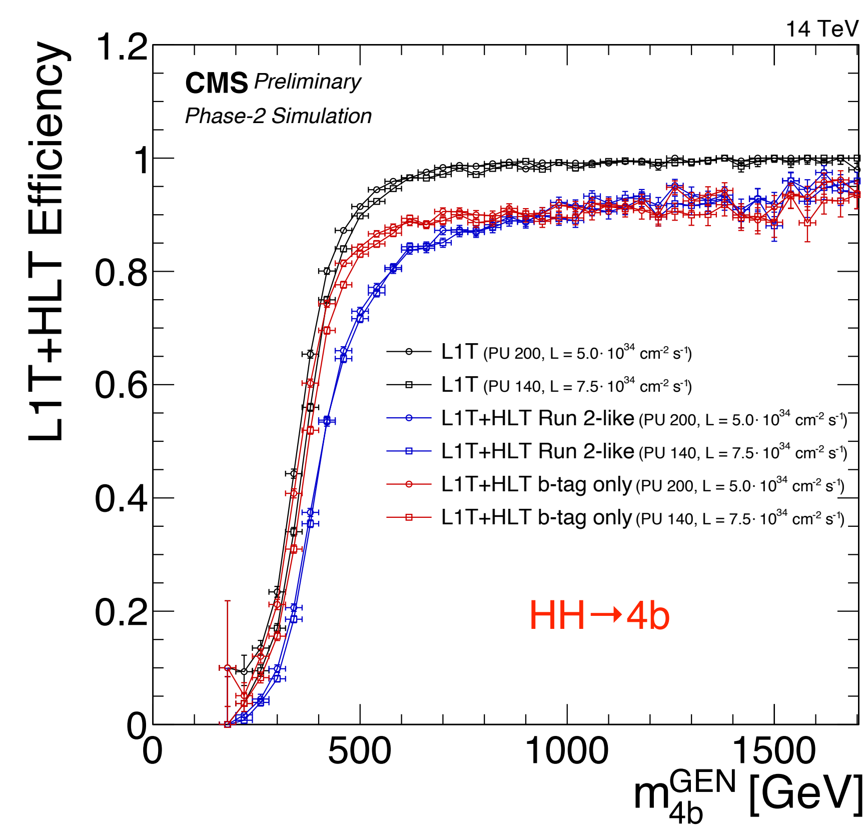
CMS DP-2021/009
CMS DP-2021/013



Electron energy resolution



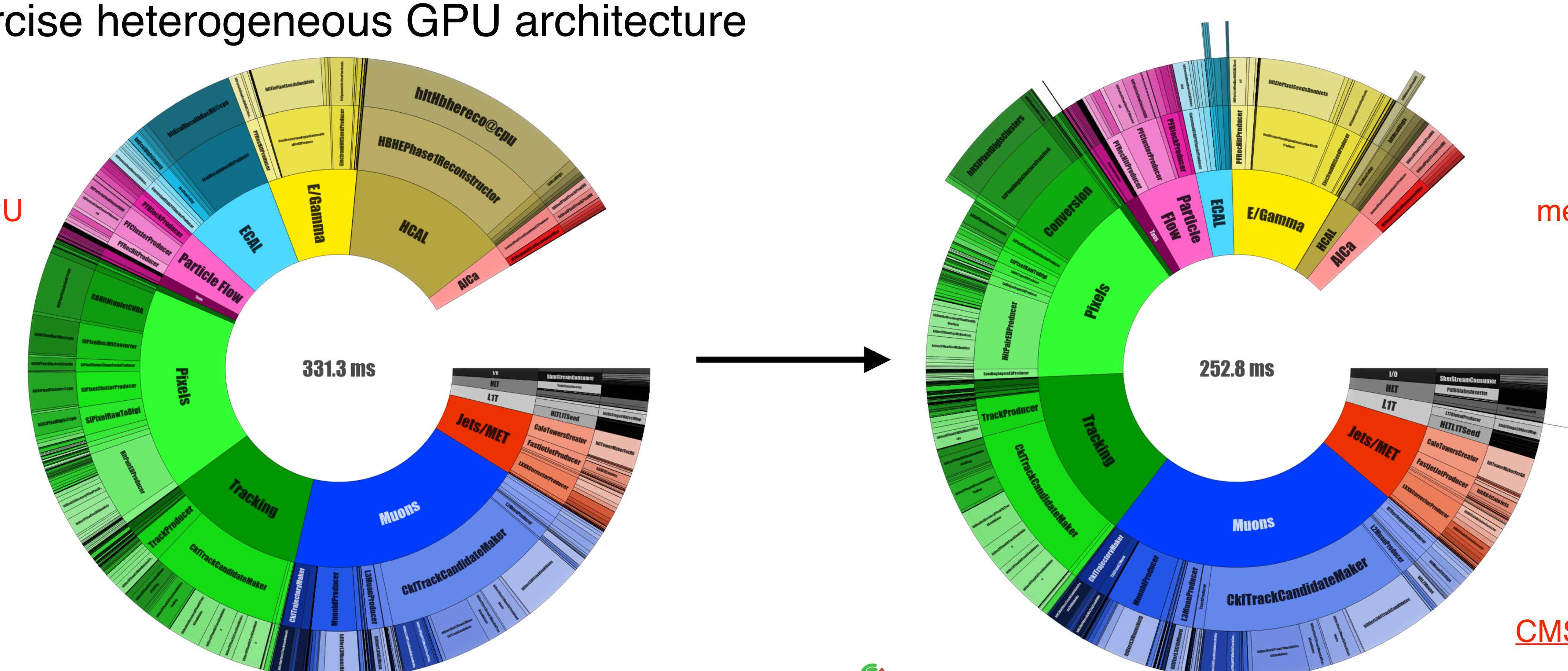
MET resolution greatly improves with PUPPI @HLT



Towards Run-3 (I)

- Some Phase-2 improvements already ready to be implemented during Run-3
- Foresee higher pileup profile compared to Run-2, new features needed to compensate the physics program
- L1 Trigger:
  - Inclusion of GEM in the muon track finder
  - HCAL depth and timing information
  - Kalman filter for muon tracks
- HLT:
  - Exercise heterogeneous GPU architecture

menu w/o GPU

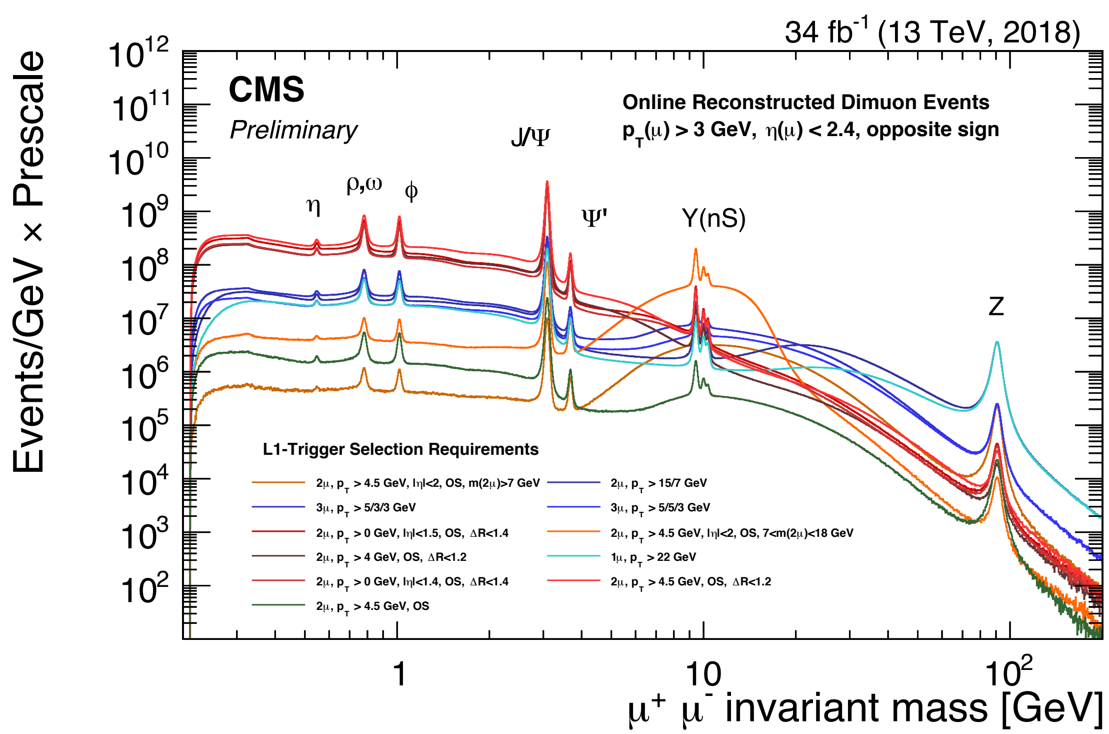


menu with GPU

CMS DP-2021/013

Towards Run-3 (II)

- Computing resource constraints: present average HLT rate limit 1 kHz at peak luminosity
  - Limited bandwidth: data recording and transfer limited to ~5 GB/s on average
  - Prompt reconstruction: all recorded data must be fully reconstructed offline within ~48h
  - The total amount of storage space is limited (tape and disk)
- Workaround to go beyond 1 kHz:
  - Reduce event size with Scouting: reduce event size by saving only online/trigger objects that will be used directly in data analyses; already established method in CMS since Run-1
  - Reduce computing resources with Parking: “park” data on tape, skipping prompt reconstruction and reconstruct the data later (during technical stops); during Run-2 large fraction of scouting data were parked
- For Run-3, expanding the reach to high rates and more exotic phase spaces



Di-muon mass spectrum using Run-2 scouting data

CMS DP-2018/055

Summary

- Trigger system is a behemoth dealing with extreme computing demands to meet the physics goals of the LHC
- Performance gains over the past years made possible by integrating new technologies and advanced algorithms
  - Increased L1 granularity
  - Improved trigger algorithms targeting rare final states
- Good performance in Run-2
  - Sharper efficiency turn-ons, rates under control
  - Little pileup dependence
- Major improvements planned for HL-LHC to extend reach to new physics processes, some already to be tested during Run-3
  - Addition of tracking and correlator layer in L1 coupled with upgraded hardware, GPUs at HLT

That's NOT all folks!

Stay tuned for exciting new physics