BPU12 CONGRESS 12th International Conference of the Balkan Physical Union

CMS High Level Trigger performance in LHC Run 2 and Run 3

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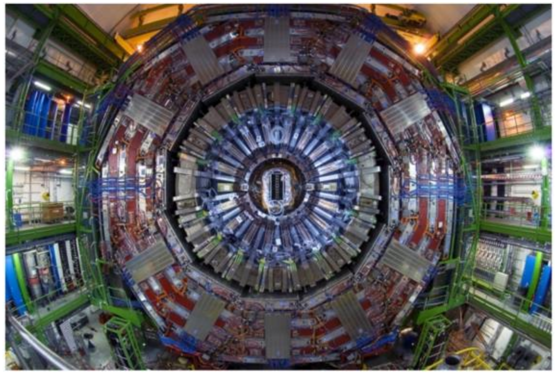
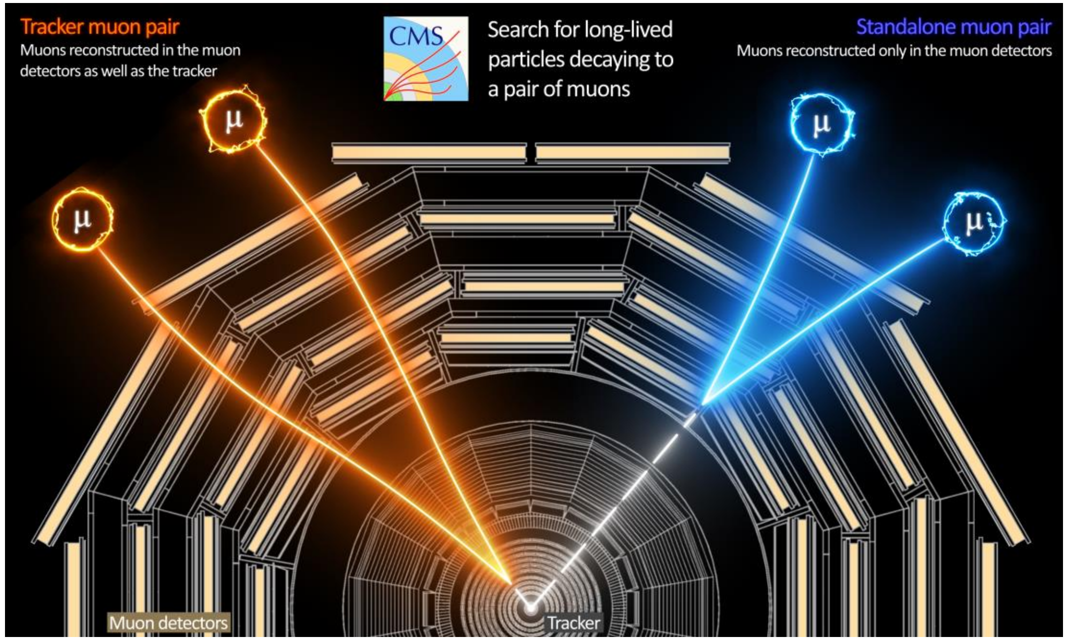
Outline of the talk



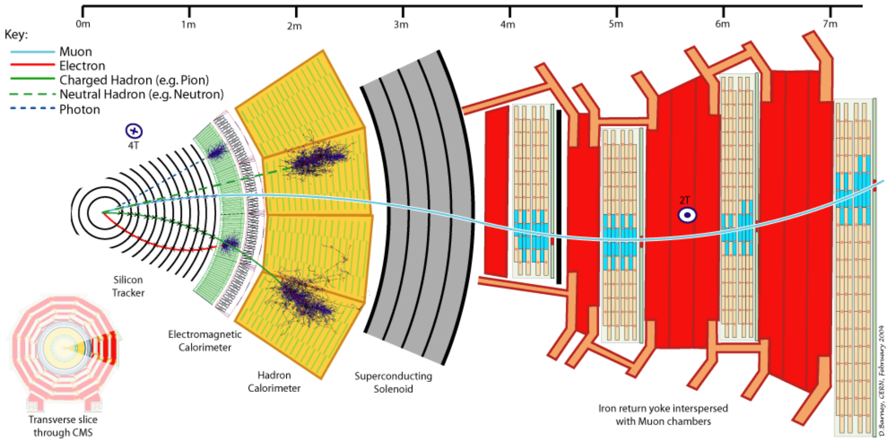
- An overview of the trigger system of the CMS experiment
- The CMS Trigger design, architecture and implementation
- Performance of the CMS High Level Trigger in LHC Run 2

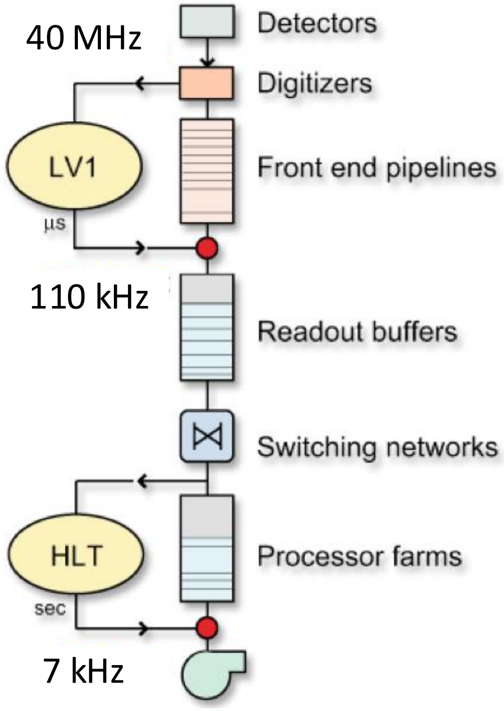


- New HLT developments for the LHC Run 3
    - improved tracking, ParticleNet triggers
    - triggers targeting Long-lived particles
    - heterogenous triggering: CPUs + GPUs
- HLT performance from the most recent data

Selecting events for physics: CMS Trigger System

- CMS: a general-purpose detector at the CERN LHC
- Real-time decision to save physics-relevant events
- Efficient and clean decision -> Trigger universality
- Rate & Time constraints: DAQ bandwidth & buffer

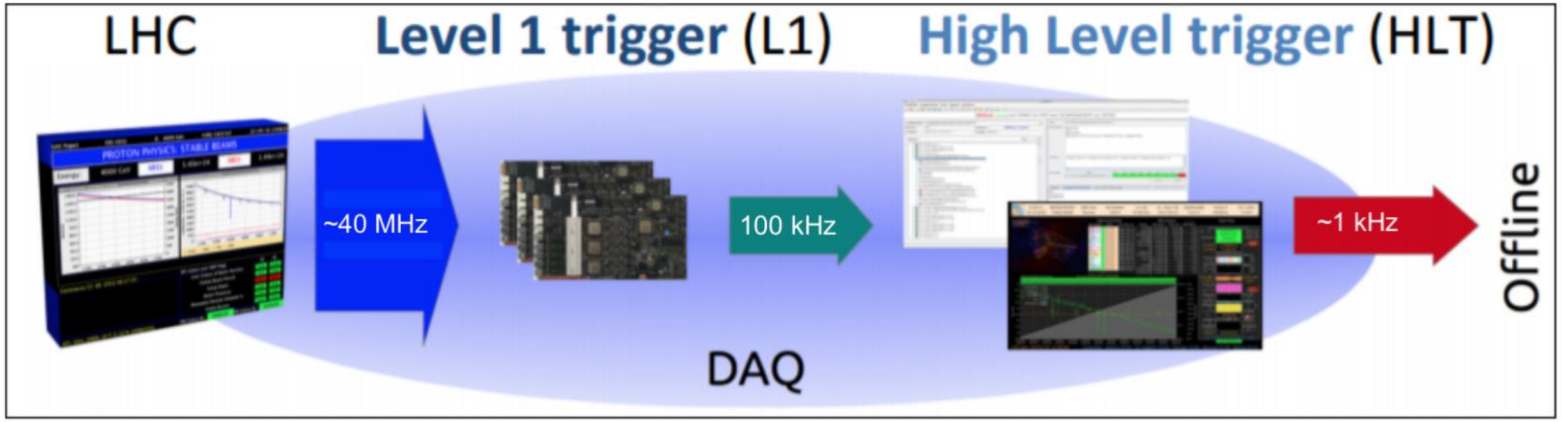




- The Trigger System of CMS Experiment is organized in two tiers/levels:
  - **Level-1 Trigger:** hardware based on custom-made electronics, with only the muon system and calorimeters being active in the readout
  - **High-Level Trigger (HLT):** filtering events using software running on a computing farm based on commercial CPUs (and now also GPUs)

CMS High Level Trigger (HLT): Design and Purpose

- High Level Trigger designed to reduce event rate from ~100 kHz to ~1(7) kHz in LHC Run 2(3)
  - the output rate from offline computing data processing constrains and storage capacities
  - uses offline reconstruction algorithms and code, but is optimized for running much faster
  - total 30,000 CPU cores used in the High Level Trigger system at the end of the LHC Run 2
  - hundreds of HLT paths constructed, targeting very broad range of (new) event topologies



PARKING data taking:
a few thousand evt/s
delayed data availability

Standard data taking: 1000 evt/s

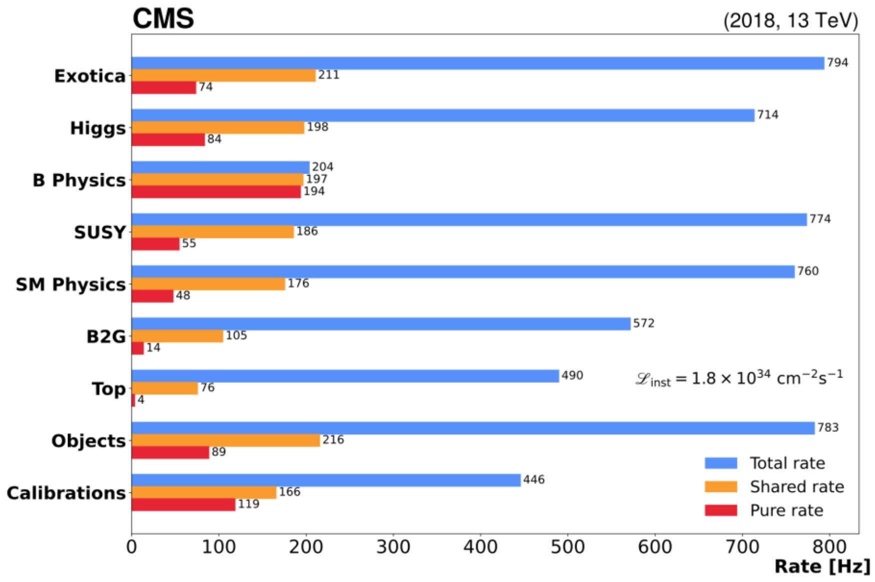
SCOUTING data taking:
10000 evt/s (or higher)
reduced format of data

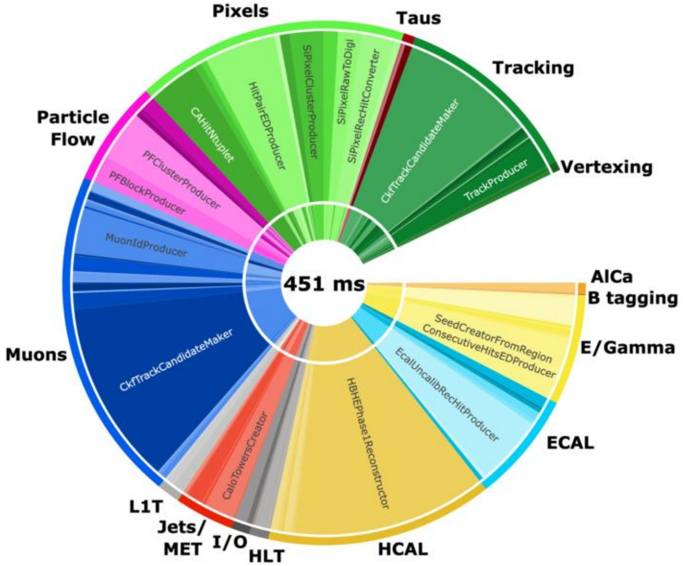
CMS HLT Menus, Rates and Processing Time in Run 2

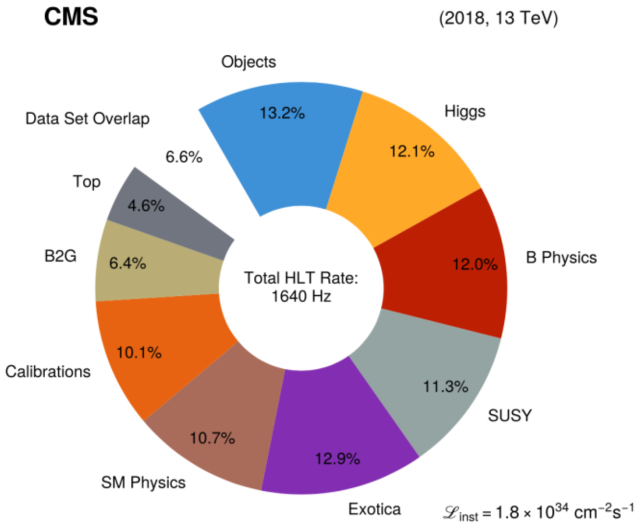
2024 JINST 19 P11021

- The HLT selects data for storage through the application of a trigger “menu”, which is a collection of individual HLT paths
- Run2 HLT menus typically had ~600 paths for p-p data taking
- HLT rates attributed to each CMS physics group (2018 menu)
- CPU time (@ HLT) for different parts of event reconstruction
- HLT rate consumption by physics group (in standard physics)

HLT path	L1 thresholds [GeV]	HLT thresholds [GeV]	Rate [Hz]
Single muon	22	50	49
Single muon (isolated)	22	24	230
Double muon	22	37, 27	16
Double muon (isolated)	15, 7	17, 8	32
Single electron (isolated)	30	32	180
Double electron	25, 12	25, 25	16
Double electron (isolated)	22, 12	23, 12	32
Single photon	30	200	16
Single photon (isolated), barrel only ($\lvert\eta\rvert < 1.48$)	30	110	16
Double photon	25, 12	30, 18	32
Single tau	120	180	16
Double tau	32	35, 35	49
Single jet	180	500	16
Single jet with substructure	180	400	32
Multijets with b tagging	$H_T > 320$ jets $> 70, 55, 40, 40$	$H_T > 330$ jets $> 75, 60, 45, 40$	16
Total transverse momentum	360	1050	16
Missing transverse momentum	100	120	49







CMS High Level Trigger: Track reconstruction in Run 2

- Charged particle tracks in the HLT are reconstructed from the hits in the pixel & strip tracker using Kalman filter, using initial estimates of the track parameters obtained from hits in the pixel detectors (i.e. “seeds”)
- The tracking efficiency and misID are obtained from simulated tt events with the mean pileup (PU) of 50

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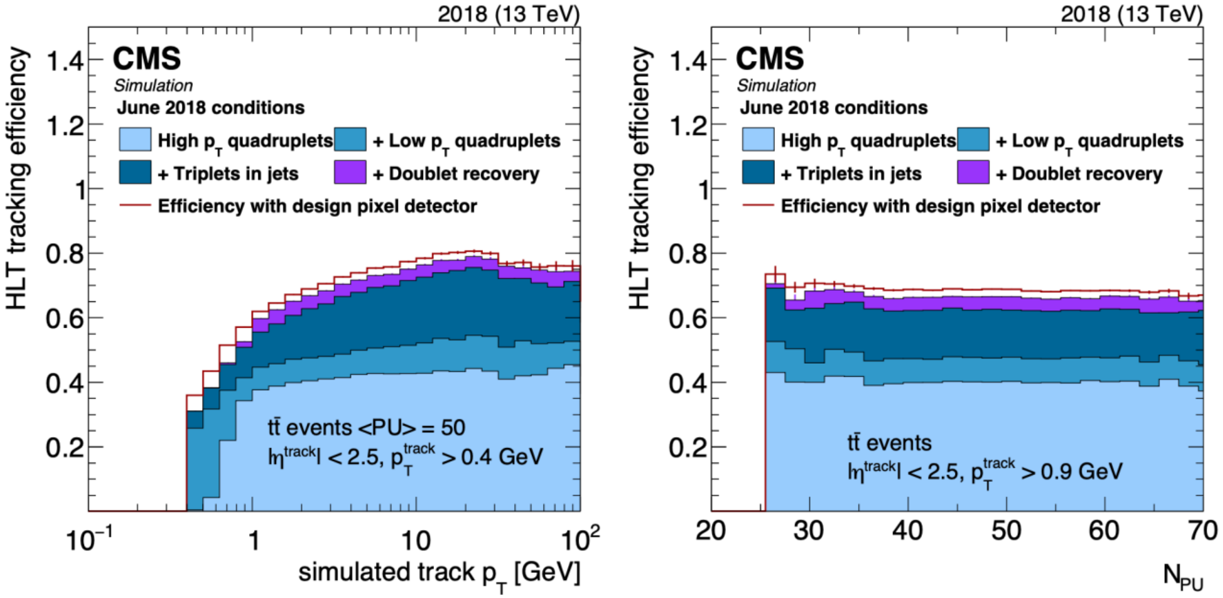

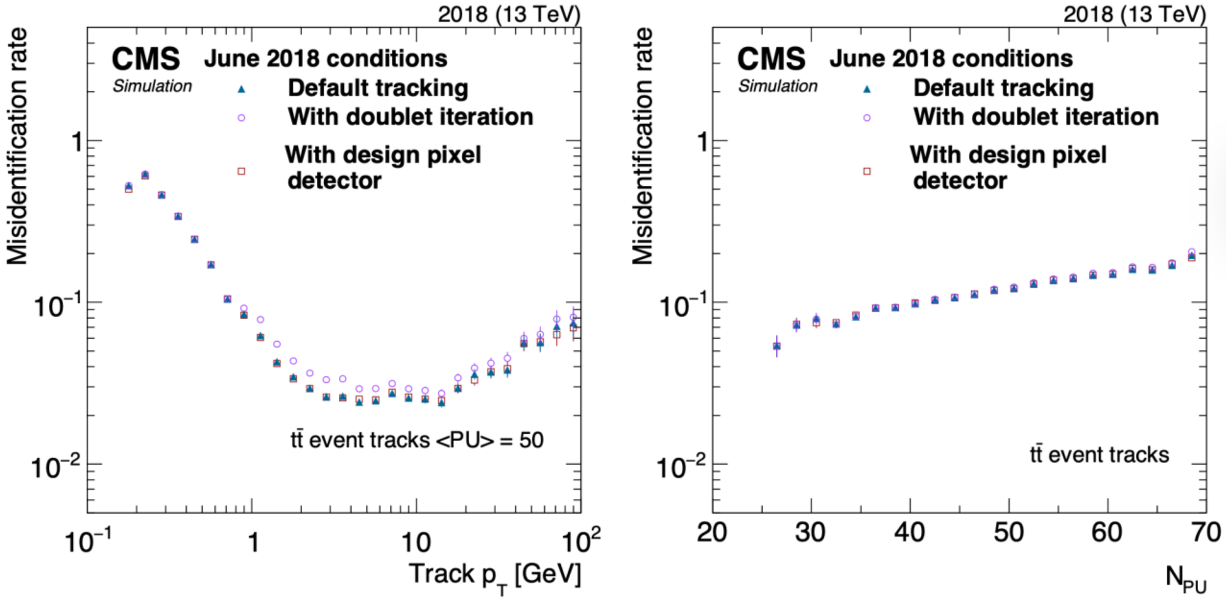

- The tracking efficiency was plotted as a function of p_{T}, number of PU interactions (N_{PU}), η, and ϕ
- The tracking misidentification rate as a function of p_{T}, N_{PU}, η, and ϕ ---> found to be steady versus PU

CMS High Level Trigger: Muon reconstruction in Run 2

- Tracking algorithms are deployed to identify and reconstruct muons measured in the muon detectors in combination with pixel and strips
- The combined L1+HLT muon trigger eff. of an isolated single-muon trigger with respect to offline-reconstructed muons is presented --->

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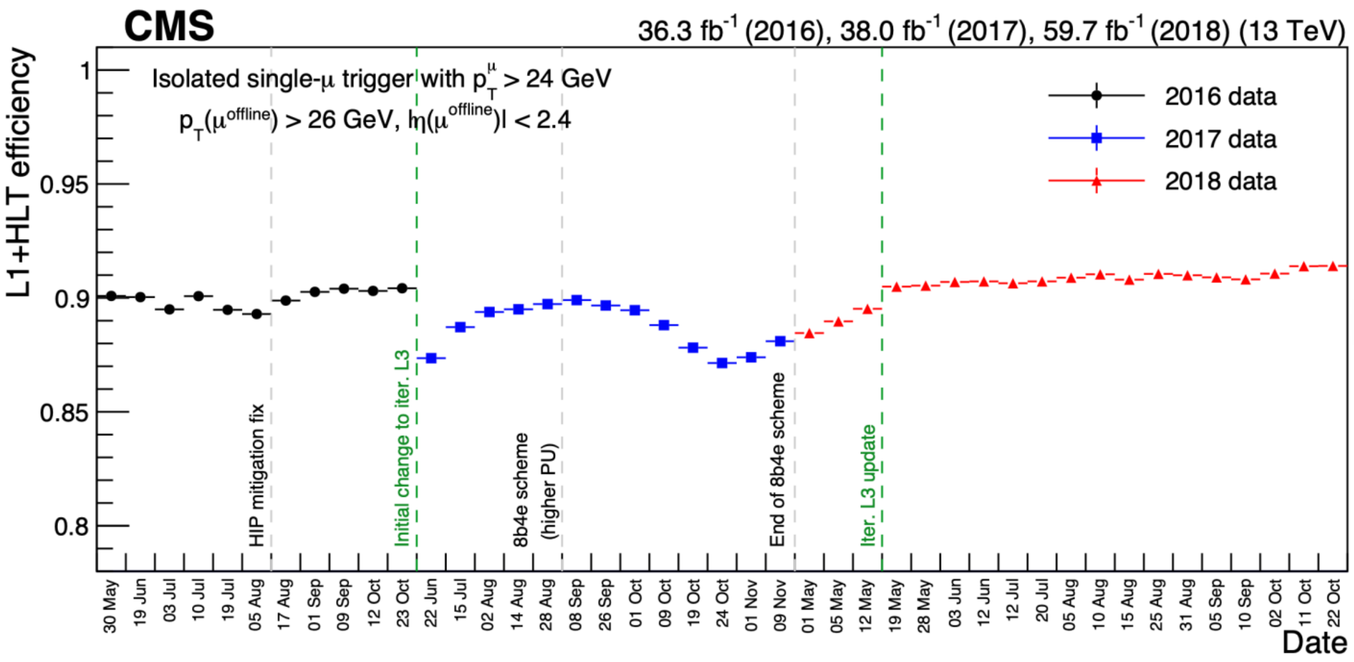

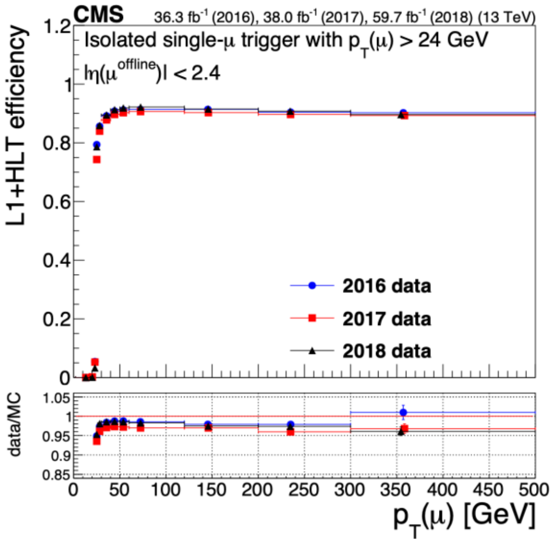

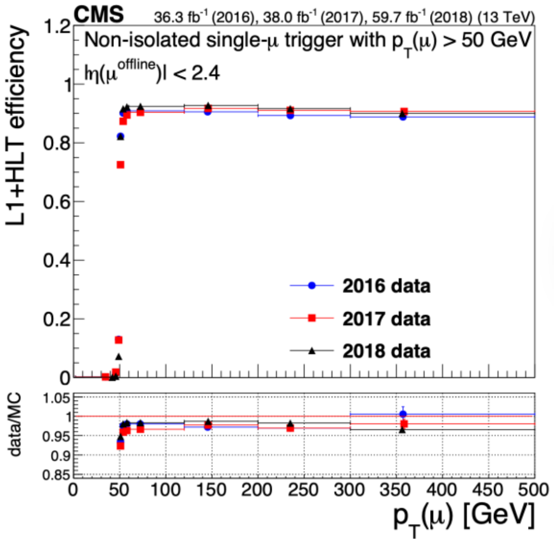

- The efficiency of the isolated single-muon trigger with p_T >24 GeV (left) and the non-isolated p_T >50 GeV (right) as a function of muon p_T, η, Nvtx for years 2016, 2017, 2018

(efficiencies versus η, Nvtx presented in the backup slides)

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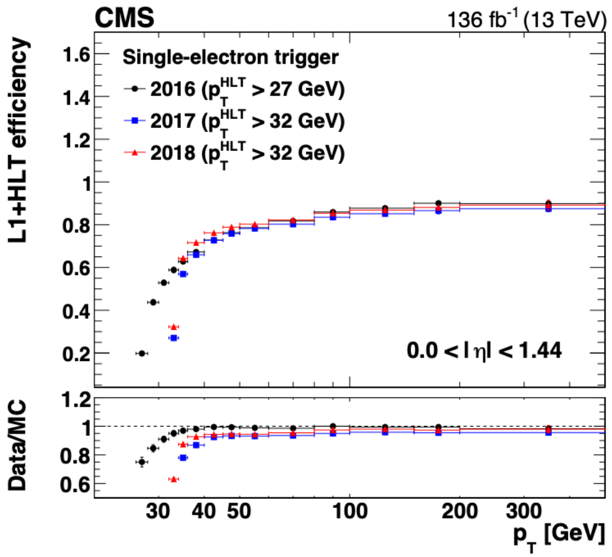
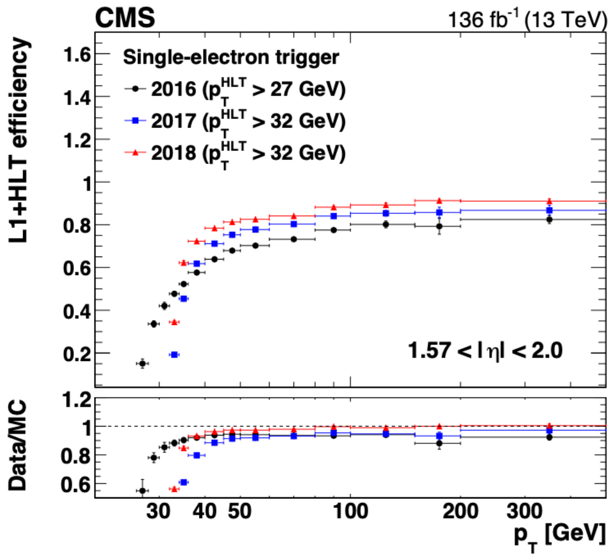
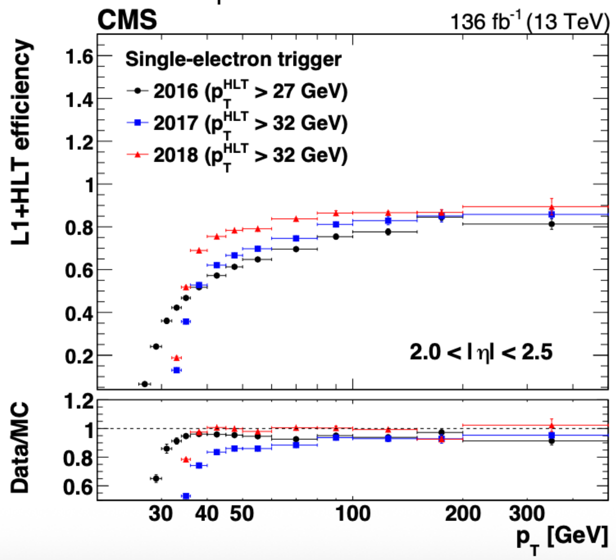
- The HLT electron and photon identification begins with the regional reconstruction of the deposited energy of ECAL crystals around the L1 candidates
- In Run2, the signals in the ECAL crystals are reconstructed by fitting the signal pulse with template functions to mitigate the out-of-time PU





- The signal amplitudes are then corrected by per-crystal correction factors and per-channel calibration techniques (radiation damage)
- The L1+HLT efficiency of the single-electron triggers with respect to offline-reconstructed electron as a function of the electron p_T and N_{vtx}, and shown for the different η regions of the supercluster



SC matched

to pixel track

-> fit with GSF

CMS High Level Trigger: jets, energy sums & MET in Run 2

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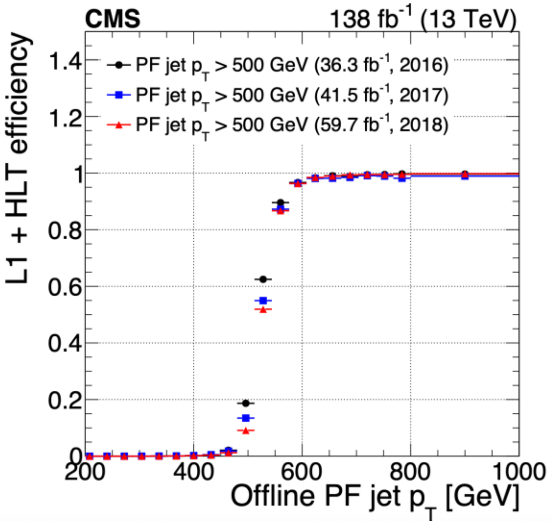
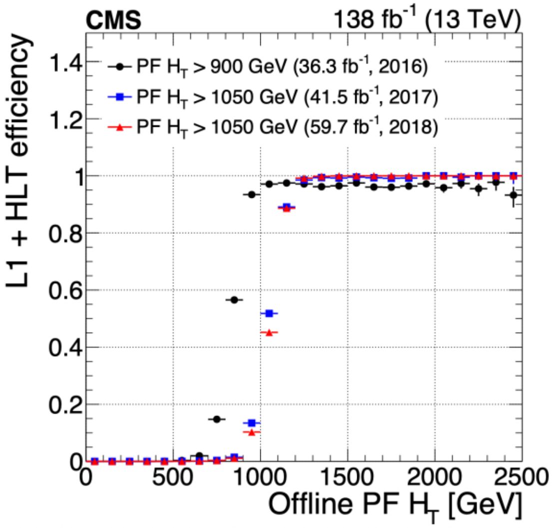
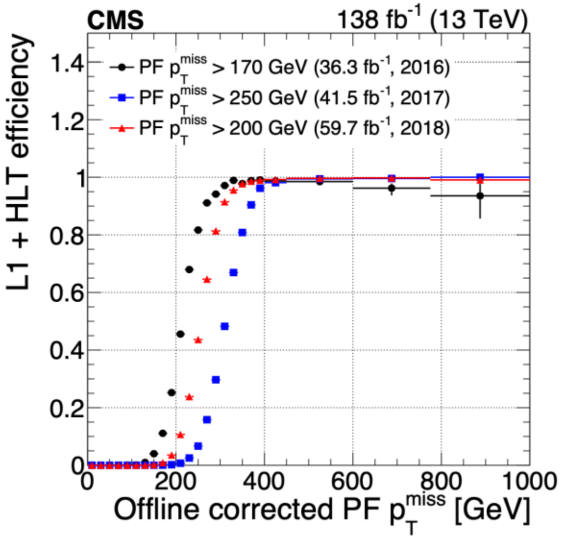
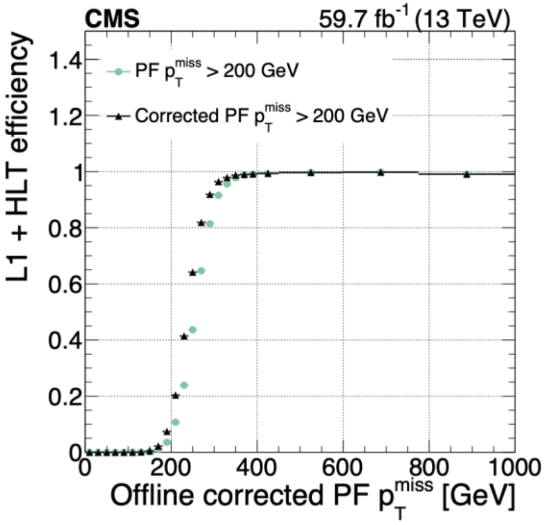
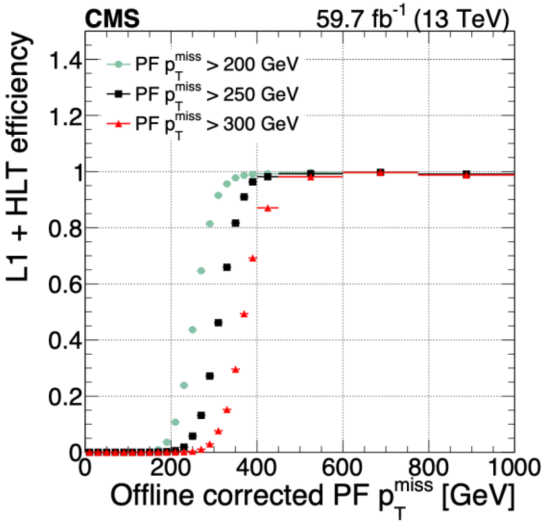
- Jets are reconstructed at the HLT using the anti-kT algo (calo or PF) with 0.4 cone size (0.8, wide jets)
- The efficiency for the unprescaled singlePFjet trigger (and H_T) as a f-ion of the offline PF jet p_T (and H_T)
- The efficiency of the pT_{miss} triggers











- At the HLT, online jet energy corrections can be propagated to the calculation of the p_T similar to that performed offline
- Here is also a comparison of the performance of nominal and corrected pT_{miss} at the HLT for the 2018 data-taking

CMS High Level Trigger: b-tagging and taus in Run 2

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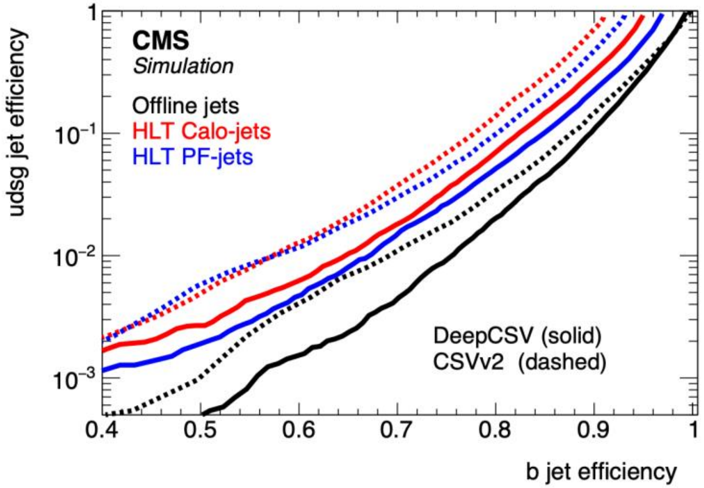
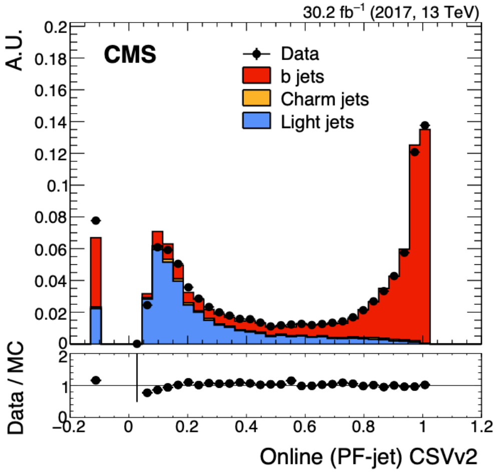
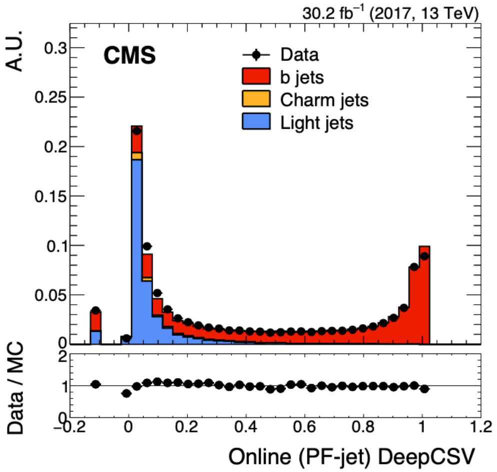
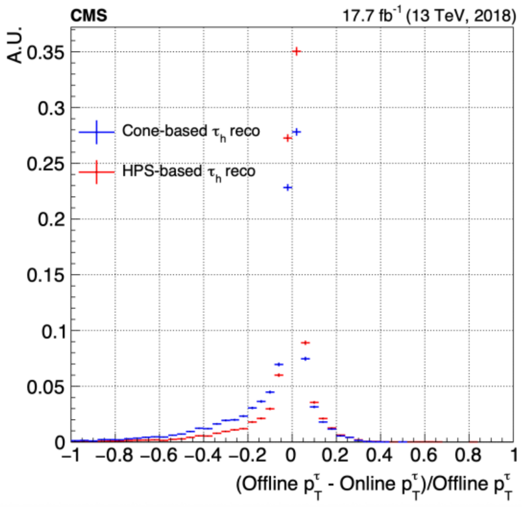
- During the 2016 data-taking, CSVv2 was the recommended algorithm for b-tag at the HLT
- DeepCSV tagger as deployed at the HLT at the start of the 2017 year data-taking period
- DeepCSV: better by 5 – 15%

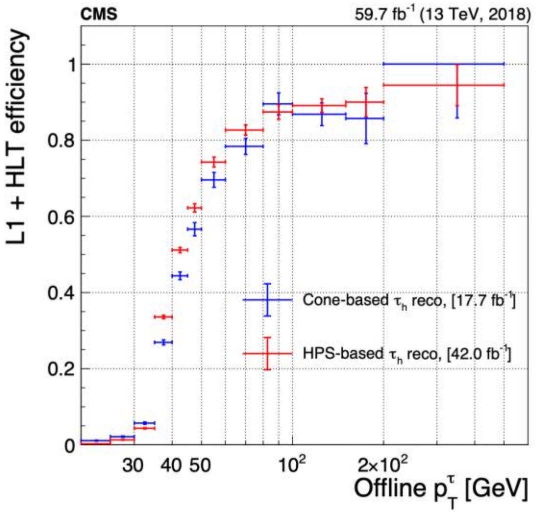


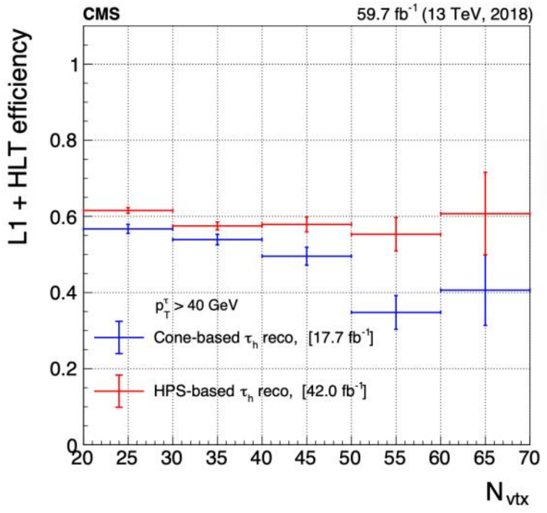




- The performance is assessed for events consistent with the tt process







- Tau leptons have a short lifetime and decay before the beam-pipe
- Hadron-plus-strip algo at the HLT
- pT resolution, L1 + HLT efficiency of cone and HPS based reconstruction

CMS High Level Trigger: New developments in Run 3

Improved tracking based on optimized pixel track reconstruction (Patatrack)

Graph Neural Network (GNN) ParticleNet triggers for b-tag, heavy flavor and tau tagging

New dedicated triggers (displaced muons/taus/jets/photons) for the Long Lived Particle (LLP) searches

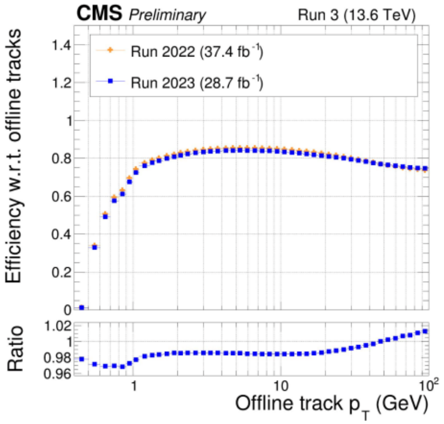
New high-rate VBF and HH->4b (4jets,1 b-tag) paths and dedicated B Physics di-muon and single muon paths in the data parking stream

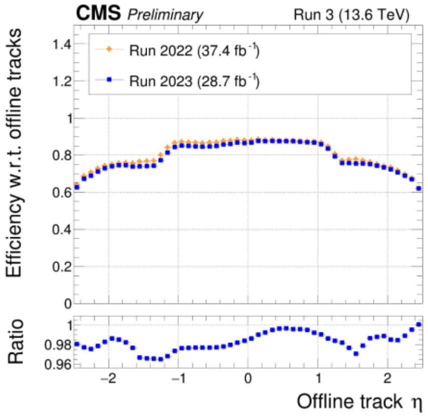
Scouting rate allocation increased to ~30 kHz with an event size of ~12 kB (vs ~1MB for Raw Event)

Heterogeneous reconstruction (CPU +GPU

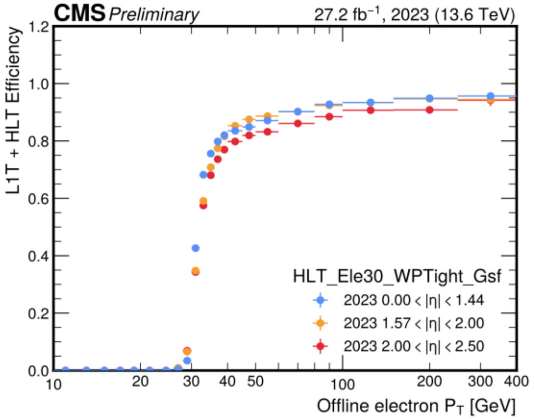
CMS High Level Trigger: Object reconstruction in Run 3

Tracking CMS DP – 2024/013

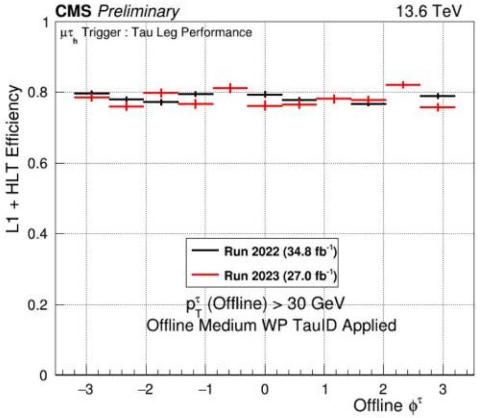


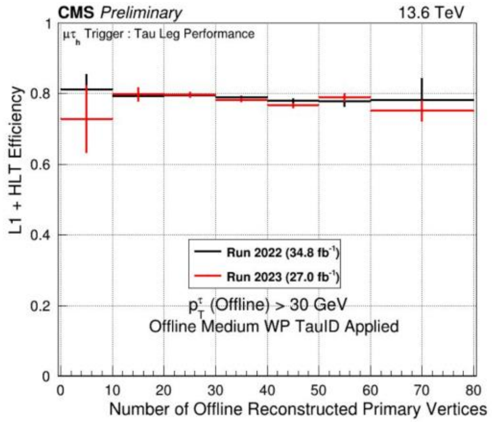


Egamma CMS DP – 2024/041

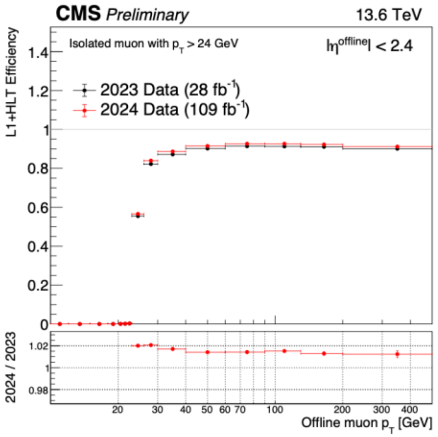


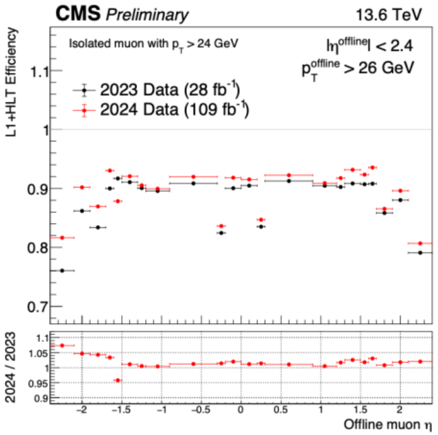
Tau CMS DP – 2024/042



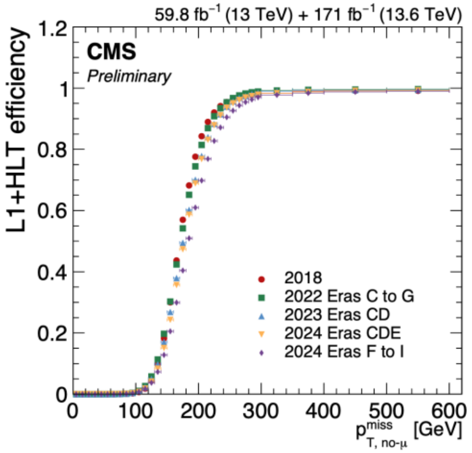


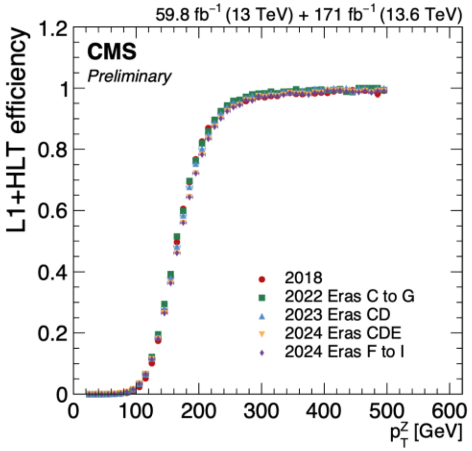
Muons CMS DP – 2025/014



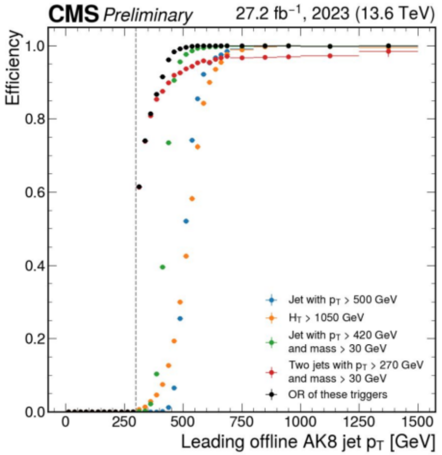


MET CMS DP – 2025/007





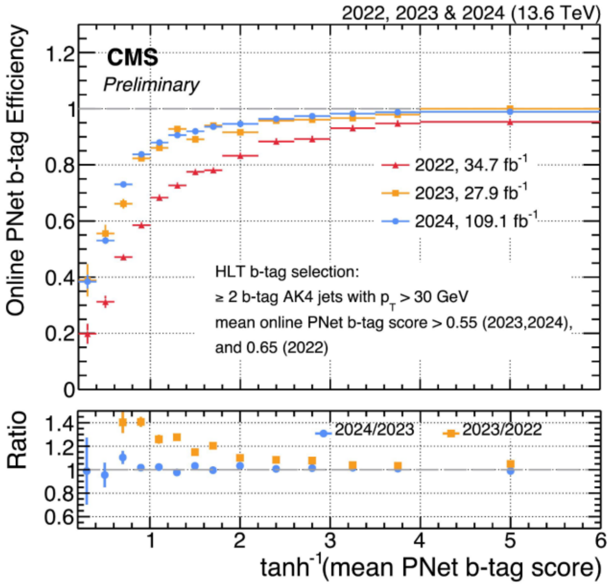
Jet CMS DP – 2023/094

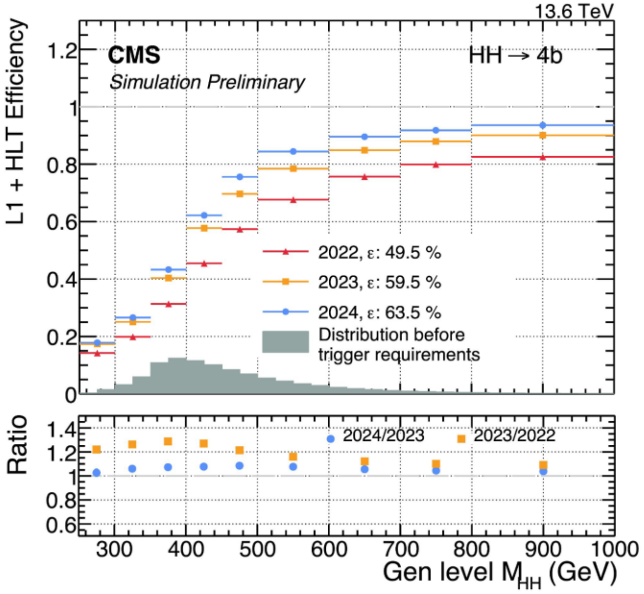


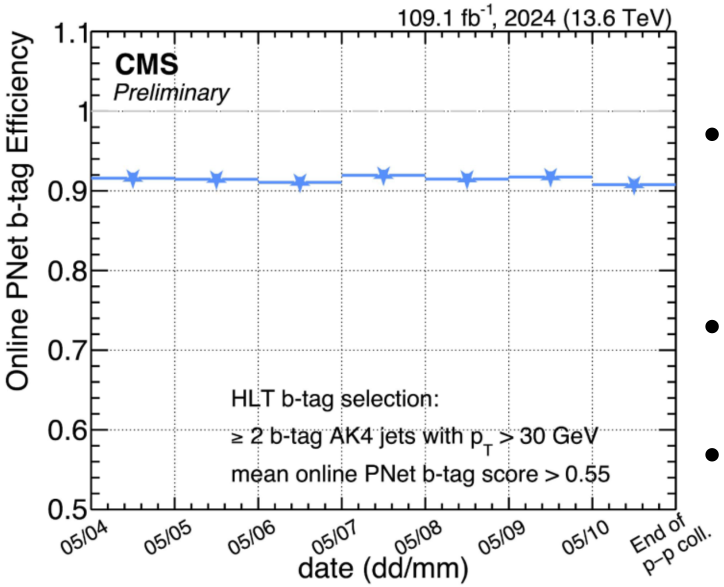
Performance of ParticleNET triggers in Run 3

- ParticleNet AK4 b-tagging and AK8 bb-tagging algos, based on graph neural networks (GNN), for HLT jets were trained for the very first time in 2022 using MC
- New triggers integrated in CMS HLT at start of Run 3, including HH->4b, HH->2b2τ and HHH->6b including both for the resolved and high-p_T (boosted) topologies
- A new Parking stream "4j + 2 bjet" deployed in 2023

CMS DP – 2025/009





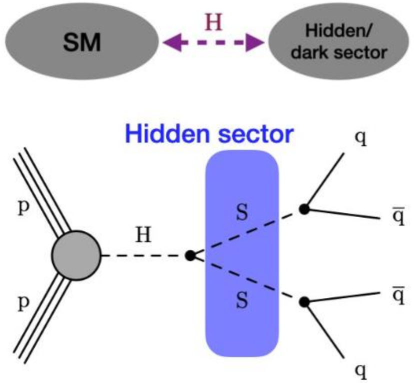


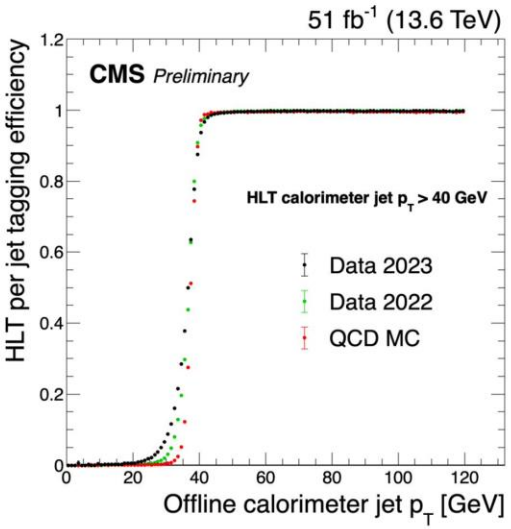
- Time evolution of the ParticleNet@HLT b-tagging efficiency as a function of the average ParticleNet b-tag score of the two leading b-tag jets (with p_T > 30 GeV)
- Each bin corresponds to one-month intervals spanning the 2024 p-p data-taking
- Stable performance of this HLT trigger found throughout the data-taking period

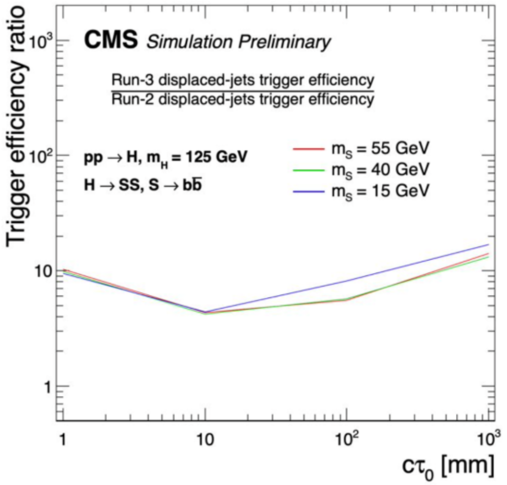
Triggering on Long-lived BSM particles (Run 3)

CMS DP – 2023/043

- New and improved dedicated long-lived particle triggers introduced in LHC Run 3
- Displaced jet triggers in Run 3 have the modified tracking to improve the signal acceptance also for the low-mass LLPs







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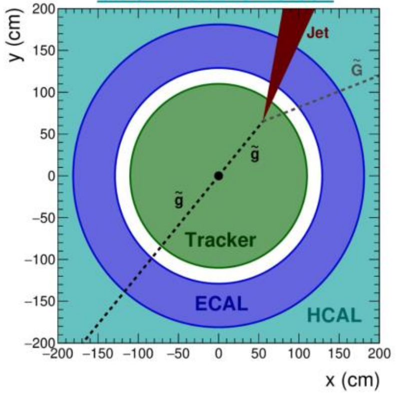
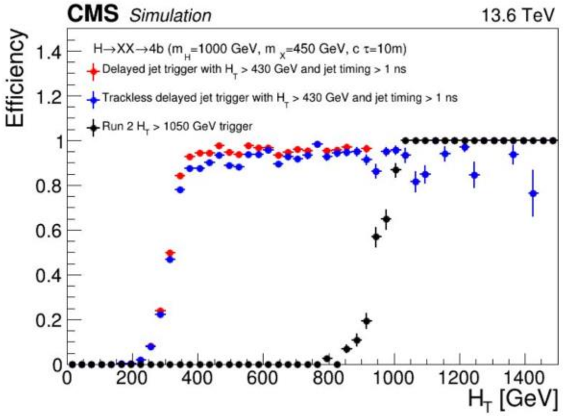
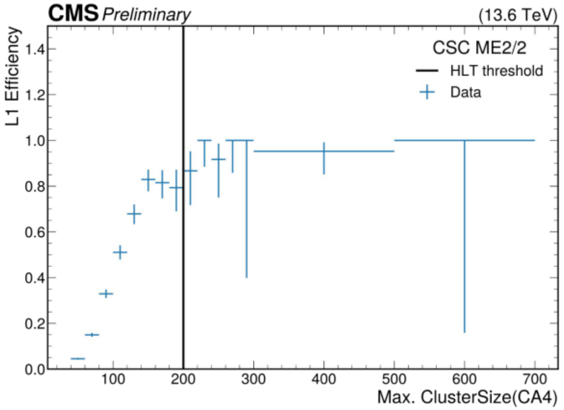
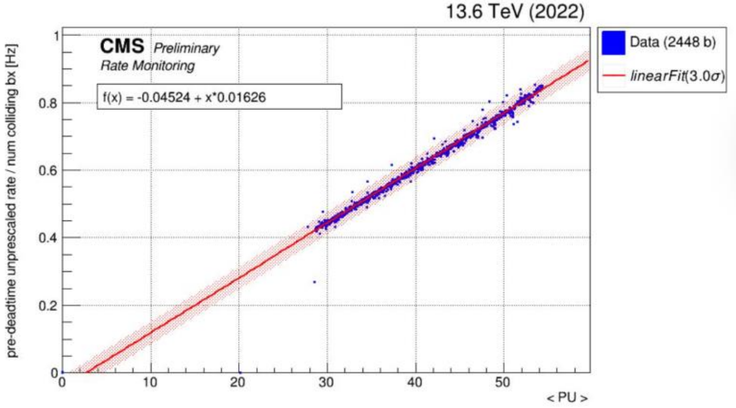




- Delayed jet trigger utilising ECAL timing were introduced in Run 3, also delayed and displaced (for the higher lifetime signal models)

- CSC high multiplicity triggers: presence of a high number of hits in CSC muons to search for LLPs
- Relies on a dedicated implementation both at the Level 1 (L1) and the High Level Trigger (HLT)

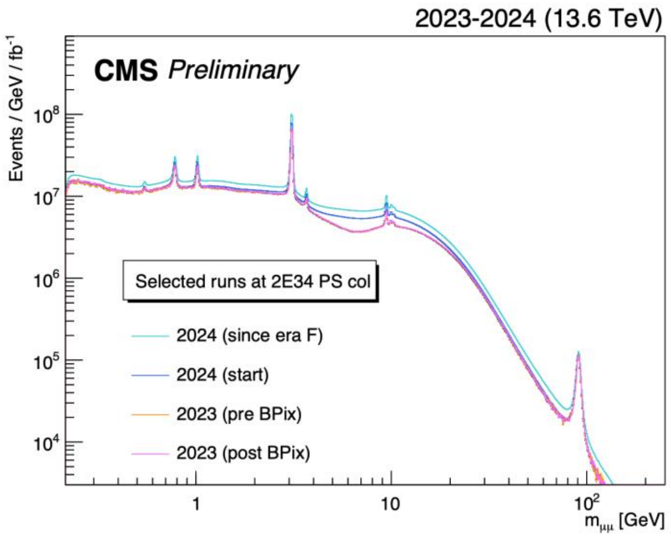


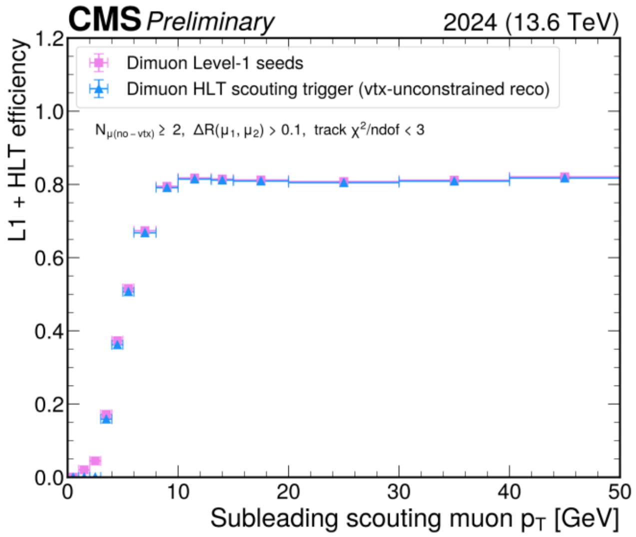


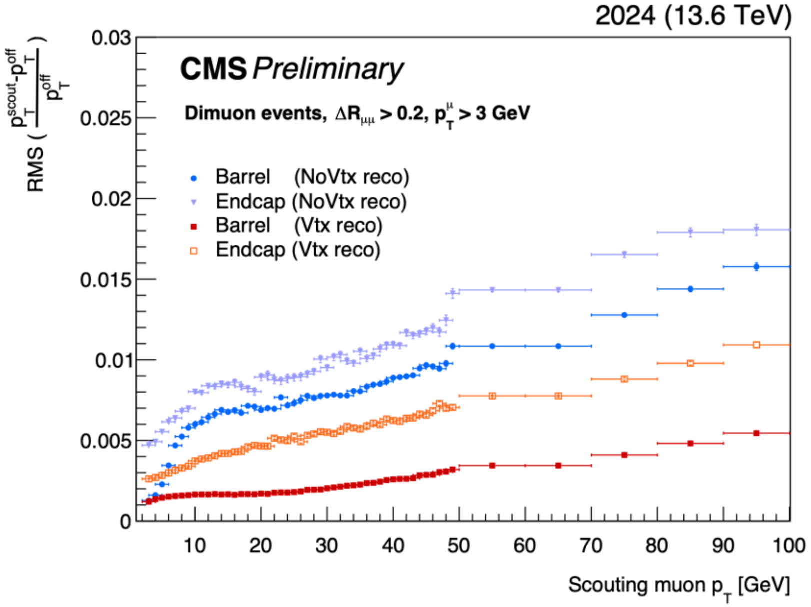
CMS High Level Trigger: Data Scouting in Run 3

- Events reconstructed at the HLT selected based on the kinematic quantities of the reconstructed objects, but with looser energy and momentum
- The online reconstructed objects are then stored directly to disk to be used in the physics analyses

CMS DP – 2025/025





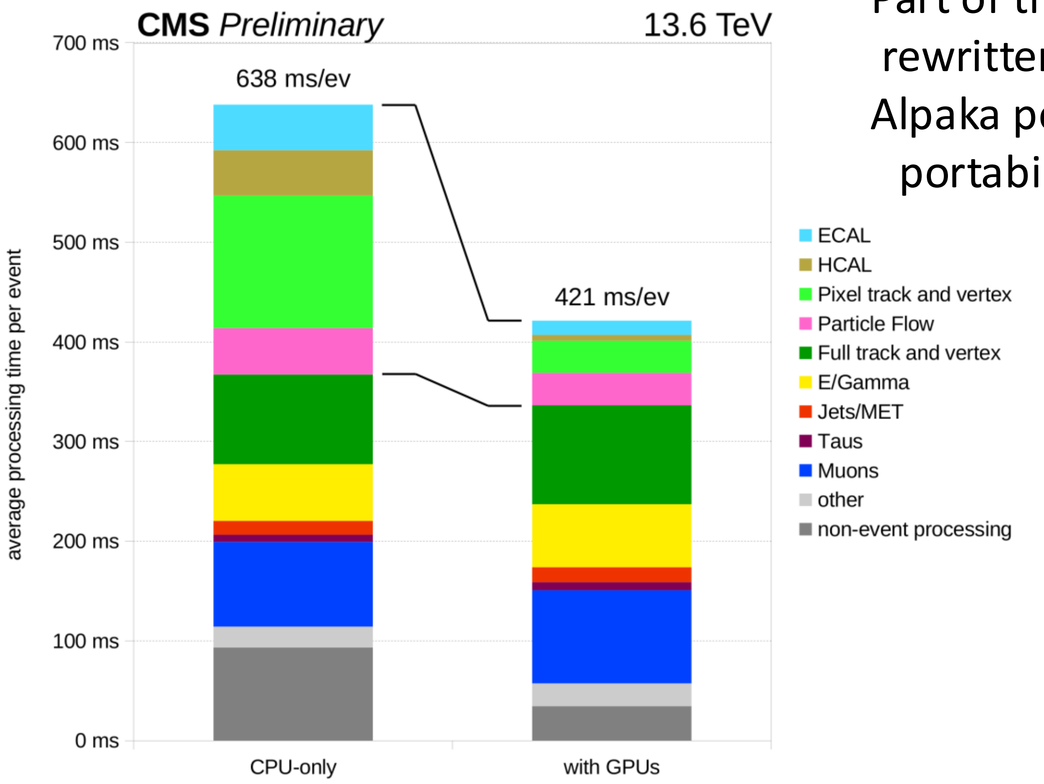


- At the start of 2024, the HLT scouting underwent large improvements, enhancing its sensitivity to the low-momentum and displaced objects
- Full HLT tracking with standard PF reconstruction was implemented
- Standard muon HLT reconstruction with vtx constraints were introduced in a new scouting single-mu path: higher efficiency, improved resolution

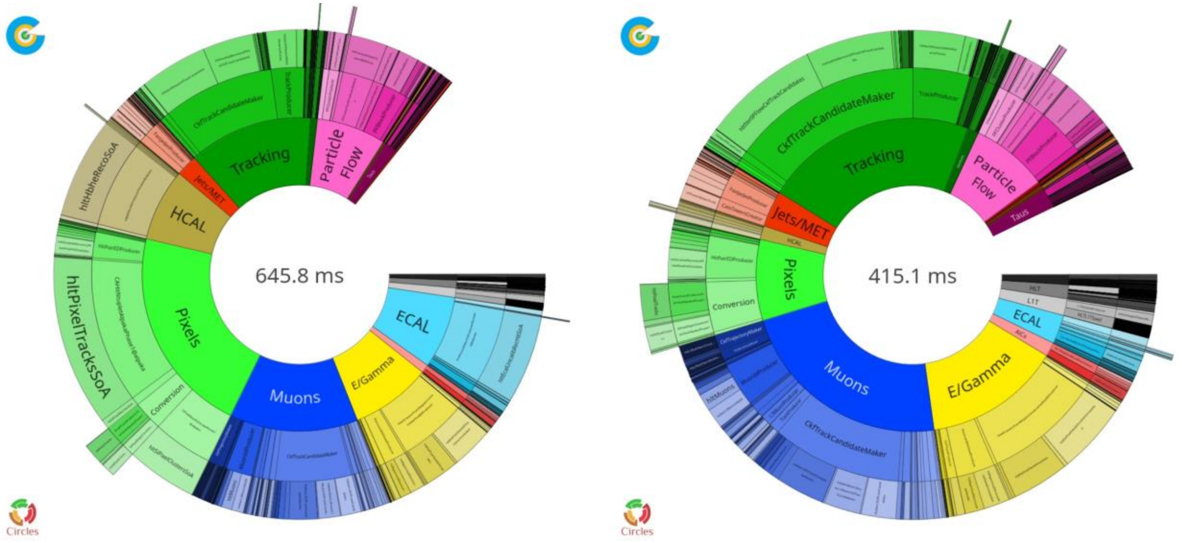
Heterogeneous reconstruction (CPU+GPU) at the HLT

CMS DP – 2024/082

- New HLT farm in service for Run 3 (July 5th, 2022)
- The throughput measurements (2024) performed over 120,000 events with an average PU of 63.8



Part of the HLT code rewritten using the Alpaka performance portability library



- Corresponds to a speed up of 55.6% ± 0.2%
- 35.7% ± 0.1% of the HLT offloaded to GPUs

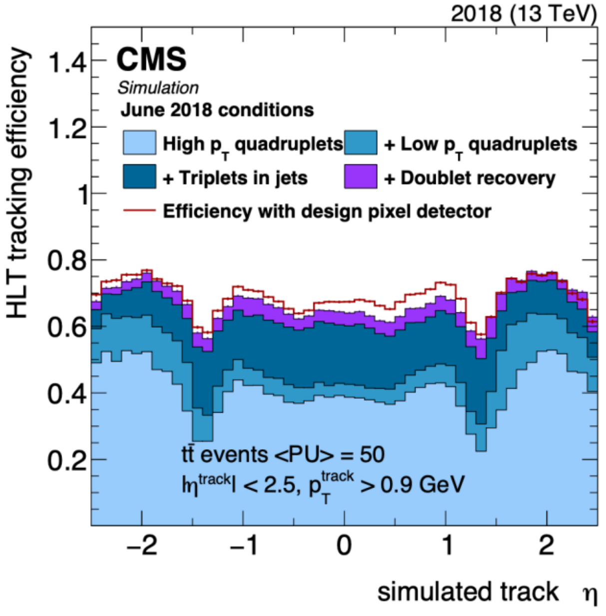
Summary and Outlook

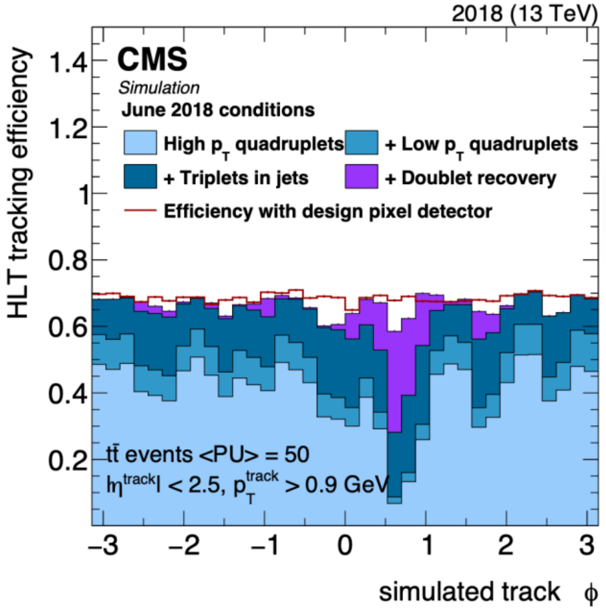
- The CMS Trigger System is robust, flexible and proven in Run 2 and Run 3
    - able to deal with large number of events to fulfill the CMS physics goals
- Excellent performance in Run2: sharp turn-ons, small pileup dependence
- Integrated new technologies, also improved/innovated trigger algorithms
- Additional improvements for the Run3, such as new tracking (Patatracks), new GNN-based ParticleNet triggers for b-tagging, heavy flavour and tau, also new triggers for Long-lived particle searches and improved Scouting

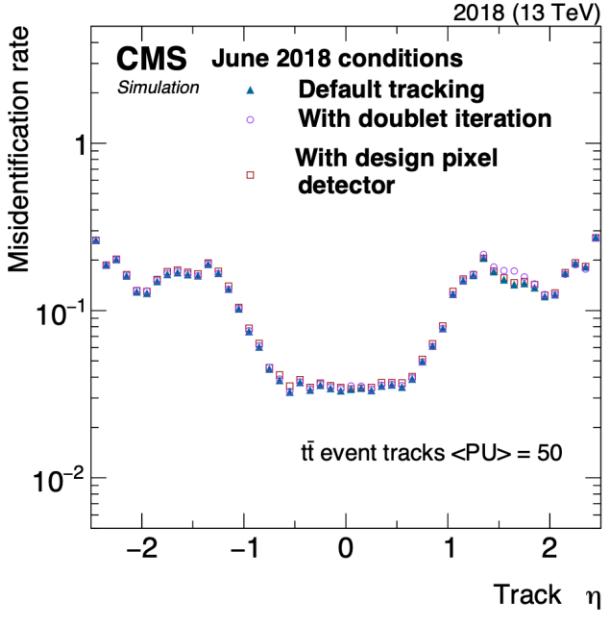
THANK YOU!

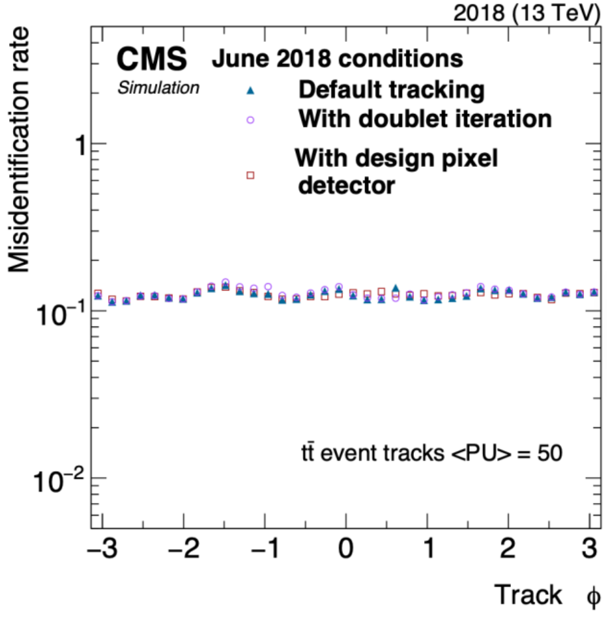
BACKUP SLIDES

CMS High Level Trigger: Track reconstruction in Run 2

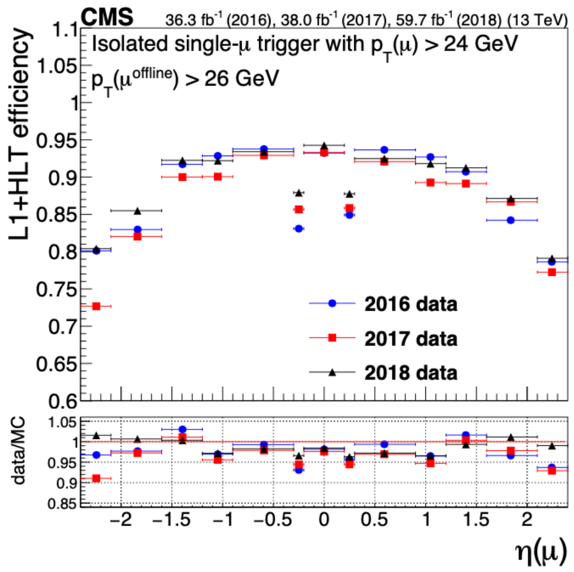


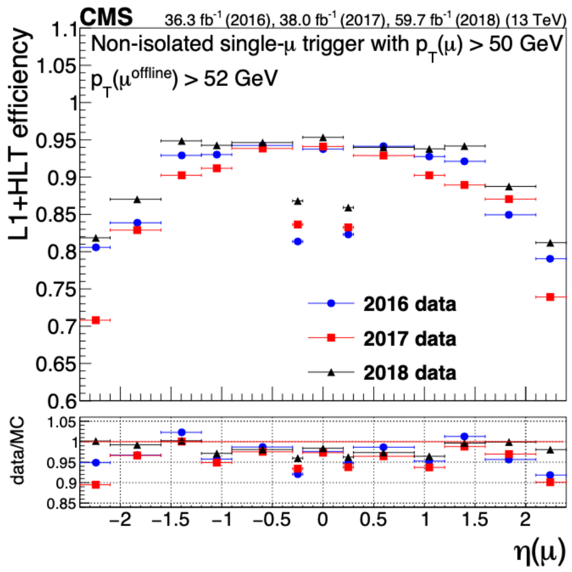


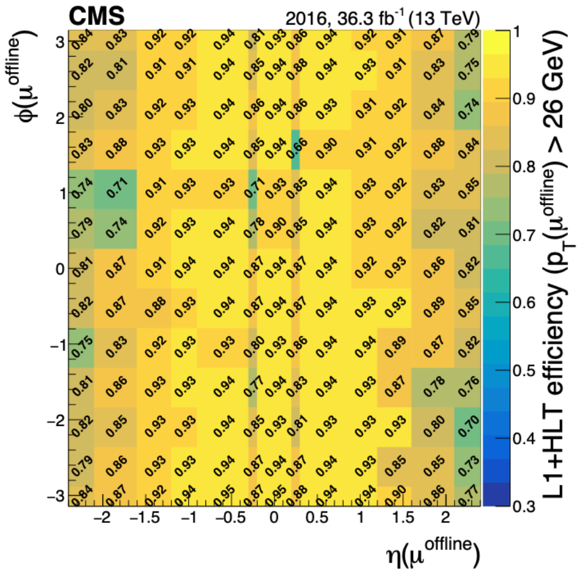


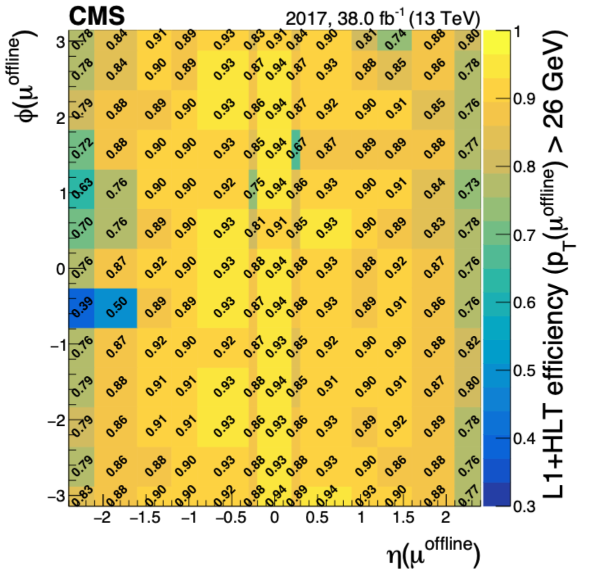


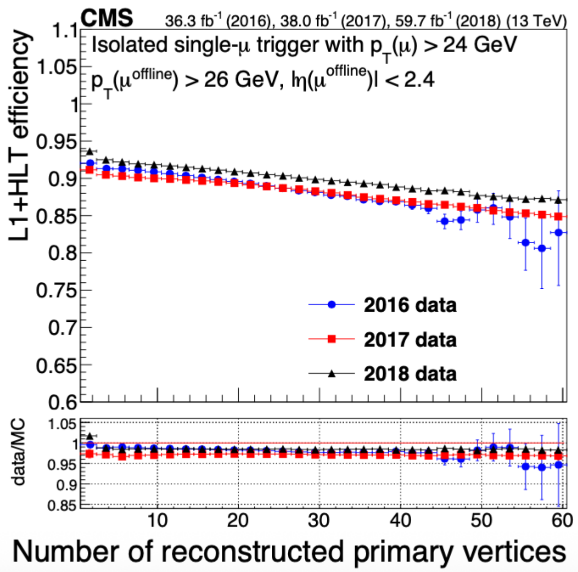
CMS High Level Trigger: Muon reconstruction in Run 2

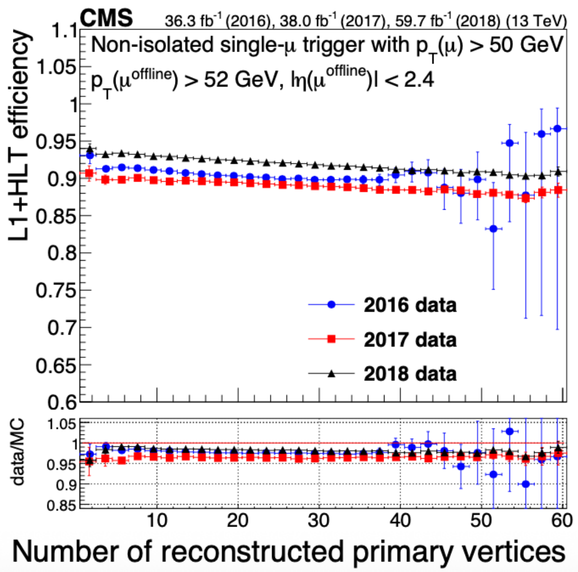


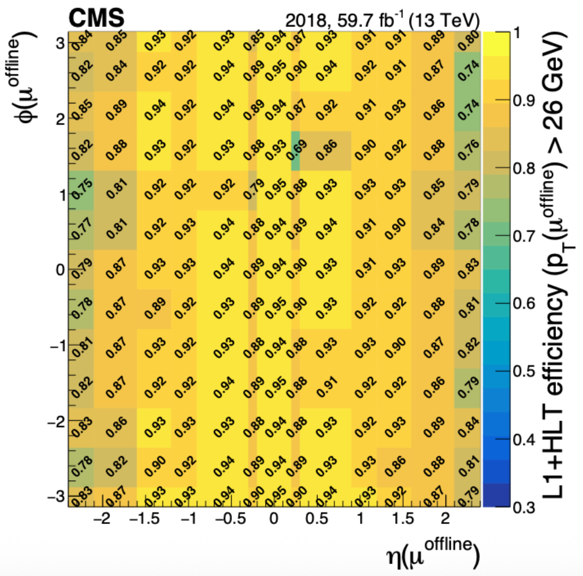




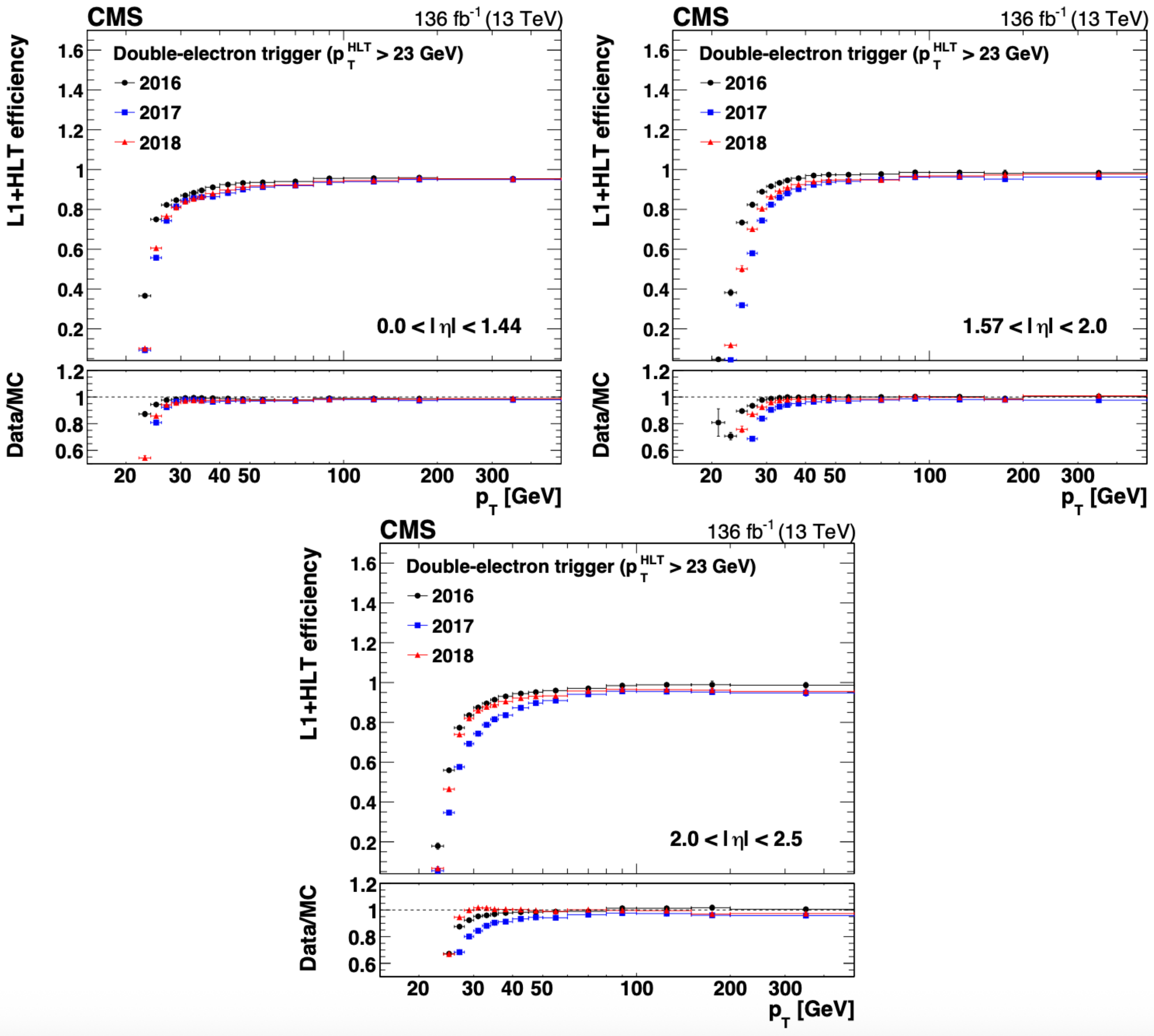




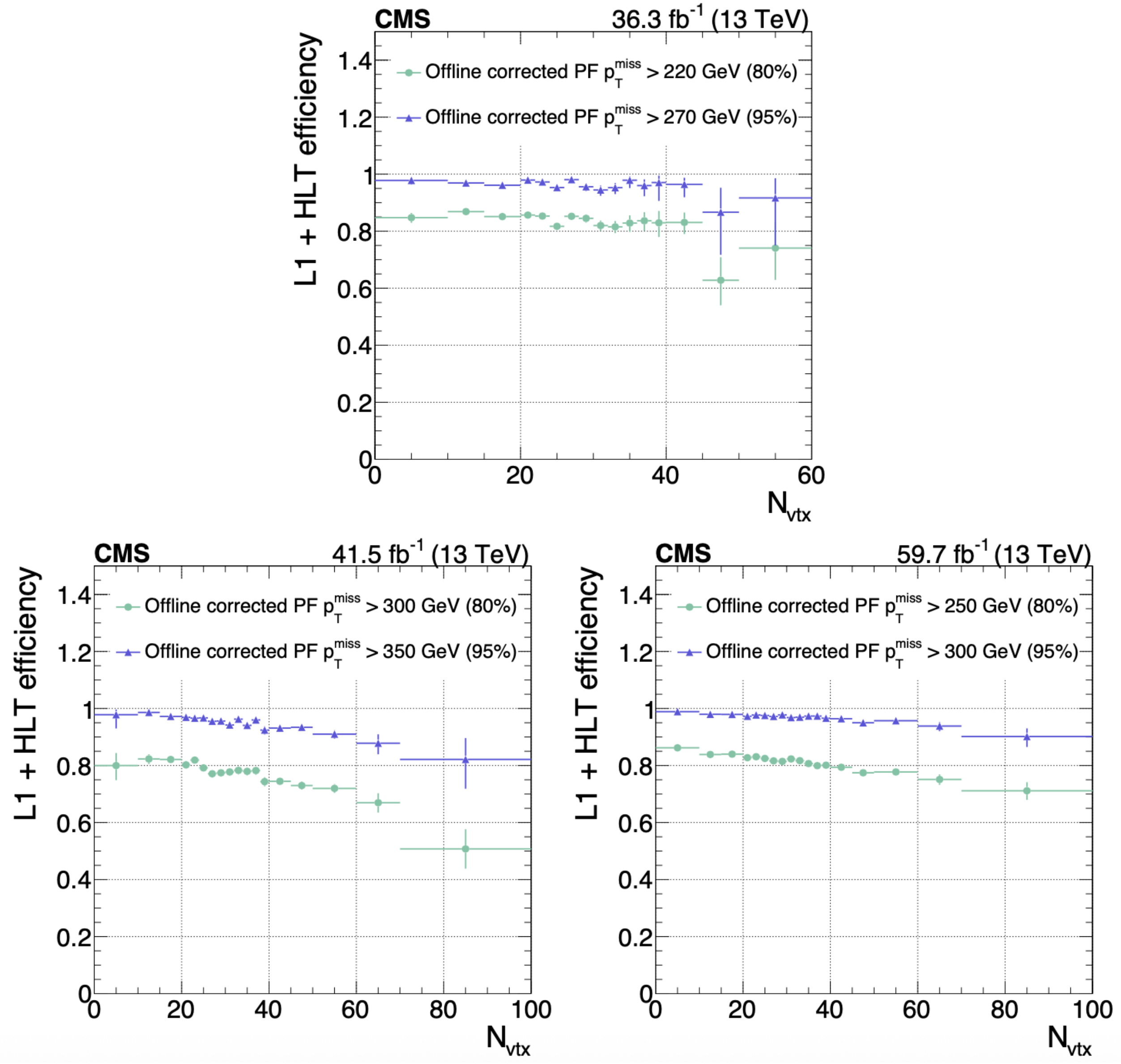




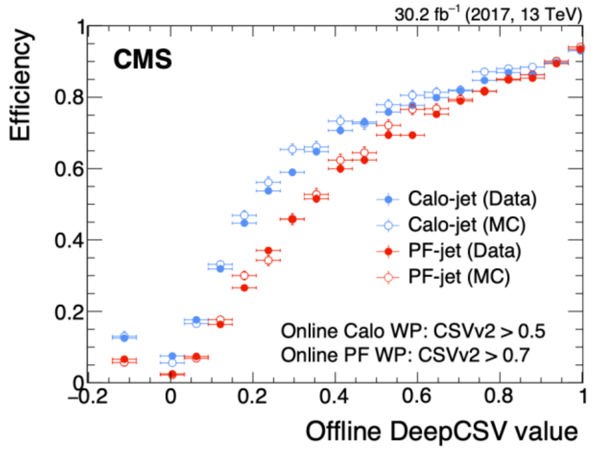
CMS High Level Trigger: e/ɣ reconstruction in Run 2

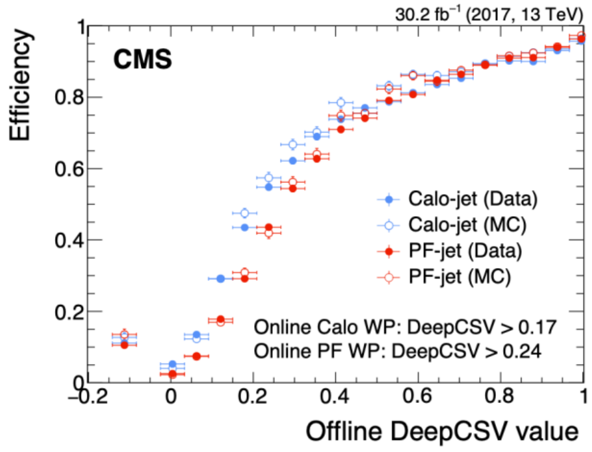


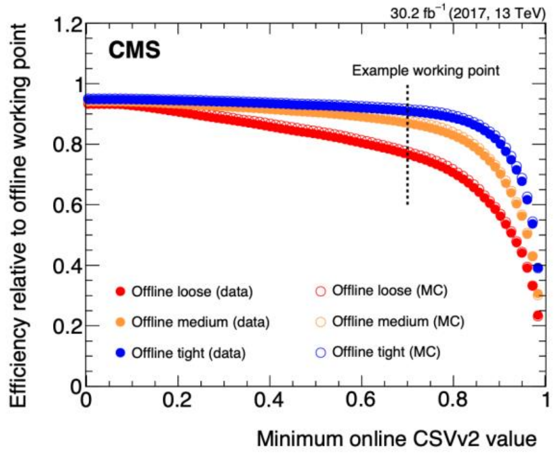
CMS High Level Trigger: jets, energy sums & MET in Run 2

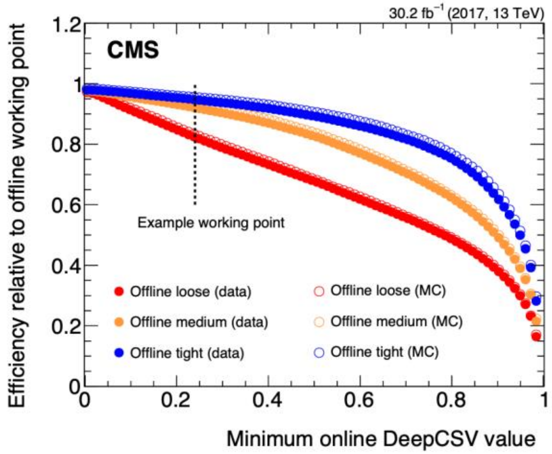


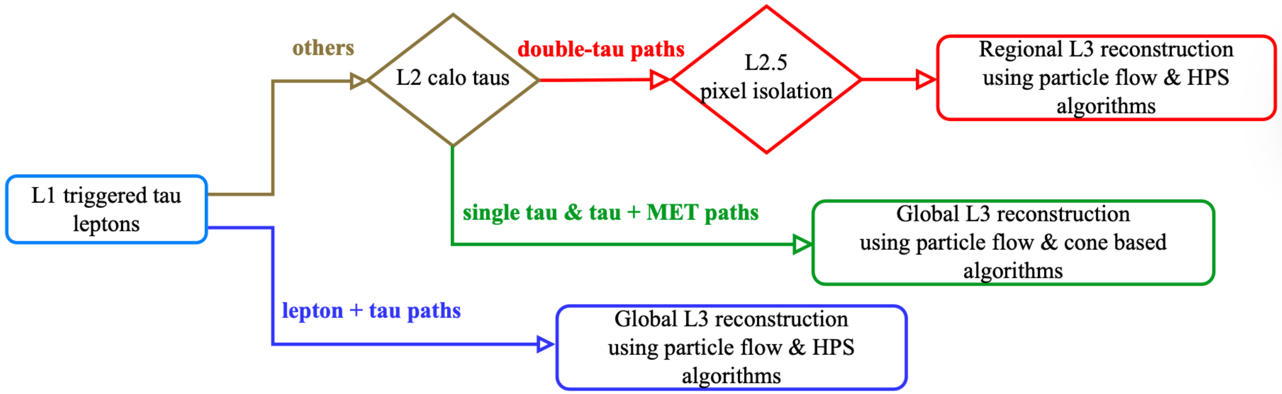
CMS High Level Trigger: b-tagging and taus in Run 2

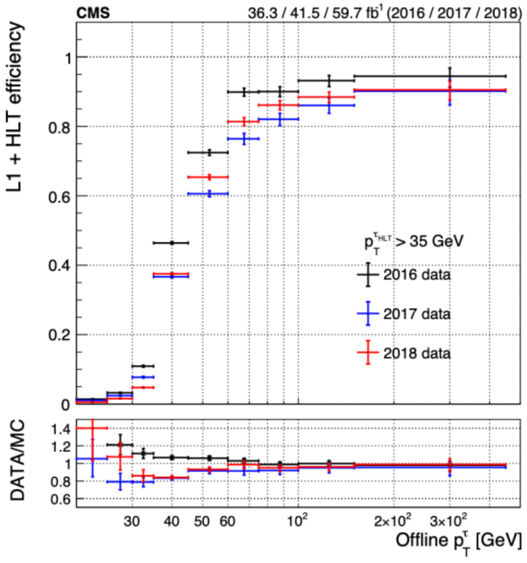


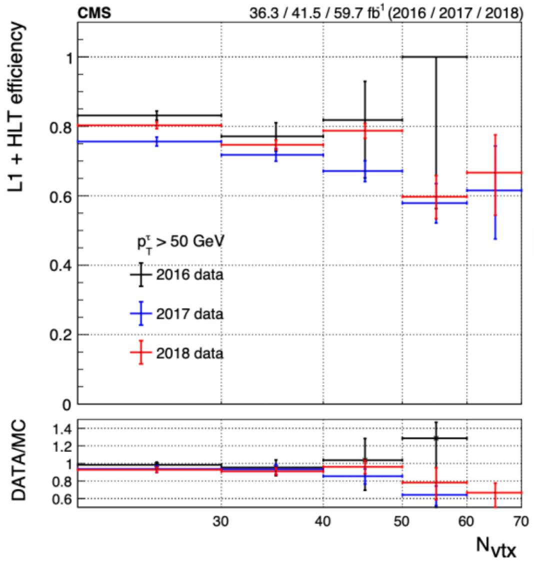




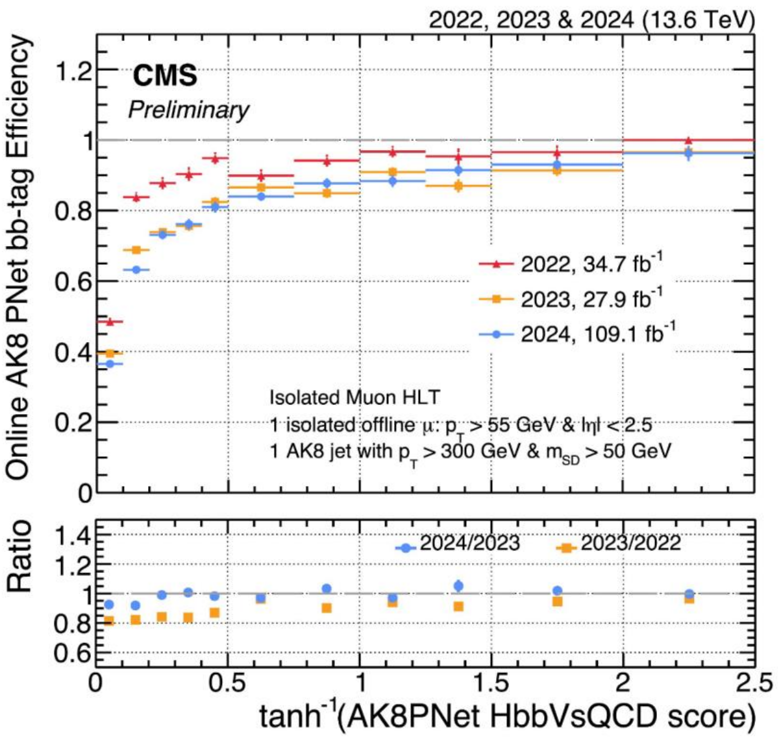


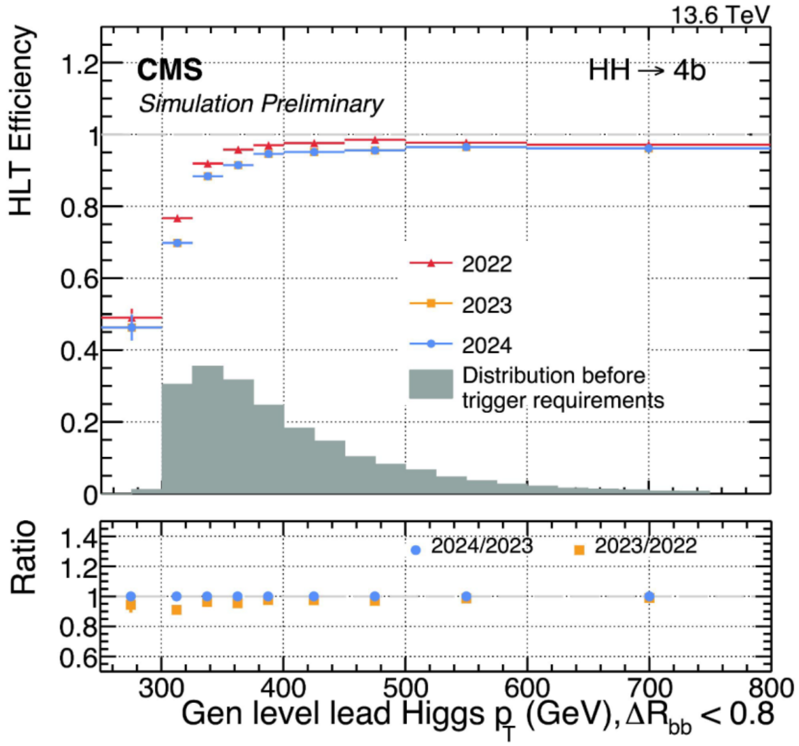


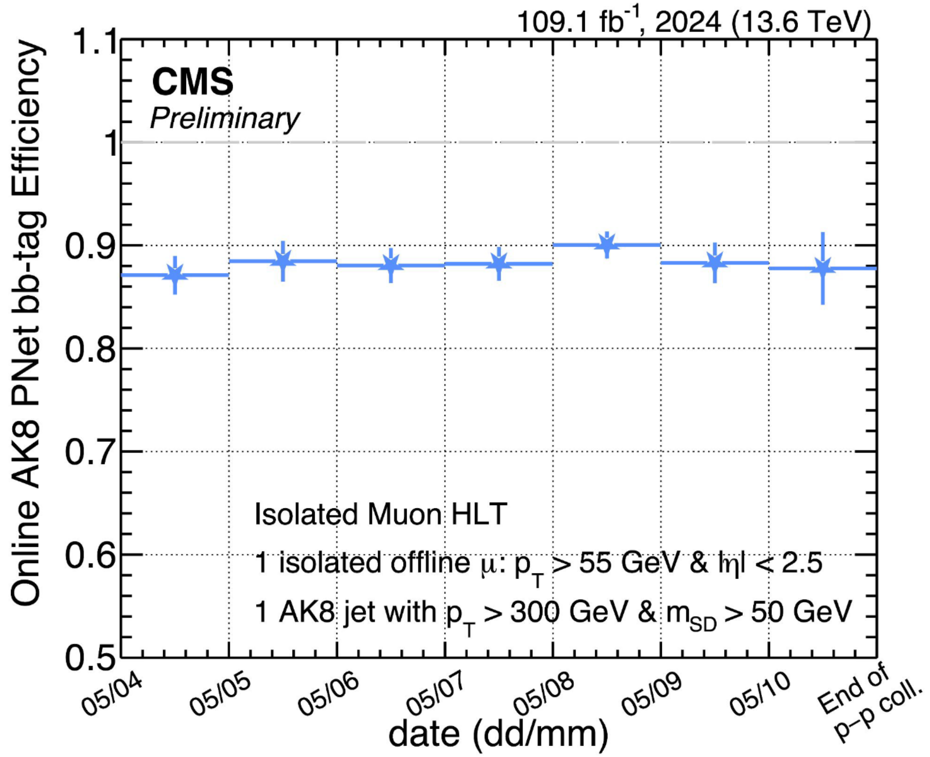




Performance of ParticleNET triggers in Run 3







Heterogeneous reconstruction (GPU) at the HLT

CMS DP – 2024/082

CPU only

Element	Time	Fraction
AlCa	5.6 ms	0.9 %
B tagging	1.8 ms	0.3 %
CTPPS	0.0 ms	0.0 %
DQM	1.3 ms	0.2 %
E/Gamma	53.5 ms	8.3 %
ECAL	48.4 ms	7.5 %
Framework	0.0 ms	0.0 %
HCAL	48.3 ms	7.5 %
HLT	5.1 ms	0.8 %
I/O	3.8 ms	0.6 %
Jets/MET	14.2 ms	2.2 %
L1T	6.4 ms	1.0 %
Muons	85.4 ms	13.2 %
Particle Flow	46.1 ms	7.1 %
Pixels	138.5 ms	21.5 %
Taus	7.7 ms	1.2 %
Tracking	82.6 ms	12.8 %
Vertices	4.4 ms	0.7 %
event setup	0.1 ms	0.0 %
idle	0.2 ms	0.0 %
other	92.4 ms	14.3 %
total	*645.8 ms*	*100.0 %*

CPU + GPU

Element	Time	Fraction
AlCa	6.0 ms	1.4 %
B tagging	1.9 ms	0.5 %
CTPPS	0.0 ms	0.0 %
DQM	1.6 ms	0.4 %
E/Gamma	58.9 ms	14.2 %
ECAL	12.4 ms	3.0 %
Framework	0.0 ms	0.0 %
HCAL	5.8 ms	1.4 %
HLT	6.0 ms	1.4 %
I/O	4.2 ms	1.0 %
Jets/MET	15.6 ms	3.8 %
L1T	7.2 ms	1.7 %
Muons	93.4 ms	22.5 %
Particle Flow	33.2 ms	8.0 %
Pixels	34.7 ms	8.4 %
Taus	8.6 ms	2.1 %
Tracking	91.2 ms	22.0 %
Vertices	4.7 ms	1.1 %
event setup	0.1 ms	0.0 %
idle	0.1 ms	0.0 %
other	29.6 ms	7.1 %
total	*415.1 ms*	*100.0 %*