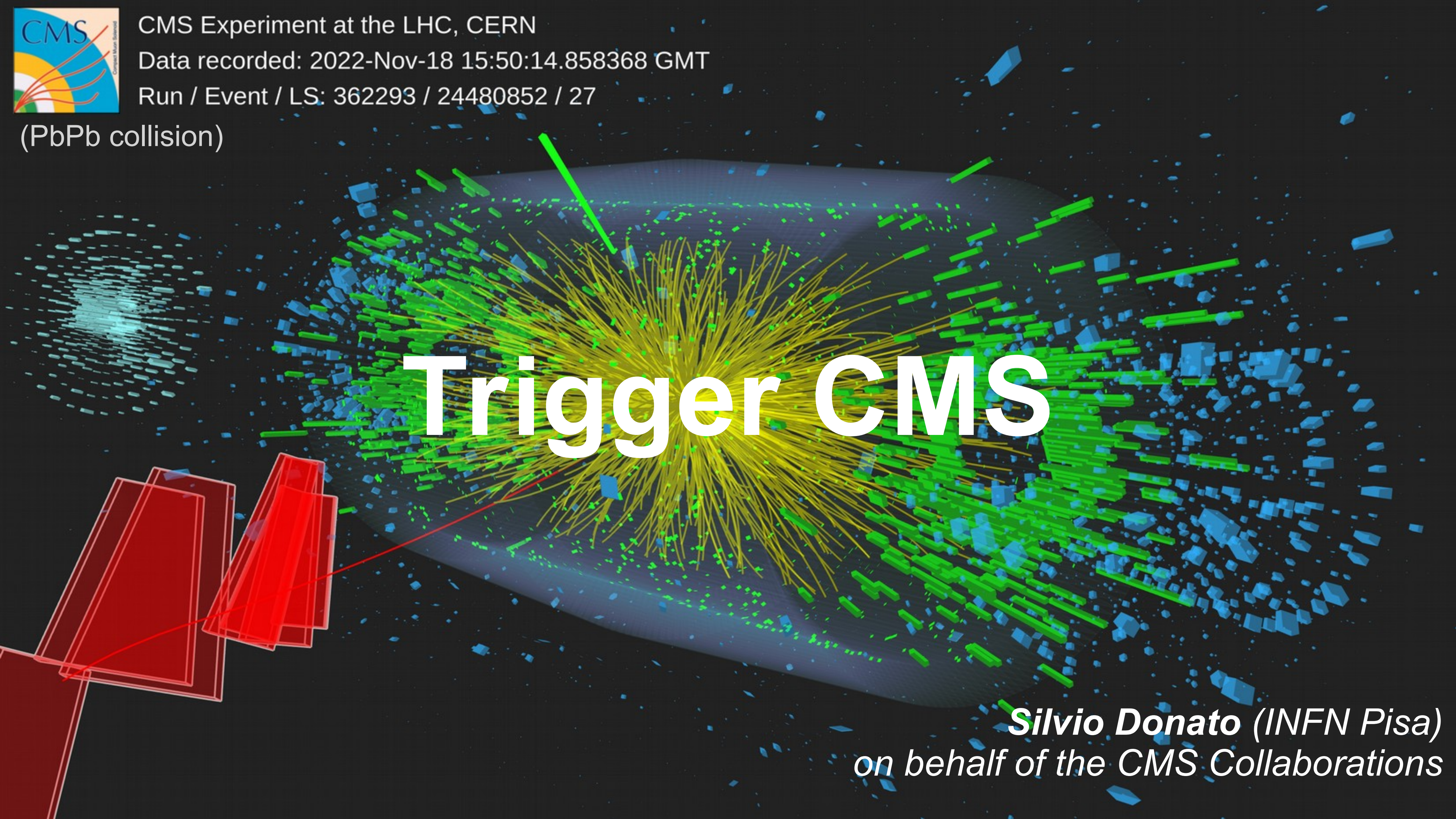
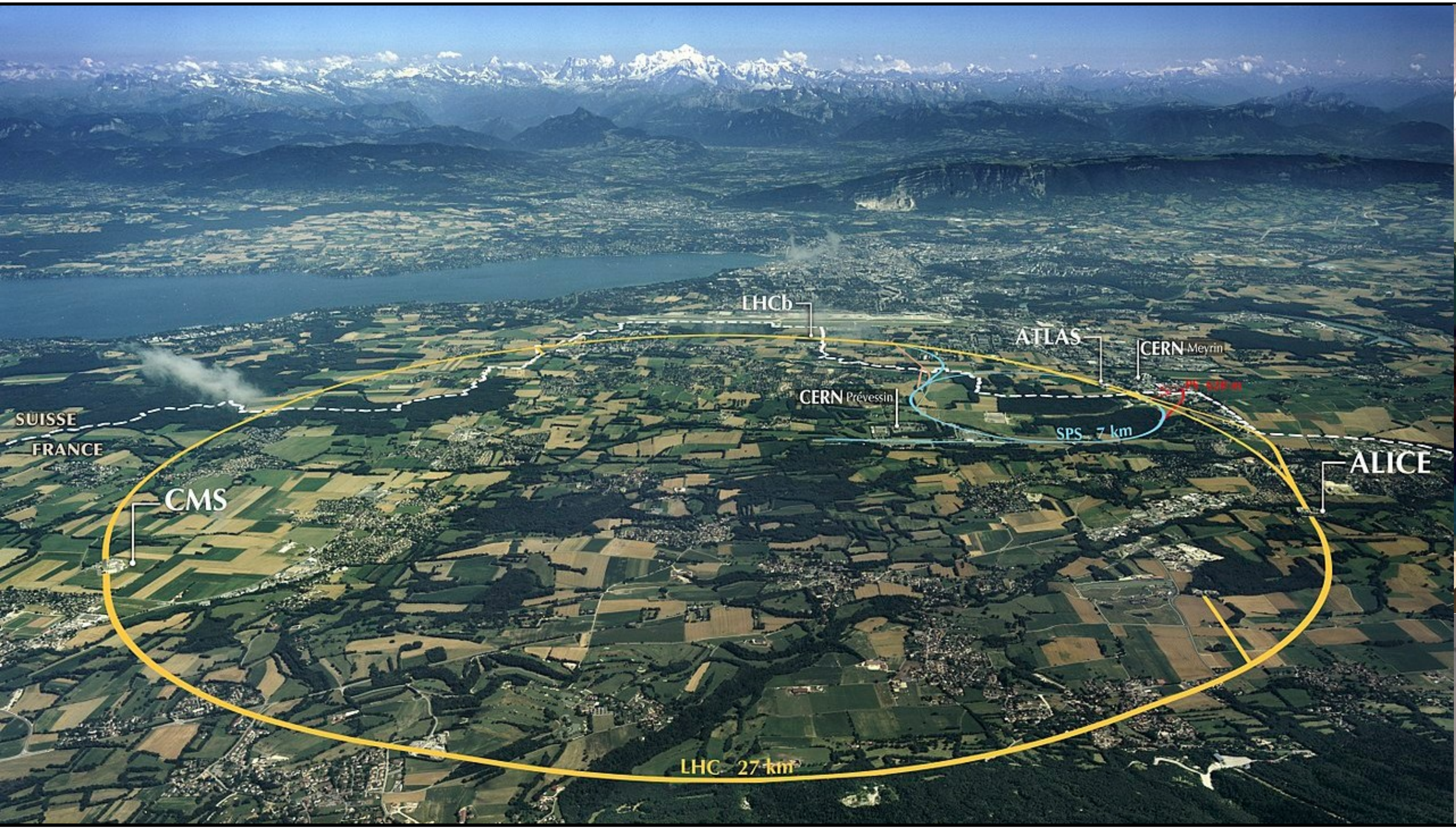
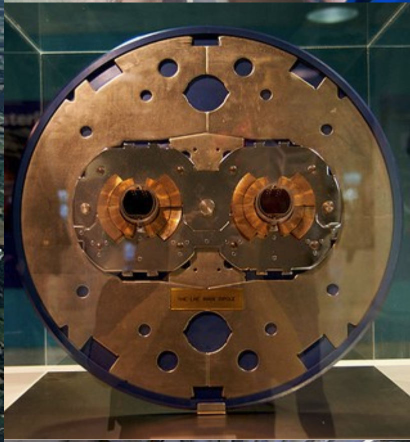


Trigger CMS

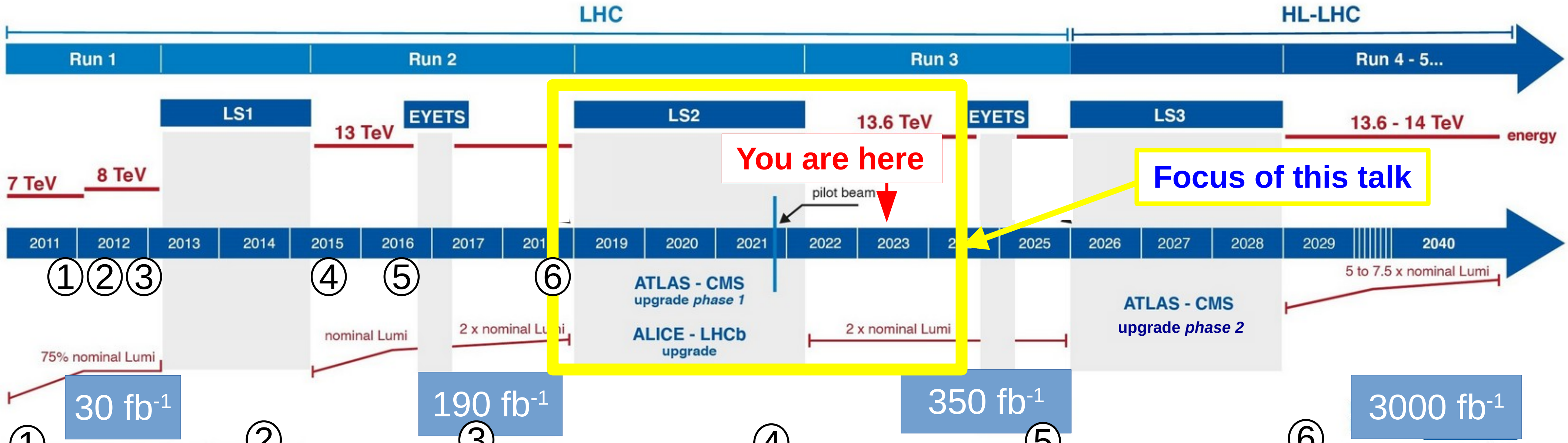
Silvio Donato *(INFN Pisa)*
on behalf of the CMS Collaborations

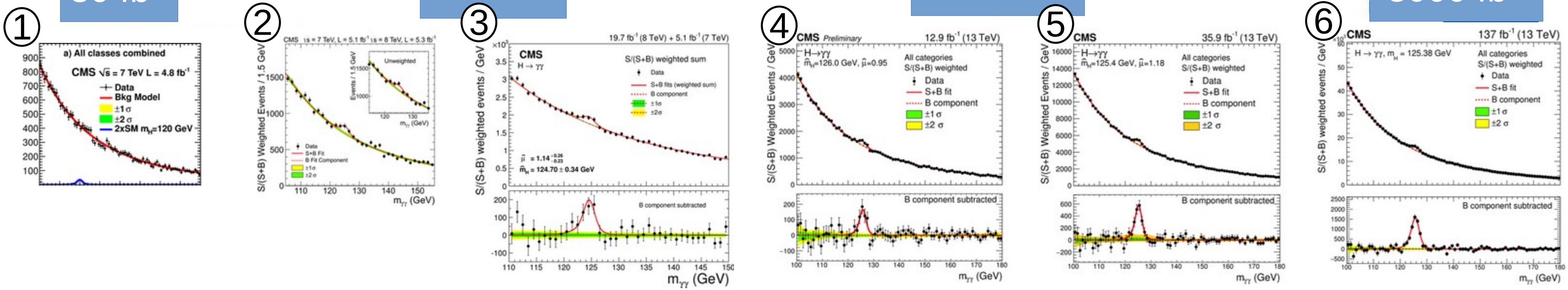
The Large Hadron Collider



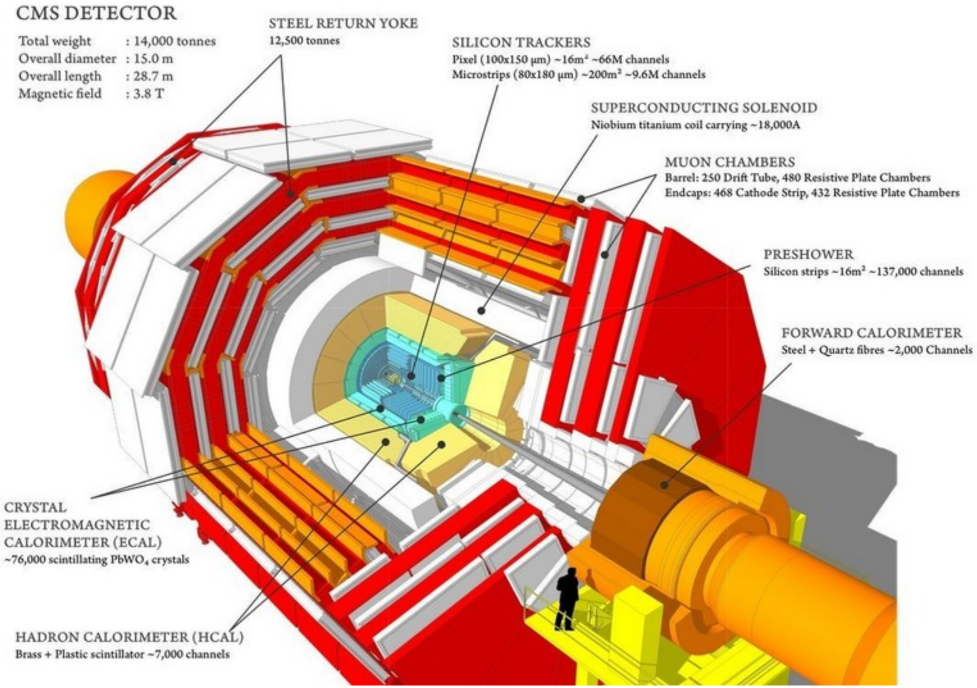


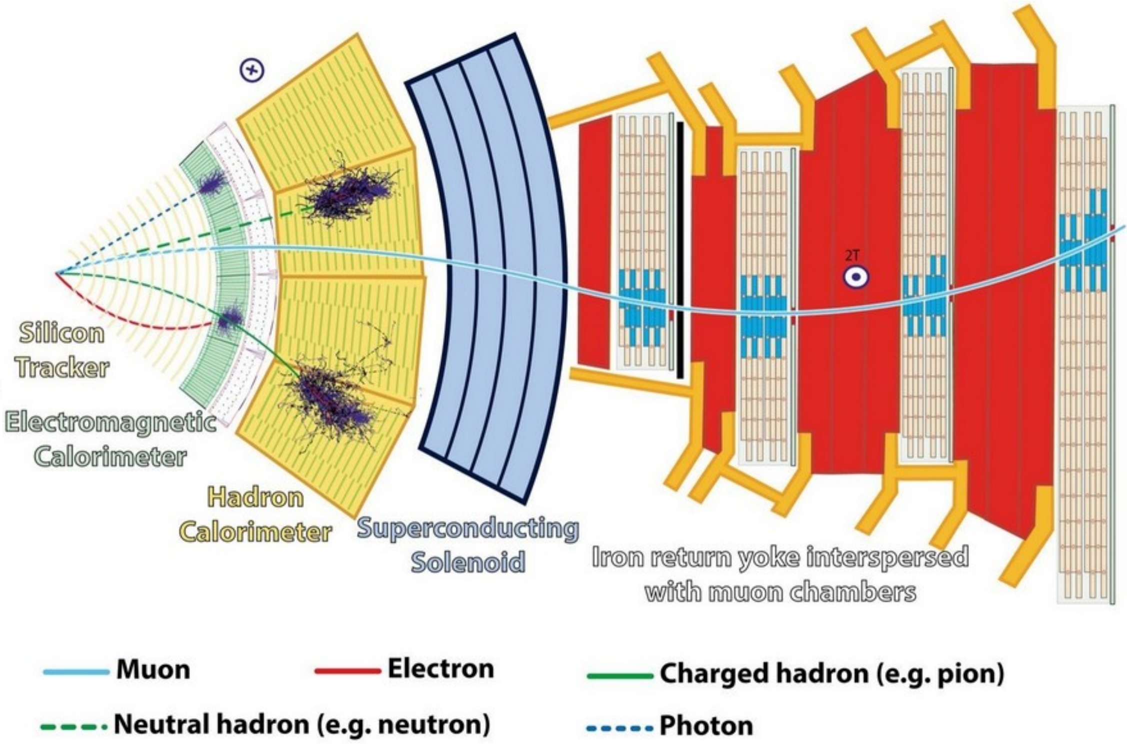
LHC schedule



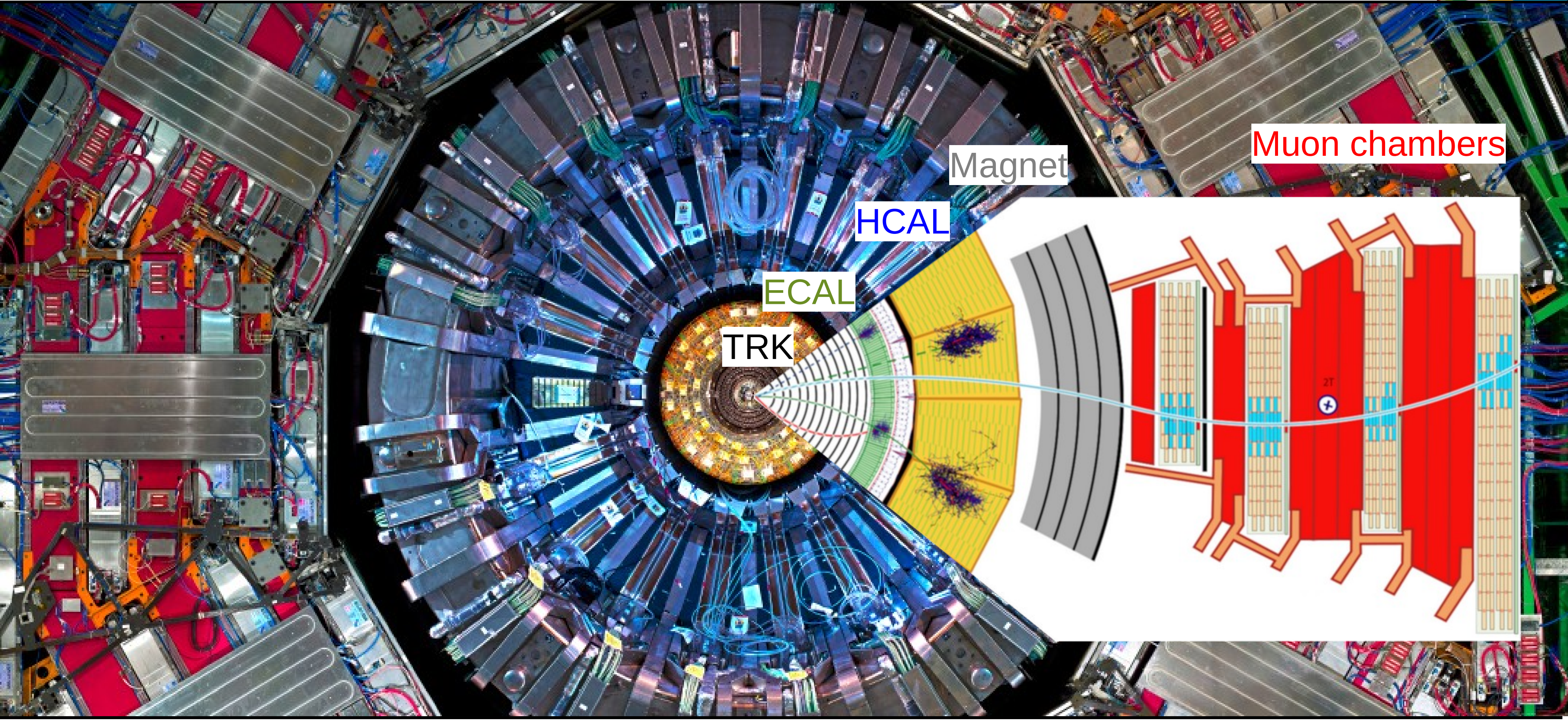


The CMS experiment



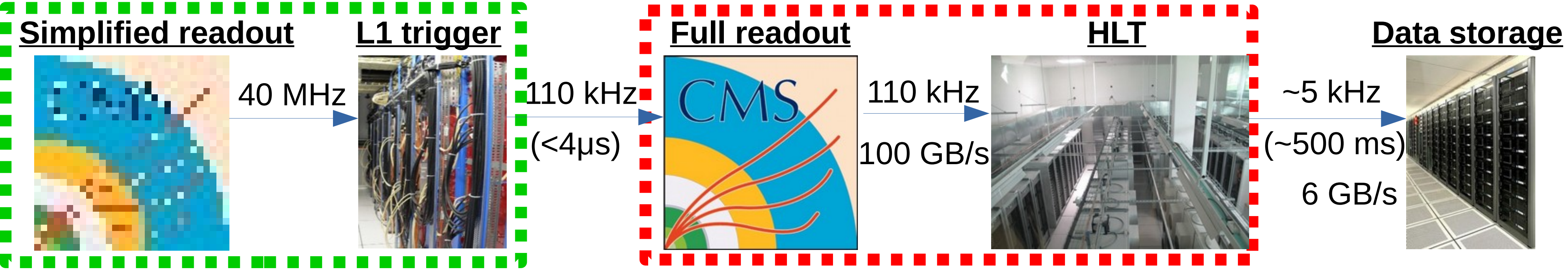


The CMS experiment



Trigger and data acquisition

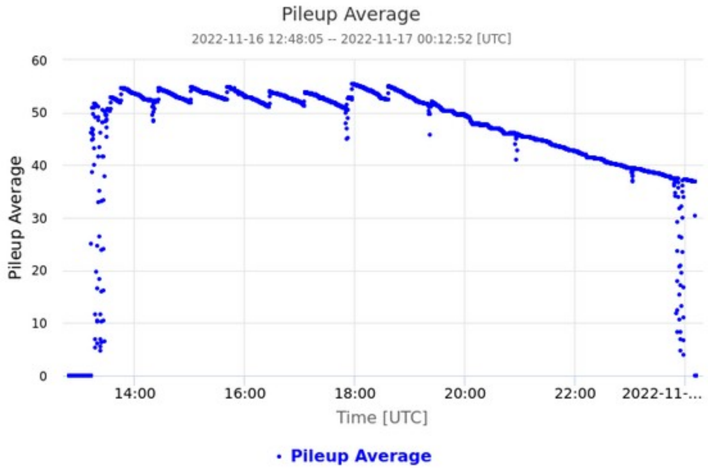
- **Hardware** trigger (L1): 40 MHz → **110 kHz**
  - simplified readout (**no tracker**), small latency (<4μs).
- **Software** trigger (HLT): 110 kHz → **~5 kHz**.
  - full event readout available (~1.2MB/event);
  - simplified reco: 51.2k CPUs → 465ms/event **on average**.

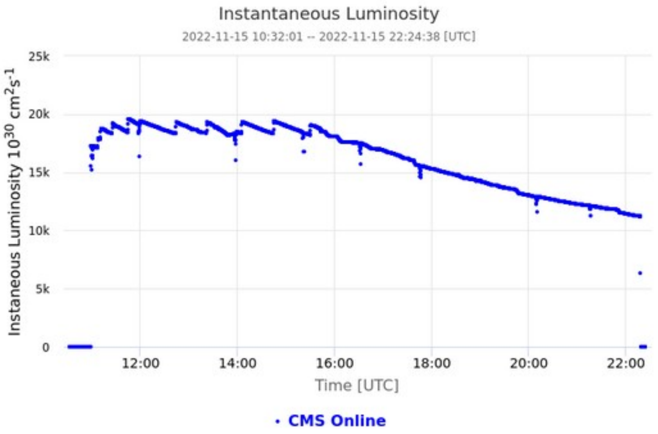


Run-3 news

LHCC2022Nov

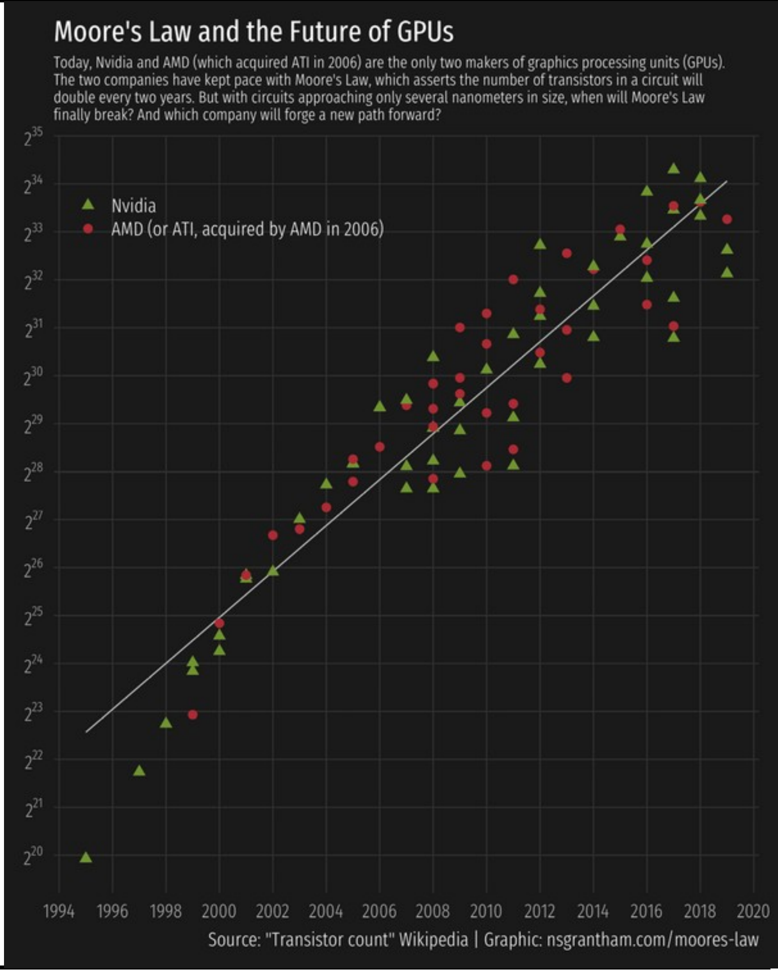
- LHC:
  - Longer fill (lumi leveling)
  - Larger luminosity: 2.0E34 → 2.15E34 $cm^{-2}s^{-1}$ (2023)
  - Large pileup: 56 →~ 62 (2023)
  - Larger energy 13 TeV → 13.6 TeV
- CMS:
  - Main Phase-I upgrades completed in Run-2 (Pixels, L1 trigger, HCAL endcap)
  - HCAL barrel: new readout
  - PPS: fully integrated in CMS (CT-PPS)
  - New muon detector (GEM)
  - **GPU at HLT**





Graphics Processing Unit (GPU)

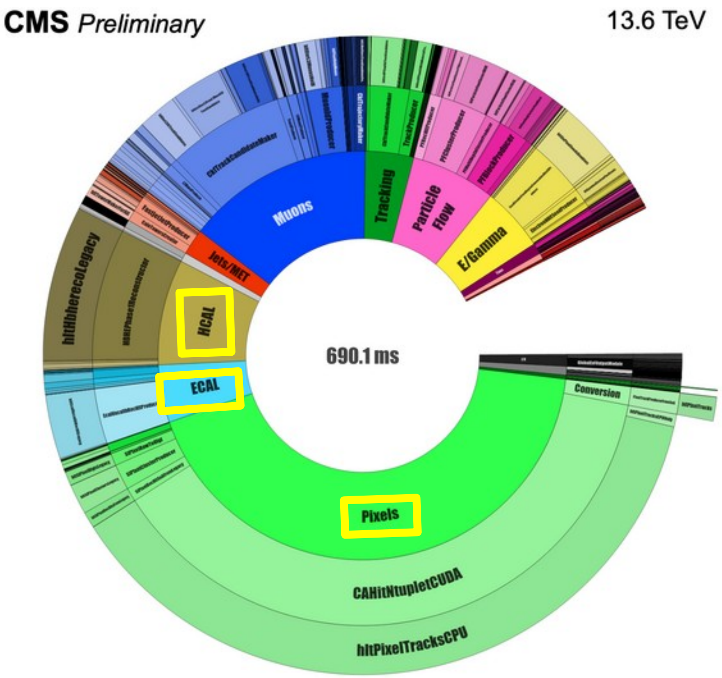
- **GPUs** very powerful in parallel computing,
  - exponential increase!
- Increasing usage in High Energy Physics
  - especially for Machine Learning.
- CMS is using GPUs in the trigger software starting from Run 3.
- Big effort in porting Pixel, HCAL, ECAL code on GPU (CUDA);
  - first step towards an **heterogeneous** era.



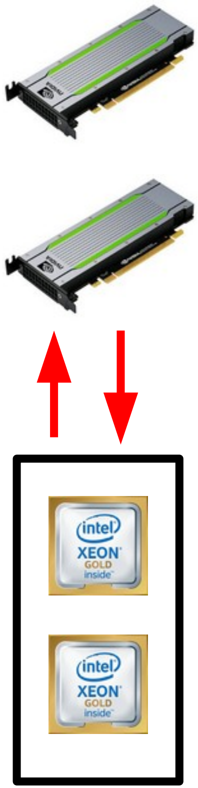
Software trigger and GPU

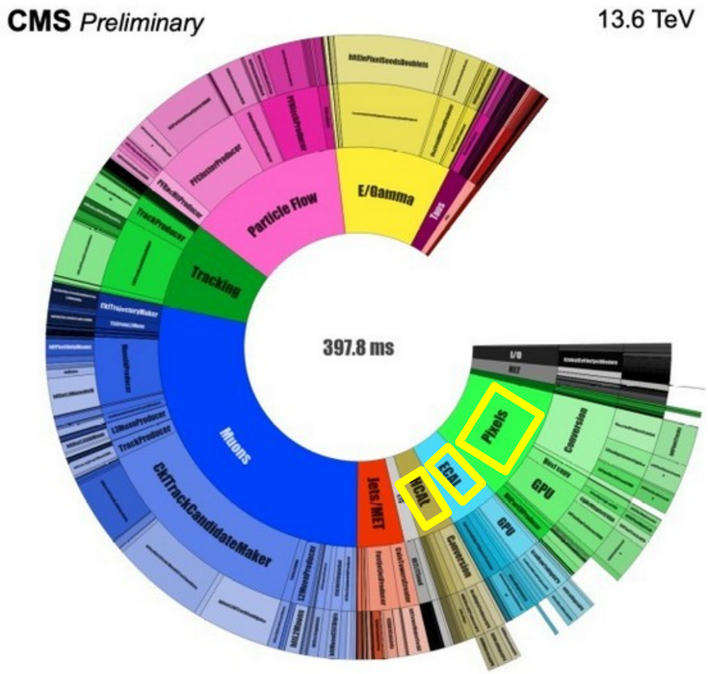
CMS-DP-2023-004

CPU only



CPU + GPU



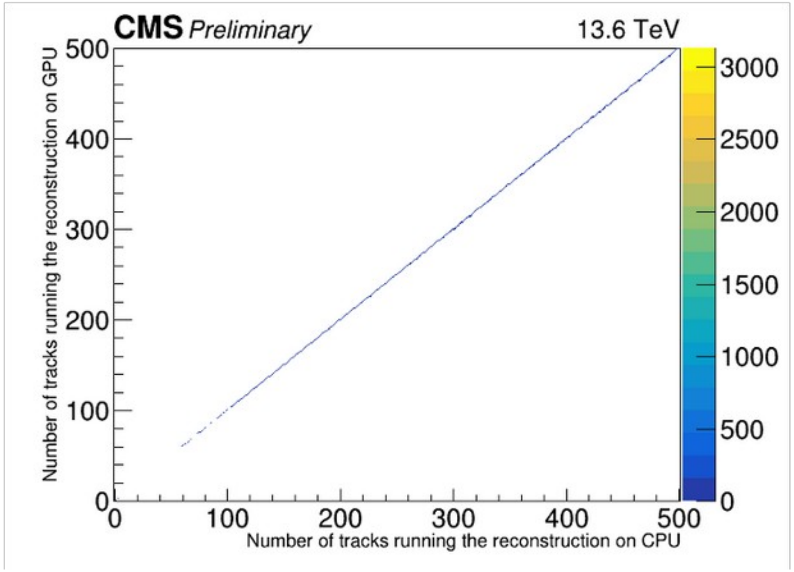


CPU: 2x AMD EPYC ``Milan'' 7763 (64 cores/CPU, 2 threads/core)
GPU: 2x NVIDIA T4

x 200 machines

GPU

- Offload to GPU:
  - HCAL, ECAL, Pixel local reconstruction
  - Pixel tracking
- Current model:
  - Two different modules running on CPU and GPU
    - Monitor of possible CPU/GPU difference
- Next step:
  - **Portability library (Alpaka):** same code running on both CPU and GPU.



Trigger menus

To be published on
HighLevelTriggerRunIIIResults
L1TriggerDPGResults

- About 300 L1 trigger and 600 HLT criteria to select physics events

L1 trigger

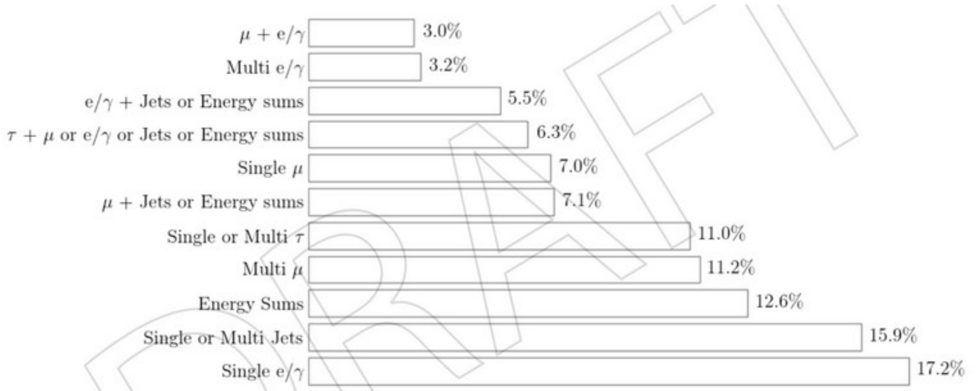
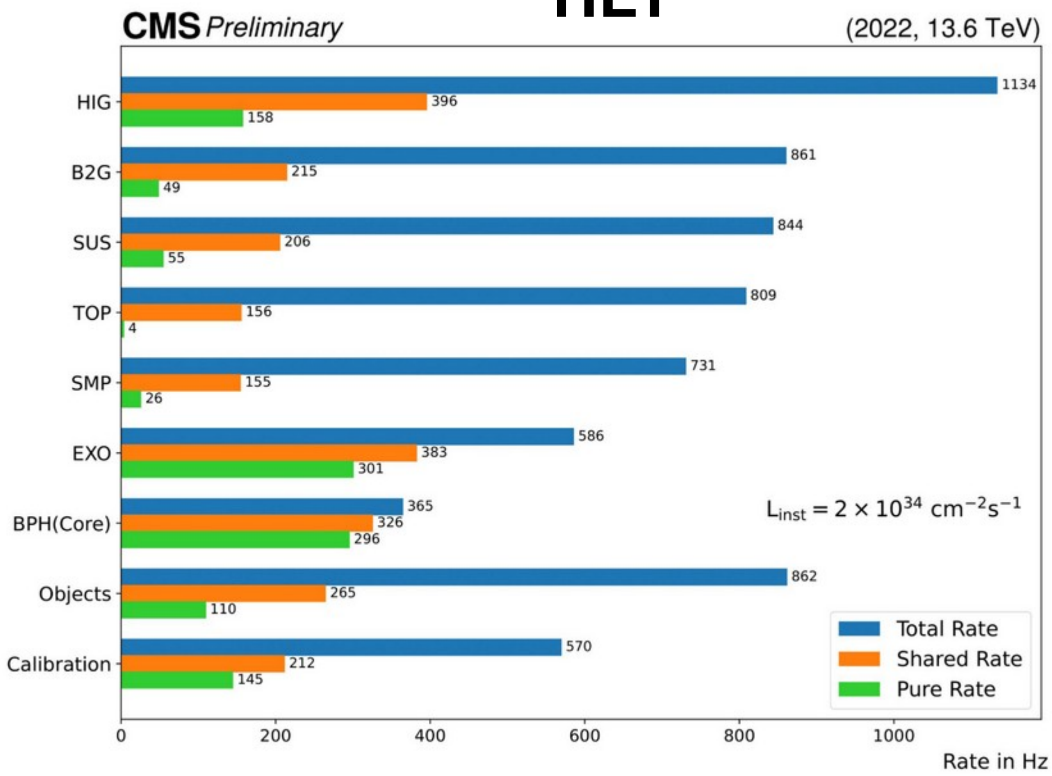


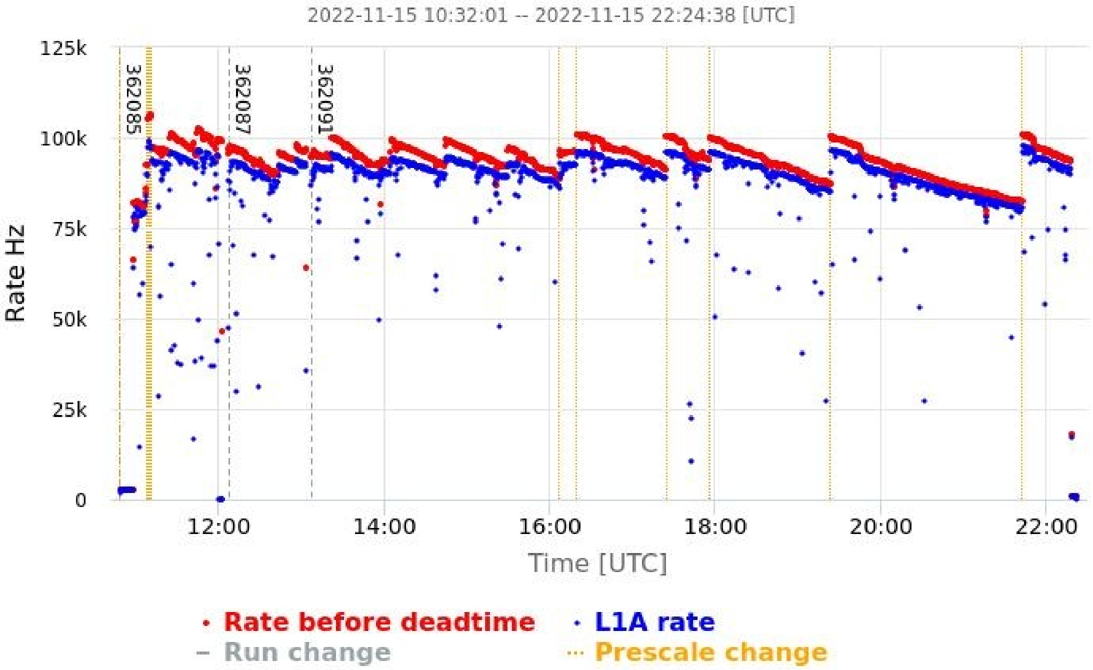
Figure 130: Fractions of the 100 kHz rate allocation for single- and multi-object triggers and cross triggers in the baseline Run 3 menu, calculated using pileup only Run 3 MC.

HLT



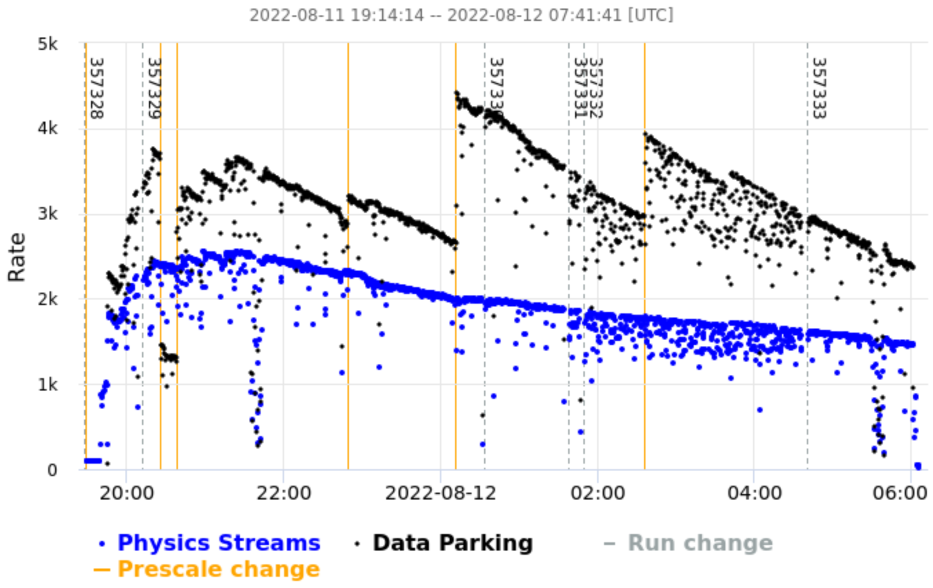
Rates (2022)

L1 trigger rate



~100 kHz L1T

HLT rate

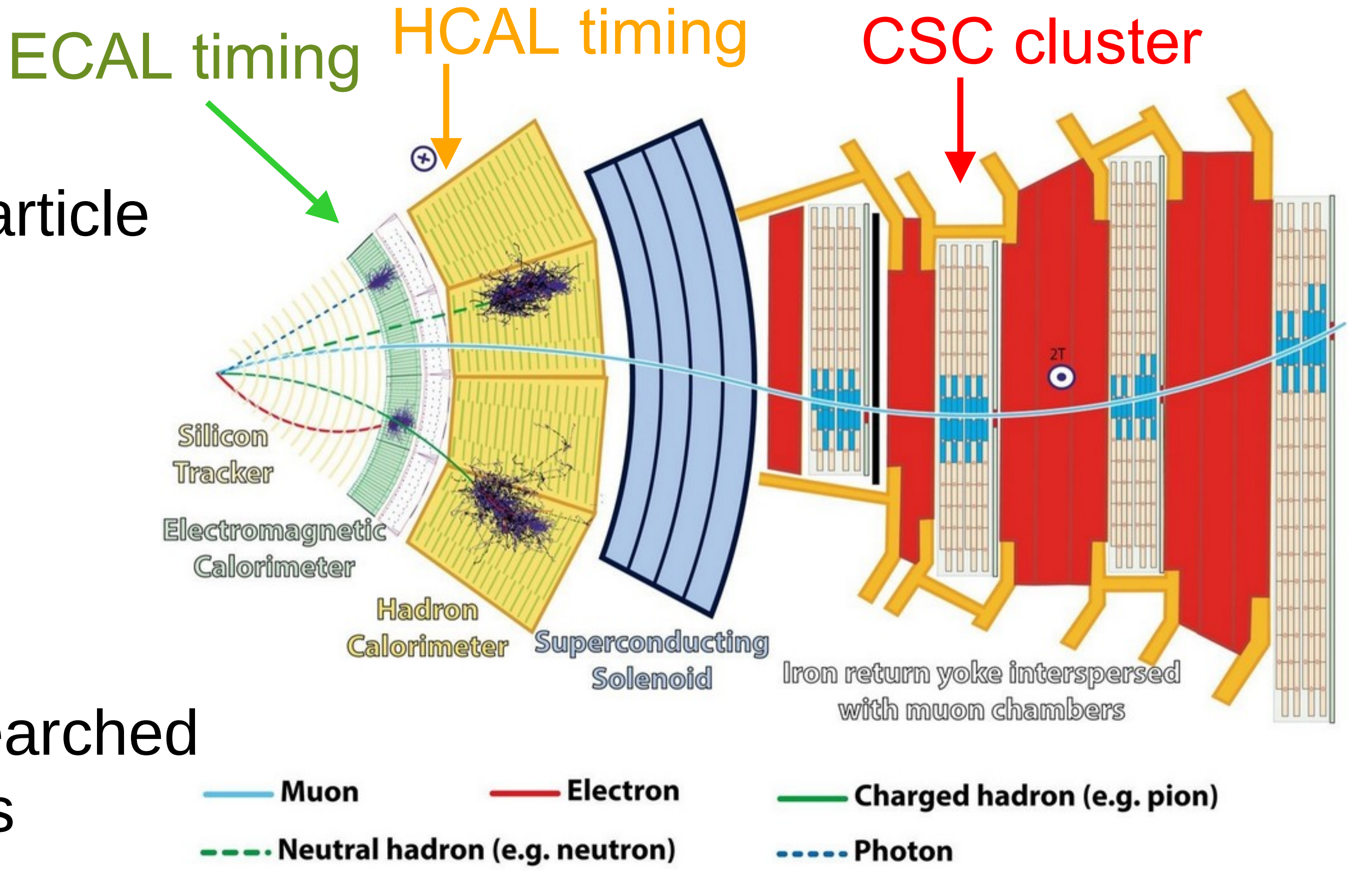


~2 kHz in prompt reconstruction

~3 kHz in delayed reconstruction

Long-lived particle

- In Run-3 new triggers targeting long-lived particle signatures:
  - ECAL delayed signal
  - HCAL delayed signal
  - Particle shower in muon chambers
- In Run-2 LLP were searched using displaced tracks

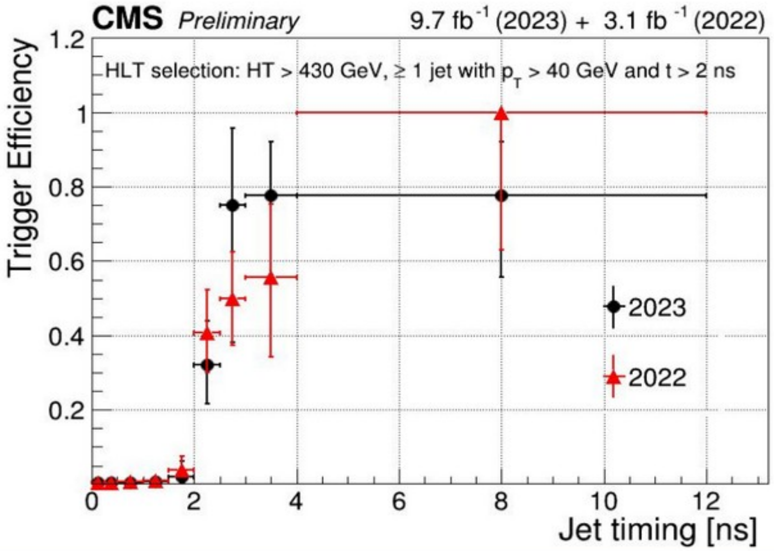


Long-lived particle

CMS-DP-2022-062
To be published in
HighLevelTriggerRunIIIResults
HcalDPGResults

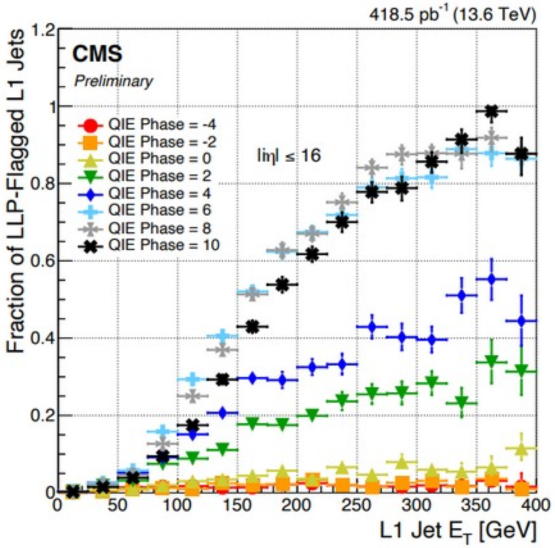
ECAL timing (HLT)

Efficiency vs ECAL timing



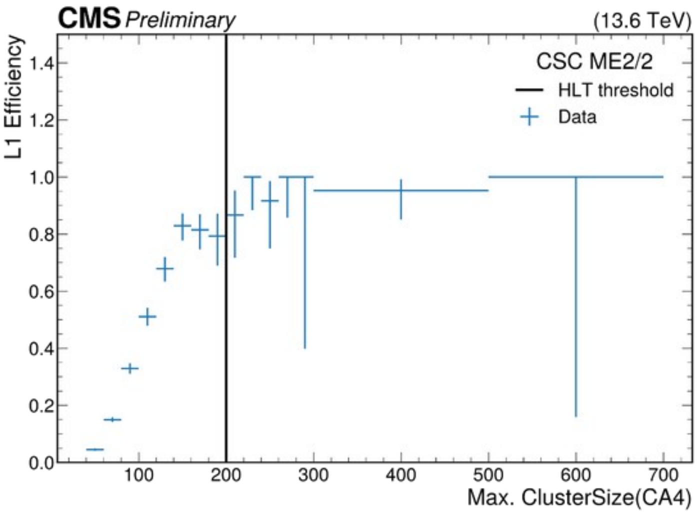
HCAL timing (L1)

Fraction of LLP flagged L1 jets for different HCAL timing offset



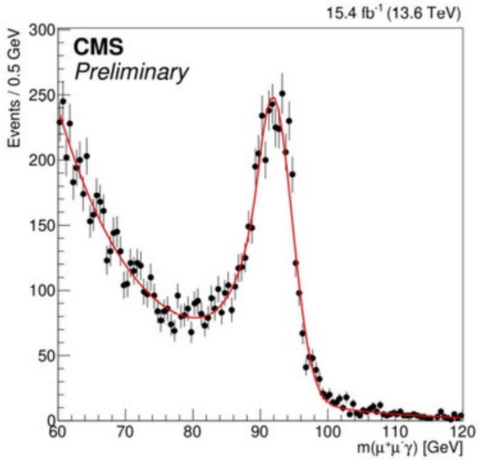
CSC cluster (L1)

Efficiency vs number of CSC signals in a CSC cluster

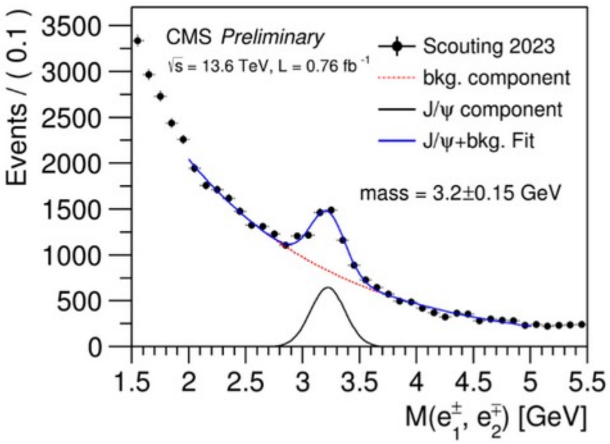


Scouting

- Scouting consists in saving only the HLT-reconstructed the physics objects.
- In Run-3 scouting have been extended to **all physics objects** (muons, electrons, photons, jets, pixel tracks)
  - ~7 kB/event
- In Run-3, we are able to run the **scouting reco at 30 kHz**!
  - 30% of L1 rate



Z(μμγ) peak

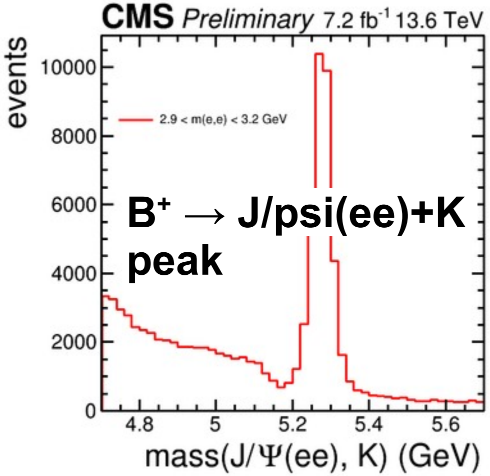


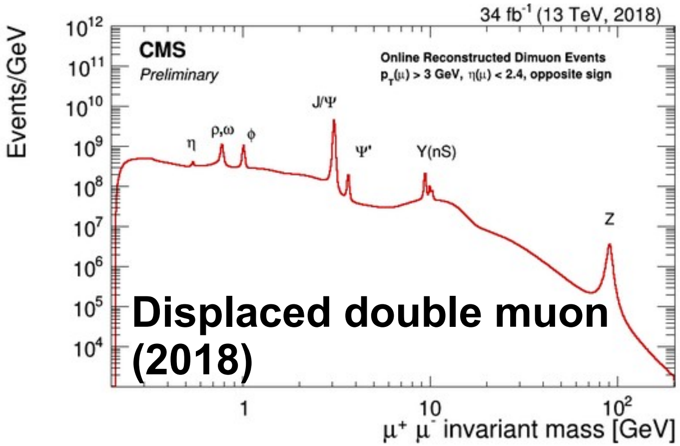
J/psi(ee) peak

B-physics trigger

CMS-DP-2018-055
LHCC2022Sep

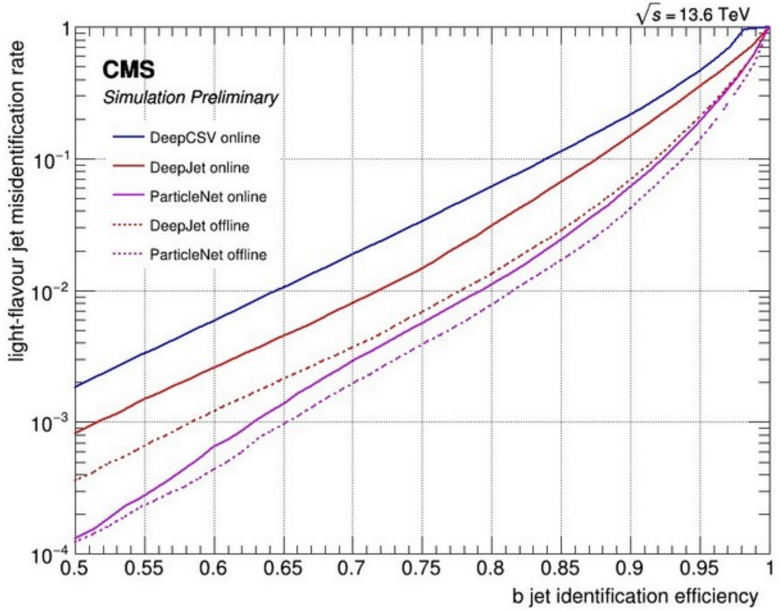
- In Run-3 we increased the rate of B-physics triggers using delayed reconstruction from ~300 Hz to 1.6 kHz.
- New inclusive dimuon trigger in mass range.
- New soft dielectron trigger
  - Improved soft electron reconstruction
- Single displaced muon active in 2018 and 2022.

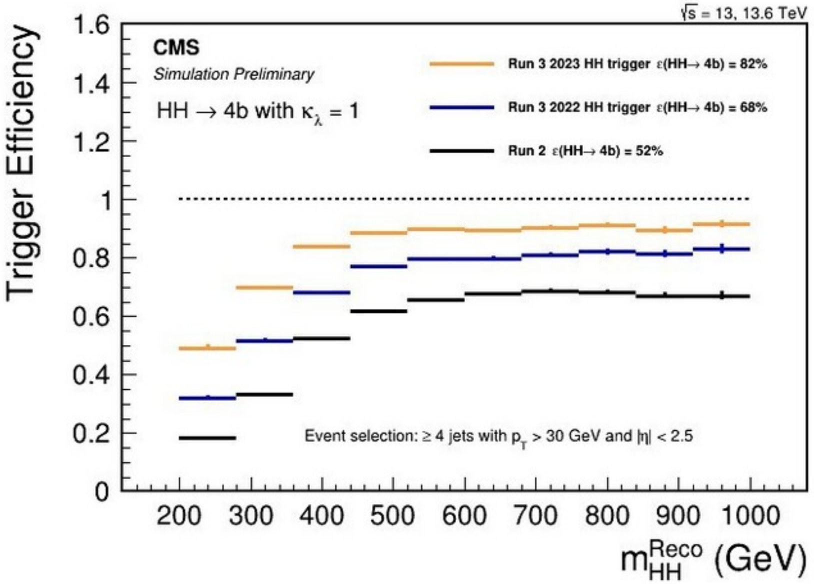




HH trigger

- New b-tagger based on **graph net** (ParticleNet) integrated at HLT
- Excellent performance both offline and at HLT





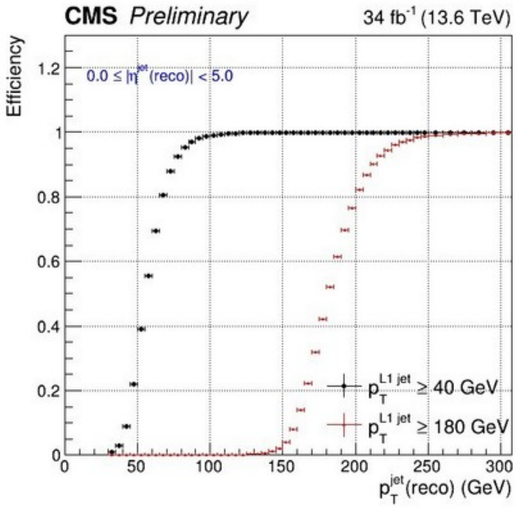
- Large efficiency increase for HH → 4b
- Further increase in 2023 using delayed reconstruction and new L1 seed

Jet

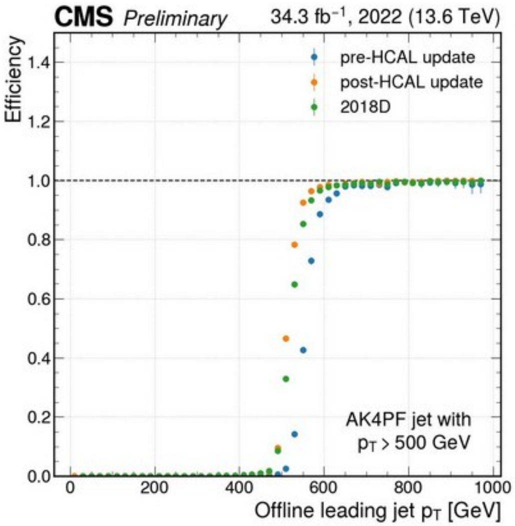
CMS-DP-2023-007
CMS-DP-2023-013

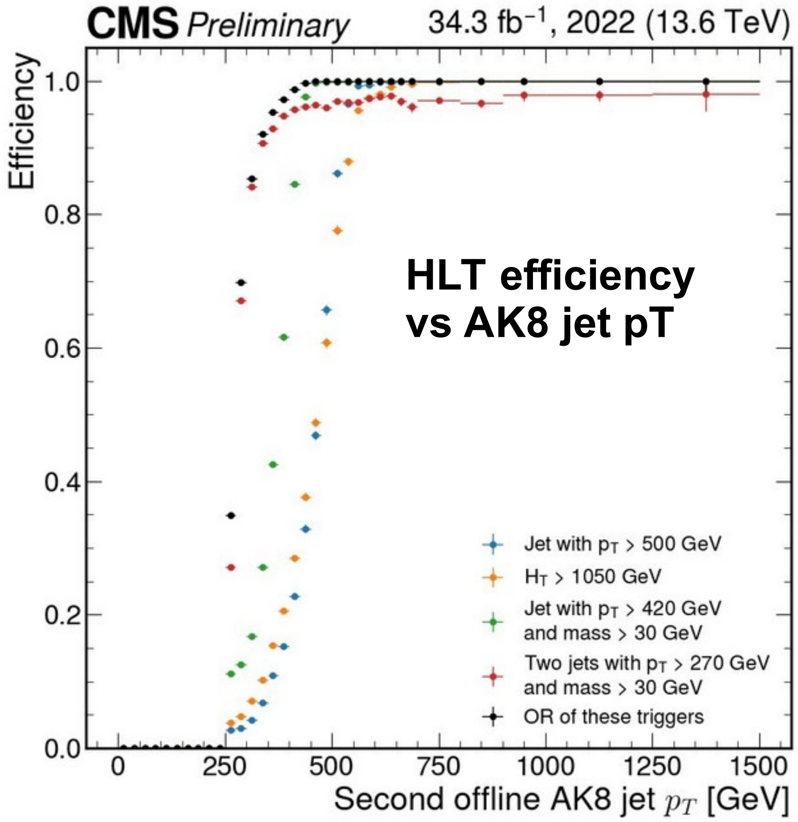
- Good jet performance in Run-3
- New boosted algoritm at HLT
  - “trimmed mass“ → “soft-drop mass“

L1 trigger efficiency



HLT efficiency vs 2018



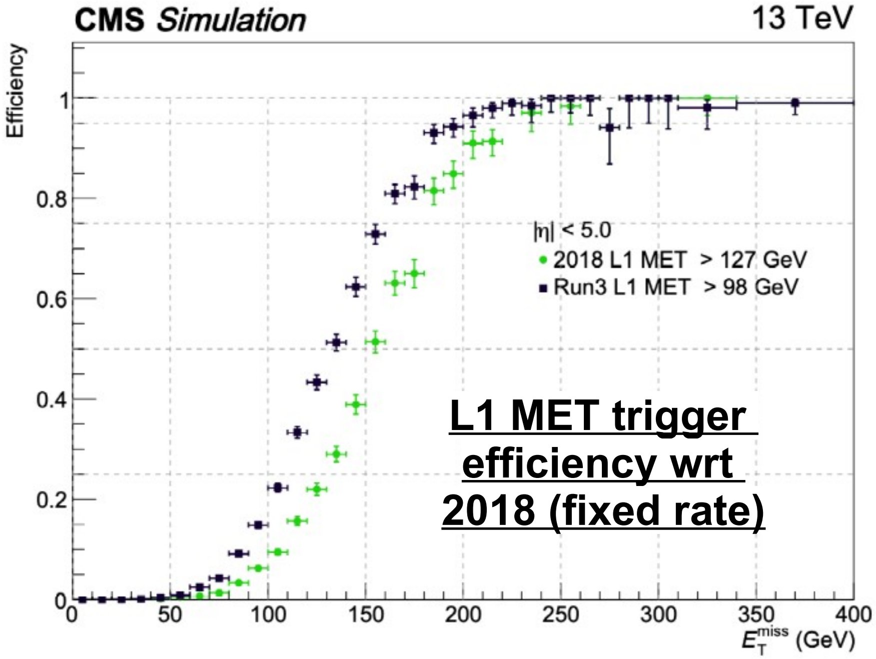


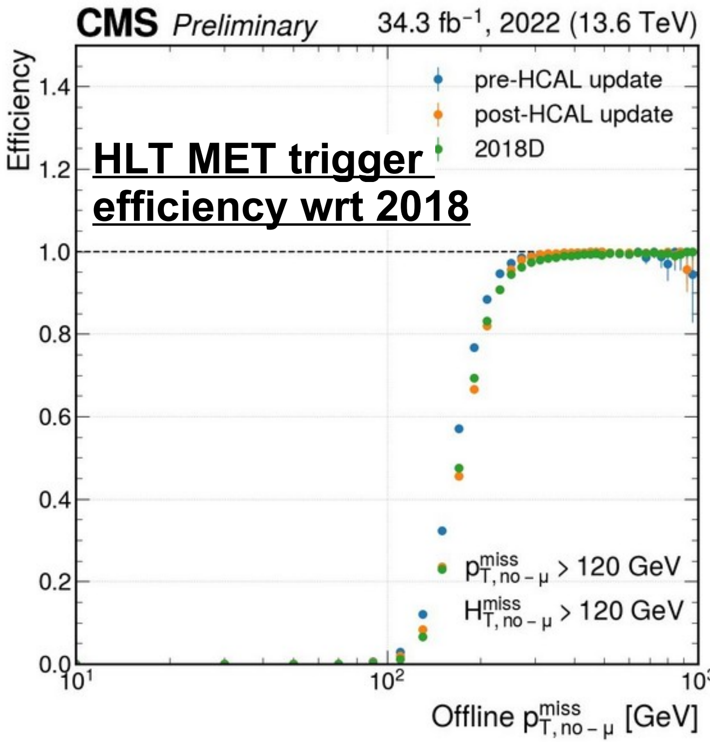
HLT efficiency vs AK8 jet pT

Missing transverse energy

CMS-DP-2023-016
will appear in
L1TriggerDPGResults

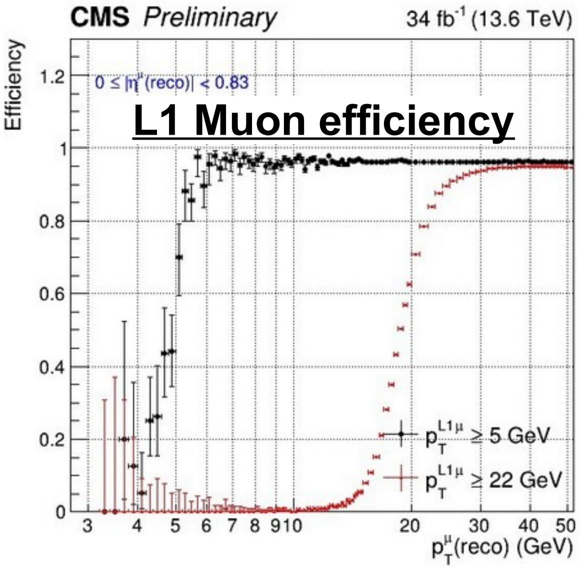
- Improved pileup subtraction at L1 trigger
- Smaller rate at fixed trigger efficiency

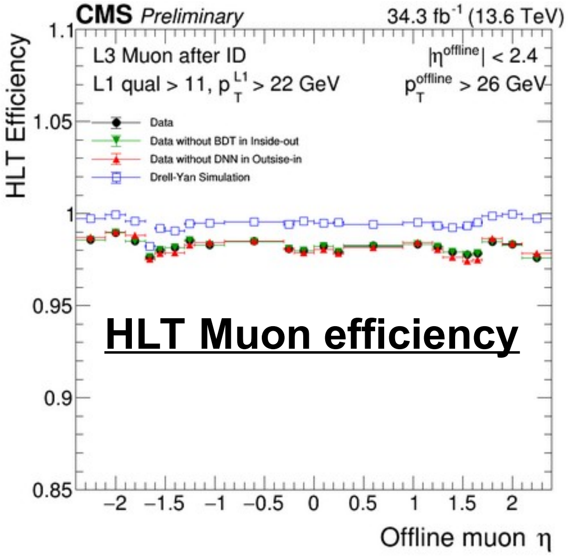


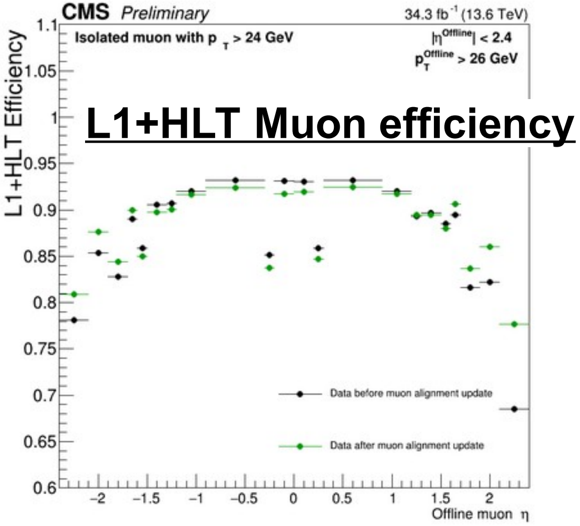


Muon

- Excellent muon efficiency both at L1 and HLT.
- ML technique used to select seeds in HLT muon reconstruction
  - speed up of +16% in the full HLT reconstruction.

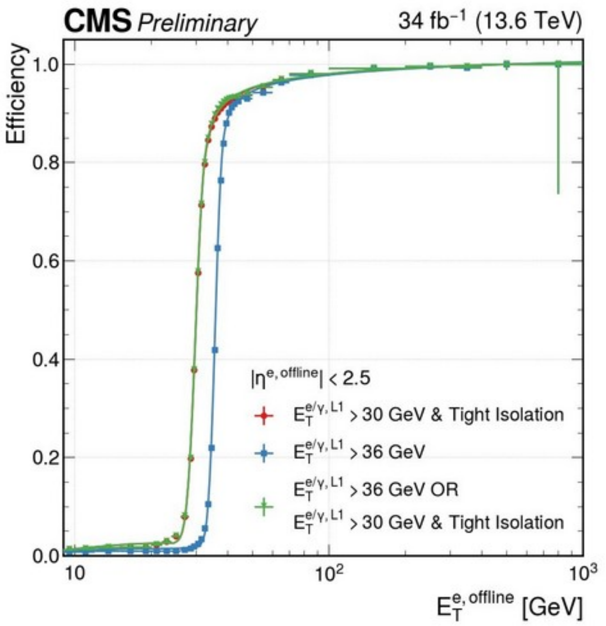




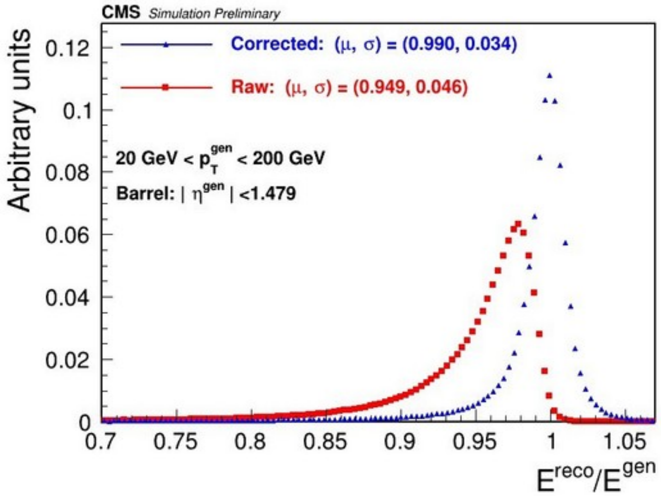


Electrons and photons

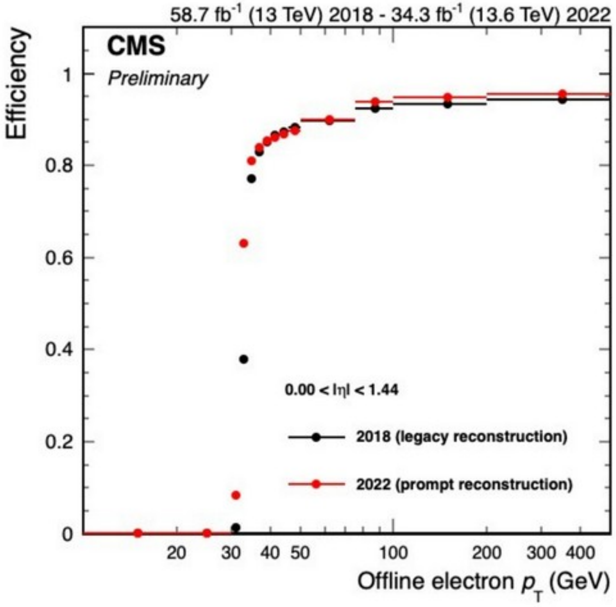
L1 Electron/photon efficiency



HLT electron response (simulation)



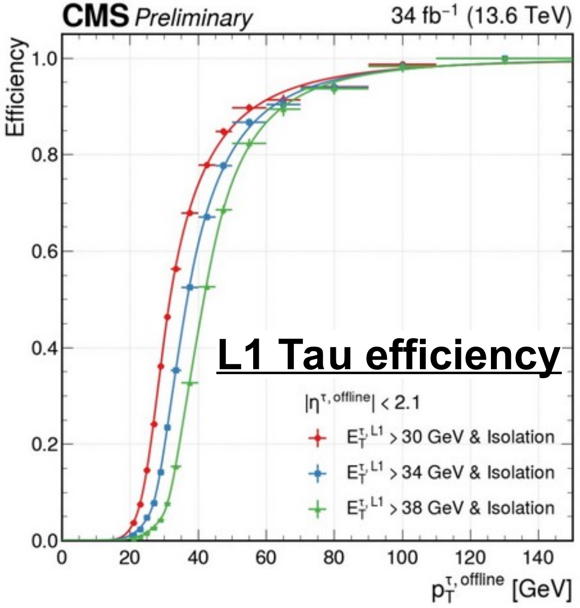
HLT electron response

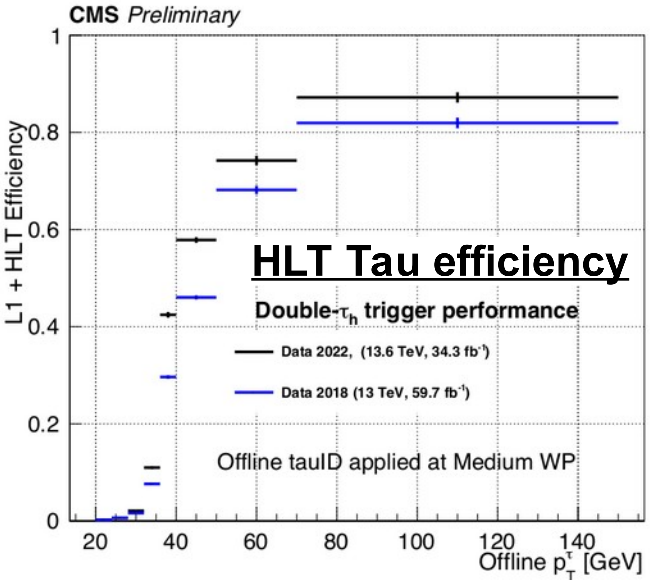


Tau

CMS-DP-2023/008
CMS-DP-2023/024

- New Tau reconstruction at HLT based on Convolutional Neural Network
  - Faster reconstruction and better performance.

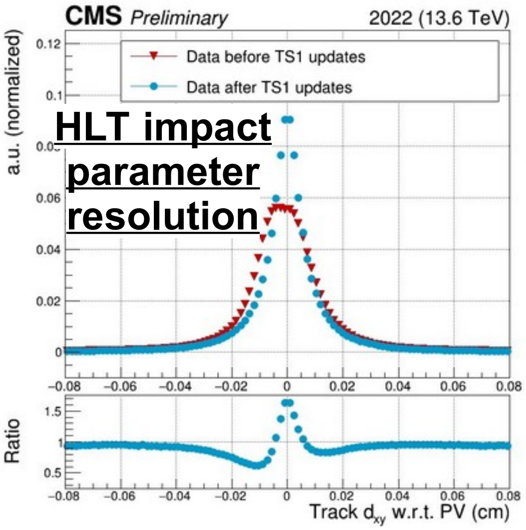


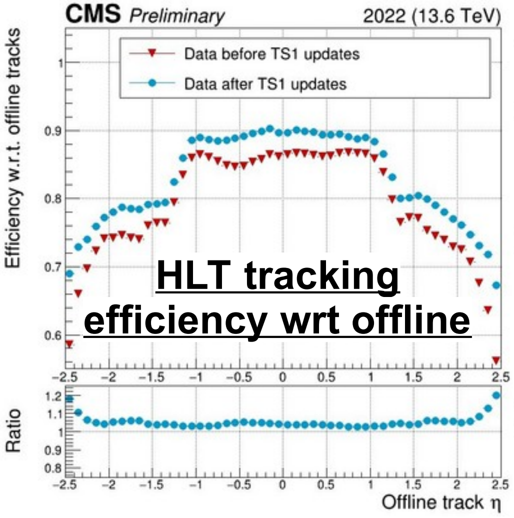


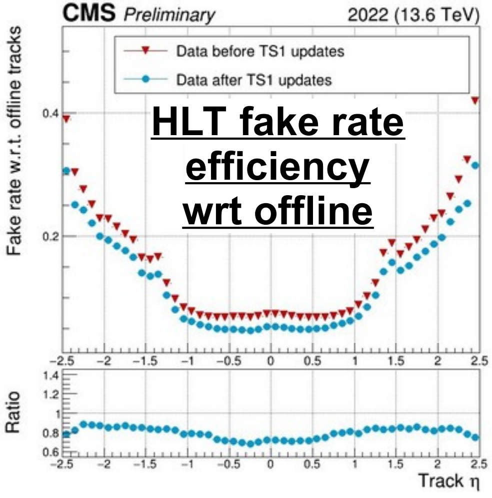
Tracking and b-tagging

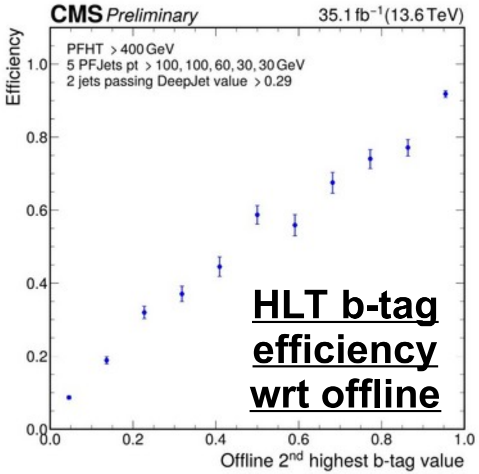
DP-2023/018
DP-2023/028
Run3TrackingHLT

- Tracking based on single iteration.
  - Pixel tracking running on GPU
- Good b-tagging performance









Conclusions

- Many improvements have been implemented in the CMS trigger after Run-2 both at L1 and HLT trigger
  - Trigger for long-lived particle (eg. ECAL and HCAL timing)
  - GPU at HLT → more powerful scouting
  - Large rate for BPH and HH (delayed reconstruction)
- The first Run-3 data confirm the good performance of the L1 and HLT
- Thanks to the new triggers Run-3 is not just “a copy of Run-2” but it is an opportunity to look for New Physics in new final states.
  - Many more news will come with Phase-2 upgrades and HL-LHC (>2029)
- Stay tuned!

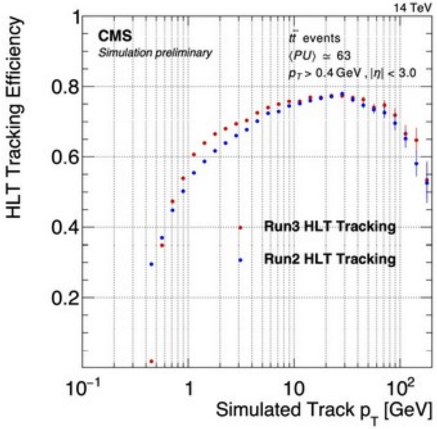

Ευχαριστώ!

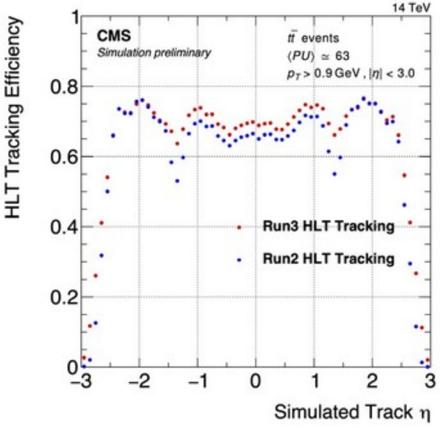
Backup

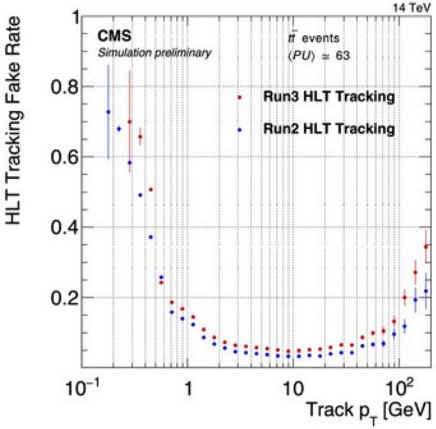
HLT

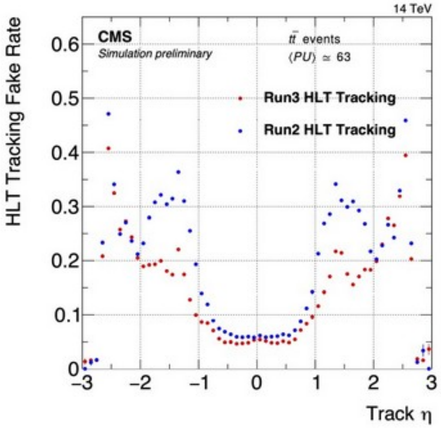
Tracking

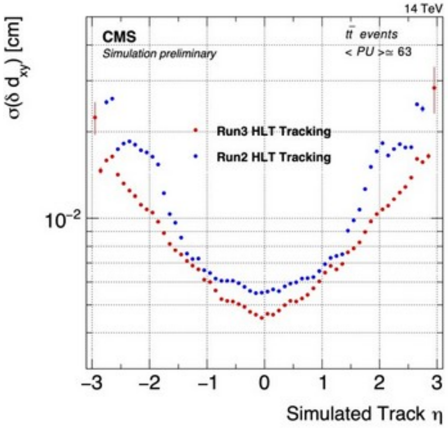
DP-2023/028





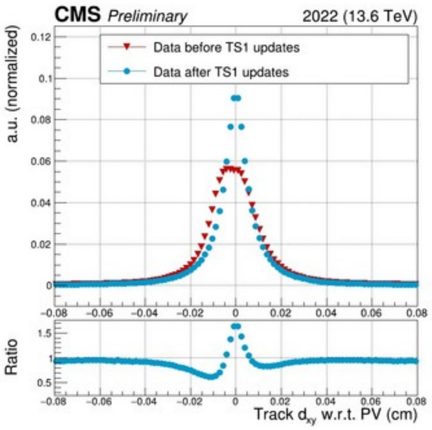


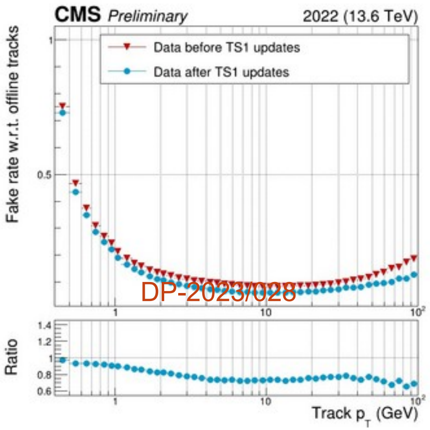




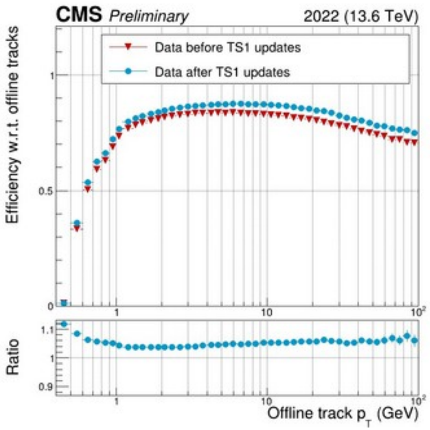
Tracking

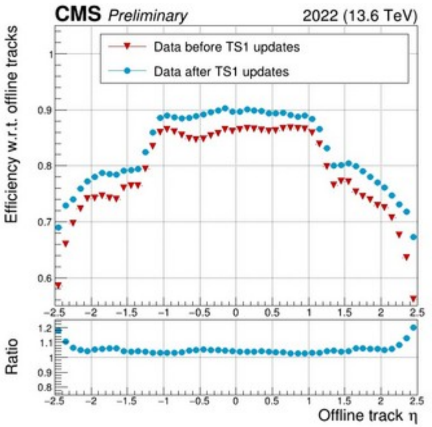
Run3TrackingHLT

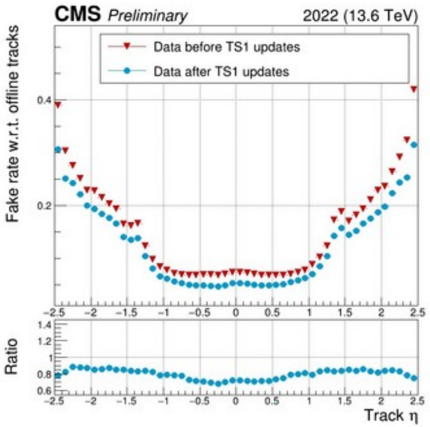




DP-2023/028

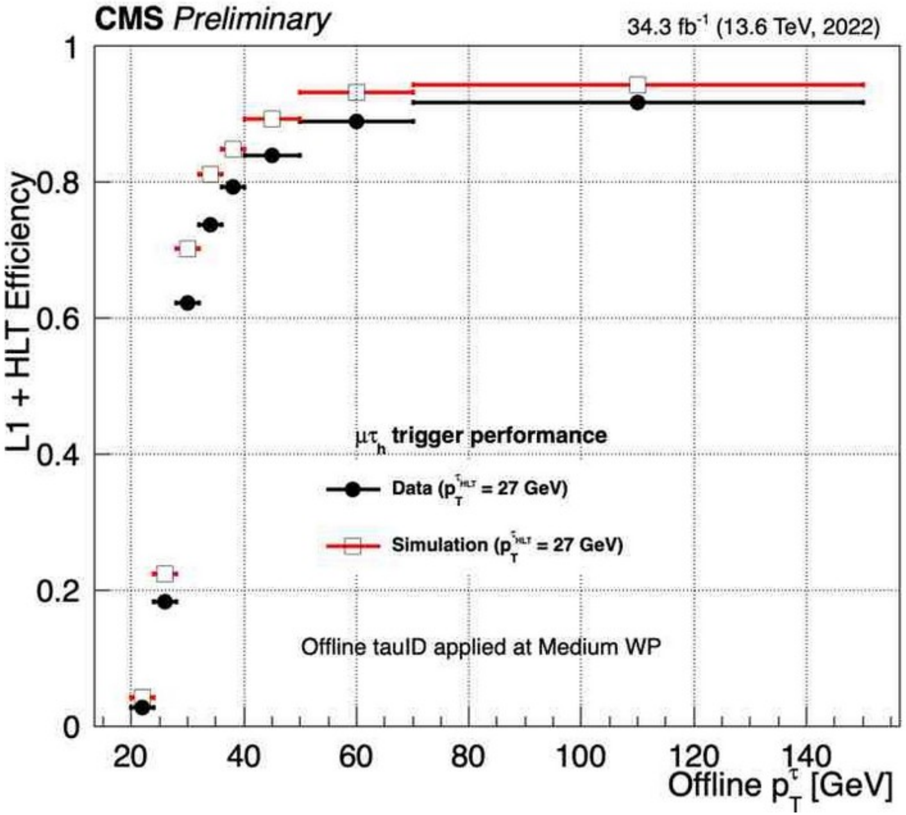




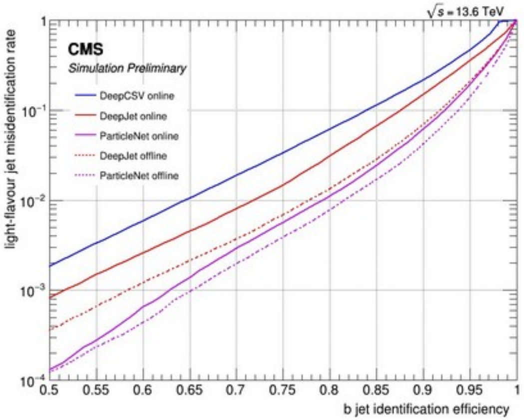


Tau

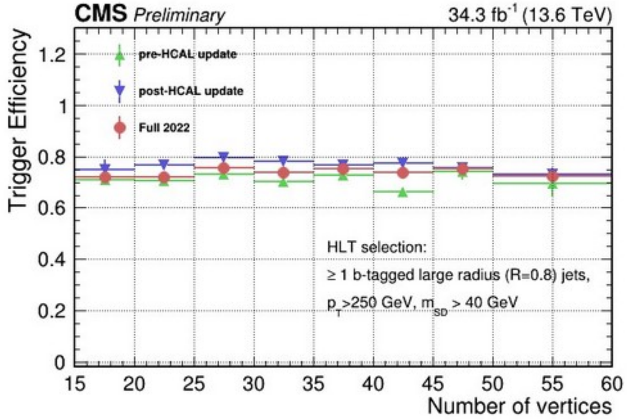
DP-2023/024



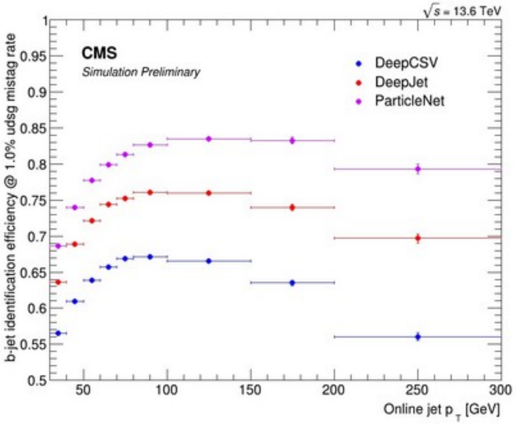
DP-2023/021



√s = 13.6 TeV
CMS
Simulation Preliminary
DeepCSV online
DeepJet online
ParticleNet online
DeepJet offline
ParticleNet offline
light-flavour jet misidentification rate
b jet identification efficiency



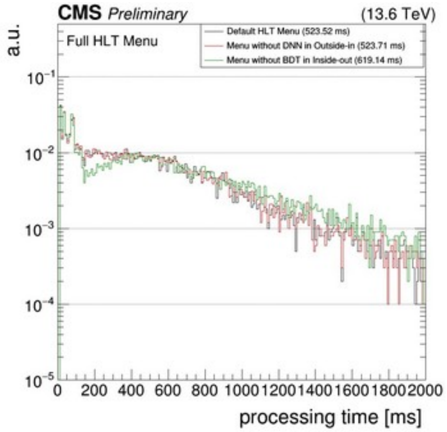
CMS Preliminary
34.3 fb⁻¹ (13.6 TeV)
pre-HCAL update
post-HCAL update
Full 2022
HLT selection:
≥ 1 b-tagged large radius (R=0.8) jets,
p_T >250 GeV, m_SD > 40 GeV
Trigger Efficiency
Number of vertices

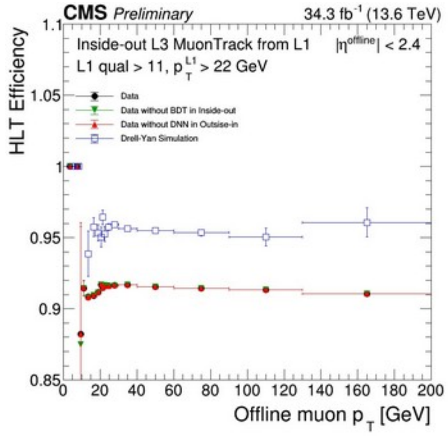


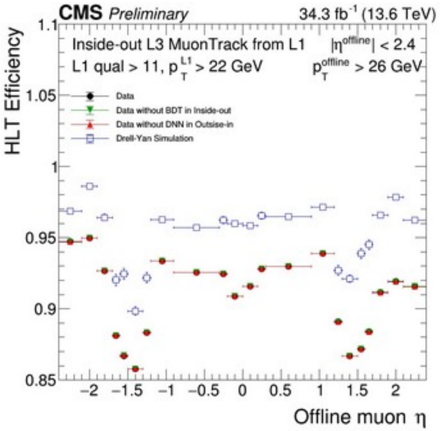
√s = 13.6 TeV
CMS
Simulation Preliminary
DeepCSV
DeepJet
ParticleNet
b-jet identification efficiency @ 1.0% udsg mistag rate
Online jet p_T [GeV]

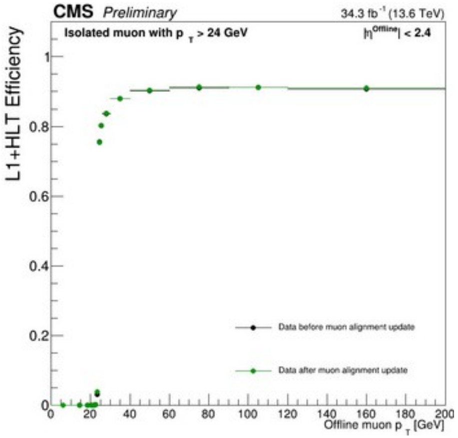
Muon

DP-2023/017



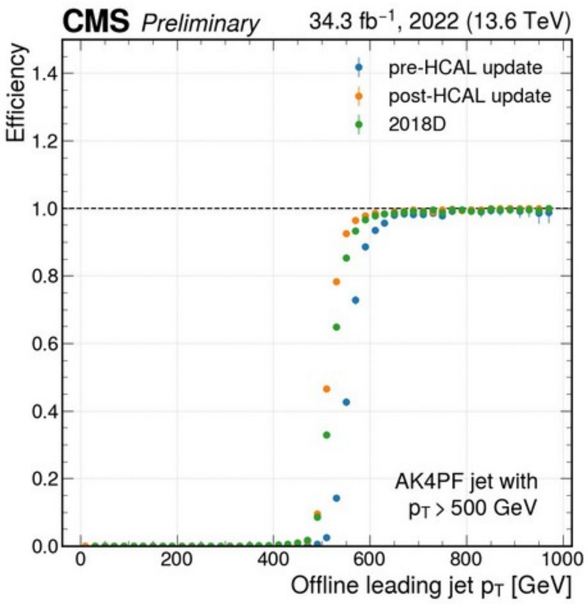


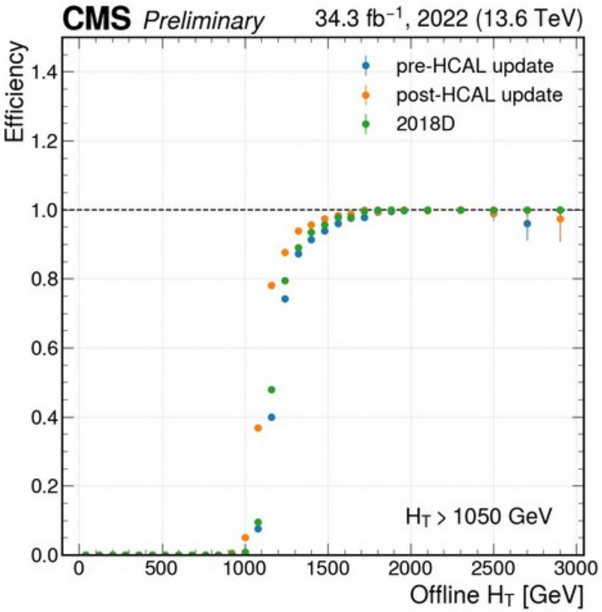


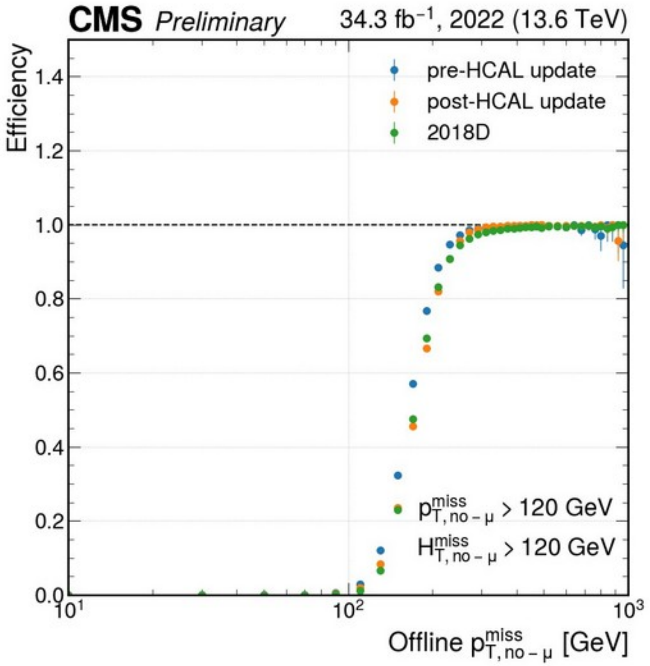


Jet/MET

DP-2023/016

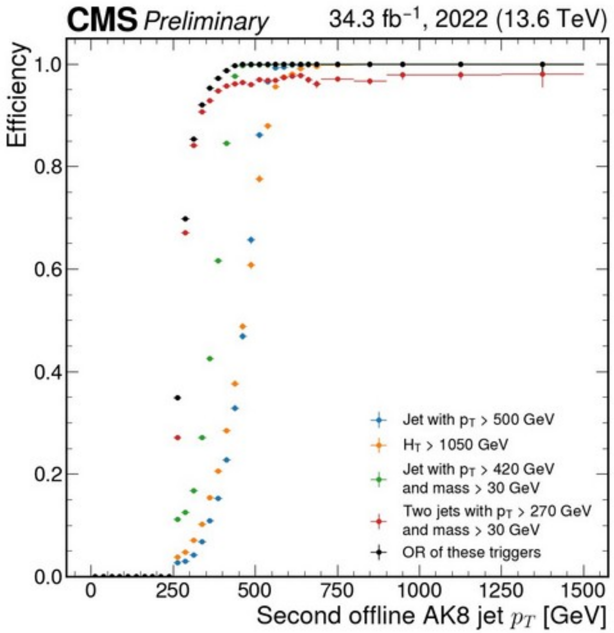


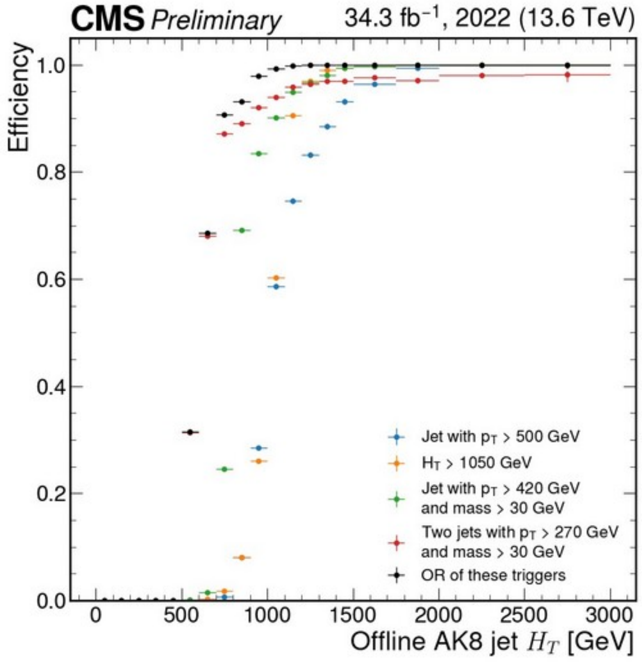


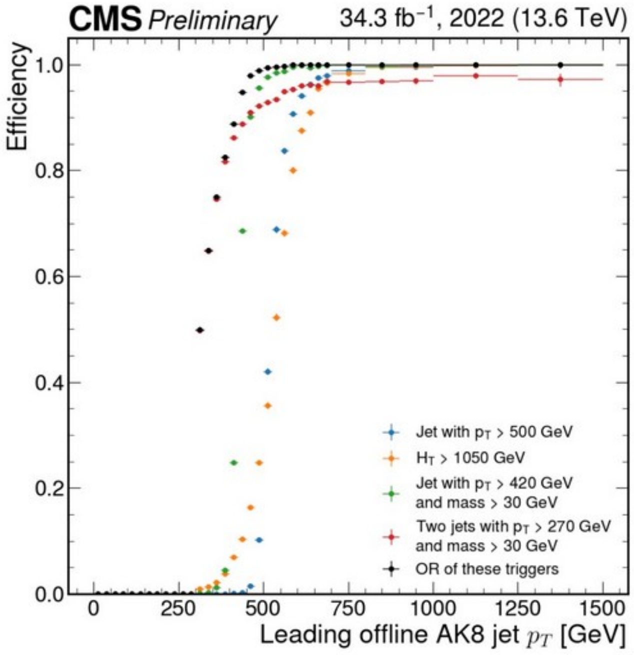


Soft Drop Mass

DP-2023/013

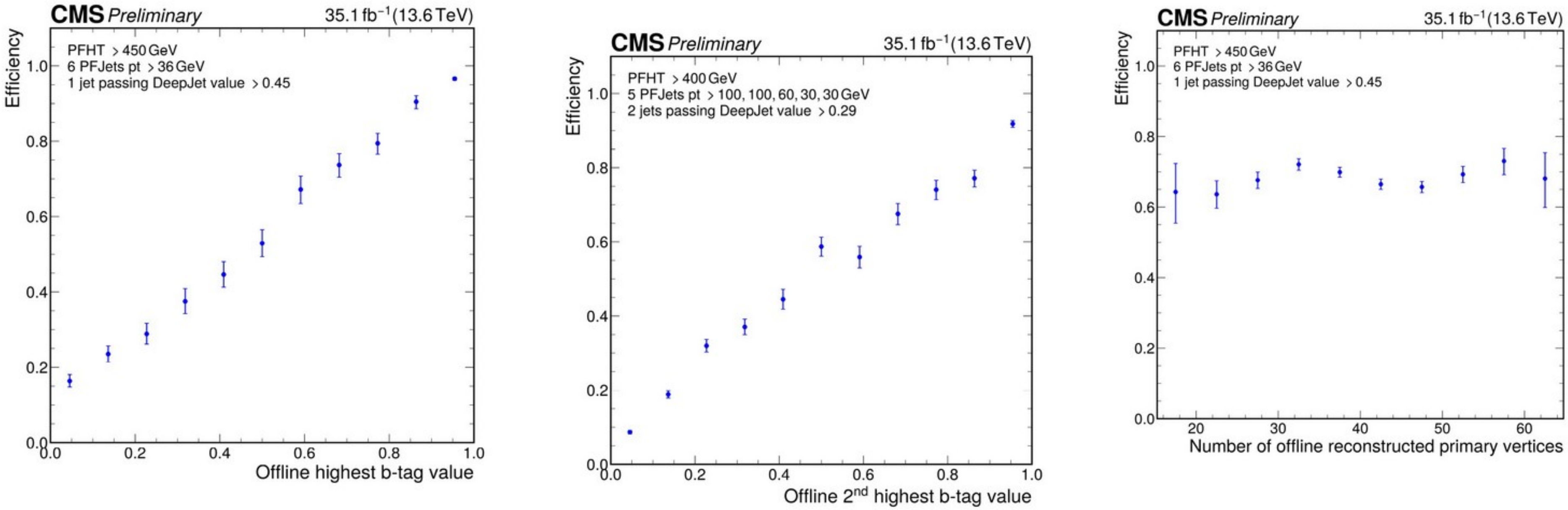






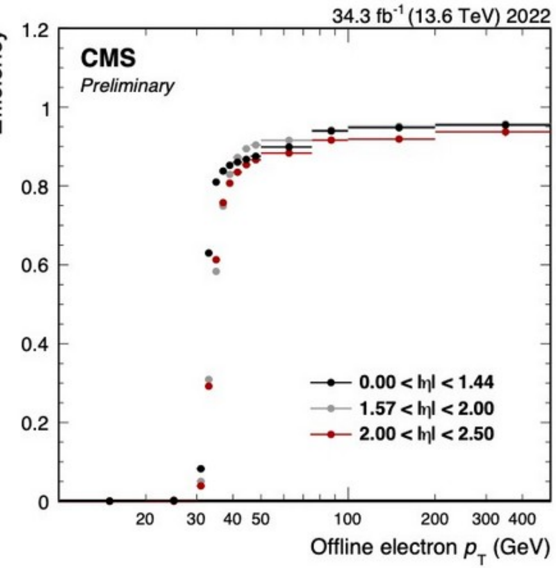
DeepCSV

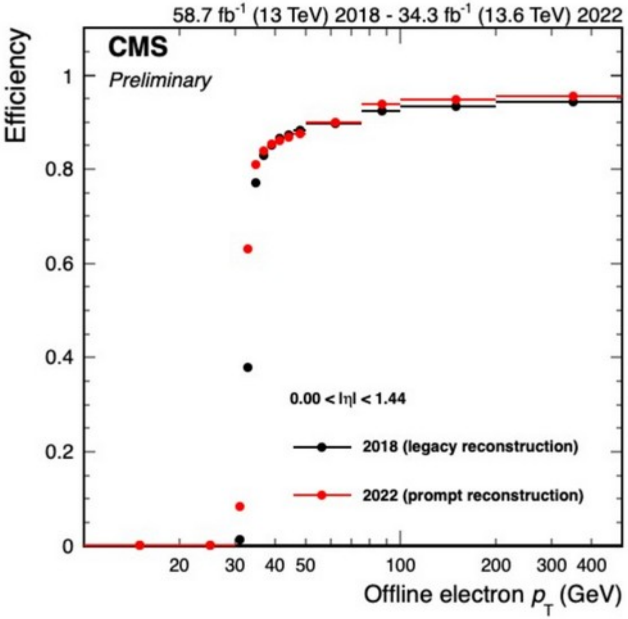
DP-2023/018

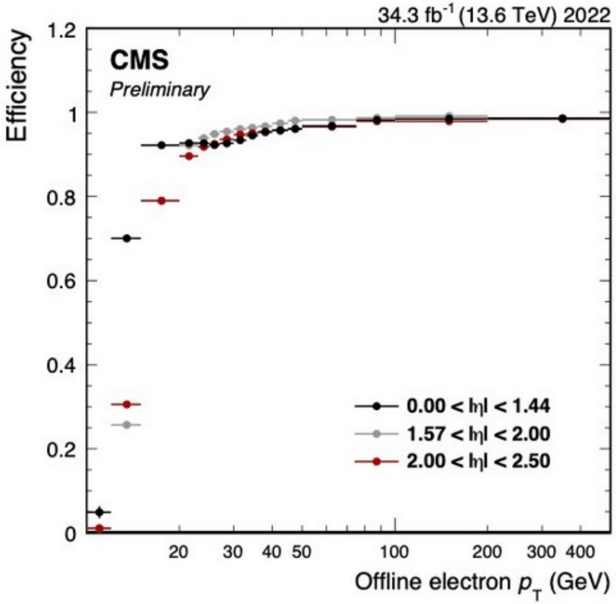


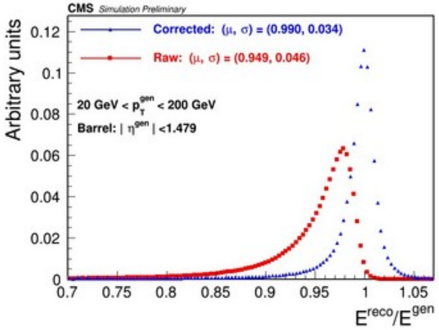
Electrons

DP-2023/015

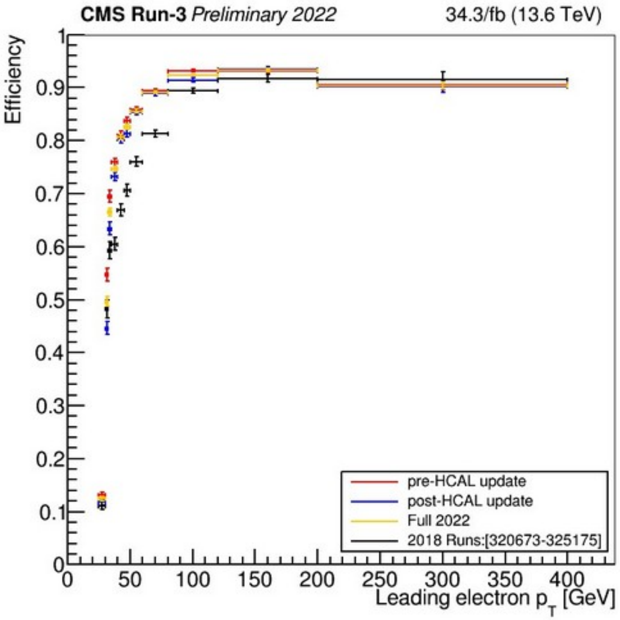


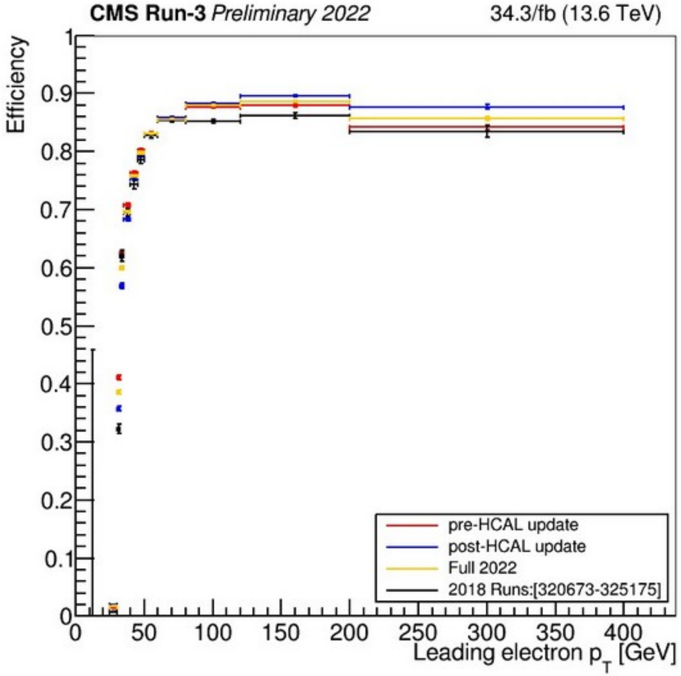


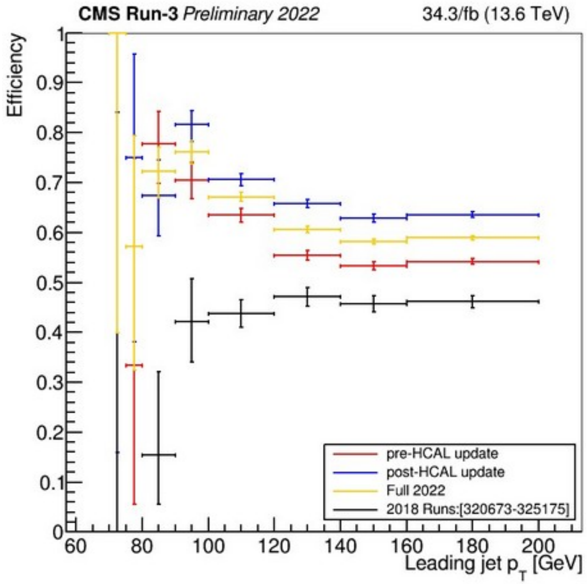




Top

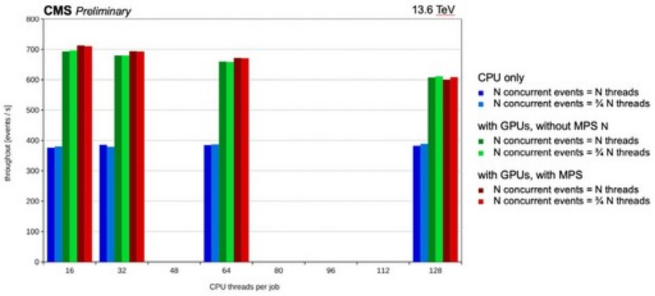

CMS Run-3 *Preliminary 2022*
34.3/fb (13.6 TeV)
Efficiency
Leading electron p_T [GeV]
pre-HCAL update
post-HCAL update
Full 2022
2018 Runs:[320673-325175]

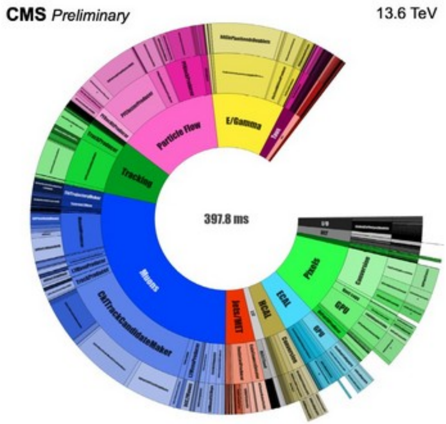

CMS Run-3 *Preliminary 2022*
34.3/fb (13.6 TeV)
Efficiency
Leading electron p_T [GeV]
pre-HCAL update
post-HCAL update
Full 2022
2018 Runs:[320673-325175]

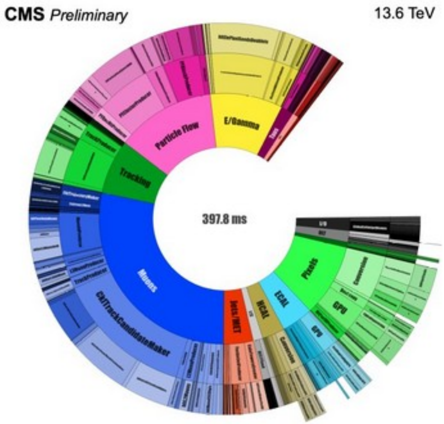

CMS Run-3 *Preliminary 2022*
34.3/fb (13.6 TeV)
Efficiency
Leading jet p_T [GeV]
pre-HCAL update
post-HCAL update
Full 2022
2018 Runs:[320673-325175]

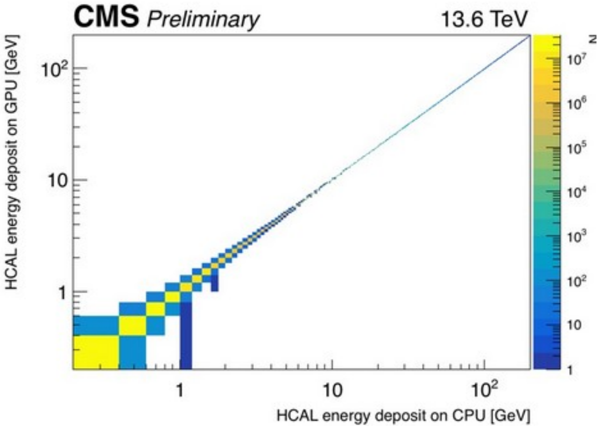
GPU

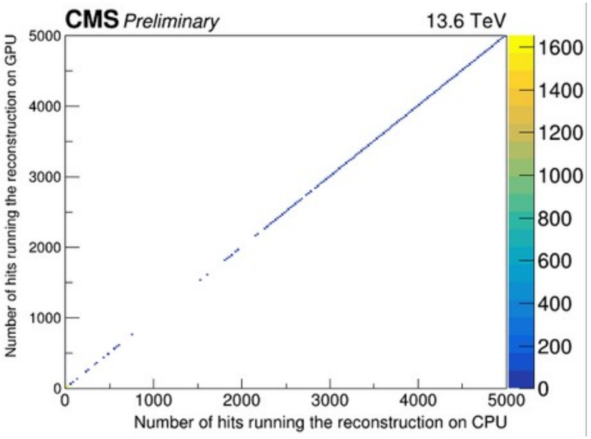
DP-2023/004

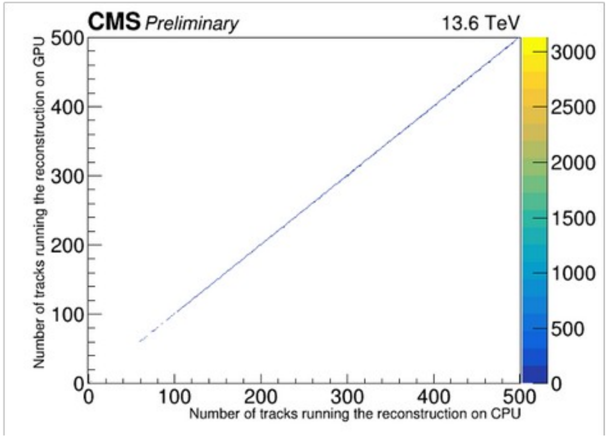






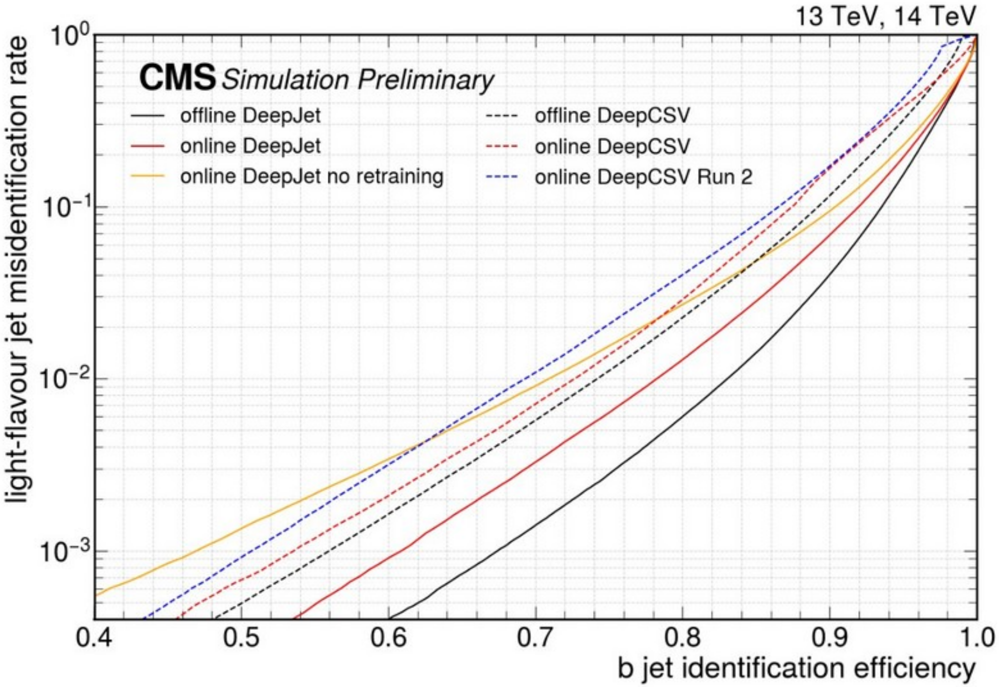






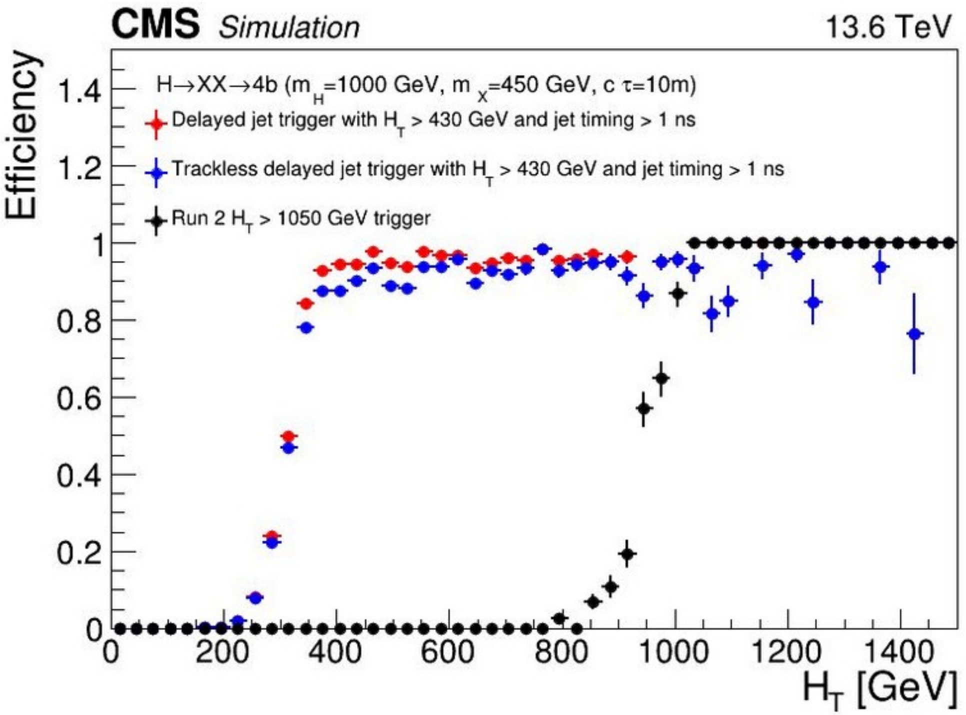
B-tagging

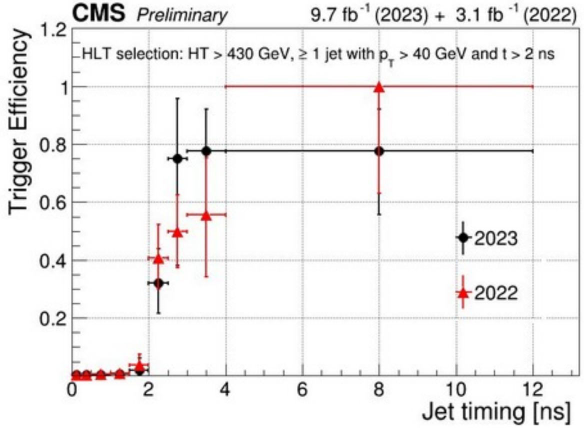
CMS-DP-2022-030

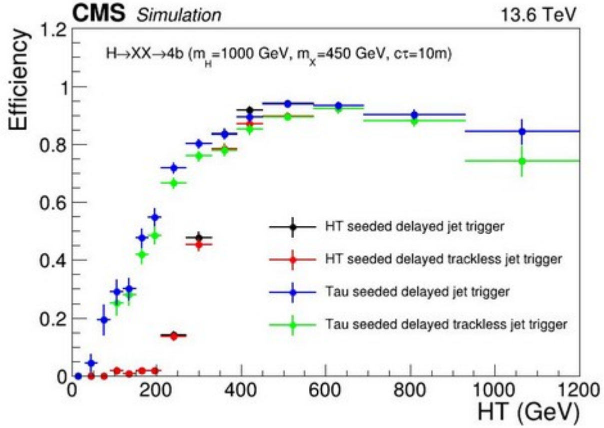


LLP – ECAL timing

will appear in
HighLevelTriggerRunIIIResults

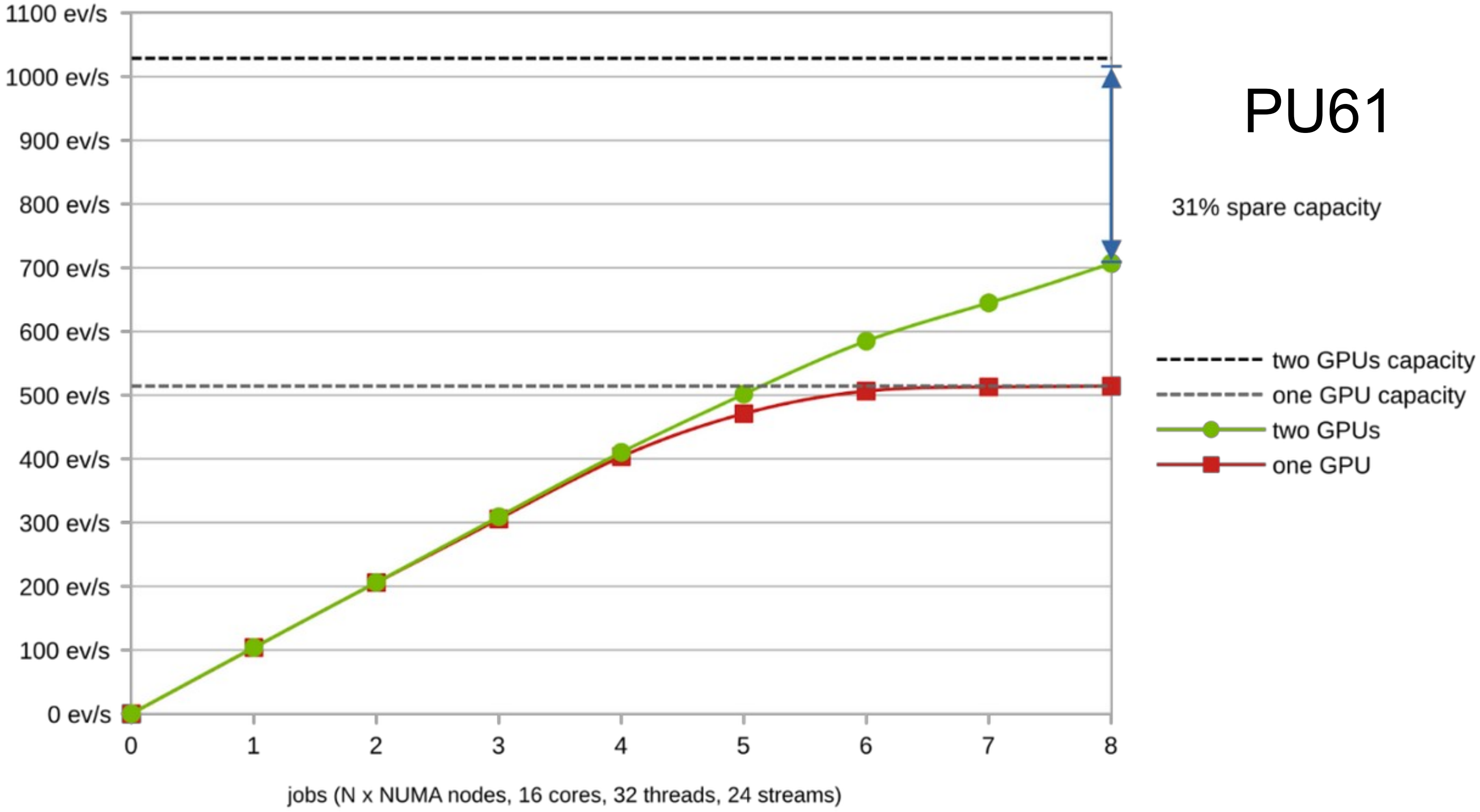






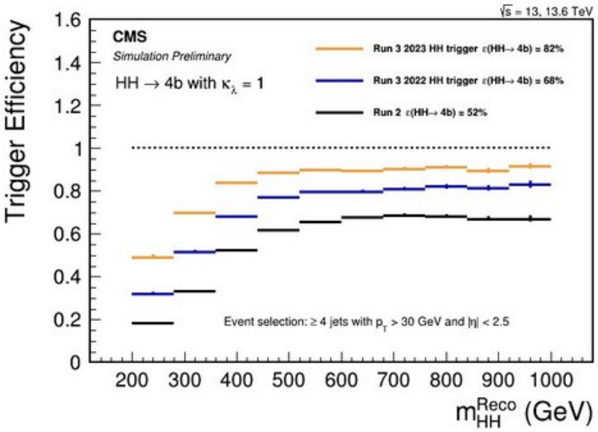
GPU

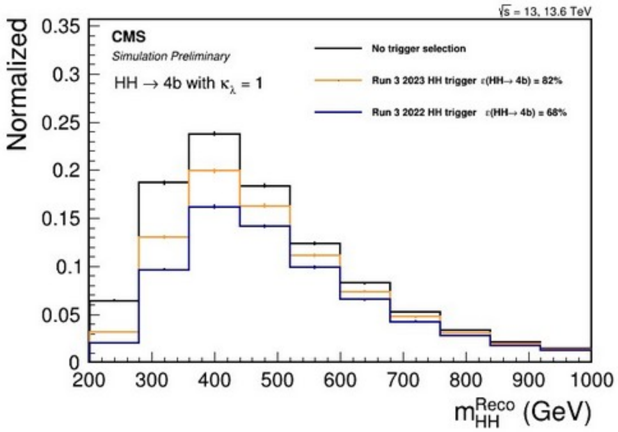
will appear in
HighLevelTriggerRunIIIResults

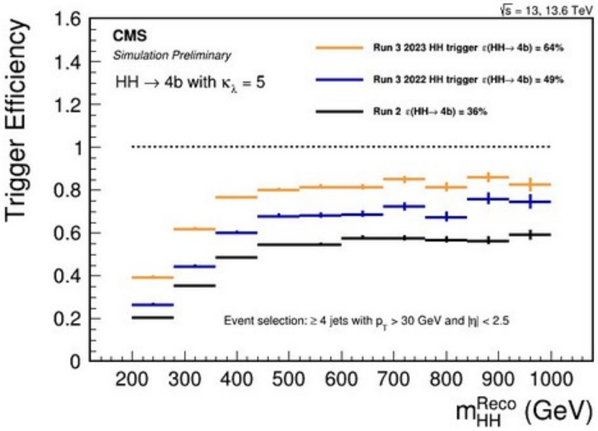


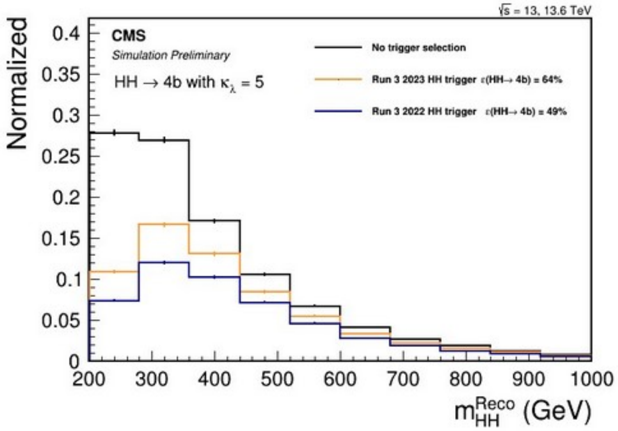
Higgs

will appear in HighLevelTriggerRunIIIResults









L1 trigger

L1 trigger

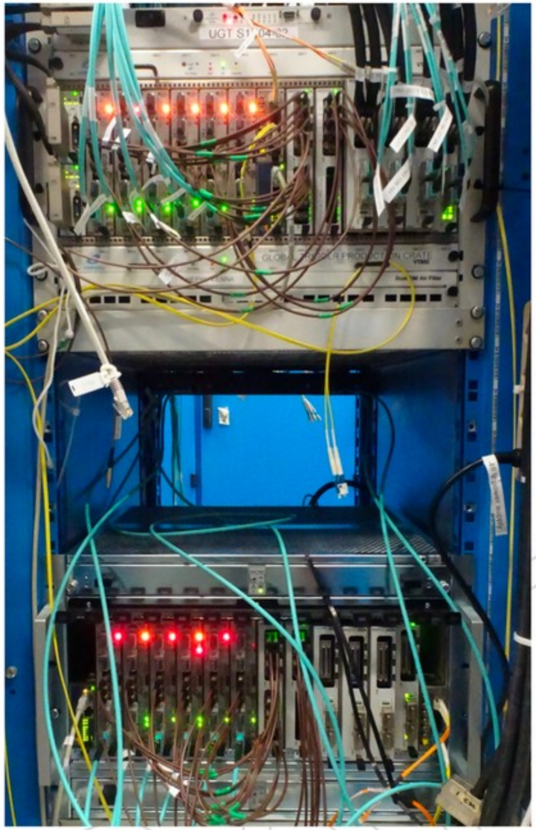


Figure 129: Production (top) and test crate (bottom) of the μGT.

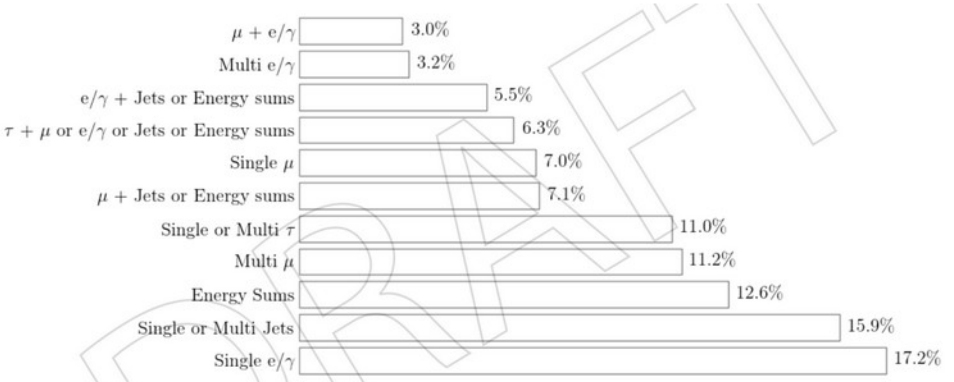
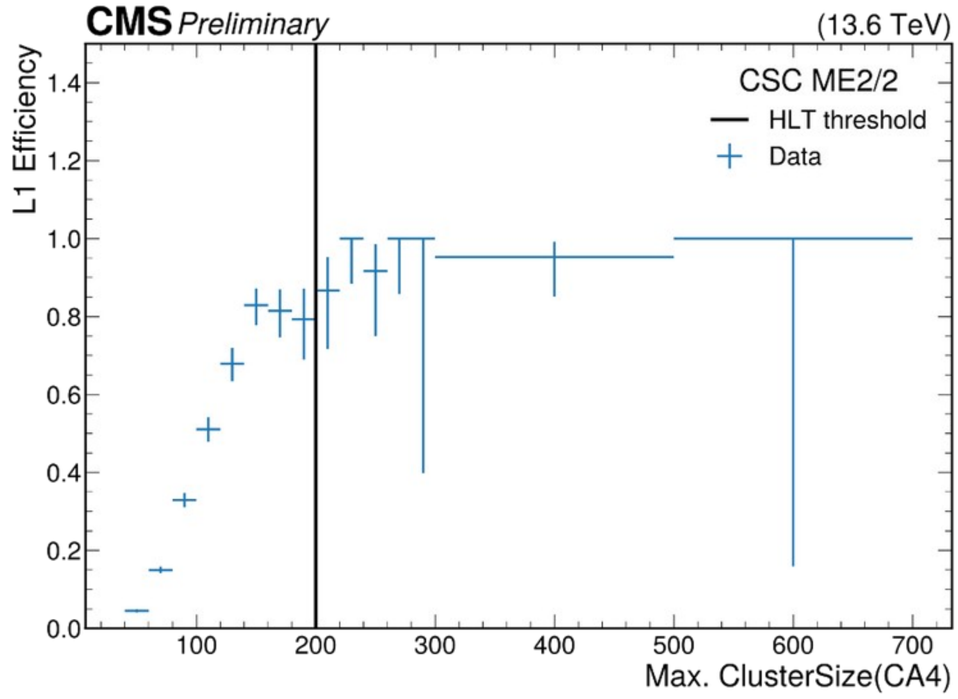
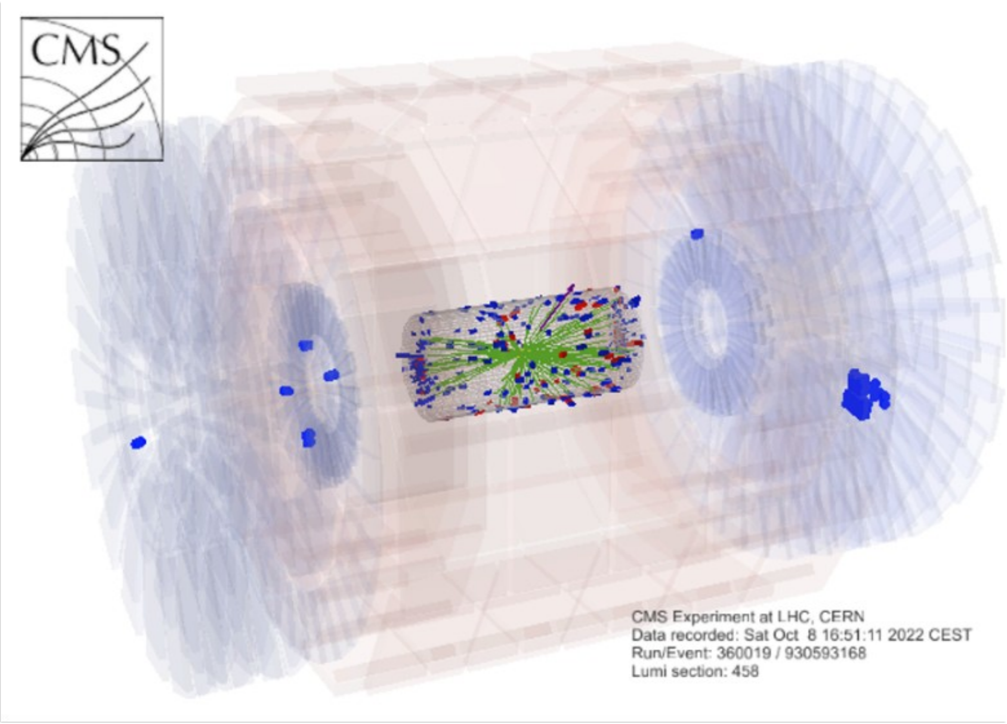


Figure 130: Fractions of the 100 kHz rate allocation for single- and multi-object triggers and cross triggers in the baseline Run 3 menu, calculated using pileup only Run 3 MC.

CSC trigger

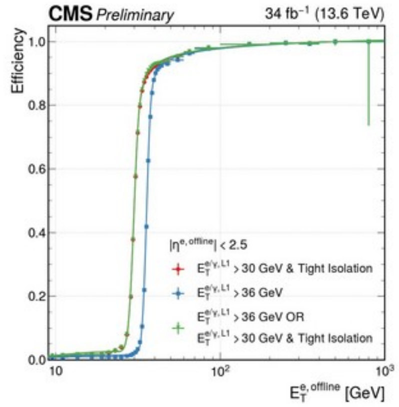
DP-2022/062

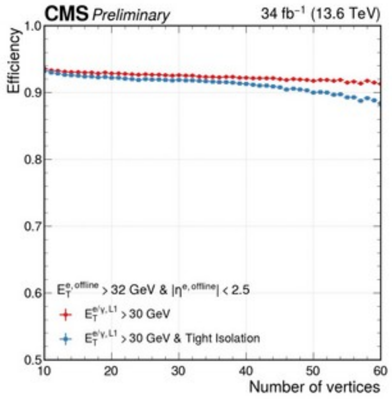


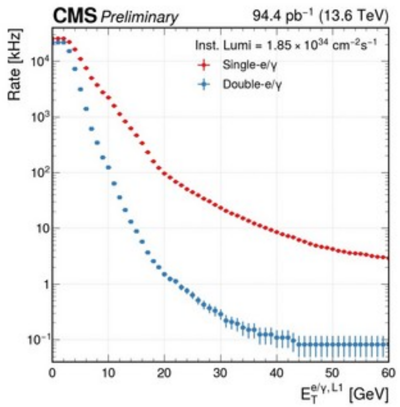


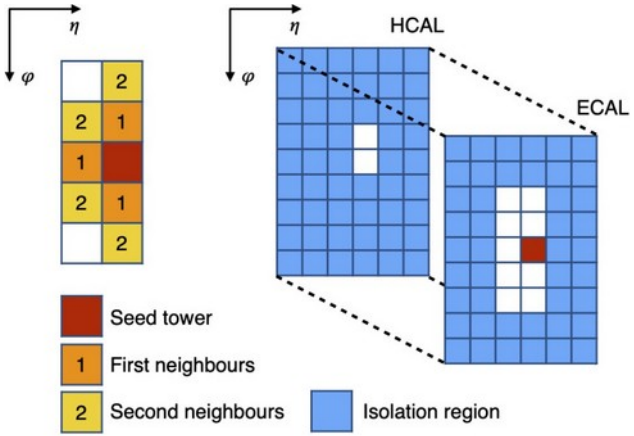
Egamma

DP-2023/008

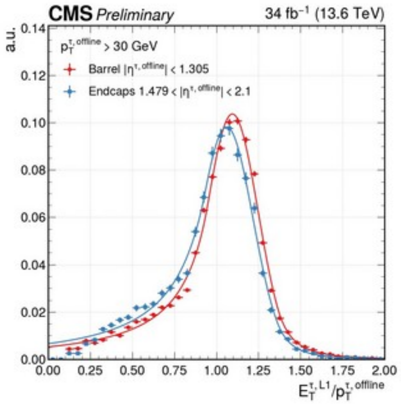


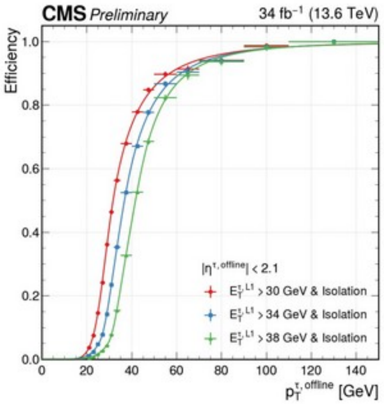


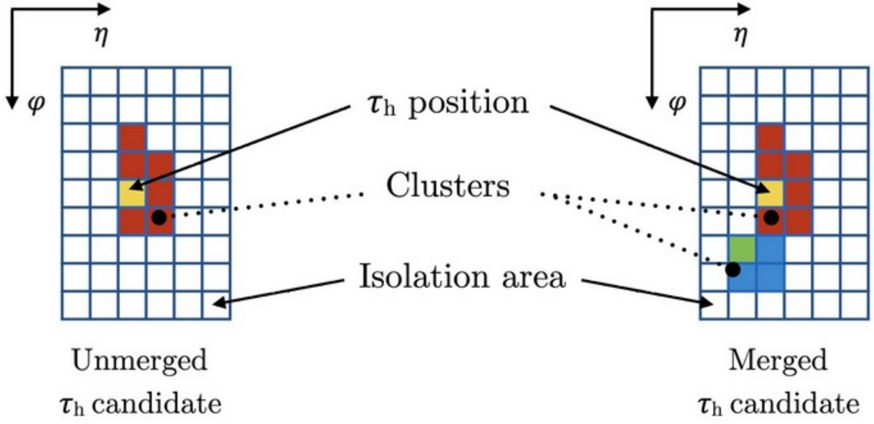


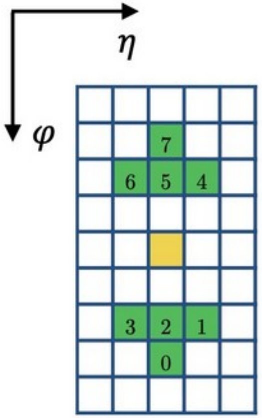


Tau


CMS Preliminary
34 fb⁻¹ (13.6 TeV)
a.u.
p_T^{τ, offline} > 30 GeV
Barrel |η^{τ, offline}| < 1.305
Endcaps 1.479 < |η^{τ, offline}| < 2.1
E_T^{τ, L1}/p_T^{τ, offline}

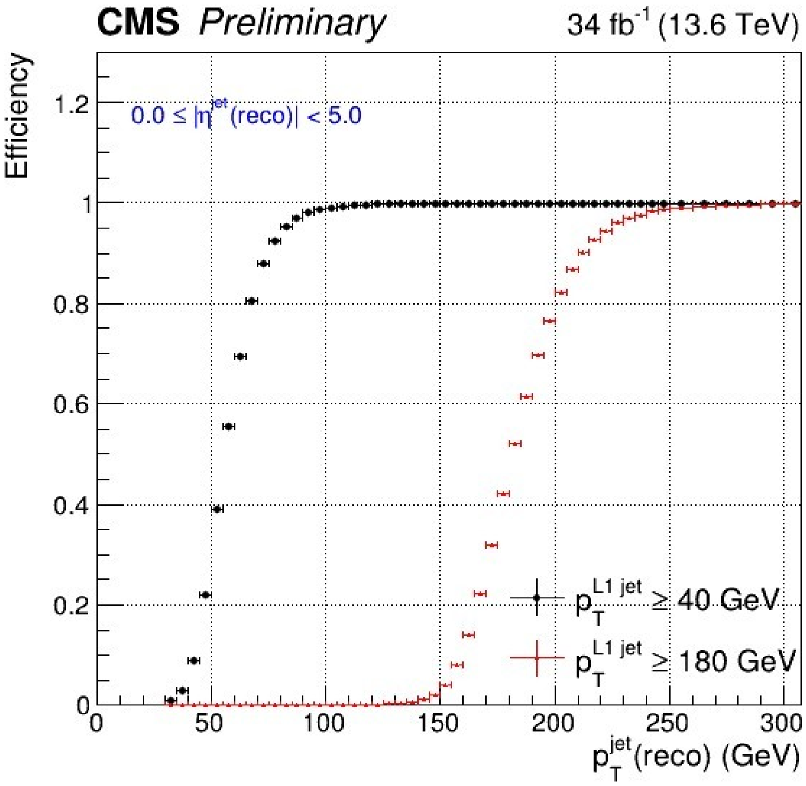

CMS Preliminary
34 fb⁻¹ (13.6 TeV)
Efficiency
|η^{τ, offline}| < 2.1
E_T^{τ, L1} > 30 GeV & Isolation
E_T^{τ, L1} > 34 GeV & Isolation
E_T^{τ, L1} > 38 GeV & Isolation
p_T^{τ, offline} [GeV]

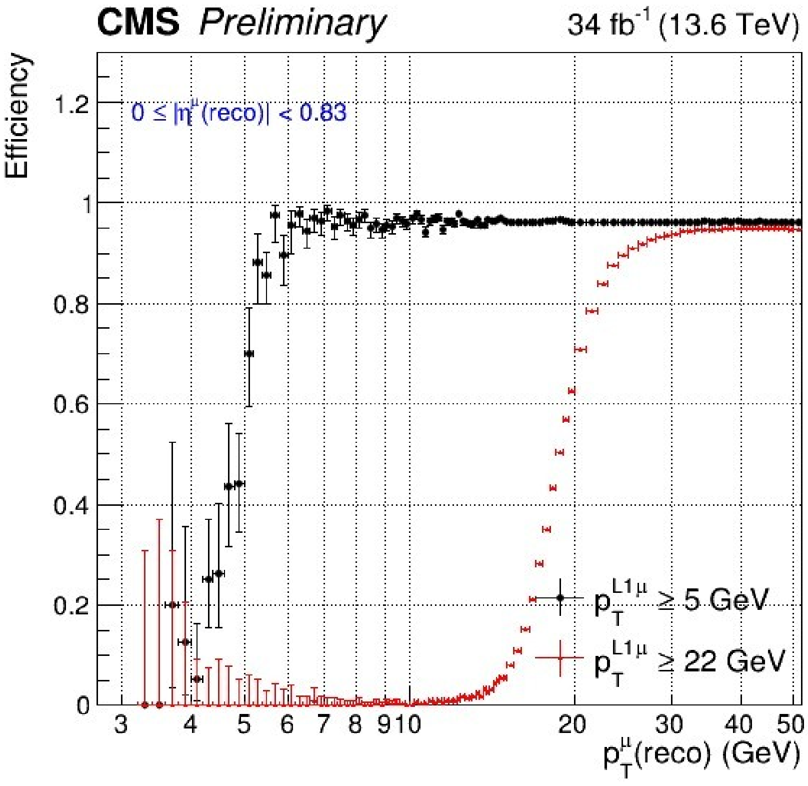

η
φ
τh position
Clusters
Isolation area
Unmerged
τh candidate
Merged
τh candidate


η
φ
7
6
5
4
3
2
1
0

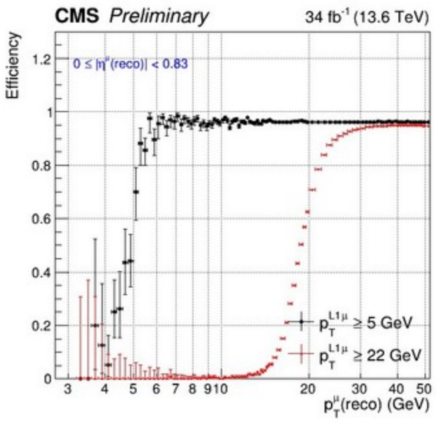
Jet

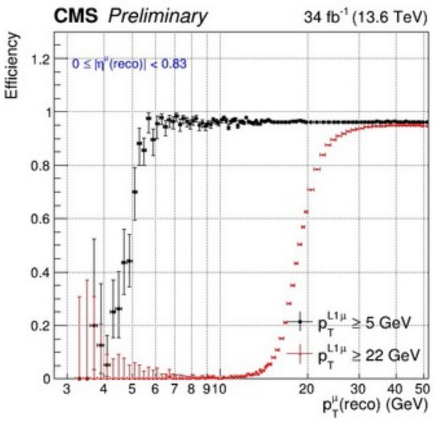
CMS-DP-2023-007

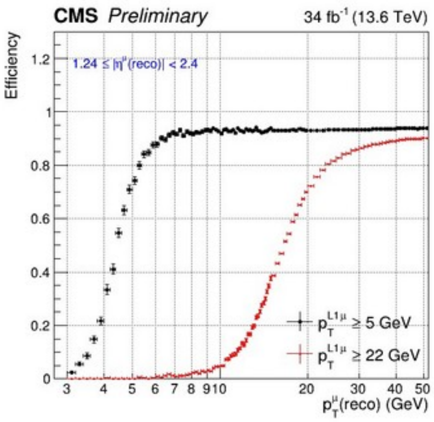




Muon







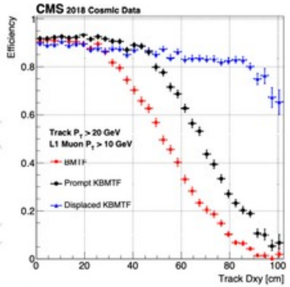


Figure 126: Displaced (blue) and prompt (black) kBMTF trigger efficiencies compared to the prompt BMTF (red) trigger efficiency with respect to muon track d_{XY} obtained using a sample of cosmic ray muons from 2018 data. The efficiencies are measured using muon candidates with $p_T > 10$ GeV. The prompt kBMTF improves BMTF efficiencies up to $\sim 90\%$ for up to 50 cm displacements, while displaced kBMTF retains efficiencies above 80% for up to 90 cm displacements.

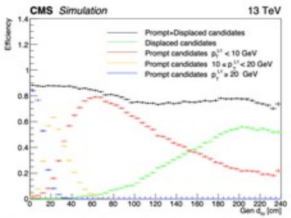


Figure 127: OMTF trigger efficiencies for displaced and prompt algorithms with respect to muon track d_{XY} obtained using a displaced muon gun sample. The efficiency curves are plotted for different values of the p_T estimate from the prompt algorithm (red, yellow, and blue), for the displaced algorithm (green), and also for the combination (black). The prompt algorithm underestimates the p_T of displaced tracks, causing most of the tracks to have $p_T < 10$ GeV. The displaced algorithm can recover these tracks and improve the efficiencies to be $\sim 80\%$ for up to 200 cm displacements.

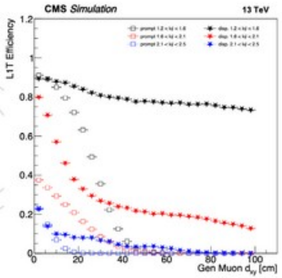
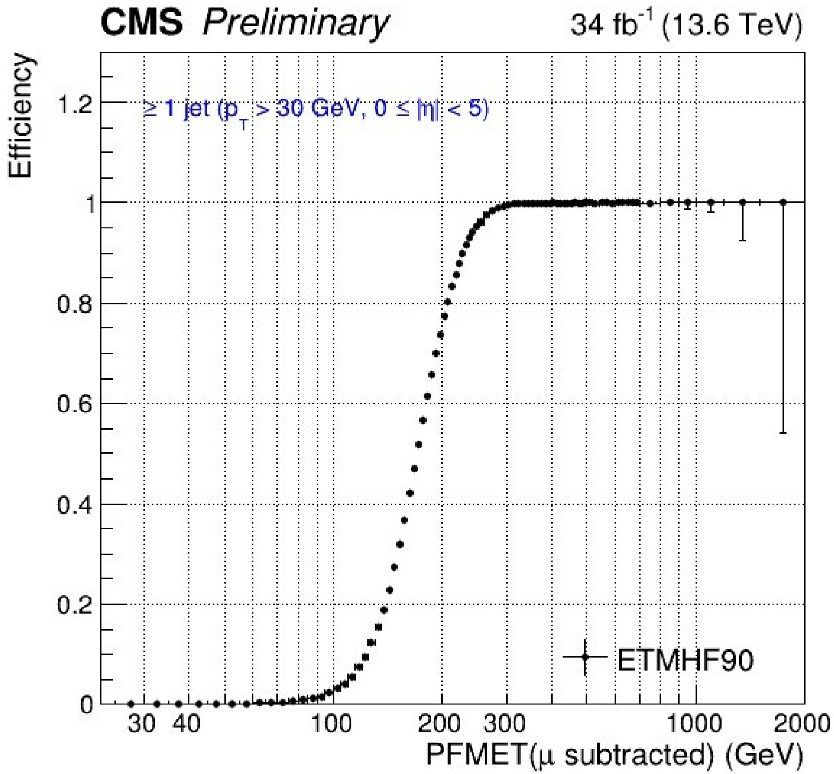
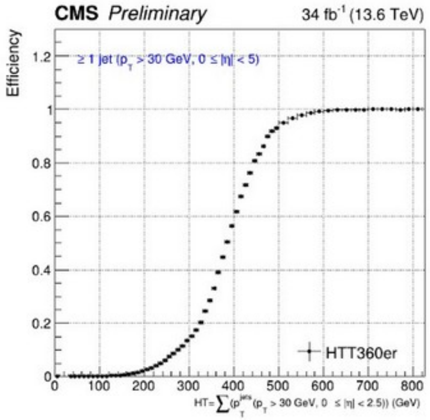


Figure 128: EMTF trigger efficiencies for prompt and displaced algorithms for L1 $p_T > 10$ GeV with respect to muon track d_{XY} obtained using a displaced muon gun sample. The solid stars show displaced NN performance while hollow squares show the prompt BDT performance. The different colors show different η regions: $1.2 < |\eta| < 1.6$ (black), $1.6 < |\eta| < 2.1$ (red), and $2.1 < |\eta| < 2.5$ (blue). The displaced algorithm shows efficiencies above 80% for $1.2 < |\eta| < 1.6$ for up to 100 cm displacements, while efficiencies for $1.6 < |\eta| < 2.1$ and $2.1 < |\eta| < 2.5$ at 60 cm displacement are around 20% and 5% respectively.

MET





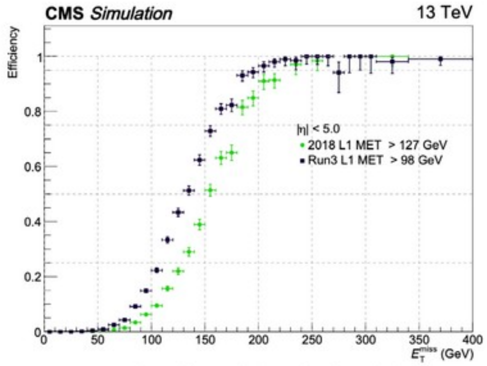


Figure 125: Comparison of the L1 MET efficiency using 2018 pileup mitigation (circles) and Run 3 pileup mitigation (squares) for thresholds that provide 4.3 kHz, in Z→ $\mu\mu$ events.