New CMS Trigger Strategies for Run 3 of the LHC

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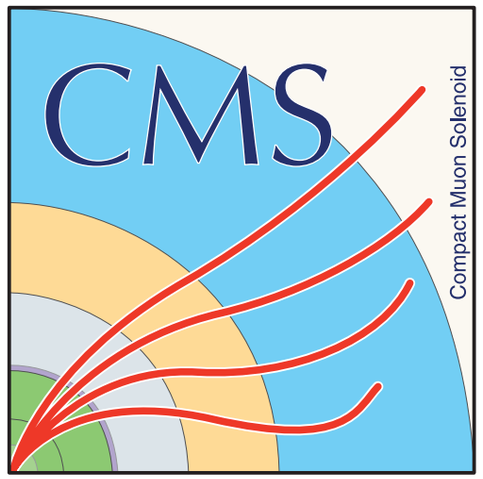
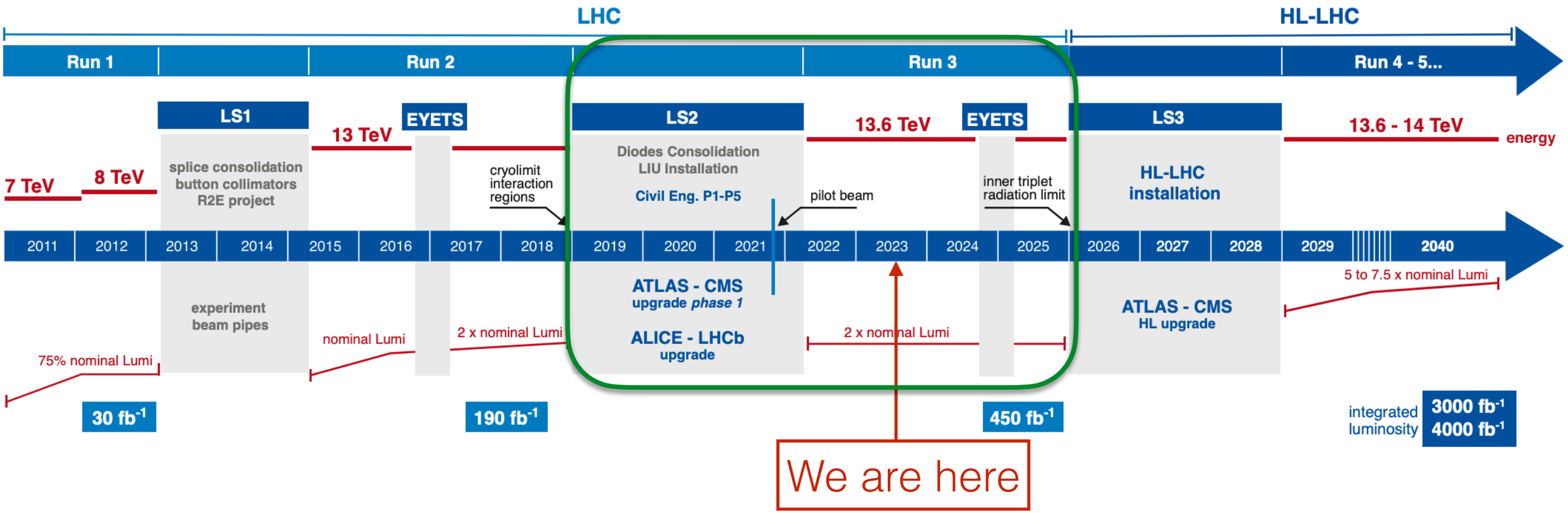
on behalf of CMS Collaboration

24th August 2023



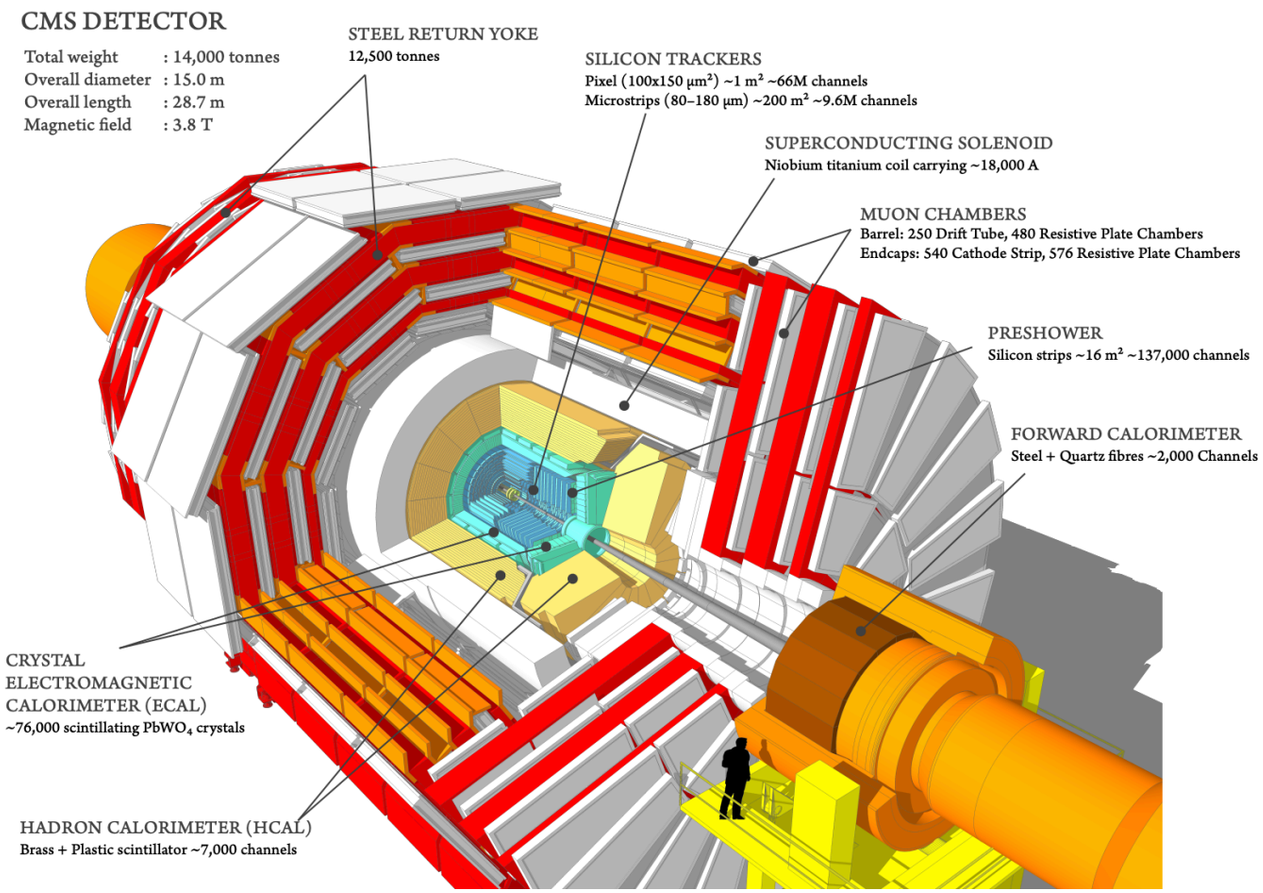
RICE

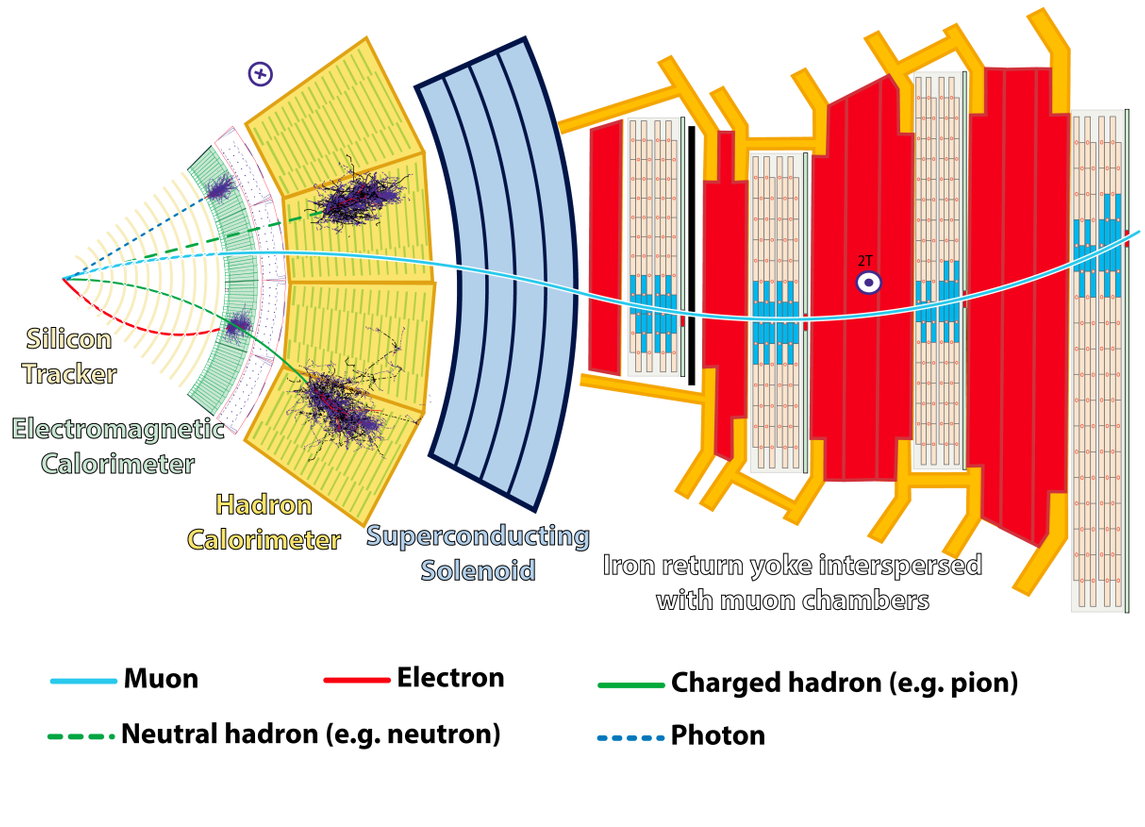
Run 3 of the LHC



- After a very successful Run 2 of the Large Hadron Collider, we are now in Run 3 with LHC running at 13.6 TeV.
  - A lot of open questions to investigate at the new center-of-mass energy with even more data.
- Run 3 will more than double the data delivered to the experiments.
  - Decent improvement for many of the existing results and new possibilities for new physics searches.
  - New trigger strategies can substantially increase capabilities of some new physics searches and rare SM processes
    - Long-lived particles, HH production, B-physics and lepton flavour universality (LFU) searches…

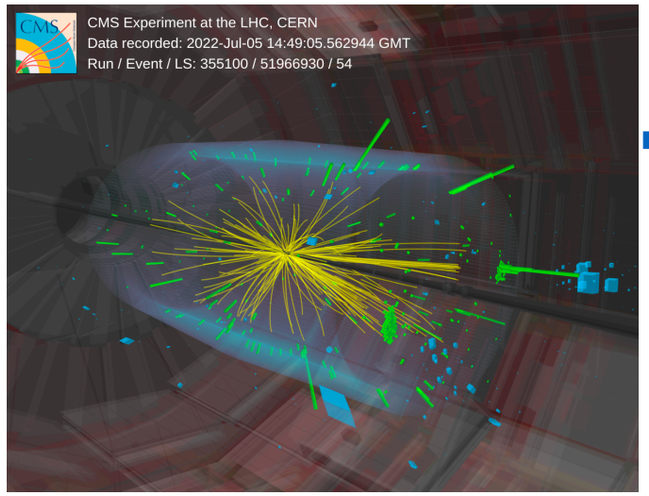
CMS Experiment at the LHC





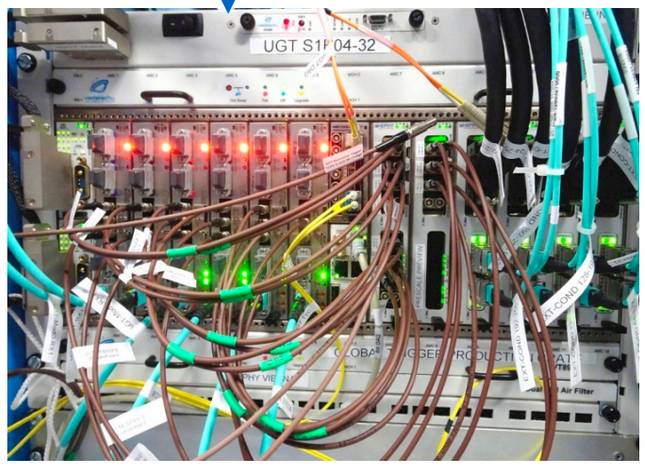
- CMS is one of the two general purpose experiments at the LHC
  - Strong solenoid magnet with 3.8 T magnetic field
  - Multi layer design including silicon tracker, electromagnetic and hadronic calorimeters and muon systems
  - A two level trigger system to select interesting events out of 40 MHz of LHC collisions.

CMS Trigger System



An event display from first 13.6 TeV collisions seen in the CMS

40 MHz
25 ns



L1T

110 kHz
<4 µs

HLT

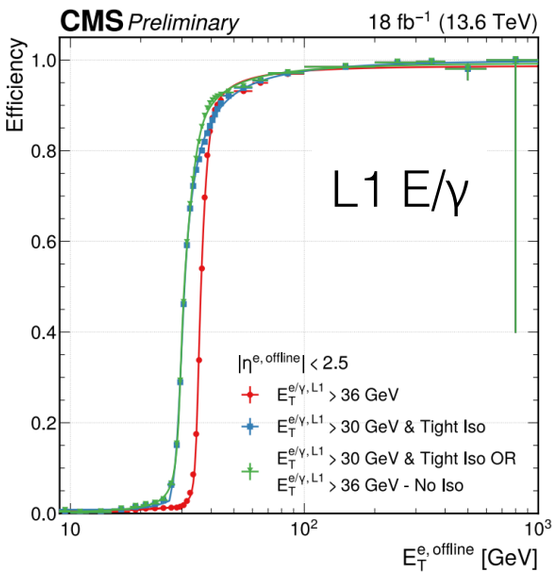
~5 kHz
~465 ms/event
~6 GB/s

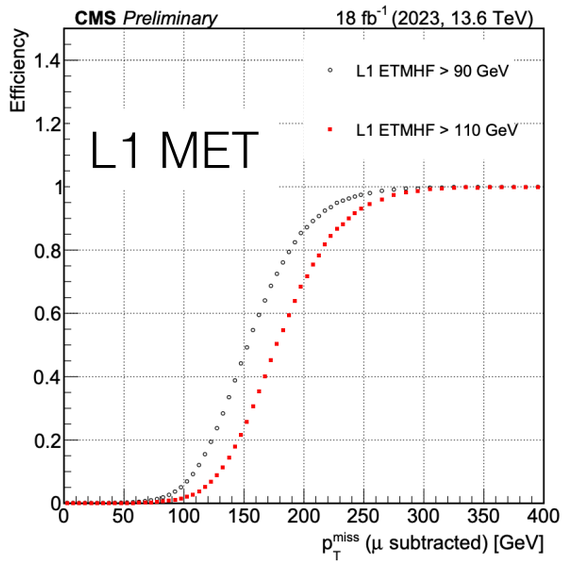
Data storage

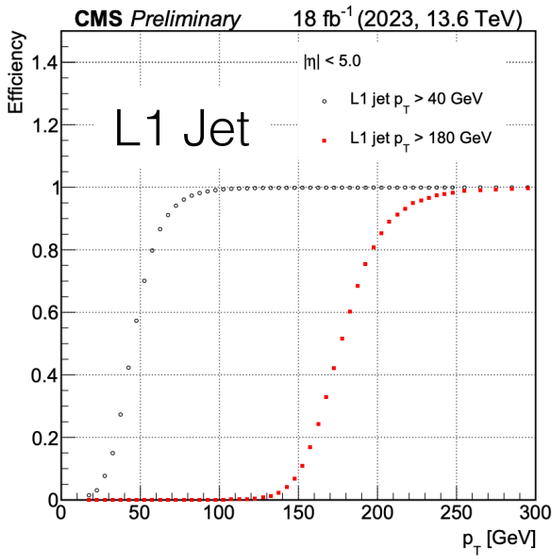
- CMS uses a two level trigger system
- Level-1 Trigger (L1T): Hardware based, using custom electronics
  - Uses simplified readout, output rate is 110 kHz.
- High Level Trigger (HLT): Software based, using CPU/GPU farms
  - Uses full event readout with simplified reconstruction, output rate is ~5 kHz for full offline reconstruction and ~22 kHz for trigger-level reconstruction.

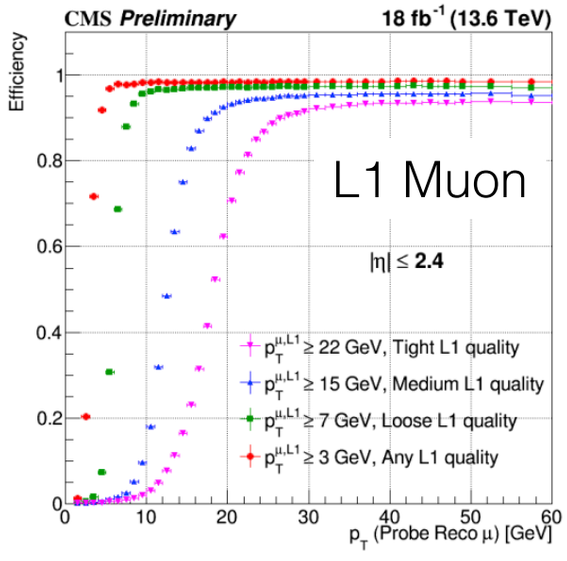
CMS Trigger System in Run 3

- LHC is providing 13.6 TeV collisions in longer fills and with unprecedented instantaneous luminosity in Run 3
- CMS trigger systems have been running with excellent performance for all standard objects and with highest L1T and HLT rates up to date.
  - See Sanu's talk for an overview of Run 3 CMS HLT performance!

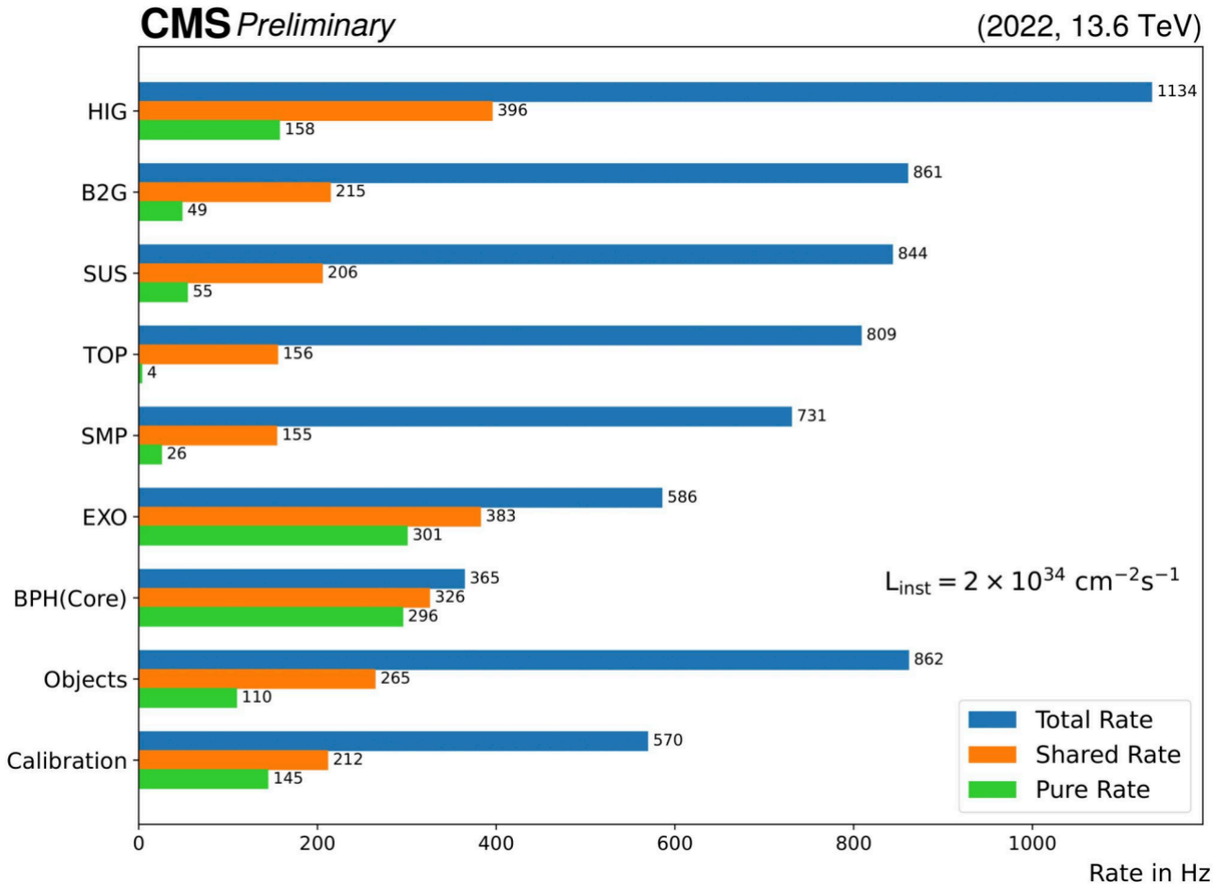








HLT rate per physics group in 2022

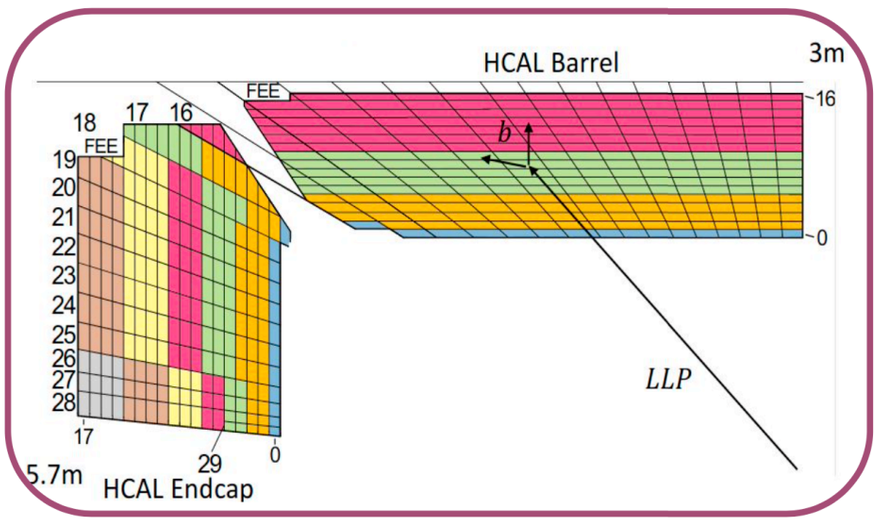


DP-2023-054, DP-2023-055, DP-2023-057

New Features in CMS Triggers

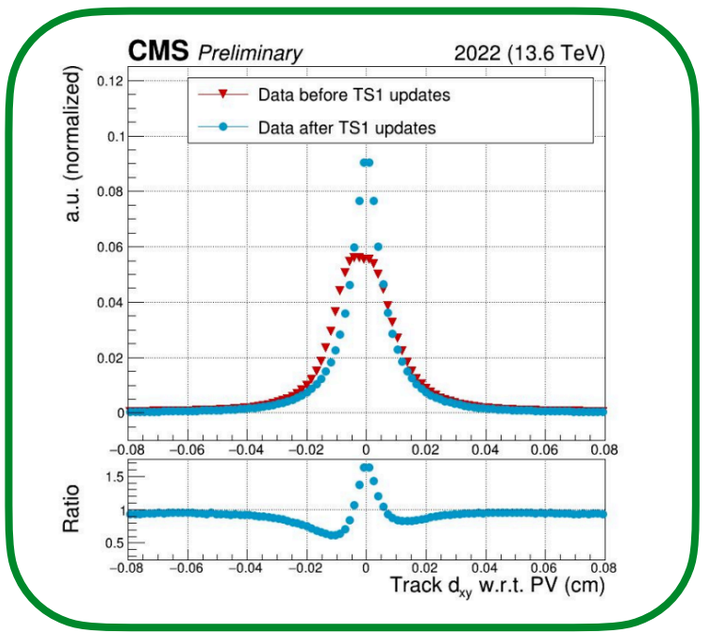
- CMS L1T added new methods for triggering on rare and unconventional signatures at Run 3. One of the main focuses of these algorithms is long-lived particles
  - Added new triggers to look for displaced muons, hadronic showers in muon systems, and displaced or delayed jets made possible by upgrades in HCAL and muon systems as well as trigger electronics.
- New HLT algorithms and reconstruction methods to boost sensitivity both for new physics searches and also to SM processes.
  - New single iteration tracking based on optimized pixel track reconstruction
  - New jet flavour tagging based on graph neural networks (ParticleNet)
  - Offloading 30% of HLT reconstruction to GPU farm and running in parallel to the CPU farm
  - Improved HLT data scouting and data parking methods for Run 3
    - Scouting significantly increases the number of events stored by saving only HLT event reconstruction
    - Parking allows us to save high rate of events without immediate offline reconstruction. The reconstruction is delayed until there are sufficient computing resources.

LLPs decaying in HCAL



DP-2023-043

Improved HLT tracking

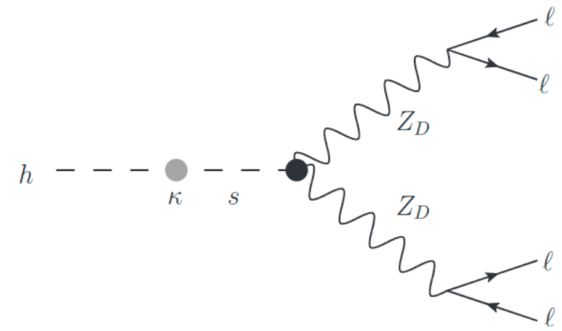


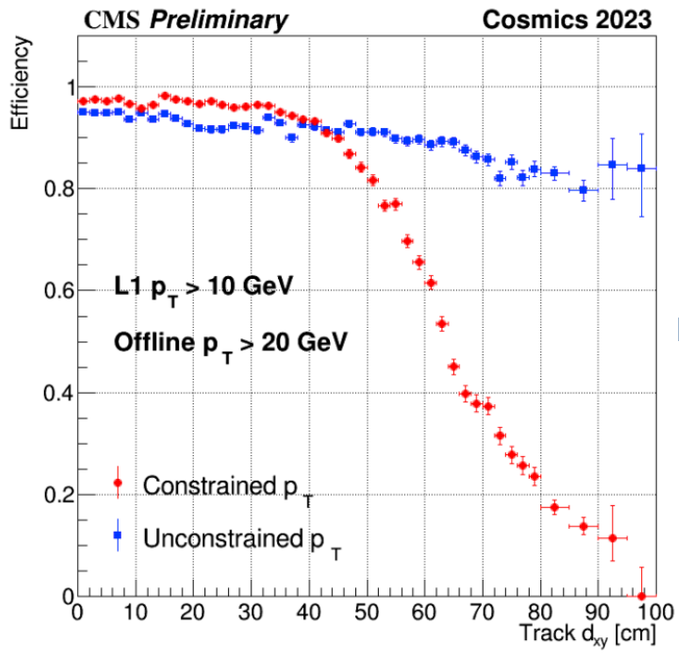
DP-2023-028

A GPU node in HLT farm

Displaced Muons

- New L1T algorithms for p_T assignment to muons originating from a displaced vertex.
  - Removes the p_T underestimation by removing the beam spot constraint.
  - In barrel muon trigger using a Kalman Filter algorithm, online since 2022
  - In endcap muon trigger using a neural network, online since June 2023.
- New HLT paths to reject more prompt background and make use of L1T upgrades.
- Provides substantial improvements to LLP searches with final state muons
  - 2-4 times improvement compared to Run 2 for large cτ for LLPs decaying to dimuons.
  - Recent results from displaced dimuons originating from a common vertex search were shown in Florencia's talk (EXO-23-014)





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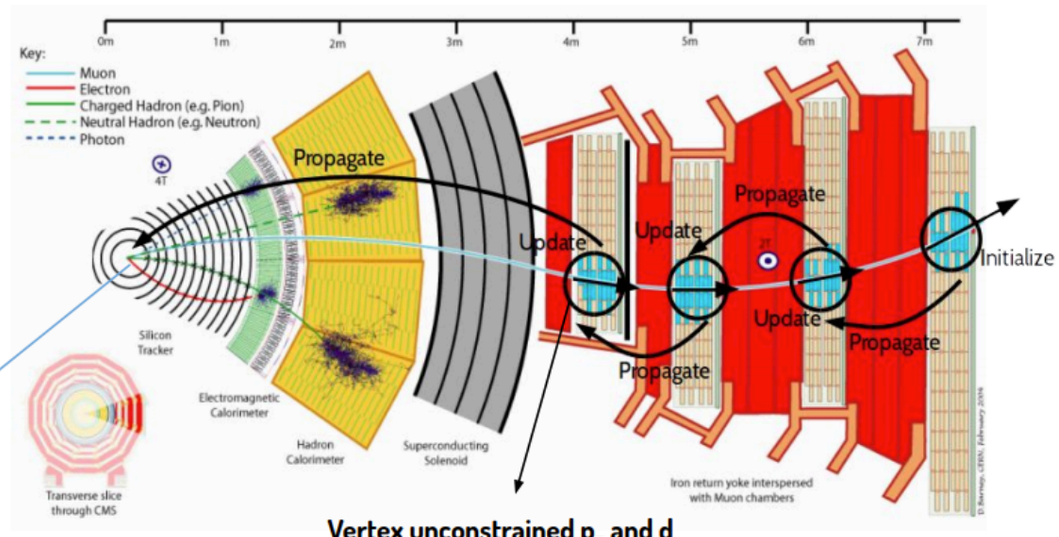
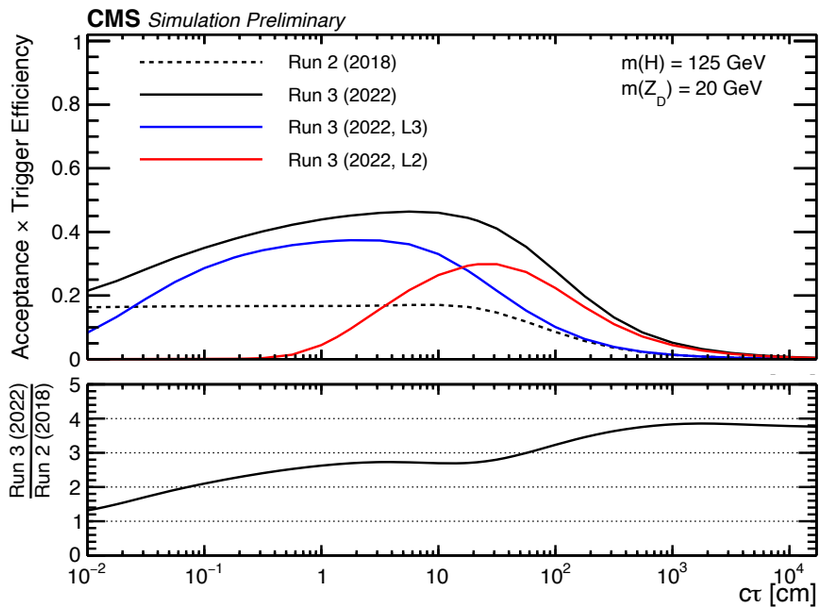


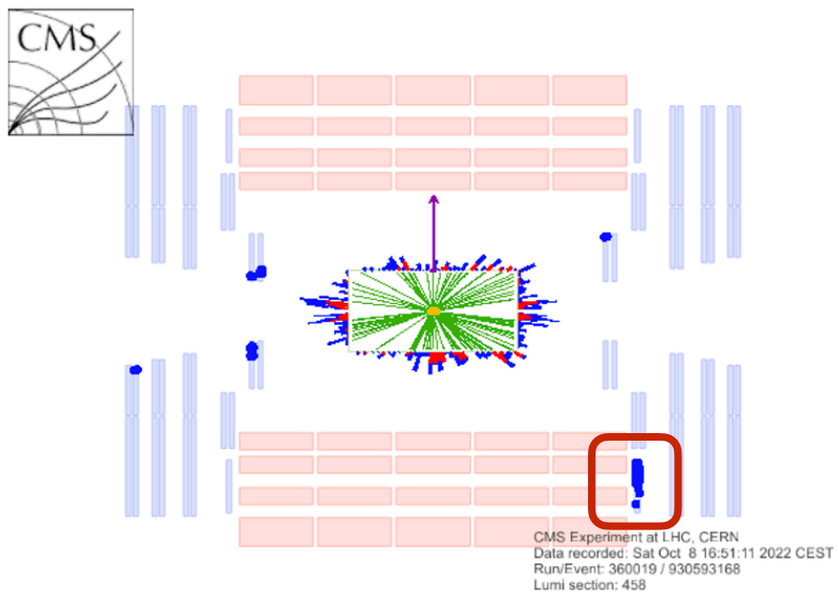
Vertex constrained p_T measurement.
Prompt kBMTF.

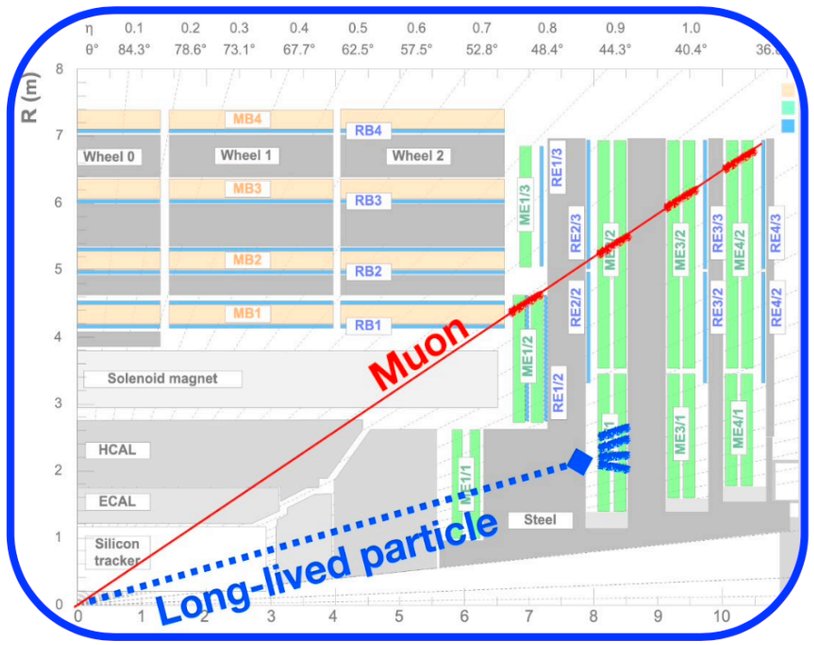
Vertex unconstrained p_T and d_{xy} measurements (NEW).
Displaced kBMTF.

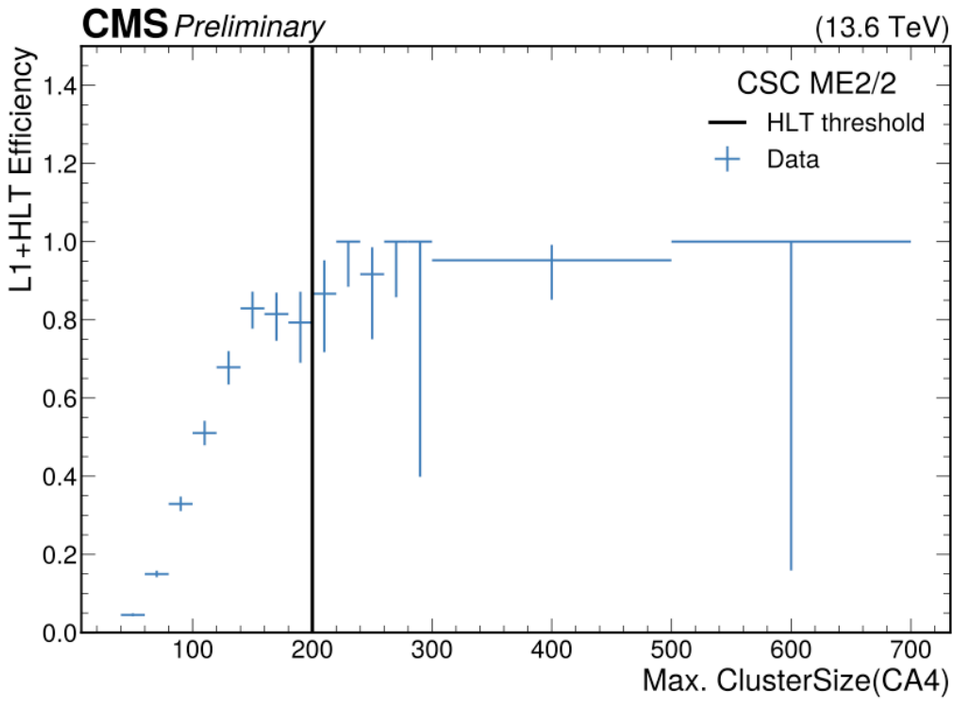


Hadronic Showers in Muon Systems

- New trigger in L1T to trigger on LLPs decaying hadronically within the endcap muon chambers.
  - Signature is high multiplicity of hits in a given chamber.
  - Using muon system as a sampling calorimeter
  - Made possible by steel shielding in front of muon chambers
- New Run 3 triggers at L1T+HLT leads to expected signal efficiency increase up to a factor 20 for H→SS→4τ signals with LLP lifetimes between 10 cm to 1 m



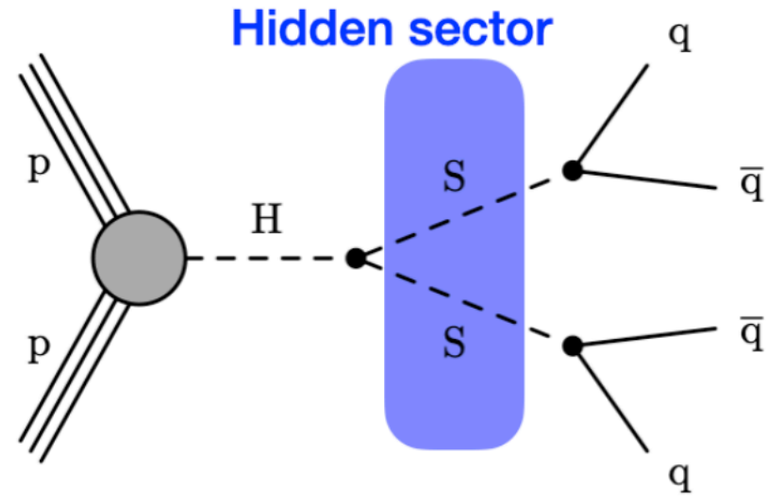


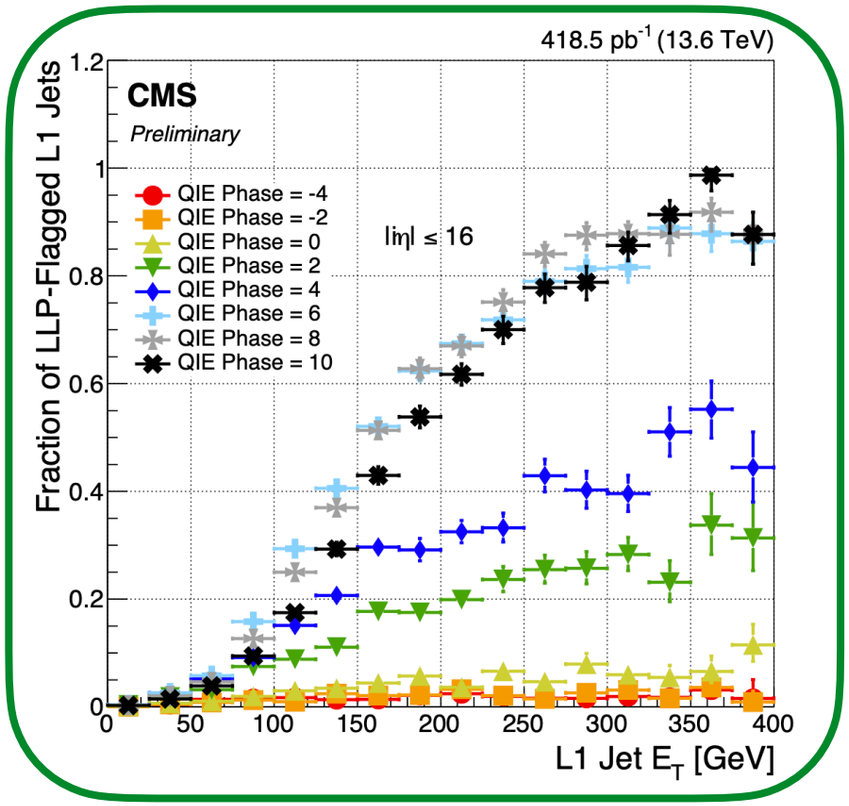


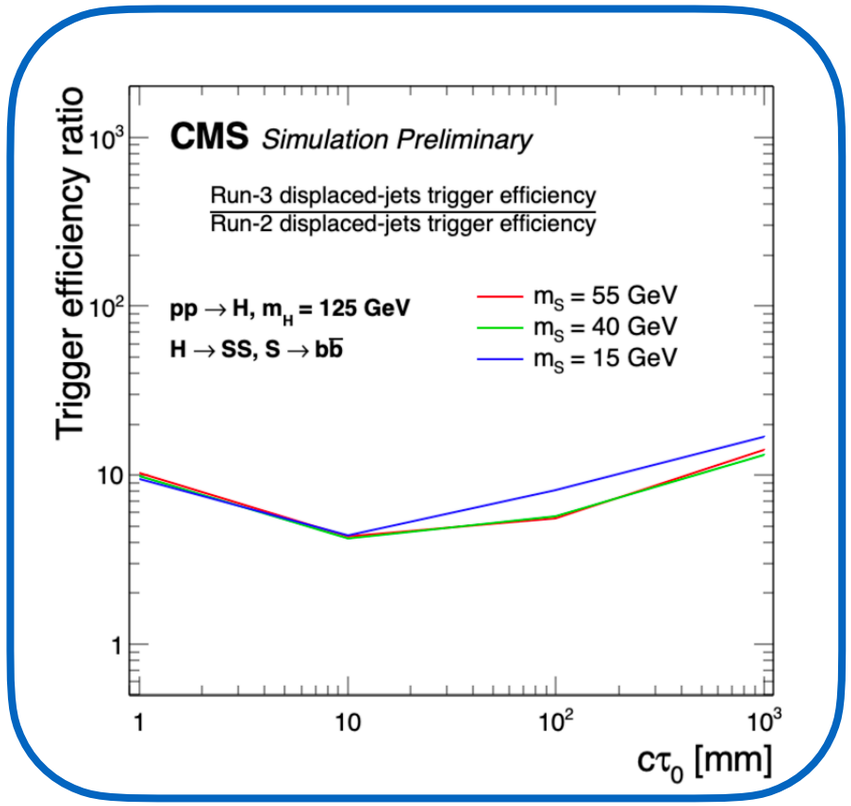
DP-2022-062

Displaced and Delayed Jets

- New L1T and HLT algorithms for tagging displaced and delayed jets
  - Made possible at **L1T** by **HCAL** upgrades to provide depth and timing information
    - Displaced and delayed jet triggers based on HCAL information improve LLP acceptance wrt standard triggers by up to a factor of 4
  - Improved tracking at **HLT** significantly increase acceptance of Run 2 displaced jet triggers
    - Uses HT triggers at L1T to seed HLT paths.
    - A factor 4-11 improvement in LLP signal efficiency for signals with displaced jets compared to Run 2 for low mass LLPs, $m_{LLP} < 100$ GeV



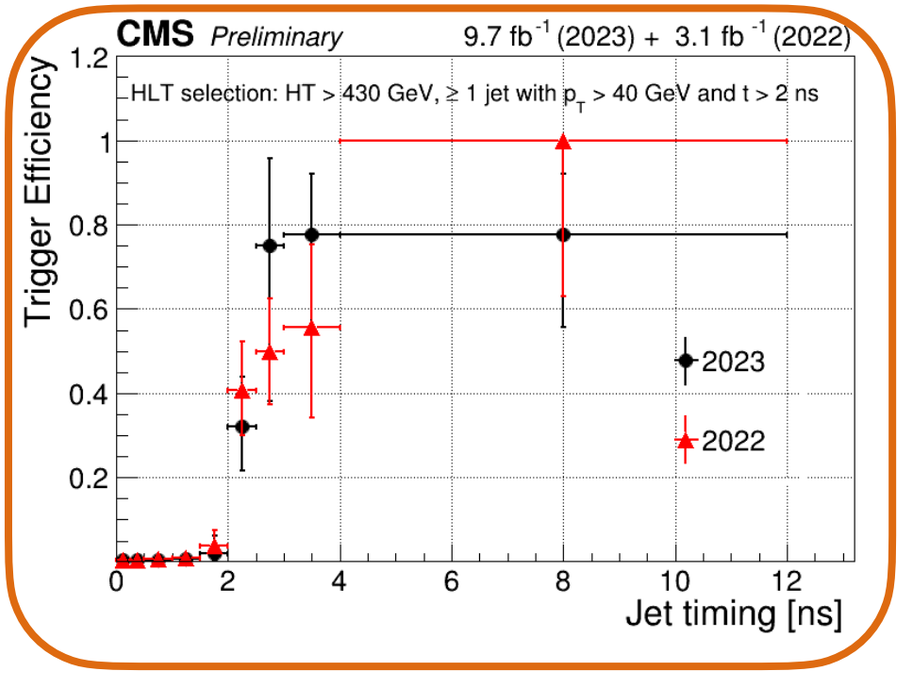


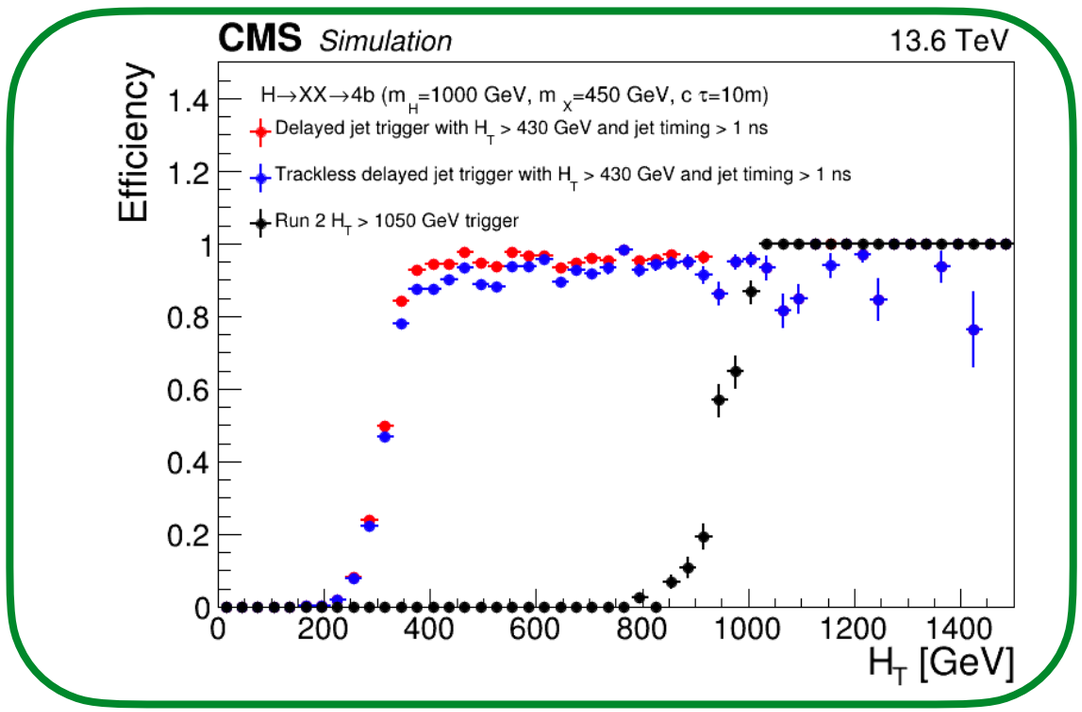


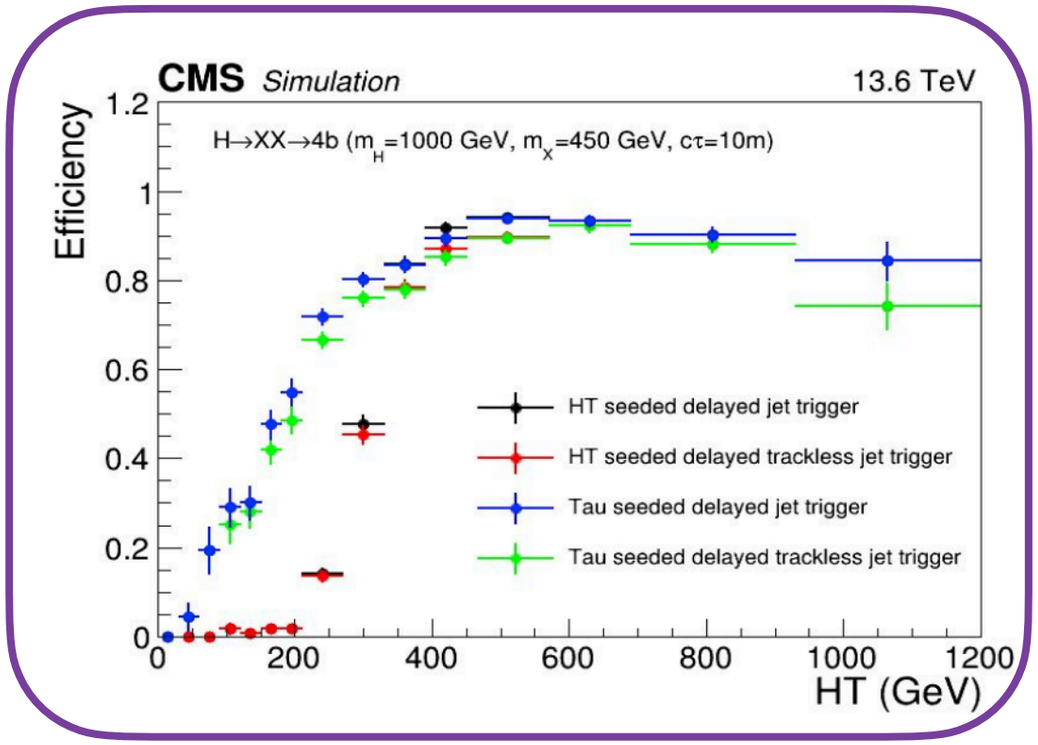
DP-2023-043

Displaced and Delayed Jets

- New dedicated **HLT** algorithm making use of **ECAL timing information** to trigger on delayed jets
- Uses lower threshold HT triggers (360 GeV) or Tau triggers (120 GeV) at L1T.
  - Enable sensitivity to new models and allow access to delayed jets from low mass LLPs
    - Efficiency ~100% for delayed jet timing beyond 4 ns.
  - Different paths targeting inclusive or trackless delayed jets
    - Significant improvement in signal efficiency for $430 < H_T < 1050$ GeV.
  - Tau seeded delayed jet triggers at HLT improve signal efficiency for signal models with heavy LLPs or LLPs decaying to taus
    - The resulting jet from a massive and displaced LLP decay can look like τ leptons
- Large gains in sensitivity for LLP searches compared to Run 2



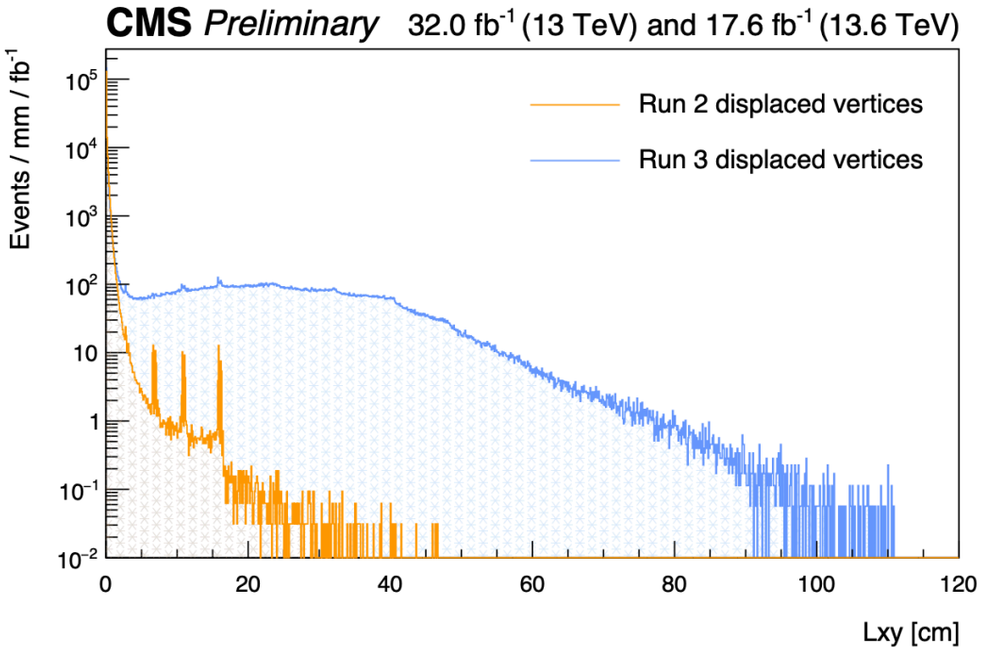


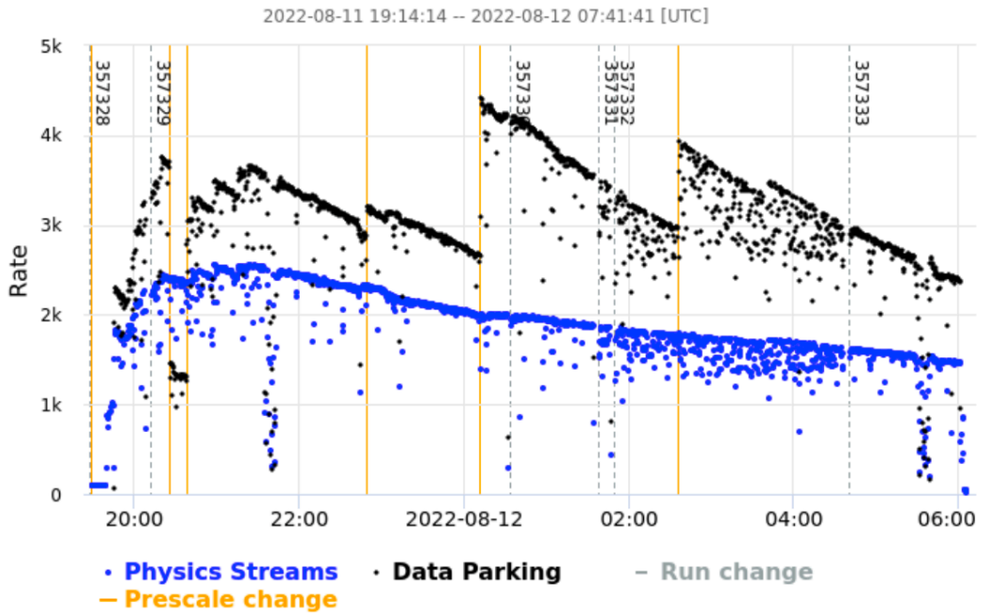


DP-2023-043

Data Scouting and Parking

- Scouting at HLT in Run 3 allows us to save HLT reconstructed objects at very high rate allowing higher rate trigger paths to be used.
  - In Run 3 scouting uses all physics objects and runs at 30 kHz input rate at HLT!
  - Possibility of exploring more complex topologies due to the new collections available in scouting for Run 3
  - Example: Displaced dimuons with scouting in Run 3
    - Run 3 scouting dataset now includes larger displacements for LLPs: $L_{xy} > 11$cm
    - Scouting triggers can target lower muon p_T and dimuon mass compared to standard triggers.
      - Leads to improved sensitivity for low mass LLPs, $m_{LLP} < 10$ GeV
- Data parking saves high rate of events without offline reconstruction.
  - In Run 3 CMS increased rate of parking for b-physics to 1.6 kHz from ~300 Hz in Run 2.
    - Includes new soft dielectron triggers and inclusive dimuon triggers.
  - CMS also introduced new parking paths targeting VBF Higgs production, HH→4b, and LLPs decaying to delayed jets in 2023.
    - Opens up the available phase space for related searches using parked data in Run 3

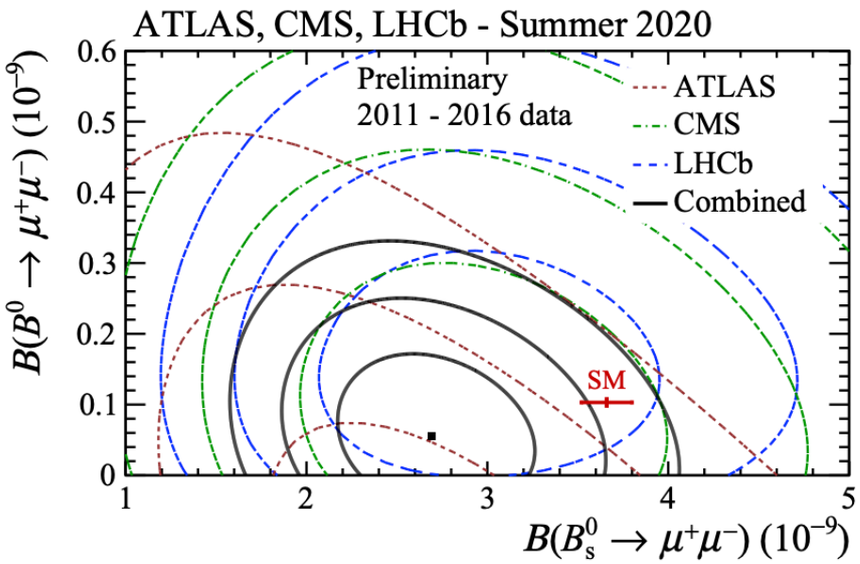




B-physics, LFU, VBF Higgs, HH→4b

- Run 3 brings many new triggering methods to increase acceptance for b-physics and LFU searches
  - Increased rate of b-parking and new soft dielectron and inclusive dimuon triggers improve CMS searches for LFU through R(K) ratio
  - New “universal” dimuon triggers targeting $B_s \to \mu\mu$ analyses keeping CMS competitive with other experiments.
  - New triple muon triggers for rare signatures such as $\tau \to 3\mu$ improving the reach beyond Run 2 level.
- New parking paths and improved HLT triggers to bring even more efficiency to VBF Higgs production and HH→4b analyses
  - New VBF parking paths relax trigger requirements for jet p_T and dijet invariant mass at L1T to open up the phase space for VBF Higgs searches
  - New HH parking with reduced HT thresholds at L1T and HLT as well as the new ParticleNet b-tagger at HLT improves trigger efficiency for HH→4b search by nearly 60%

$B_s \to \mu\mu$ combination



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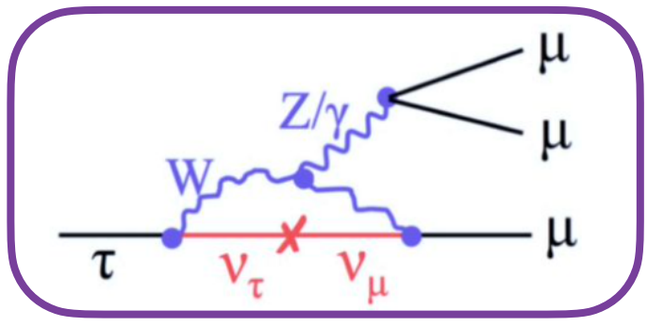
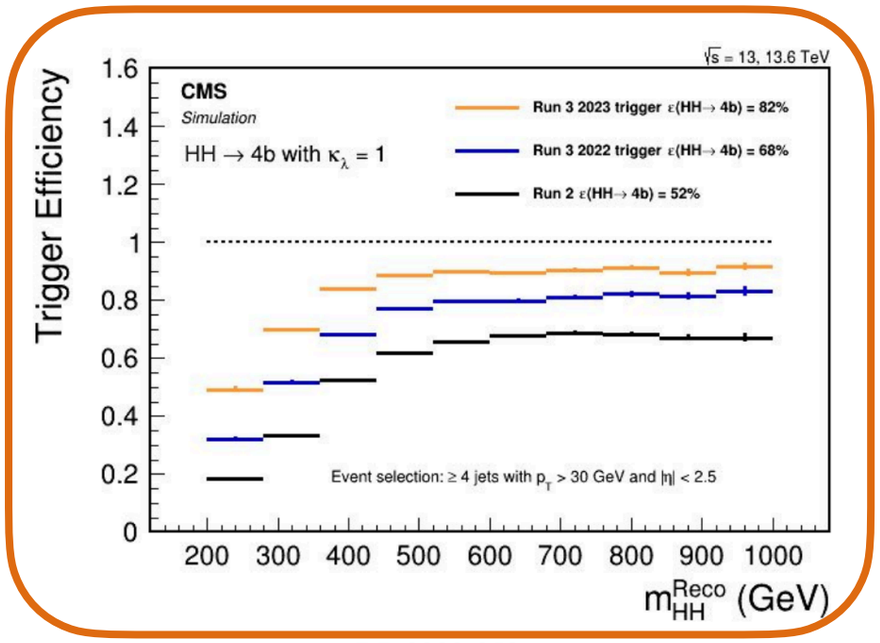
$\tau \to 3\mu$



HH→4b



DP-2023-050

Conclusions

- Run 3 of the LHC brings new opportunities to search for rare and unconventional signatures
- CMS is improving triggering methods to increase sensitivity to many physics processes beyond the capabilities of Run 2
  - Displaced and delayed particles resulting from LLPs
  - Rare Higgs processes and HH production
  - B-physics, LFU, and other precision tests of the SM
- Run 3 is going to bring more than what we had in Run 2
  - Exciting times for new physics searches thanks to new triggers
  - A lot of new ideas for triggering to make use of and learn lessons from
- More interesting developments are in progress for HL-LHC!

Thank you!

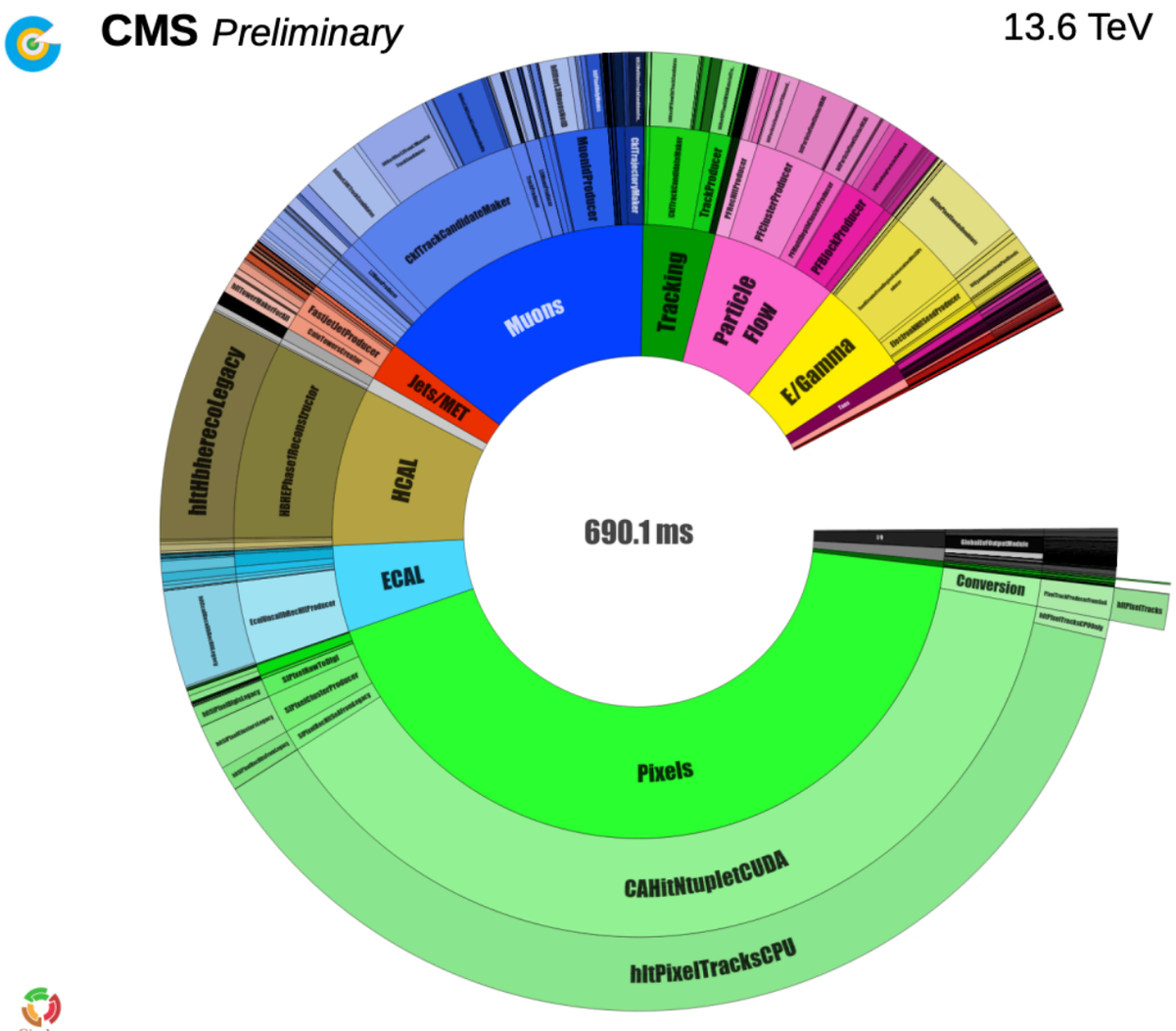
Acknowledgement

- This material is based upon work supported in part by the U.S. Department of Energy, DOE Grants: DE-SC0023351 and DE-SC0010103

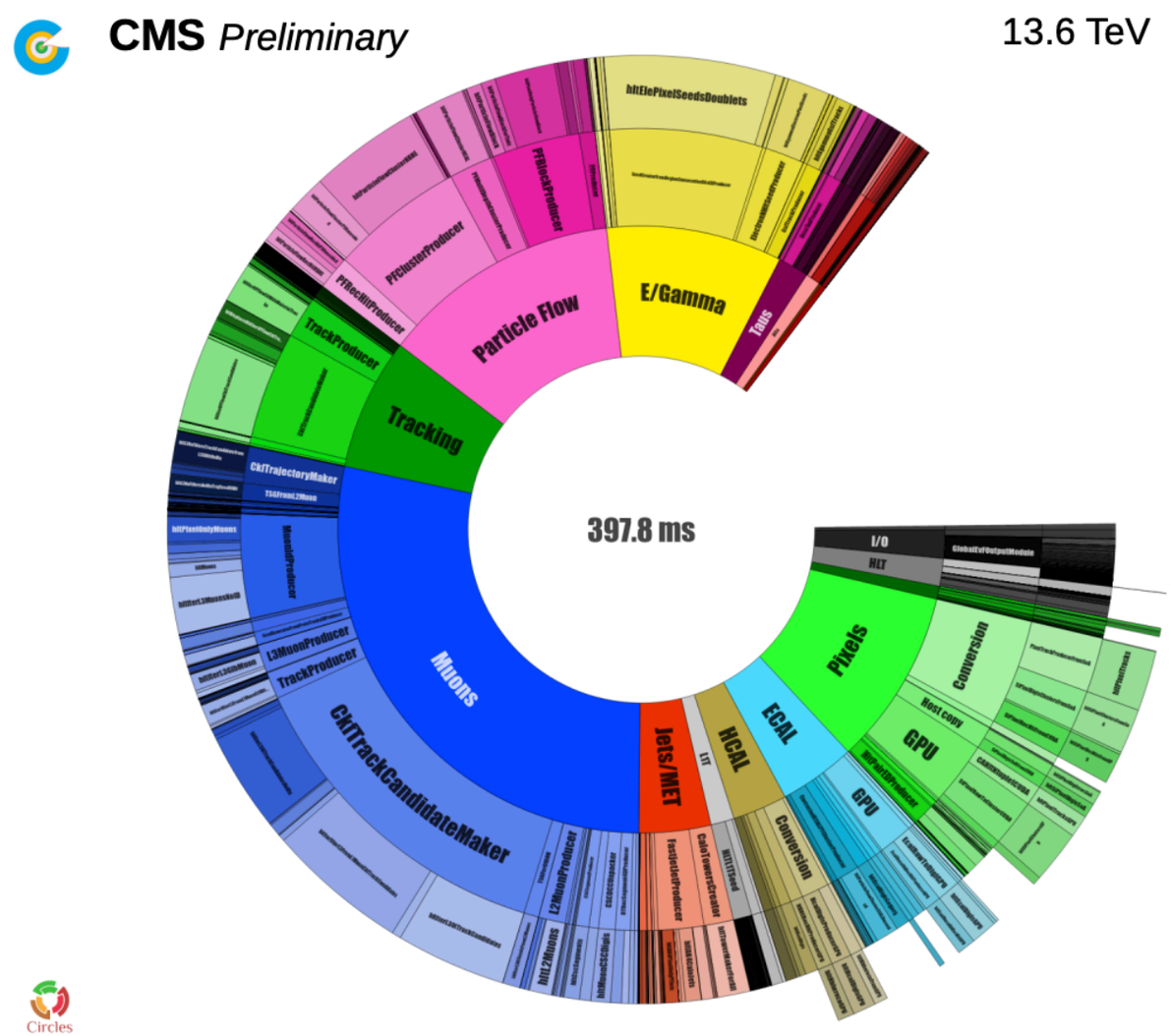
Backup

GPU Timing

CPU only



CPU+GPU



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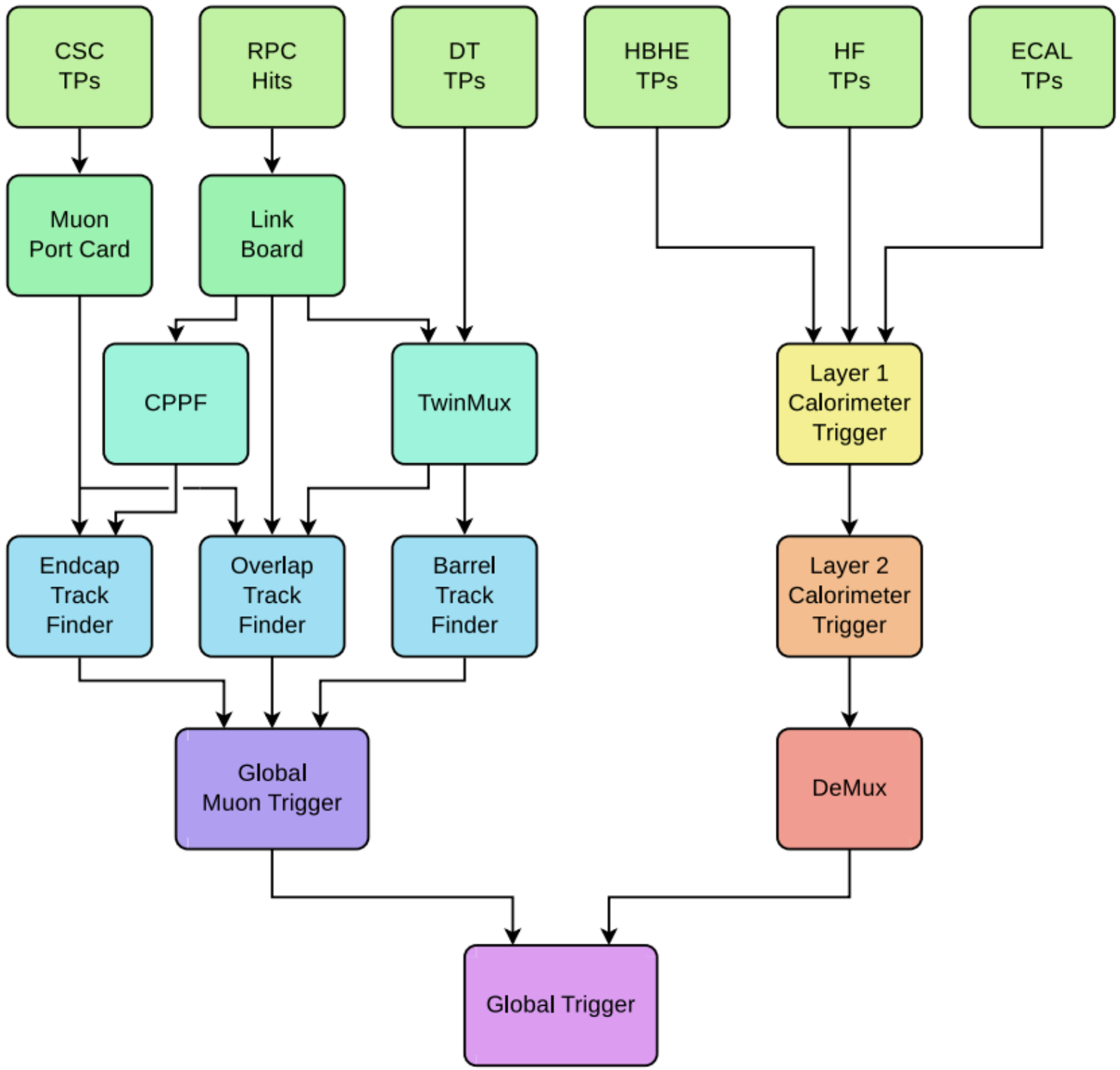
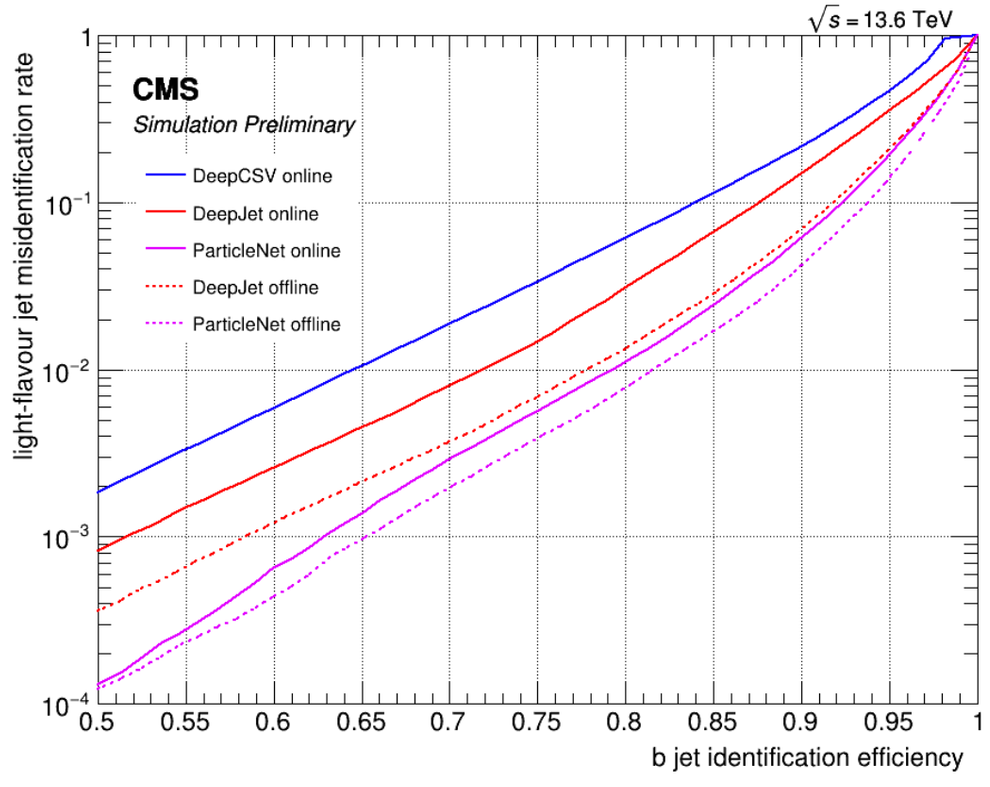
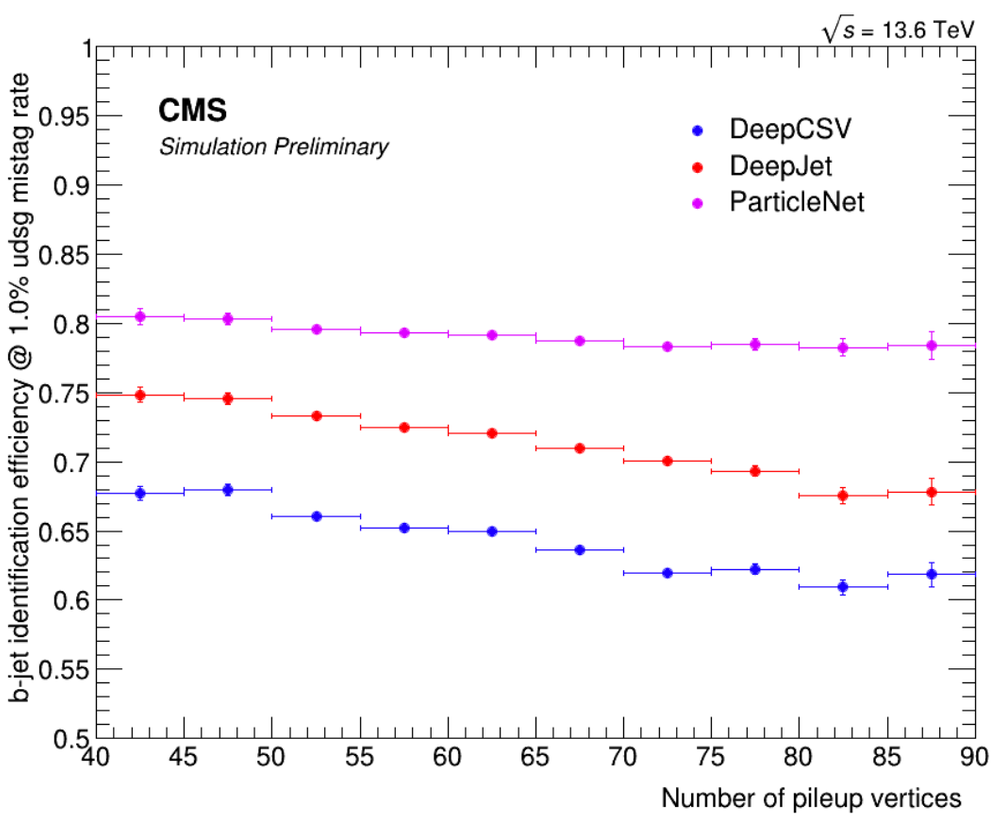
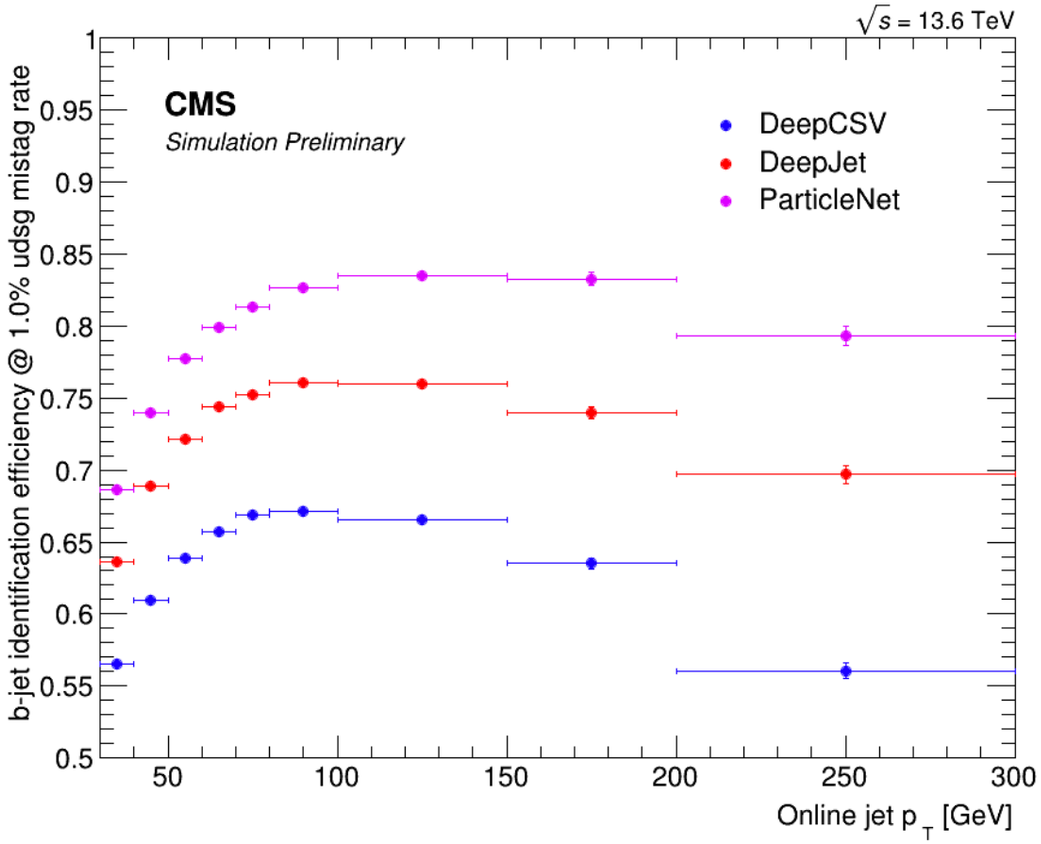
CMS L1T


CSC TPs
RPC Hits
DT TPs
HBHE TPs
HF TPs
ECAL TPs
Muon Port Card
Link Board
CPPF
TwinMux
Layer 1 Calorimeter Trigger
Endcap Track Finder
Overlap Track Finder
Barrel Track Finder
Layer 2 Calorimeter Trigger
Global Muon Trigger
DeMux
Global Trigger

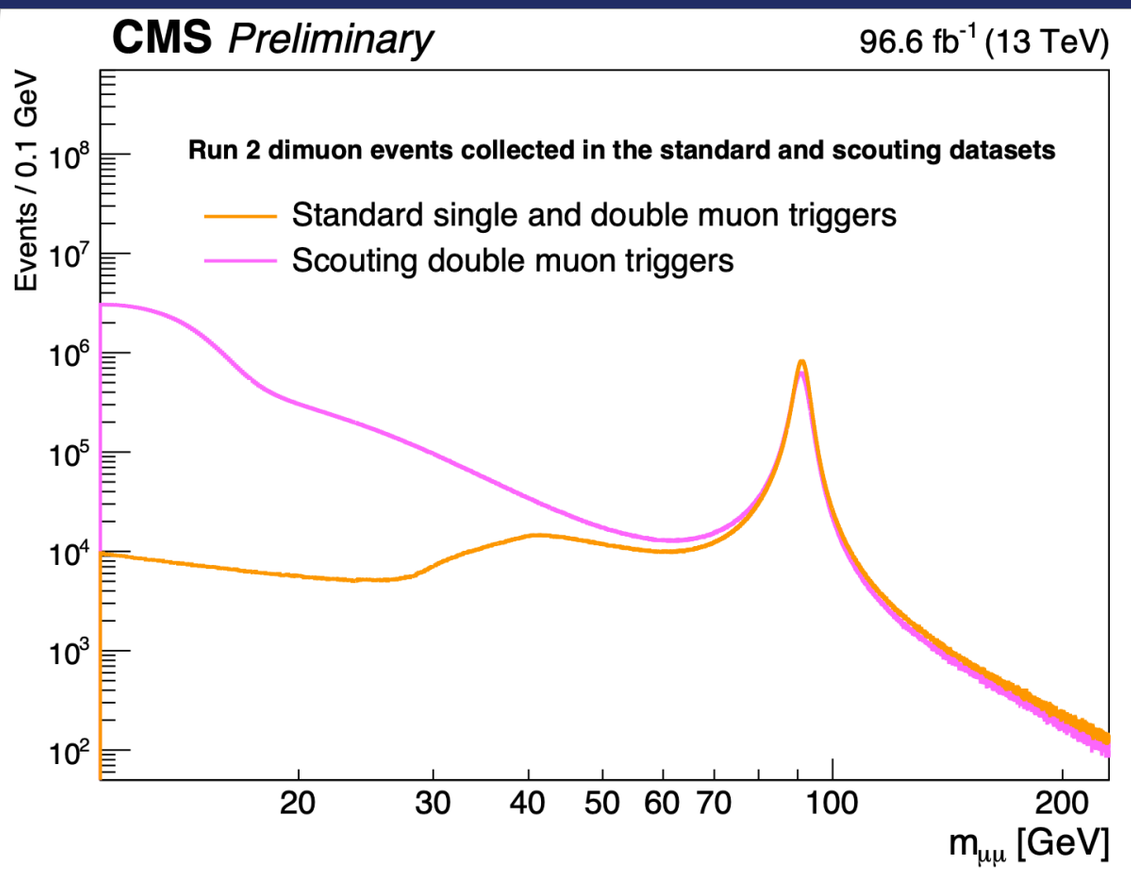
ParticleNet Performance

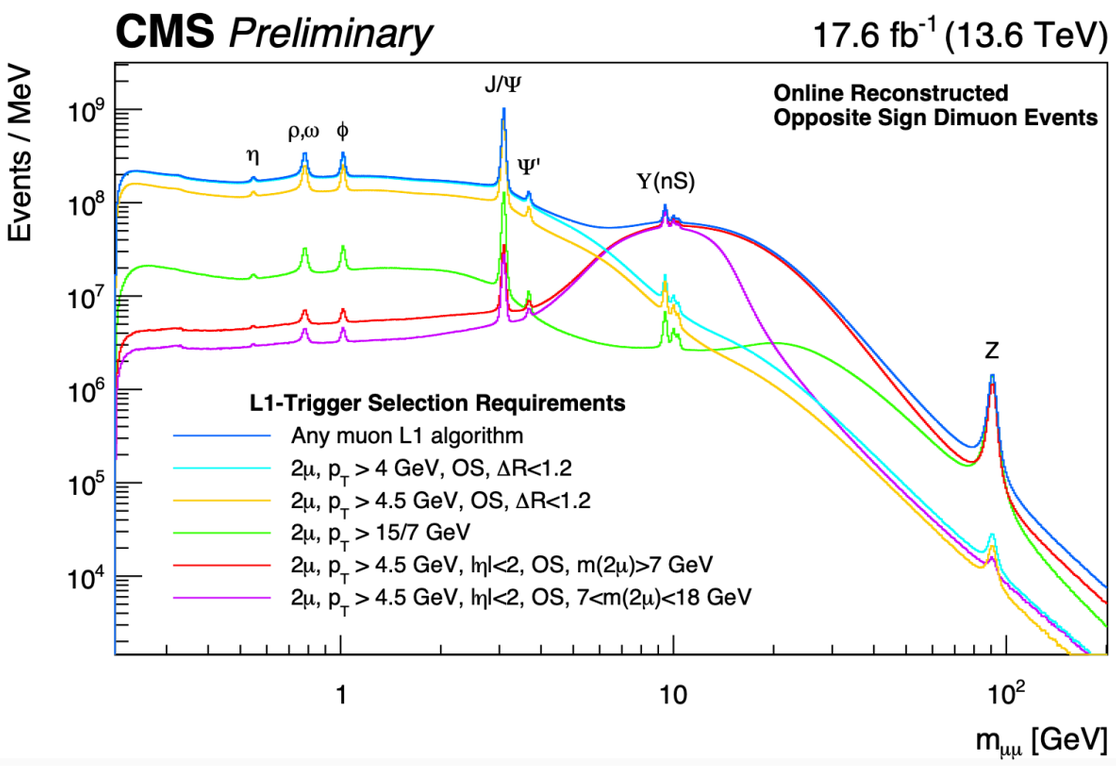


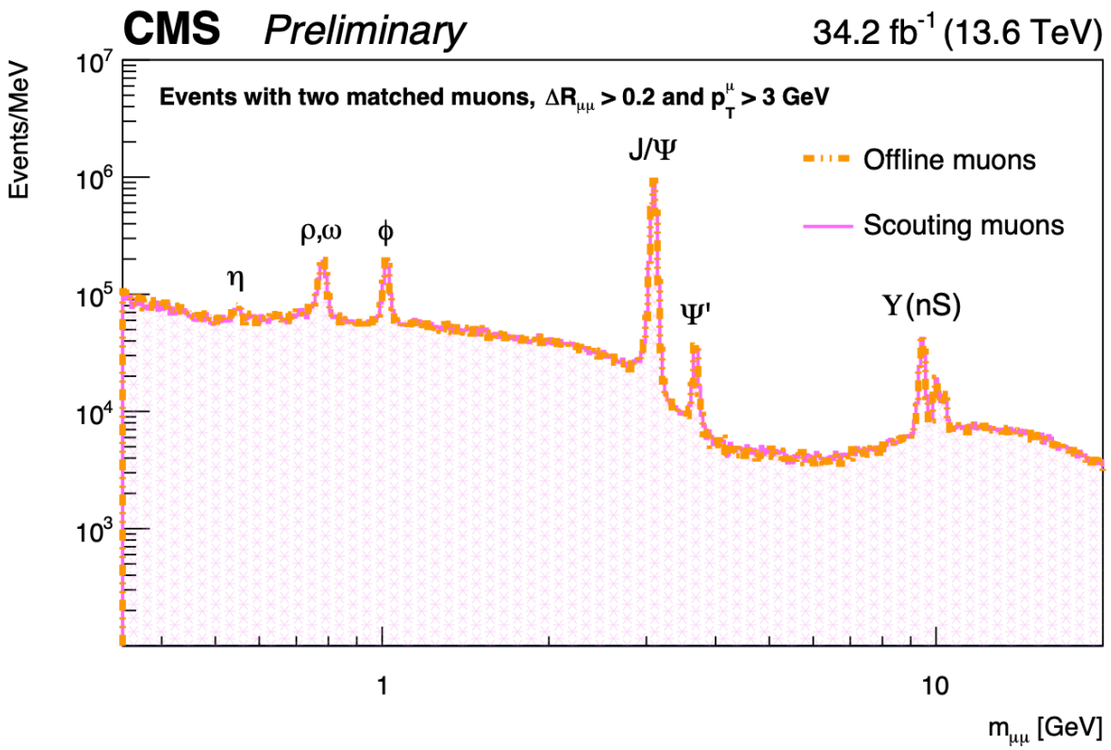




HLT Scouting







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