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New algorithms and performance for the Level 1 Muon Trigger of the CMS experiment, targeting the Run 3 era of the LHC

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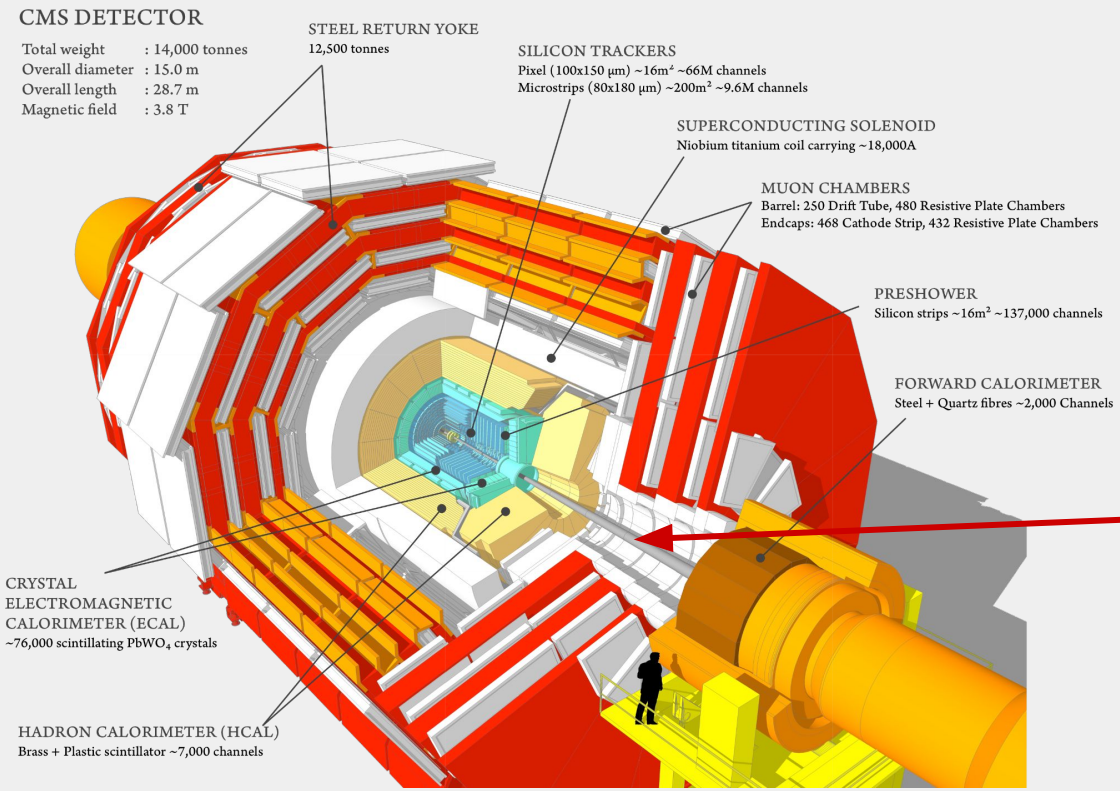
(University of Ioannina)

on behalf of the L1 Trigger Group and the CMS Collaboration

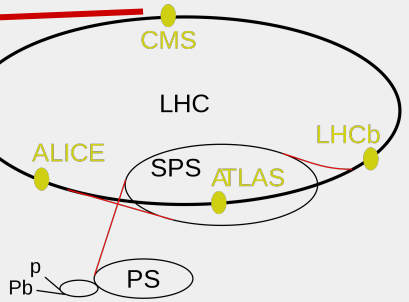
16th Topical Seminar on Innovative Particle and Radiation Detectors

(IPRD23) 25-29 September 2023 Siena, Italy

The CMS experiment at CERN



- The LHC and other accelerators provide colliding bunches at 4 experiments, 2 of them are “general purpose”, the CMS and ATLAS
- The Compact Muon Solenoid (CMS) is an apparatus featuring multiple detectors (silicon tracker, calorimeters, and muon chambers)
- The experiment uses a two-level Trigger, the Level-1 that runs on custom hardware, and the software-based High Level Trigger.



Presentation Outline

- Level 1 Trigger Overview – Triggering Objects
  (with focus on the Muon System)

- Barrel Muon Trigger Performance (Prompt Muons and Displaced)
- Overlap Muon Trigger Performance (Prompt Muons)
- Endcap Muon Trigger Performance (Prompt Muons and HMT for hits in CSCs)
- Global Muon Trigger Performance for Run 3

- Misc. Projects in the Level 1 Trigger
  (Level 1 Scouting)

Level 1 Trigger Overview – Triggering Objects

Electrons & Photons[2]

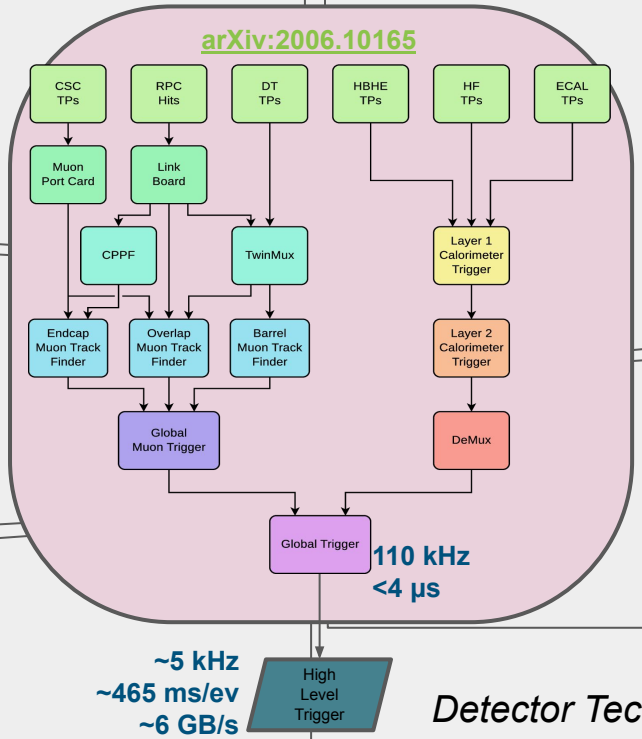
Reconstructed from energy deposits in the calorimeters, clustered together around one "seed" deposit that is above thresholds

Jets[3]

Reconstructed with 9x9 energy deposits from the calorimeters in pseudorapidity and azimuthal angle. Once reconstructed, the jets are calibrated to account for extra pile-up energy

Tau Leptons[2]

Similar reconstruction to e/γ from calorimeter energy deposits. For tau objects the clustered energy deposits can be merged, based on proximity, to account for hadronic decay products



Prompt & Displaced Muons[4],[5]

Reconstruction using information from 3 technologies of muon detectors. Track reconstruction and momenta assignment using techniques like Kalman Filter, Naive Bayes Classifier, and Boosted Decision Tree

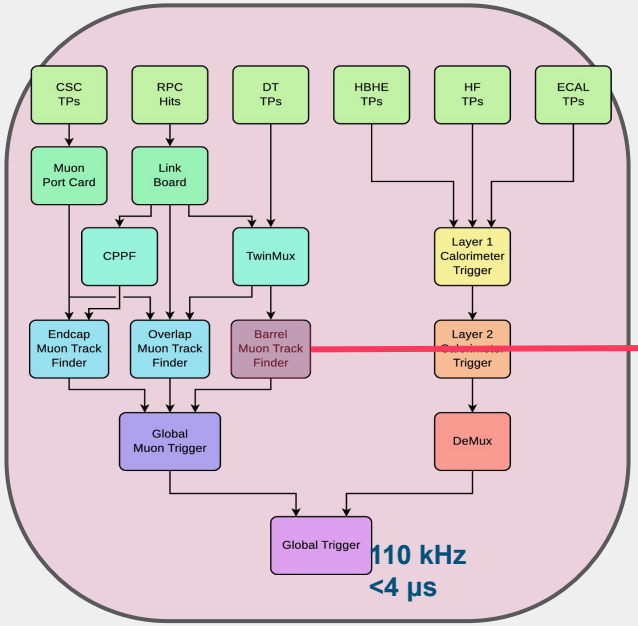
Energy Sums[3]

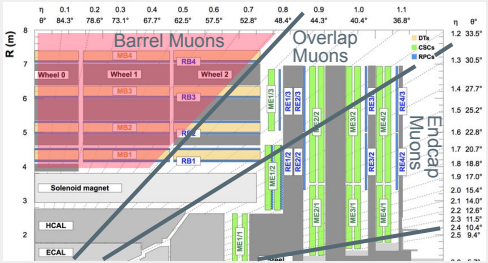
The Energy Sums are vector or scalar sums of calorimeter energy deposits. Also, a pseudorapidity dependent threshold selects the deposits that are used to mitigate the pile-up effects.

Detector Technologies

ECAL: Electromagnetic Calorimeter
HBHE: Hadronic Cal. Barrel & Endcap
HF: Hadronic Calorimeter Forward
DT: Drift Tubes
RPC: Resistive Plate Chambers
CSC: Cathode Strip Chambers

Level 1 Trigger Overview – Barrel Muons





Prompt & Displaced Muons[4],[5]

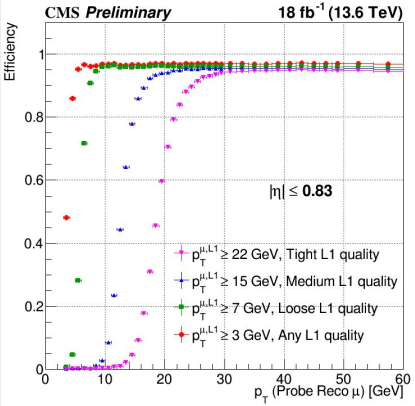
Reconstruction using information from 3 types of muon detectors. Track reconstruction and momenta assignment using techniques like Kalman Filter, Naive Bayes Classifier, and Boosted Decision Tree

The Muon Trigger

Barrel Muons : Region of interest → $|\eta| < 0.83$
Track Finder Algorithm → Kalman Filter

Level 1 Trigger Overview – Barrel Muons

The Barrel system implements a Kalman Filter on the FPGA to reconstruct the track and assign the transverse momenta. The algorithm processes the hits in the muon detector starting from the outermost station and propagates to the center of the CMS assuming that the muon has passed from there. However, this procedure offers the capability to also provide vertex unconstrained momenta measurements, which predict the transverse momenta of muons from displaced vertices more precisely.



DP-2023-057

- High efficiency, above 95%, for all single muon trigger working points
- Sharp turn on that allows Level 1 to reach >80% efficiency already at the threshold values

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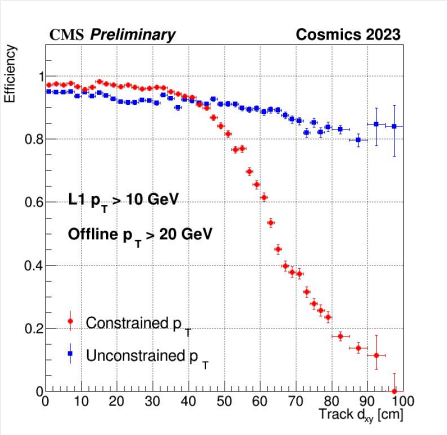

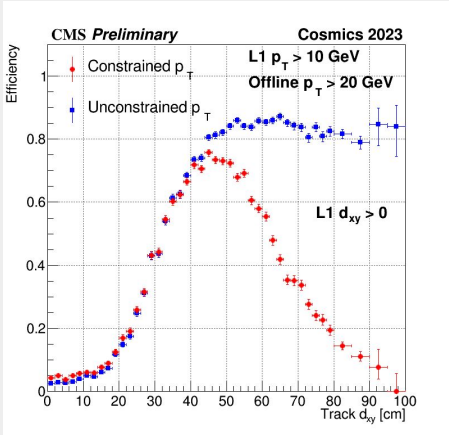

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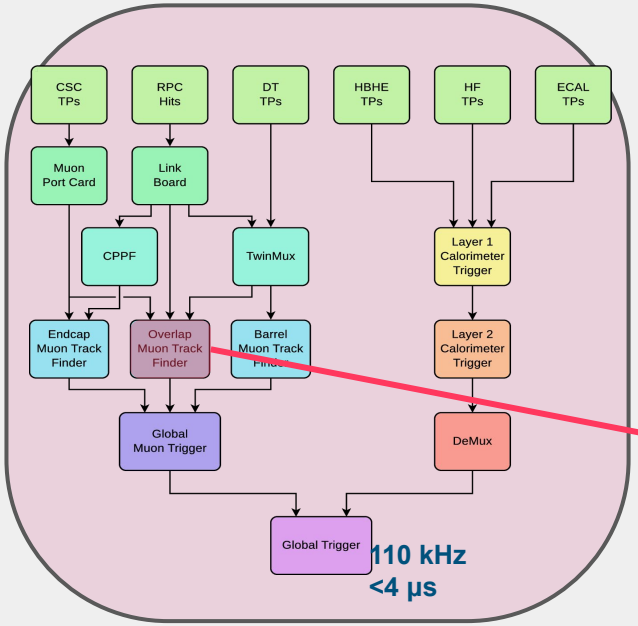
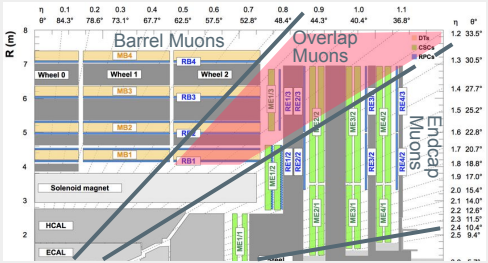
- The unconstrained measurement improves the efficiency of triggering on muons from secondary decays (80% up to 1m displacement)
- The transverse displacement measurement shows clear turn-on that allows to discard prompt muon tracks

Level 1 Trigger Overview – Overlap Muons





Prompt & Displaced Muons[4],[5]

Reconstruction using information from 3 types of muon detectors. Track reconstruction and momenta assignment using techniques like Kalman Filter, Naive Bayes Classifier, and Boosted Decision Tree

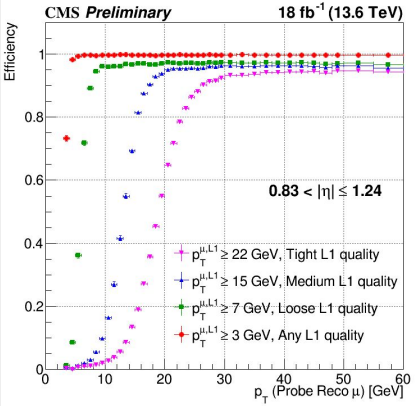
The Muon Trigger

Barrel Muons : Region of interest → $|\eta| < 0.83$
Track Finder Algorithm → Kalman Filter

Overlap Muons : Region of interest → $0.83 < |\eta| < 1.24$
Track Finder Algorithm → Naive Bayes Classifier

Level 1 Trigger Overview – Overlap Muons

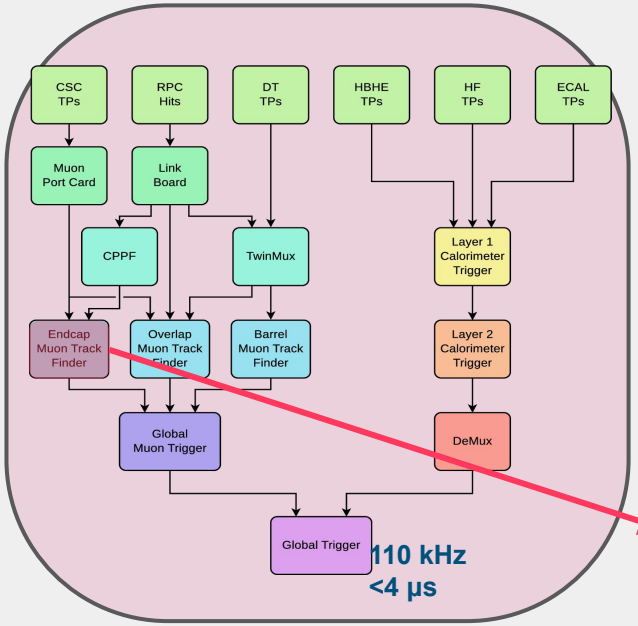
The Overlap system performs track identification and momentum assignment in one step. This approach can be considered as a naive Bayes classifier that assigns the most probable momentum value to the track based on the pattern of the hits in the muon detectors. The displaced muon triggering capabilities of the system are still under development and foreseen to be introduced and commissioned in 2024.

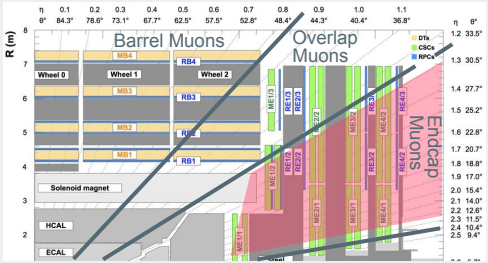


DP-2023-057

- High efficiency, above 90%, for all single muon trigger working points
- Significant impact of the quality on the plateau. Looser muon qualities are used in multi muon triggers
- Sharp turn on that allows Level 1 to reach >70% efficiency already at the threshold values

Level 1 Trigger Overview – Endcap Muons





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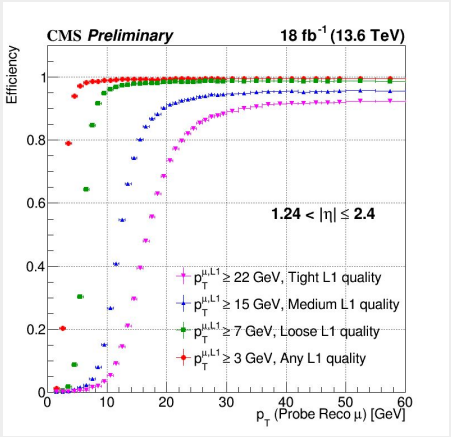
Overlap Muons : Region of interest → $0.83 < |\eta| < 1.24$
Track Finder Algorithm → Pattern Classifier

Endcap Muons : Region of interest → $1.24 < |\eta| < 2.4$
Track Finder Algorithm → Pattern Recognition & BDT

Level 1 Trigger Overview – Endcap Muons

The Encap system uses a 3 step reconstruction. Pattern recognition selects hits compatible with a track pattern, the track is built by associating the hits to the pattern, and finally the momenta from a BDT is assigned to the tracks using a look-up table. Recently, a neural network was implemented in the FPGA to provide vertex unconstrained transverse momenta and displacement measurements (in commissioning for 2024). Also, a "High Multiplicity Trigger" implemented jointly by Level 1 and High Level Trigger, targets events with high multiplicity of CSC hits in a given chamber that result from hadronic decays of long-lived particles.



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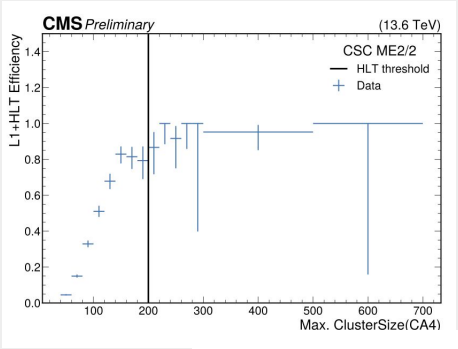

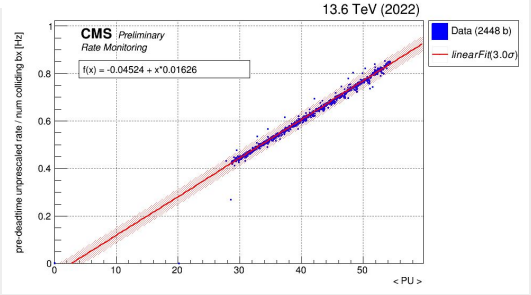

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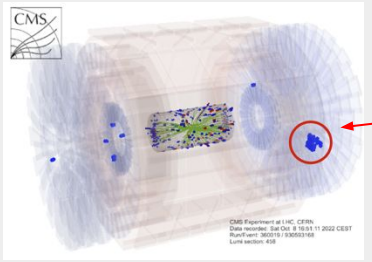
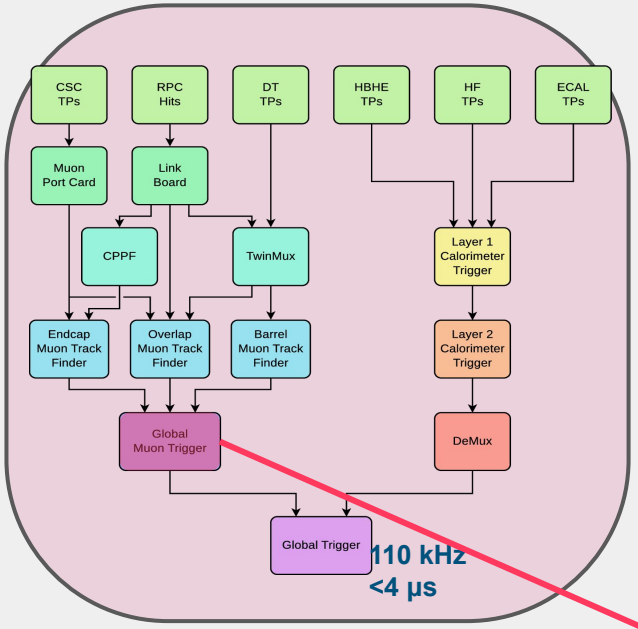
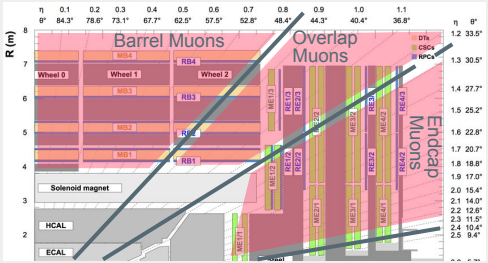


A candidate shower at the CSC, forward of the detector

- Cumulative efficiency (Level 1 + HLT) and Level 1 rate for the HMT implementation, ~100% efficient plateau
- Linear scaling of the Level 1 rate with the Pile-Up, 1.1kHz (PU30) to 1.8kHz (PU50)

Level 1 Trigger Overview – Global Muons





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Global Muon Trigger : Collector of Muon Candidates & Cleaning of duplicates

Level 1 Trigger Overview – Global Muons

The Global Muon Trigger acts as a collector for the Muon candidates and prepares them to be used by the Global Trigger, the last stage of the Level 1 system. Its responsibilities include sorting the Muons in transverse momentum and quality, and also cleaning the duplicate candidates.

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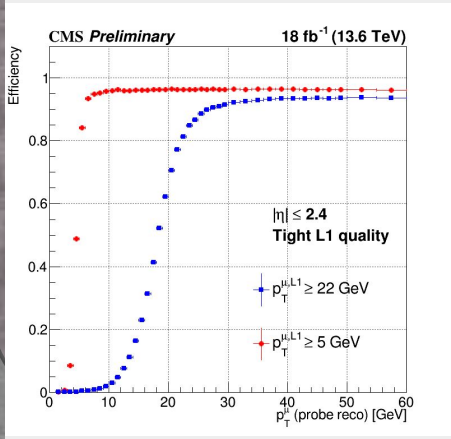
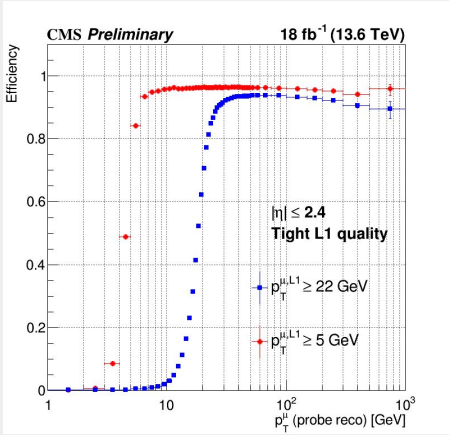
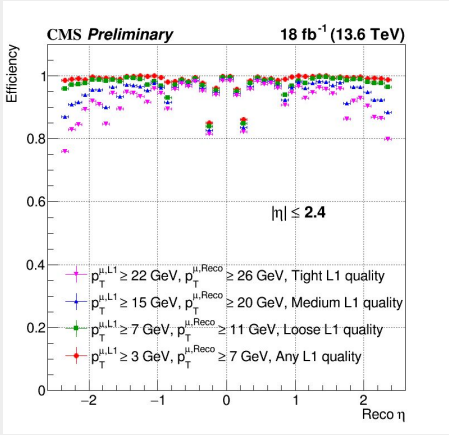
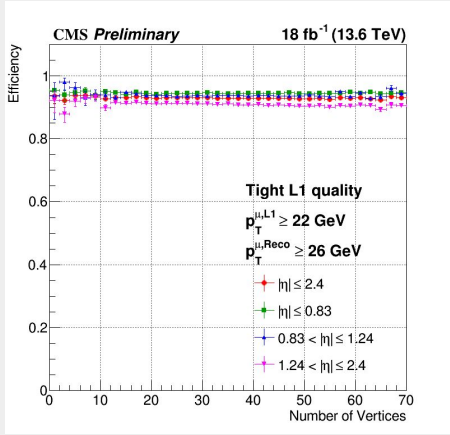




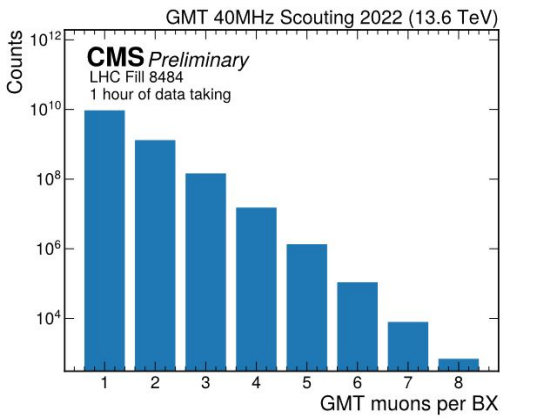




- High efficiency also after cleaning of duplicates. High momentum muons go through multiple scattering that reduced the efficiency at high transverse momenta values.
- The Muon system illustrates excellent performance across the entire pseudorapidity of the detector and is also stable under the challenging conditions of the Run 3 (>90% efficiency even at high pile-up).

Level 1 Scouting Muons @ 40MHz

- The 40MHz Scouting is a novel data acquisition system parallel to the Level-1 that collects primitives without triggering
- Demonstrated in 2018 and implemented for Run 3
- Data Sources:
  Global Muon Trigger *outputs*
  Calorimeter Layer 2 *outputs*
  Global Trigger *outputs*
  Barrel Muon Track Finder *inputs*
- *This "in parallel" system targets improvements of the current performance, "proof of concept" studies for the LHC Phase-2,* ***and also physics searches in phase spaces not selected by the triggers***



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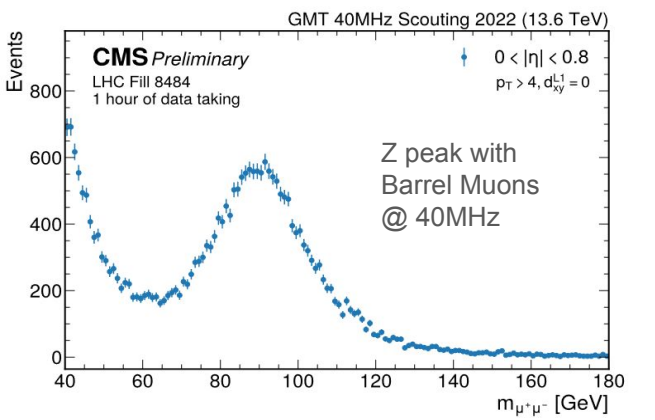
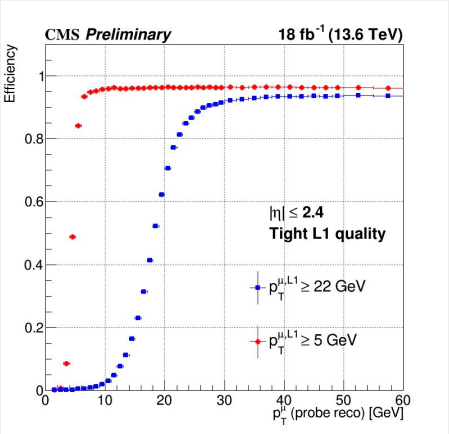
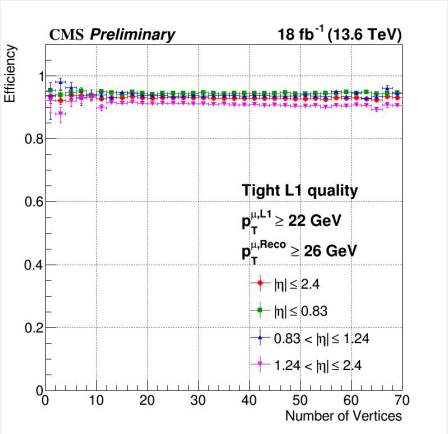


Summary

- Stable & high performance of the Level 1 Muon Trigger for the Run 3
  …even at demanding Pile-Up conditions

- The system is constantly being improved by introducing new algorithms to provide the required performance for the physics programme of the CMS Experiment





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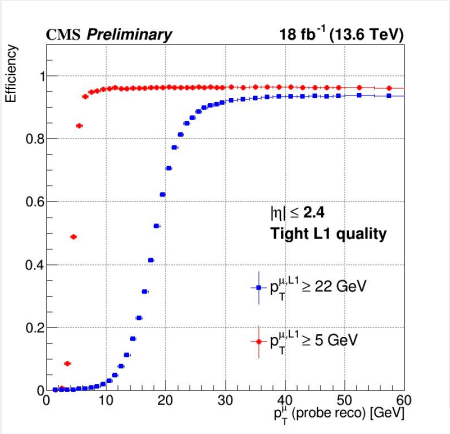
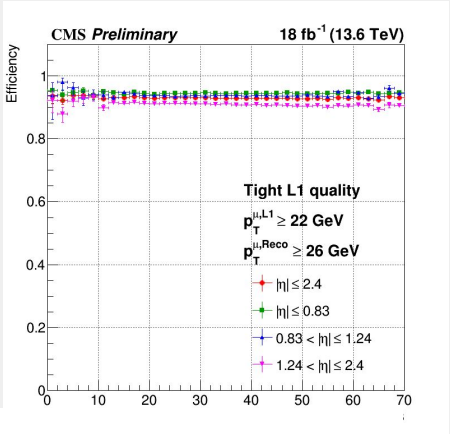
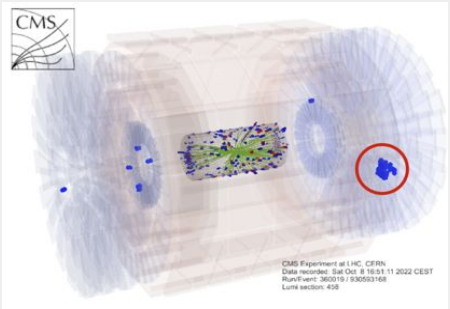
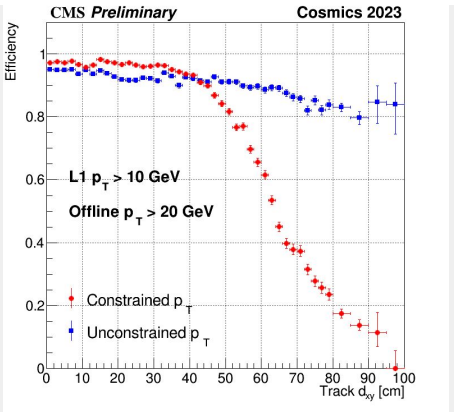
- New algorithms in the Level 1 system improve the capabilities of the CMS for the long-lived particle searches









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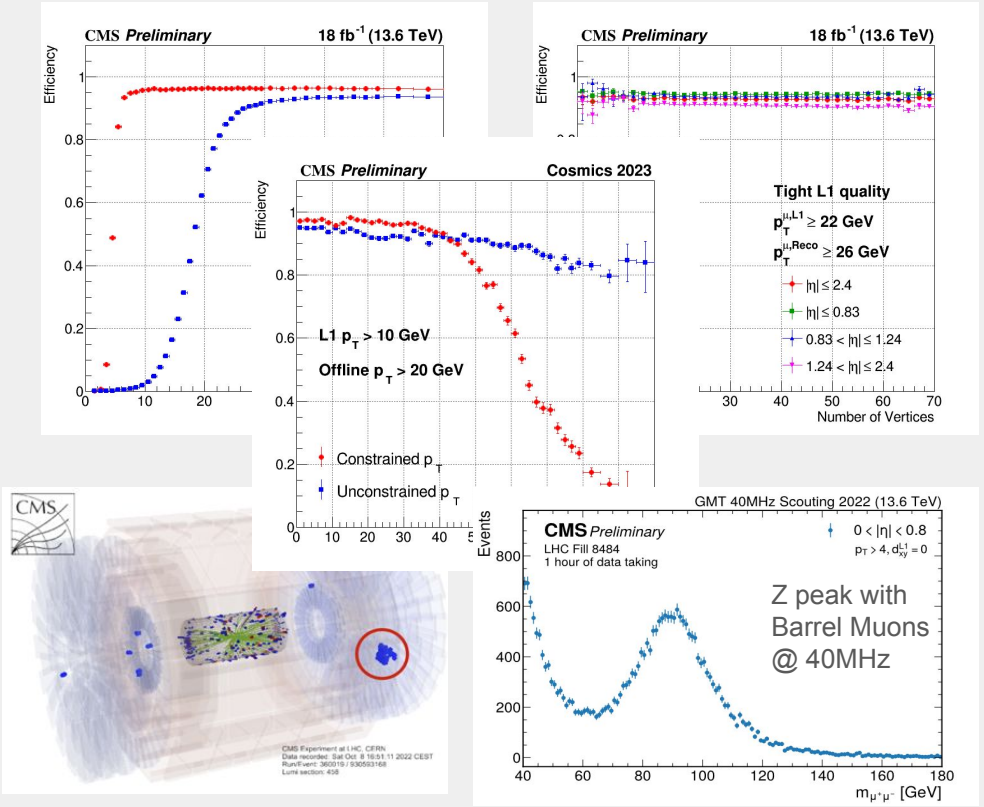
- The system is constantly being improved by introducing new algorithms to provide the required performance for the physics programme of the CMS Experiment
- New algorithms in the Level 1 system improve the capabilities of the CMS for the long-lived particle searches
- Exciting new ideas are being implemented to further improve the Run 3 system, as well as to illustrate ideas for the phase-2 upgrade and the HL-LHC era



Back up

References

(1) CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at √s= 13 TeV, arXiv:2006.10165

(2) CMS Collaboration, Performance of Level-1 Trigger e/γ and τ in Run 3, https://cds.cern.ch/record/2868792

(3) CMS Collaboration, Performances of L1 Jets and MET Trigger in early Run3, https://cds.cern.ch/record/2868796

(4) CMS Collaboration, Level-1 Muon Trigger Performance with part of 2023 dataset, https://cds.cern.ch/record/2868794

(5) CMS Collaboration, Displaced BMTF Efficiency Using 2023 Data, https://cds.cern.ch/record/2868797

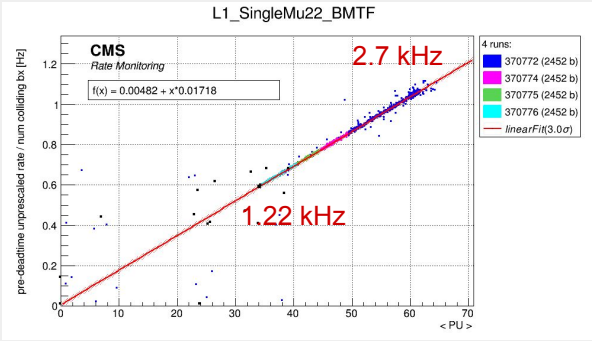
(6) CMS Collaboration, CSC High Multiplicity Trigger in Run 3, https://cds.cern.ch/record/2842376

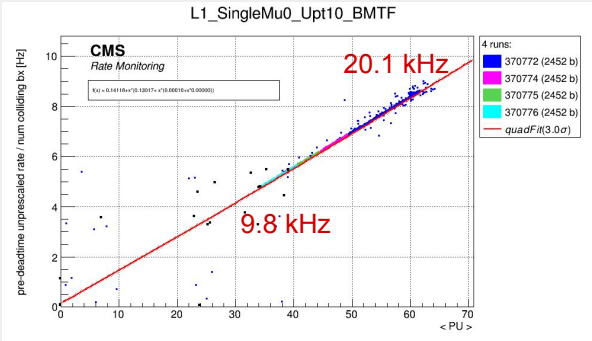
(7) CMS Collaboration, 40MHz Scouting Muon Studies, https://cds.cern.ch/record/2859463

Run 3 Level-1 Rates – Single Muon Barrel Triggers

Run: 370772
Date: 16/7/23
Time: 07:48-16:03 [UTC]

LHC Delivered: 578.70 pb^{-1}
CMS Recorded: 539.93 pb^{-1}





Run 3 Level-1 Rates – Single Muon Overlap Triggers

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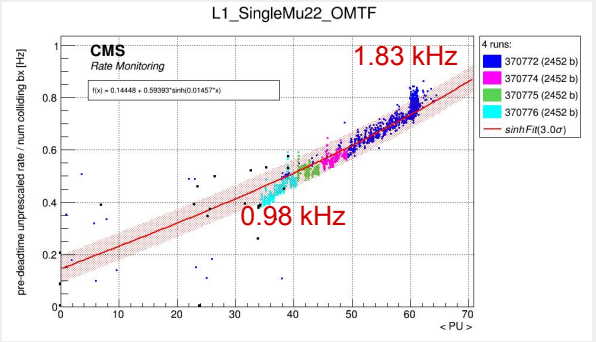

Run 3 Level-1 Rates – Single Muon Endcap Triggers

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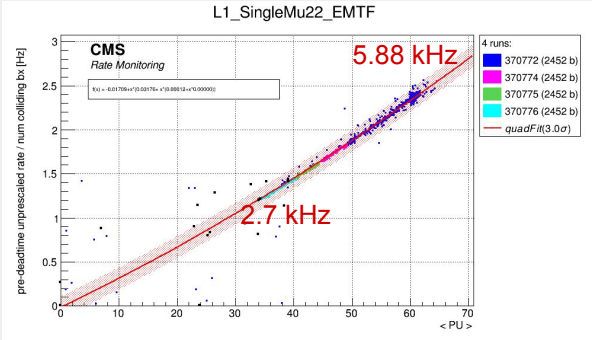

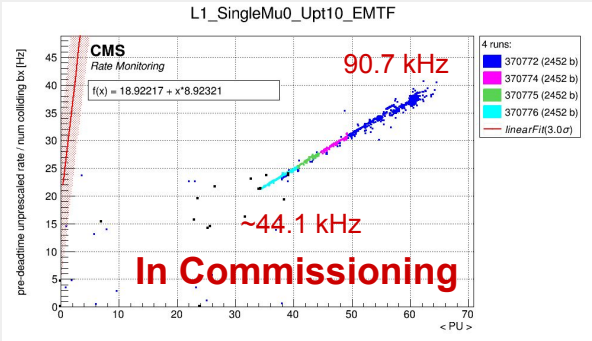

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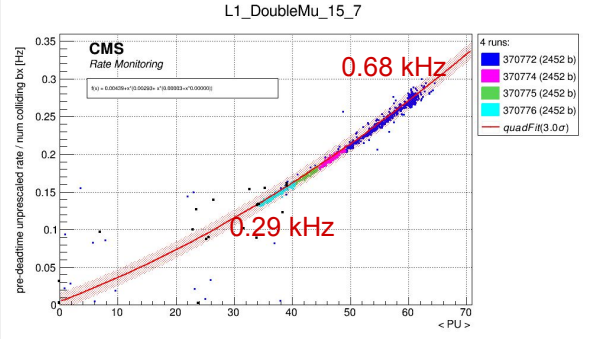
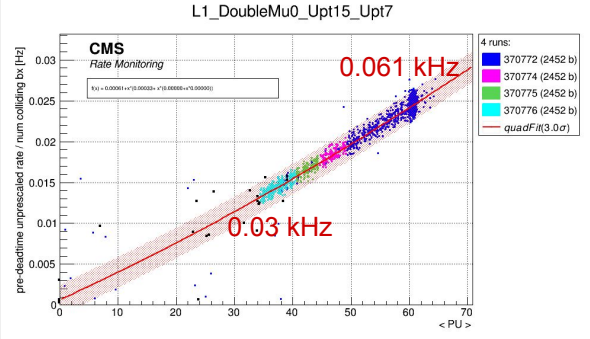
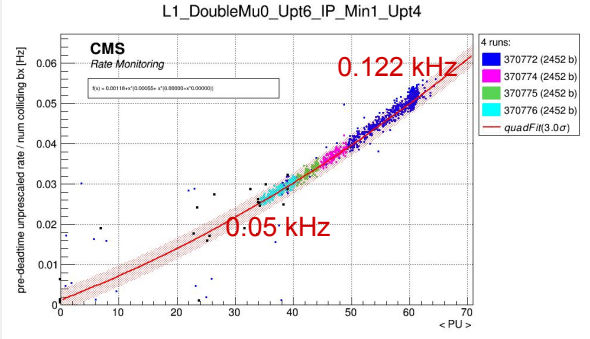


di-muon triggered with transverse momenta at the center of the CMS



di-muon triggered with transverse momenta at the point of distance of closest approach to the muon track (unconstrained pT)



di-muon triggered with unconstrained transverse momenta and minimum transverse distance of 25 cm