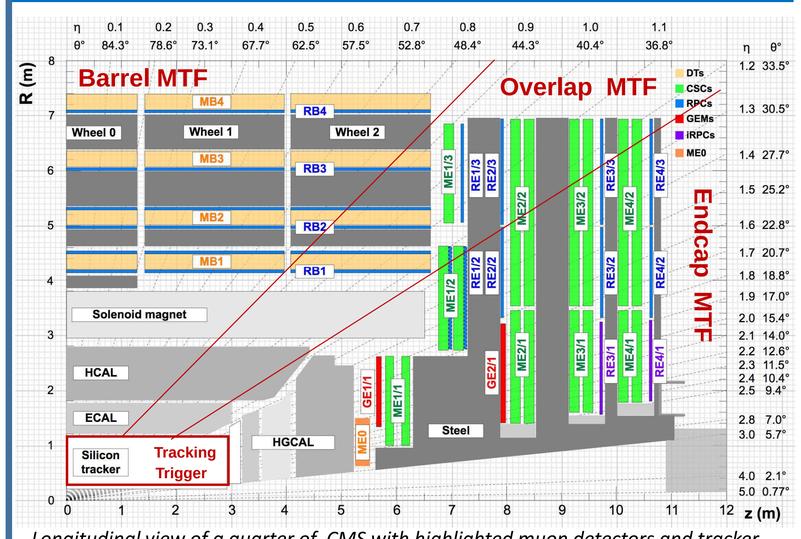
Level-1 Muon Triggers for the CMS Experiment at the HL-LHC

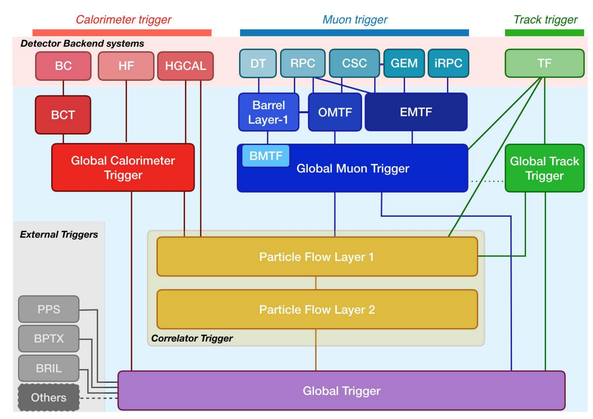
Marianna Głażewska, Marcin Konecki
University of Warsaw, Poland, on behalf of the CMS Collaboration

Level-1 muon trigger system



Longitudinal view of a quarter of CMS with highlighted muon detectors and tracker . The approximate boundaries between three muon sub-triggers are indicated.

- The High Luminosity upgrade of the Large Hadron Collider (HL-LHC, Phase-II) will commence in 2029. The luminosity increase by a factor of 5 to 7.5x10^{34} $cm^{-2}s^{-1}$ will result in a higher rate of potentially interesting events for physics studies, but also an event pileup of ~200, which will make event selection more complex.
- A new trigger has been designed to cope with the harsher HL-LHC conditions. The new Level-1 trigger will reduce the current 40 MHz pp collision rate down to 750 kHz - this is affordable for CMS High-Level Trigger, where the rate is further reduced to ~7.5kHz.
- Similarly to Run-2 and Run-3, the CMS detector will be equipped with three stand-alone muon triggers (Muon Track Finders, MTFs), namely: BMTF (Barrel), EMTF (Endcap) and OMTF (Overlap), operating in distinct pseudorapidity regions.
- Each MTF will process data from all locally available muon detectors already in initial reconstruction for optimal event selection.
- The Global Muon Trigger (GMT) will further improve the muon trigger deliverables thanks to stand-alone track candidates delivered by the Track Trigger, which operates on Outer Silicon tracker signals.



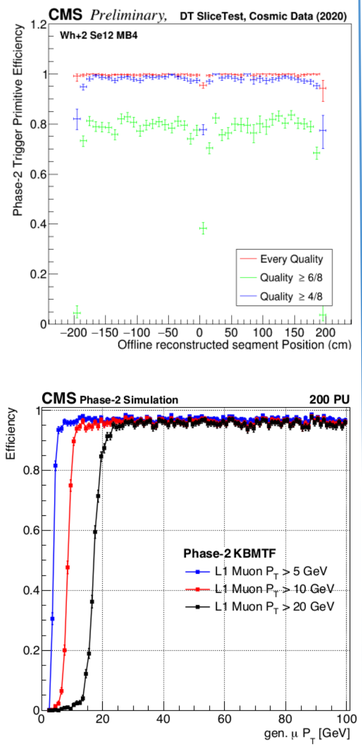
- The CMS muon system will become more redundant and will consist of several types of muon detectors: Drift Tube (DT) chambers, Resistive Plate Chambers (RPCs), Cathode Strip Chambers (CSCs) and Gas Electron Multiplier (GEM) detectors. The detector data will be pre-processed, concentrated and split by Barrel layer-1 segment finder, RPC and iRPC concentrators, and optionally CSC concentrators.

Stand-alone Muon Track Finders

EMTF and OMTF - events processed sequentially in dedicated boards, BMTF - implement in GMT board

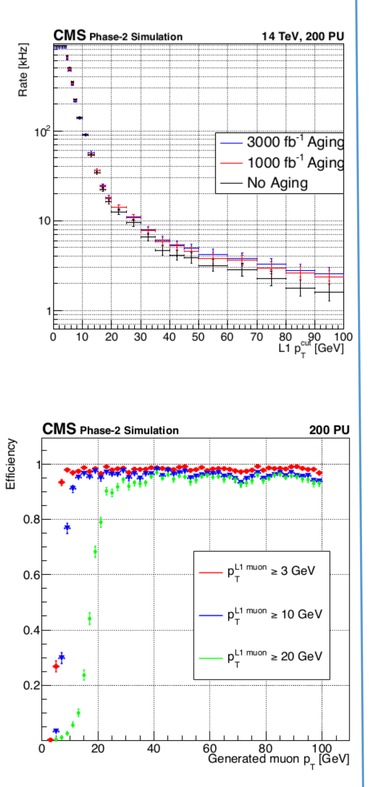
Barrel

- KBMTF algorithm based on Kalman Filter, developed for Run-3 but used in 2018 fulfils high luminosity requirements.
- Will rely on trigger primitives - muon track segments - sophistically reconstructed in Barrel Layer-1 (dedicated for Phase-II), that provide muon position and muon incident angle (bending) in each barrel station.
- A muon track segment will be constructed from combined DT superlayers supplemented with RPC hits for better efficiency and time resolution.



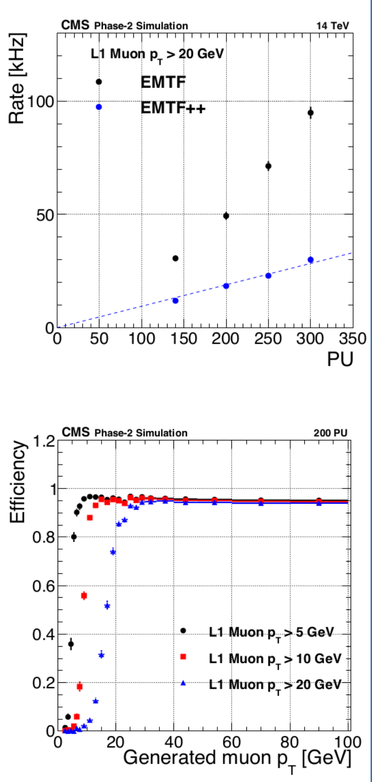
Overlap

- The OMTF Run-2 and Run-3 algorithm is well suited for HL-LHC.
- Naive Bayes Classifier based on comparison of actual hit pattern (DT,RPC,CSC), with a limited set of "Golden Patterns" holding PDF information about track bending wrt a selected reference hit.
- Overlap region potentially most sensitive to DT aging effect – no significant performance degradation.
- Additional improvements due to p_T estimate from Neural Networks and quality assignment tuning.



Endcap

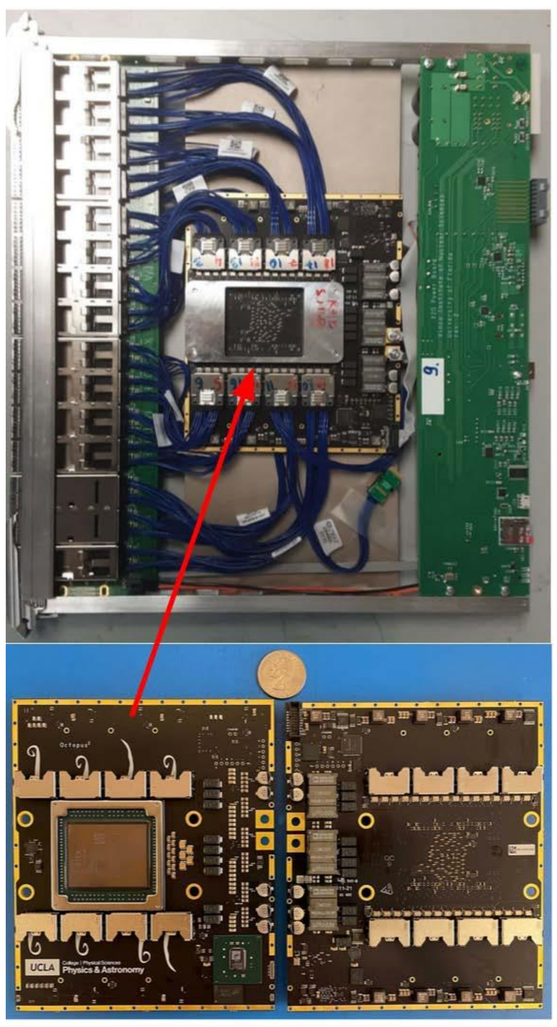
- Twofold muon candidate identification process:
  1) pattern recognition to select track hits,
  2) candidate kinematics assignment.
- New EMTF++ algorithm with improved pattern recognition and Neural Network based p_T assignment due to non-linear dependance of rate with pileup of the Phase-I EMTF algorithm.
- Neural Network features: 2D positions, time, bending angle of trigger primitives reconstructed from CSCs, RPCs and GEMs detectors.



All MTFs apart of providing single- or multi-muon trigger candidates may run additional local stand-alone algorithms like a search for displaced tracks.

X2O board

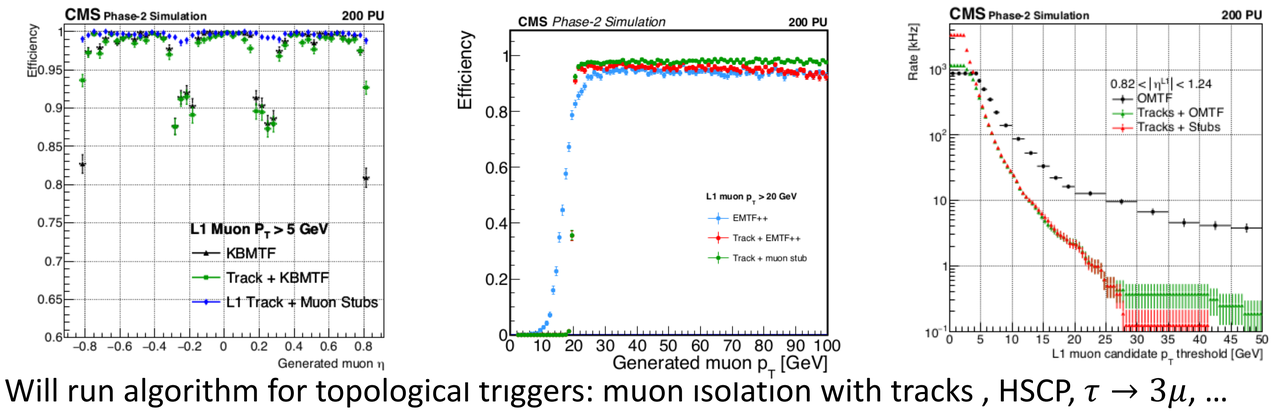
- X2O (successor of OCEAN) board developed for implementation of MTF and GMT.
- Modular design:
  - power module features a SoC;
  - optical module thermally decoupled, optics 3.2-25 Gb/s;
  - processing module Xilinx UltraScale+ VU13P FPGA
    3,7M LogCells, 1,7M LUTs, 94Mb BRAM, 12k DPS.
- Prototyping completed
- 36 board in the muon trigger system: 12 EMTF, 6 OMTF, 18 GMT.



Global Muon Trigger

Implemented in Time-Multiplexed Technique

- Good momentum resolution of tracker tracks enables assignment of kinematic parameters from tracker reconstruction to muon signals. Key task – identification of tracks as muons.
- Various options of identification, possible optimization in various regions:
  - track+MTF: match propagated track to stand-alone MTF muons
  - track+muon stubs: match propagated track directly with muon trigger primitives.



- Will run algorithm for topological triggers: muon isolation with tracks , HSCP, $\tau \rightarrow 3\mu$, …

Summary

Thanks to developed sophisticated algorithms the new Level-1 muon trigger will well handle high event pileup. The moderate (Run-2, Run-3) trigger thresholds will be preserved to benefit from the large number of events provided by the HL-LHC. The modular design and accessibility of trigger primitives and tracks at various steps of processing allow for flexible and optimal implementation of necessary algorithms.

Main reference: CMS Collaboration, "The Phase-2 Upgrade of the CMS Level-1 Trigger", CERN-LHCC-2020-004, CMS-TDR-021

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