The CMS Level-1 Endcap Muon Trigger at the High-Luminosity LHC

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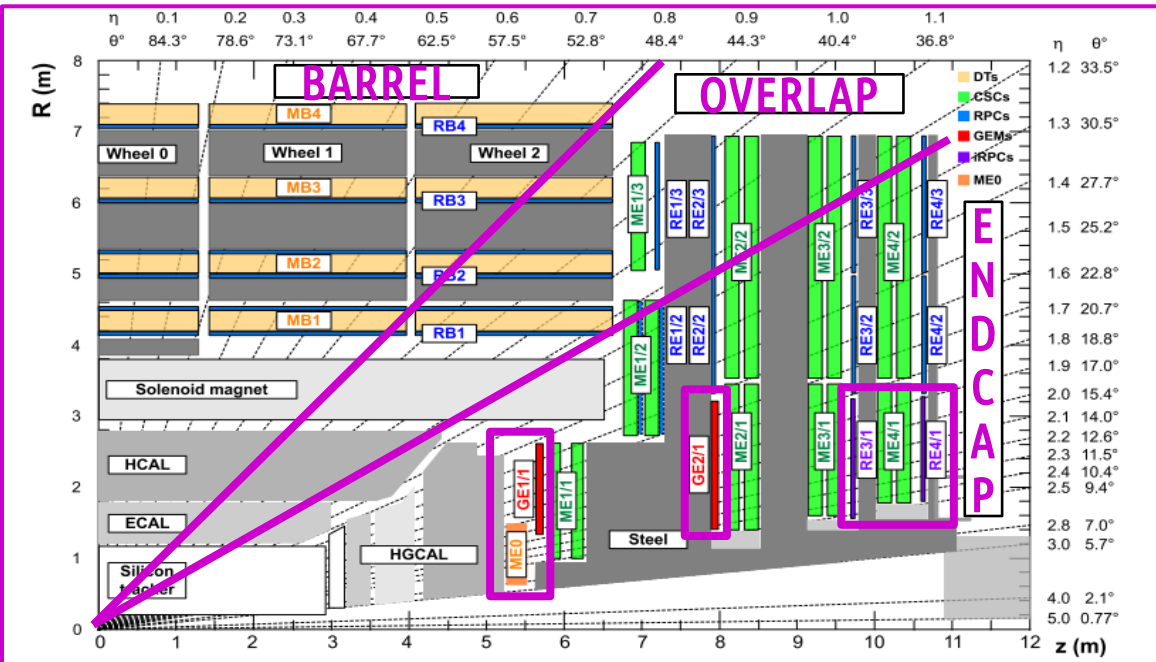CMS — Compact Muon Solenoid

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CMS Phase-2 Muon Detectors & Level-1 Trigger Upgrade
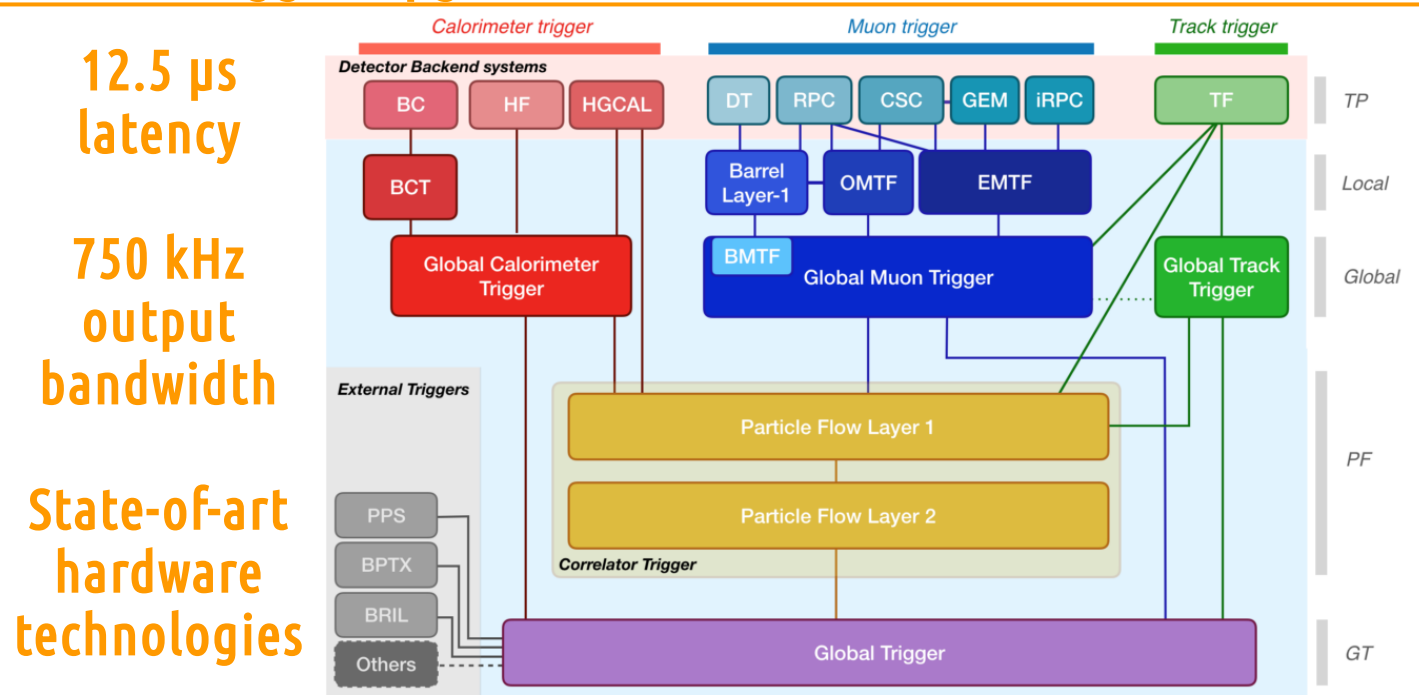
New territory to be explored at the High Luminosity-LHC

- $\sqrt{s}$ = 14 TeV pp collisions, 7.5 x 10^{34} cm^{-2} s^{-1} instantaneous luminosity, 200 pile-up (PU)
- Challenging data-taking conditions: High particle multiplicity & intense radiation environment
- Upgrades to overcome challenges & fully exploit 4000 fb^{-1} of integrated luminosity

Muon Subdetectors Upgrade

- Consolidated electronics in current Phase-1 chambers
- More accurate information for the Level-1 trigger
  - Position, time, quality & bend of local hits (stubs)
- <u>Extended coverage in forward region (up to |η|=2.8)</u>

Level-1 Trigger Upgrade

12.5 µs latency

750 kHz output bandwidth

State-of-art hardware technologies

- Architecture with four independent trigger paths:
  - Calorimeter, muon, <u>tracker & particle-flow</u>
- <u>New correlator layer:</u>
  - Multiple objects correlation & high-level triggers generation
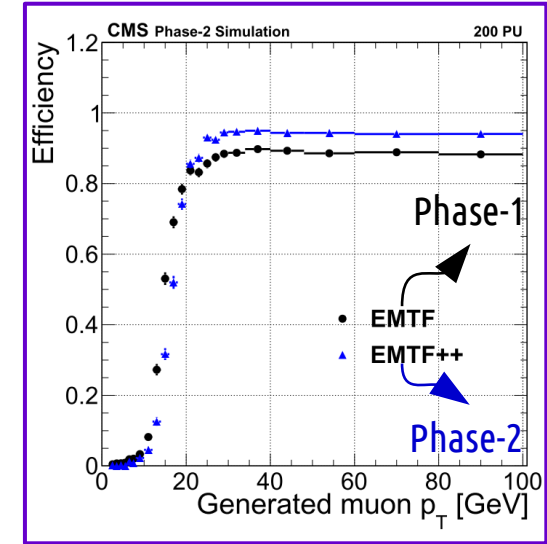
Triggering on endcap muons at the HL-LHC

Momentum resolution improvement is key → Rate mitigation & access to lower trigger thresholds

L O C A L

Endcap standalone prompt muon reconstruction (EMTF++)
Region with complex detector geometry, nonuniform magnetic field & punch-through
- Set of stubs compatible with a muon track are found via <u>pattern recognition</u>
- Stub information is then used to get <u>P_T-assignment using a neural network(NN)</u>
- ~20 kHz rate at 20 GeV P_T threshold → ~2.5 x lower rate w.r.t. Phase-1 algorithm (EMTF)
- Similar technique allows for displaced muon reconstruction

CMS Phase-2 Simulation   200 PU
Efficiency — Generated muon p_T [GeV]
Phase-1
Phase-2
● EMTF
▲ EMTF++

G M T

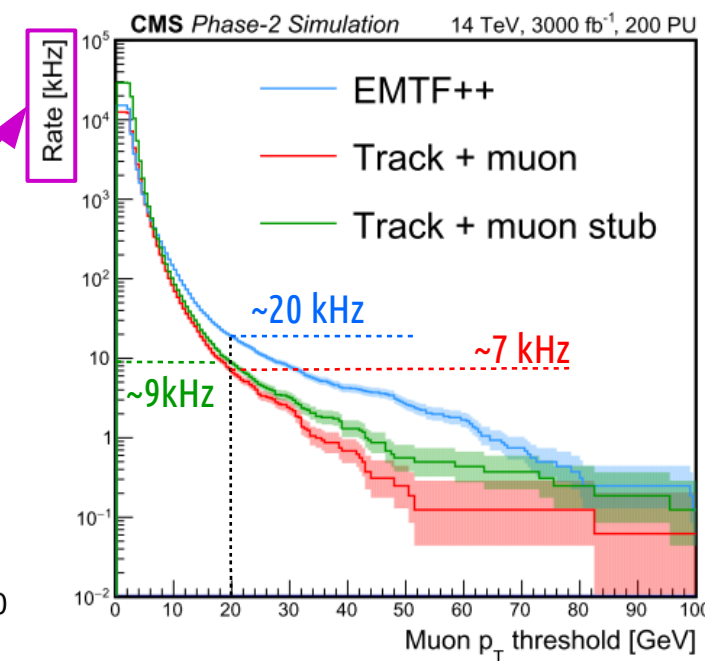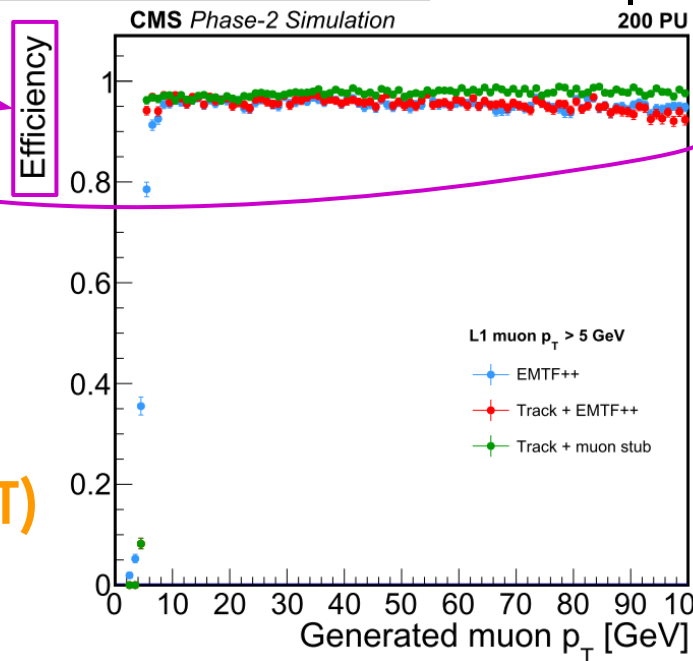## Track-correlated muons in Global Muon Trigger (GMT) / Correlator
<u>Tracker tracks (Tk) are matched to EMTF++ tracks or individual muon stubs</u> via P_T-dependent
$\Delta\varphi/\Delta\eta$ windows to push further the performance:
- Tk + EMTF++: 15-30%→3% P_T resolution
- Tk + muon stub: ~99% efficient for P_T >5 GeV

<u>Topological muons</u>, e.g. 'Muon-jet' with 3 objects
- Better acceptance at low P_T & forward region
  $\tau{\rightarrow}3\mu$ decays: ~5-10 x better than Phase-1 trigger

CMS *Phase-2 Simulation*   200 PU
Efficiency — Generated muon p_T [GeV]
L1 muon p_T > 5 GeV
● EMTF++
● Track + EMTF++
● Track + muon stub

CMS *Phase-2 Simulation*   14 TeV, 3000 fb⁻¹, 200 PU
Rate [kHz] — Muon p_T threshold [GeV]
— EMTF++
— Track + muon
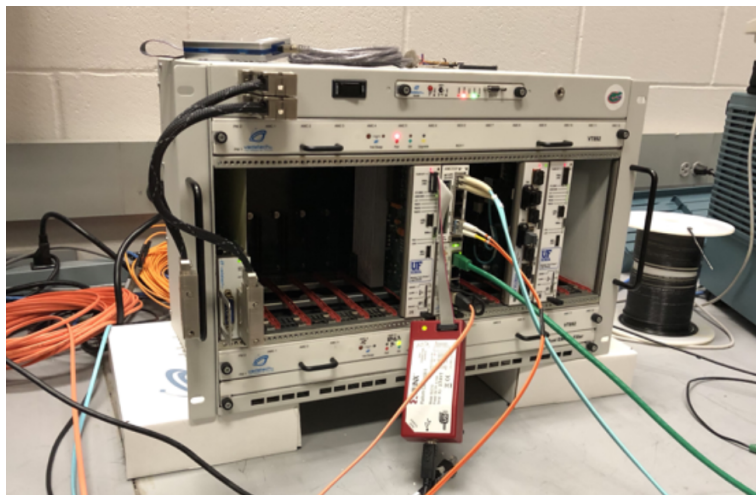— Track + muon stub
~20 kHz
~7 kHz
~9kHz

G T

All GMT objects are sent to the global trigger (GT)
to issue the L1 decision based on
the menu of (muon) algorithms

HL-LHC Endcap Muon Trigger Prospects

Preliminary hardware demonstration

Endcap muon trigger demonstrator setup

We have tests already performed with Virtex 9 Ultrascale+ (VU9P) FPGA
- EMTF++ algorithm
    - Phase-1 track-building firmware
    - NN firmware is written in Vivado HLS via HLS4ML software
    - Resources will be able to accommodate prompt & displaced muons
- Tk + EMTF++ correlator
    - Firmware implementation is validated with simulated muons
    - Resource usage is modest & dominated by look-up tables

Summary and Outlook
- Broad physics phase space will be explored given the Phase-2 upgrades & the unprecedented large dataset
- The new and improved endcap muon trigger objects will enable a large part of the HL-LHC program
- First hardware demonstrators shows the feasibility of the new endcap muon algorithms
- A rich software, firmware and hardware program is on-going

References:
[1] CMS Collaboration, The Phase-2 Upgrade of the CMS Muon Detectors, CERN-LHCC-2017-012 (2017)
[2] CMS Collaboration, The Phase-2 Upgrade of the CMS Level-1 Trigger, CERN-LHCC-2020-004 (2020)