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

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Motivation

- HL-LHC will open an unprecedent window for HEP, allowing for:
  - High-precision SM measurements
  - Extending BSM searches: unconventional signatures, corners of the phase space.

- The detector readout electronics and DAQ will be upgraded to allow an increased L1 trigger rate (750 kHz) and latency

- Maintain trigger thresholds despite the harsher environment: 200 pileup interactions and (possible) degradation of the muon detectors will be the first challenge of the Phase-2 L1 trigger upgrade

- Two allow for a rich physics program, our L1 trigger should cover a larger phase-space:
  - Increased acceptance: improved the sensitivity for several SM measurements and BSM searches.
  - Improved muon efficiency and momentum resolution thanks to the availability of tracking information at L1
  - Record exotic signatures such as long-lived particles: displaced muons, Heavy Stable Charged Particles (HSCP)
The CMS muon system

- **DT**
  - $|\eta| < 1.2$
  - Precise spatial resolution (250 $\mu$m)

- **RPC/iRPC**
  - $|\eta| < 1.9$ (RPC)
  - $1.9 < |\eta| < 2.5$ (iRPC)
  - Great time resolution (1.5 ns)

- **CSC**
  - $0.9 < |\eta| < 2.4$
  - Precise spatial resolution (150 $\mu$m)
  - Robust against larger background

- **GEM**
  - $1.6 < |\eta| < 2.5$
  - Robust against larger background

**Tracker tracks will also be available at L1**
The Phase-2 L1 Muon trigger

More details on the full L1 trigger system in Cecille’s talk.
Local trigger reconstruction

DT, CSC, (i)RPC, GEM
DT+RPC local reconstruction

- Design of a **chamber-level** local trigger reconstruction
  - Using RPC and DT hits from every superlayer (SL)
  - Higher resolution in timing, position and slope
  - RPC integration facilitate bunch-crossing (BX) determination if not enough DT-hits.

- **Algorithms:**
  - Start from individual hits and look for **straight patterns**
  - BX determination correlated with the slope
  - Using info from 2SL improves resolution
  - Two different approaches being considered
DT trigger primitives

- **Analytical Method (AM):**
  - For a given hypothesis of muon trajectory within a SL, using info from at least 3 cells.
  - TPs are found independently in the two SL
  - Correlation: matching segments within a $\pm 25 \, ns$ window is 99% efficient. Parameters are then updated.
  - Recent developments allow to use information from the two SL at once.

- **Histogram-based (HB):** MMT (majority mean-timer) for BX identification and CHT (compact Hough Transform) for pattern recognition
  - MMT: processing hits in the same SL, picks the most voted BX time
  - CHT: straight line equation to be solved for slope and position
    - processing three sets of hit pairs at once: SL1, SL3 and mixed pairs, find the maximum. Looking at both SL at once.

- **Resolution** of 0.2 mrad (1.6 ns) with close to 100% efficiencies.

- **FW status:**
  - AM Implemented 1SL on a Virtex 7, current logic occupation < 40%.
  - Taking data with a spare DT chamber installed at Point-5 (CMS, CERN)
CSC+GEM+(i)RPC local reconstruction

- New detectors will be installed for the HL-LHC
- GEM and CSC hits are received through fiber. TPs are built combining GEM and CSC hits
  - Local trigger efficiency improved thanks to redundancy.
  - GEM-CSC bending angle could help control trigger rate by cutting out low pT muons at EMTF level
- Integration of (i)RPC key to reduce rate and allow for HSCP triggering.
- Firmware development has been demonstrated.
Muon track finders (MTF)

- Information from the previous layer (TPs) is used to try to run pattern recognition algorithms across all muon chambers.
  - Magnetic field, multiple scattering...

- Different regions of the detector present different challenges:
  - Three distinct approaches: Barrel, Overlap and Endcap

- Phase-II design will extend greatly the capabilities of the MTFs:
  - (displaced) Stand-alone muons

- **Correlation** with tracker tracks info will allow to:
  - Tracker+muon stubs / track+muons
  - Heavy Stable Charged Particles (HSCP)

- Some of these algorithms shown here might be already tested during Run-3

\[
\begin{align*}
\text{BMTF:} & \quad |\eta| < 0.83 \\
\text{OMTF:} & \quad 0.83 < |\eta| < 1.24 \\
\text{EMTF:} & \quad |\eta| > 1.24
\end{align*}
\]
BMTF: Kalman filter

- Iterative track finding algorithm combining stub measurements with predictions using a Kalman filter approach based on phi, bending angle, and curvature
  - Starts from outermost muon station, propagates inward and updates at each station

- Provides both vertex constrained and unconstrained measurements

- A preliminary version has been already implemented in FW, with small logic occupancy (<20%) and a total latency of 10 BX
  - Already used at the end of 2018 data taking.
Many new-physics scenarios involve muons that are significantly displaced from the beamline and, in those cases, tracks from the track trigger cannot be reconstructed for muons having an impact parameter, $|d_{xy}| > 1\text{cm}$.

Removing the vertex constrain from the fit allows to recover those muons.

- A highly displaced muon might look like a low-pt muon: rate increase.
- Adding a tracker track veto reduces rate.

A customized displaced KBMTF improves efficiency by a factor of 6 at 80cm displacement:
- Displaced = max of vertex constrained and unconstrained $P_T$
- Prompt = vertex constrained $P_T$
OMTF: Naïve Bayes Classifier

- Perform muon identification and momentum measurement in one step by minimizing a Likelihood.

- Algorithm principles:
  - The algorithm is based on the classic machine learning algorithm: naïve Bayes classifier
  - It is assumed that the log-likelihood that a muon has a given $p_T$ $p(p_T|h)$ is just a sum of the log-likelihoods of the muon hit phi positions in each detector layer $p_{layer}(p_T|\phi_{dist})$
  - Maximum log-likelihood $p_T$ is chosen as the muon $p_T$
  - Simple extension of the Phase-1 algorithm works for HL-LHC conditions: similar efficiencies no degradation w.r.t PU
  - Rate scales linearly with luminosity
**EMTF: Neural Networks**

- Incorporate new muon detectors: better efficiency, timing and momentum assignment.
  - Redundancy will help with local efficiency reconstruction, $p_T$ resolution, rate reduction and resilience to ageing effects

- Performance at PU=200:
  - Sharper turn-on curve than the Phase-1 EMTF and higher efficiency
  - Significant gain in efficiency due to new detectors.

- Ideas for Phase-2: **EMTF++** is a Neural-Network-based modified track building and $p_T$ assignment algo, following same design as current EMTF:
  - Making new track patterns to take advantage of the additional stations and redundancy
  - $p_T$ (and PU) assignment based on Neural Networks
Towards a muon correlator

- One of the great features of Phase-2 L1T schema is that tracker tracks will be available at L1:
  - i.e. we will be able to precisely determine the momentum at L1

- A muon correlator is therefore needed to match trigger tracks and muon stubs/hits:
  - Similar to offline tracker muons
  - When using tracks+muon stubs will improve efficiency
  - Matching with standalone muons can also be implemented to improve momentum assignment

- Access to tracker and other sub-detector information allows to improve momentum and timing resolution
  - Allowing to trigger on HSCP

- Different solutions being considered
Several theoretical models, including many inspired by supersymmetry (SUSY), predict the existence of HSCP. Since such particles are slow moving, they look like muons except speed significantly smaller than c.

In the simplest physics case: the HSCP is produced at (or close to) IP, so there there is a high-$p_T$ track. The task is to tag it as HSCP.

(i) RPC chambers will provide hits with a time resolution of ~1.5 ns. Tracks from 15 BX will be sent to muon correlator.

Two options:

- **RPC-only hits**: linear fit of RPC hits in space-time to determine the speed
- **Match tracker tracks to muon stubs in (up to) 3 additional BXs**, using the Bayes Classifier. Timing of a given segment/hit in the muon chamber vs the tracker track BX determines the probability model:

\[ P(\beta|t^1 \ldots t^L) = P(\beta|t^1) \times \ldots \times P(\beta|t^L) \]
Summary

- Extraordinary new capabilities available for L1 muon triggers in HL-LHC:
  - Higher bandwidth and latency
  - Triggering in unique signatures will be possible already at L1

- L1 trigger primitive generation will significantly extend Phase-1 capabilities thanks to the use of FPGAs and the combination of different sub-detector information

- Muon track finders exploit new features and able to improve momentum assignment making use of tracker tracks. Triggering on unconventional signatures (displaced, HCSP) will be possible

- FW Implementation of all the algorithms has been demonstrated (not covered today)

- A Technical Design Report is expected by the beginning of next year.

- Exciting times ahead with the Run 3 and the preparation for the HL-LHC
Back-up
Changes for Phase-2

- Higher number of interactions per bunch-crossing (BX): > 200
  - Higher rates expected everywhere

- Possible degradation of the muon detectors (ageing)
  - Decrease hit efficiency

- The detector readout electronics and DAQ will be upgraded to allow an increased L1 rate (750 kHz) and latency

- Plan taking full advantage of advances in Field Programmable Gate Array (FPGA) and optical link technologies
  - Both for local reconstruction and track finding

- Tracker tracks are now available at L1

- **Muon triggers** will still be the **core triggers** used by CMS.

- The CMS upgrade towards the HL-LHC will allow:
  - Track+muon matching
  - Displaced muons and Heavy Stable Charged Particles (HSCP)
The L1 Trigger system
HSCP triggering

- HSCP will look like muons but with much smaller speed.

- Simple case:
  - If $\beta \approx 0.2$ the muon hits/segments can be in BX$\pm 2$
  - We need to match ttTracks with muon stubs in a window of BXs, this will increase the rate and create pre-firing.

- Algorithm idea:
  - The timing of a given segment/hit in the muon chamber vs the ttTrack BX determines the LH:
    \[ P(\beta|t^1 \ldots t^L) = P(\beta|t^1) \times \ldots \times P(\beta|t^L) \]
  - From this we can probably determine $\beta$ and its uncertainty.
  - Ghost-busting between BX is necessary.