# Upgrades of the CMS muon detectors: from Run-3 towards HL-LHC


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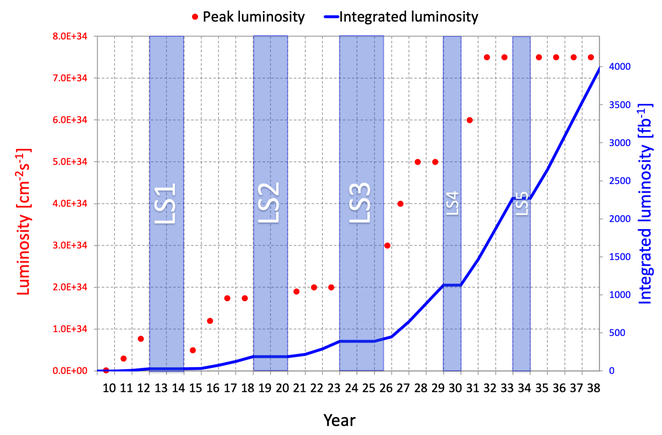
## The High Luminosity LHC project:

The **High-Luminosity LHC** (HL-LHC) [1] is an **upgrade of the LHC collider** planned to provide proton-proton collisions at instantaneous luminosities up to 7.5 x $10^{34}$ $cm^{-1}s^{-1}$, corresponding to a pile-up of 200 collisions per crossing. It is aimed at integrating up to 4000 $fb^{-1}$.




## The CMS muon system, from today to HL-LHC:

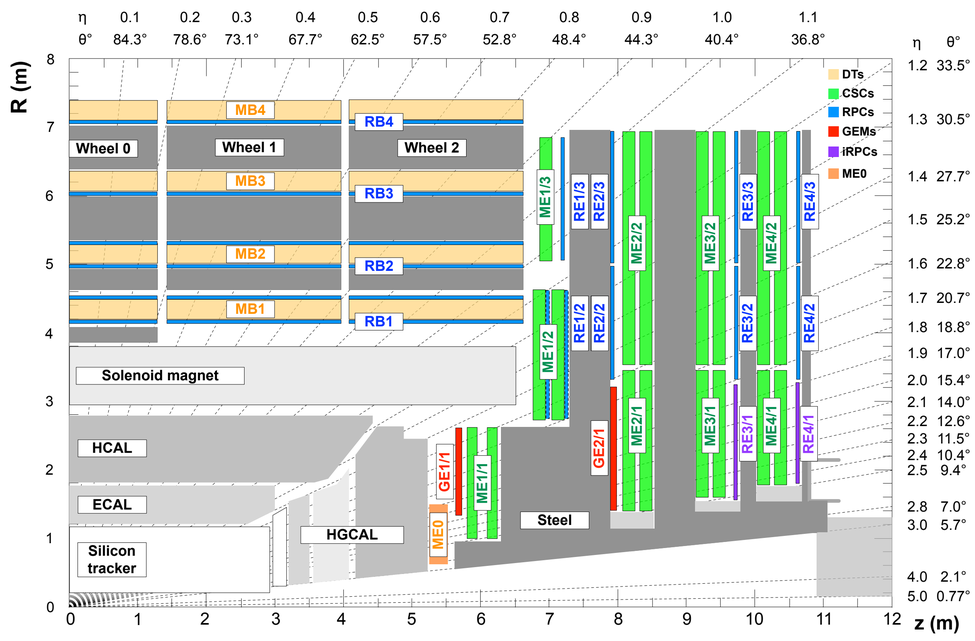
**The present CMS muon spectrometer** consists in three different detector technologies. It is designed to efficiently reconstruct and trigger muons:

- Drift Tubes (DT) : $|\eta| < 1.2$
- Resistive plate chambers (RPC) : $|\eta| < 1.9$
- Cathode Strip Chambers (CSC) : $0.9 < |\eta| < 2.4$

The goal of the Phase-2 **muon system upgrade** [2] is to **maintain present detector performance** under the harsh conditions expected at HL-LHC.

It consists both in a **consolidation** of the existing detectors, mostly achieved by an **upgrade of the electronics**, and in the **installation of new chambers** in the spectrometer's end-caps:

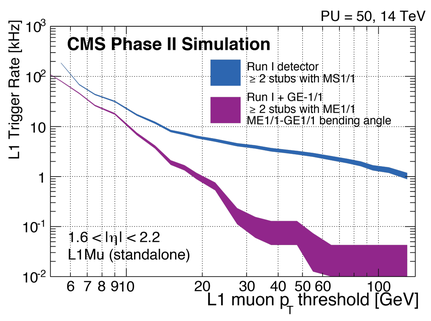
- Double-layer triple-GEM (GE) : $1.6 < |\eta| < 2.1$
- Improved RPC (iRPC) : $1.8 < |\eta| < 2.4$
- Six-layer triple-GEM (ME0) : $2.1 < |\eta| < 2.8$

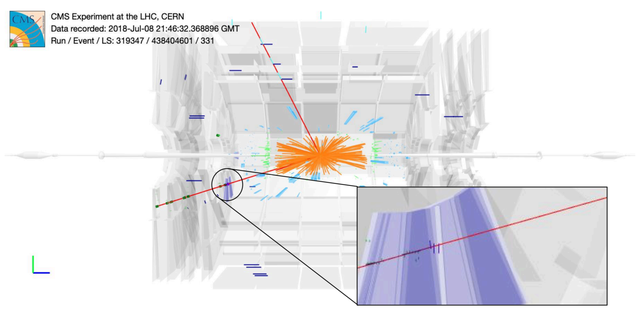



## GEM detectors for the LHC Run-3:

The **innermost station of double layer GEM detectors** (GE1/1) will **operate already during Run-3** [3], improving the performance of the muon L1 trigger (L1T). Integrated GEM - CSC trigger stubs will increase efficiency and, due to the larger level-arm of combined GEM+CSC segments, the measure of the muon momentum at L1T will improve, resulting in a reduction of trigger rates.

**A slice-test** of 10 GE1/1 chambers was **installed already at the end of Run-2** to mature experience in installation, integration and operation of such detectors.




## Longevity studies at the Gamma Irradiation Facility:

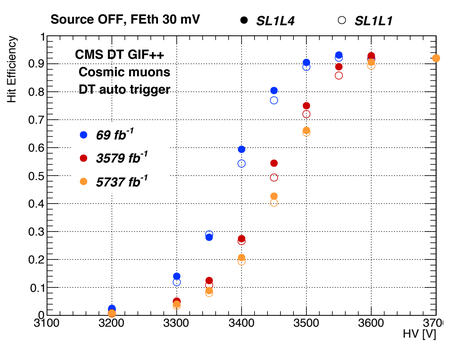
At HL-LHC, the muon system will operate at **background rates and doses** which **will exceed LHC specifications**.

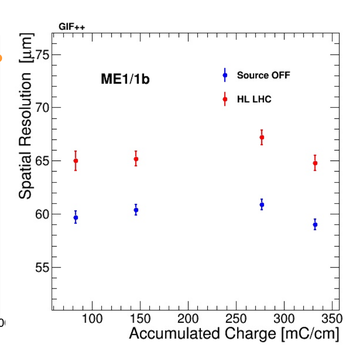
Ageing of detectors and electronic components in presence of radiation is hence being studied at the Gamma Irradiation Facility (GIF++) at CERN.

**Present studies indicate that** existing and new **detectors can operate** throughout HL-LHC **with no or moderate degradation** [4]. Nonetheless, mitigation strategies have been put in place to maximise longevity.

Instead, **electronic components are predicted to fail** and, hence, **will be replaced**.

| $\|\eta\|$ range | DT 0-1.2 | CSC 0.9-2.4 | RPC 0-1.9 | iRPC 1.8-2.4 | GE1/1 1.6-2.15 | GE2/1 1.6-2.4 | ME0 2.0-2.8 |
|---|---|---|---|---|---|---|---|
| neutron fluence ($10^{12}$ n/cm$^2$) | 0.4 | 40 | 1 | 7 | 20 | 12 | 200 |
| total ionization dose (kRad) | 0.12 | 10 | 2 | 3 | 3 | 7 | 490 |
| hit rate (Hz/cm$^2$) | 50 | 4500 | 200 | 700 | 1500 | 700 | 48000 |
| charge per wire (mC/cm) | 20 | 110 | - | - | - | - | - |
| charge per area (mC/cm$^2$) | - | - | 280 | 330 | 6 | 3 | 280 |



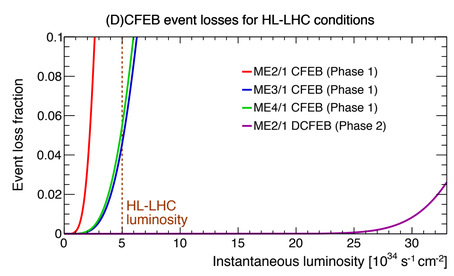

## Upgrade of the muon system electronics:

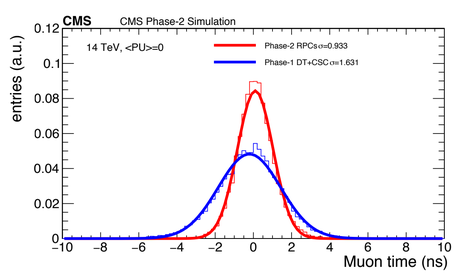
The **detectors presently installed** in the muon system will undergo an **upgrade of their electronics**.

**CSC** front-end boards will be replaced to prevent saturation effects due to high hit-rate.

The **RPC** link system, presently recording hit time every 25 ns, will be replaced. The new readout will allow to access RPC timing with full resolution.

The on-board **DT** electronics will be replaced with TDCs streaming data to a back-end that will reconstruct DT L1T stubs exploiting full detector granularity and ultimate DT cell resolution.

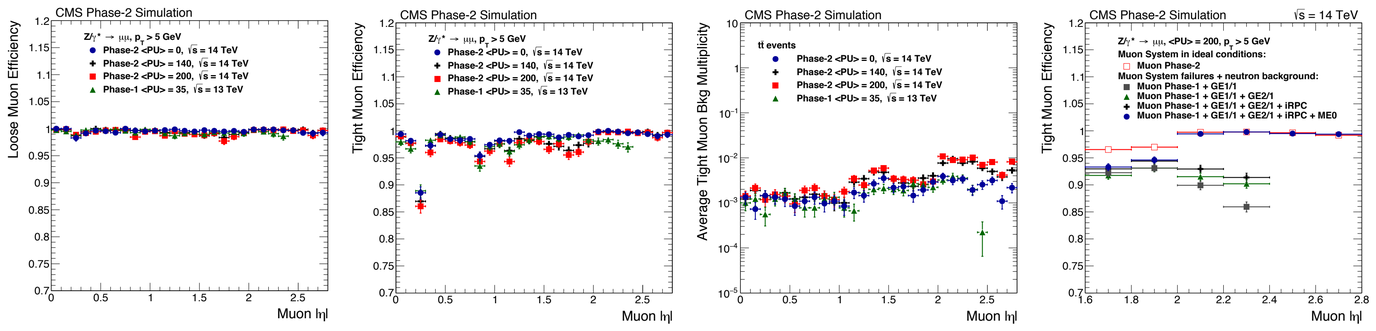



## Performance of offline reconstruction and identification:

**Muon reconstruction and identification were studied** using simulated Drell-Yan dimuon decays and $t\bar{t}$ events **under different pile-up conditions** and **comparing present and upgraded detector geometries**.

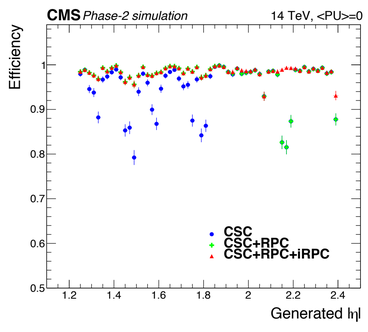
A **remarkable efficiency**, with **background** yields that **remain under control**, is maintained in Phase-2 conditions. The addition of ME0 stations allows for **efficient identification of muons op to $|\eta| = 2.8$**. The addition of new detectors makes the muon system **robust in case of failures** of the existing ones.

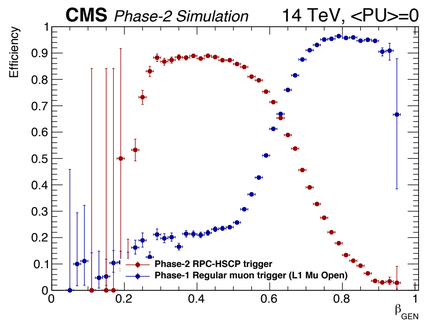


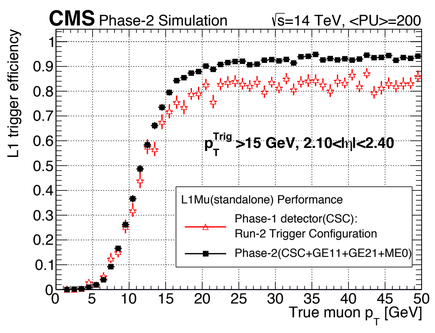

## Impact of the muon system upgrade to the L1 muon trigger:

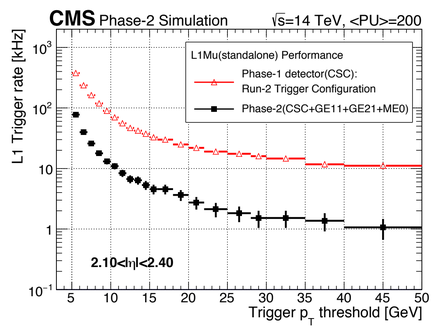
New detectors will provide **additional hits along the muon trajectory** that will be **exploited by an upgraded L1T**. Additionally the upgraded L1T will be able to process information from the inner tracker that will be matched with stubs or tracks from the muon system, as presently done in offline muon reconstruction.

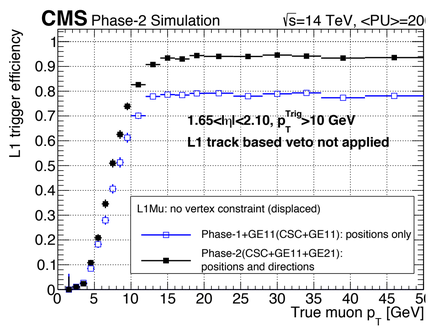
**Combining (i)RPC hits and CSC stubs** is possible to **increase the efficiency** of the muon L1T with respect to a CSC-only trigger. Accessing **(i)RPC information with full precision** will improve the timing resolution at L1T and **allow the design of dedicated triggers for slow-moving particles**. Hits from **GE** and stubs **ME0** chambers will **improve the standalone measure of the muon $p_T$** reducing trigger rates in the end-caps. They will also significantly impact the performance of **triggers for displaced particles** that are **presently being developed**.

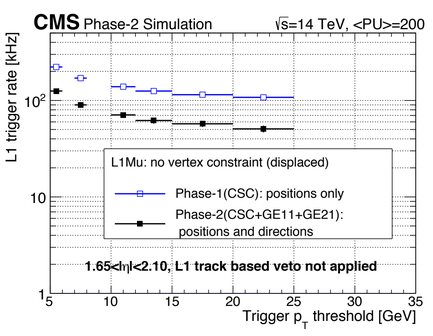



## References:


[1] High-Luminosity Large Hadron Collider (HL-LHC) Technical Design Report, DOI: 10.23731/CYRM-2017-004.

[2] The CMS Collaboration, "The Phase-2 Upgrade of the CMS Muon Detectors", CERN-LHCC-2017-012.

[3] CMS Technical Design Report for the Muon Endcap GEM Upgrade, CERN-LHCC-2015-012.

[4] CMS muon system public results TWIKI: https://twiki.cern.ch/twiki/bin/view/CMSPublic/MuonDPGResults