Upgrade plans and ageing studies for the CMS muon system in preparation of HL-LHC

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On behalf of the CMS Muon Group

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• Hadrons are copiously produced at LHC
• Almost all hadrons, electrons, and photons are absorbed in calorimeters
• Trigger, identification and measurement of muons is of great importance in searching for interesting and rare processes
Higgs $\to$ ZZ $\to$ 4$\mu$

The golden channel

Bs $\to$ 2$\mu$ rare decay
Pseudorapidity $\eta$

$\eta = -\ln[\tan(\theta/2)]$

where $\theta$ is the angle relative to the beam axis

Higher $\eta$ region has higher particle rate

Different detector technologies are chosen based on particle rates in different $\eta$ regions (and different magnet field)
Three gas detector technologies

Drift Tube (DT):  
- $0 < |\eta| < 1.2$  
- 250 chambers  
- Spatial resolution 100 $\mu$m  
- Time resolution 2 ns  
Low rate

- The trajectory of a muon passes 4 stations, 2 types of detectors (except for the high $\eta$ region)  
- Robust trigger and efficient reconstruction

Resistive Plate Chamber (RPC):  
- $0 < |\eta| < 1.8$  
- 480 (barrel) + 576 (endcap) chambers  
- Spatial resolution 0.8-1.3 cm  
- Time resolution ~ 2 ns

Cathode Strip Chamber (CSC):  
- $0.9 < |\eta| < 2.4$  
- 540 chambers  
- Spatial resolution 50-140 $\mu$m  
- Time resolution 3 ns  
High rate
Why upgrade?
HL-LHC environment defines detector upgrades

- CMS detector was designed for the LHC specifications
- Higher integrated luminosity - are the present Muon detectors sufficiently radiation hard?
- Higher instantaneously luminosity - the L1 (hardware) trigger rates 500 kHz and latency 12.5 µs would be too high for the Muon system electronics (100 kHz and 3.5 µs as of today)

### Luminosity and Integrated Luminosity

<table>
<thead>
<tr>
<th></th>
<th>LHC design</th>
<th>HL-LHC design</th>
<th>HL-LHC ultimate</th>
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</thead>
<tbody>
<tr>
<td>peak luminosity (10^{34} cm^{-2}s^{-1})</td>
<td>1.0</td>
<td>5.0</td>
<td>7.5</td>
</tr>
<tr>
<td>integrated luminosity (fb^{-1})</td>
<td>300</td>
<td>3000</td>
<td>4000</td>
</tr>
<tr>
<td>number of pileup events</td>
<td>~30</td>
<td>~140</td>
<td>~200</td>
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Muon detector longevity

- Exposure to HL-LHC radiation could potentially cause detector deterioration and permanent failure
  - Gas gain decrease, spurious hits, self-sustained discharges, HV breakdown
- Full-size DT, CSC, RPC chambers are exposed to high rates at the CERN Gamma Irradiation Facility (GIF++)
  - Accelerated irradiation - accumulated charge per cm of wire or cm² area is the measure of “radiation exposure”
  - Extrapolated to HL-LHC based on present HV current in CMS as of today
- In addition, a safety factor of 3 is applied

GIF++ photon flux map
Cs137, 13.5 TBq, 662 keV photons
Muon detector longevity

DT

About 15% of chambers (the ones most exposed to background) are expected to see noticeable gas gain decrease.

Muon reconstruction efficiency will remain high, thanks to multiple layers of DT on the path of a muon.

Mitigation measures are being implemented (no gas recirculation, HV adjustment, shielding for chambers, etc).

CSC

No noticeable performance degradation up to 3 x HL-LHC (330 mC/cm).

RPC

No noticeable performance degradation so far (2xHL-LHC); the test is being continued.
Electronics upgrade

- DT
  - New on-chamber electronics, to cope with higher rate and radiation
  - New trigger logic system to be in the service cavern - easier to maintain

- CSC
  - Selective replacement of electronics for inner ring chambers - Cathode FE board in station 1 moved to stations 2,3,4, while newer generation boards installed in station 1

- RPC
  - The “link system” (connecting the FE board to the trigger processors) to be replaced
    - For convenience of operation and maintenance
    - To fully exploits the intrinsic time resolution ~1.5 ns

- Muon timing improvement by adding RPC

- Experimental Cavern
  - DT chamber
    - Minicrate TDC
    - CuOF
  - Service Cavern
    - DT chamber
      - Minicrate 2 TDC on FPGA
      - CuOF
      - TwinMux
      - uROS

- Backend: L1 processors Readout Pipeline
  - to FED/cDAQ @10 kHz
  - to FED/cDAQ @750 kHZ

- Muon timing improvement by adding RPC
New detectors in the high $\eta$ region

- Very challenging region
  - High rate from random hits, hadron punch-through, and muons
  - Low magnetic field $\Rightarrow$ small bending of muon trajectory
- Despite harsher environment, this region has fewer hits measurement as of today
  - $1.8 < |\eta| < 2.4$ covered only by CSC
- Endcap stations 3&4; $1.8 < |\eta| < 2.4$ (RE3/1, RE4/1)
- Double-gap RPC units (same as the present RPC)
- Improved performance
  - Higher rate capability (lower resistivity, smaller gas gain)
  - Two-side strip readout
    - Providing true 2D hits with $O(1)$ cm resolution in both dimensions

Perform well at $2 \text{ kHz/cm}^2$ (3xHL_LHC)
GEM (Gas Electron Multiplier)

- Avalanches in strong electric field concentrated in pin holes
- Known to operate reliably at high rate (MHz/cm²); excellent longevity
- Triplet GEM: gas gain $10^4$
- Spatial resolution $\sim 100 \, \mu m$
- Two layers triple-GEM to be added at endcap stations 1&2
  - GE1/1: $1.6 < |\eta| < 2.2$
  - GE2/1: $1.6 < |\eta| < 2.4$
- A pilot system of 5 pair GEM chambers were installed in CMS at the beginning of 2017
**ME0 - high η muon tagger**

- The same technology as GE1/1, GE2/1
- **Six layers** - providing “segments”
  - Muons of high p despite low pT
- Covers very high η region: $2.0 < |\eta| < 2.8$
  - $2.0 < |\eta| < 2.4$: CSC-ME0 tandem largely reduces trigger rate
  - $2.4 < |\eta| < 2.8$: enlarged muon geometrical acceptance
  - Taking advantage of the extended acceptance of upgraded CMS inner pixel detector
  - Could be used not only in offline, cut also in trigger
Muon trigger improvement

- CSC-GEM tandem (in endcap stations 1&2) improves trigger-level muon momentum measurement
- Background has steeply falling momentum spectrum

=> Trigger rate reduction
(otherwise raising trigger thresholds would harm physics acceptance)
Lepton flavor violating \( \tau \rightarrow 3\mu \) search

- \( \tau \)-lepton produced at LHC are of boosted to high \( \eta \) region (the dominant source is D/B mesons decay to tau)
- With MEO detector, the signal acceptance is doubled at reconstruction level
- MEO muon segments can also be used in trigger (in a multi-object trigger pattern)
- Sensitivity gain 17% by adding MEO detector
Physics performance by examples

Benefit from extended muon acceptance

Double parton scattering pp→W+W−

- Events with both muons in the highest eta directions are the best in discriminating between different theoretical models

- Sensitivity gain 50% by adding ME0 detector
Physics performance by performance

Trigger on unconventional signals

- Adding GEM makes it possible to build trigger-level muons without assuming muons come from the collision point
  - Trigger on highly displaced muons
- The upgraded RPC link system fully exploits the RPC time resolution
  - Allowing better suppression of out-of-time background
  - Enabling to identify patterns of delayed hits from one station to the next, with a precision of ~1 ns
    - Trigger on Heavy Stable Charge Particles

![Graph: Trigger efficiency on HSCP with RPC timing](image)
More information — Posters

- Performance of the CMS Muon System in LHC Run-2, Carlo Battilana
- Measurement and simulation of the background in the CMS muon detectors, Cesare Calabria
- Upgrade program of the RPC system of the CMS Muon Spectrometer, Andrea Gelmi
- Commissioning and performance of the GE1/1 slice test detectors, Ilaria Vai
- Aging Phenomena and Discharge Probability Studies of the triple-GEM detectors for future upgrades of the CMS muon high rate region at the HL-LHC, Francesco Fallavollita
- Impact of Single-Mask Hole Asymmetry on the properties of GEM Detectors, Aashaq Shah
- Production and quality control of the new chambers with GEM technology in the CMS muon system, Rosamaria Venditti
Summary

• CMS Muon system upgrade
  • Present DT, CSC, RPC detectors will stay
  • Electronics to be selectively replaced to meet HL-LHC requirements
  • The high $\eta$ region to be enhanced with additional iRPC, GEM and ME0 detectors
  • Upgraded detector capabilities open windows for new physics opportunities
• CMS Muon Upgrade TDR is published
• Installation starts in the Long Shutdown 2 (2019-2020); continues in Year-End-Technical-Stops; and finishes in the Long Shutdown 3 (2024-mid 2026)
Back-up
<table>
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<tr>
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<th>HL-LHC needs</th>
<th>CMS 2017</th>
<th>CMS upgraded</th>
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<tbody>
<tr>
<td>Level-1 trigger accept rate (kHz)</td>
<td>500</td>
<td>DT: &lt; 300</td>
<td>DT: (\gg) 500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSC: &lt; 250</td>
<td>CSC: 4000</td>
</tr>
<tr>
<td>Level-1 latency ((\mu)s)</td>
<td>12.5</td>
<td>DT: 20</td>
<td>DT: (\gg) 12.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSC: 3.6</td>
<td>CSC: 28.8</td>
</tr>
<tr>
<td>Total DAQ data transfer rate (Gbit/s)</td>
<td></td>
<td>DT: 42</td>
<td>DT: 3600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSC: 230</td>
<td>CSC: 2764</td>
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Eco-friendlier gas

• New regulations
  • In 2014, the European Commission adopted a new regulation limiting the total amount of important fluorinated greenhouse gases (F-gases) that can be sold in the EU from 2015 onward and phasing them down in steps to one-fifth of 2014 sales in 2030
• CSC and RPC F-gas footprint
  • 1700 m³/hr of CO2 equivalent (yearly, 12K cars)
  • F-gases used by CSC and RPC prevent ageing and ensure reliable operation
• Solutions
  • new eco-friendlier gas options -> RPC explore operation with CF3I, C3H2F4 (GWP 0,4)
  • F-gas consumption reduction -> CSC explore operation with 2% CF4
  • Other measures being explored