Upgrade of the CMS muon system

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on behalf of the CMS collaboration
The muon system

A robust, efficient and redundant muon system

- Muon identification
- Measurement of muon transverse momentum
- Bunch crossing (BX) assignment

Planar endcap region:

- 4 planar stations interleaved with the iron return yoke plates (the 4th is partially descoped).
- Cathode Strips Chambers and Resistive Plate Chambers

Cylindrical barrel region:

- 4 coaxial stations interleaved with the iron return yoke plates. The stations are grouped into 5 wheels around the beam line
- Drift Tubes and Resistive Plate Chambers
The detectors

- **250 Drift Tube Chambers**
  - Barrel region, for $|\eta|<1.2$
  - 4 stations, 5 wheels, 12 sectors
  - (4+4) layers measuring $\phi$
  - 4 layers measuring $z$ in stations 1-3
  - Local segment per chamber
  - Spatial resolution $\sim 250 \, \mu m$

- **540 Cathode Strip Chambers**
  - Endcap region, for $0.9 < |\eta| < 2.4$
  - 2×4 stations, 1-3 rings, 18-36 sectors
  - 6 layers of strips per chamber measuring $\phi$
  - 6 layers of anode wires per chamber measuring $r$
  - Local segment per chamber
  - Spatial resolution $\sim 150 \, \mu m$

- **480 + 432 Resistive Plate Chambers**
  - Both regions, for $|\eta|<1.6$
  - Barrel: 4 stations, 1-2 layers, 5 wheels, 12 sectors
  - Endcap: 2×3 stations, 2 rings, 36 sectors
  - Local hit per chamber
  - Time resolution $< 3 \, ns$
…and their excellent performance

DT average local trigger efficiency:
- 93.5% in 2011 and 93.7% in 2012
- Lower efficiency points due to the crack between W+1 and W-1

CSC efficiency for ME1 trigger primitives:
- Similar result for other stations

RPC efficiency, in 2011-12:
- Different p correction algorithms applied
- Average efficiency in 2011: 93.97%
LHC luminosity evolution

Phase II (post LS3, 2022-23) essentially means integrated luminosity, Pile Up, etc. an order of magnitude greater than the design values of the LHC experiments

...And the detectors will be more than 10 years old!
Muon system and physics reach

- Conservative scenario: focus on precision measurements on Higgs coupling
- Muon system is critical for both bosonic and fermionic couplings:
  - $H \rightarrow WW$ and $ZZ$ are key to the precision on $HVV$ couplings
  - $H \rightarrow \tau \tau$ is key for measuring fermion coupling
    - Muon + hadronic tau is the most sensitive channel; fully relies on muon trigger

- $H \rightarrow ZZ \rightarrow 4\mu$ channel:
  - Acceptance increases by 30% if muon reconstruction coverage extends from $|\eta_{\text{max}}| 2-4 \rightarrow 3.5$

Need to get that “last” muon!
Strategies for muon upgrades

- Maintain current offline and trigger coverage - especially important to strengthen the region $1.8 - 2.0 < |\eta| < 2.4$ despite increasing luminosity and Pile-Up
  - May require additional redundancy, i.e. additional stations
  - Obvious existing space where RE1/1, 2/1, 3/1, 4/1 were envisioned
  - Technologies considered: GEMs, Glass and other improved RPCs,

Increase of the muon tagging coverage up to $2.4 < |\eta| < 3.5 - 4.0$
  - Offline verification of a high-Pt track being a muon
  - Adds acceptance for muons, could improve MET resolution and recognition

Increase muon trigger coverage into $2.4 < |\eta| < 3.5 - 4.0$
  - Need a new magnetic field, solenoidal is insufficient

|\eta| < 2.4 - highest rate and least redundancy
First step toward the “upgrade” of the muon system

The CMS Forward Muon RPC system presently consists of 3 endcap stations and is equipped with chambers up to $|\eta|=1.6$, while the CMS Muon Technical Design Report describes a system with 4 stations and a detector up to $|\eta|=2.1$

Complete the system with the fourth station and achieve better trigger performance and robustness of the system, as it was originally designed.
**GOAL:** Install the 4th layer - 144 chambers! (RE4/2-3) - during LHC LS1 (2013-2014) to complete the system up to $|\eta|=1.6$.

Construction sites: CERN, Korea, India, Belgium
Final QC and commissioning @ CERN

Huge organisational effort!

- First Super-Module (pairs of RE4/2 and RE 4/3) assembled some weeks ago
- 53/144 chambers built so far
- 10/72 super-modules ready
1. Trigger latency and rate increase
   - At Phase 2 baseline 10 μs and 500 kHz lose ~1% of cathode data,
     • Plan to replace CFEBs if latency is to exceed 10 μs

2. ME1/1 chamber aging tests
   ✓ Aging effects measurable, but not found to inhibit chamber performance
     • Otherwise, no particular upgrades anticipated
DT upgrades, up to 2017

New θ TRB (Trigger board)

New faster Read Out server

Luminosity increase will affect processing speed of the Read-Out-Server (ROS) boards
Will reuse Twin Mux hardware (based in high speed standard uTCA)

Sector collector re-location

Guarantee reliable operation and allow future upgrades
Copper links transduced to optical to cover cavern-counting room distance (65 m)

New multiplexer (Twin Mux)

High speed data to CMS L1 Trigger Track Finder system
Full chamber trigger information forwarded
Aim to allow merging information from other subdetectors (RPC, etc)
DT upgrades for Phase II

No indications of aging effects during LHC, nor in previous dedicated tests
Plan to take preventive actions (HV, gas, etc)
Perform simulations of the impact of chamber aging (efficiency loss, noise, etc)
Pile-up effects also reevaluated in complex regions

New Minicrates: chamber digitization

Evaluating radiation and longevity of present Minicrates
R&D in new design: time digitization and direct data forwarding (fundamental architectural differences)
Simple, robust and low power
A trigger primitive generator using readout data could be developed (it should provide better resolution)

Chamber longevity studies
All detectors foreseen for post-LS3 with the aim of restore redundancy or increase coverage should stand a rate capability higher then the present:
- Because installed in high-\(\eta\) regions
- From 1 kHz/cm\(^2\) \(\rightarrow\) 5-10 kHz/cm\(^2\)

In addition we could be willing to improve also:
- Time resolution – from \(o(1\ \text{ns})\) \(\rightarrow\) \(o(100\ \text{ps})\)
- Spatial resolution – from \(o(1\ \text{cm})\) \(\rightarrow\) \(o(1-0.1\ \text{mm})\)

Given requirement on rate capability, choice of the technology will be driven by the physics case:
- plus robustness, cost, easiness of construction, etc.
For instance, \(o(100\ \text{ps})\) would push us toward RPC multigaps solutions
After LHC LS1 the $|\eta|< 1.6$ endcap region will be covered with 4 layers of CSCs and RPCs; the $|\eta|>1.6$ region (most critical) will have CSCs only!

- Restore redundancy in muon system for robust tracking and triggering
- Improve L1 and HLT muon momentum resolution to reduce or maintain global muon trigger rate
- Ensure ~ 100% trigger efficiency in high PU environment
The technology: Gas Electron Multipliers

Developed by F. Sauli in 1997

Each foil (perforated with holes) is a 50 µm kapton with copper coated sides (5 µm).

Typical hole dimensions: Diameter 70 µm, pitch 140 µm

- Electron multiplication takes place when traversing the holes in the kapton foils.
- Many foils can be put in cascade to achieve $O(10^4)$ multiplication factors.

Main characteristics:

- Excellent rate capability: up to $10^5/cm^2$
- Gas mixture: Ar/CO$_2$/CF$_4$ – not flammable.
- Large areas ~1 m x 2m with industrial processes (cost effective).
- Long term operation in COMPASS, TOTEM and LHCb.
Detector performance

- Very good time resolution
  Depending critically on the gas mixture
  Long R&D on gas (and other issues)
- Excellent spatial resolution
- Full efficiency at $10^4$ overall gain

A new VFAT3 baFE electronics being developed to fully profit from all these characteristics.

\[\sigma_t = 4 \text{ ns}\]

Gain = $10^4$

\[\sigma_s = 150 \mu\text{m}\]
Path to approval

- Over 4 years of R&D started since 2009 in the RD51 framework
- CMS GEM Collaboration established in 2011 with about 120 people from 20 institutes; today about 40 institutes and 180 people
- R&D for a *High-*\(\eta\) *Trigger and Tracking Detector for CMS*, SLHC RD 10.02 approved in April 2012, after submission of Technical Proposal for GE1-2/1 in LS2

- Approval for developing prototype DAQ and installing slice (= GEM demonstrator) in 2016-17 to demo GE1/1 incorporation into trigger
- Current expectation is that GE1/1 will be included in Phase 2 Technical Proposal, with intent to install during LS2
  - GEM Demonstrator = 2 Super Chambers covering a 20° sector
  - LS 2 complete project: 2x36 Super Chambers (144 triple-GEMs)
And beyond… R&D on glass RPC

New “low” resistivity (10^{10} \, \Omega \text{cm}) glass used for high rate RPC

- RPC rate capability depends linearly on electrode resistivity
- Smoother electrode surfaces \rightarrow reduces the intrinsic noise
- Improved electronics characterized by lower thresholds and higher amplification
- Single and multi-gap configurations under study

Mylar layer (50\mu)
PCB (1.2mm) + ASICs (1.7 mm)
PCB support (polycarbonate)

Readout ASIC (Hardroc2, 1.6 mm)

PCB interconnect
Readout pads (1cm x 1cm)

Gas gap (1.2 mm)
Cathode glass (1.1 mm) + resistive coating
Ceramic ball spacer

Excellent performance at localized beam tests
- Rate capability \sim 30 \, \text{kHz/cm}^2 \text{ (multi-gap)}
- Time resolution 20-30 ps
Conclusions

• The **CMS muon system has been operating extremely well**, delivering very good data for physics:
  – After 3 years of LHC at increasing luminosity and 6 years from the end of construction, the detector performance is within specifications both for triggering and as a reconstruction system

• Conditions after LS3, in terms of instantaneous and integrated luminosity, will pose an **incredible challenge for the system**

• CMS is developing a **strategy to cope with the new conditions**, so that the overall performance remains stable despite increased Pile Up, luminosity, background.

• **New detectors with improved performance** (GEMs, GRPC, improved RPCs) are promising candidates for the improved CMS muon system of the future
Thank you!