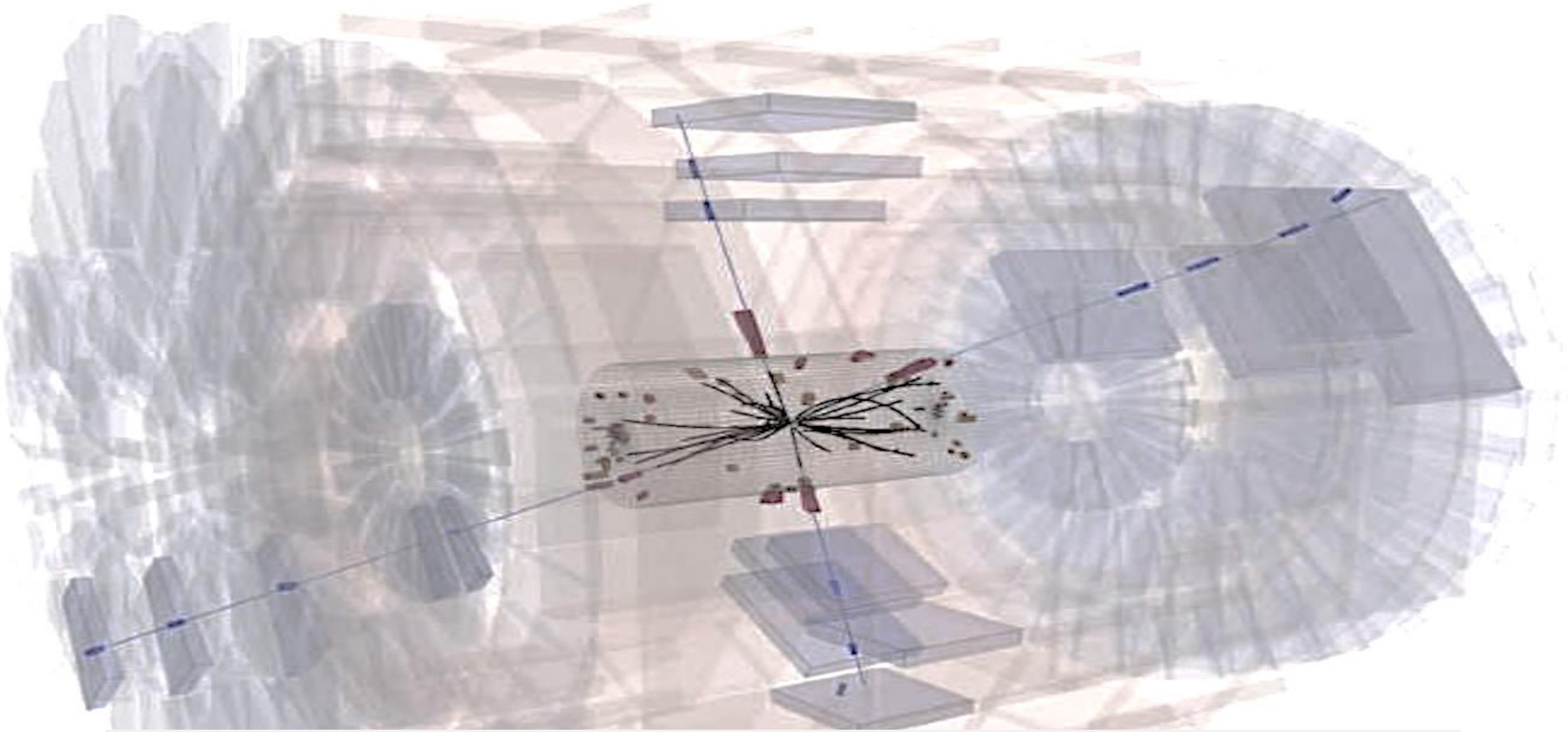

CMS Muon system
Design and optimisation considerations

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On behalf of the CMS Muon group

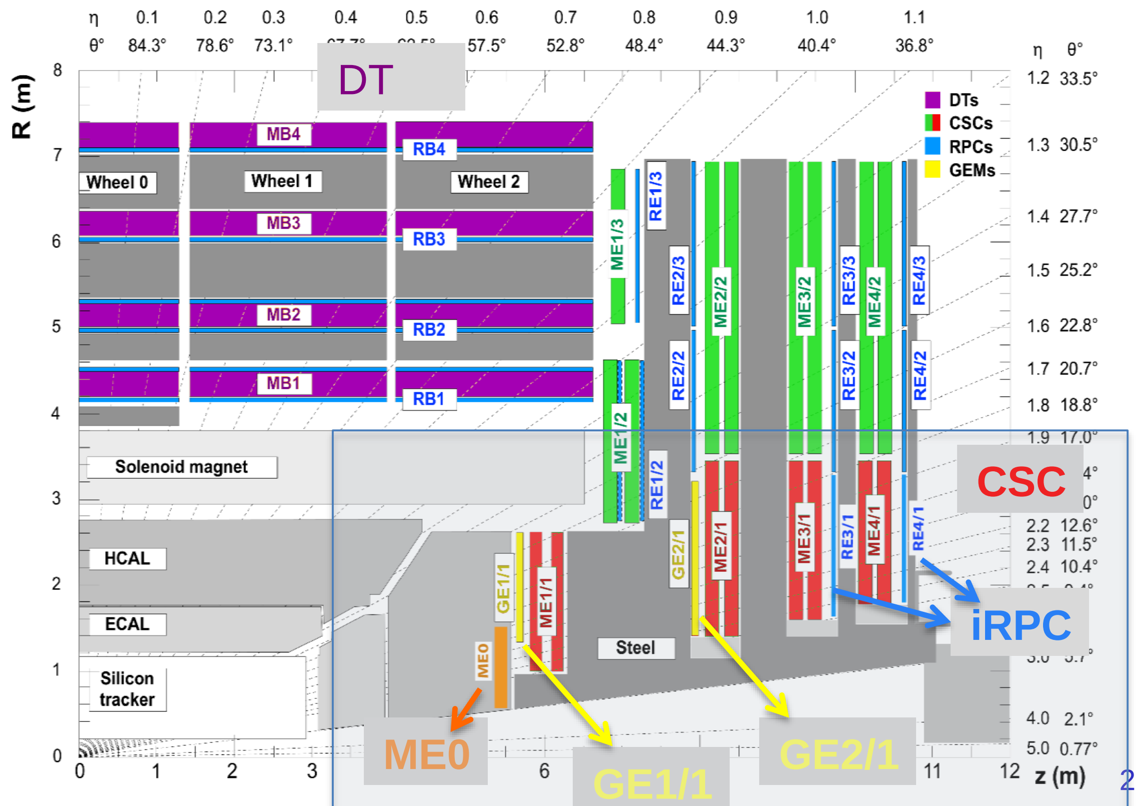
3rd ECFA Workshop on High Luminosity LHC- 3-6 October, 2016 Aix-Les-Bains, France

CMS muon upgrade scope

Goal: maintain excellent triggering, ID, and measurement of muons under harsher HL-LHC conditions (instantaneous and integrated L) up to $|\eta|<3$

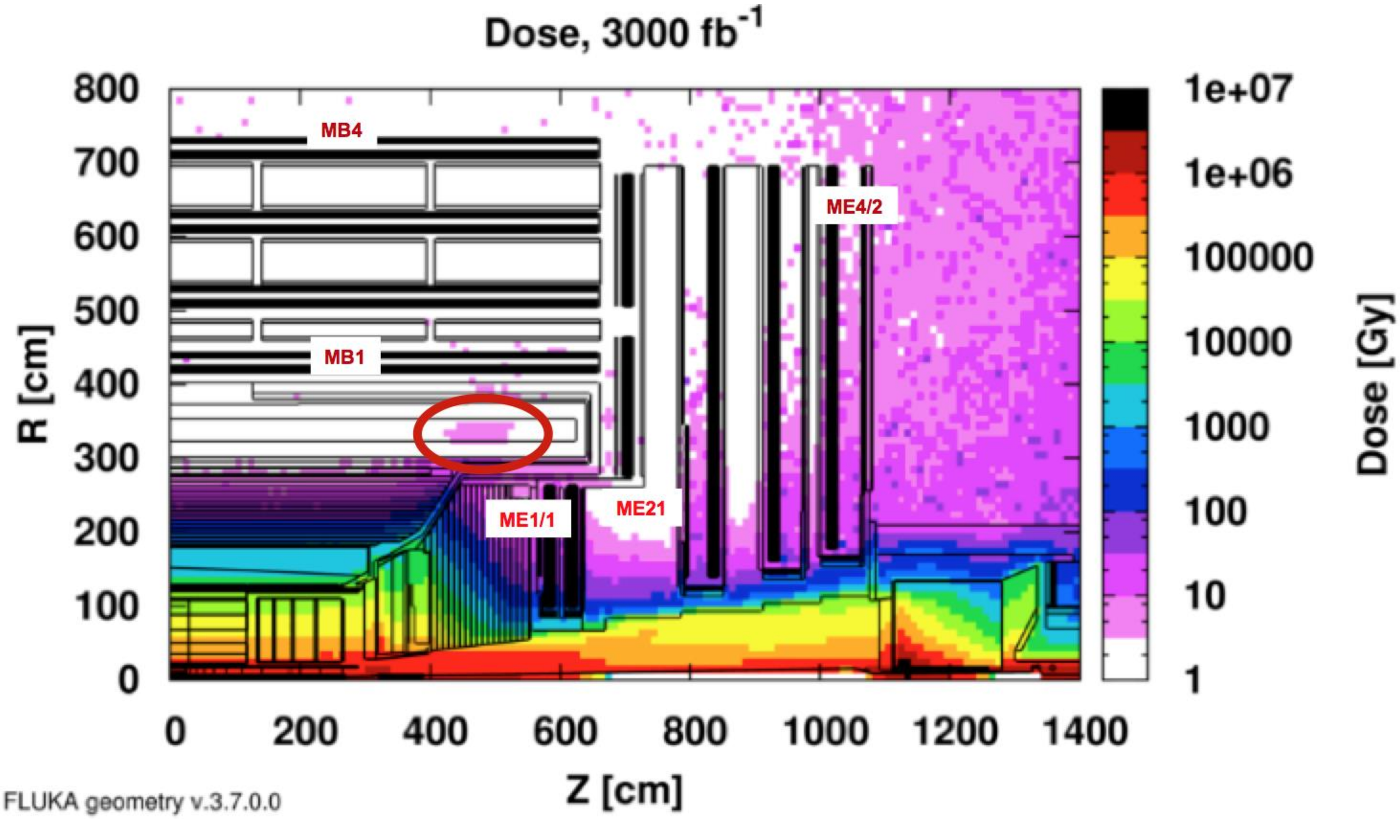
1. Existing detectors: consolidation of detector operation; barrel DT and endcap CSC electronics upgrade
2. New forward muon detectors: GEM in GE1/1 (approved), GE2/1, and ME0; improved RPC in RE3/1 and RE4/1

- DT and CSC electronics replacement to handle longevity issues and L1 trigger (750 kHz) rate and latency (12.5 μs)
- New forward detectors to handle most difficult region, with high background trigger and readout rates, and limited bending
- ME0 extends offline muon coverage up to η=2.9



Radiation Environment

HL-LHC background – 5x rates and 6x total doses with respect to LHC



Exceed the design tolerances of several components of the muon system:

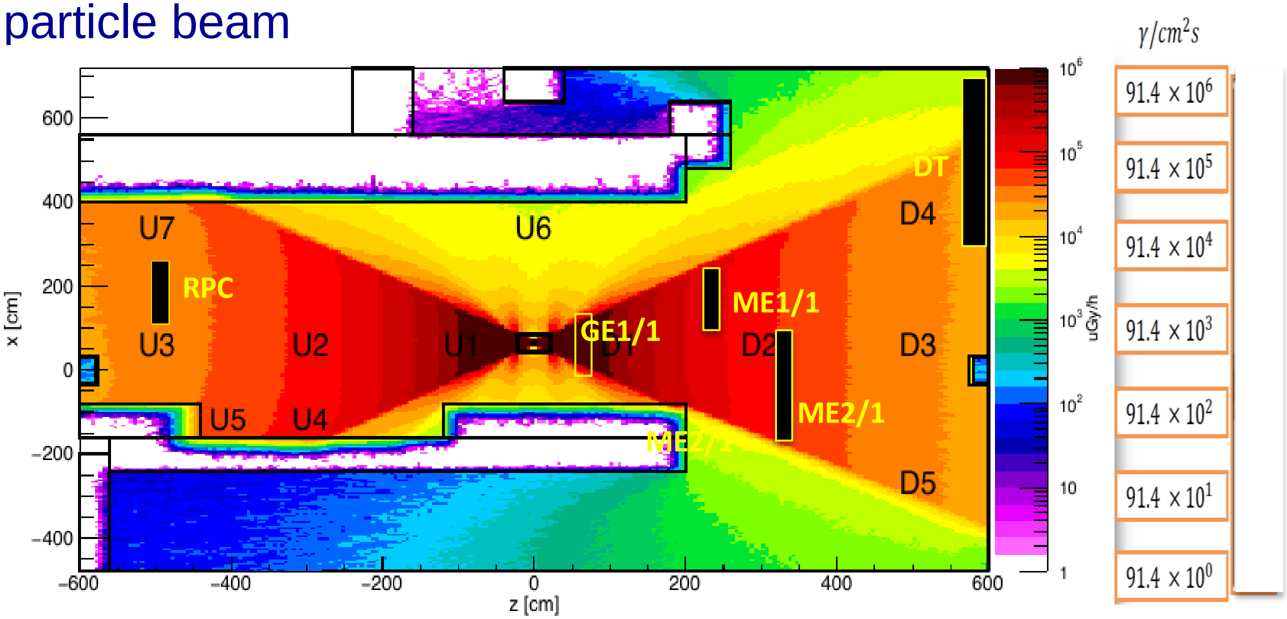
- new assessment of the chambers and electronics longevity, operation and performance

Consolidation: studies and plans

1. Improve detector shielding
2. Aging campaign at GIF++ ongoing to assess longevity of existing detector at HL-LHC
3. Monitor detector operation in CMS and develop mitigation strategies
   - Stability of the gas gain, RPC electrode resistivity hit efficiency, cluster-size, noise, I vs HV.
   - Optimize gas gain and HV working point between different detector region to prolong the system lifetime
   - Mitigate the failure rates of detectors and electronics modules with preventive maintenance during LHC stops
4. Gas studies:
   - Stricter EU regulation on gas emission might restrict the use of greenhouse gases
     - R&D program on searching and studying possible substitutes for $C_2H_2F_4$, CF_4, SF_6
     - develop an operational model maintaining acceptable performance with reduced percentage of greenhouse gases in the mixtures.

Muon consolidation studies at GIF++

CERN GIF++: 662 keV photons emitted by an intense 14 TBq ^{137}Cs source + high momentum particle beam



CSC: 1 ME1/1 and 1 ME2/1

DT: 1 MB1

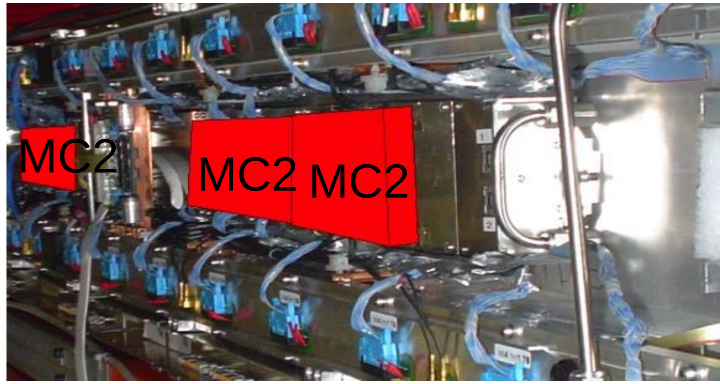
GEM: 1 GE1/1

RPC: 1 RE2 and 1 RE4

Strategy:

- Longevity studies of full size chamber under realistic with an accelerator factor which allows to accumulate radiation dose (in < 2 years) corresponding to x3 the expected after 3000 fb-1
- In parallel an accelerated aging test on small prototypes to study mitigation strategies in case of aging and test of new mixtures (CSC/RPC)
- If any aging is observed in the chambers and/or new mixtures found (RPC/CSC) undertake new longevity tests on full size chamber under the new operation conditions.

The DT Electronics upgrade



Main concerns come from Minicrates:

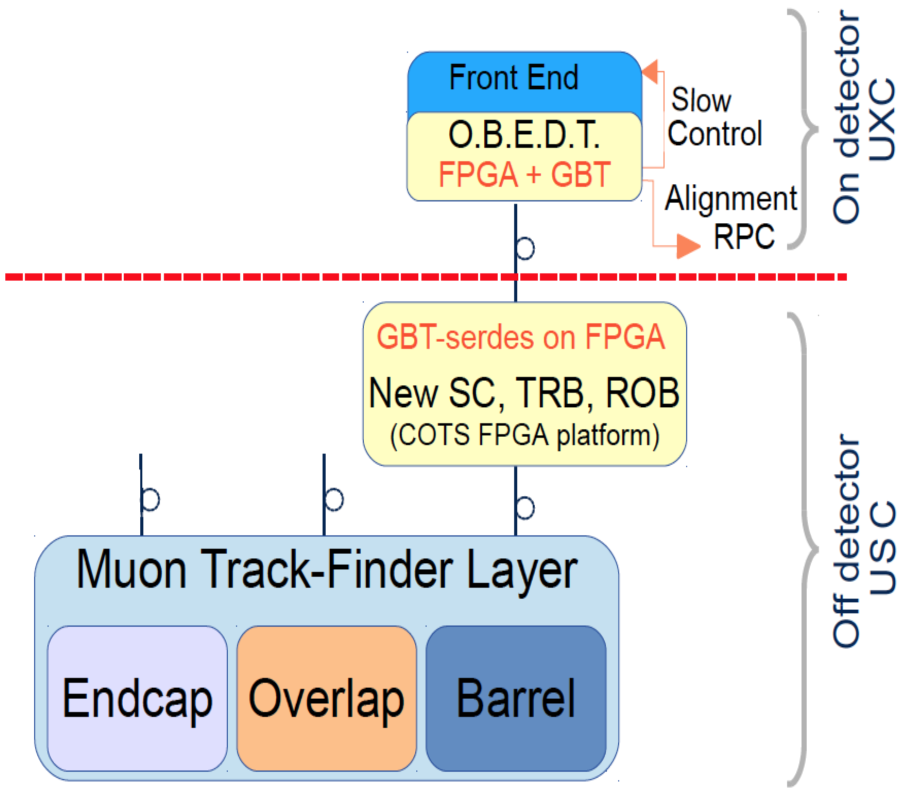
- Each DT chamber is equipped with a on-chamber MiniCrate containing Trigger, Read-out, Control and Link electronics
  - Current minicrates are large and containing 17 boards of 6 different types.
  - Some components certified only up to 500 fb^{-1}
  - Maintenance only possible during long shutdowns and intervention on detector is increasingly difficult

- L1 trigger accept rate limited to 300 kHz: readout limitation

Upgrade system:

- Move the large fraction of the functionality outside the experimental cavern
  - Trigger primitives directly generated from TDCs (as done now at HLT)
- The new minicrates (MC2) will be very small and only containing TDCs, optical links and slow control services.

The DT Electronics upgrade



On-Board-Electronics-DT (OBDT) with high-resolution TDC data continuously transmitted through optical fibers.
LV power supplies in cavern will be replaced to appropriate to match to new low-power electronics

Commercial processors in service cavern performing Trigger and high-speed Read-Out (1 MHz without data loss) operations of the TDC data

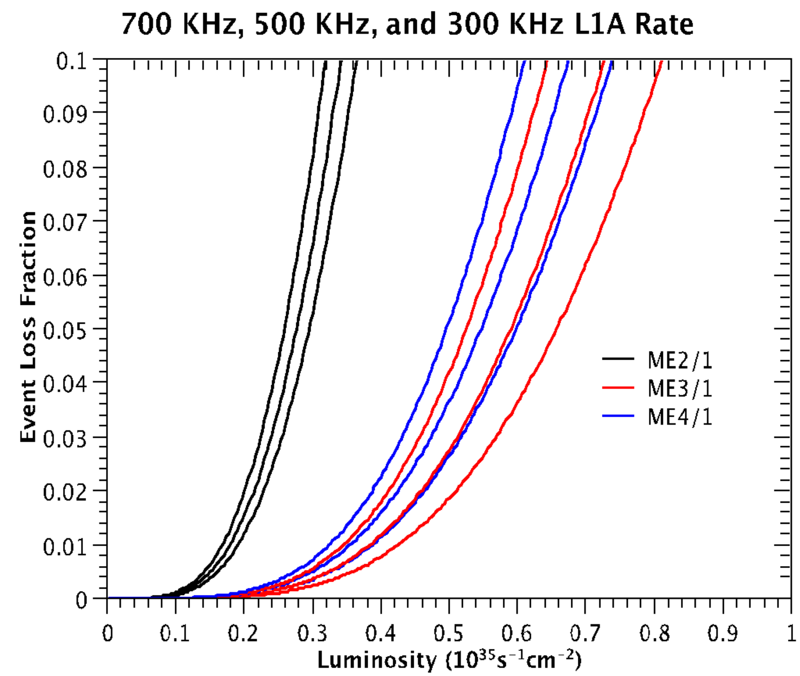
- new trigger primitive generation with a resolution close to those of present HLT reconstructed segments
- rate reduction and efficient matching with Track-trigger

Full electronics system replacement in LS3

The CSC Electronics upgrade

Main concerns come from **Cathode Front-end Board (CFEB)** where data storage is done inside a switched-capacitor analog ASIC with very limited buffering:

- At HL-LHC latency and rate, data storage buffers fill up and CFEB becomes inefficient
- large data loss level is reached for all inner chambers MEX/1 at 750 kHz and 12.5 us latency



On-detector electronics upgrade largely as built for the first station of inner chambers (ME1/1) and already done in LS1:

- CFEB replaced with **DCFEB** (Flash-digitize every strip at 40 MHz, and large digital data memory storage) and optical data output on 3.2 Gbps optical links

The CSC Electronics upgrade

Components to be replaced are highlighted in yellow

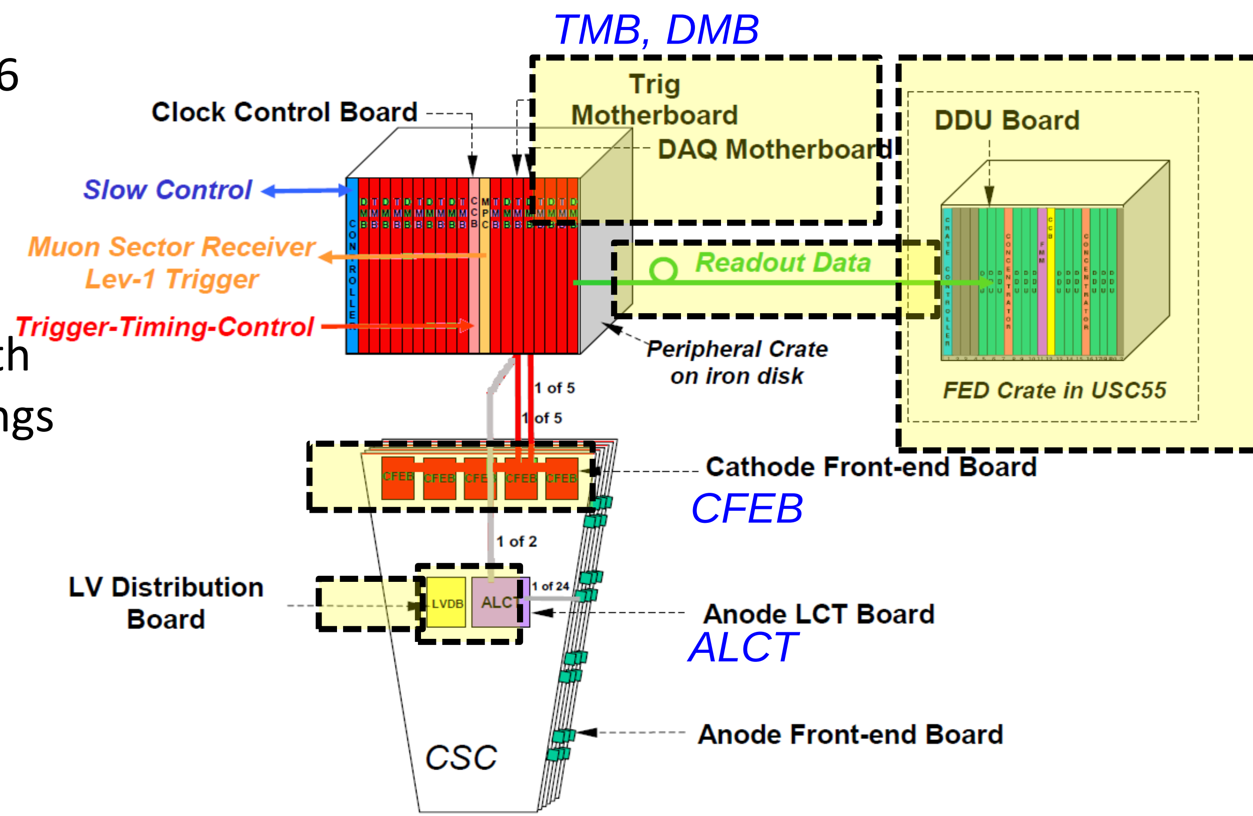
Current Electronics Configuration for CSC Readout

On-chamber

- CFEB replaced with DCFEB (108 chambers)
- ALCT mezzanine cards in situ (396 chambers)

Off- chamber

- Trigger Mother Boards (TMB) with Optical-TMB (OTMB) for inner rings
- Data Mother Boards (DMB) with new Optical-DMBs (ODMB)
- Readout (FEDs) with standard commercial modules



- Access for on-chamber electronics replacement possible only in LS2.
- Replacement of DMB and FED electronics in LS3

The forward muon system challenges

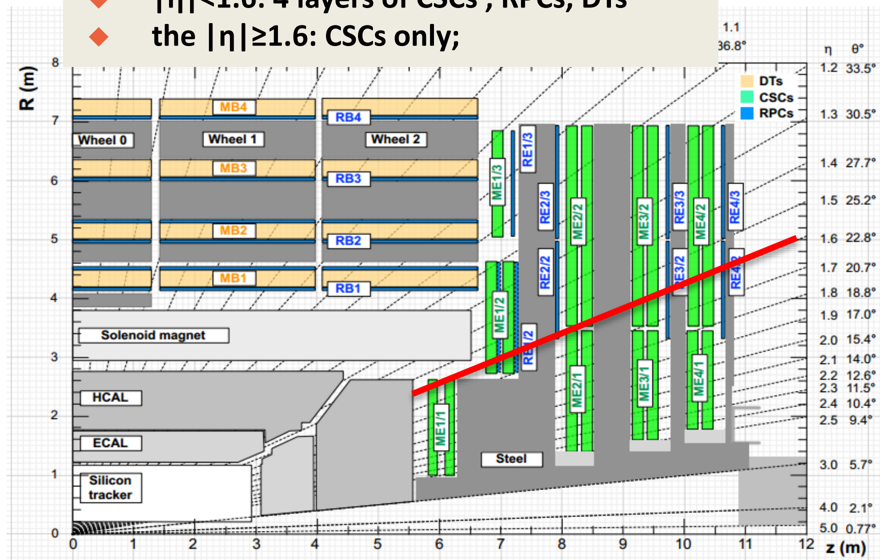
The forward region |η|≥1.6 is very challenging

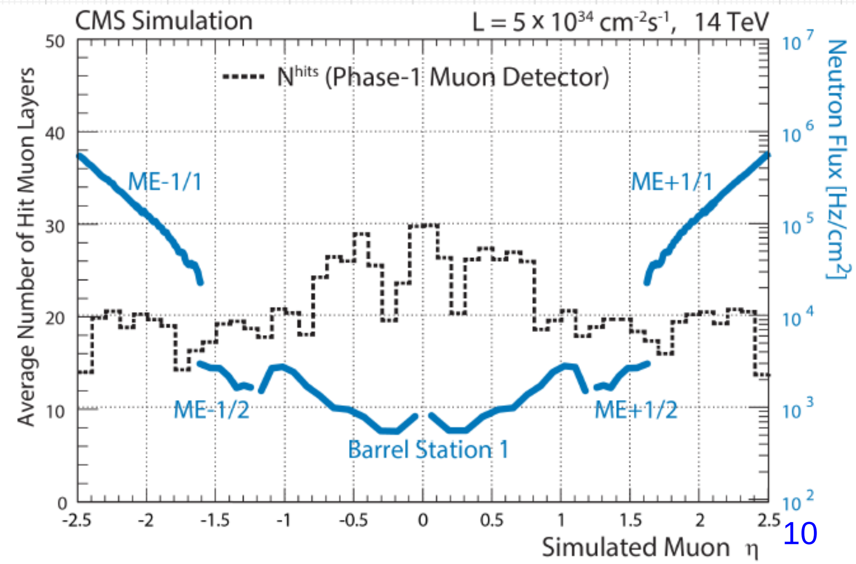
- **Redundancy**: the highest rates in the system but meanwhile fewest muon layers
  - the trigger and offline performance can degrade due to aging of existing detectors

- **Rate**: high background and higher towards higher eta
  - worse momentum resolution will degrade trigger performance in forward region.

→First step to address this is installation of GE1/1 during LS2

Eta coverage:
- |η|<1.6: 4 layers of CSCs , RPCs, DTs
- the |η|≥1.6: CSCs only;



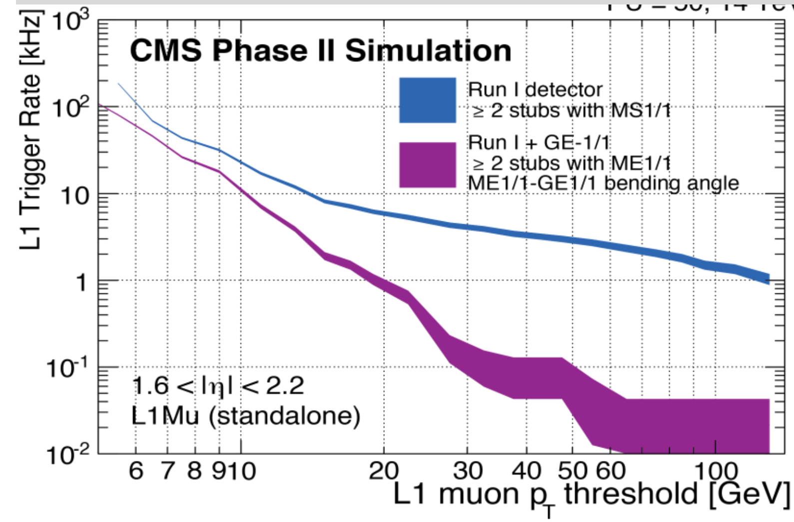


The forward Muon Upgrade Scope

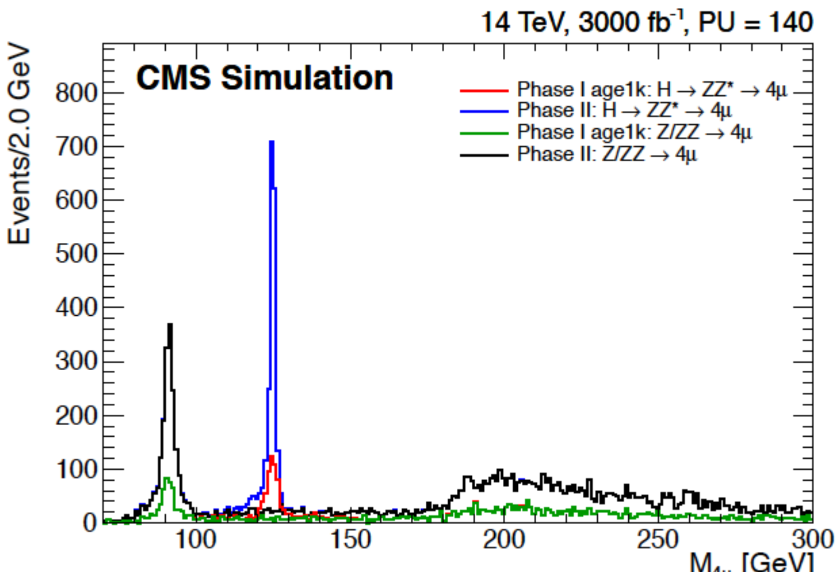
Address challenges with muon trigger/reconstruction:

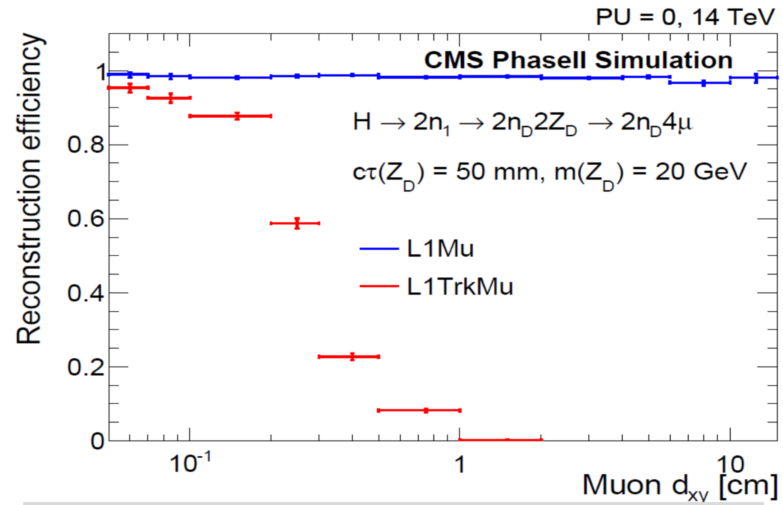
- Maintaining low muon momentum thresholds for triggering on soft muon: Higgs, SUSY, b physics, EXO scenarios
- Preserving sensitivity to displaced signatures (exotic physics models: HSCP, Dark Matter..)
- Cope with background and PU with precise timing detectors

Maintain 15 GeV online threshold, keep < 5 kHz rate→ rate reduction x5



Increases offline acceptance





Track-Trigger Mu inefficient for dxy >1 cm.

The forward muon system upgrade

GE1/1:

Trigger and reconstruction

- 1.55 < |η| < 2.1
- **baseline detector for GEM project**
- 36 super-chambers (SC)- two layers of triple-GEM chambers- per disk, each SC spans 10°
- **Installation in LS2.**

TDR approved in Sept. 2015

ME0:

- **Trigger and reconstruction**
- 2 < |η| < 2.9
- each chamber spans 20°
- 6 layers of GEM-like technology

GE2/1:

Trigger and reconstruction

- 1.55 < |η| < 2.46
- 18 SC per endcap, each chamber covers 20°
- 2 layers GEM-like technology

Installation before LS3

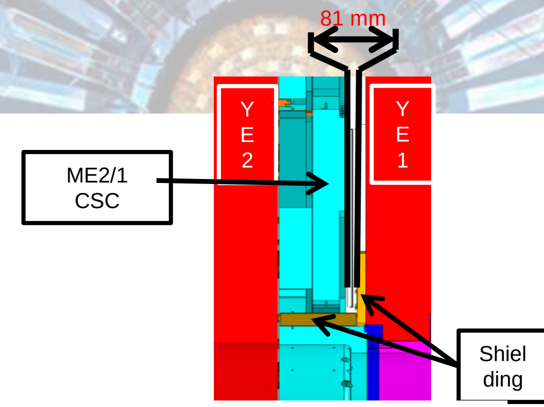
RE 3/1 –RE4/1 :

Trigger and reconstruction

- 1.8 < |η| < 2.4
- 18 chambers per endcap, each chamber spans 20°
- 1 layer RPC-like technology

Installation before LS3

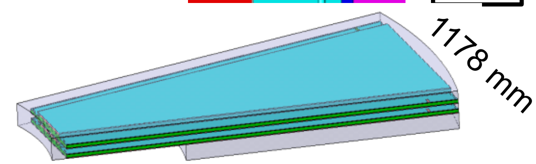
The GE2/1 detector



The station GE2/1 consists of 72 triple-GEM chambers arranged in 36 20^0 Super-chambers, covering $1.60<|\eta|<2.46$.

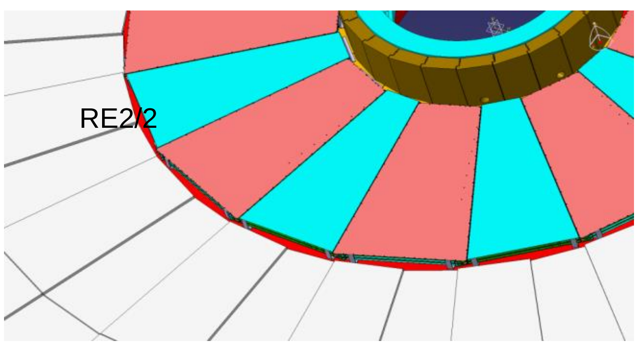
Layout is similar to GE1/1, but covering much larger surface:

✓ Will be the largest triple-GEM chambers built

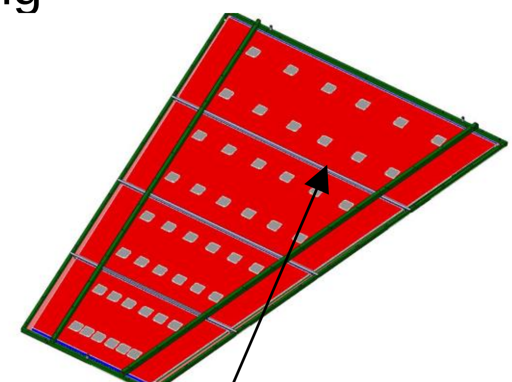


Optimization of engineering design for mass production on-going

GE2/1



- only 81 mm clearance including services
- four foil modules structure per 20-degree chamber, 6 ϕ-sectors × 8 η-sectors total



Reinforcement elements

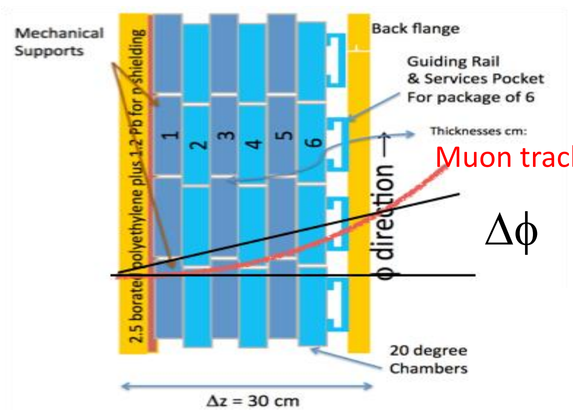
- Option for μ-R-Well technology as compact and low cost large detector (G. Bencivenni et al., 2015_JINST_10_P02008)

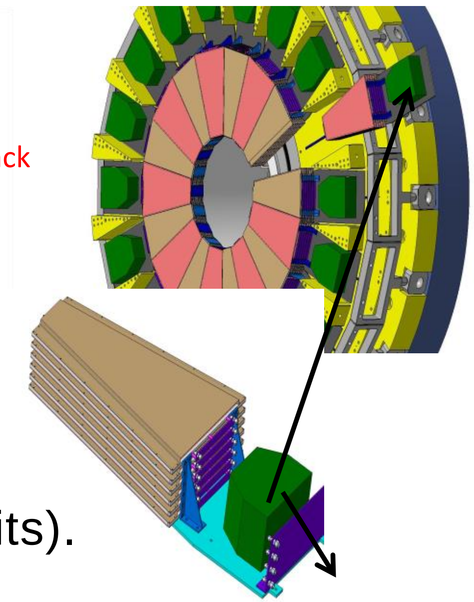
The ME0 Detector

- Extend muon tagging coverage up to η~2.9 and enhance trigger to η~2.4 range using space available in the back of the new endcap calorimeter
- ME0 baseline is 6 layers of triple-GEMs arranged in 20^0 super-module wedges.

High granularity spatial segmentation for:

- Position and bending measurement of the muon stubs for efficient matching of offline pixel tracks.





Multi-layered structure to:

- improve local muon track reconstruction
- discriminate muon (segment) against neutrons (uncorr hits).

Option: precision timing

- Option for Fast Timing Micro-pattern (FTM) detector to reject background hits from pile-up and neutron background – small prototype under study

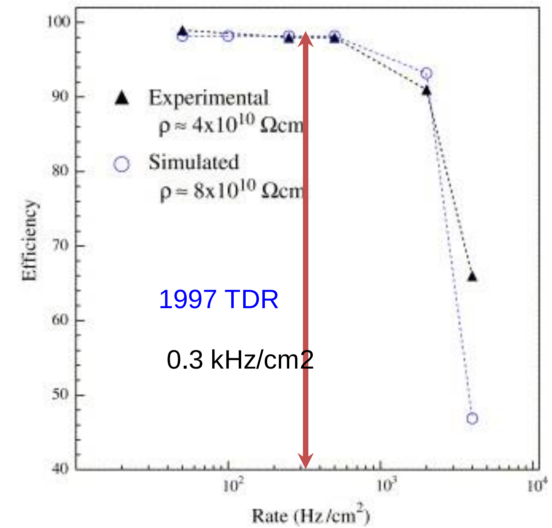
(**Maggi, De Oliveira, Sharma** arXiv:1503.05330v1)

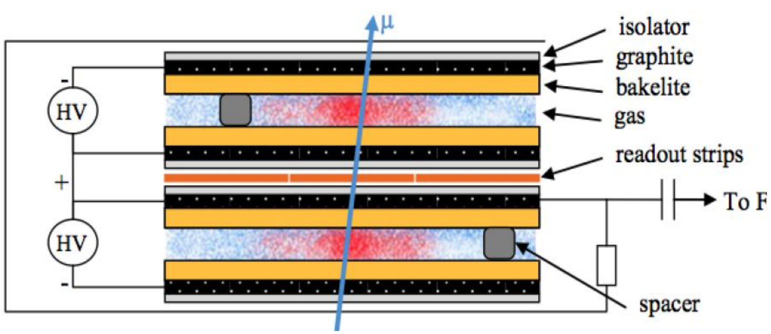
RPCs for RE3/1 and RE4/1

Restore redundancy with two 72 RPC stations with improved rate capabilities 2.0 kHz/cm^2 (vs present 0.3 kHz/cm^2) and stable performance at HL-LHC.

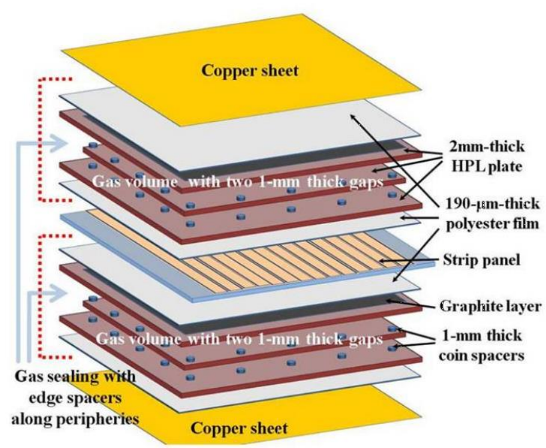
Detector R&D on-going:

- Reduced electrode resistivity: about 10^{10} Ωcm (bakelite or glass option)
- Reduced electrode and gas gap thickness (<1.5 mm vs present 2 mm)
- New generation low-noise FE electronics for high efficiency/less aging
- Finer pitch option for high spatial resolution: 1-2 mm vs. current ~1 cm
- Multigap option for high timing accuracy

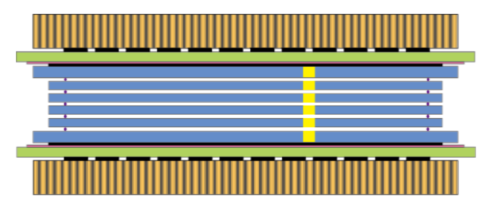




- **Baseline "Double-gap" configuration**
  - HPL (bakelite) electrodes,

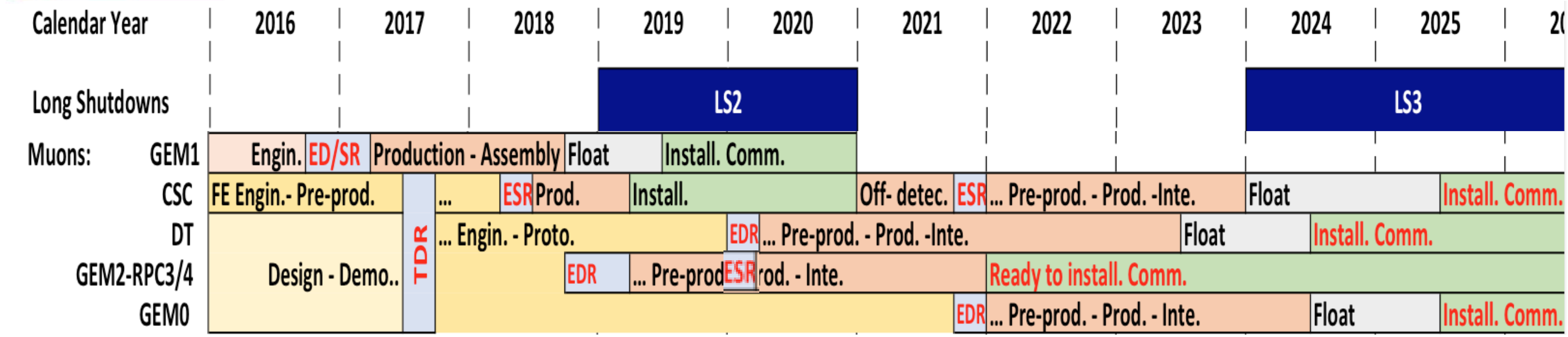


Thin 2-double-gap HPL-bakelite



Multi-gap glass

Muon upgrade timeline

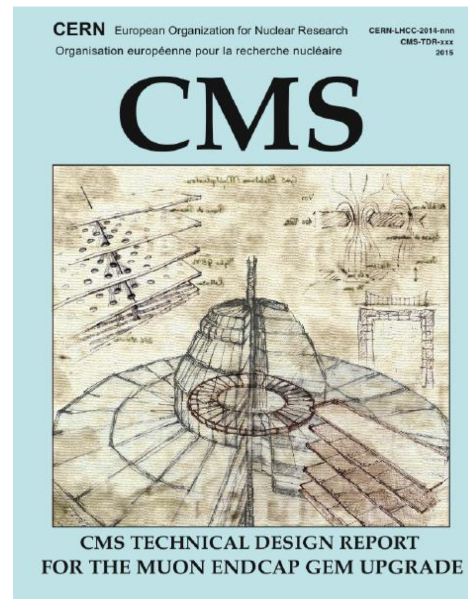


- GE1/1 Technical Design Report (TDR) approved as being the first CMS Phase II TDR, following the need of early operation in LS2.

- Muon TDR Q4-2017: Design and demonstration phases for Detectors and Front-end electronics Upgrade by Q4-2017

- CMS upgrade activity optimization requires
  - Anticipation of CSC Front-end upgrade in LS2
  - Installation of GE2/1 and RE3/1-RE4/1 detectors in Extended Technical Stops before LS3

- DT electronics, CSC back-end electronics and ME0 upgrade in LS3



Summary

Muon Upgrade program will allow for continued excellent muon performance throughout the whole Phase 2:

- Consolidation of existing detectors:
  - ✧ mitigation strategies in place in case of detector aging.
  - ✧ DT and CSC electronics replacement to handle longevity issues and L1 trigger rate and latency

- Enhancement of the forward region $1.6 < \eta < 2.4$ in order to preserve the standalone muon trigger efficiency and reconstruction capabilities in the HL- LHC era.

- Extension to the most forward region $|\eta|>2.4$ with a muon station to increase acceptance to new signals and to improve background rejection.

Design and demonstration phases for Detectors and Front-end electronics Upgrade are ongoing

Work is starting to put together the Phase II Muon TDR (Q4 2017)