GEM detectors for the Upgrade of the CMS Muon Forward system

NEC'2019: XXVII *International Symposium on Nuclear Electronics and Computing*

Becici, Budva, Montenegro
30 September-4 October 2019

Martina Ressegotti (INFN Pavia & University of Pavia, Italy)
on behalf of the CMS Muon Group

Outline

- *Motivation for the GEM Upgrade*
- *The GEM Upgrade Project*
  - The GEM Technology
  - GEM Stations and their Timeline
- *The GE2/1 Station*
- *The ME0 Station*
- *The GE1/1 Station*
  - The GE1/1 Demonstrator («Slice Test»)
  - GE1/1 Assembly and Quality Controls
  - Test installation (Summer 2019)
  - Final installation: schedule and commissioning plans

Motivation for the GEM Upgrade

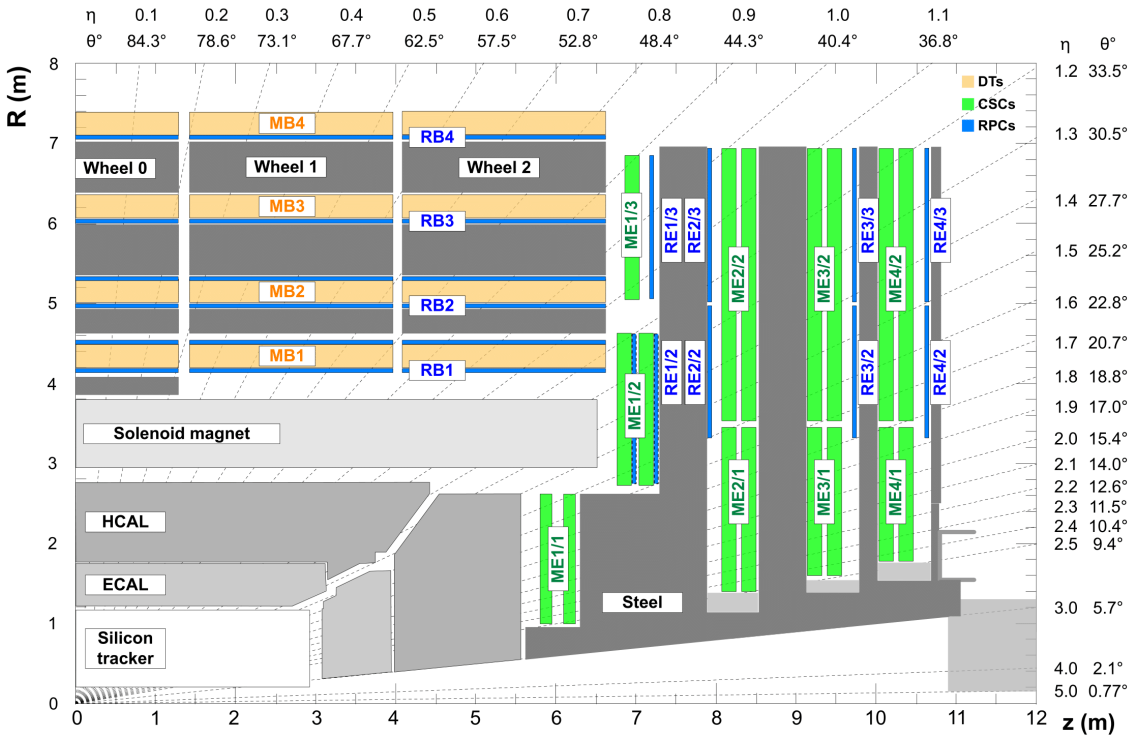
The current CMS Muon System:

3 Technologies

- Drift Tubes (DTs)
- Cathode Strip Chambers (CSCs)
- Resistive Plate Chambers (RPCs)

Status

- Complementary technologies available up to $|\eta| < 1.6$
- Region $1.6 < |\eta| < 2.4$ currently covered only by CSCs
- The muon system is currently uninstrumented at $|\eta| > 2.4$



Motivation for the GEM Upgrade

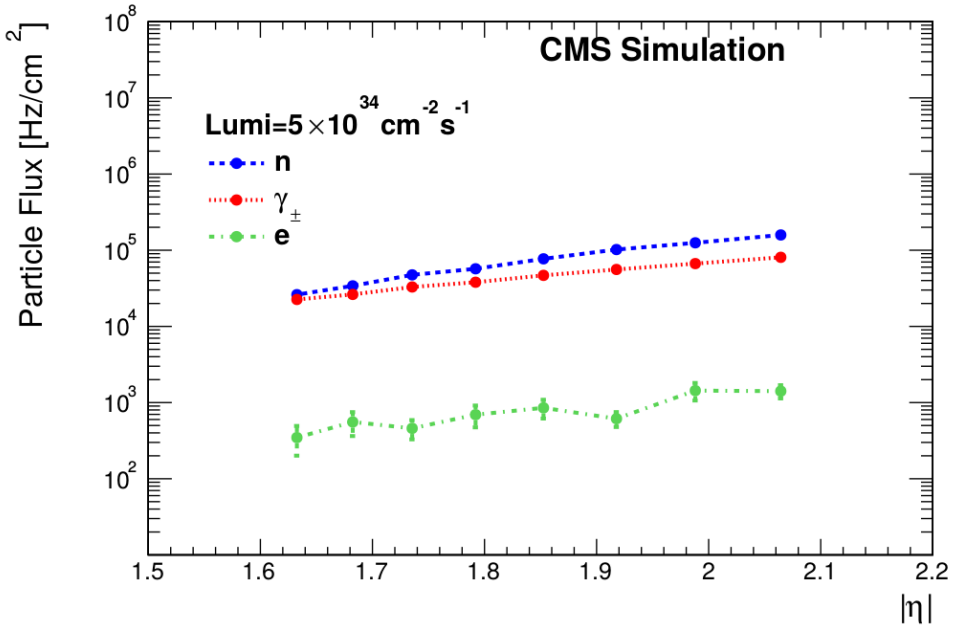
The High Luminosity LHC (HL-LHC)

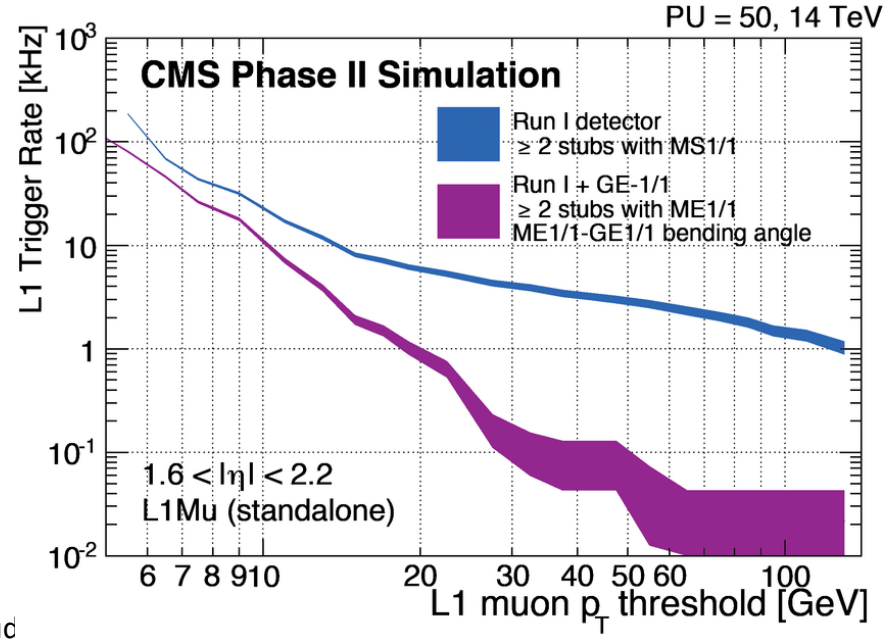
- By 2023 an instantaneous luminosity of **5 to 7.5 x 10^{34} $cm^{-2}s^{-1}$** will be reached
- The particle background will increase up to **10^{6} $cm^{-2}s^{-1}$**
- The pileup will increase from 30 to 200

→

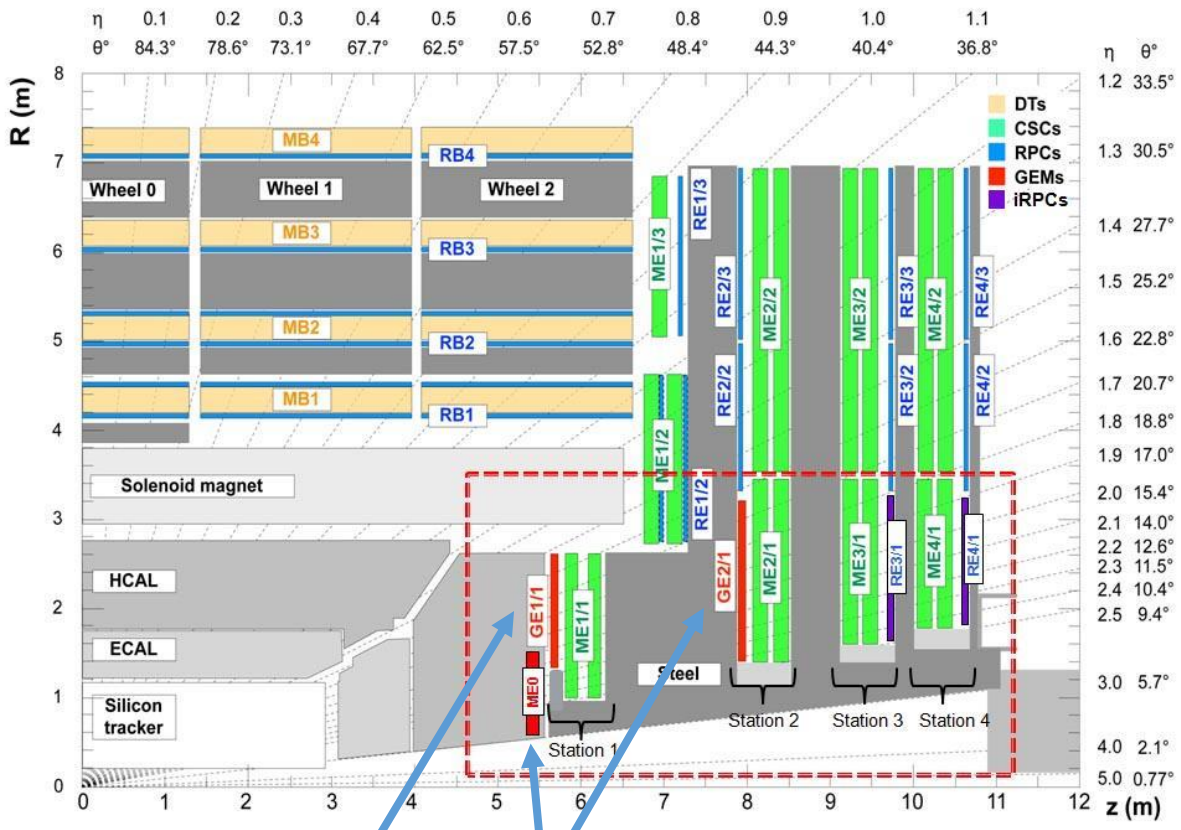
- In the current configuration, an acceptable L1 trigger rate will not be achieved in the forward muon endcap
- especially in the very forward region

→ **GEM Upgrade**





The GEM Upgrade Project

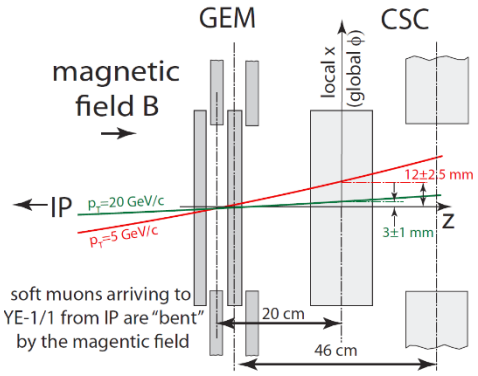


Installation:

GE1/1 **2019-20!**

GE2/1 2022-23

ME0 2024



Three new muon stations using **Gas Electron Multiplier** (GEM) technology

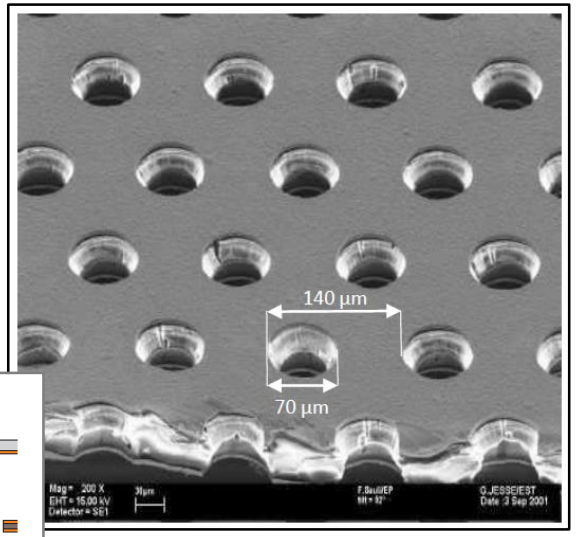
- **GE1/1** at $1.55 < |\eta| < 2.18$
- **GE2/1** at $1.6 < |\eta| < 2.49$
- **ME0** at $2.0 < |\eta| < 2.8$

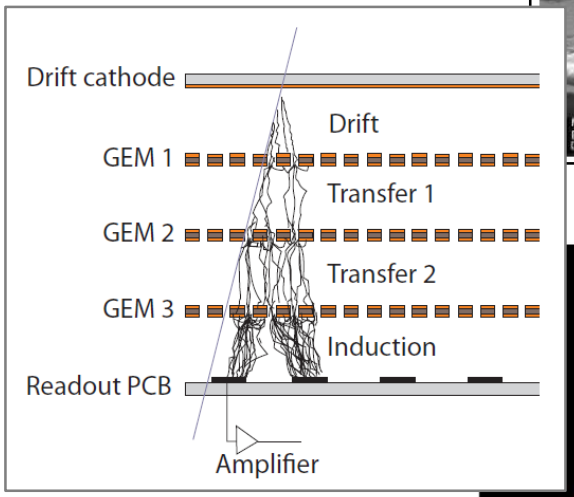
- They **add redundancy** to the existing muon system → more hits to reconstruct muons more efficiently
- The ME0 station also extends the muon system to higher pseudorapidity

The Gas Electron Multiplier (GEM)

DESIGN

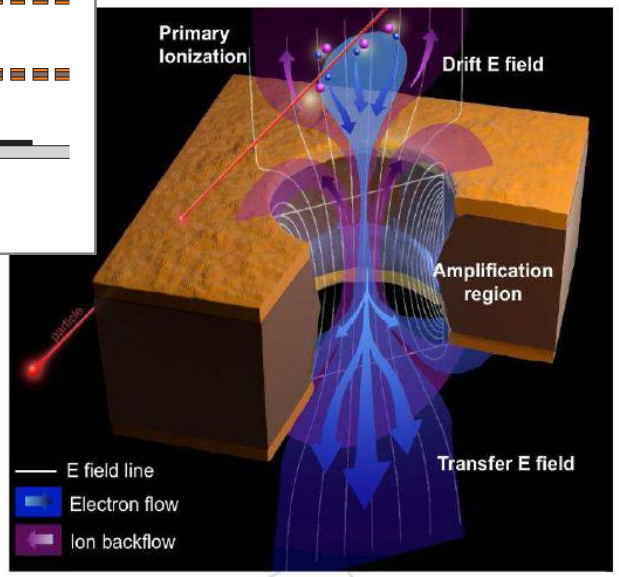
- A GEM foil is a 50 µm thick polymer foil coated with 5 µm copper on each side
- Regular (hexagonal) pattern of holes
- Biconical holes with maximum diameter of 70 µm, interspace 140 µm
- A triple-GEM is a stack of three GEM foils





OPERATION

- Potential difference applied on copper sides of GEM foil
- Electric field between foils causes charges to drift in opposite directions
- High electric field inside holes causes avalanche multiplication of electrons entering the holes
- Signal collected with appropriate electronics



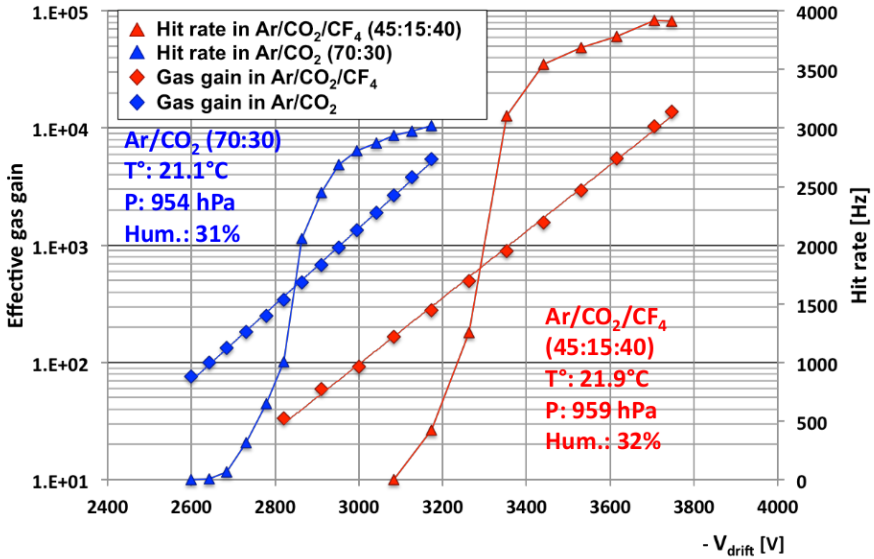
Why GEM detectors?

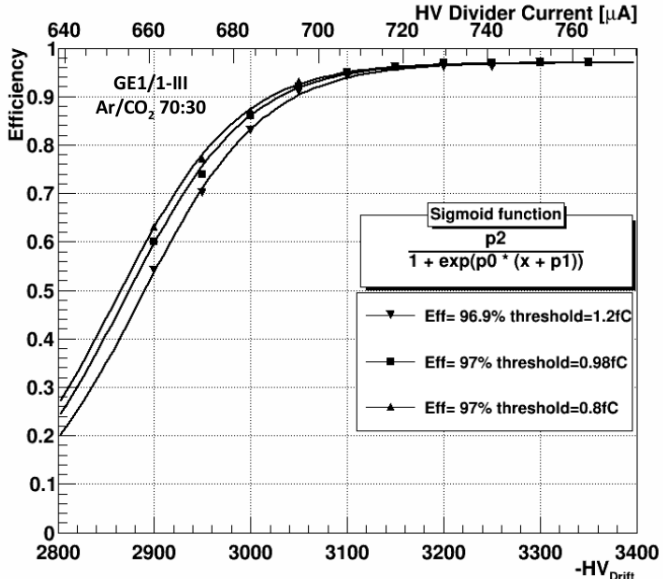
Requirements for the GEM Upgrade

- **rate capability of 10 kHz/cm² or higher**
- **survive after a high integrated charge (200 mC/cm² or more)**
- timing resolution of 10 ns or better
- good spatial resolution (300 μrad or better)

Triple-GEM detectors

- Gain **up to 10^4**
- Muon hit efficiency **up to 97%**
- Spatial resolution of **140 μm**
- Time resolution of **7 ns** with Ar/CO_2 70/30 gas mixture
- Rate capability of **>10 kHz/cm²**
- Radiation hardness up to **1.56 C/cm^2**





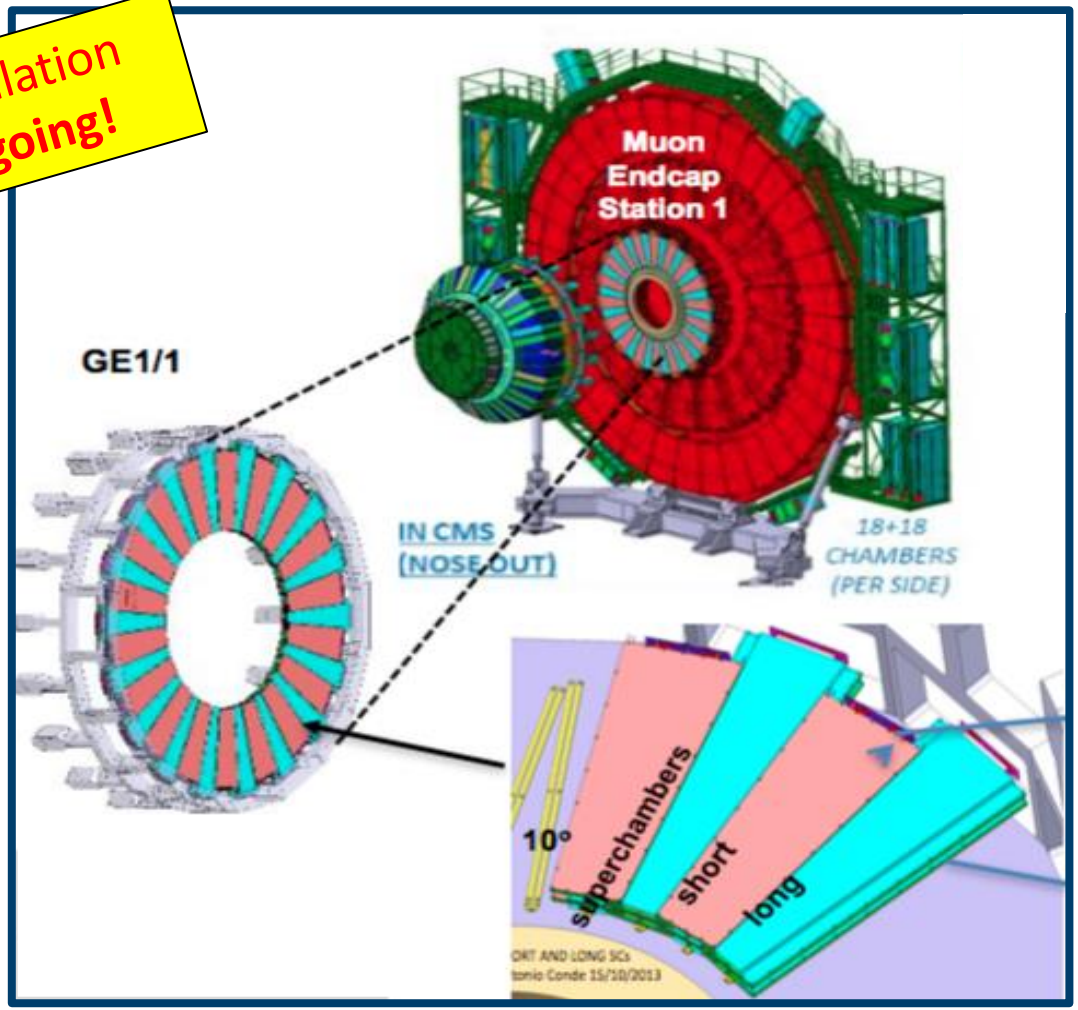
The GE1/1 Station

- **FIRST GEM Station** to be installed in CMS

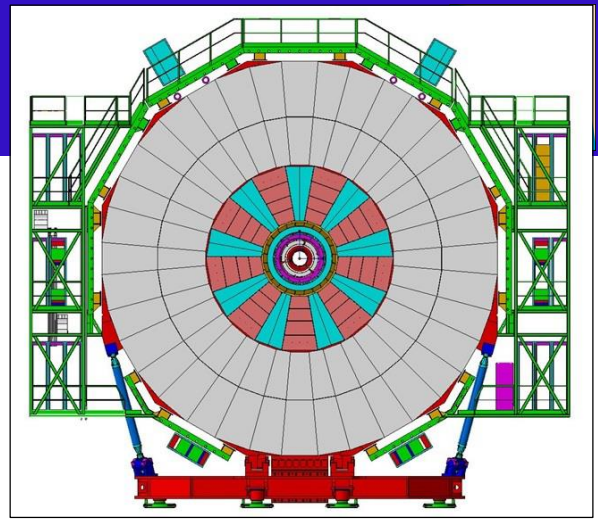
Installation **ongoing!**

- Composed of 36 superchambers («*Gemini*») per endcap, spanning 10° each
- Each superchamber is made of two stacked triple-GEM detectors («*Layers*»)

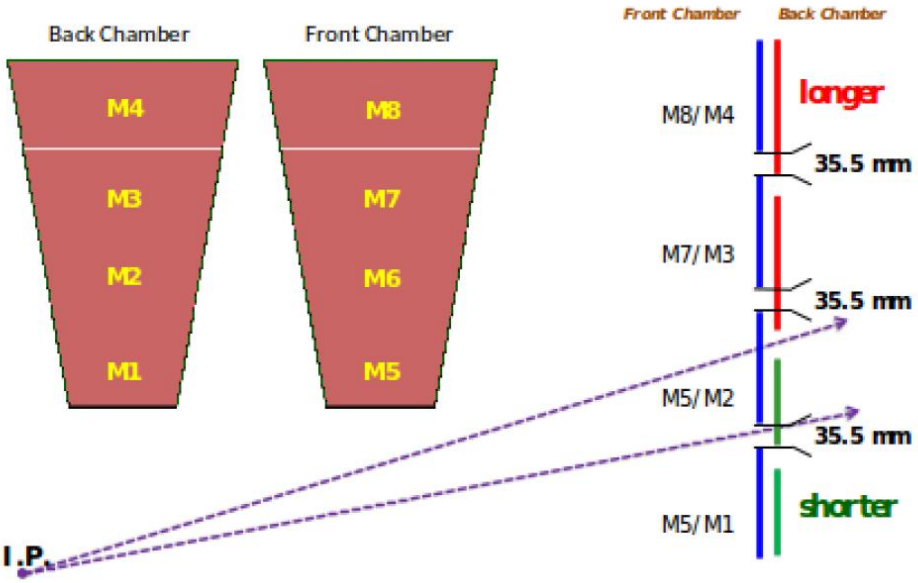
- The rate capability of the chambers is orders of magnitude above the expected background rate in that region



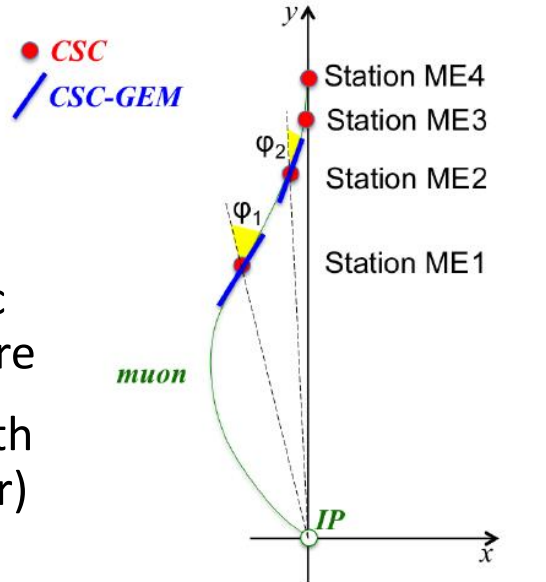
The GE2/1 Station



- second ring of GEM detectors next to CSC ME2/1 chambers, to complement them
  → play the same role in sustaining triggering in the 2nd station as GE1/1 in the 1st station



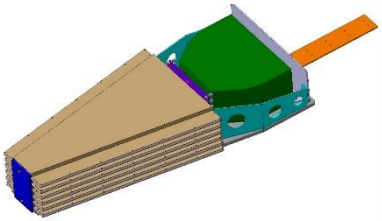
- 18 superchambers per endcap, spanning 20° each
- GE2/1 chamber surface considerably larger (**1.45 m²**) than GE1/1 detectors
- partly extend beyond GE1/1 (up to $|\eta|$<2.4)

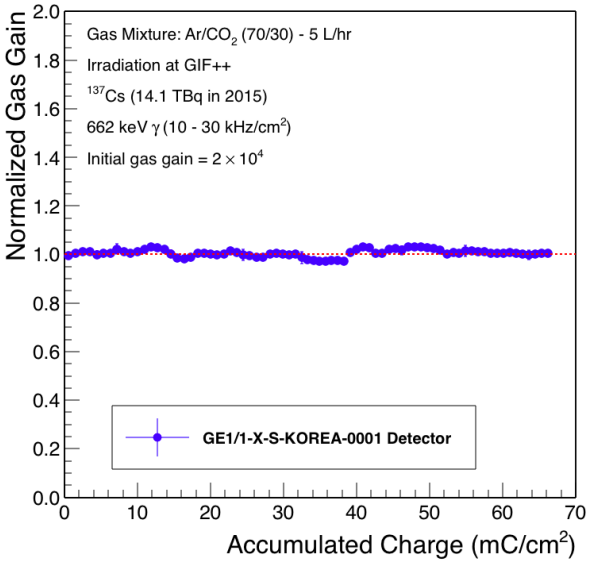


- takes advantage of experience gained with GE1/1 → same basic design, same front-end ASIC, same DAQ and readout architecture
- chambers segmented in 4 modules in eta, each with module with 12 sectors and 128 radial strips (6000 strips in total per chamber)

The ME0 Station

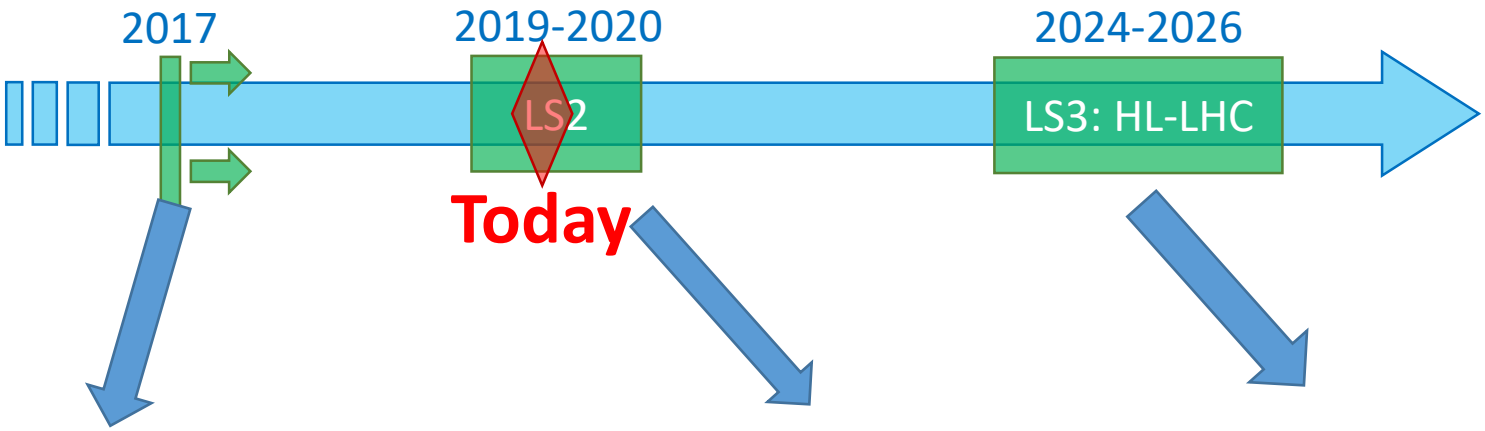
- partially overlapping with existing muon system → complement CSC ME1/1 station to improve trigger performance (like other GEM stations) in this region
- 18 20°-chambers per endcap, radially segmented in 8 sectors → 2x18x6=216 detectors
- **extend the CMS muon system** up to to $|\eta|$<2.8 (7° with respect to beam axis)
  - **six detector layers** to ensure redundancy and reject neutron-induced background
  - relevant for **multi-muon final states** (e.g. $H \rightarrow 4\,\mu$) and for **forward particle production**
  - L1 standalone ME0 based trigger not feasible in the "extended" region
    → Level-1 cross-triggers
    → in HLT used to identify very forward (tracker) muons
- small space available behind HGCAL (∼30 cm)
  → chambers are **3.34 cm thick**



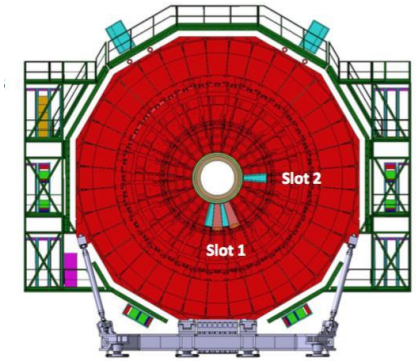


- much higher background rate than other GEM stations up to ∼10^5 Hz/cm^2
  - total expected integrated charge of 283 mC/cm^2
    → ageing tests ongoing with X-rays and at GIF++ → no ageing effects observed so far

GEM Upgrade timeline

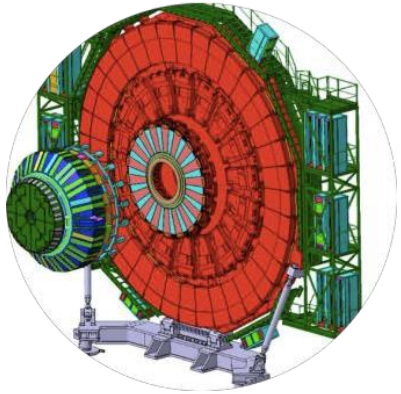


Slice Test



GE1/1 Demonstrator

GE1/1

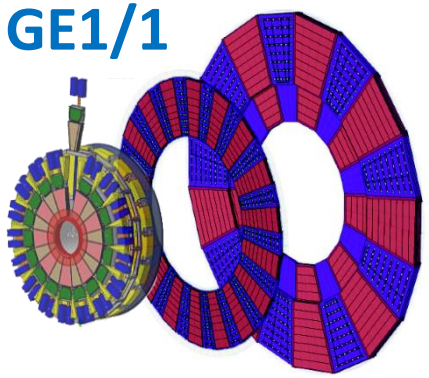


Installation of **GE1/1** during **Long Shutdown 2**

GE2/1

GE1/1

ME0

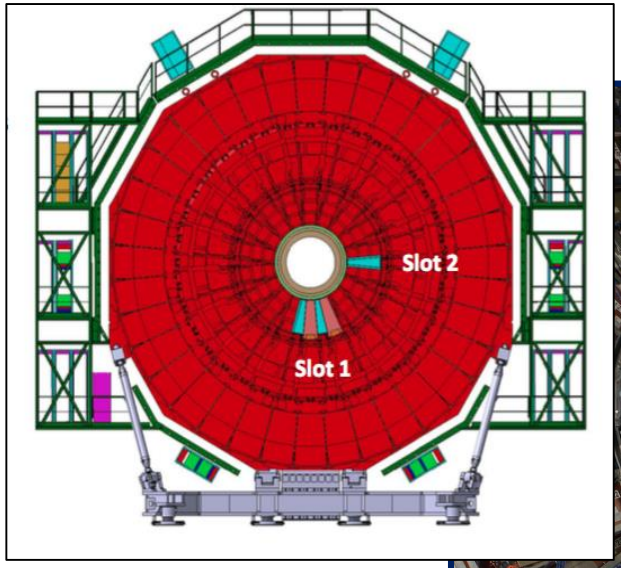


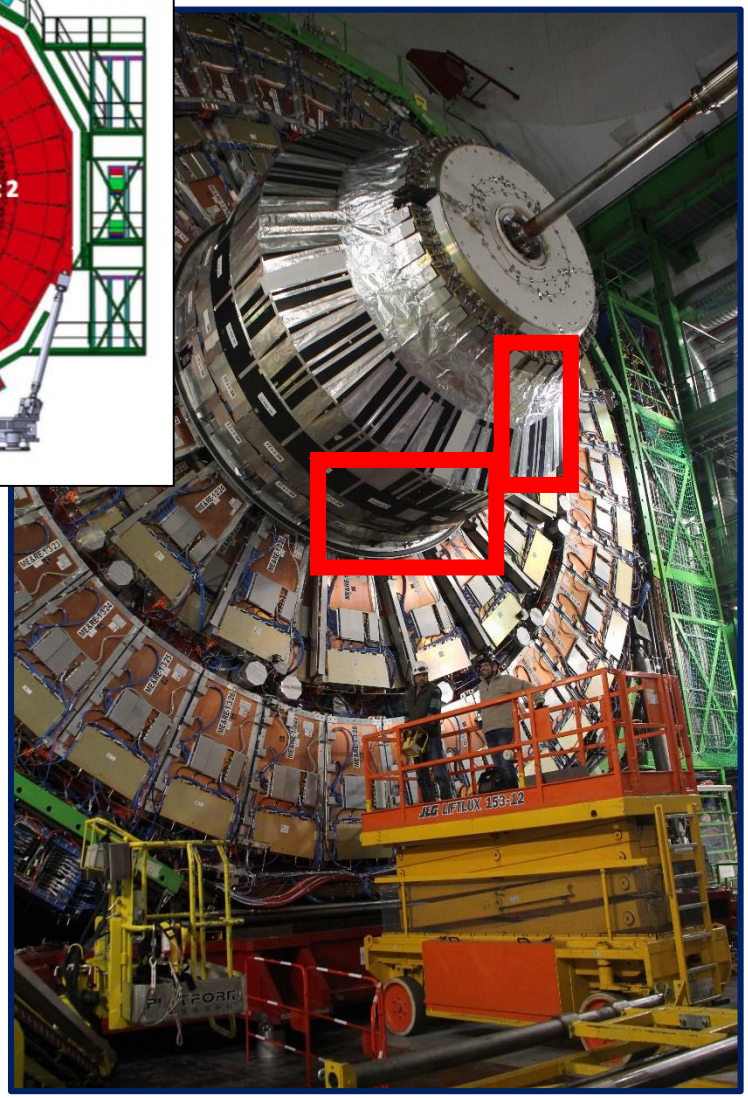
GE2/1 & **ME0** installed by end of **Long Shutdown 3**

2017-18: The GE1/1 “Slice Test”

The GE1/1 Demonstrator

- 5 superchambers out of 2x36 (50° in total) have already been installed in the CMS negative endcap at the beginning of 2017
- Operated in 2017-18
- 1 out of 5 with final readout electronics and HV





Goals

- prove the system’s **operational** conditions
- demonstrate the **integration** into the CMS online system
- prove the **operability** of the system
- acquire **expertise** in the above fields…

“Slice Test” Main Results

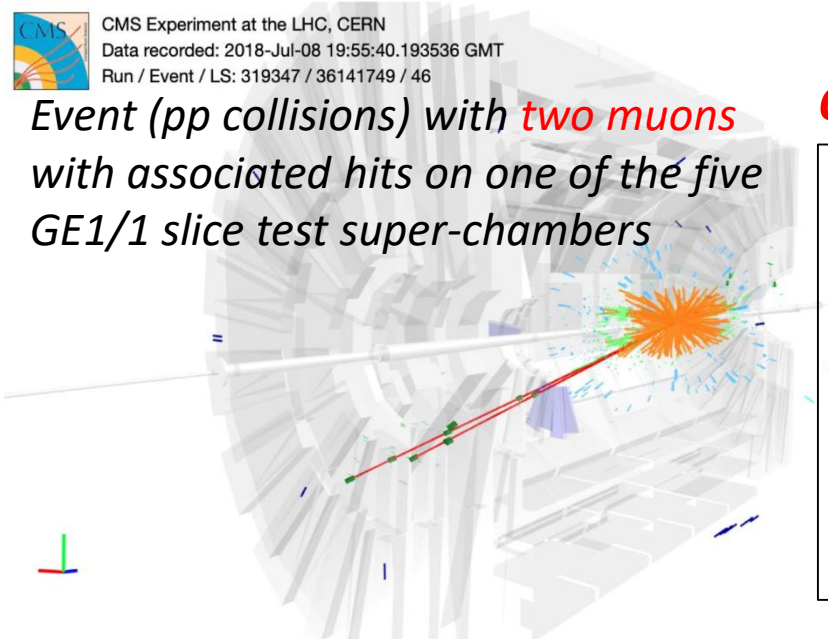
Installation

- 5 superchambers successfully installed
- this experience lead to the development of a dedicated insertion jig for the installation of chambers

Integration into CMS

Experience gained in commissioning, DCS and DAQ systems:

- **DCS** → followed the LHC operations together with the rest of CMS
- **DAQ** → data acquired in central DAQ during cosmics runs and runs with beam
- **online DQM** → successful test of a full chain processing (RAW data→Digitization→Reconstruction →DQM)



Event (pp collisions) with two muons with associated hits on one of the five GE1/1 slice test super-chambers

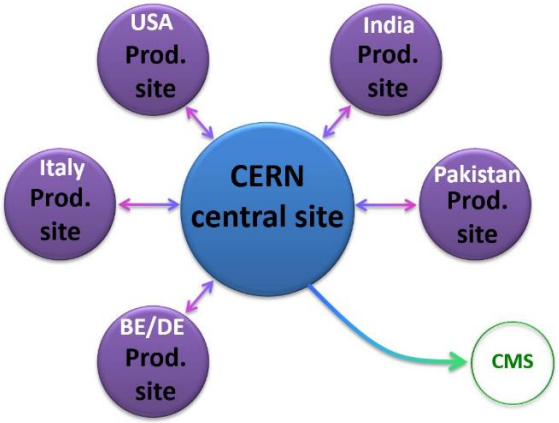
Operability

- Detectors proved to be stable over the full period of operation
- Measured reconstruction efficiency and cluster size reached the values expected from qualification
- First collision data with GEMs reconstructed in 2018 ☺

GE1/1 Assembly

Production sites

- Chamber production distributed in various sites to share the effort
- Using same procedure, infrastructure and quality controls
- Training experts also for the assembly of GE2/1 and ME0 stations



Assembly

Phase I - Preparation of the components in laboratory

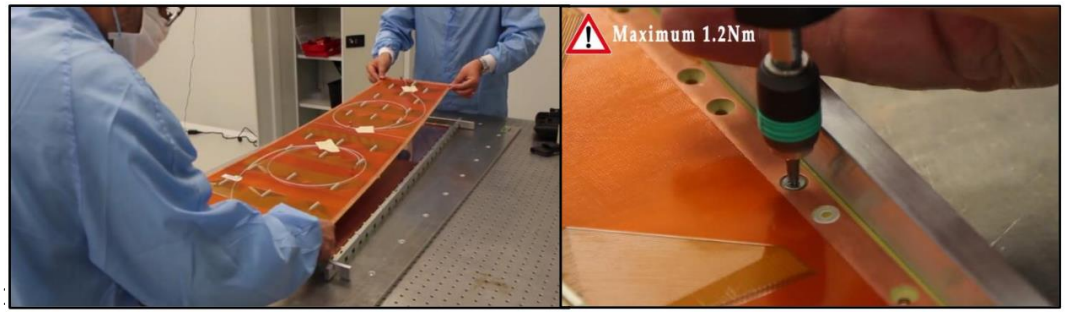
- Cleaning of the components
- Preparation of the HV circuit
- Mounting of the pull-outs
- Selection of the O-ring

1/2 day

3-4 hours

Phase II – Assembly in clean room

- Fast test of the GEM-foils
- Mounting of the stack
- Closing of the chamber



1 day is enough to fully assemble a GE1/1 detector

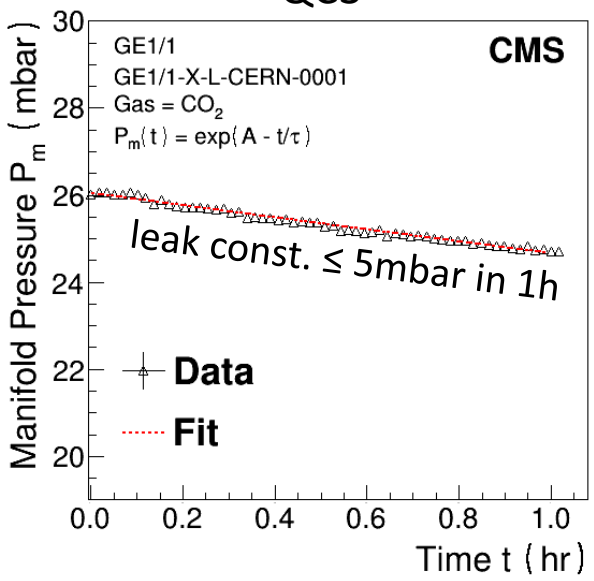
GE1/1 Quality Controls and Assembly

CERN
- QC1 — *Material inspection*
- QC2 — *GEM foils test*

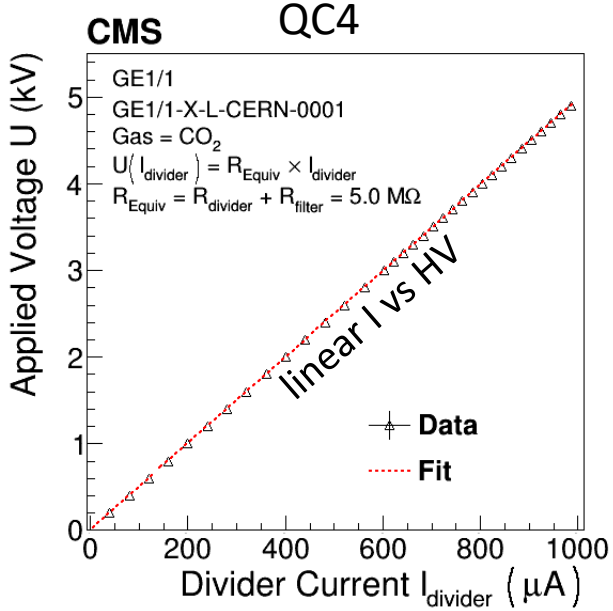
Production Sites
- Assembly
- QC2 — *GEM foils test (fast)*
- QC3 — *Gas leak test*
- QC4 — *HV test*
- QC5 — *Gas gain calibration*

CERN
- QC6 — *HV stability test*
- QC7 — *Electronics connectivity test*
- QC8 — *Cosmics test*

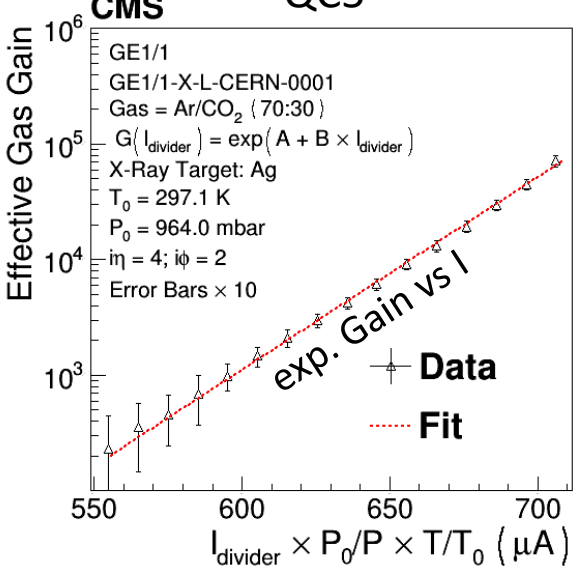
QC3



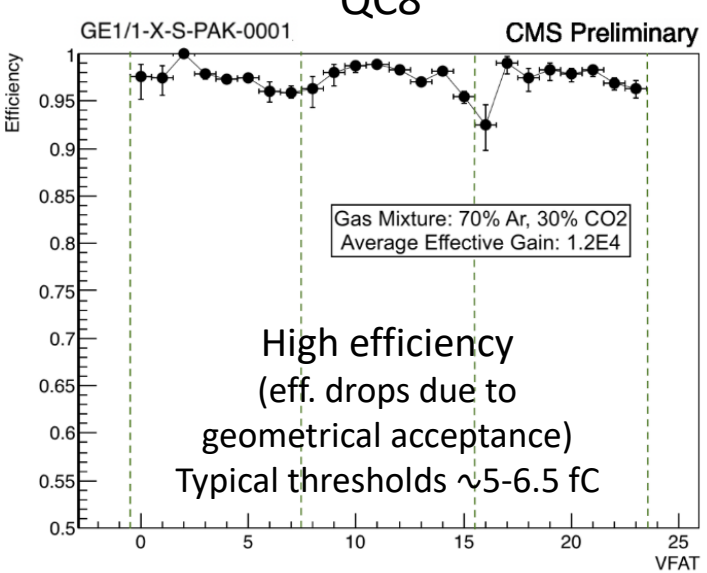
QC4



QC5

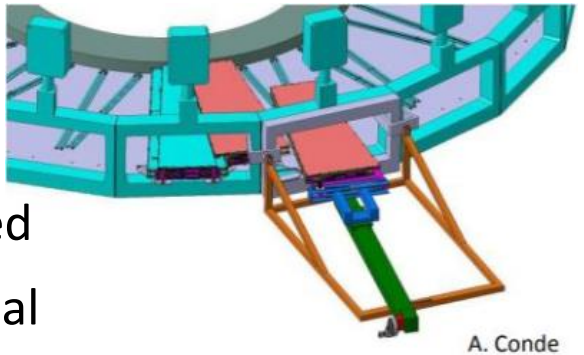


QC8

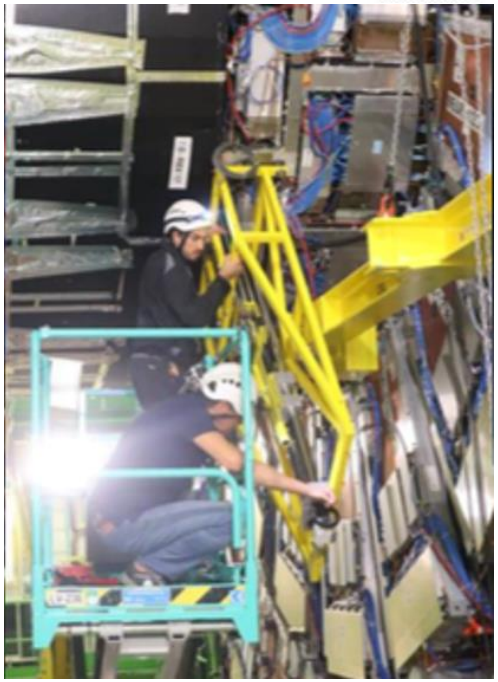


GE1/1 Test Installation

Installation and early commissioning of 2 superchambers on 24-25 July 2019


A. Conde

- transportation tool system reliable and practical to be used
- installation jig and procedure fully certified and operational
- proved that installation of 2 SC/day is feasible



First operation of the detectors on 26-28 August 2019

- Used “temporary flying” cables, power supply and cooling system to be able to operate them (final infrastructure not yet complete)
- **Success:**
  - ✓ **Communication verified**
  - ✓ **Calibration successful**
  - ✓ **Noise measurement very satisfying**

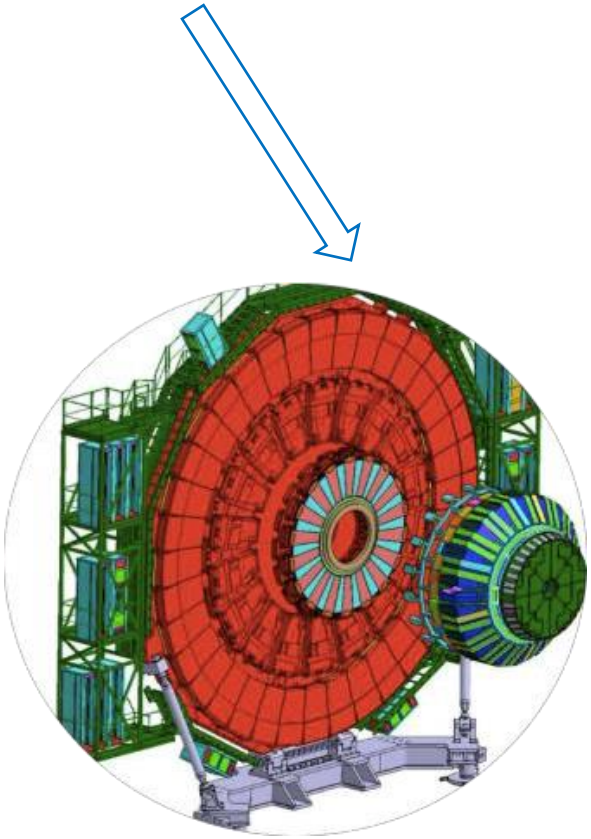
GE1/1 Final Chamber Installation

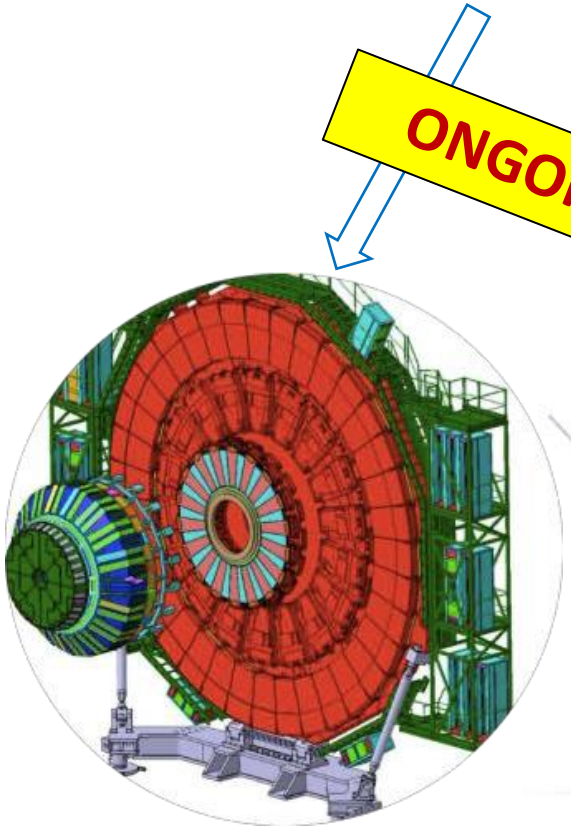
Positive endcap:

- Spring 2020

Negative endcap:

- 18 September – 3 October
- 14 October – 23 October





GE1/1 Commissioning Plans

Tools for the GE1/1 commissioning were developed and "adapted" from the Slice Test and QC8: DAQ, analysis tools, DCS ready to be used

Step 1 – Standalone tests

- Connectivity tests of DCS and DAQ
- Validation of DCS a DAQ systems
- Electronics test

⇩

Step 2 – Tests with central infrastructure

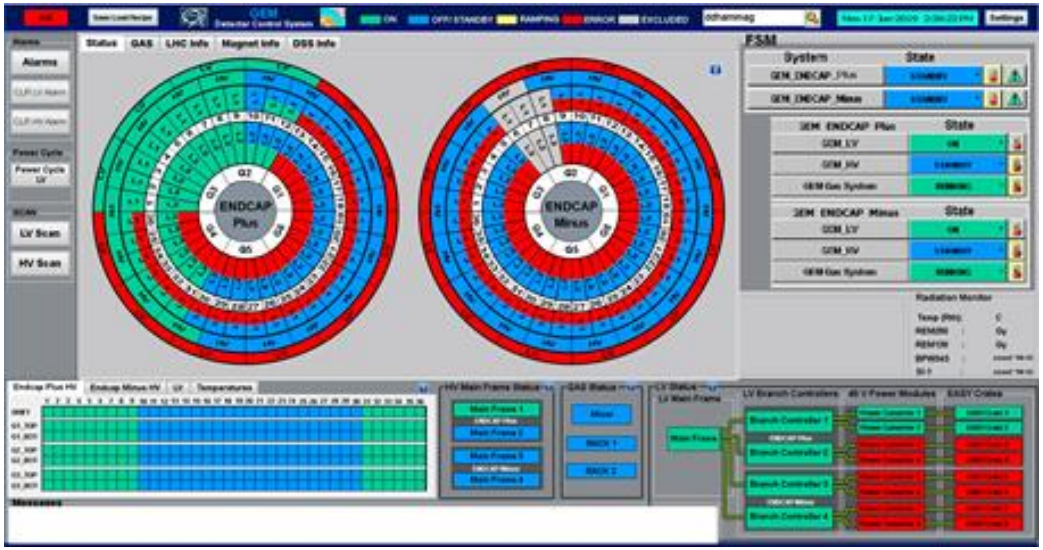
- Definition of the working point of the chambers
- First runs with trigger from CMS muon system

⇩

Step 3 – Final integration

- Into central DCS and central DAQ

Summer/Fall 2020



GEM DCS "upgraded" from Slice Test version (deployed at the end of July 2019)

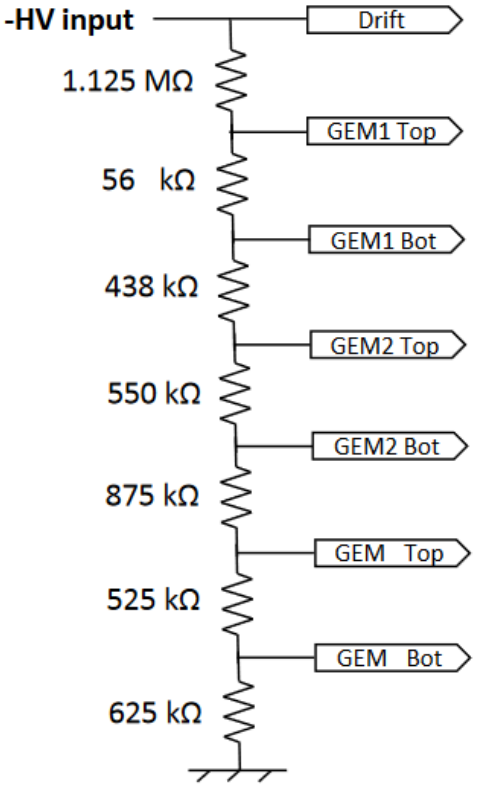
Summary #1/2

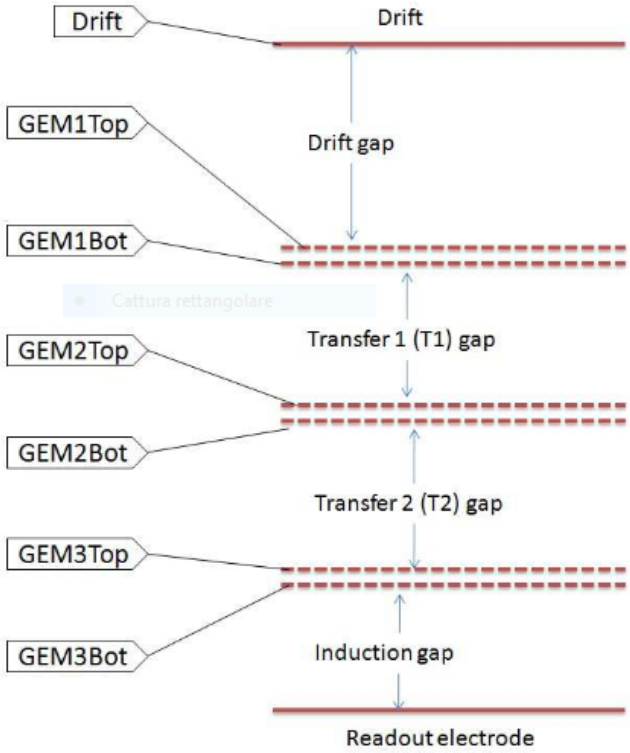
- **The GEM Project**
  - The GEM Upgrade is foreseen to help sustaining trigger in the muon forward region during HL-LHC
  - GEM technology chosen because of rate capability, radiation hardness, good time and spatial resolution
  - It involves three stations at different eta regions: GE1/1, GE2/1, ME0 GE1/1 the first one being installed in time
- **The GE1/1 Demonstrator («Slice Test»)**
  - Proved operability of the system in CMS environmnet
  - Development of installation tools and procedure
  - On-field development and experience of DAQ, DCS, DQM, that will be the starting point for the full installation

Summary #2/2

- **The GE1/1 chamber Assembly and Quality Control**
  - Assembly distributed in several production sites, also training experts for the future stations
  - Detectors undergo a chain of 8 quality controls to be ready for the installation
- **The GE1/1 Full System**
  - A test installation of 2 superchambers successfully made in July 2019, successfully calibrated inside CMS with good noise measurement in August 2019
  - Installation of negative endcap currently ongoing, positive endcap will follow in spring 2020
  - First version of DAQ, DCS, DQM developed from slice test experience, ready to start commissioning chambers

Backup


-HV input
Drift
1.125 MΩ
GEM1 Top
56 kΩ
GEM1 Bot
438 kΩ
GEM2 Top
550 kΩ
GEM2 Bot
875 kΩ
GEM Top
525 kΩ
GEM Bot
625 kΩ


Drift
Drift
Drift gap
GEM1Top
GEM1Bot
Transfer 1 (T1) gap
GEM2Top
GEM2Bot
Transfer 2 (T2) gap
GEM3Top
GEM3Bot
Induction gap
Readout electrode

VFAT2

Main features:

- A 128 channel chip for charge sensitive readout of multi-channel silicon & gas particle detectors
- Trigger: Provide intelligent “FAST OR”information for the creation of a trigger.
- Tracking: Binary “hit” information for each of the 128 channels
- 40MHz signal sampling (dead time free)

Reference:

- “VFAT2: A front-end system on chip providing fast trigger information, digitized data storage and formatting for the charge sensitive readout of multi-channel silicon and gas particle detectors”, Proceedings of TWEPP Prague, Czech Republic, 3-7 September 2007, ISBN 978-92-9083-304-8, p.292
- P. Aspell, CERN

VFAT3

VERSION SPECIFIC for GEM detectors

- Derived from VFAT2, but every block **re-designed** to be optimized for **GEM signal charge characteristics** and CMS phase 2 system requirements
  - GEM charge pulses are long (compared to silicon) and statistical fluctuations cause randomness in the shape of the signal

Main features

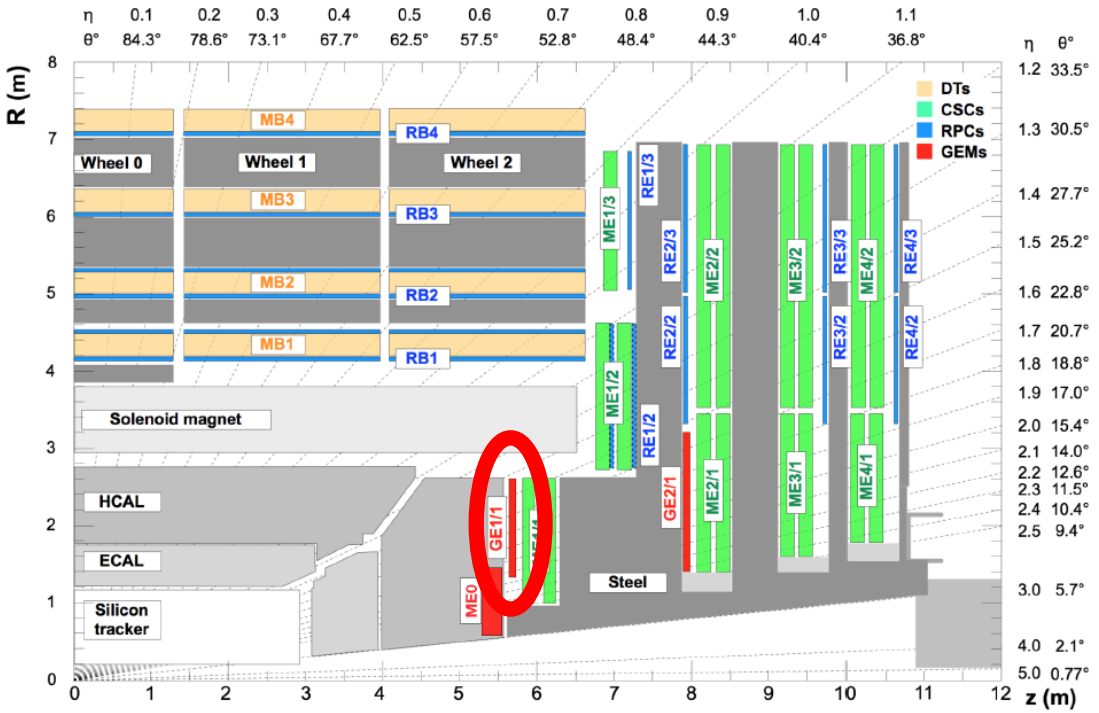
- Additional input protection on front-end
- Programmable signal charge polarity
- Programmable gain and shaping time.
- Allows 2 options for treating GEM signal:
  - "leading edge": fast shaping, reacts to the leading edge of the GEM signal → Good for time resolution but lower S/N
  - "full charge + CFD": Slow shaping time to integrate the full charge of the GEM signal → Good time resolution but lower S/N
- Detector capacitance from 20pF to 80pF
- Operation at high particle rate

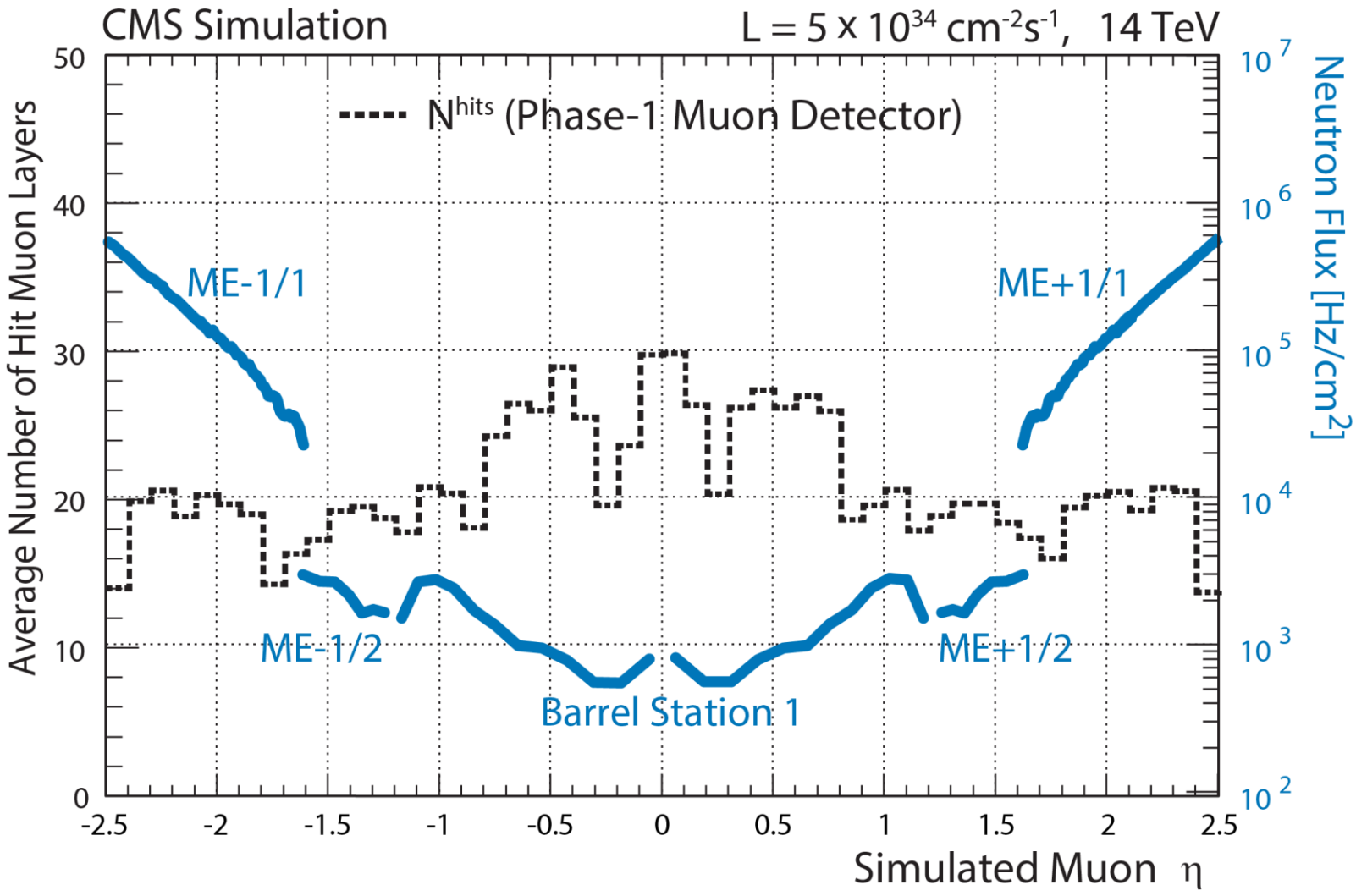
Reference:

- P. Aspell, CERN, "VFAT3 for the CMS GEM Muon upgrades", https://indico.cern.ch/event/689062/

GE1/1 Station

- Installation of **triple GEM detectors** scheduled in 2019-2020 in the region 1.6<|η|<2.2 of CMS muon system
- **Advanced R&D status**
- **In view of the high luminosity (Phase II):** GE1/1 will allow to keep <5 kHz trigger rate without increasing threshold on muon's momentum
  - Will be added in front of CSCs to measure the muon bending angle in magnetic field
  - Adds redundancy




CMS Simulation
L = 5 x 10^34 cm^-2 s^-1, 14 TeV
N^hits (Phase-1 Muon Detector)
ME-1/1
ME+1/1
ME-1/2
ME+1/2
Barrel Station 1
Average Number of Hit Muon Layers
Neutron Flux [Hz/cm^2]
Simulated Muon η
0
10
20
30
40
50
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
10^2
10^3
10^4
10^5
10^6
10^7