22nd International Workshop on Radiation Imaging Detectors

The new GEM station GE1/1 of the CMS muon detector: status, commissioning and early performance studies

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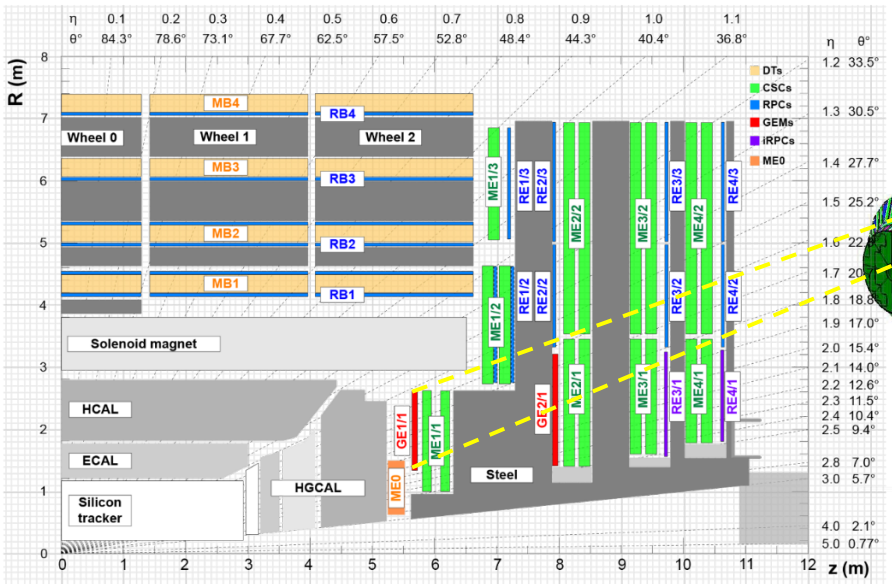
[1] University and INFN Bari, Italy

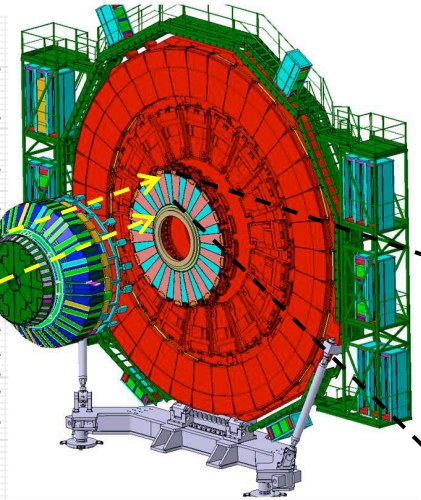
iWoRiD2021 – 27 Jun-1 Jul 2021, Ghent University

Outline

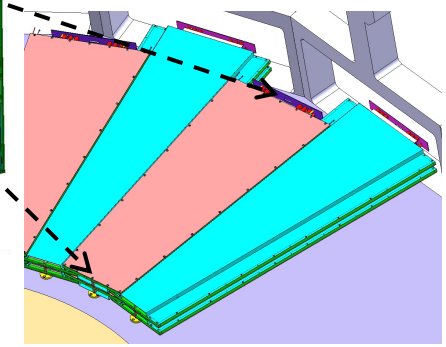
- GE1/1 station:
  - Motivations and project overview
- Commissioning and readiness for Run 3:
  - Services
  - Online control and monitoring tools
    - Detector Control System (DCS)
    - online Data Quality Monitor (DQM)
- Cosmic runs
  - GE1/1 DAQ
  - Offline alignment and performance studies
- Plans towards Run 3

The phase-I CMS muon endcap upgrade: GE1/1





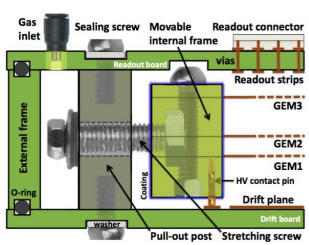
short and long SCs
to maximise coverage
$1.55 < |\eta| < 2.18$

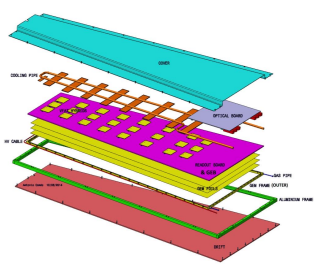


36 *superchambers* (SC) per endcap

144 triple-GEM detectors:

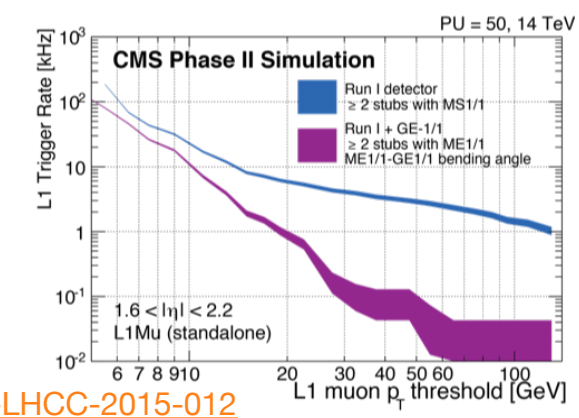
- 3/1/2/1 mm gaps
- mature technology based on mechanical foil stretching
- 10-years-long R&D on design, components and materials (longevity, outgassing studies, etc.)

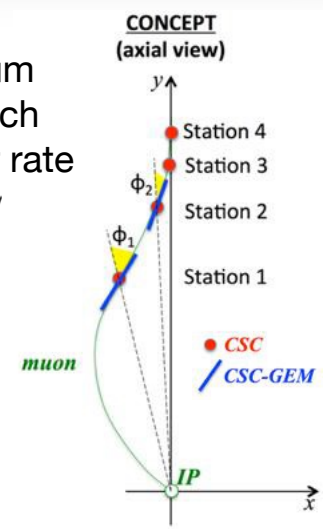




Impact on the muon trigger

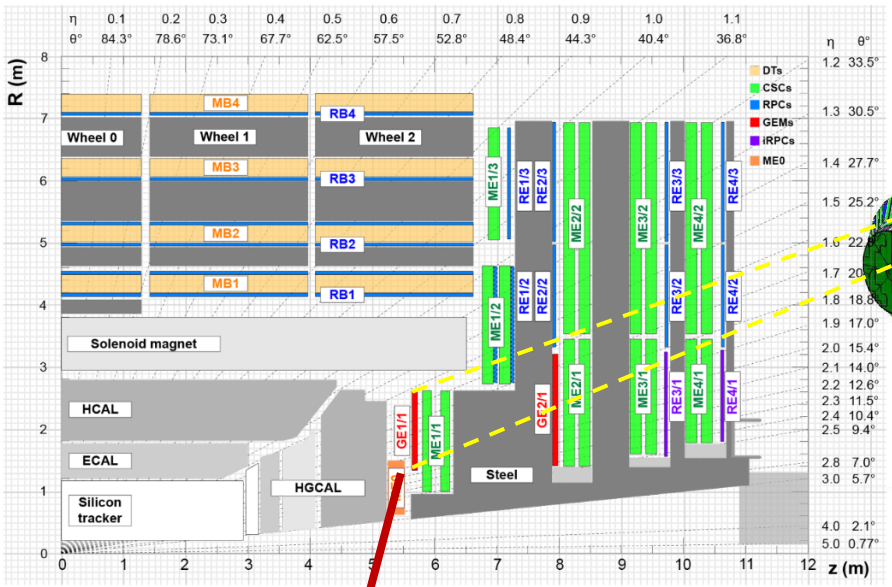
- GEM+CSC allow for muon momentum measurement in a single station, which helps reduce considerably L1 trigger rate

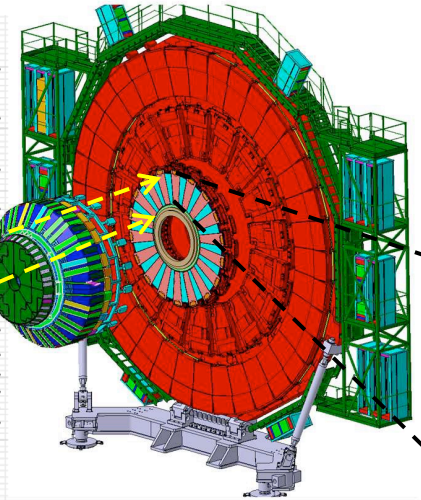




CERN-LHCC-2015-012

The phase-I CMS muon endcap upgrade: GE1/1





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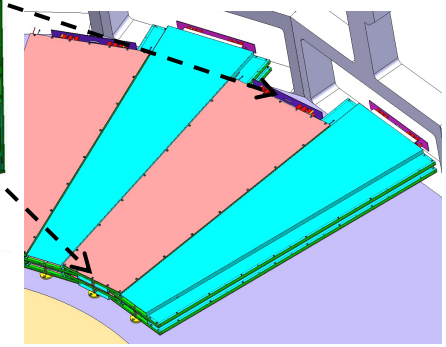

36 *superchambers* (SC) per endcap

More about background simulation studies for the GE1/1 station in this poster by S. Kumar

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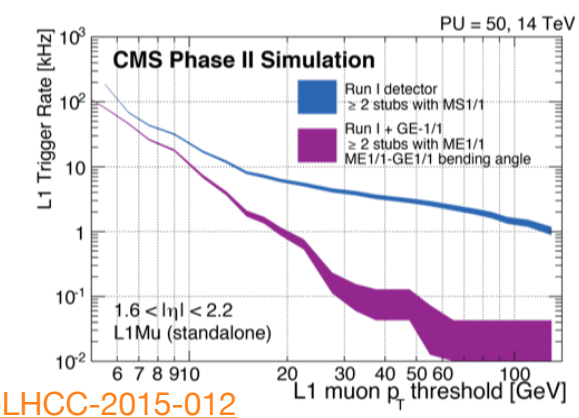
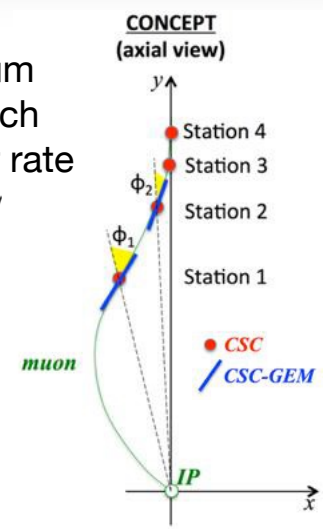
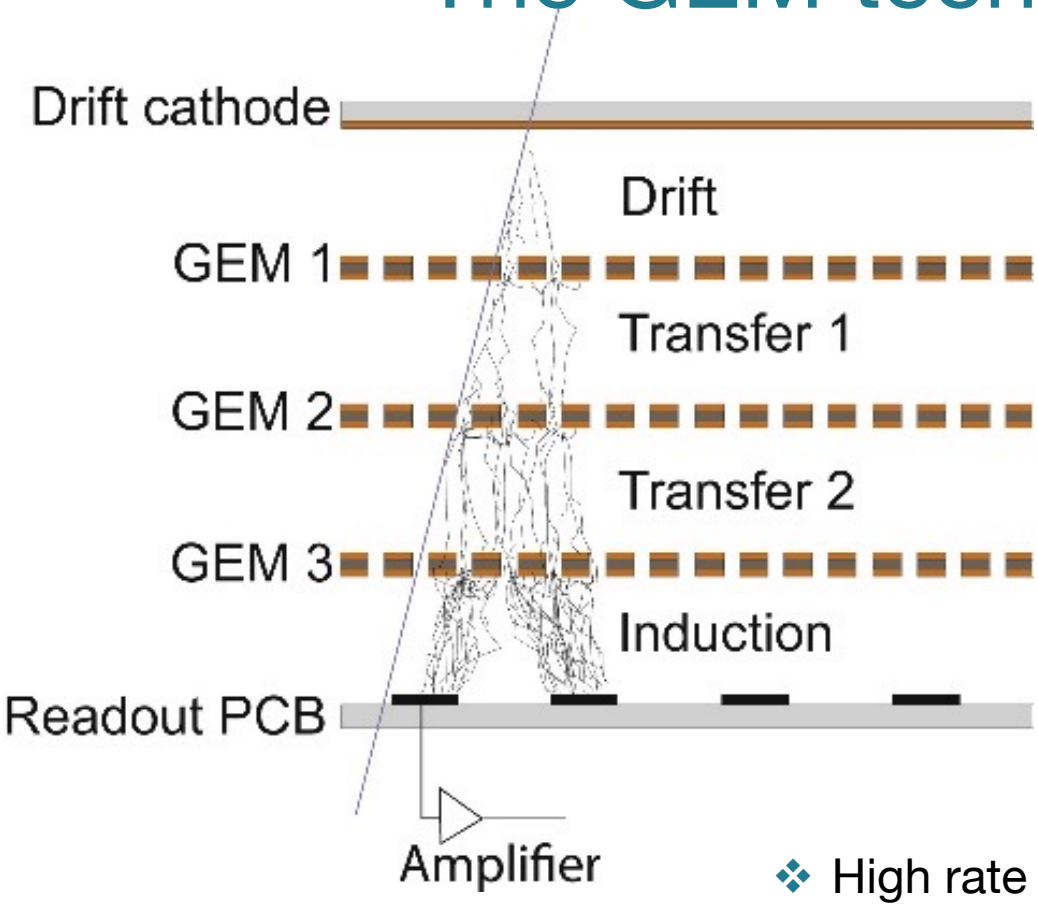
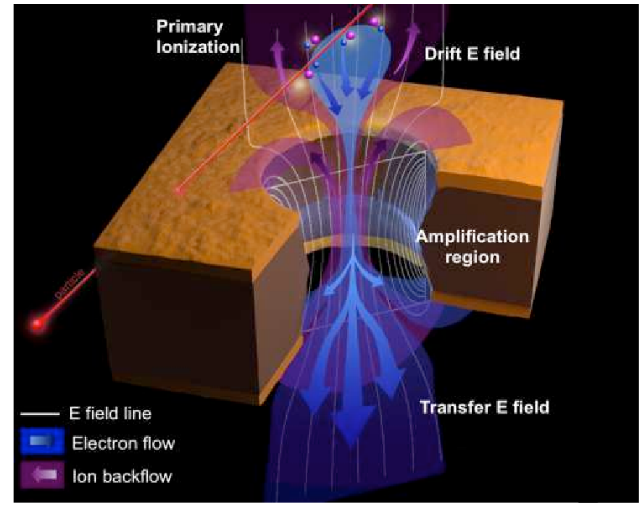


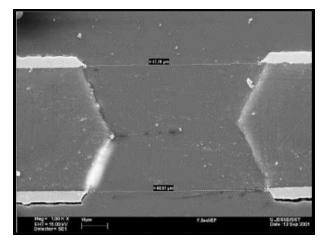


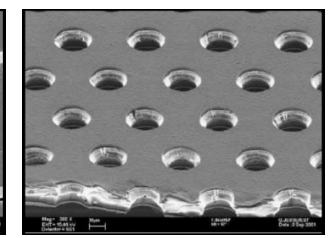
CERN-LHCC-2015-012

The GEM technology





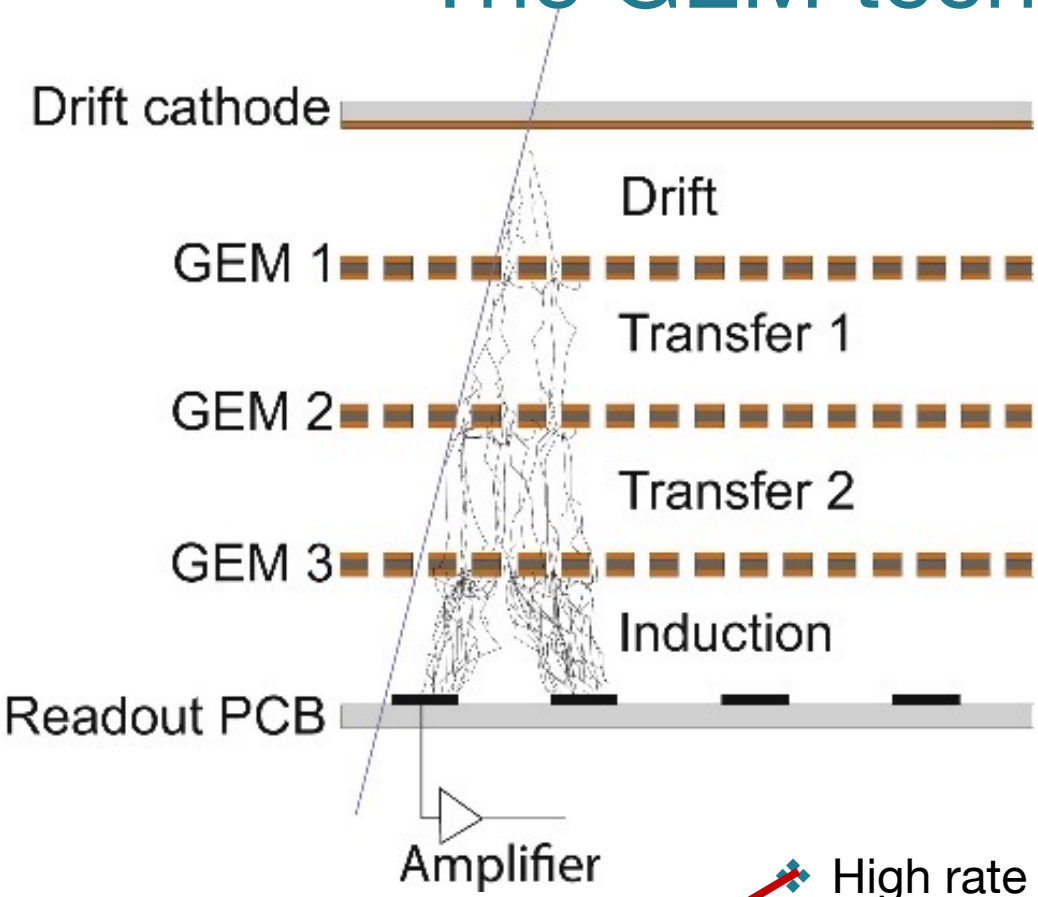


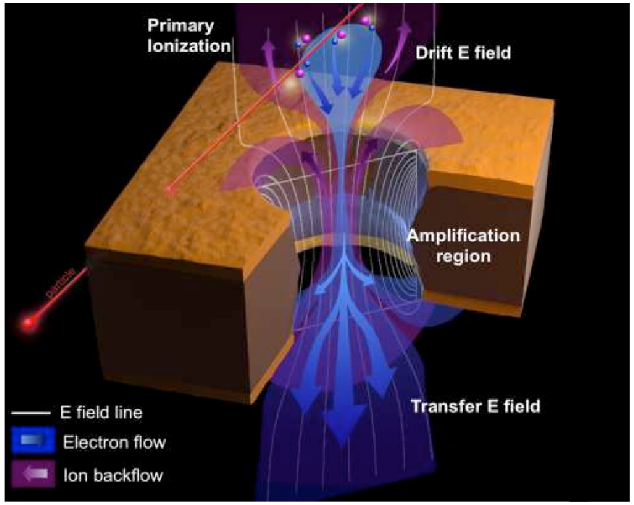


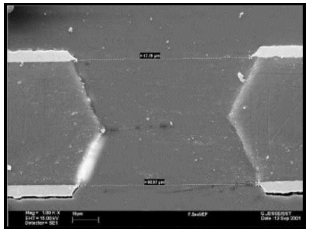
- High rate capability, up to O(MHz/cm^2)
- Efficiency > 98%
- Space (time) resolution ≈ 300 μm (8 ns) [1]
- Gas mixture: Ar/CO_2 70/30

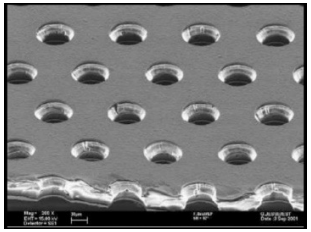
[1] CMS Technical Design Report for the Muon Endcap GEM Upgrade, CERN-LHCC-2015-012

The GEM technology









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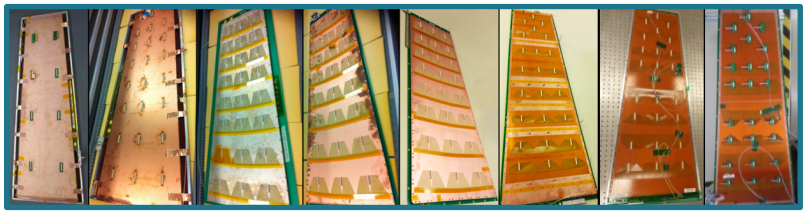
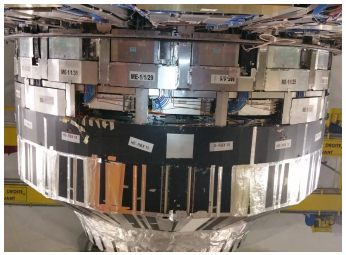
More about rate capability studies for Phase II in this poster by F. Fallavollita

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

The GE1/1 project

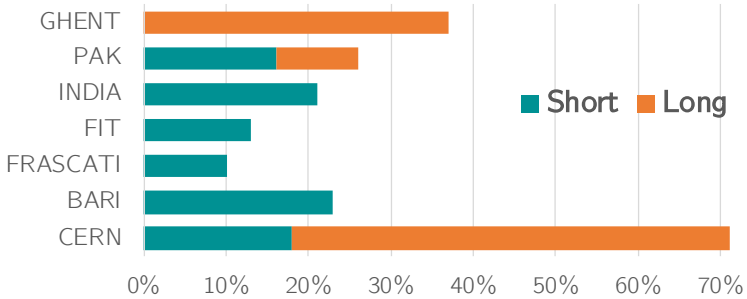
N. Pozzobon 2019 JINST 14 C11031
JINST 15 (2020) P05023

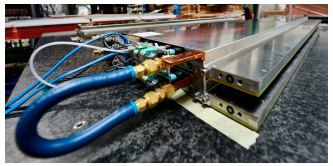


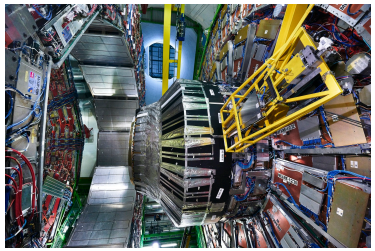


2009 — 2017

- BIRTH OF GE11 PROJECT
- GE11 proto. I
- GE11 proto. II — NIMA 972 (2020) 164104
- GE11 proto. III — Mechanical stretching
- GE11 proto. IV
- GE11 proto. V
- GE11 proto. VI - VII
- DAQ/ electronics prototyping
- SLICE TEST INSTALLATION AND COMMISSIONING







completed!

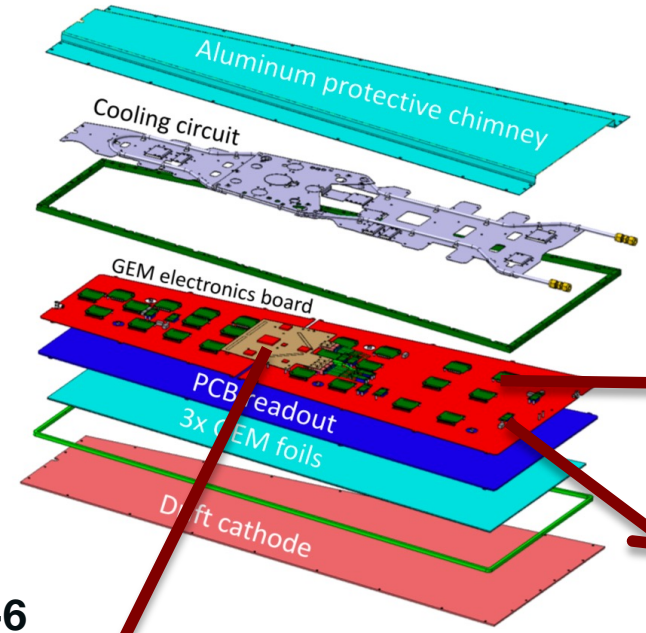
Oct-2017 — Dec-2018 — Jul-Oct 2019 — Jul-Sep 2020

NEGATIVE ENDCAP INSTALLED!

POSITIVE ENDCAP INSTALLATION

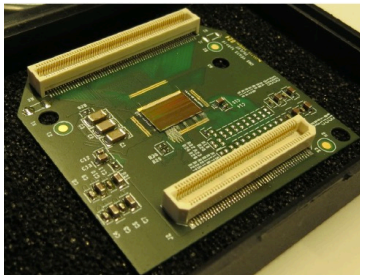
DETECTOR MASS PRODUCTION → **SUPERCHAMBER PRODUCTION**

GE1/1: Readout Electronics



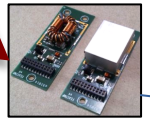
GE1/1 system:

- 72 Super-Chambers (SC)
- 3456 VFAT3 chips
- 432 GBT + VTRx optical link (DAQ path)



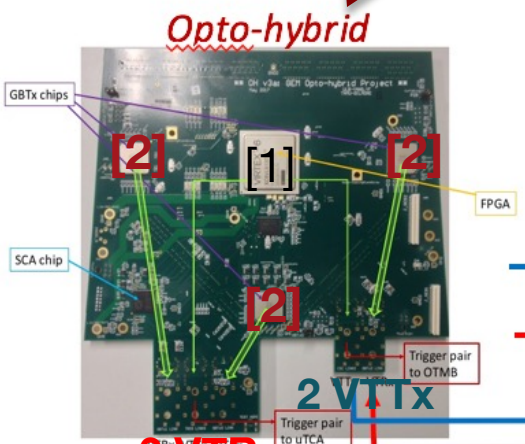
FE chip: VFAT3

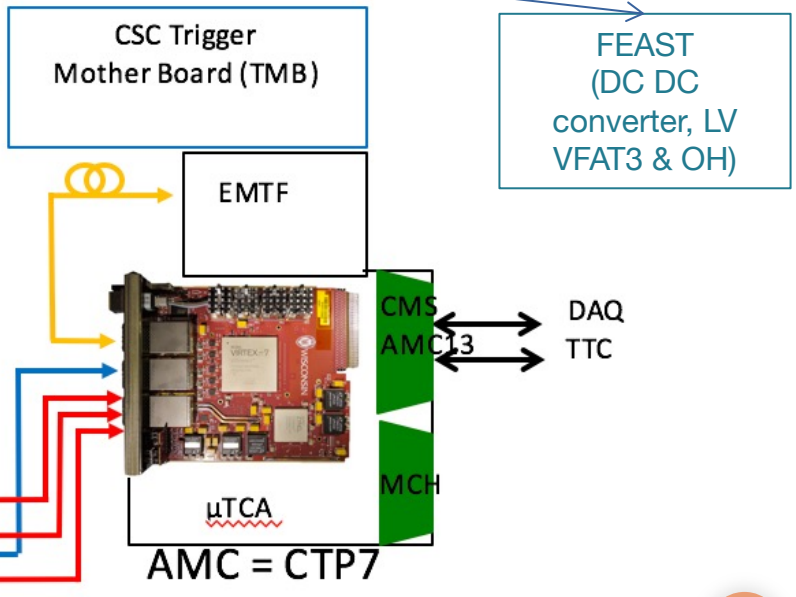
- 24 VFAT3 / chamber
- 128 channels / chip
- Binary readout
- Tracking + Trigger data



[1] Virtex-6
[2] GBTx

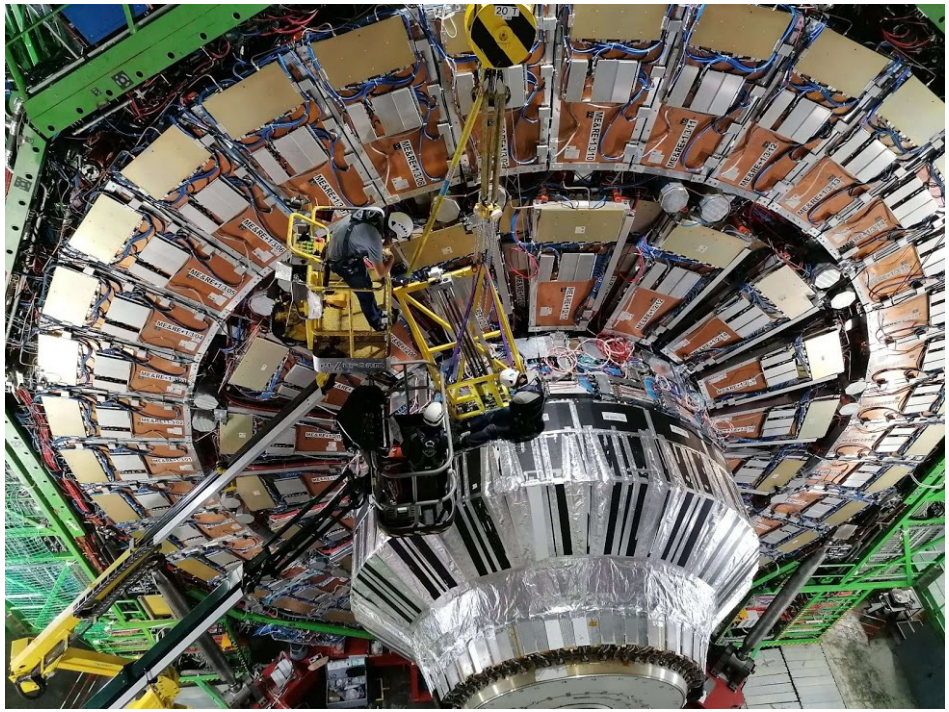
GE1/1 Electronics

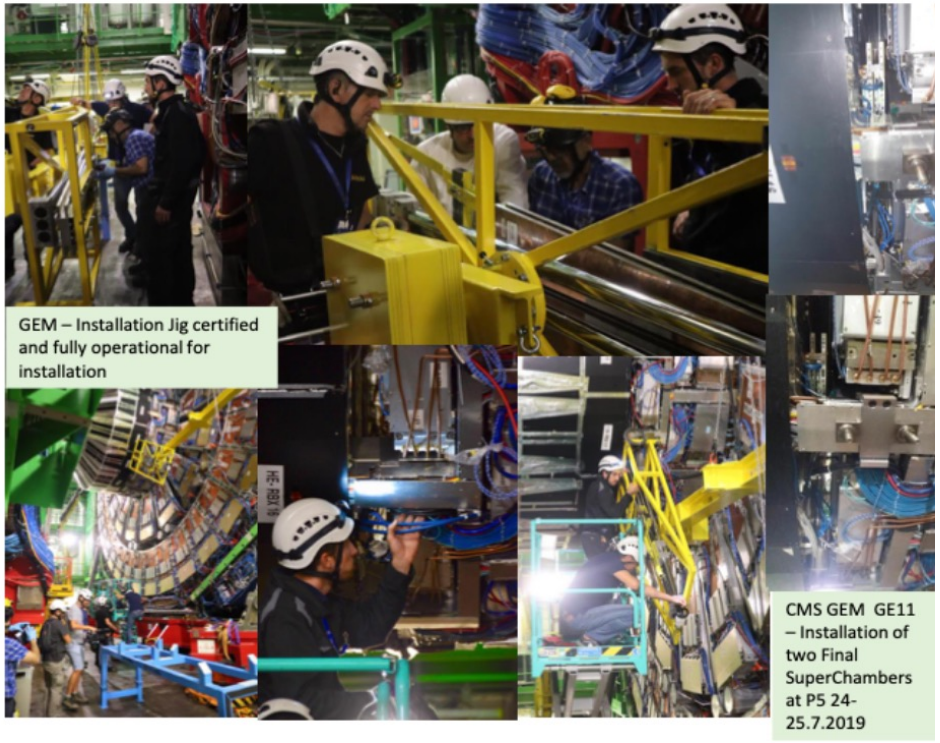




- VFAT3: A Trigger and Tracking Front-end ASIC for the Binary Readout of Gaseous and Silicon Sensors
- A micro-TCA based data acquisition system for the CMS Triple-GEM detectors

A new station in the CMS muon endcap





http://cds.cern.ch/record/2684028

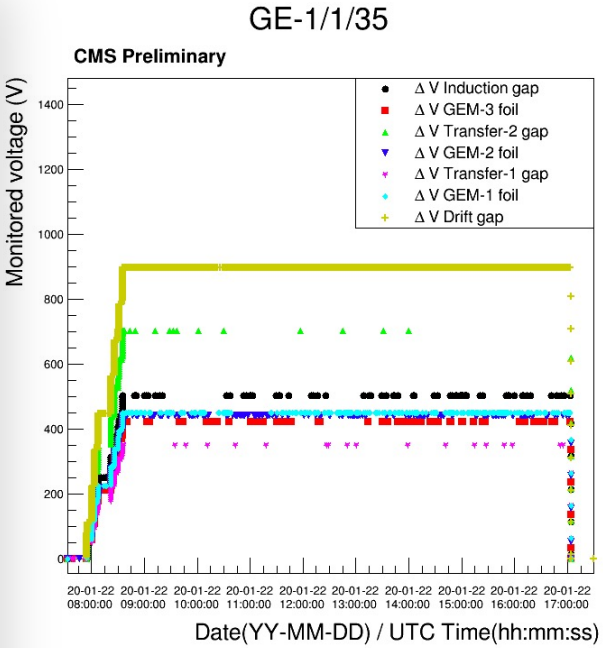
https://www.youtube.com/watch?v=fU0ujGWbeQ0&feature=youtu.be

https://www.facebook.com/CMSMuon/

GE1/1 status and initial commissioning phase (1)

Services installation: fully completed

- ✓ **High Voltage**: multi-channel power supply. GEM electrodes powered independently. Voltage, current and channel status logged in database.
- ✓ **Low Voltage**: it provides power to the frontend electronics
- ✓ R/O **fibers** and link-to-CSC fibers: optical fibers for readout and trigger
- ✓ Fibers for **temperature sensors**
- ✓ RADMON sensor cables for **radiation monitoring**
- ✓ **Gas system** → more about gas monitoring system in this poster by D. Fiorina
- ✓ Water **cooling** for frontend chips and FPGA



Early commissioning steps

- Detector HV stability: HV training in pure CO_2
  HV training in Ar/CO_2 final mixture
- Frontend calibrations using internal pulse: noise, thresholds
- HV-LV mapping cross-check using cosmics
- Connectivity tests of GEM-EMTF (Endcap Muon Track Finder) trigger links

GE1/1 status and initial commissioning phase (2)

Main issues found and solutions:

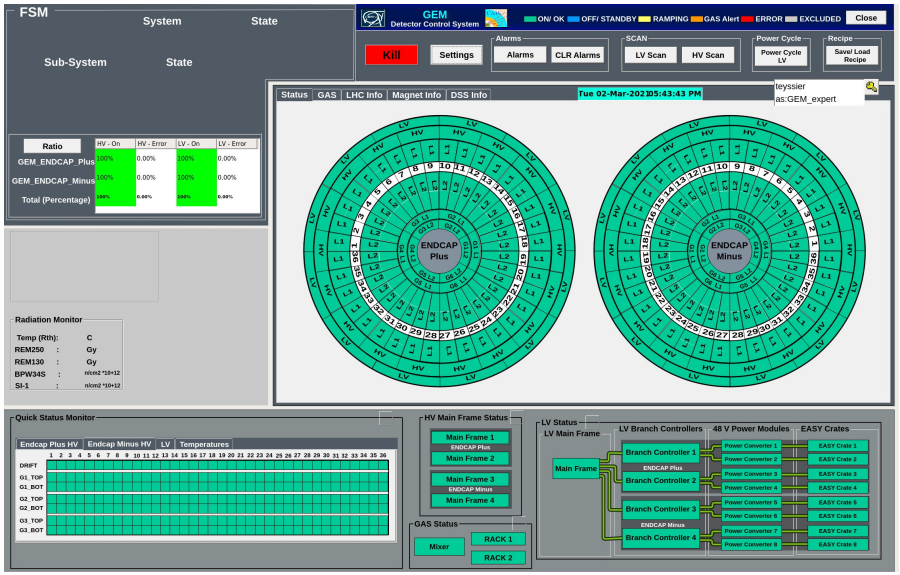
- Electronic noise due to LV system
  - intervention on the LV cables and installation of filters
  - successfully lowered noise level

- Instabilities in the frontend communication
  - GBTx not locking: implemented automatic recovery at configuration
  - issue due to VTRx chip failures, CERN wide problem, under investigation

- High voltage: discharges in the detector
  - Gas Electron Multiplier technology suffers from discharges due to pollution/dust, gain fluctuations and HIP
  - HV training procedure has been implemented to ensure stable detector operation

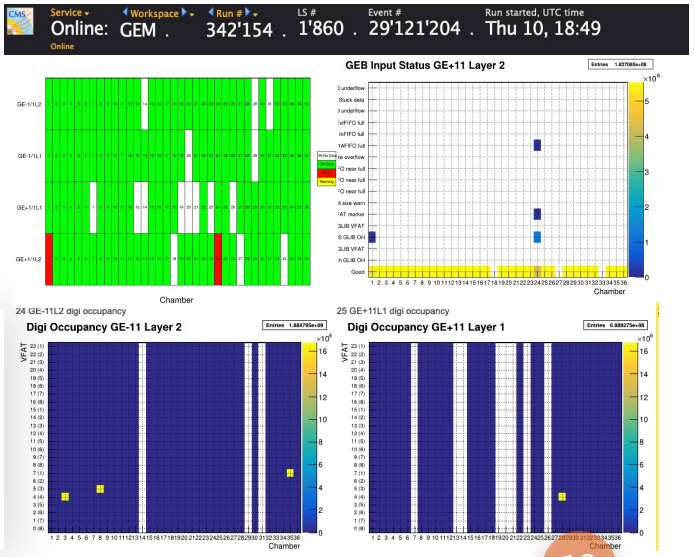
Commissioning of online control and monitoring tools: **Detector Control System (DCS)**

- DCS: control and monitoring of HV, LV (channels and racks), FPGA temperature, gas system
- Extensive usage of the DCS during HV training and DAQ tests (LV).
- DCS commissioned during CMS data taking runs with cosmics
- Successfully included into central CMS DCS
- Finalising few missing elements (RADMON, temperature, racks monitoring, LV automatic recovery)



GEM Online Data Quality Monitoring (online DQM)

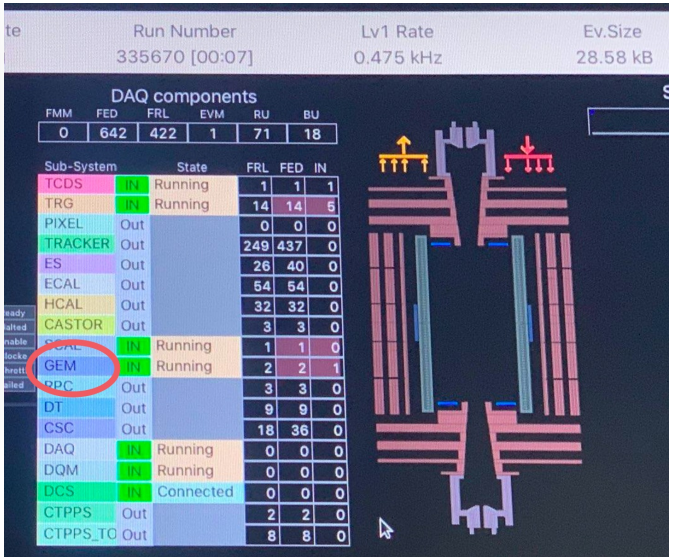
- GE1/1 detectors fully integrated into CMS online DQM
- Online monitoring for DAQ errors, frontend status
- Commissioned during cosmic runs



CMS cosmic data-taking runs (1)

Data taking exercises:

- During Long Shutdown, CMS takes **cosmic data** for few days continously
- Purpose is to **test and commission** subdetectors, trigger, DAQ software in view of pp collision runs (2022)

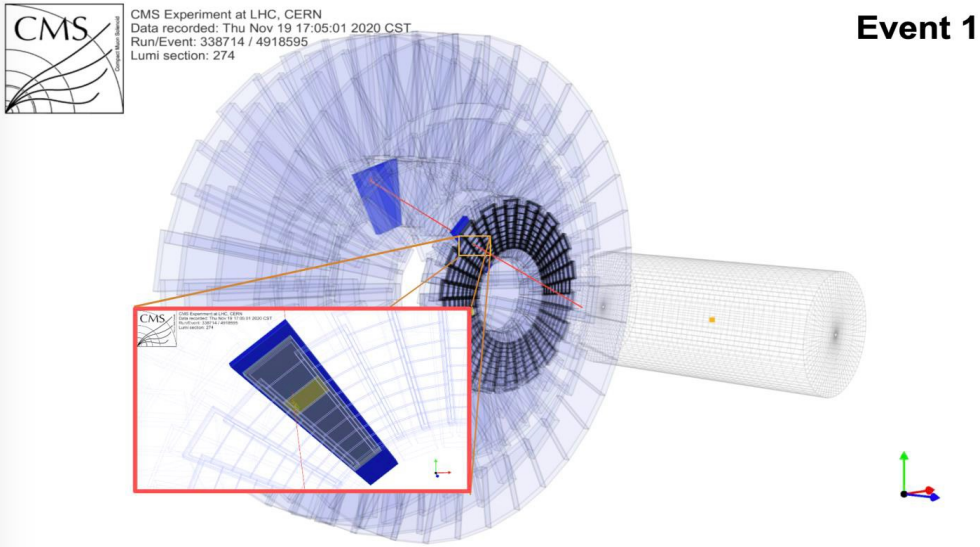


GE1/1:

<u>September 2020</u>: GEM DAQ included in global data-taking for the first time

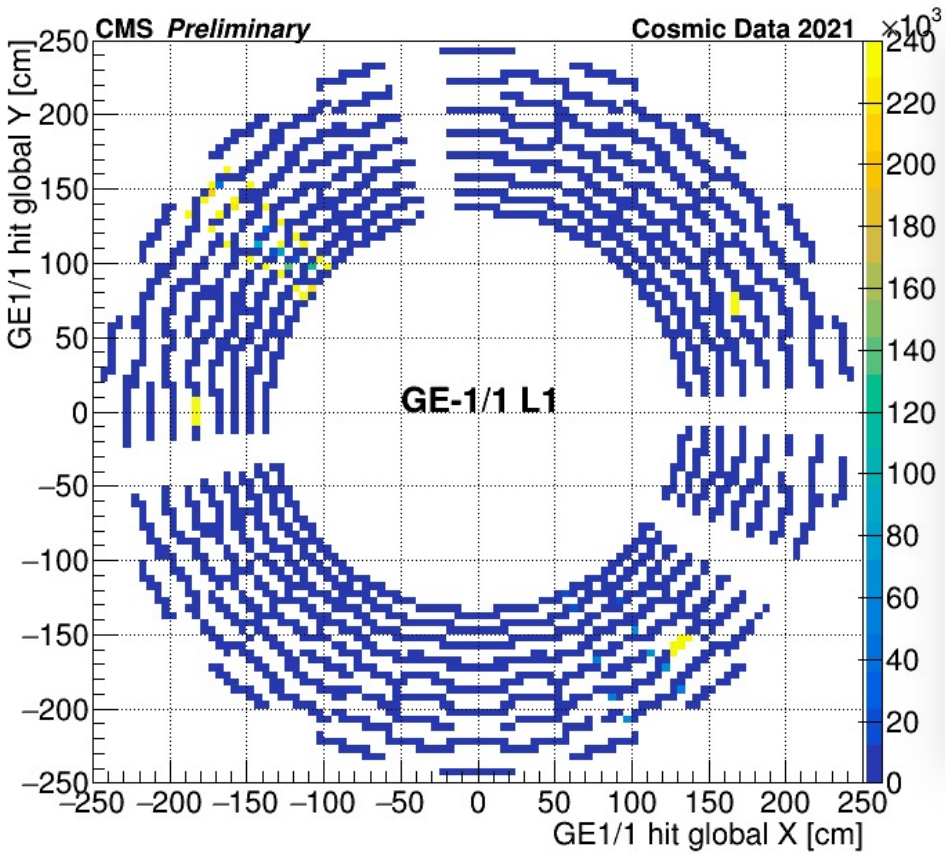
<u>2020-2021</u>:

- DAQ software commissioning (under development)
- Calibrations: latency scan
- GEM-EMTF trigger link connectivity tests
- Cosmic muon data taking



Cosmic ray muon candidate – November 2020

CMS cosmic data-taking runs (2)



GE1/1 Station – Layer 1, Negative endcap

Reconstructed hits in the GE1/1det. Cosmic run – April 2021

- 137 out of 144 chambers successfully readout
- Seven chambers not configured in the DAQ or not powered
- Approximately 0.4% noisy readout sectors

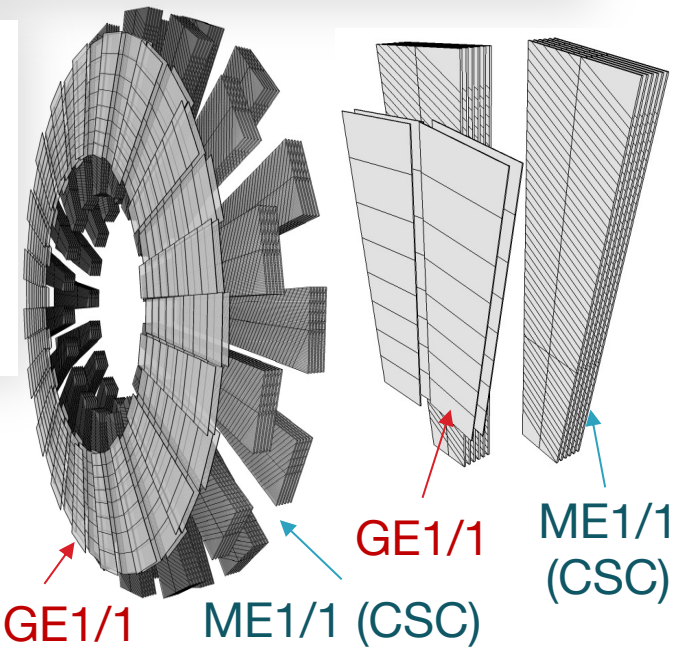
Commissioning of offline monitoring and prompt data analysis (1)

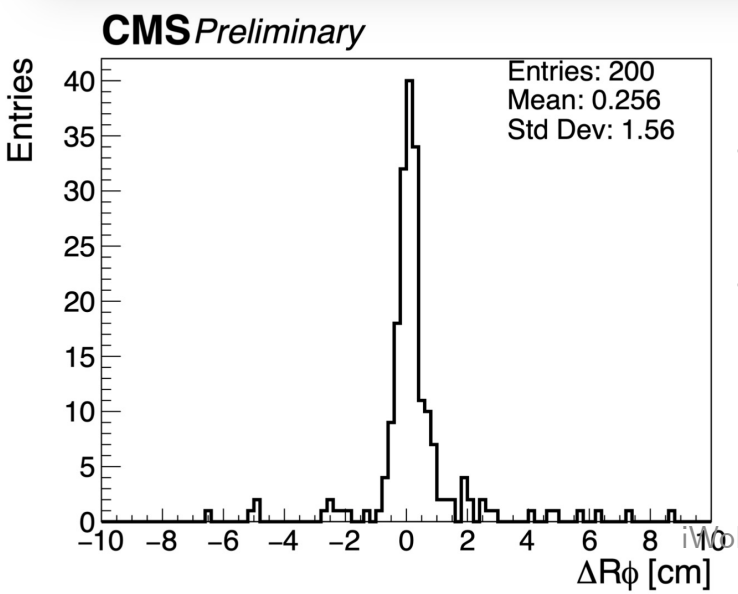
GEM offline Data Quality Monitoring (offline DQM)

- GE1/1 integrated into central CMS offline DQM
- Provides early performance information on promptly reconstructed data
- Tested during commissioning runs with cosmic muons

Detector alignment for data correction

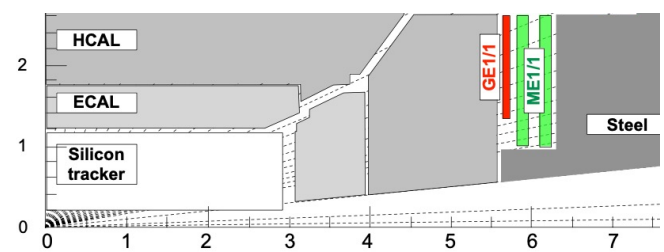
- Run 3: trigger from GE1/1+CSC information
- Important to correct offline for any GEM-CSC misalignment
- Preliminary studies on cosmic muon simulated samples.
- Compared with CMS data taking commissioning runs.





Procedure:

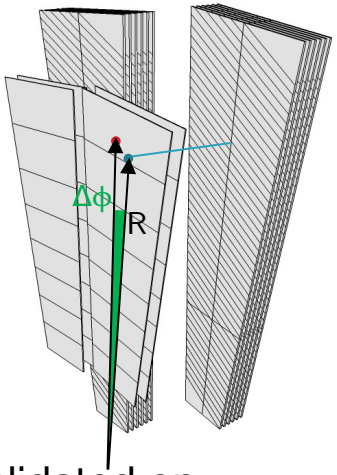
- propagate muon tracks detected by CSC to GEM surface
- look at residuals (distances between propagated hits and GEM muon hits)

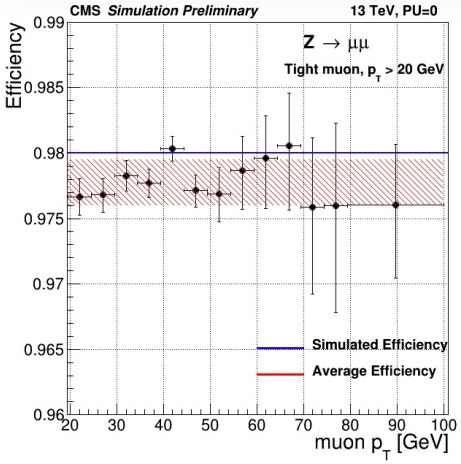


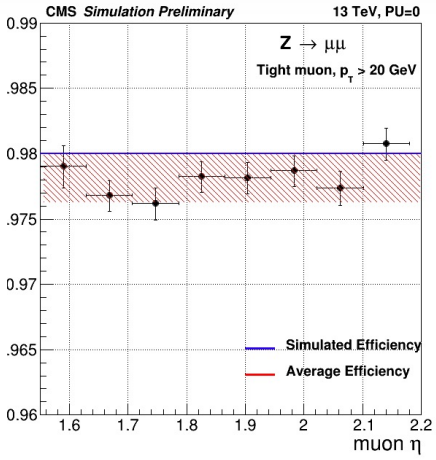
Commissioning of offline monitoring and prompt data analysis (2)

Prompt data analysis for GE1/1 performance monitoring

- Analysis of prompt data for feedback during operations
- Will be used during pp collisions to spot issues and report to DAQ/detector experts within few-days time scale
- Analysis targets:
  - Muon detection efficiency
  - Detector spatial resolution





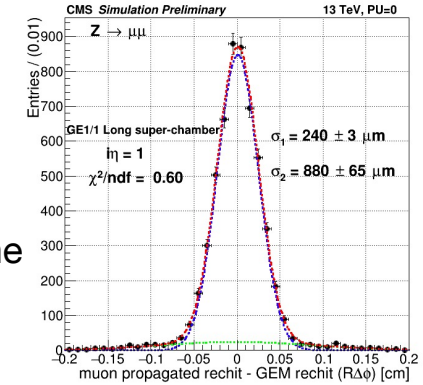


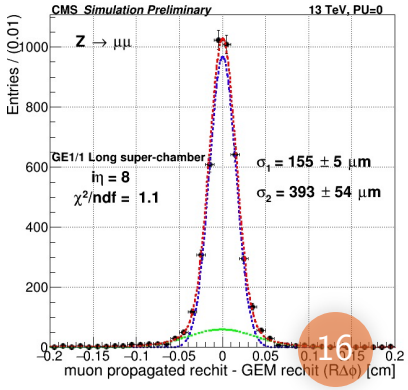
Efficiency measurement validated on **Z→μμ simulation**:

- propagate muon track to GE1/1 surface
- match propagated position with GEM hit in the vicinities ($R\Delta\varphi$<1 cm)
- Eff. = fraction of propagated muon hits matching with GEM hit

GE1/1 spatial resolution on **Z→μμ simulation**:

- residual distribution
- ideal geometry and alignment
- Note: GE1/1 strip pitch changes with distance from the beam pipe





Next steps – towards Run 3 (1)

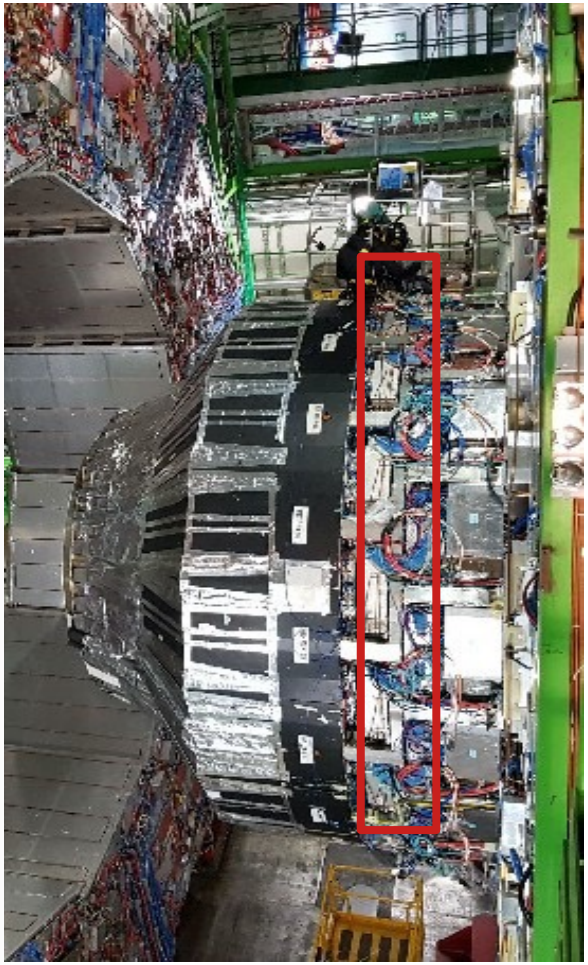
GE1/1 commissioning: next steps

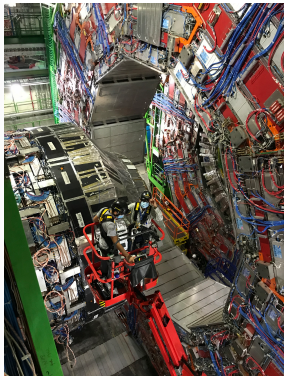
- **Readout:**
  - Electronic noise optimisation, tuning of frontend thresholds
  - Need to understand communication instabilities (affecting < 5% of the entire system)
  - commission the GEM-EMTF and GEM-CSC trigger chains

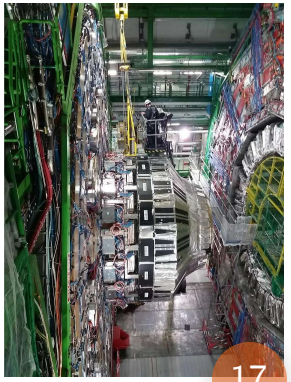
- **Detector Control System:** All ready for pp collision.

- **DAQ software:** final version under development

- **Offline data analysis:** validated using simulation, to be fine-tuned (detector acceptance, muon reconstruction quality, matching criterion on real data)







Next steps – towards Run 3 (2)

CMS long cosmic runs:

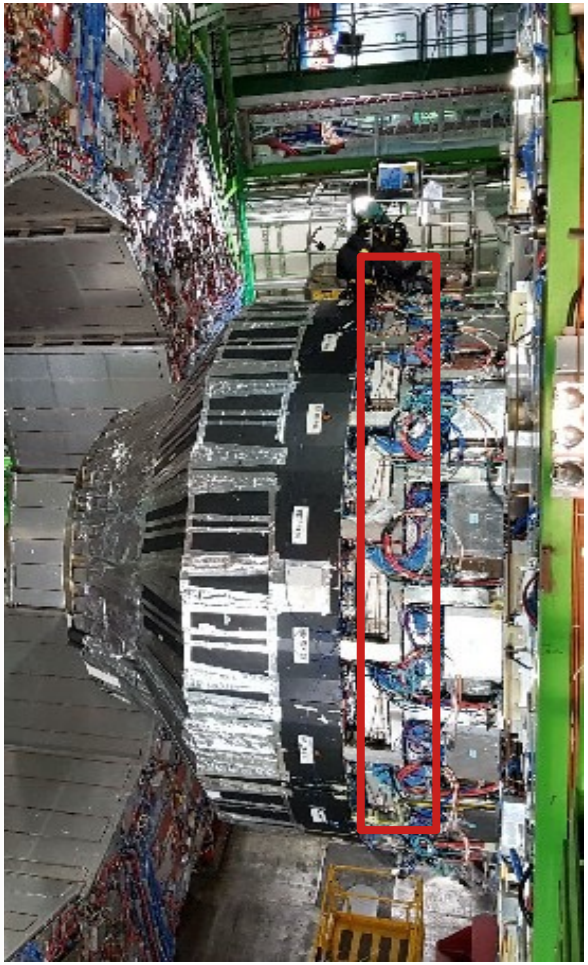
- Cosmic RUn at ZEro Tesla (CRUZET): July-August 2021
- Cosmic Run At Four Tesla (CRAFT): Sept 2021

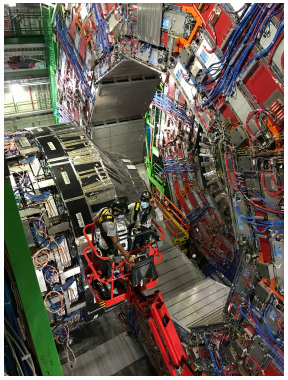
Will allow for **final commissioning** and deep tests of GEM DAQ software

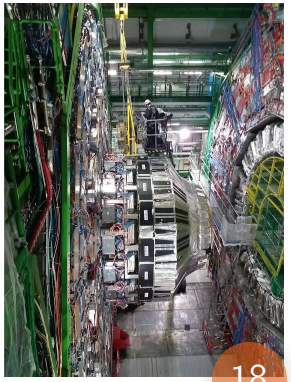
Goal to accumulate sizable samples of cosmic muon events from which to **study the overall detector performance.**

Towards Run 3 pp collisions:

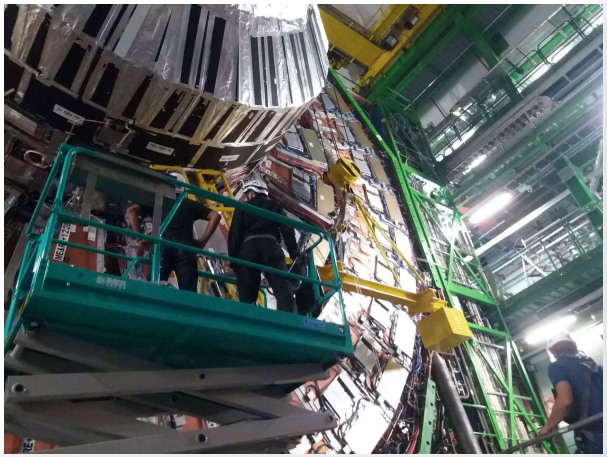
- Pilot beam data taking: Oct 2021
  test collisions at $\sqrt{s} = 900$ GeV





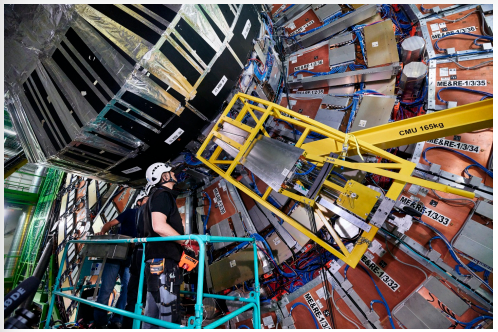


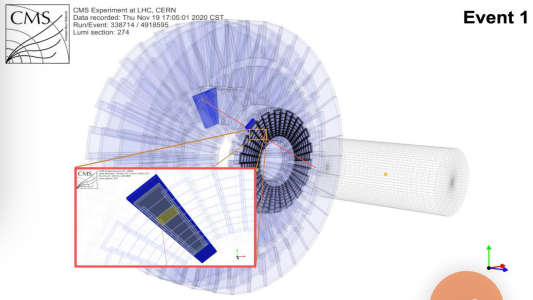
Conclusions



- GE1/1 station: two layers of triple-GEM detectors instrumenting the two endcaps of the CMS muon detector
- 144 detectors built and validated (Sep 2017 to Dec 2018) using a standardized quality control protocol
- Successfull installation

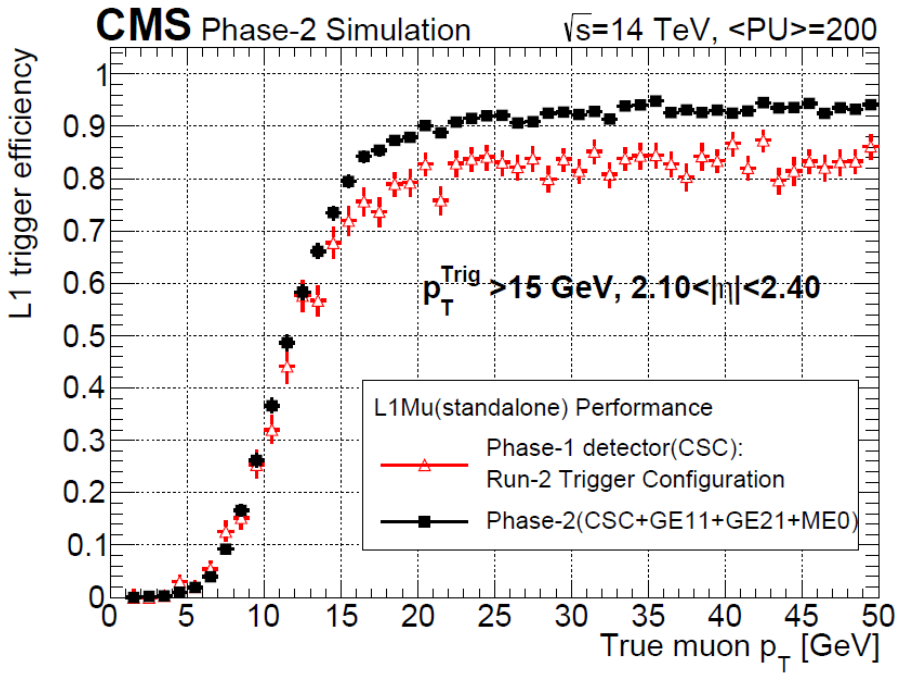
- Commissioning of detector readout and services:
  - Some issues spotted and solved
  - final DAQ software under development
- Joined cosmic runs together with other CMS subdetectors: precious test for DAQ, DCS, DQM
- Next step: study overall detector performance using long cosmic run data





Backup material

Impact of the new muon stations



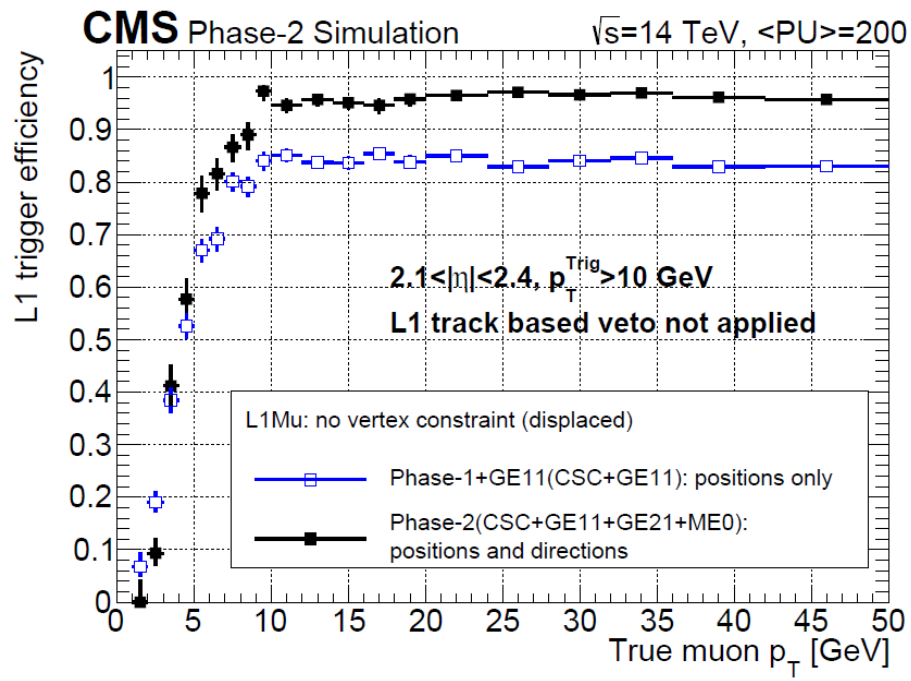
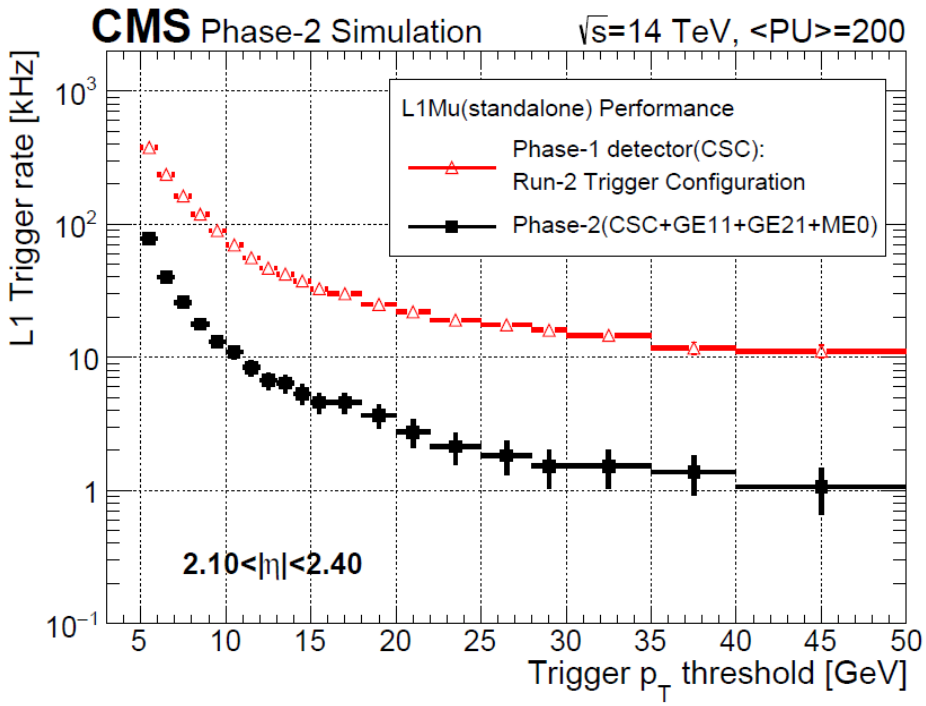


Figure 1.22: L1 Muon trigger efficiency for the prompt muon trigger (left) and displaced muon trigger algorithm (right), as a function of a true muon pT in the region 2.1 < eta < 2.4. The L1 trigger pT threshold is 15 GeV (left) and 10 GeV (right).

Impact of the new muon stations



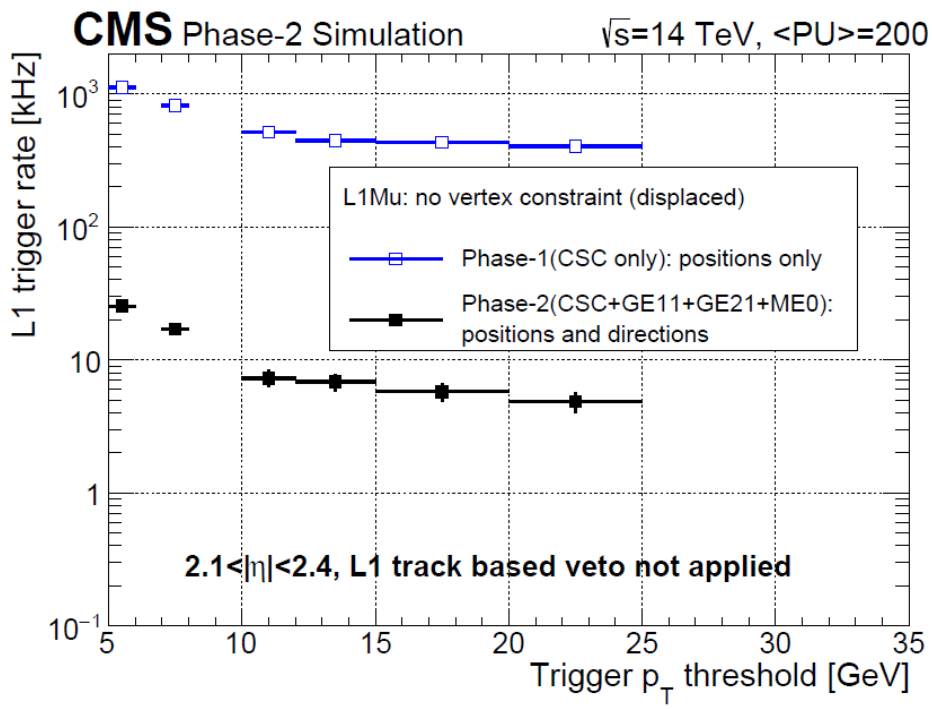
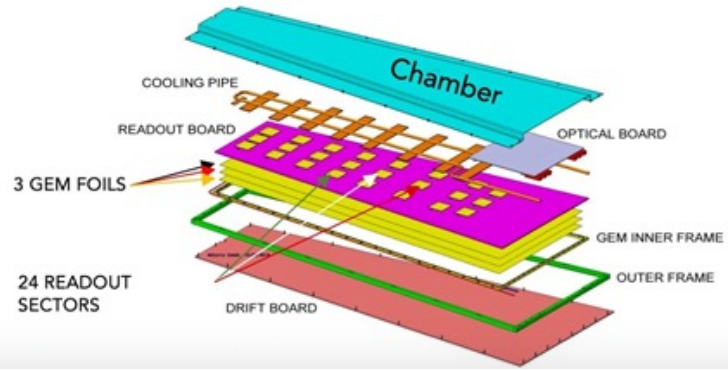


Figure 1.23: L1 prompt (left) and displaced (right) muon trigger rates, with and without GEM chambers, as a function of muon trigger pT threshold in the region 2.1 < eta < 2.4. The L1 track based veto is expected to further reduce the displaced muon trigger rate by a factor of 3–8.

GE1/1 detectors: production and quality controls

CERN
- QC1 — Foils and materials inspection
- QC2 — HV Test on single GEM foils

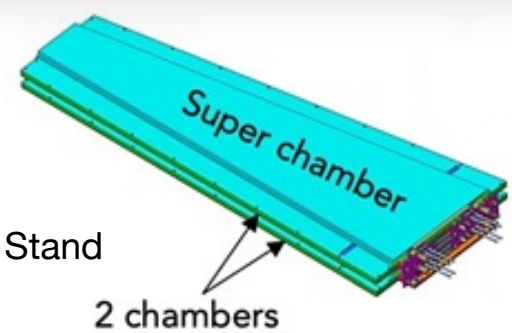


Production sites
- Assembly
- QC2 — HV Test on GEM foils
- QC3 — Gas leak test
- QC4 — HV stability (divider)
- QC5 — Gain and response uniformity

Production shared among different sites:
CERN, India, Pakistan, USA (Florida), Belgium, Italy

- ✓ Standardized setups and procedures
- ✓ Network of Institutes ready for GE2/1 and ME0 production (and more institutes joined)

CERN
- QC6 — HV stability (multichannel)
- QC7 — "Super chamber" assembly
  Readout electronics connectivity test
- QC8 — Efficiency measurement at the Cosmic Stand



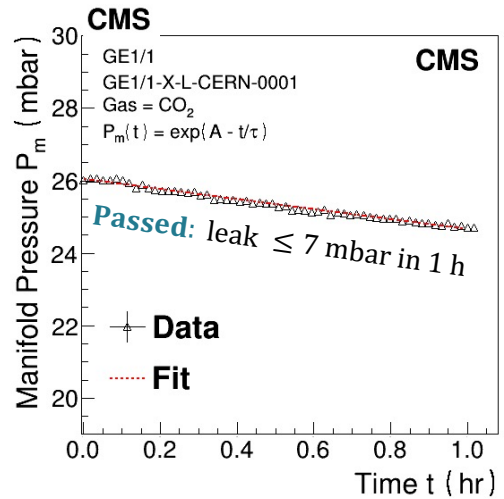
Quality controls up to QC5: overview

CERN
- **QC1** — Foils and materials inspection
- **QC2** — 1° HV Test

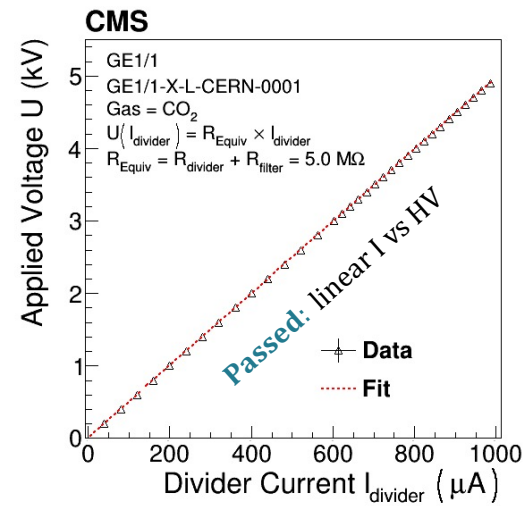
Production sites
- **Assembly**
- **QC2** — 2° HV Test
- **QC3** — Gas leak test
- **QC4** — HV stability (divider)
- **QC5** — Gain and response uniformity

CERN
- **QC6** — HV stability (multichannel)
- **QC7** — Readout electronics connectivity test
- **QC8** — Efficiency measurement at the Cosmic Stand

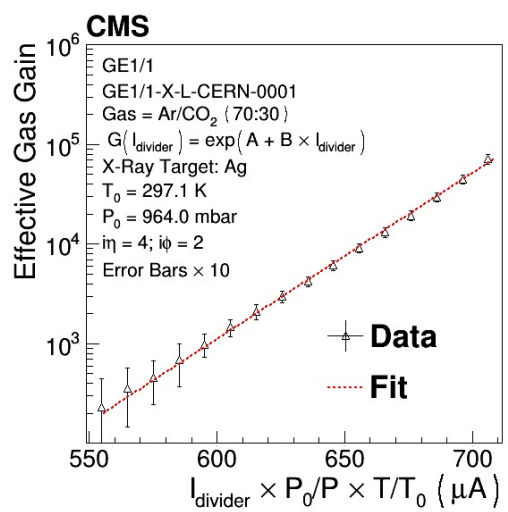
QC3: gas leak test



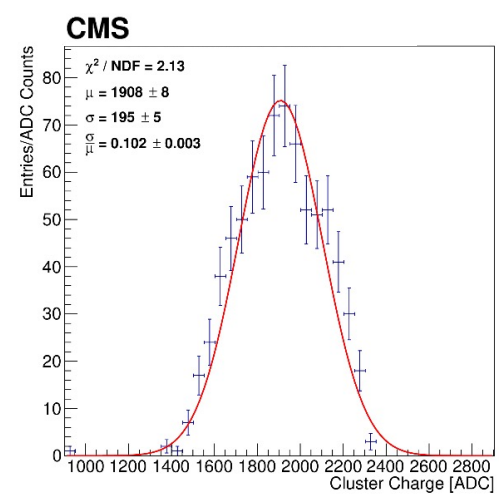
QC4: HV test



QC5: Effective gain



QC5: response uniformity



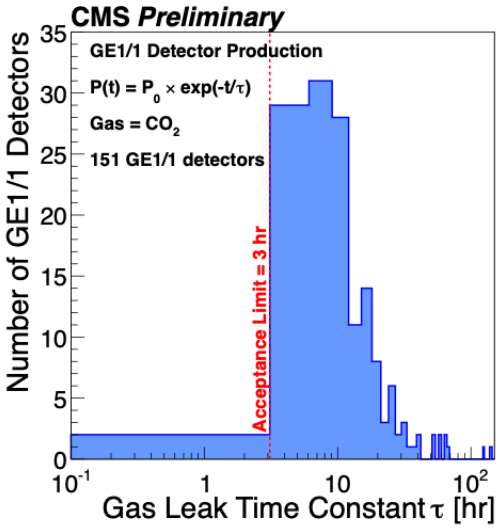
Quality controls up to QC5: summary

CERN
- **QC1** Foils and materials inspection
- **QC2** 1° HV Test

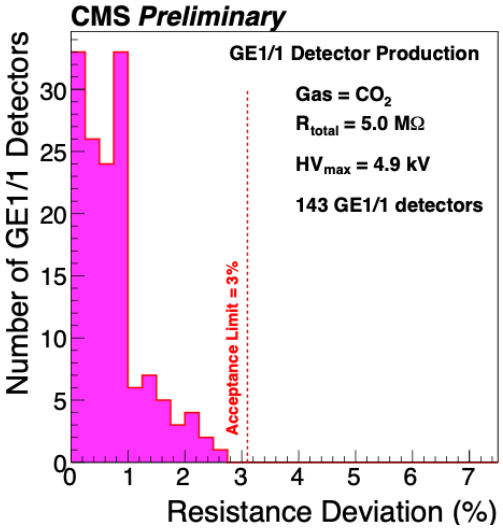
Production sites
- **Assembly**
- **QC2** 2° HV Test
- **QC3** Gas leak test
- **QC4** HV stability (divider)
- **QC5** Gain and response uniformity

CERN
- **QC6** HV stability (multichannel)
- **QC7** Readout electronics connectivity test
- **QC8** Efficiency measurement at the Cosmic Stand

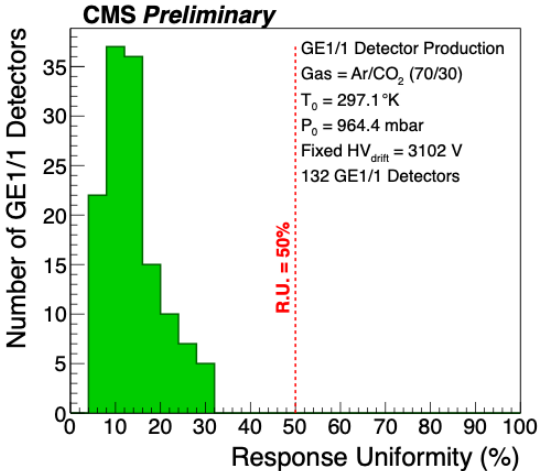
QC3: gas leak test



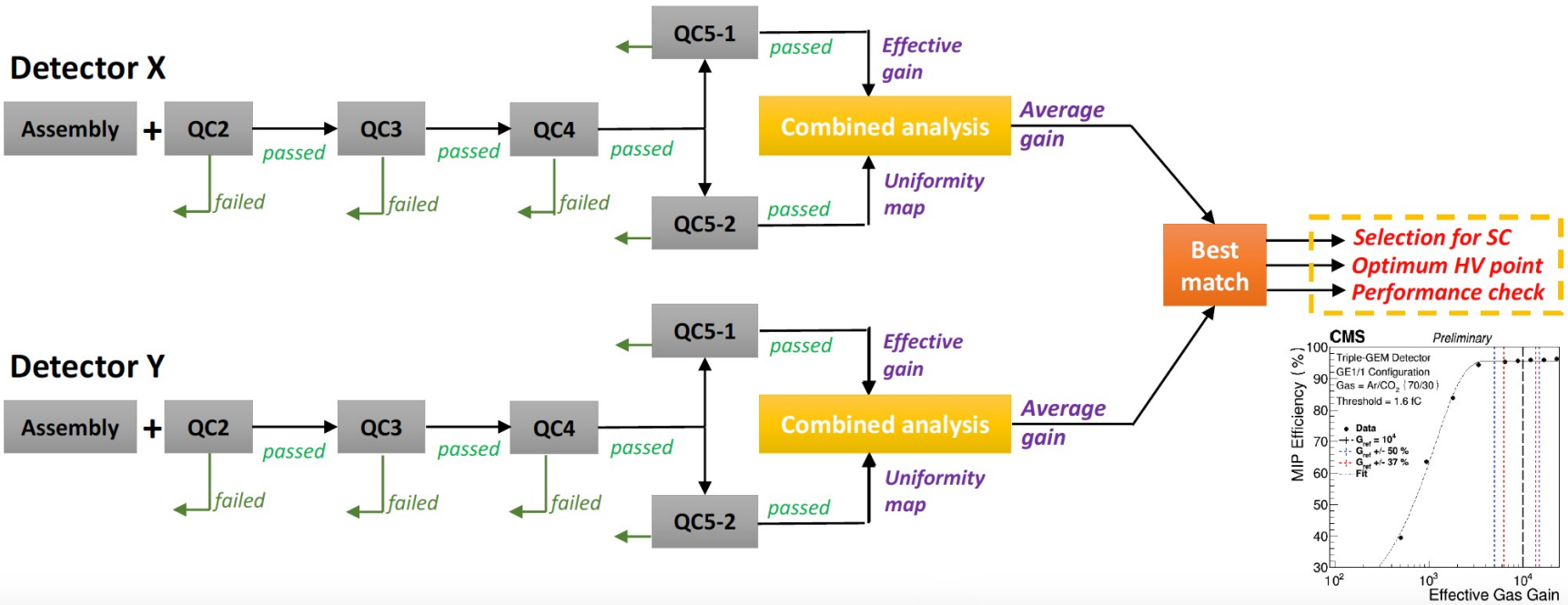
QC4: HV test



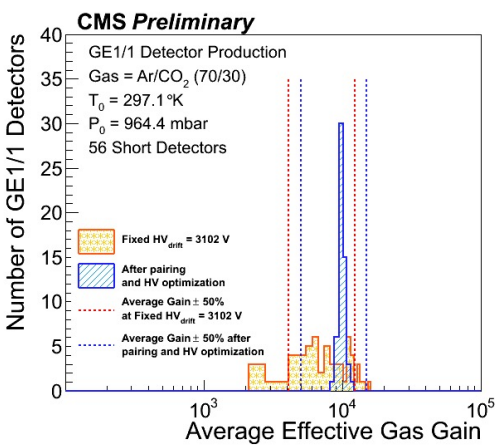
QC5: response uniformity

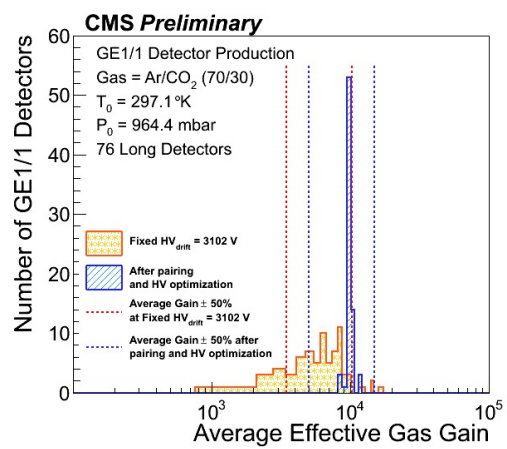


QC5 results and superchamber pairing



QC5 summary: average effective gain



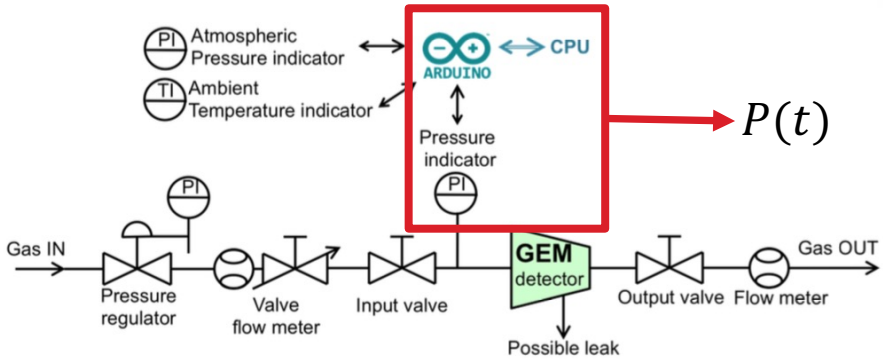


Chambers pairing

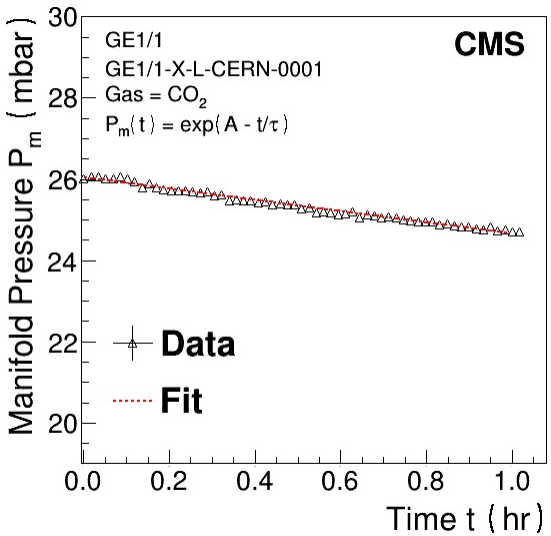
- 1 superchamber = 2 triple GEM detectors
- At P5 common HV power supply
- HV point optimization:
  - Chambers sorted by gain at standard HV
  - Adjacent chambers paired

GE1/1 quality controls: «QC3» gas leak test

1. Setup



2. Typical output



$P_0 = 25$ mbar initial over-pressure

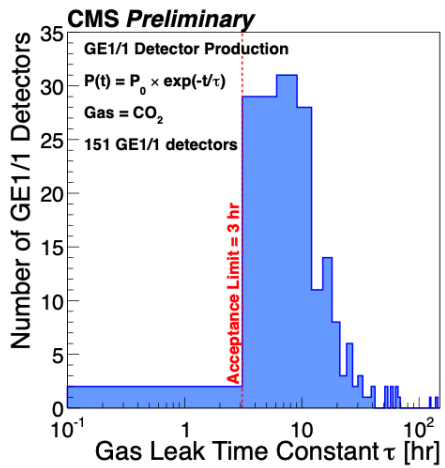
$P(t) = P_0 e^{-t/\tau}$, τ from exp. fit

3. Acceptance criteria

$$\tau > 3h$$

(max leakage flow rate $\sim 0.02\, l/h$)

4. Summary of results



QC3 test:

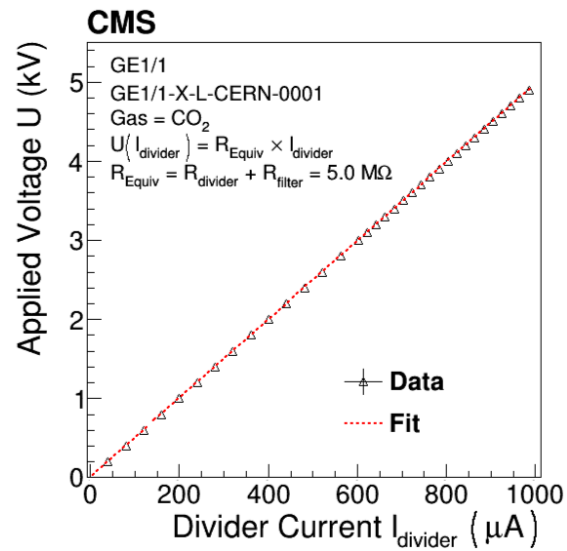
- performed on 151 (144+7 spares) chambers
- 149 validated detectors

GE1/1 quality controls: «QC4» (I) HV stability

1. Procedure

- chamber powered in step of 100V through a ceramic divider (pure CO2)
- powered up to $V_{drift} = 49$ kV
- for each step, the current drawn by the divider is recorded → V-I curve

2. Typical output



V-I characteristics of the full HV circuit

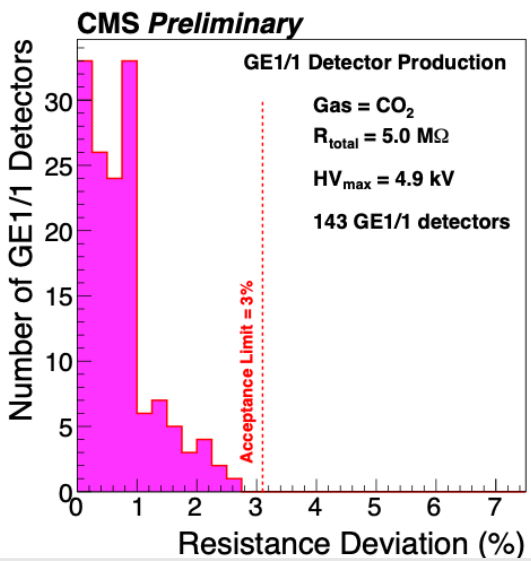
$\Delta R/R = (R_{equiv.meas.} - R_{fit})/R_{equiv.meas}$

3. Acceptance criteria

$$\Delta R/R < 3\%$$

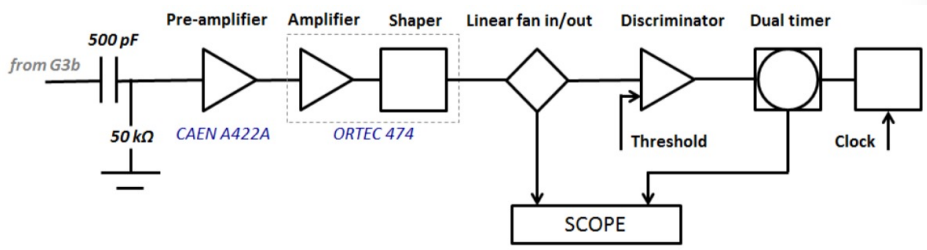
Deviation w.r.t. ohmic behaviour

4. Summary of results



GE1/1 quality controls: «QC4» (II) intrinsic noise rate

1. Setup



2. Procedure

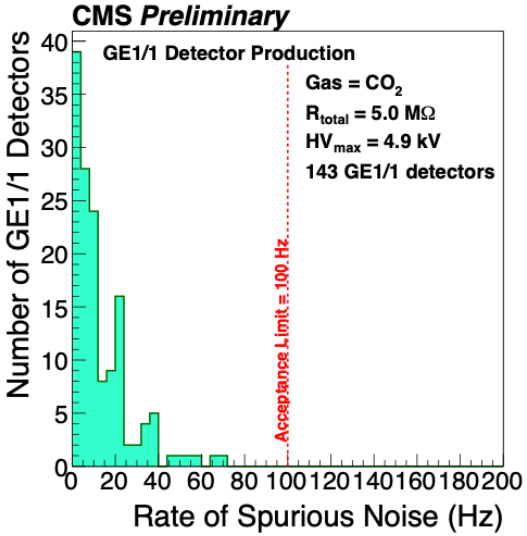
- chamber powered in step of 100V (ceramic divider, pure CO2)
- powered up to V_{drift} = 49 kV
- for each step, the number of spurious pulses from G3B is recorded

3. Acceptance criteria

$$R_{max} < 100\ Hz\ (\sim 10^{-2}\ Hz/cm^2)$$

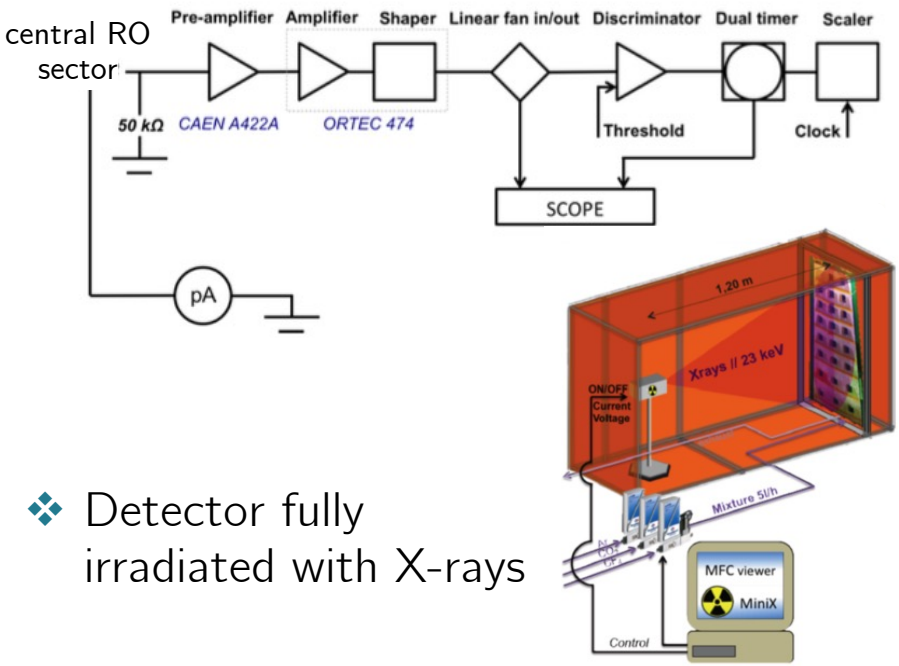
exp. rate at GE1/1 station > 4.5 kHz/cm^2

4. Summary of results



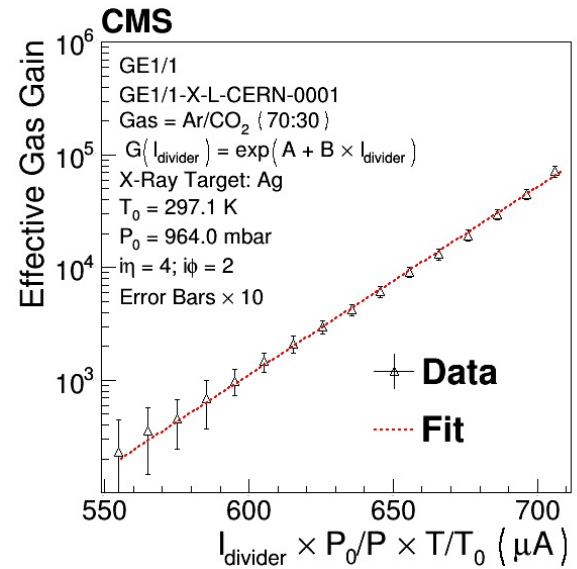
GE1/1 quality controls: «QC5» (I) effective gain

1. Setup and procedure



- Detector fully irradiated with X-rays
- For each HV point:
  - measure the signal rate
  - measure the current induced on the readout I_{RO}

2. Typical output



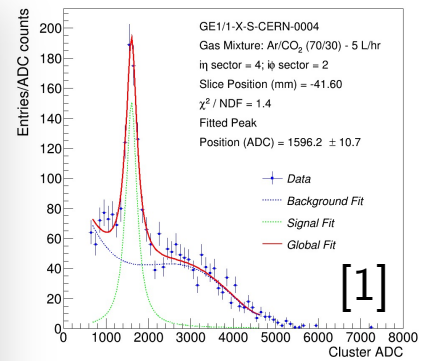
$$G = \frac{I_{RO,\,xray\ ON} - I_{RO,\,xray\ OFF}}{R \times e \times N_p}$$

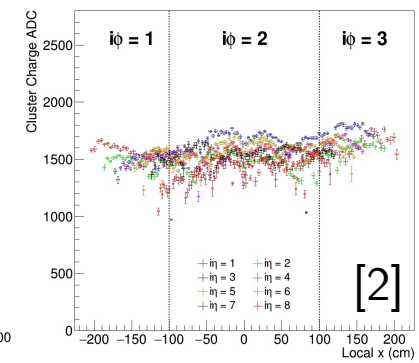
- Signal rate curve plateux assumed as source rate (R)
- N_p = expected number of primary electron-ion pairs

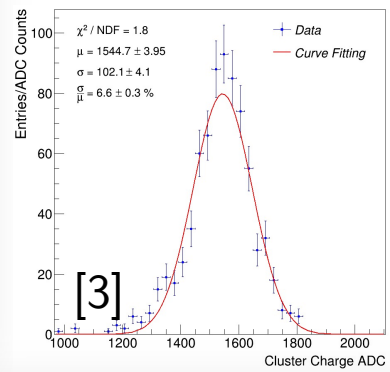
GE1/1 quality controls: «QC5» (II) response uniformity

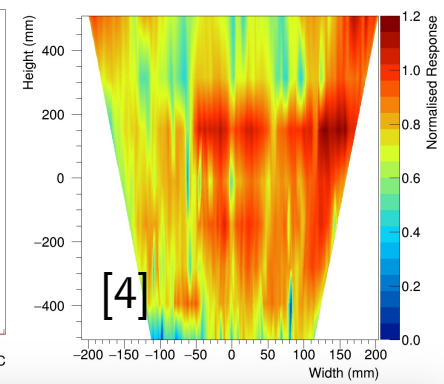
Response uniformity and gain map

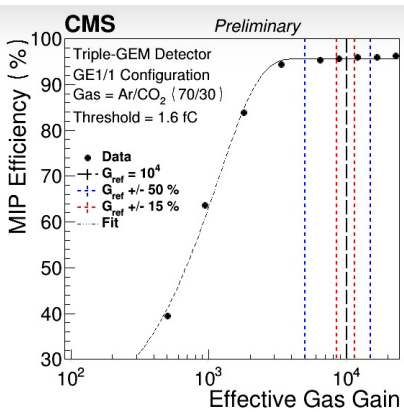
- Detector fully irradiated with X-rays
- RO based on analog electronics (APV25)
- [1] Measure the **copper fluorescence** for every readout channel (3 strips ≈ photon cluster size)
- [2] Compare ionization peak positions
- [3] Distribution of the cluster charge ADC ⟹ $\boldsymbol{R = \sigma/\mu \cdot 100}$ **(Response uniformity)**
- [4] Gain in the central RO sector + uniformity map = gain map ⟹ **avg. gas gain ± std. dev.**

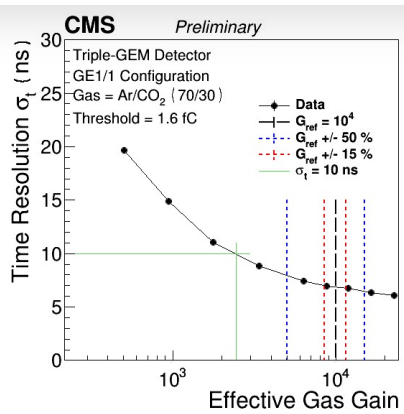












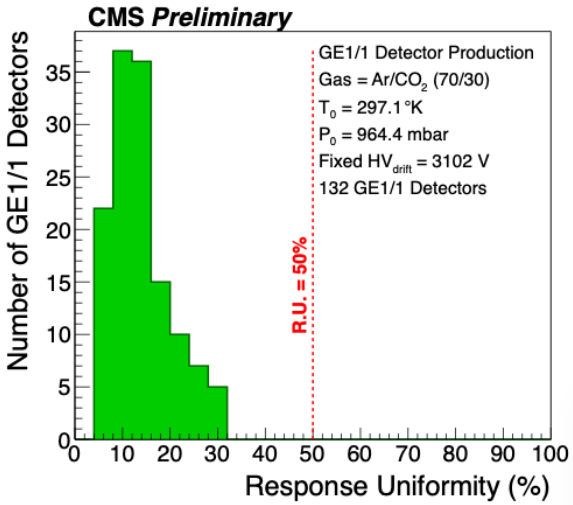
Large active area → gain fluctuations
(foil thickness variations, holes diameter, bending...)

$$\sigma_{gain} \sim 37\%$$

GE1/1 efficiency & time res. **stable** in a large gain range: $\mathbf{G_{ref} \pm 50\%}$ **(**$\mathbf{G_{ref} = 10^4}$**)**

GE1/1 quality controls: «QC5» results and SC pairing

1. Summary: response uniformity

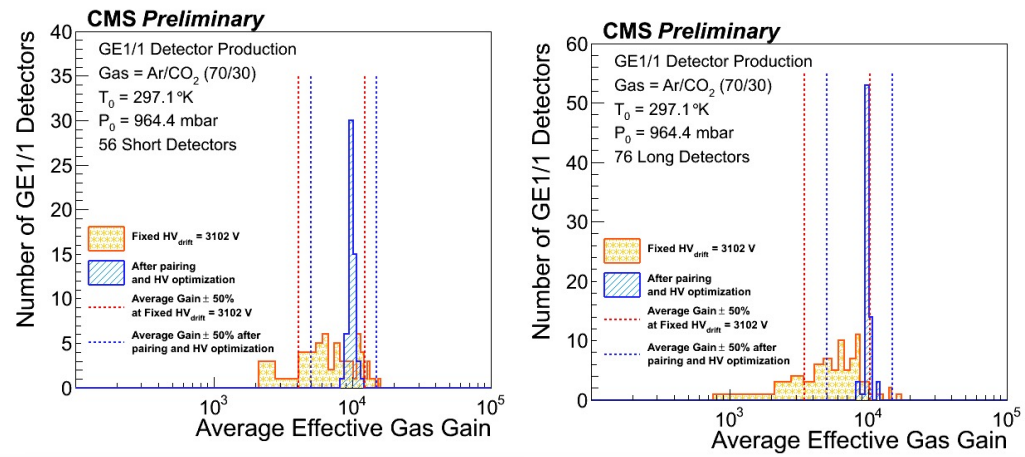


2. Acceptance criteria

$$R < 50\%$$

Max response uniformity to ensure stable performances

3. Summary: average effective gain



4. Chambers pairing

- 1 super chamber = 2 triple GEM detectors
- Common HV power supply ⟹ same HV setting
- HV point optimization:
  - Chambers sorted by gain @ standard HV
  - Adjacent chambers paired
  - Optimal HV = avg between the two

Final quality controls: QC6/7 overview

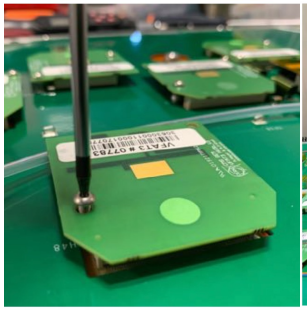
QC6: HV stability

First HV stability test in final gas mixture, with final HV filter and power supply.

Very long procedure updated to prevent discharges when operating in Ar/CO2

1. Stress test at 550V per foil
2. Continuity test
3. Stress test up to 1000 V per foil
4. HV scan #1 (IV measurement)
5. long-term stability (> 12 hours)
6. HV scan #2 (IV measurement)

Mounting of readout electronics



QC7: RO electronics connectivity test

Test the connectivity of the electronics components, monitor the communication stability, check noise level

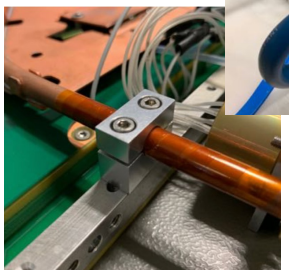
1. Connectivity
2. Calibration
3. Identification of dead/hot channels
4. Global threshold scans (SBIT line) per VFAT
5. ENC measurement (S-curves)
6. Local threshold scans (SBIT line) per channel (to identify disconnected channels)

} repeated after installing cooling plate and chimney

Common issues and solutions

- Faulty FEASTs (non-working, unstable or inducing noise)
- Defects on the GEBs and/or on the SAMTEC connectors
- Dirty PANASONIC connectors
- Unplugged/damaged/problematic VFATs
  → replug or replace components

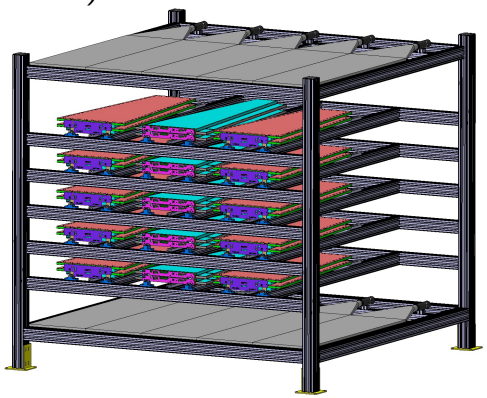
- ground loops created by cooling plate
  → insulation implemented
- Noise issues → optimised chamber grounding (star point)



Final quality controls: QC8 overview

Cosmic test stand: a large sized experiment in the lab

- 15 Super Chamber slots + two layers of scintillators (trigger rate ≈ 90Hz)
- 92k readout channels with CMS-like DAQ based on uTCA backend
- Services (LV, HV, DAQ system, cooling, FW, SW) as in P5
- Gas mixture: Ar/CO2 (70/30%) + CO2 / Pure Air line
- Dedicated DCS:
  - HV, LV control and monitoring (data stored in DB)
  - environmental conditions and gas mixture monitoring (stored in DB)
- Dedicated Offline DQM
- Full simulation and reconstruction implemented in CMSSW

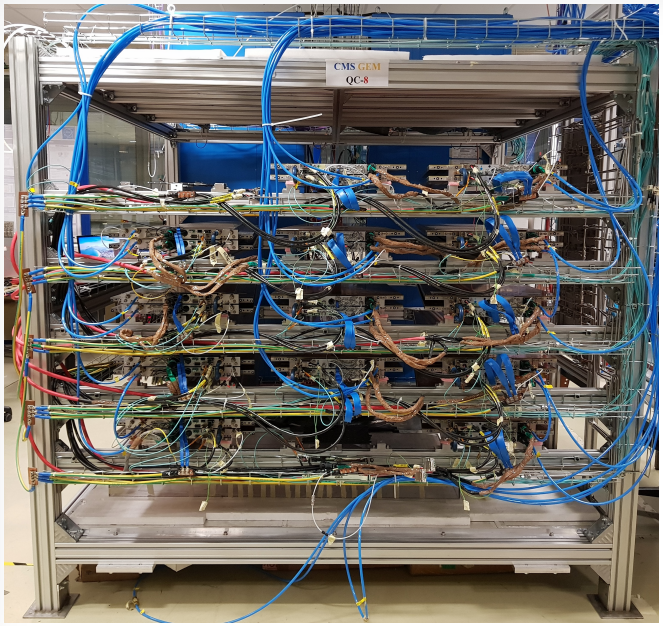


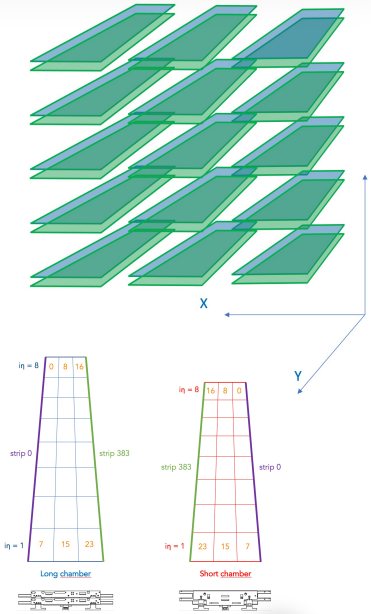
Configuration and test procedures:

- Configuration of DAQ parameters
- Trimming, masks, thresholds @ 100Hz noise
- Before data taking: HV training procedure in Ar/CO2 to prevent discharges

QC8 test:

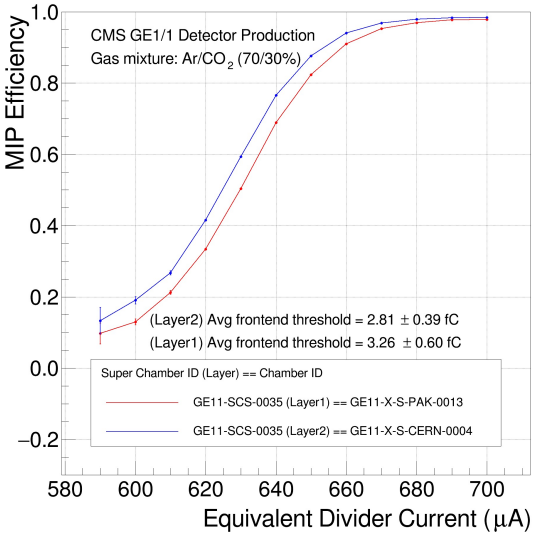
- HV scan with cosmic muons:
  ~12h cosmic run for each HV point
- Analysis in CMSSW Framework:
  - Software alignment implemented,
  - Muon track reconstruction for efficiency measurement,
  - Final results stored in DB



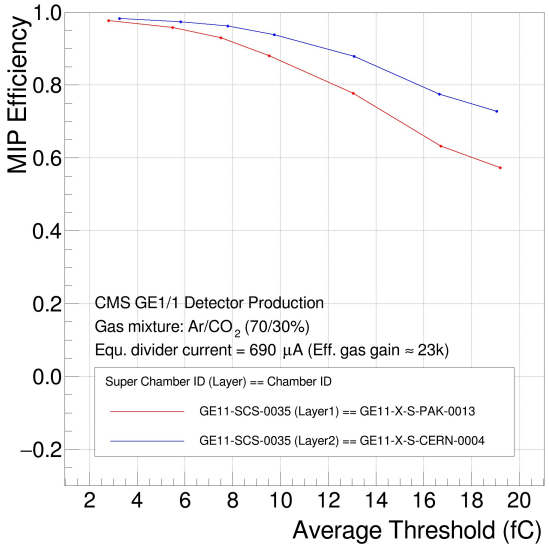


Final quality controls: QC8 results and status summary

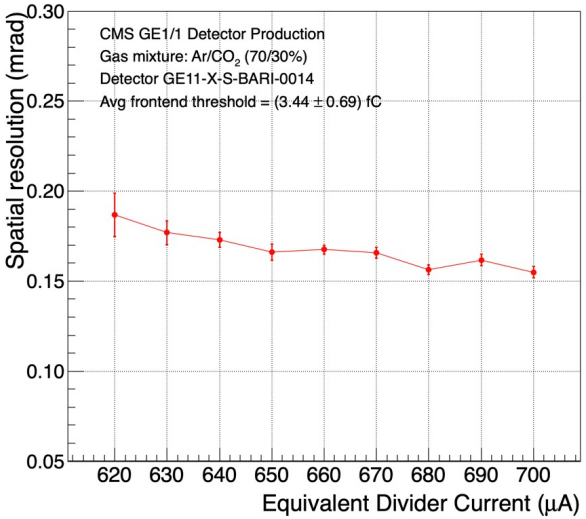
Efficiency vs HV scan



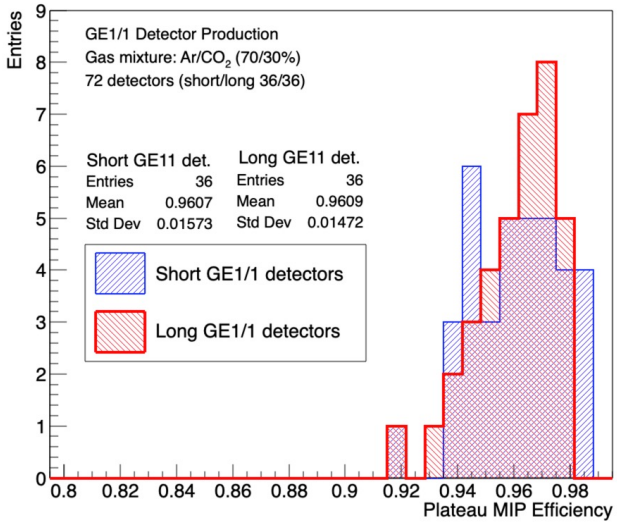
Efficiency vs thresh. scan



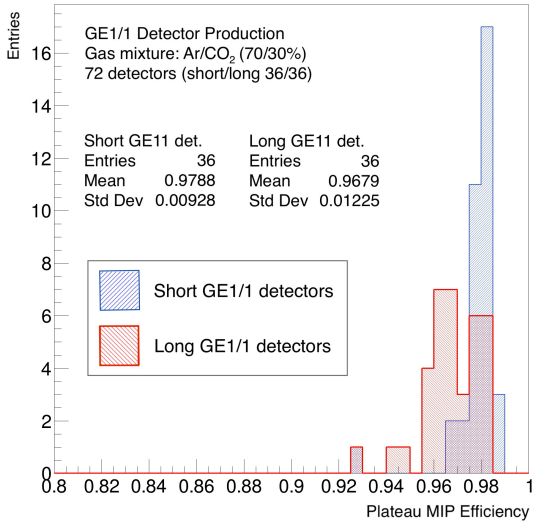
Spatial resolution



Efficiency summary at QC8 for the negative endcap



Efficiency summary at QC8 for the positive endcap

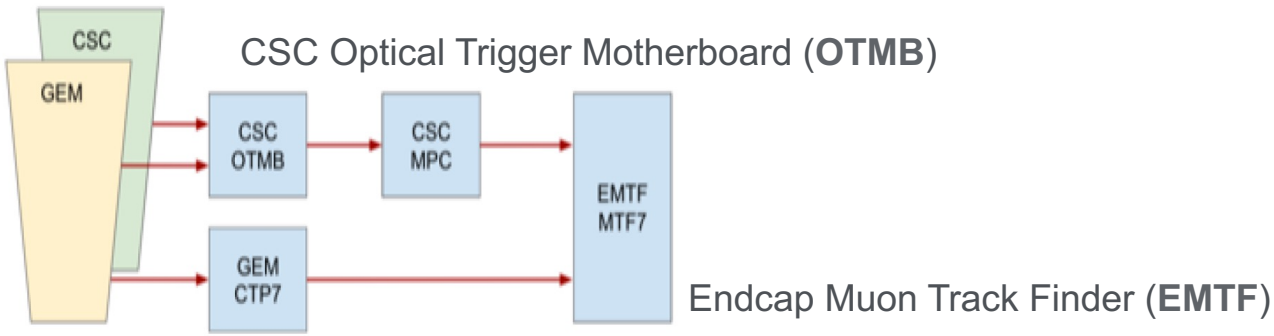


GE1/1 Local Trigger

- Each GEM layer sends up to 8 clusters (local position+hits size) per BX
  - Trigger data also includes frame marker, special marker for BC0, cluster overflow flag
- Overflow rate = 1.18E-05 @ PU140
- Identical trigger data is sent to CSC OTMB and EMTF(through CTP7)
  - GE1/1 trigger data will be ready once GE1/1 commissioning is done
  - GEM+CSC local trigger integration (next slide) and EMTF with GEM integration could be parallel

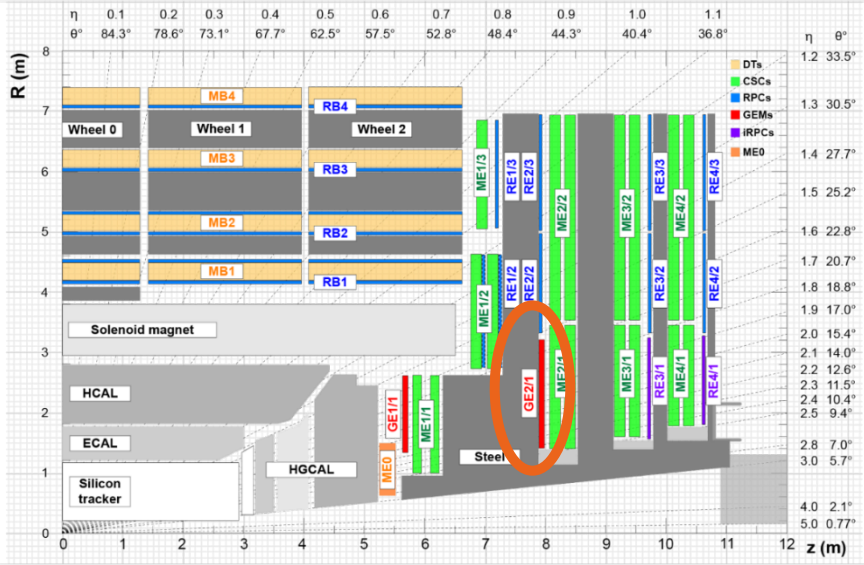
GEM trigger cluster dataformat

	N bits
Phi sector	2
Eta partition	3
Pad number	6
Cluster size	3
Total	14

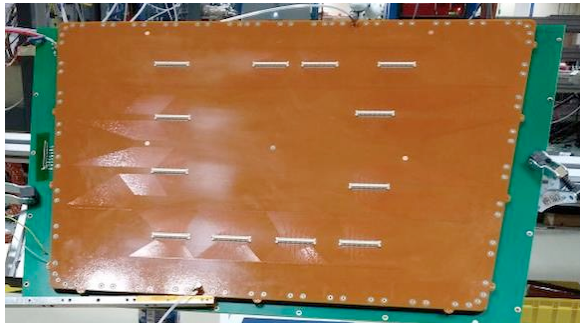


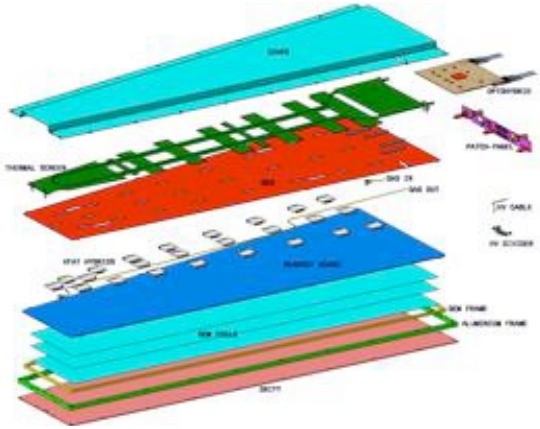
- GEM+CSC algorithm was well stimulated and established in CMSSW back to 2014
  - Recent development: adding GEM trigger data unpacker for emulation study
- GE1/1 commissioning enables the GE1/1-ME1/1 joint local trigger
  - OTMB receives GEM hits and CSC hits, both through fibers, and build robust local trigger
- GEM+CSC local trigger bring following advantages:
  - Improve the trigger efficiency with additional redundancy from GEM
- GEM-CSC bending angle will help to control the trigger rate by cutting out low pT muons at EMTF level
- GEM+CSC local trigger in OTMB is to assure that CSC information could arrive in EMTF

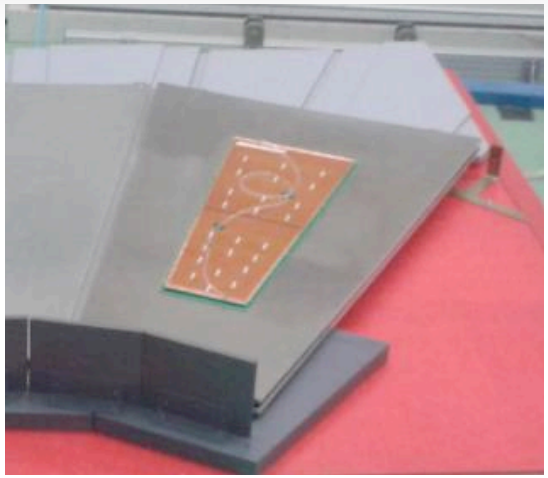
Phase II upgrade: GE2/1



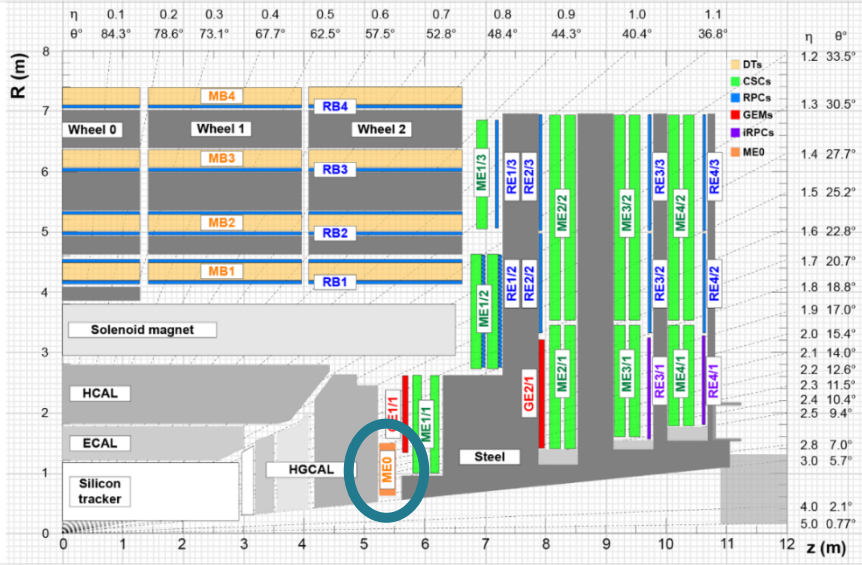
- GE2/1: together with GE1/1, it will add **redundancy** and **improve the p_T resolution**, contribute to dedicated muon trigger for **displaced muons** in the endcaps.
- 36 superchambers - 20° each
  - 40 "modules" will be assembled and tested in Bari
- eta coverage $1.6 < |\eta| < 2.2$



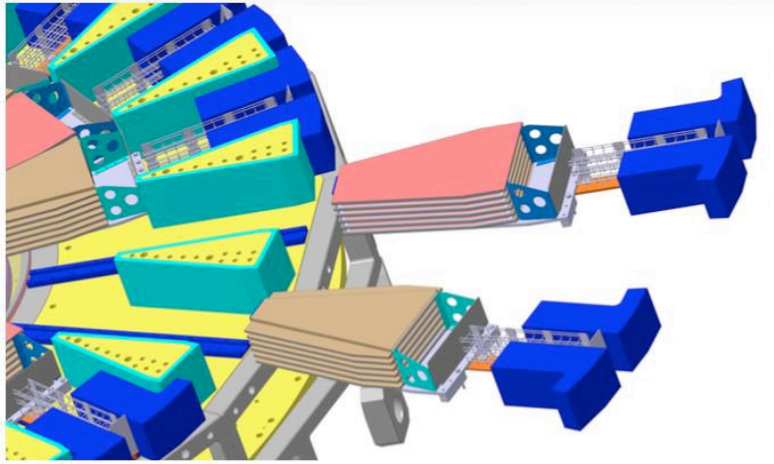


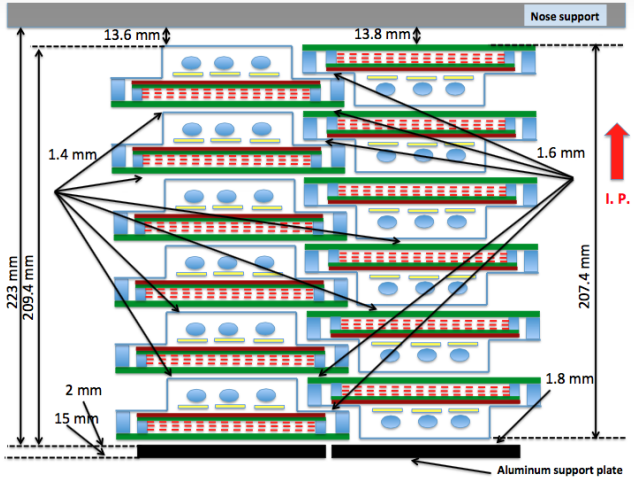


Phase II upgrade: ME0

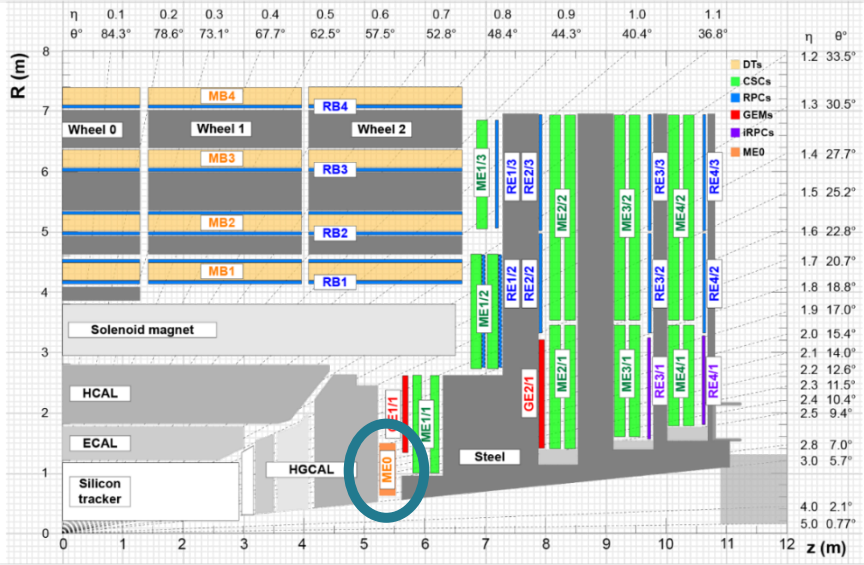


- ME0: extending the eta coverage up to *η=2.8* (presently ***η < 2.4)***
- 6 triple-GEM detector layers.
- Trigger for multi-muon signature





Phase II upgrade: ME0



- ME0: extending the eta coverage up to *η=2.8* (presently ***η < 2.4)***
- 6 triple-GEM detector layers.
- Trigger for multi-muon signature

Acceptance increase fundamental for forward Tau->3mu (cLFV) search

Table 25: (Top) The expected numbers of signal and background events in the mass window 1.55 -2.0 GeV for CMS. An integrated luminosity of 3000 fb^{-1} and a signal $\mathcal{B}(\tau \to 3\mu) = 2 \times 10^{-8}$ is assumed. (Bottom) The search sensitivities for the combined categories.

	Category 1	Category 2
Number of background events	2.4×10^6	2.6×10^6
Number of signal events	4580	3640
Trimuon mass resolution	18 MeV	31 MeV
$\mathcal{B}(\tau \to 3\mu)$ limit per event category	4.3×10^{-9}	7.8×10^{-9}
$\mathcal{B}(\tau \to 3\mu)$ 90% C.L. limit	3.7×10^{-9}	
$\mathcal{B}(\tau \to 3\mu)$ for 3-σ evidence	6.7×10^{-9}	
$\mathcal{B}(\tau \to 3\mu)$ for 5-σ observation	1.1×10^{-8}