Status of the installation and commissioning of the new GE1/1 station for the CMS experiment

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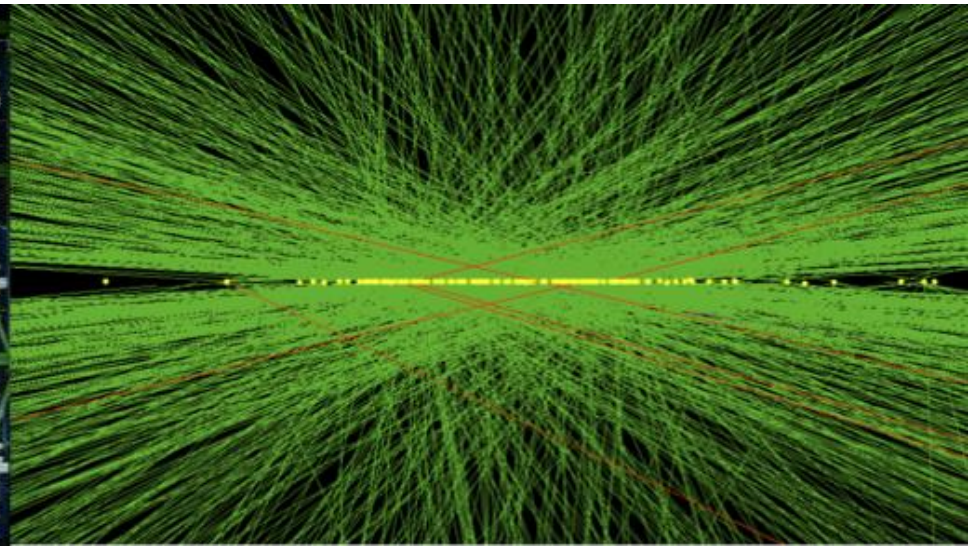


Introduction

Goals of this presentation

Update the community **on the status of the mass-production, installation and commissioning of the new GE1/1 station in the CMS experiment**

Table of contents:

CMS Forward Muon System Upgrade

Run 2 CMS endcap muon detectors:

- CSC + RPC covering $0.9 < |\eta| < 1.6$
- Only CSC covering $1.6 < |\eta| < 2.4$

From 2026: High - Luminosity LHC

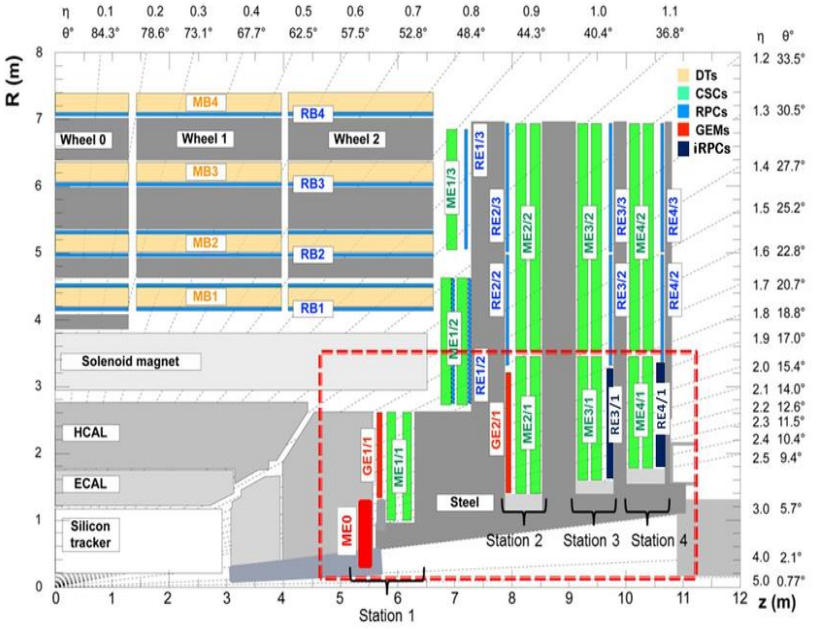
→ Increase luminosity to $5 \times 10^{34}\ s^{-1}cm^{-2}$ $(5 \times \text{LHC design value})$

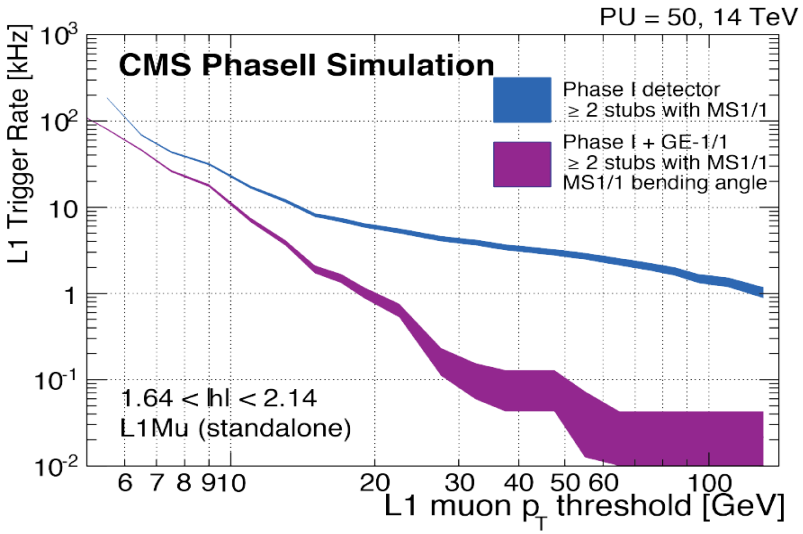
→ Upgrade current Muon Forward System:

- Increase redundancy in endcaps
- Improve p_T measurements in low B field
- Reduce the trigger rates
- Sustain higher particle flux

Future GEM installation $1.5 < |\eta| < 2.8$

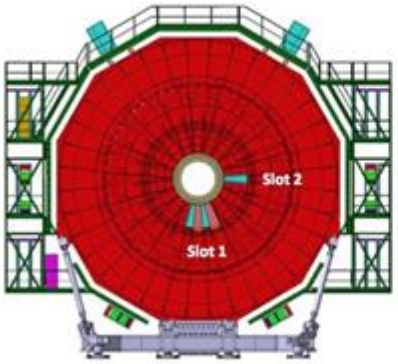
- GE1/1, GE2/1 and ME0 project
- iRPC project





GEM in CMS: integration plans

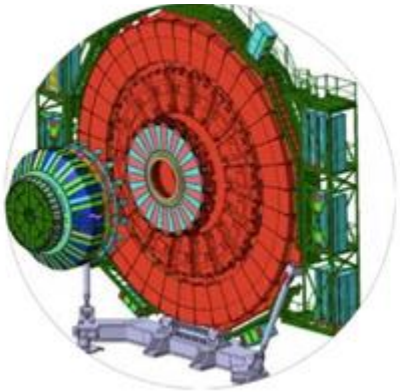
Slice Test



Slice Test = commissioning of 10 GE1/1 detectors in CMS

2 out of 10 with final readout electronics and HV

GE1/1



Installation of GE1/1 during Long Shutdown 2

144 chambers in two endcaps
GE1/1: $1.5 < |\eta| < 2.2$

GE2/1

GE1/1

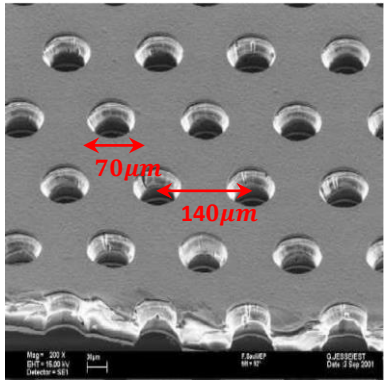
ME0

GE2/1 and ME0 installed by the end of Long Shutdown 3

GE2/1: $1.5 < |\eta| < 2.2$
ME0: $2.0 < |\eta| < 2.8$

Gas Electron Multiplier Technology

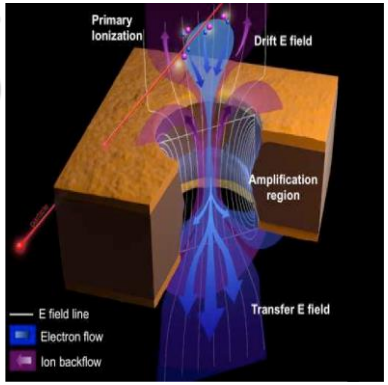
Micro-Pattern Gas Detectors (MPGD) due to their proven performance at HEP experiment (high rate capability and fine space resolution, high gain stability) are ideal tools for the Upgrade of the Forward Muon Spectrometer in CMS



GEM-based technology as adopted detector!

GEM foils:

- $50\ \mu m$ thick polyimide foils clad on each side with a $5\ \mu m$ copper layer
- Holes $(\mathbf{diameter}\ =\ 70\ \mu\mathbf{m})$ in hexagonal pattern $(\mathbf{pitch}\ =140\ \mu\mathbf{m})$

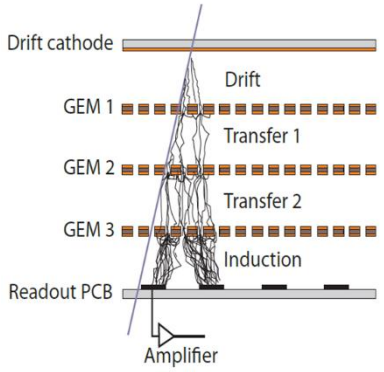


GEM chamber:

- Gas detectors: charged particles ionize gas
- HV applied: amplification process inside holes $(\mathbf{E} \sim \mathbf{60\ kV/cm})$
- One or multiple GEM- foils $(\mathbf{e.g.\ triple - GEM = 3\ foils})$

Performance:

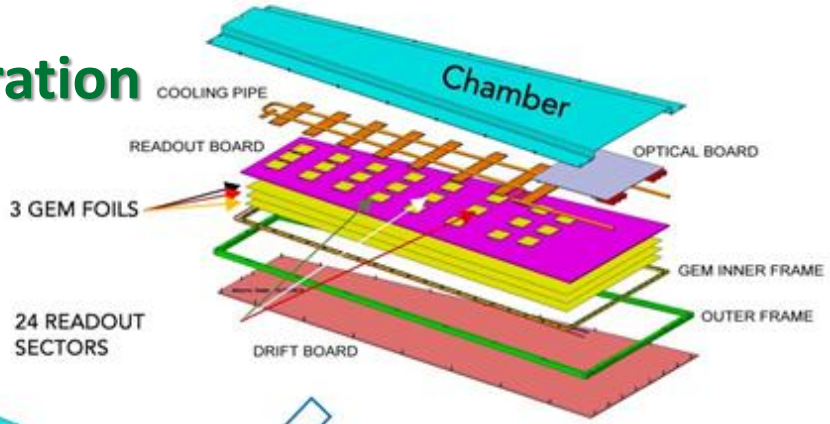
- Rate capability: up to $\mathbf{O(kHz/cm^2)}$
- Triple-GEM chamber efficiency $> 98\%$ for MIPs
- No aging effects after foreseen integrated luminosity of HL-LHC
- High spatial $(\sim 140\ \mu m)$ and good time $(\sim 7\ ns)$ resolution



CMS GEM GE1/1 Project

The 1st project of the CMS GEM Collaboration

GEM Endcap Ring 1 Station 1

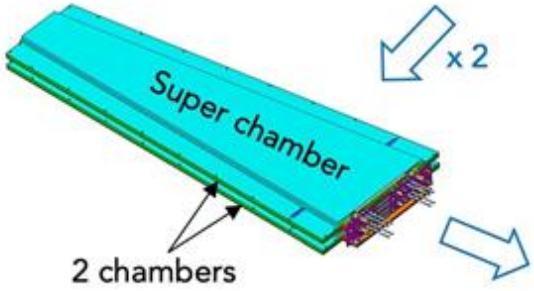


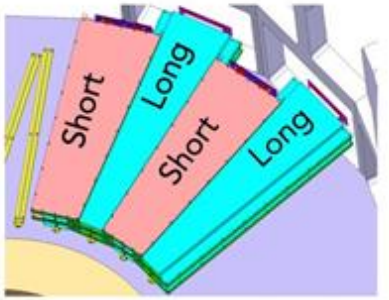
GE1/1 chamber

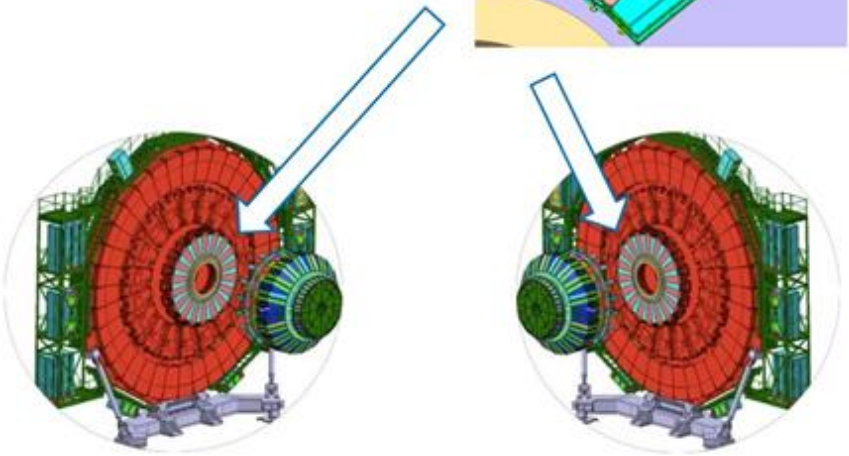
- Triple-GEM chambers
- Gas mixture Ar/CO_2 $(70/30\%)$
- Large area $O(m^2)$
- Covering $1.5 < |\eta| < 2.2$

- 144 trapezoidal Long and Short chambers
- 24 readout sectors per chamber
- 128 radial strips for each sector
- Digital readout

- 72 Super Chambers $(2$ coupled chambers$)$
- Each Super Chamber covers $10.15°$ (overlap)







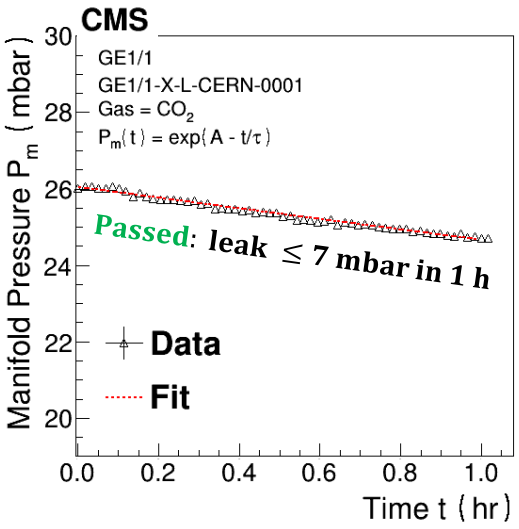
GE1/1 Detector QC Overview

CERN
- QC1 — Material Inspection
- QC2 — GEM-foils Test

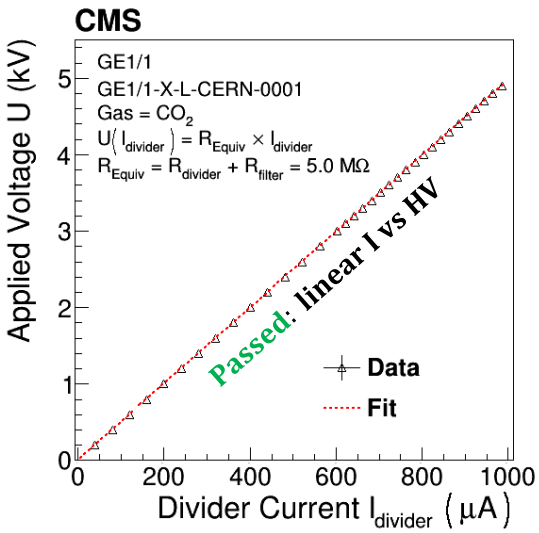
Production sites
- Assembly
- QC2 — GEM-foils Test (fast)
- QC3 — Gas Leak Test
- QC4 — HV Test
- QC5 — Gas Gain Calibration

CERN
- QC6 — HV Stability Test
- QC7 — Electronics Connectivity Test
- QC8 — Cosmic Test

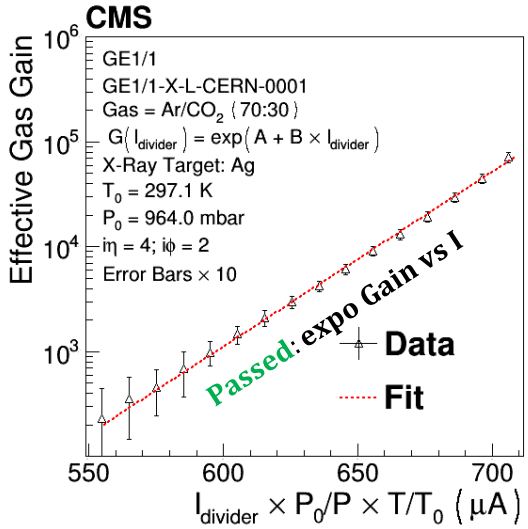
QC3 - Gas Leak Test



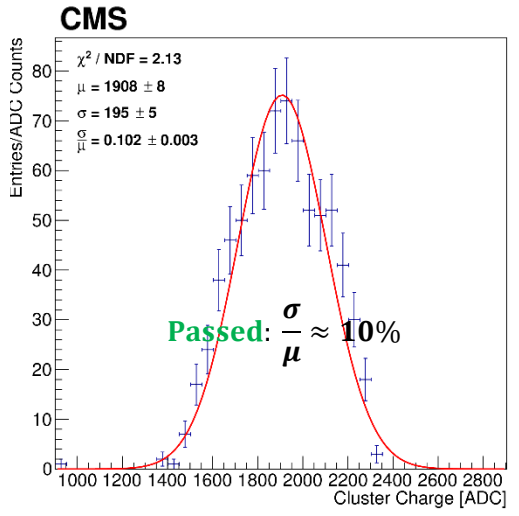
QC4 - HV Integrity



QC5 - Effective Gas Gain



QC5 - Gas Gain Uniformity



GE1/1 Detector QC Overview

GE1/1 Electronics Assembly Procedure

Mounting of the front-end electronics:

~1 hr

- *Mounting of the GEB (GEM Electronics Board)*
- *Routing of the on-chamber services*
- *Installation of the FEASTs + Opto-Hybrid + VFATs*

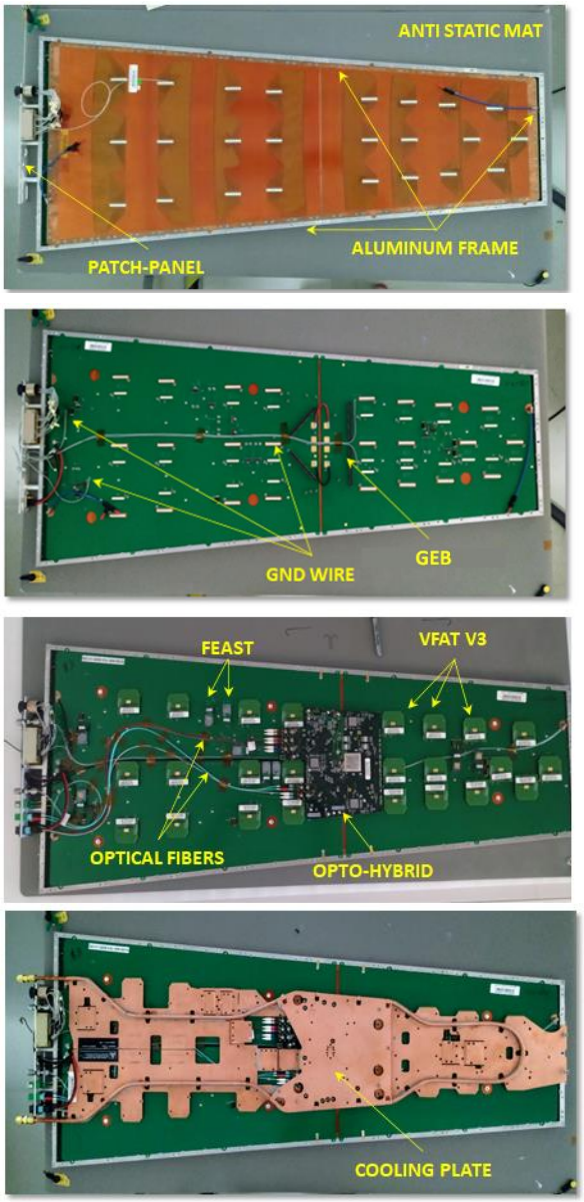
(FEAST is a DC-DC converter; VFAT is a trigger and tracking front-end ASIC device)

Electronics and connectivity test:

~1/2 d

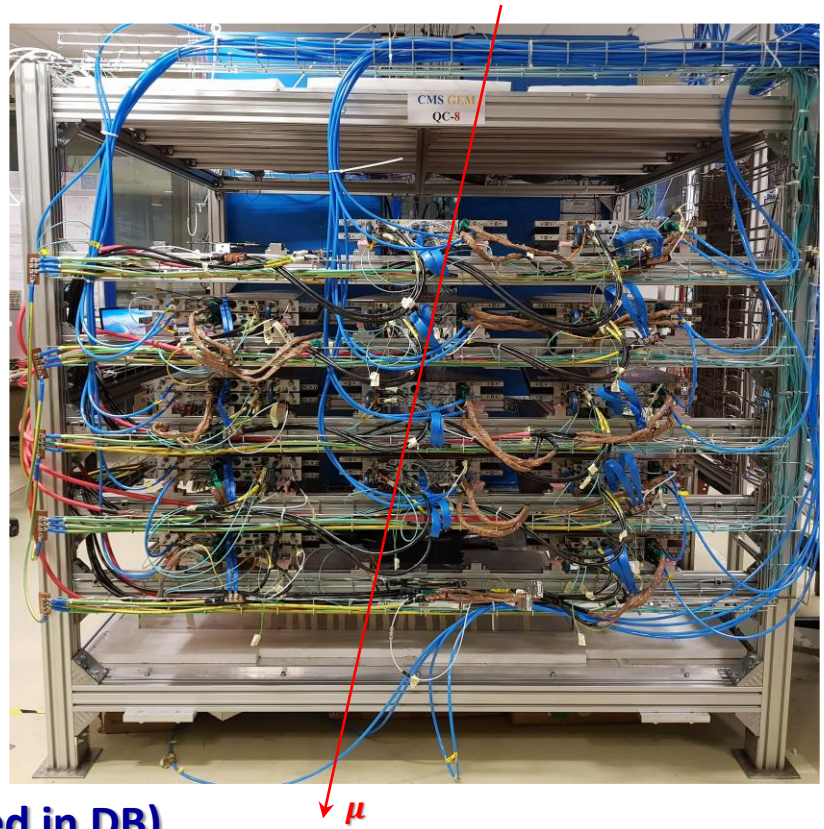
- *Check connectivity of the electr. components*
- *Calibration of front-end elect. parameters*
- *Monitor the communication stability*
- *Noise level measurement (Equivalent Noise Charge)*
- *Identification the noisy/dead channels*

1 day is sufficient to fully assemble and test the GE1/1 on-chamber elestronics



Cosmic Test Overview

Cosmic test stand: a large sized experiment in the lab.

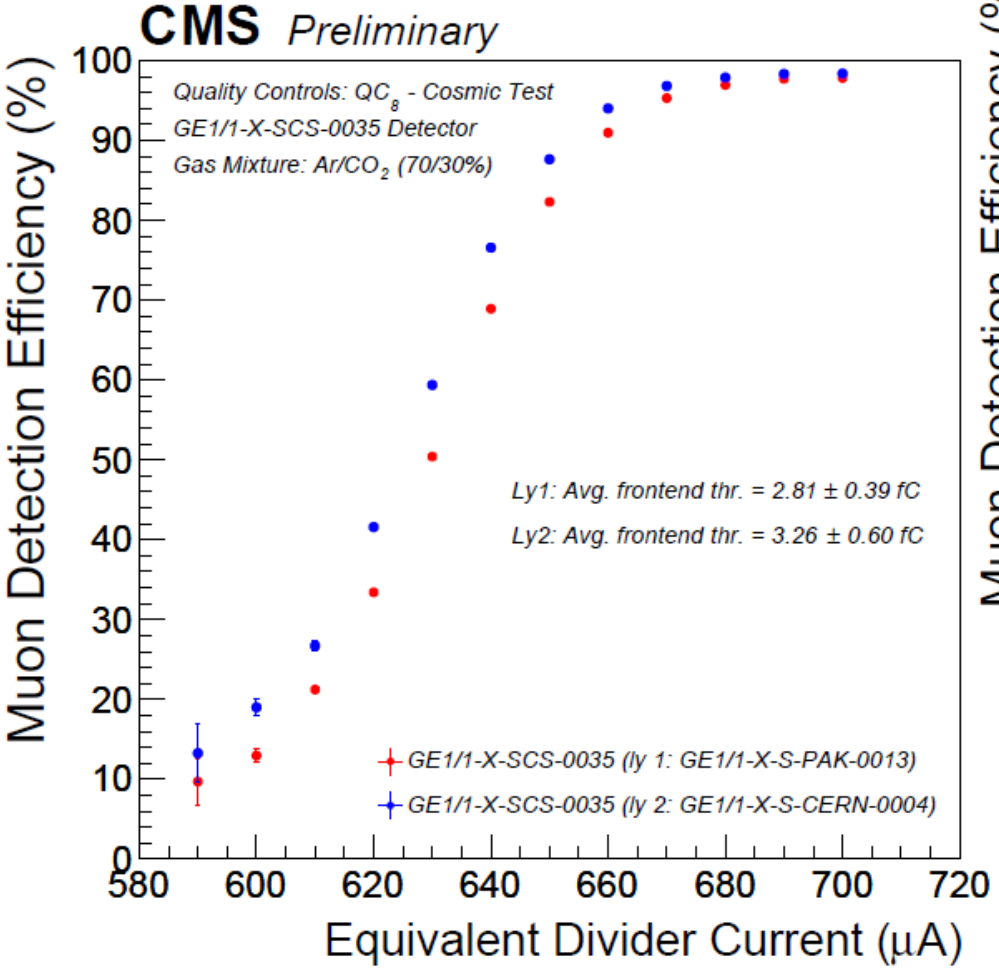


- **15 Super-Chamber slots**
- **2 layers of scintillators (as a trigger - rate $\sim 90\ Hz$)**
- **$92k$ readout channels with CMS-like DAQ based on μTCA back-end**
- **Services (HV, LV, DAQ system, cooling, FW, SW) as in CMS**
- **Gas mixture: Ar/CO_2 $(70/30\%)$ line**
- **Dedicated Detector Control System:**
  - **→ HV, LV control and monitoring (data stored in DB)**
  - **→ environmental conditions and gas mixture monitoring (data stored in DB)**
- **Dedicated Data Quality Monitoring**

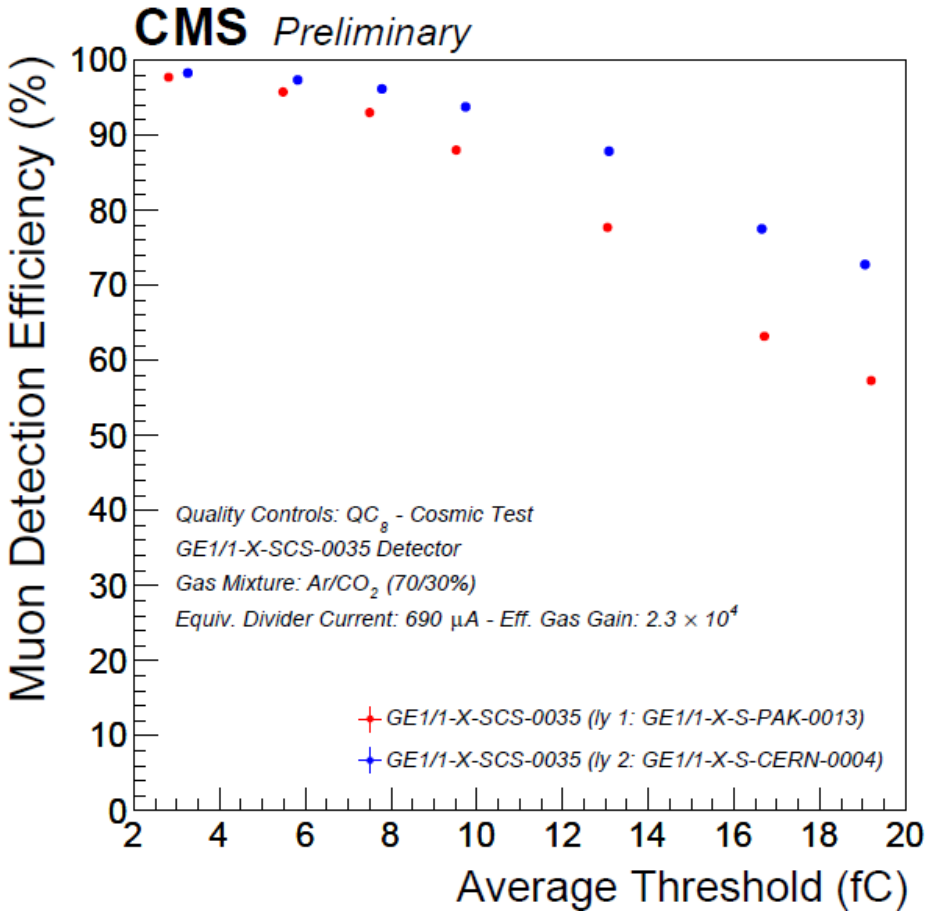
Cosmic Test Result

Results for some of the detectors tested:

Example of Efficiency vs. HV scan



Example of Efficiency vs. THR. scan

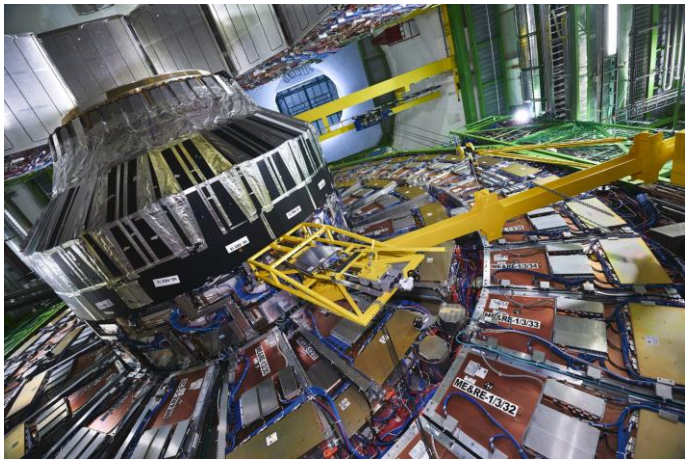


Tip: to get HV at the cathode, just need to multiply the current by $\sim 4.7\ M\Omega$ ($700\ \mu A = 3290\ V$)

GE1/1 Super-Chamber Installation

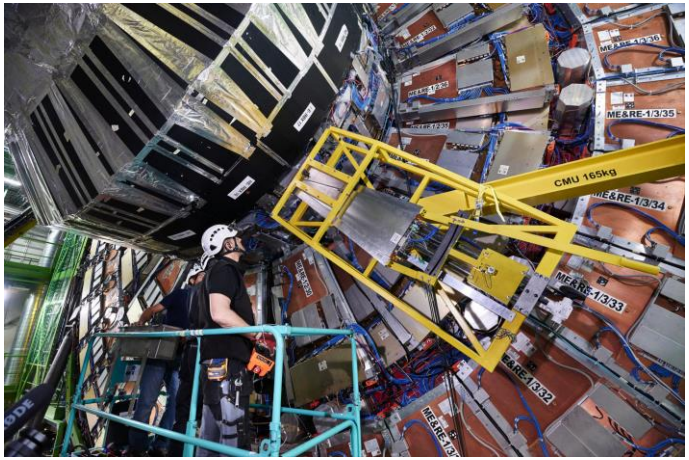
GE-1/1 SCs in the negative end-cap

- **Installation of all 36 Super-Chambers for the first end-cap completed in Oct. 2019**
- **Multiple installation windows from July 2019 to October 2019**
- **Commissioning phase is underway (delayed due to the COVID-19 stop)**



GE+1/1 SCs in the positive end-cap

- **Installation of all 36 Super-Chambers for the second end-cap completed in Sept. 2020**
- **Multiple installation windows from July 2020 to September 2020**
- **Installation and commissioning phase delayed due to the COVID-19 stop**

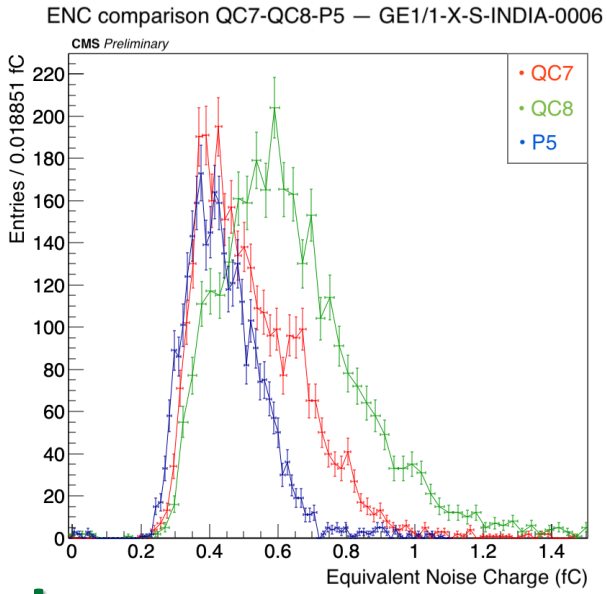


Nice pictures and movies of this story available at: http://cds.cern.ch/record/2684028 & https://www.youtube.com/watch?v=fU0ujGWbeQ0&feature=youtu.be

GE1/1 Super-Chamber Commissioning

First end-cap "pre-commissioning" phase

- HV training procedure in pure CO_2 to prevent discharge successfully performed
- Electronics connectivity checks successful for all the chambers installed
- Optical readout fibers mapping checked
- Noise level assessed for all the chambers installed
- DCS and DAQ fully operational in local mode



Plan for commissioning after COVID-19 stop

- Complete integration of DCS, DAQ, DQM in central CMS system
- Full configuration of the frontend and backend electronics
- High Voltage training of the chambers in final gas mixture $\mathbf{Ar/CO_2\ (70/30\%)}$
- Latency and efficiency scans to determine optimal working point (combined with CSC sub-detector)

GE1/1 DCS: State of the Art

Detector Control System:

- GEM - DCS fully operative and tested in local mode
- Intense use of the GEM - DCS during the HV and LV testing for the GEM-foil HV training and front-end electronics test

Main GEM - DCS panel:

- HV and LV system monitoring

(detector status, HV and LV status, trending plots, etc.)

- Gas system monitoring

(gas mixture status, rack and flow status, etc.)

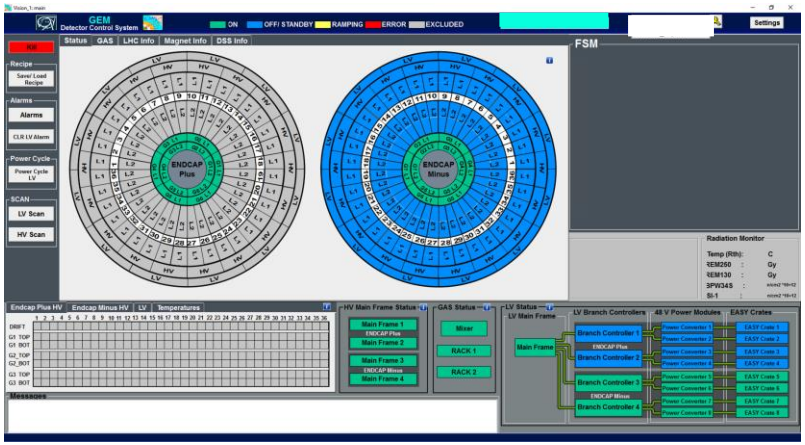
- RADMON system monitoring

(absorbed radiation dose monitoring)

- Temperature system monitoring

(electronics overheating monitoring)

- Alarms and Archiving



Main GEM - DCS panel

Finite State Machine:

- The FSM was added to prepare the system for the operation in central CMS DCS
- The final integration of the GEM DCS in CMS is planned for the end of the year

GE1/1 DAQ & DQM: State of the Art

Data Acquisition System:

- The GEM DAQ and SW architecture significantly rewritten since 2017 Slice Test
- The recent SW release scales to data taking (cosmic or physical) demands
- Many ongoing long-term projects towards the start of the Run-3 data taking: calibration and analysis suite, monitoring suite, online database, etc.
- First full-scale test: deployment during the Mid-Week Global Runs in September 2020

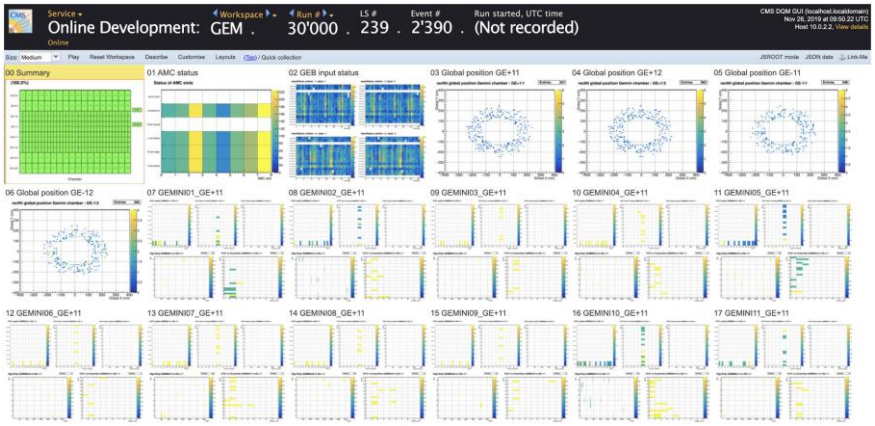
DAQ components

FMM	FED	FRL	EVM	RU	BU
39	642	422	1	71	17

Sub-System		State	FRL	FED	IN
TCDS	IN	Running	1	1	1
TRG	IN	Running	14	14	5
PIXEL	Out		0	0	0
TRACKER	Out		249	437	0
ES	Out		26	40	0
ECAL	Out		54	54	0
HCAL	Out		32	32	0
CASTOR	Out		3	3	0
SCAL	IN	Running	1	1	0
GEM	IN	Running	2	2	1
RPC	Out		3	3	0
DT	Out		9	9	0
CSC	IN	Running	18	36	36
DAQ	IN	Running	0	0	0
DQM	IN	Running	0	0	0
DCS	IN	Connected	0	0	0
CTPPS	Out		2	2	0
CTPPS_TO	Out		8	8	0

Data Quality Monitoring:

- The inclusion of GEMs into the global runs entails also the need of monitoring the quality of data collected as well as the performance of the detectors



Conclusions

In the coming years, the CMS Muon system will go through a series of upgrades in order to cope with the foreseen increasing of LHC performance

GEM technology has been selected for the upgrade of the first disk of the CMS Muon end-cap through the GE1/1 project, and for the future GE2/1 and ME0 project

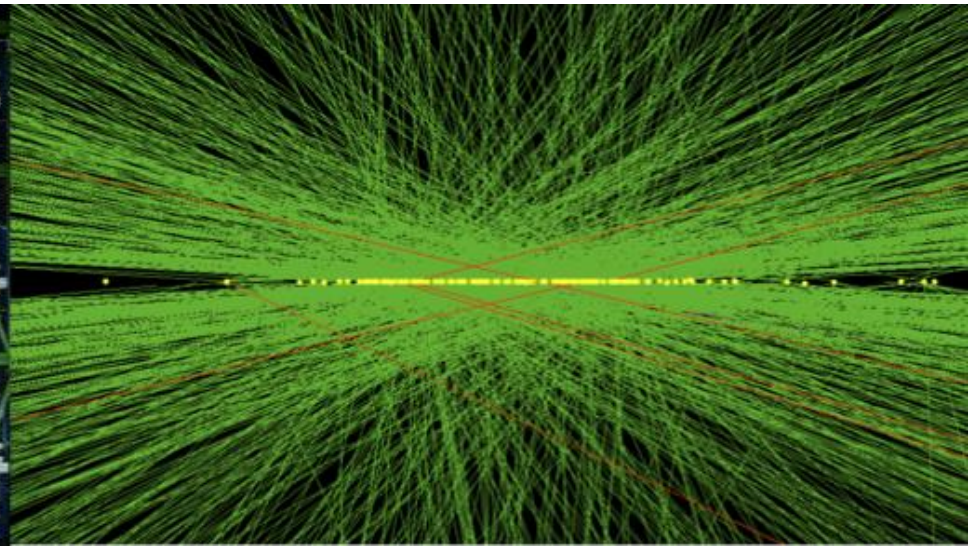
GE1/1 detector mass-production:

- **Successful and on-time production of both endcaps (>144 GE1/1 detectors) from Sept. 2017 to Dec. 2018**
- **72/72 GE1/1 super-chambers have been fully assembled and validated**
- **Complex mechanics + electronics required many changes in final assembly and quality control procedures**
- **We gained valuable experience for the future GE2/1 and ME0 upgrade project**

GE1/1 installation and commissioning:

- **GE1/1 station successful installed in CMS from July 2019 to Sept. 2020**
- **A first "pre-commissioning" phase already took place for the negative end-cap**
- **Commissioning activities fully resumed after the COVID-19 stop**

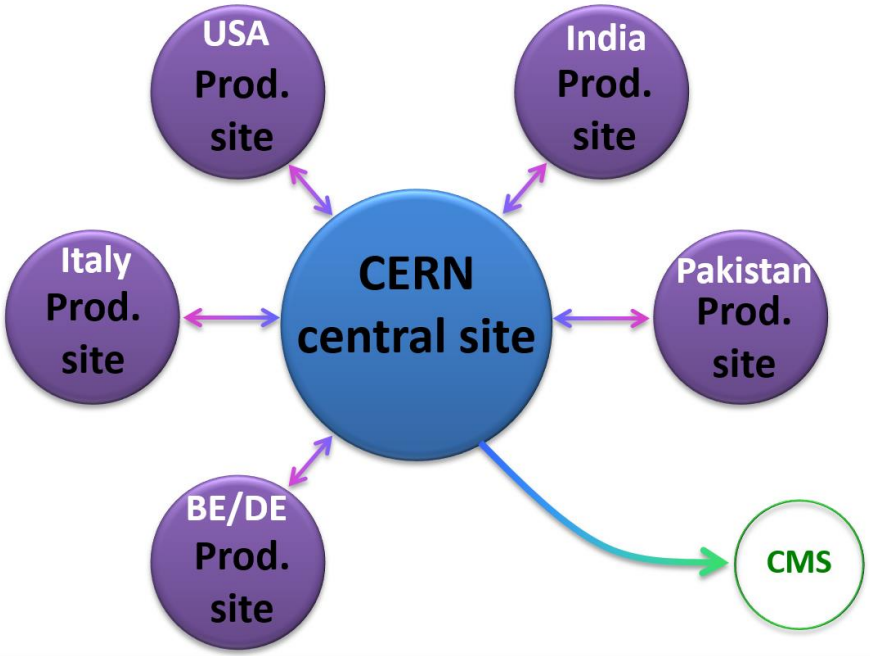
BACKUP SLIDE



GE1/1 Production Site

→ **Distribution of the production in various sites:**

- **Share the effort with CMS - GEM institutes**
- **Generate a large community of GEM experts**
- **Equip production sites with infrastructure, tooling and knowledge for GE2/1 and ME0 productions**



→ **2-years training program**

- **Using same procedure**
- **Using same infrastructure**
- **All Quality Control deliverables validated by the production community**

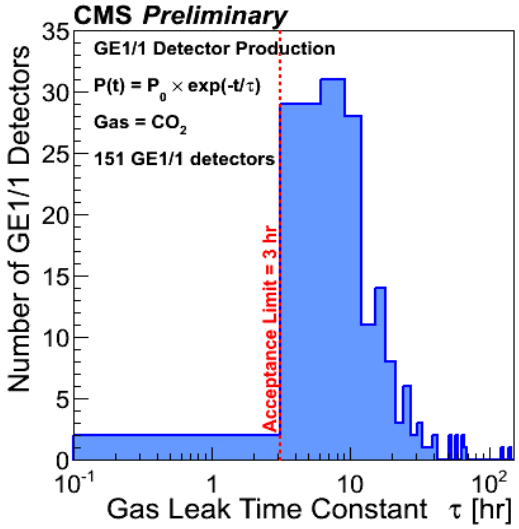
Quality controls up to QC5: summary

CERN
- QC1 — Material Inspection
- QC2 — GEM-foils Test

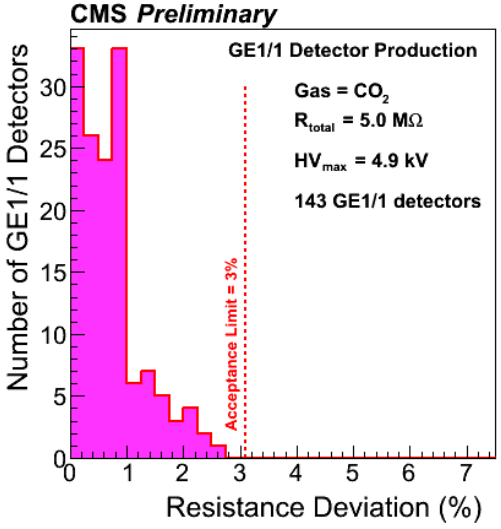
Production sites
- Assembly
- QC2 — GEM-foils Test (fast)
- QC3 — Gas Leak Test
- QC4 — HV Test
- QC5 — Gas Gain Calibration

CERN
- QC6 — HV Stability Test
- QC7 — Electronics Connectivity Test
- QC8 — Cosmic Test

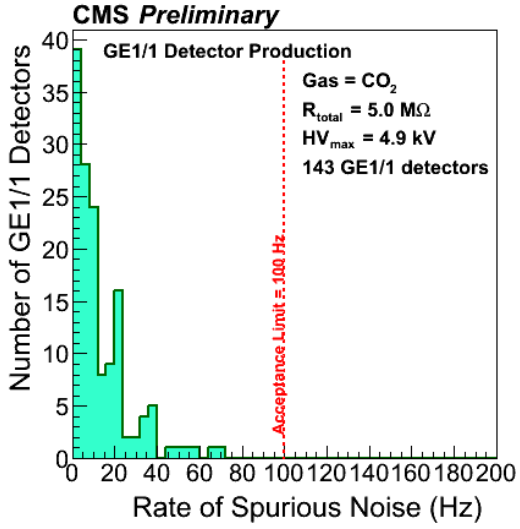
QC3 - Gas Leak Test



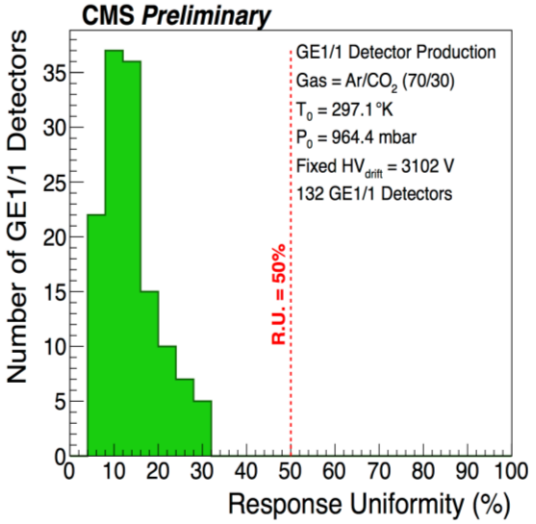
QC4 - HV Integrity



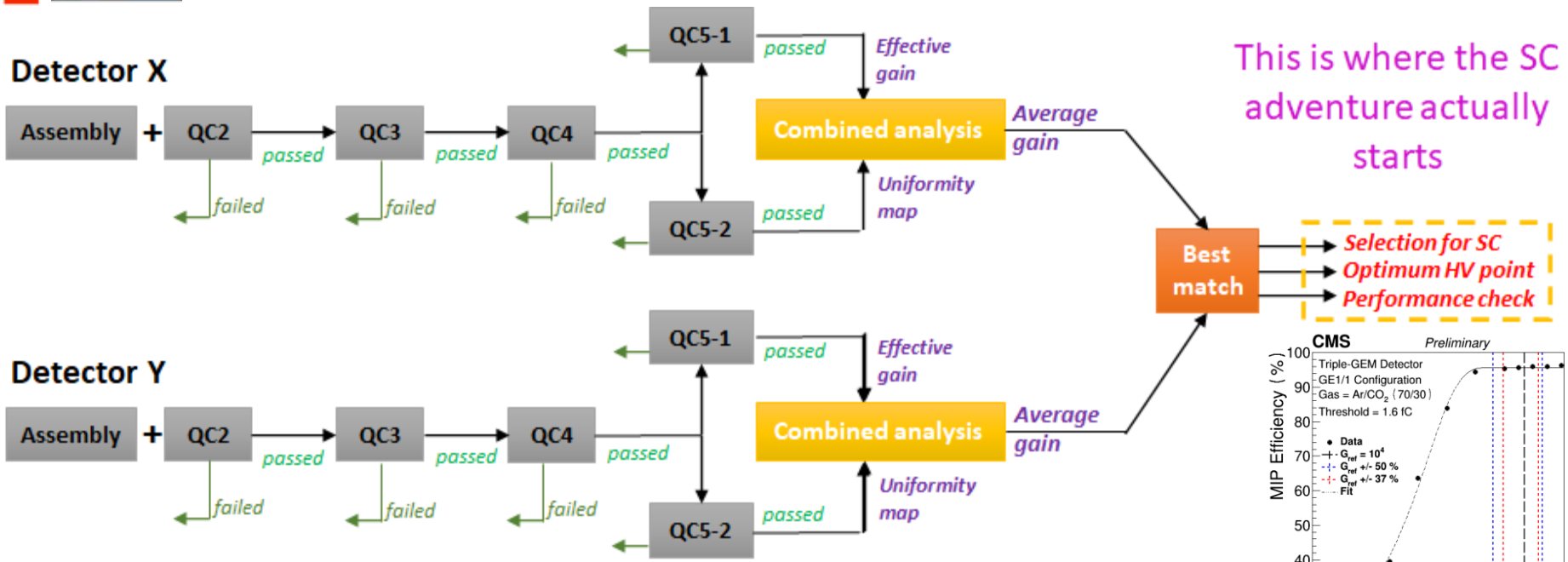
QC4 - Intrinsic Noise Rate



QC5 - Gas Gain Uniformity

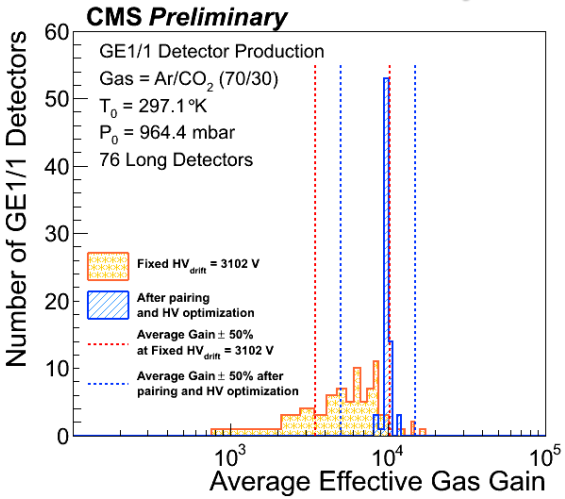


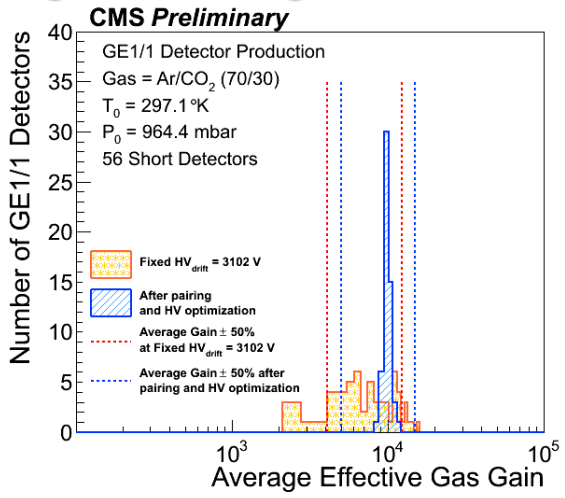
QC5 results and super-chamber pairing



This is where the SC adventure actually starts

QC5 summary: average effective gain





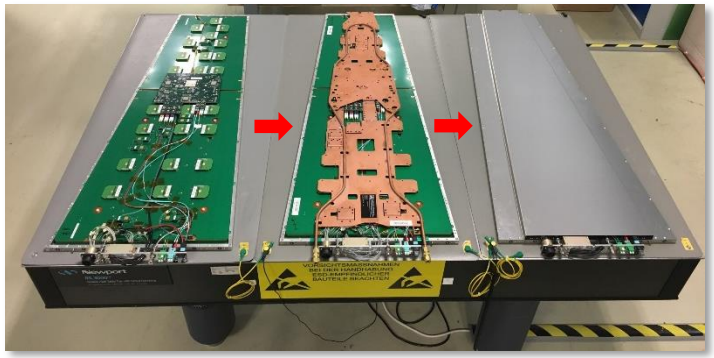
Chambers Pairing

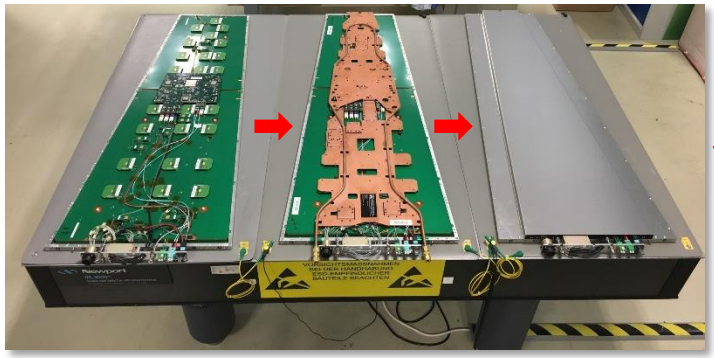
- **1 super-chamber = 2 triple GEM detectors**
- **At P5 common HV power supply**
- **HV point optimization:**
  - **→ Chambers sorted by gain at standard HV**
  - **→ Adjacent chambers paired**

GE1/1 Detector QC Overview

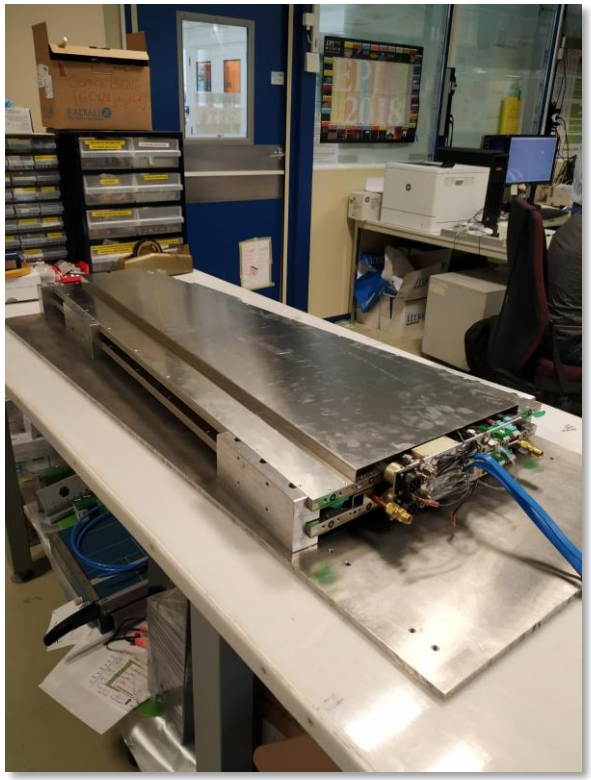
GE1/1 Super-Chamber Assembly

GE1/1 CHAMBER LAYER 1





GE1/1 CHAMBER LAYER 2



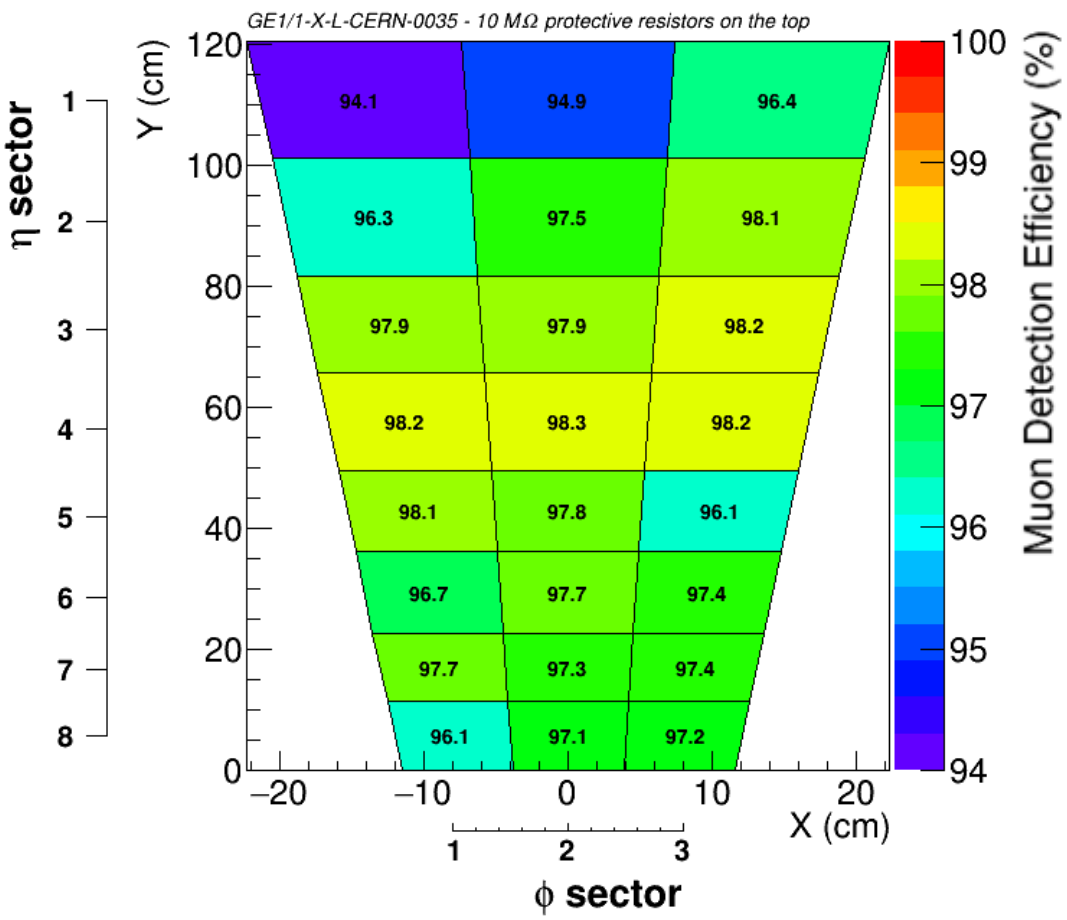
SC ready for the Cosmic Test

A GE1/1 Super-Chamber is obtained by mounting one single chamber onto the other through a custom alignment jig, by fixing the appropriate mechanical supports and interconnecting the two cooling systems.

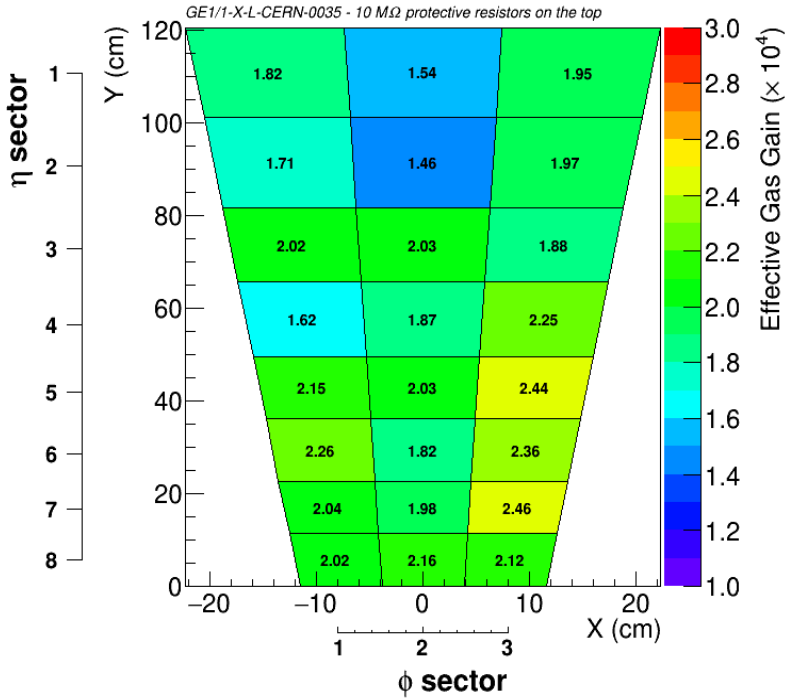
Cosmic Test Result

Results for some of the detectors tested:

Example of Efficiency per



Example of Gas Gain per readout partition

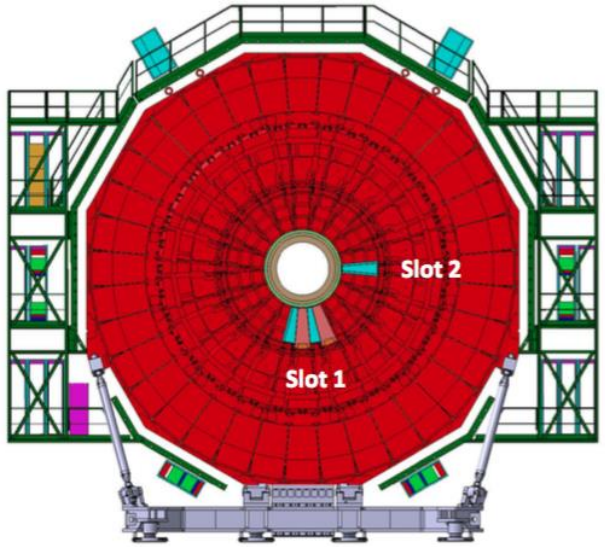


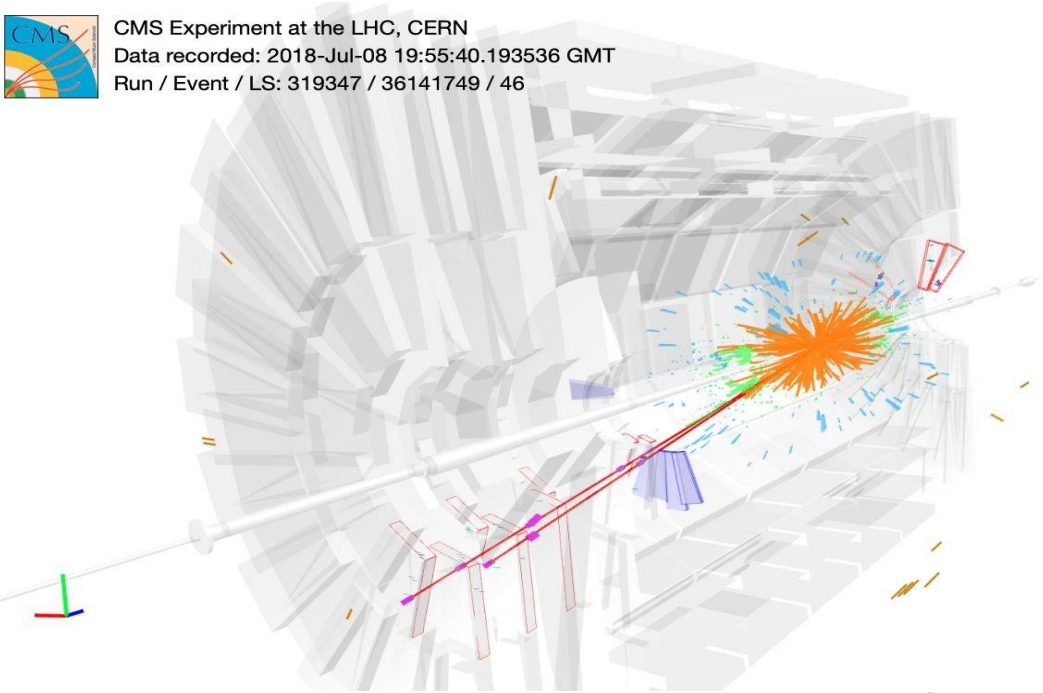
Possibility to generate the *efficiency maps* for all detectors and identify possible weak regions (and correlate with the *gas gain maps* obtained in QC5)

GE1/1 Slice Test Overview

A demonstrator with 5 SuperChambers (or *GEMINI*) took place in 2017-18 with the goals to:

- **Proving the system's operational conditions**
- **Developing the integration into the CMS online system**
- **Start acquiring installation and commissioning expertise**



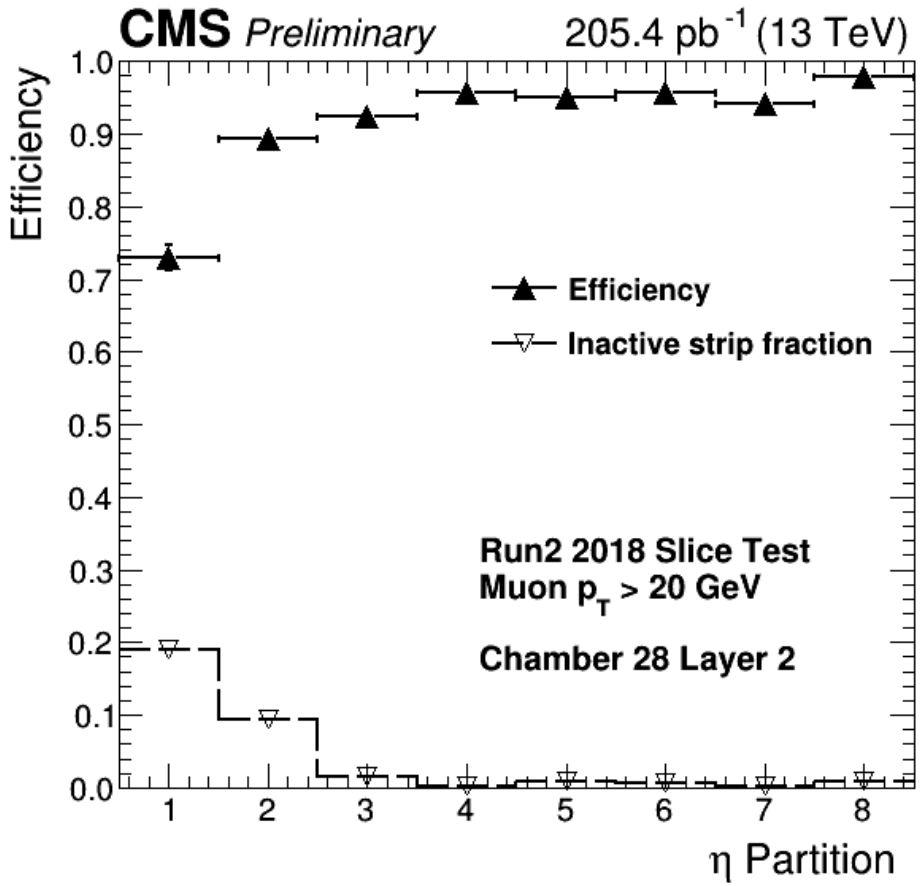


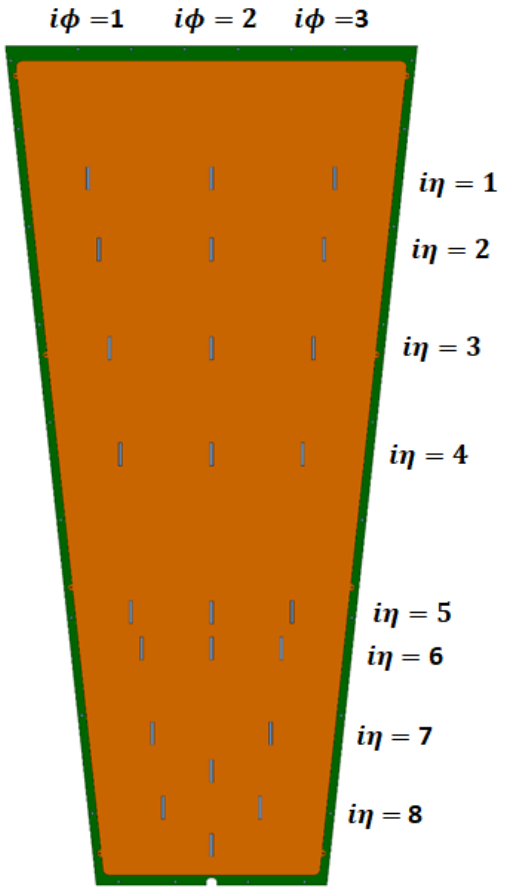
LHC run2 2018C p-p collision event display showing two muons (red lines), associated with hits on one of the five GE1/1 slice test super-chambers (blue trapezoidal boxes) at station 1 of the endcap muon system. The antimuon ($p_T = 30.11\ GeV/c^2, \eta = -1.956$) and muon ($p_T = 53.597\ GeV/c^2, \eta = -1.993$) has a combined invariant mass of $3.011\ GeV/c^2$ (J/Ψ *meson particle*).

GE1/1 Slice Test Result (I)

Efficiency results for a super-chamber:

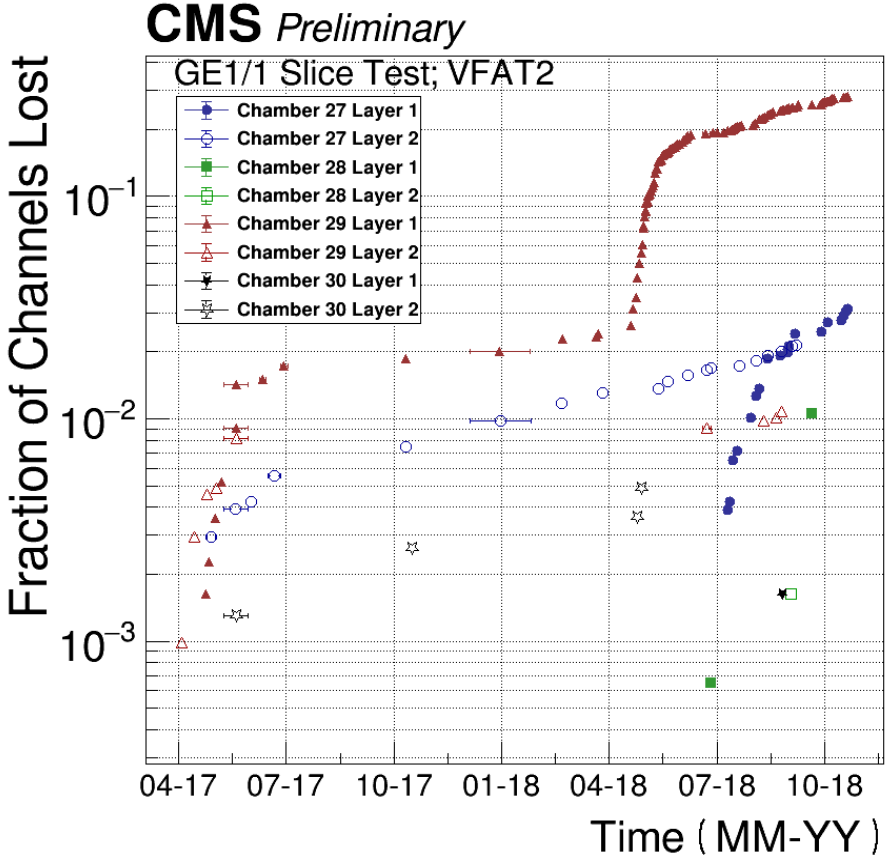
- Detection efficiency of super-chamber 28 layer 2 as a function of η partition
- Global muons with $p_T = 20\ GeV/c^2$ extrapolated to GEM GE1/1 chambers





GE1/1 Slice Test Result (II)

Damages on front-end readout channels



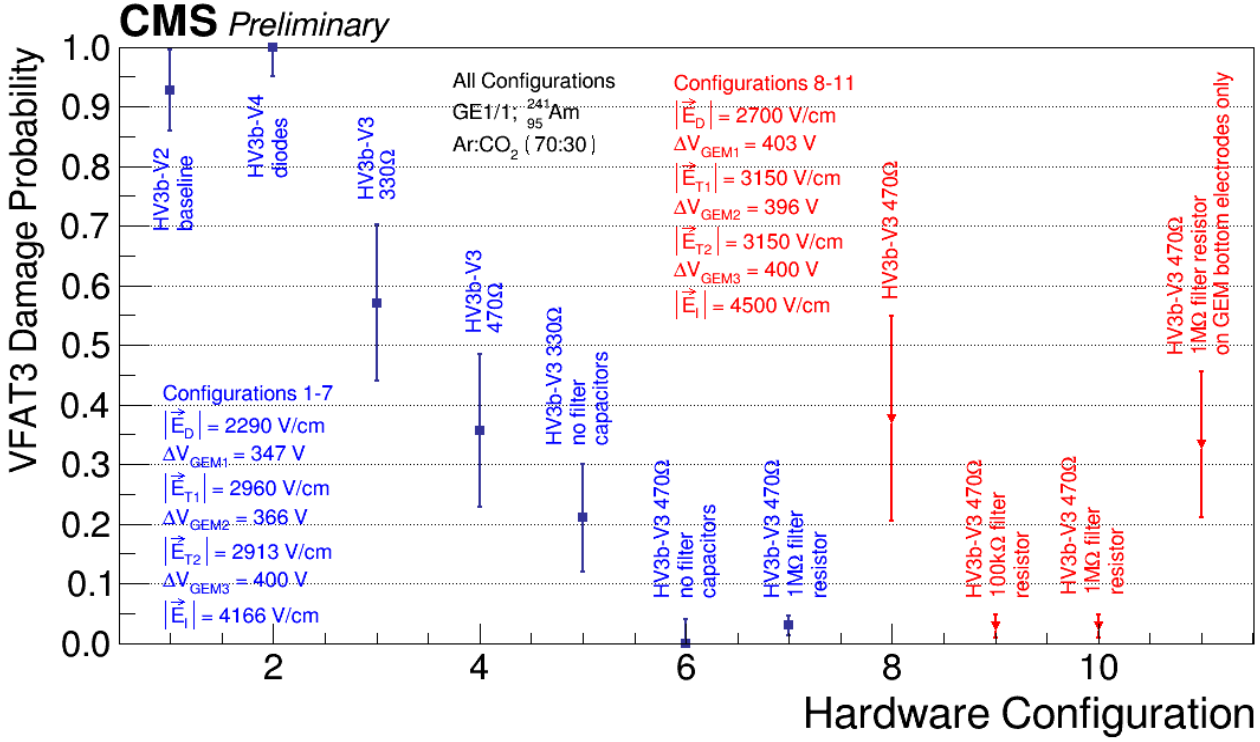
- High Voltage discharges across the GEM-foils
- Chance of having discharges propagating to the readout
- Energy of the discharge can damage front-end electronics readout channels
- Slice test electronics: $> 90\%$ damage probability after propagated discharge

N.B. : Number of dead channels depended on specific detector

VFAT hybrid for GE1/1 detectors

Front-end readout electronics improvement

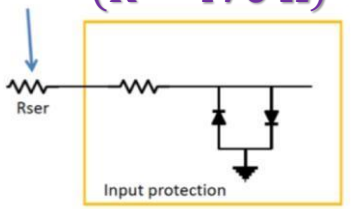
- **On-chamber front-end chip = VFAT3 hybrid**
- **Study to minimize probability of discharges damaging channels: additional resistors or diodes as channels input protection**

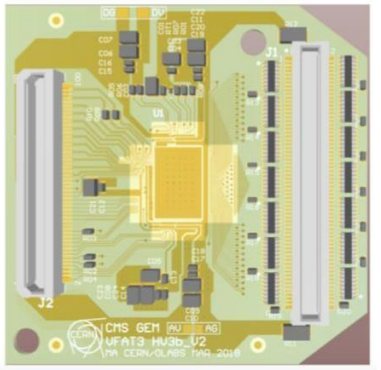


HV3b - V3

Ext. input protection

(R = 470 Ω)





Final front-end electronics chip: VFAT3 (HV3b_v3) with 470Ω input protection resistor
From original > 90% damage probability after a propagating discharge to ~3% !!!