ULB

The CMS ME0 GEM detector for the HL-LHC

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for the CMS Collaboration

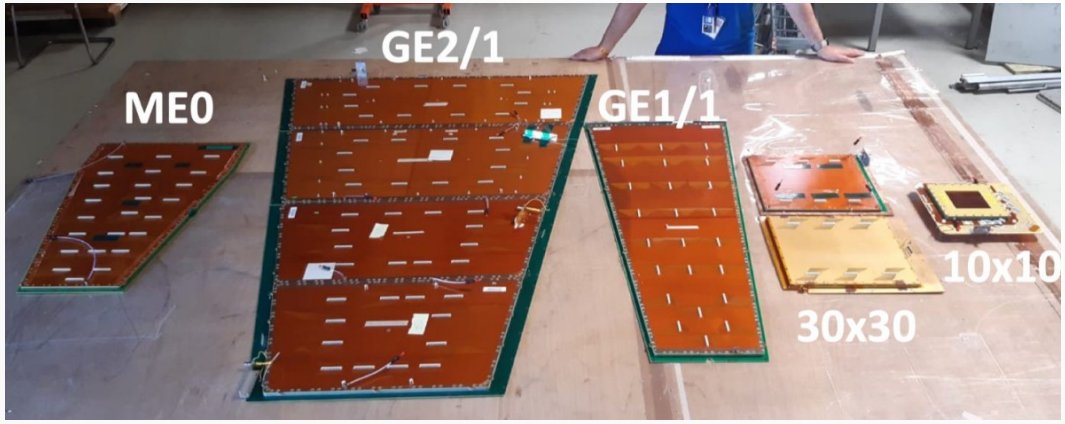
Introduction

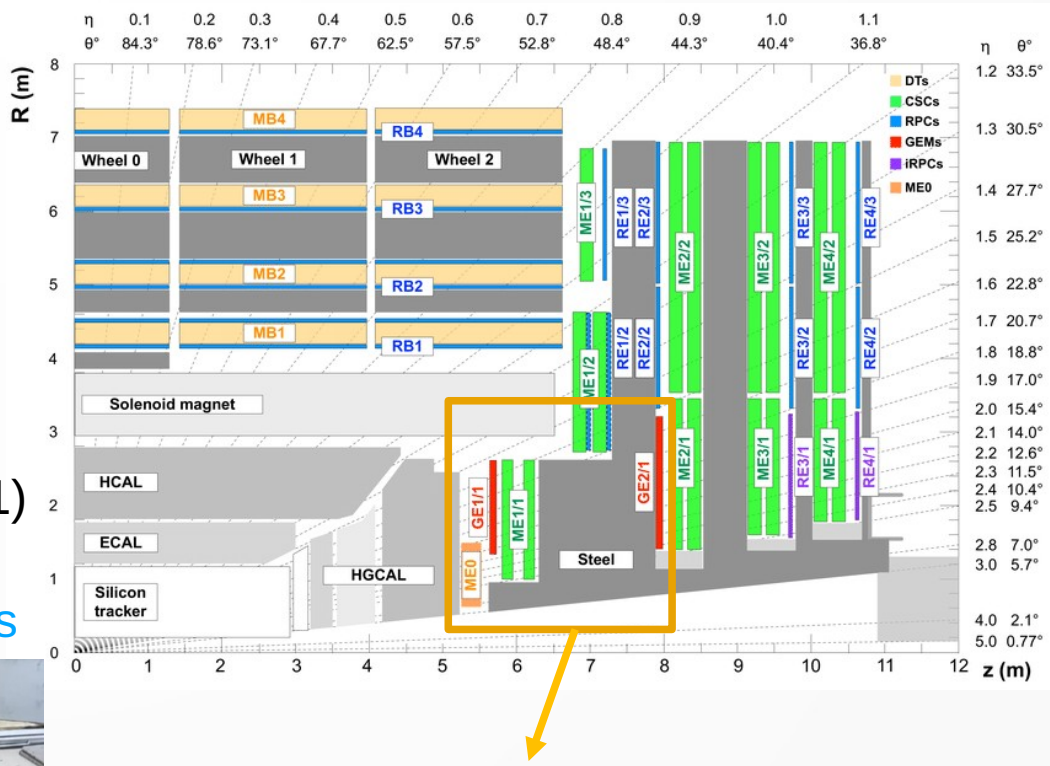
CMS (Compact Muon Solenoid):

- general purpose experiment at LHC
- major upgrades planned to handle higher instantaneous luminosity

GEM muon system:

- triple-GEM technology
- Ar/CO_2 (70/30%) gas
- background rates from few kHz/cm^2 (GE2/1) to 150 kHz/cm^2 (ME0)
- operational: full GE1/1 + 7 GE2/1 chambers





GEM upgrade: 3 new detectors based on triple-GEM technology (GE1/1, GE2/1, ME0)

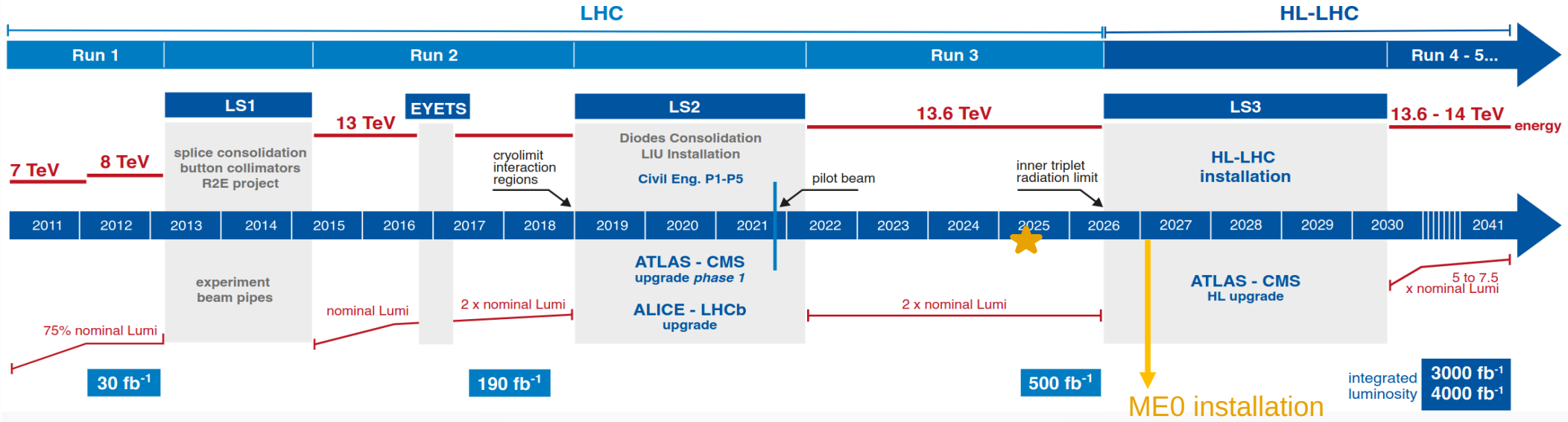
→ complement Cathode Strip Chambers (CSCs) in forward region, improving muon identification

→ increase muon system acceptance to |η|=2.8

Introduction

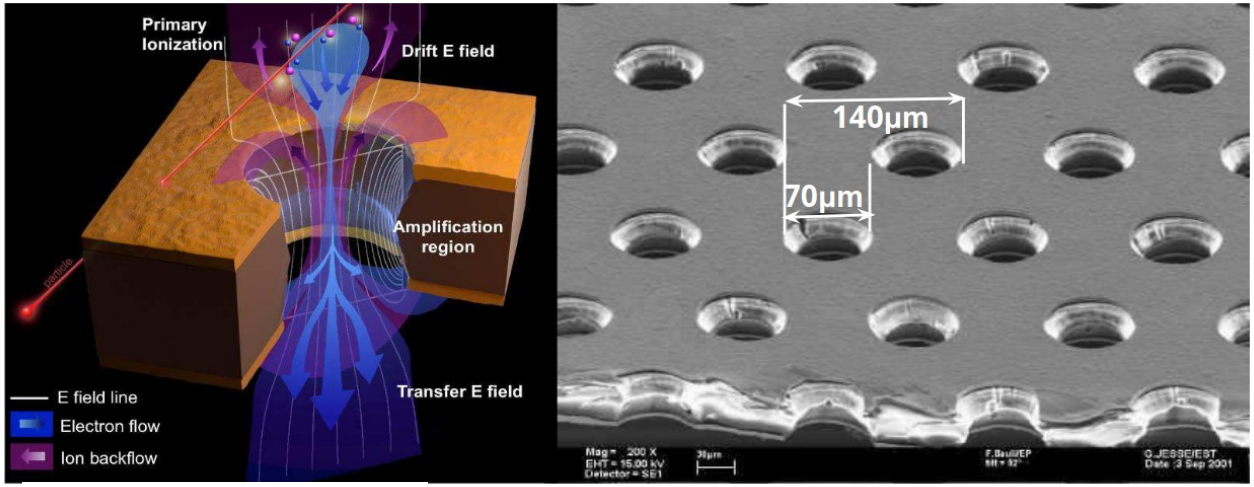
HL-LHC (High Luminosity LHC):

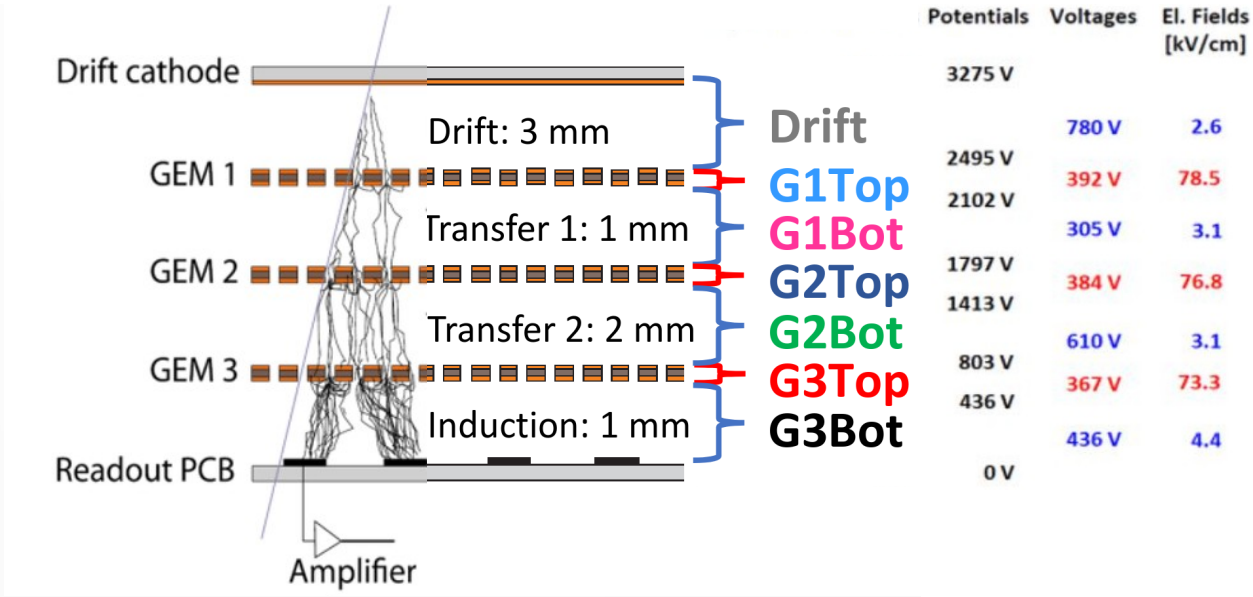
- instantaneous luminosity of up to 7.5 times the nominal ($1x10^{34}$ $cm^{-2}s^{-1}$) LHC value
- up to 200 interactions per bunch crossing every 25 ns
- collecting up to 3000-4000 fb^{-1} of data
- at nominal energy of 14 TeV
- challenges for ME0: work at high particle rate and survive harsh radiation environment



CMS triple-GEM technology

- GEM foils, consisting of thin Kapton insulator with a copper layer on both sides
- Voltage difference across foils, creating strong E field inside the holes
- Charge multiplication as electrons are accelerated by the E field when they pass through the holes and cause further ionization
- Electrons are collected on segmented readout plane
- 3 foils are used for a higher overall gain

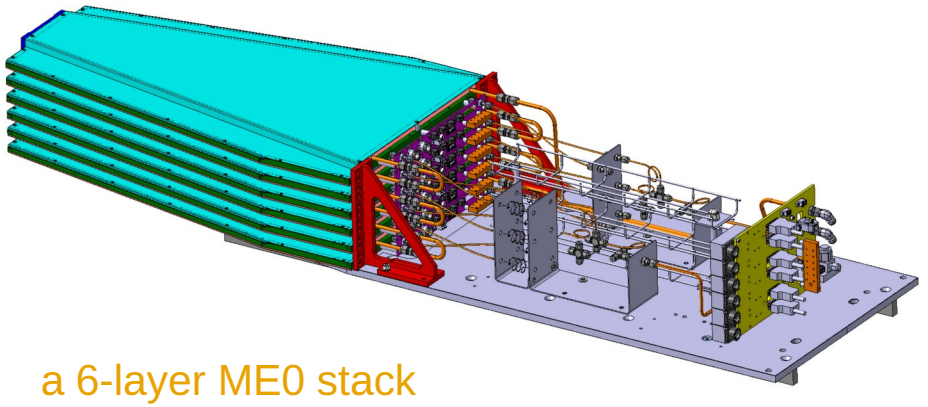




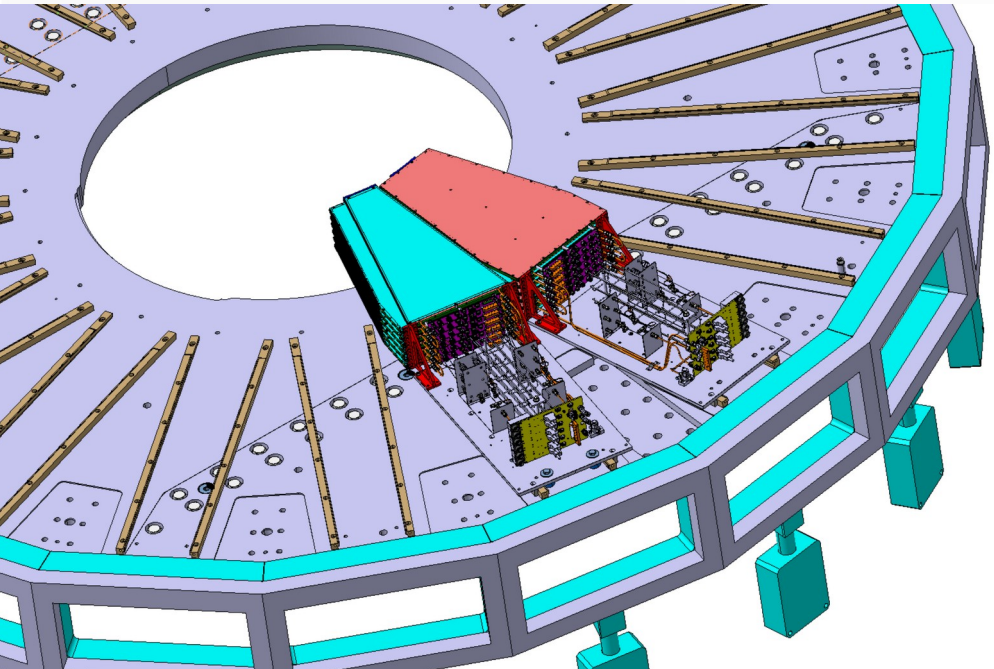
The ME0 detector

ME0 detector:

- 18 ME0 stacks per endcap (CMS has 2 endcaps)
- 6 layers (= modules) per stack
- coverage: $2.0 < |\eta| < 2.8$
- 216 ME0 modules needed (+15 spares)



a 6-layer ME0 stack

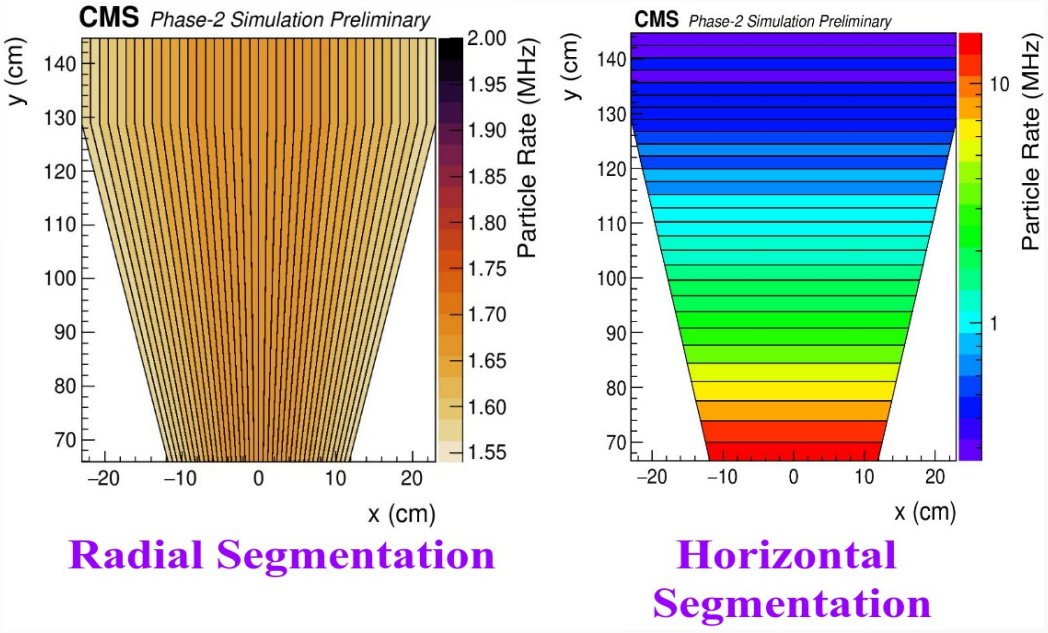


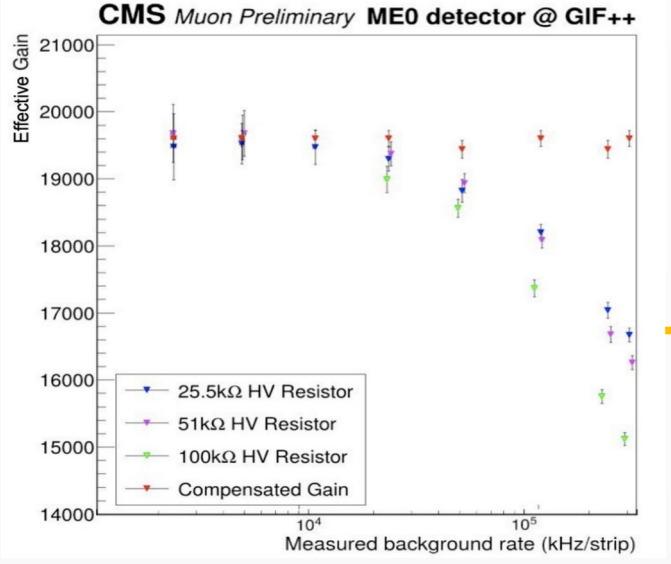
System requirements:

- efficiency > 97 % per module
- ≤ 500 μrad point resolution in φ
- 8 − 10 ns time resolution
- ≤ 15% gain uniformity
- work in high-rate environment: 150 kHz/cm^2
- survive harsh radiation environment: 7.9 C/cm^2
- discharge rate that does not impede performance or operation

The ME0 detector design

- Radial HV segmentation
- Same background particle rate per HV sector
- Uniform voltage drop (dependent on particle flux)
- Voltage compensation, by applying overvoltages to the electrodes

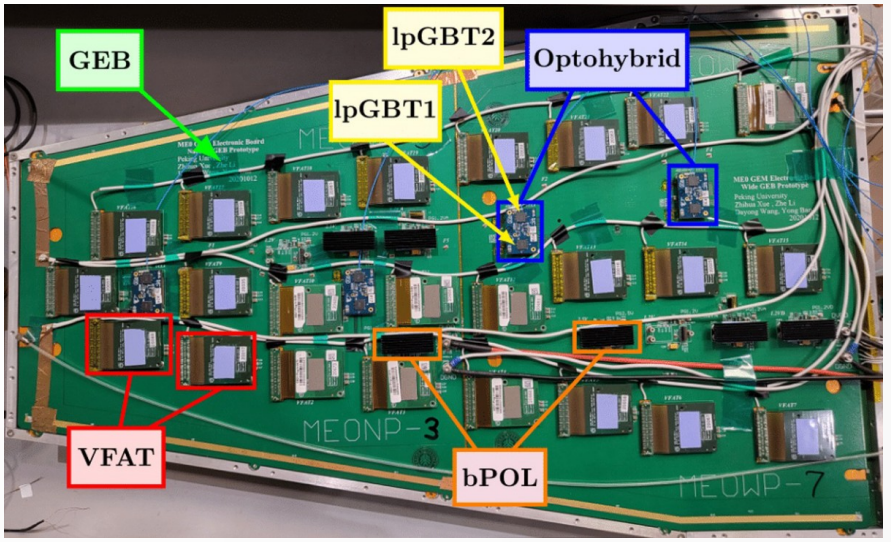




gain recovery demonstrated up to 2.2MHz/HV sector (= 280kHz/strip)

ME0 electronics

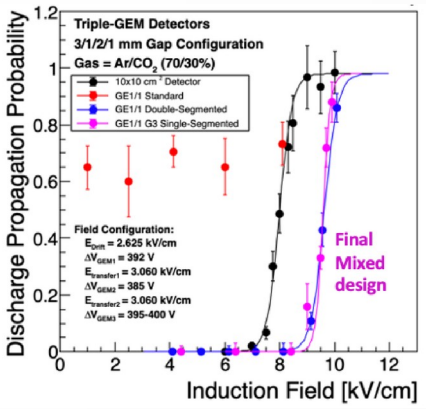
- **VFAT3 plugin cards**
  digitizes and reads out ionization signals
- **OH (Optohybrid)**
  sends data from 6 VFATs to back-end
  → **lpGBT (low power Gigabit Transceiver)**
  chips used for data processing on the OHs
- **GEB (GEM Electronics Board)**
  routes connections between VFATs and OHs
- **bPOL**
  DC-DC converters supplying voltage to front-end electronics

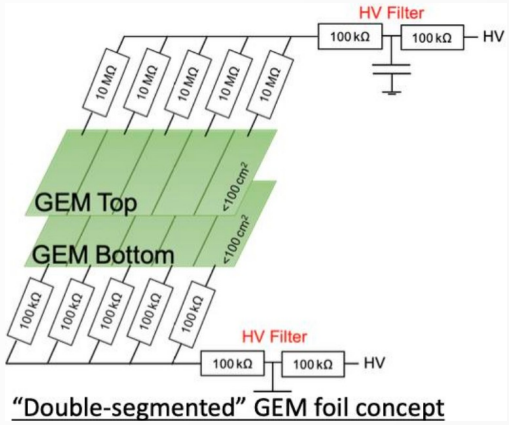


Lessons learned from GE1/1

Observed channel losses in GE1/1 slice test
→ traced back to **discharges** propagating to the readout

Solution: **double segmented GEM foils**, but keep GEM3 foil (closest to readout strips) single segmented to avoid cross-talk

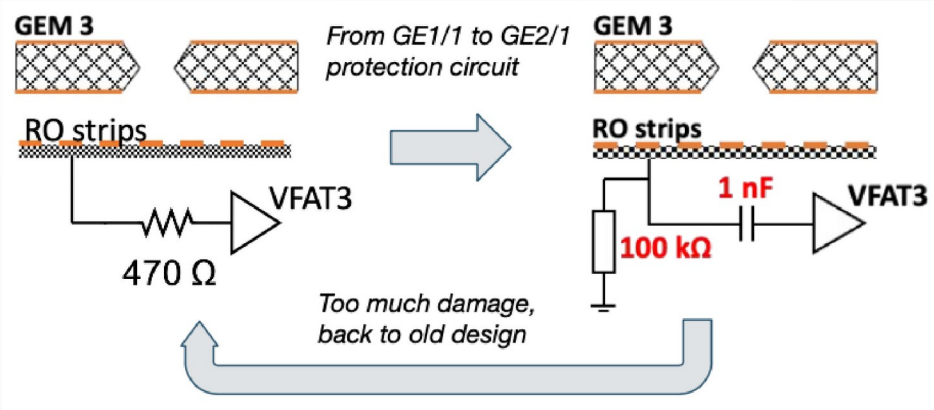




"Double-segmented" GEM foil concept

In addition: many different **protection circuits** were studied for GE2/1

- solution tested successfully in the lab, but again channel loss during test beam
- back to old design, which worked under background radiation
- noticed electronics resets in coincidence with discharges

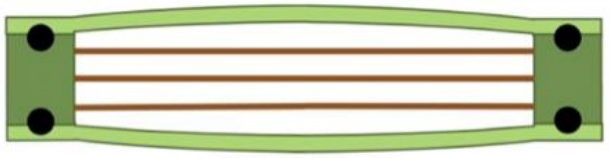


→ **resets traced back to be due to leakage current to VFAT GND**
Solution: **improved grounding** on readout board with copper bars

Lessons learned from GE1/1

GE1/1 Basin Effect: up to 40% variation in gain measured in gain uniformity tests during mass production

drift and readout PCBs bend, deforming gas gaps inside detector

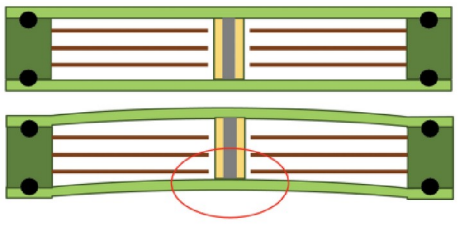


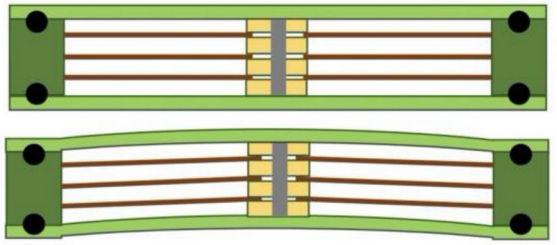
Solution:

- add pillars (for GE2/1 and ME0)
- not fixed for GE1/1: requires new foil mask with holes for pillars, PCBs with holes, ...

pillar (v1) maintains total gap size

pillar (v2) maintains individual gap sizes

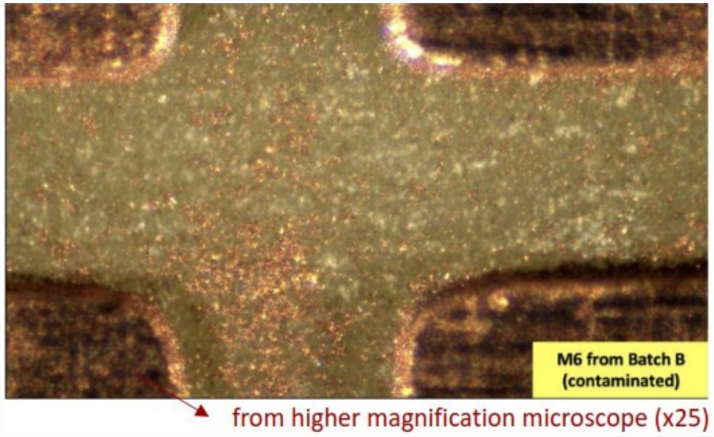




Lessons learned from GE2/1

During summer 2023 increasing problems when closing GE2/1 modules: **shorts** forming on GEM foils

- found **copper dust** on readout PCBs
- **no passivation** applied on drift and readout PCBs to protect against oxidation



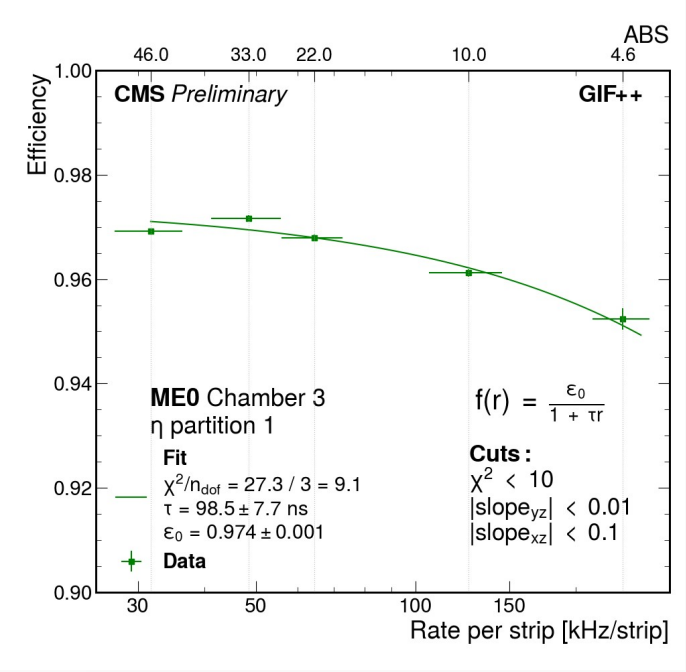
Solution for ME0:

- passivation applied on already produced ME0 PCBs
- reviewed PCB production procedure
- added microscope inspection of all boards

Performance

Rate capability:

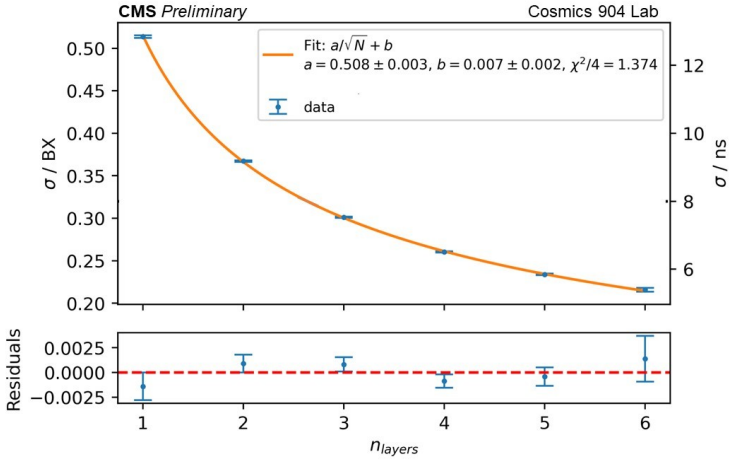
- **High rate capability** of micro-pattern gaseous detectors for small areas
- For global irradiation, voltage drop is successfully compensated by increasing voltage → proved by testing with muon beam and gamma-rays at GIF++ (CERN)
- Long flat plateau at **~97% efficiency** 👍
- However, **VFAT3 limits** were reached for ME0:
  - measured VFAT3 dead time 400 - 1000 ns corresponds to inferred dead time τ of 98.5 ns to 182.2 ns which is reduced by the different cluster sizes of muon hits (~3) and background hits (~1)
  - max. expected rate (high-η) ~150 kHz/cm² ≈ 180 kHz/strip
  - tested up to ~255 kHz/strip → 2.5% efficiency loss
  - requiring at least 4 layers for segment reconstruction →0.5% loss 👍
  - **caution:** Fluka simulations come with large uncertainty typically one uses a safety-factor 3...☹️



Performance

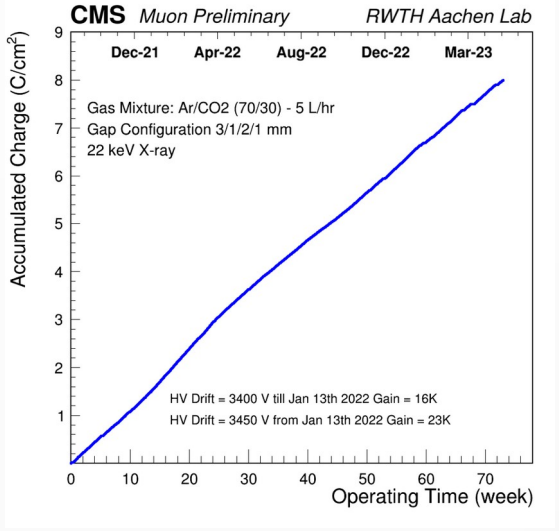
Timing:

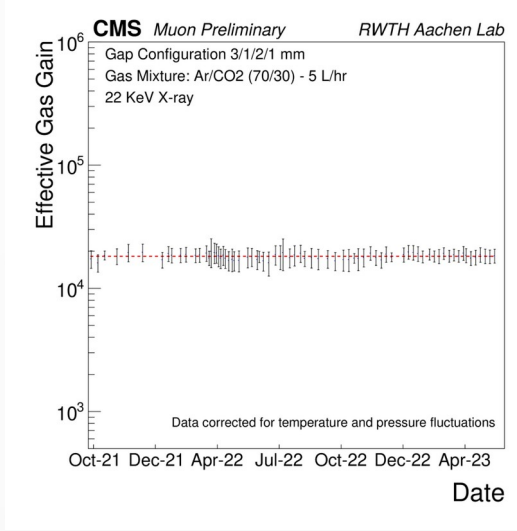
- Studied with cosmic rays in the lab and under background irradiation at GIF++
- Scales with 1/√N layers
- Comparable resolution for 5 layers in the lab and at GIF++
  → **6 ns** 👍



Longevity:

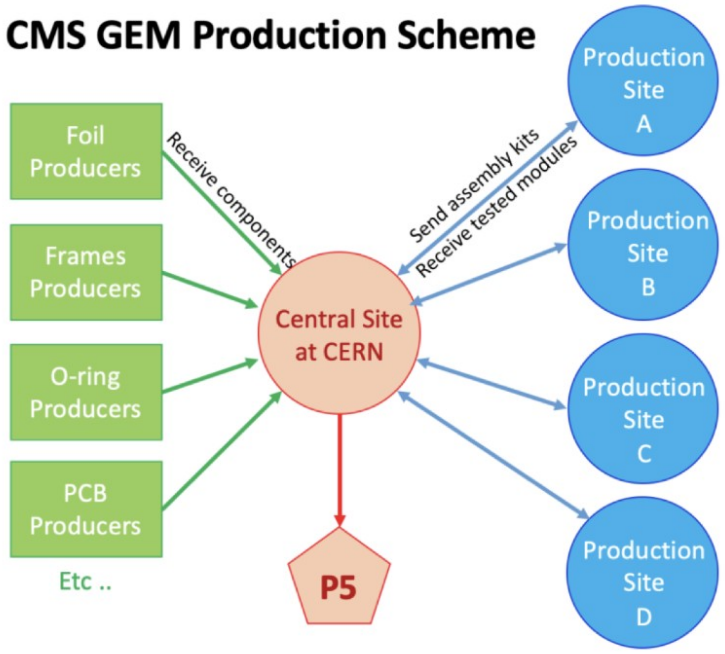
- Reached expected accumulated charge (safety factor = 1) at hottest point (high-η) of 8 C/cm² in ~1.5 years
- Gas gain measurement corrected for temperature and pressure shows **stable performance** 👍



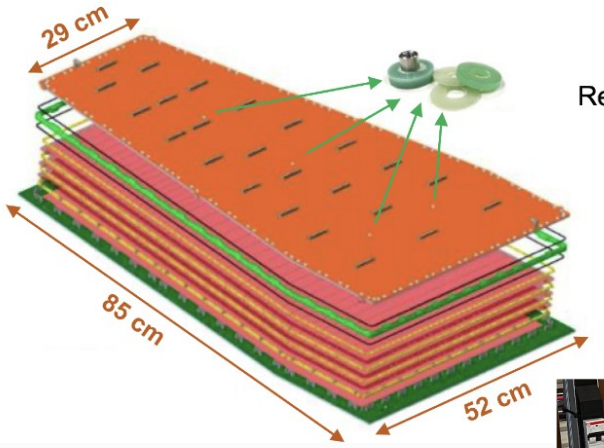


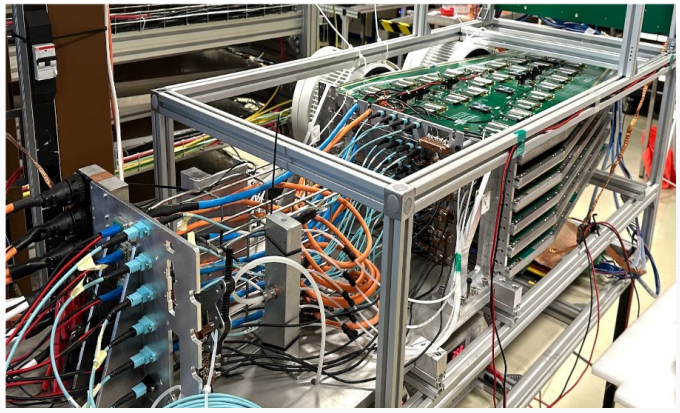
Production

Distributed assembly of ME0 modules:



- 1 production site at CERN (with double capacity)
- 3 production + 1 QC sites in EU (Gent, Bari, Frascati, and Aachen)
- 1 production site in China (PKU)
- 2 production sites in India (Panjab & Delhi)



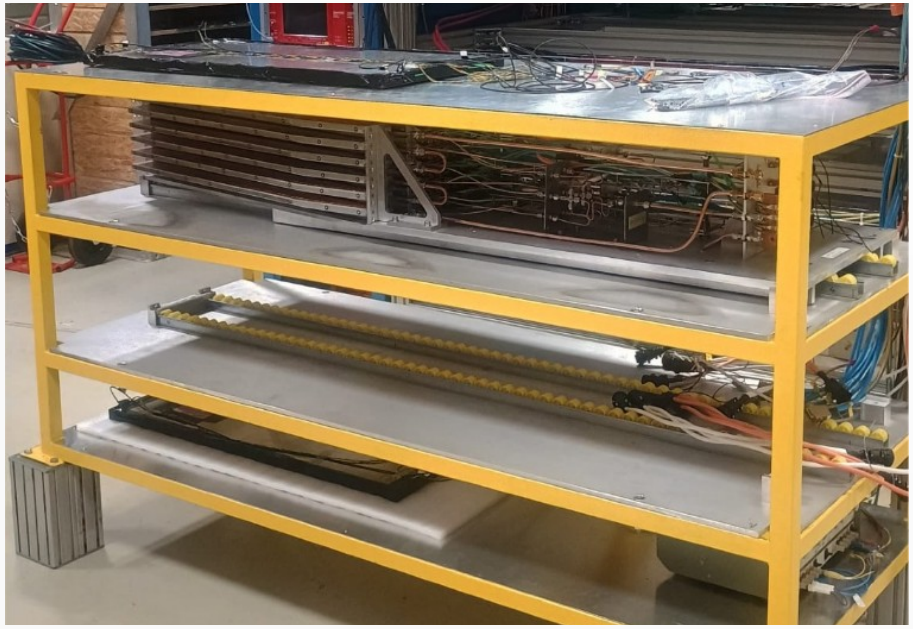


Then, the modules are “dressed” at CERN site with electronics, cooling plate, cables, etc. and assembled into stacks of 6 modules.

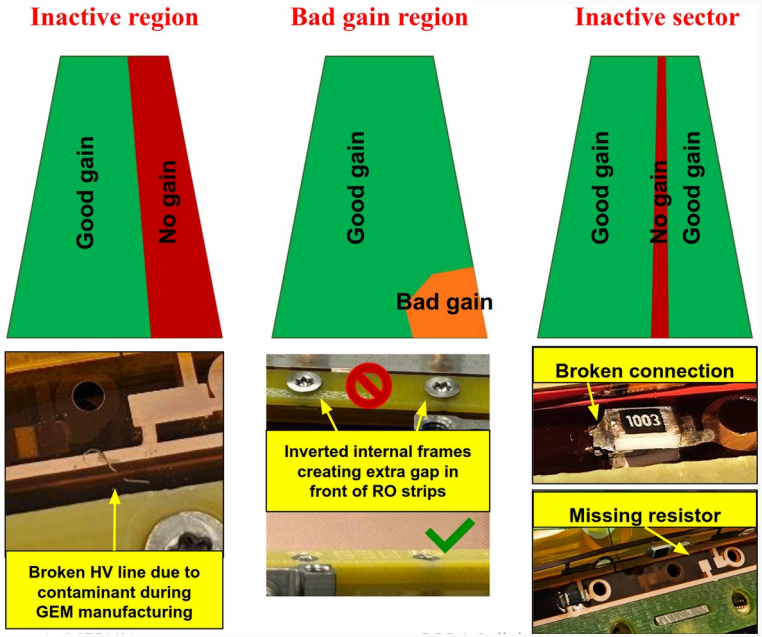
Validation

Modules tested for:

- gas leaks → monitor internal pressure
- HV linearity → monitor V vs I (up to 150% of nominal V)
- effective gain
- response uniformity
- HV stability → trip limit > 550V and discharge monitoring at high V
- electronics connectivity



Examples of issues found thanks to QC:

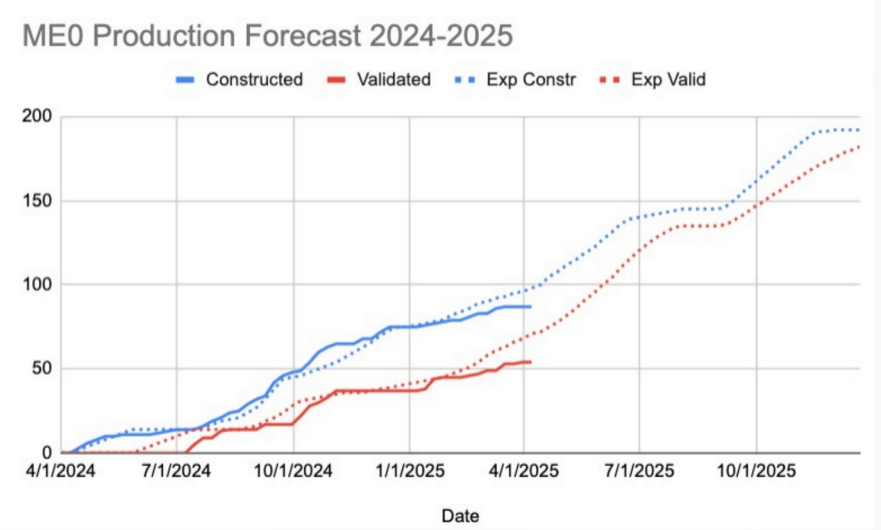


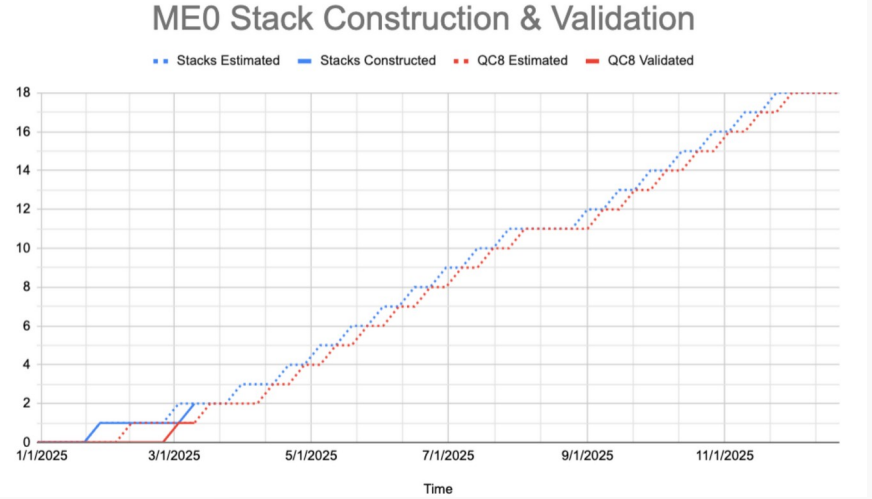
Stacks tested using cosmic stand:

- full configuration and operation as close as possible to situation of cosmic data-taking at CMS
- scintillators covering almost entire ME0 area
- check noise, efficiency, timing, and their uniformity over the area and vs. HV

Production & validation status

- Module production is ongoing smoothly
- Stack production started
- Cosmic stand for validation up and running
  → first stack looking good
- Expected to produce full first endcap
  (18 stacks) in 2025!





Summary

New **ME0 GEM detector** will be installed in CMS in 2 years from now,

- complementing Cathode Strip Chambers (CSCs) in forward region, **improving muon identification**
- **increasing muon system acceptance** to |η|=2.8

Many **lessons learned** during design and production of existing GE1/1 and GE2/1 GEM detectors

ME0 showing **good performance** in test beam studies

ME0 **production ongoing** smoothly!