The CMS Muon Endcap (ME0) GEM Detector

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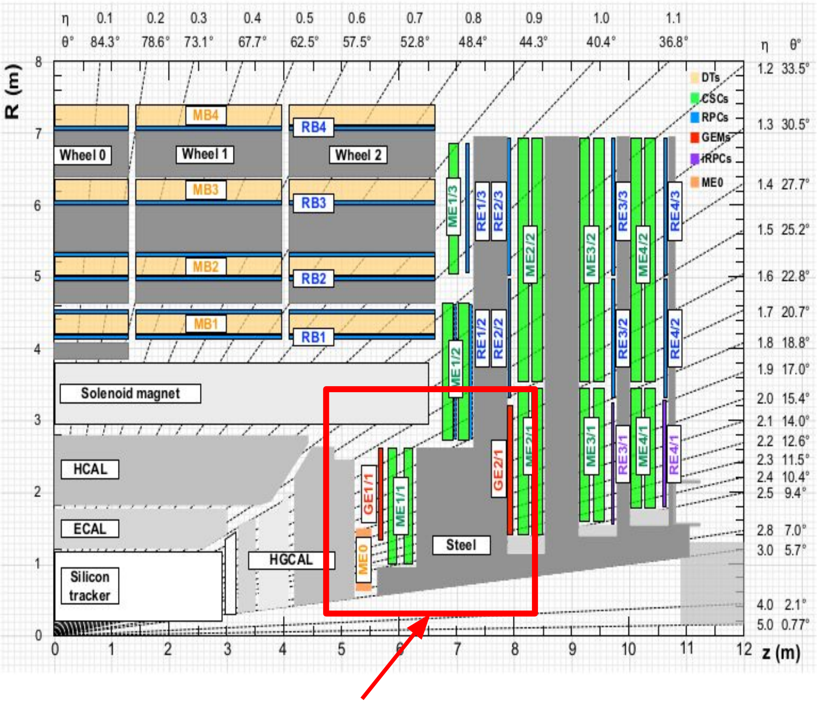
Introduction

CMS (Compact Muon Solenoid)

- ➢ General purpose experiment at the Large Hadron Collider (LHC) at CERN.
- ➢ Measures proton-proton and heavy-ion collisions.
- ➢ Successfully running at 13.6 TeV, with an LHC luminosity exceeding 10^{34} cm^{-2} s^{-1} .

High Luminosity LHC (HL-LHC)

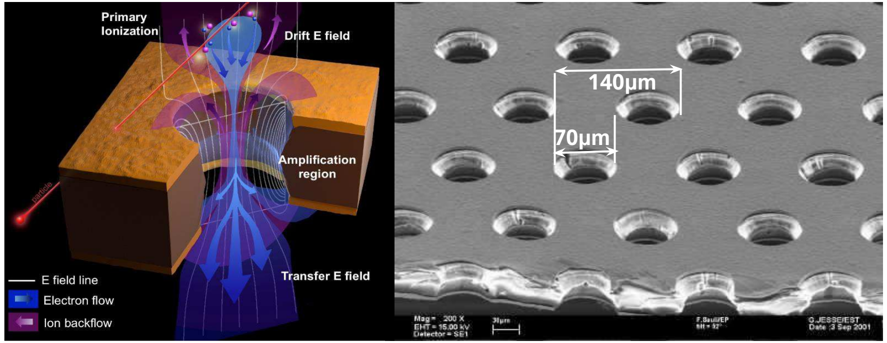
- ➢ ***Integrated Luminosity***: Tenfold increase compared to original design.
- ➢ ***Center of Mass Energy***: Increase to 14 TeV.
- ➢ ***Proton-Proton Interactions***: Up to 200 interactions per bunch crossing every 25 ns.
- ➢ ***Challenges***: Longevity validation and completion of muon chambers

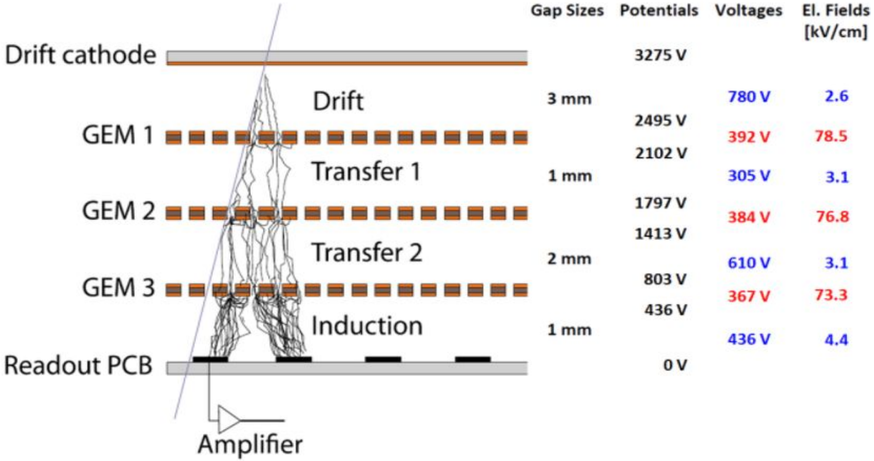


The GEM upgrade: three new stations GE1/1, GE2/1 and ME0 based on the triple-GEM technology

Introduction to GEM Technology

- **GEM Basics**
  - ➢ ***Construction***: Thin copper-clad Kapton foils with high-density holes (50 to 100 per mm²)
    - ○ The hole exhibit a bi-conical structure
  - ➢ ***Gas Mixture***: Typically filled with Ar (70%) and CO2 (30%)
  - ➢ ***Performance***:
    - ○ High rate capability (~MHz/cm²)
    - ○ Gain ~ 2 x 10^4
    - ○ Spatial resolution ~300μm
    - ○ Time resolution ~8 ns
- **Generations of GEM Detectors**
  - ➢ ***GE1/1 and GE2/1***: Complementing Cathode Strip Chambers (CSC) in the forward region
  - ➢ ***ME0***: Extending muon system acceptance to higher pseudorapidity regions

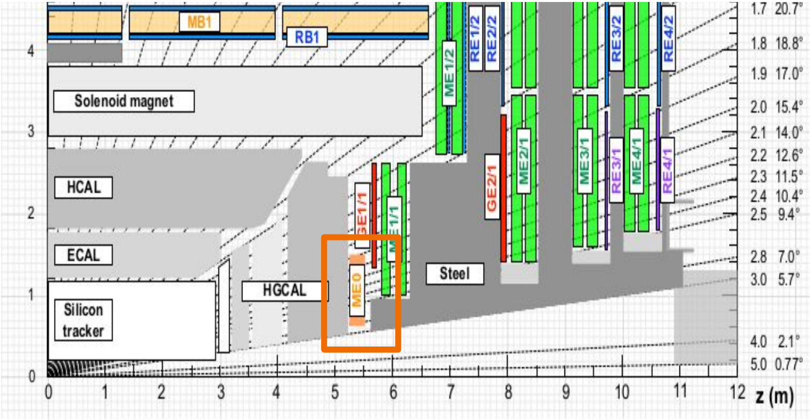


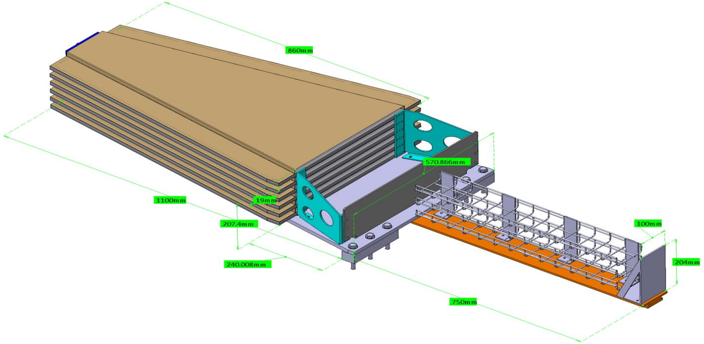


The ME0 upgrade

The label "*ME0*" uses '*ME*' to indicate Muon Endcap system and '*0*' to indicate that this new muon station is located in front of the original muon endcap system.

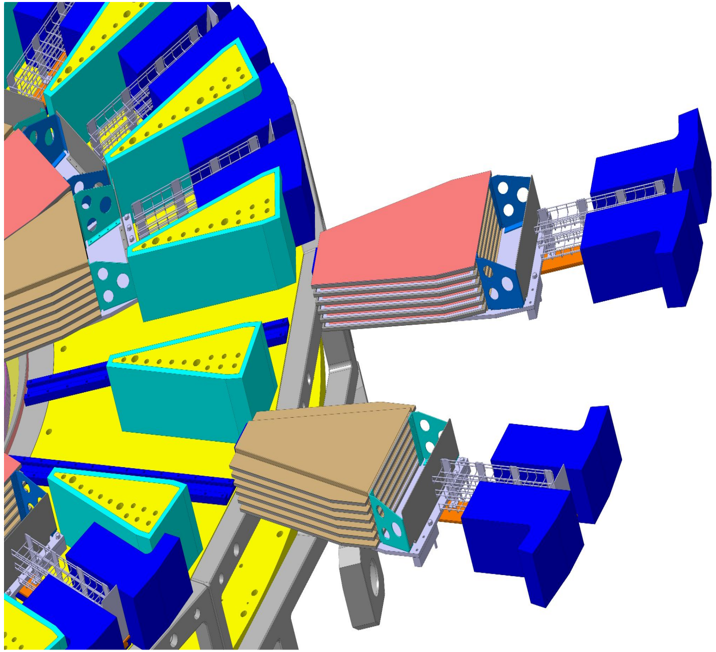
- **Motivation**
  - ***Current Detector Challenges***: Aging Infrastructure, detector efficiency, resolution and accuracy in higher collision rates and high-radiation environments.
  - ***Geometrical Acceptance***: The new ME0 detector is designed to increase the geometrical acceptance for muons, crucial for multi-muon final states and forward particle production..
  - ***Improved Muon Identification***: The ME0 GEM detectors will improve the trigger system, enabling more efficient and accurate event selection and event reconstruction.





ME0 Design and Construction

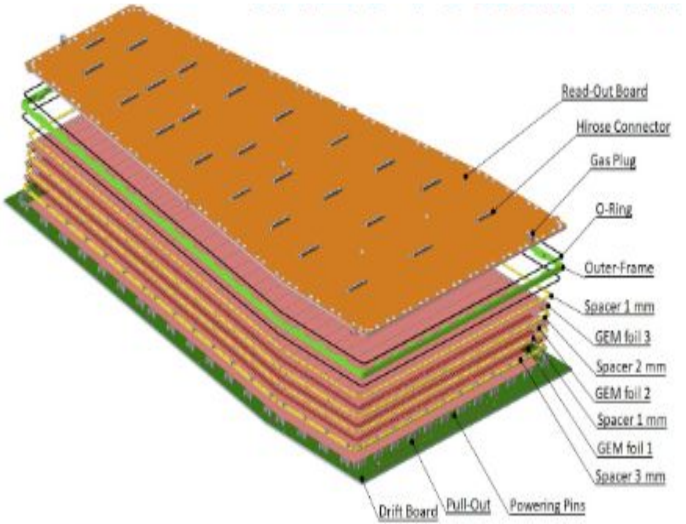
- **Design**
  - ➢ ***Structure***: Trapezoidal stacks in a planar ring with an inner radius of ~0.6 m and an outer radius of ~1.5 m.
  - ➢ ***Number of Chambers***: 216 triple-GEM modules (18 ME0 stacks per endcap)
  - ➢ ***Dimensions (active volume)***: Length: 78.8 cm (center line), Width: (23.6–51.4) cm, Hight: 1.8 cm
  - ➢ ***Radial distance from beam line***: 63 cm
  - ➢ ***Coverage***: $2.0 < |\eta| < 2.8$. Each stack covers $\delta\phi = 20°$
  - ➢ ***Installation***: The ME0 station will be installed in the endcap nose directly behind the new high-granularity calorimeter (HGCAL).
  - ➢ ***Readout Partitions***: Module segmented into 8 readout partitions in η and 3 in φ (24 total readout sectors).
  - ➢ ***Layers***: Six layers of triple-GEM chambers to form ME0 stack.



3D drawing of the insertion of two adjacent stacks of six ME0 modules (pink/brown) into the endcap nose.

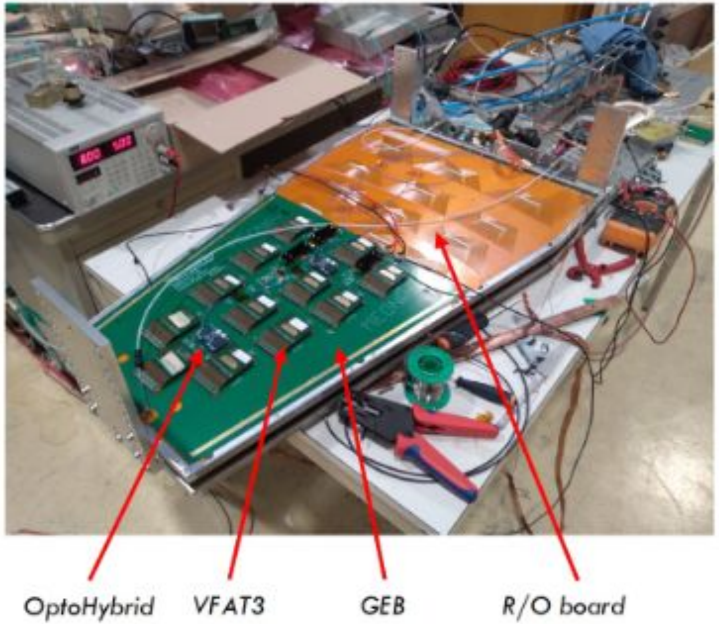
ME0 Performance Expectations

- **Performance Metrics**
  - ➢ ***Geometric Acceptance***: Maximum possible acceptance.
  - ➢ ***Efficiency***: Single-module efficiency of >97%, stack efficiency of 98.8%.
  - ➢ ***Rate Capability***: At least 150 kHz/cm².
  - ➢ ***Spatial (Angular) Resolution***: 390μm (≤500 μrad).
  - ➢ ***Timing Resolution***: 8–10 ns.
  - ➢ ***Gain Uniformity***: ≤15% across and between modules.
  - ➢ ***Longevity***: No gain loss after 840 mC/cm² of integrated charge. Survive harsh radiation environment: 7.9C/cm^2
  - ➢ ***Discharge Rate***: Minimal impact on performance or operation.



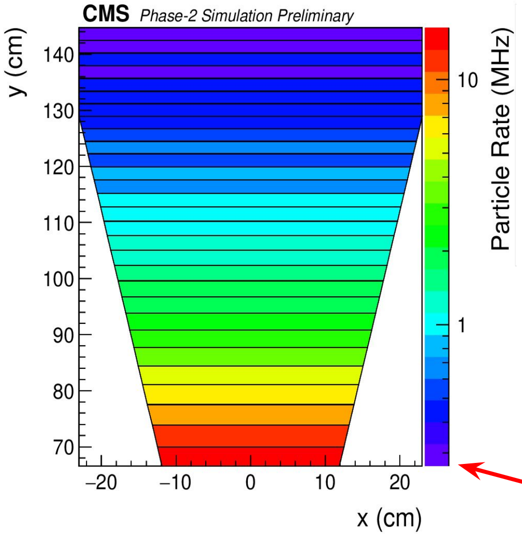
ME0 Electronic

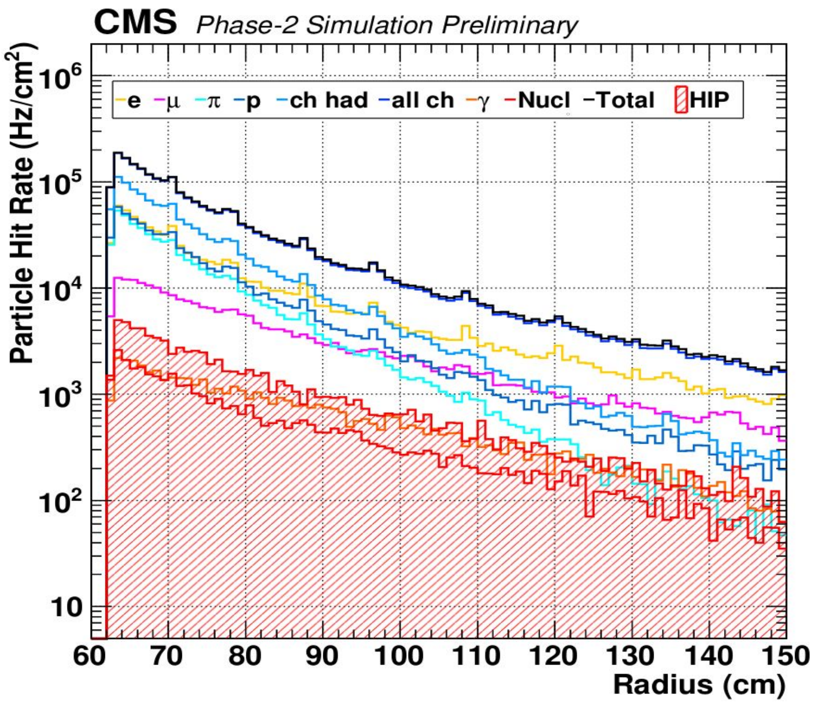
- **Front-end Components**
  - ➢ ***VFAT3 Chips***: Digital readout for 128 strips.
  - ➢ ***GEM Electronic Board (GEB)***: 1mm PCB providing electric links and shielding.
  - ➢ ***bPOL DC-DC Converters***: Adjust input LV power for on-detector electronics.
  - ➢ ***OptoHybrid (OH)***: Front-end concentrator reading out 6 VFATs.
- **Status**
  - ➢ All components are in production and have been extensively tested in labs and test beams.



ME0 Background and Challenges

- ***Expected Rates***: Up to 150 kHz/cm^2 in the highest-η region
- Expected background particle flux on an ME0 chamber for HL-LHC as a function of the distance from the beam line.
  - ➢ Dominated by charged hadrons
  - ➢ Highly uneven background as a function of distance from beam line

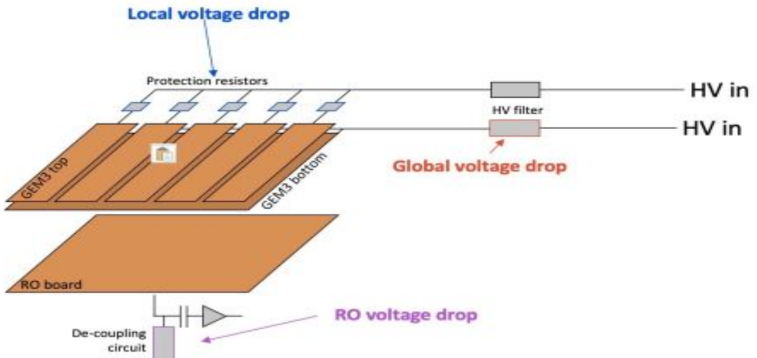


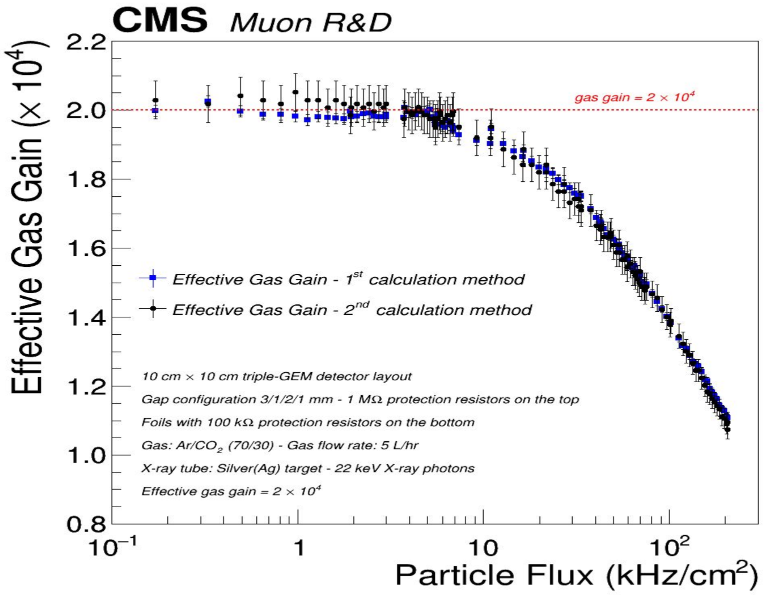


Highly non-uniform rate along the chamber profile

GEM Rate Capability

- **Rate Capability**
  - ➢ ***Measurement***: Performed on a triple-GEM detector irradiated by x-ray generators.
  - ➢ ***Voltage Drop***: on the protection and filter resistors
    - depends on the integrate particle flux per GEM foil sector
    - rate capability of $\mathcal{O}(10^4\ \text{Hz/cm}^2)$
    - It can be tuned by changing the HV design parameters





https://ieeexplore.ieee.org/document/9875626

Blue dots show the gain measured under irradiation
Black dots shows the gain when only resistive voltage drops are expected

Voltage Compensation Method

Voltage Drop Dependance: It depends on the particle flux, number of primary electron-ion ionisation pairs and protection resistance:

$$V_{eff} = V_{set} - R_{electode} \times \varphi \times G \times n_0$$

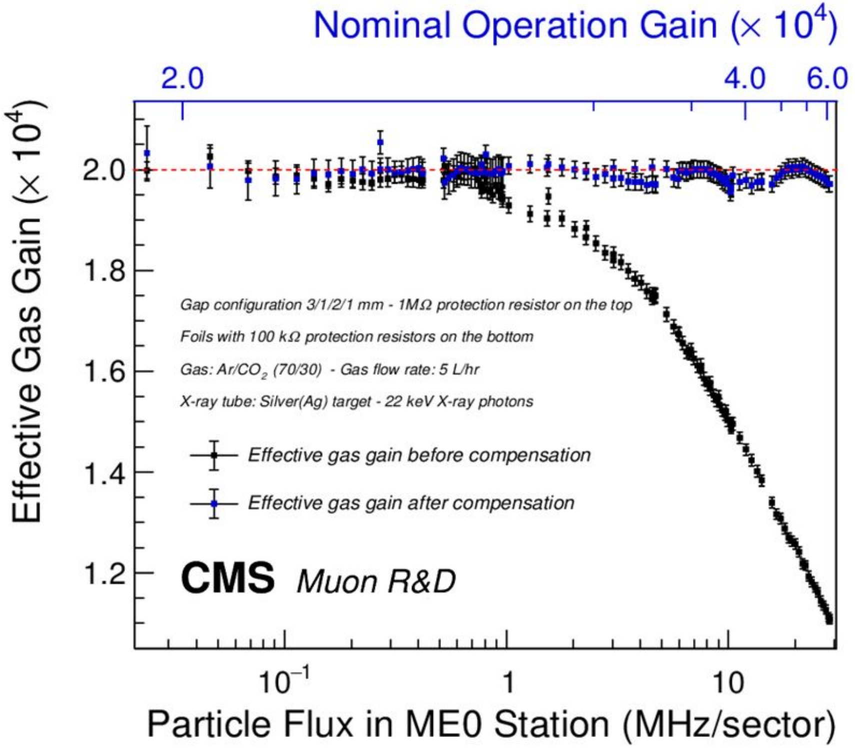
Flux on the electrode
Number of primaries
Global electrode resistance
Effective gain

1 – 10V in the ME0 BKG range

Compensation Procedure:

- ***Iterative Determination***: Determine the effective operating voltage iteratively to maintain nominal gain.
- ***Application***: Successfully applied to triple-GEM prototypes under x-ray irradiation.

Application in ME0 Challenges: ME0 experiences a large voltage drop in the highest η sector due to expected high rates (up to 10 MHz)



ME0 GEM Foil Segmentation

Non-uniform background as a function of η

Issue:

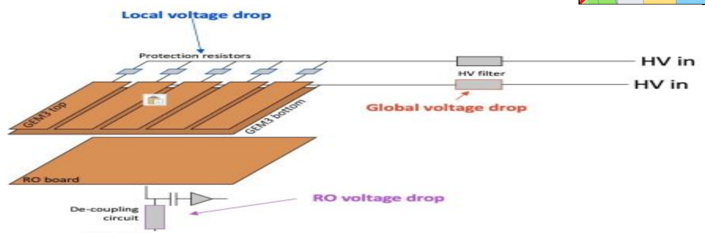
- ○ Standard segmentation leads to highly uneven voltage drop
- ○ Not possible to apply compensation method

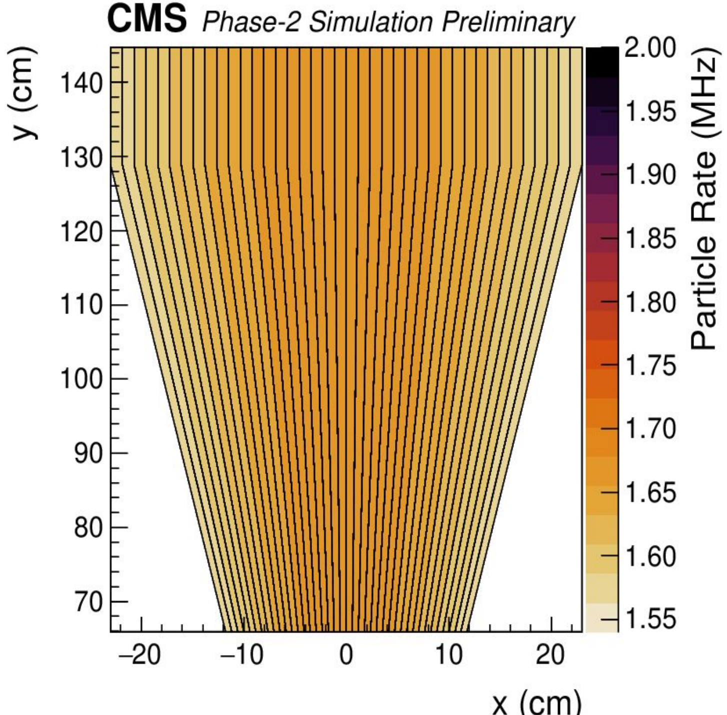
Solution: Radial GEM foil segmentation w.r. to beam line

- Achieve equal background particle rate per sector
- Uniform gain drop per HV sector (at 140PU we expect 1.6 MHz/sector)

ME0 segmentation design:

- ***Details***: Divided into 40 sectors. Each sector is smaller than 100 cm² to minimize discharge energy.
- Drawback: dead area at sector separation

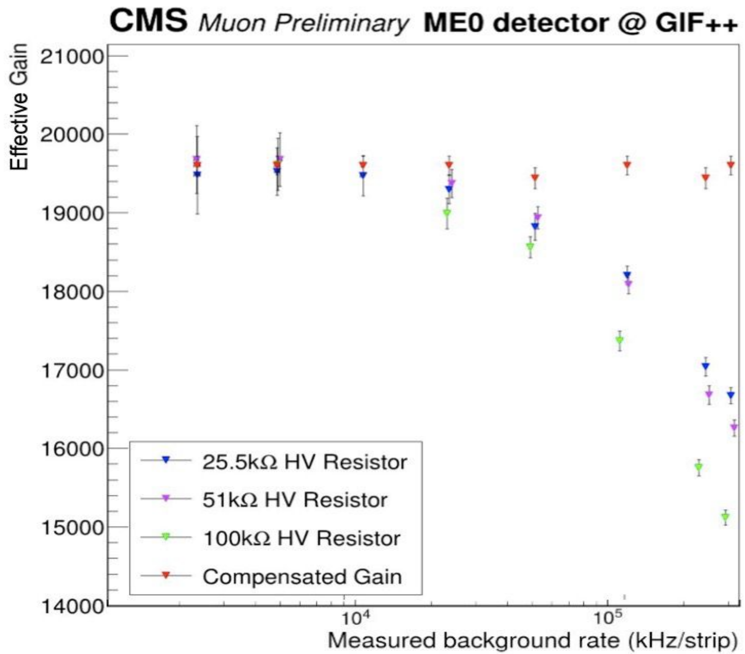




ME0 Rate Capability Studies at the GIF++

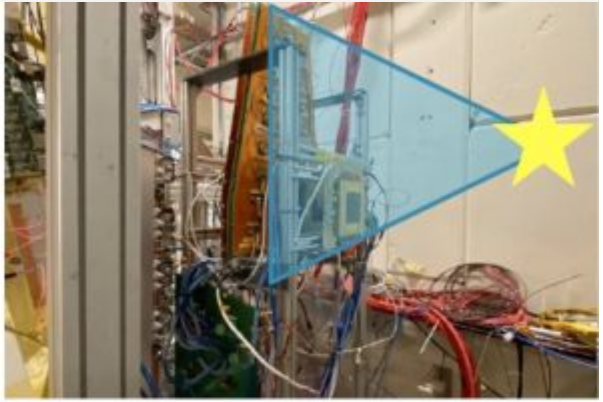
Compensation demonstrated with different HV filters

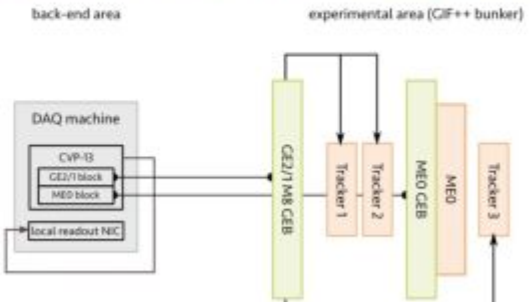
- Gain recovery demonstrated up to 2.2 MHz/sector or 280 kHz/strip and with different HV filters up to 100 kΩ



Setup: ME0 layer + reference GEM tracker
• Placed inside the source cone for uniform and intense irradiation
• Full RO chain (VFAT3 frontend)

Source:137 Cs (14TBq) γ (662 keV)

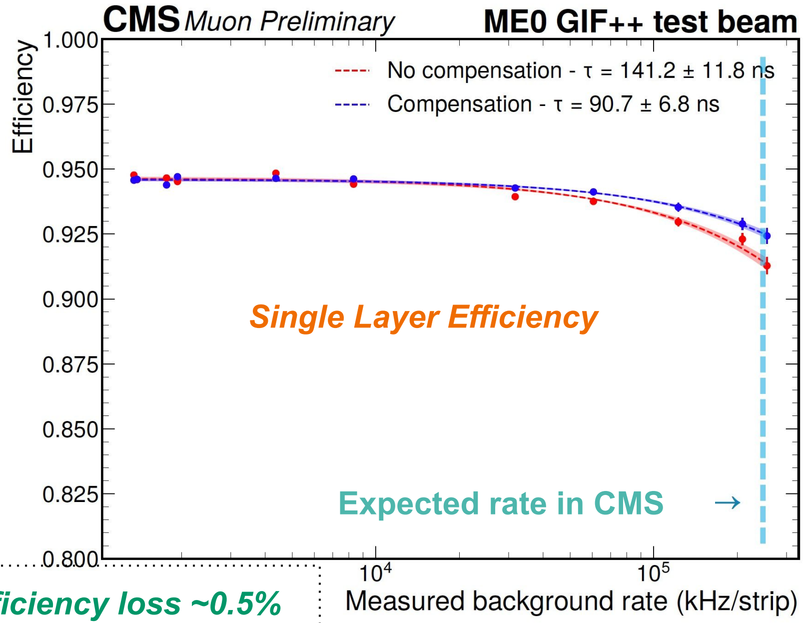




ME0 Efficiency at the GIF++

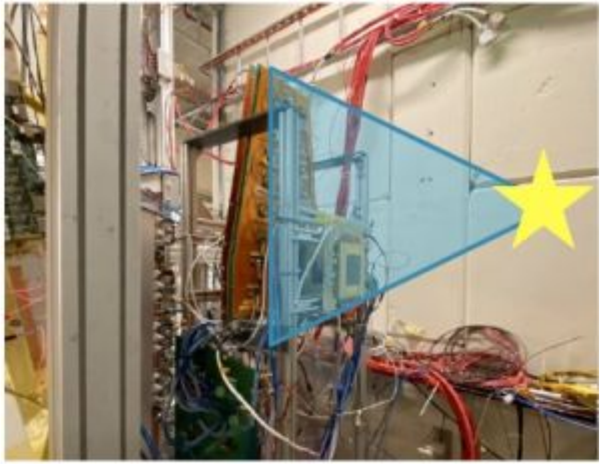
Validation of detector + RO electronics

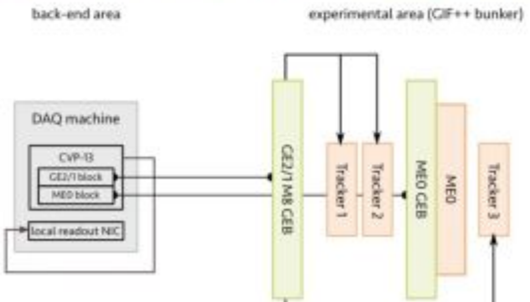
- Single Layer Efficiency loss not recovered by voltage compensation.
- Cause of efficiency loss: dead time of VFAT3 > 300 ns.
- Limited impact (2.5%) at CMS expected rate.



Stack efficiency loss ~0.5%

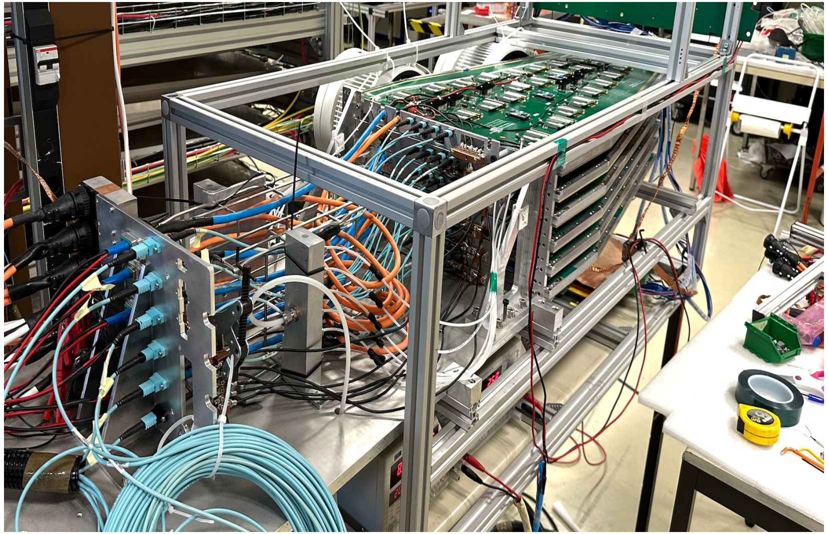
Background: SPS beam of 80 GeV muons + 137 Cs (14TBq) γ (662 keV)





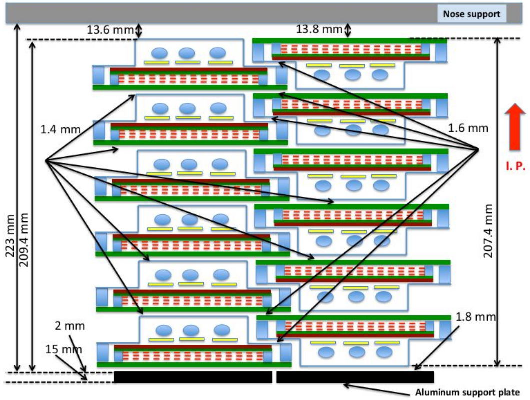
Conclusions and Current Status

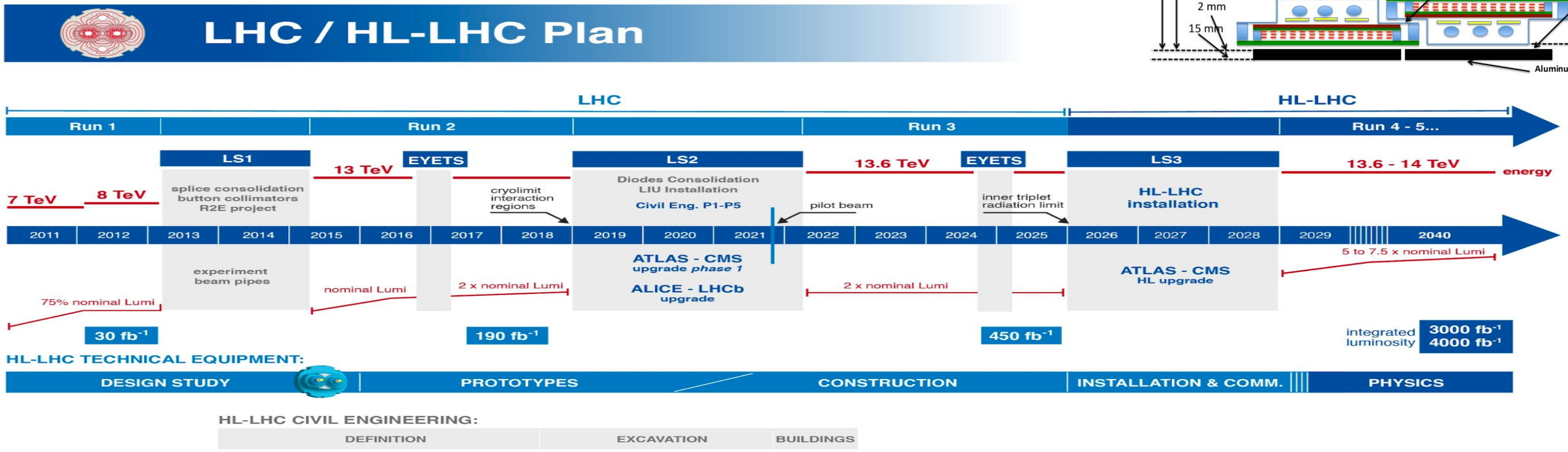
- ***Achievements***:
  - ***Rate Capability Studies***: Successfully accessed and analyzed rate capability studies.
  - ***Mitigation Strategies***: Implemented strategies including radial HV segmentation and voltage drop compensation.
  - ***Impact Quantification***: Quantified the impact of HV filters on performance.
  - ***Design Validation***: Validated and finalized the design.
- **Production and Assembly**
  - ***R&D phase***: Completed the research and development phase.
  - ***Production:*** Mass production started
  - ***Assembly:*** 16 Modules for ME0 already assembled and undergoing Quality Control tests.
  - ***Installation:*** Planned in 2026 and 2027.



Backup: HL-LHC and ME0 Longevity

- **Projected Integrated Luminosity**
  - Increase from 300 fb^{-1} to 3000 fb^{-1} over two decades.
- **ME0 Longevity**
  - Must integrate 840 mC/cm^2 over its lifetime without gain loss.





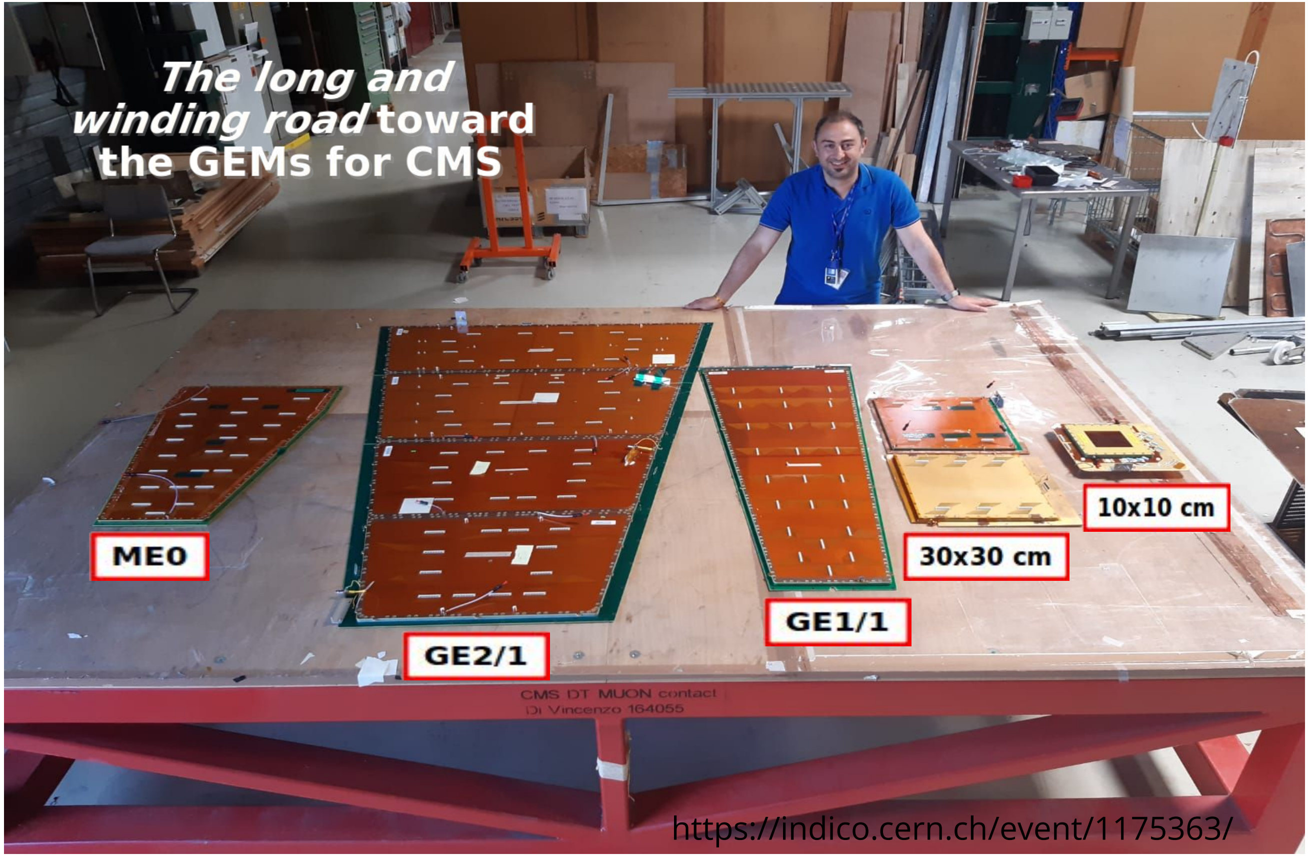
Backup: ME0 Specifications and Layer Structure

Specification / Parameter	ME0
Detector technology	Gaseous detector; micro-pattern gas detector (MPGD)
Charge amplification element	GEM foil (triple, cascaded, tensioned at ≈ 6 cN/cm)
Number of modules in overall system	216 (108 in each endcap)
Chamber shape (active readout area)	Trapezoidal; opening angle 20°
Chamber dimensions (active vol.)	L: 78.8 cm (center line), W: (23.6–51.4) cm, H: 1.8 cm
Total module thickness	H: 3.34 cm
Active readout area	0.296 m^2
Active module volume	2.1 liters
Radial distance from beam line	63 cm (at inner edge of active readout area)
Geometric acceptance in $\lvert\eta\rvert$	2.03–2.8
Signal readout structure	Truly radial readout strips
Readout strip dimensions	0.94 mrad angular pitch
Number of η-segments in readout	8
Number of readout strips per η-segment	384
Number of readout strips per module	3072
Counting gas mixtures	Ar/CO_2 70:30
Nominal operational gas flow	1 module volume per hour
Number of gas inlets	1
Number of gas outlets	1
Nominal HV applied to drift electrode	3200 V (Ar/CO_2)
Nominal operational gas gain	$1\text{–}2 \times 10^4$
Demonstrated rate capability	100 MHz/cm^2

Layer	Material	Thickness [mm]
Protective cover	Al	1.0
Cooling pipe	Cu (filled with H_2O)	8 external ⊘, 6 inner ⊘
Cooling pads	Cu	1.0
GEB board	Cu/FR4	0.140/0.856
Readout board	Cu/FR4/Cu	0.035/3.2/0.035
Induction gap	Ar/CO_2	1.0
GEM 3	Cu/polyimide/Cu	0.005/0.050/0.005
Transfer gap 2	Ar/CO_2	2.0
GEM 2	Cu/polyimide/Cu	0.005/0.050/0.005
Transfer gap 1	Ar/CO_2	1.0
GEM 1	Cu/polyimide/Cu	0.005/0.050/0.005
Drift gap	Ar/CO_2	3.0
Drift board	Cu/FR4/Cu	0.035/3.2/0.035

Muon subsystem	RE3/1 + RE4/1	GE1/1	GE2/1	ME0
Detector technology	iRPC	GEM	GEM	GEM
$\lvert\eta\rvert$ range	1.8–2.4	1.6–2.15	1.6–2.4	2.0–2.8
Number of chambers	36 + 36	144	72	216
Number of channels	13 824	442 368	442 368	663 552
Number of layers/station	1	2	2	6
Surface area of all layers	93 m^2	54 m^2	105 m^2	64 m^2
spatial resolution	~ 0.3 cm	200–340 μm	200–410 μm	160–390 μm
time resolution	1.5 ns	8 ns	8 ns	8 ns

GEMs



(For the first time, such large (>1 m long) Triple-GEM detectors are used in such a harsh environment)