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An introduction to gas electron multipliers and their time to shine during the CMS Phase 2 upgrade

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on behalf of the CMS Muon System
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April 1, 2025

T20.1 Invited Topical Talks I

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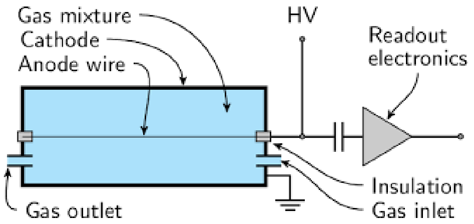
  - First stage of GEM detector (GE1/1) operation in CMS
  - Future GEM chambers (ME0) for CMS



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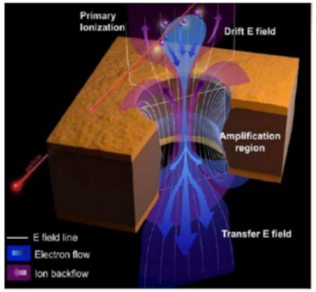

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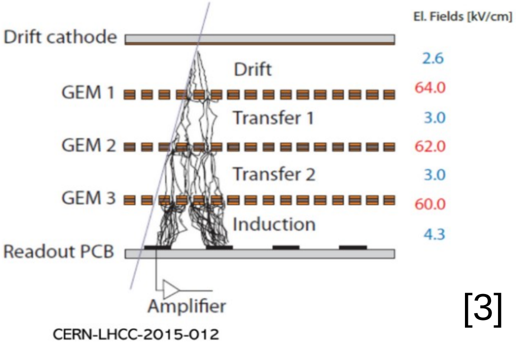

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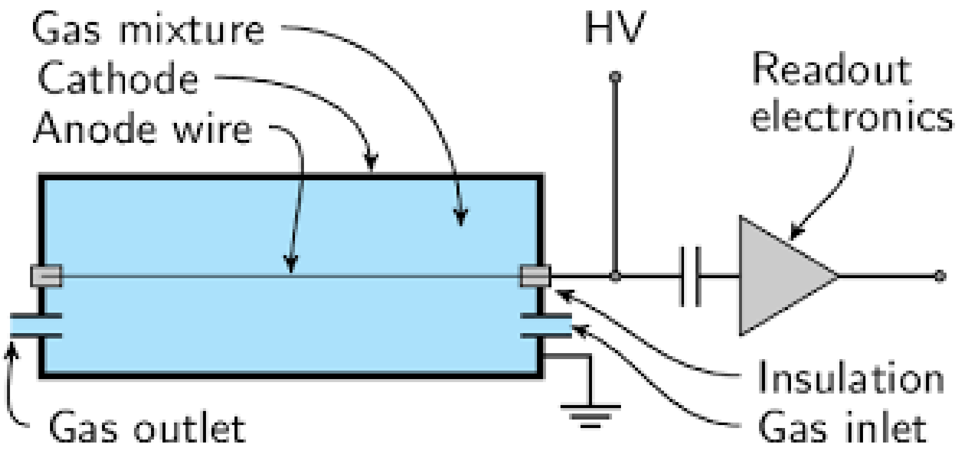
Review of Gas Detector Fundamentals



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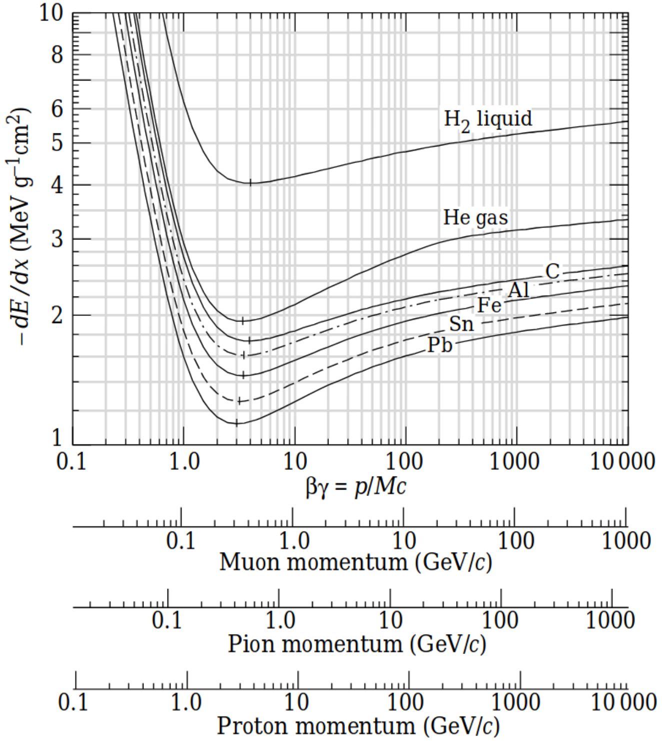
Bethe-Bloch and Minimally Ionizing Particles

- Particles lose energy as they travel through matter
- Example Applications:
  - Particle ID
  - Detector design
  - Radiation therapy
  - Cosmic Ray studies
  - High energy physics
- Depends on charge, mass, velocity of particle and material properties of what the particle is moving through



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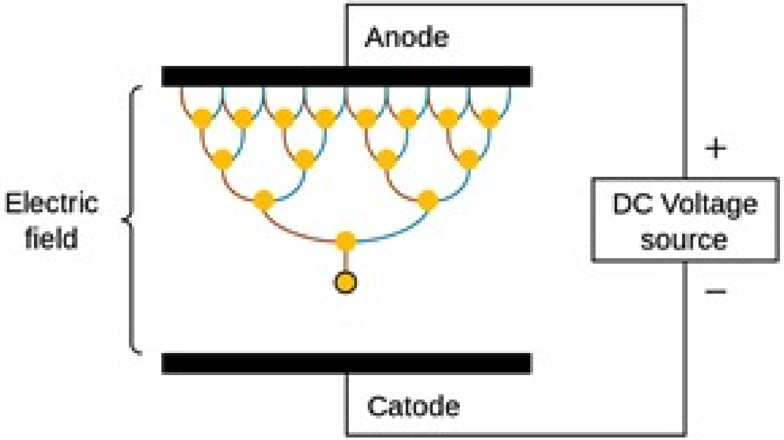
Gas Detector Principles



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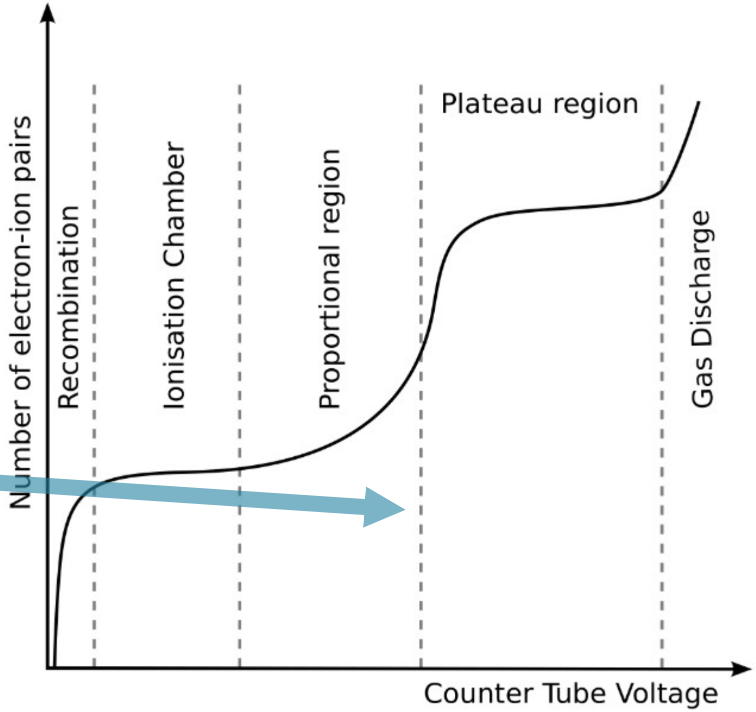

- Number of electronic signals depends on amplification (applied voltage)

Gas Counters

- Simplest gas counter is proportional counter
- Anode wire in gas mix surrounded by cathode exterior
- Passing ionizing particles liberate electrons from gas particles
- E-field increases closer to anode
- Anode collects electrons and this signal is sent to readout electronics
- Multiwire proportional counter
    - Nobel Prize for Charpak for first gas-based tracking chamber

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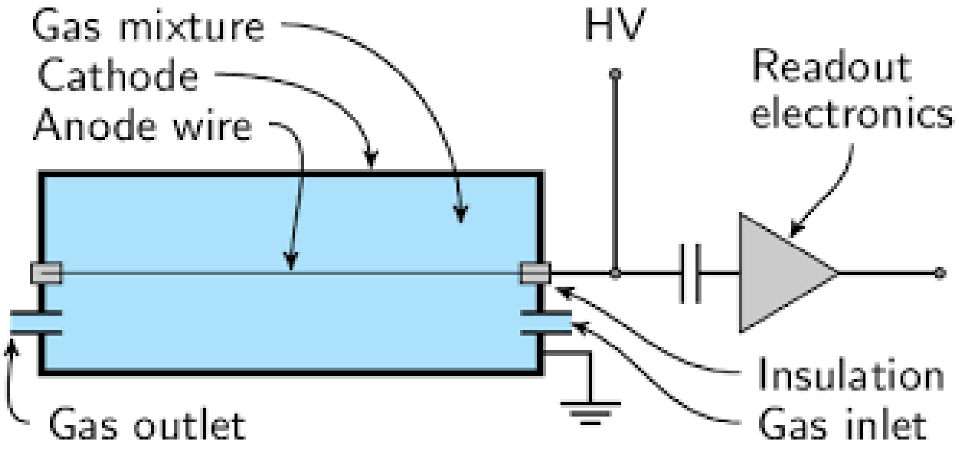

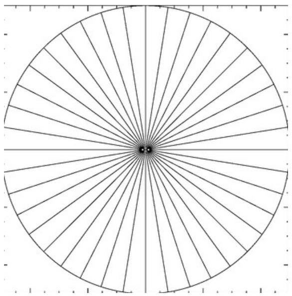

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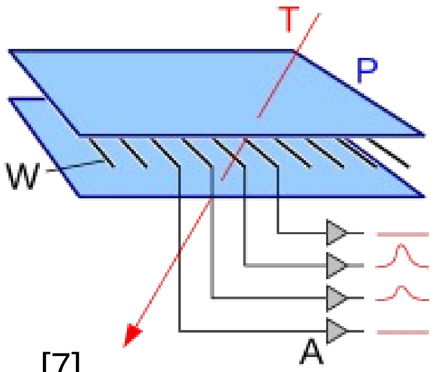

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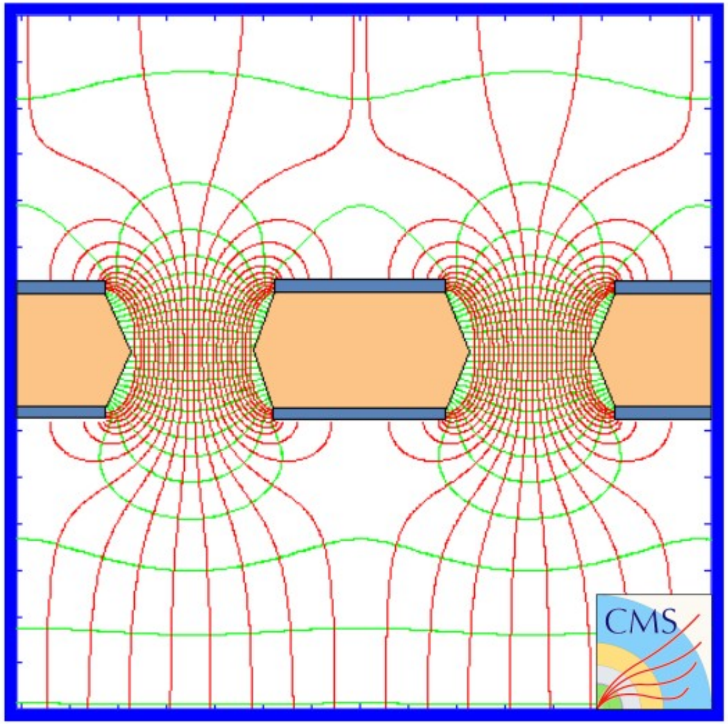
Micro Structured Gas Detectors

Gas Electron Multipliers (GEMs)



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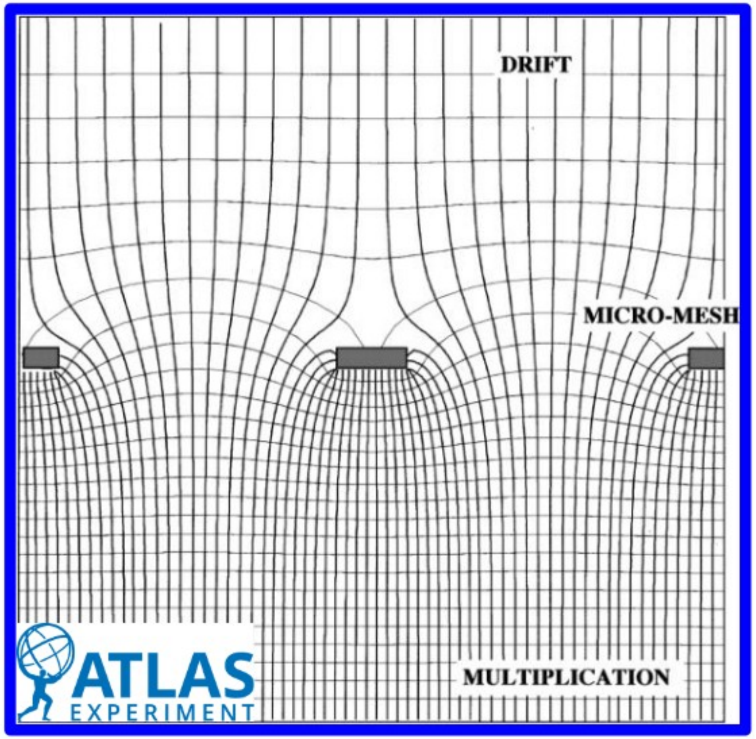
Micromesh Gaseous Structures (MicroMegas)



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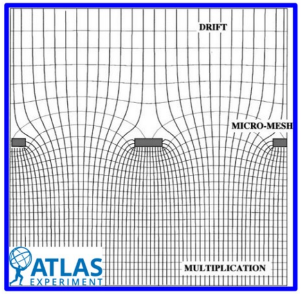
Micro Megas Working Principle

- Thin-gap parallel-plate design
- Thin micro-mesh placed above anode shaping electric field lines
- Electrons created by interaction with ionizing particle drift to mesh and are accelerated in multiplication region
    - High spatial resolution
    - High rate capability
    - Good time resolution
- Currently being installed in the ATLAS New Small Wheel



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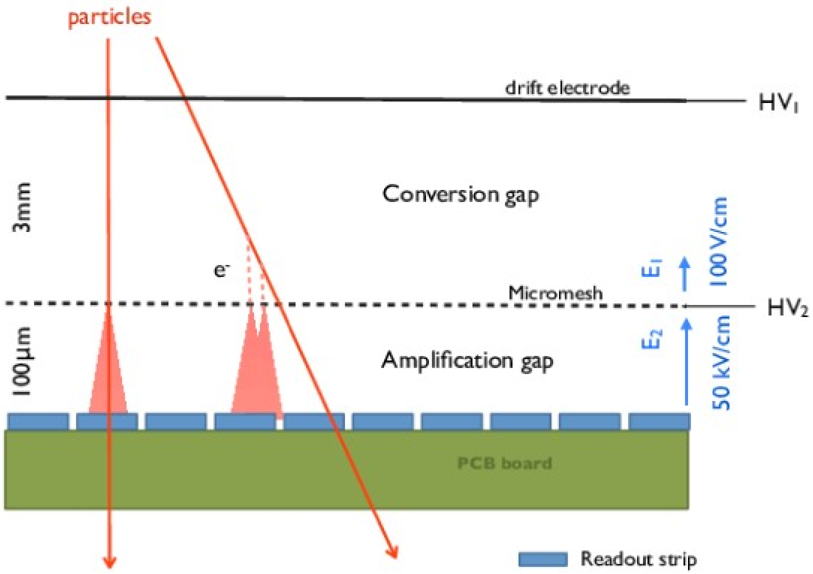
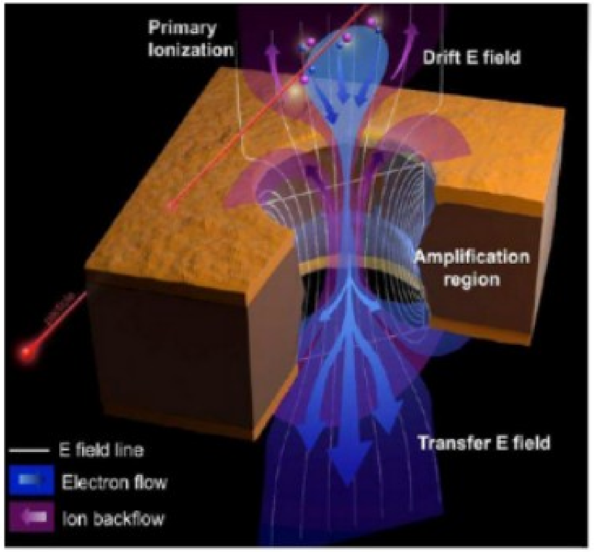


Introduction to Gas Electron Multiplier (GEM) Technology and Applications



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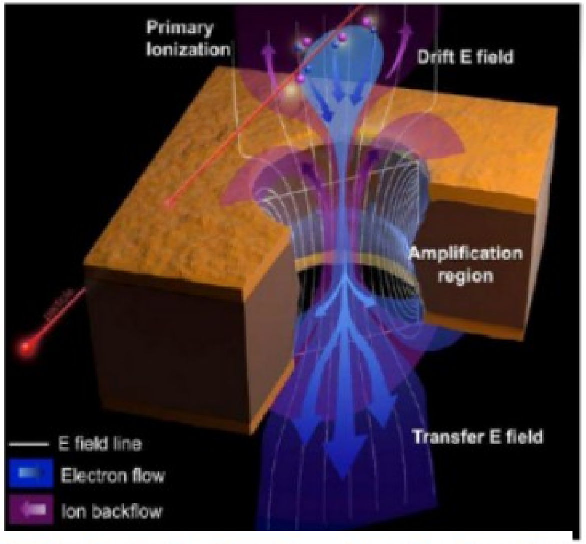
Gas Electron Multiplier (GEM)

- GEM Detection principle similar to proportional counter – replace anode wire with copper mesh of chemically etched holes
- 70 μm diameter holes spaced 140 μm hexagonally apart from each other
- Copper-clad Kapton foil (5 μm Cu)
- One voltage applied to one side of the GEM foil, different voltage to the other side O(400 V)
- Potential difference creates large E-field inside GEM foil holes O(60 kV/cm)
- Provides amplification (gain) ~ 20 per GEM foil



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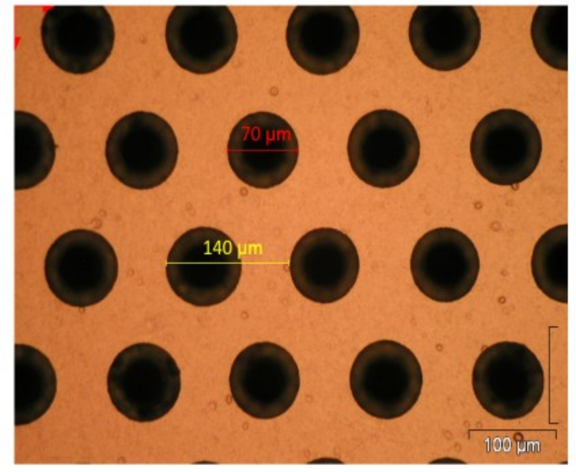
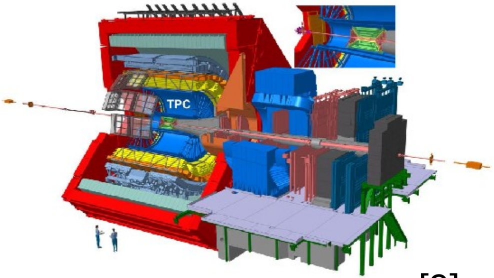


GEM Use Cases

- GEM used in many different applications, for example:
  - Time Projection Chamber example: ALICE



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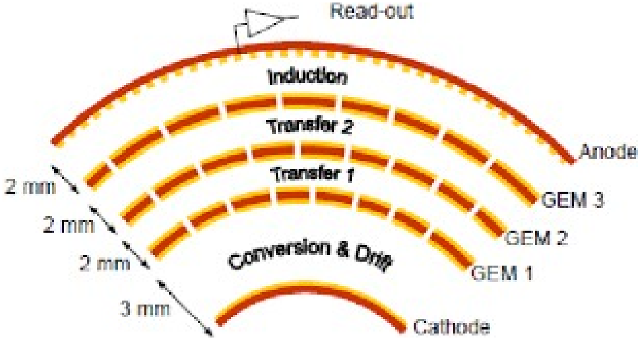
  - Tracking example: KLOE II



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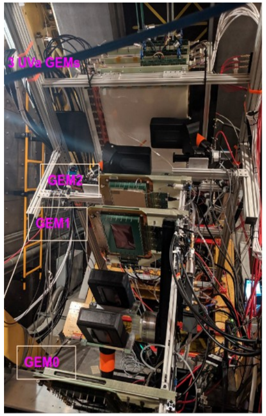
  - PREX-II



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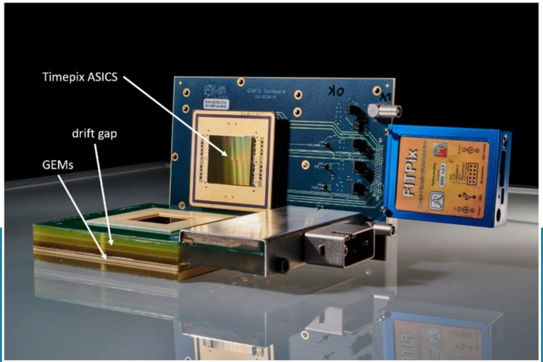
  - and medical physics applications (GEMPIX)



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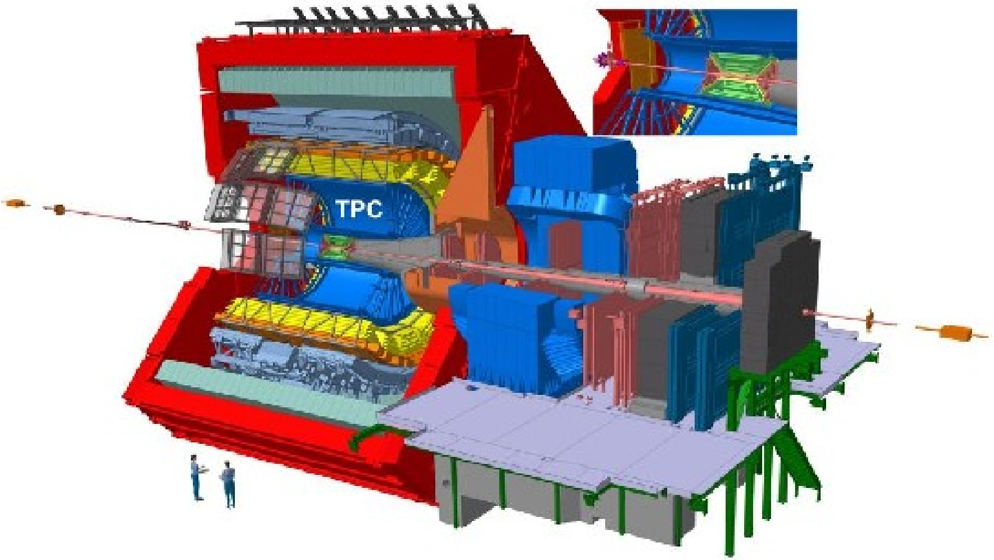
GEMs in a TPC: ALICE

- Upgrade from traditional MWPCs
- GEM as a readout
- Triple-GEM design
- Improves:
  - 3-d tracking
  - Measures energy loss
  - Higher readout-rate
  - Reduced ion backflow (E-field distortions)



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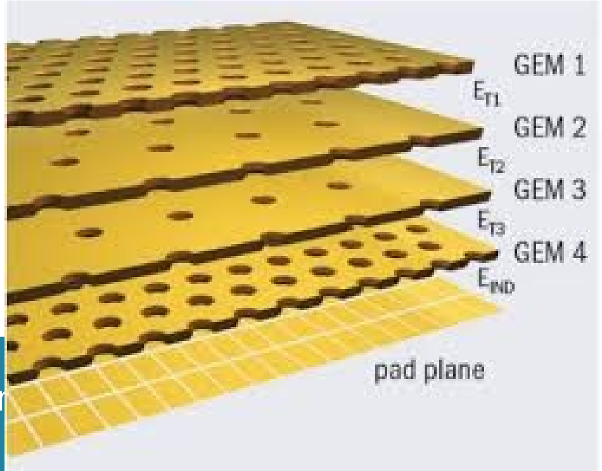
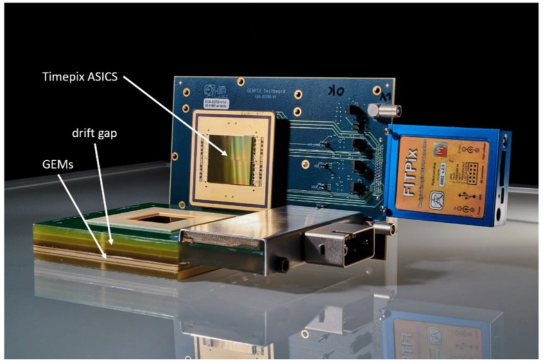
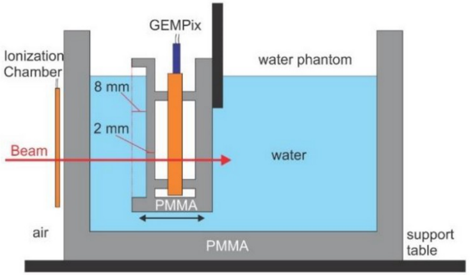
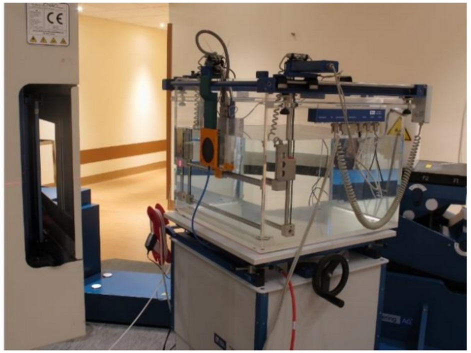


Medical Physics Application: GEMPIX

- Application: Radiation imaging
- Incoming radiation ionizes gas in GEMs which amplify signal
- Pixelated readout (Timepix) gives high spatial resolution readout
- Essentially like a medical x-ray but can use a much wider range of incoming radiation types







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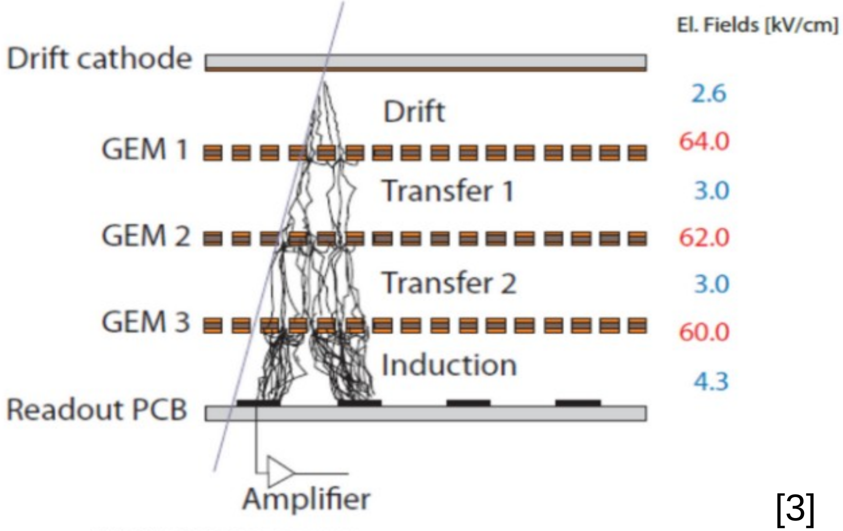
GEM Detectors in CMS



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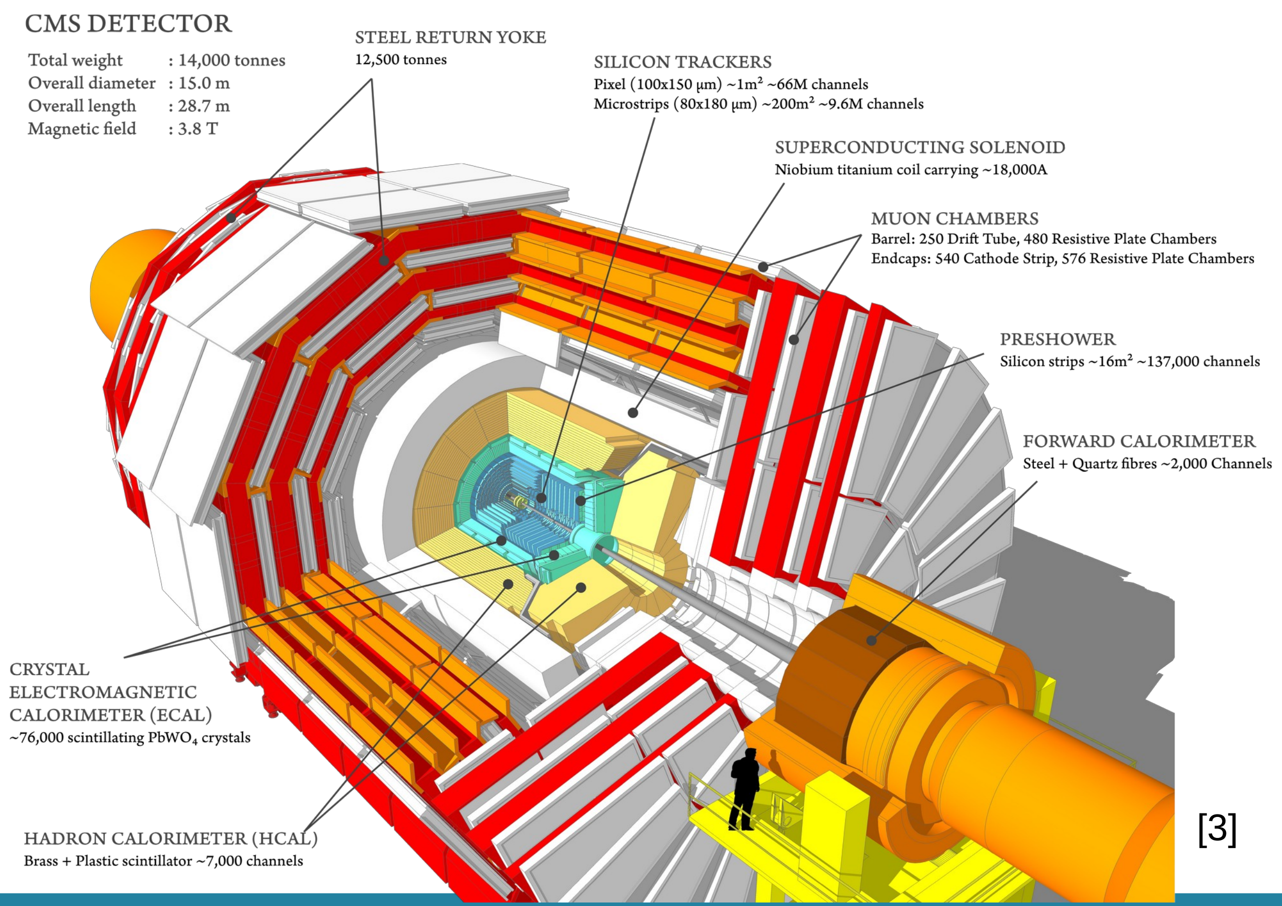
[3]

The CMS Experiment



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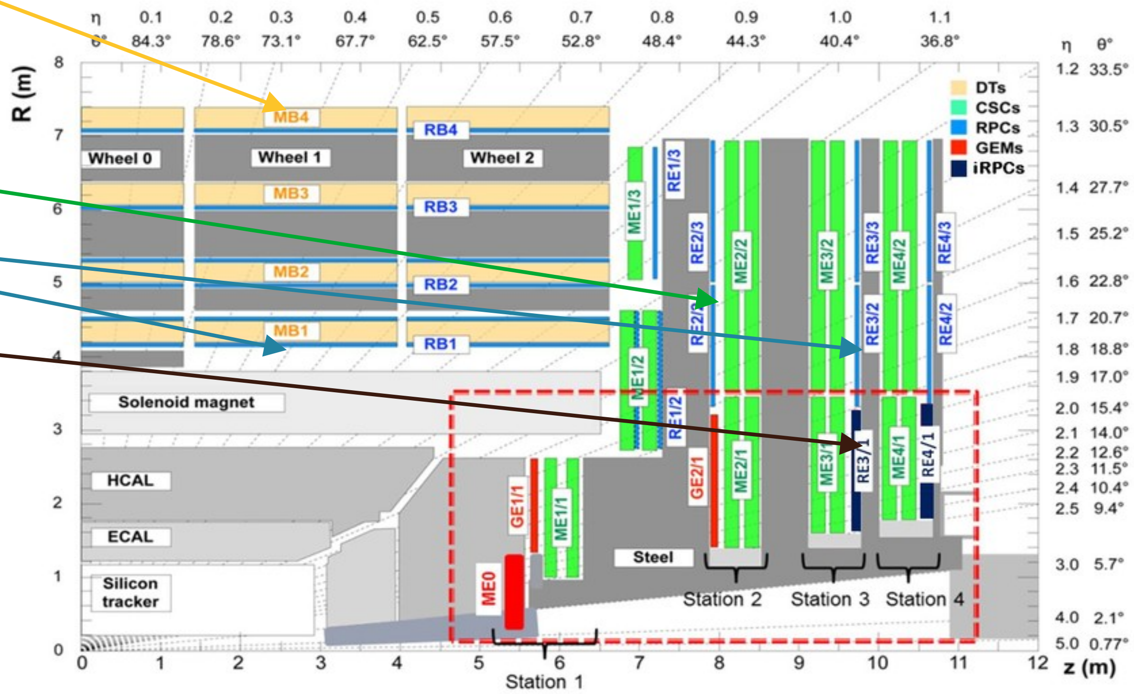
CMS Muon System

- Drift Tubes (DTs) in CMS barrel
- Cathode Strip Chambers (CSCs) in CMS endcap
- Resistive Plate Chambers (RPCs) in barrel and endcap regions
- RPC upgrade (iRPC) to be installed



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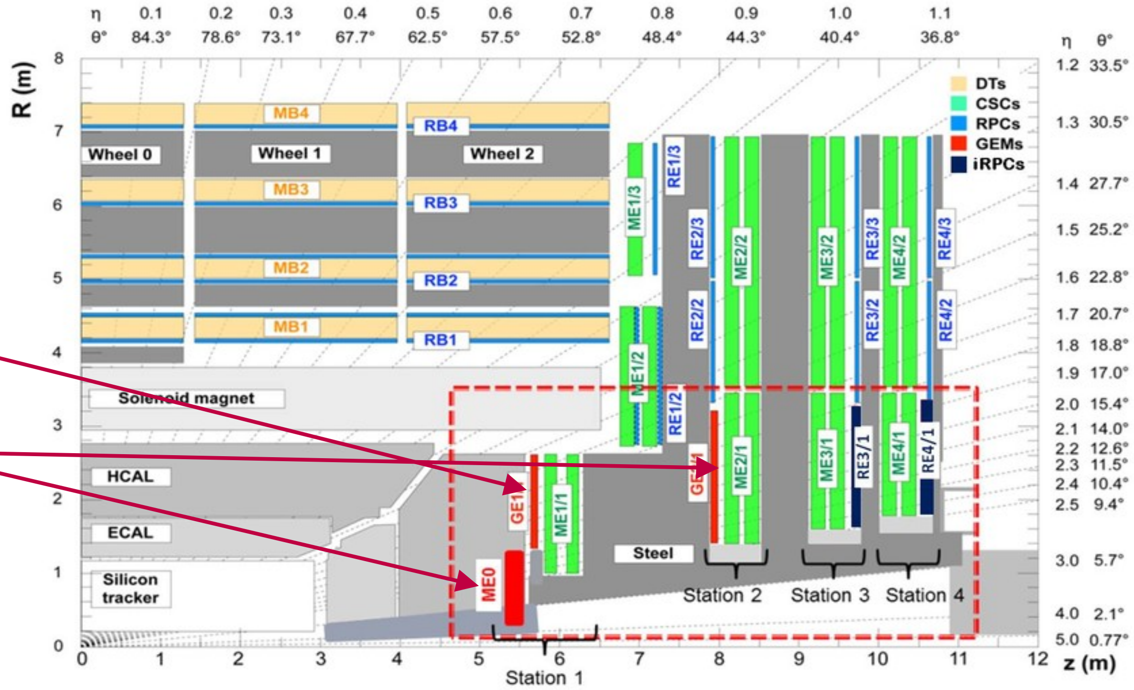
GEMs in CMS Muon System

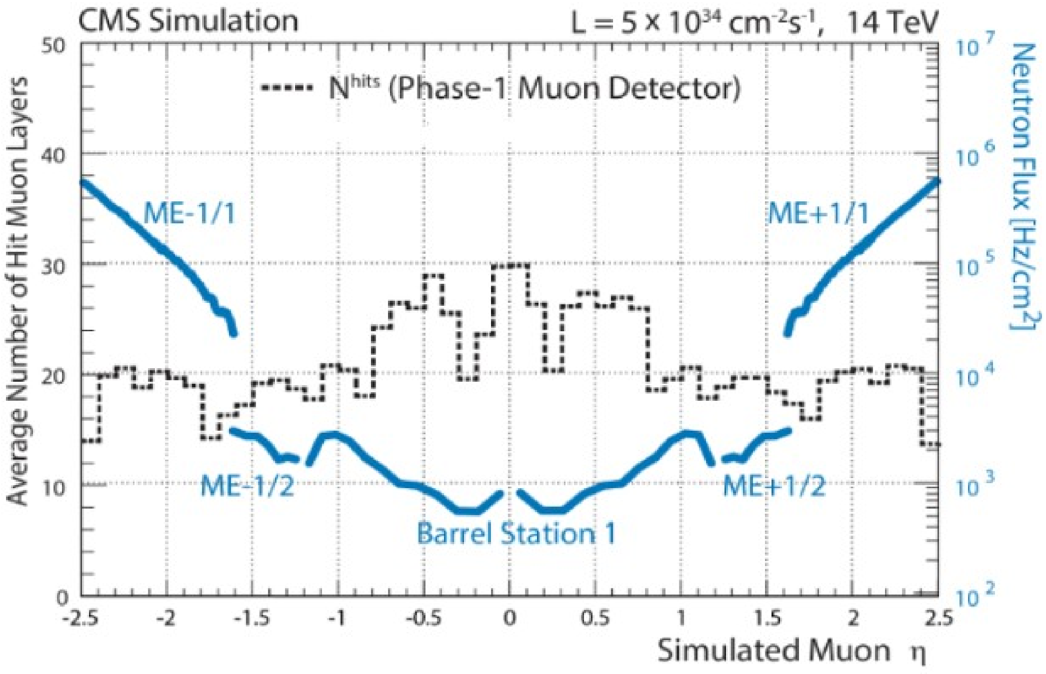
- GEM upgrade (red)
  - GE1/1 already installed
  - ME0 in production
  - GE2/1



[3]

CMS Muon Endcap Challenges

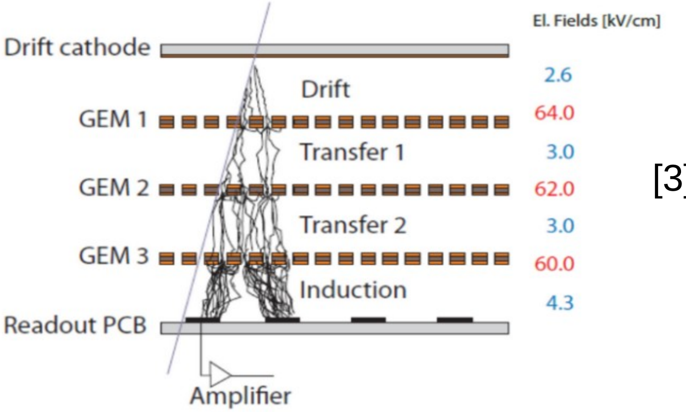
- Before GEM no redundancy (CMS has large redundancy)
- Improves lever arm from CSC
- Muon endcap $|\eta| > 1.6$
- Need added redundancy endcap; has highest rates but fewest measurement points
  - Difficult due to higher flux of highly energetic particles (radiation hardness)
- Efficiency often less due to tighter cuts
  - Reduce background
- Improves:
  - Spatial resolution
  - Radiation hardness



[3]

GEM Design for CMS

- 70:30 mix Ar(count):CO_2(quench) flushed through GEM chamber
- Passing particle ionizes gas producing primary electrons in drift region
- 3 layers (triple GEM) GEM foils used to generate O(10^4) gain per GEM chamber
- Signal collected and read-out at induction plane
- Spatial Resolution O(250 µm)



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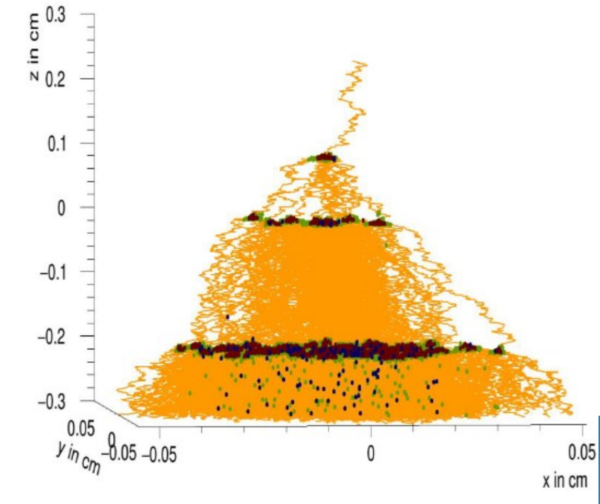

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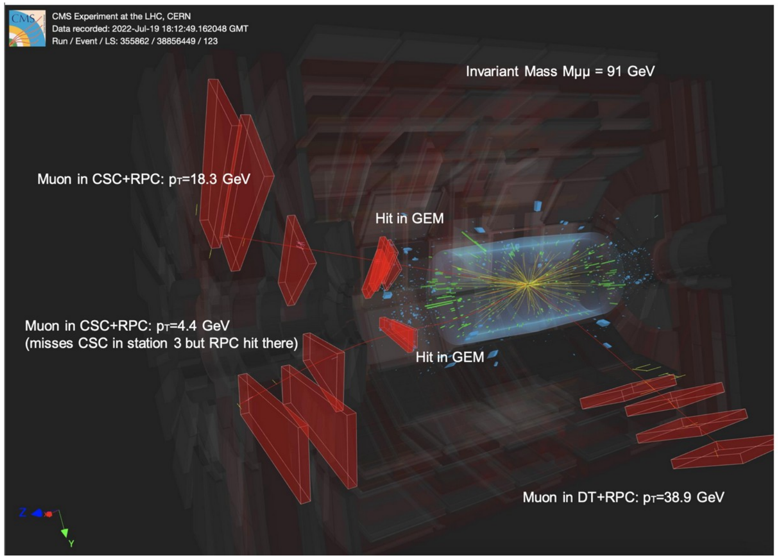
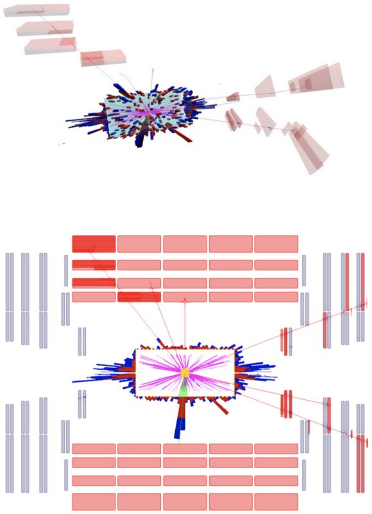
GE1/1 in CMS

- The GEM project in CMS was started formally in 2009
- Development of GE1/1 went on through 2019 when assembly and installation of first chambers occurred
- Full GE1/1 system installed in Fall 2021
- GEM took first collision data with beginning of Run 3 on 5 July 2022
- Primary Parameters for GEM data:
    - Muon reconstruction efficiency
    - Electronics stability
    - Cluster size





GE 1/1 Chambers

- GEM chamber consists of:
  - Drift board w/ 3 x GEM foils
  - Readout board with 24 x Very Forward ATLAS and TOTEM (VFAT3) chips and optohybrid
  - Cooling circuit
  - Frame and chimney
- 2 x triple GEM chambers (individually layer) form a superchamber (SC)
- The chambers come in long and short versions and alternated in installation
- (Slightly) Overlapping chambers spanning 10.15° → 36 SCs (72 chambers) per endcap and 72 SCs (144 chambers) in entire GE1/1 system

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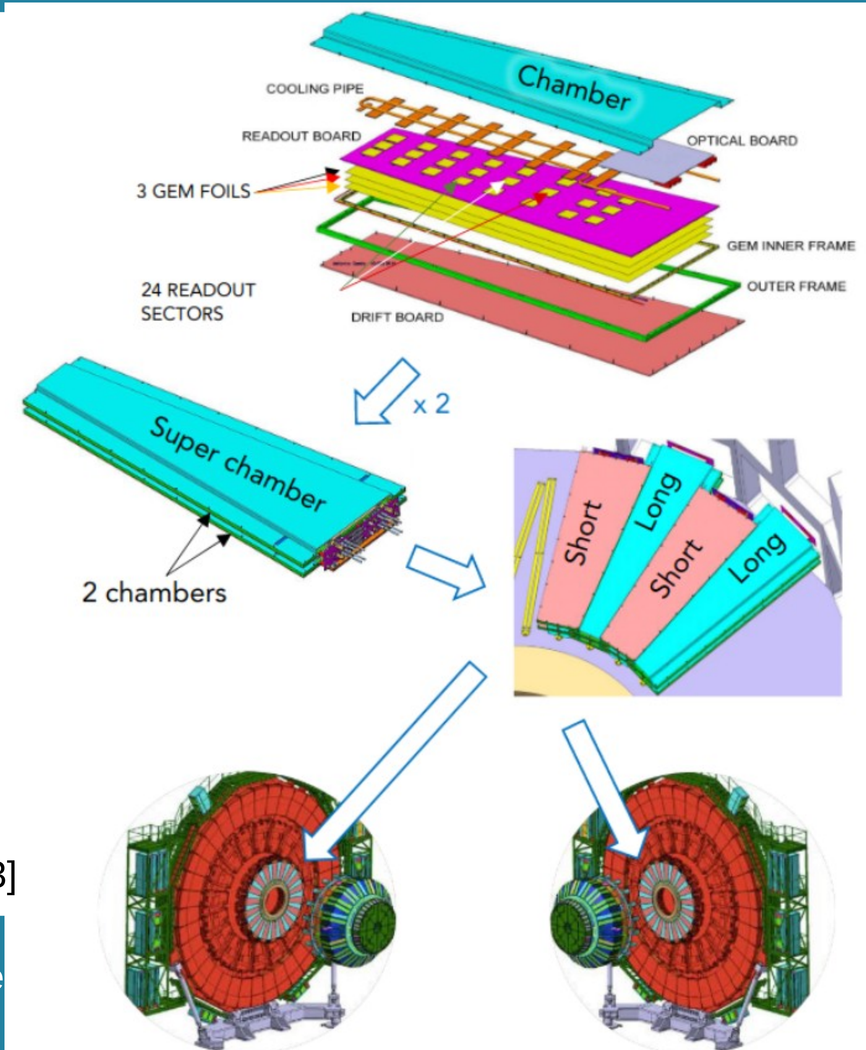
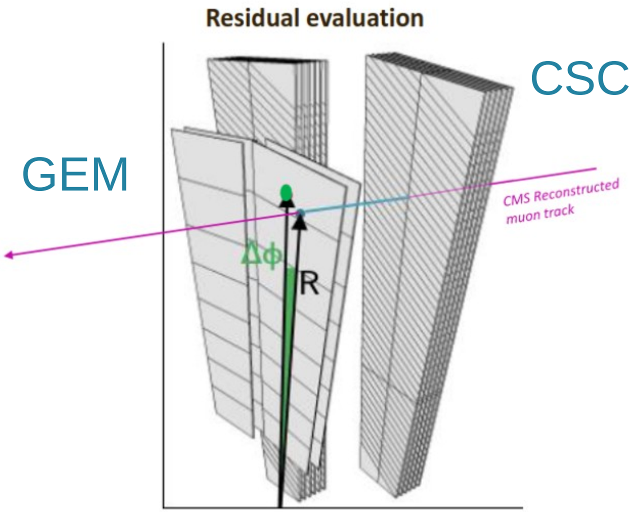


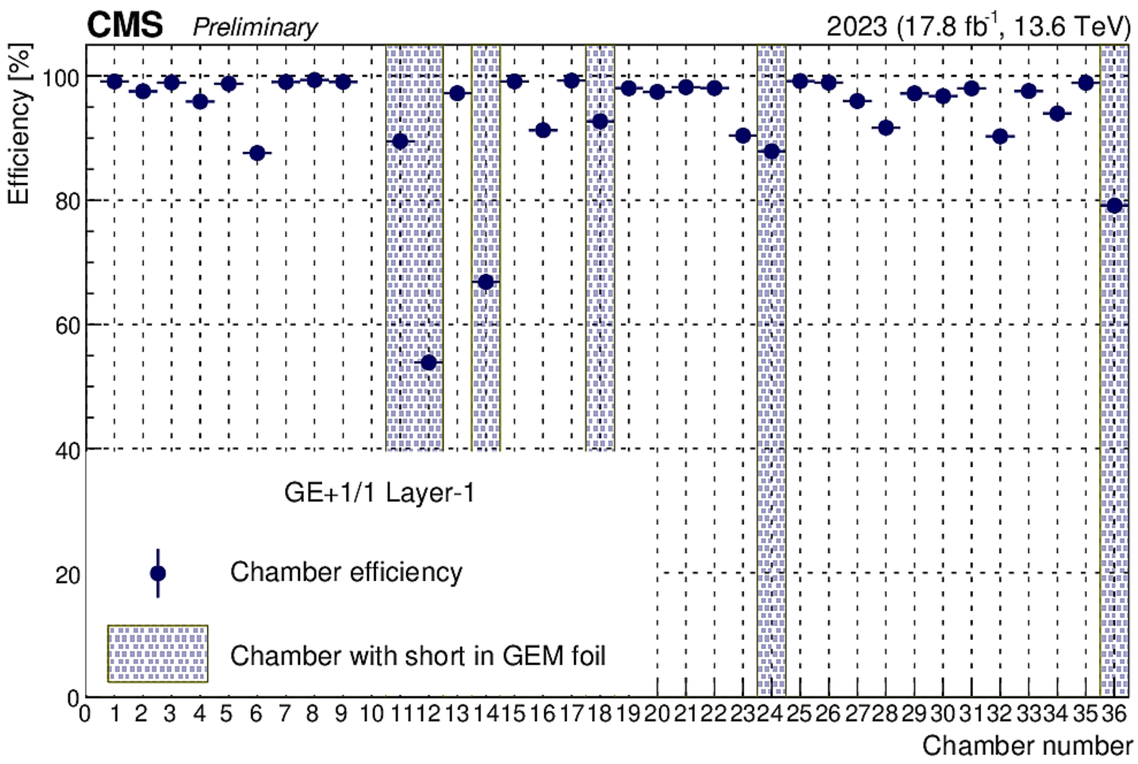
Prompt Feedback Analysis for Chambers at CMS



[14]

- Check performance of chambers in pp collisions
- The primary quantity that determines if GEMs are operating well is reconstruction (RECO) efficiency (eff)
- Propagate hits from CSC to GE1/1 surface
- N_m = # Matched GEM RECO hits
- N_p = # Propagated hits from CSC to GEM (far left)
- Eff = N_m / N_p
- Consider hits in the GE1/1 acceptance region

GE1/1 Efficiency by Chamber



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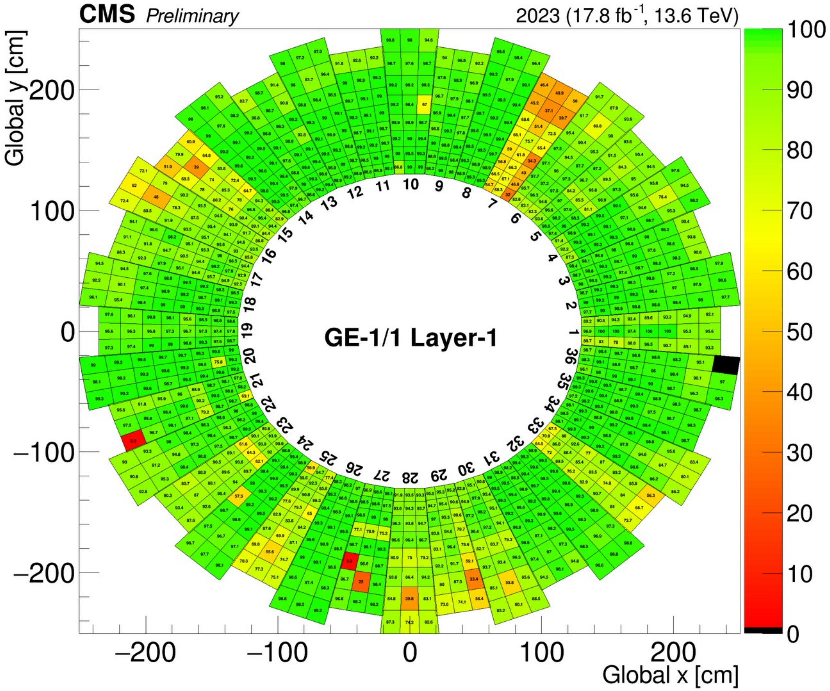
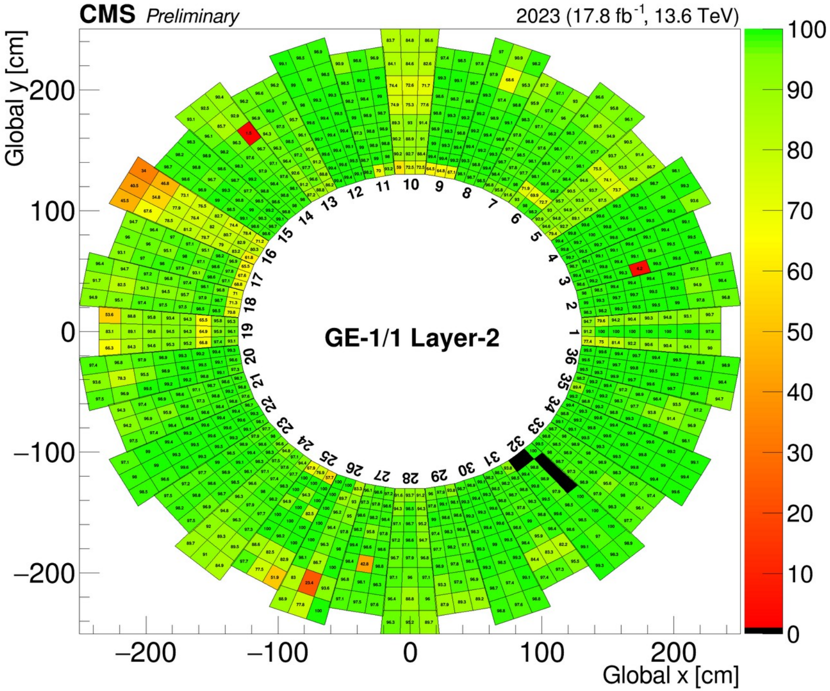
- Overall good efficiency per chamber
- ε > 95 % for most chambers

GE1/1 2023 Efficiency by Readout Sector





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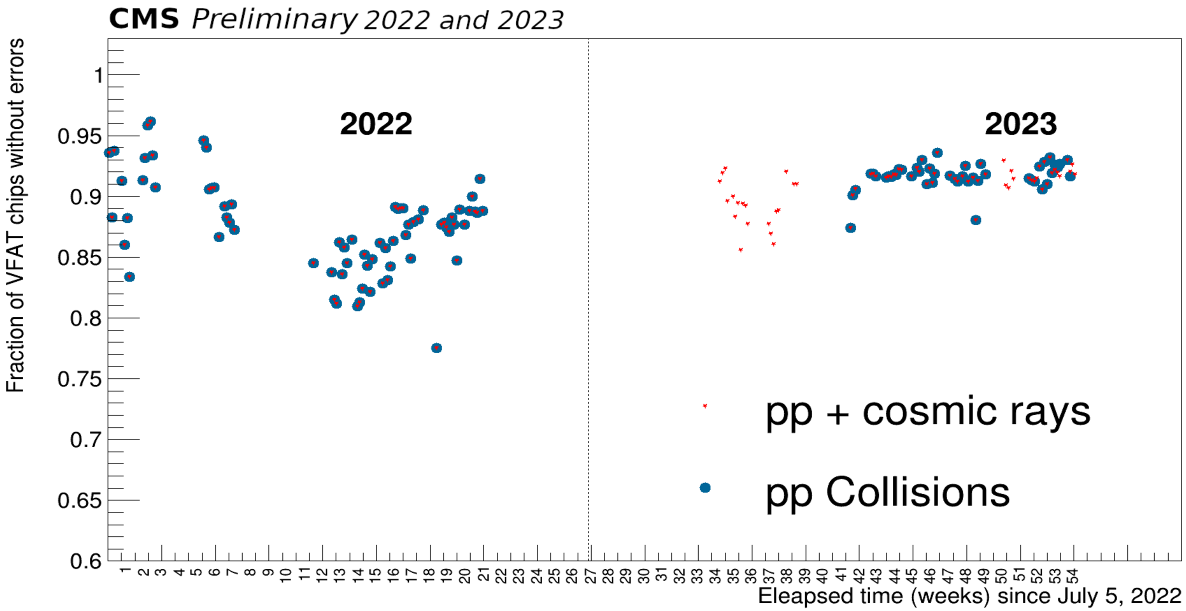
Challenges for GE1/1 stability at Start of Run 3

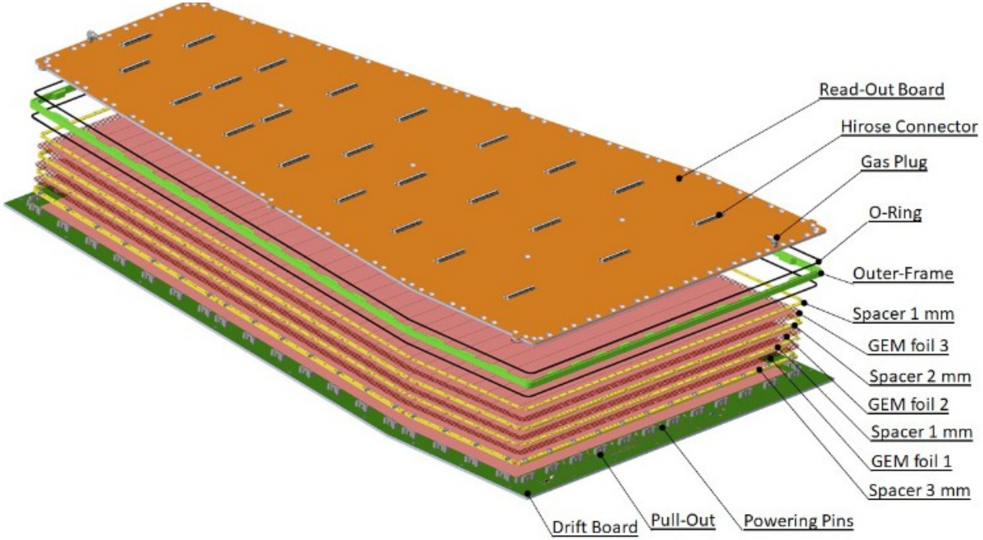
- GEM electronics stability a little “rocky” at start of Run 3
- At first difficult to disentangle due to short runs collected by CMS in first months
- Issue with gigabit transceiver (GBT) noticed
- Problems with optical coupling



[16]

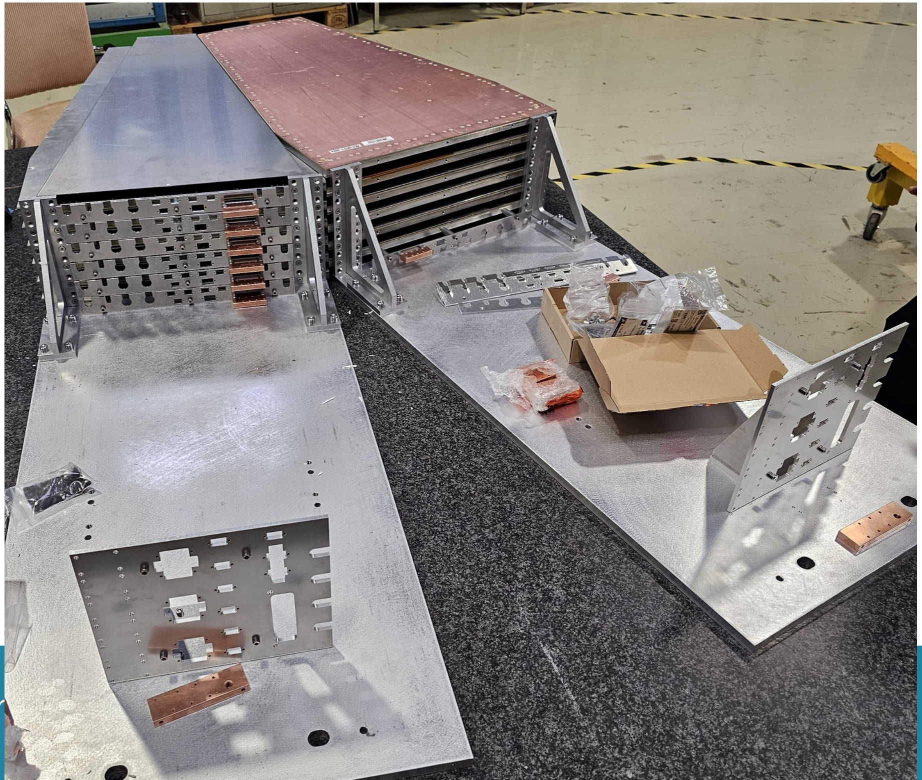
Next Project: ME0 Station

- New priority is ME0
- Extends muon acceptance to η ~ 2.8
- 18 ME0 stacks per endcap,
- Each stack has six triple-GEM layers
- Each ME0 stack spans 20°
- Connected to end of HGCAL
- High radiation and background conditions expected

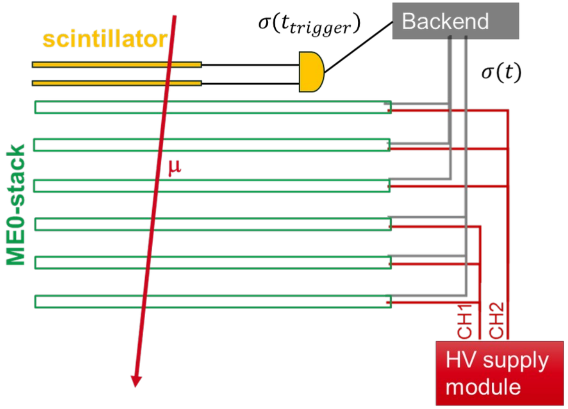


ME0 Stack Production Status

1st completed stack and has undergone test beam studies



ME0 Timing Study Setup And Strategy



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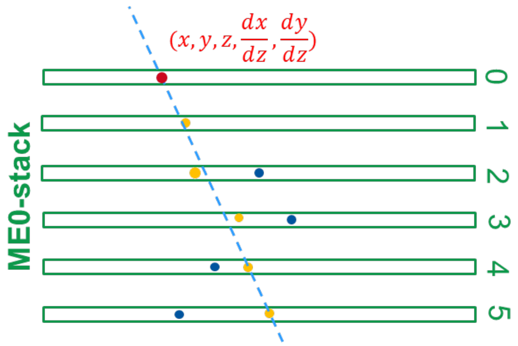
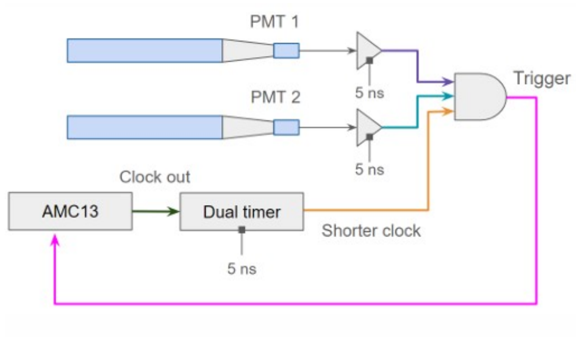
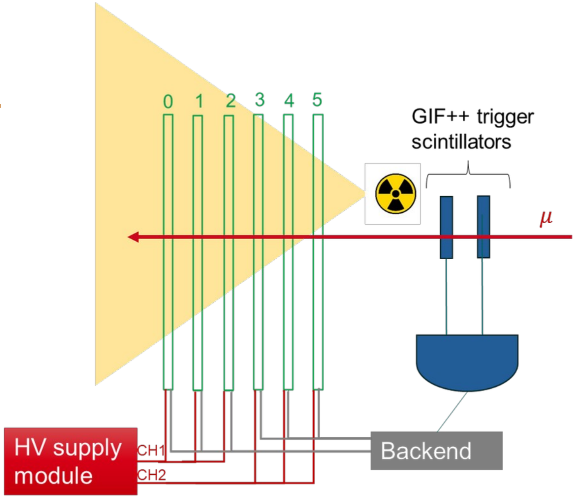




- First six layers prototype
- Cosmic rays and testbeam + bkg
- 2 scintillators 30×30 , whose coincidence is used as trigger
- Track reconstruction from chamber 0
- Moving the trigger to using a CFD improved the readout

ME0 Timing Beats TDR requirement

- Time resolution < 6 ns for both cosmics and beam + bkg
- Time resolution per BX follows nice exponential fit per layer
- ME0 fullfills time resolution requirement from TDR!!



Cosmics

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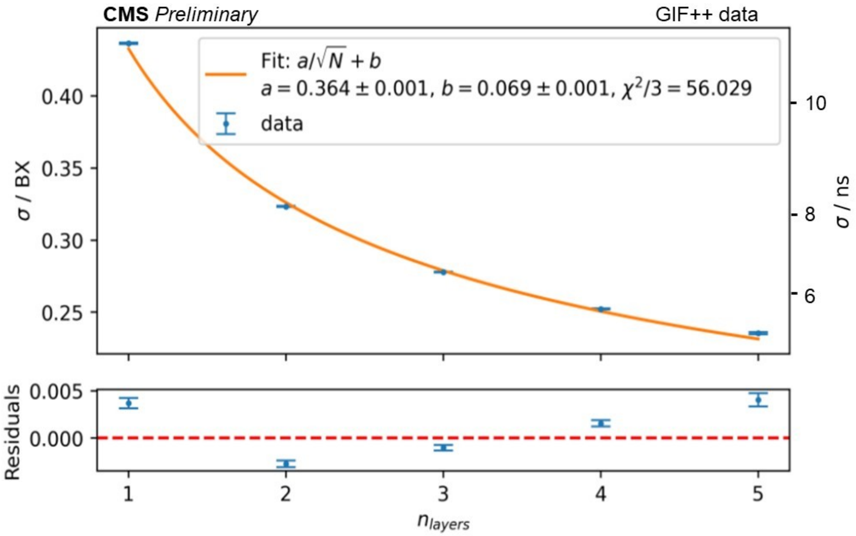
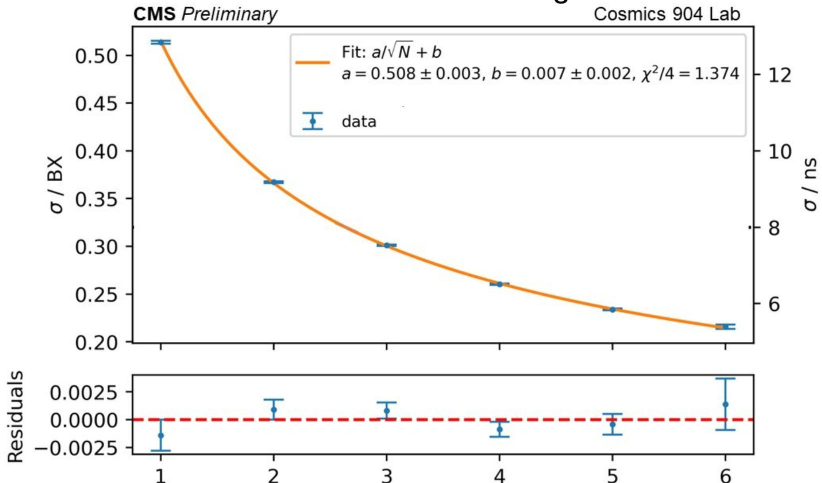
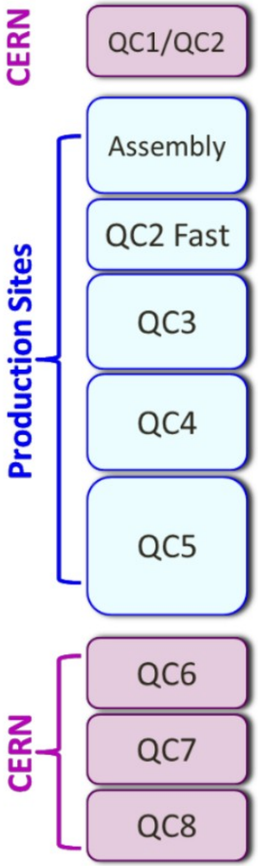
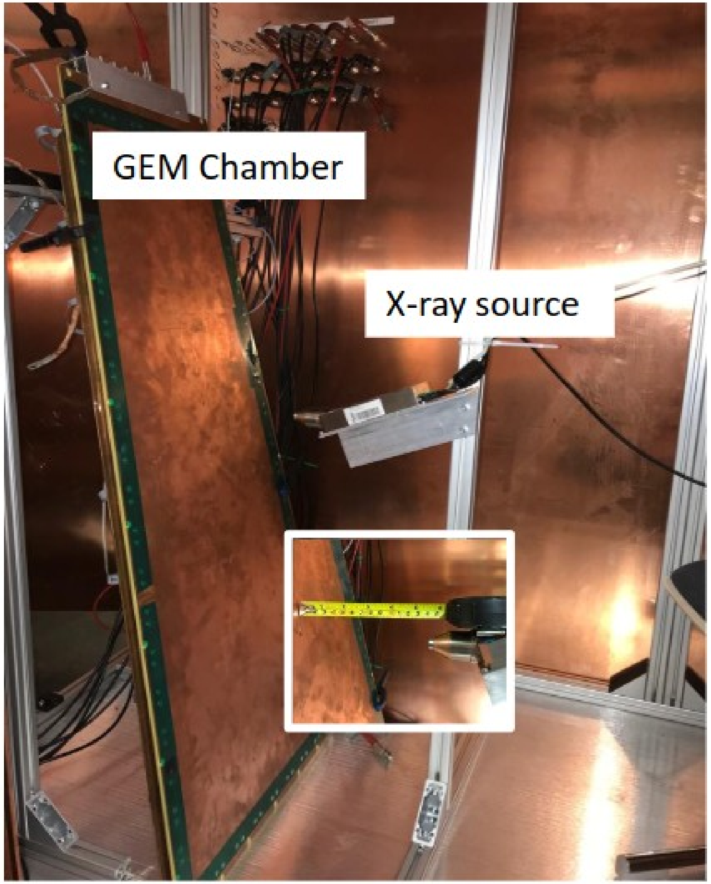


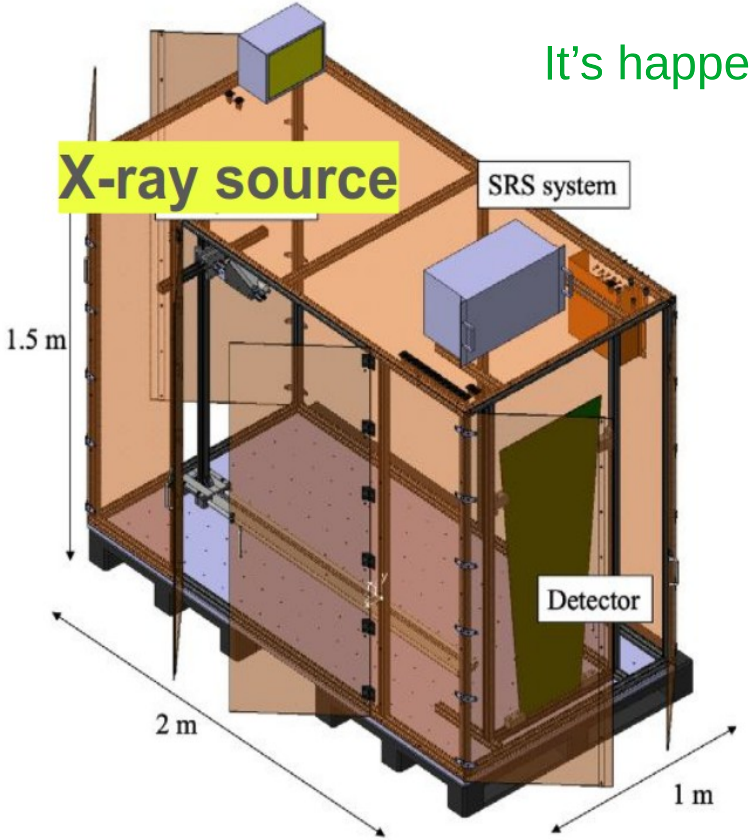
Testbeam + bkg



ME0 Quality Control

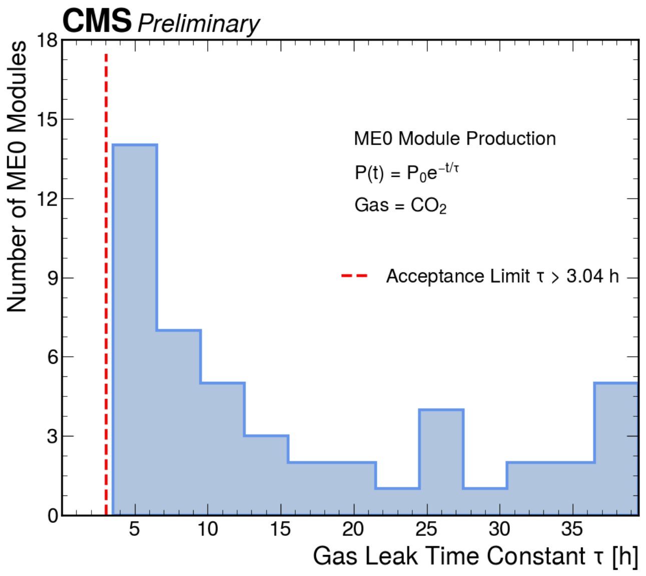






It's happening NOW!

ME0 QC Results



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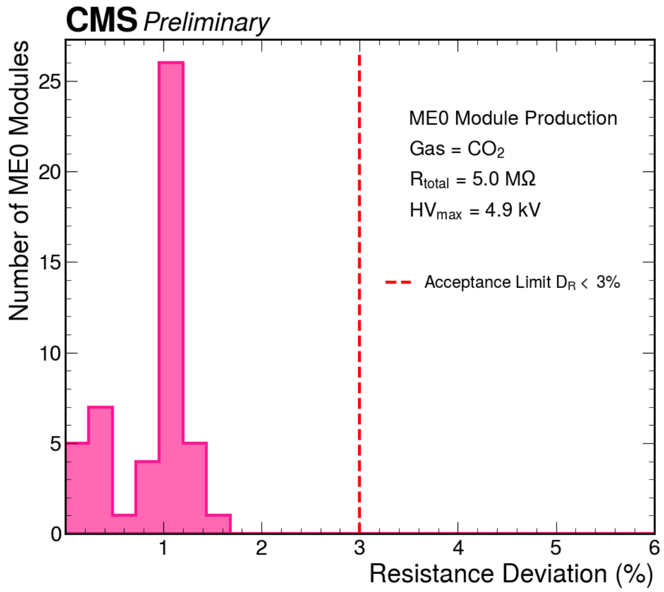


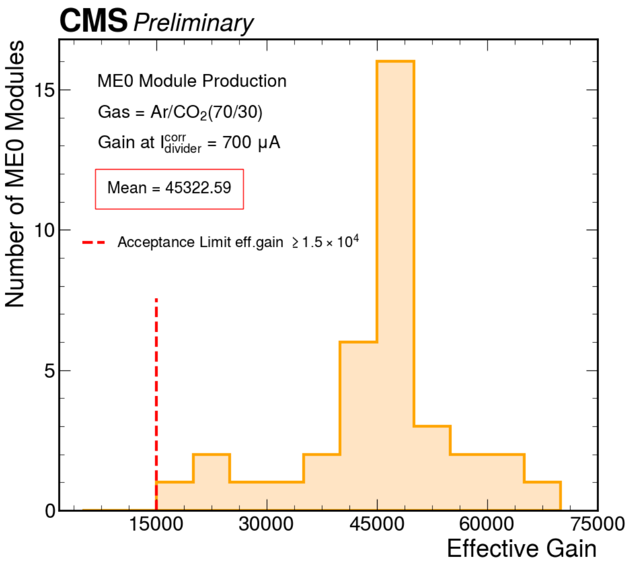
QC3: Gas Tightness

- Overpressure: 25 mbar
- Δp < 7 mbar per hour ($\tau > 3.04$ h)

QC4: HV Stability

- HV scan 200 – 3700 V
- Hold each data point 60 s
- $D_R < 3$ %

ME0 QC Results



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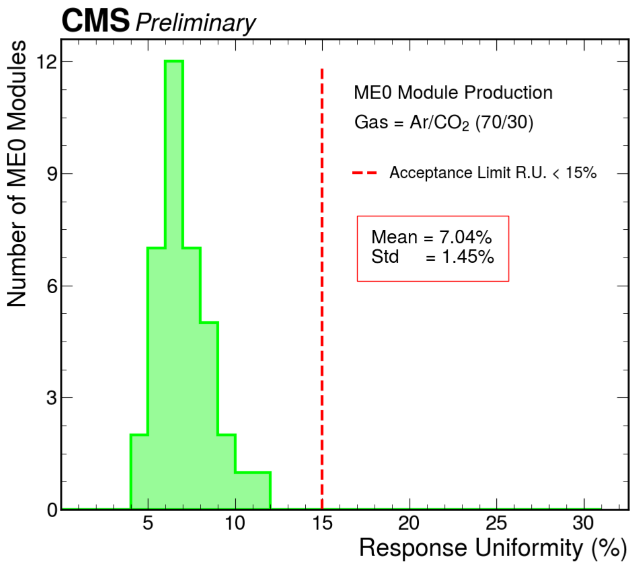


QC5 p1: Effective Gain

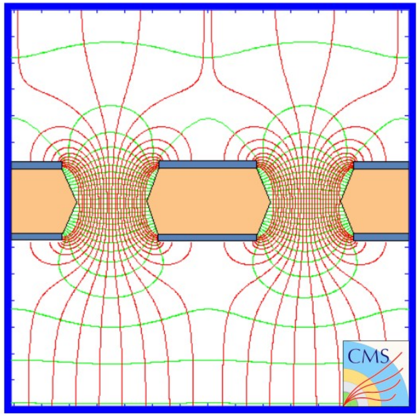
- Measure counts and current for single readout sector
- Check gain as function of HV
- Gain > $1.5x10^4$ @ HV = 3500 V

QC5 p2: Gain Uniformity (R. U.)

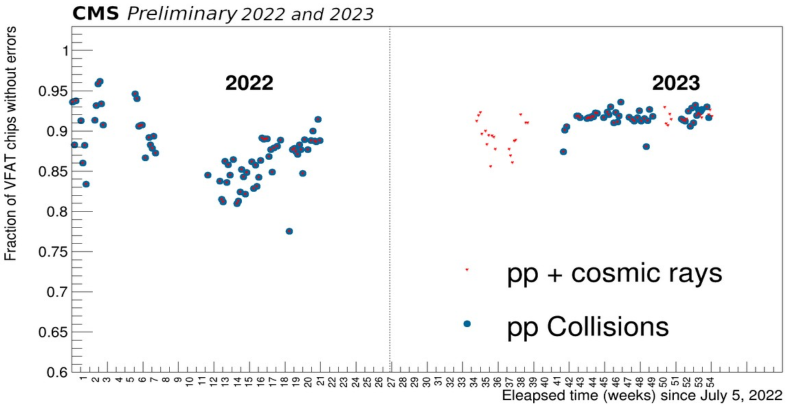
- Measure for all readout sectors
- R. U. < 15 %

Summary

- Micro Structure gas detectors are providing improved resolution and tracking
- First GEM chambers performance looks good so far in Run 3 – Stable!
- More chambers coming for the new upgrade



[2]



[16]

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Questions?

Thanks for your attention!

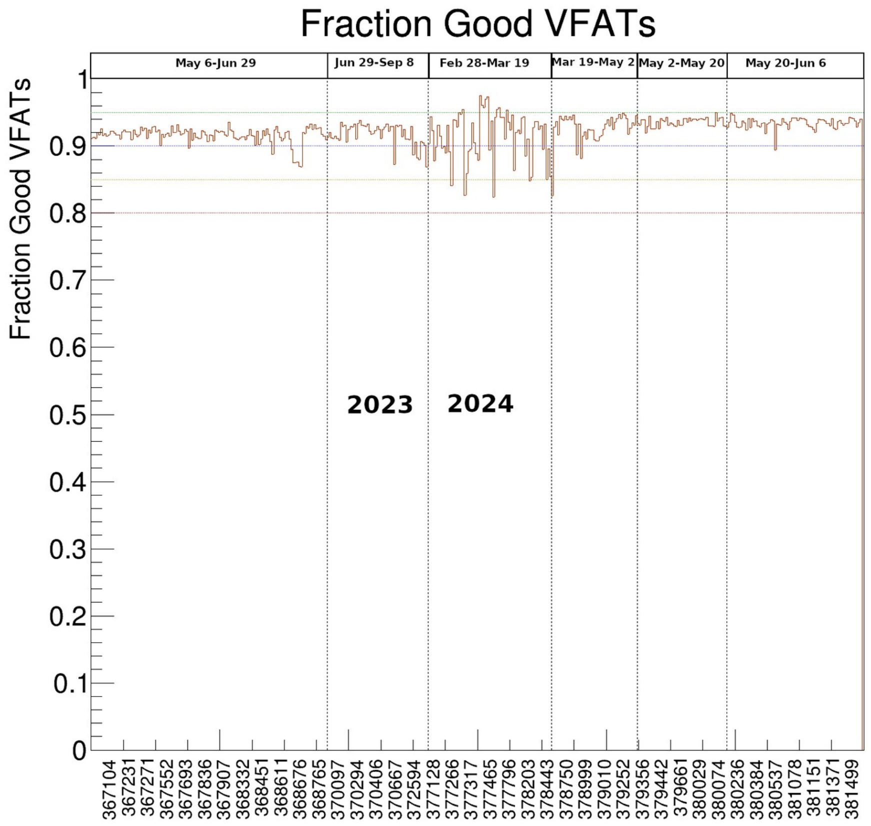
Any Questions?

BACKUP

- BACKUP SLIDES

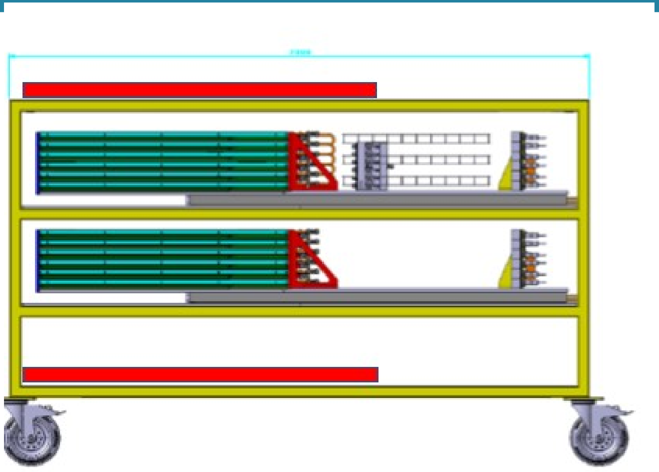
Stable 2024 GEM Front-end Read-out Performance

- In 2023 studies of this performed
- On detector electronics optimization helped solve this problem allowing some “recoverability” of chambers
- Since 2023 GEM electronics readout has been stable
- Current stability is ~94%



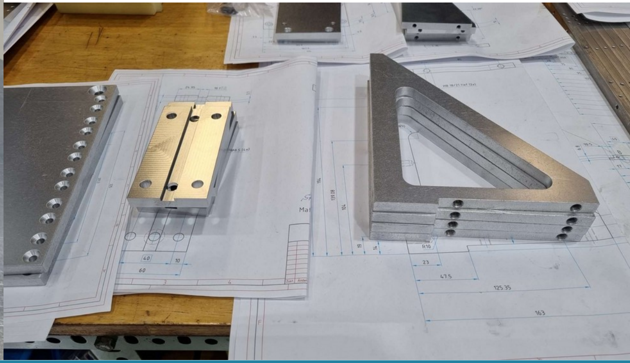
[19]

ME0 Stack Mechanics



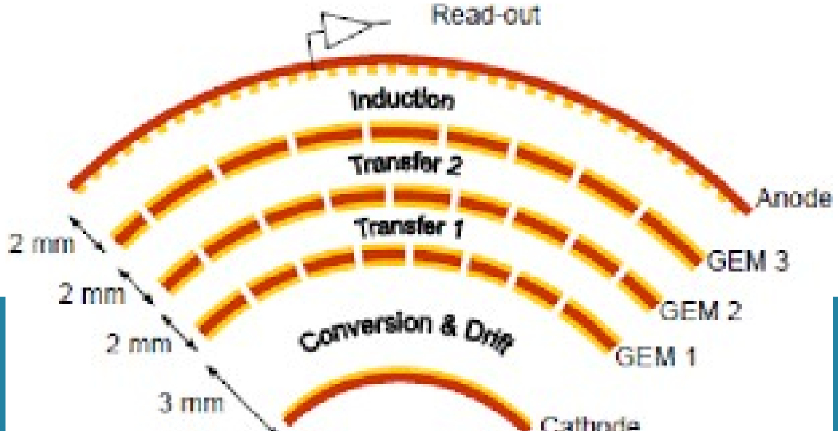
- Aachen has manufactured 15 different components for 220 chambers
- Chamber thickness is critical for disk assembly
- Aachen will also contribute to cosmic ray test stand

  (QC8 -- top)



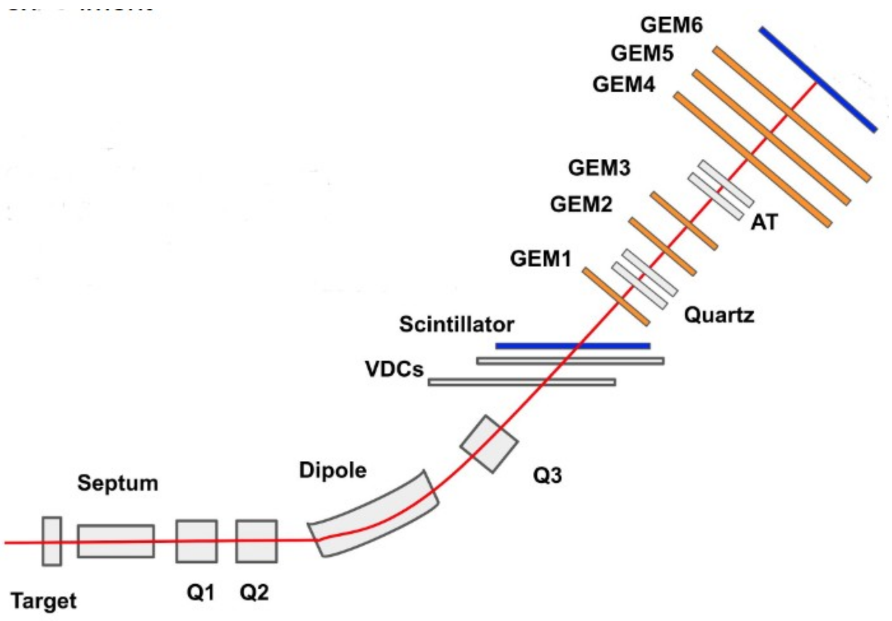
GEMs as Tracking Chamber: KLOE II

- Cylindrical GEM chambers integrate with original Drift chamber
- 4 concentric cylindrical triple GEM detectors
- Higher granularity and improved spatial resolution:
  - Enhanced vertex resolution and tracking precision
  - Higher reconstruction efficiency
  - Coupled with drift chambers yields a more robust tracking system



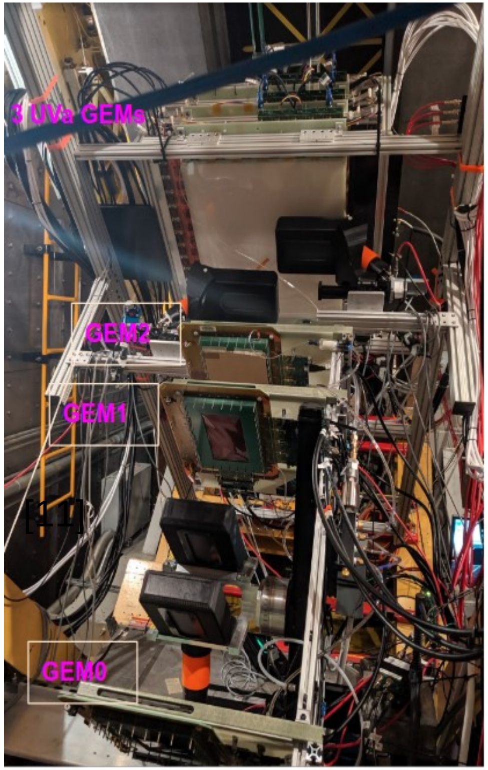
[10]

GEMs in Astrophysics: PREX-II



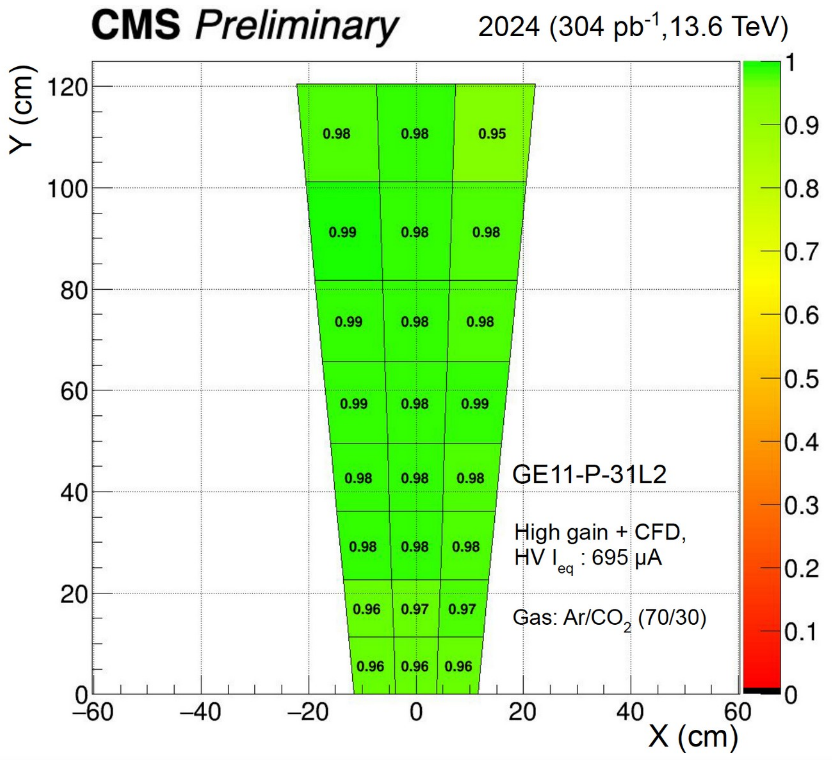
[11]

- Nuclear physics experiment measuring Pb-208
- Spin polarized electrons impinge on “neutron skin” of Pb nucleus
- Scattering asymmetry related to radius of neutron distribution
- Helpful for understanding physics of neutron stars



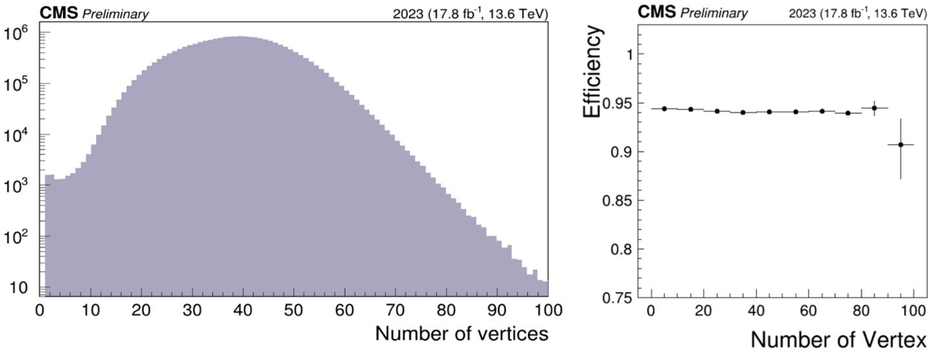
[11]

GE1/1 Efficiency by VFAT



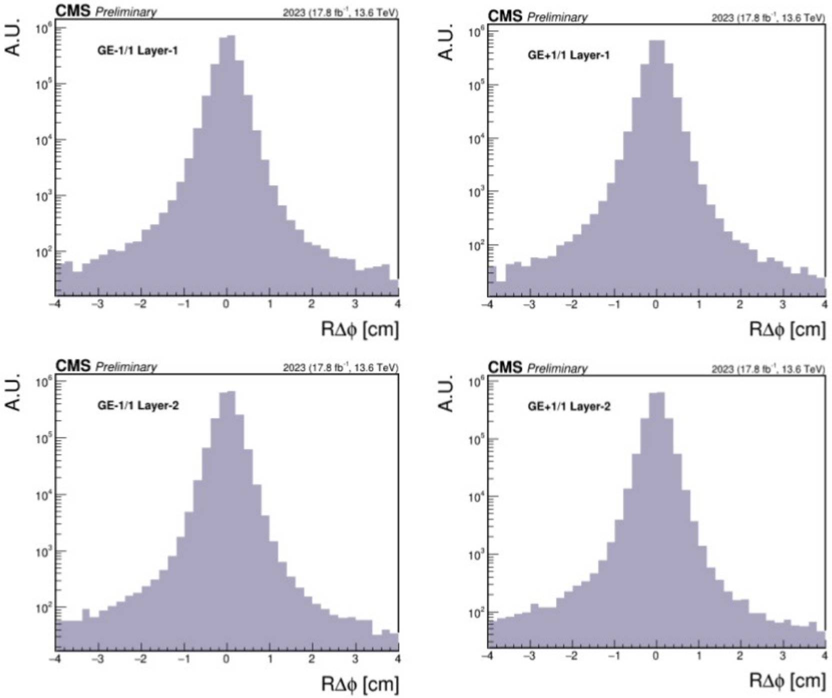
[15]

- Test chamber shown from Positive end cap (GE11-P-31L2)
- Data collected for 304 pb^{-1} using high gain with constant fraction discriminator at HV= 3.45 kV
- Granularity is at VFAT level (128 readout strips)
- Efficiency is ~uniform and high across entire chamber


CMS Preliminary
2023 (17.8 fb-1, 13.6 TeV)
Number of vertices
CMS Preliminary
2023 (17.8 fb-1, 13.6 TeV)
Efficiency
Number of Vertex

[15]

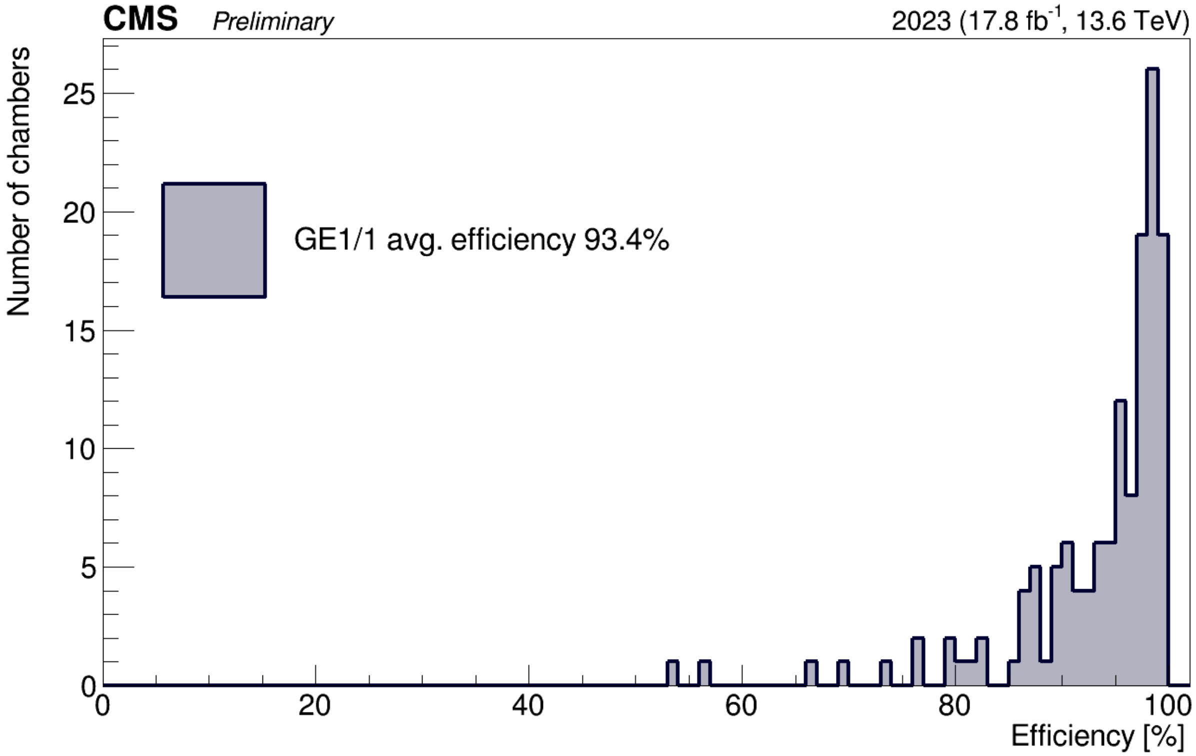
GE1/1 Residual



[15]

- Measure of misalignment
- R(δφ) used due to cylindrical geometry
- Centered on 0 for all parts of detector
- Small spread

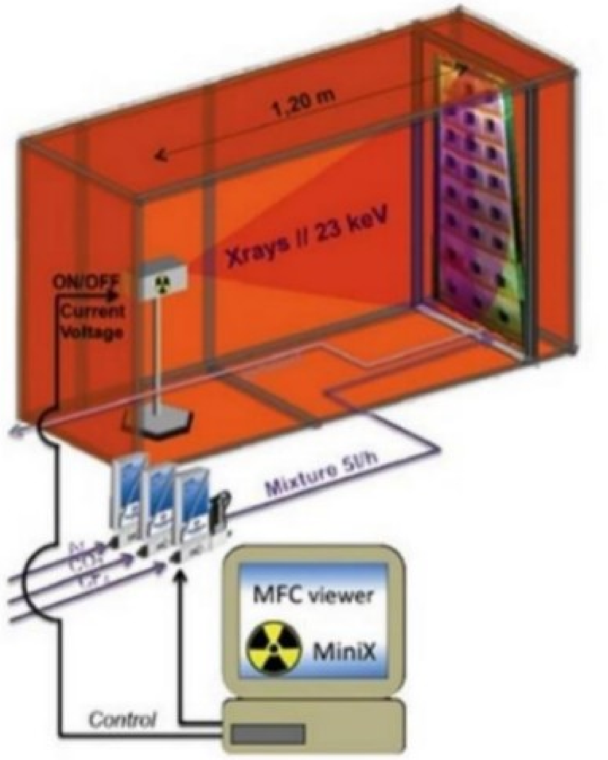
Overview of GE1/1 Chamber Efficiency



[15]

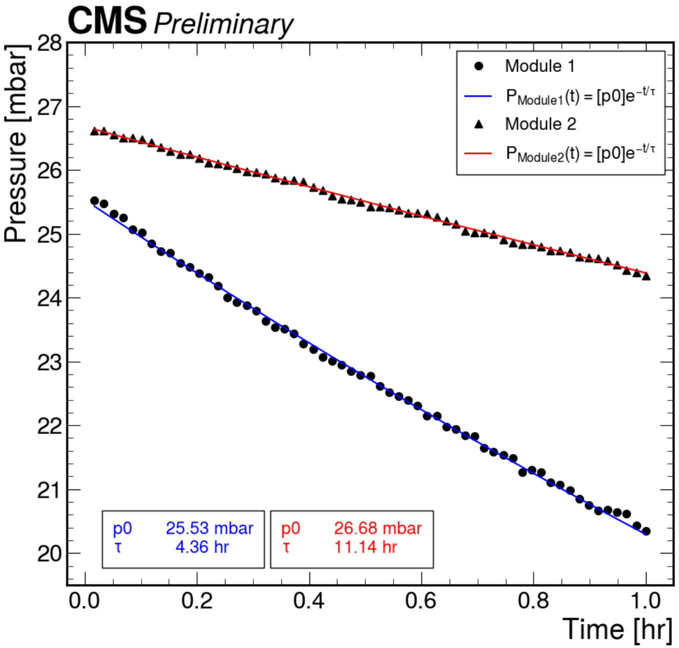
- Most chambers at/above 95% efficiency
- Overall GE1/1 efficiency ~ 93.4 %
- Skewed by few outlier chambers

QC5 part 2



- Measure gain response of entire ME0 chamber
- Chambers flush 5 l/hr Ar:CO_2 > 5 hours with HV = 3.125 kV
  - Gain ~ 800
- Measure 5M events ~24 hours
- Response uniformity (σ/μ) < 15 %
- After passing all QC steps ship back to CERN for completion of remaining QC steps

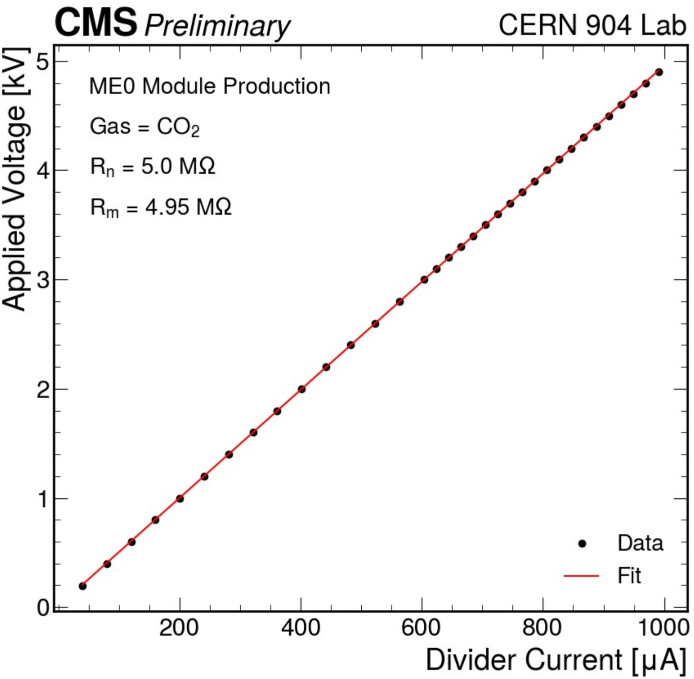
ME0 QC3



[18]

- QC3: Gas Tightness
- 25 mbar overpressure
- 60 minutes
- $\Delta p < 7$ mbar ($\tau > 3.04$)
- 48 chambers tested (all pass)

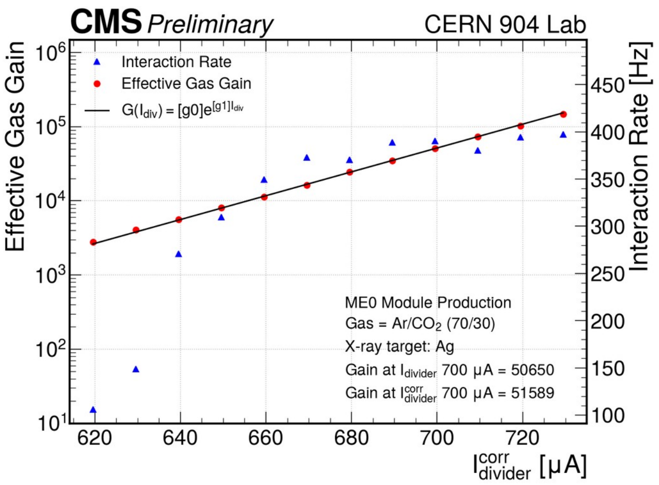
ME0 QC4



[18]

- QC4: HV stability
- Change voltage from 200-3000 V in 200 V steps, 3000-5000 V in 100 V steps
- Hold the voltage at each point for 60 s
- Check relative change in resistance of the chamber

ME0 QC5 part 1

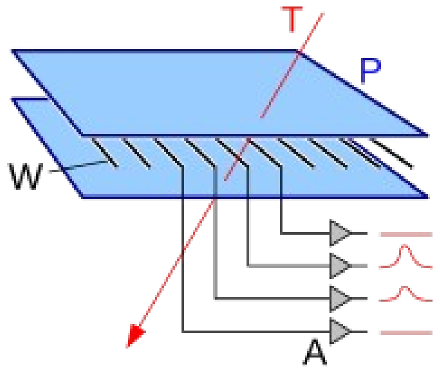


[18]

- QC5p1: Effective Gain
- Flush chamber with 5 l/hr Ar:CO_2
- HV scan 2.9 – 3.7 kV in 50 V steps
- Measure number of counts from single readout
- Measure current from same readout
- Calculate Gain
- Gain > 1.5 x 10^4 @ HV = 3.5 kV

Multiwire Proportional Counters (MWPCs)

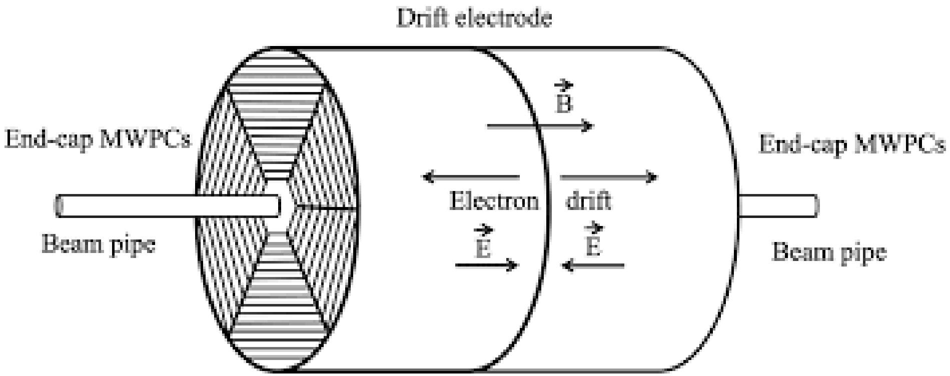
- Similar to traditional proportional counter but has multiple anodes
- Each wire connected to its own readout channel
- With additional anodes spatial resolution increases
- Strongest signal (highest collected charge amplitude) is nearest wire



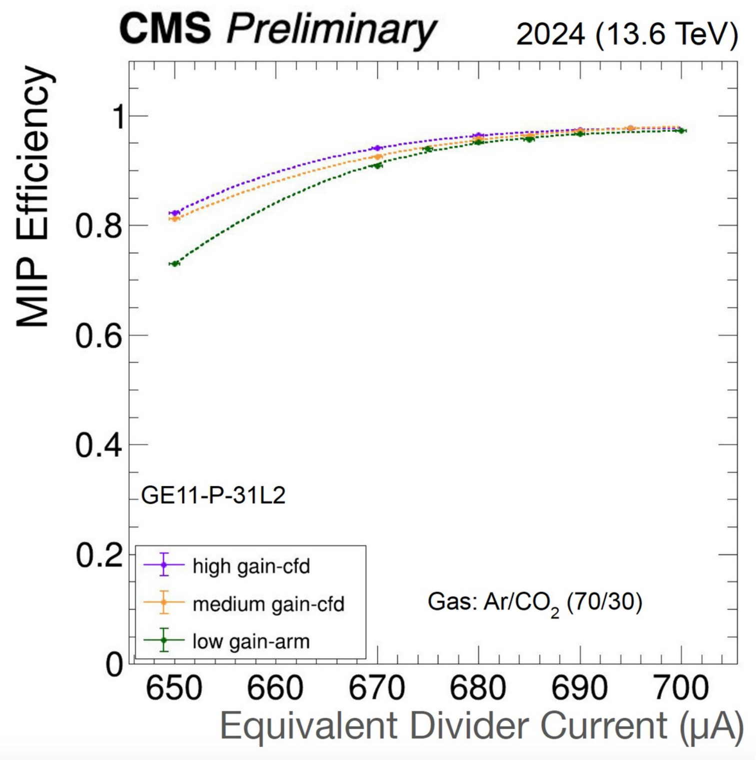
[7]

Time Projection Chambers

- Cylindrical gas volume split with electric field in opposite directions (Each half has its own electric field)
- Ends of chamber capped by MWPCs
- Magnetic field applied to reduce electron diffusion
- Anode wires arranged in azimuthal direction for radial sensitivity
- Cathode plane divided into strips in radial dimension to provide azimuthal sensitivity
- Z-coordinate measured from drift time



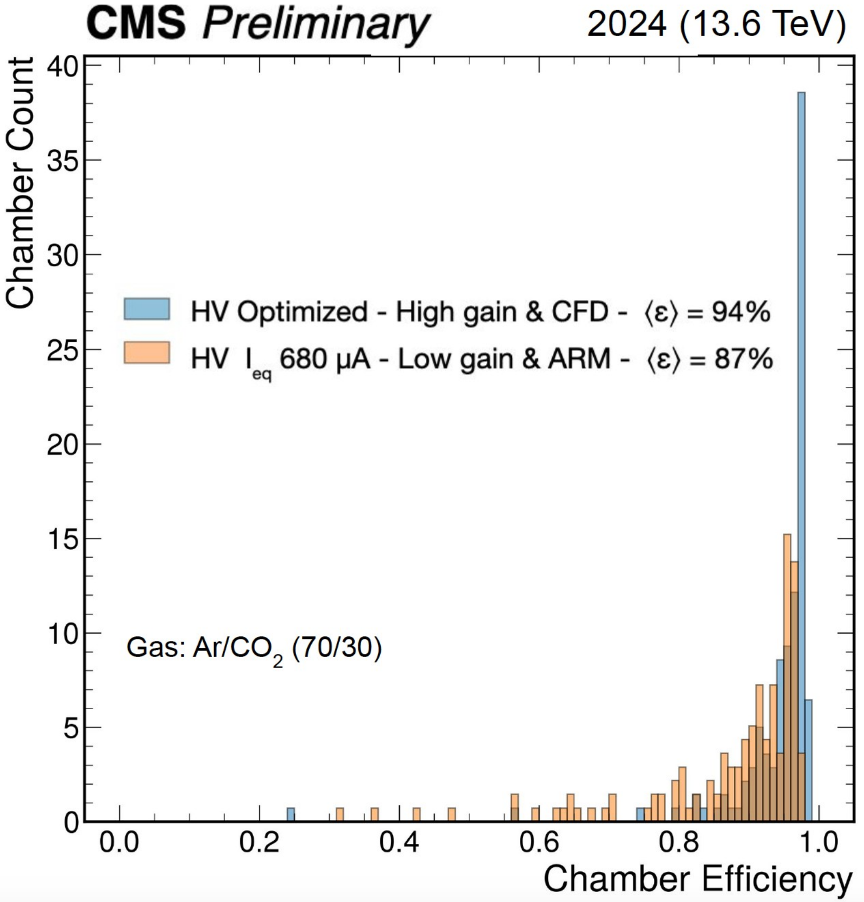
GE1/1 2024 MIP Efficiency vs HV



[19]

- Test chamber shown from Positive end cap (GE11-P-31L2)
- HV scan (3.25 – 3.50 kV)
- Low, medium, high gain shown
- Constant fraction discriminator used
- Reconstruction efficiency increases as HV and gain increase

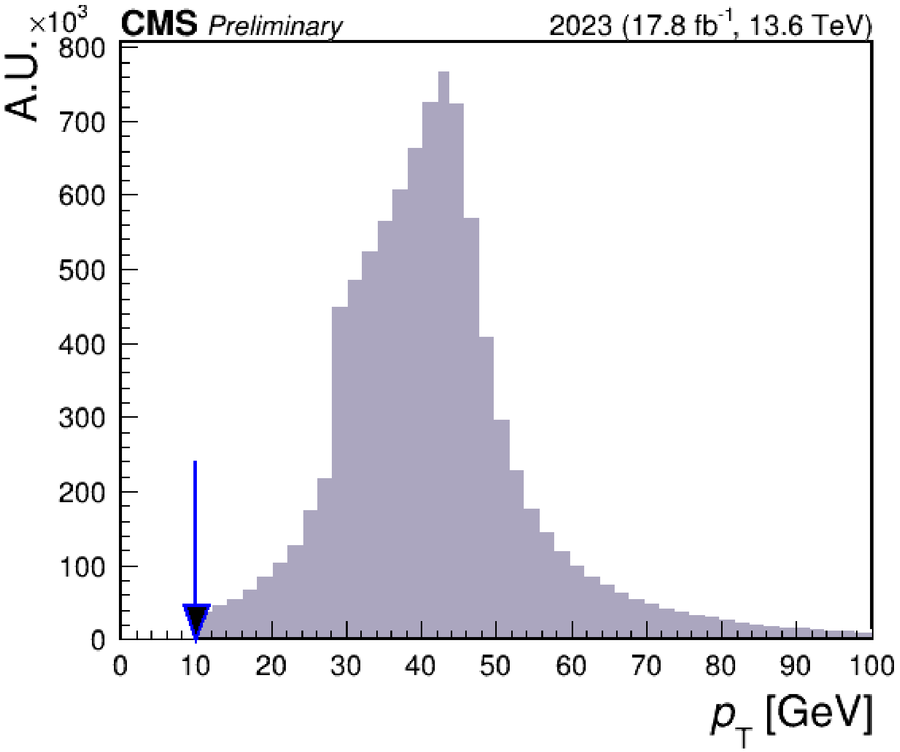
Efficiency Optimized for Gain



[19]

- Measurable difference between low & high gains as well as with/without constant fraction discriminator
- Almost all chamber efficiencies improve

GE1/1 2023 Performance Data set



[15]

- 17.8 fb^{-1} data
- Muon data collected by GEM
- 10 GeV < p_T < 100 GeV