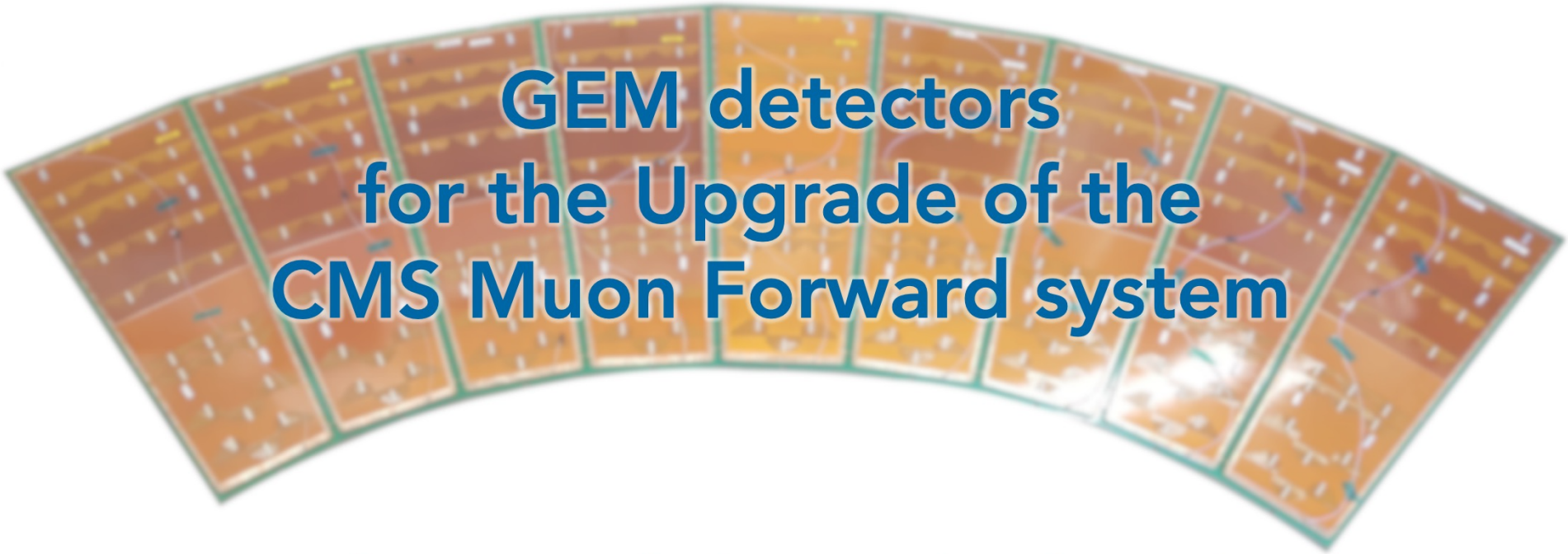


GEM detectors for the Upgrade of the CMS Muon Forward system

Giovanni Mocellin (RWTH Aachen, Germany)

on behalf of the CMS Muon Group

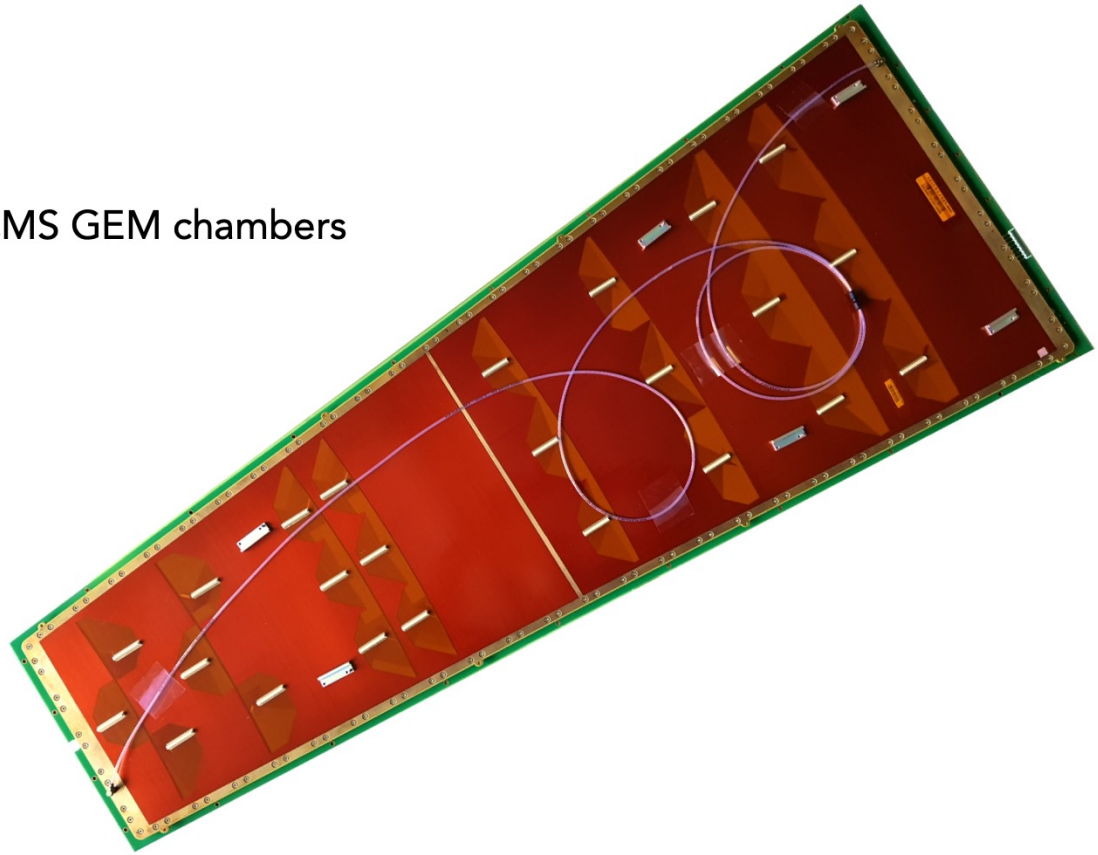
Bundesministerium für Bildung und Forschung

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Outline

- Endcap muon upgrade overview
- GEM in CMS integration plans
- GEM technology
- CMS GEM detectors
- Production and Quality Control of CMS GEM chambers
- Slice test in CMS
- Summary



CMS Forward Muon system upgrade

Present 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 (HL-LHC)

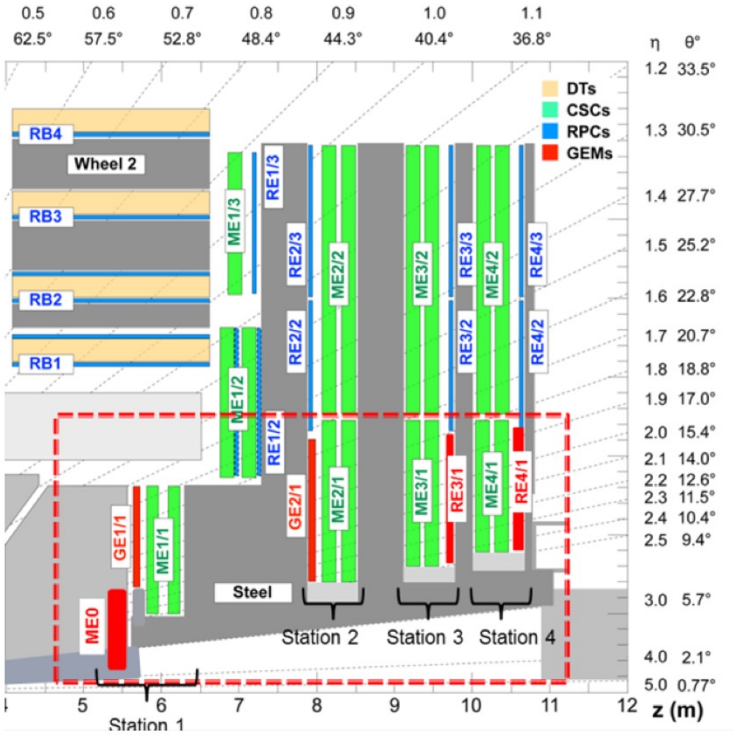
⇒ Increase luminosity to 5×10^{34} $s^{-1}cm^{-2}$ (5x nominal)

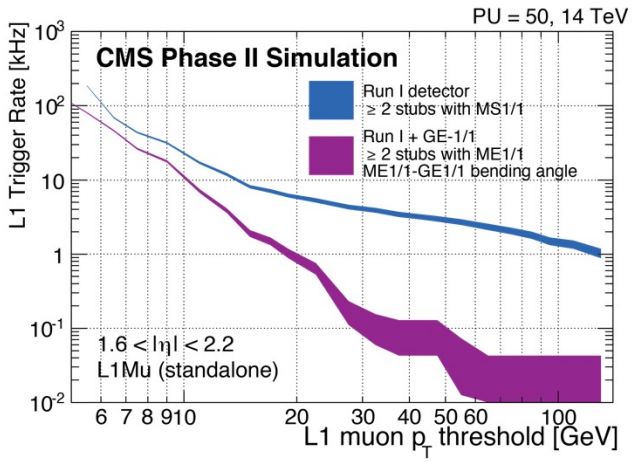
⇒ Upgrade current Muon Forward system:

- Increase redundancy in endcaps
- Improve p_T measurements in low B field (solenoid)
- Control increasing trigger rates

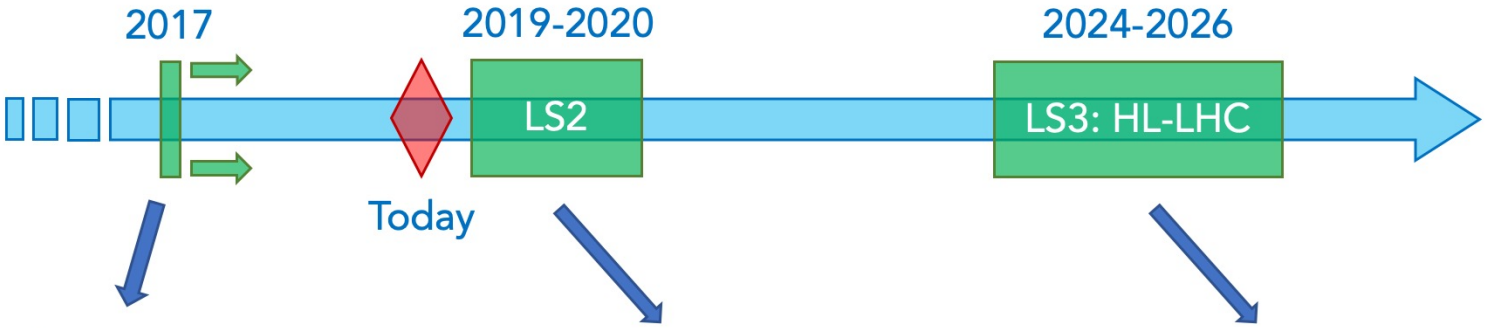
Future installations ($1.5 < |\eta| < 2.8$):

- **GEM** in 1st & 2nd stations
- iRPC in 3rd & 4th stations

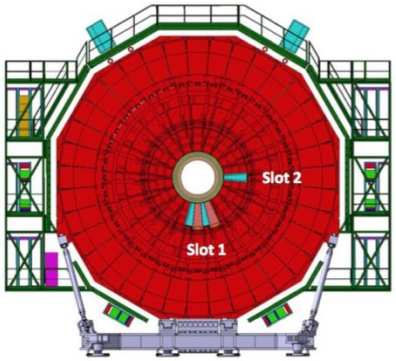




GEM in CMS: integration plans



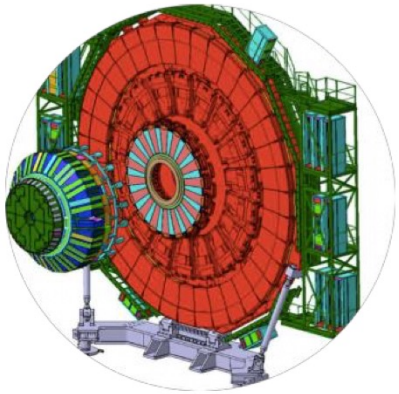
Slice Test



Slice Test = commissioning of 5 **GE1/1** detectors in CMS

1 out of 5 with final readout electronics and HV

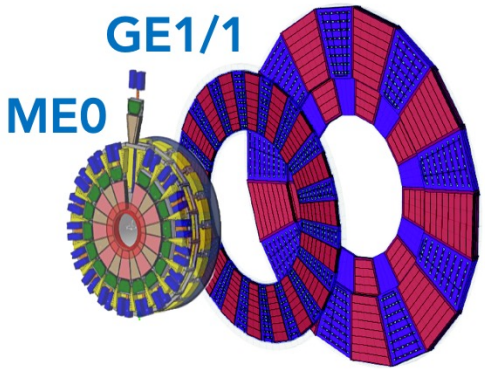
GE1/1



Installation of **GE1/1** during **Long Shutdown 2**

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

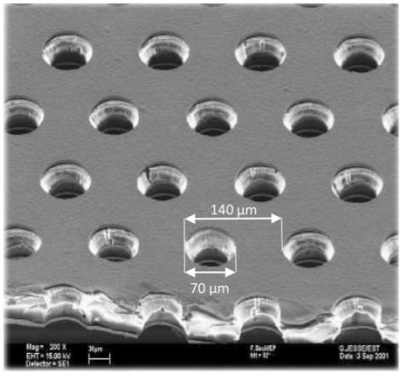
GE2/1



GE2/1 & **ME0** installed by end of **Long Shutdown 3**

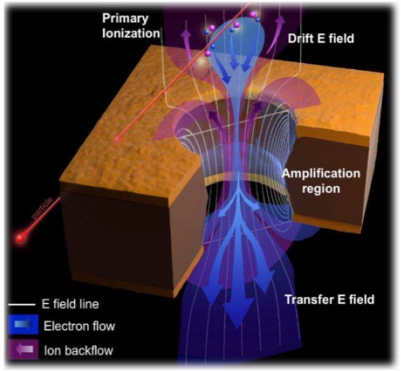
GE2/1 : $1.6 < |\eta| < 2.4$
ME0 : $2.0 < |\eta| < 2.8$

Gas Electron Multiplier technology



GEM foils:

- 50 µm thick copper-cladded polyimide foils
- Holes (diameter = 70 µm) in hexagonal pattern (pitch =140 µm)

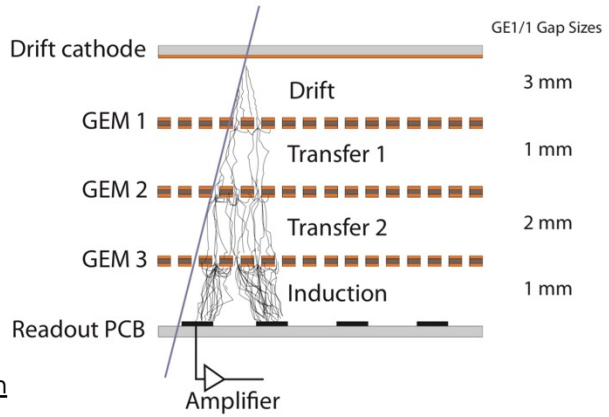


GEM chambers:

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

Performance:

- Rate capability: up to O(MHz/cm^2)
- Triple-GEM chamber efficiency > 97% for MIPs
- No aging effects after 3000 fb^{-1} (and even up to 460 mC/cm^2)



References: https://cds.cern.ch/record/2021453/?ln=en , http://cds.cern.ch/record/2283189?ln=en

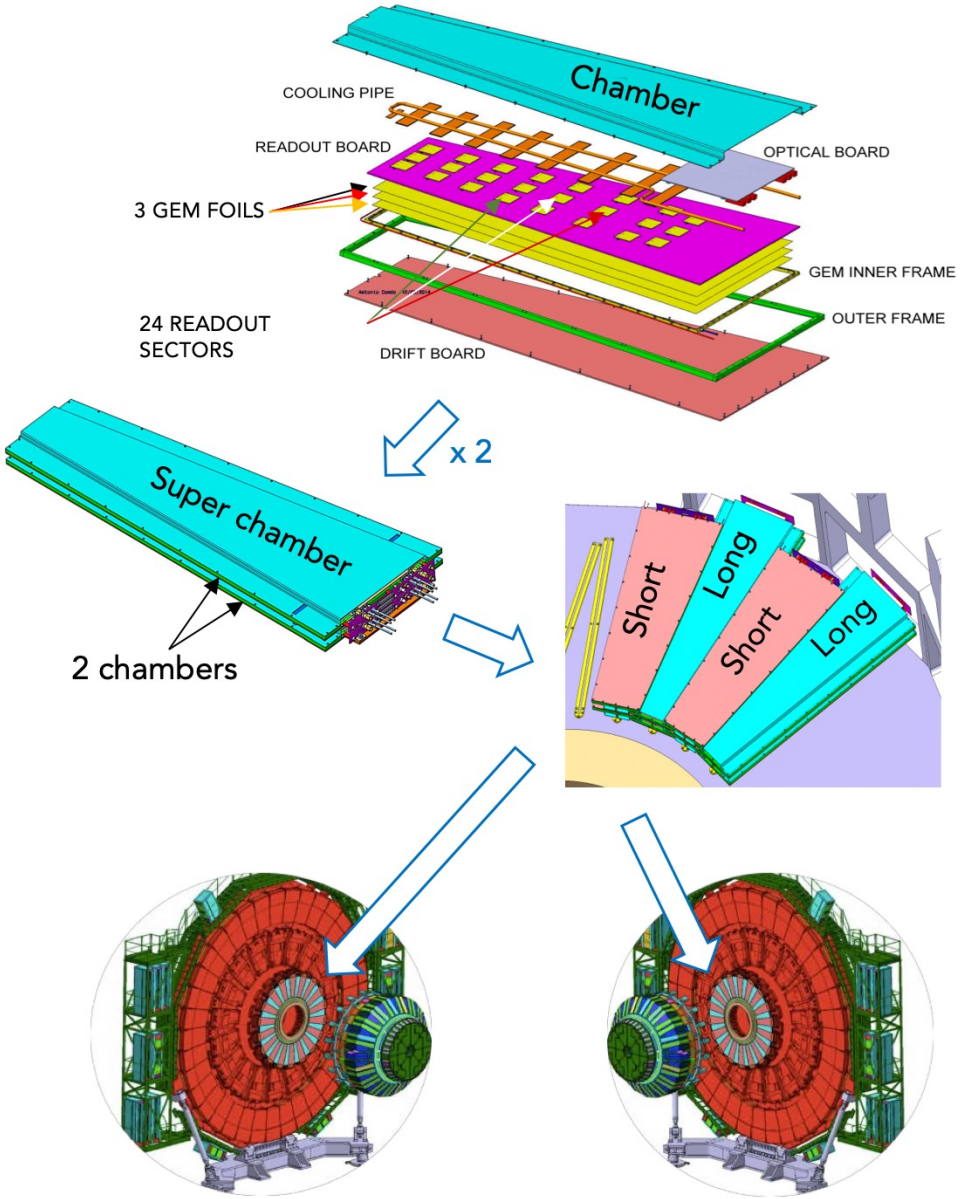
GEM CMS implementation

GE1/1 chambers:

- Triple-GEM chambers
- Gas mixture Ar/CO_2 (70/30 %)
- Large area ($O(m^2)$)
- Covering $1.5\text{-}1.6 < |\eta| < 2.2$

- 144 trapezoidal Long & Short chambers
- 24 readout sectors (8-η x 3-φ) per chamber
- 128 radial strips for each sector
- Digital readout

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



Production steps and Quality Control

Components received at CERN

- QC1: Inspection, tests & cleaning

Shipping to production sites

- QC2: leakage current test

Assembly of chambers

(Shipping to test sites – e.g. Aachen)

- QC3: Gas leak test
- QC4: HV test
- QC5: Gain uniformity test

Shipping to CERN

- QC6: Gas leak + HV tests
- QC_{EL}: Electronics test

Super Chambers are built

- QC8: Cosmic Ray Stand test (CERN)
- QC9: HV stability
- QC10: final gas leak + HV tests

Super Chambers ready for installation

If needed: to production sites for repair

Expected time:

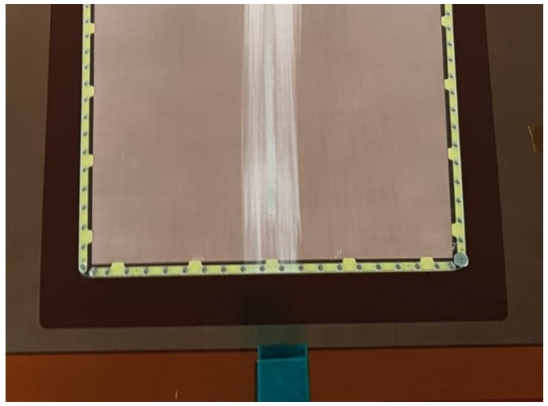
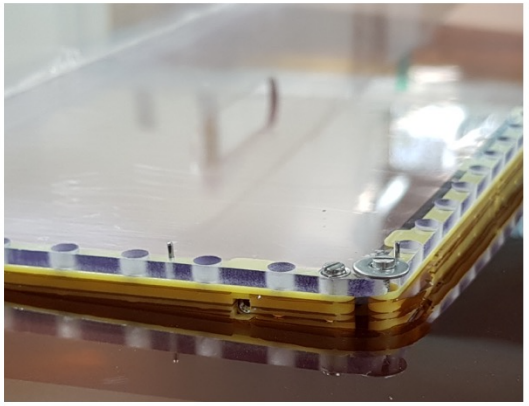
- Each QC test: 1-2 days

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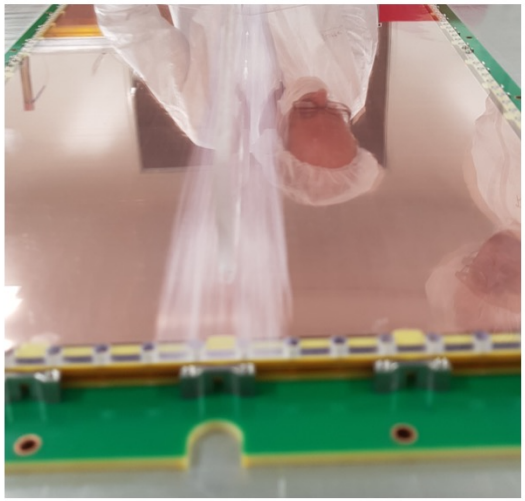
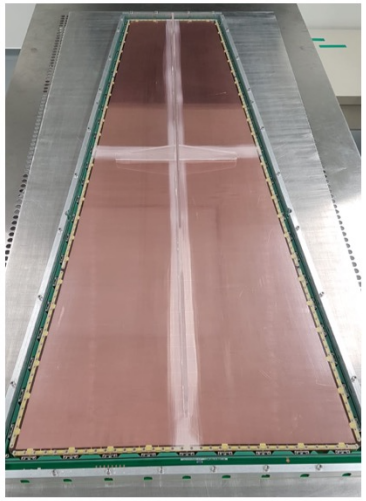


Assembly of a GEM chamber

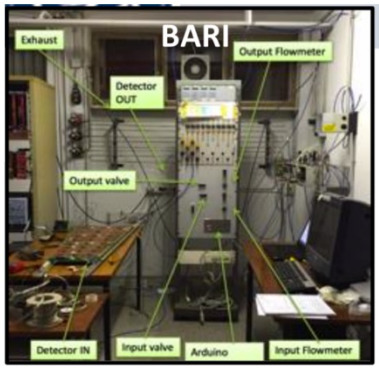
From single foils to triple GEM stack with spacing frames (3/1/2/1 mm) on plexiglass supporting plates.

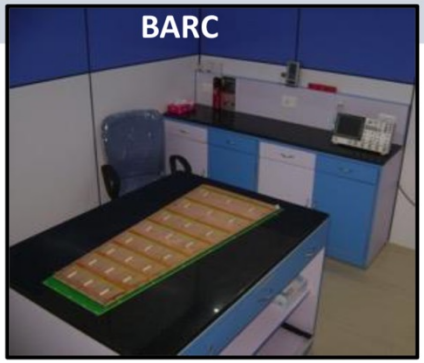




From plexiglass to drift PCB. Stretching of the foils. External frame and readout PCB to finalize the assembly.

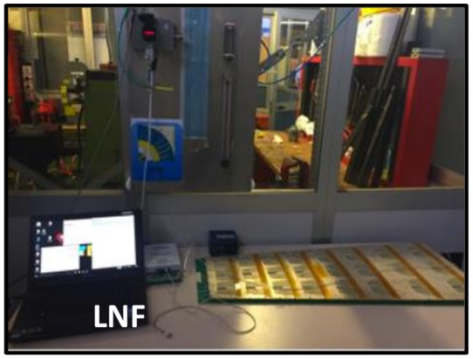

GEM production and test sites









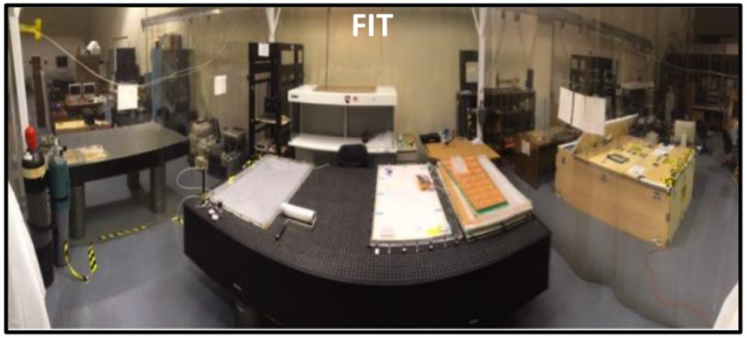








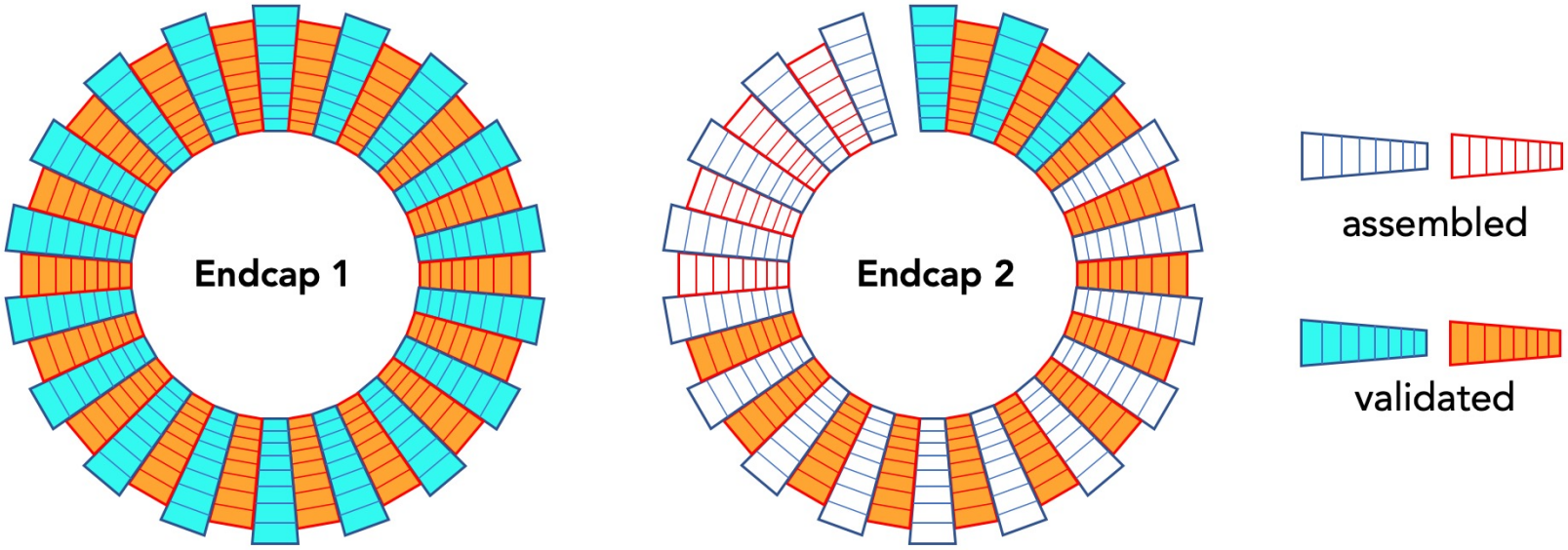




Production and tests status

GE1/1 chamber production status (mid-Sept):

- Total number of single chambers = 144
- Chambers assembled = 142 (99%)
- Chambers validated up to QC5 = 104 (72%)
- 100% of long chambers and 97% of short chambers assembled
- 57% of long chambers and 86% of short chambers validated up to QC5

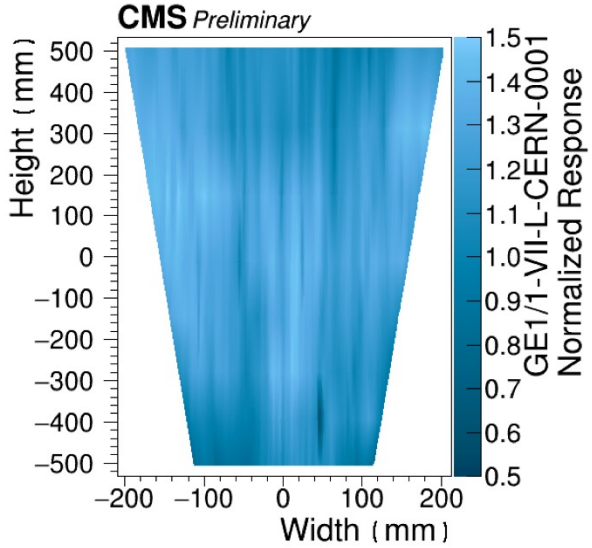


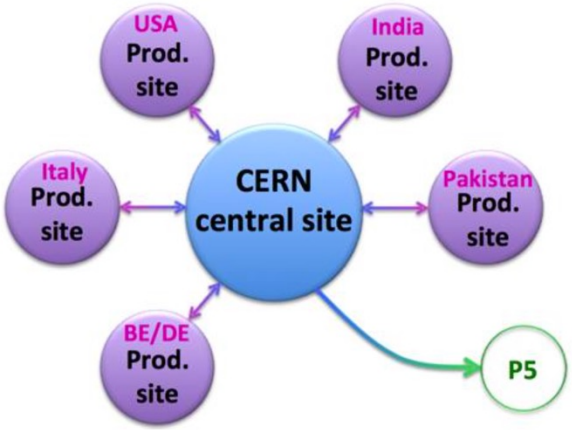
Quality Control Motivations

QC specific reasons for CMS GEM chambers:

- GEM detectors = well known technology, used in other CERN experiments (LHCb, COMPASS)
- CMS GEM chambers: **larger area** ⇒ specific tests to guarantee uniformity
- Production/test sites spread in 7 countries around the globe ⇒ **OK** for sharing knowledge and efforts in the community, **BUT** need to have similar performance everywhere

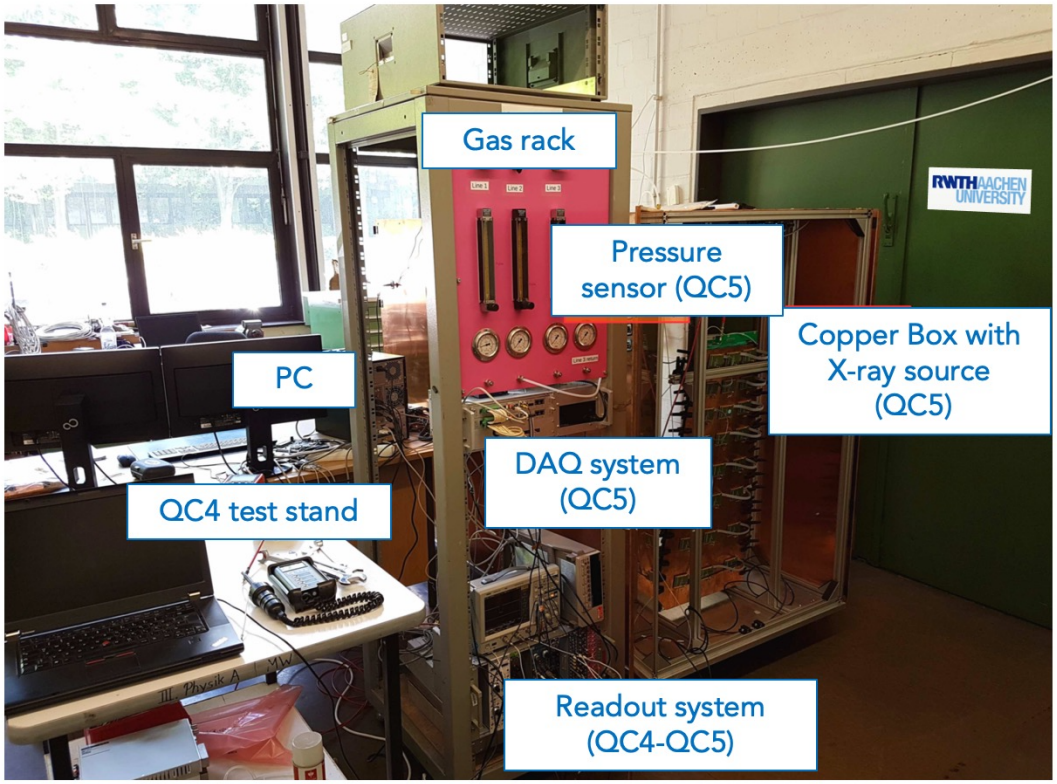
⇒ **Uniformity tests**: gain uniformity (QC5), efficiency map (QC8)





Plot from: https://indico.cern.ch/event/578210/contributions/2343287/attachments/1359406/2058394/GEM_DPS_NOTE_v3.pdf

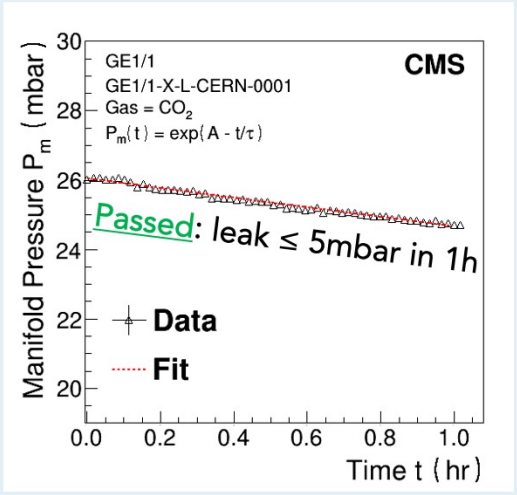
GEM Quality Control Lab in Aachen



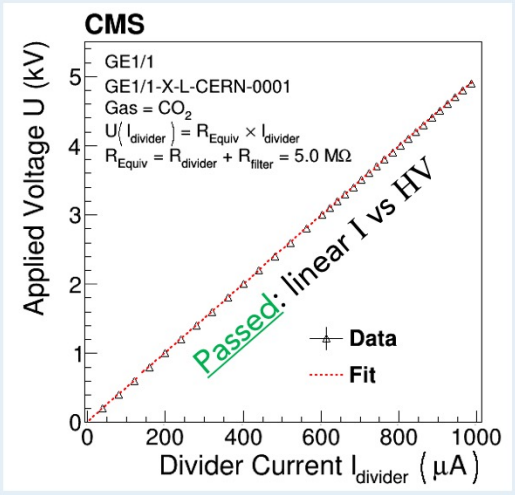


QC3-4-5: single chamber tests

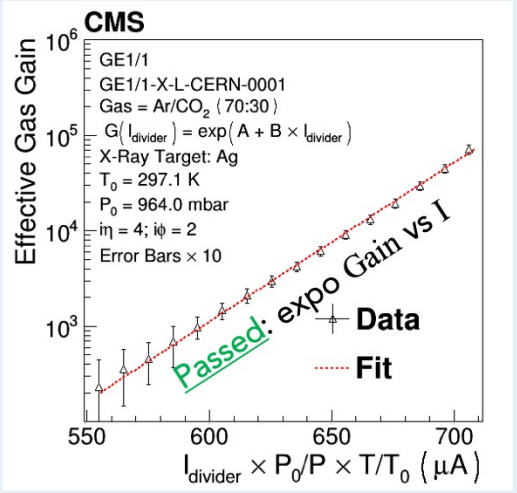
QC3 - Gas leakage test:



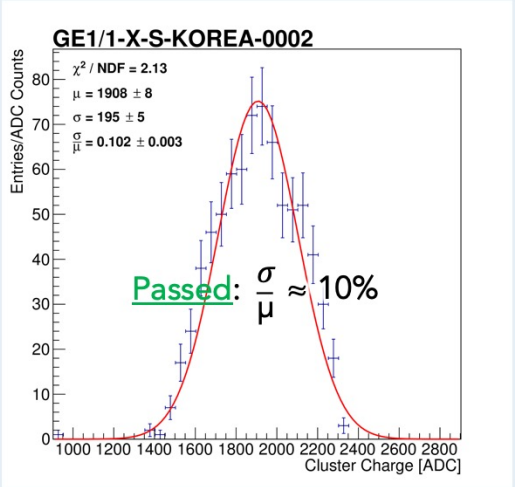
QC4 - HV integrity:



QC5.1 - Effective gas gain w/ X-ray source:



QC5.2 - Gas gain uniformity w/ X-ray source:

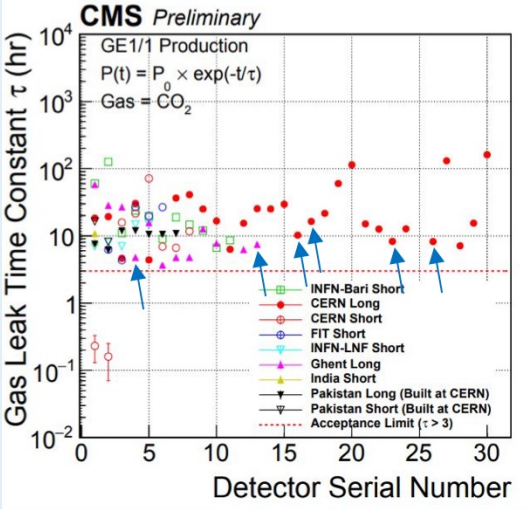


Plots from: https://twiki.cern.ch/twiki/bin/view/CMSPublic/GEMDPGPublic#Public_Results_2018

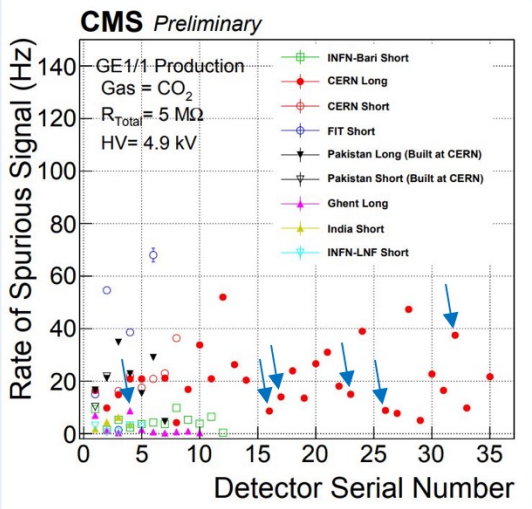
QC3-4-5: Summary results → Tested by:

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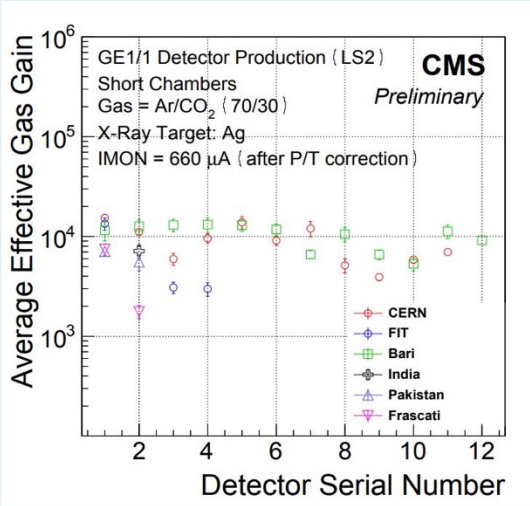
QC3 - Gas leakage test:



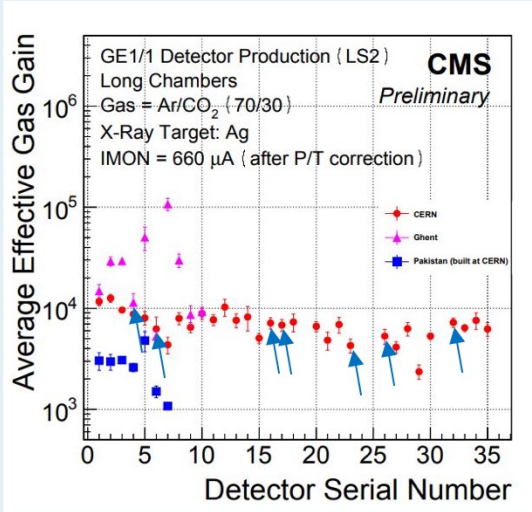
QC4 - HV integrity:



QC5 - Effective gas gain Short Chambers:

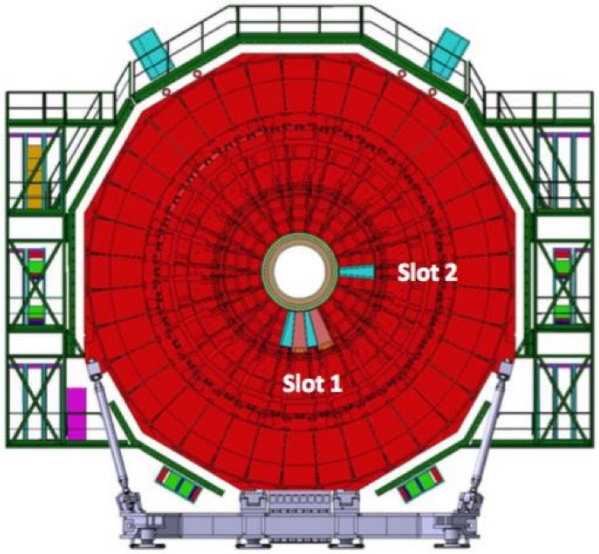


QC5 - Effective gas gain Long Chambers:



Plots from: https://twiki.cern.ch/twiki/bin/view/CMSPublic/GEMDPGPublic#Public_Results_2018

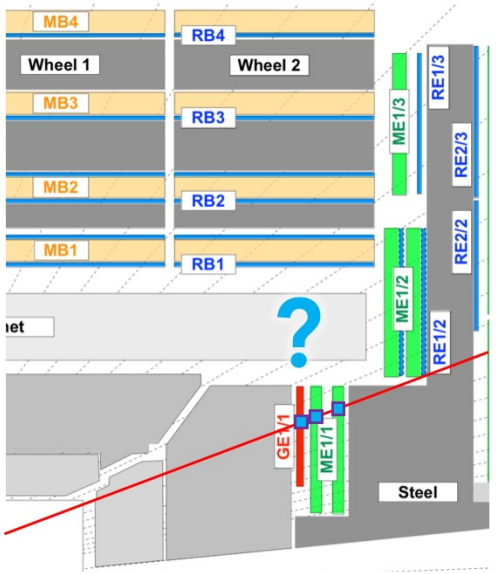
Integration in CMS: Slice Test



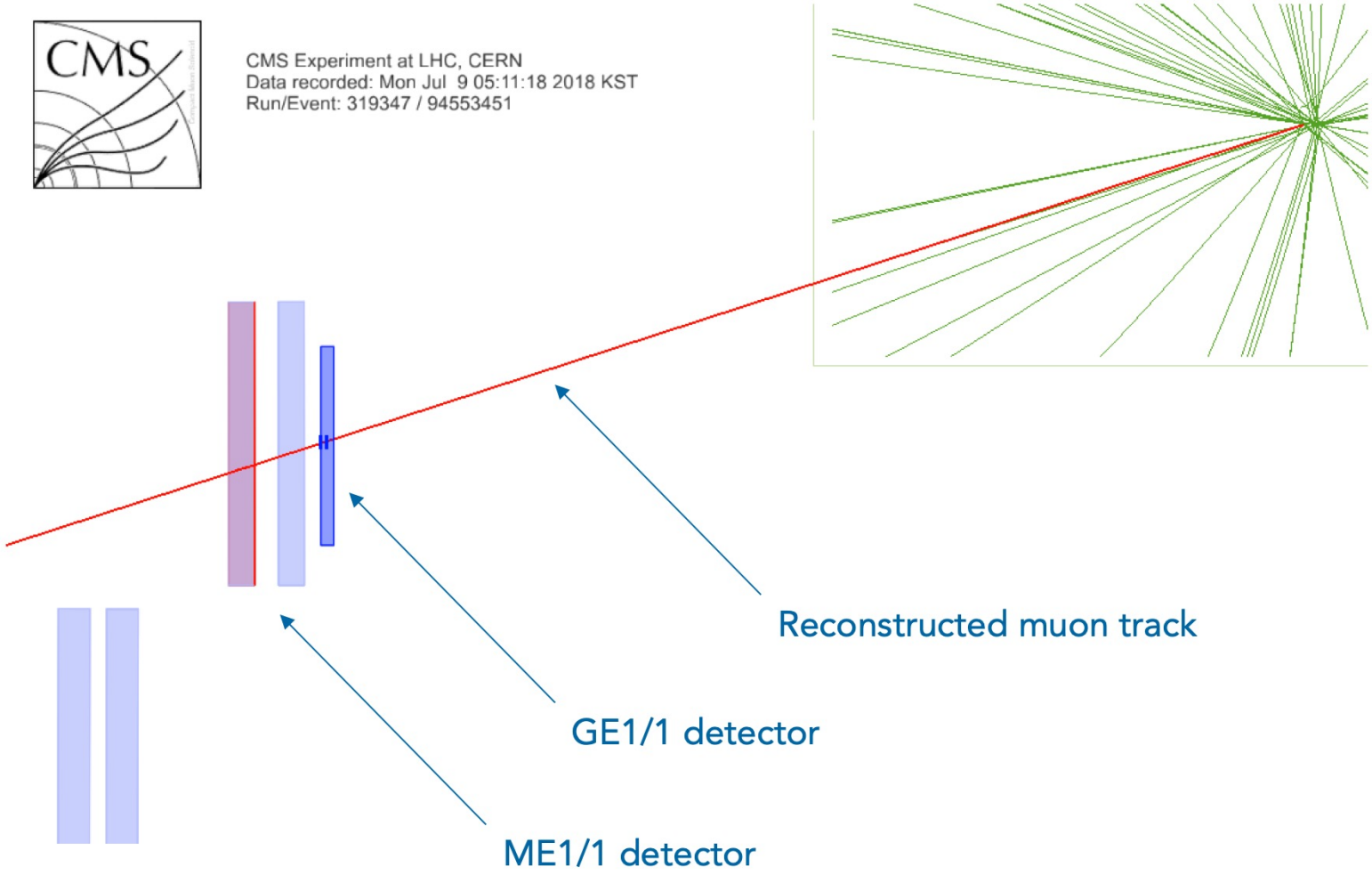
- 5 **GE1/1** detectors under commissioning in one of the endcap of CMS
- Detector in 'Slot 2' equipped with final readout electronics and HV power supply
- For future installation, essential to have an integration of some detectors both in Detector Control System and Data Acquisition

GEM subdetector in CMS:

- CMS is a complex and already fully operational experiment with many subdetectors
- Challenging but successful participation into global operations (DCS & DAQ)
- Local scans and data collected in collisions used for performance studies and for parameter optimization



Slice Test: **Success!**



Summary

CMS Forward Muon upgrade:

- New **GEM** detectors: - increase redundancy in CMS endcaps
  - keep/improve trigger/reco performance at high **η**

- Already **99%** of GE1/1 single **chambers assembled** & 72% fully validated up to QC5

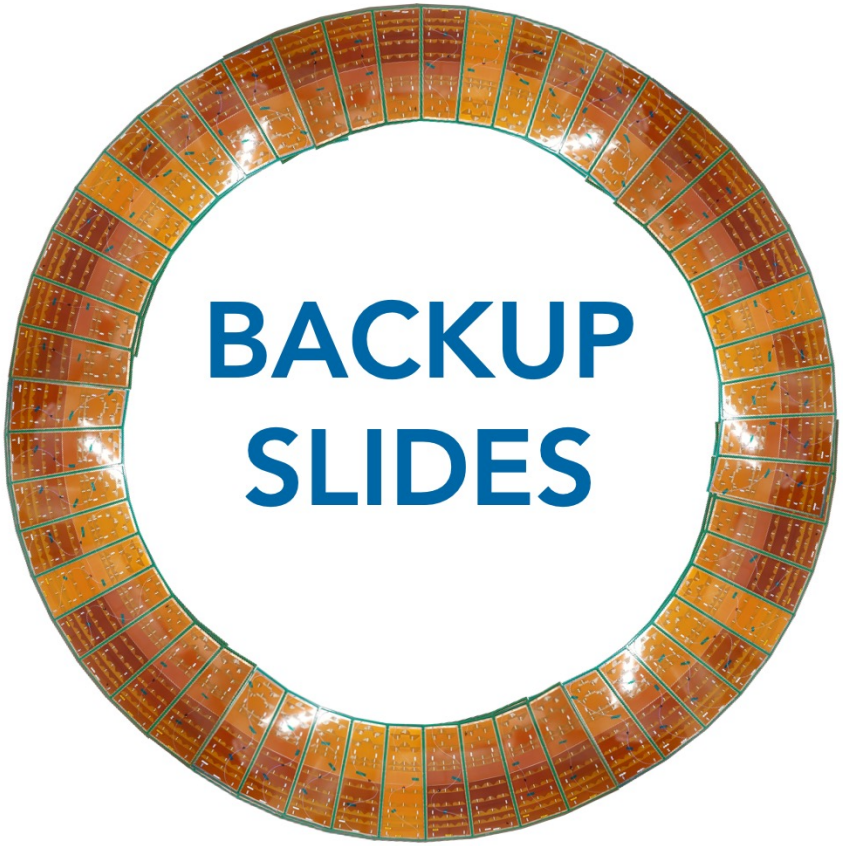
Tests for CMS GEM detectors:

- In test sites (e.g. Aachen) ⇒ Quality of components and assembly of Chambers:
  - Gas leakage
  - HV integrity
  - Effective gas gain / Gas gain uniformity

- Test @ CERN ⇒ Slice test:
  - Participating in global operations (DCS & DAQ)
  - Local scans and global data taking

Ready for scaling up the slice test and install all the detectors next year – looking forward to new discoveries!

THANK YOU!

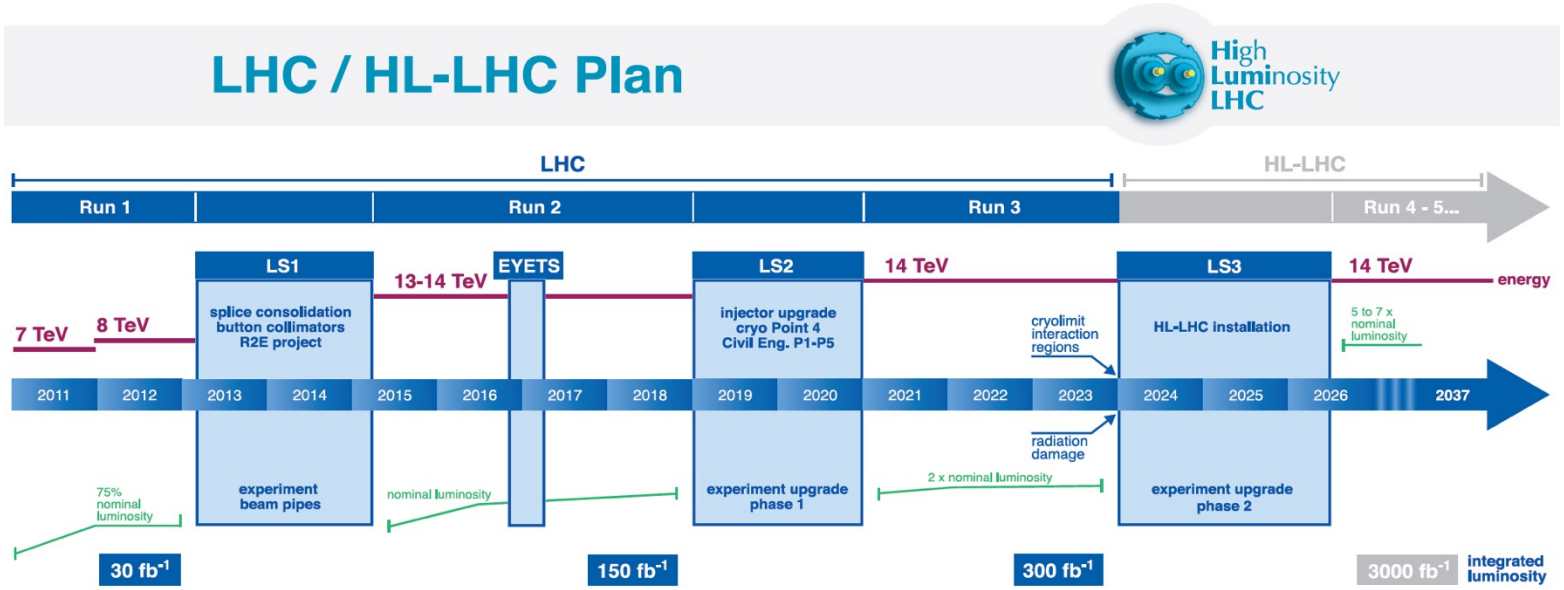


BACKUP SLIDES

Motivation for CMS upgrade

LHC Phase II: High-Luminosity LHC (HL-LHC)

⇒ Increase luminosity to 5×10^{34} $s^{-1}cm^{-2}$ (5x nominal)

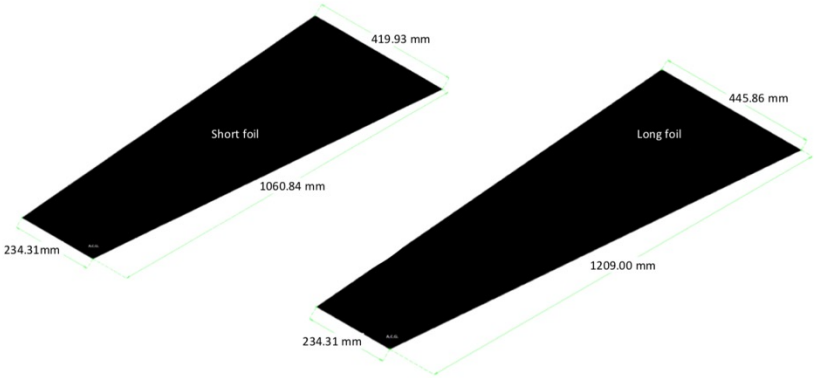


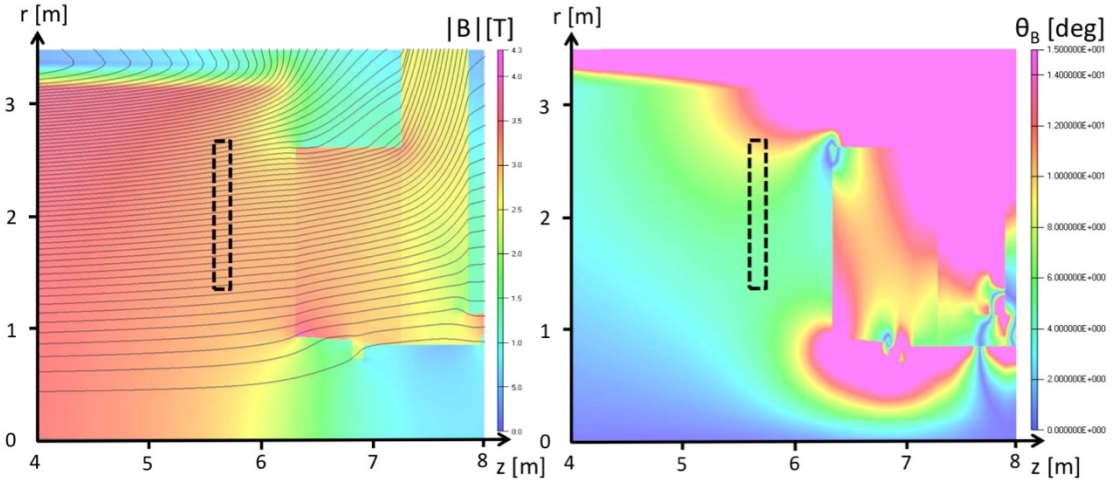
LHC experiments need upgrades to:

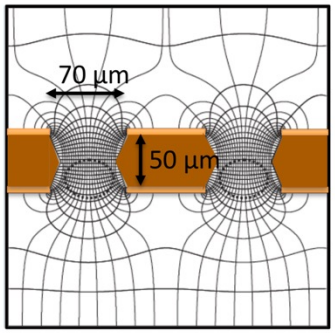
- Maintain the performance with higher rates
- Improve the particle identification with increased pile-up
- Keep low trigger rates

GEM foils & GE1/1 specs

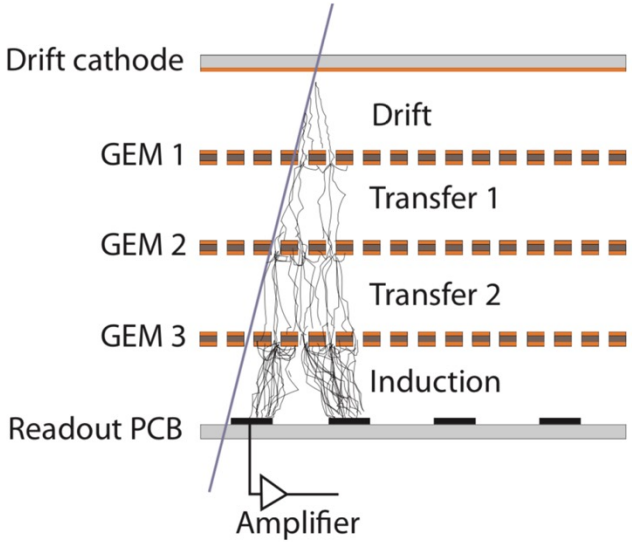
Specification / Parameter	GE1/1
Detector technology	Gaseous detector; micro-pattern gas detector (MPGD)
Charge amplification element	GEM foil (triple, cascaded, tensioned at ≈ 5 N/cm)
Number of chambers in overall system	144 (72 in each endcap)
Chamber shape (active readout area)	Trapezoidal; opening angle 10.15°
Active area overlap in adjacent chambers	2.6 mrad (corresponds to 5.7 readout strip pitches)
Short chamber dimensions (active vol.)	L: 106.1 cm (center line), W: (23.1 - 42.0) cm, D: 0.7 cm
Long chamber dimensions (active vol.)	L: 120.9 cm (center line), W: (23.1 - 44.6) cm, D: 0.7 cm
Total chamber thickness	D: 3.5 cm
Active readout area	0.345 m^2 (short ch.); 0.409 m^2 (long ch.)
Active chamber volume	2.6 liters (short ch.); 3 liters (long ch.)
Radial distance from beam line	130.2 cm (at inner edge of active readout area)
Geometric acceptance in η	1.61 - 2.18 (short ch.); 1.55 - 2.18 (long ch.)
Signal readout structure	Truly radial readout strips
Readout strip dimensions	230 μrad angular strip width; 463 μrad angular pitch
Number of η-segments in readout	8
Number of readout strips per η-segment	384
Number of readout strips per chamber	3,072
Counting gas mixtures	Ar/CO_2 70:30 or $Ar/CO_2/CF_4$ 45:15:40
Nominal operational gas flow	1 chamber volume per hour
Number of gas inlets	1
Number of gas outlets	1
Nominal HV applied to drift electrode	3200 V (Ar/CO_2); 4000 V ($Ar/CO_2/CF_4$)
Nominal operational gas gain	1-2 $\times 10^4$
Demonstrated rate capability	100 MHz/cm^2



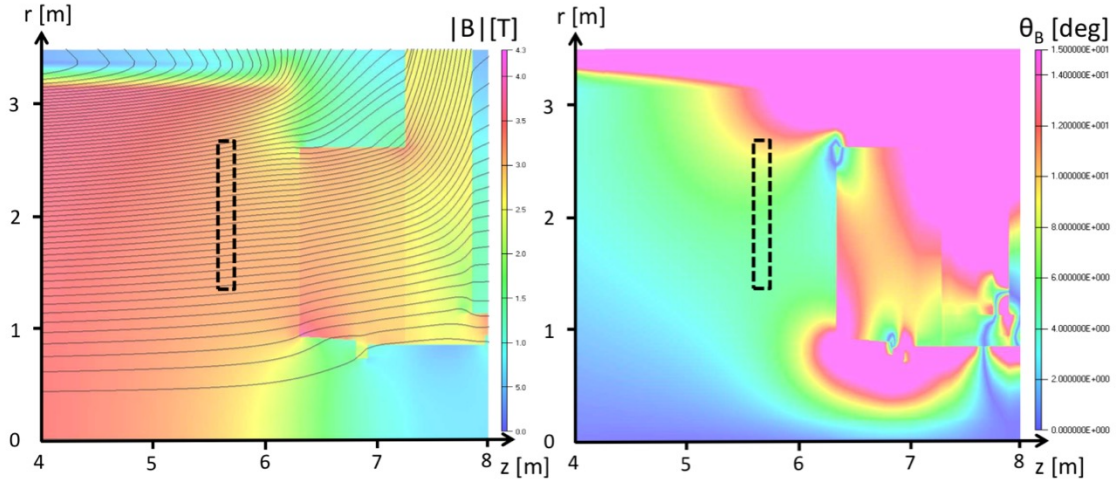


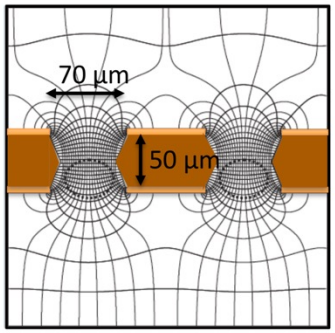


GEM foils & GE1/1 specs

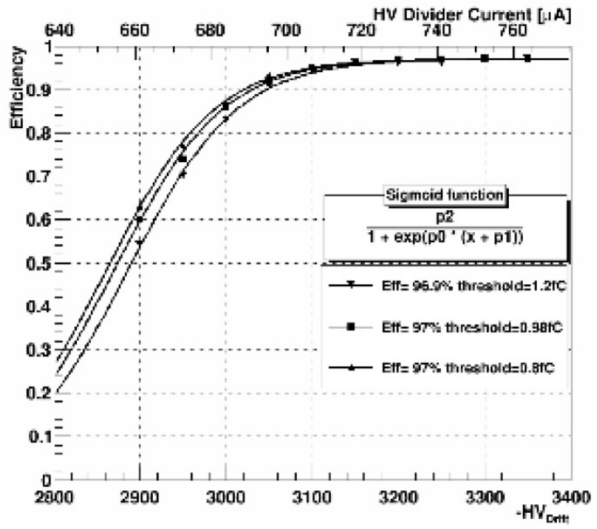


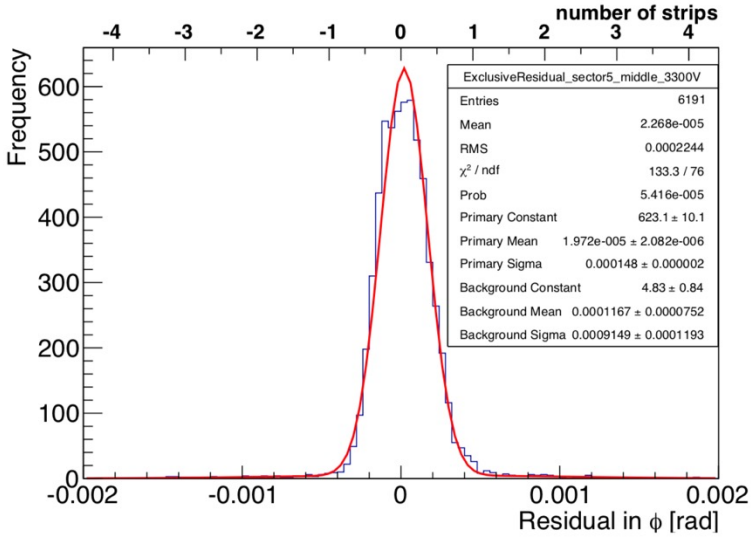
GE1/1 Gap Sizes	Typical Potentials	Typical Voltages	Typical El. Fields [kV/cm]
	3200 V		
3 mm		770 V	2.6
	2430 V	380 V	64.0
	2050 V		
1 mm		300 V	3.0
	1750 V		
	1380 V	370 V	62.0
2 mm		600 V	3.0
	780 V		
	430 V	350 V	60.0
1 mm			
	0 V	430 V	4.3

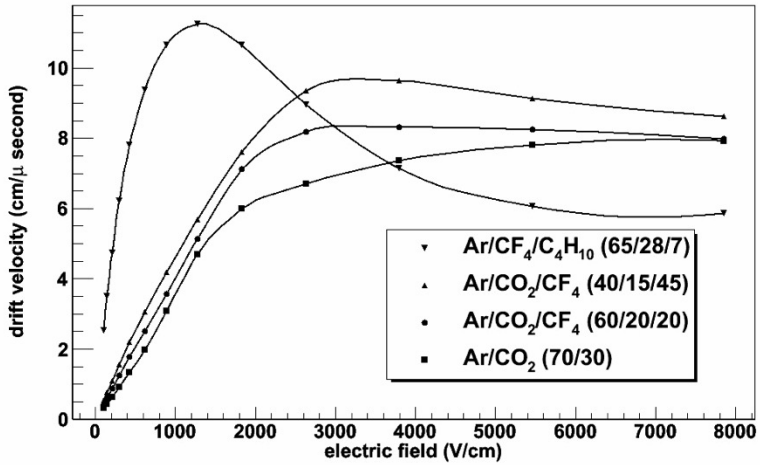


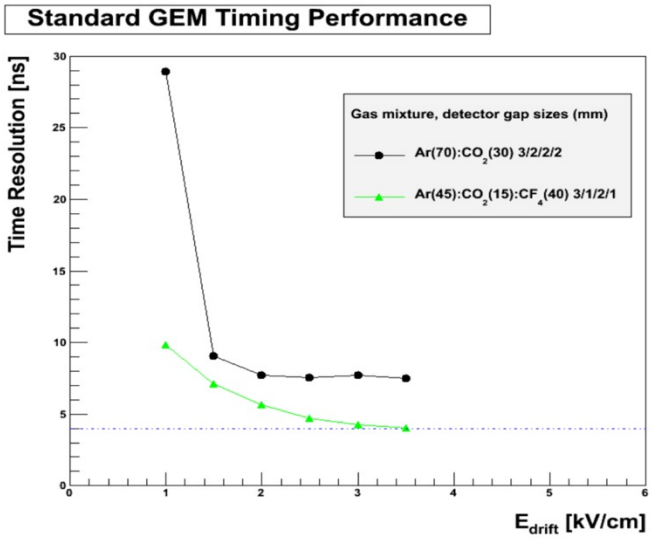


GEM foils & GE1/1 specs









GEM uniformity requirements

