Status and Experience from ATLAS and CMS Muon Detector and Component Production

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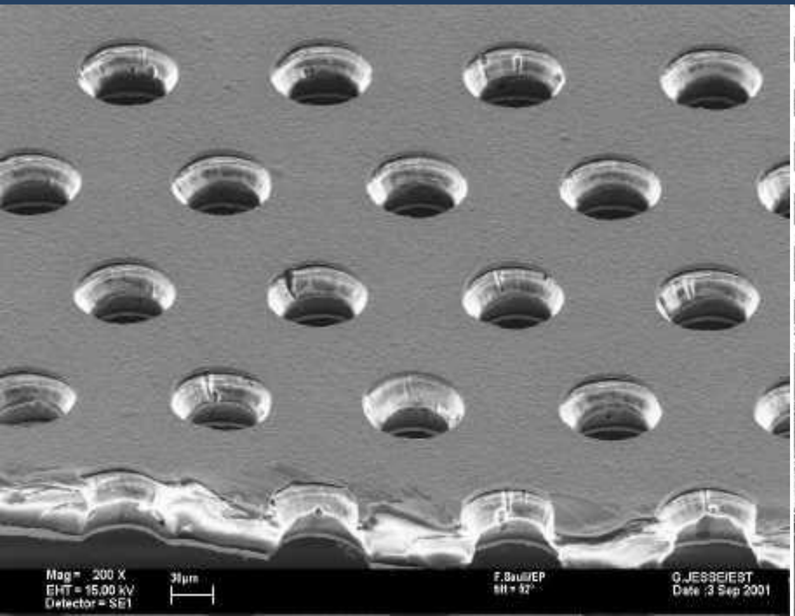
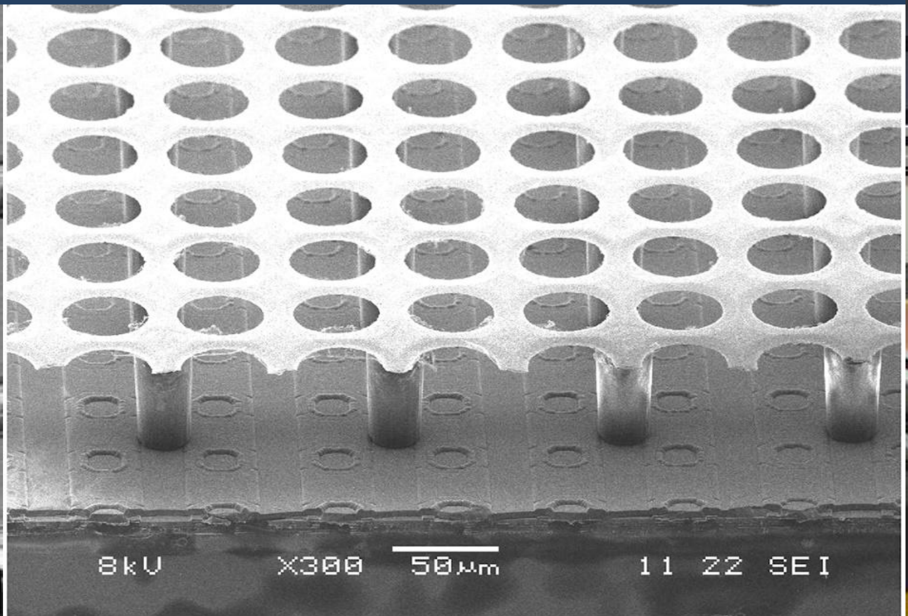
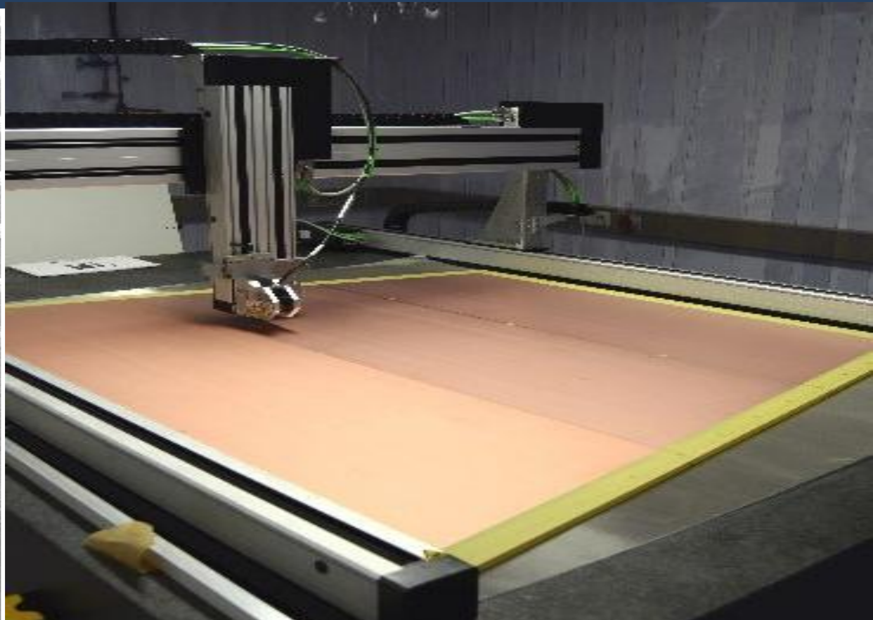
Terascale Detector Workshop, Bonn, March 2025







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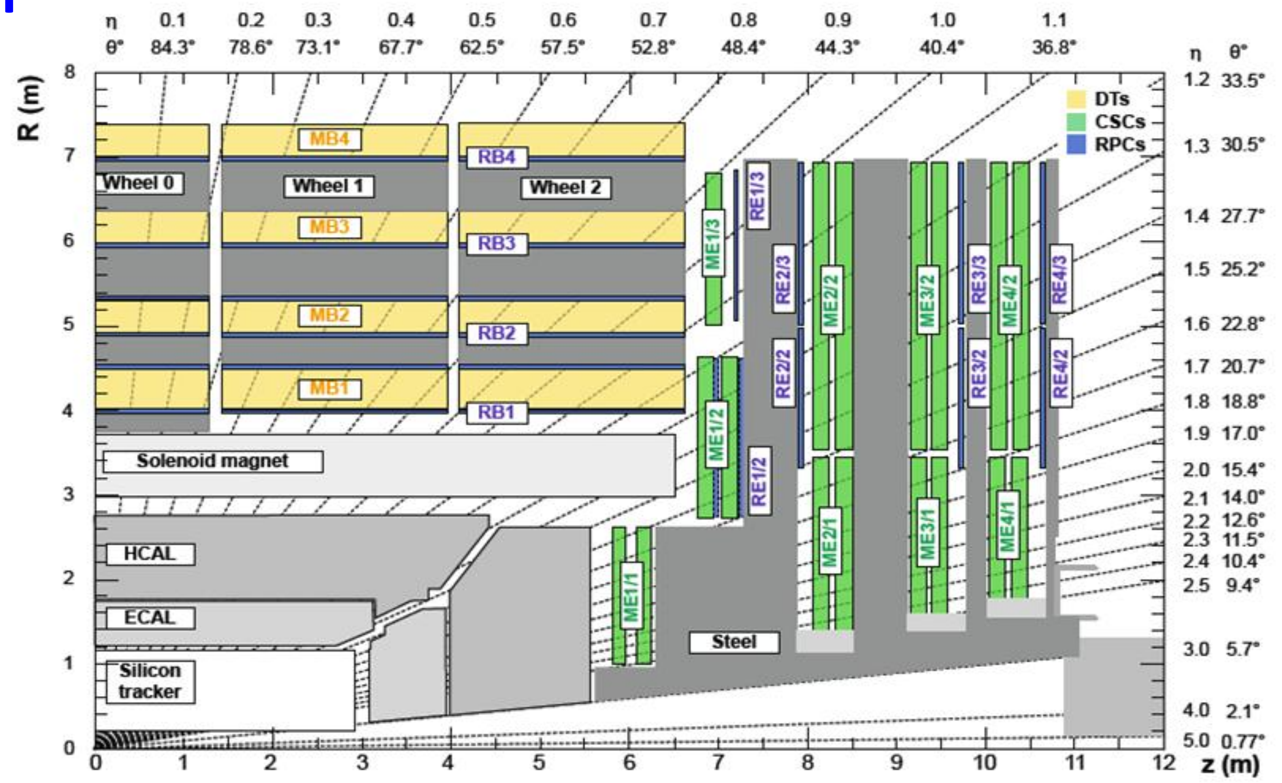
5 Summary

Legacy CMS Muon System

Highly hermetic and redundant muon system

- Drift tubes (DT) in barrel
- Cathode-Strip Chambers (CSC) in endcaps
- RPCs to ensure adequate redundancy
- Trigger coverage up to $|\eta|=2.4$

- Installed in iron return yoke → resolution limited by multiple scattering



Detectors and electronics largely installed 2010

Chambers: No indications of aging or detector performance degradation at phase-2 conditions.

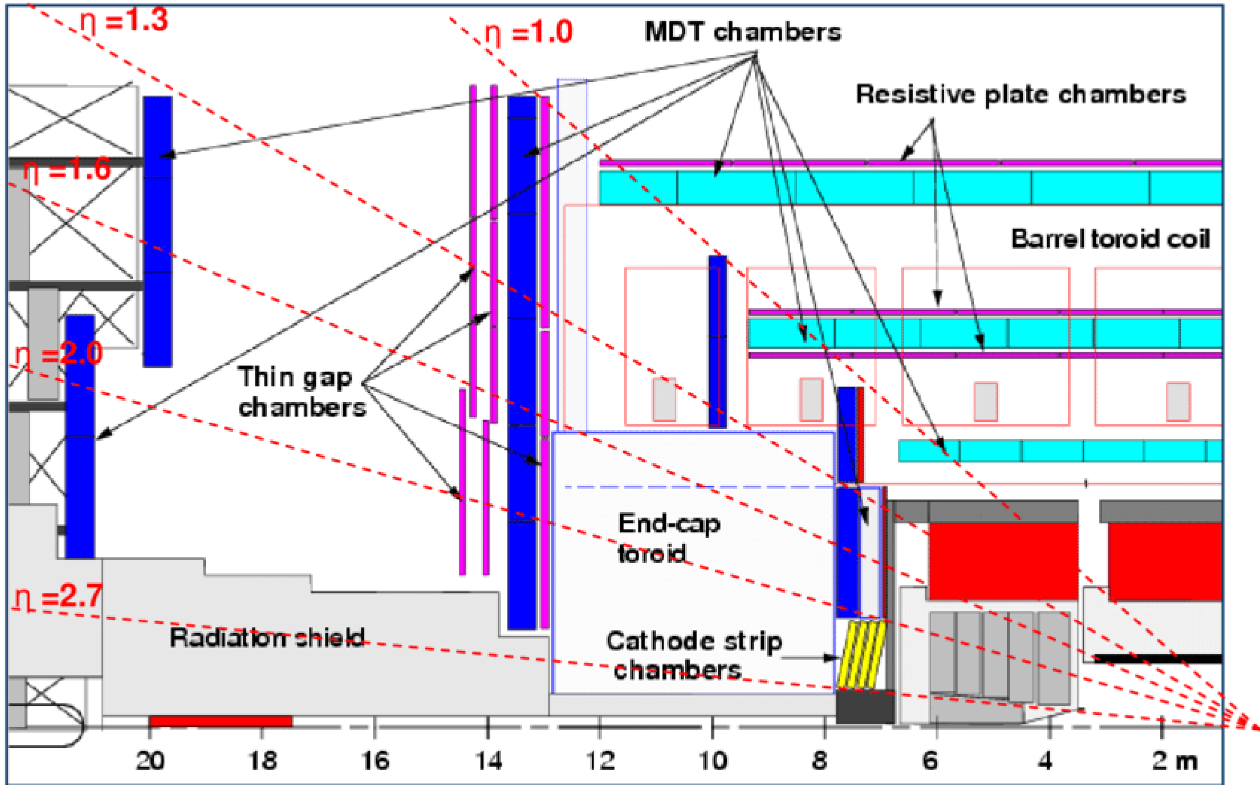
Upgrade: concentrates on **trigger, electronics and additional detectors** for weakly instrumented areas.

Legacy ATLAS Muon System

Very large muon system due to toroid geometry

- Monitored DTs (MDT) in barrel and EC
- Thin-gap chambers (TGC) in endcaps
- RPC in barrel
- CSC in very forward region

Very high resolution, not limited by multiple scattering, less absorption of particles

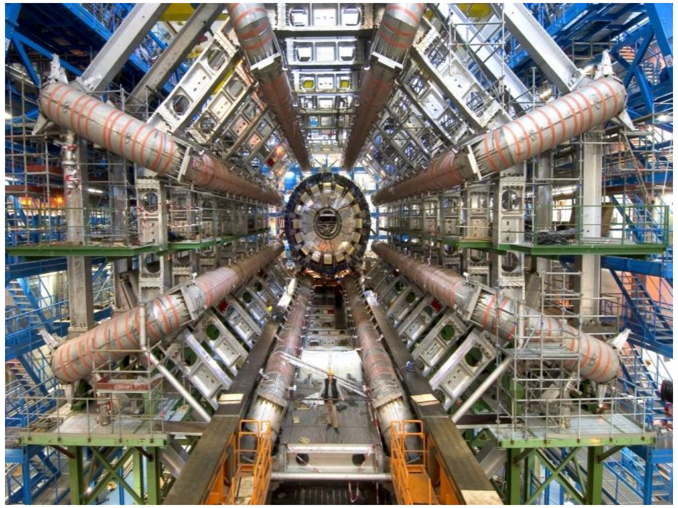


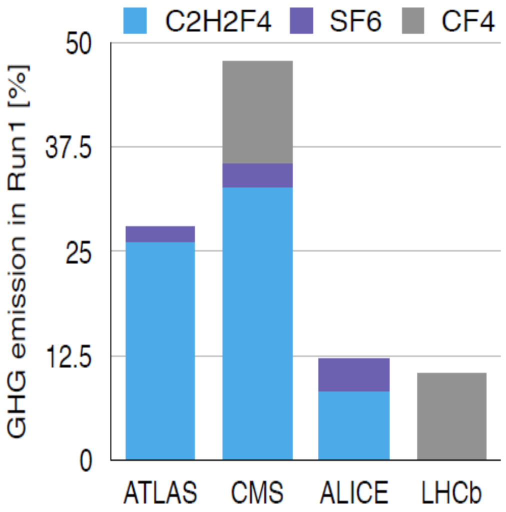
Detectors and electronics largely installed 2010

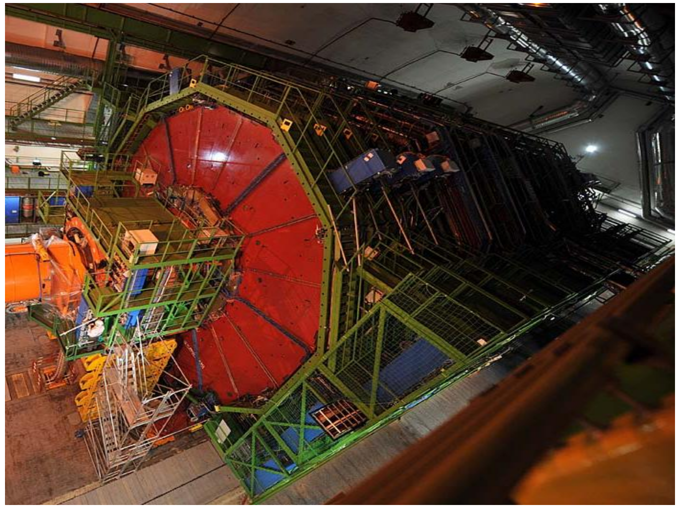
Chambers: No indications of aging or detector performance degradation at phase-2 conditions.

Upgrade: improve **trigger**, increase # hits along tracks. **Upgrade electronics, additional detectors**

F-Gases in ATLAS and CMS







In ATLAS F-gases used in Barrel RPC system

- RPC gas mixture: $C_2H_2F_4$+iC_4H_{10}+SF_6 (94.7+5+0.3)%

In CMS F-gases used in two muon detector systems: CSC (Endcap) and RPC (Barrel + Endcap)

- RPC gas mixture: $C_2H_2F_4$+iC_4H_{10}+SF_6 (95.2+4.5+0.3)%
- CSC gas mixture: Ar+CO_2+CF_4 (40+50+10)%

Why $C_2H_2F_4$ and SF_6 in RPC gas mixture? to guarantee: **Stable detector performance** (high efficiency, large avalanche stability plateau, prevention against ageing effects) **for 10 years of LHC operation**

Solution for **today: Recirculation & recuperation**

But Global Warming Potential (GWP)
$C_2H_2F_4$ = 1000
CF_4 = 7400
SF_6 = 22800

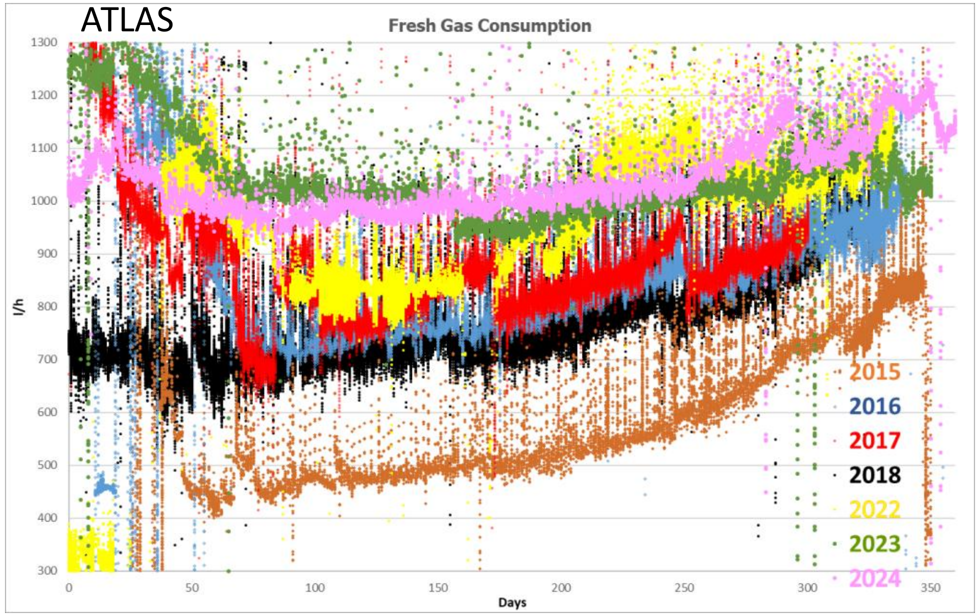
Ref. Talk P. Camarri „Gas leak problem of the ATLAS legacy RPC“ DRD1 coll. Meeting Febr 2025
See also talk R. Guida „CERN and the environment“ https://indico.cern.ch/event/1456577/

Gas Leaks in Legacy RPCs (ATLAS/CMS)

Legacy RPCs **developed gas leaks**

Caused by different types of **material aging**

- CMS polyethylene pipes becoming brittle and crack
- ATLAS cracks develop in polycarbonate moulded in/outlets
- Mechanical stress on gas connectors



Multiple **repair campaigns** during shutdowns.

- Reduce mechanical stress
- Replace, bypass or seal gas tubes
- Reduce gas distribution multiplicity

Chamber access difficult. In CMS barrel needed to extract entire DT + RPC. CMS EC RPCs are not leaking.

More details in Talks at DRD1 coll. Meeting Febr 2025 :P. Camarri „Gas leak problem of the ATLAS legacy RPC", Anton Dimitrov „ Gas distribution for first generation CMS RPC: problems and improvements"

For Future: Reduce CF_4 in CSC (CMS)

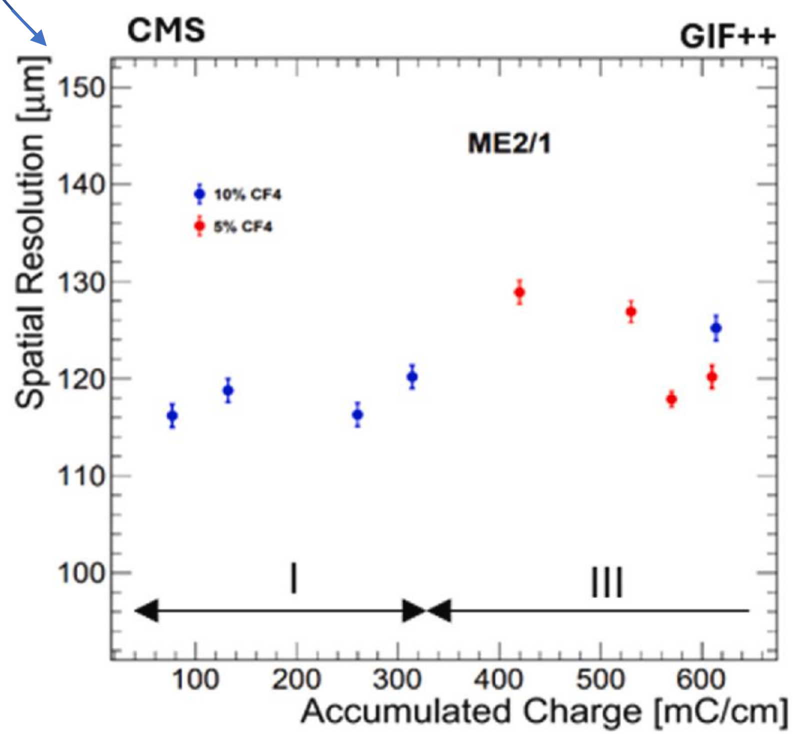
Attempts to reduce fraction of gas with high GWP,

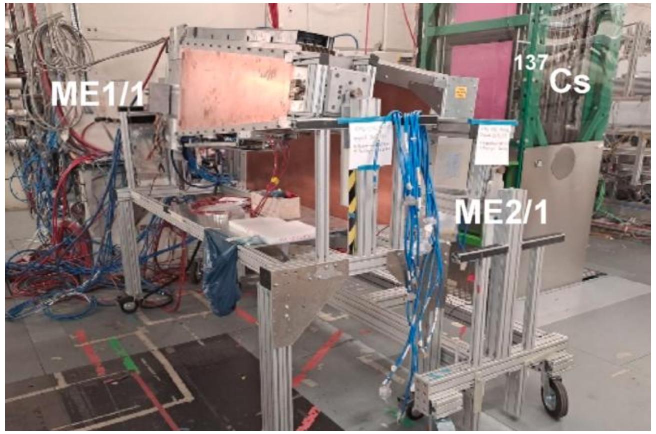
CSC chambers contain wires. Work in avalanche mode.

e.g. CMS CSC CF_4 **10% → 5%**

No performance degradation (spatial resolution, dark current) seen at aging tests at GIF++ up to 800 mC/cm

- **Anode deposits clearly seen for 2% and less**



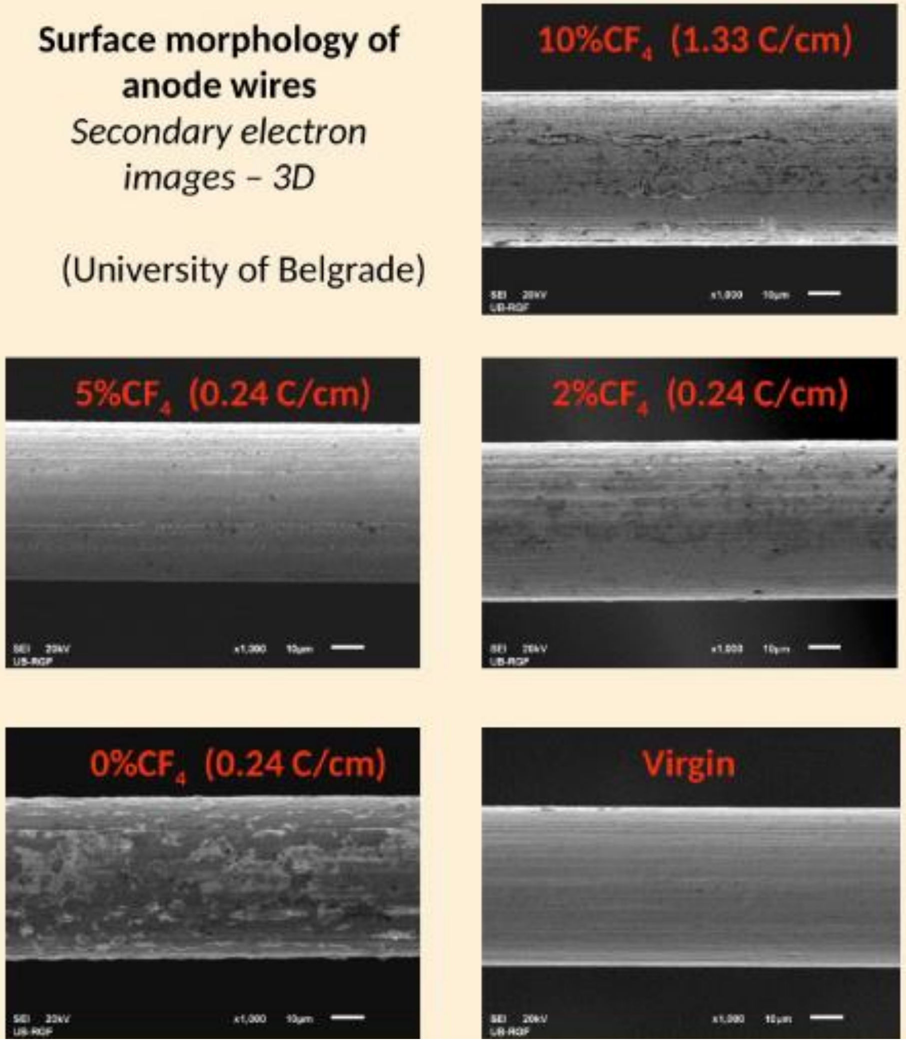


Tests of CSC chambers with varying CF_4 fraction at GIF++ 10% (I), 2% (II), 5% (III), 0% (IV)

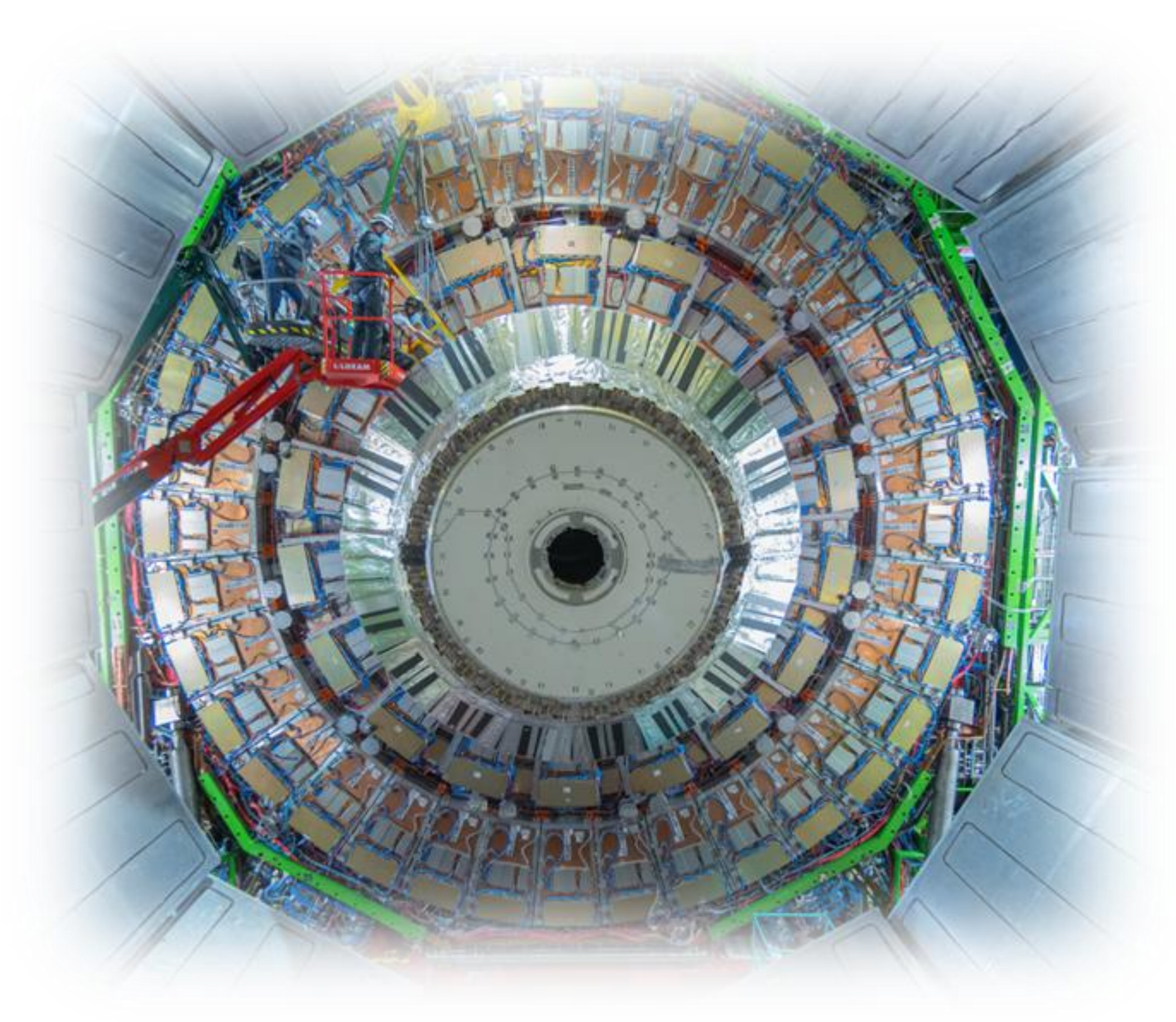
Surface morphology of anode wires

Secondary electron images – 3D

(University of Belgrade)

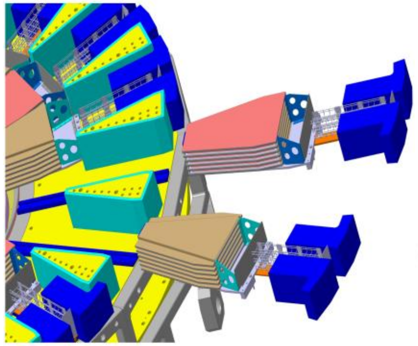


See also https://inspirehep.net/files/b4249f34857aa6a5510faa6e3a108db8 https://doi.org/10.1016/j.nima.2024.170169



CMS Muon Forward Upgrade with GEMs and improved RPCs

CMS Upgrade of Forward Muon Region



High Rates up to 150 kHz/cm²!

Thin-gap RPC

iRPC:

- Thinner RPC technology
- For 3rd and 4th EC station where bending is weaker
- Timing resolution 0.5 ns
- $1.9 < |\eta| < 2.5$
- Max rate 700 Hz/cm²
- Installed YETS 2024/2025

Triple GEM

ME0:

- Triple GEM technology
- Last station of HGCAL
- 6 layers form one stack
- $2.0 < |\eta| < 2.8$
- Under construction

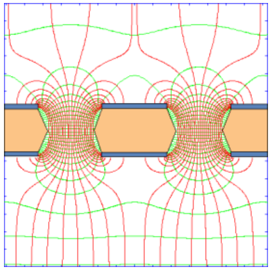
GE1/1 and GE2/1:

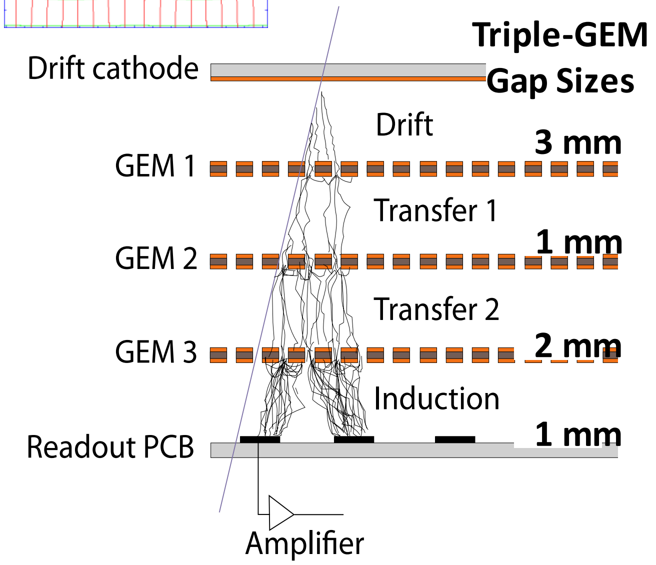
- Triple GEM technology
- For 1st and 2nd EC station where bending is strong
- Two layers per trapezoidal chamber
- $1.55 < |\eta| < 2.1$
- GE1/1 operational, GE2/1 postponed

Gas Electron Multiplier (GEM)
Micro-pattern gaseous detectors (MPGD)

CERN-LHCC-2017-012, "CMS TDR for the Muon Endcap Upgrade"

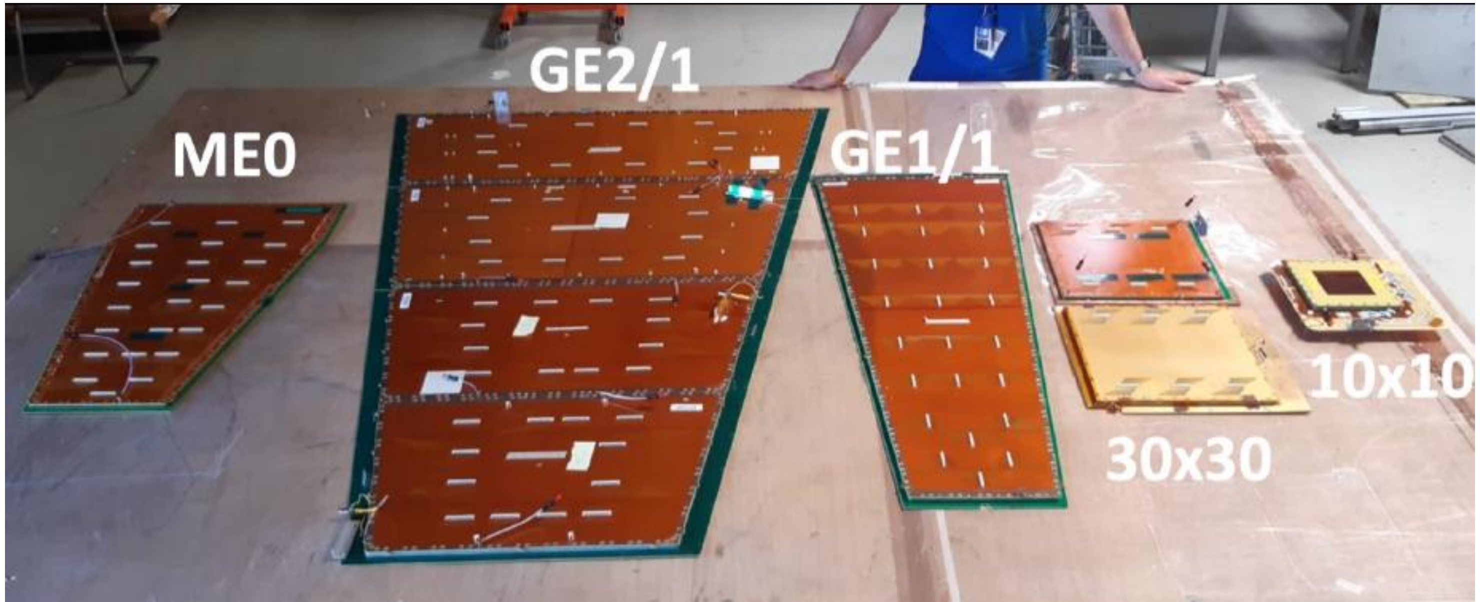
CMS Triple-GEM Technology

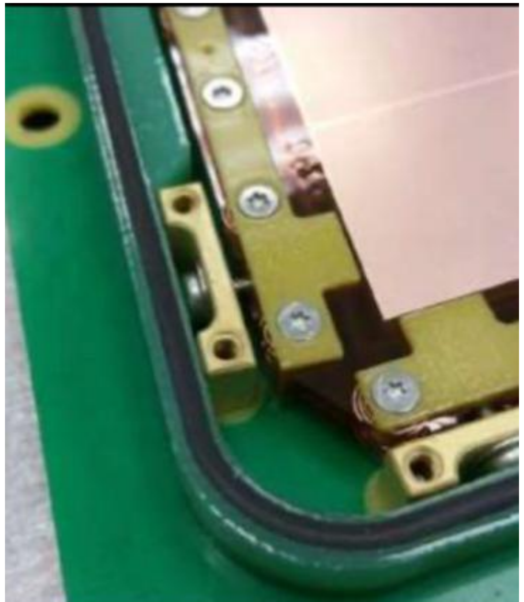




CMS triple-GEM common design:

- Three detector projects based on same triple-GEM technology and same material. Slight design adaptations per station.
- GEM configuration: 3 (drift)/1/2/1 mm
- Gas mixture: 70% Ar + 30% CO_2
- Max bkgr rates: few kHz/cm^2 (GE/2/1) to 150 kHz/cm^2 (ME0)
- Nearly 700 detectors: 600 m^2 of GEM foils for 1.5 M RO channels

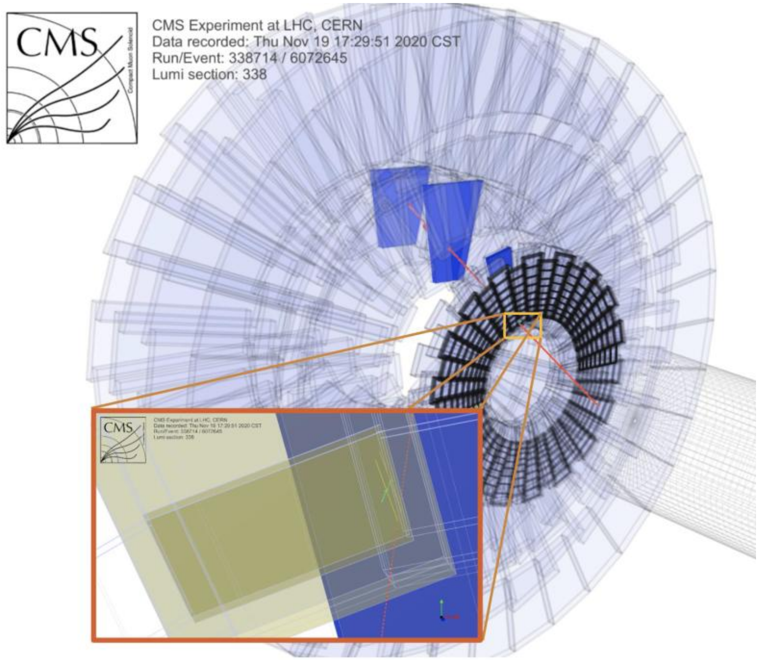




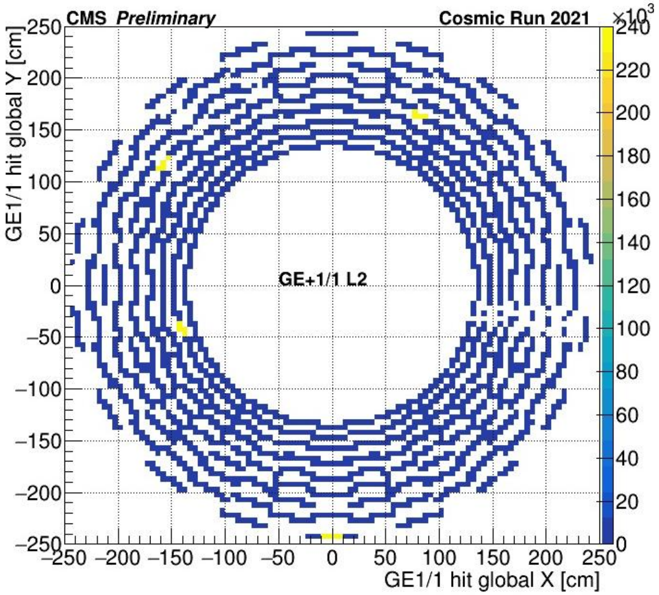
Self-stretching assembly technology developed by CMS GEM for fast mass production (no gluing!)

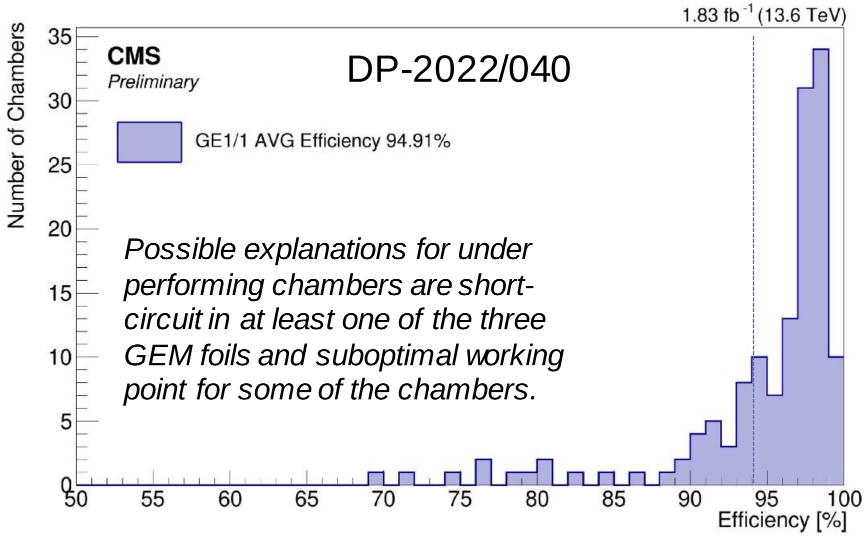
GE1/1 Operates as Part of CMS

Installed in LS2. Routine operation since start of Run-3

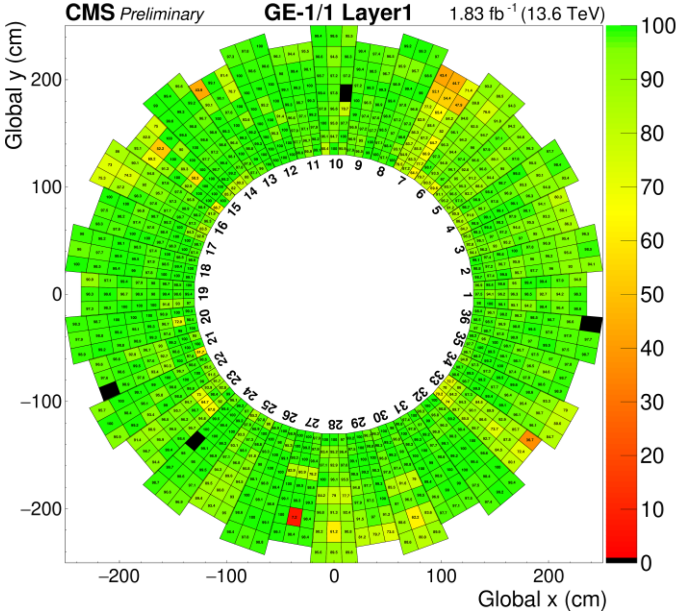


Occupancies for reconstructed hits



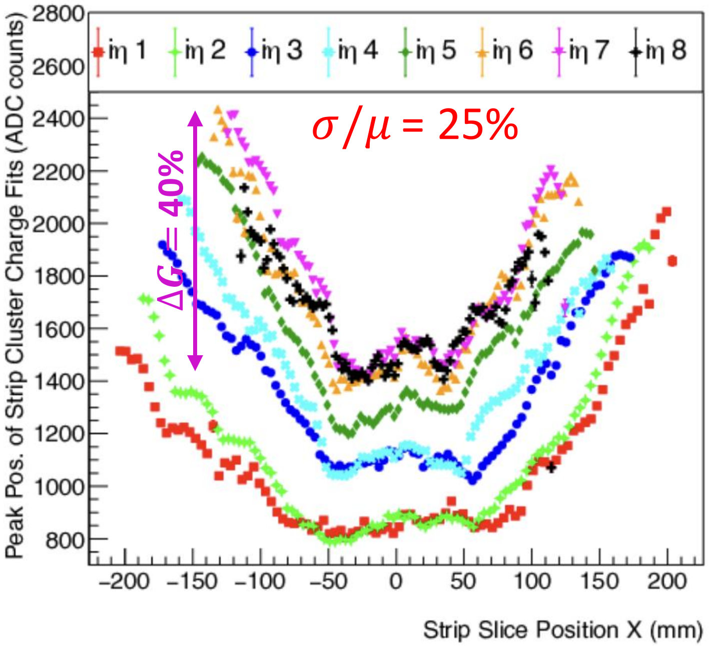


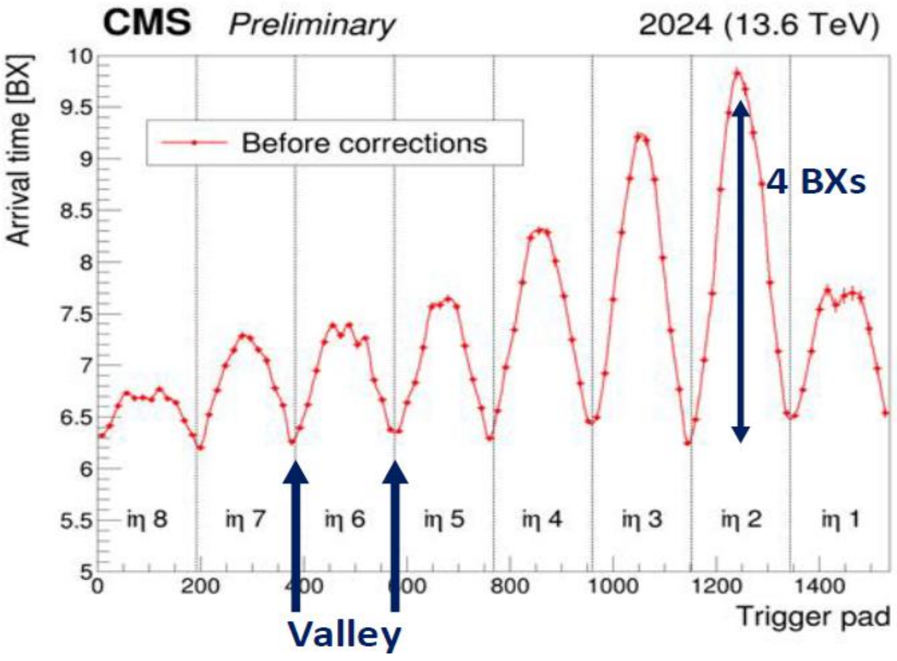
Efficiencies



Importance of GEM Gap Size

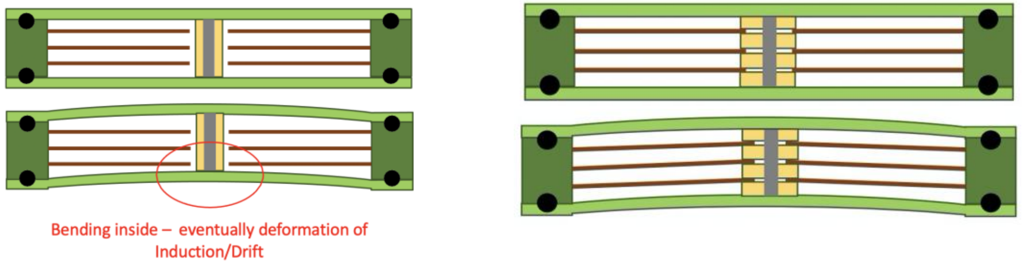
- GE1/1 in spacerless design to reduce dead area. GEM foils stretched (8-10 cN/m applied at ~50 positions along the foil stack)
- Gain Uniformity showing deviations up to 40% → Drift & RO PCBs **bend** and deform gas gaps inside detector
- Effects seen in Detector Occupancy & Efficiency & **Timing**





Pillar (v1) maintains total gap size

Pillar (v2) maintains indiv gap sizes



→ Use central pillars with inner rings in ME0 station

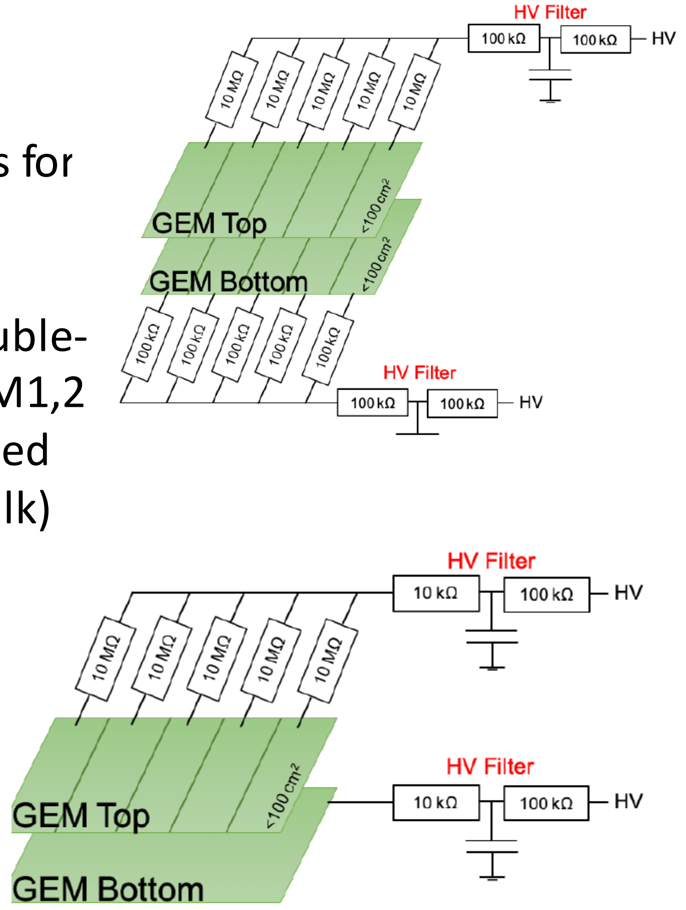
More details in Talk S. Calzaferri DRD1 coll. Meeting Dec 2024 and P. Verwilligen DRD1 coll. Meeting Febr 2025

Present Focus – GEM ME0

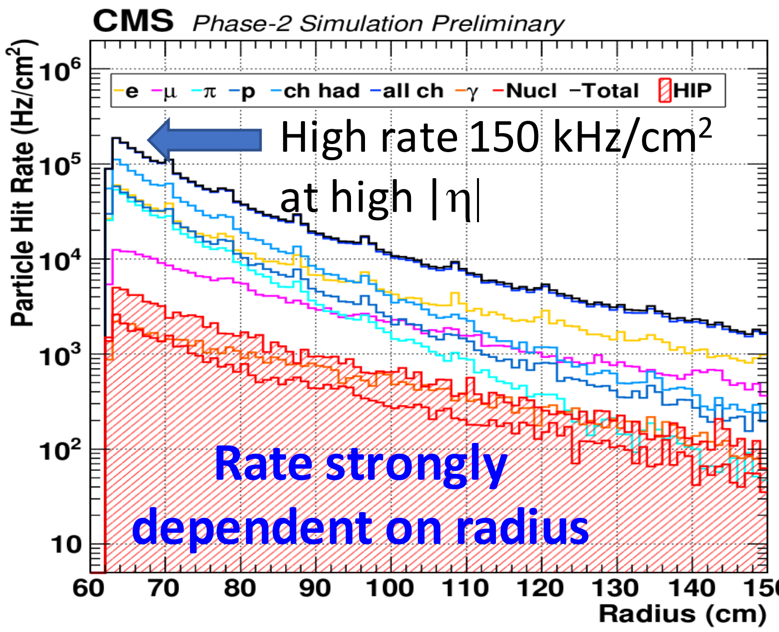
Optimization of HV segmentation to mitigate discharge propagation

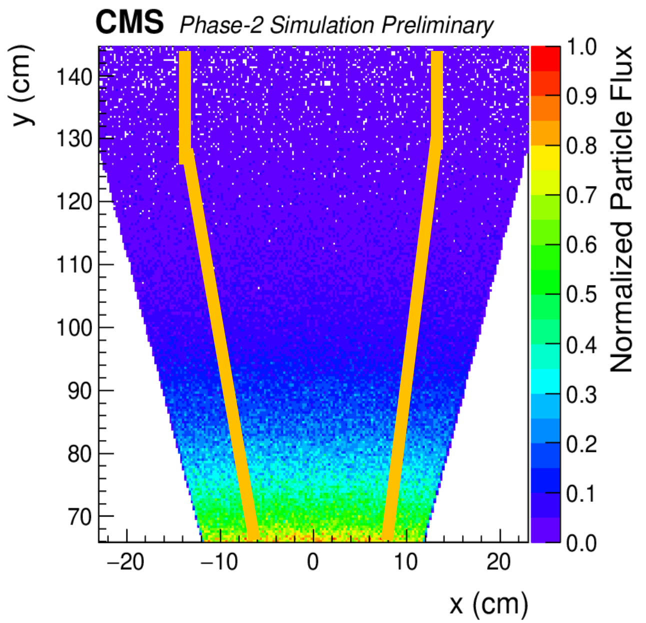
GE1/1 single-segmented foils for all 3 stages

GE2/1,ME0 double-segmented GEM1,2 Single-segmented GEM3 (less x-talk)



Switch to radial HV segmentation for similar flux on all segments. Each segment sees same gradient of particle rate. Allows **uniform voltage compensation** of the entire detector.

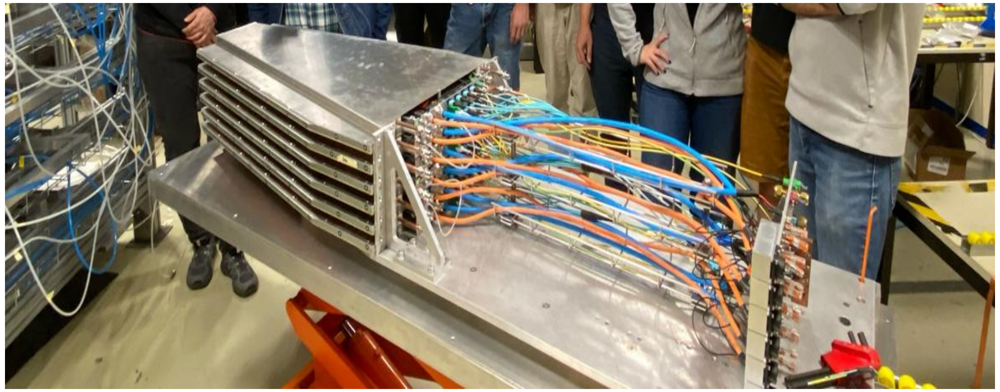


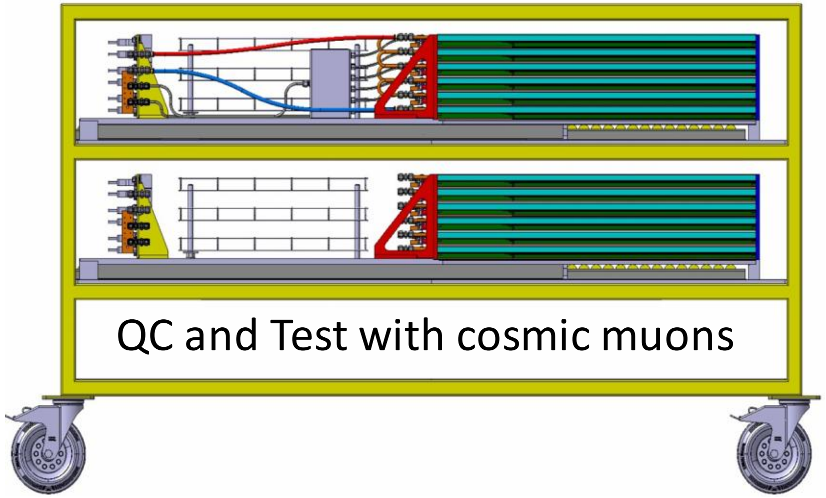


ME0 - Status

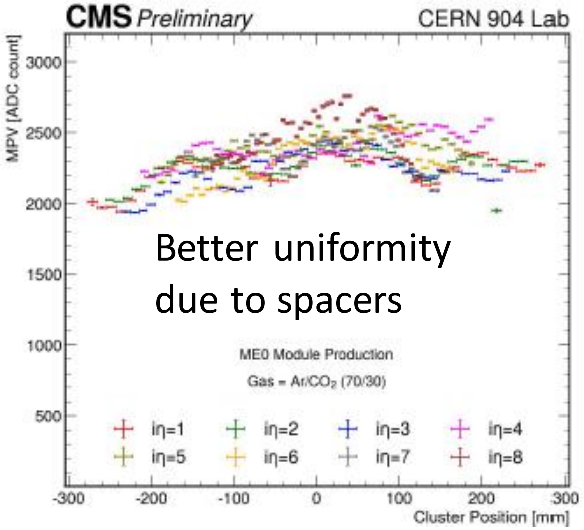
Challenge: build in 2 years 36 + 2 stacks = 228 + 3 chambers

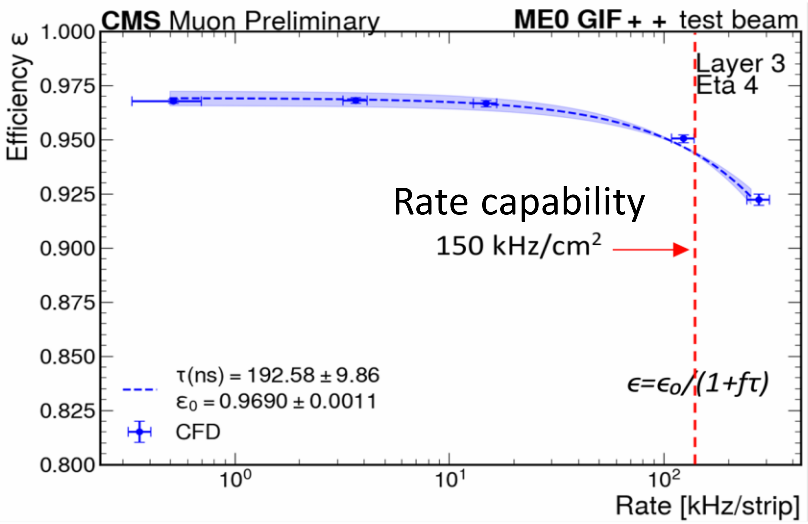
Spring 2024: First stack with 6 chambers equipped with latest electronics. Before stack assembly tested each chamber individually.

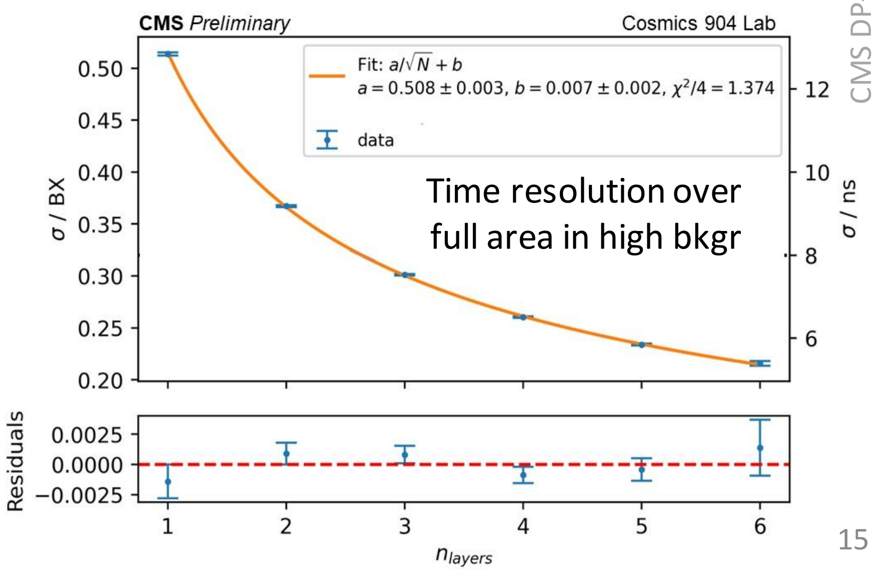




Stack performance and time resolution in muon test beam in presence of high background (GIF++). **Satisfies TDR requirements**

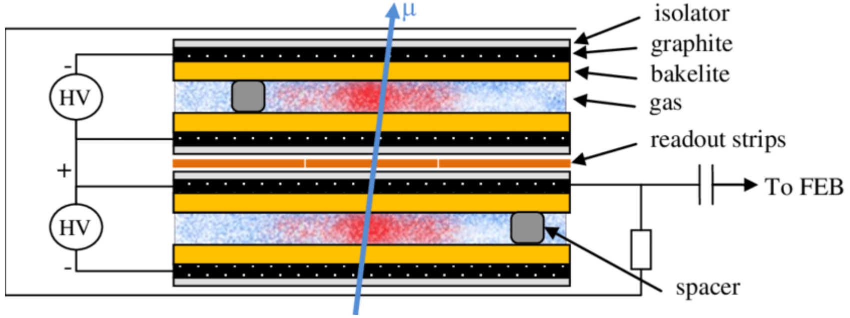


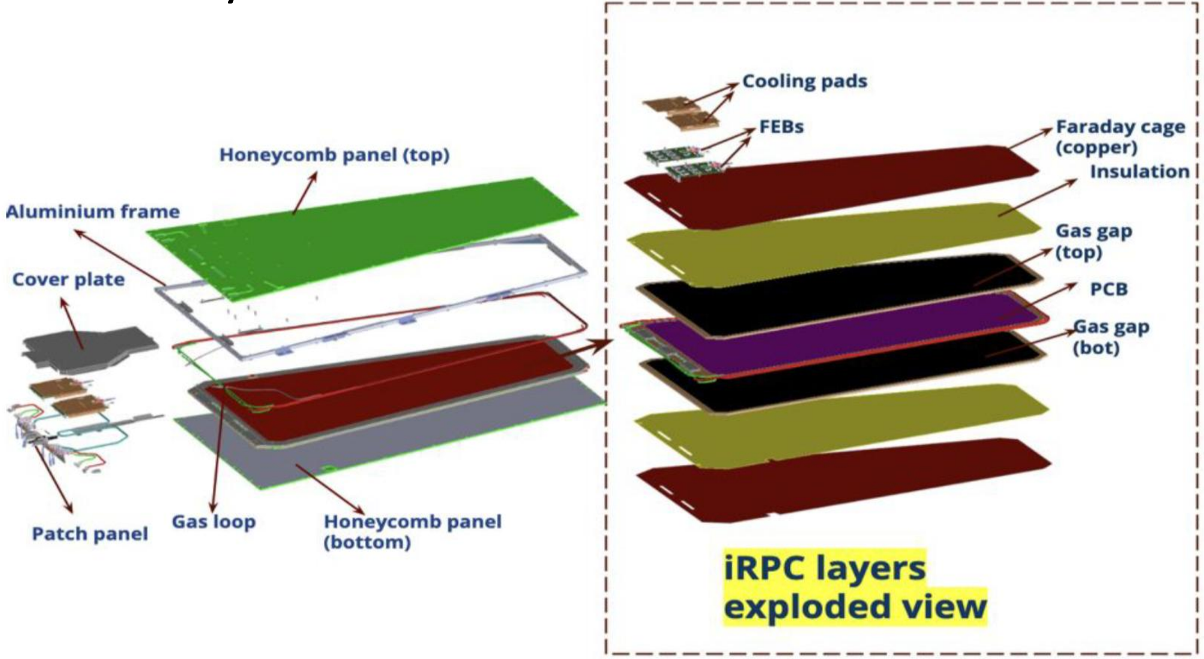




Improved iRPC for CMS Muon Forward

- RPC = **Fast** parallel-plate detector with **high resistivity** electrodes operated in avalanche or streamer mode (CMS = avalanche)
- In 2010 no RPC in very forward because of rate capability
- For upgrade improved rate capability: reduced gap size, low-resistivity bakelite





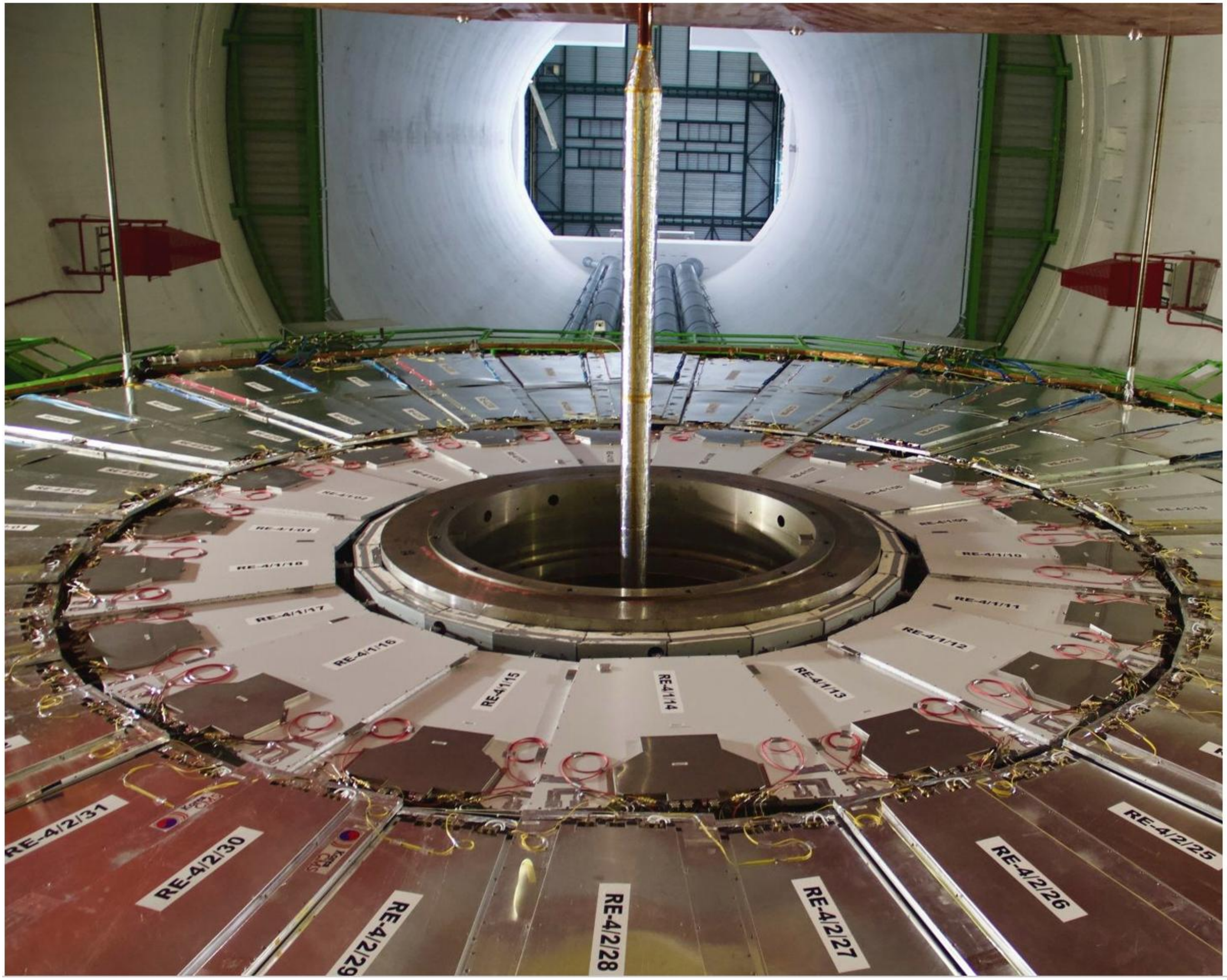
	RPC	iRPC
HPL thickness (mm)	2	1.4
Number of gas gaps	2	2
Gas gap thickness (mm)	2	1.4
Resistivity (Ωcm)	1 - 6 x 10^{10}	0.9 - 3 x 10^{10}
Charge threshold (fC)	150	30 - 40
Space resolution in η (cm)	20 - 28	1.5
Space resolution in φ (cm)	0.8 - 1.9	0.3 - 0.6
Intrinsic timing resolution (ns)	1.5	0.5

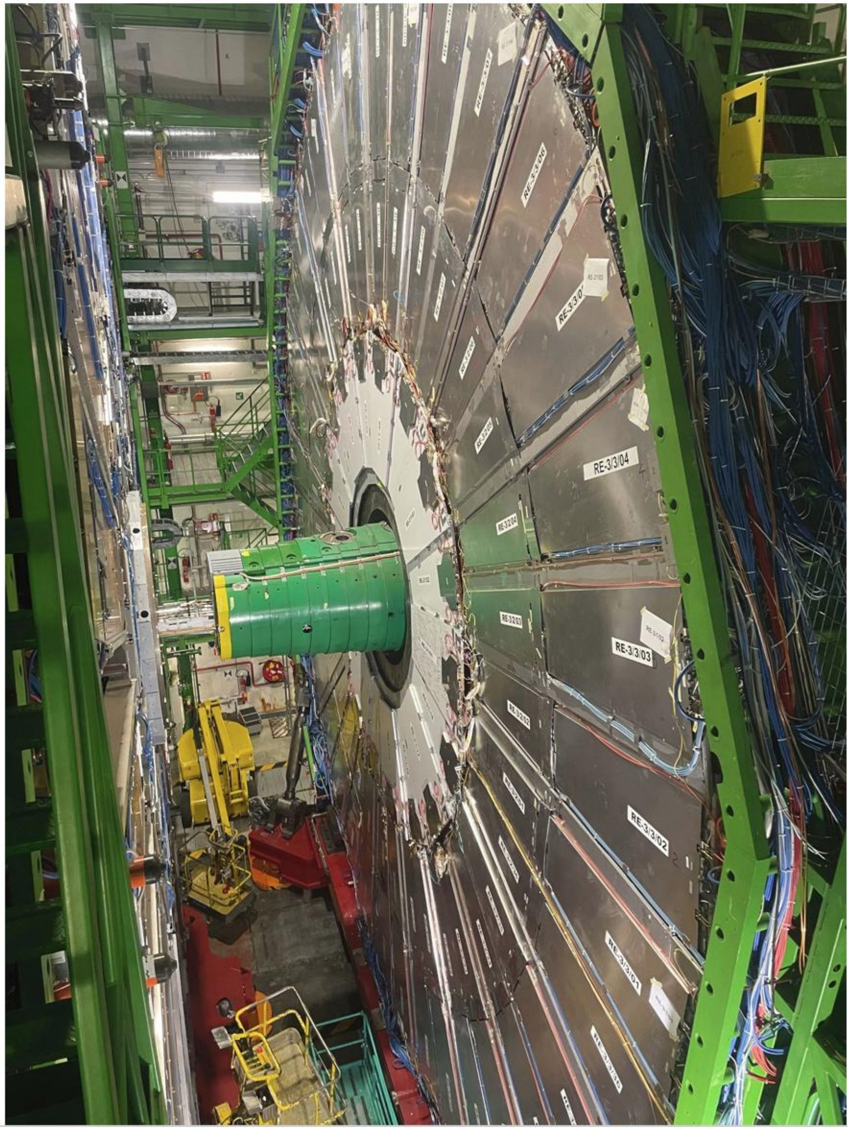
iRPC FEB is equipped with low noise front-end electronics that can detect signals with a charge as low as 30 fC

2d readout for iRPC.

Ref. Talk at RPC2024 by J. Vandenbroeck, Mehar A. Shah „Innovative RPCs for CMS Phase 2 Upgrade"

iRPC installed in last YETS 24/25





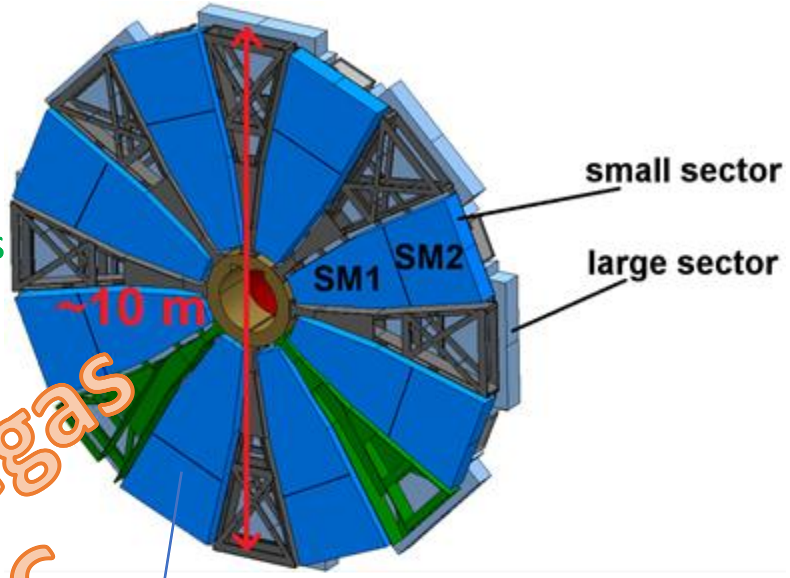
ATLAS Muon Upgrade with „New Small Wheel“ and new barrel RPCs

ATLAS New Small Wheel (NSW)

Upgrade of ATLAS muon system in phase-1.

Motivation: reduce fake muon triggers, precision tracking at high HL-LHC rates

Small Thin Gap Chambers (sTGC) for trigger
MicroMegas for tracking
8 + 8 quadruplets

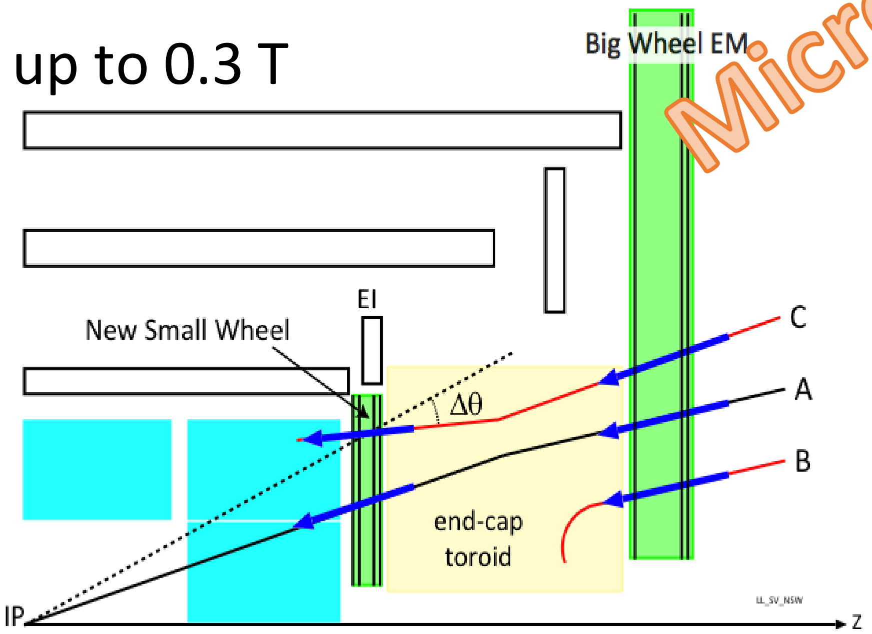


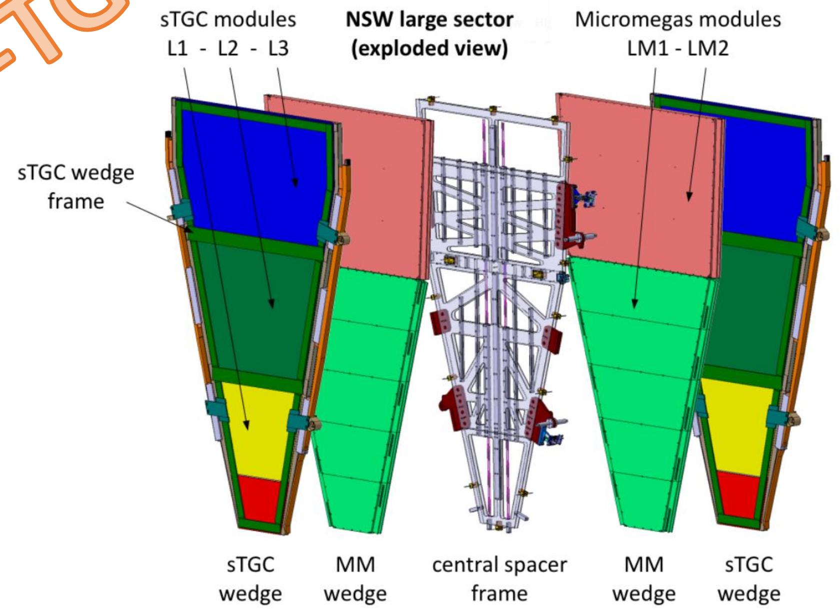
Requirements:

- Rate capability ≤20 kHz/cm^2
- Inhomogenous B-field up to 0.3 T
- $\Delta p_T/p_T$ ~15% @ 1TeV

Micromegas
s-TGC

Detector area 2400 m^2, 2.1 M readout channels





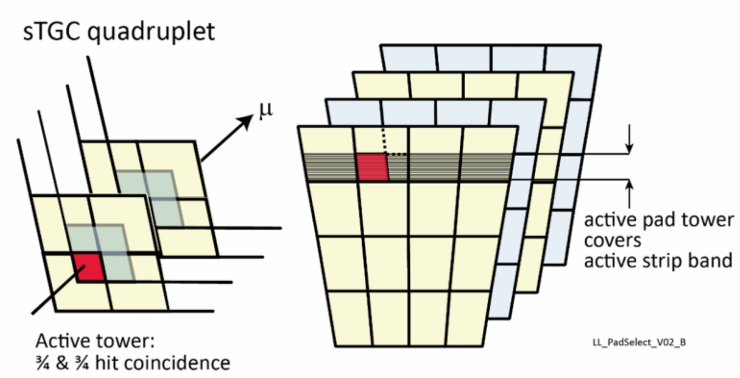
ATLAS New Small Wheel: Technical Design Report, CERN-LHCC-2013-006, ATLAS-TDR-020

Small-strip Thin Gap Chambers (sTGC)

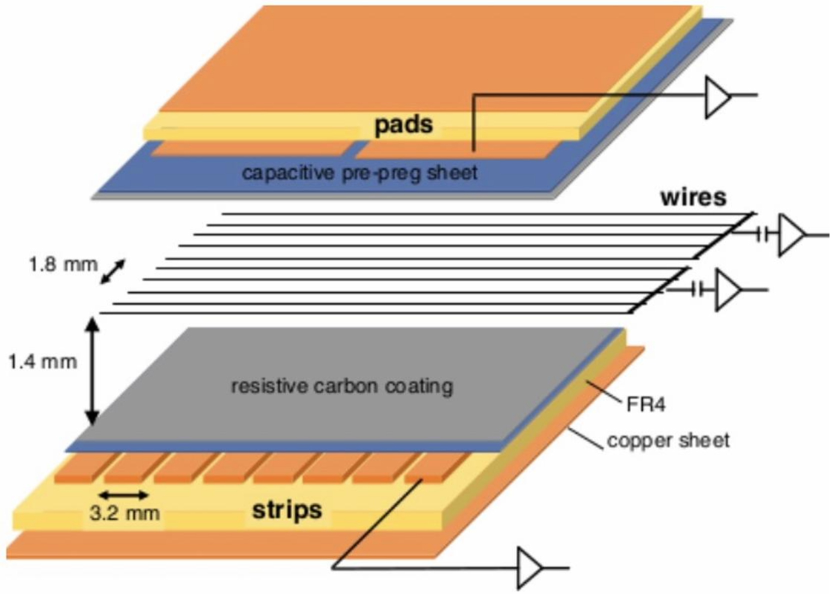
Multi-wire proportional chambers with resisitive cathode an three-fold readout of **wires, pad and strip**

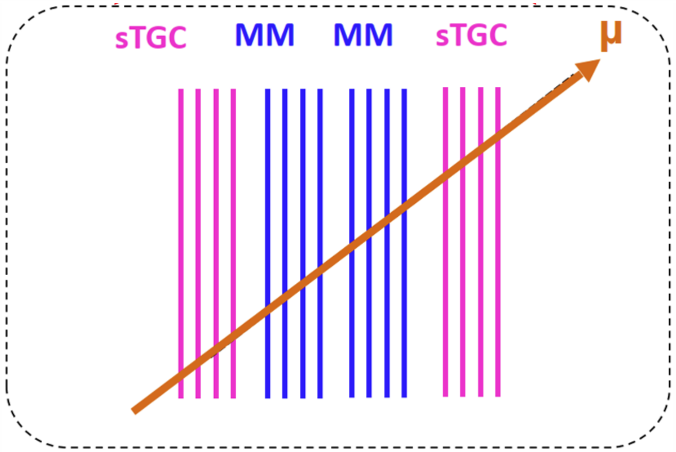
Evolution of TGC technology towards higher rates

- Pad and strip-segmented cathodes covered resistive layer.
  → Lowered surface resistivity for faster charge evacuation
- Strips for high spatial resolution for trigger & track reco
  → smaller pitch (3.2 mm)



Pads provide pre-trigger to select only strips of interest to transmit to Trigger processors





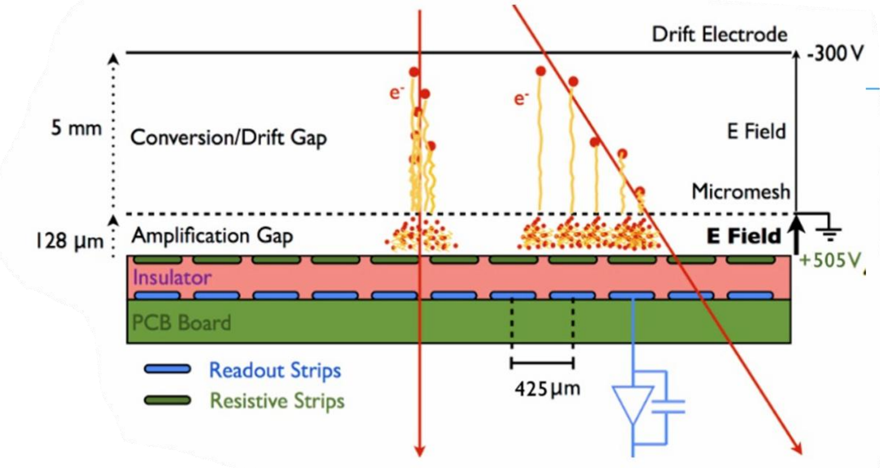
sTGC and Micromegas
16 layers

- Wires provide second coordinate → pitch 1.8 mm
- Thin gap (2.9 mm) → good time resolution for BX ID
- Gas mixture: CO2:n-pentance (55:45)

https://cds.cern.ch/record/2842618/files/ATL-MUON-SLIDE-2022-625.pdf

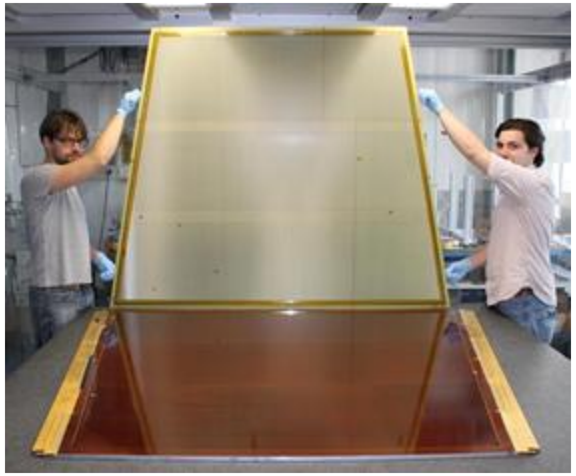
MicroMesh Gaseous Structure (Micromegas)

MPGD. Separating ionisation (5 mm) from amplification (128 um) -> ion tail suppression -> high rate capability

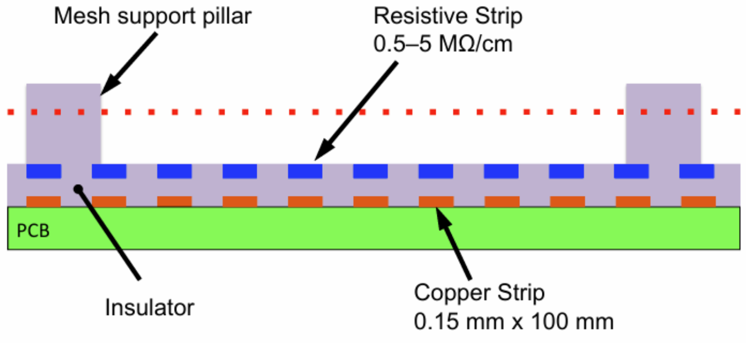


Go directly from R&D to mass production

- *Large modules of 2-3 m^2 with 4 MM layers each*
- *Detector area 2400 m^2, 2.1 M readout channels*



- New technology for large-area MM: amplification mesh integrated in drift panel and separated from readout. Advantages: facilitates detector opening, separates PCB production from mechanical production



- Developed new scheme with resistive strips → strong spark suppression in harsh environment
- Narrow copper readout strips (425 - 450 um) for high precision

Experience from Construction

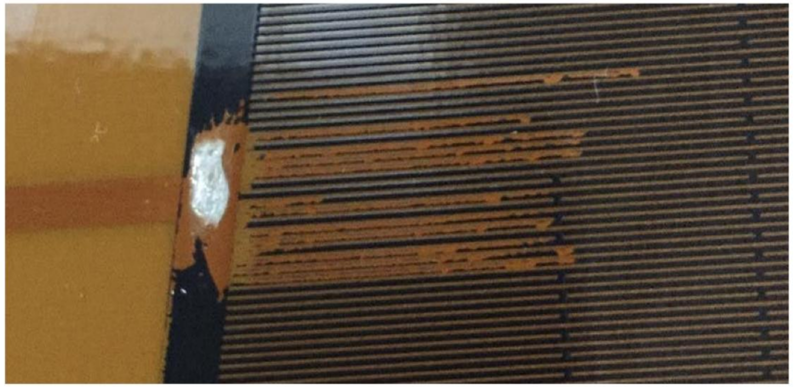
MPDG small dimensions , component effects are more important

Panel **material expansion** with humidity to be accounted during production

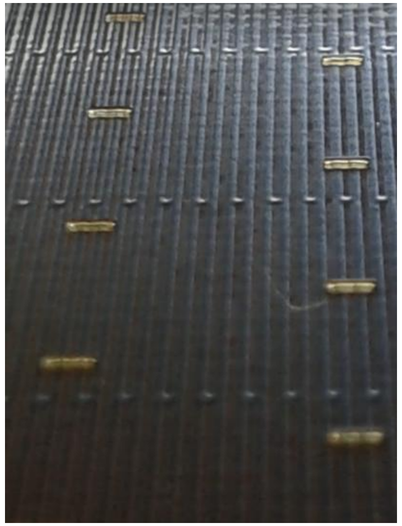
Knowledge of strip position and deformation crucial for precise tracking
Expansion ~400 um -> SF for each company developed. After pro-duction 4 weeks relaxation in controlled humidity

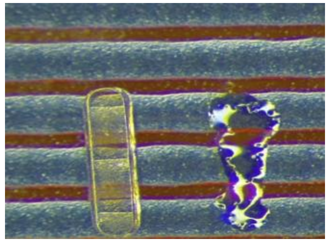
Resistive paste, three crisis

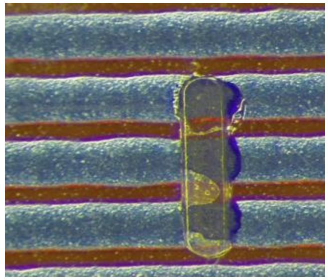
1) Resistivity too high, traced to change of solvent
2) Low adhesion of resistive strips, traced to insufficient curing at foil printing company
3) Producer changed location of paste production without transfer of knowledge.



Pillars, ~20.000 pillars/board
Missing single pillar creates sagitta and impacts amplification
Developed repair procedures to recover boards.
Pillar height 120/128 um





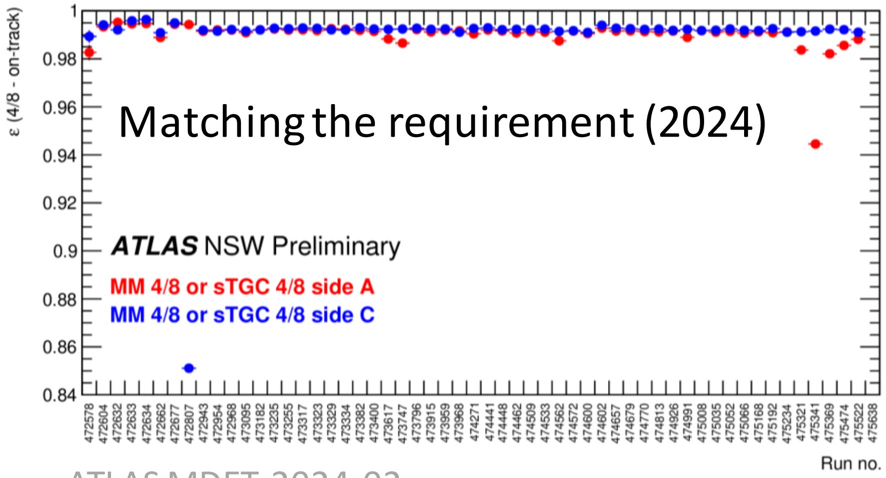


More details in Talk Fabien Jeanneau „Industrial production of MPGD: experience from ATLAS Micromegas“, DRD1 coll. Meeting Febr 2025

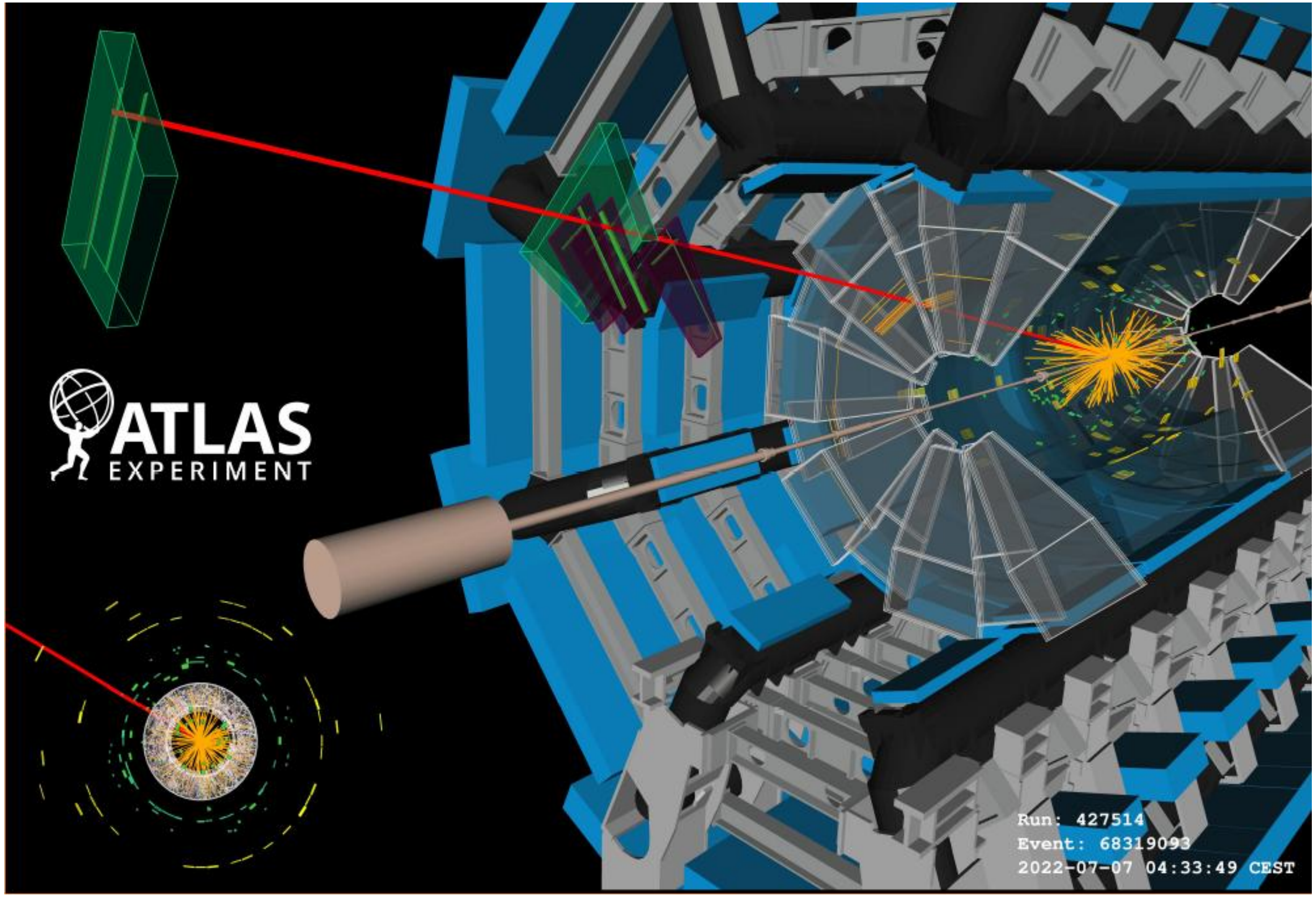
Both New Small Wheels Operate in ATLAS

Commissioning in 2022. Since 2023 fully contributing to ATLAS trigger and physics program

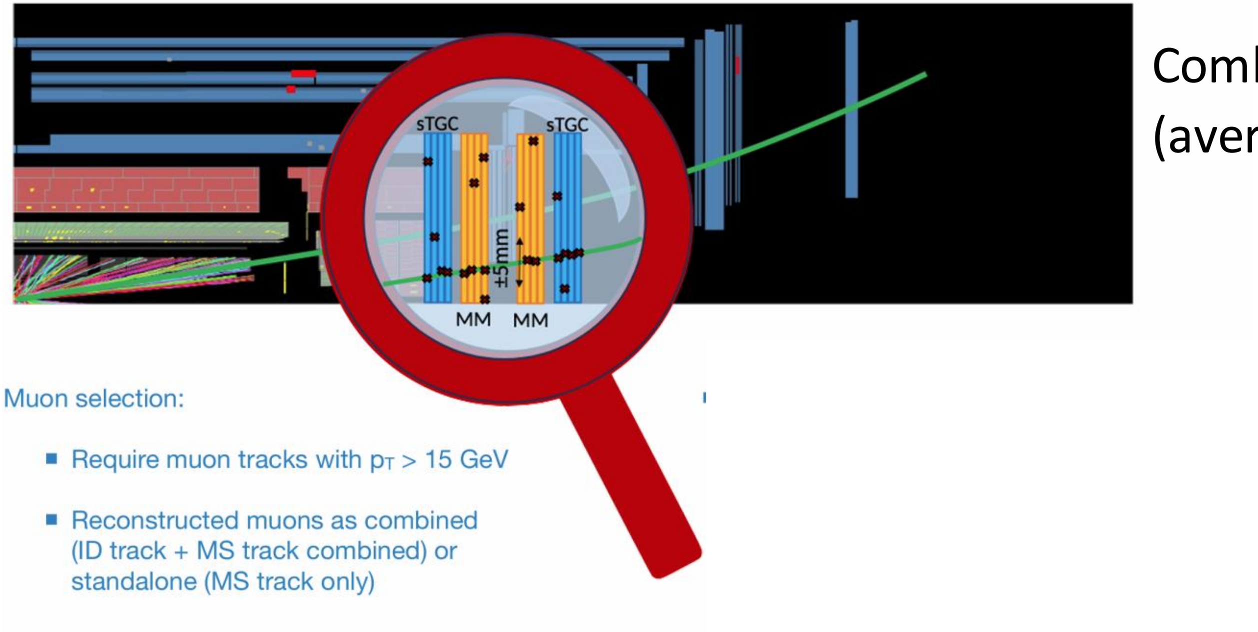
Integrated in ATLAS TDAQ, reconstruction and DCS



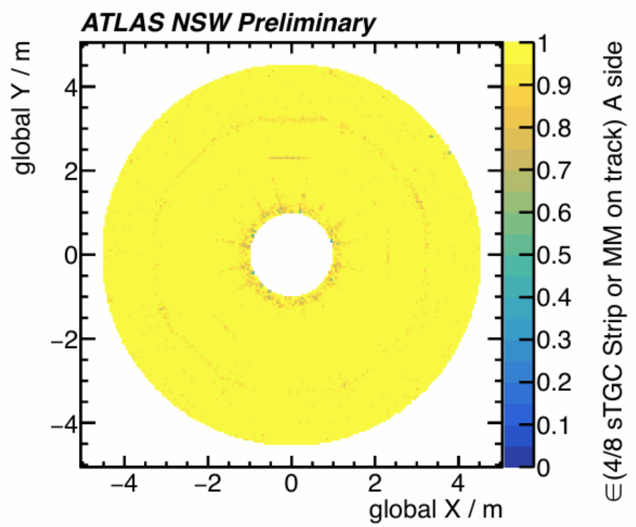
ATLAS MDET-2024-02

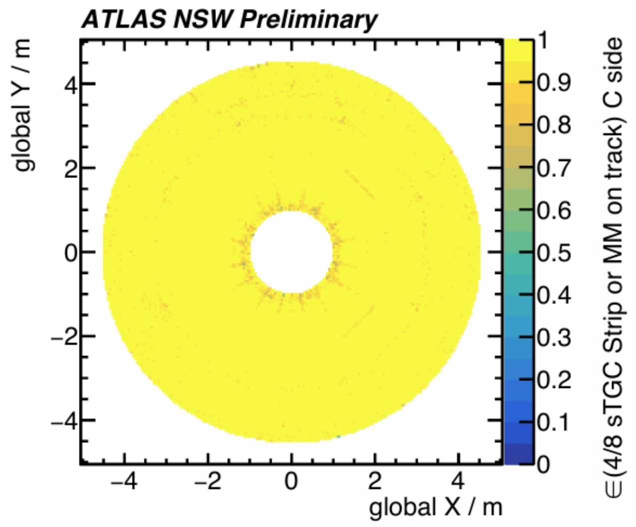


Operational Experience (Efficiency)



Combined efficiency **>95%** thanks to high redundancy (average 4/8 layers either MM or sTGC)





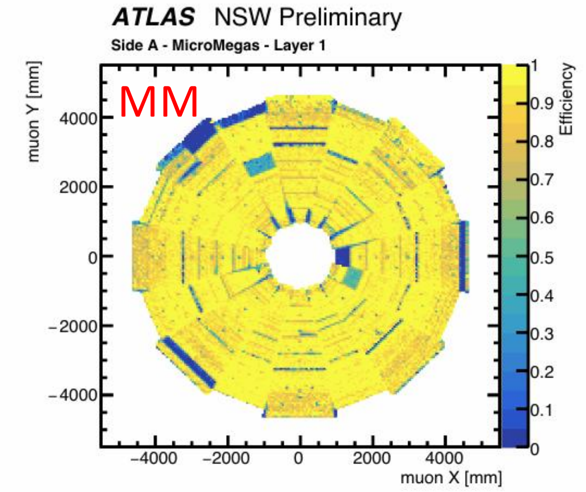
4/8 MM

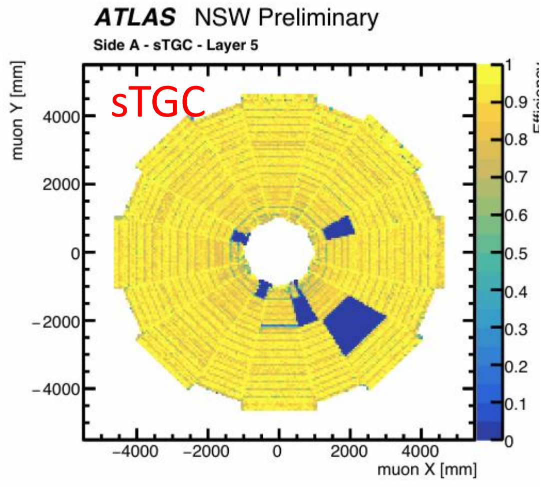
or

4/8 sTGC

(on-track)

Single layer efficiency. Inefficiencies in some regions due to HV/LV/readout issues during data taking.

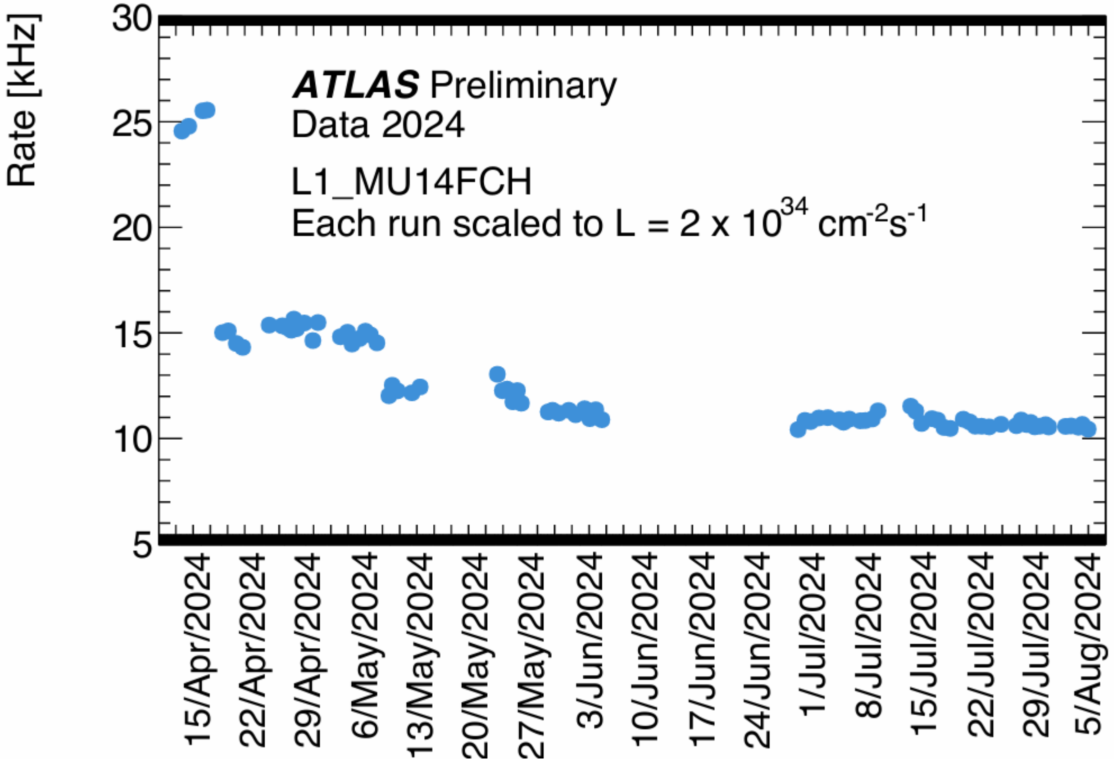


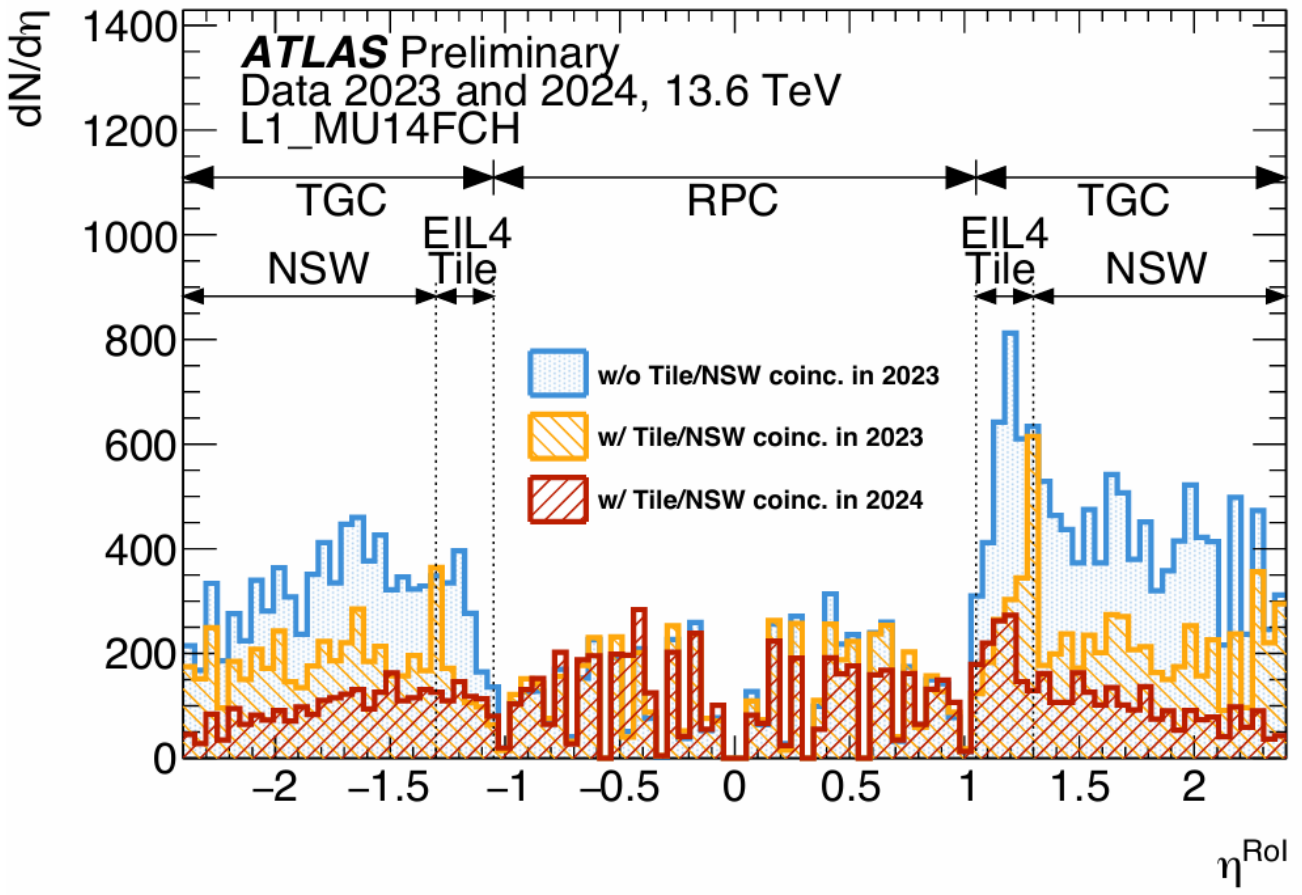


More details Talk at VCI Feb 2025: S. Tsigaridas „The performance of the ATLAS NSWs in the heart of LHC Run-3“

Trigger Goal is Achieved

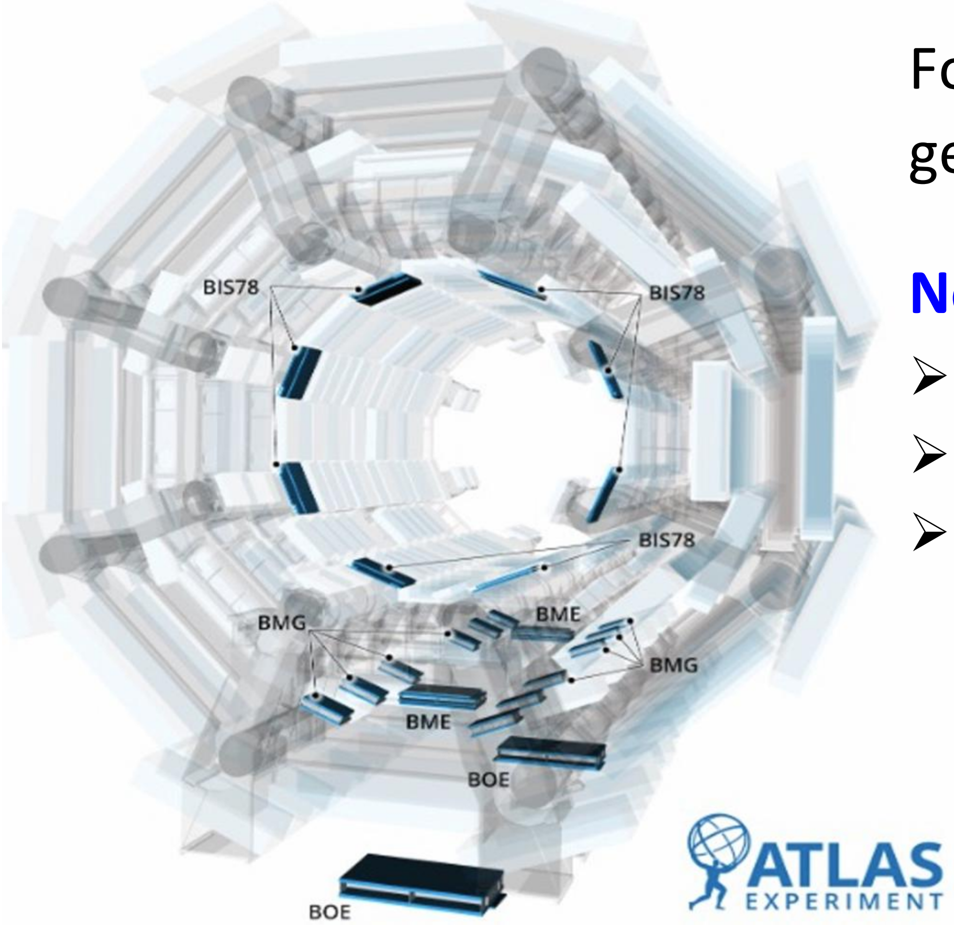
In total coincidence of Big wheel, tile calorimeter and NSW (all sTGC + MM sectors) about halved the primary L1 muon trigger rate





See Talk at VCI Feb 2025: S. Tsigaridas „The performance of the ATLAS NSWs in the heart of LHC Run-3"

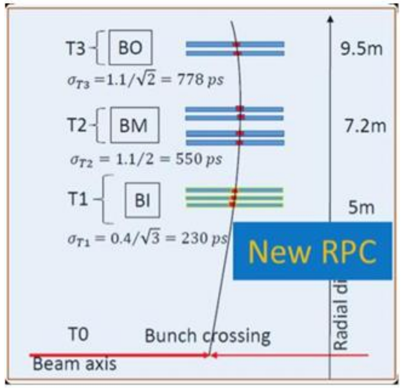
New Generation ATLAS RPC

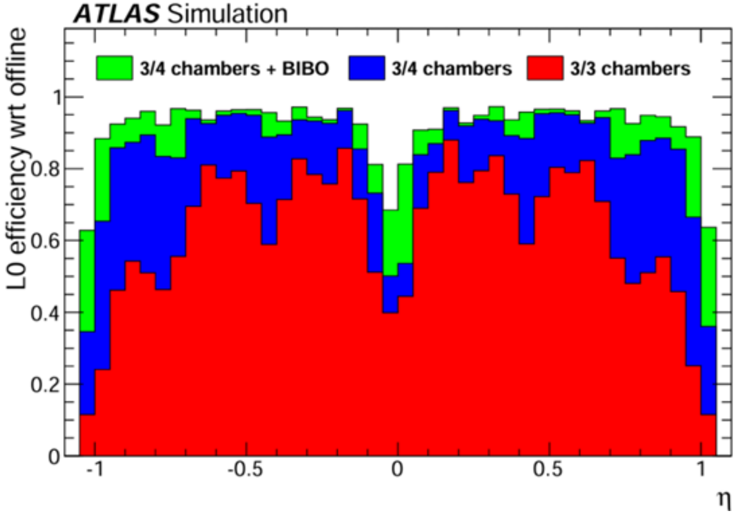


For HL-LHC upgrade barrel inner region (BI) with ~300 new gen. RPC triplets to improve trigger redundancy (6 → 9 layers)

New generation RPC:

- Thinner electrodes (1.4 vs 1.8 mm), lower resistivity (500 vs 320 kΩ/cm)
- Smaller gas gap (1 vs 2 mm) for improved time response (0.4 vs 1 ns)
- New FE electronics with better sensitivity (1-2 fC), improved time resolution (250 ps)





Status: production started in 2023. Two new production centers (Munich, Hefei China)

Improved RPC rate capability

Motivation similar to NSW: reduce fake triggers in barrel-EC transition

Ref. Cern seminar P. Iengo „ATLAS Run 3 detector configuration" May 2024, Talk P. Camarri at RPC2024 „ATLAS RPC Phase II upgrade" Sept 2024

Summary

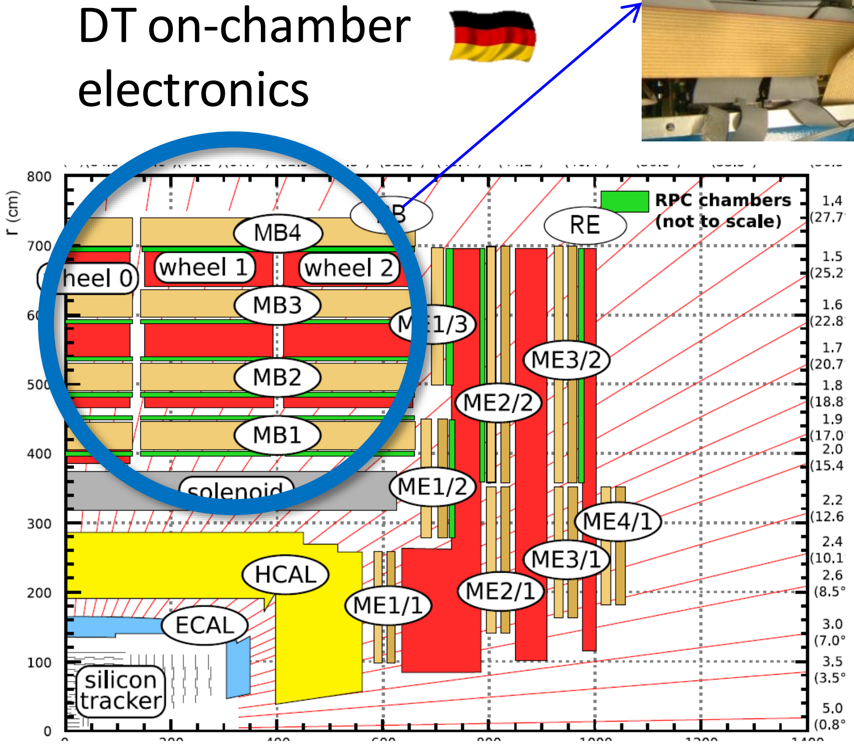
- Legacy ATLAS/CMS muon systems work very well
- Need to reduce F-gases because of high GWP
- No need for full system replacement. Upgrades to strengthen weakly instrumented areas, improve trigger purity at HL-LHC
- CMS upgrade of very forward muon region with Triple-GEM detectors and improved RPC.
- ATLAS NSW upgrade in the forward regions and additional (thin) RPCs in barrel.
- Largest MPGD systems ever built.

Backup

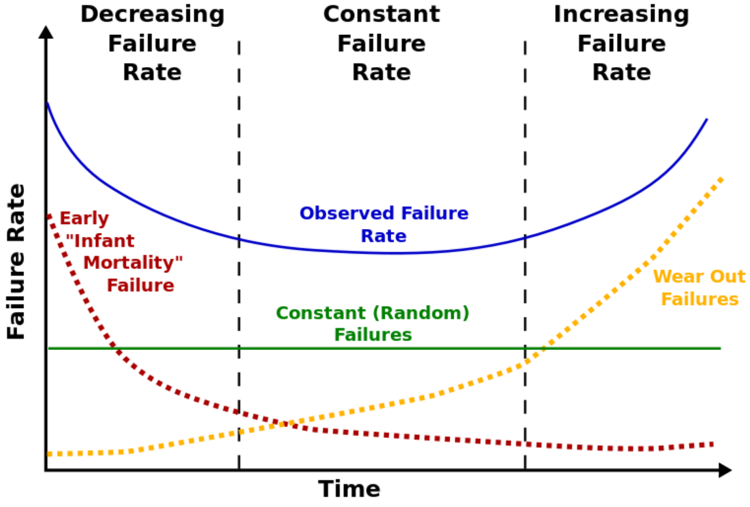
Experience & Upgrade DT Electronics

Concept of tracking trigger impacts needed latency and rate	Level 1 Latency from 3 μs	⇨	10 μs
	Level 1 Rate from 100 kHz	⇨	1 MHz

L1 rate needs replacement of the DT on-chamber electronics



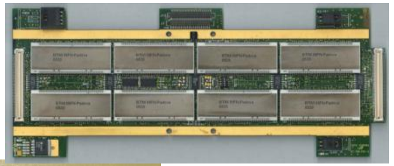
Another argument: electronics is old. Wear-out failure may increase

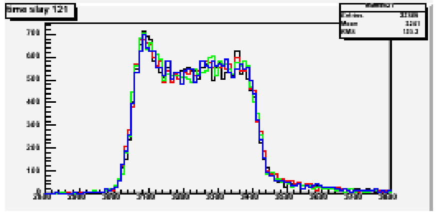


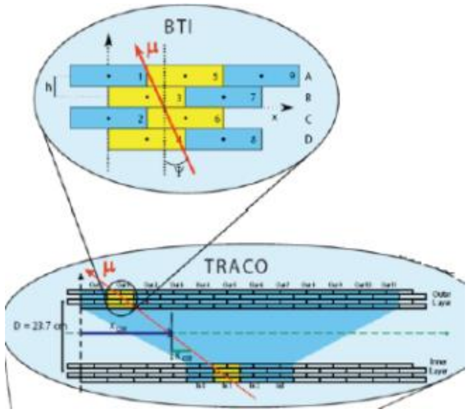
Upgrade of DT on-chamber electronics

Legacy Minicrates

- Highly integrated and complex system
- Many boards with various ASICs for specific tasks
- Trigger primitive generation performed inside each chamber
- Filtered information sent to counting room







Trigger
segment finding, angle measurement=> single chamber trigger generation

Readout
Time digitization
Event matching

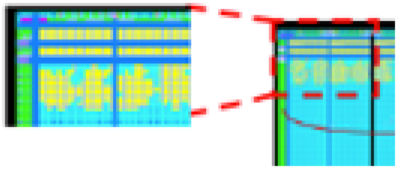
Phase-2 Minicrates

- On-chamber electronics performs time digitization of all chamber signals
- Digital information sent through optical link to counting room
- Complexity is brought into the counting room

Radiation tolerant FPGAs which perform 1 ns time digitization (no filtering)

GBT link for data forwarding

Zoom of first 4 TDC channels



* Allows readout at 1 MHz Level 1 and 20 us latency

* Trigger primitive generation:
- -maximum chamber resolution
- -room for pt resolution increase

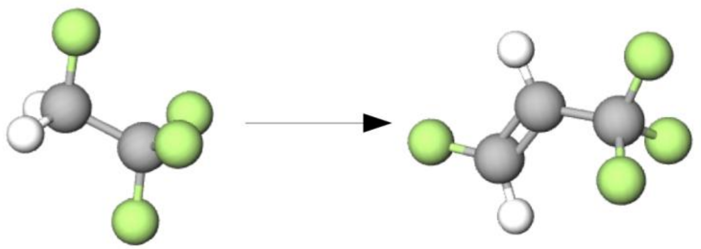
Eco-friendly Gas Mixtures

Finding alternatives

Several gases with low GWP scrutinized with:

- Good F/C ratio that plays significant role for Si etching
- No hazardous characteristics (toxic, flammable, etc.)
- Relative short molecules (long chains tend to polymerize, i.e. may cause anode/cathode ageing)

→ **not so many good candidates found!**

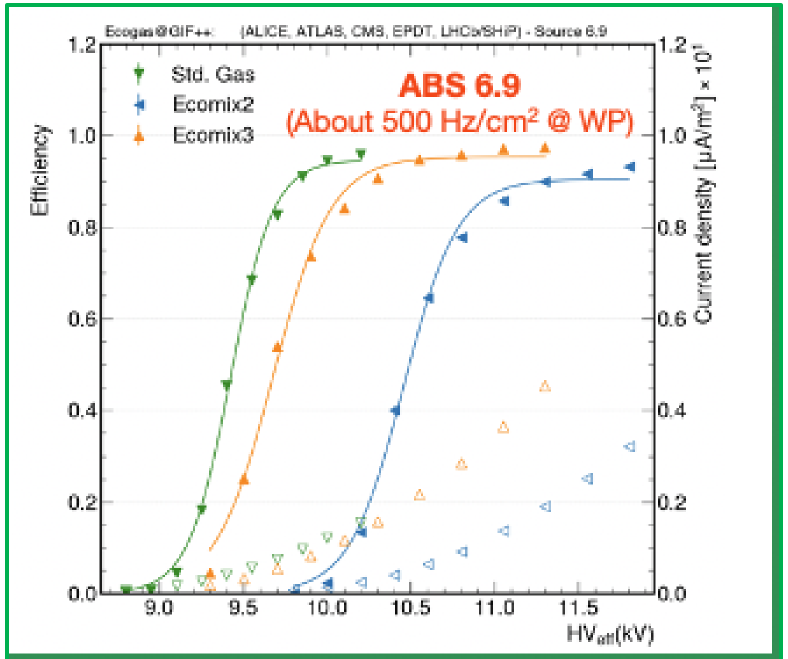


GWP ($C_2H_2F_4$) ~ 1430

GWP ($C_3H_2F_4$) ~ 6

HFO1234ze

RPC chambers without wires. Work in streamer or avalanche mode

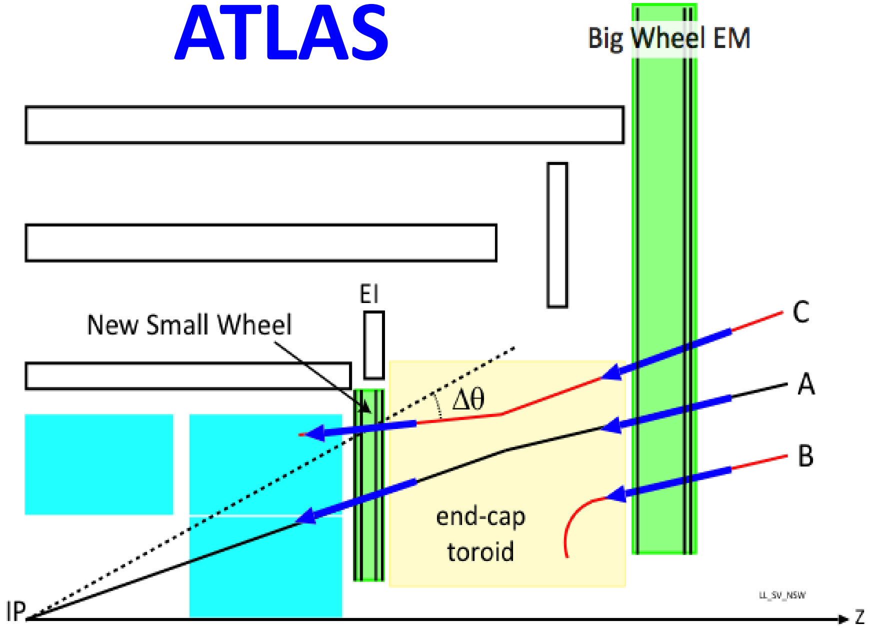


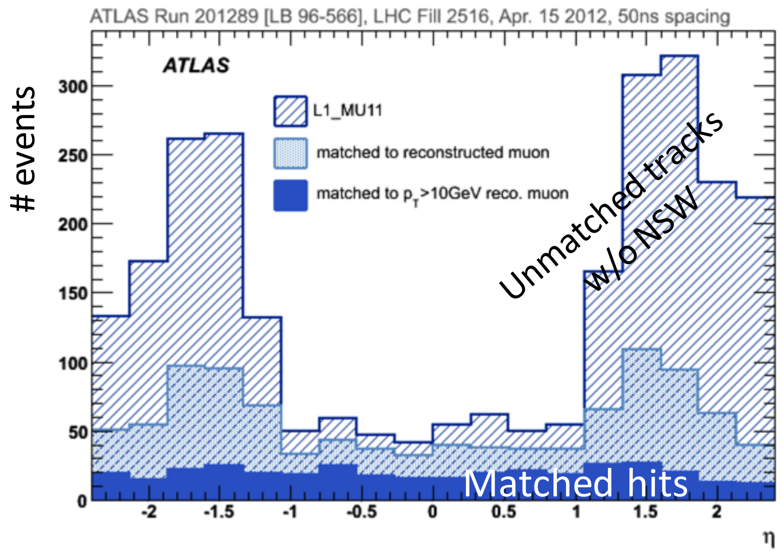
- **HFO1234ze Accelerated longevity studies with CSC:**
  - + no gain degradation up to 1.2 C/cm^2
  - - significant increase in dark current after 0.6 C/cm
  - Significant modification of the anode wire surface with formation of tungsten oxide

- **RPC EcoGas@GIF++ collaboration** tested mixtures of HFO (25 – 45%) + CO_2 (50 – 70%) + iC_4H_{10} (4%) + SF_6 (1%)

Muon Endcap Trigger Challenge

ATLAS





Goal: **efficient** muon triggering at increasing luminosities

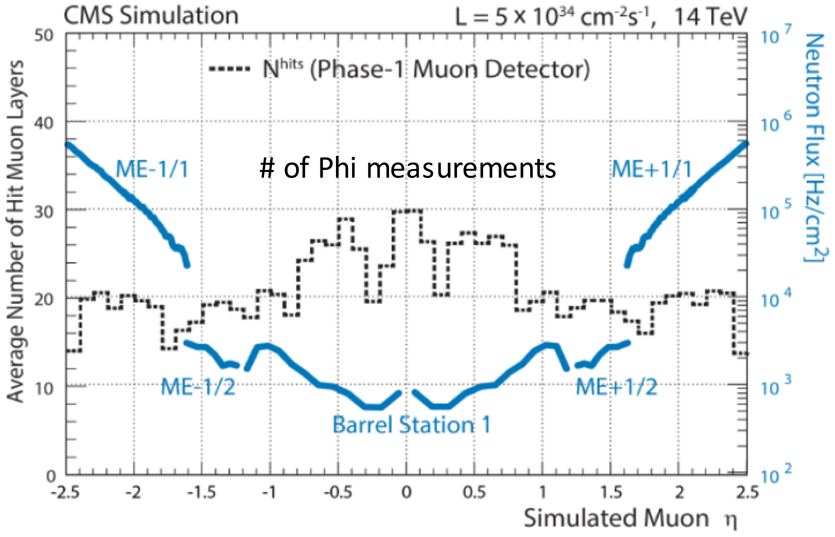
→remove fake and unmatched low momentum muons

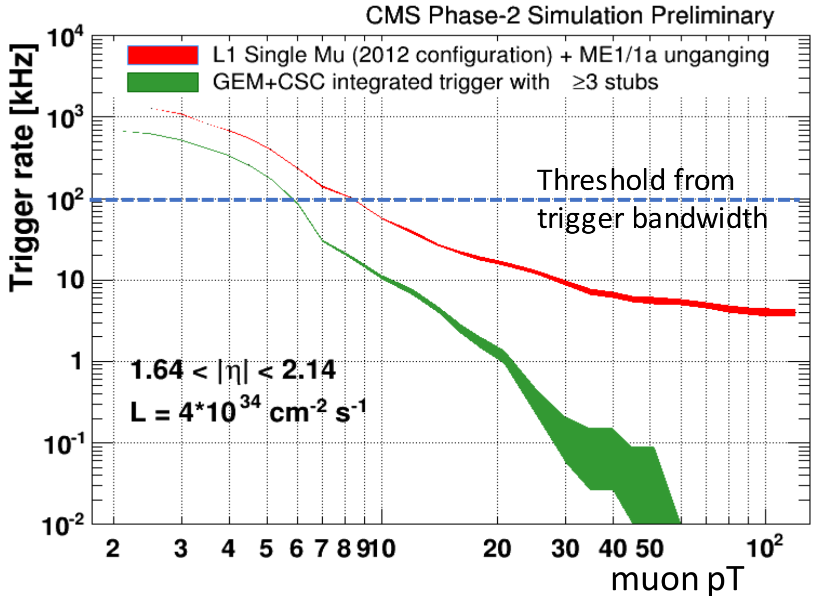
L1 trigger rate to stay within bandwidth and keep threshold

add more

measurement points

CMS



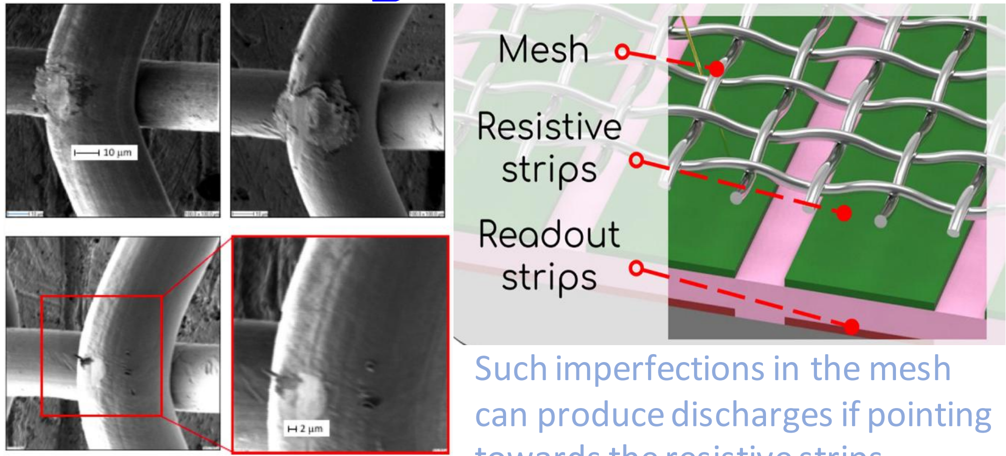


ATLAS Micromegas HV Stability

Cleaning is essential (brushing, washing, drying) to remove any dirt and solid deposits on readout boards.

Implement mesh polishing with fine sandpaper removing mechanical imperfections.

→Find microscopic imperfections on O(m²) surfaces

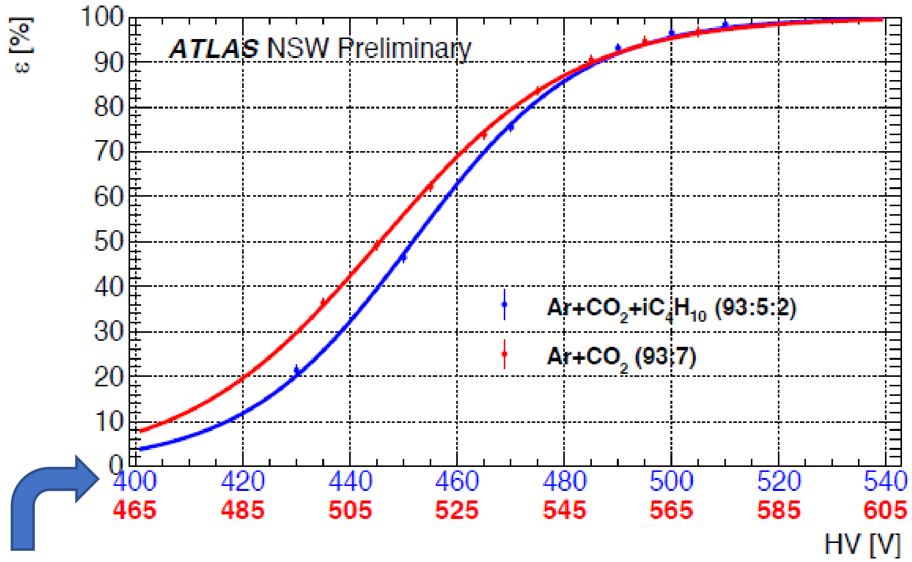


Such imperfections in the mesh can produce discharges if pointing towards the resistive strips

Gas mixture to reduce HV

Foreseen mixture Ar:CO_2 93:7 at HV_{RO} = 570 V is a low quenching mixture

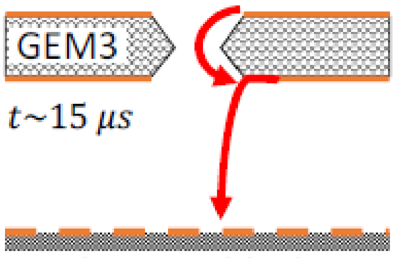
Added iC_4H_{10} to reduce amplification voltage to 520 V = better stability, higher gain, less sparks



Lower HV with Ar:CO_2:Iso 93:5:2

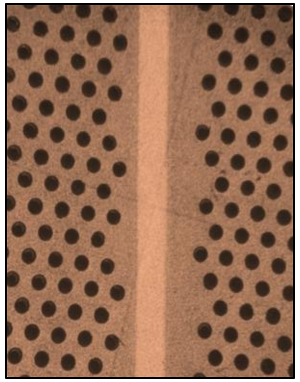
GEM Discharge Protection

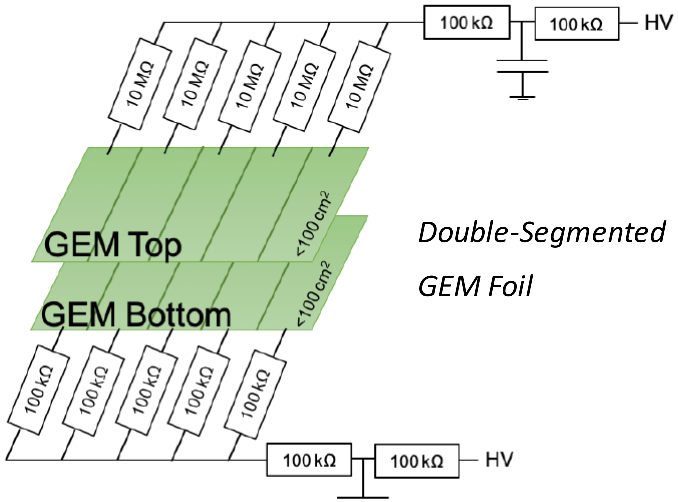
MPGD issue: due to small distance, formation of **spark** can easily be followed by **discharge** and damage detector or readout



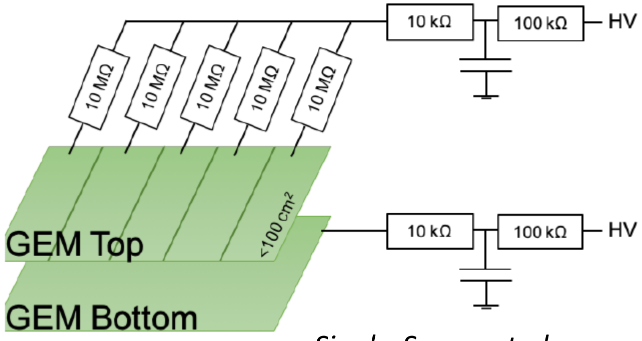
Large GEM foil = large capacitance = large reservoir of energy to feed the discharge

Discharge probability		Discharge propagation
Adressed by multiple GEM stages with lower HV/stage	x	Adressed by foil segmentation and resistors





Double-Segmented GEM Foil



Single-Segmented GEM Foil

GE1/1 single-segmented foils for all 3 stages

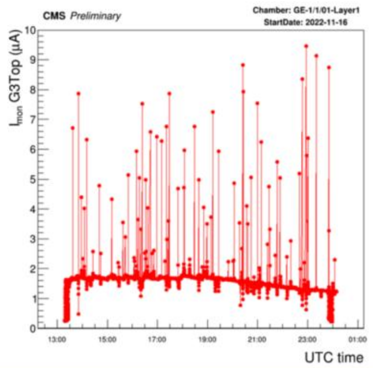
GE2/1,ME0 double-segmented GEM1,2. Single-segmented GEM3

Separate HV sectors. If one fails, the rest continues to work.

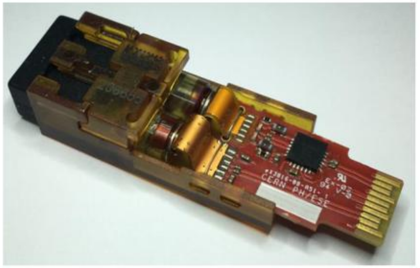
GE1/1 & GE2/1 Operational Experience

Installed GEM detectors: full GE1/1 system installed since LS2 and operational in regular CMS DAQ during Run-3. Four GE2/1 chambers for tests & demonstration.

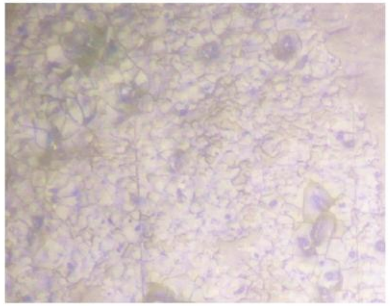
Issues summary



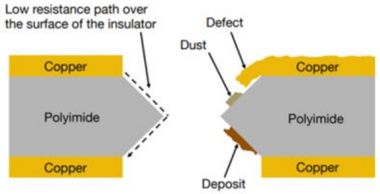
DISCHARGES
Impact:
HV instability, short circuits in GEM foils, reset and dead channels in electronics



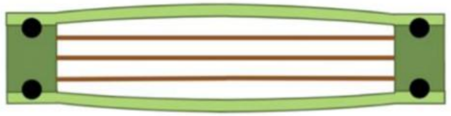
VTRx instability
Impact:
Areas of electronics (part or full detectors) not read



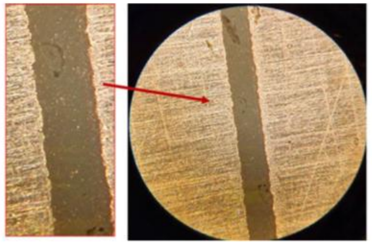
Non passivation of PCBs copper
Impact:
Oxidation signs



SHORT CIRCUITS IN GEM FOILS
Impact:
Inefficient areas, lower voltage applied to the whole foil



PCB bending
Impact:
Local difference in electric fields (and so lower efficiency).
Degradation of hit time of arrival (and so time resolution)



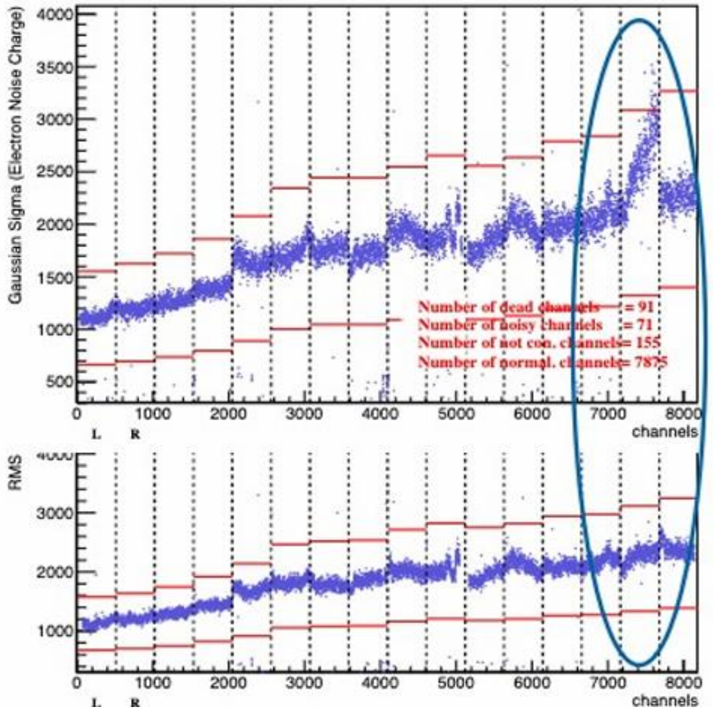
Copper dust on GE2/1 PCBs
Impact:
Generation of short circuits

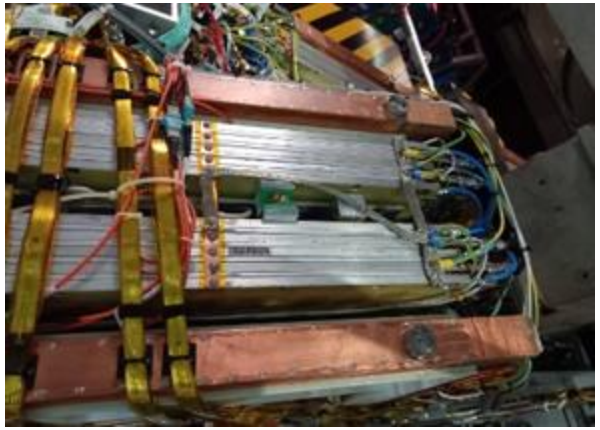
More details in Talk Simone Calzaferriat DRD1 coll. Meeting Dec 2024

Issue during MM Commissioning

Large system → many problems,
complex system → tricky problems

- Observed increase of electronic noise on both sTDC and Micromegas after mounting on wheel on surface
- Identified to mostly come from LV power supply and sub-optimal grounding
- Actions taken, solved the problem on surface
  - Refurbishment of LV power supply (additional filters added)
  - Modification of grounding scheme and improvement of detector ground
  - Addition of Faraday cage on FE elx boards
- After installation in ATLAS discovered a remaining high noise on longest Mircomegas strips, correlated with magnetic field → masked ~% channels

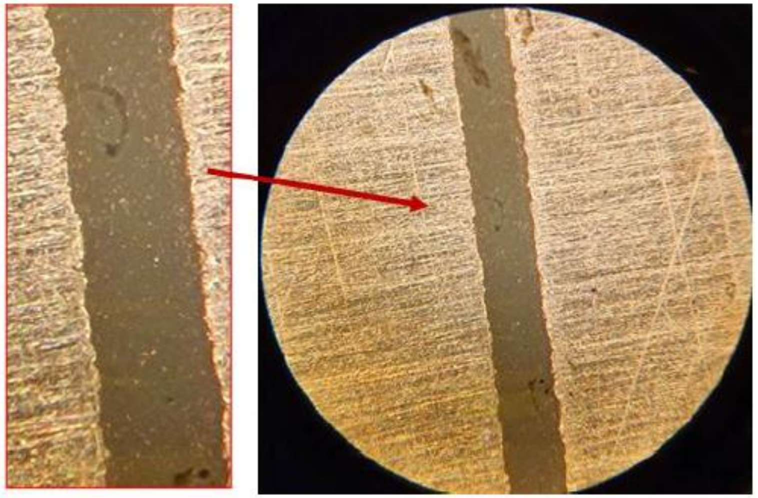




More details in CERN Detector Seminar P. Iengo „The Detector Configration of the ATLAS experiment for Run 3 of the LHC" 17 May 2024

Passivation of GEM PCBs

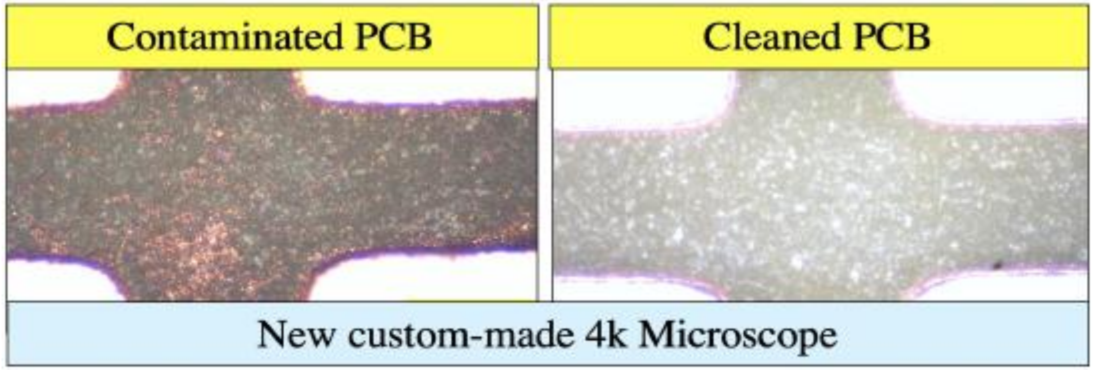
- PCB is a critical component that hosts the Drift electrode, the RO strips and forms the main body of the modules
- Discovered summer 2023 that PCBs were not passivated → copper dust in detectors



- Signs of **oxidation** in irradiated area of GE1/1 ageing detector

GE2/1 issues discovered during QC. Interrupted mass production. Five demonstrator chambers operate in CMS. Behaviour is monitored.

- **Developed cleaning procedure**
- Adapted QC protocol (microscopic inspection of RO board)



More details in Talk Jeremie Merlin DRD1 coll. Meeting Dec 2024

LHC schedule

- LHC Run-3 on-going reached 300 fb-1 already before the LS3 for the upgrade to HL-LHC
- EYETS at the moment till mid-March 2025, stable beam collisions expected on May 2025
- Goal is to reach the target for the delivered luminosity before the major upgrade during LS3