# Improved Resistive Plate Chambers for Phase-II upgrade of the CMS detector in LHC

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on behalf of CMS Collaboration

16TH PISA MEETING ON ADVANCED DETECTORS

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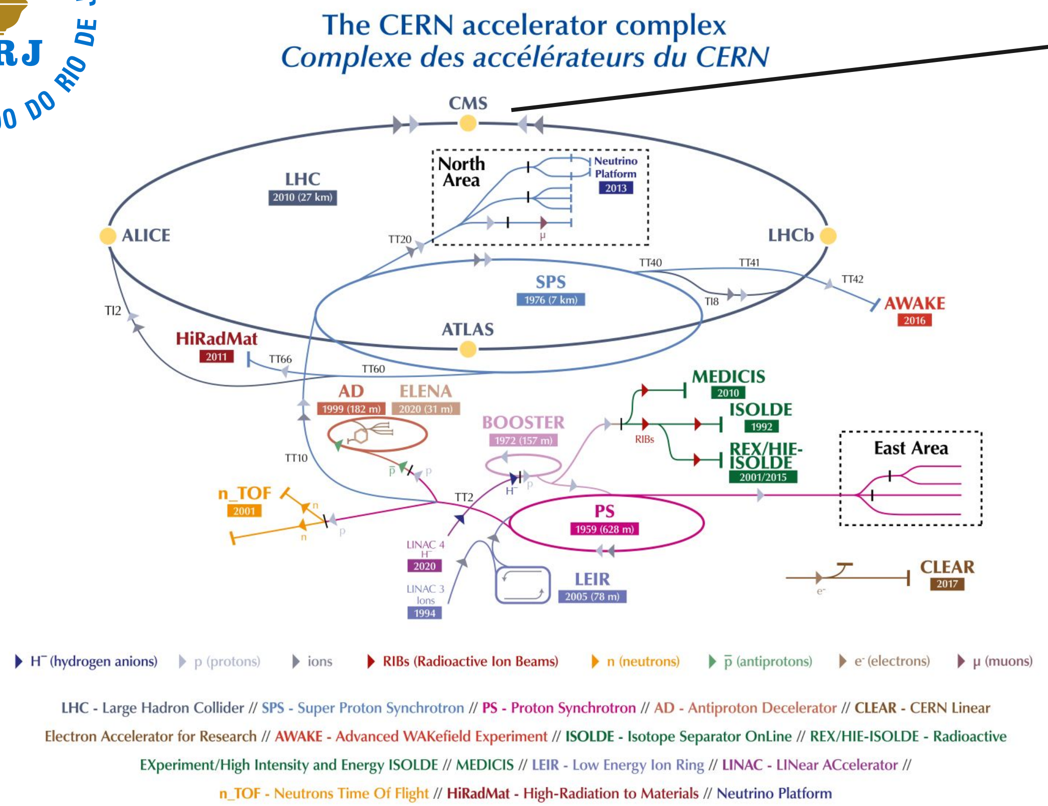
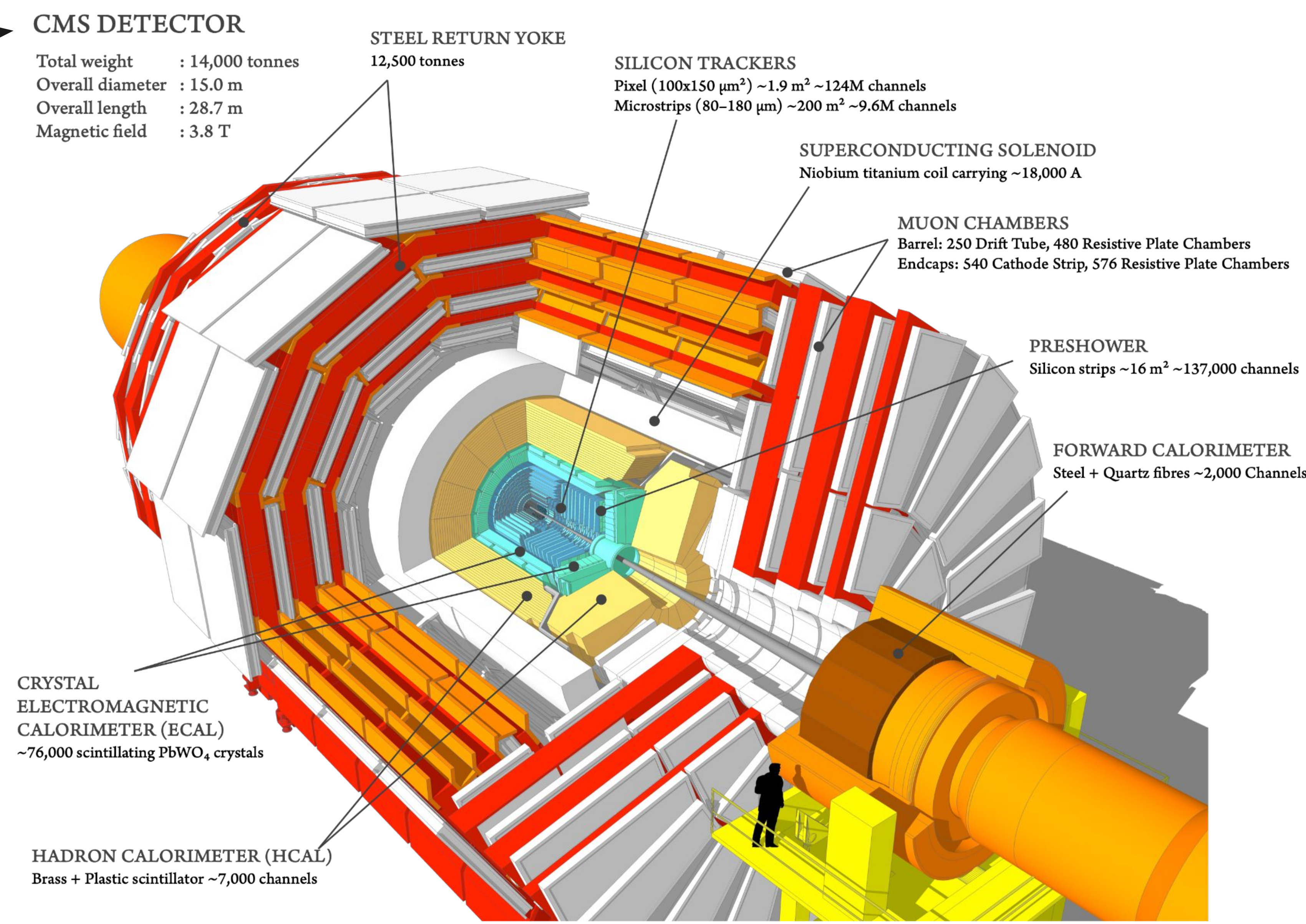
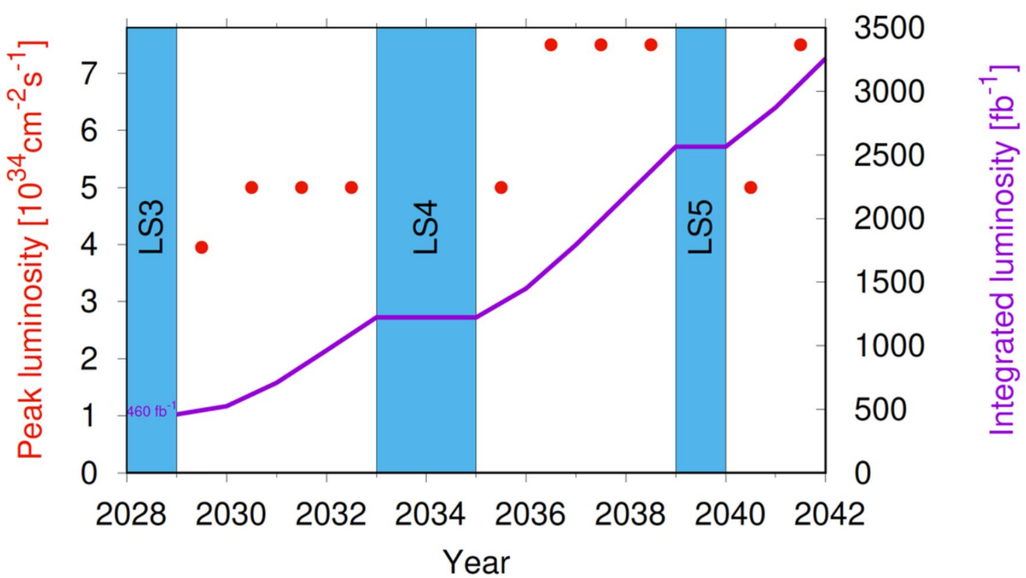
# Outline

- The Compact Muon Solenoid (CMS) for the HL-LHC
- The improved Resistive Plate Chambers (iRPCs) in CMS
- iRPC production and quality control
- Timing and space resolution
- Performance of iRPCs under gamma background
- Installation in CMS
- Conclusions and Perspectives

# The Compact Muon Solenoid for HL-LHC




CMS is under Run III data taking and in the process of preparation for the High-Luminosity period starting in 2029, anticipated to feature a higher Instantaneous Luminosity

Images: CERN Document Server courtesy

# The Compact Muon Solenoid for HL-LHC

**Upgrade of the CMS Tracker detector for the High Luminosity LHC**
Talk by Anna Macchiolo

**3D silicon pixel sensors for the CMS experiment tracker upgrade**
Poster by Davide Zuolo

**Performance of planar pixel modules for the Phase 2 Upgrade for the CMS Inner Tracker**
Poster by Bianca Raciti

**First Results on the final readout chip for the High-Luminosity LHC upgrade for the CMS Inner Tracker**
Poster by Michael Grippo

**Noise and performance tests results of the PS modules for the phase-2 CMS outer tracker**
Poster by Ilirjan Margjeka

**Precision Timing with the CMS MIP Timing Detector for High-Luminosity LHC**
Talk by Frank Golf

**Quality Control of LYSO:Ce crystals for the CMS Barrel MIP Timing Detector**
Poster by Ruben Gargiulo

**Low-gain Avalanche Diodes for the CMS Endcap Timing Layer**
Poster by Leonardo Lanteri

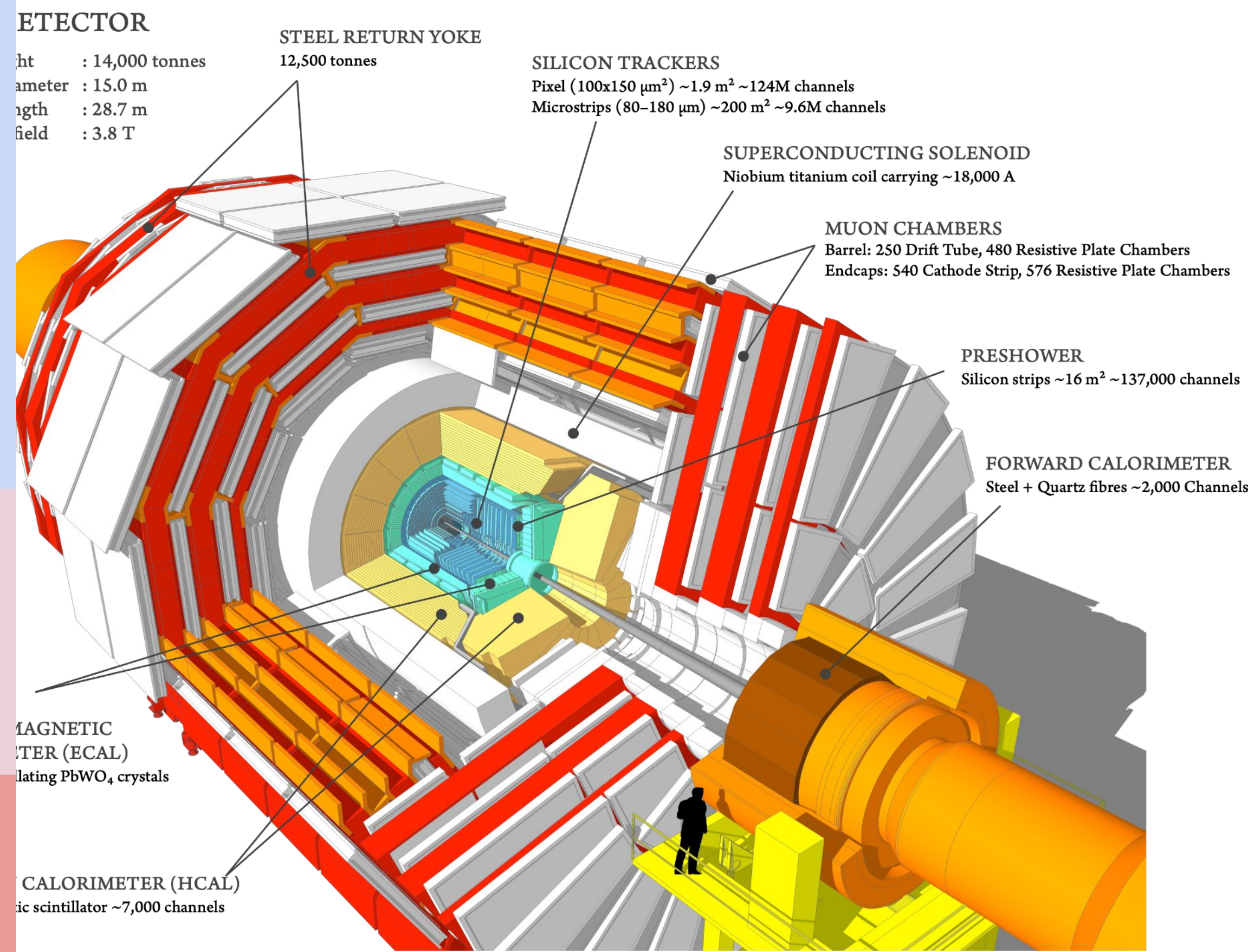
**Performance and test of the new CMS ECAL barrel front-end electronics for HL-LHC**
Poster by Cecilia Borca

**Surface-state induced inter-electrode isolation of n-on-p divides in mixed-field and gamma radiation environments**
Poster by Timo Peltola

**The Run 3 timing detector of the CMS Precision Proton Spectrometer: status and performance**
Poster by Milla-Maarit Rantanen

**Design and perspectives of the CMS Level-1 trigger Data Scouting system**
Poster by Rocco Ardino

**TetraBall: a single-moderator neutron spectrometer for HL-LHC**
Poster by Marco Costa

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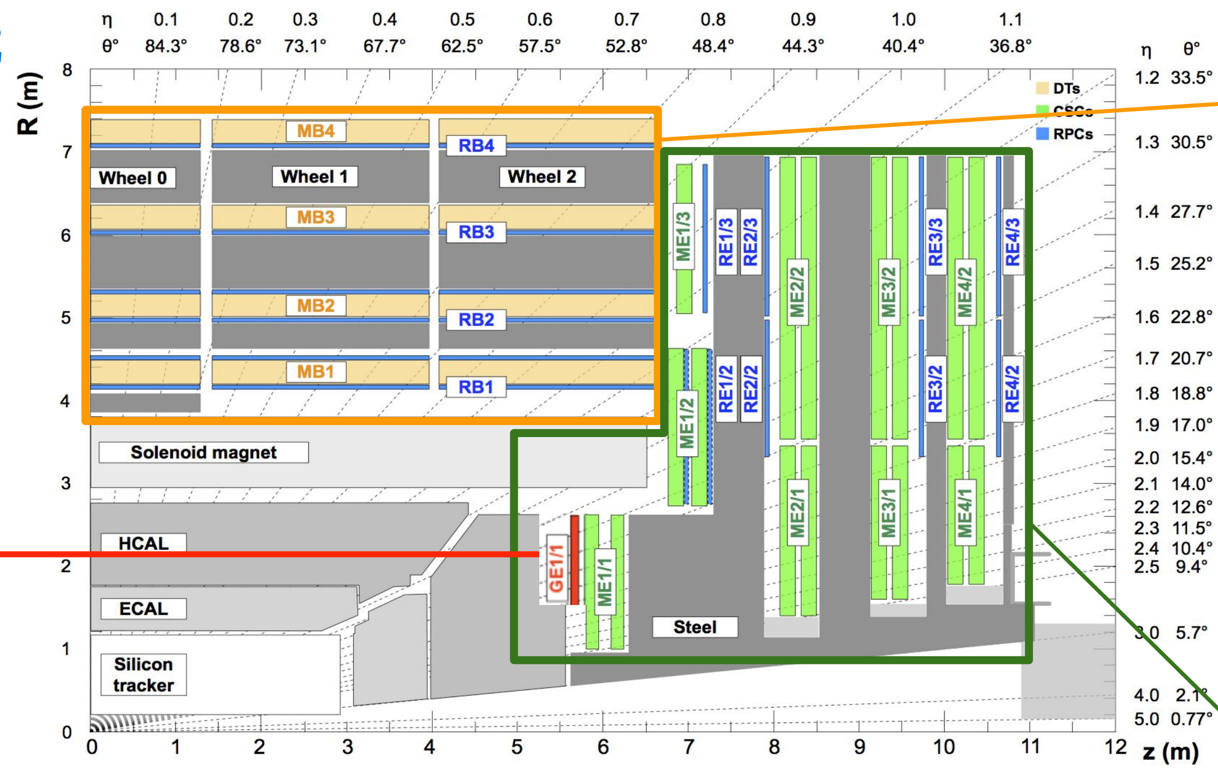
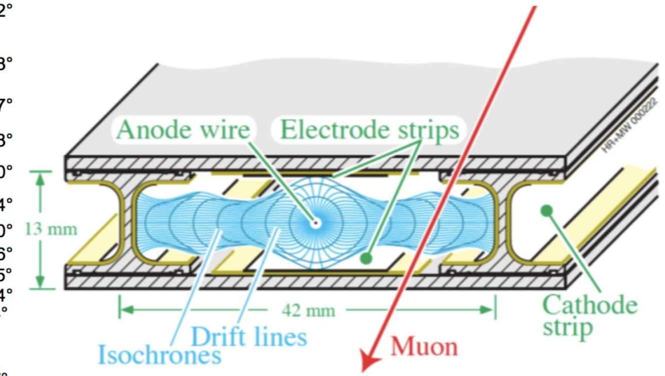
# CMS Muon System Spectrometer

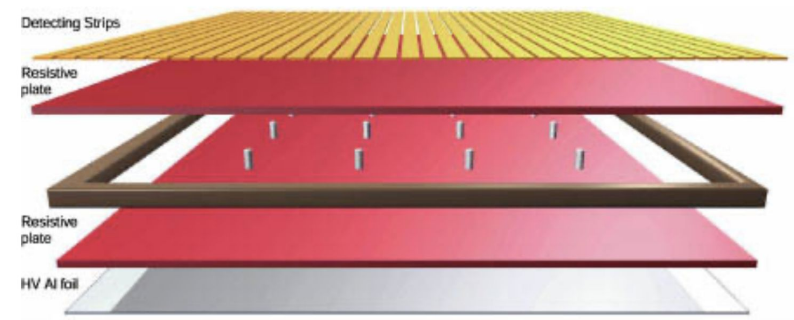



CERN Document Server courtesy

**Barrel of CMS: 250 Drift Tubes chambers**
**+ 480 Resistive Plate Chambers**



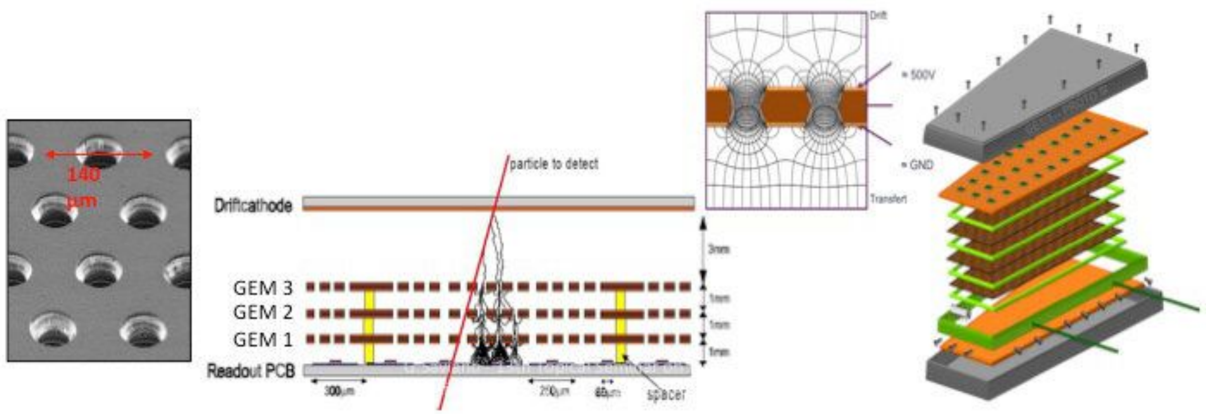

DT working principle




RPC gap layout

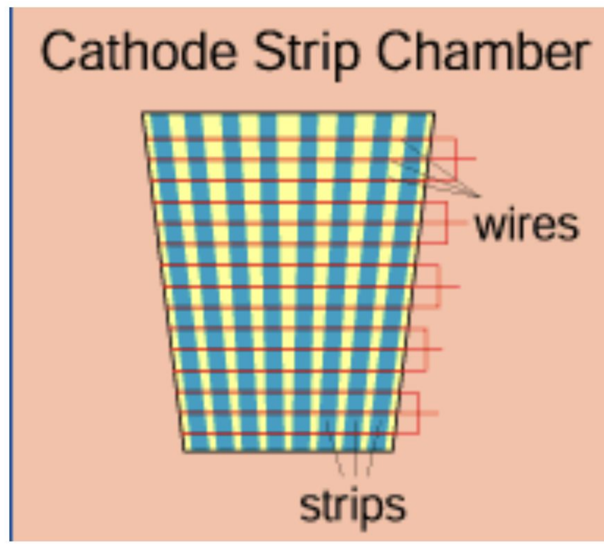
**End cap of CMS: 540 Cathode Strip Chambers**
**+ 576 Resistive Plate Chambers**

**Good performance** and **stable operation** of CMS Muon System during Run II of LHC (JINST 14 (2019) C11031)

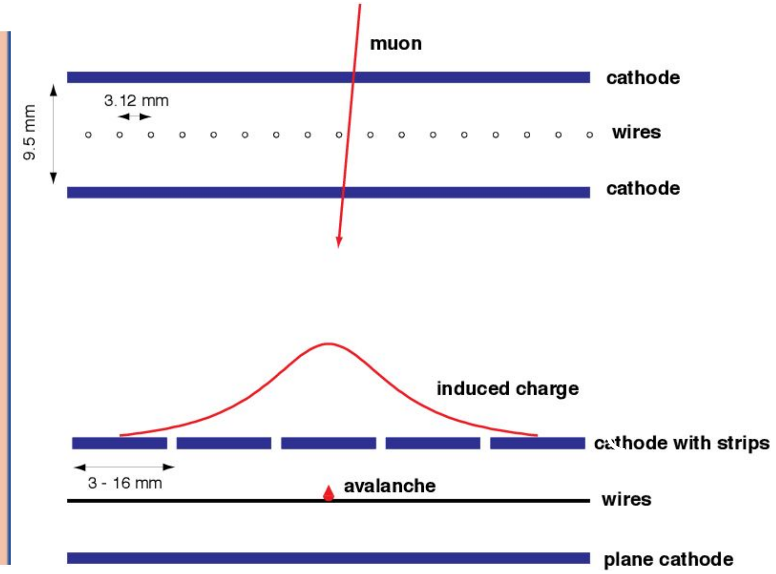



Verwilligen, Piet. (2023). GEM detectors for the CMS endcap muon system: status of three new detector stations. Journal of Instrumentation. 18. C07006. 10.1088/1748-0221/18/07/C07006.

72 triple-GEM chambers installed during Long Shutdown 2 (2019-2020) are having a **good performance** during Run III data taking period (CERN-LHCC-2015-012)

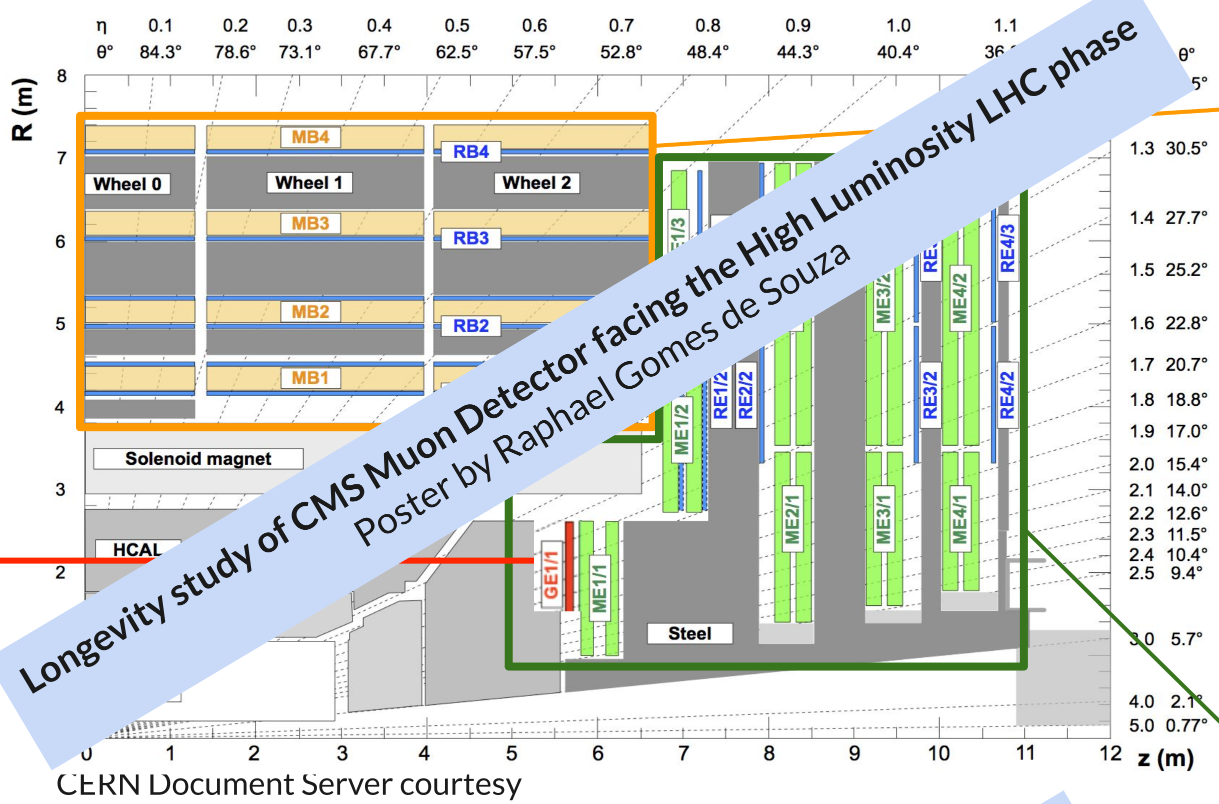



CSC layout




CSC working principle

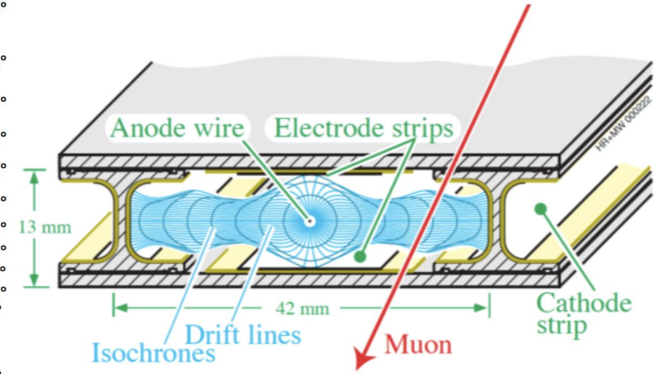
# CMS Muon System Spectrometer



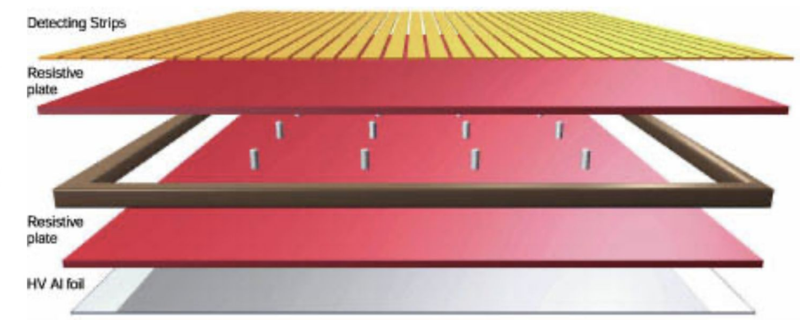

CERN Document Server courtesy

**Longevity study of CMS Muon Detector facing the High Luminosity LHC phase**
Poster by Raphael Gomes de Souza

Barrel of CMS: 250 Drift Tubes chambers
\+ 480 Resistive Plate Chambers



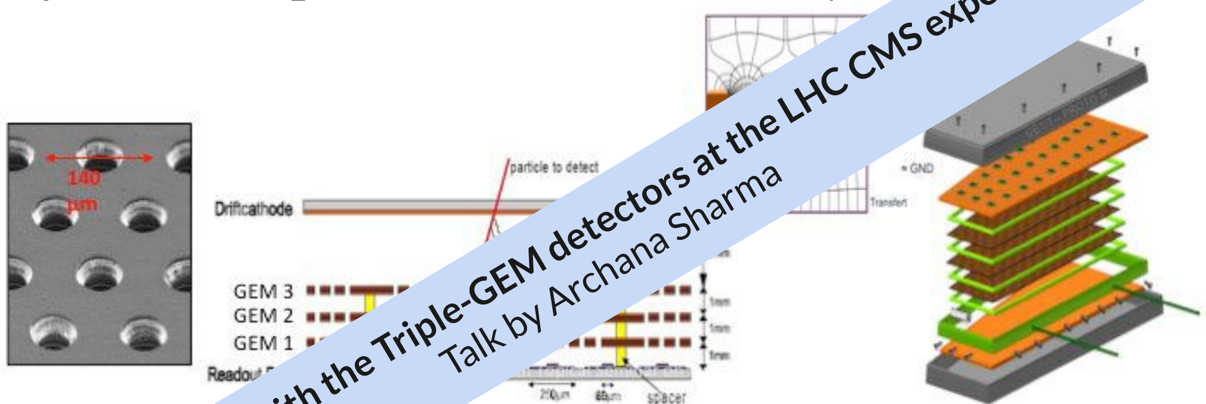

DT working principle




RPC gap layout

End cap of CMS: 540 Cathode Strip Chambers
\+ 576 Resistive Plate Chambers

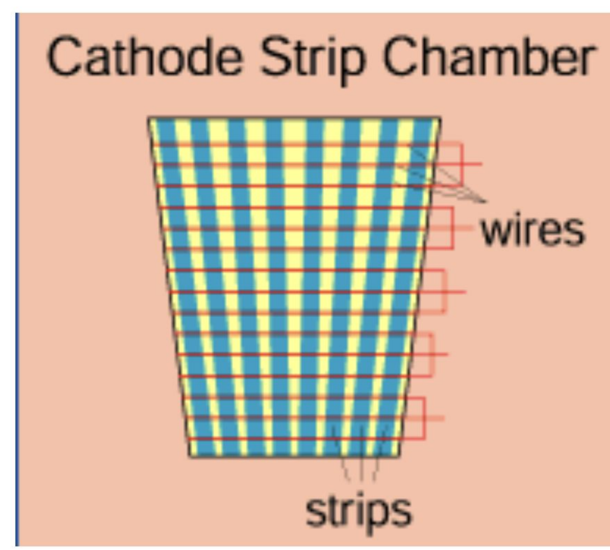
**Good performance** and **stable operation** of CMS ... on System during Run II of LHC (JINST 14 (2019...



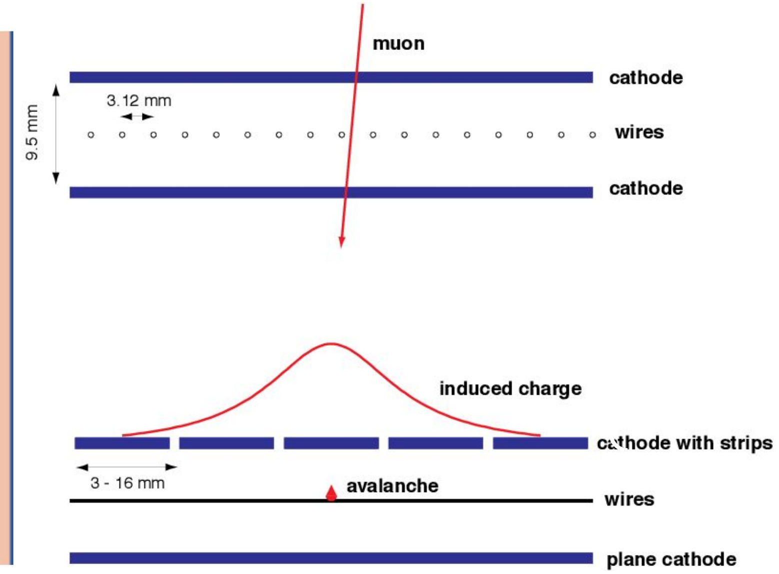

**Experience with the Triple-GEM detectors at the LHC CMS experiment**
Talk by Archana Sharma

Verwilligen, Pi... for the CMS endcap muon system: status of three new detector stations. Journal of Instrumen... ...68/1748-0221/18/07/C07006.

T... chambers installed during Long Shutdown 2 (2019-2020) are ... **good performance** during Run III data taking period (C...N-LHCC-2015-012)

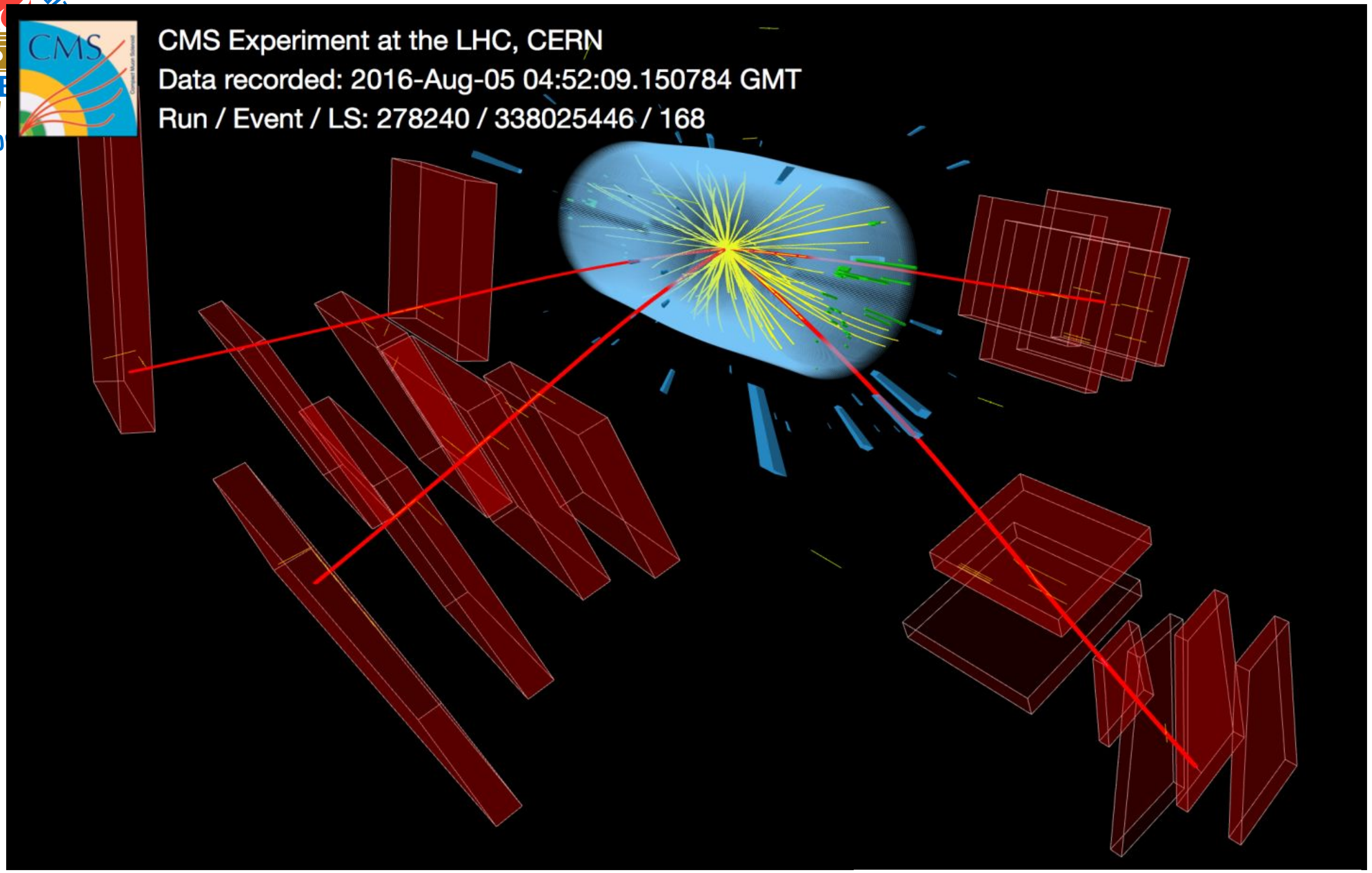


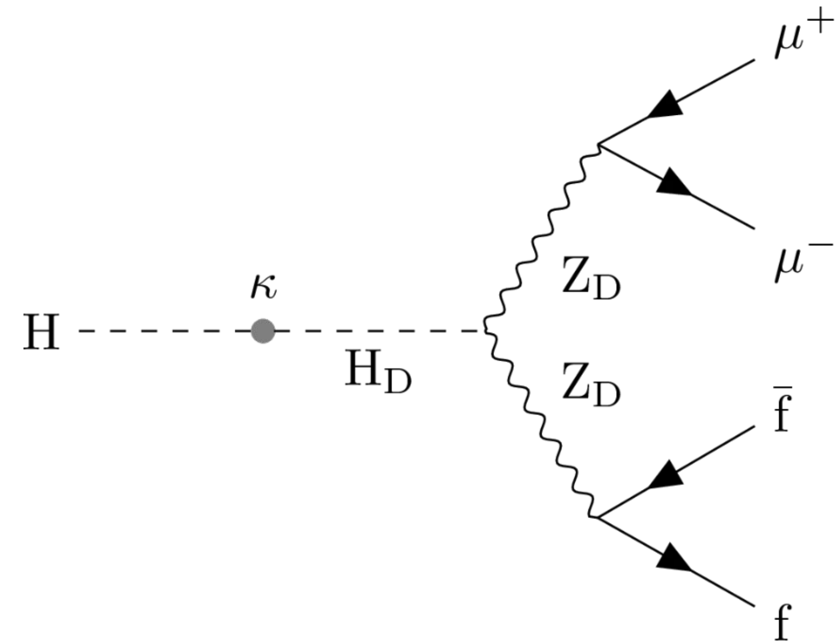

CSC layout

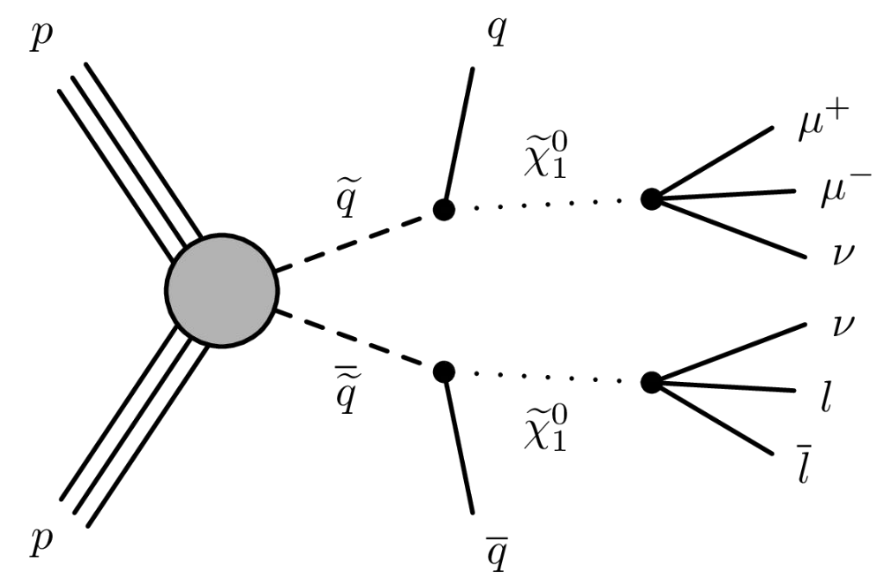



CSC working principle

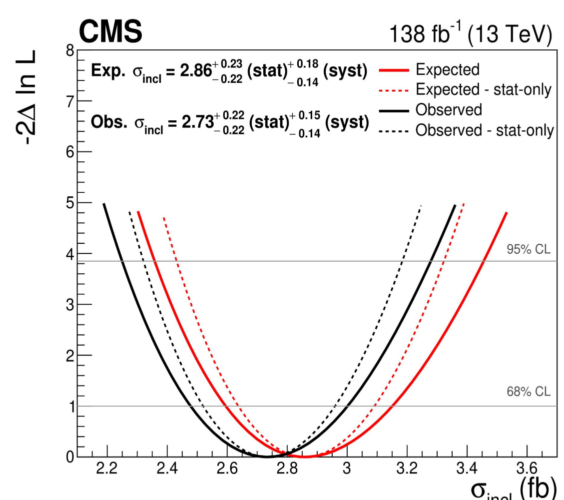
# The Compact Muon Solenoid at LHC: Physics!



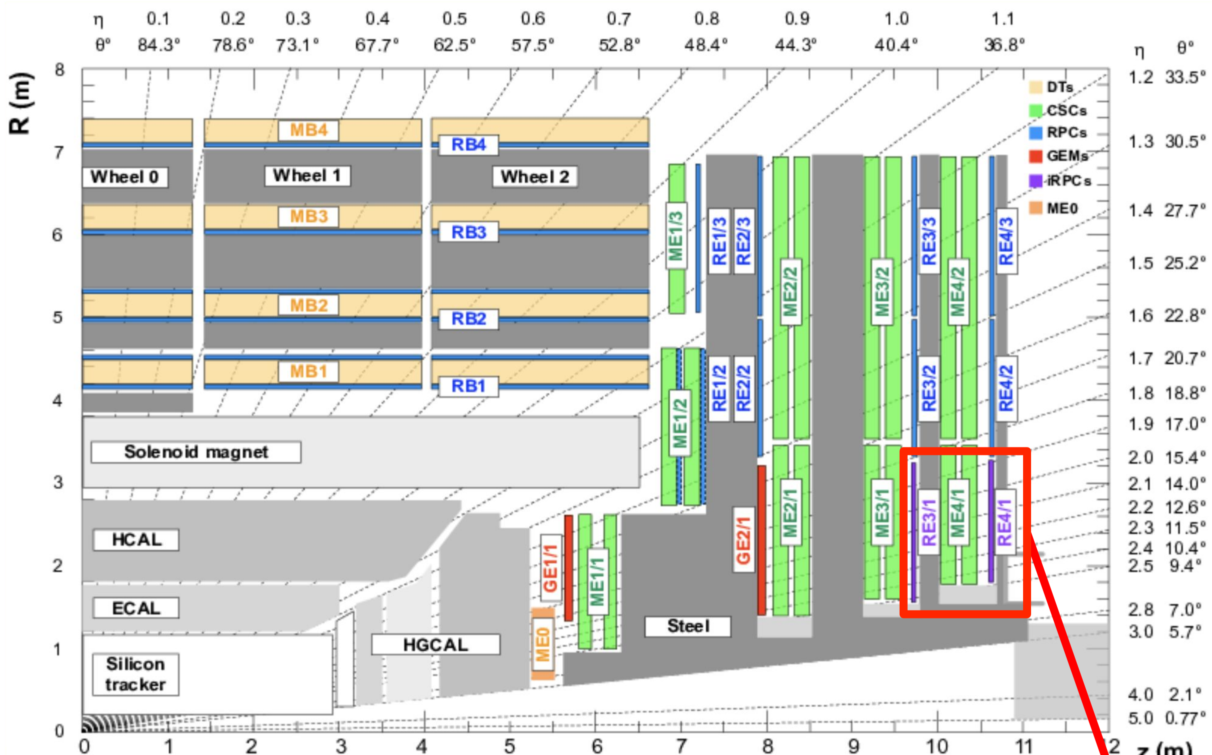




**Measurements of inclusive and differential cross sections for the Higgs boson production and decay to four-leptons in proton-proton collisions at √s=13 TeV (JHEP 08 2023 040)**

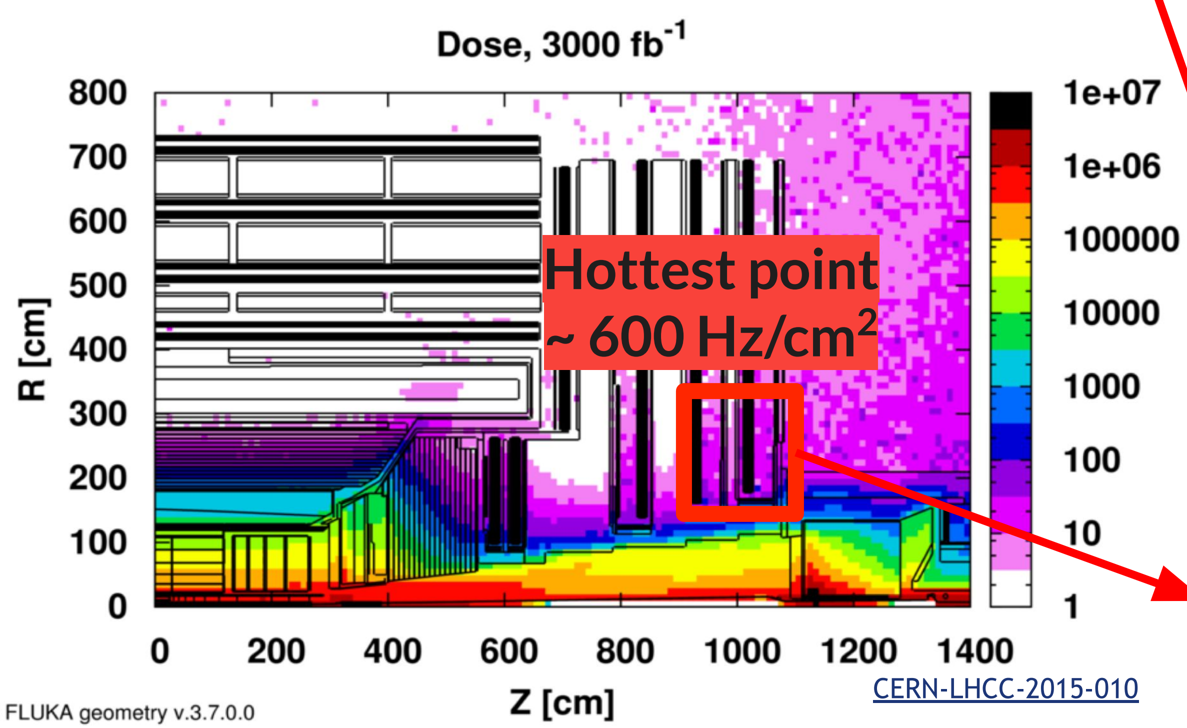



**Search for long-lived particles decaying to final states with a pair of muons in proton-proton collisions with 2022 data**
Accepted to JHEP 2024

# CMS Muon LHC Phase-II Upgrade

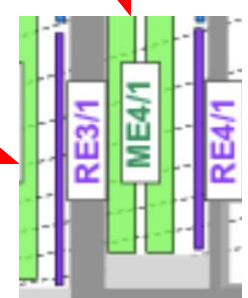



CERN Document Server courtesy



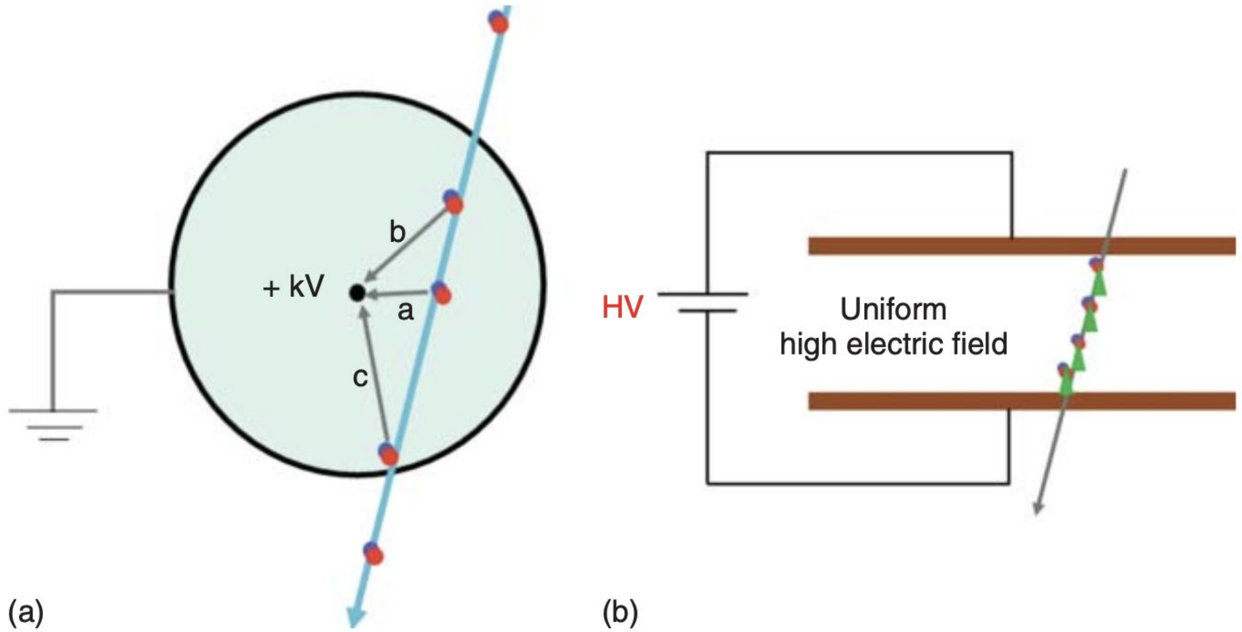

CMS FLUKA geometry v.3.7.0.0

CERN-LHCC-2015-010

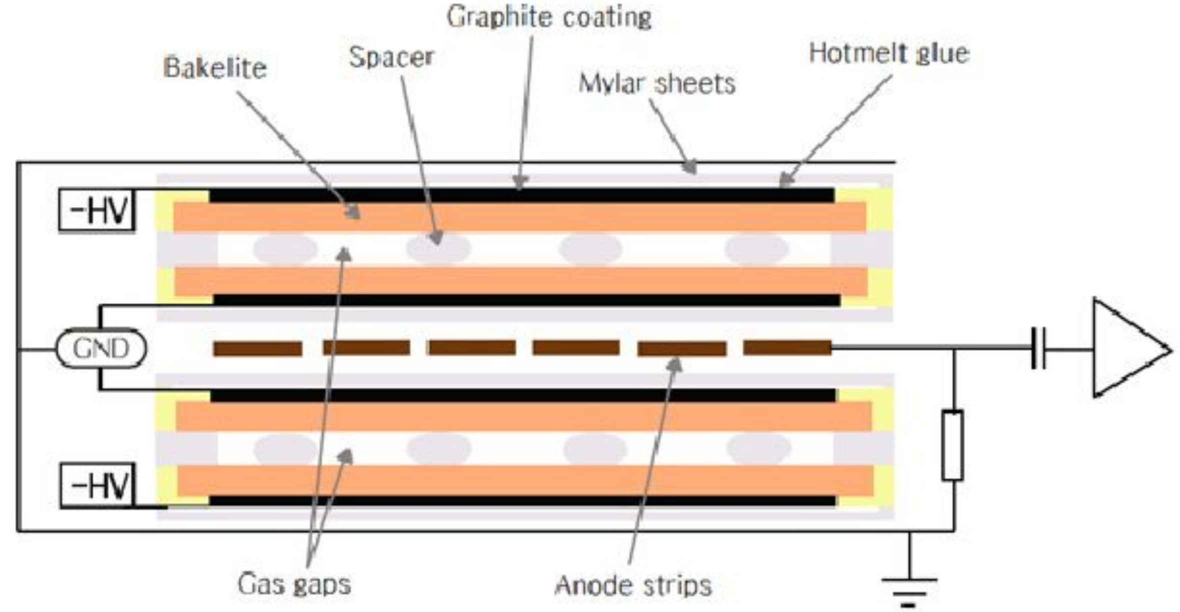



- Increasing the luminosity, the forward region of CMS becomes challenging → **improve trigger redundancy!**
- Interesting **Physics** in the forward region (CERN-LHCC-2017-012):
  - long-lived particles decaying leptonically;
  - final states with low *p*T muons;
  - heavy slowly moving charged particles;
  - highly boosted di-muons;
- Muon System Upgrade for HL-LHC (|η| < 2.8):
  - Existing DTs, CSCs and RPCs:
    → **Upgrade the Electronics!**
  - Installation of new detectors in the forward region:
    - **Gas Electron Multipliers:** ME0 and GE21
    - **Improved Resistive Plate-Chambers:** RE31 and RE41

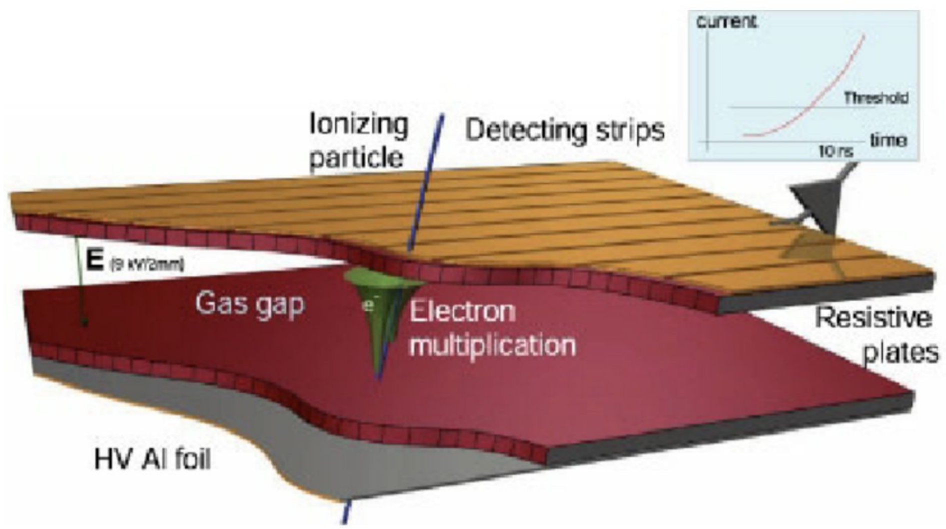
# The Resistive-plate Chambers in CMS



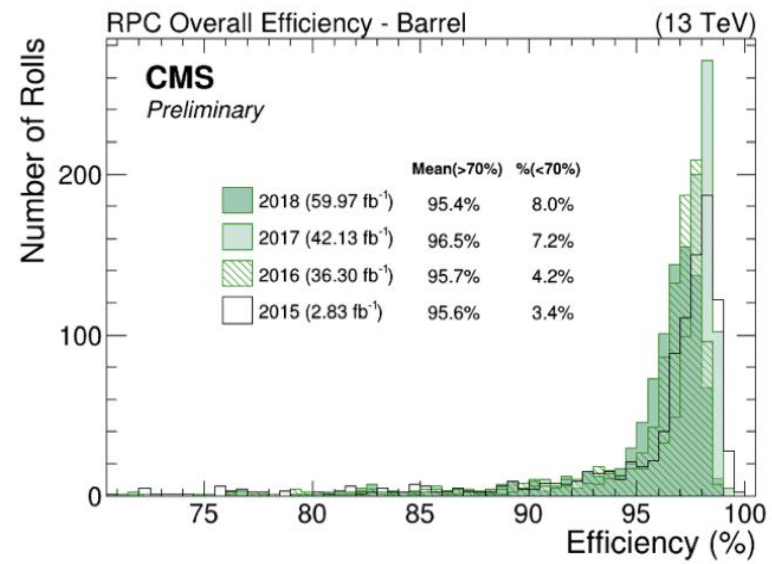

Abbrescia et al, 2018

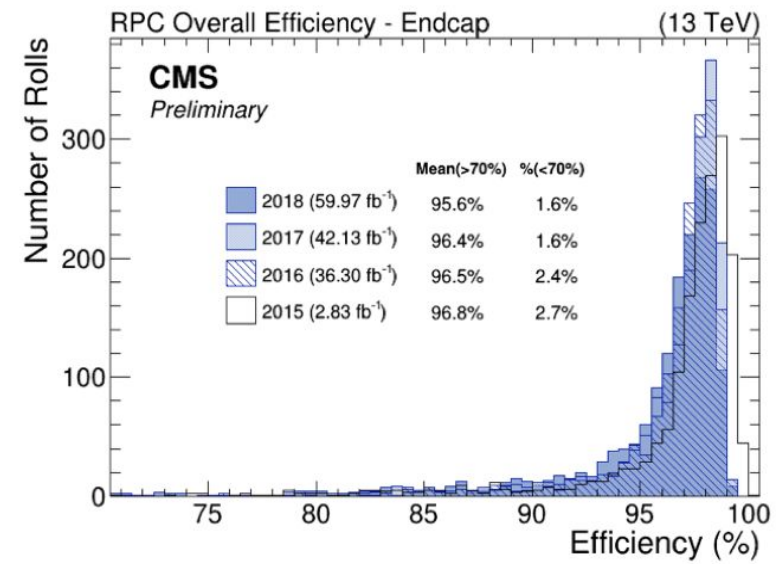



Park, S et al (2012). CMS endcap RPC gas gap production for upgrade. Journal of Instrumentation. 7. P11013. 10.1088/1748-0221/7/11/P11013.




Guiducci, Luigi & Montanari, Alessandro & Odorici, Fabrizio & Rossi, Antonio. (2006). Design and Test of the Off-Detector Electronics for the CMS Barrel Muon Trigger

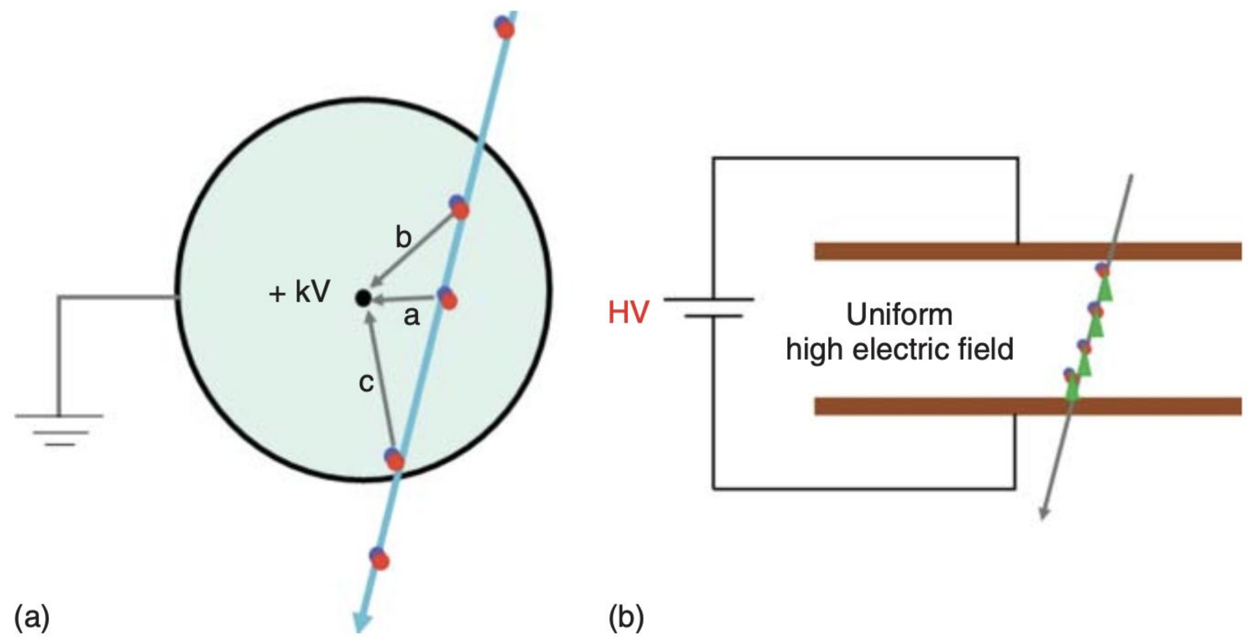



RPC barrel and end cap efficiency during Run II (2015-2018)

Gas mixture used in CMS/RPC: 95.2 % $C_2H_2F_4$ + 4.5 % i-$C_4H_{10}$ + 0.3 % $SF_6$

# The Resistive-plate Chambers in CMS

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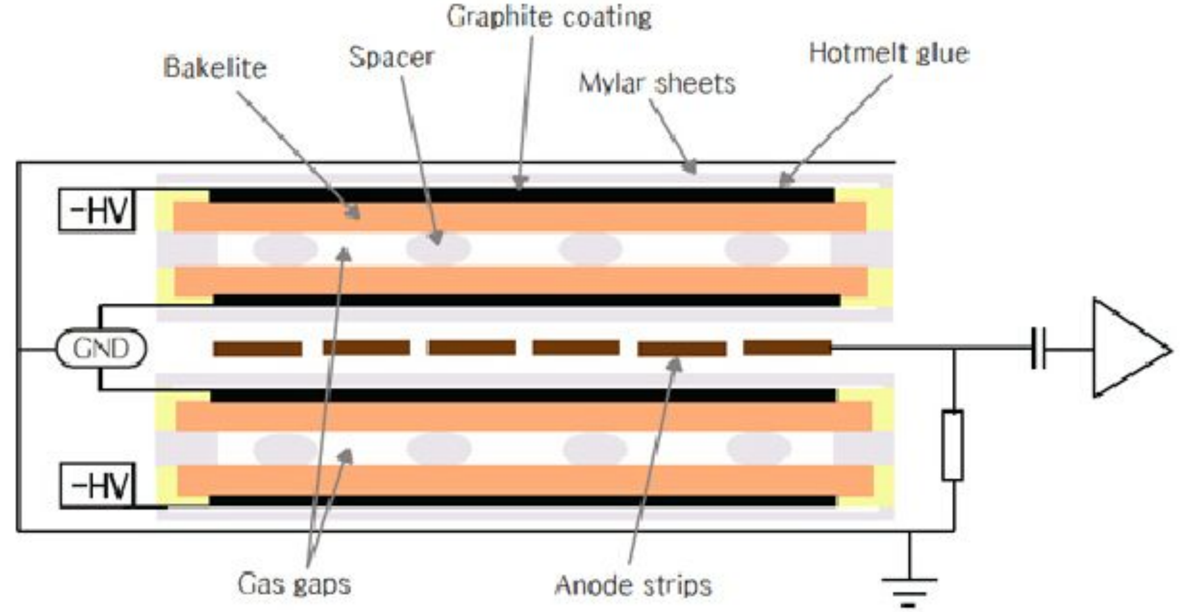


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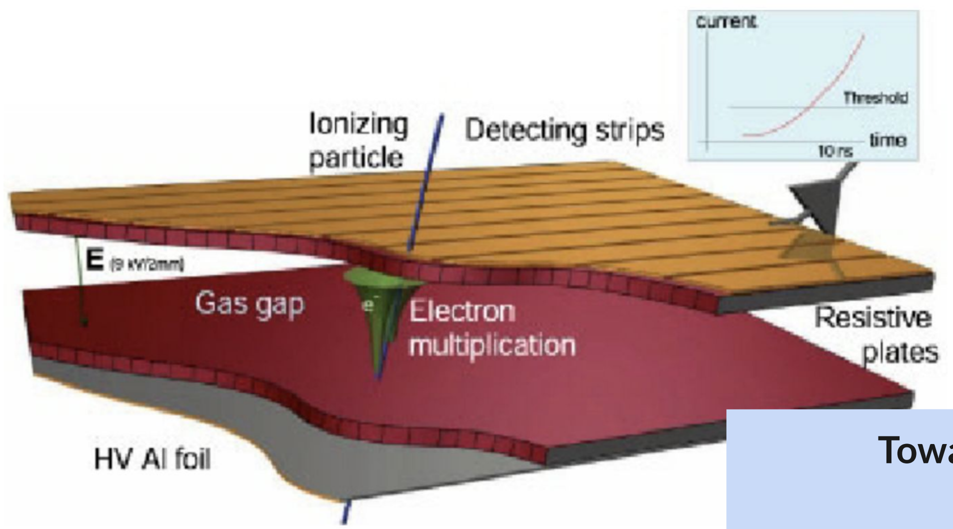
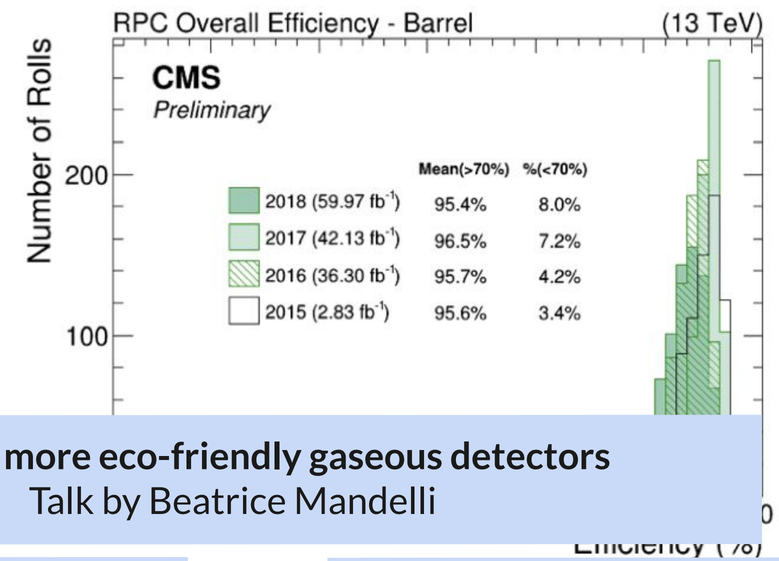
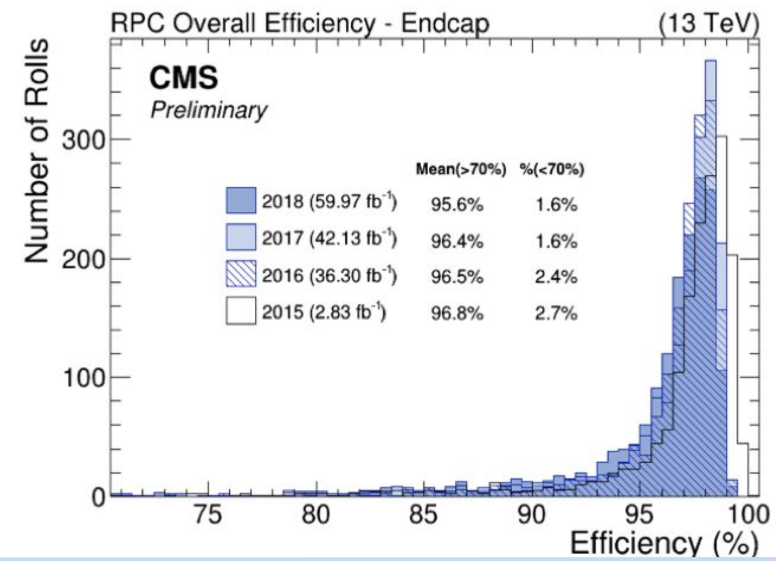



**Towards more eco-friendly gaseous detectors**
Talk by Beatrice Mandelli

Guic
Desi

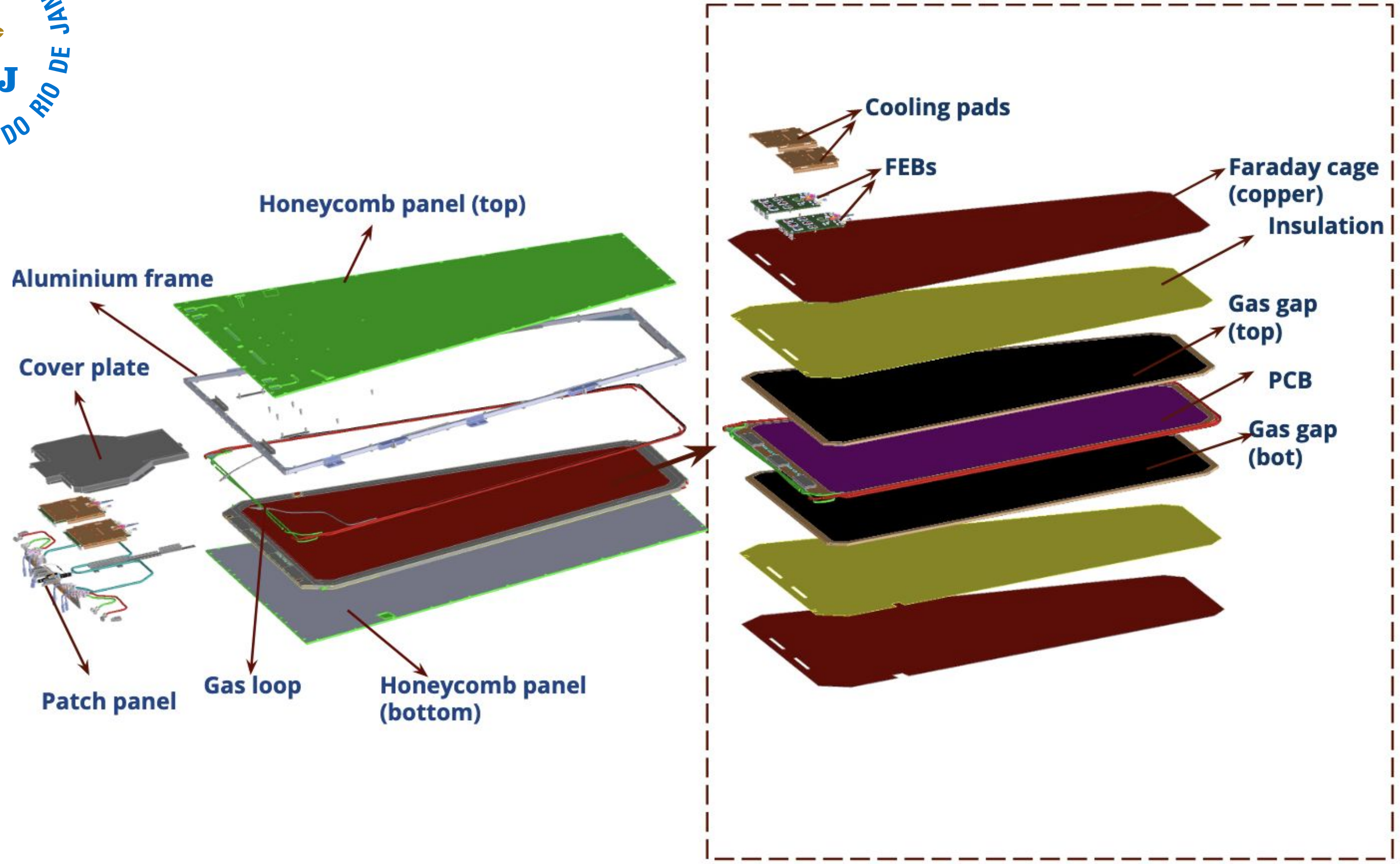
**New RPC Gas Mixtures for Sustainable Operation in the CMS Experiment**
Poster by Dayron Ramos Lopez

PC bar

**Recuperation systems for fluorinated gases at the CERN LHC Experiments**
Poster by Beatrice Mandelli

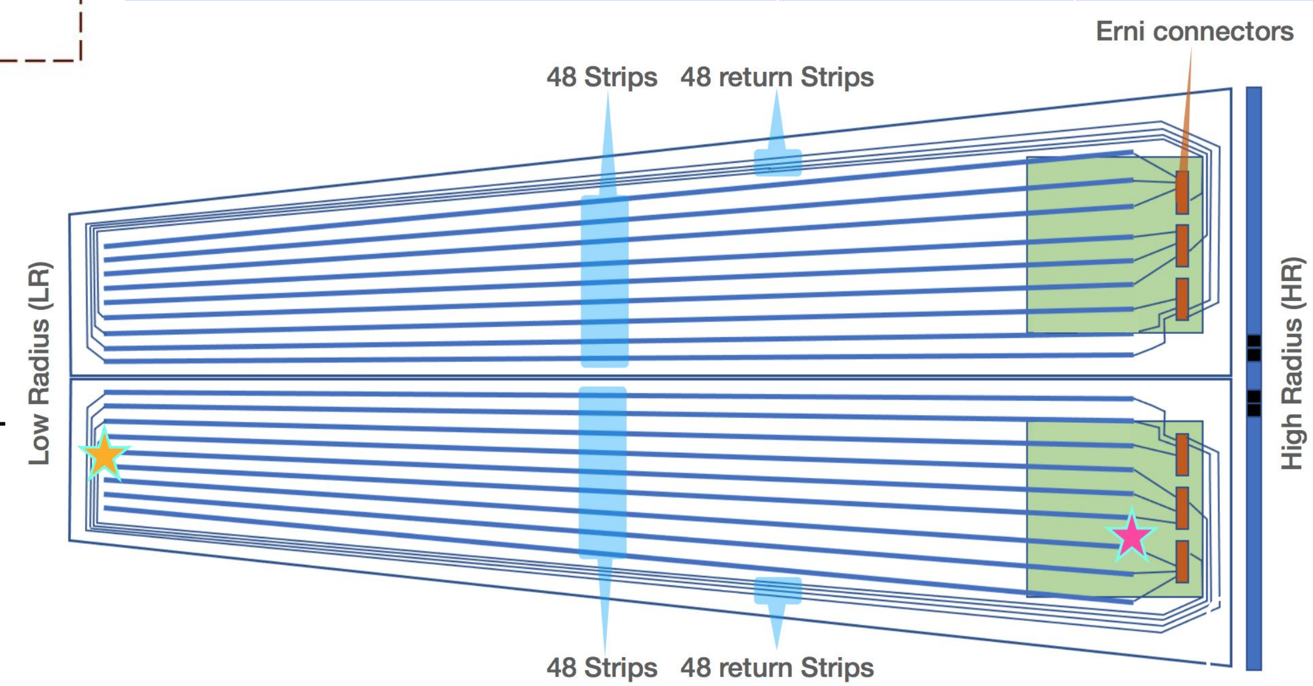
Gas mixture used in CMS/RPC: 95.2 % $C_2H_2F_4$ + 4.5 % i-$C_4H_{10}$ + 0.3 % $SF_6$

# The improved Resistive-plate Chambers in CMS

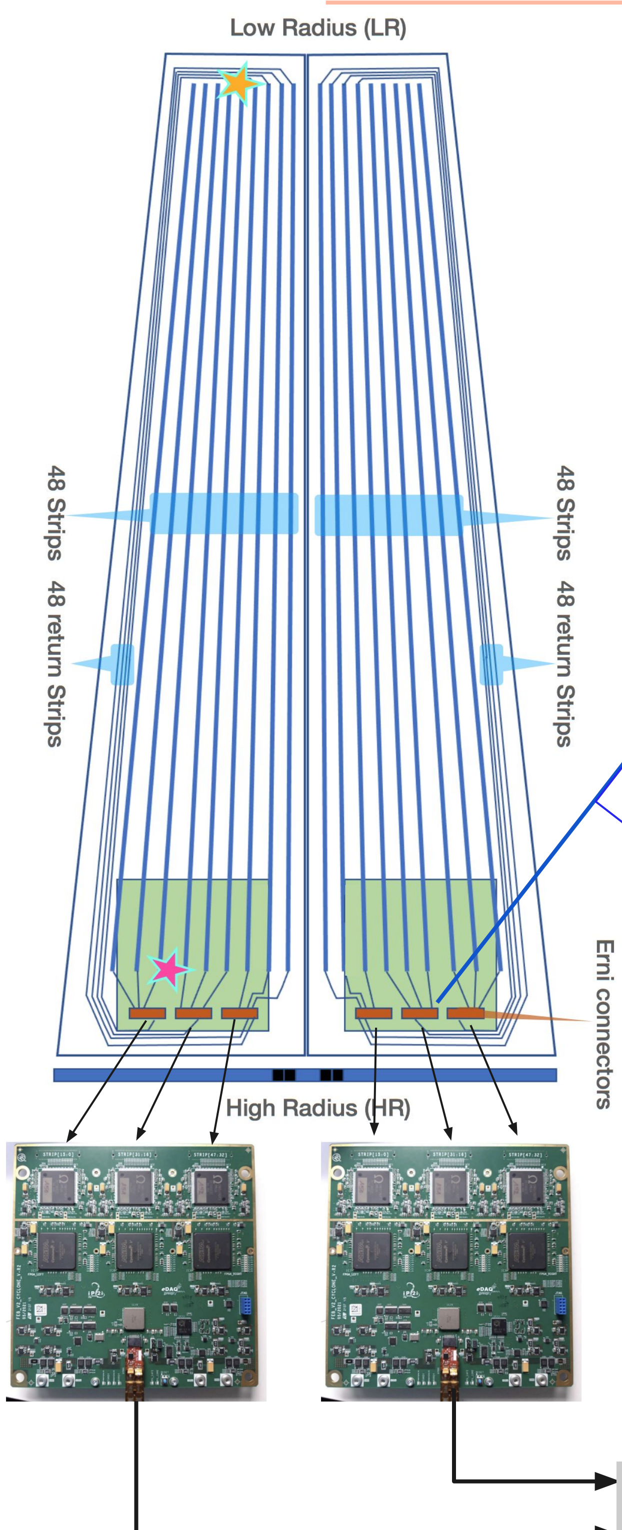


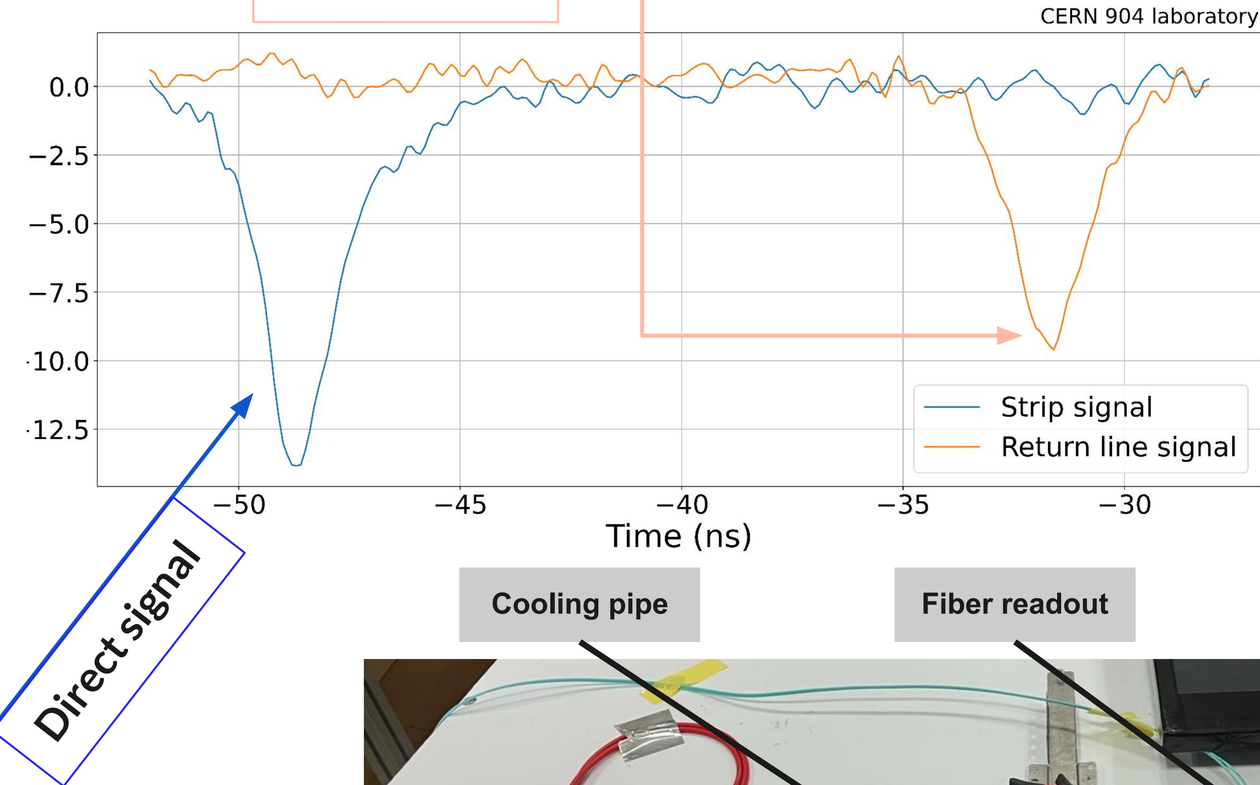

| | RPC | iRPC |
|---|---|---|
| HPL thickness (mm) | 2 | 1.4 |
| Number of gas gaps | 2 | 2 |
| Gas gap thickness (mm) | 2 | 1.4 |
| Resistivity (Ωcm) | 1 - 6 x $10^{10}$ | 0.9 - 3 x $10^{10}$ |
| Charge threshold (fC) | 150 | 30 - 40 |
| Space resolution in η (cm) | 20 - 28 | 1.5 |
| Space resolution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

- + 72 chambers in RE3/1 and RE4/1 positions
  - 20 ° coverage in ϕ per chamber
  - Variable strip width from 0.6 cm to 1.23 cm
  - trapezoidal geometry ~1.2 x 1.6(3) $m^2$ for RE 3(4)/1
- Double readout in the strips high and low radius
- Charge threshold between 30 and 40 fC

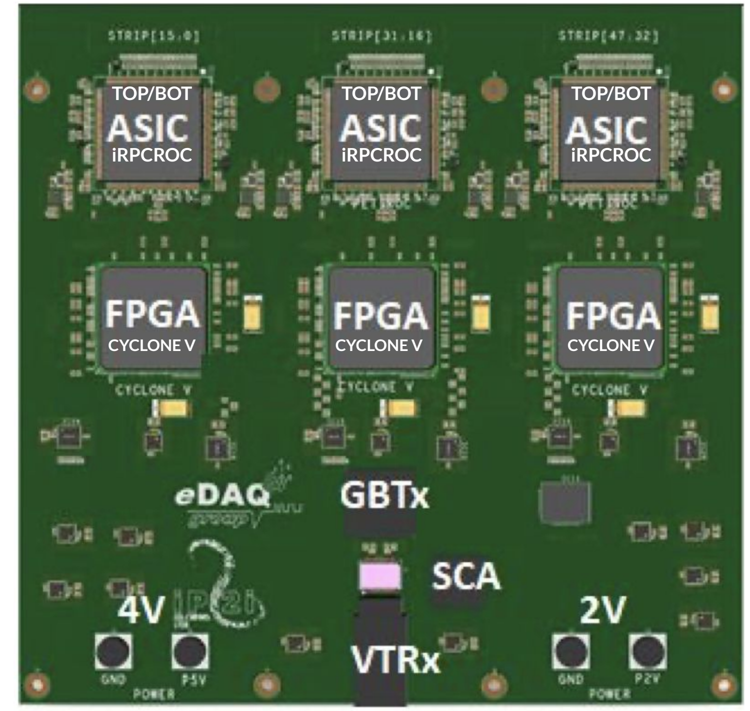


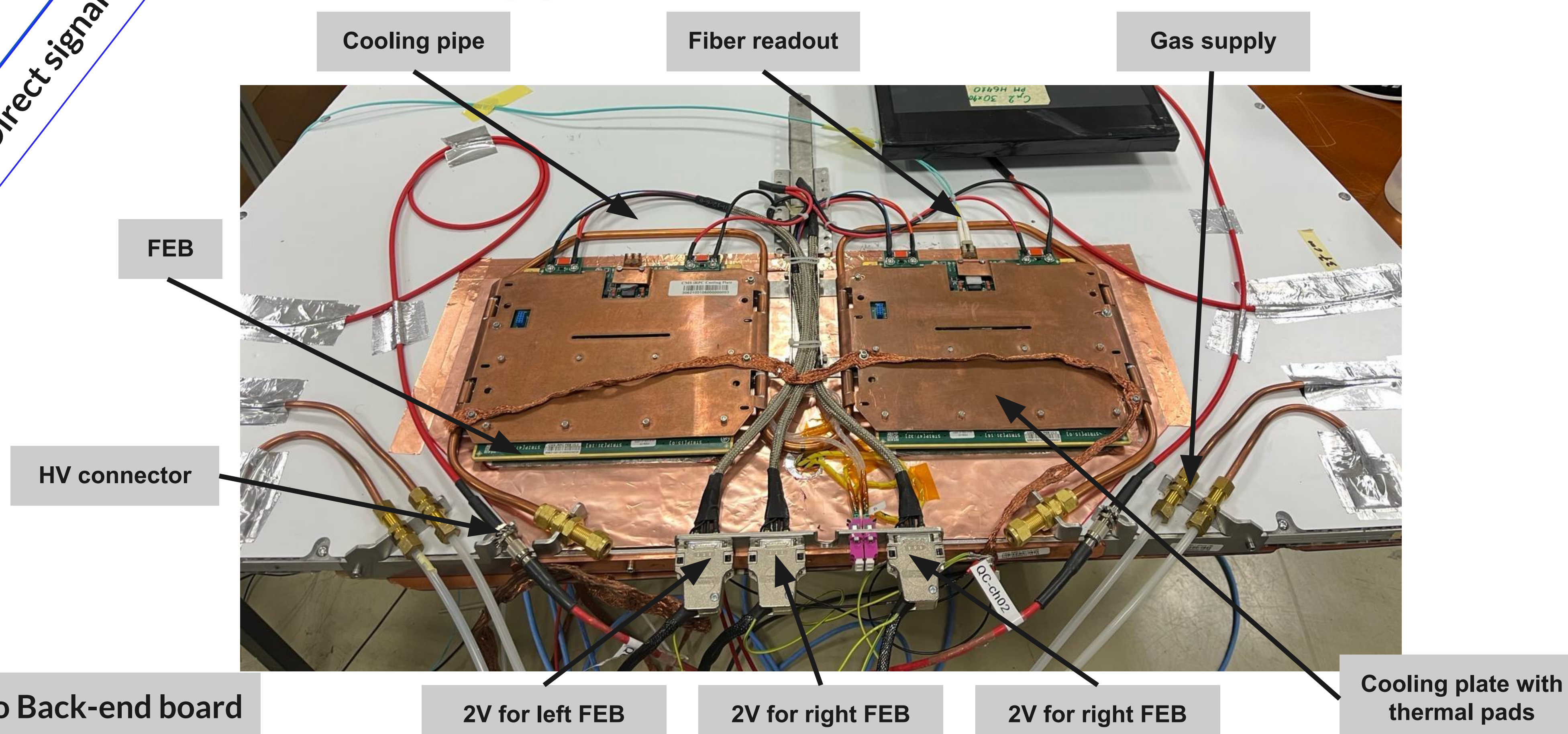
# The iRPC Front-end electronics



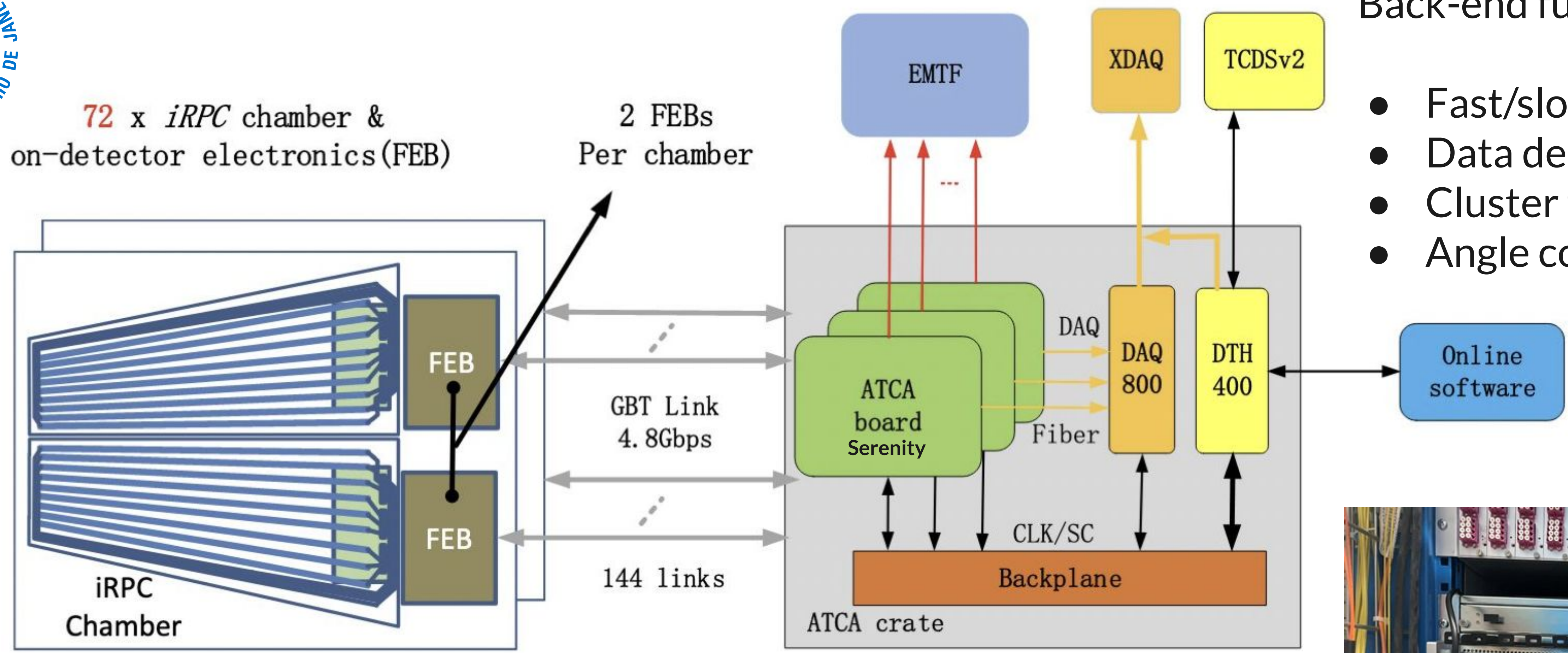




Front-end Electronics for iRPC



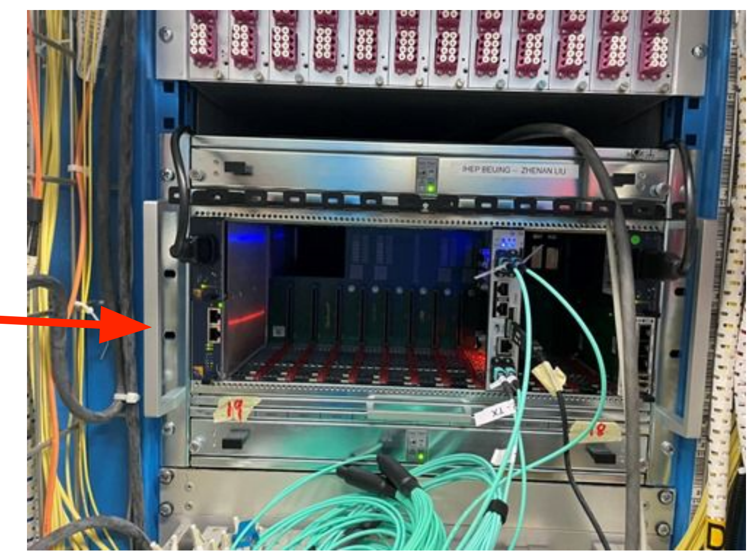
# The iRPC back-end electronics



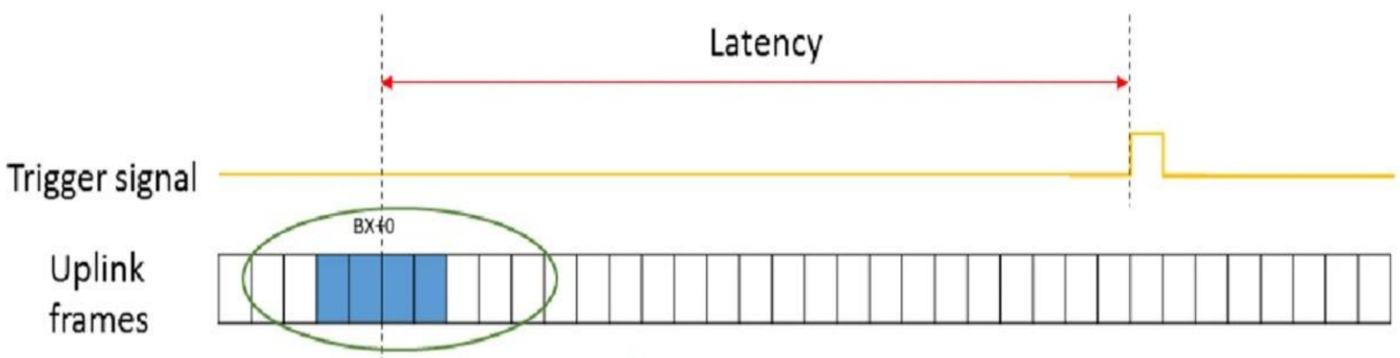

Back-end functions include:

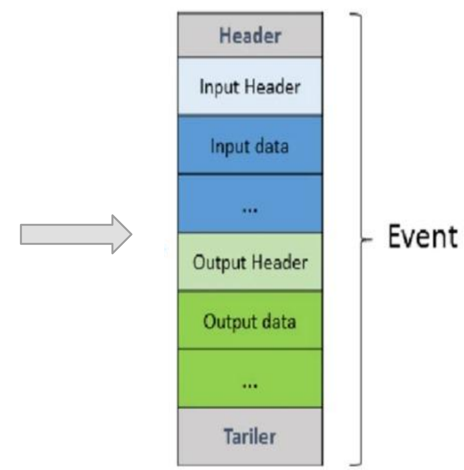
- Fast/slow control
- Data decompression
- Cluster finding
- Angle conversion

For now, microTCA-based with custom back-end board by IHEP is in use



CMS Underground Service Cavern

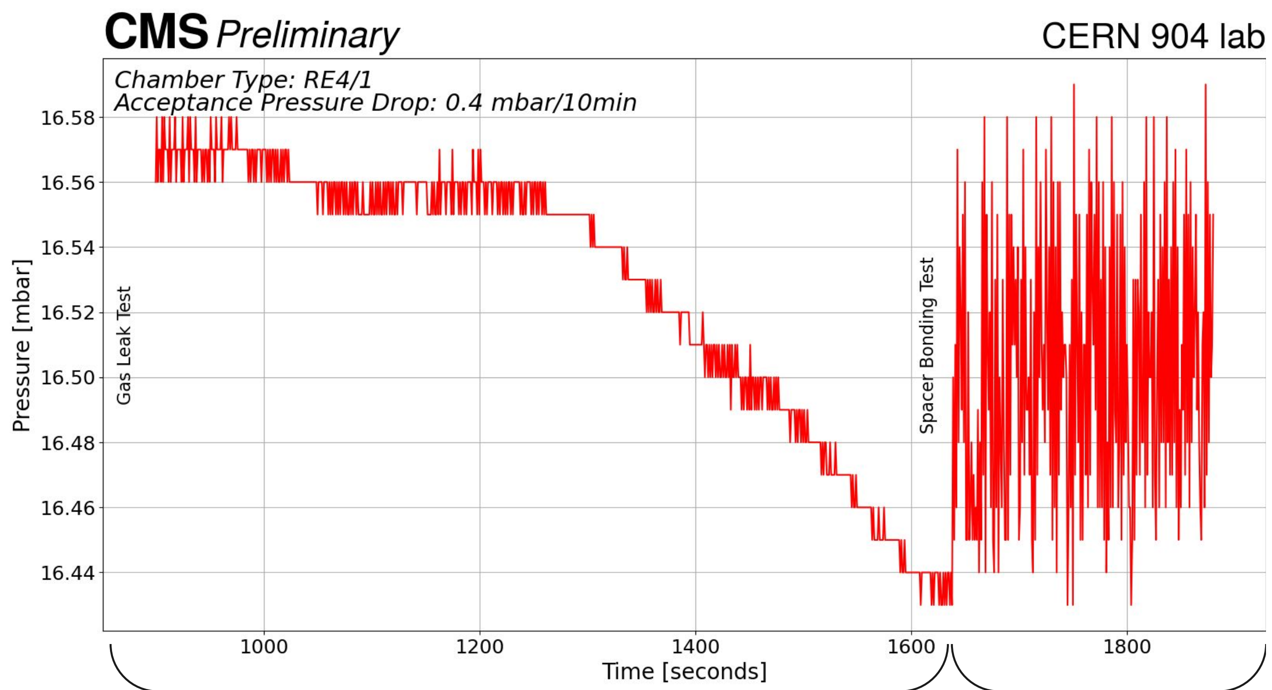


# iRPC production and Quality Control

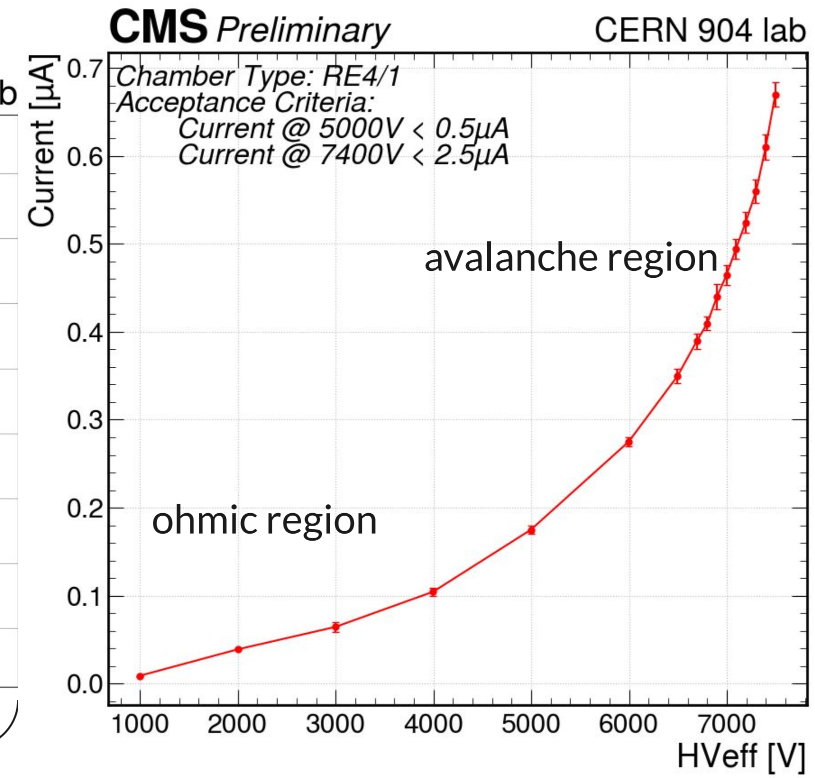
- First step of Quality Control performed in the **original sites** of components assembly
- Second step is also component level, but performed in the **assembly sites** (CERN and Ghent University)


Cosmic stand for gaps validation




Leak test (drop < 0.4 mbar/10 min)

Spacer bonding test



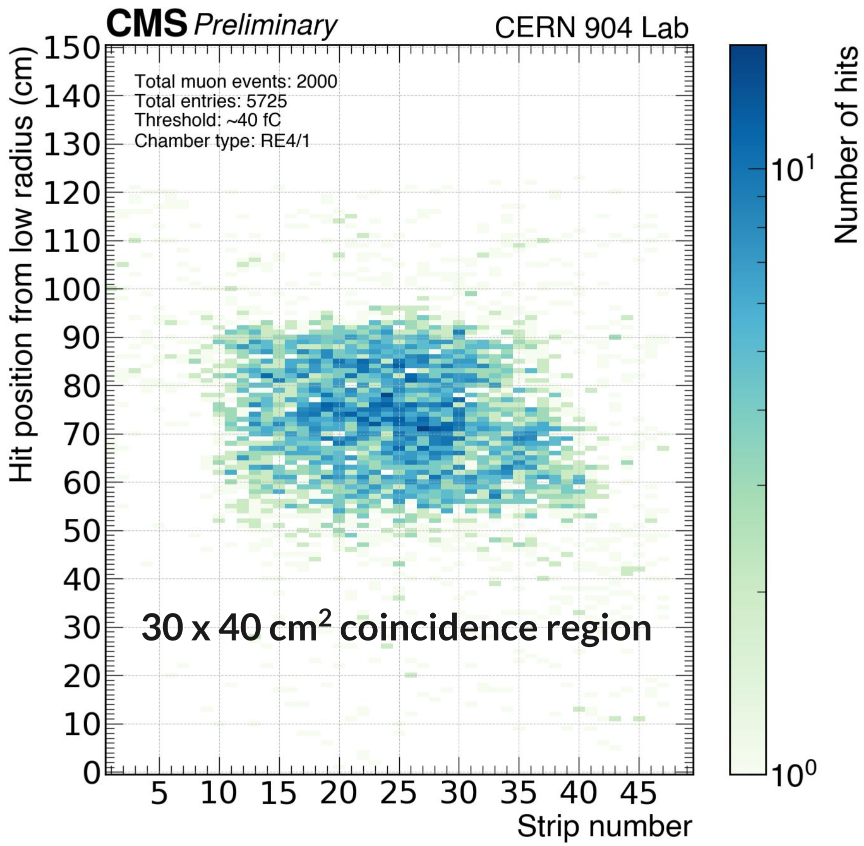

Dark current test (< 2.5 uA)

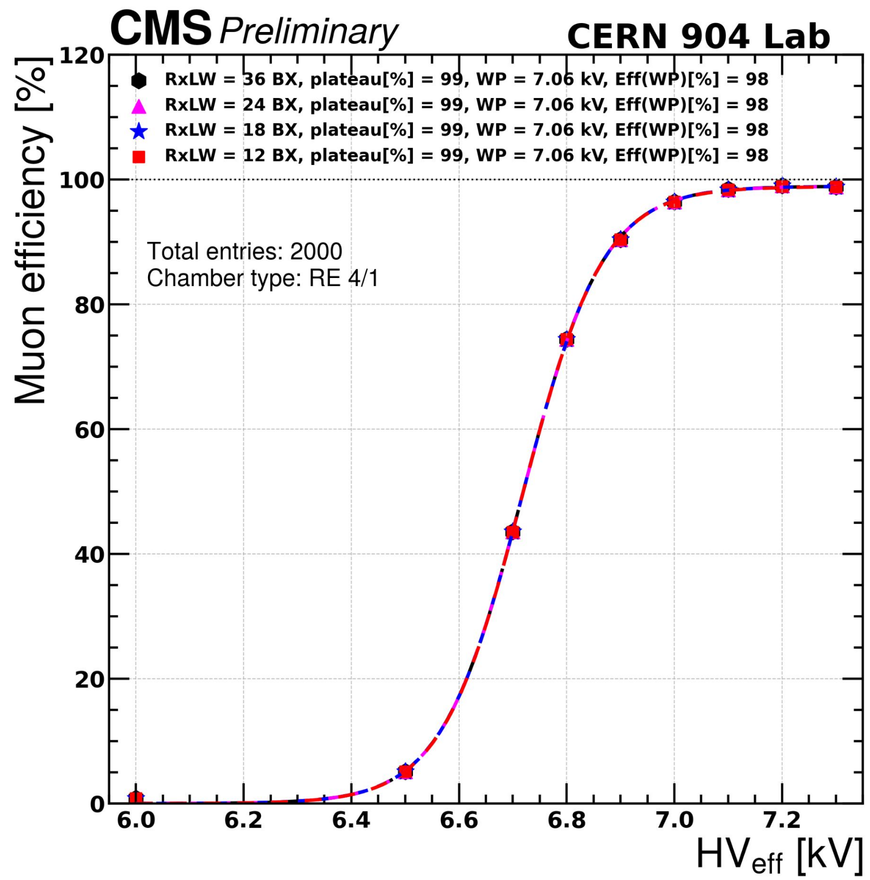
**Chamber assembly with validated components:**

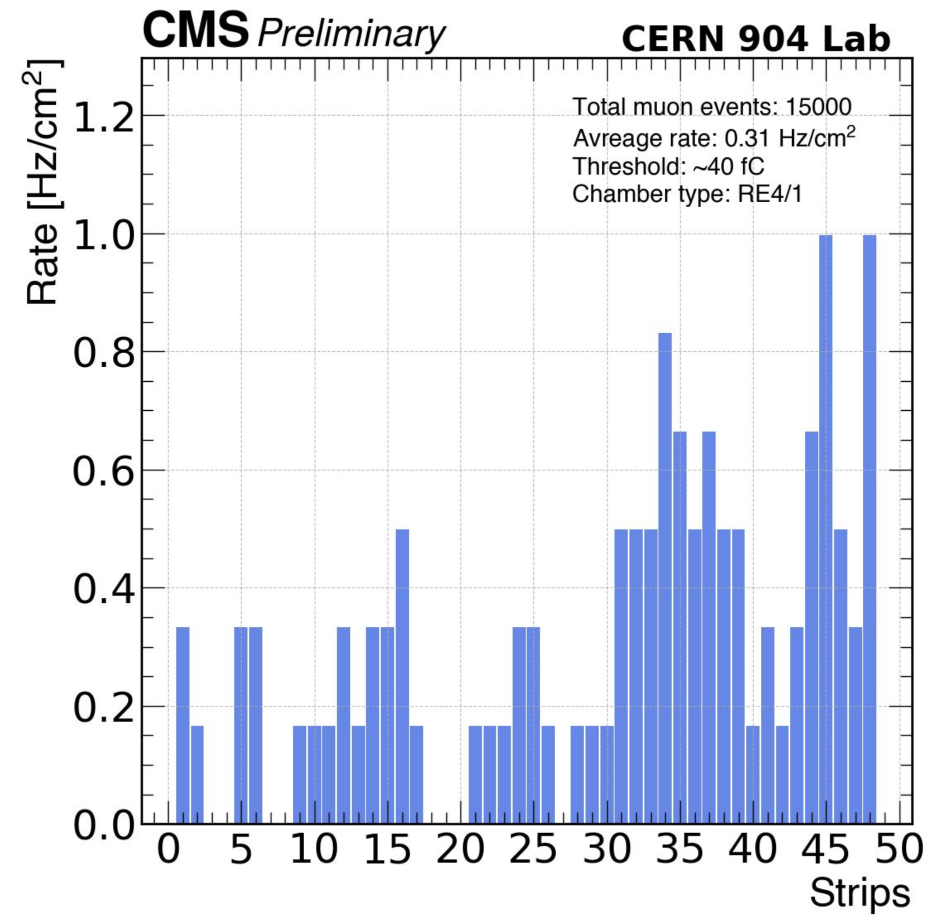
# iRPC production and Quality Control

3rd step: **Cosmic efficiency** with portable **FEB v2.3**

**3 scintillators for coincidence + veto**




After TDC channel mapping, the hit position along the strips are obtained by the arrival time between LR and HR signals:

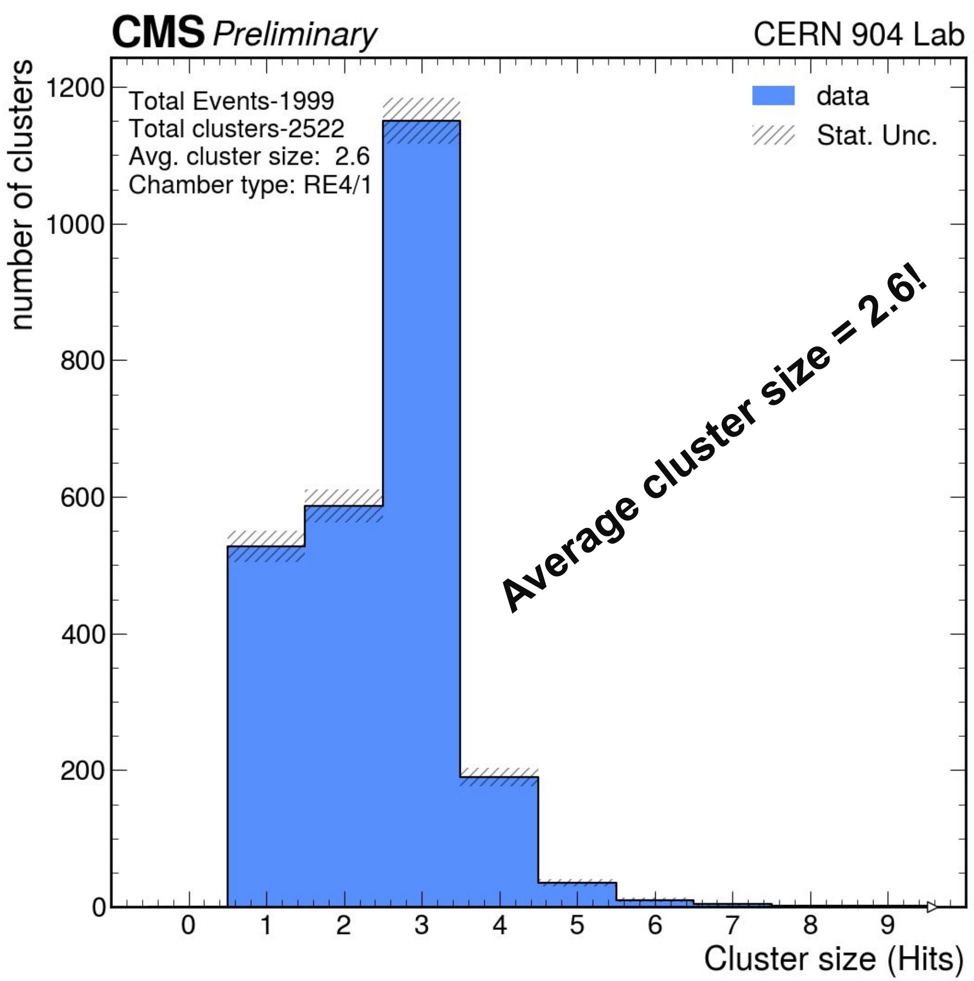
$$r = \frac{1}{2}L - \frac{(t2 - t1)}{2} * v$$

Efficiency of 98% and working point around 7050 V is stable up to 12 BX readout window!

Average noise < 1 Hz/cm$^2$ measured in dedicate random scans

# iRPC production and Quality Control

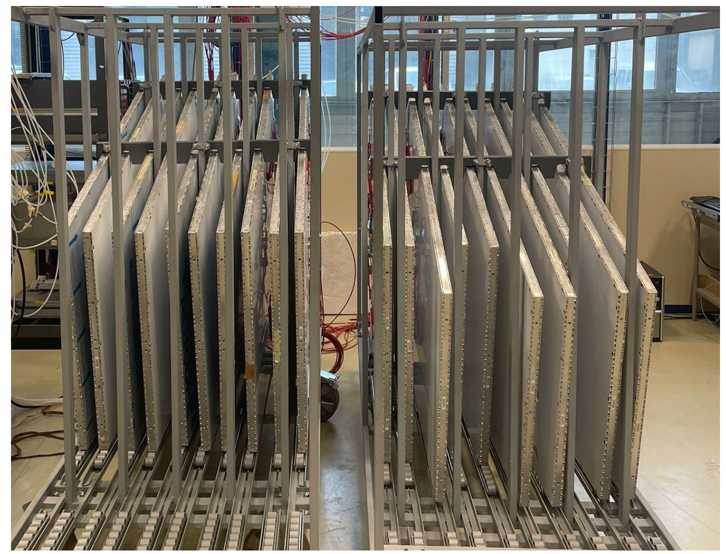
## Cluster size in cosmic test with FEB v2.3

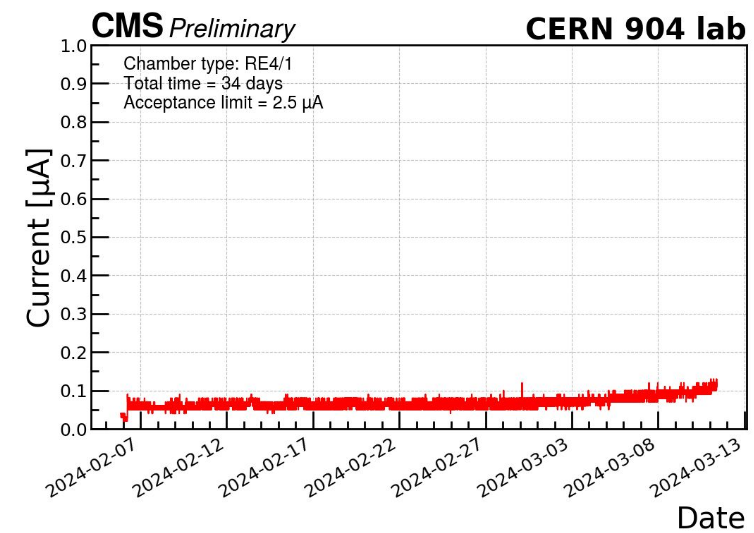



- Cluster size is defined as **the number of adjacent strips fired** when a muon crosses the detector
- The strips pitch in the coincidence region is **~1 cm**

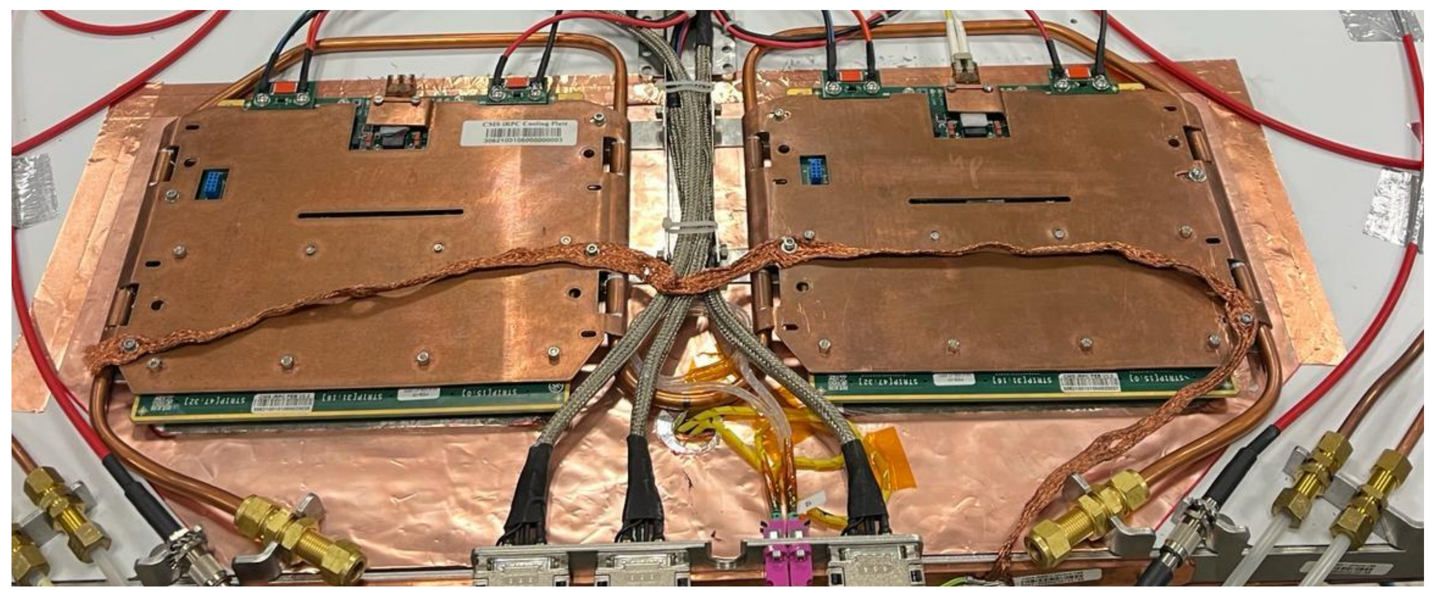
## Step 4: Final chambers with final FEBs (v2.3)

→ **Long stability test:** current monitoring @ WP for 1 month



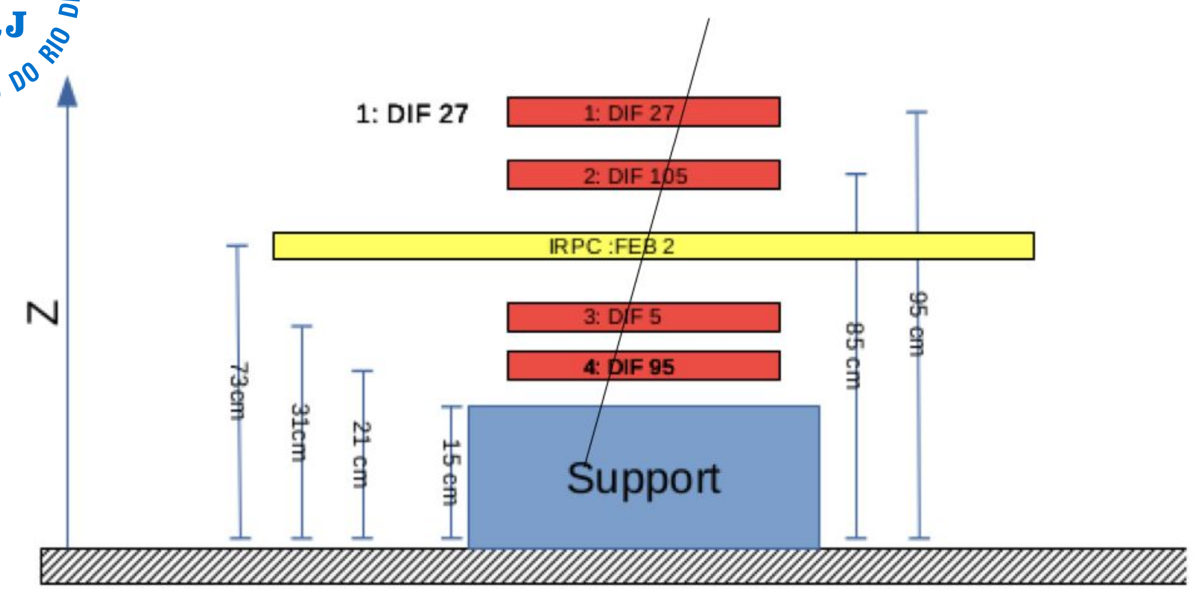


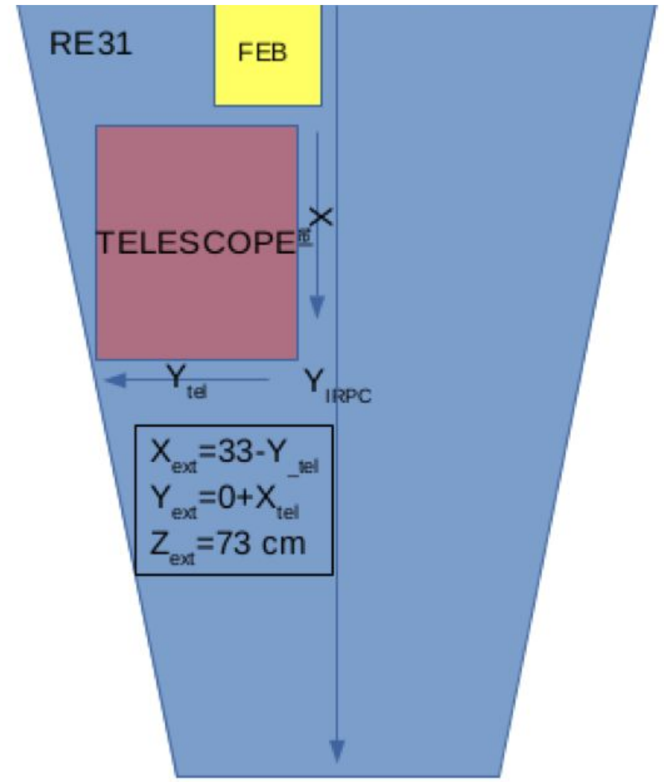

→ **Final cosmic test** with final FEB v2.3 + cooling system



\+ cover (not shown in the picture)

# Space resolution



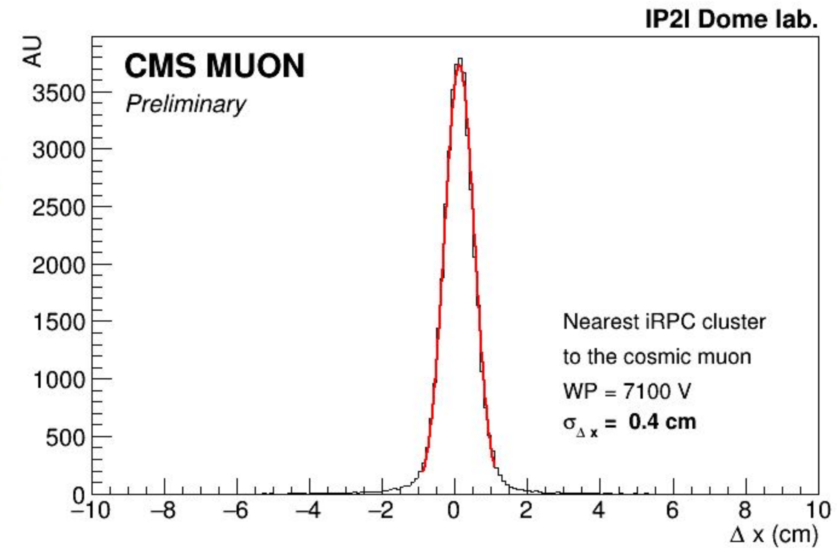

- Telescope in Lyon University IP2I made up with **4 RPC chambers** (2 mm double gap 30 x 50 cm$^2$)

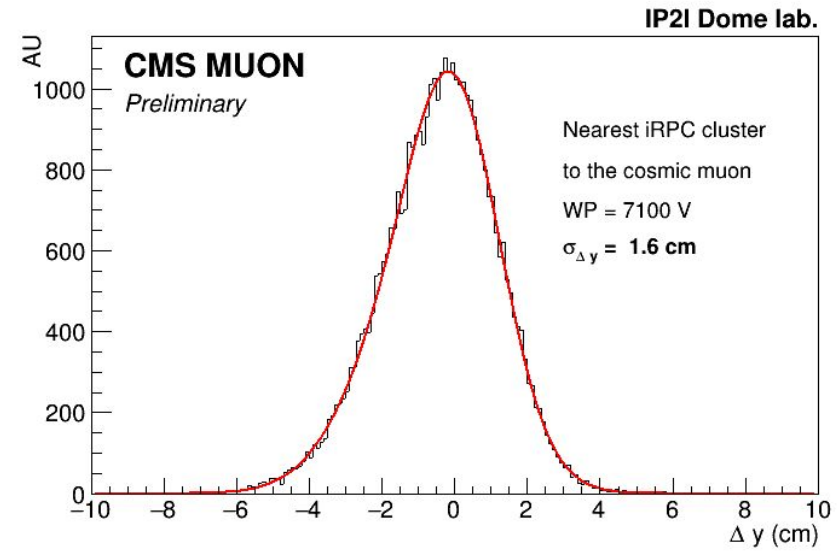
- X-axis resolution depends on **strip pitch** in the telescope region:
  - 0.8 - 0.9 cm

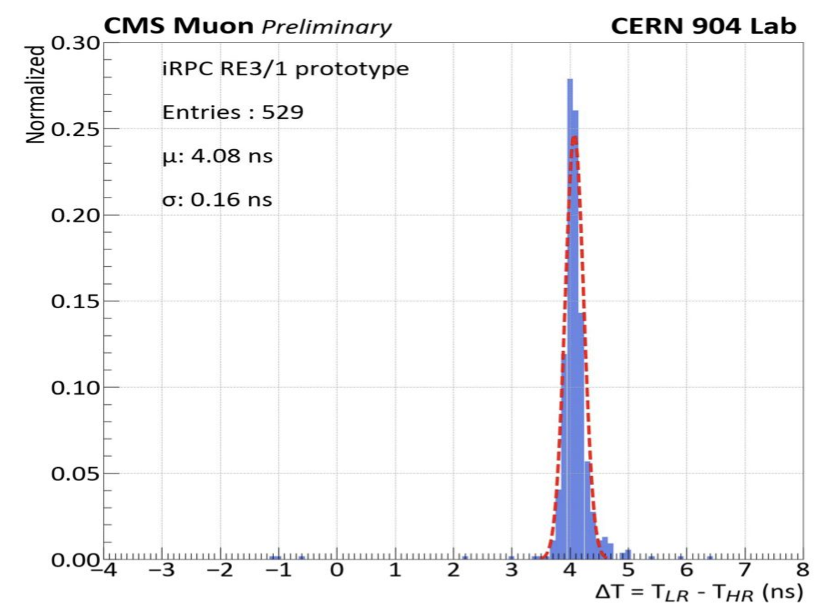
$$\rightarrow \sigma_x = 0.4 \text{ cm}$$

- In y-axis, resolution depends on $\Delta T = T_{HR} - T_{LR}$

$$\sigma_{\Delta T} \approx 150 \text{ ps} \ \rightarrow \sigma_y \approx 1.6 \text{ cm}$$



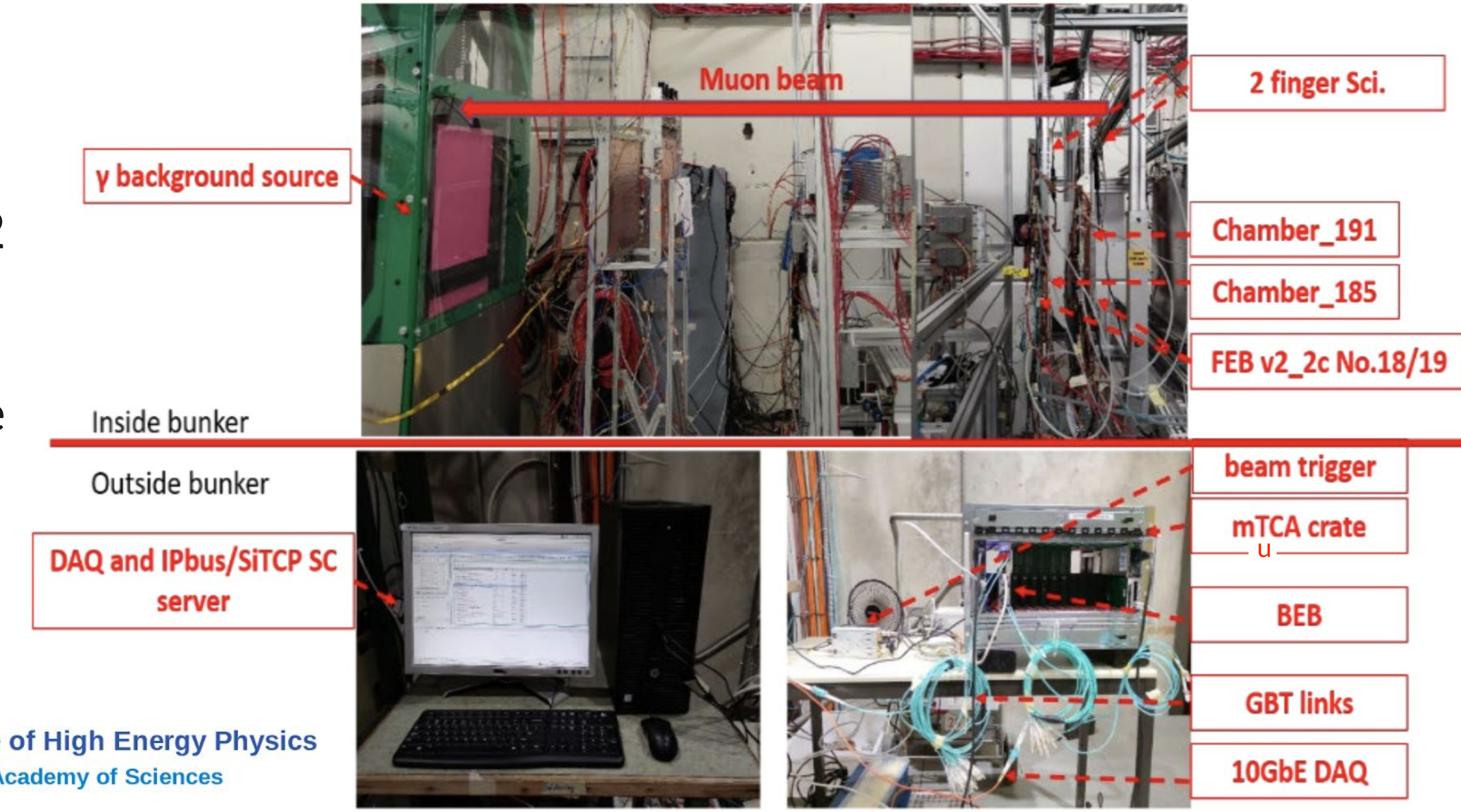



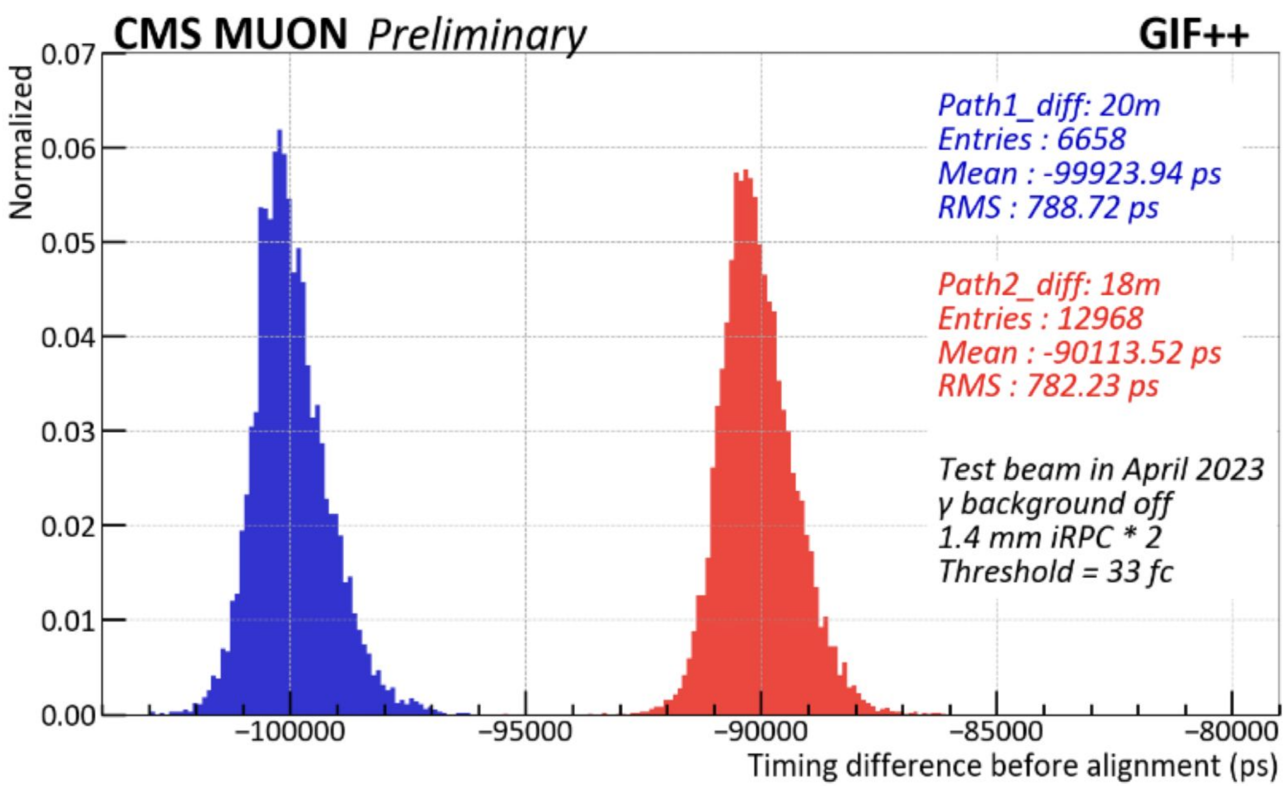



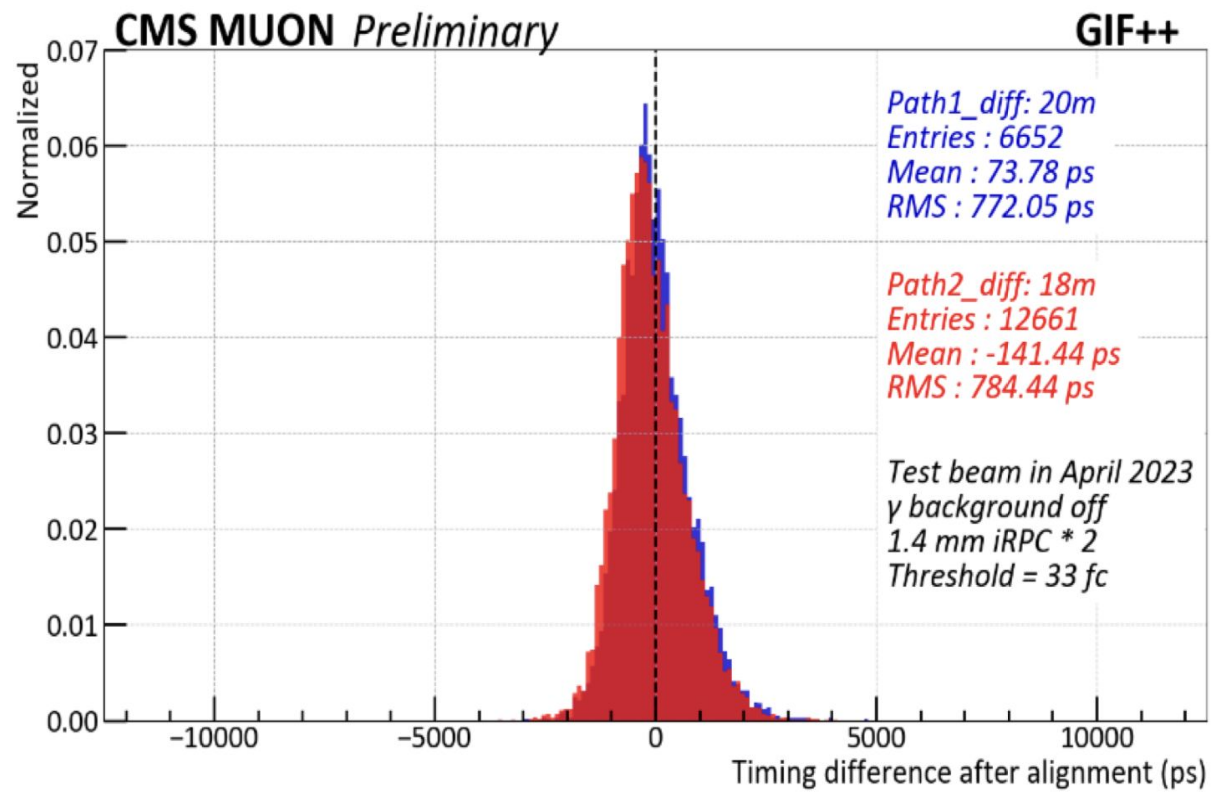
# Timing resolution

- Timing resolution performed with 2 identical chambers and a muon beam
- Absolute timing resolution of the system after alignment by back-end:

$$\frac{780}{\sqrt{2}} \approx 550 \text{ ps}$$



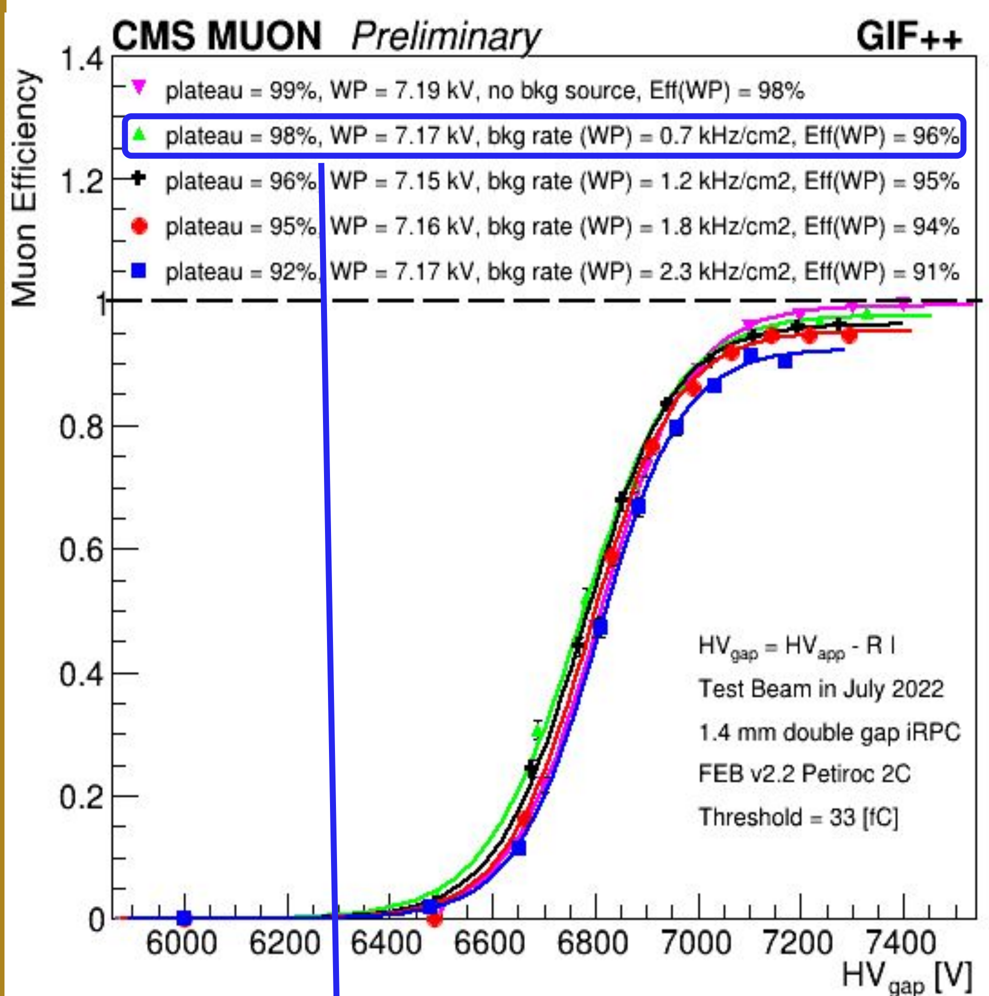



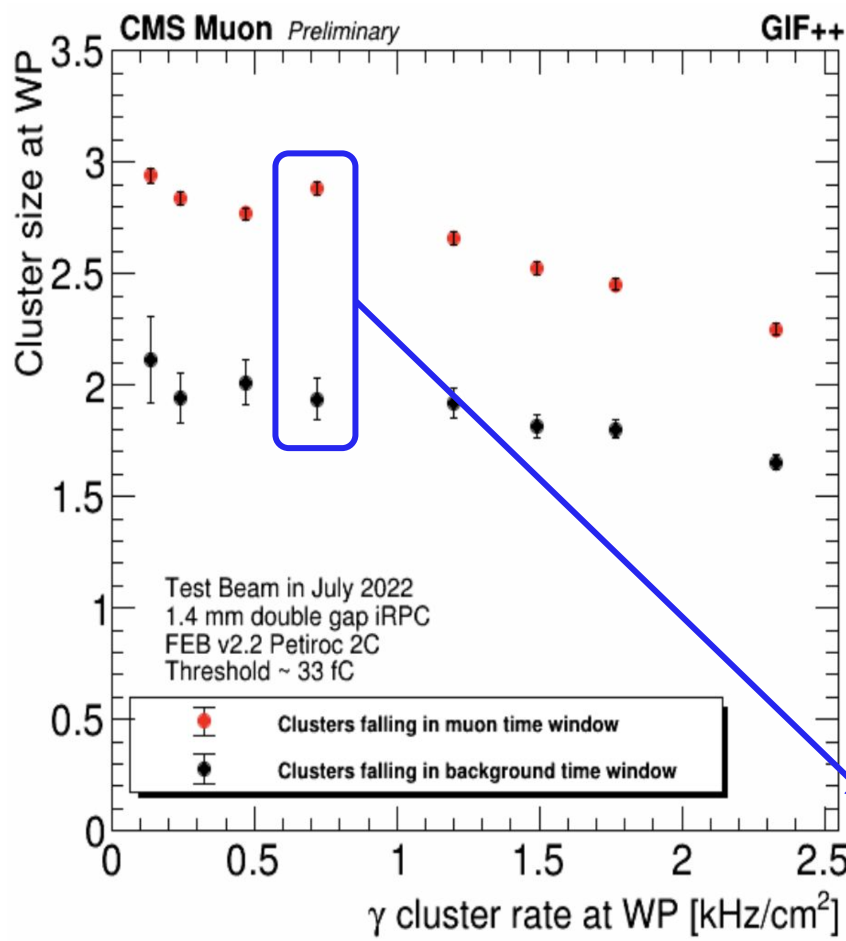



# Performance of iRPC under gamma bkg (FEBv2.2)

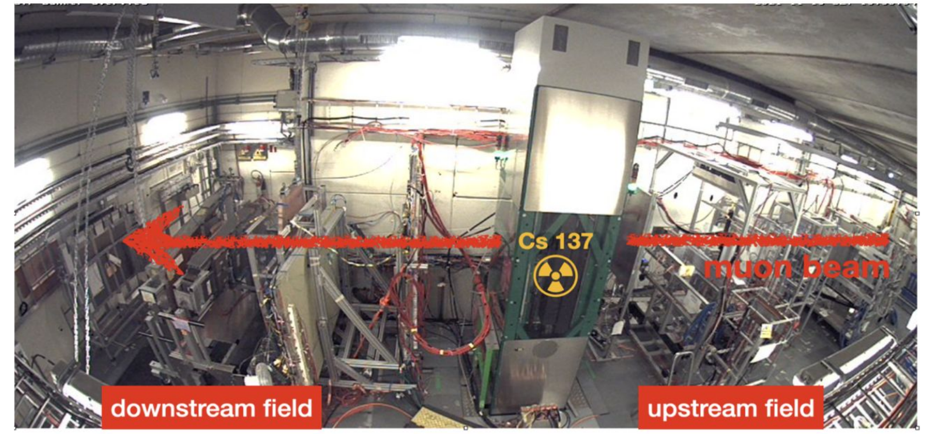
Performance of a iRPC chamber in Gamma Irradiation Facility ++ at CERN

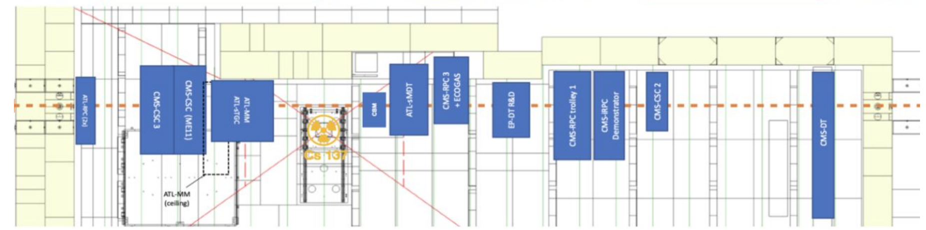
→ 12 TBq $^{137}$Cs gamma source 662 MeV
→ Muon beam ~ 100 Gev/c




plateau = 98%, WP = 7.17 kV, bkg rate (WP) = 0.7 kHz/cm2, Eff(WP) = 96%



Gamma Irradiation Facility ++

**iRPC performance validated under background gamma rate within a safety factor of 3!**

Around 600 Hz/cm$^2$:

→ Efficiency ~96%
→Working Point ~7170 V
→ Gamma cluster size ~2 strips
→ Muon cluster size ~2.7 strips

# Installation in CMS

4 demonstrator chambers were installed in CMS in the end of the Long Shutdown 2 (2021), 4 FEBs v2.1 and 4 FEBs v2.2:

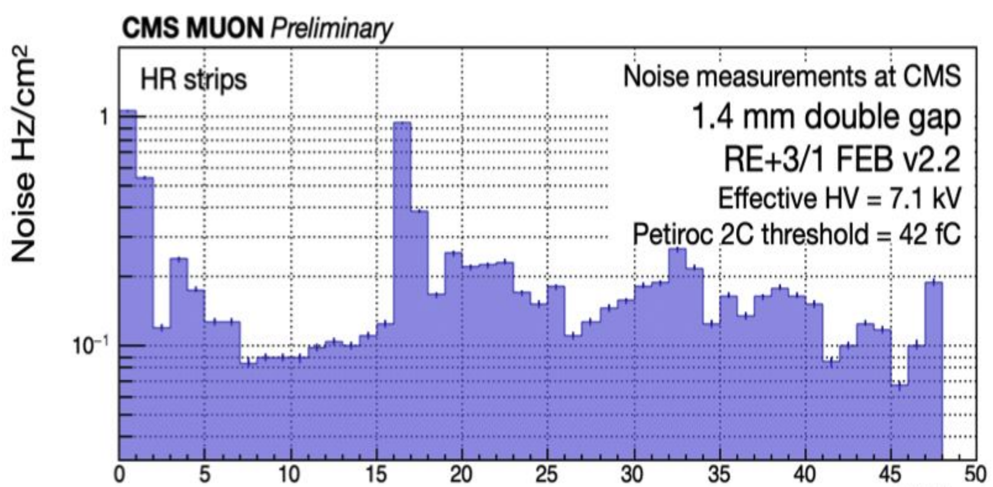
- **Noise < 1Hz/cm$^2$** with final end cap disk grounding
- FEB **temperature stable** in CMS endcap closed mode with water cooling
- HV currents showing **smooth operation** during LHC Run III
- **Normal operation** in 3.8 T magnetic field

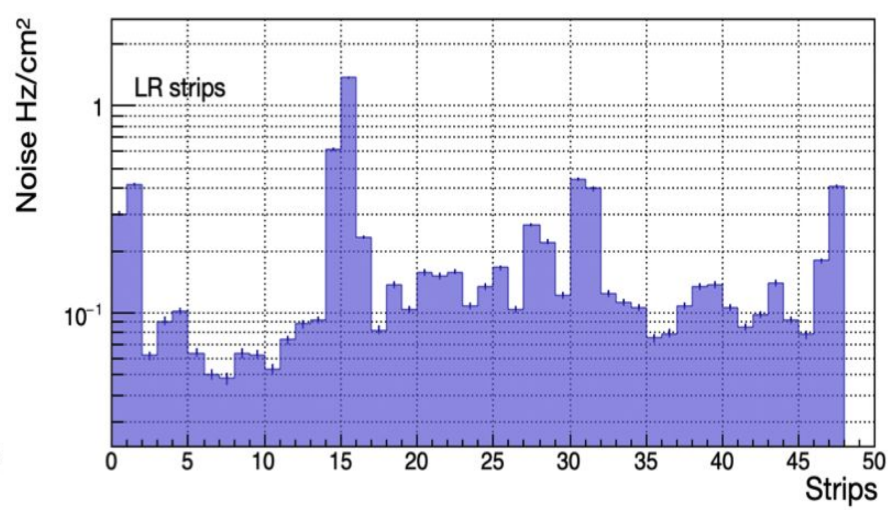
2 mass production final chambers with final FEBs installed in CMS last winter:

- RE-3/1/16 and RE-3/1/18

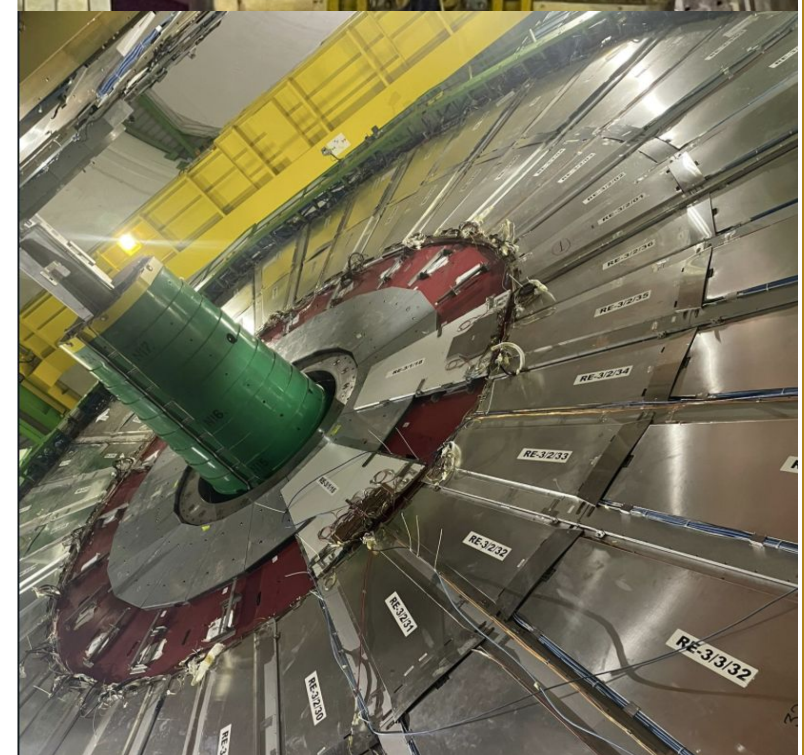
The **services are already installed** since LS2 waiting for all 72 chambers

**All 70 remaining chambers are expected to be installed next YETS 2024-2025 access time**




Average noise ~ 0.2 Hz/cm$^2$



# Conclusions and perspectives

- Existing RPC chambers are **stably operating** in CMS for more than 15 years
- iRPCs production and quality control for installation in CMS **are ongoing** in 2 assembly sites
- iRPC **space resolution** is $\Delta x$ = 0.6 cm and $\Delta y$ = 1.6 cm
- iRPC **timing resolution** is $\Delta t$ ~ 0.5 ns
- At 600 Hz/cm$^2$ and with a threshold of ~32 fC, the iRPC chambers have a performance of:
  - ***96% muon efficiency***
  - ***Working point ~ 7200 V***

  **(preliminary results with final FEB version are even more promising)**
- Demonstrators in P5 have already shown **less than 1Hz/cm$^2$ of noise** and **stable operation** with CMS grounding, water cooling and magnetic field of 3.8 T
- First 2 chambers **completed, installed and commissioned** last December 2023 in CMS, chamber construction **expected to be completed by the end of 2024**, installation planned during next YETS access time

CMS-RPC TEAM

# Thanks for your attention!

# Questions?

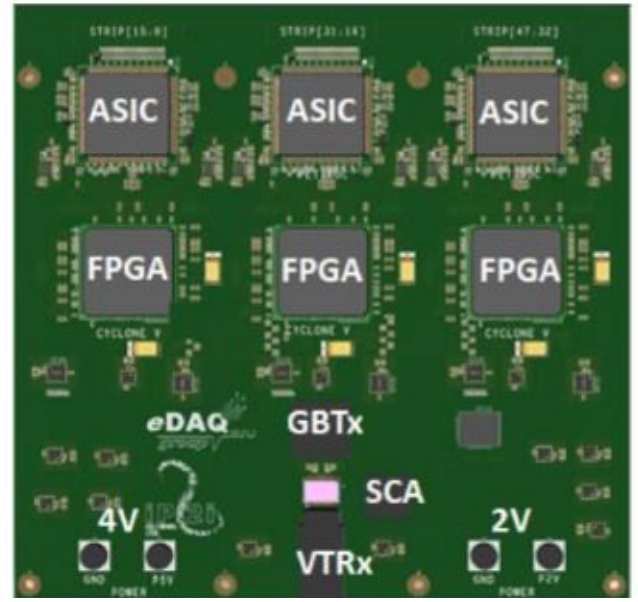
# Backup slides

# Front-end Board evolution

FEB components:

- 3 Erni connectors with 32 channels each
- 6 ASIC iRPCROC (PetiROC2C)
- 3 FPGAs CYCLONE V (96 + 6 TDC channels)
- GBTx / GBT-SCA / VTRx
- Separated power zone for Analog and Digital components

Front-end Electronics for iRPC

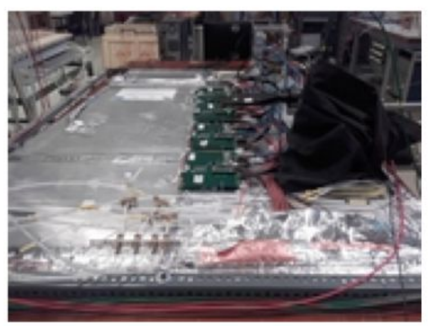



**First proto**
2017
proof of principle for
CMS-MUON-TDR-016

2 PetiROC2A
+ FPGA Cyclone II
+ ETHERNET
directly on strip PCB
(50 cm)

**Feb V0**
2018
First FEB (Conf. note)

1 PetiROC2A +
MEZZANINE with
FPGA Cyclone II
+ ETHERNET



**Feb V1**
2019
FEB without
mezzanine

2 PetiROC2B
+ FPGA Cyclone V
+ ETHERNET

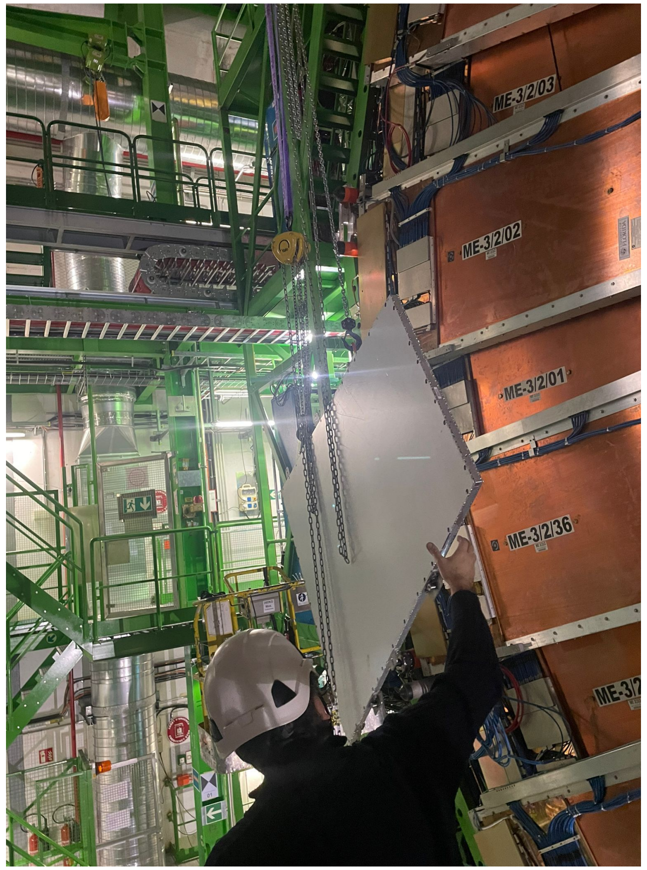
**Feb V2_1,2**
2021
Non-rad hard
for iRPC Demo

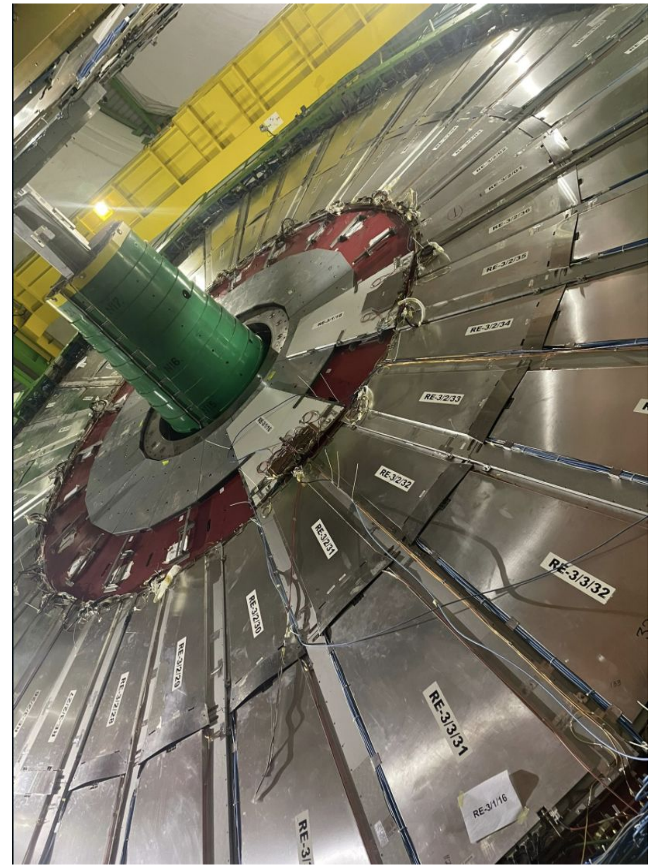
6 PETIROC2C
+ 3 FPGA Cyclone V
+ Optical GBT

**Feb V2_3**
2021
Mass production
prototype

FEBv2_1 + firmware
update feature by
optical GBT

# Installation in P5 YETS23/24





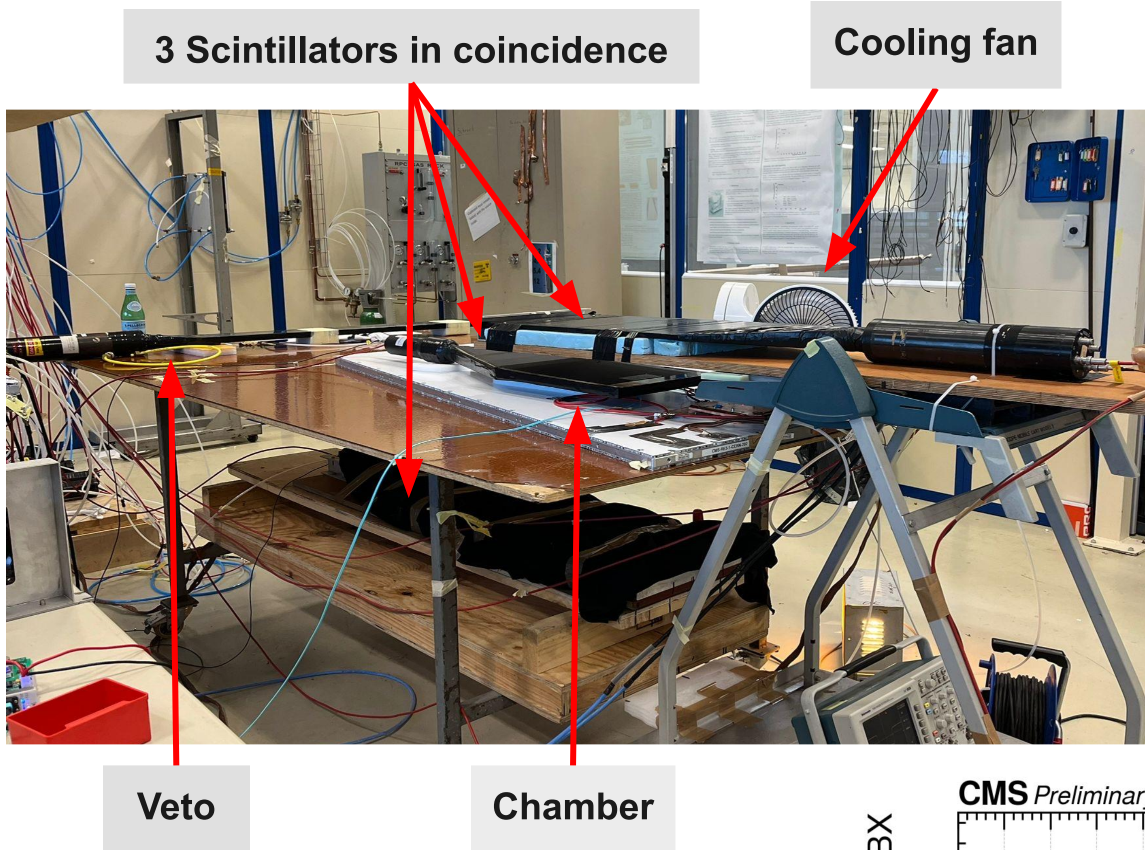
- 2 mass production final chambers with final FEBs installed in CMS last winter:
  - RE-3/1/16 and RE-3/1/18

- The **services are already installed** since LS2 waiting for all 72 chambers

- All 70 remaining chambers are expected to be installed next YETS 2024-2025 access time

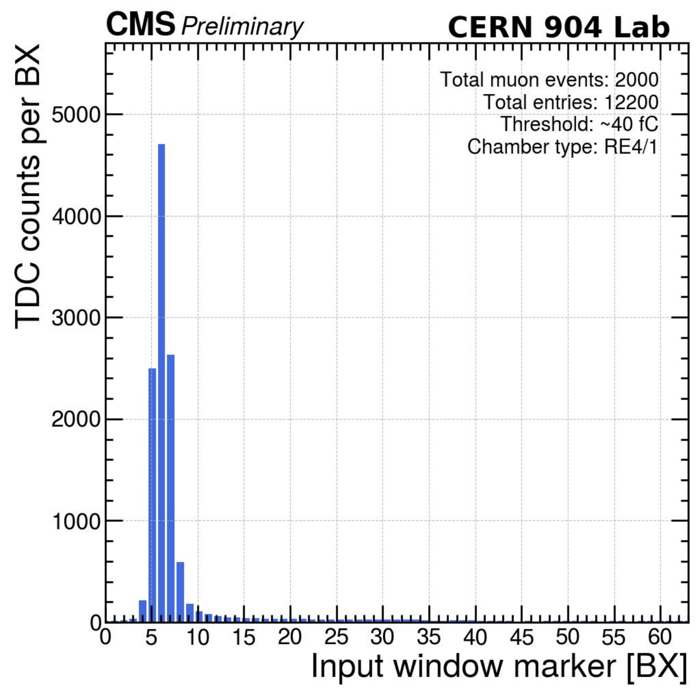
# RPC production at CERN and Ghent University

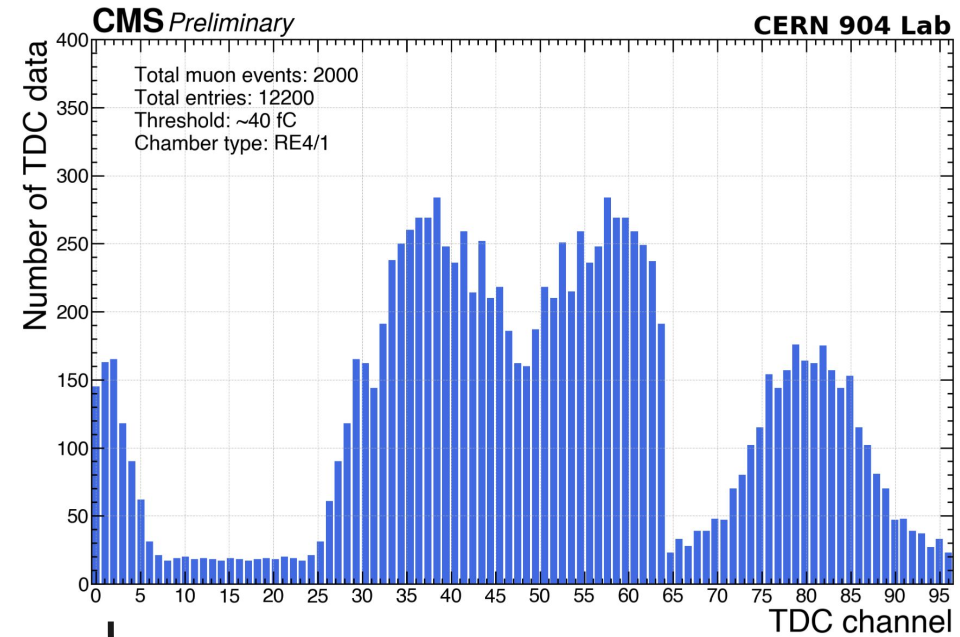
3rd step: Cosmic efficiency with portable **FEB v2.3**



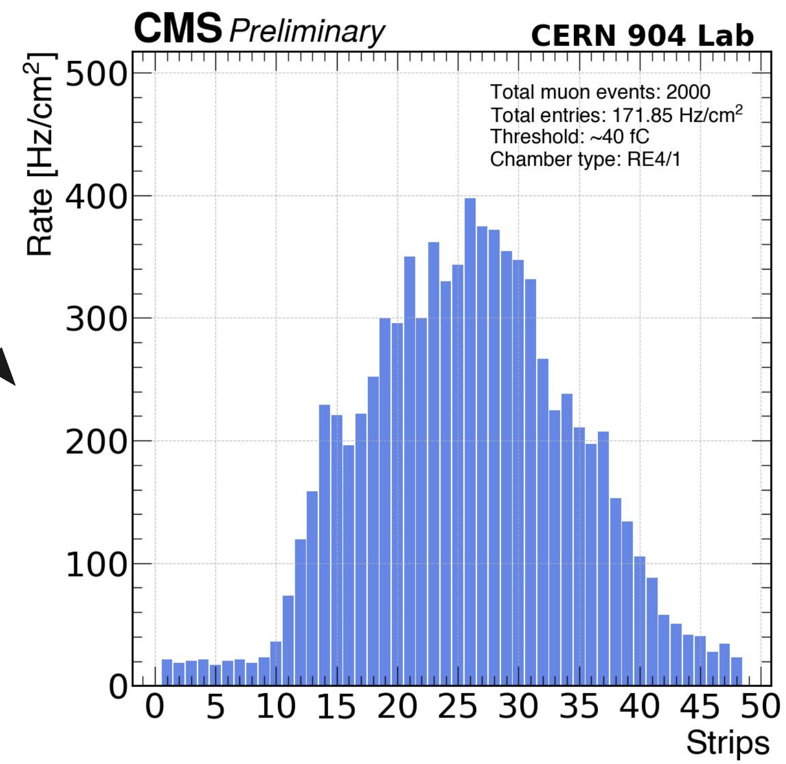

- Number of Time to Digital Converter (TDC) data recorded for different readout window markers

- For each BX, every 25 ns, a maximum of 3 TDC data can be transmitted by the FEB




**mapping between TDC channel and strip number**




**High occupancy in the coincidence region**