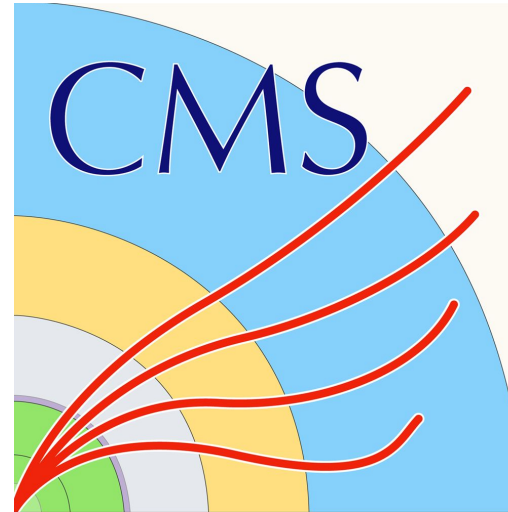
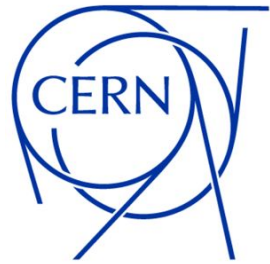
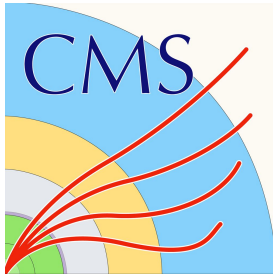




Improved Resistive Plate Chambers (iRPC) Mass Production and Performance for the CMS Phase-II Upgrade

**Eduardo Coelho and Katherine Maslova
on behalf of the CMS Collaboration**

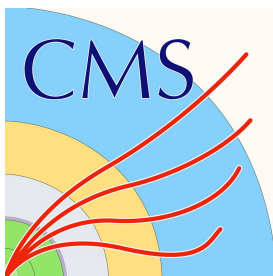




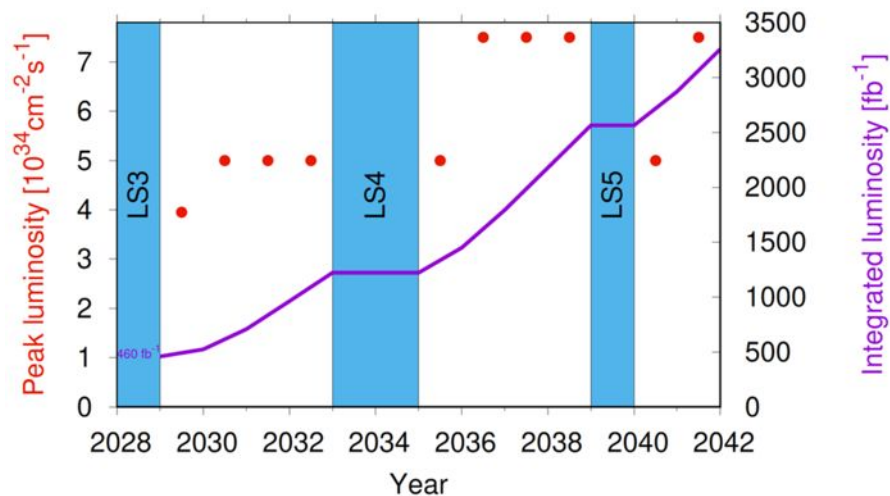
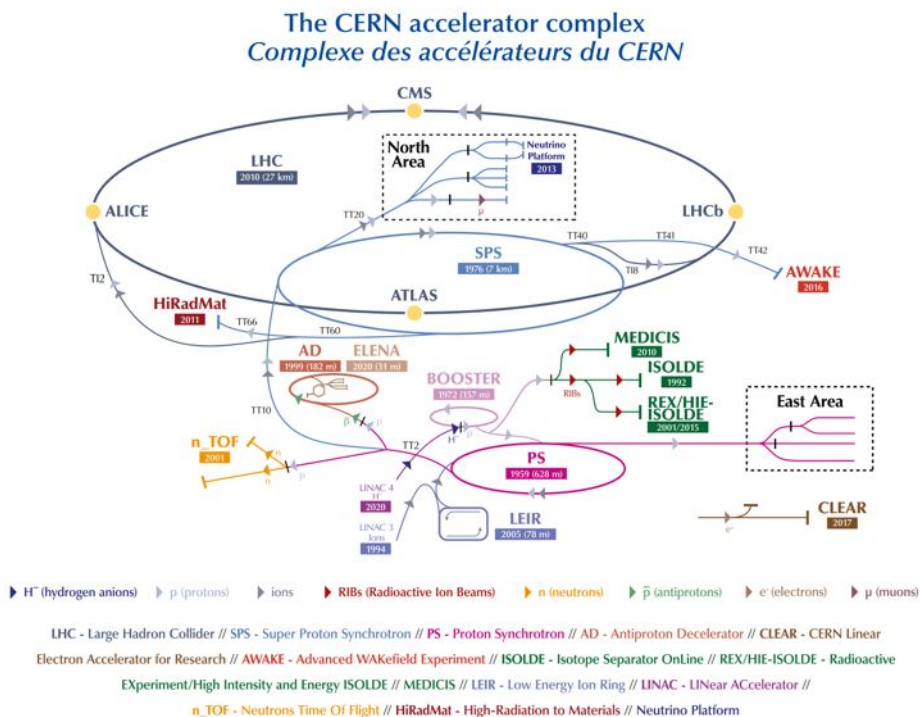
Outline



- CMS detector;
- CMS RPC Upgrade project;
- Improved Resistive Plate Chamber (iRPC) and description;
- Quality Control (QC);
- Summary of the mass production;
- iRPC performance and measurements at GIF++;
- iRPC in CMS;
- Summary.

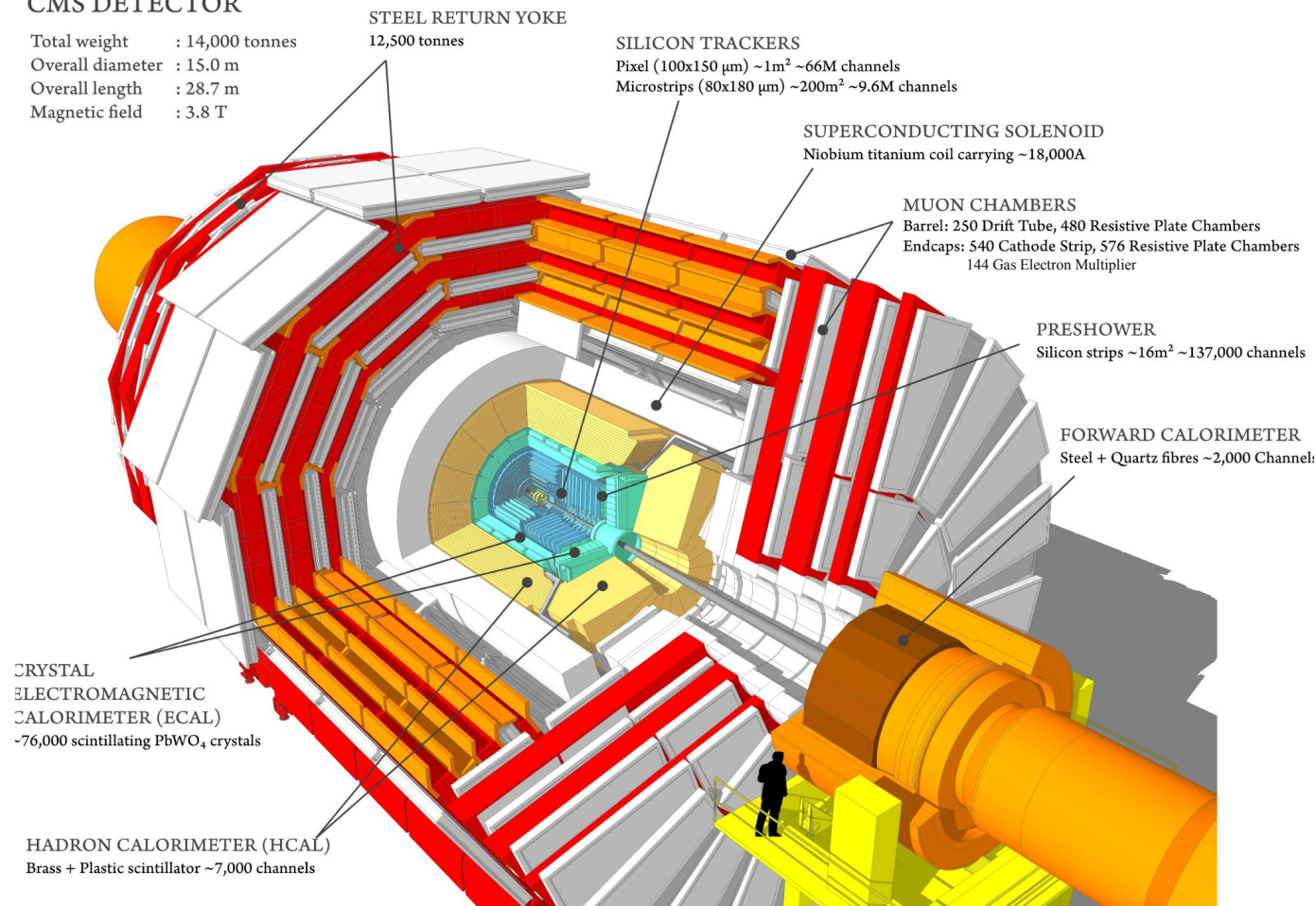


The Compact Muon Solenoid (CMS)

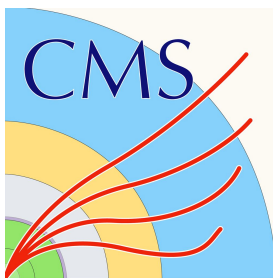


CMS DETECTOR

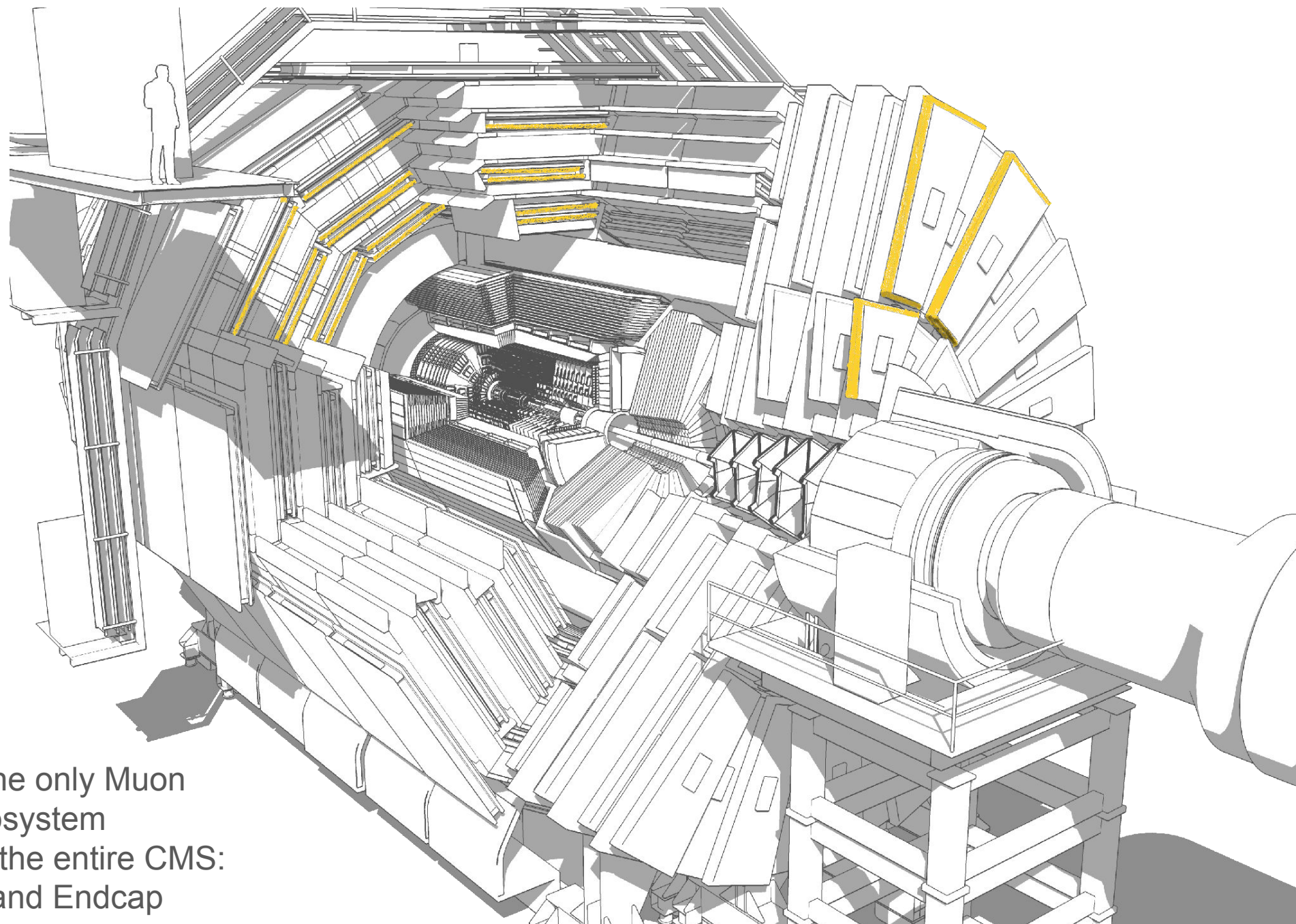
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



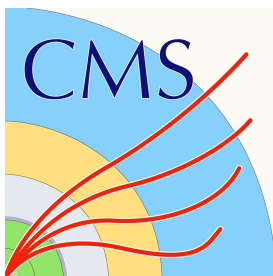
CMS just finished LHC Run 3 data taking and in the process of preparation to extend its sensitivity to new physics searches for the High-Luminosity LHC period starting in 2029, anticipated to feature a higher Instantaneous Luminosity to around 3000 fb^{-1} .



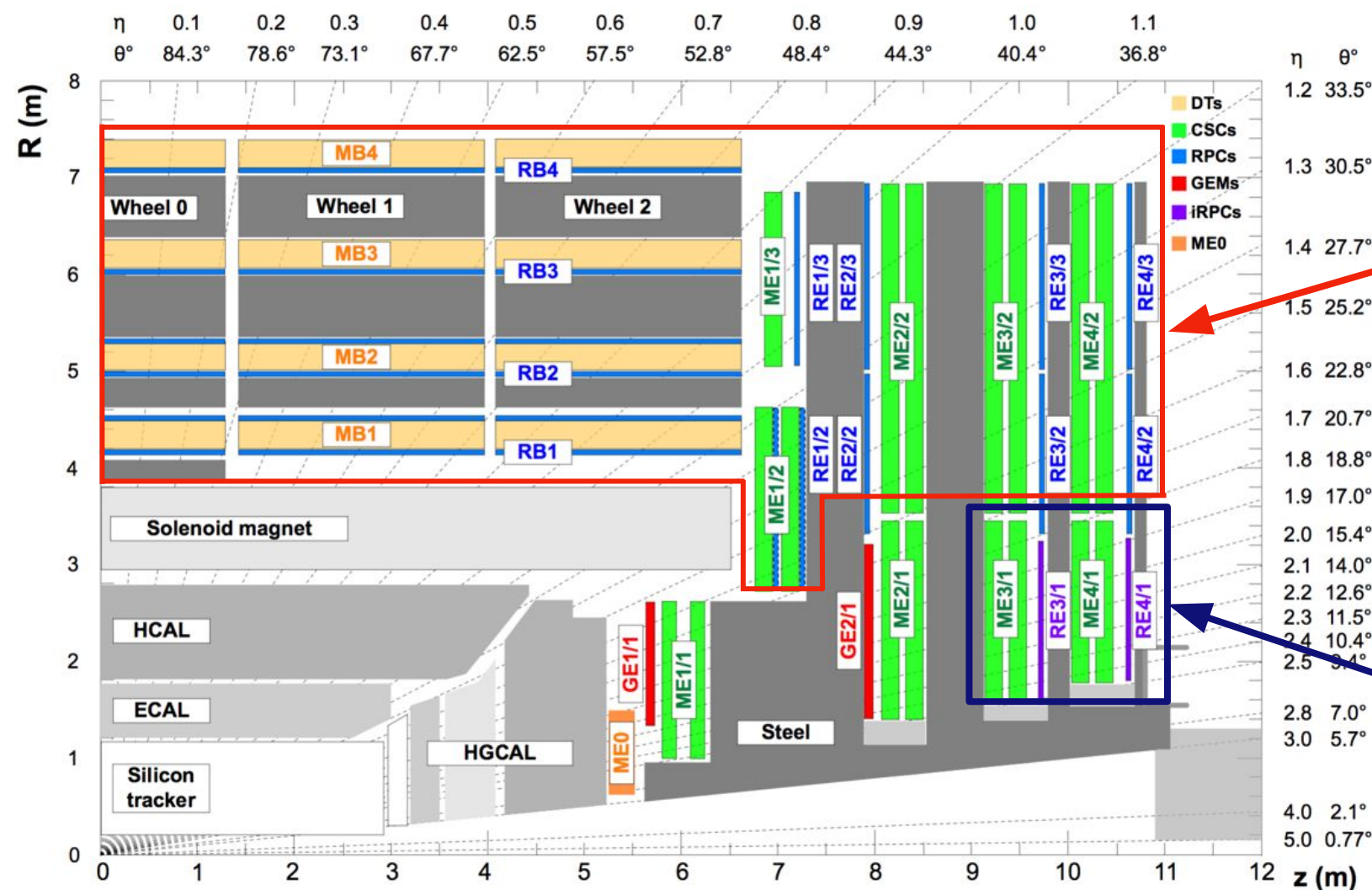
The Compact Muon Solenoid (CMS)



RPC is the only Muon
subsystem
that covers the entire CMS:
Barrel and Endcap



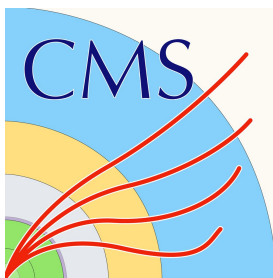
CMS RPC upgrade project



Upgrade of the Link System to improve timing resolution to 0.5 ns for existing RPC system. Replace all off-chamber electronics

iRPC: extend the coverage up to $|\eta| = 2.4$ in high eta region in stations 3 and 4

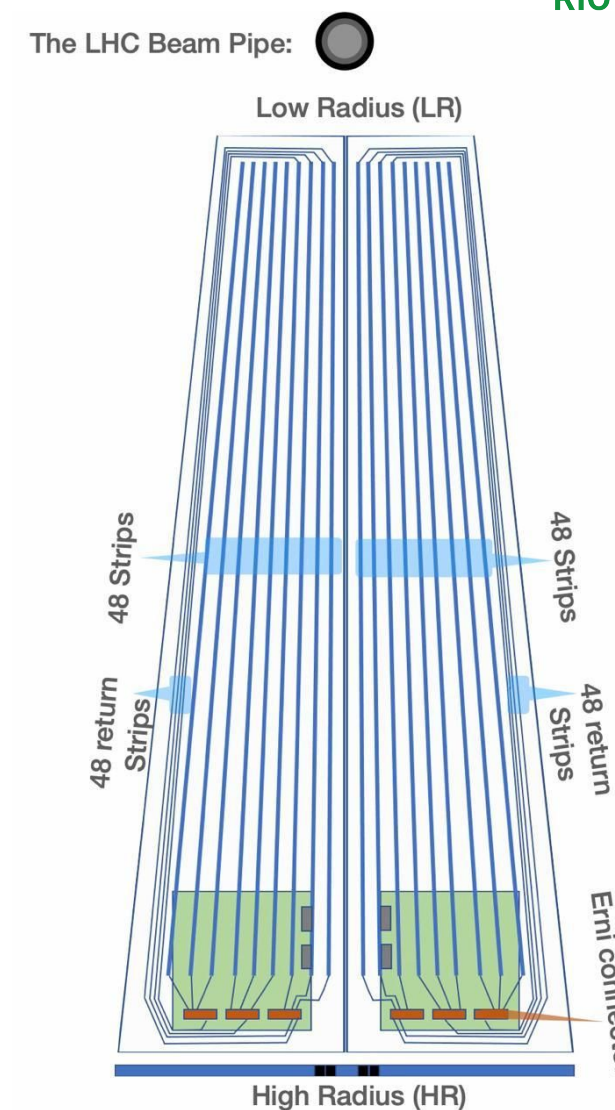
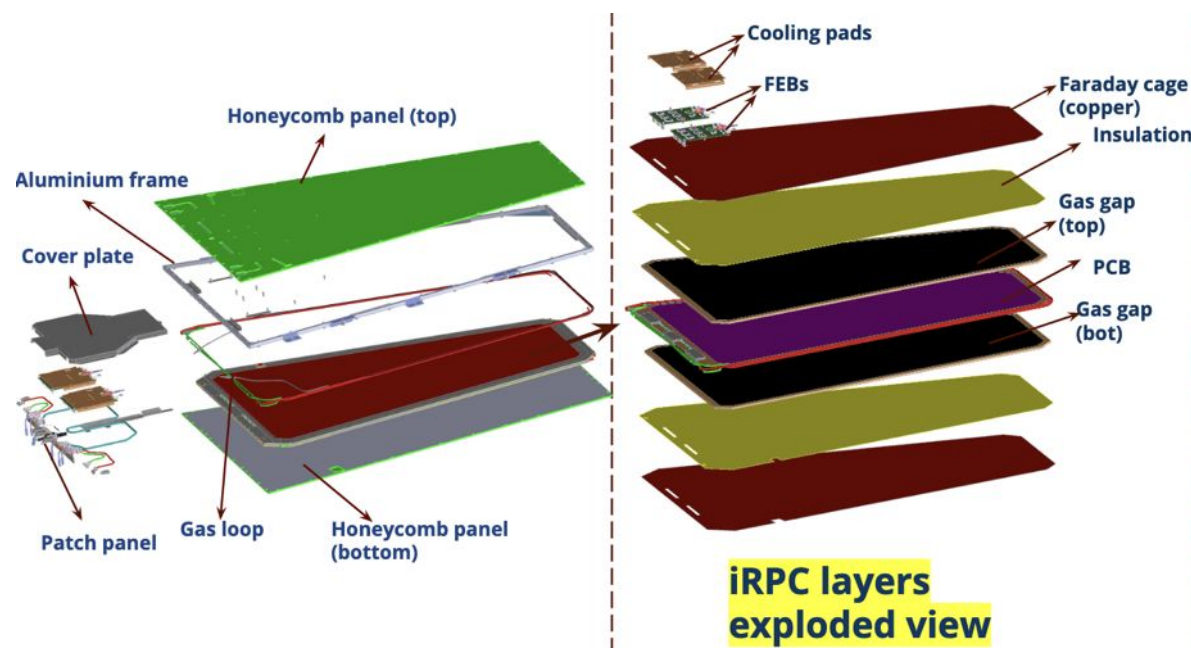
Focus of the talk is iRPC!



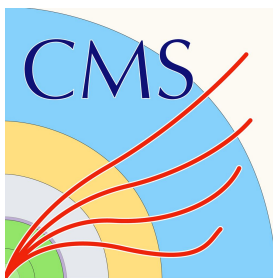
iRPC: Improved Resistive Plate Chamber



- Gas mixture used in CMS: $95.2\% \text{C}_2\text{H}_2\text{F}_4 + 4.5\% \text{i-C}_4\text{H}_{10} + 0.3\% \text{SF}_6$
- Relative humidity of 40-50%
- + 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 $\sim 1.2 \times 1.6(3) \text{ m}^2$ for RE 3(4)/1
- Double readout in the strips high and low radius:
 - Charge threshold between 30 and 40 fC.



FEB positioned external and @ HR (lowest dose region)



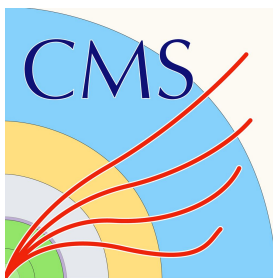
iRPC characteristics



	RPC	iRPC
HPL thickness (mm)	2	1.4
Number of gas gaps	2	2
Gas gap thickness (mm)	2	1.4
Resistivity (Ωcm)	$1 - 6 \times 10^{10}$	$0.9 - 3 \times 10^{10}$
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

2d readout for iRPC

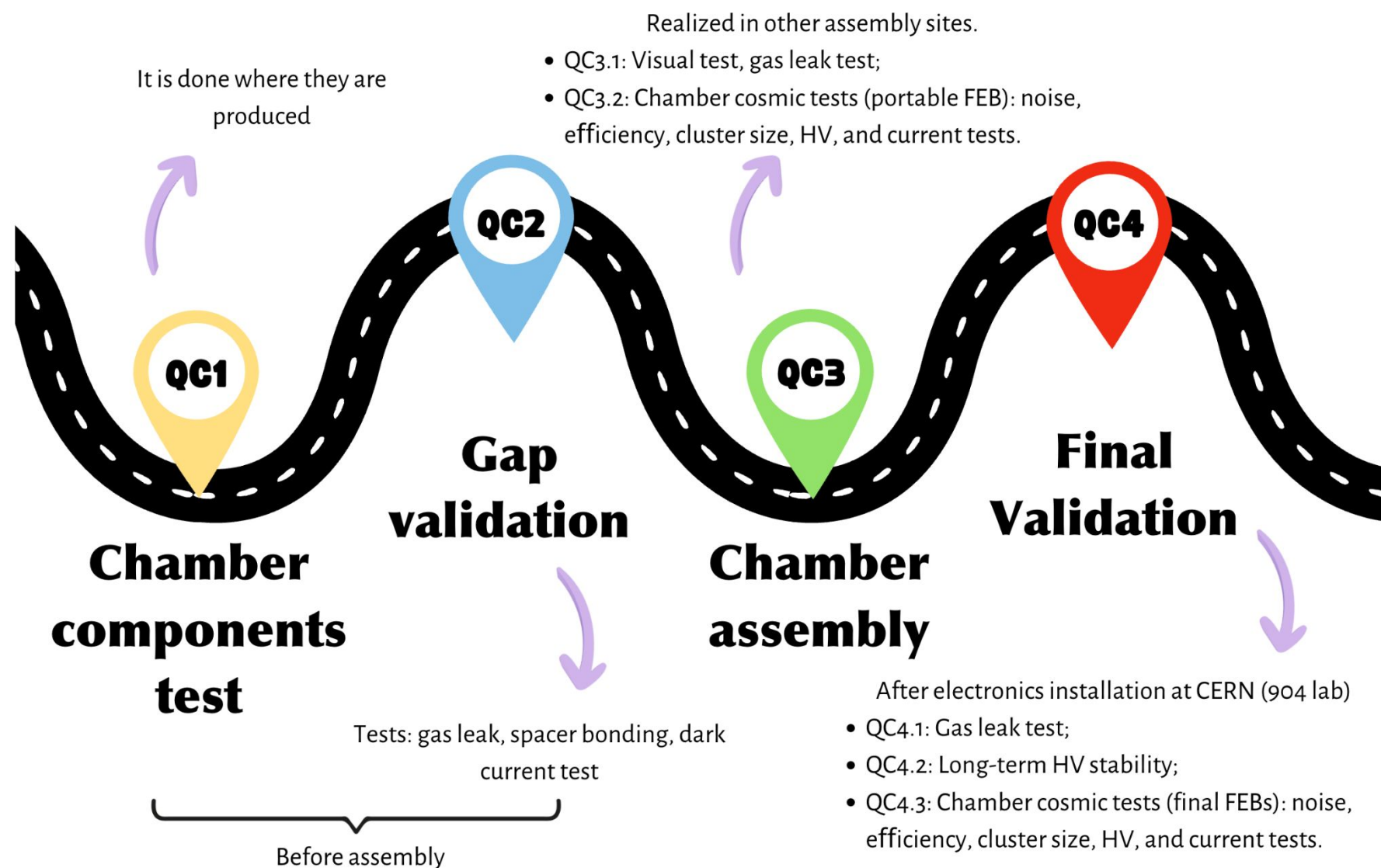
iRPC FEB is equipped with low noise front-end electronics that can detect signals with a charge as low as 30 fC

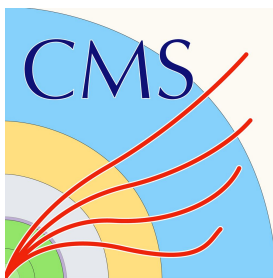


iRPC production and quality control



Procure and test components → Send components to assembly sites → Assemble chambers at assembly sites (CERN 904, Ghent) → Ship chambers to CERN → Final QC of chambers at CERN 904

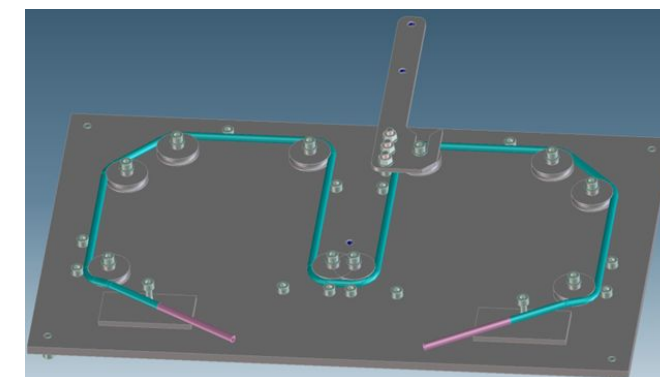
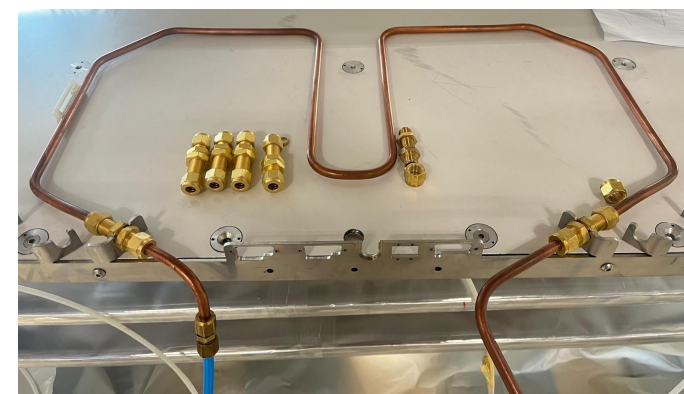
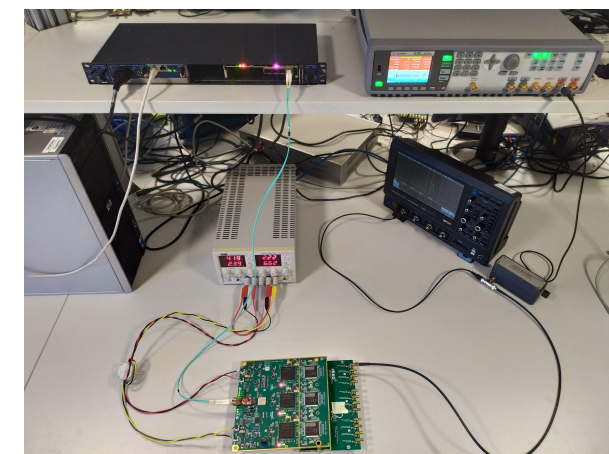
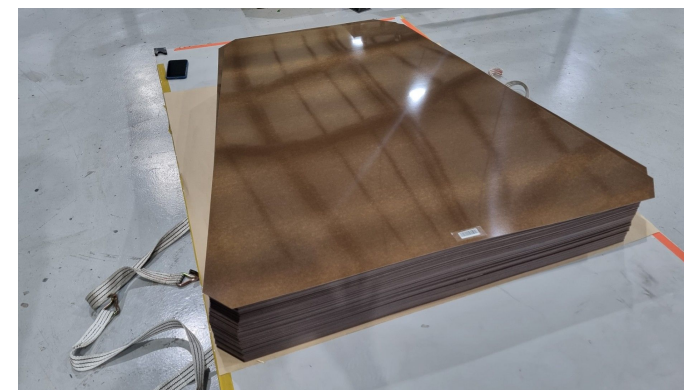


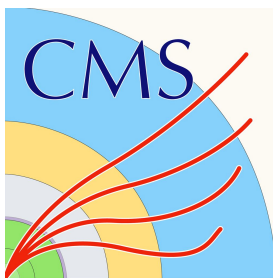


QC1: chamber components



- ❑ **Strip PCB Quality Control:** @ Lyon
 - ❑ connectivity, impedance, attenuation, propagation
- ❑ **HPL** @ Firm under INFN Pavia supervision
- ❑ **Chamber mechanics** @ ALDOWA in the Netherlands
- ❑ **Cooling system**
 - ❑ Cooling frames tested at 20 Bar pressure (with N_2): tested @CERN 904 lab
 - ❑ FEB cooling plates: @ Georgia
- ❑ **FEB v2.3 production** @ FEDD France and QC in Lyon





QC2: gap validation



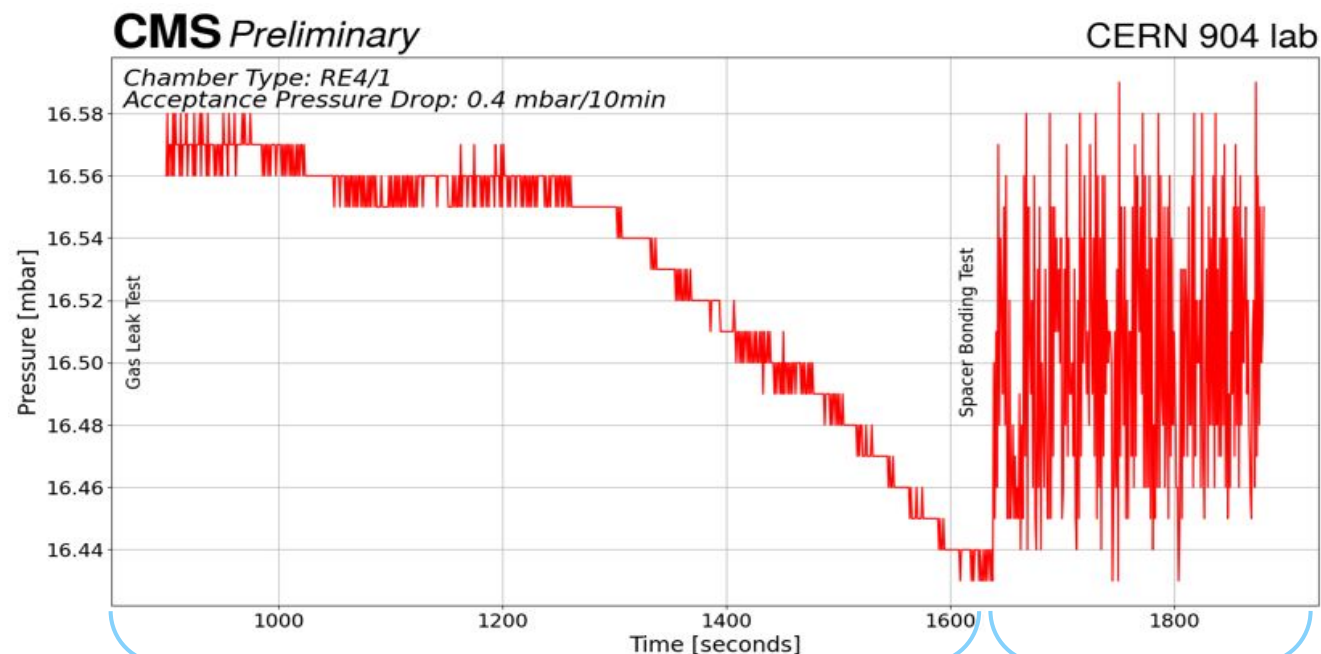
Gap pressure and spacer bonding test

- ❑ 15 mbar for 20 min monitor pressure loss
- ❑ spacer bonding test by applying pressure

Dark current test

- ❑ monitor gap current over high voltage range

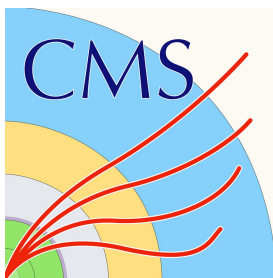
→ current acceptance criteria to validate gaps



Leak test (drop < 0.4 mbar/10 min)

Spacer bonding test

https://cds.cern.ch/record/2916744/files/DP2024_104.pdf



QC3: chamber QC



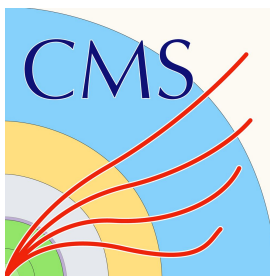
QC3.1 Chamber assembly tests

Visual test, connectivity test, gas leak test, dark current test

QC3.2 Cosmic test

- ❑ Tests with portable FEBv2.3 as initial procedure
- ❑ 3-fold coincidence ($15 \times 105 \text{ cm}^2$ each scintillator area)
- ❑ 1 double gap scan, 2 single-gap scans, noise & current scans
- ❑ 11 HV points with 2000 events/HV-point for efficiency and 15000 for noise





QC4: final chamber validation



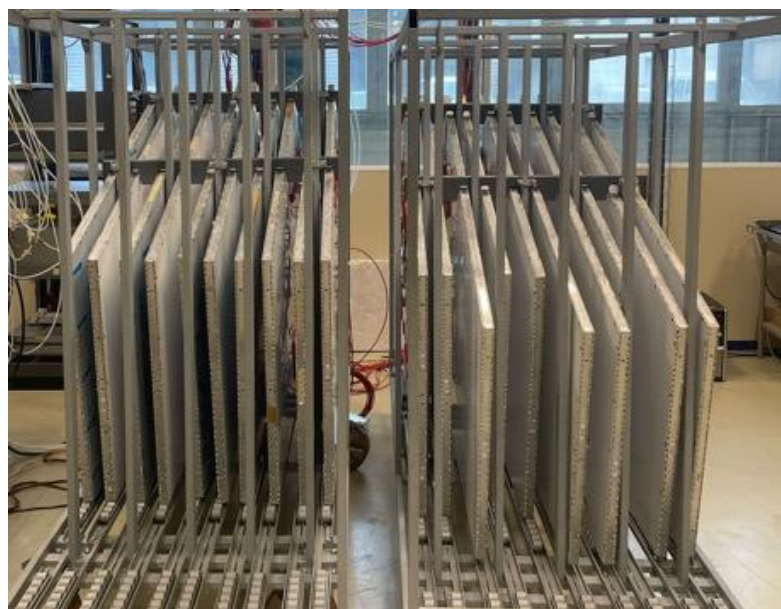
QC4.1 Cooling & Gas leak test

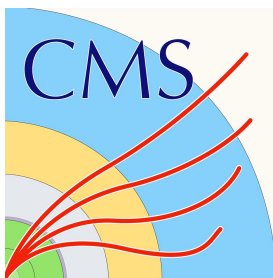
- ❑ cooling test follows QC1 procedure
- ❑ gas leak test follow QC2.1 with 5 mbar

QC4.2 HV current stability

- ❑ current monitoring at WP for 1 month
- ❑ acceptance: current $< 2.5 \mu\text{A}$

QC4.3 Final cosmic test



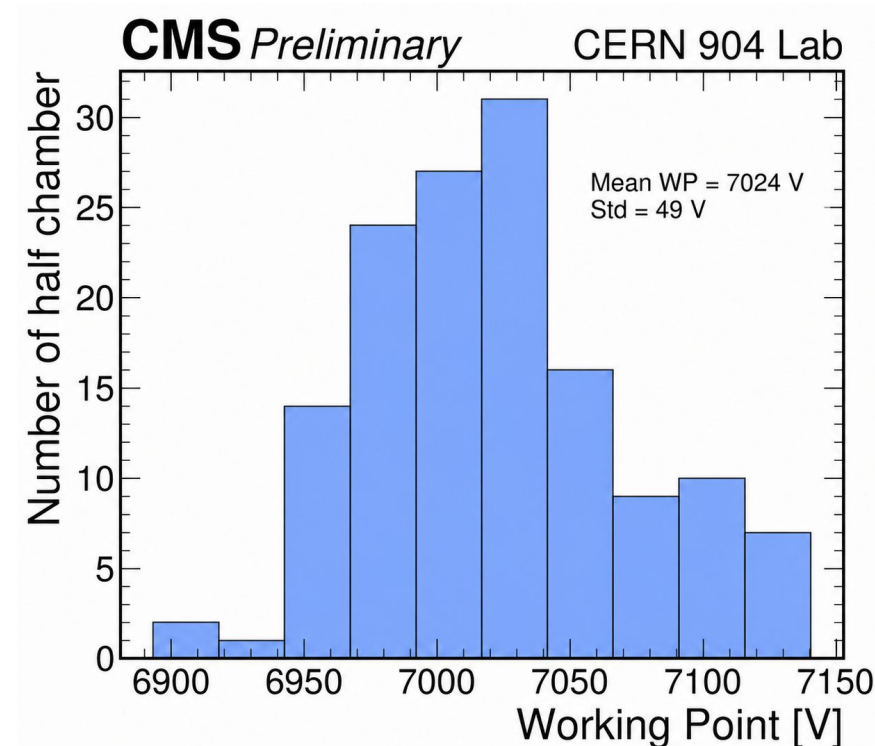
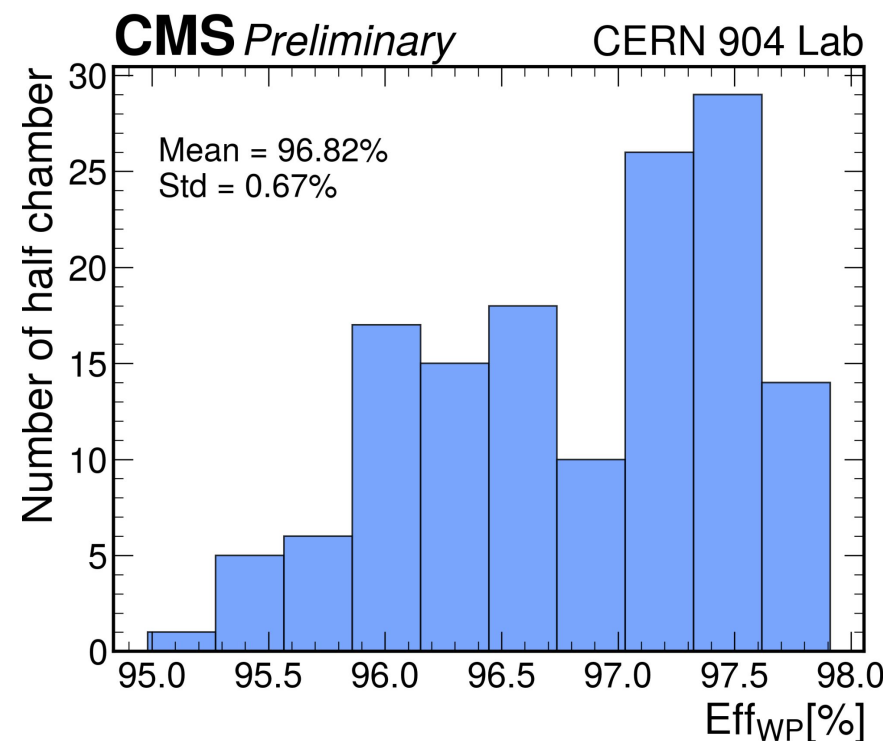


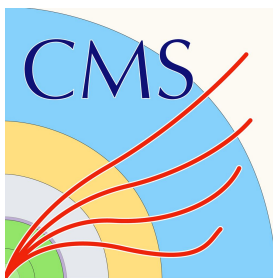
Summary of QC with Cosmic Rays

QC4.3 Cosmic test - efficiency and working point

- ❑ 1 double gap scan, 2 single-gap scans, noise & current scans
- ❑ 11 HV points with 2000 events/HV-point for efficiency and 15000 for noise

Efficiency required: >95%



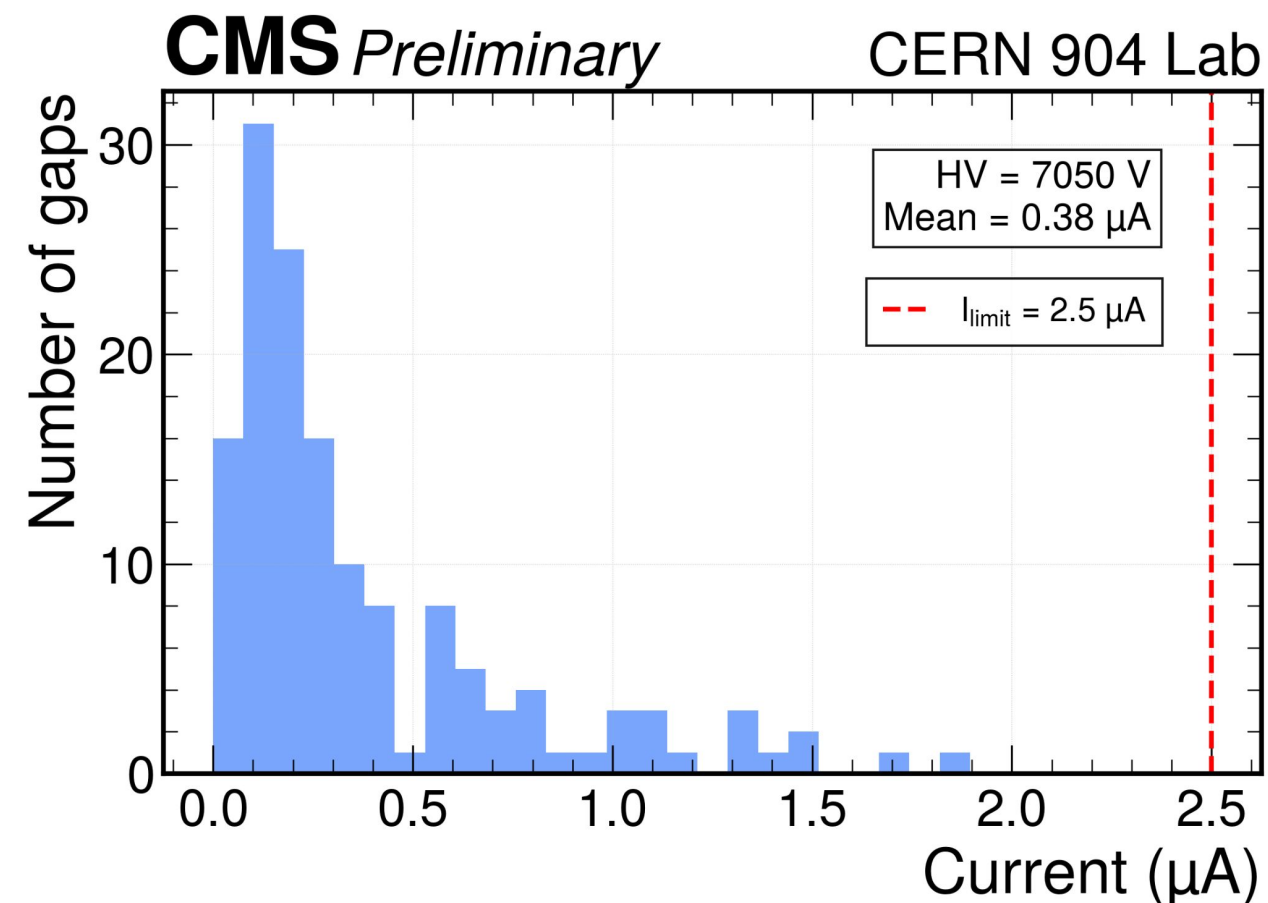
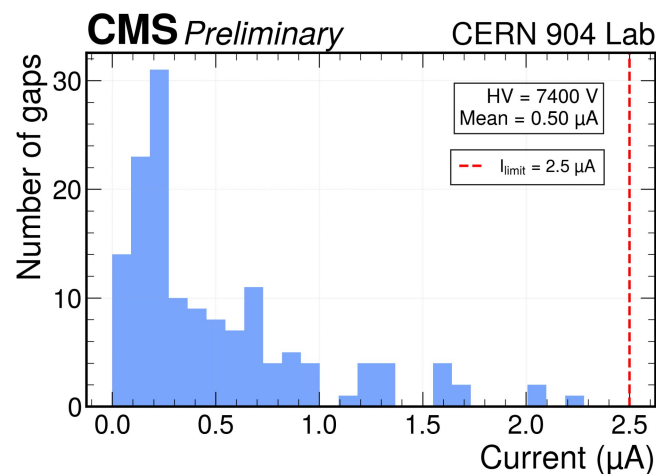
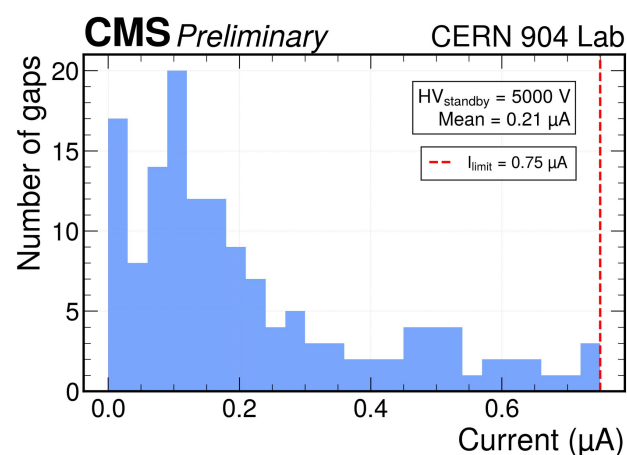


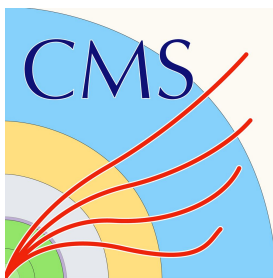
Summary of QC with Cosmic Rays



QC4.3 Cosmic test - current

- Current in different HV points
- Current acceptance: $< 0.75 \mu\text{A}$ at 5000V and $< 2.5 \mu\text{A}$ at the WP

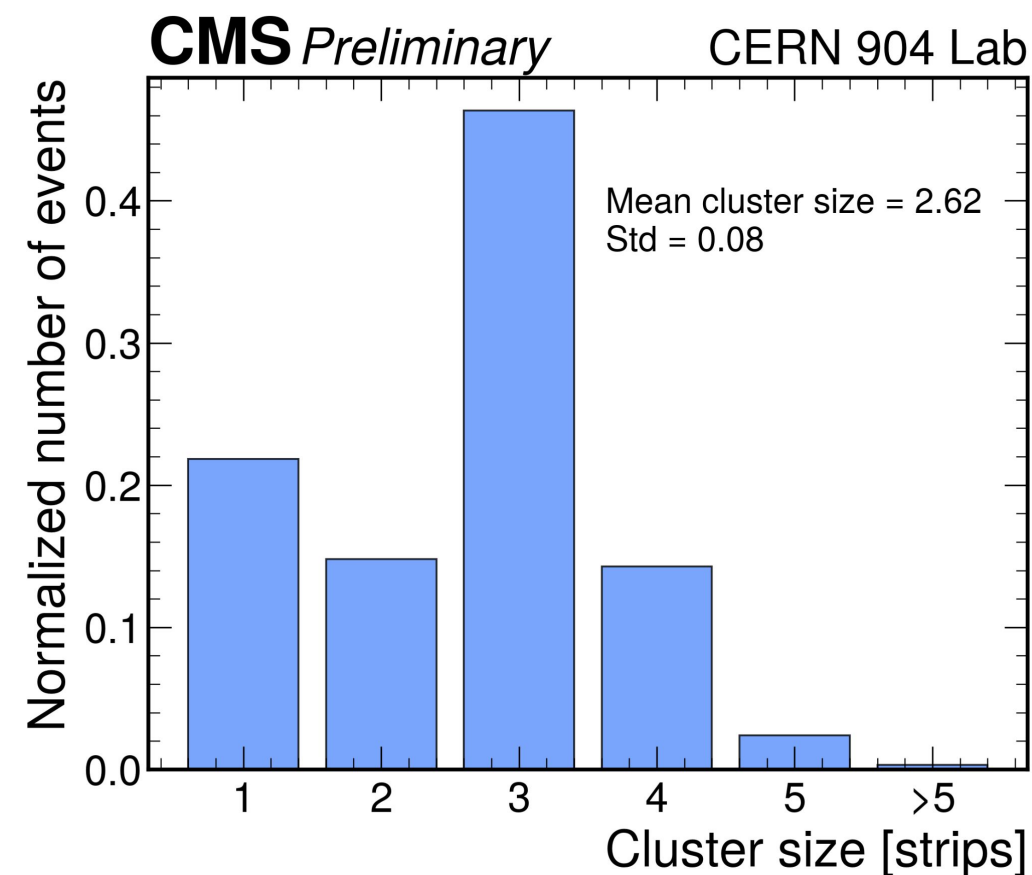
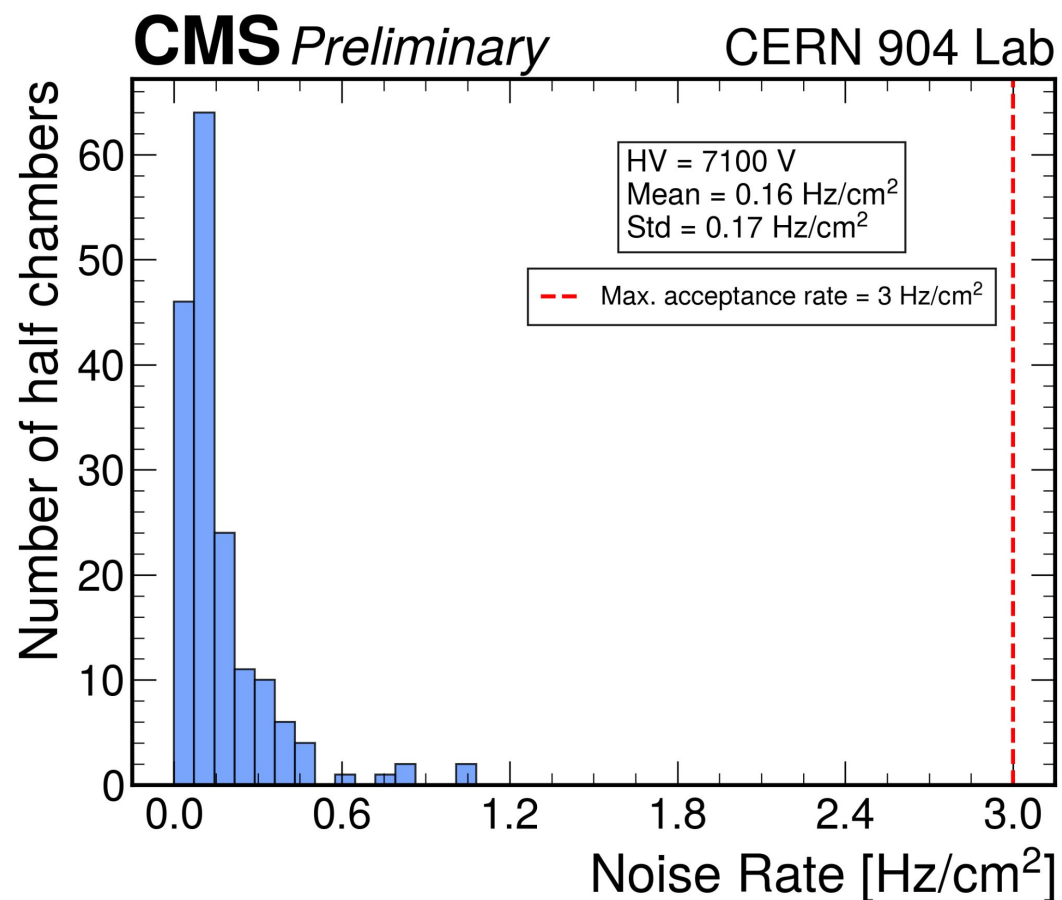


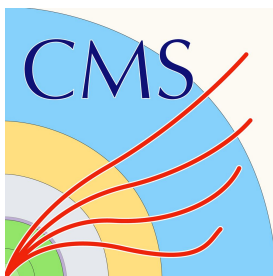


Summary of QC with Cosmic Rays

QC4.3 Cosmic test - noise and cluster size

- Noise rate acceptance: $< 3 \text{ Hz/cm}^2$
- Cluster size: around 3 strips

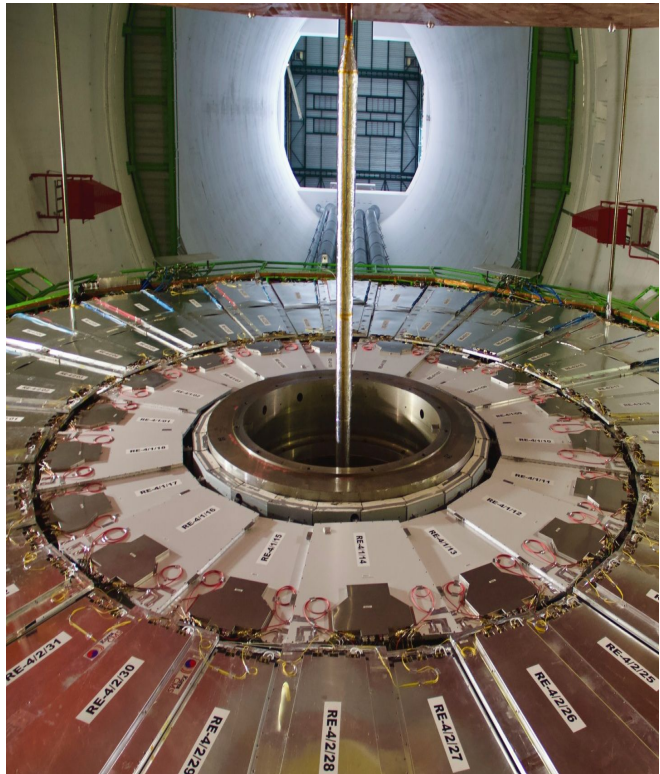




iRPC construction overview



	Required	Assembled	QC4.2 Long-term stability	QC4.3 Cosmic test	Installed
RE3/1	36	41	40	40	18
RE4/1	36	40	40	40	18
Total	72	81	80	80	36

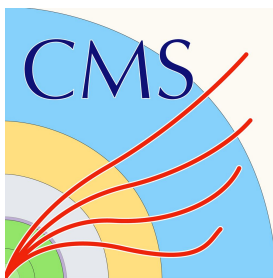


<https://cds.cern.ch/record/2925269?ln=en>



iRPC production completed!

- 18 RE-3/1, 18 RE-4/1 installed in YETS24/25;
- Others RE+3/1 and RE+4/1 **READY** for installation at earliest opportunity

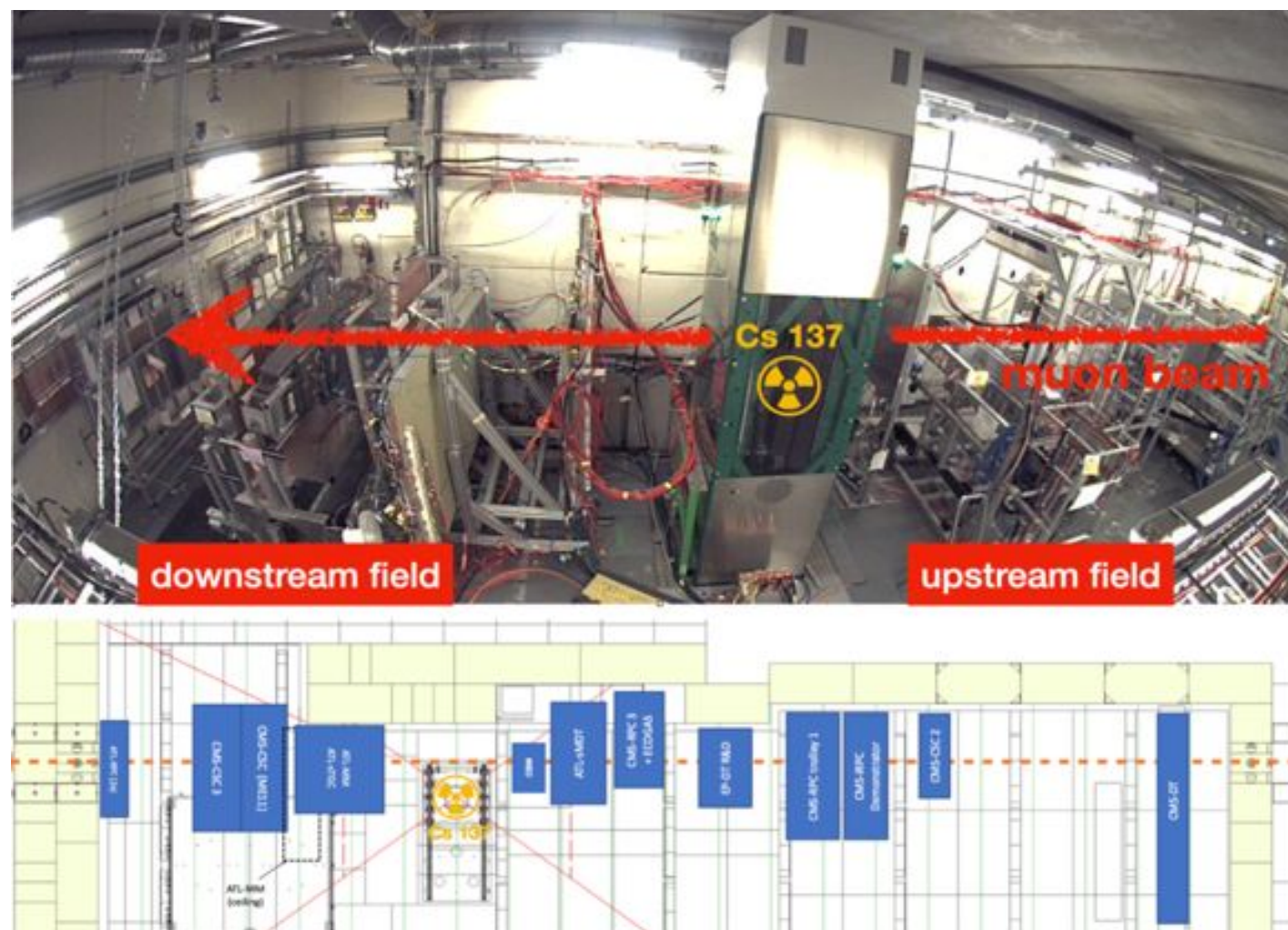


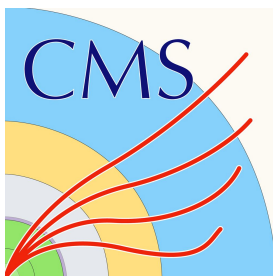
iRPC performance at GIF++

Gamma Irradiation Facility ++



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





iRPC performance at GIF++

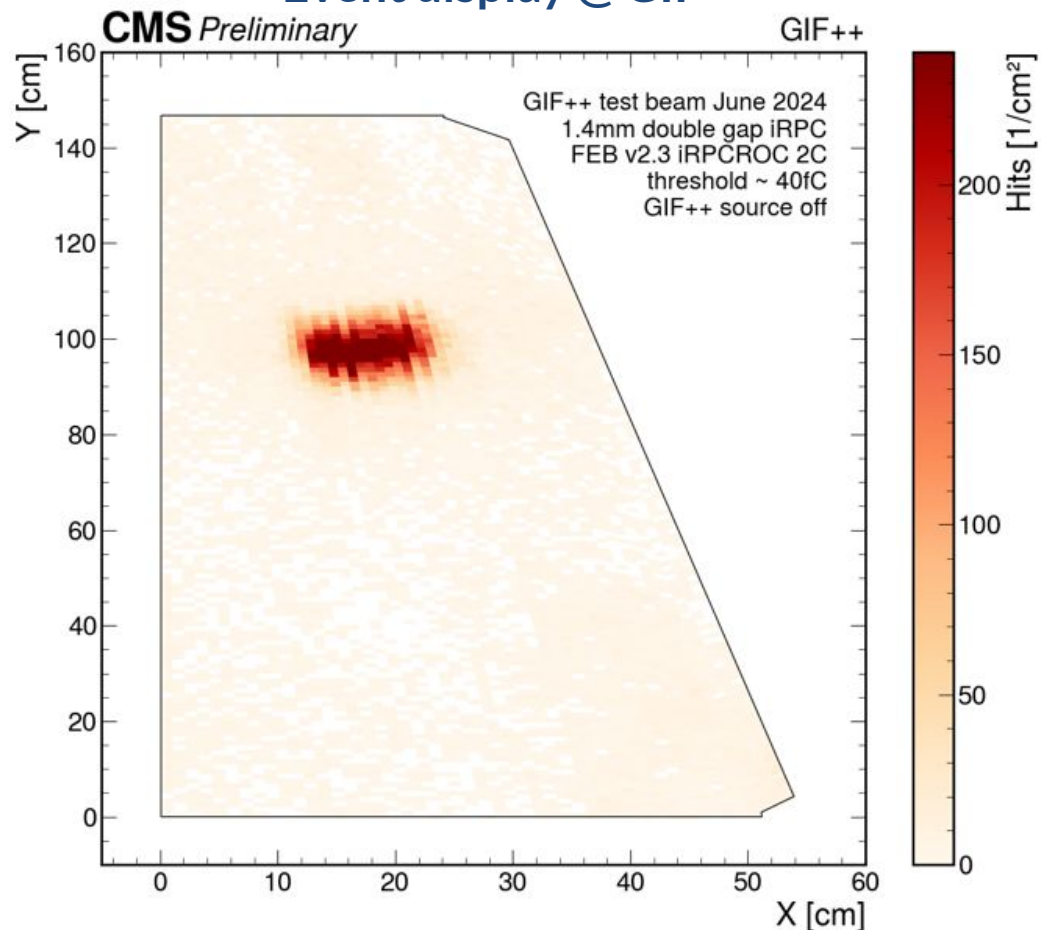
https://cds.cern.ch/record/2920454/files/DP2024_130.pdf



Performance of iRPC chamber at Gamma
Irradiation Facility (GIF++) at CERN

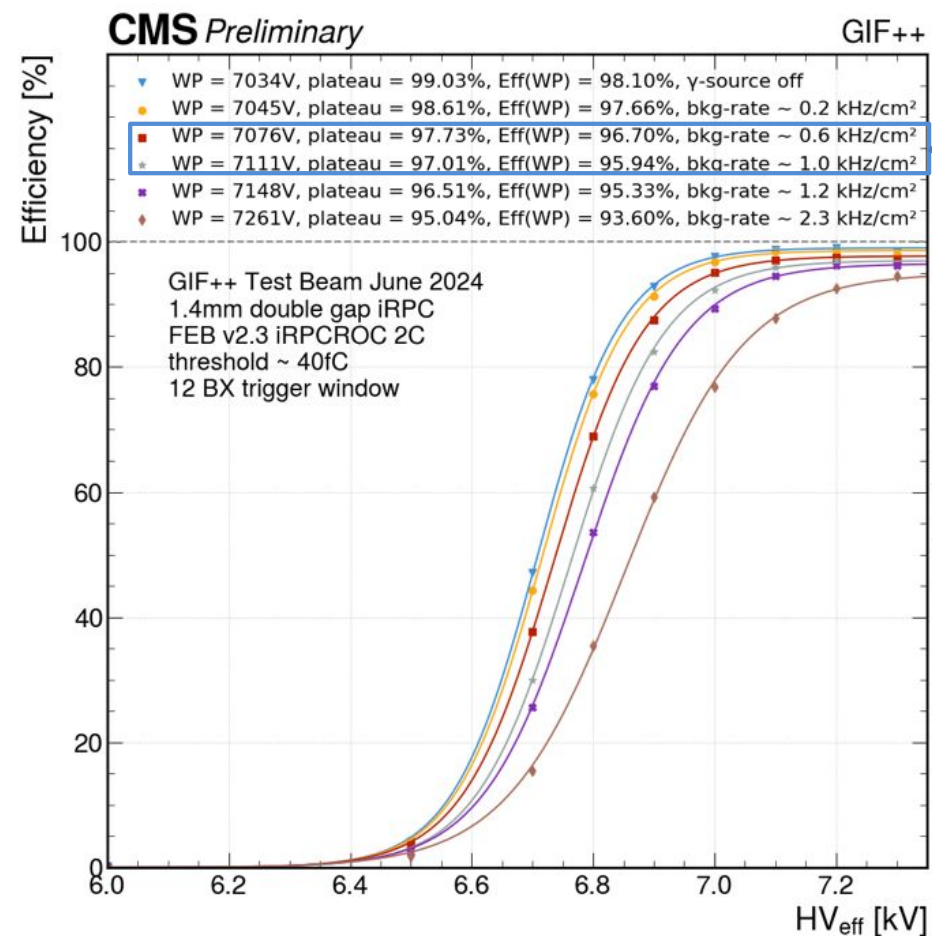
- 12 TBq ^{137}Cs gamma source - 662 keV
- Muon beam ~ 150 GeV/c

Event display @ GIF++



Efficiency curves

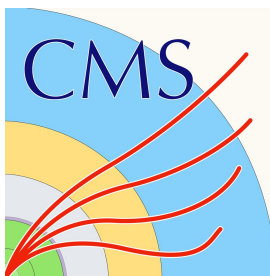
- threshold @ ~ 40 fC
- 12 BX trigger window



@ bkg-rate = 600-1000 Hz/cm²:

→ Efficiency = 96 - 96.7 %

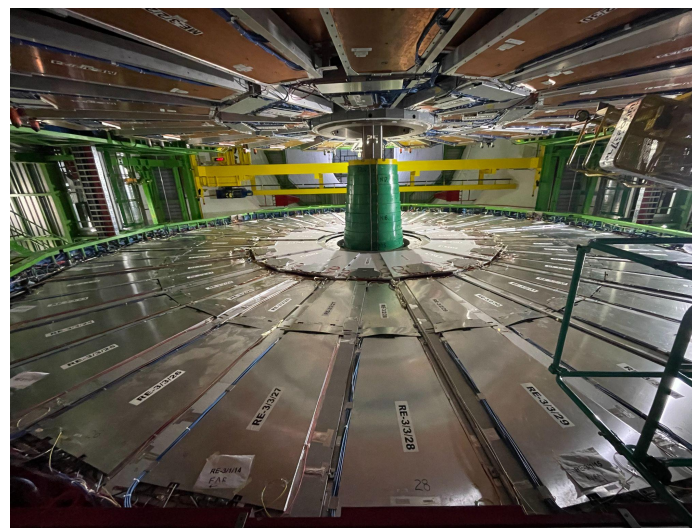
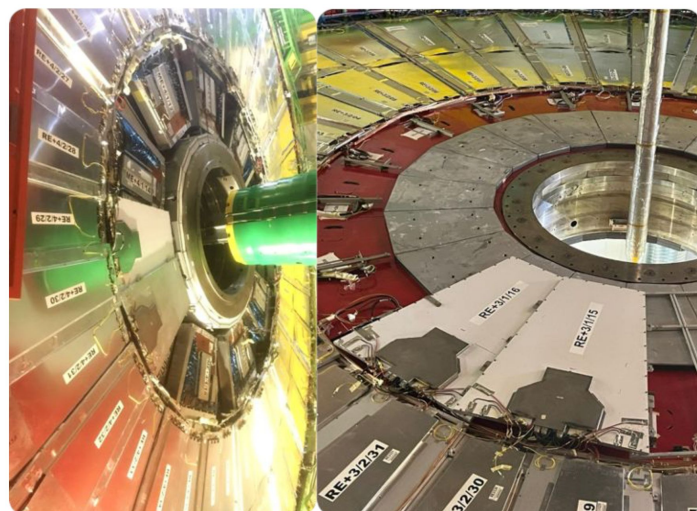
→ Working Point = 7.07 - 7.11 kV



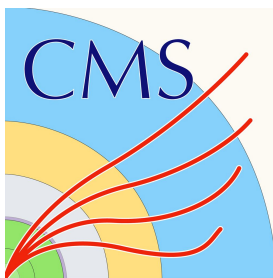
iRPC installation in CMS



- 4 demonstrator chambers (RE+4/1/15,16 and RE+3/1/15,16) were installed at CMS in the end of the LS 2 (2021-2022);
- 36 mass production final chambers installed in disks RE-3/1 and RE-4/1 in CMS in YETS 2024/2025:
 - ☐ Noise < 1Hz/cm² with final endcap disk grounding
 - ☐ FEB temperature stable at CMS endcap closed mode with water cooling
 - ☐ HV currents showing smooth operation during LHC Run 3
 - ☐ Normal operation at 3.8 T magnetic field.
- 36 remaining chambers are ready and waiting to be installed in disks RE+3/1 and RE+4/1.



<https://cds.cern.ch/record/2922015?ln=en>



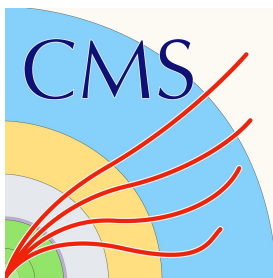
Summary



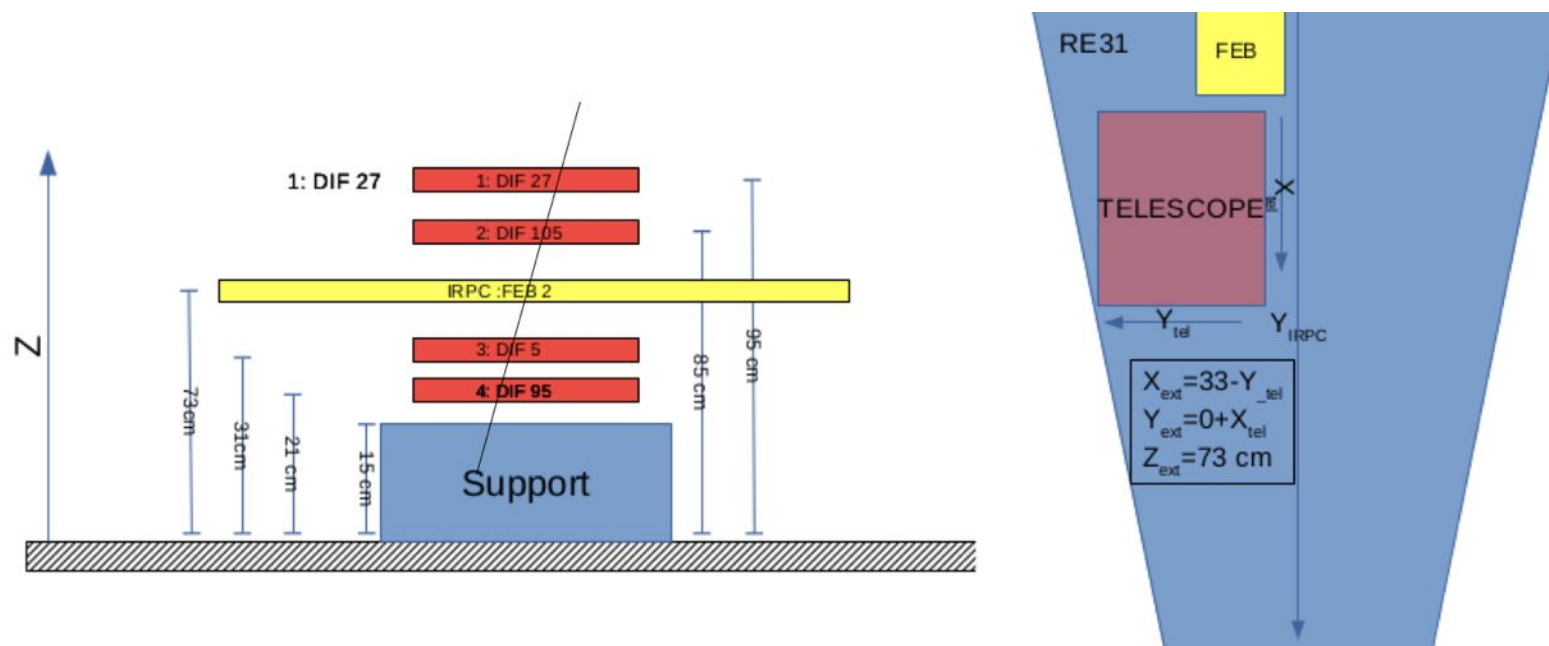
- iRPC is an **innovative design detector** to operate at CMS at High Eta region with HL-LHC;
- The full mass production and certification campaign of the CMS iRPC chambers has been successfully completed;
- The verification of the QC test results distributions shows that the whole production run is uniform and well within the requirements;
- iRPC performance was validated under high background gamma rates (safety factor of 3 above expected LHC conditions): efficiency of **96 - 96.7%** at working point;
- **36 chambers (18 RE-3/1 + 18 RE-4/1)** already installed at CMS during YETS 2024/2025 and operating normally, including stable HV currents and FEB temperature;
- These results validate the robustness of the iRPC quality assurance program and confirm the **readiness of the remaining chambers for installation** in the CMS detector;
- iRPC will pave the way for precise timing of CMS muon at the High Lumi frontier.

Thank you!

Backup slides



iRPC space resolution



- Telescope in Lyon University IP2I made up with 4 RPC chambers (2 mm double gap 30 x 50 cm²)

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

○ 0.8 - 0.9 cm

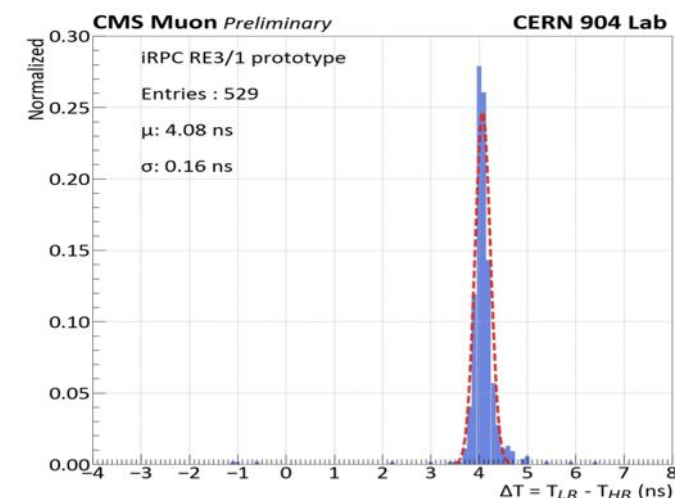
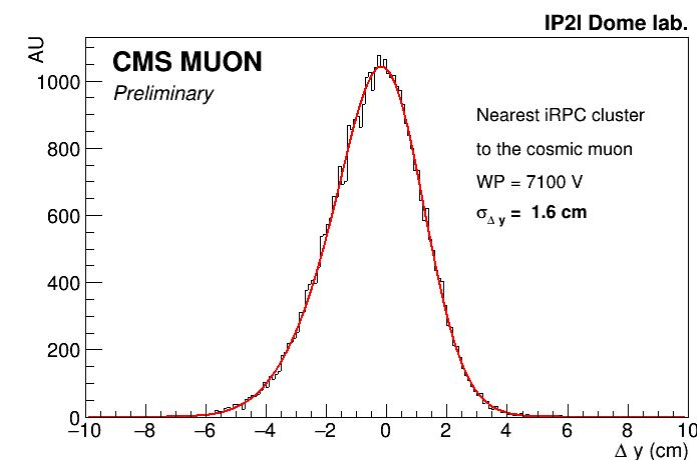
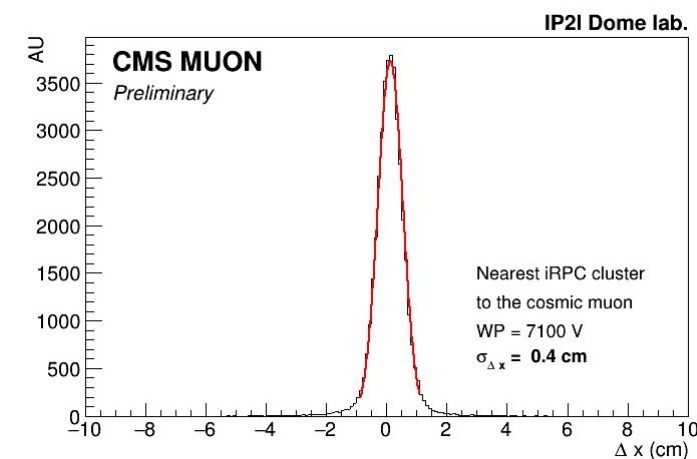
$$\sigma_x = 0.4 \text{ cm}$$

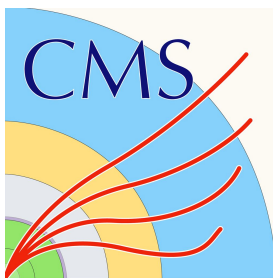
- In y-axis, resolution depends on $\Delta T = T_{HR} - T_{LR}$

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

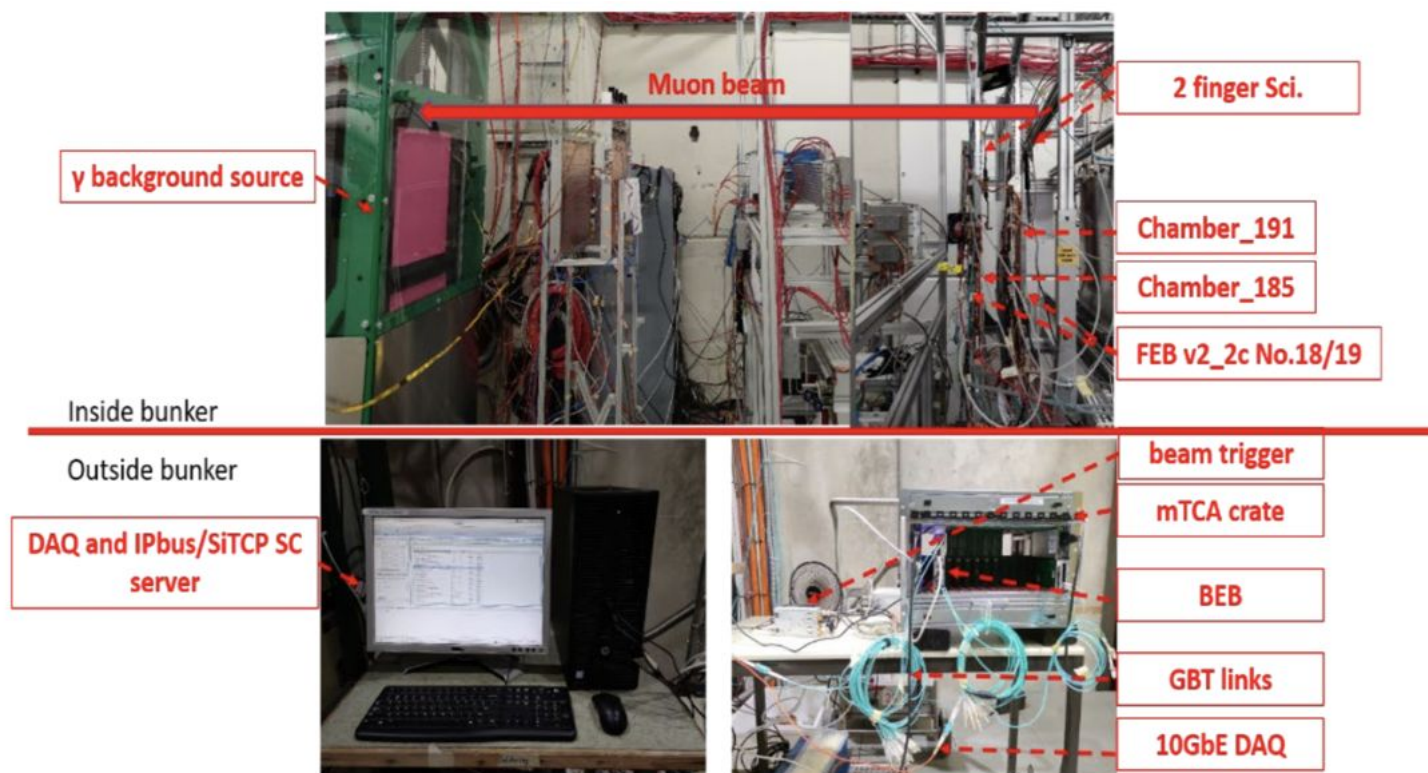


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Chinese Academy of Sciences





iRPC time resolution



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

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

