CERN CMS Physics Institute III A | RWTH AACHEN UNIVERSITY

CERN | EP-DT Detector Technologies

Longevity studies for the CMS Muon System towards HL-LHC

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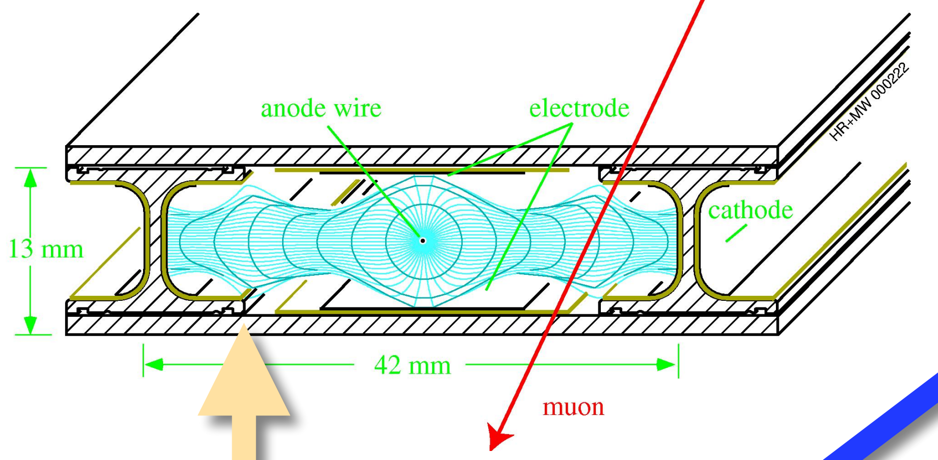
On behalf of the CMS Collaboration

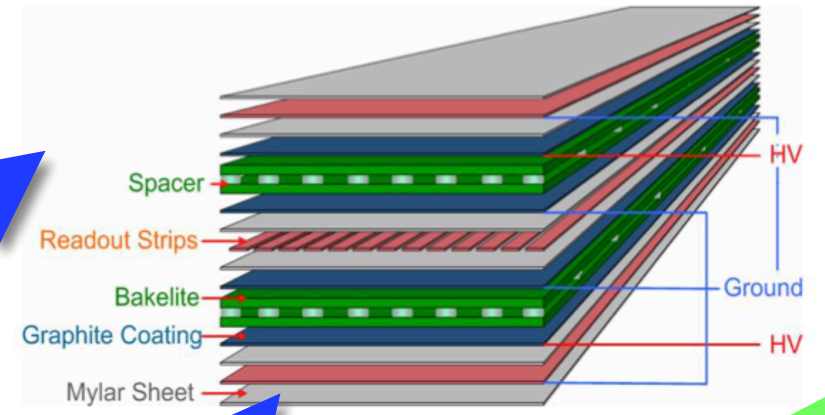
15th Pisa Meeting 2022: 15th Pisa Meeting on Advanced Detectors
22-28 May 2022, INFN, Isola d'Elba (Italy)

The CMS Muon Spectrometer and its Upgrade

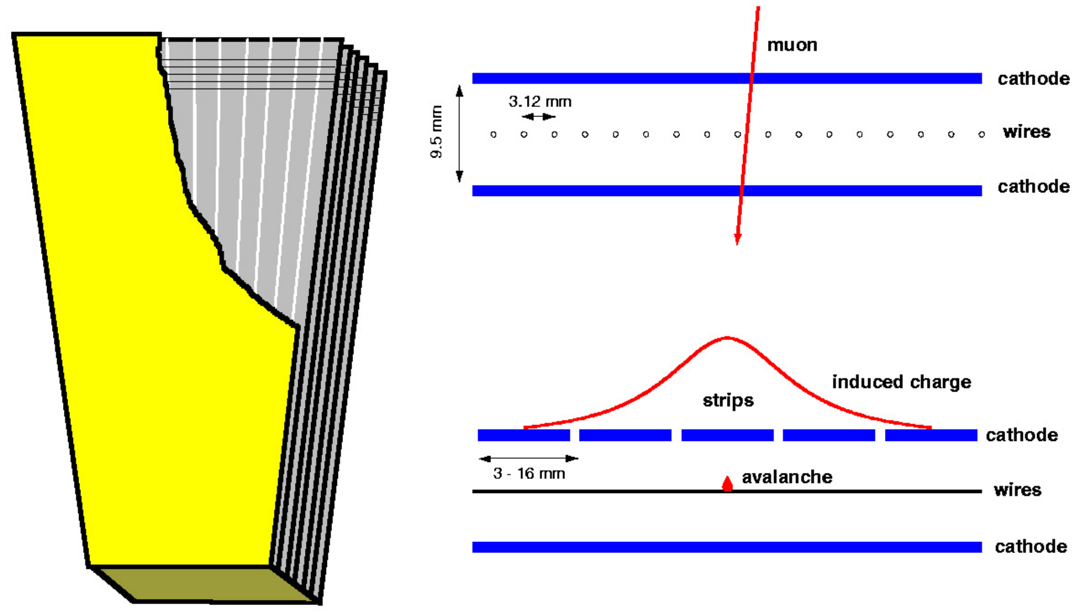
Drift Tubes (DT)
|η|<1.2
250 Barrel Chambers



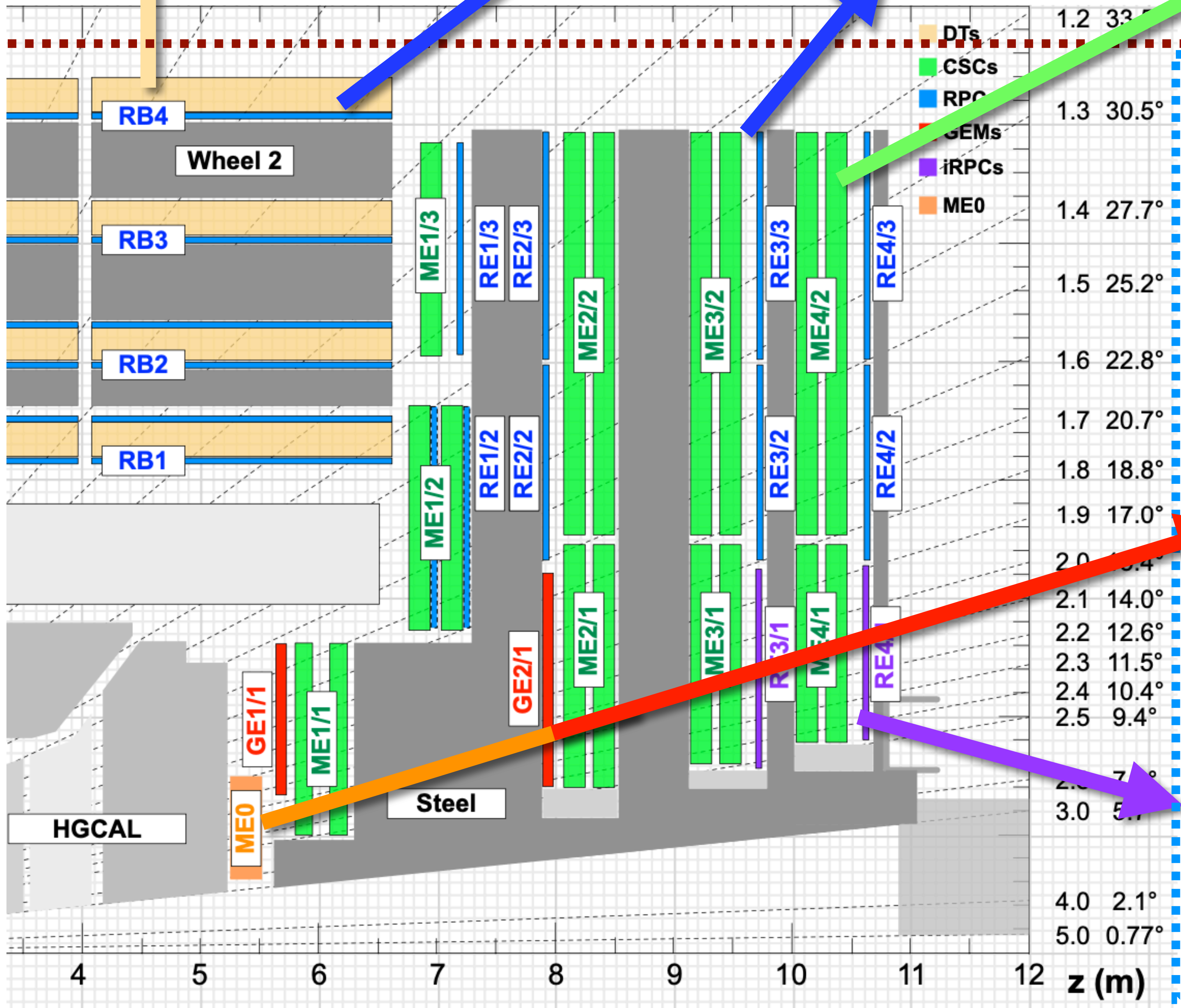
Resistive Plate Chambers (RPC)
|η|<1.9
480 Barrel Chambers
576 EndCap Chambers



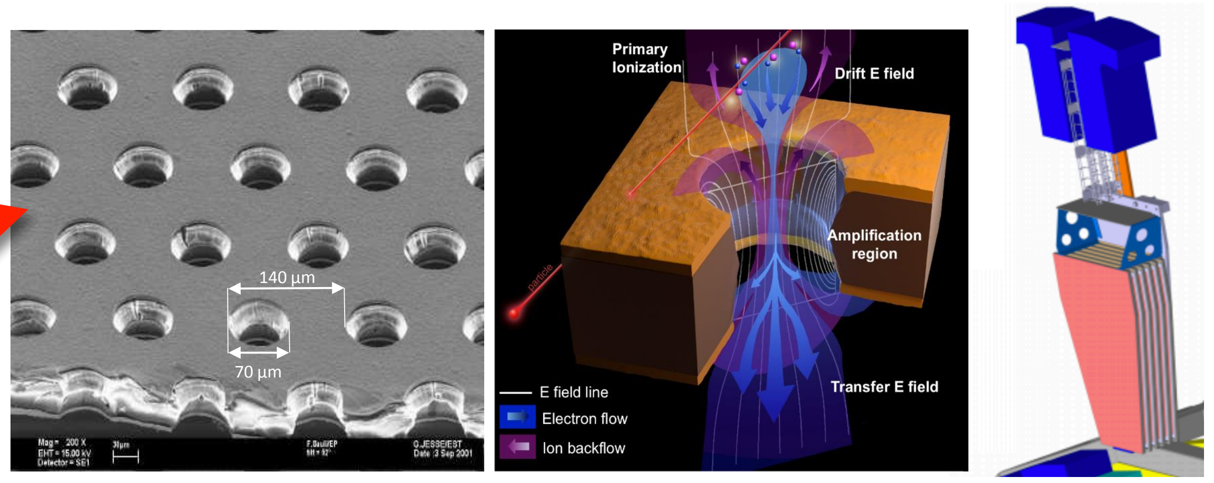
Cathode Strip Chambers (CSC)
0.9<|η|<1.9
540 Endcap Chambers



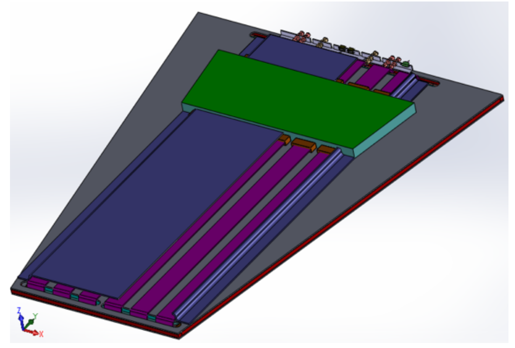
"Legacy" Detectors



Gas Electron Multipliers (GEM)
1.6≤|η|≤2.8
GE 1/1 Installed in LS2
GE 2/1 Planned for 2024/25
ME0 Planned for LS3 (2026→)



Improved RPC (iRPC)
72 Chambers
Planned for 2024/25
1.8<|η|<2.4



"New" Detectors

The Muon Spectrometer uses different gaseous detector technologies

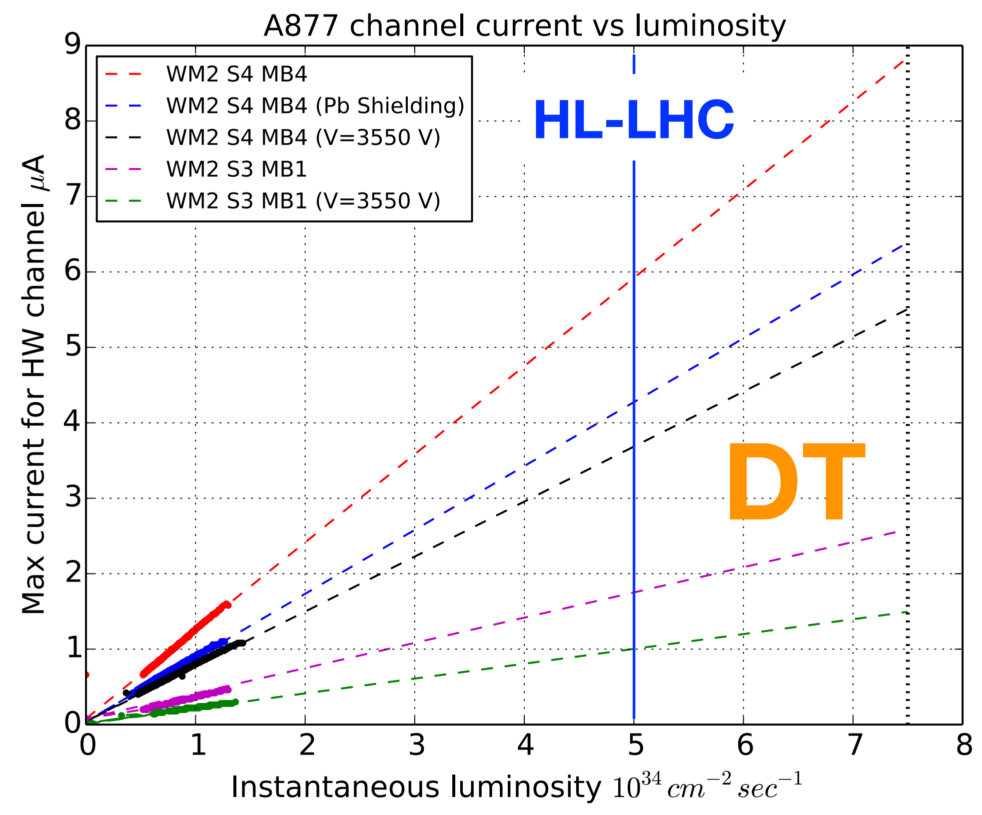
- Developed for LHC
- It showed **excellent performances** in **triggering**, **identification** and **reconstruction** of **muons**

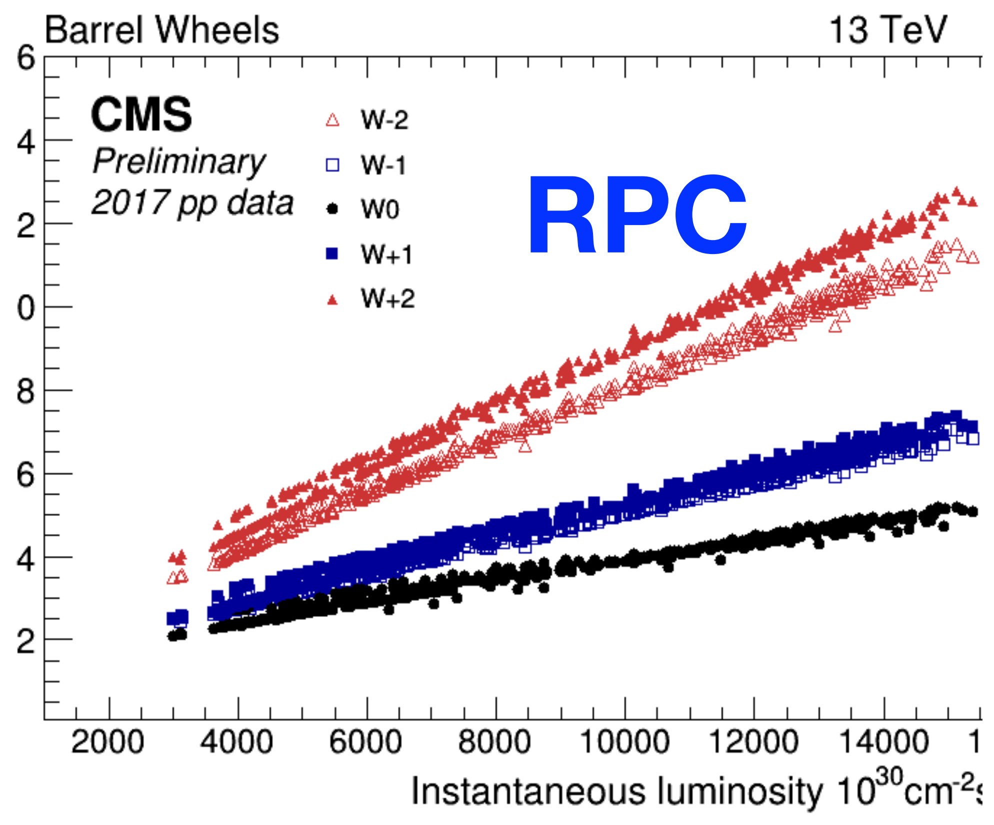
The **Muon Upgrade** will cope with the new operating condition and **extend** the physics potential of CMS

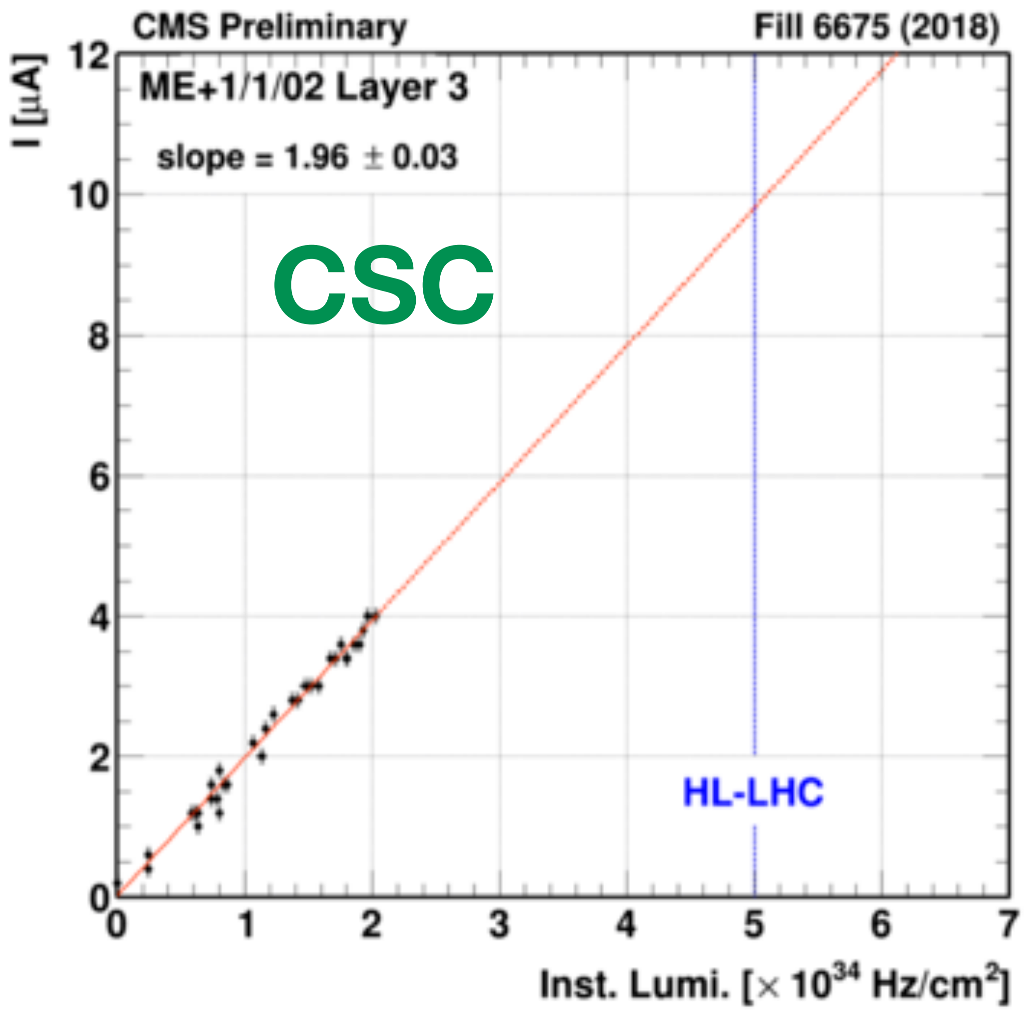
- **Peak luminosities of 5(7)·10^{34} cm^{-2}·s^{-1}**
- ~140 (200) PileUp events
- an **integrated luminosity at least ten times** the LHC design value
- **Test of the longevity of all the detectors critical part of the Upgrade Program**

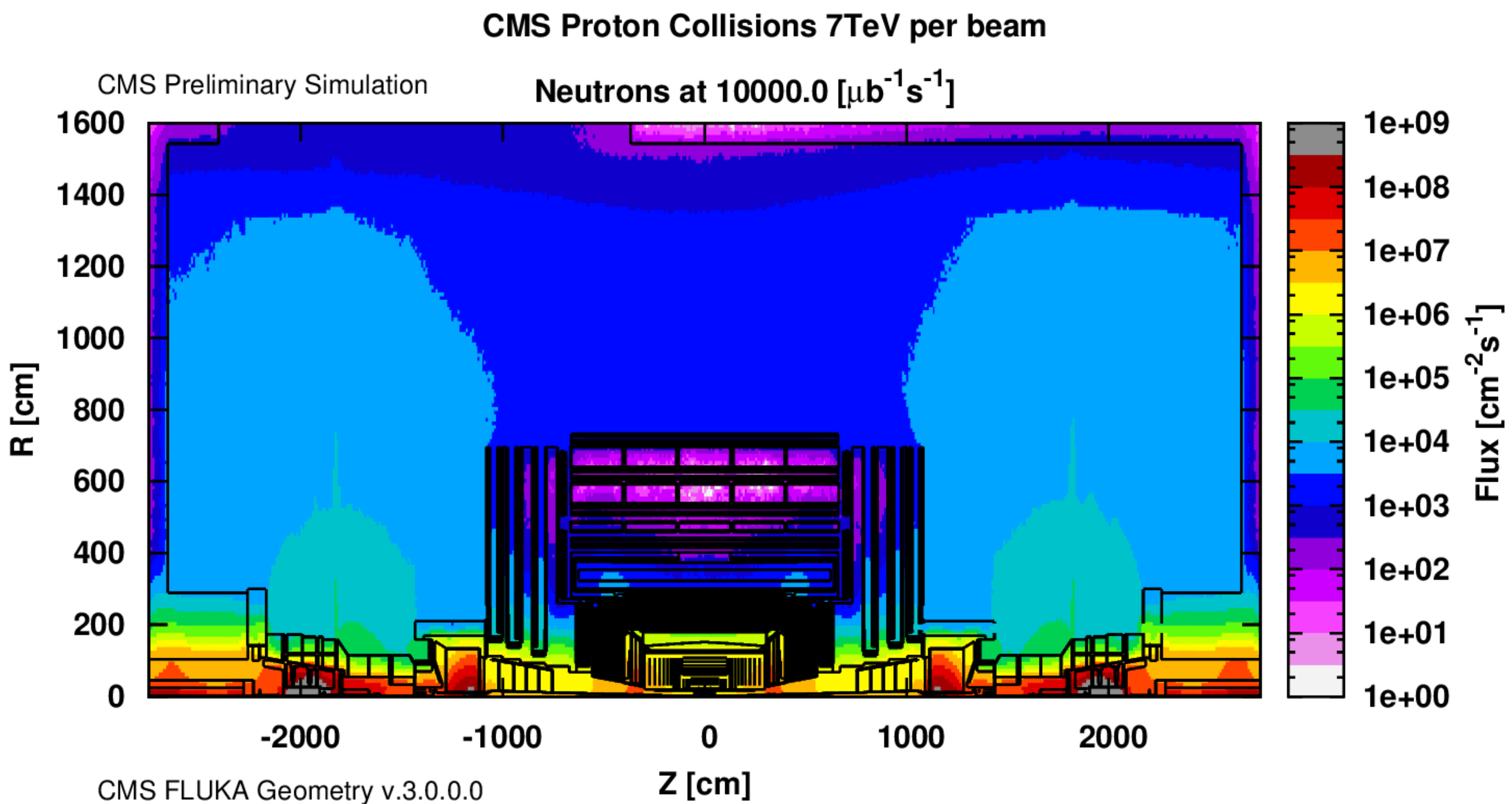
Background and Longevity

- Aging of the gases detector dominated by the background reaching the muon spectrometer
- **Expectations for HL-LHC come from two sources:**
  1. **Detailed study of the background**
     - **Study of currents** and hit rates as a function of LHC instantaneous luminosity
  2. **Simulation studies with FLUKA:**

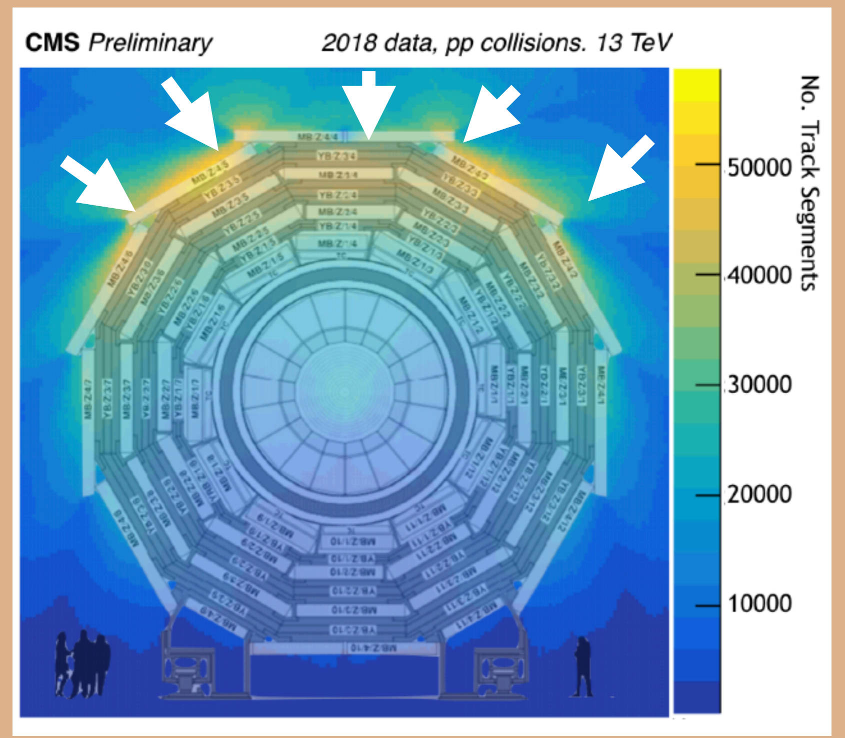


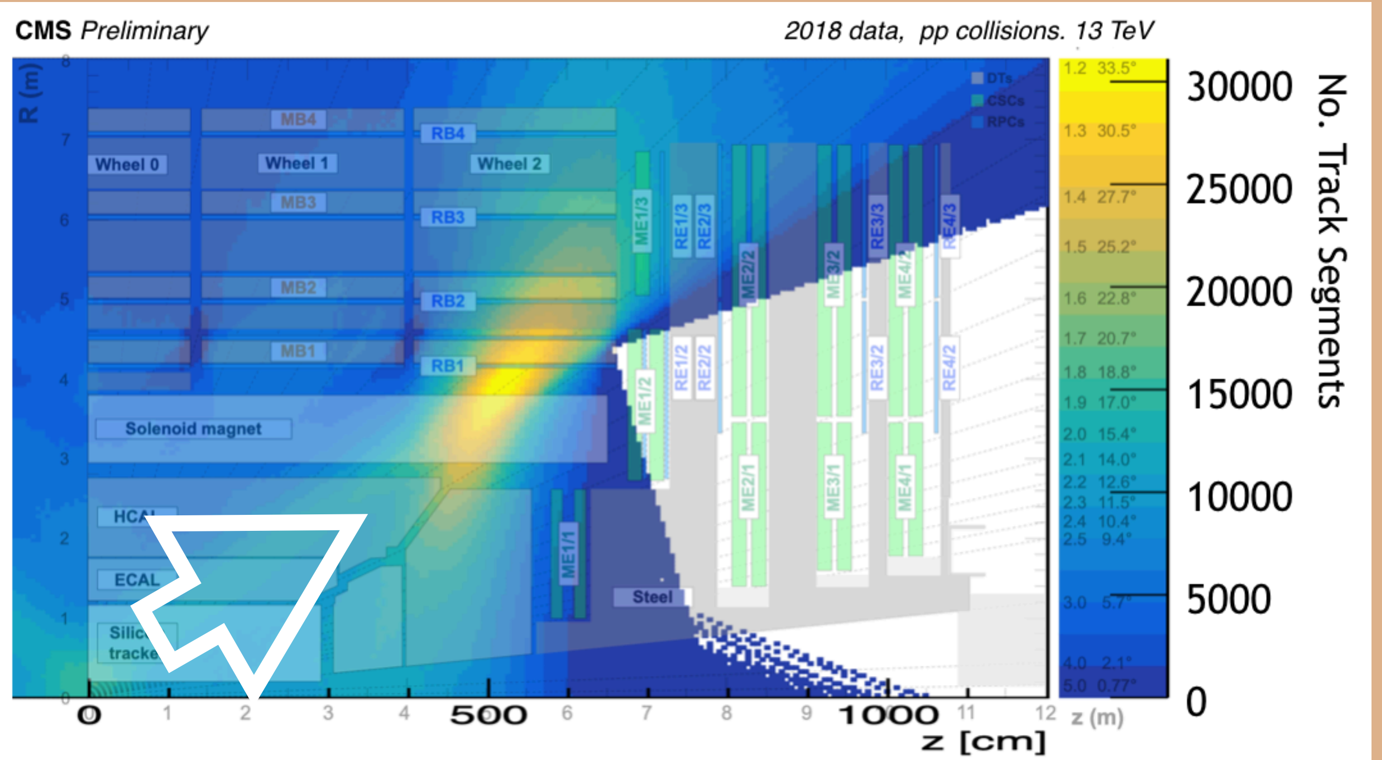




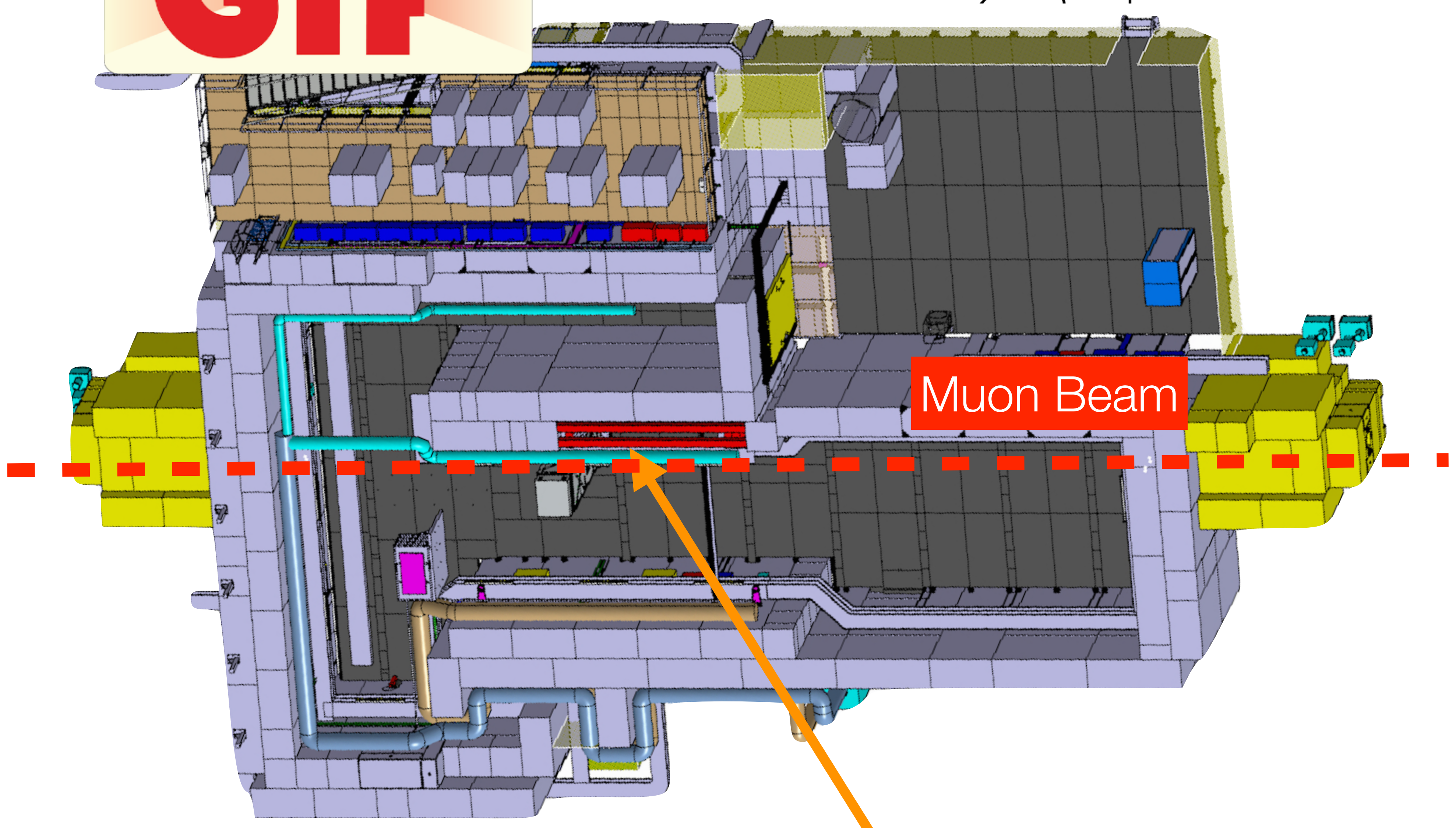


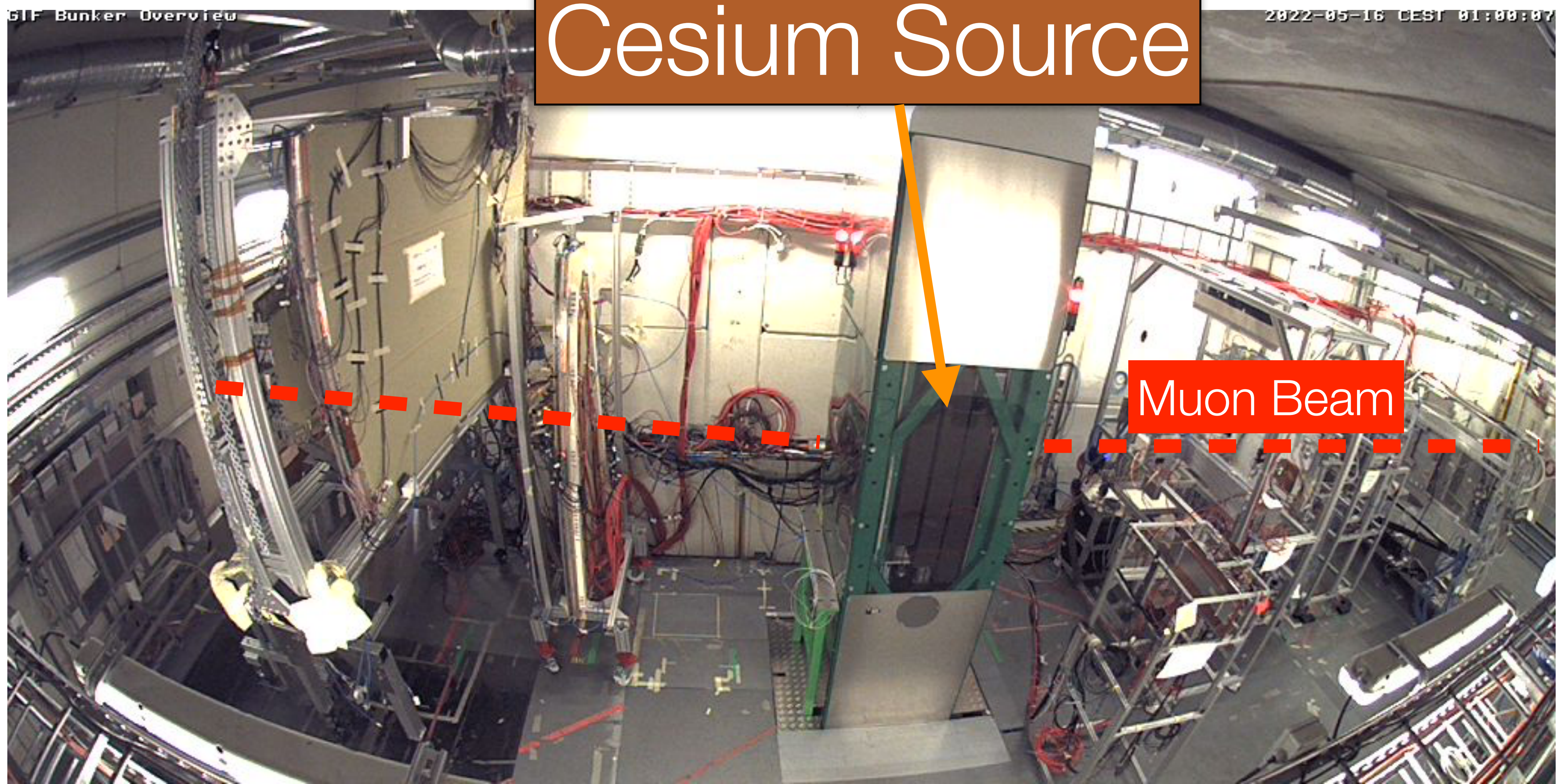
- **Two main types of background identified:**
  - Direct background coming from collisions (punch through)
  - Neutron Gas forming in the experimental cavern



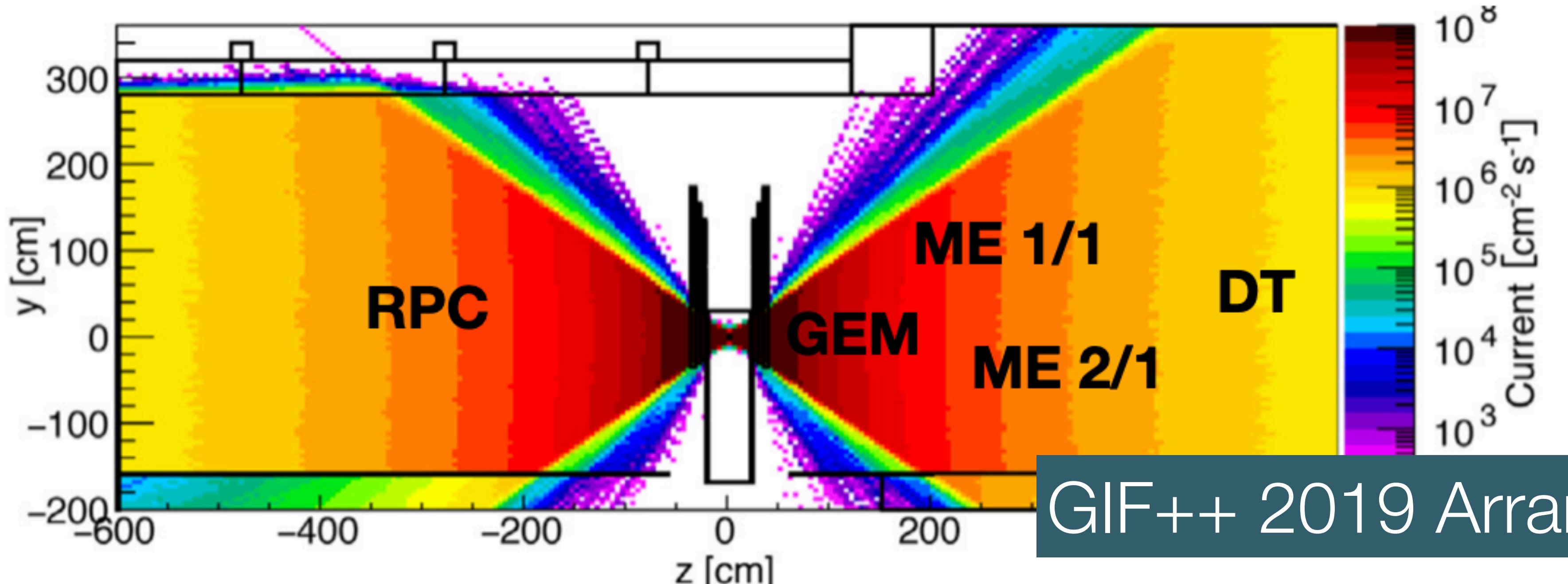


The GIF++ Irradiation Setup



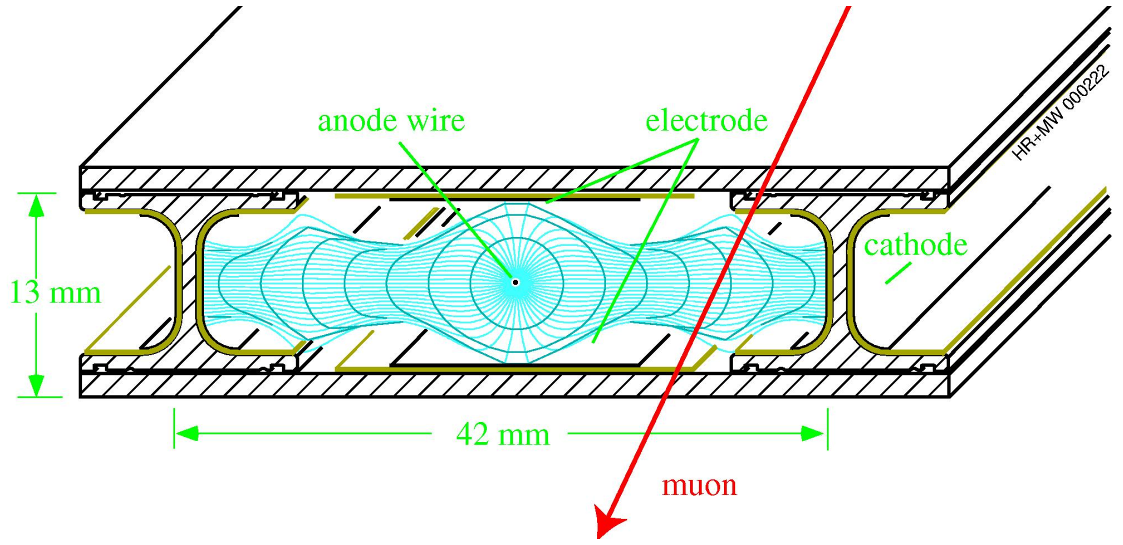


- Most of the CMS Muon aging program is being performed at CERN's upgraded Gamma Irradiation Facility (GIF++)
  - It combines a 100 GeV/c muon beam and a 12.2 TBq ^{137}Cs gamma source for **accelerated aging and testing**
- Provides reasonable modeling of neutron-induced background and simulation of the 'worst-case' HL-LHC collision environment
  - Spatial distance from source and regulable filters allow to satisfy the different need of multiple setup
  - Chambers tested:
    - CSCs: 1 ME1/1 and 1 ME2/1
    - DTs: 1 MB1, 1 MB2
    - GEMs: 1 GE1/1, 1 GE2/1
    - RPCs: 1 RE2, 1 RE4, 1 iRPC large prototype

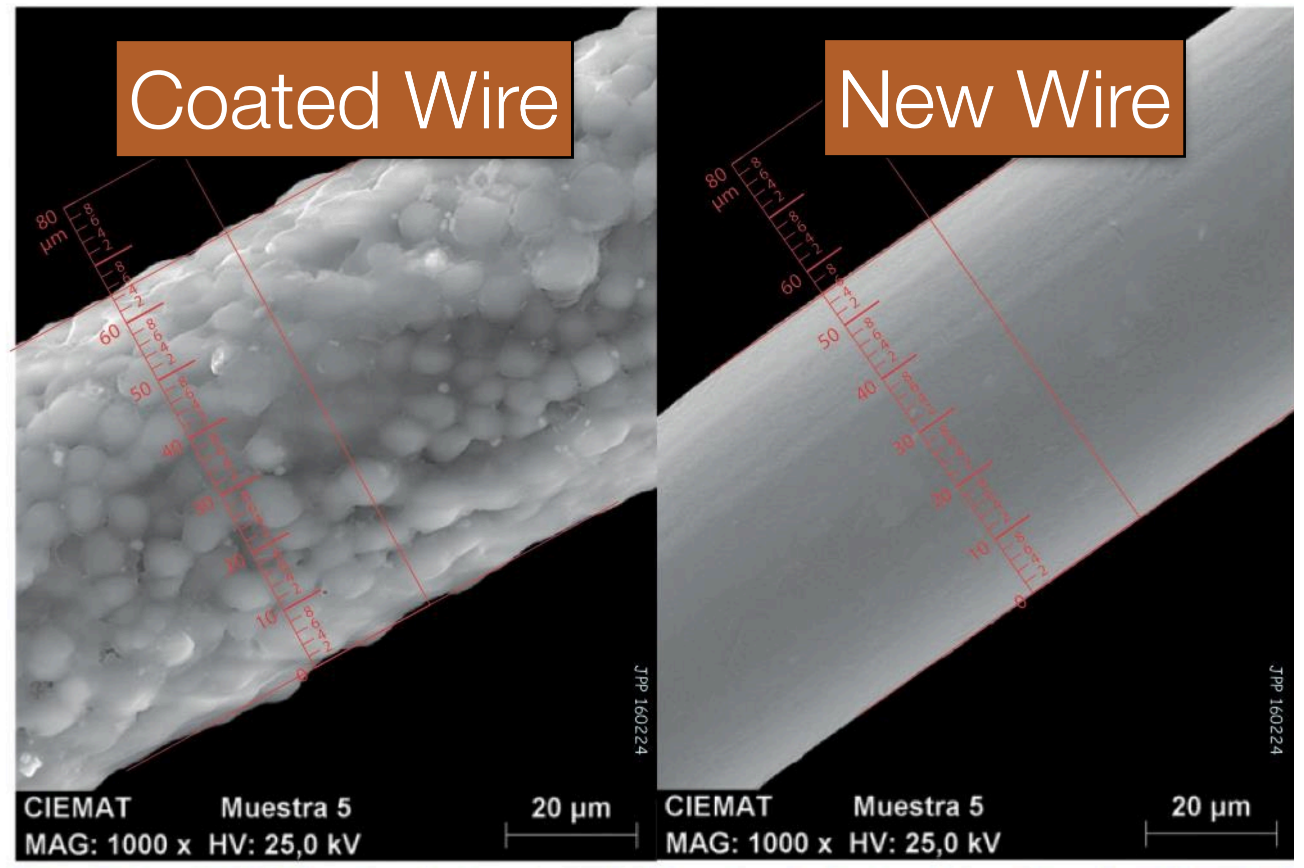


GIF++ 2019 Arrangement

DT Aging Studies

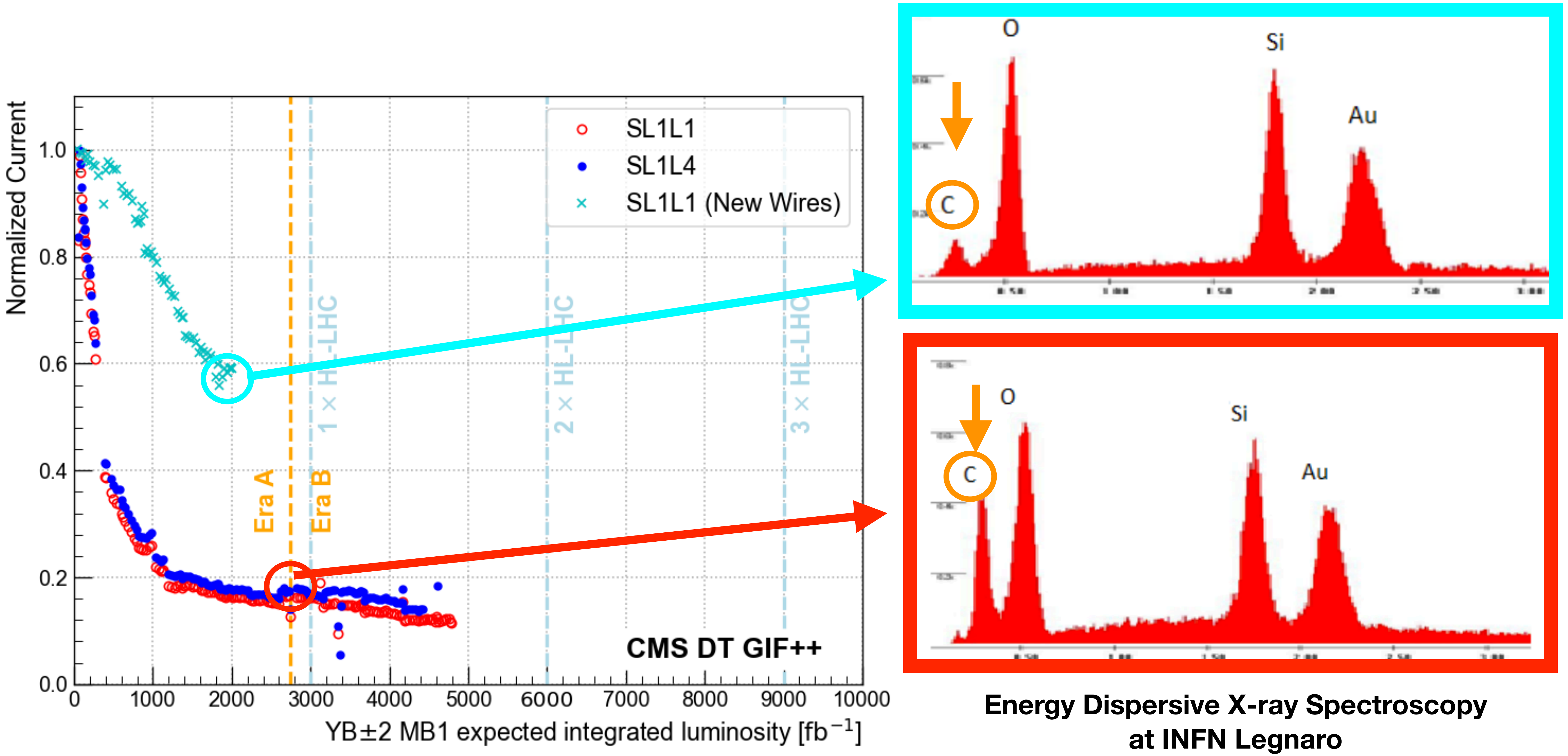


- The DT basic detector element is a rectangular drift cell, filled with an **Ar/CO_2 (85/15%)** gas mixture, and a gold-plated steel wire that acts as the anode.
- DT aging studies started in 2015, and showed a fast degradation of the detector gain with integrated charge
  - The electron avalanche conditions enable chemical reactions of impurities and **create a coating on the wire**, affecting the detector efficiency.



Wire with deposit (left): 65 µm diameter; clean wire (right): 56 µm diameter. The deposit layer is thus about 4.5 µm thick.

Microscopy analysis from CIEMAT

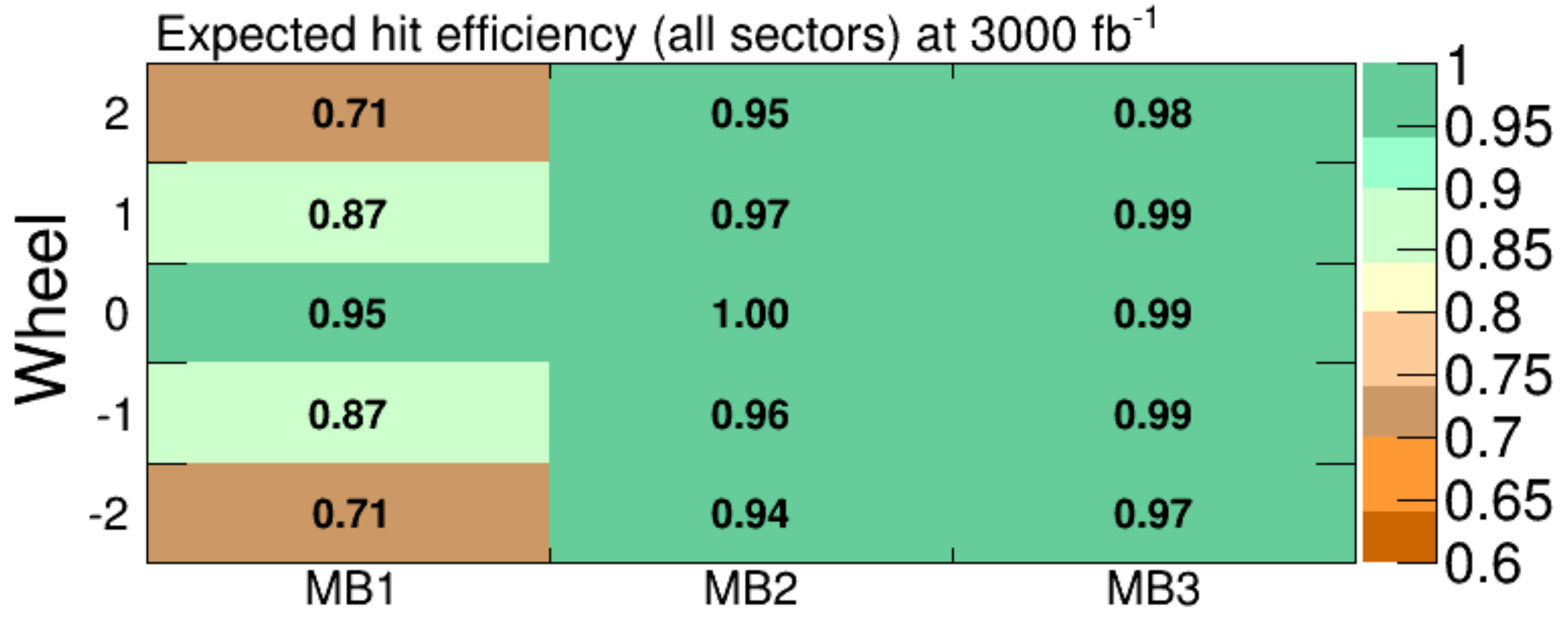


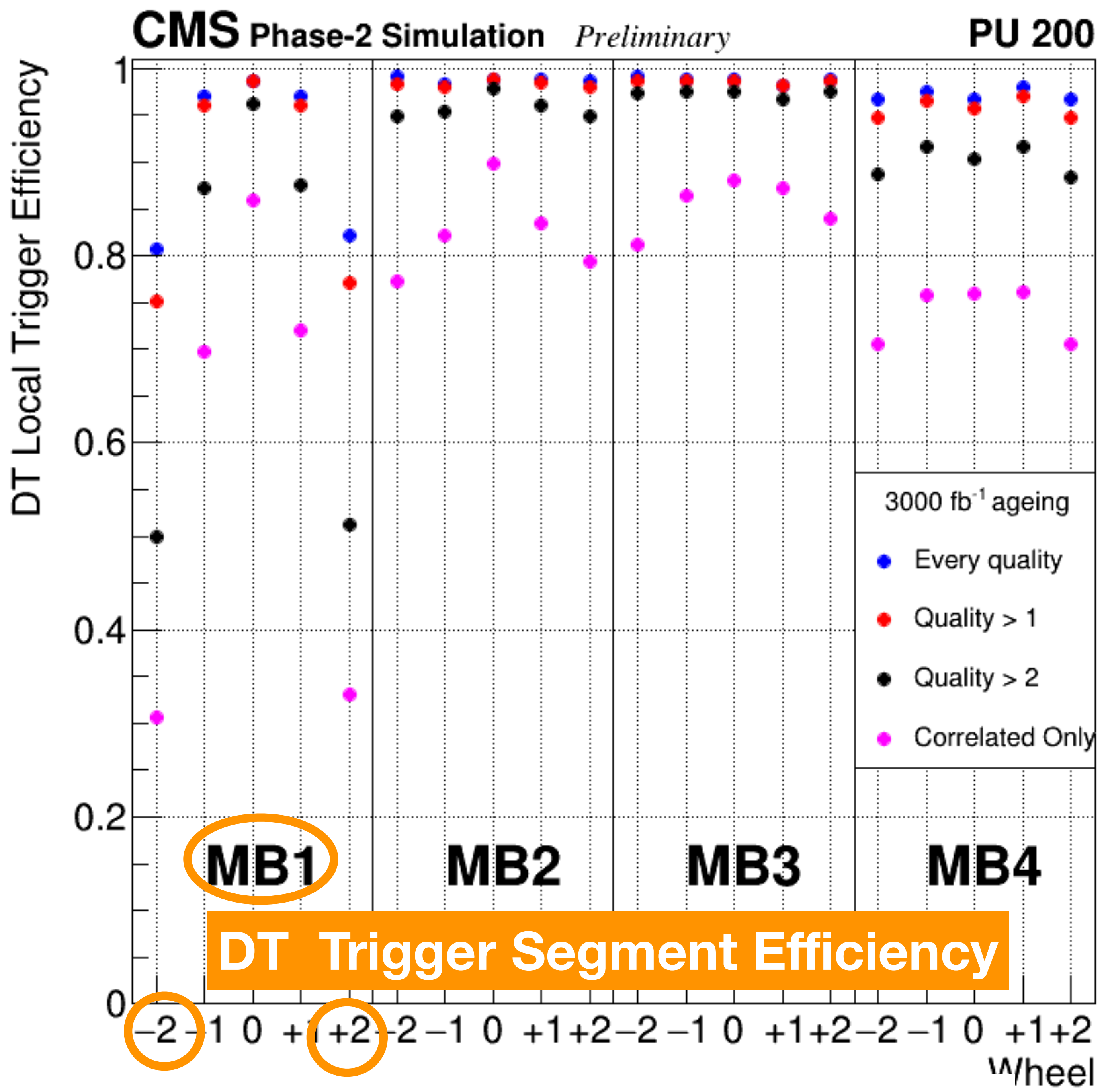
Energy Dispersive X-ray Spectroscopy at INFN Legnaro

- At CMS up to now (~200 fb^{-1}) no signs of aging
- A more recent irradiation of virgin wires showed:
  - Slower reduction of gain
  - Reduced presence of Carbon in the chemical analysis of the coating
  - Slower loss of efficiency
  - **Additional irradiation period is ongoing**

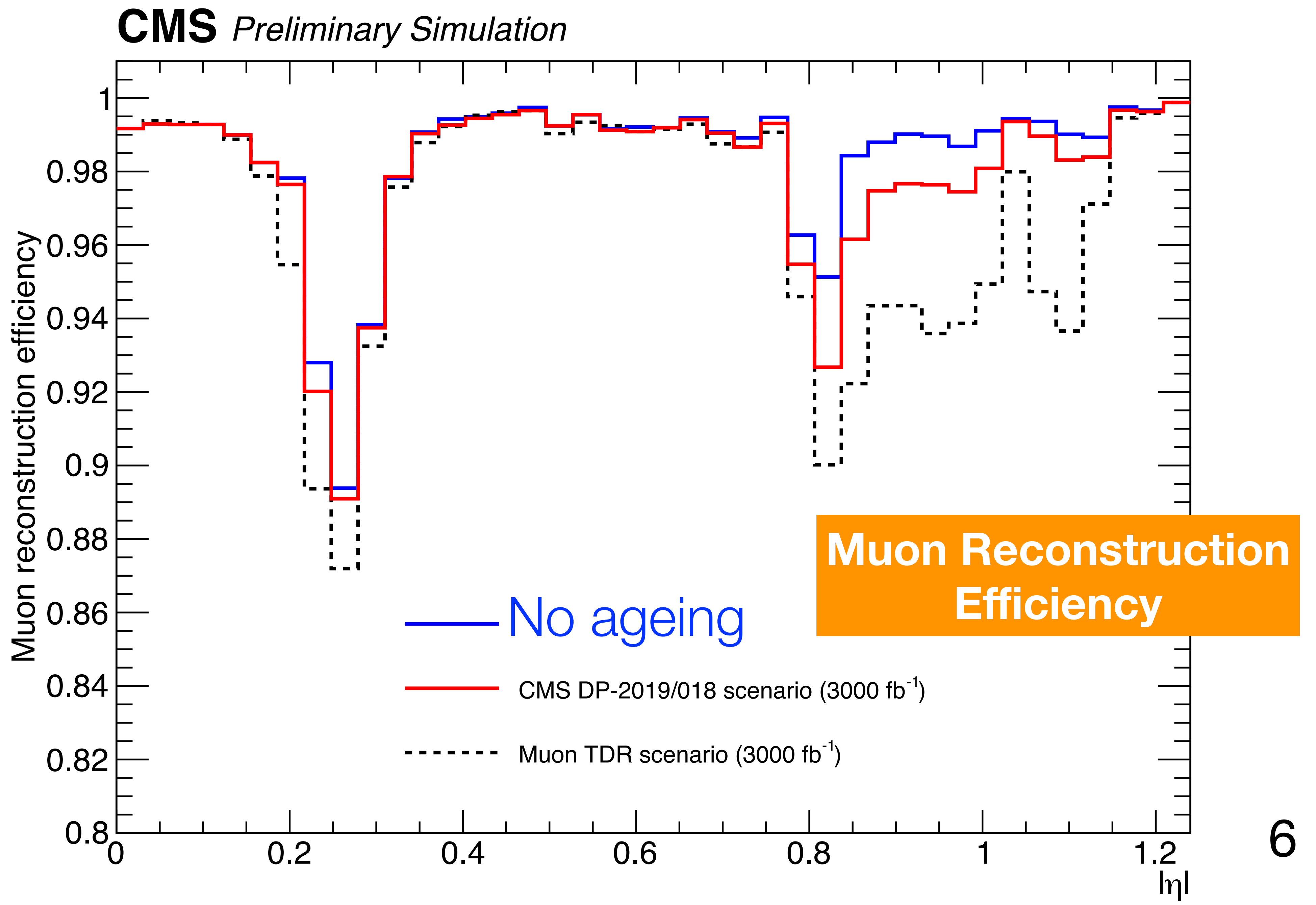
Effect of DT aging on physics performances

- **Hit efficiency has been evaluated using the test beam and cosmic data**
  - Expected hit efficiency **from first irradiation period (showing fast aging)** used as an input for evaluating the final impact at th end of HL-LHC



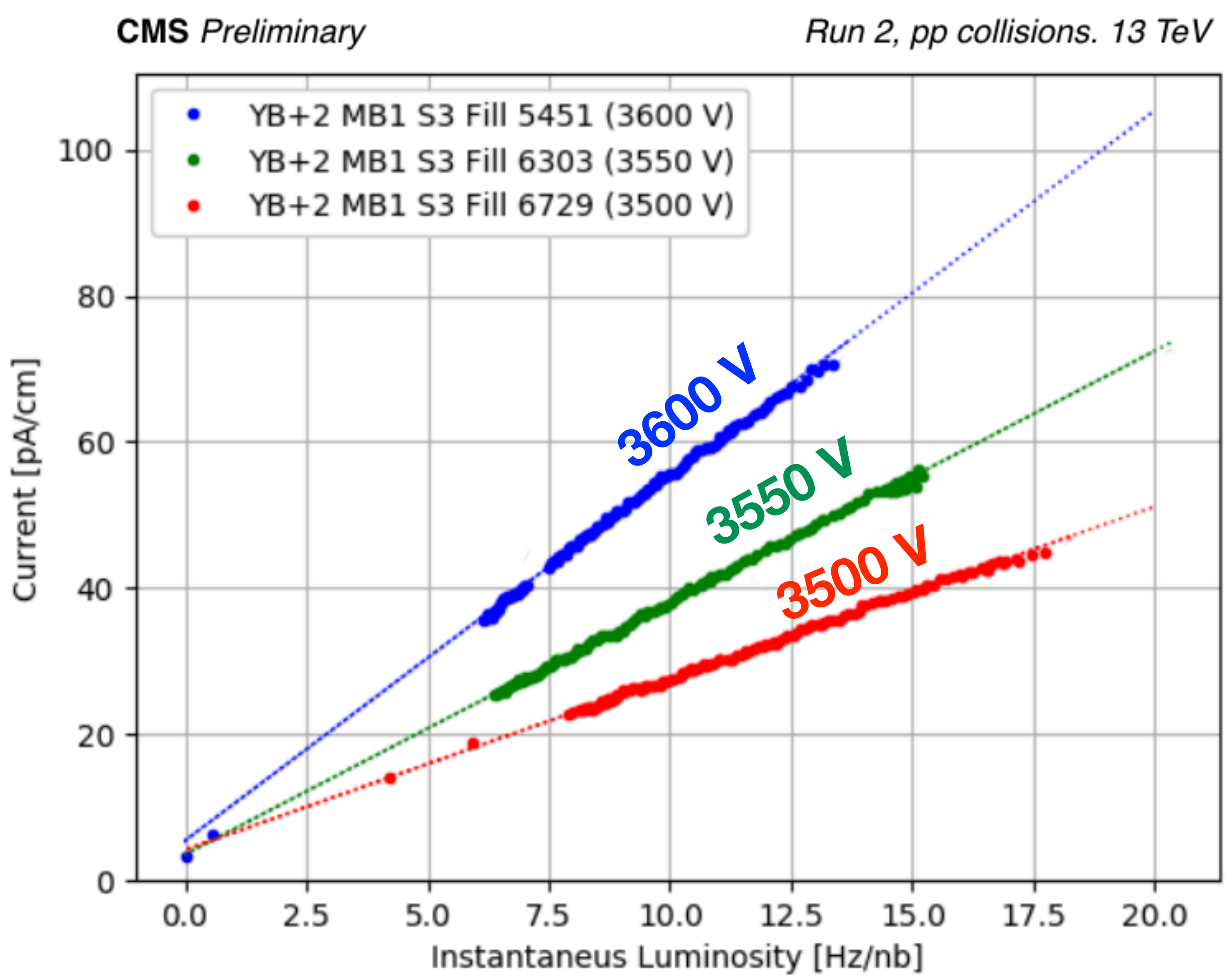


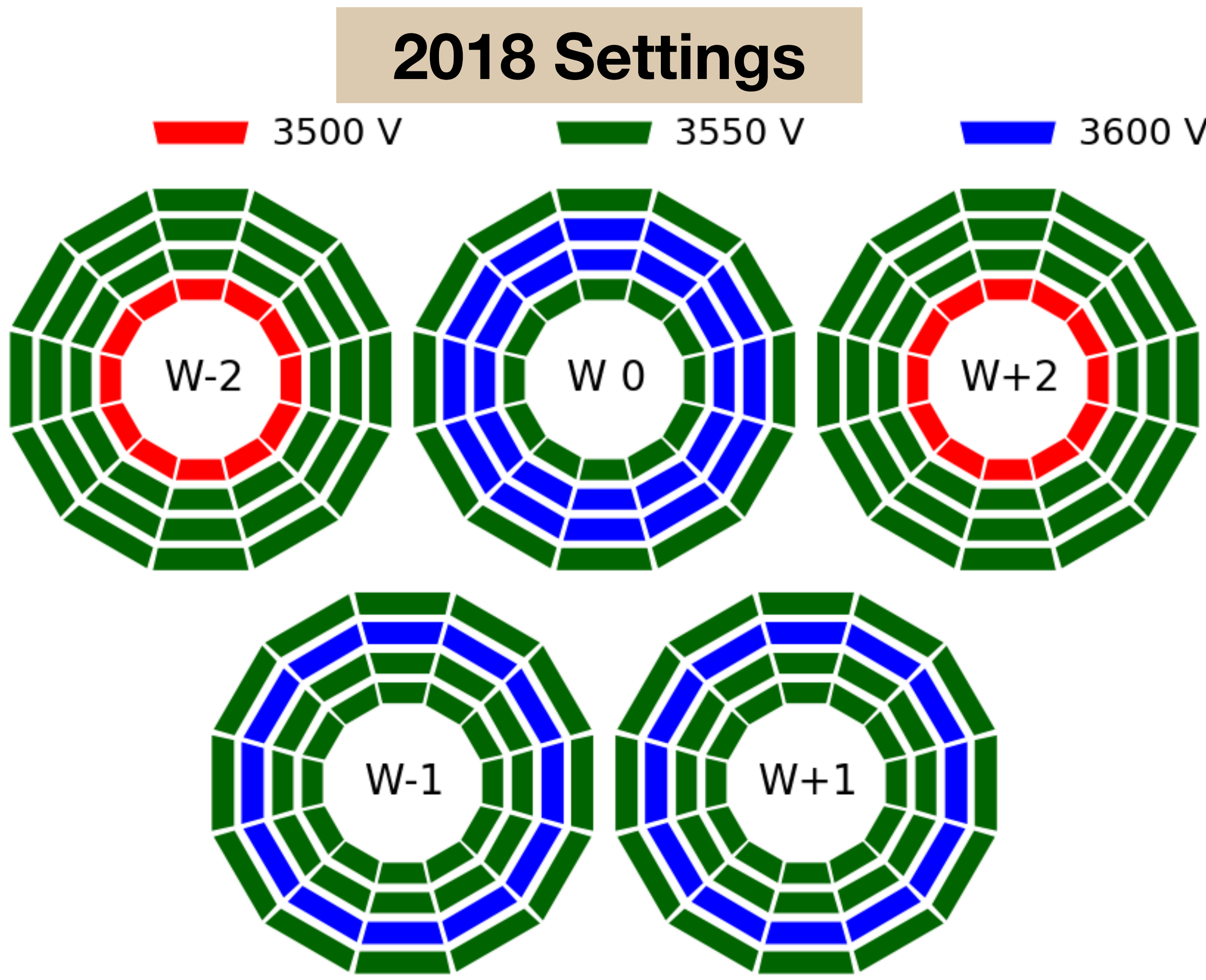
- **This impact is reduced at different levels**
  - Thanks to the **multiple layers of a DT chamber:** out of **8** r-φ layers, ≥ **3** are needed to build an offline segment
  - Thanks to the **handling of TDC hits in the backend** in Phase-2
    - The new algorithms are tested against aging and failure scenario
  - **Thanks to the redundancy of the CMS muon system:** in the region of the DTs most affected by aging, there is a coverage of 3 DT/CSC stations + 4-5 RPC layers along the trajectory of a prompt muon
- Loss of hits in YB+/-2 MB1s has hence "just" a **marginal impact on overall standalone muon reconstruction efficiency**

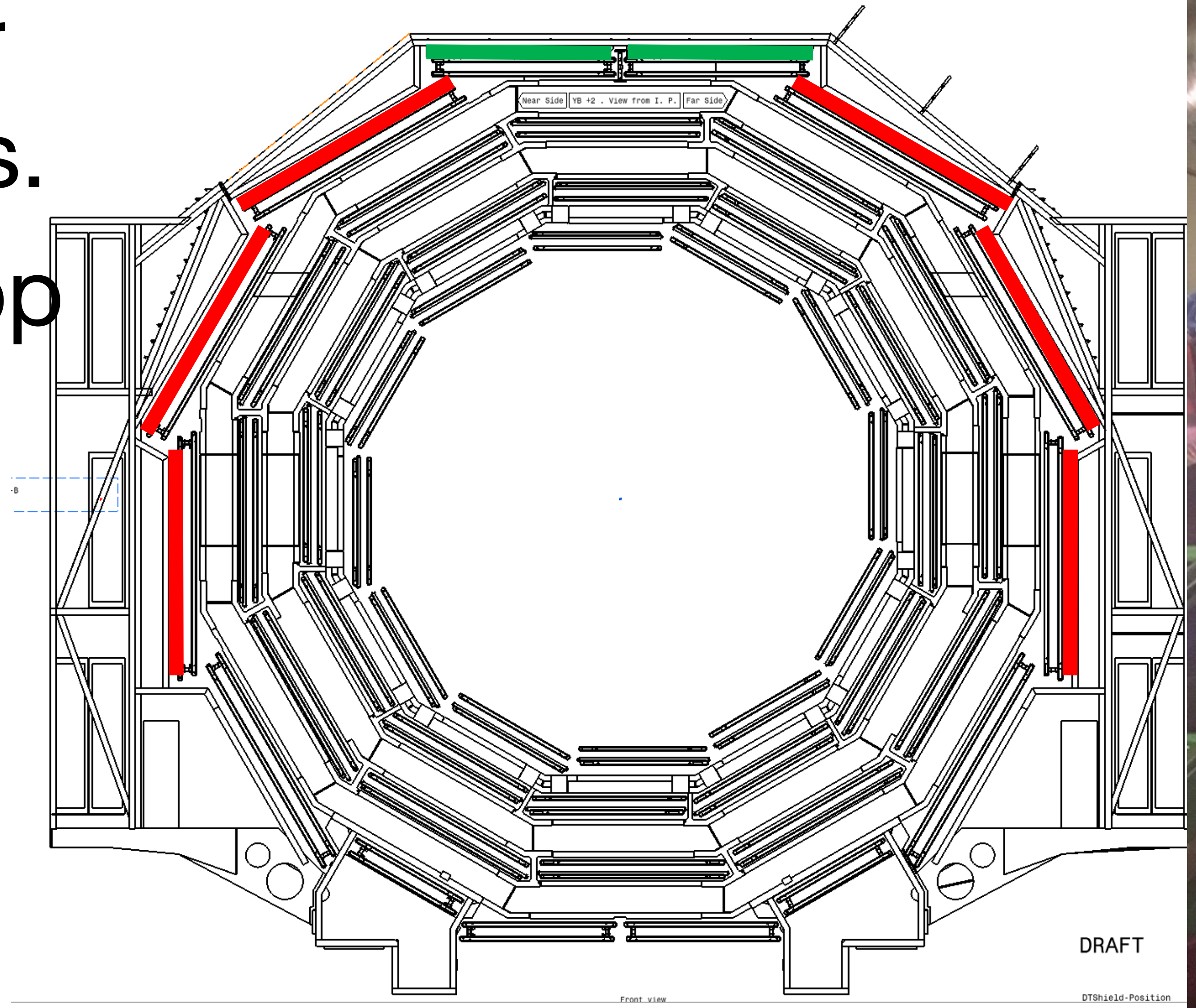


Mitigation Strategies for DT aging

- **Different mitigation strategies have been deployed:**
  - **Wires voltages reduced** from 3600 V to 3550/3500 V in the most exposed chambers
    - Each step of 50 V decreases integrated charge of **~30%**
    - Reducing readout threshold have kept the detector performances
  - **The gas system modified in 2017** from closed loop to open loop operation, in order to minimize the redistribution of free radicals.
  - To reduce the neutron background on the top of the detector, a **shielding has been installed in LS2**
    - Layers of Borated Polyethylene + lead
    - **Expected reduction of dose from neutrons of 30/40%**

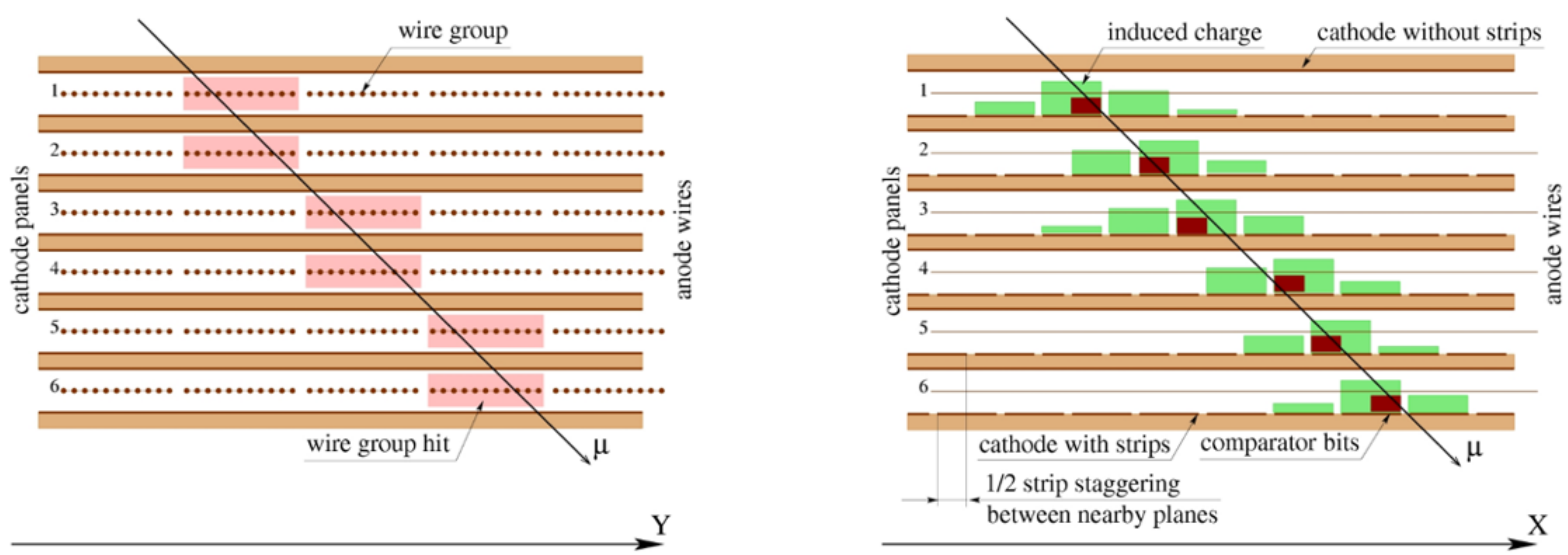


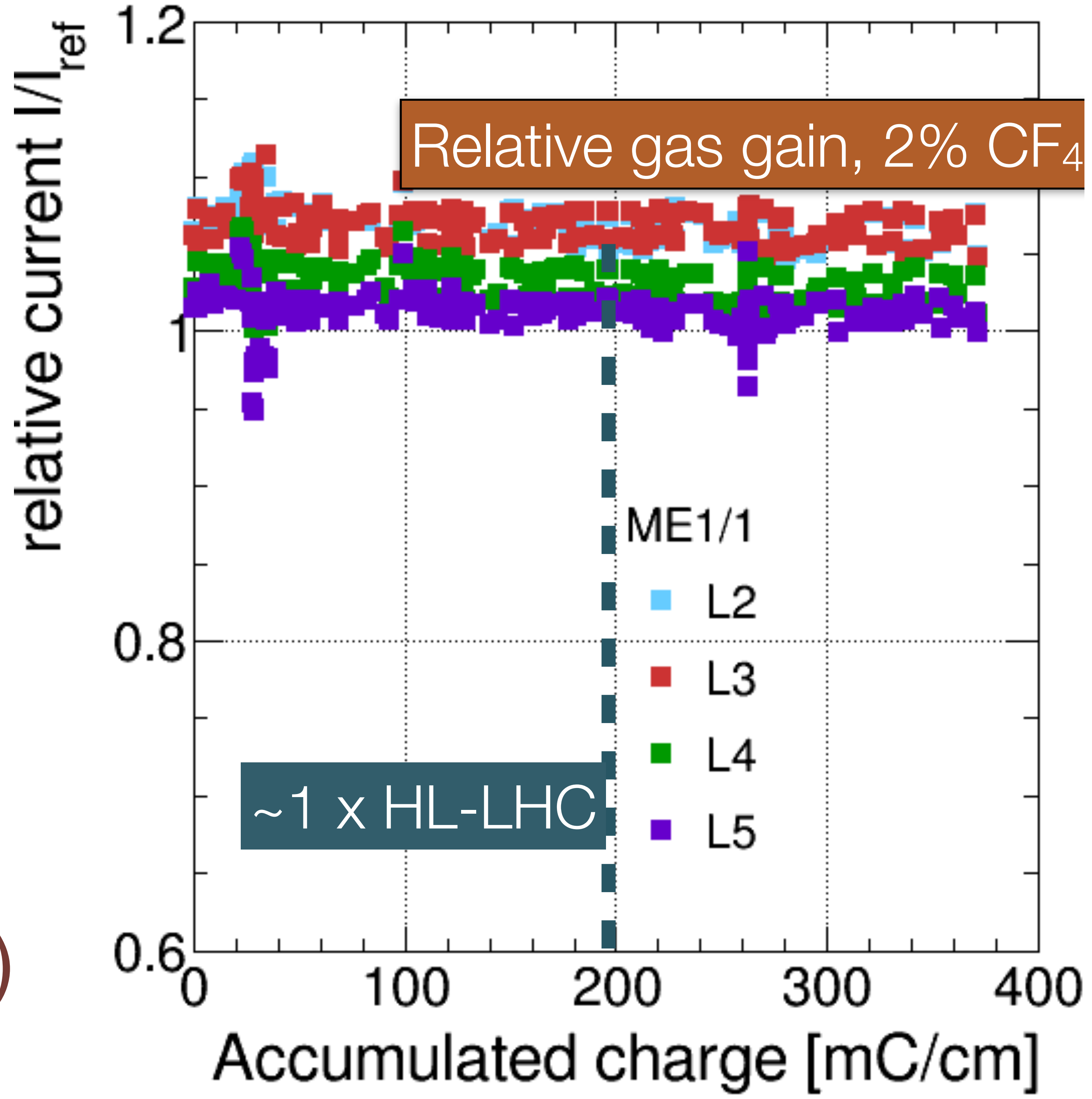


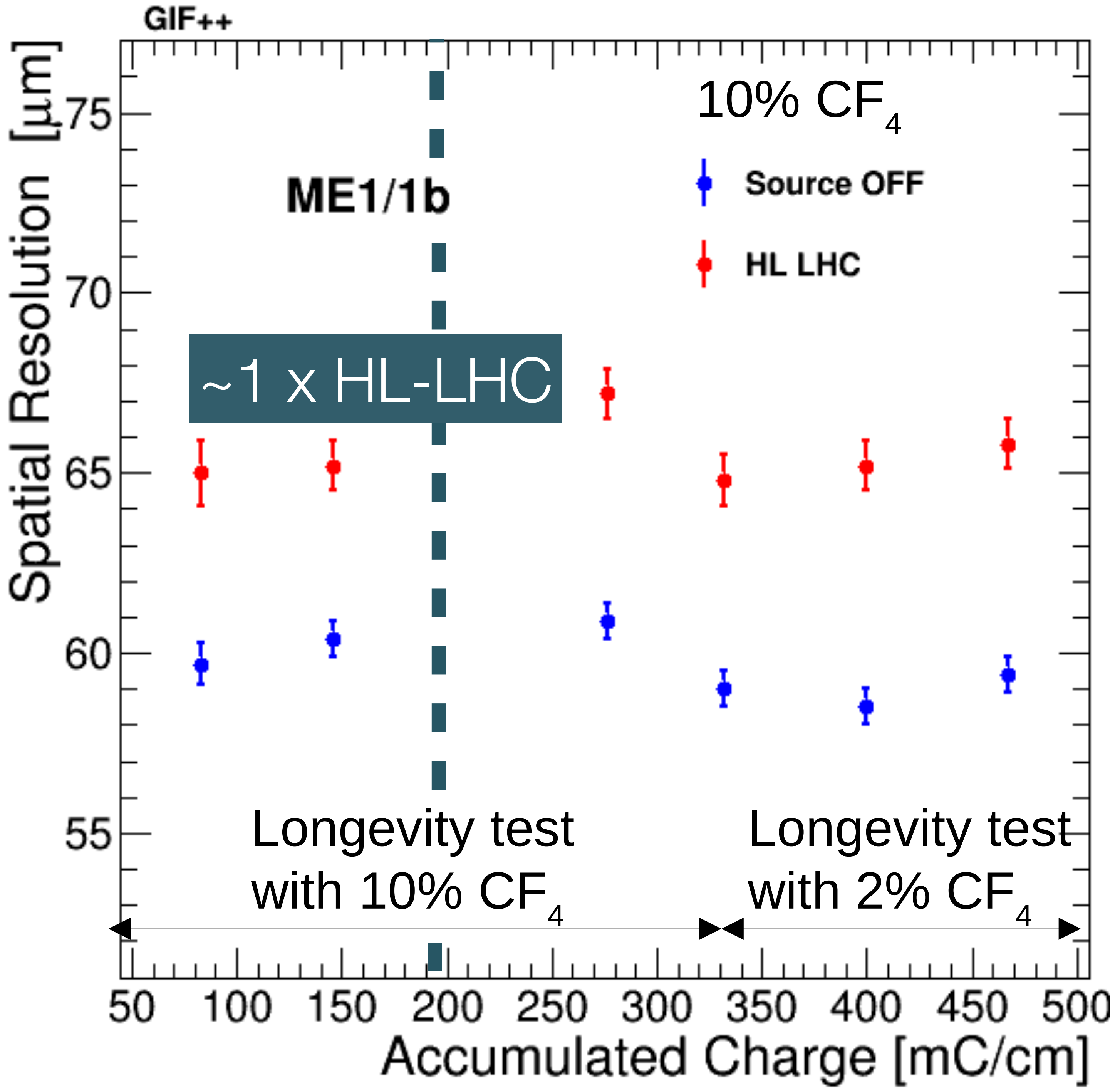


CSC Aging test

- CSC are **Multiwire Proportional Chamber** with 6 gas gaps each with radial cathode strips and perpendicular wire groups
- Gas mixture: **40% Ar, 50% CO_2, 10% CF_4**
- 2016-2021 accelerated (factor ~25) irradiation campaign at GIF++ with
  - the nominal gas mixture (**10% CF_4**)
  - reduced CF_4 gas mixture: 40% Ar + 58% CO_2 + **2% CF_4**
- Accumulated charge per unit length serves as dose measure
  - For most exposed chambers Q(HL-LHC) ~ 190 mC/cm;
- no significant signs of chamber degradation





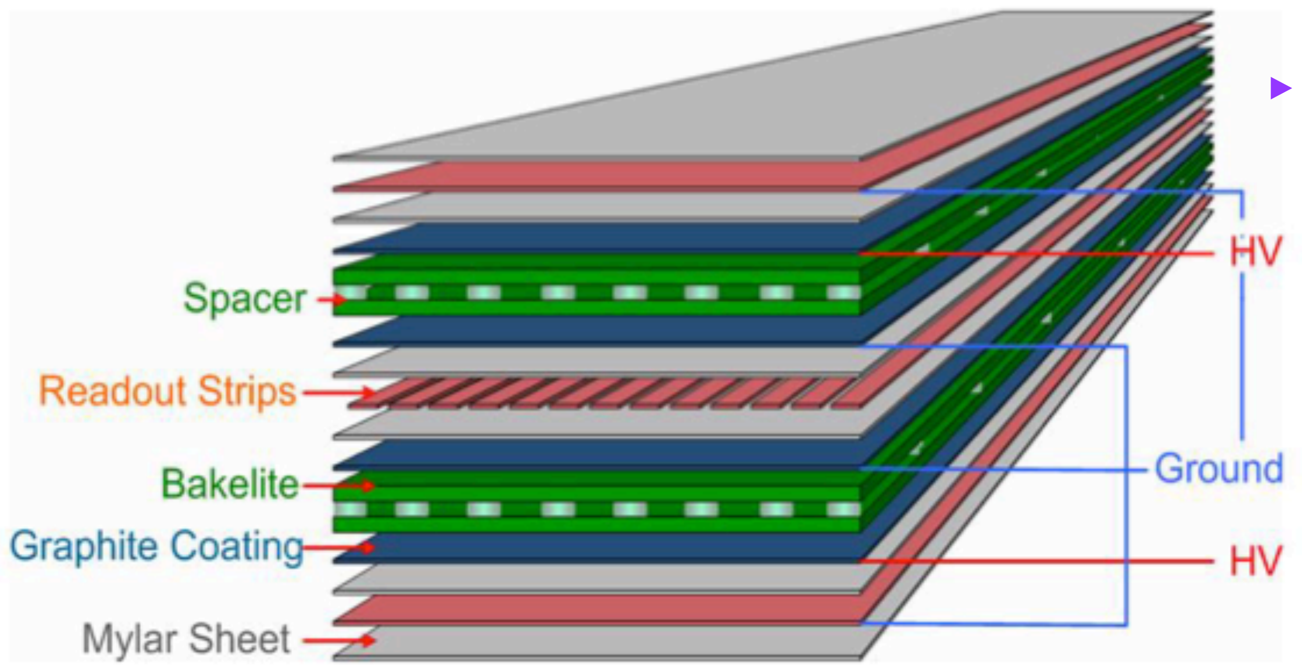


CSC expected to successfully operate in the HL-LHC program

RPC Aging test at GIF++

The RPC Detector

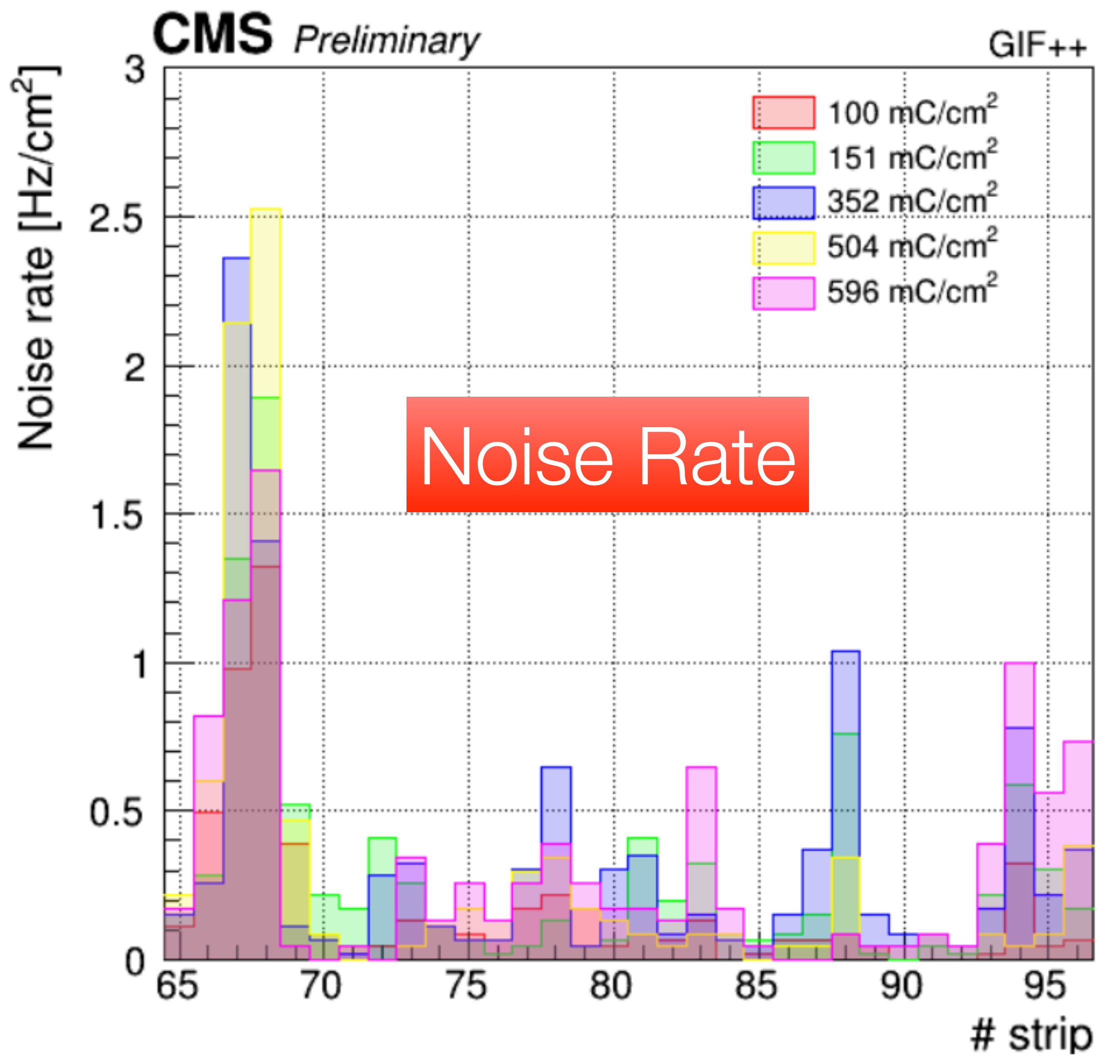
- Double gas gap chamber: 2mm gap width
- Bakelite bulk resistivity: ρ = 1~6 x 10^{10} Ωcm
- Strip width: 1-4cm
- Gas mixture: $C_2H_2F_4$(95.2%)+iso-C_4H_{10}(4.5%)+SF_6 (0.3%)
- Operated in avalanche mode

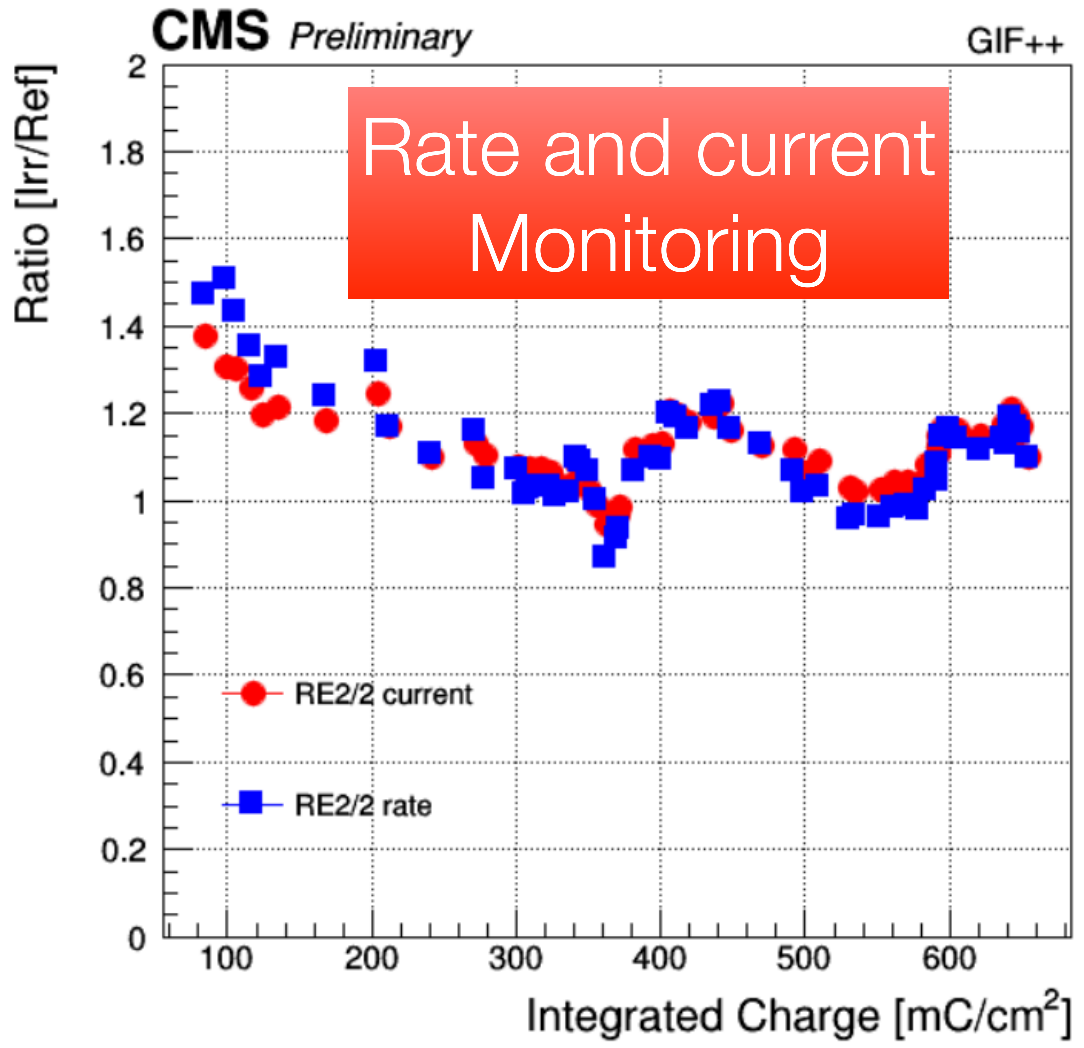


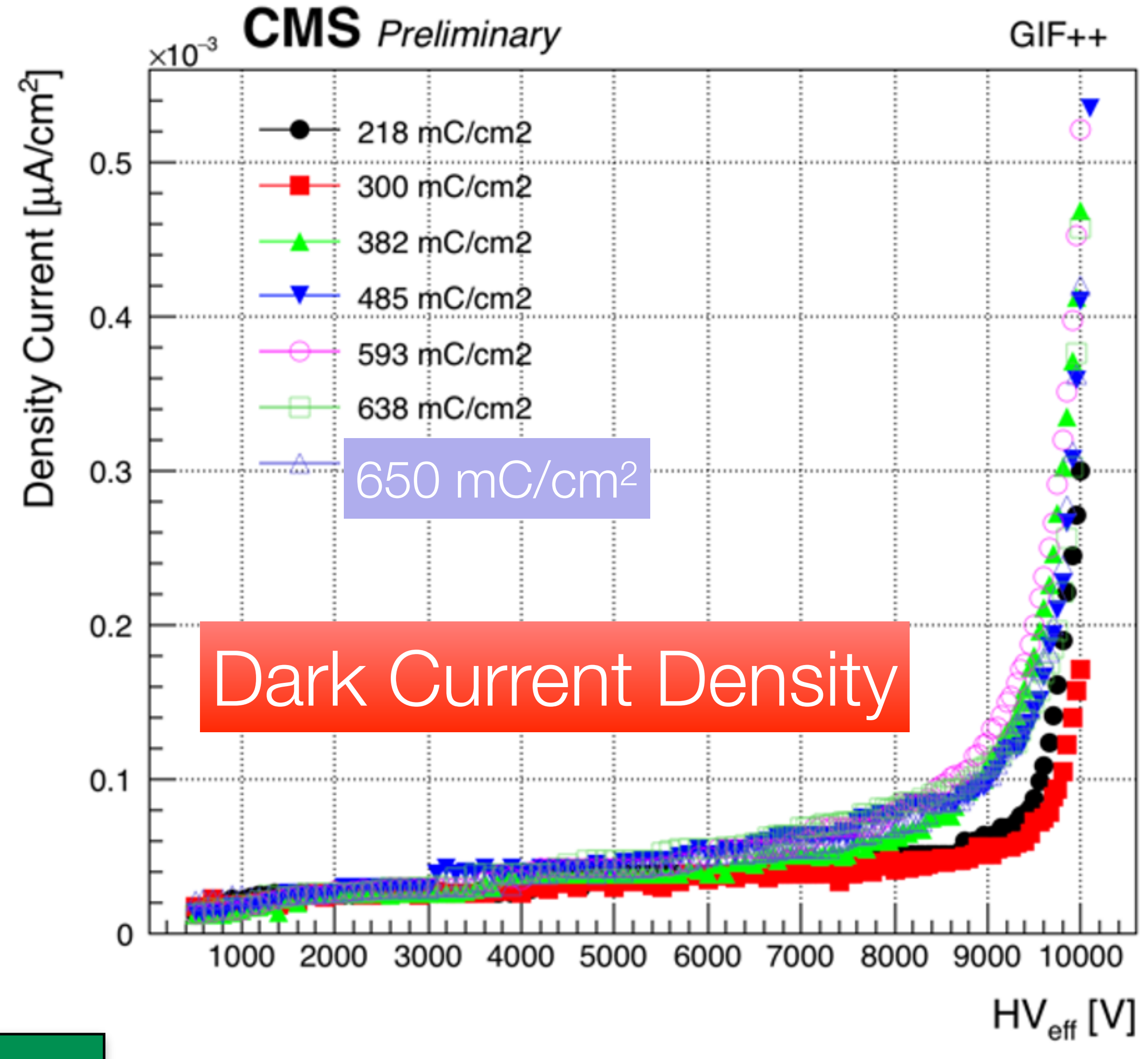
- iRPC differences:
  - Gas gap 1.4 mm
  - Resistivity 0.9~3 x10^{10} Ω cm
  - Strip width 0.7~1.2 cm

Highest integrated charge for RPC at 3xHL-LHC: ~ 3×280 = 840 mC/cm

- Few spare RPC chambers are under irradiation at GIF++
- After having collected ~ 650 mC/cm² from 2016:
  - **stable performance**
  - **stable noise rate**
  - **stable ohmic current**



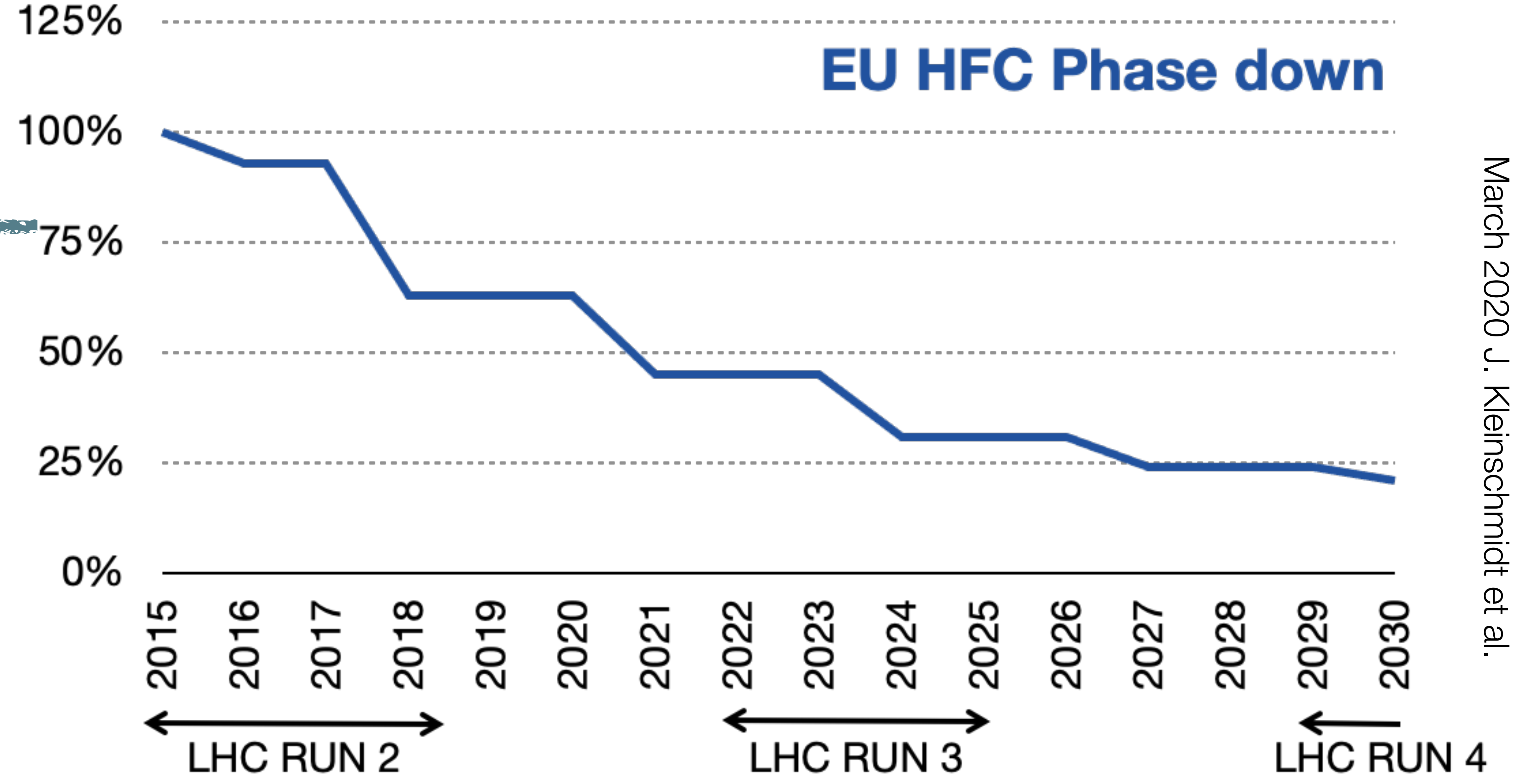




RPC can successfully operate in the HL-LHC program

Greenhouse gasses (GHG)

- Even if RPC and CSC has been fully qualified for running at HL-LHC, a major problem is the **use of greenhouse gases** (CF_4, $C_2H_2F_4$, SF_6 ...)
  - European Union has a specific regulation for a phase down of HFC gases



European Environment Agency, Fluorinated greenhouse gases 2019 report March 2020 J. Kleinschmidt et al.

CERN Strategies to reduce GHG emissions

Common program supported/funded by CERN Environmental Protection Steering board

Short Term

Optimization of current technologies

Gas leak was identified in many **barrel** RPC chambers due to cracked or broken pipes

- **The RPC leak repair campaign has given the highest priority during LS1**

CERN EP-DT Gas team is involved in the development of recuperation systems

- CF_4 Plant for CSC operational since 2012, with a lot of tuning and upgrades realized
  - **Current recuperation efficiency ~65%**
- **R&D ongoing for the first $C_2H_2F_4$ recuperation system for RPC:**
  - **Prototype0 installed in CMS in December 2019 and connected to RPC exhaust.**
  - The system is running since January 2020.

Long Term

Use of alternative gases

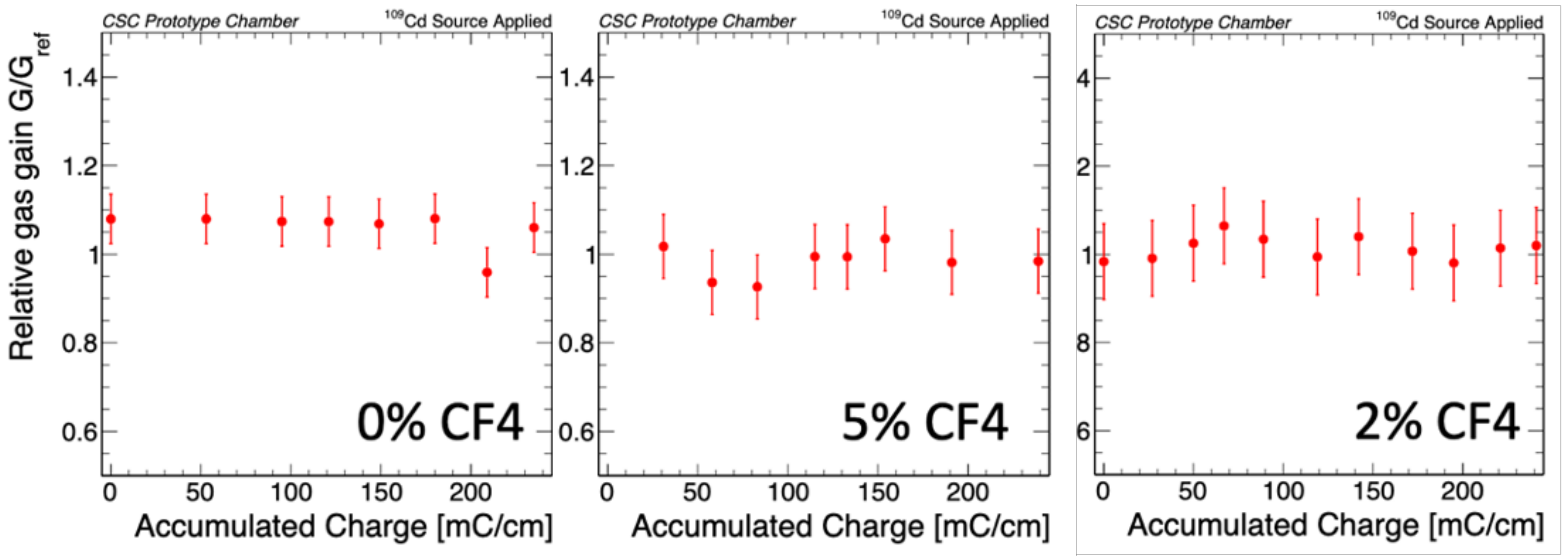
CSC eco-gas studies

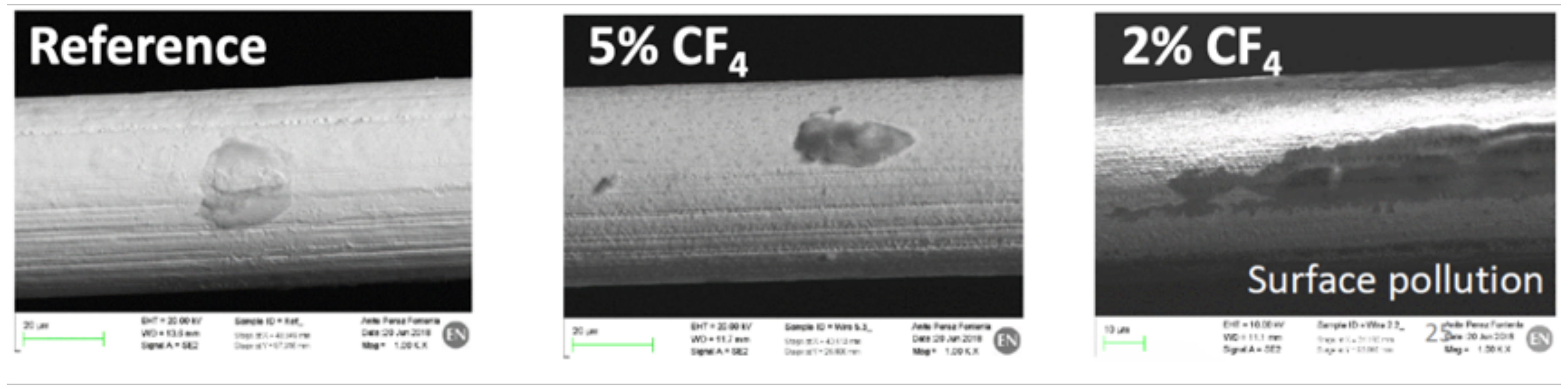
- **CF_4 has 6500x the global warming potential (GWP) of CO_2**

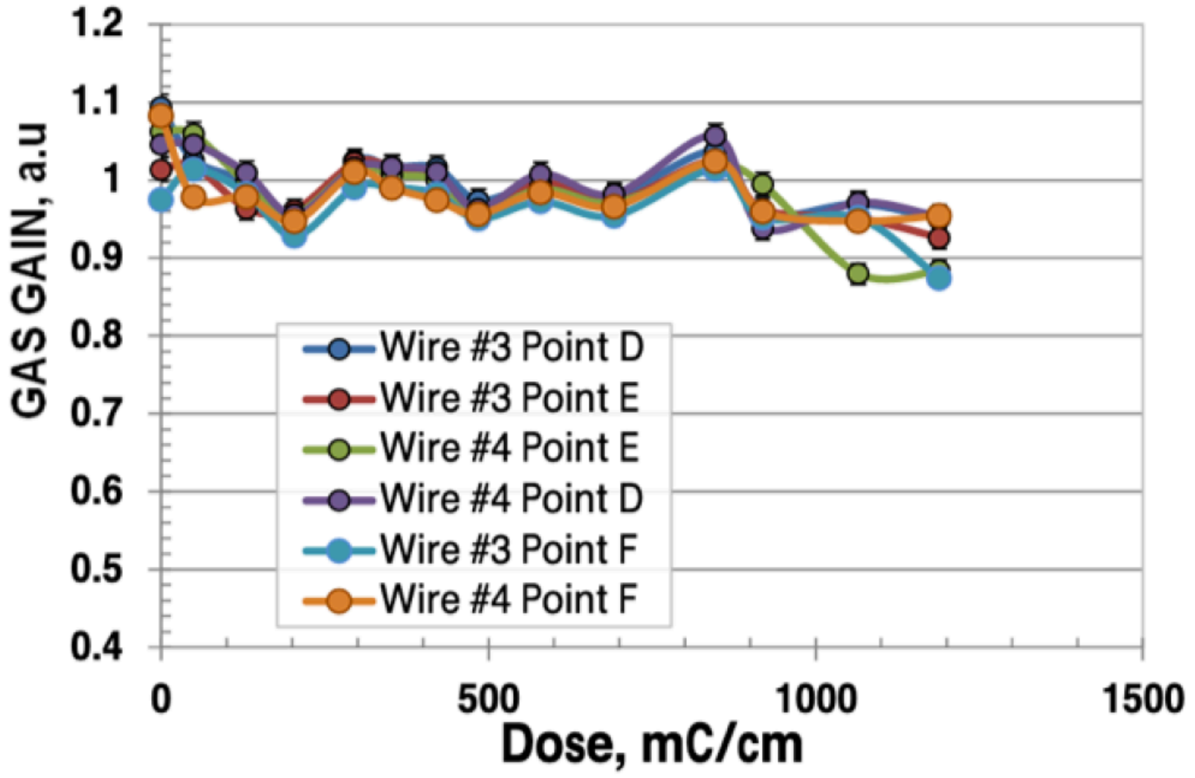
Reduce its use

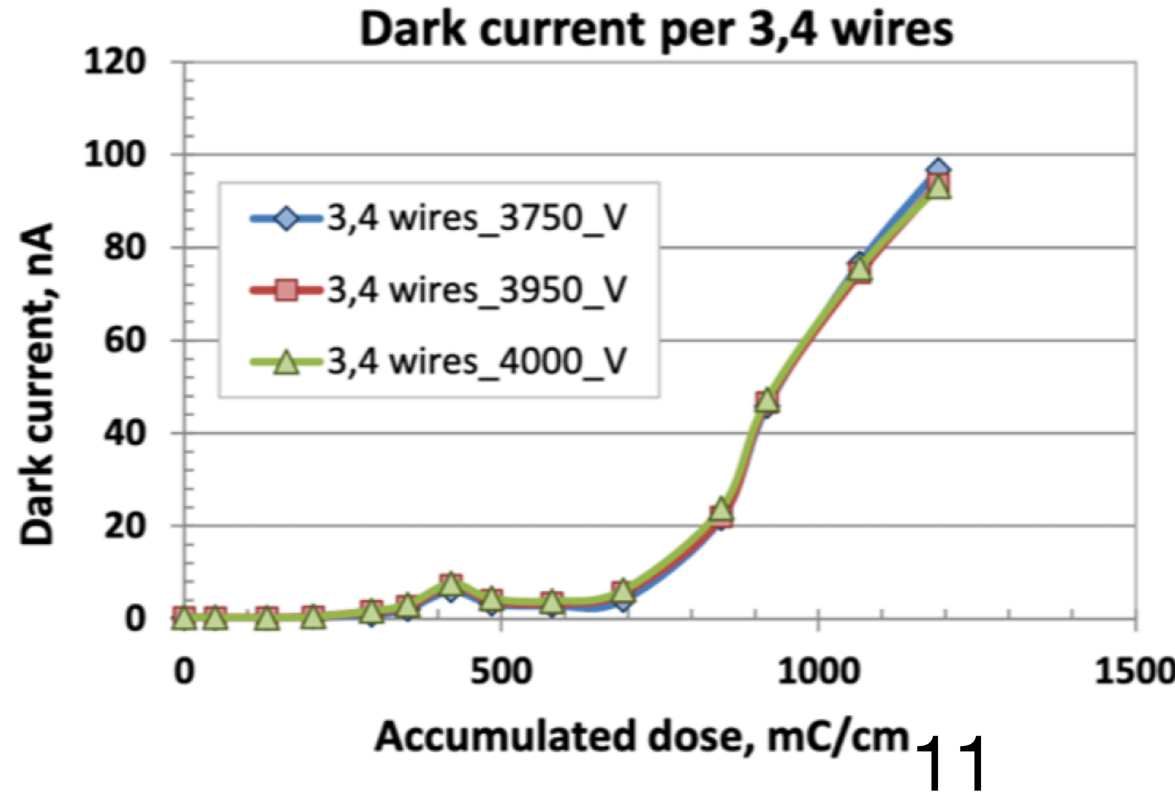
Find an alternative

- Since 2018, performing irradiation tests with reduced CF_4 content
  - no sign of performance degradation up to Q=2.5 x Q(HL_LHC)
  - However, visible darkening = surface pollution with 2% mixture prompts caution
- Large campaign ongoing also to **test alternative gas mixtures**, for example CF_3I (GWP<1) and HFO-1234ze (GWP ~7) were investigated
  - Studies implies both testing of performances and assessing aging effect under irradiation
  - **Studies with HFO1234ze (local irradiation):**
    - **no gain degradation up to 1.2 C/cm (>10 HL-LHC)**
    - **significant increase in dark current after 0.6 C/cm (~6 HL-LHC)**





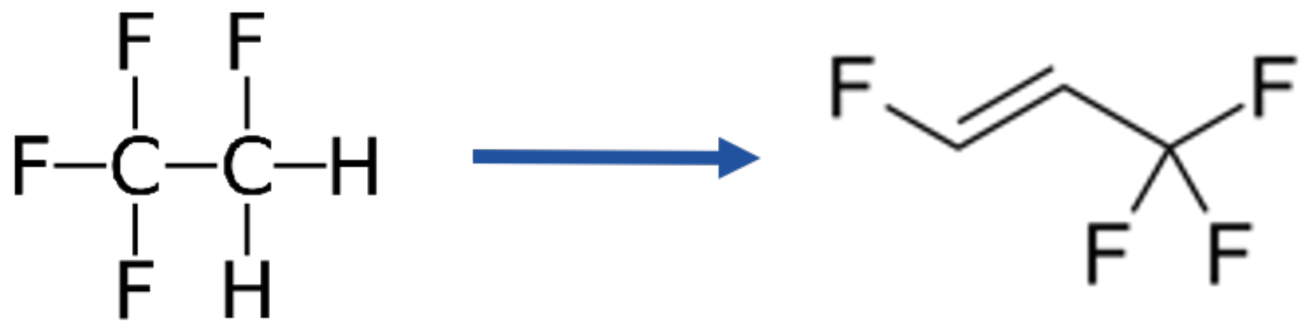




Eco-gas studies for RPC and iRPC

EP-DT
Detector Technologies

- Many experiment using RPC detector share the problem of finding a substitute for $C_2H_2F_4$ (GWP 1430)
  - Good alternatives have been found with a HFO-CO_2 based gas mixture from indipendente studies at different laboratories
  - Difficult to fulfill all the requirements for already installed RPCs at LHC
    - Fixed layout
    - Need to study long term performances



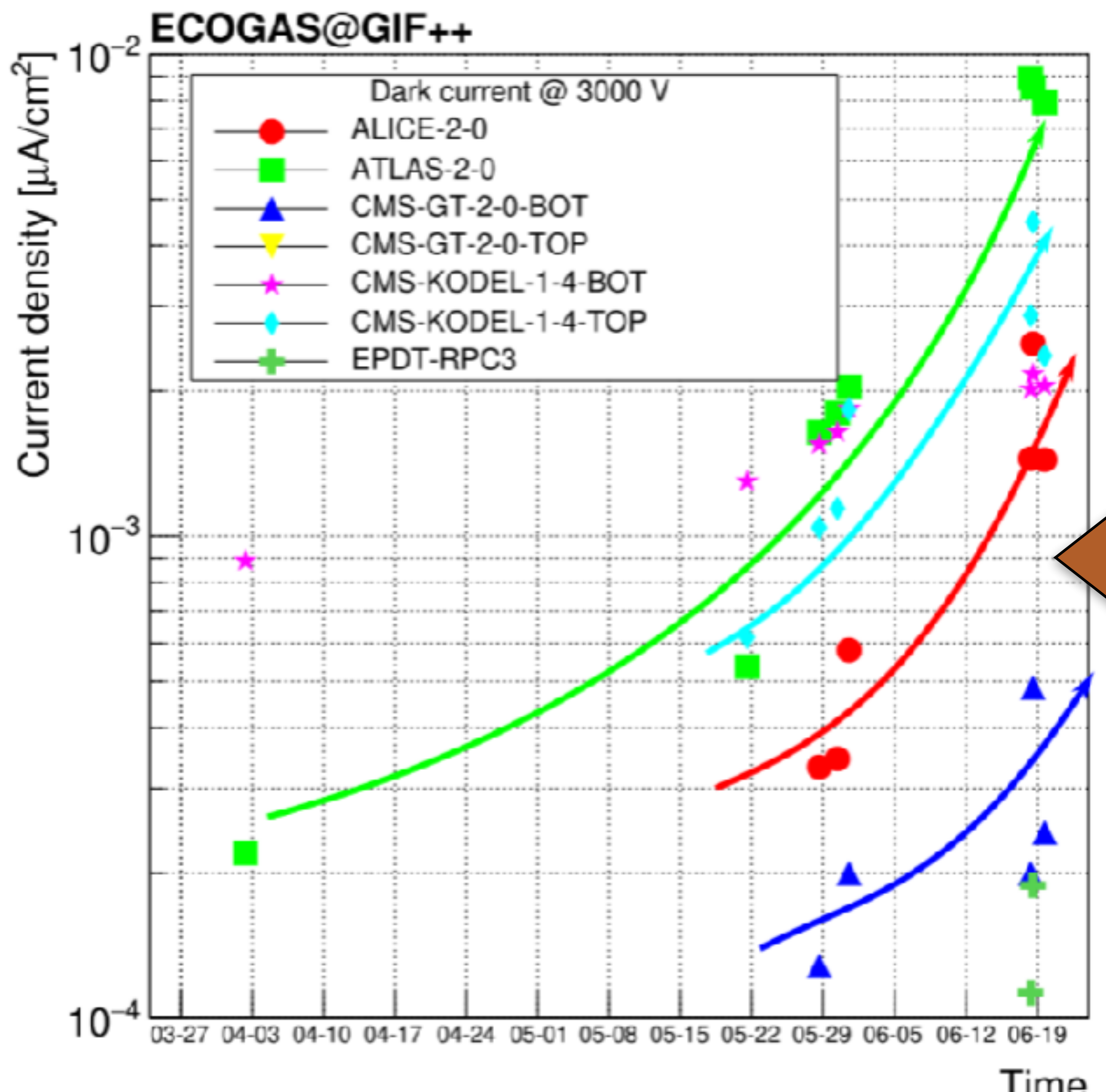
R134a
($C_2H_2F_4$)
GWP 1430

HFO-1234ze
($C_3H_2F_4$)
GWP 6

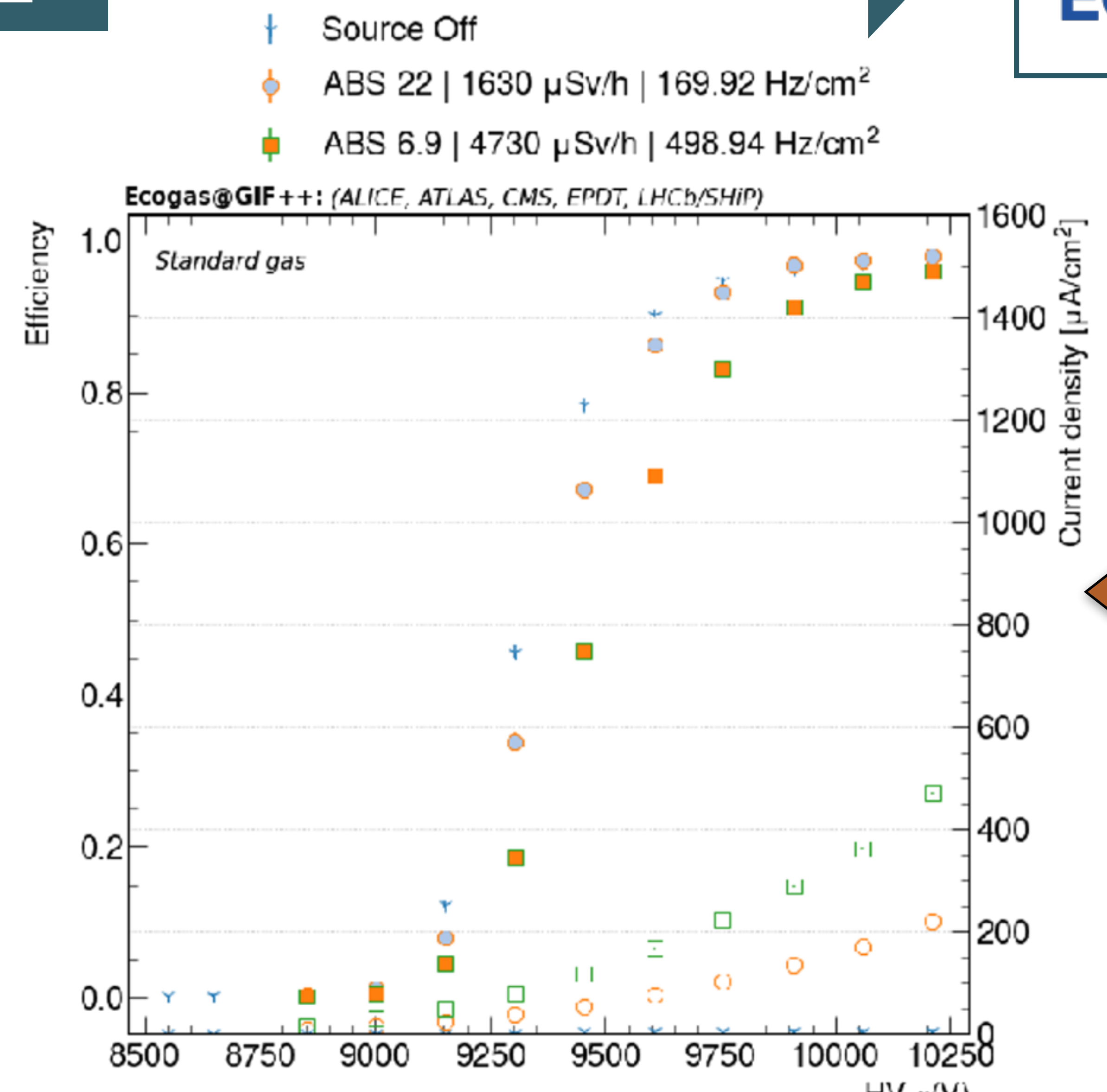
Formed the **ECOGAS@GIF++** collaboration as a joint effort between CERN Gas Team, ATLAS-RPC, CMS-RPC, LHCb-SHIP communities within the **AIDAinnova Task WP 7.2**

Tested Different mixtures

ECO1: CO_2 50%, HFO 45%, iC_4H_{10} 4%, SF_6 1%
ECO2: CO_2 60%, HFO 35%, iC_4H_{10} 4%, SF_6 1%
ECO3: CO_2 69%, HFO 25%, iC_4H_{10} 5%, SF_6 1%



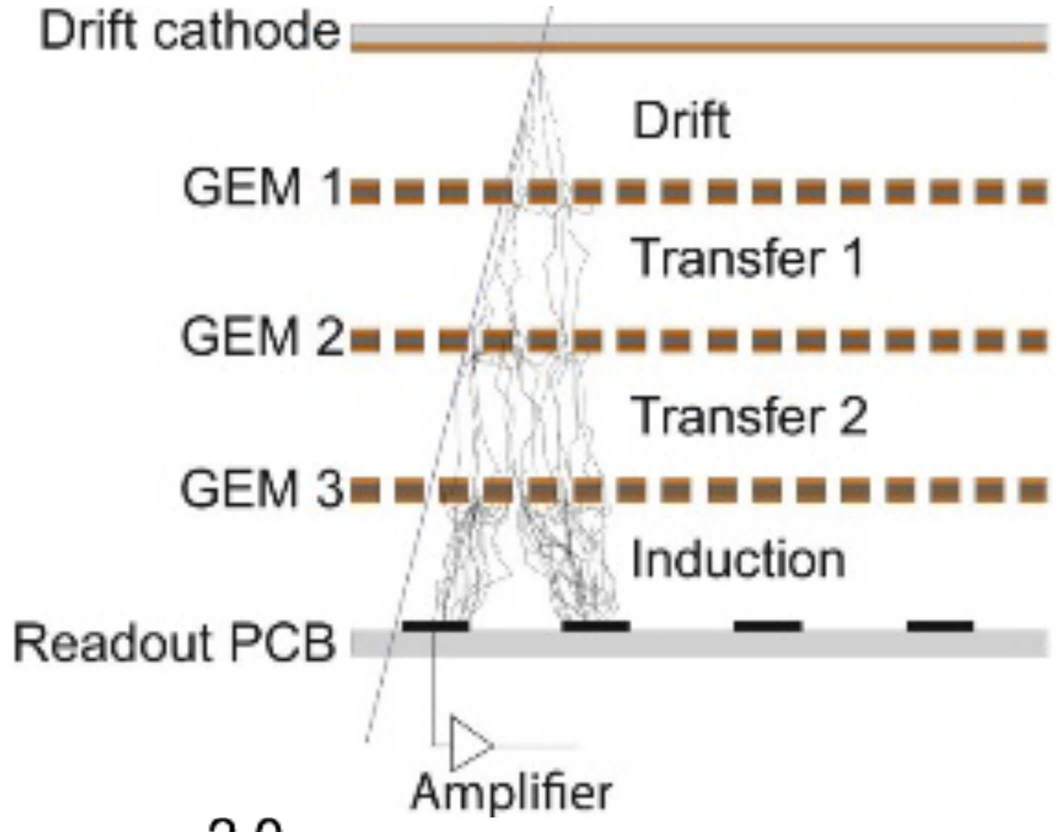
ECO1 already discarded due to increase of dark currents



ECO2 and **ECO3** characterized with test beam and now will be used for long term irradiation

GEM aging at GIF++

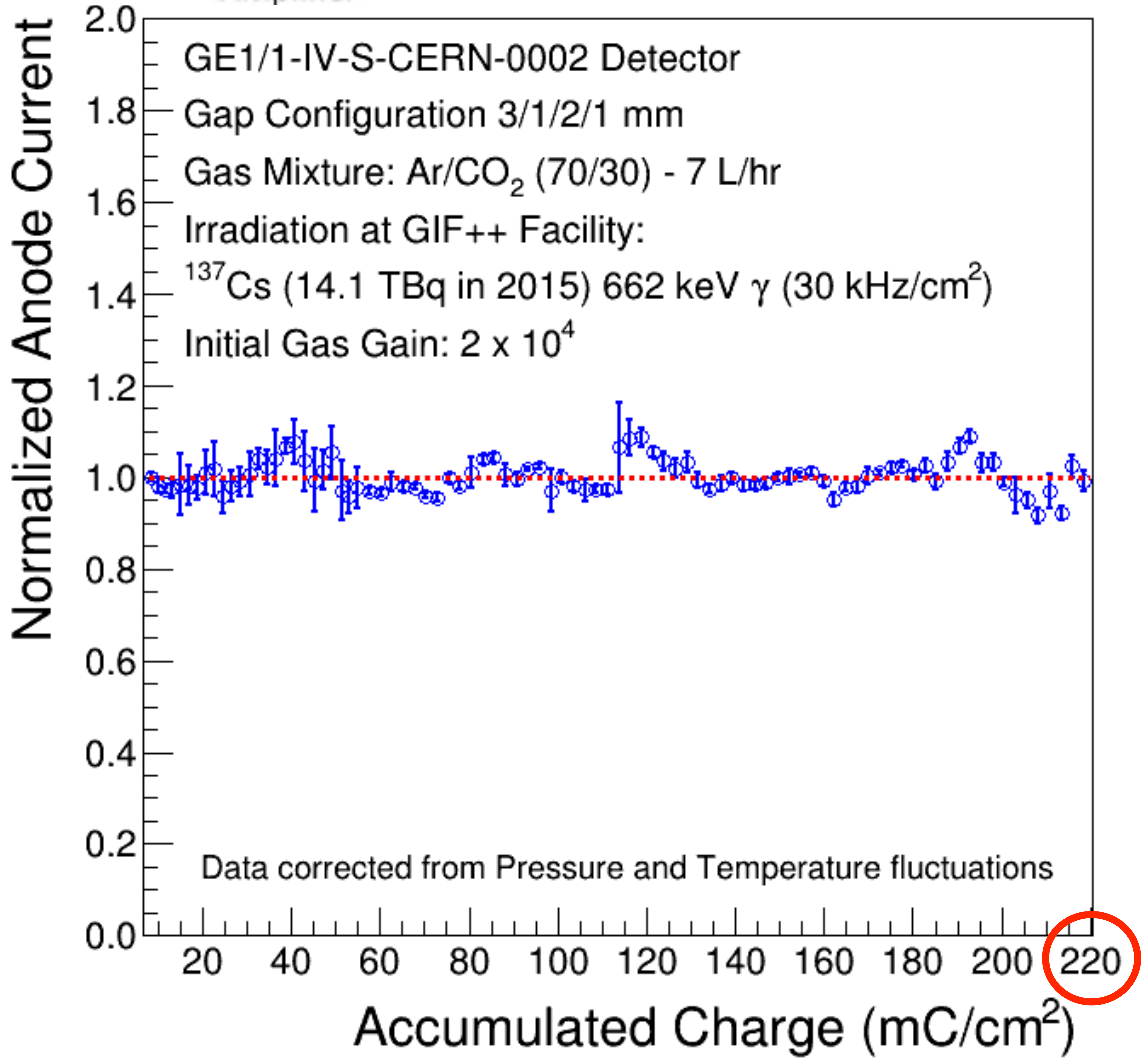
- Triple-GEM detectors are micro-pattern gaseous detectors made of a cascade of three GEM foils
- Gas mixture Ar/CO_2 70/30%



- Large difference in the operation condition of GE and ME0

	Expected acc. Charge in 10 years (mC/cm²)
GE1/1	**30**
GE2/1	**60**
ME0	**7900**

- Irradiation campaign performed at GIF++
- Anodic current monitored via Keithley 6487 pico-ammeter

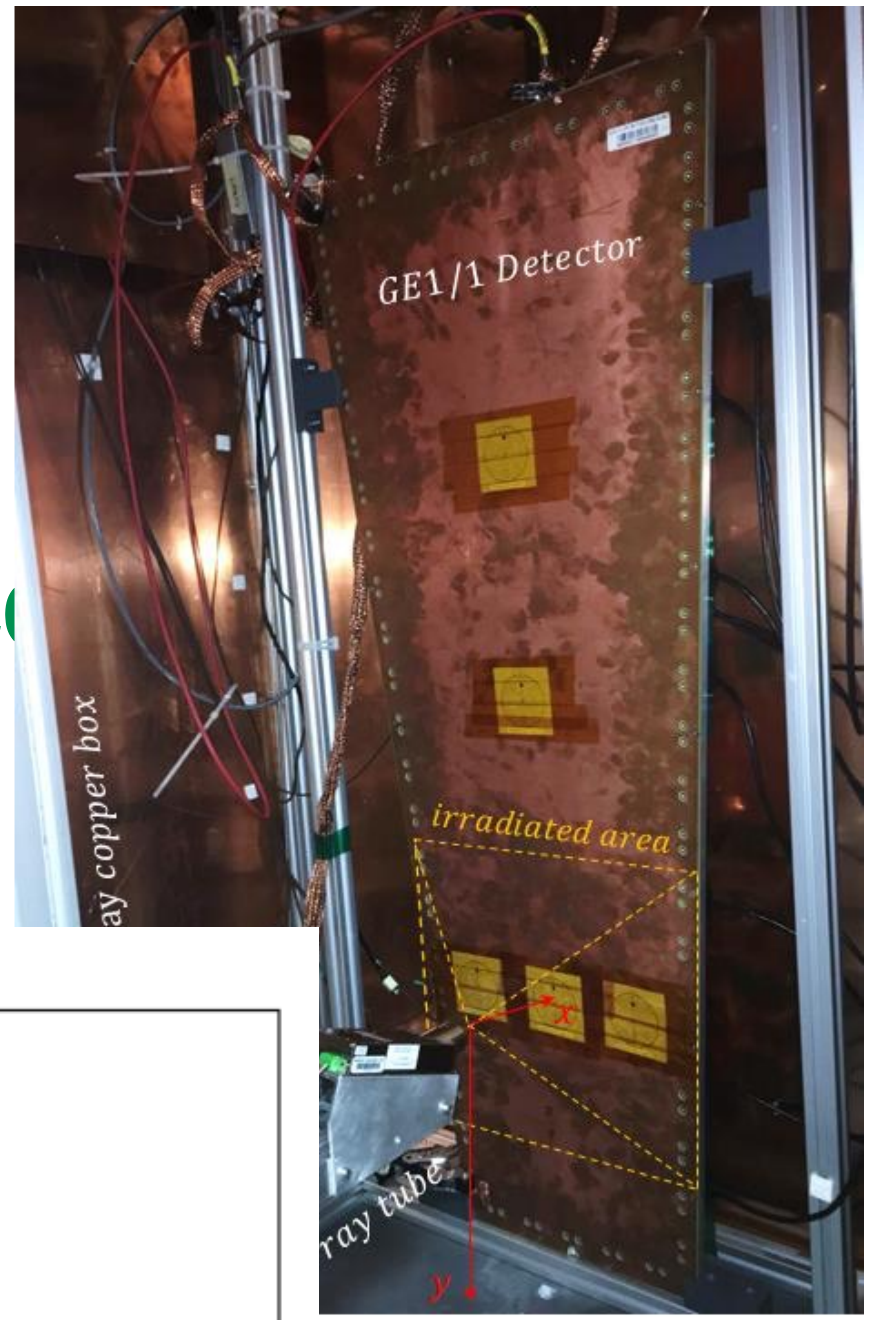


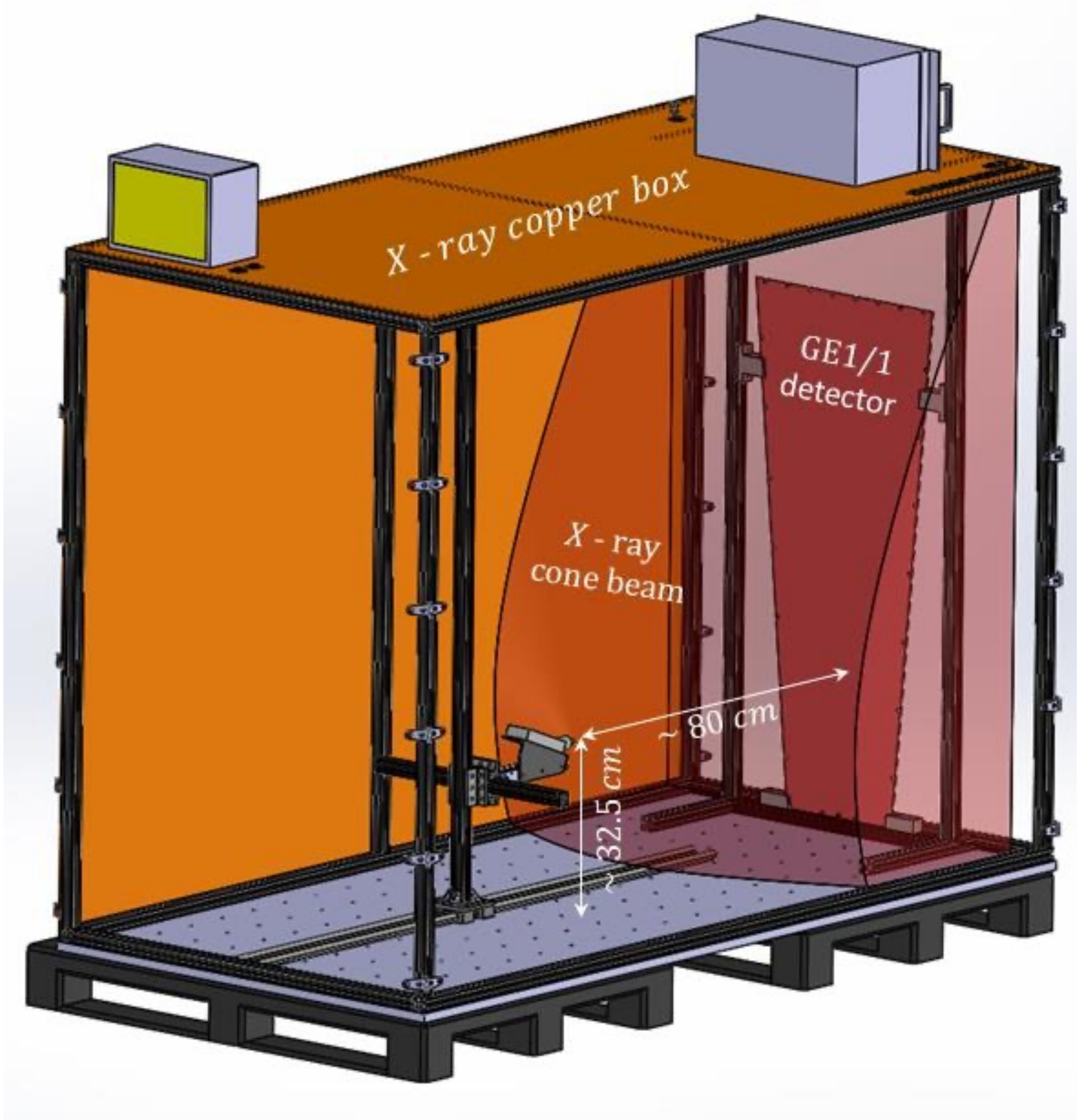
No Effective Gas Gain loss up to 218 mC/cm²

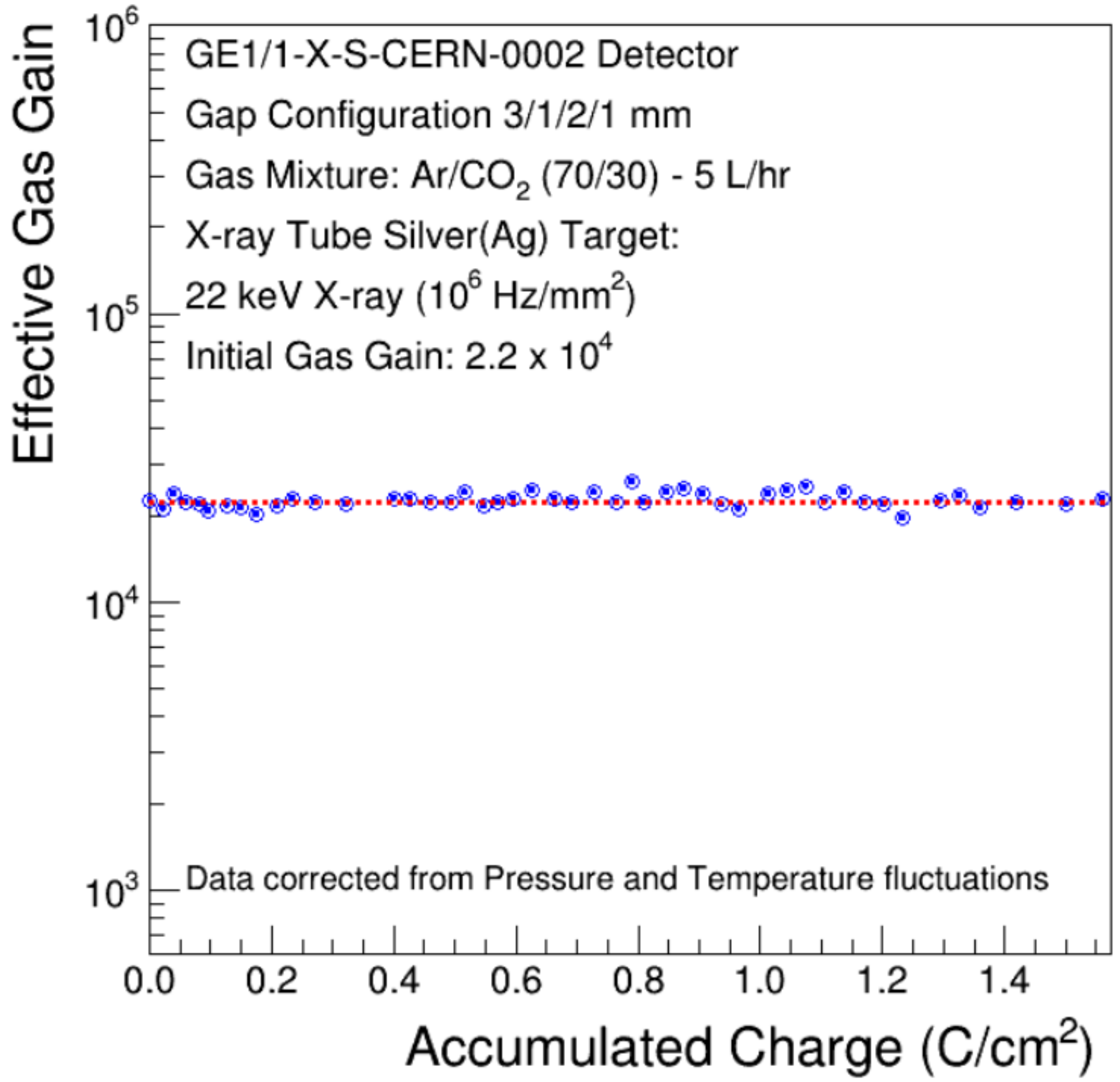
- GE2/1 validated with SF~7
- GE1/1 validated with SF~3.6
- ME0 NOT validated (SF~0.03)

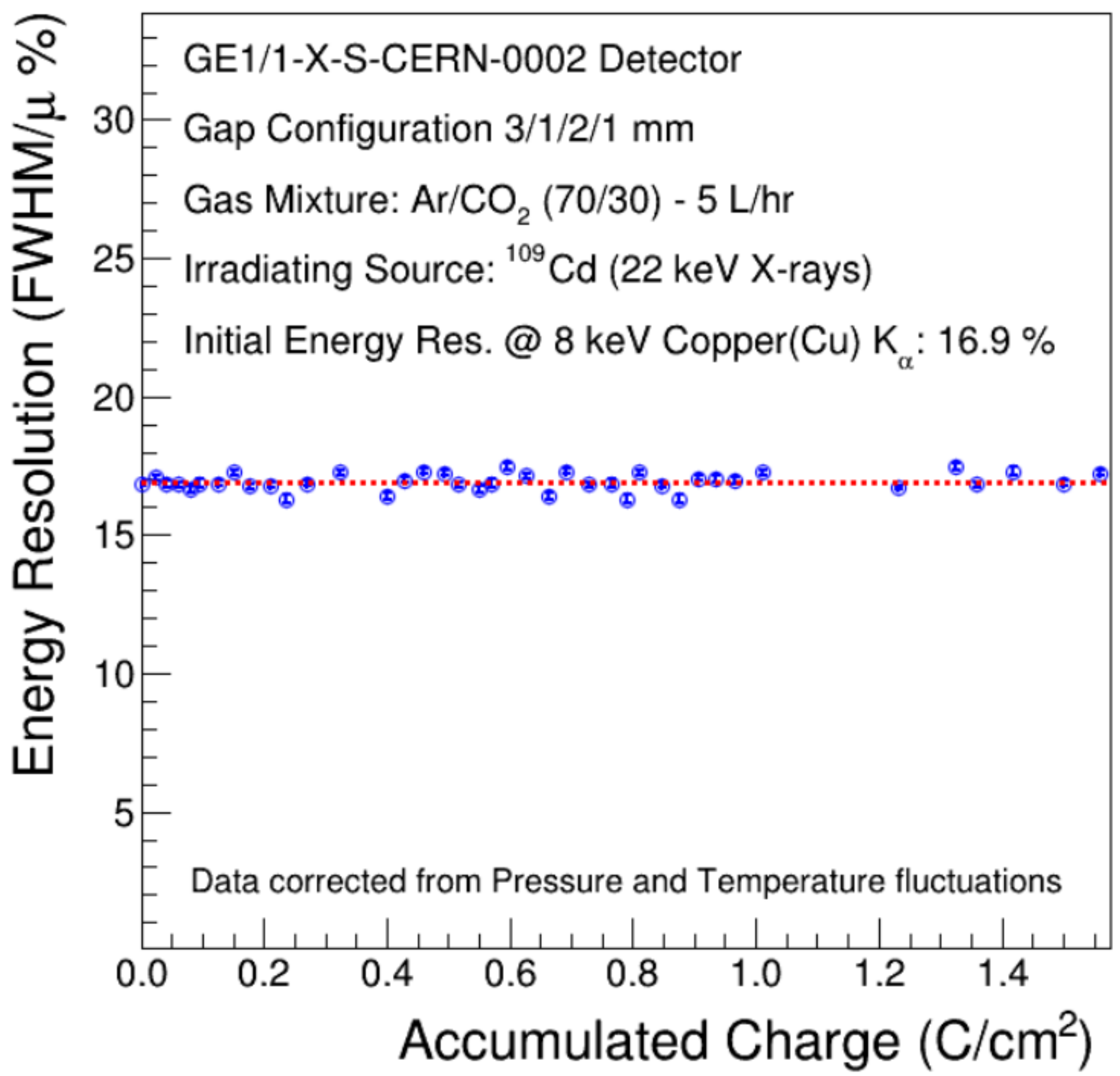
GEM Aging with X-ray Gun

- To expand the GIF++ facility limits chambers are irradiated with an X- ray gun
  - Acceleration factor is 8 times higher than at GIF++
- Different facilities involved in Aachen and Seoul
- **First irradiation campaign successfully validated in order to validate ME0 up to ~1.5 C/cm²**
  - **Additional campaigns ongoing**





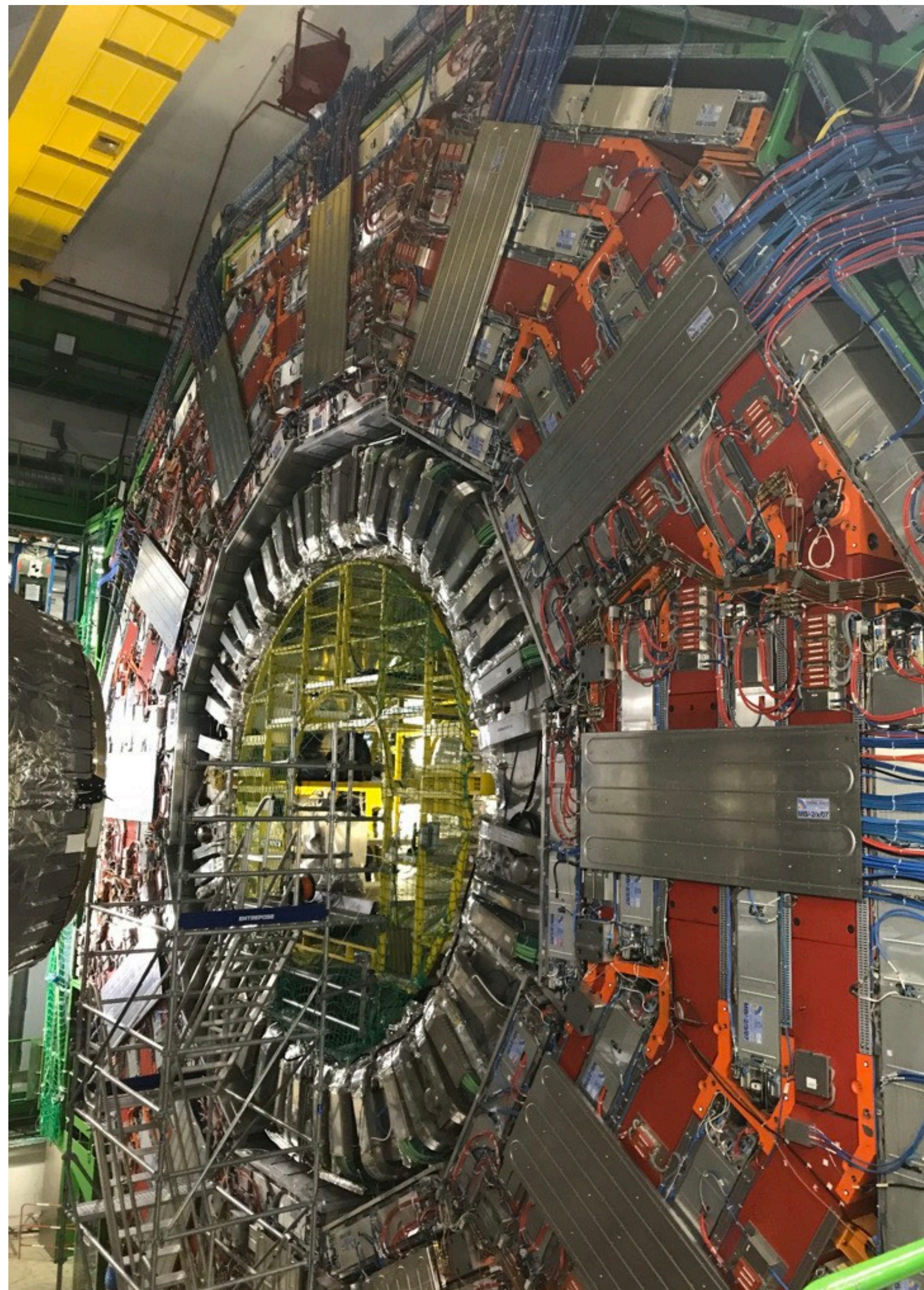




New campaigns are ongoing, in order to reach the updated value of 7.9 C/cm

Summary

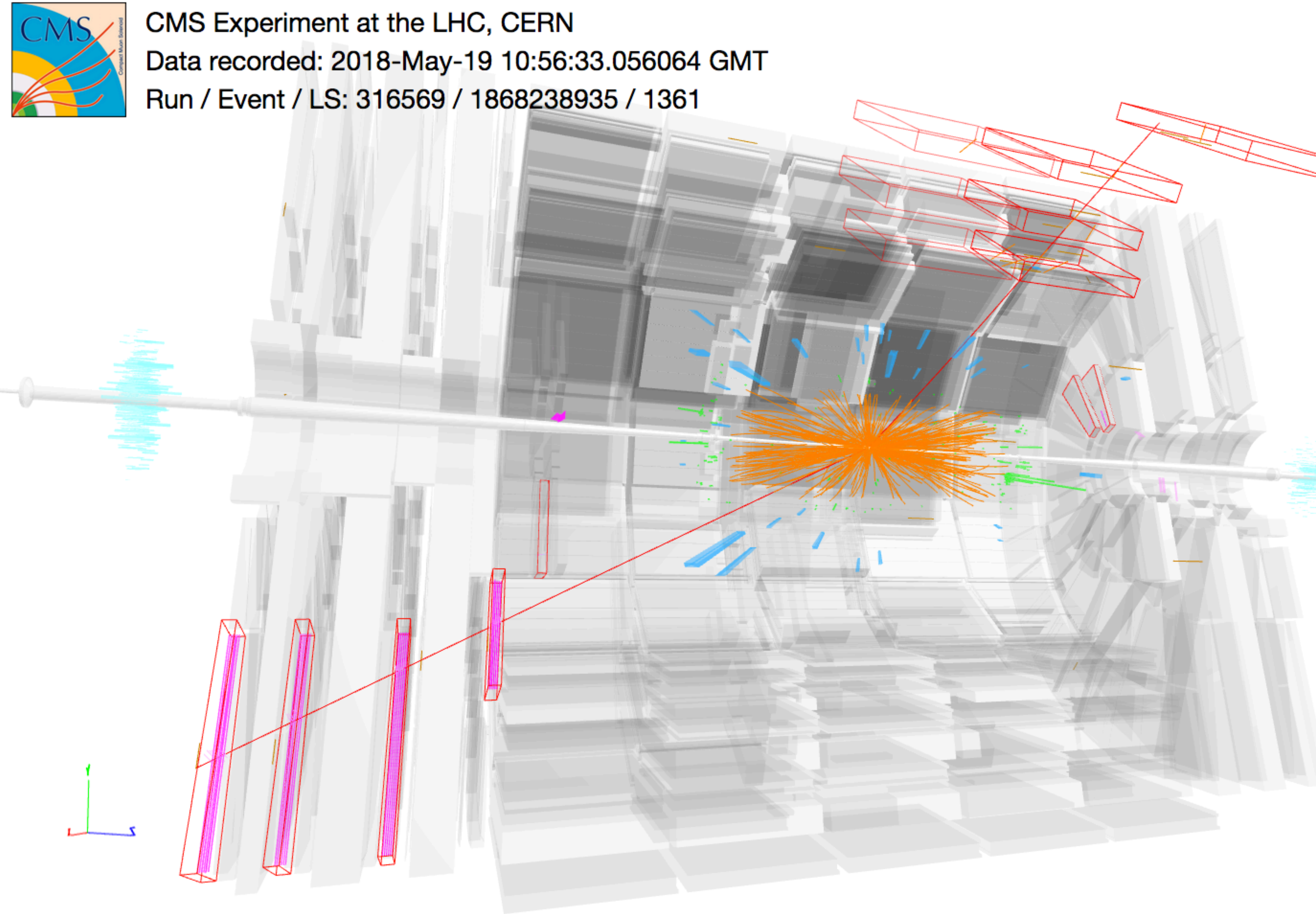
- **The longevity of the different detectors of the CMS Muon Spectrometer has been largely studied**
  - All legacy detector will be able to operate at HL-LHC keeping good efficiency
    - Results coming from GIF++ helped developing mitigation strategies for future operation
  - New detectors tested for the harsh regions in which they have to operate
  - Final assessment of all the studies is expected within an year from now
- Huge effort from CERN to reduce the use of greenhouse gases
  - Action already ongoing, using recuperation system and addressing the leak rate
  - Large campaign of R&D common between the different CERN experiments



CMS Muon Spectrometer posters at the Conference:

- **The Phase 2 upgrade of CMS Drift Tubes (DT) detectors for high luminosity LHC**
  Archie Sharma (Rheinisch Westfaelische Tech. Hoch. (DE))
- **Novel GEM foil layout for high-rate particle environment in the CMS ME0 muon detector**
  Antimo Cagnotta (Universita e sezione INFN di Napoli (IT)
- **Development of Readout Electronics for the CMS ME0 Muon Detector**
  Abhisek Datta (University of California Los Angeles (US)
- **Commissioning and operation in magnetic field of CMS GE1/1 station**
  Simone Calzaferri (Università degli studi di Pavia - INFN Pavia)
- **Performance of triple-GEM detectors for the Phase-2 CMS upgrade and a high-resolution GEM telescope measured in a test beam**
  Antonello Pellecchia (Universita e INFN, Bari (IT)
- **Performance of improved RPCs demonstrator for the CMS Phase 2**
  Ece Asilar (Hanyang University)

BACKUP


CMS Experiment at the LHC, CERN
Data recorded: 2018-May-19 10:56:33.056064 GMT
Run / Event / LS: 316569 / 1868238935 / 1361

References

- Muon Detector Operation public results:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/MuonDPGResults
- Main publications on CMS Muon Performances:
  - Performance of the CMS muon trigger system in proton-proton collisions at $\sqrt{s}$ = 13 TeV [JINST 16 (2021) P07001]
  - Performance of the reconstruction and identification of high-momentum muons in proton-proton collisions at $\sqrt{s}$ = 13 TeV [JINST 15 (2020) P02027]
  - Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s}$ = 13 TeV [JINST 13 (2018) P06015]
- GIF++ Main Page:
  - https://ep-dep-dt.web.cern.ch/irradiation-facilities/gif
- AIDAinnova:
  - https://aidainnova.web.cern.ch

LHC/HL-LHC program

	LHC design	HL-LHC design	HL-LHC ultimate
peak luminosity ($10^{34}\,cm^{-2}s^{-1}$)	1.0	5.0	7.5
integrated luminosity (fb^{-1})	300	3000	4000
number of pileup events	$\sim$30	$\sim$140	$\sim$200