LONGEVITY STUDIES OF THE CMS MUON SYSTEM FOR HL-LHC

Lisa Borgonovi
(Università e INFN, Sezione di Bologna)
on behalf of the CMS Collaboration

INFN BOLOGNA
Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088

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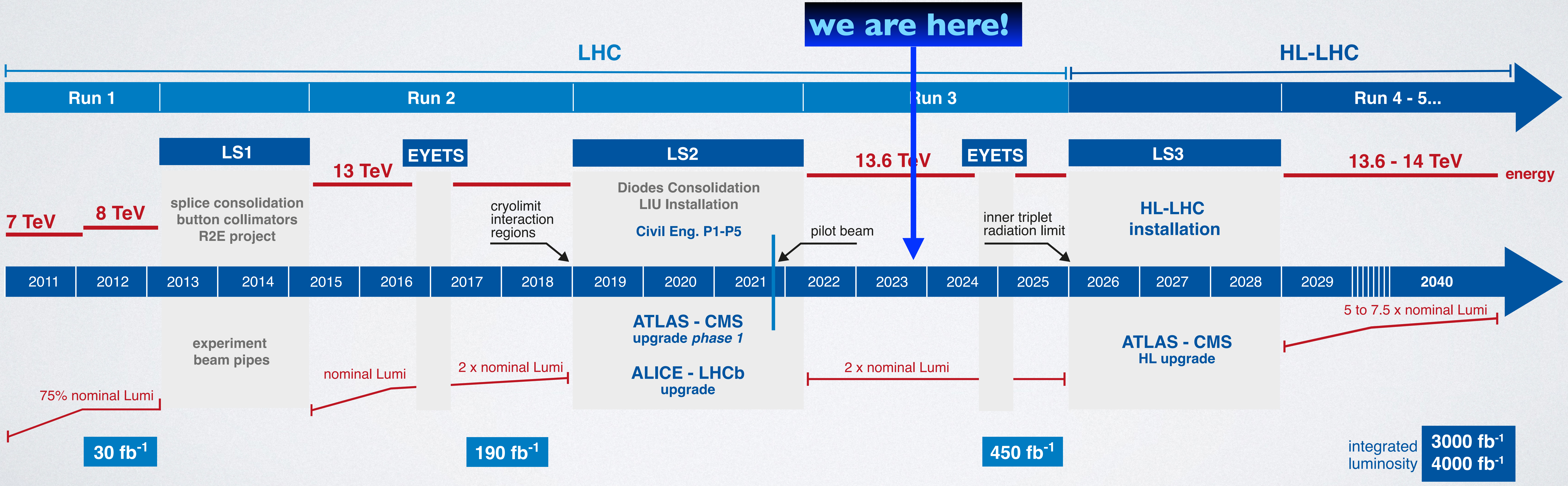
Overview of HL-LHC challenges

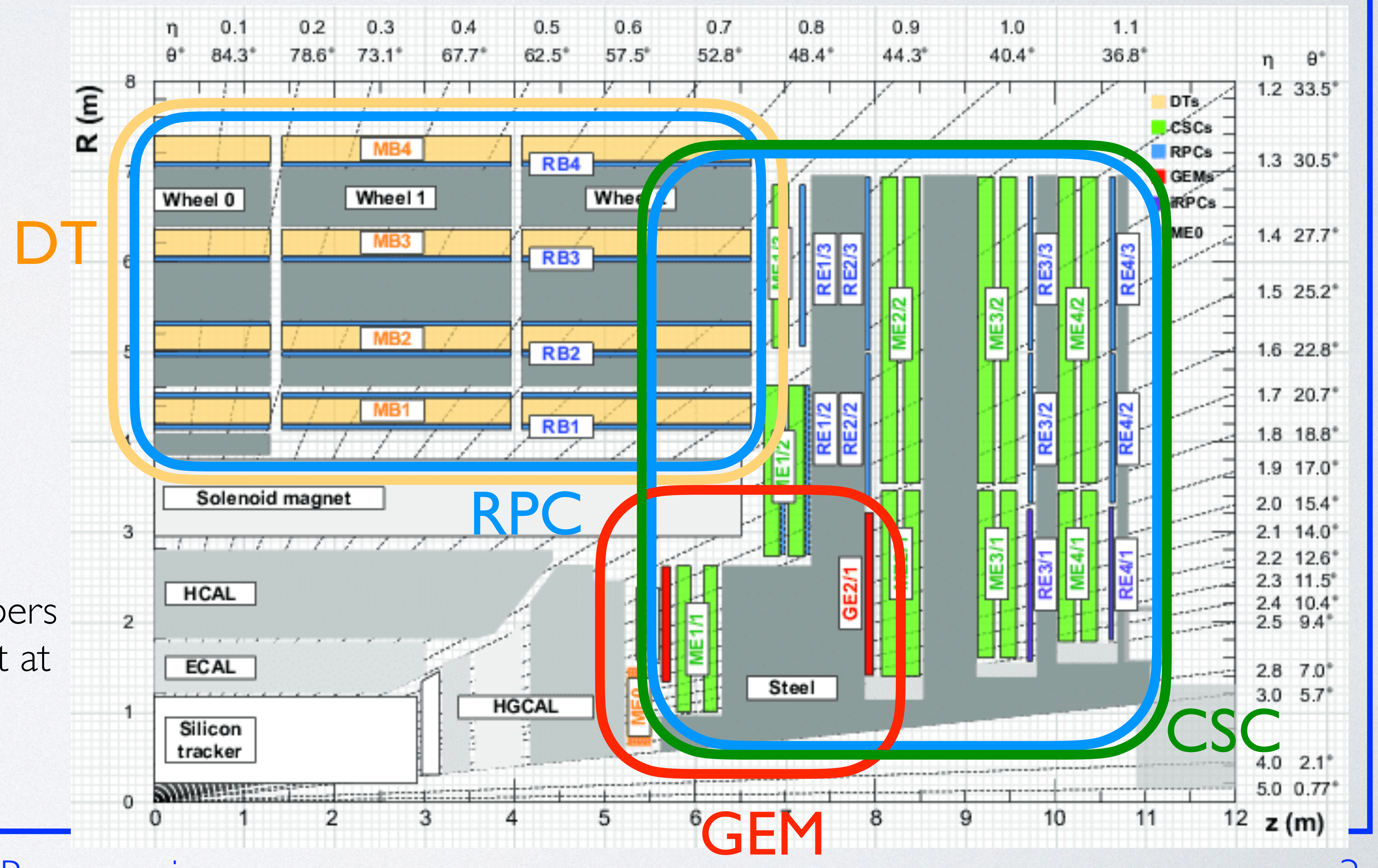
- Significant upgrade of LHC foreseen during Long Shutdown 3 (**LS3**) : the **High Luminosity LHC**
  - expected instantaneous luminosity of 5-7.5 x 10^{34} $cm^{-2}s^{-1}$ and integrated luminosity of 3000 fb^{-1}(10 times larger LHC design!), with pileup up to 140-200
- **CMS detectors will need significant upgrades (Phase 2) to cope with worse background conditions during HL-LHC**
  - expected accelerated **aging** of detectors and electronic components due to increased radiation
  - greater demanding requirements on the electronics due to increased trigger rates



Muon system for Phase 2

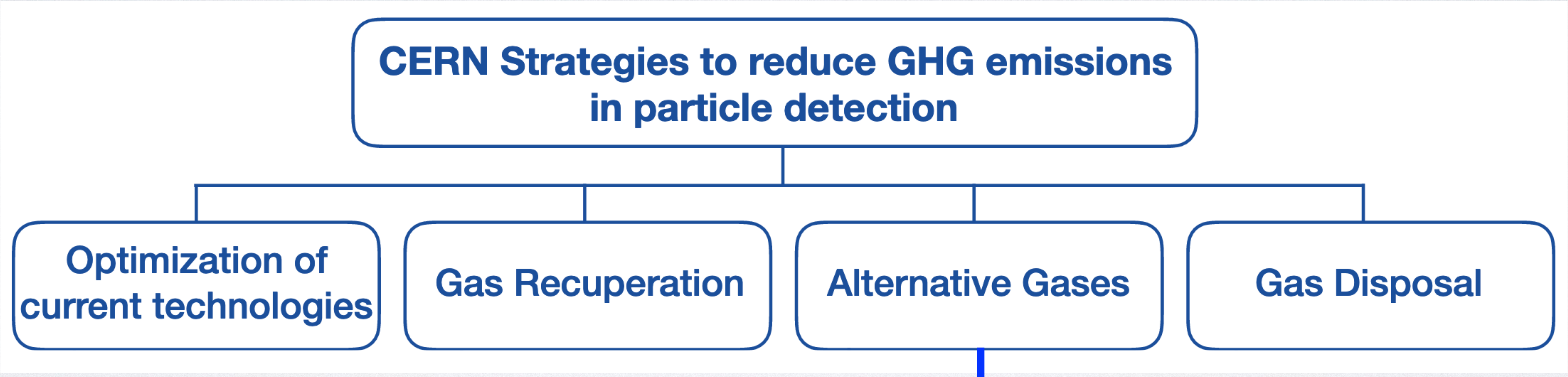
- The **CMS Muon Spectrometer**, composed of **gaseous detectors (DTs, RPCs, CSCs and GEMs)**, was designed to deal with the **LHC** conditions
  - proved excellent performance for both efficiency and resolution
  - essential for **trigger** and **reconstruction of muons** in both barrel and endcap regions
- The main challenge for the Muon System is to cope with the increased rate and maintain the present excellent performance along the 10 years of HL-LHC operations
  - upgrade of the on-detector electronics of the existing detectors (more on Gabriella Pugliese's talk)
    - Drift Tubes (DTs), Resistive Plate Chambers (RPCs), Cathode Strip Chambers (CSCs)
  - installation of new muon stations improving the redundancy of the system and providing more precise measurements of muon parameters in the forward region (higher background and a lower magnetic field) - already started during LS2
    - Gas Electron Multipliers (GEMs), improved RPCs (iRPCs)
  - **long-term irradiation studies** to evaluate the muon chambers performance at high values of integrated charge (mainly carried out at the GIF++ facility)

this talk's topic!



CERN GHG mitigation campaign

- European Union "F-gas regulation" to reduce Green House Gases (GHG) emission:
  - **Limiting the total amount of the most important F-gases** that can be sold in the EU from 2015 onwards and phasing them down in steps t one-fifth of 2014 sales in 2030.
  - Banning the use of F-gases in many new types of equipment where less harmful alternatives are widely available.
  - Preventing emissions of F-gases from existing equipment by requiring check, proper servicing and recovery of the gases at the end of the equipment's life.



"long term"
shared wide effort between
CERN experiments

this talk's topic!

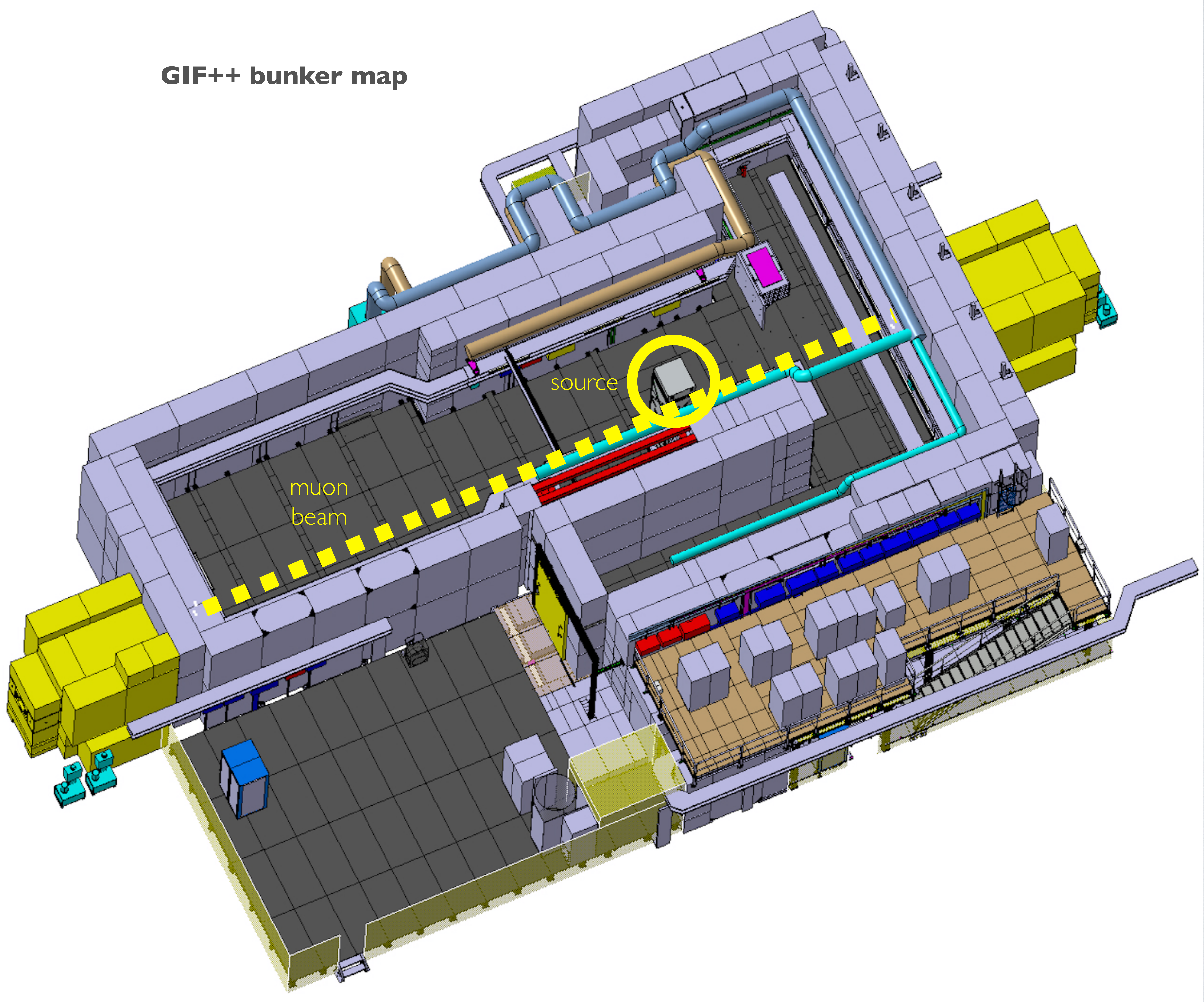
+ Gianluca Rigoletti's talk

The Gamma Irradiation Facility

- The **Gamma Irradiation Facility (GIF++)** is equipped with:
  - a 13 TBq ^{137}Cs gamma source to reproduce the expected background
    - movable filters to vary the gamma flux and **to generate background conditions similar to the ones expected at HL-LHC**
  - a high energy muon beam (~100 GeV/c)
- **Muon longevity program overview**

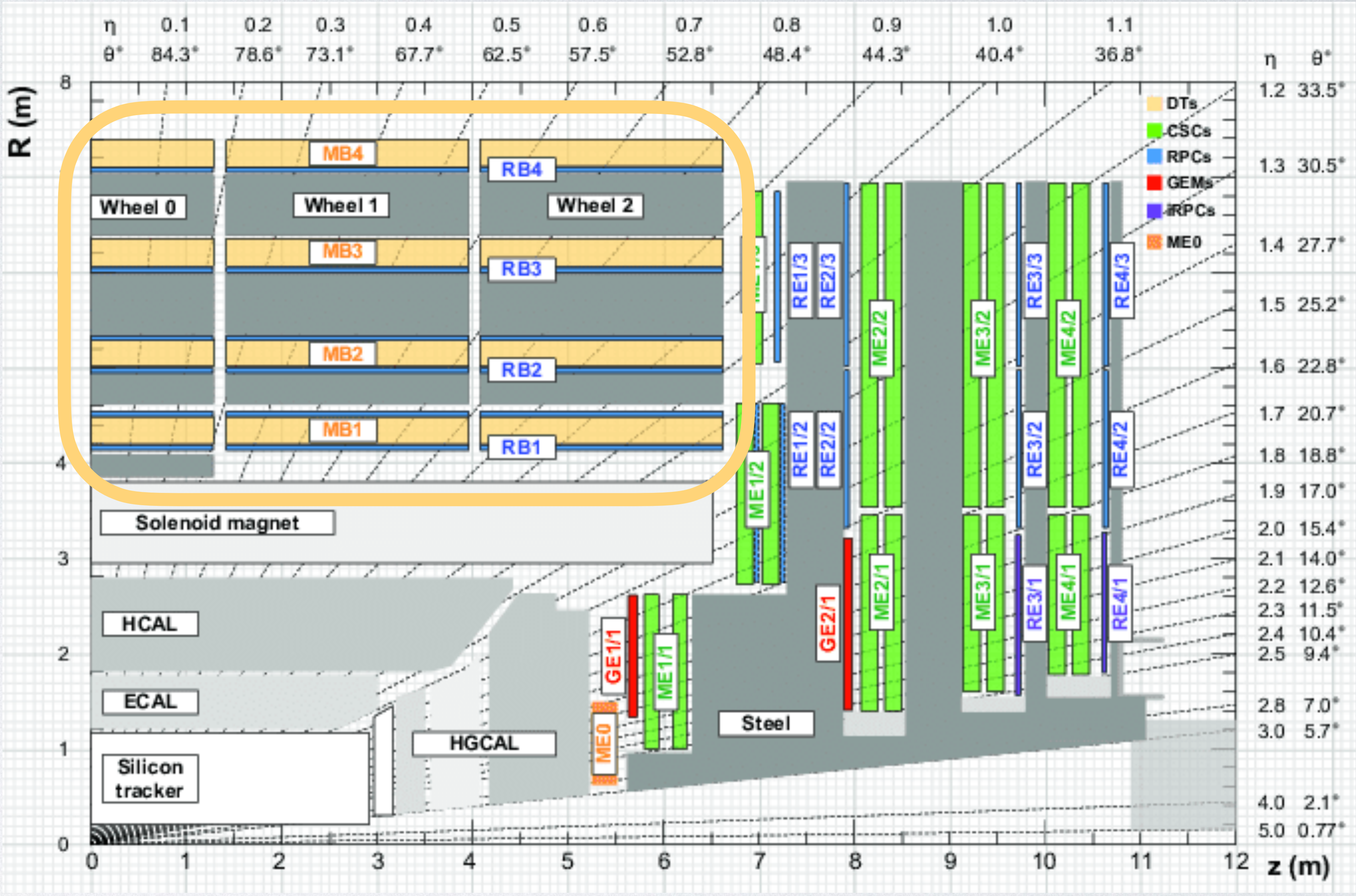
Muon detector	Irradiation w/ nominal gas	Irradiation w/ alternative gas
DT	✅	NOT needed
CSC	✅	ongoing
RPC	97% (RE2), 57% (RE4)	ongoing
GEM GE1/1 and GE2/1	✅ *	NOT needed
GEM ME0	30% *	NOT needed

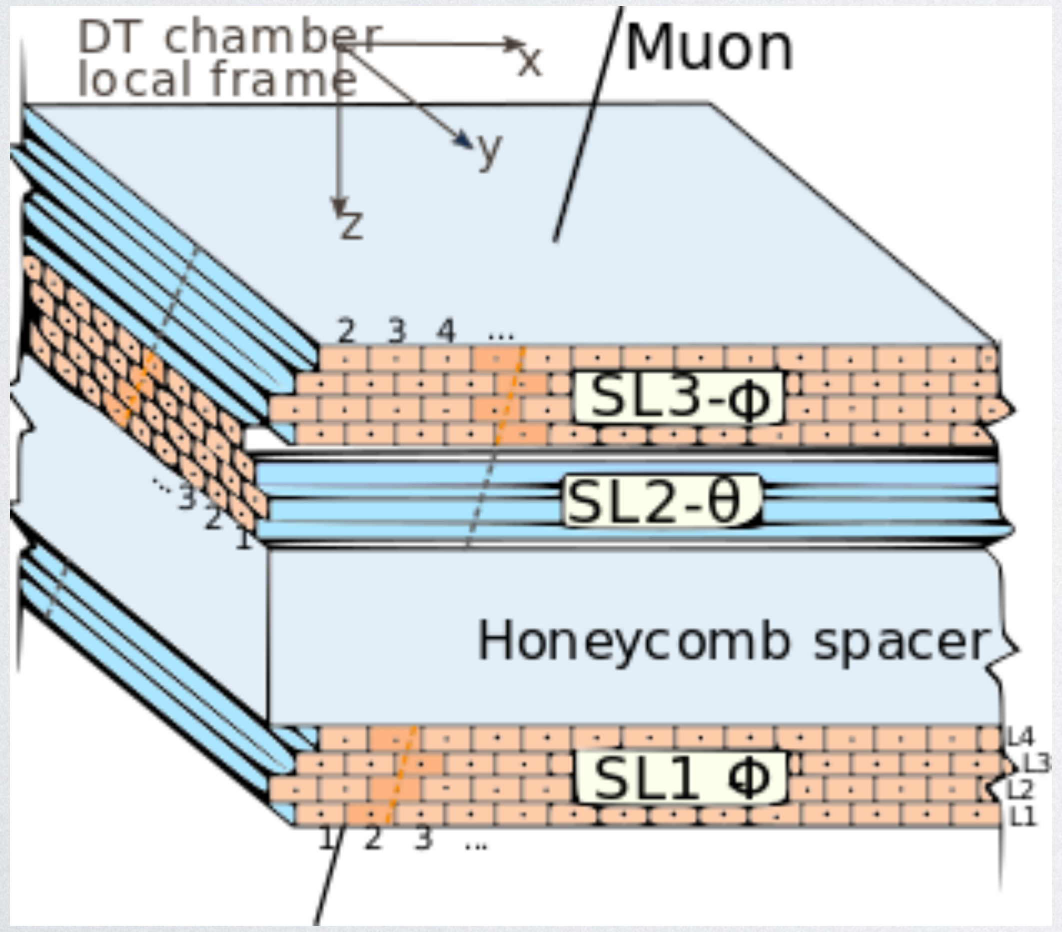
* Studies NOT (fully) carried out at GIF++

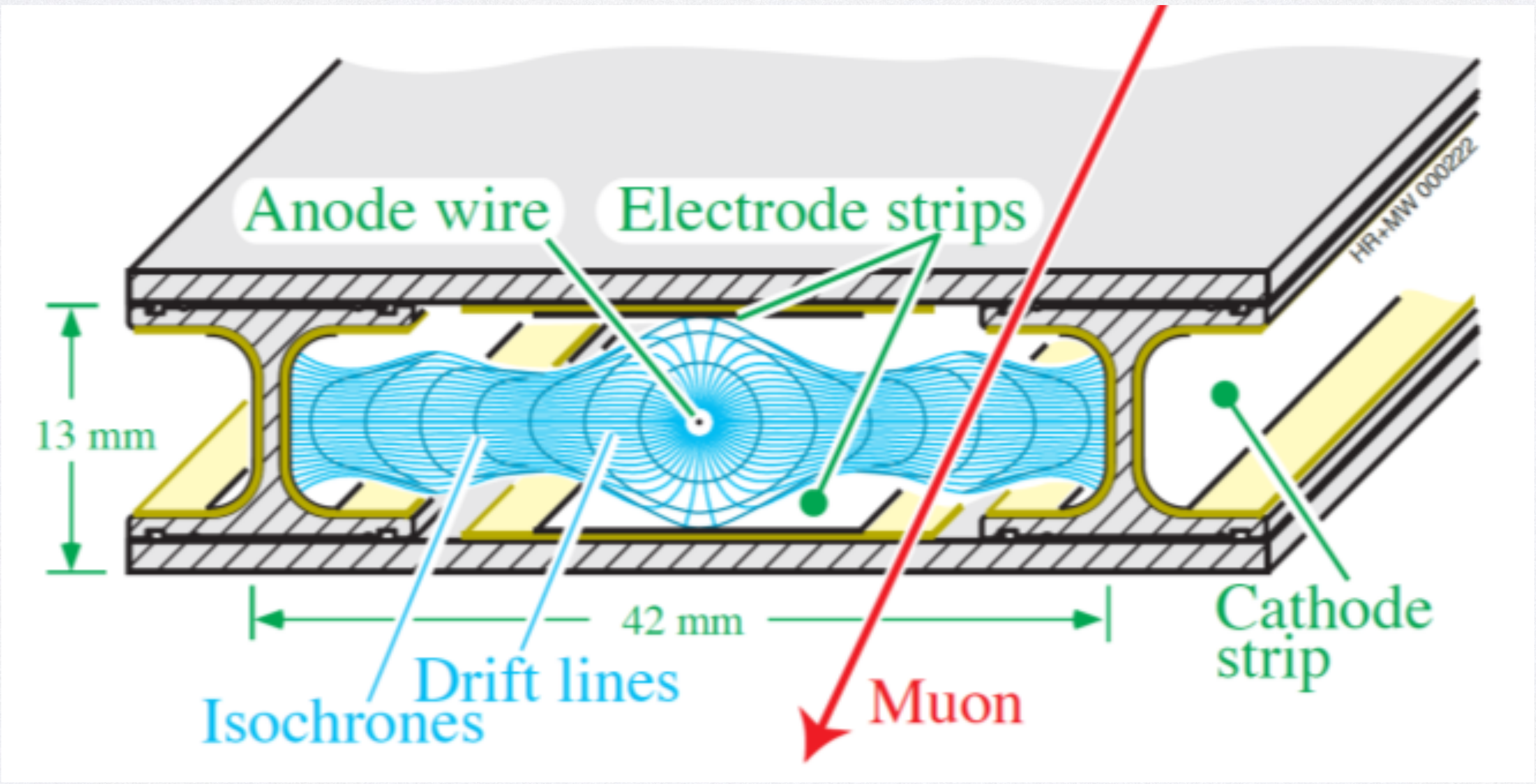


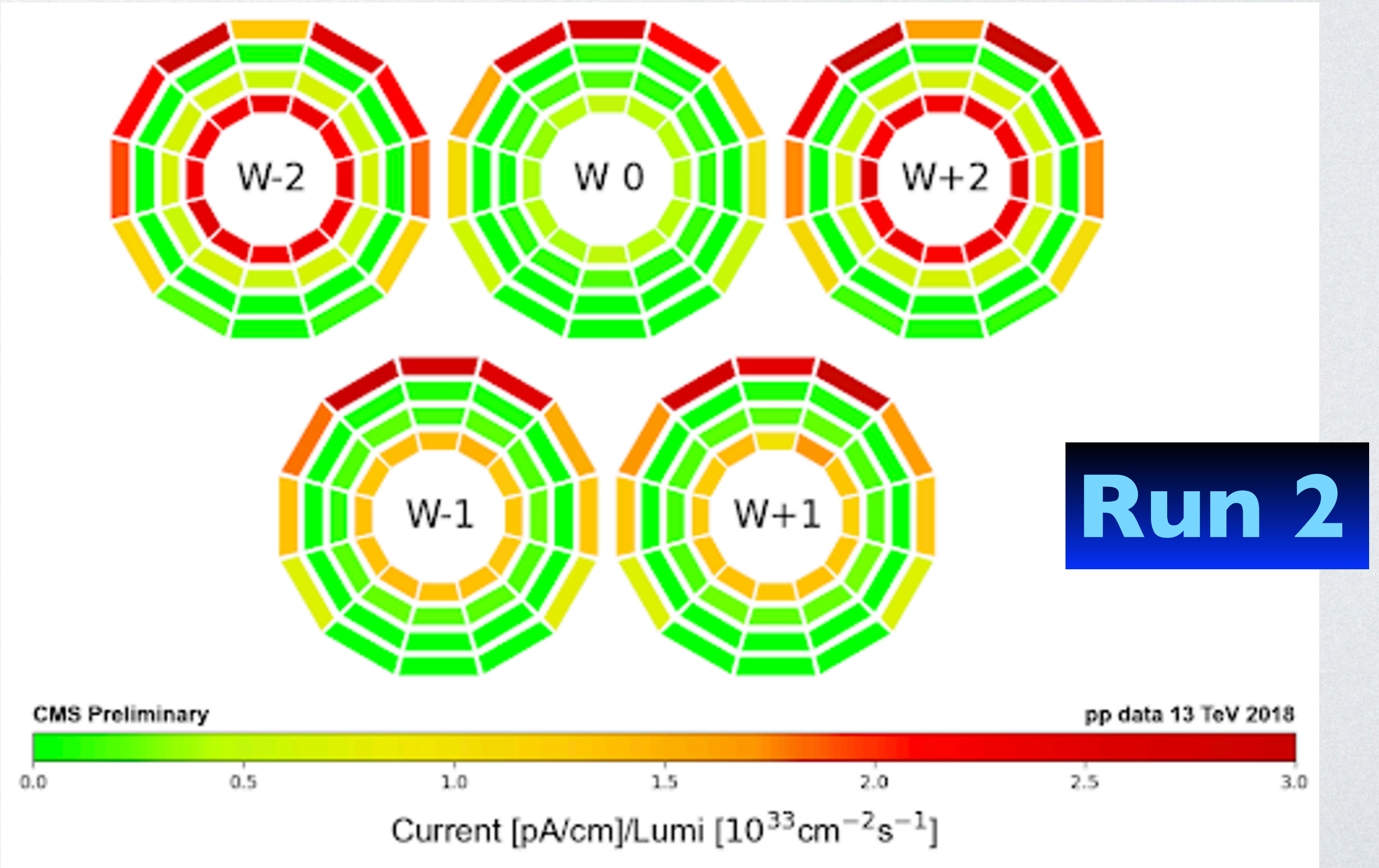
Drift Tubes (DTs)

- In the **CMS barrel region**, **250 DT**s are responsible for muon tracking and triggering
  - >170k channels, organized in 5 wheels, 12 sectors per wheel, 4 stations per sectors
- A DT chamber 2.5m x 2(4)m consists of 12(8) Layers (L) arranged in 3(2) Super Layers (SL), each one containing up to hundreds of cells:
  - the **drift cell** is the basic element of the DT chamber: a rectangular 4.2x1.3 cm drift cell filled with **Ar/CO_2 (85/15 %)** gas mixture, nominally operated with 3550 V on the anode wire and -1200V on the cathode
  - the electrons from muon ionization drift towards the anode wire, registering a time measurement (the hit-position is computed thanks to the constant v-drift 55 um/ns)
  - muon track segments are built with at least 3 hits in any SL



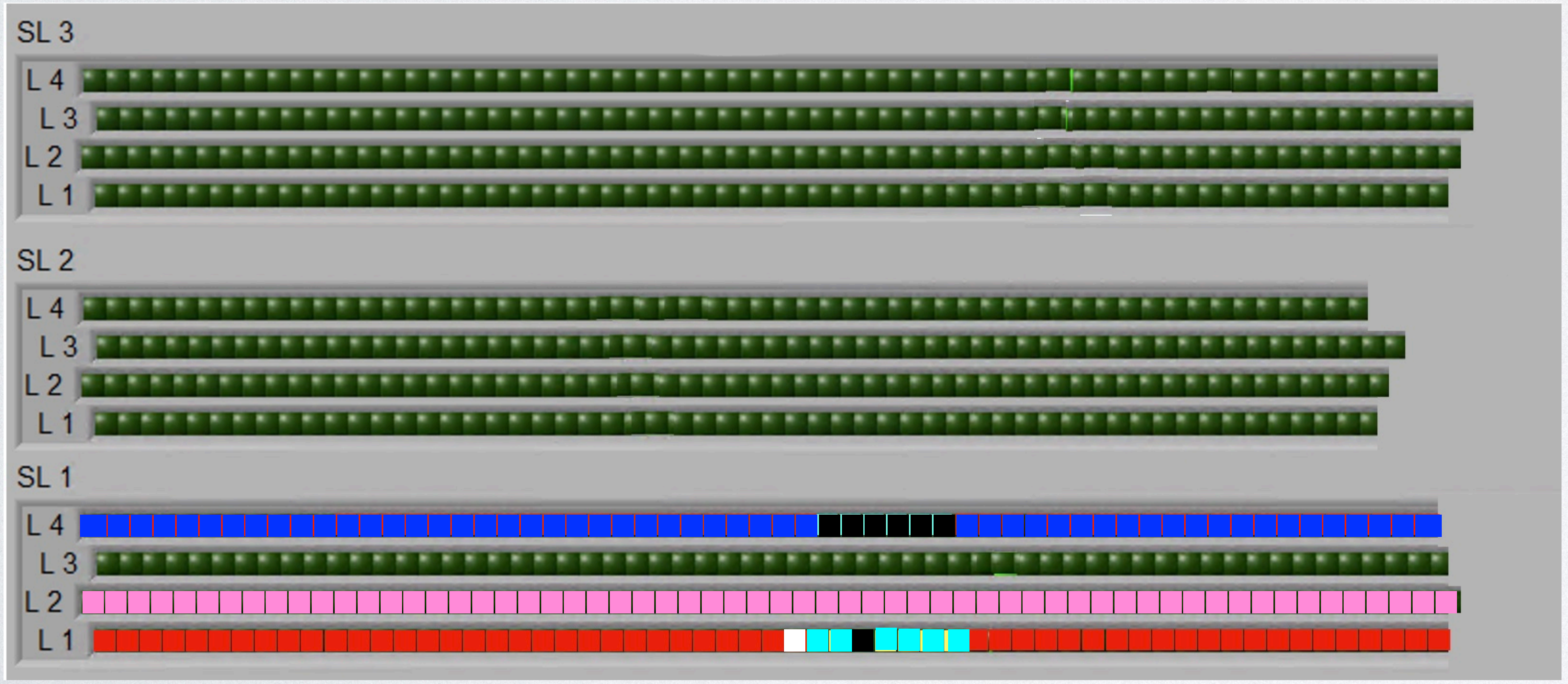


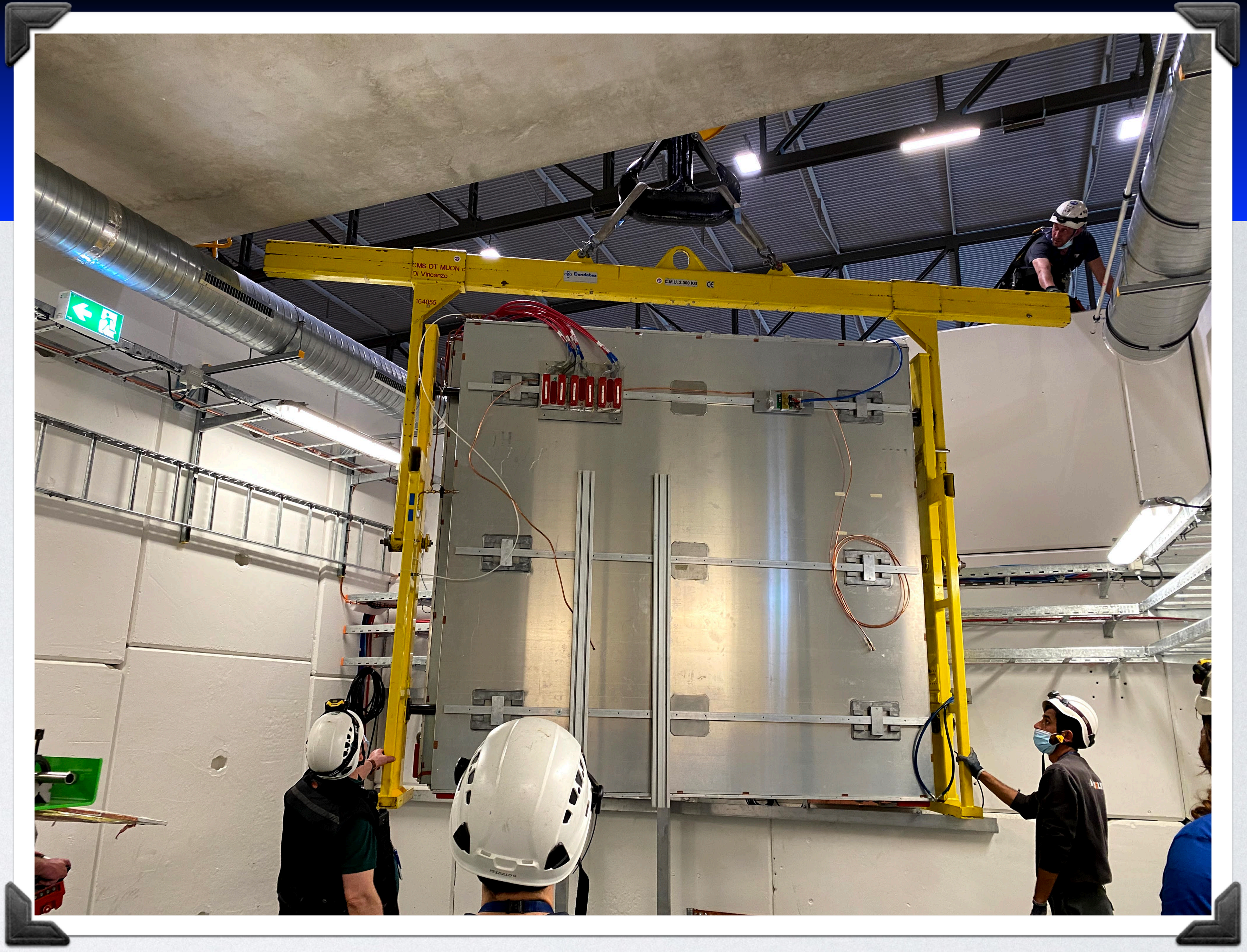


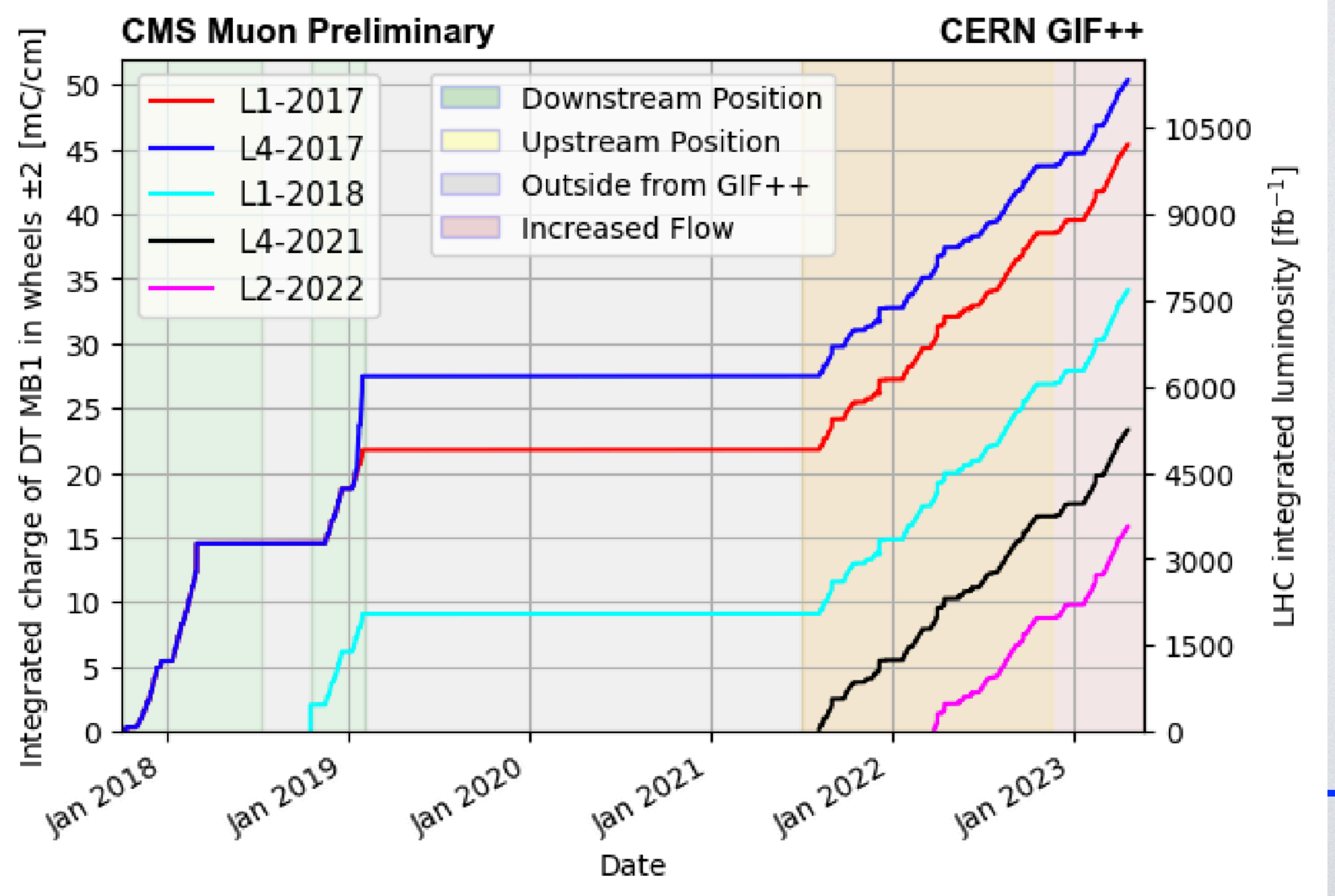


DTs at GIF++

- A spare MB2 chamber irradiated at GIF++ since the 2017:
  - only L1, L2 and L4 of SL1 on during the irradiation, while L3 is kept off to be used as reference (**L1-2017**, **L4-2017**, L2-2022)
  - SL2 and SL3 kept off during irradiation and used for internal auto-trigger
  - in Summer 2018, 8 wires in L1 were extracted, analyzed, and replaced with new wires (**L1-2018**)
    - among the new replaced, 1 has been extracted and analyzed in the 2021
  - the same happened in the 2021 for 5 substituted wires in L4 (**L4-2021**)

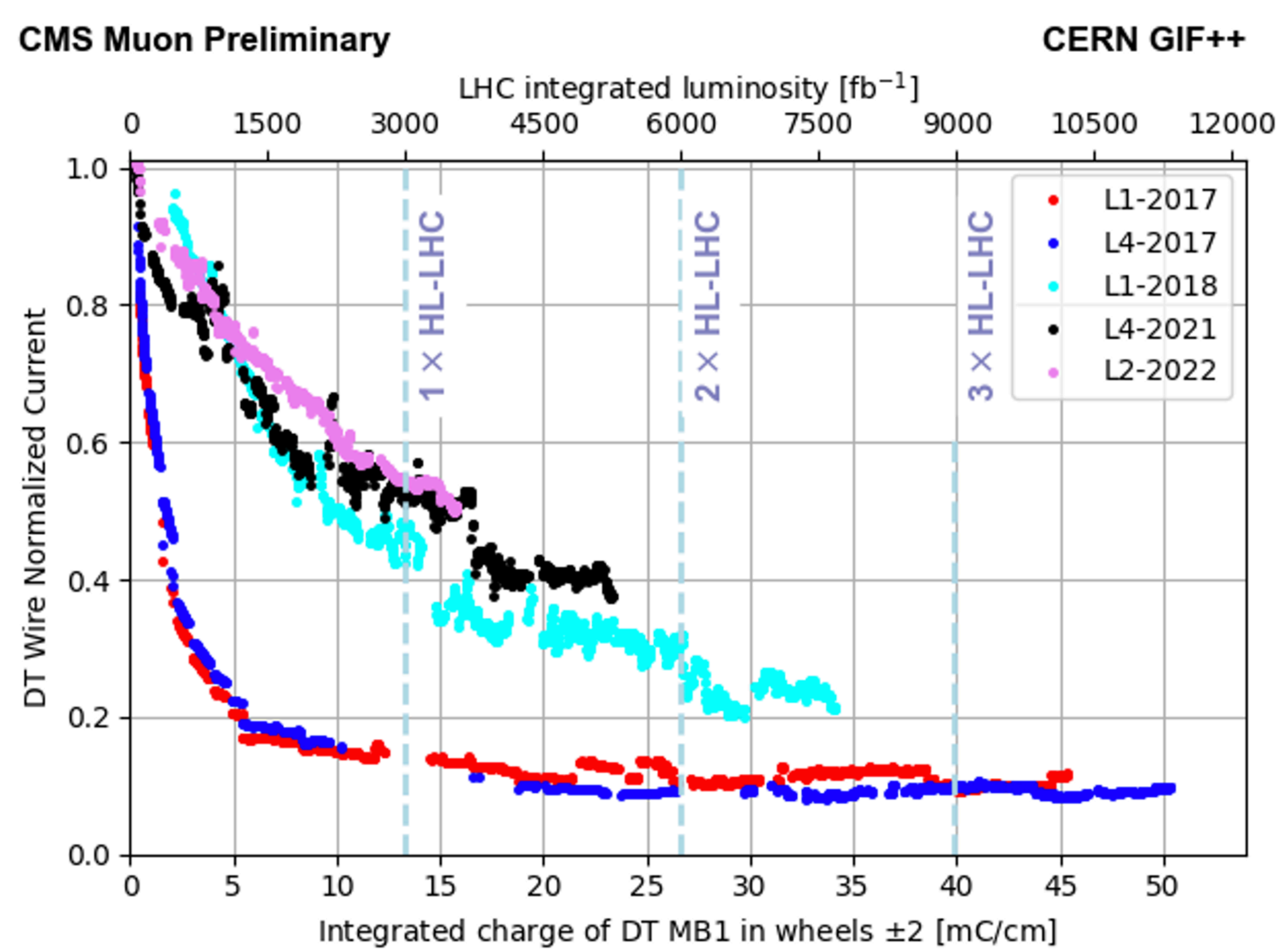


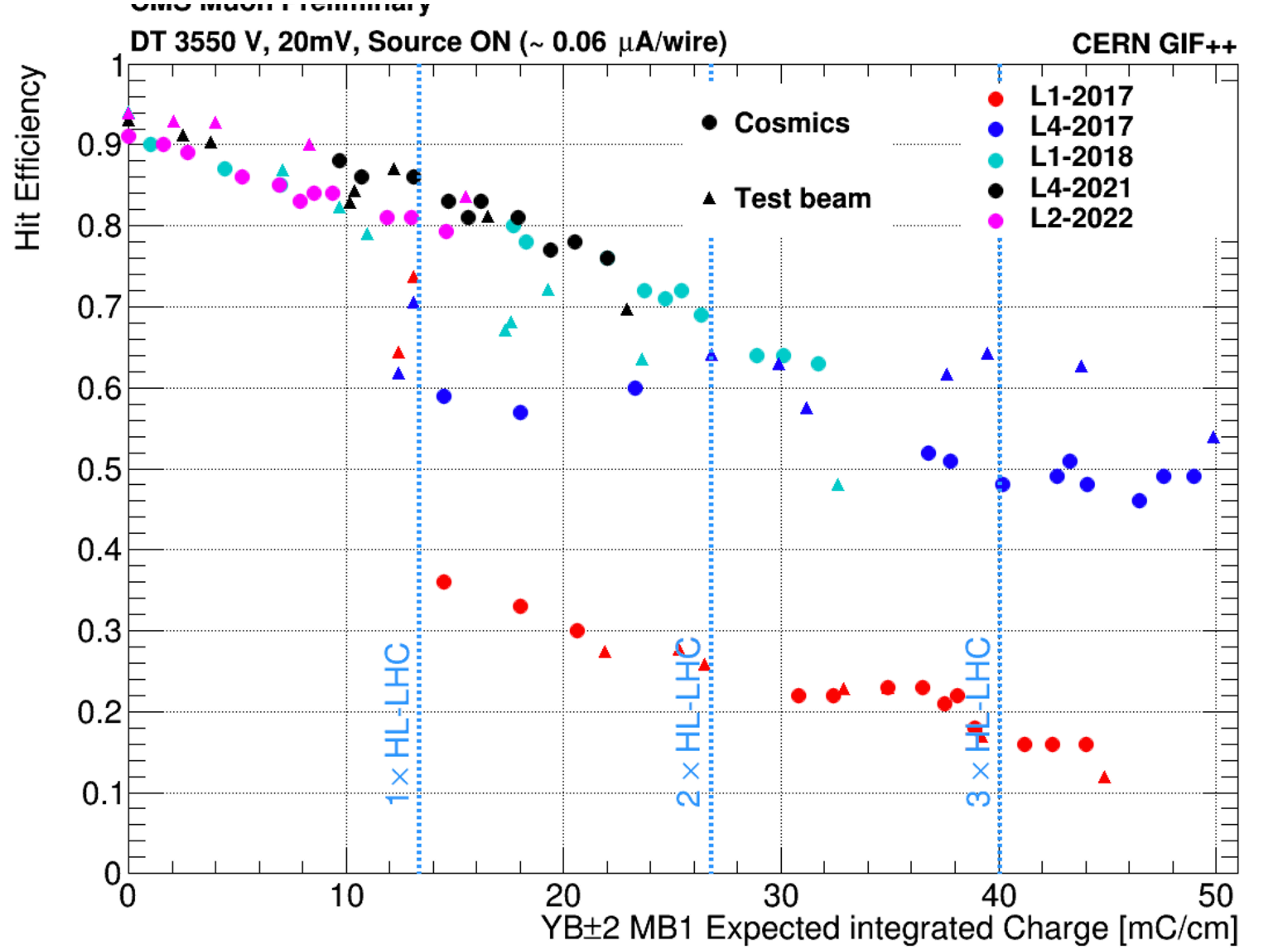


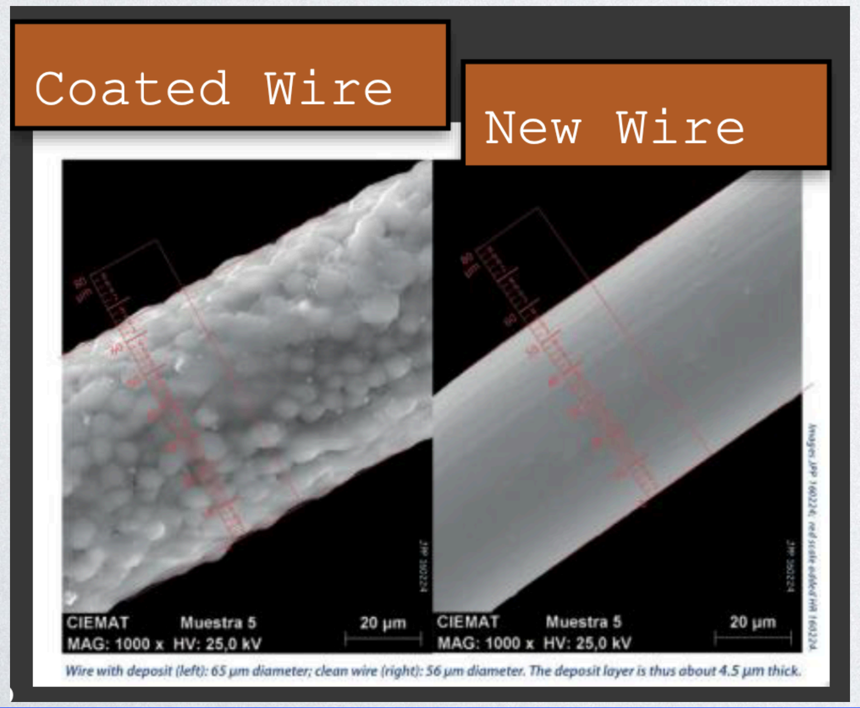


DT irradiation studies

- Analysis of the **currents** monitored by the HV boards gives an estimation of the **gain**
- Using cosmic muons (internal auto-trigger) to estimate the **hit efficiency** mainly to study the behaviour among the different irradiation periods, than to obtain the absolute expected efficiency
- The wires irradiated since the beginning show a fast degradation in the performance (L1-2017, L4-2017)
- The replaced wires show a slower reduction of gain and smaller loss of efficiency (L1-2018, **L4-2021**), similarly to what is observed in the most recent irradiated wires in L2 (L2-2022)
- Results are correlated to the presence of a carbon peak in the spectroscopy analysis
- **background conditions expected only in the MB1 of the external wheels (±2)**, similar in the top sectors of the MB4 (10 times smaller in the MB2 and negligible in the MB3)



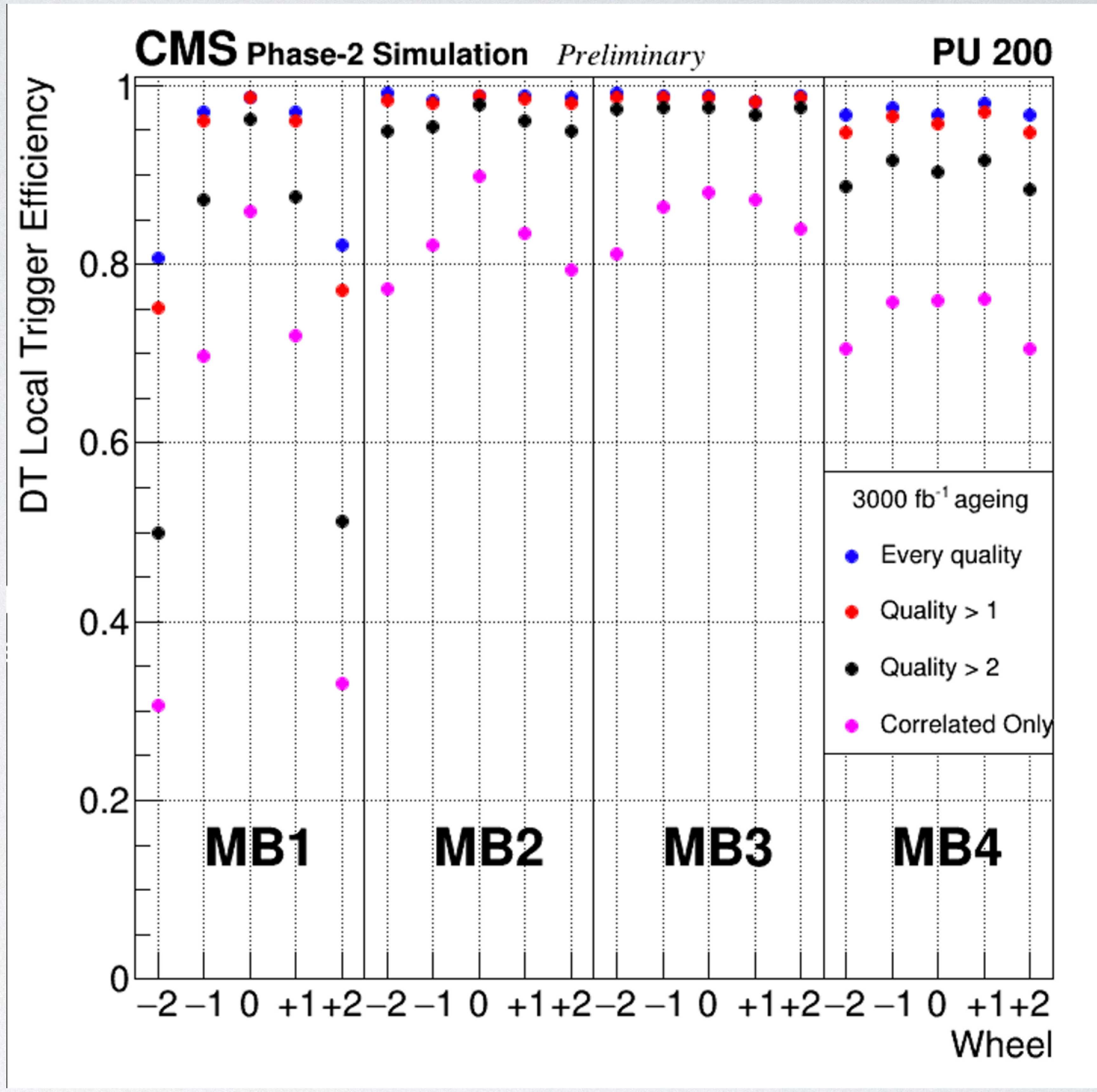


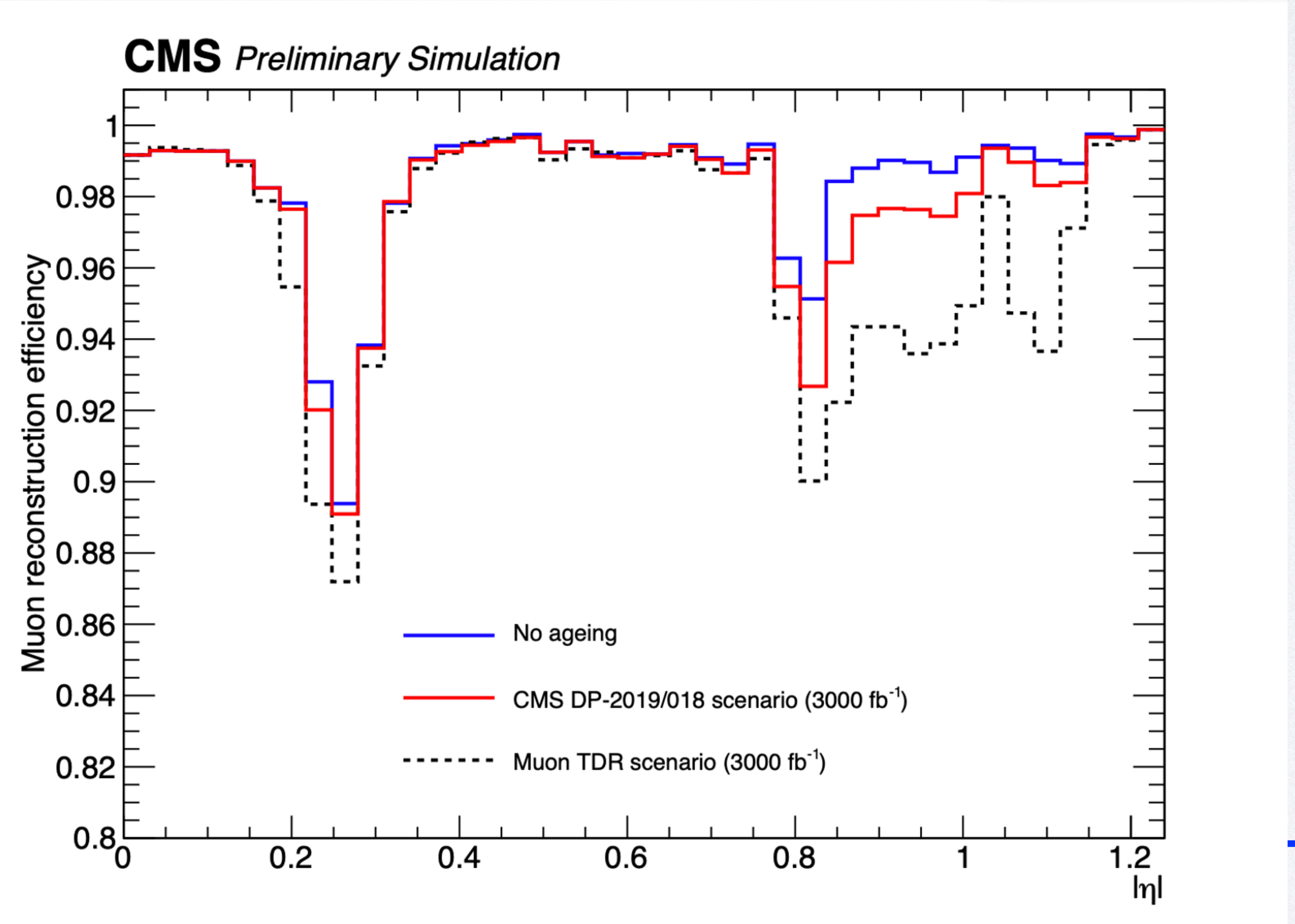


- The electron avalanche enable chemical reactions of impurities creating a coating on the wires

DT aging on physics performance

- The expected hit efficiency (in the worst scenario) has been used to evaluate the final impact at HL-LHC with a safety factor 2:
  - the major effect seen in the DT local trigger efficiency of MB1 is effectively **mitigated** by:
    - multiple layers per chamber (3 out of 8 are needed)
    - different handling of TDC hits in the **Phase 2 backend**
    - **redundancy of the CMS muon system**: the most aged DT region is also covered by up to 3 CSC stations and 4-5 RPC layers along a prompt muon trajectory

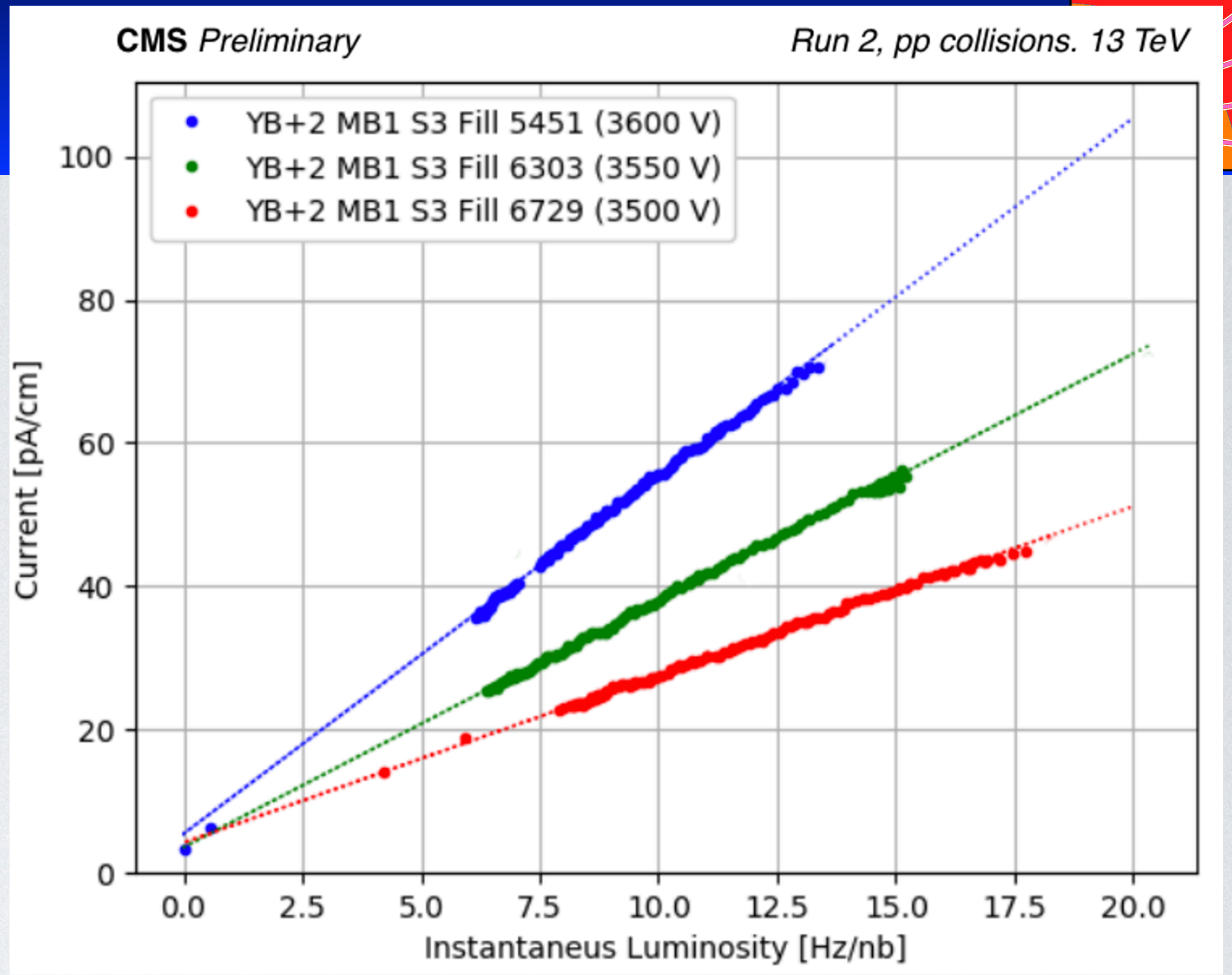




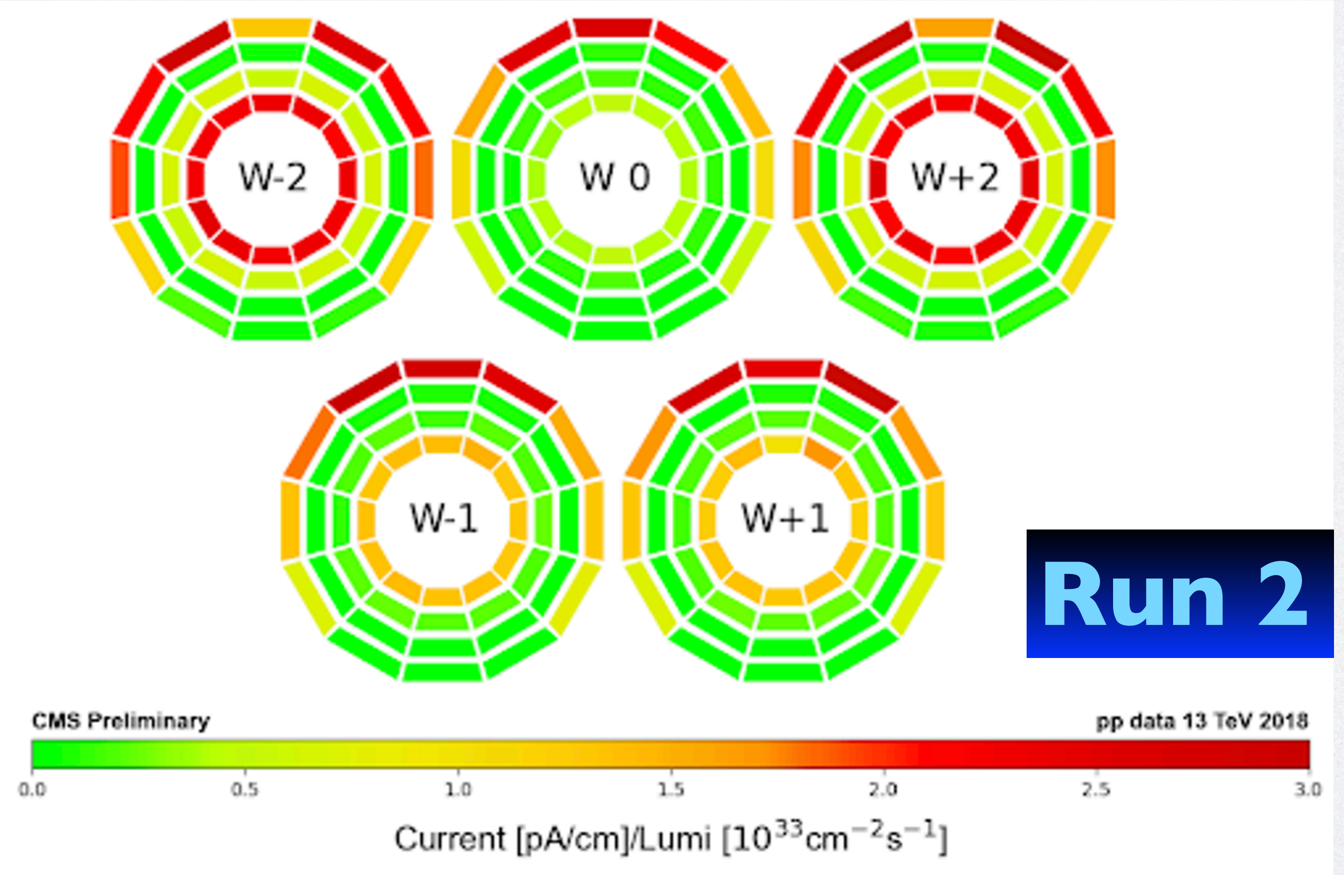
- Minor impact on the overall reconstruction of the standalone muons

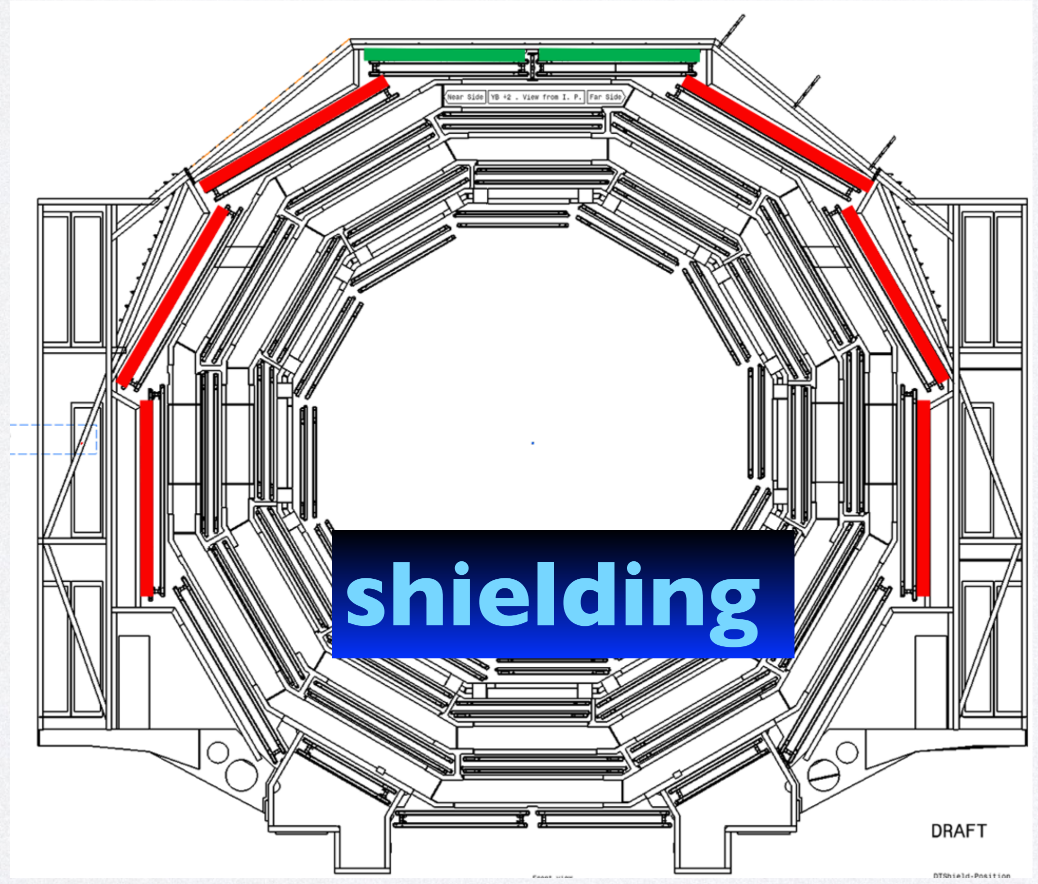
DT mitigation strategy

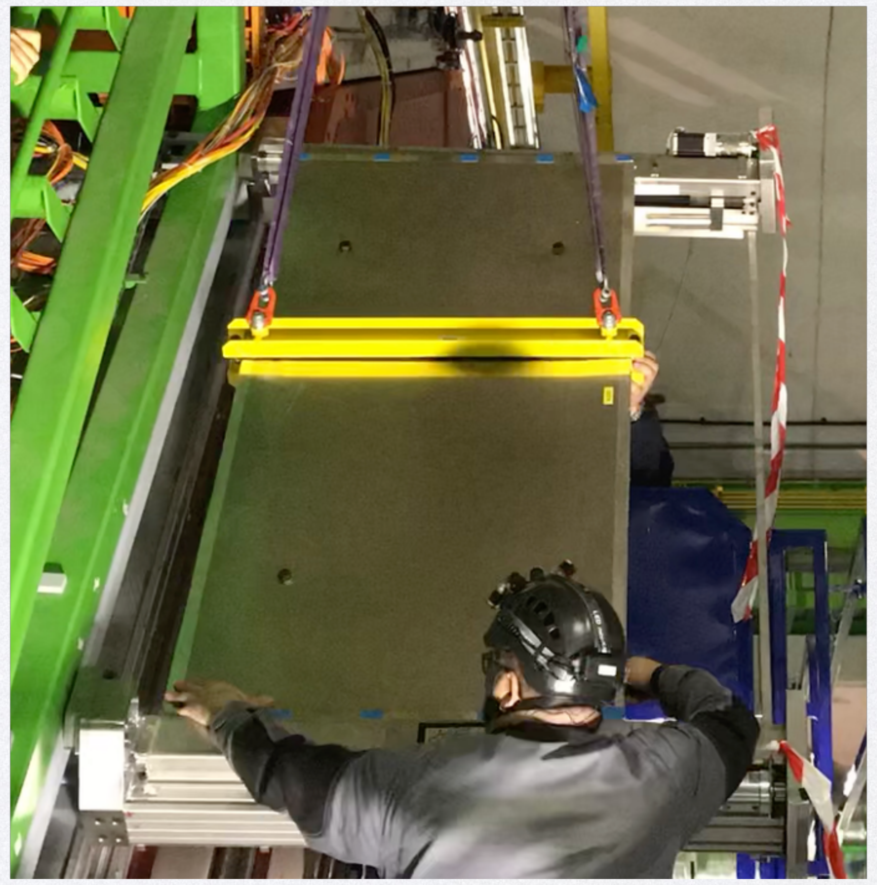
- A **strategy to mitigate the DT aging** has been already adopted:
  - since 2016 the **voltage of the wires in the most exposed chambers has been reduced** (each step of 50 V decreases the integrated charge of the 30%); the readout thresholds has been consequently reduced from 30 to 20 mV
  - in 2017 the **gas system** at CMS has been modified to operate **in open mode** to minimize the recirculation of the impurities (closed loop only when not in collisions)
    - irradiation test performed at GIF++ operating with a doubled gas flow shows no significant difference in the performance

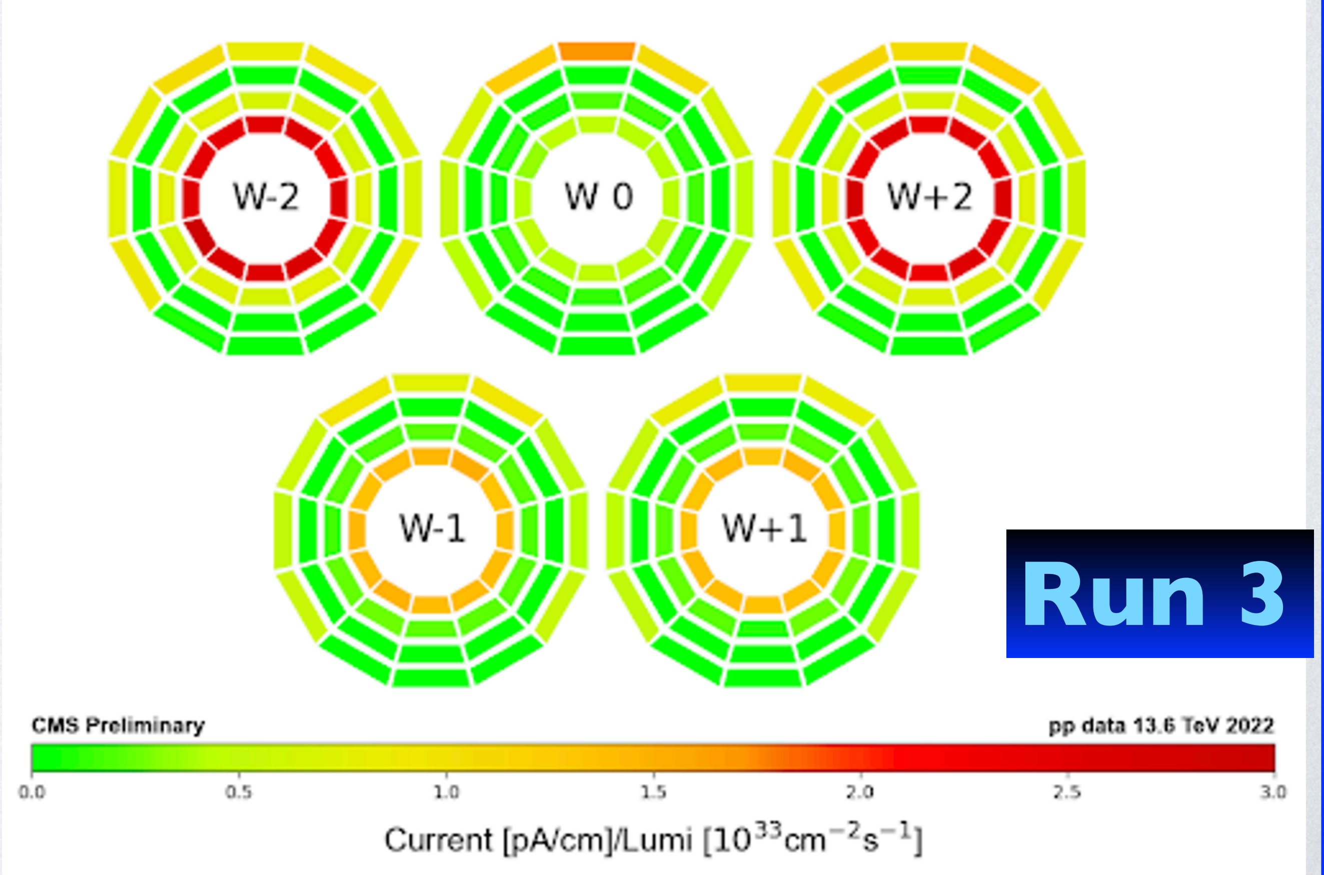


- During LS2 a Lead + Borated Polyethylene **shielding installed** for the neutron+gamma background reduction **in the top sectors** has been installed
  - 25% less background in the experimental cavern
  - 50-70% of background reduction in the MB4 chambers



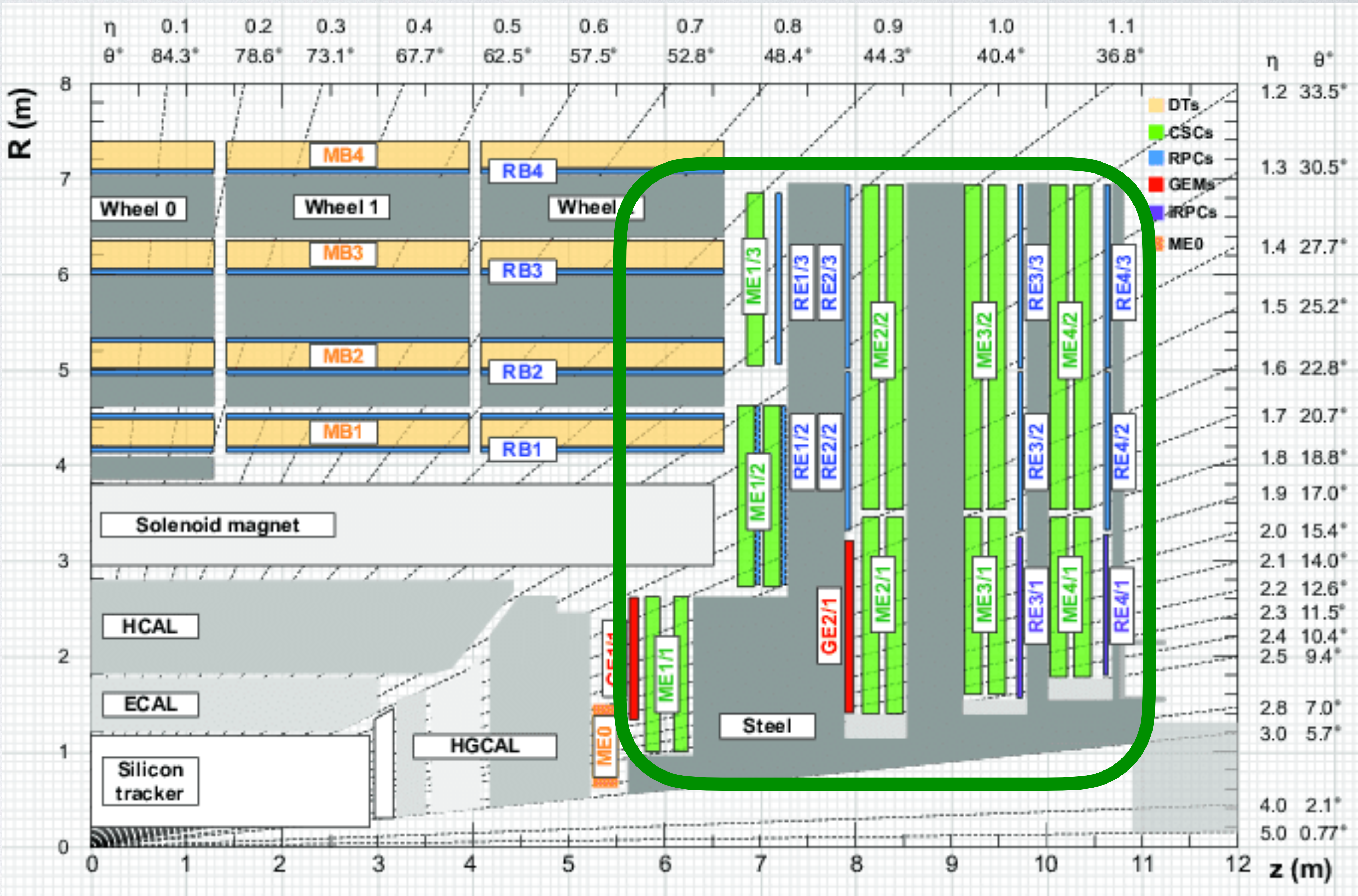


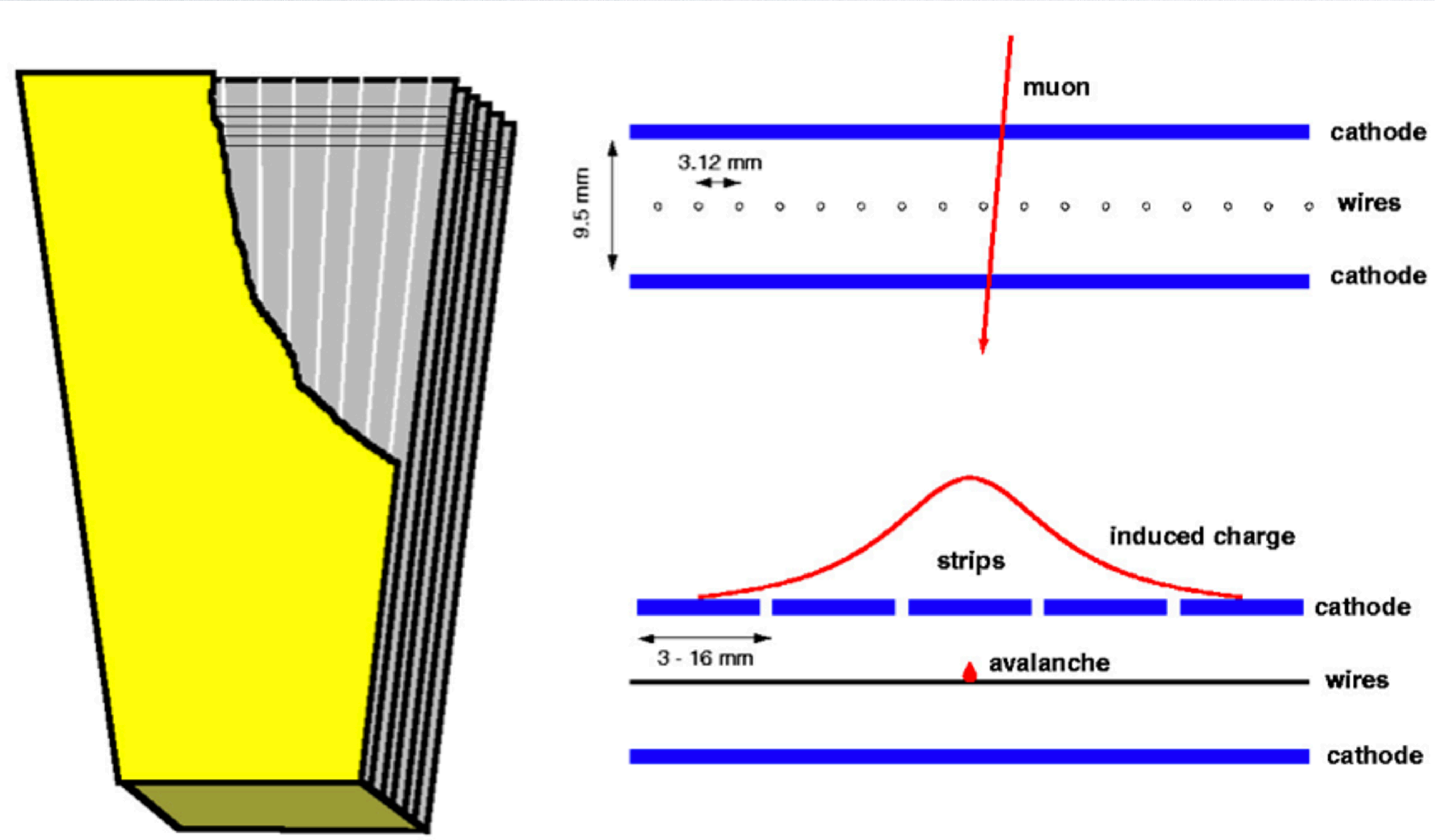




Cathode Strip Chambers (CSCs)

- CSCs are used in the **endcap disks** (4 disks per endcap) where the magnetic field is uneven and particle rates are higher than in the barrel
- The CSCs are trapezoid-shaped **multi-wire proportional chambers** with six planes (gaps): the strips run along the radial direction to measure the phi coordinate whereas the wires, which measure the r coordinate, run orthogonal to the strips
- A muon passing through the gas gap causes ionization of gas molecules which result in an avalanche of electrons around the wire and an induced change on the cathode strips
  - both electrons and ions are respectively read giving two coordinates per each detected particle segment tracks are reconstructed in 3D





- The gas gaps are filled with a **40% Ar, 50% CO_2, 10% CF_4** gas mixture
  - CF_4 has a high global warming potential but also protect against anode wire aging caused by Silicon and Carbon polymers

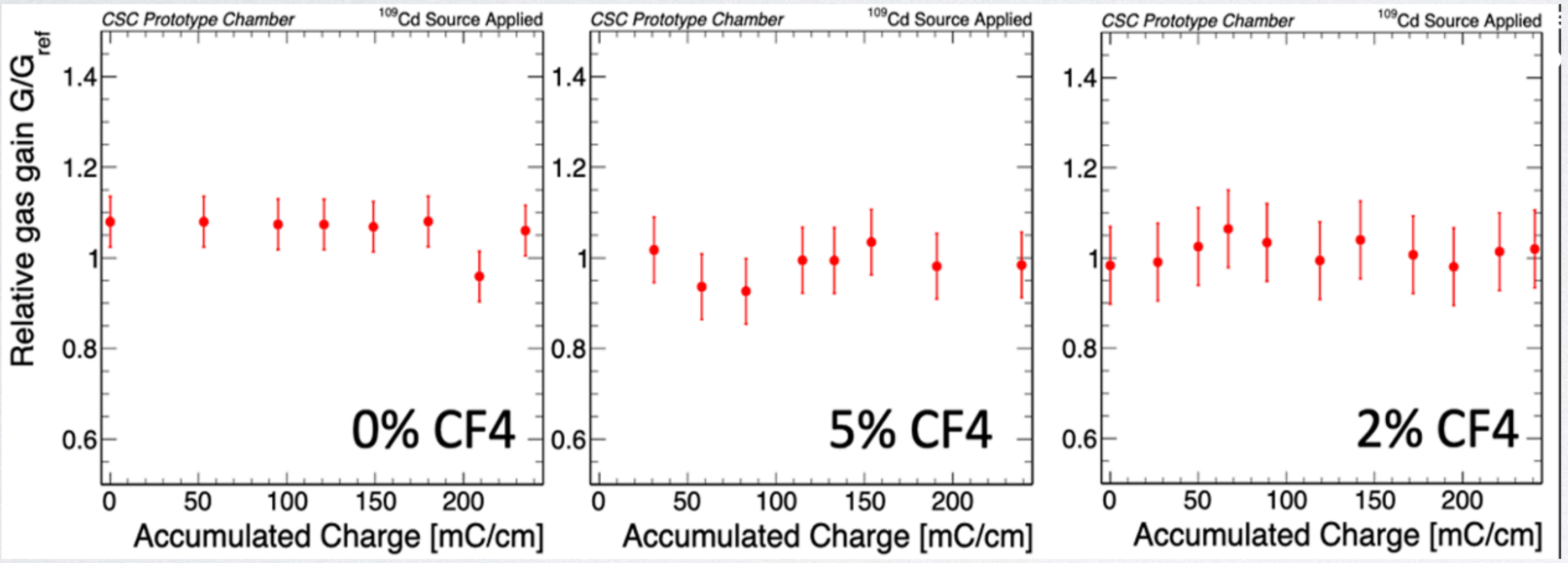
CSCs at GIF++

- Accelerated (~25) irradiation campaign is ongoing at the GIF++ with goal of consolidate a strategy to efficiently operate even **reducing the use of CF_4**
- How to reduce the use of CF_4:
  - **recuperation**: efficiency of the CF_4 recuperation plant increased from 30% to 60% during LS2
  - **reduction**: irradiation tests with 2% and 5% of CF_4
  - **substitution**: alternative HFO-1234ze
- Irradiation setup:
  - 2 ME1/1 chambers
  - 1 ME2/1 chamber
  - high Voltage kept ON on 4 layers while 2 layers are kept off to be used as reference

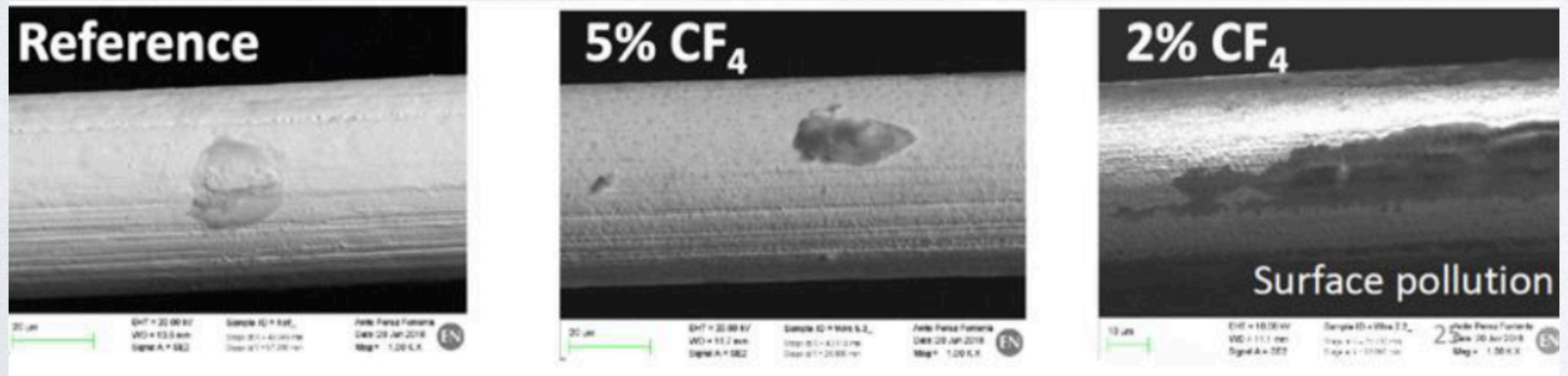
- The amount of integrated charge expected at 1 HL-LHC estimated using the Run 2 currents scaled with the Fluka simulation (HL-LHC/Run2 ratio):
  - ME1/1: 200 mC/cm → 600 with a safety factor 3
  - ME2/1: 130 mC/cm → 390 with a safety factor 3

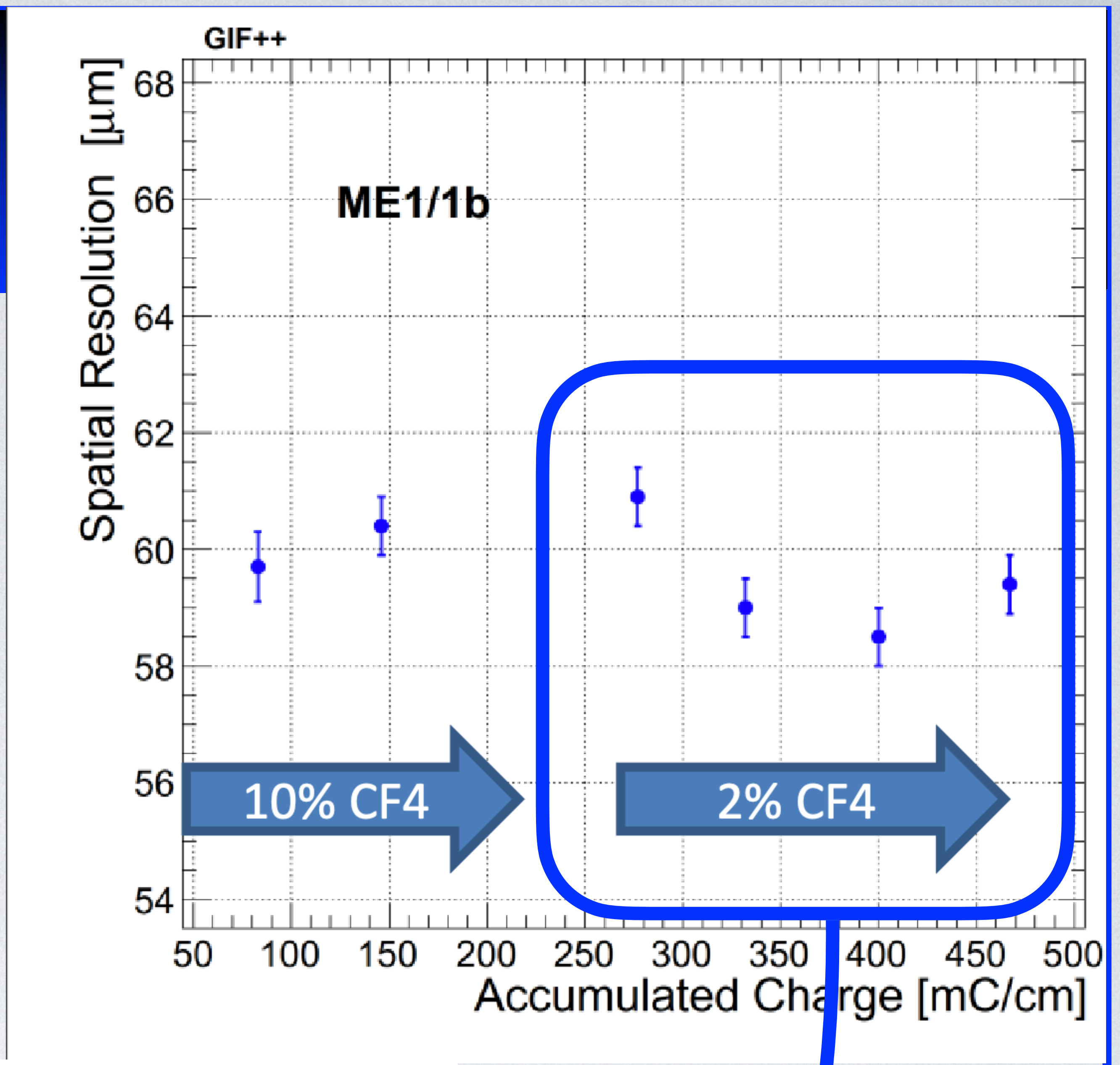
CSCs aging studies

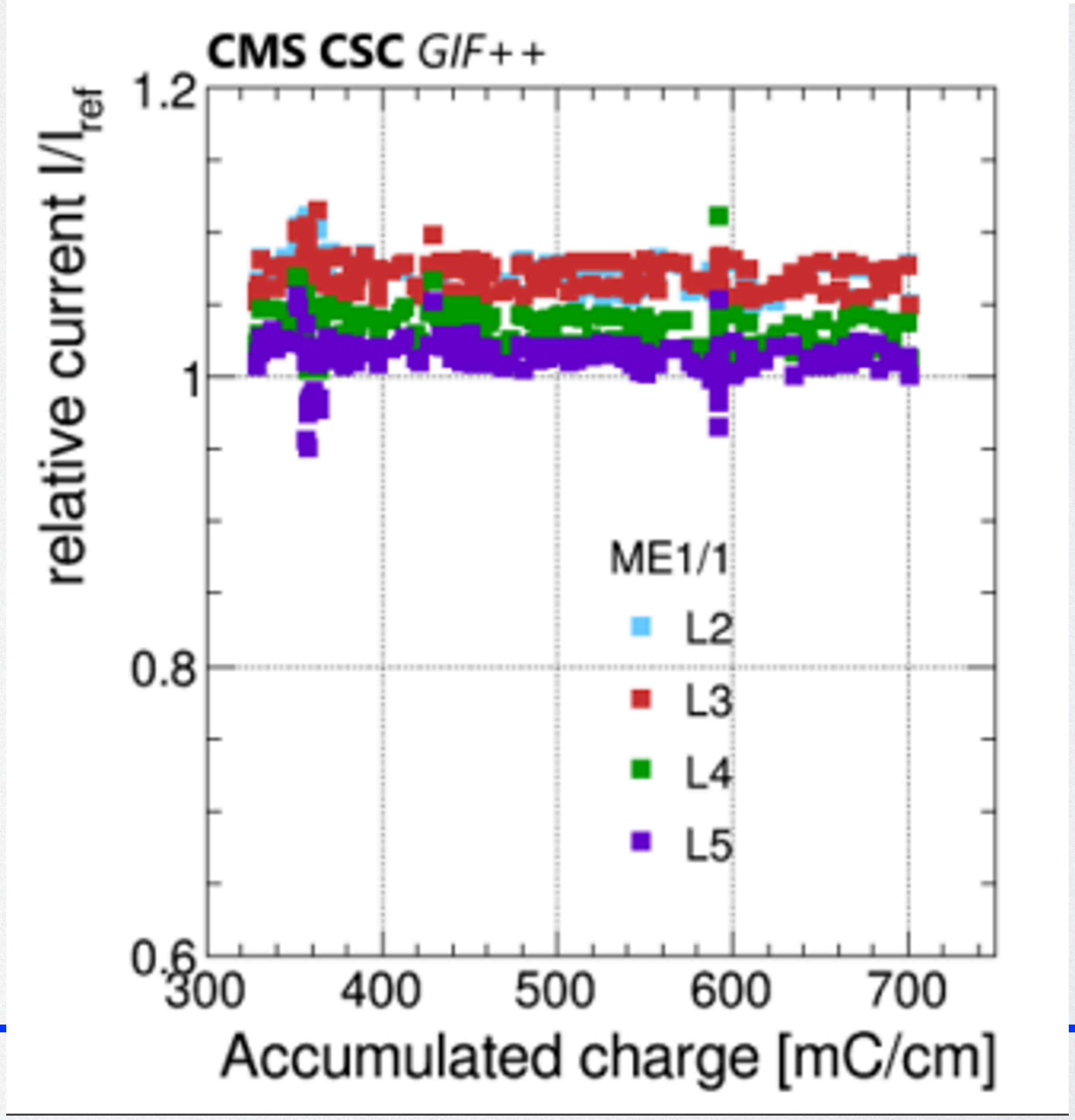
- Studies with nominal gas mixture (2016-2021):
  - ME1/1 and ME2/1 received 330 mC/cm using 40% Ar, 50% CO_2, 10% CF_4
  - ME1/1 received further 370 mC/cm using only the **2% of CF_4**
- **No significant sign of aging**, no visible effects on gas gain with different CF_4 % (validated up to 2 HL-LHC)
  - however, increased **pollution** is visible on the wire



- Deposits on the anode wires show that operating with 2% CF_4 might be a risky choice, while running with **5% CF_4 looks more sustainable** (irradiation ongoing)



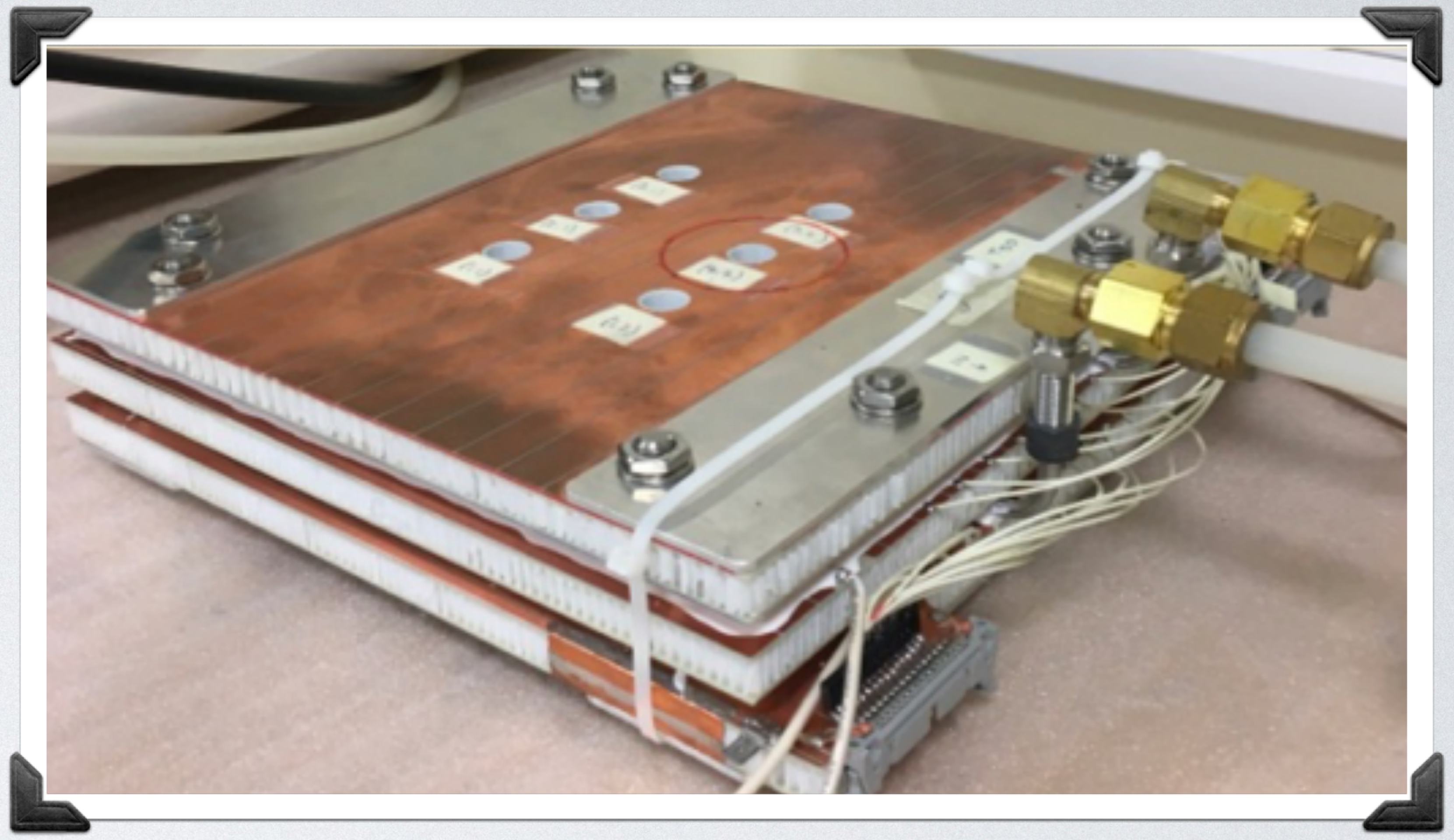


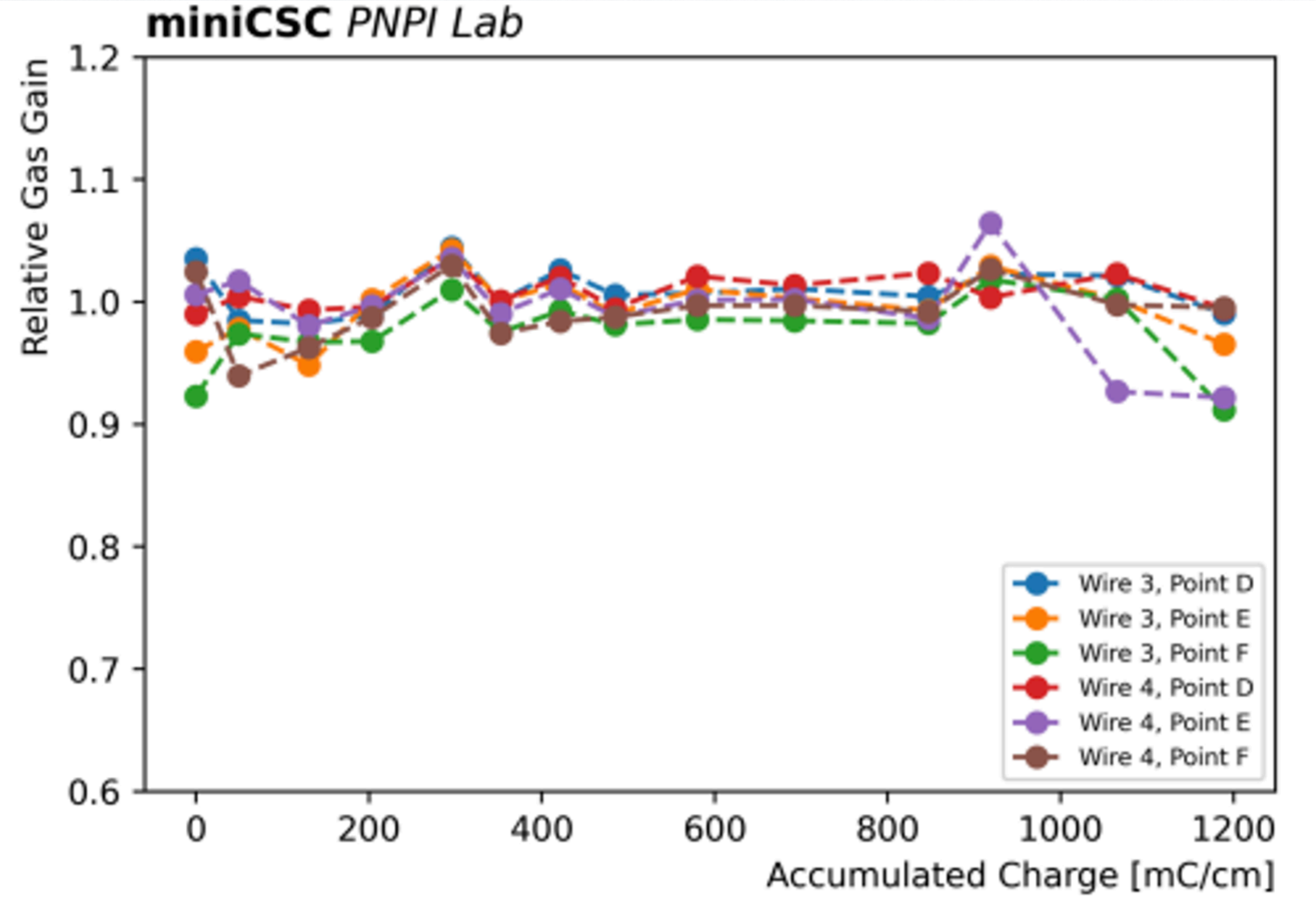


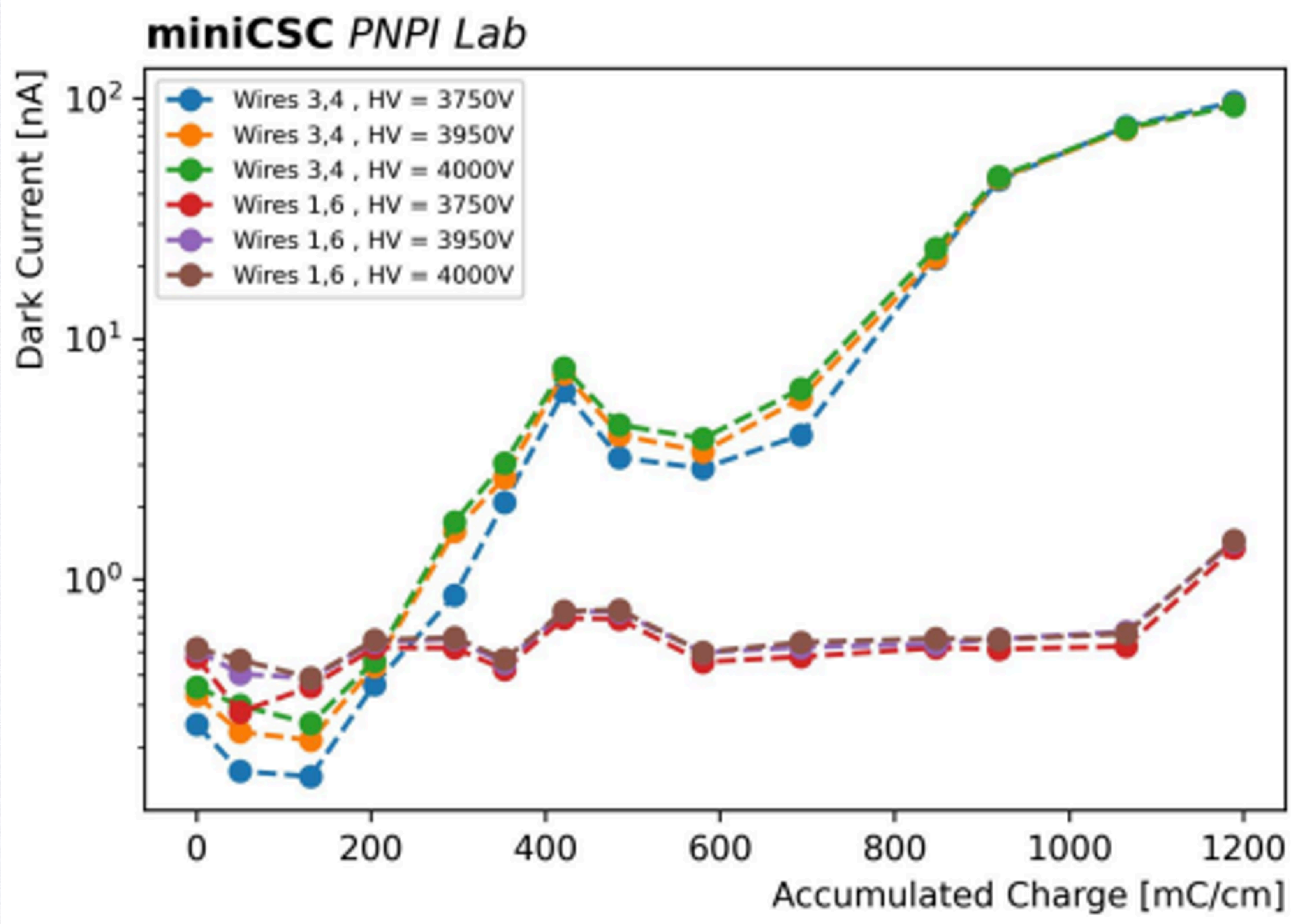
- Relative gain with the 2% of CF_4

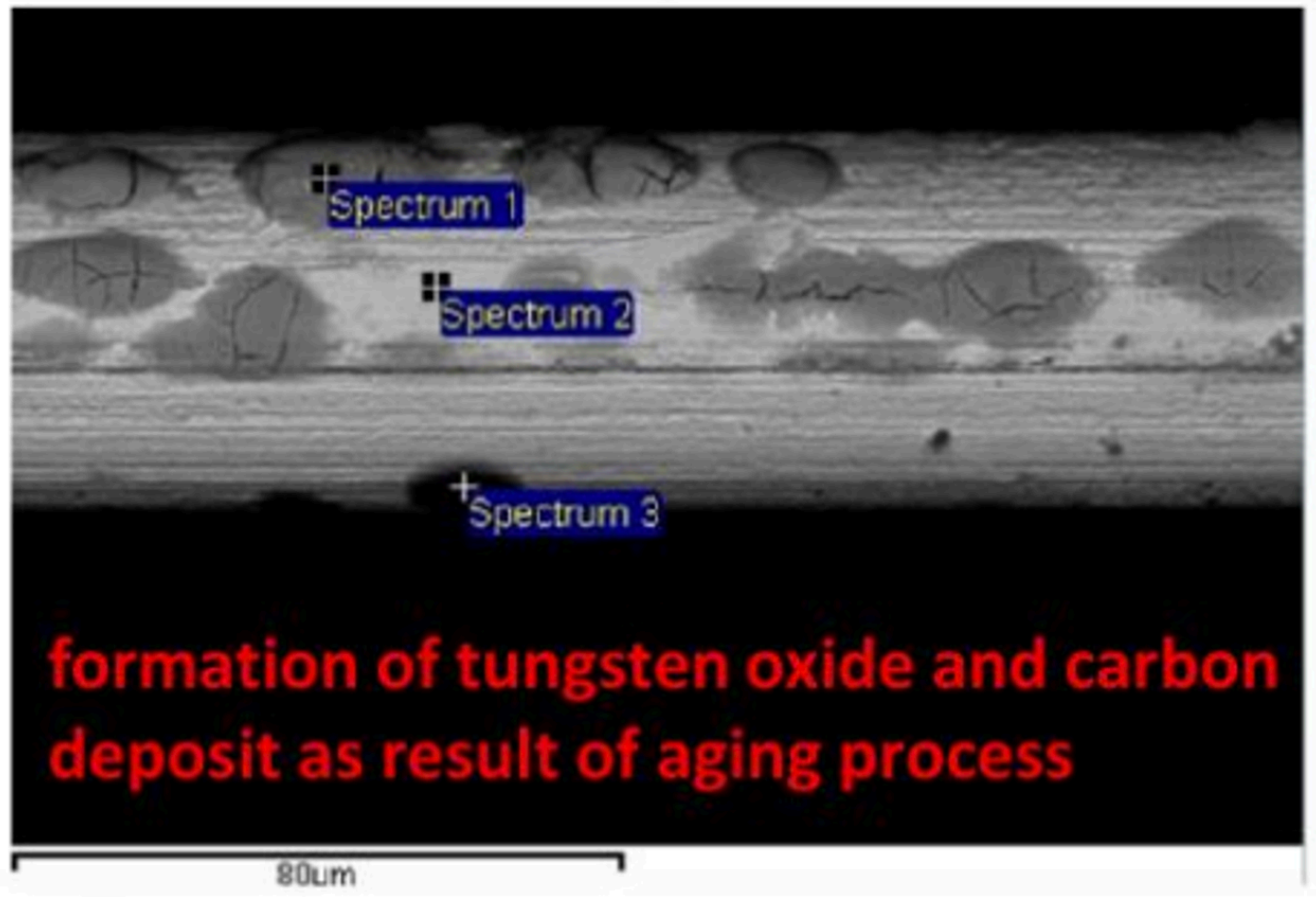
CSCs eco-gas studies

- Preliminary study, performed on a "mini-CSC" (30x30 cm2 CSC prototype), on the **alternative HFO**-1234ze gas:
  - stable gain up to 10 HL-LHC instantaneous luminosity
  - high increases of dark current only for HFO-1234ze gas mixture
    - probably due to a too high density of charge on the mini-CSC prototype, **to be repeated on a standard spare CSC**
  - presence of pollution is also seen







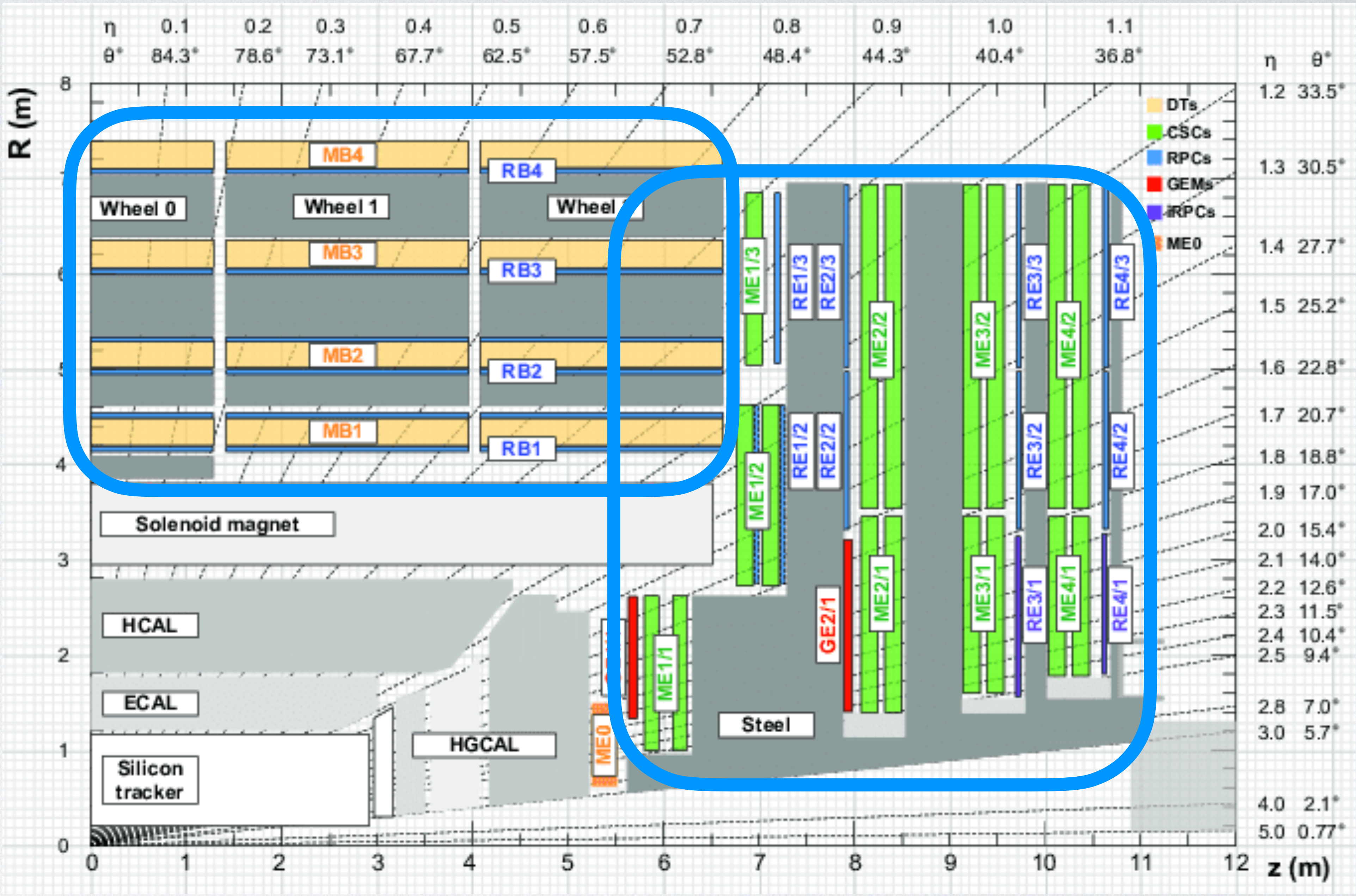


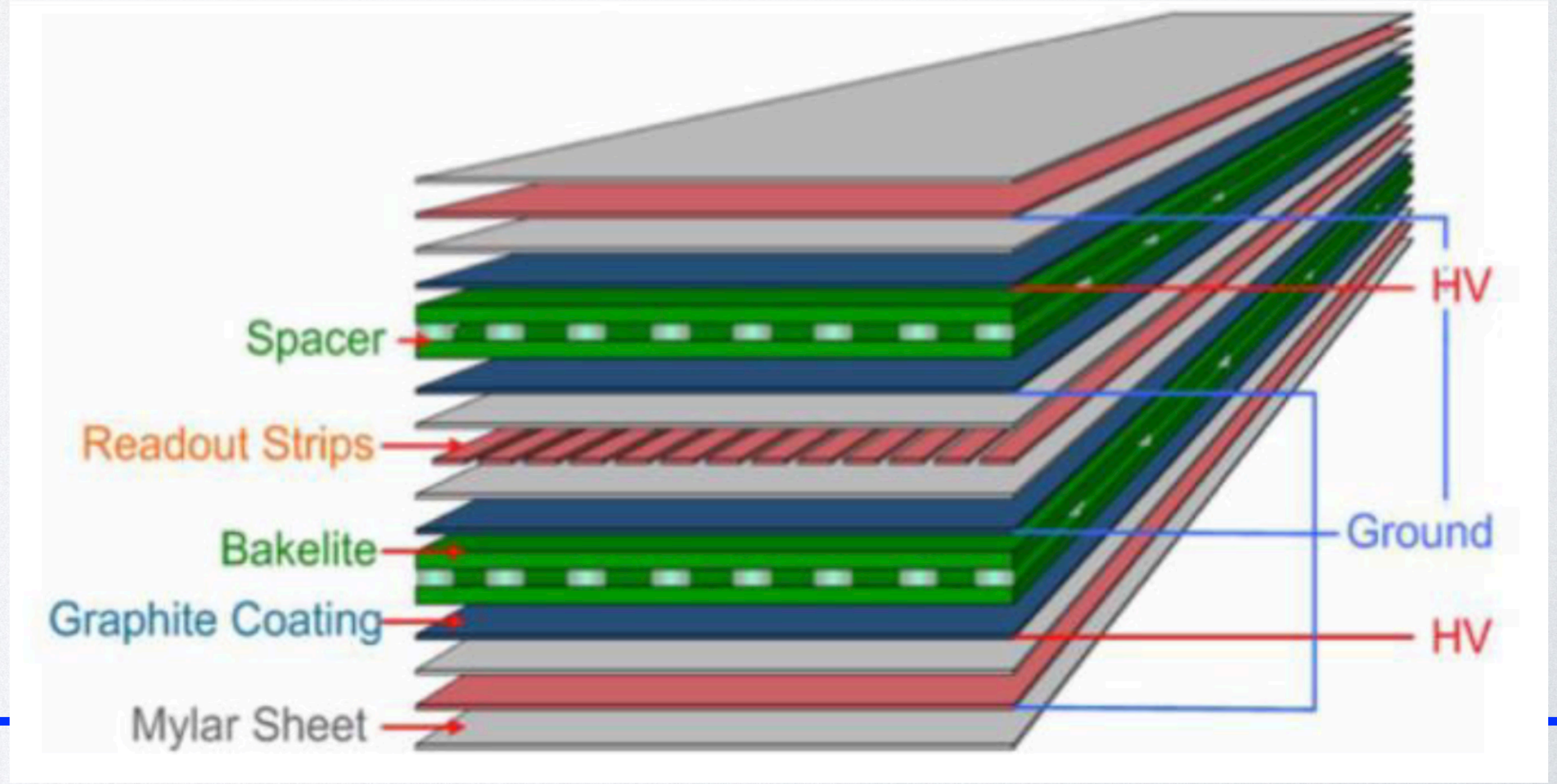
All results in weight%

Spectrum	In stats.	C	N	O	F	Al	Si	Cl	W	Au	Total
Spectrum 1	Yes	4.86	0.00	24.42				0.00	69.83	0.88	100.00
Spectrum 2	Yes	5.61	4.75	1.13				0.00	4.57	83.95	100.00
Spectrum 3	Yes	60.95	5.87	3.85	5.86	0.71	0.21	0.69	0.37	21.47	100.00

Resistive Plate Chambers (RPCs)

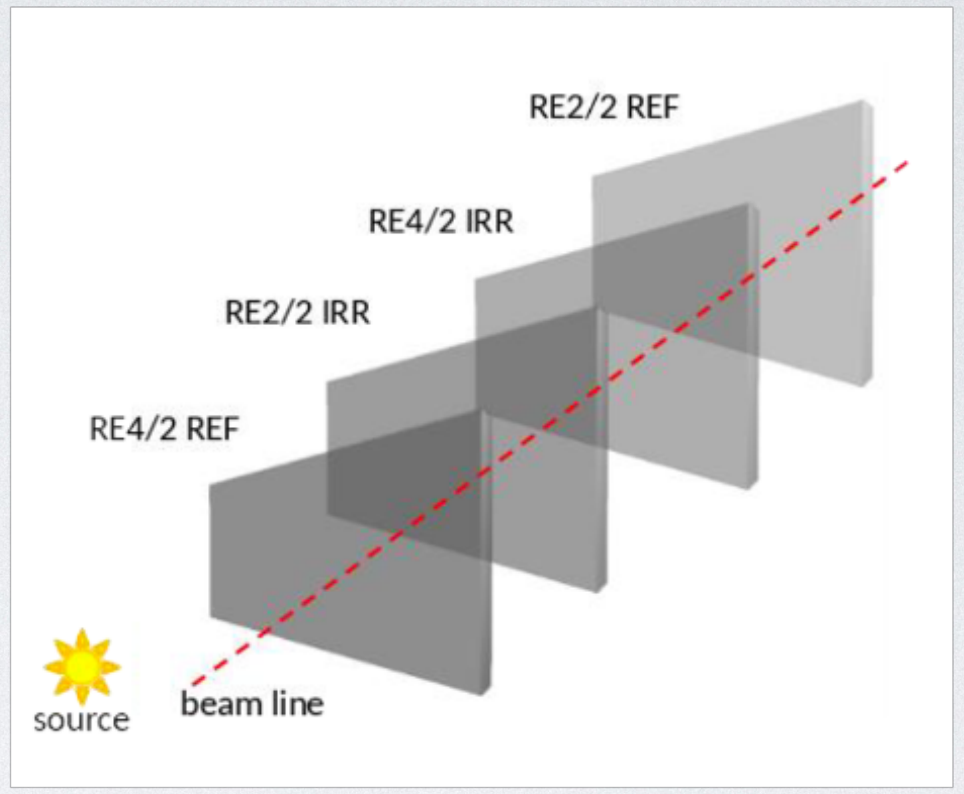
- RPCs are fast gaseous detectors located both in the **barrel** and in the **endcap**, that provide a **muon trigger system parallel** to those of the DTs and CSCs
- RPCs consist of two parallel plates (**double gap**), a positively-charged anode and a negatively-charged cathode, both made of a very high resistivity plastic material (bakelite bulk resistivity $\rho = 1 \sim 6 \times 10^{10}\ \Omega\text{cm}$) and separated by a thin gas volume
    - the electrodes are transparent to the signal (the electrons of the avalanche produced by the passage of a muon), which are instead picked up by external metallic strips after a small but precise time delay
        - RPCs combine a good spatial resolution with a time resolution of just one nanosecond
    - 2 mm gap width filled with **$C_2H_2F_4$(95.2%)+iso-C_4H_{10}(4.5%)+SF_6 (0.3%)** gas mixture, operated above 9000 V in avalanche mode

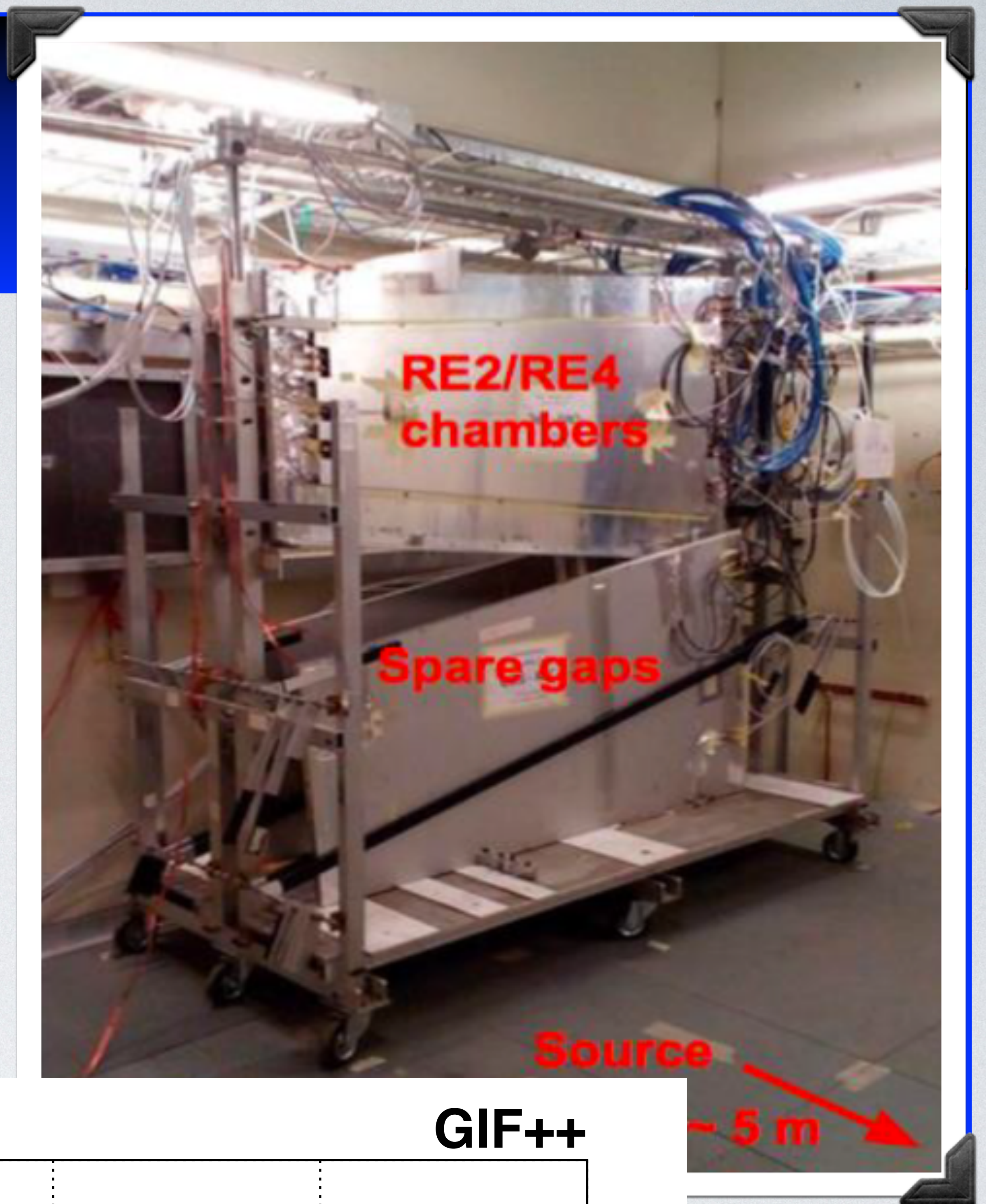


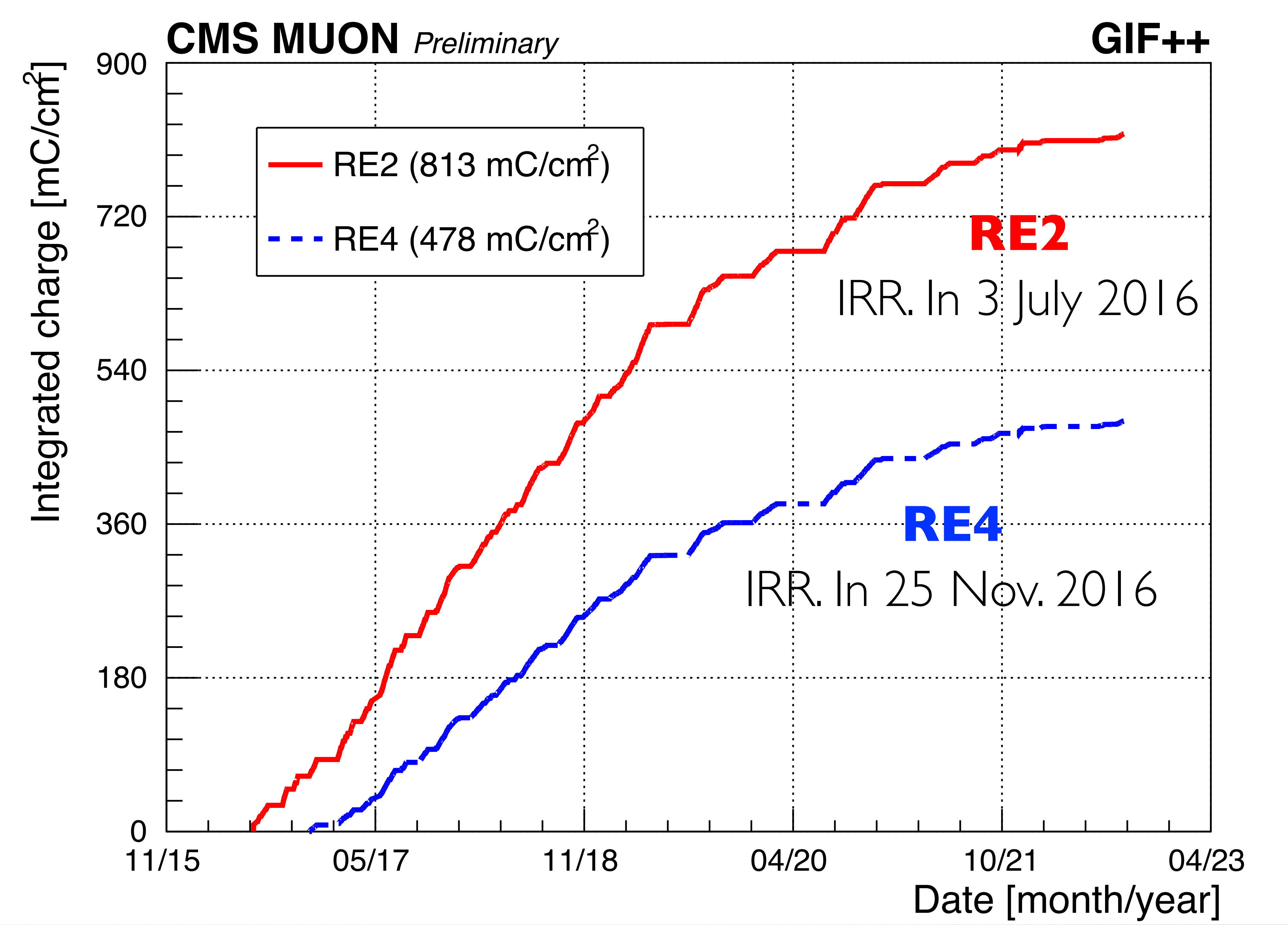


RPCs at GIF++

- Setup at GIF++ since July 2016
  - 2 RE2 chambers (one irradiated, one as reference)
  - 2 RE4 chambers (one irradiated, one as reference)
- Expected Integrated charge at HL-LHC:
  - Max Integrated Charge: ~ 280 mC/cm2 → ~ 840 mC/cm2 (safety factor 3)
  - barrel chambers have a factor 2 less
- Expected rate at HL-LHC:
  - Max Rate: ~ 200 HZ/cm2 → ~ 600 HZ/cm2 (safety factor 3)
  - barrel chambers have a factor 2 less
- Rates measured in the Run 3 data confirm the improvements due to the shielding installation

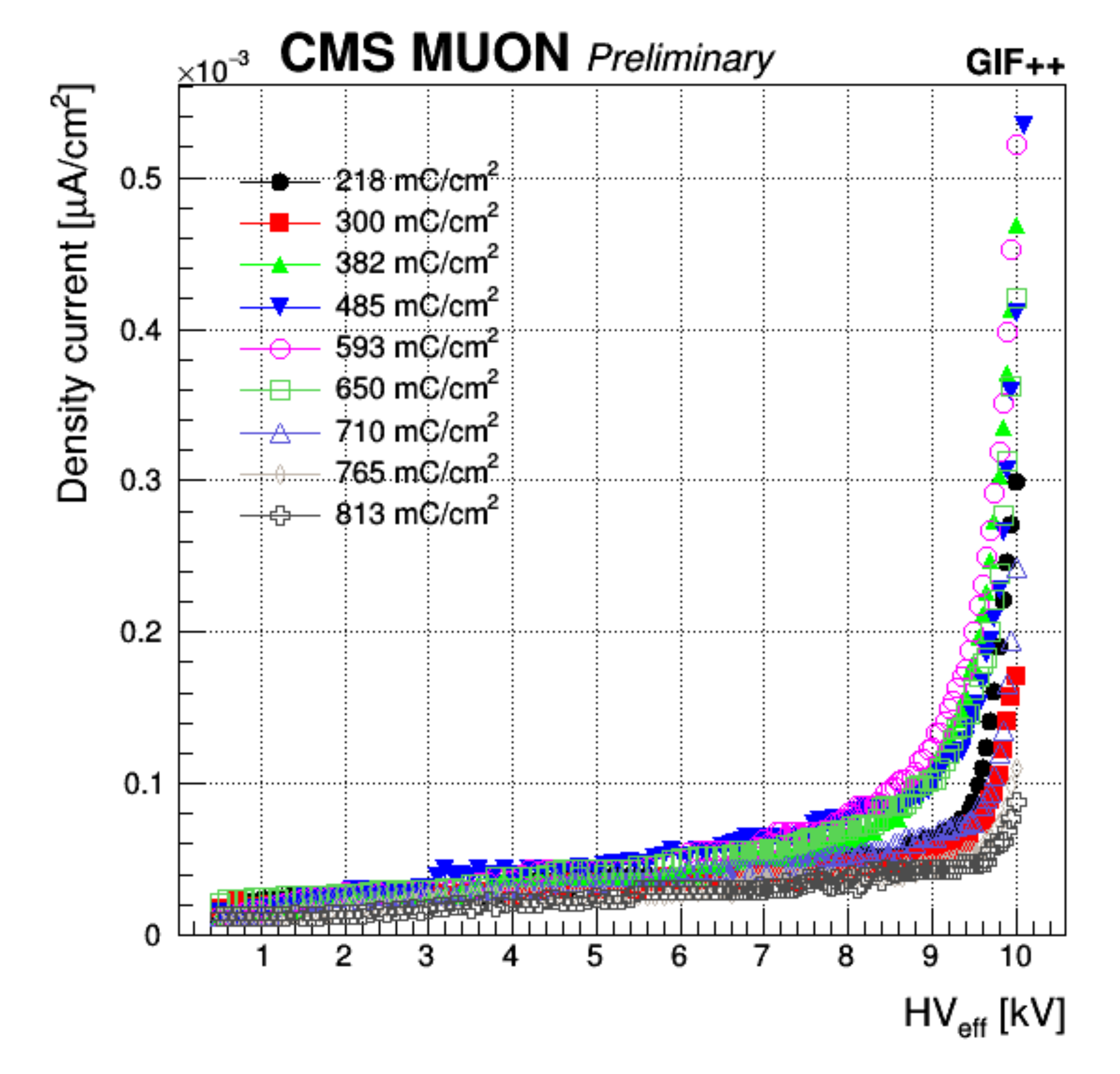


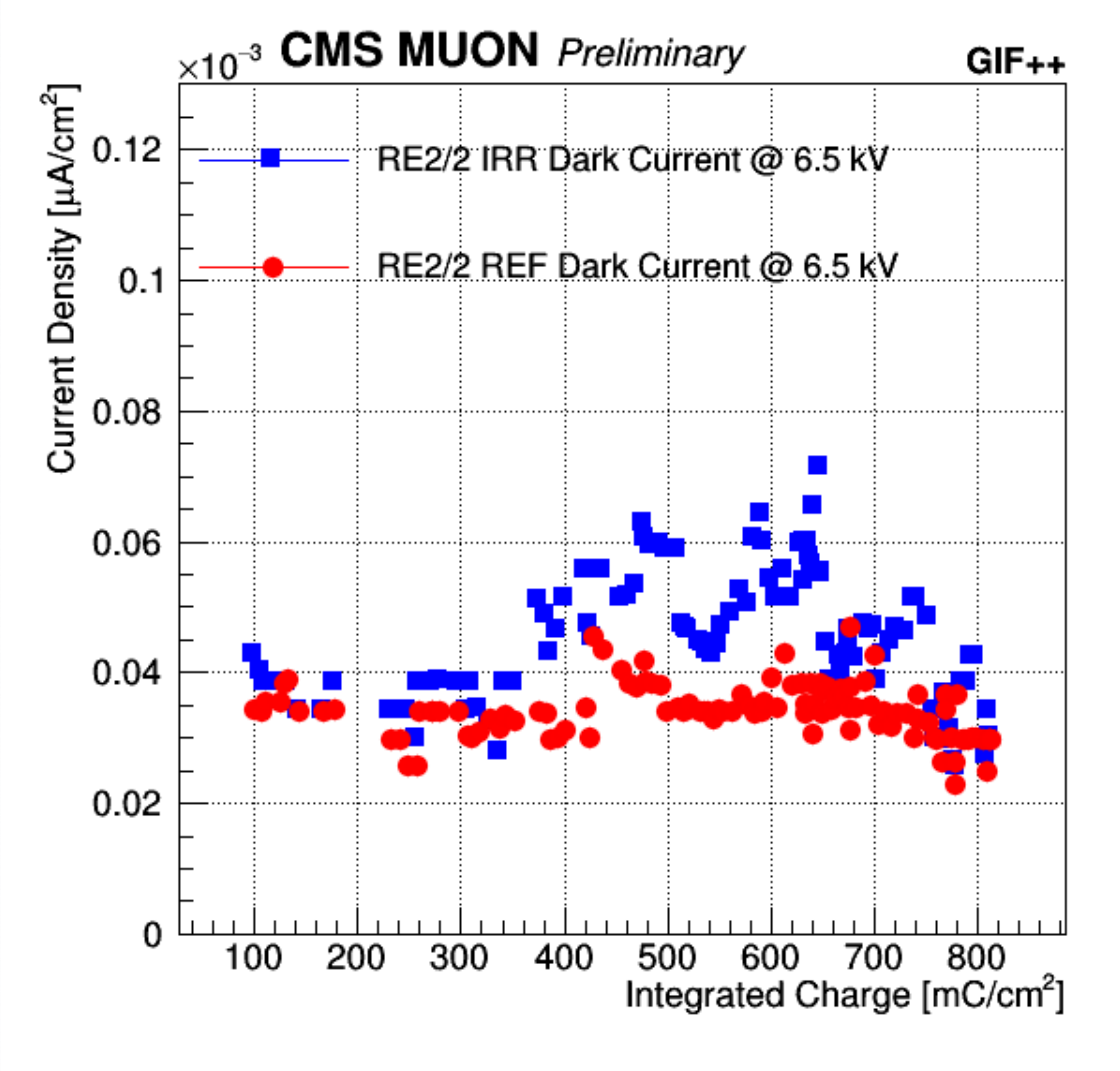


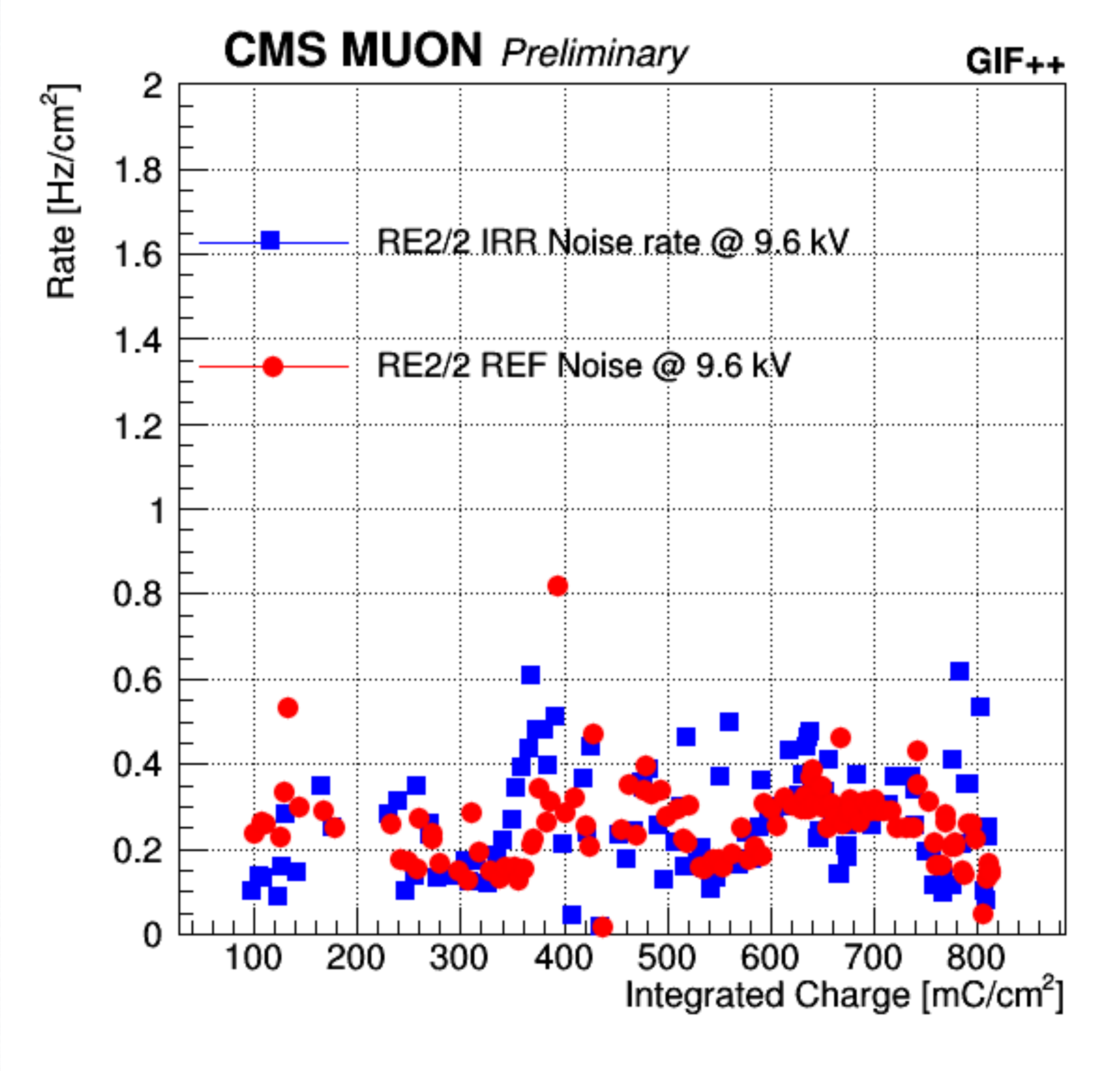


RPCs longevity studies

- **Dark current almost stable** with time up to 3 HL-LHC (different curves) and in agreement with values before the irradiation for both irradiated and reference chambers
- **Noise rate is almost stable** with time, with average noise rate less than 1 Hz/cm^2
  - fluctuations, even large, don't show a stable trend of increase
  - results obtained with source off

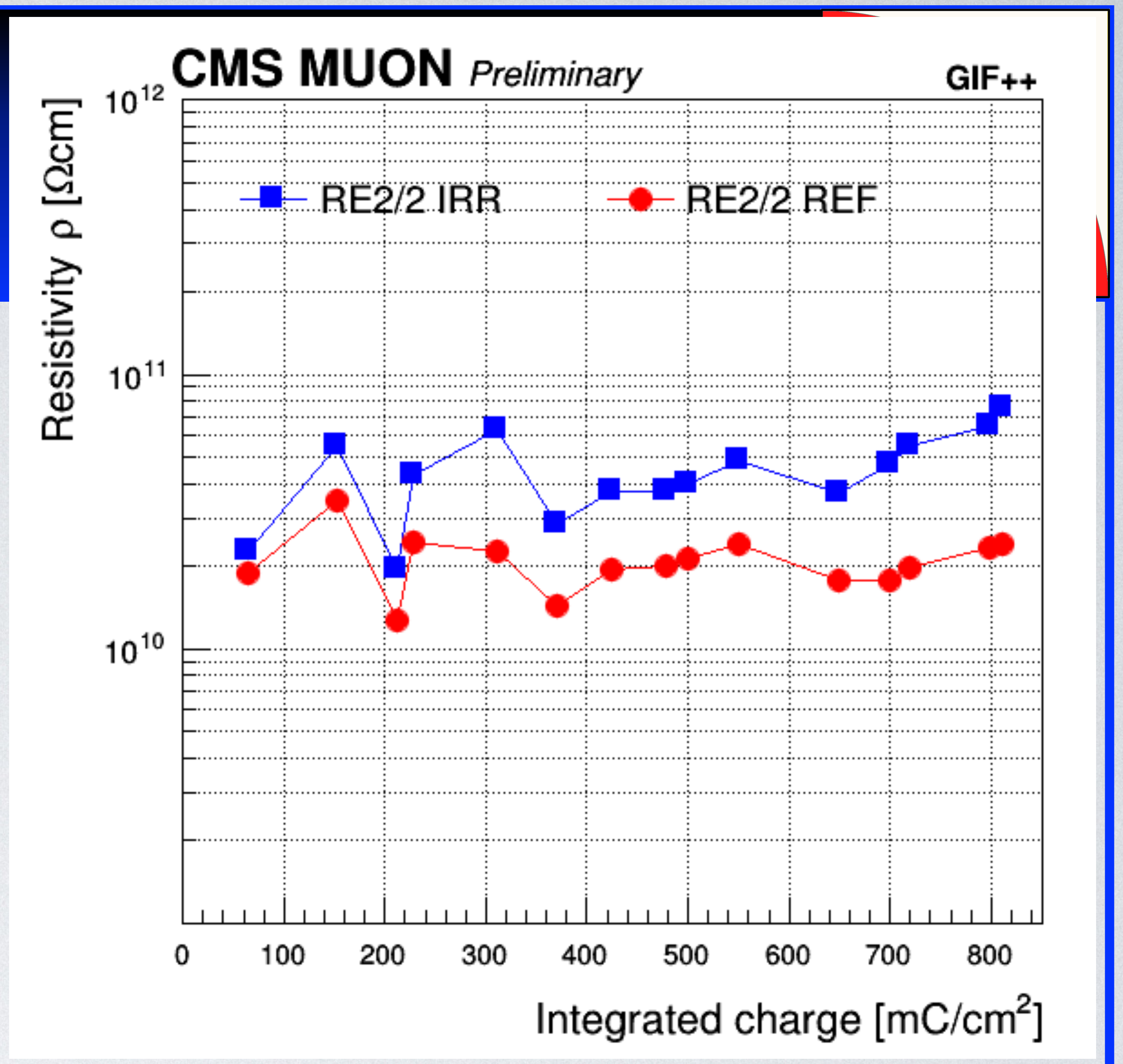




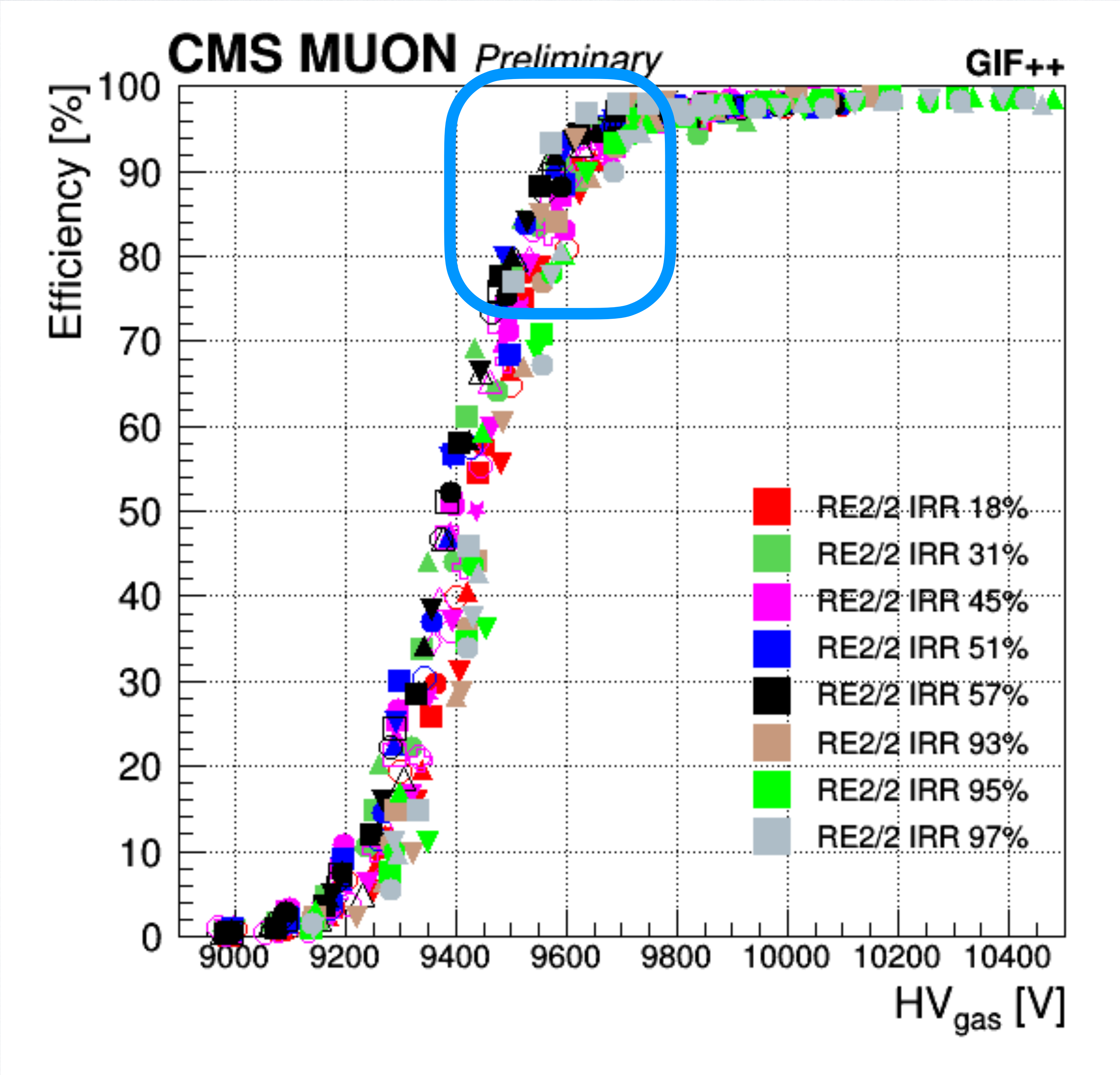


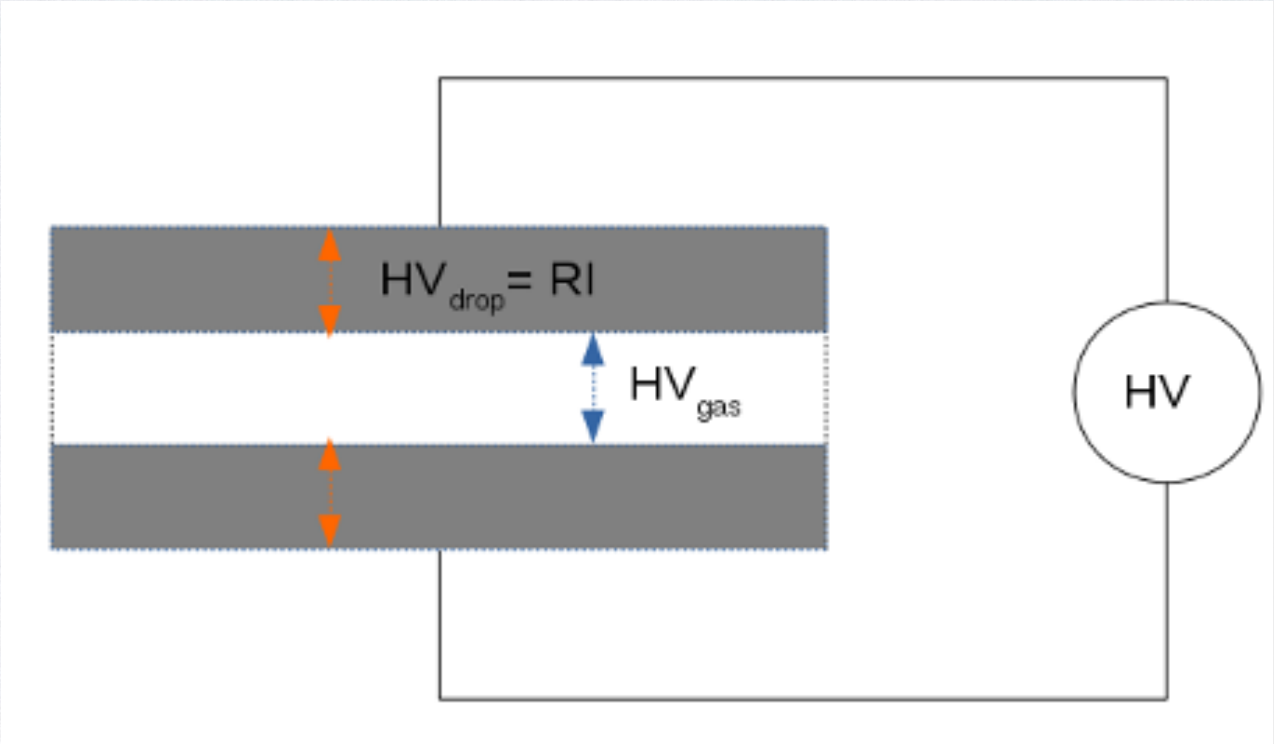
- Ohmic current (up to 6.5 KV) is the most stable
- Total current (around 9.5 KV) is also stable with larger fluctuations

RPCs resistivity and effective HV



- **Resistivity** is periodically measured running the chambers with pure Argon in a self-sustained streamer mode:
  - trend of rise in the irradiated chamber
  - **changes in the resistivity can be compensated** by increasing the effective HV = HV_{gas} + RI (voltage drop)

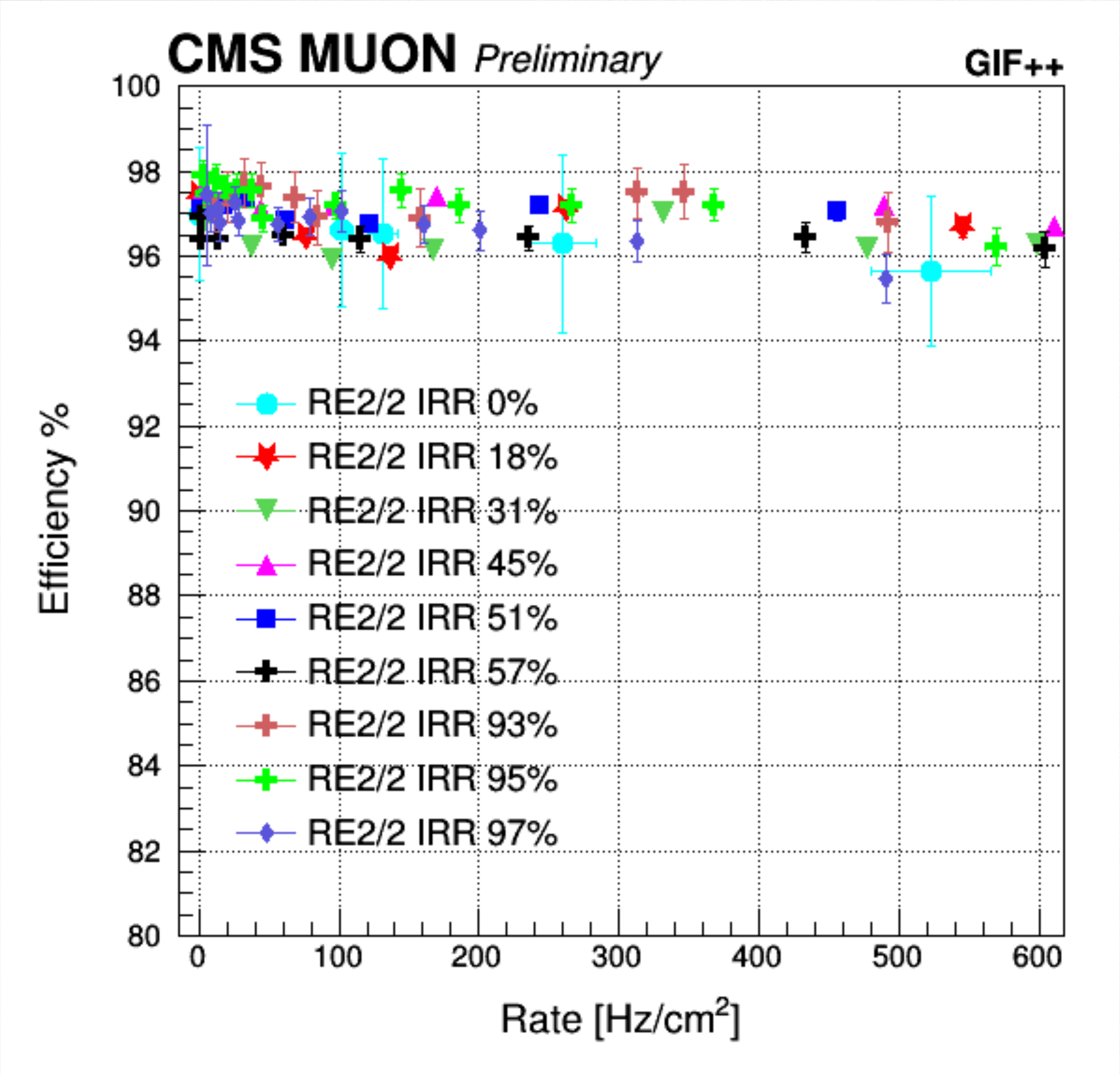


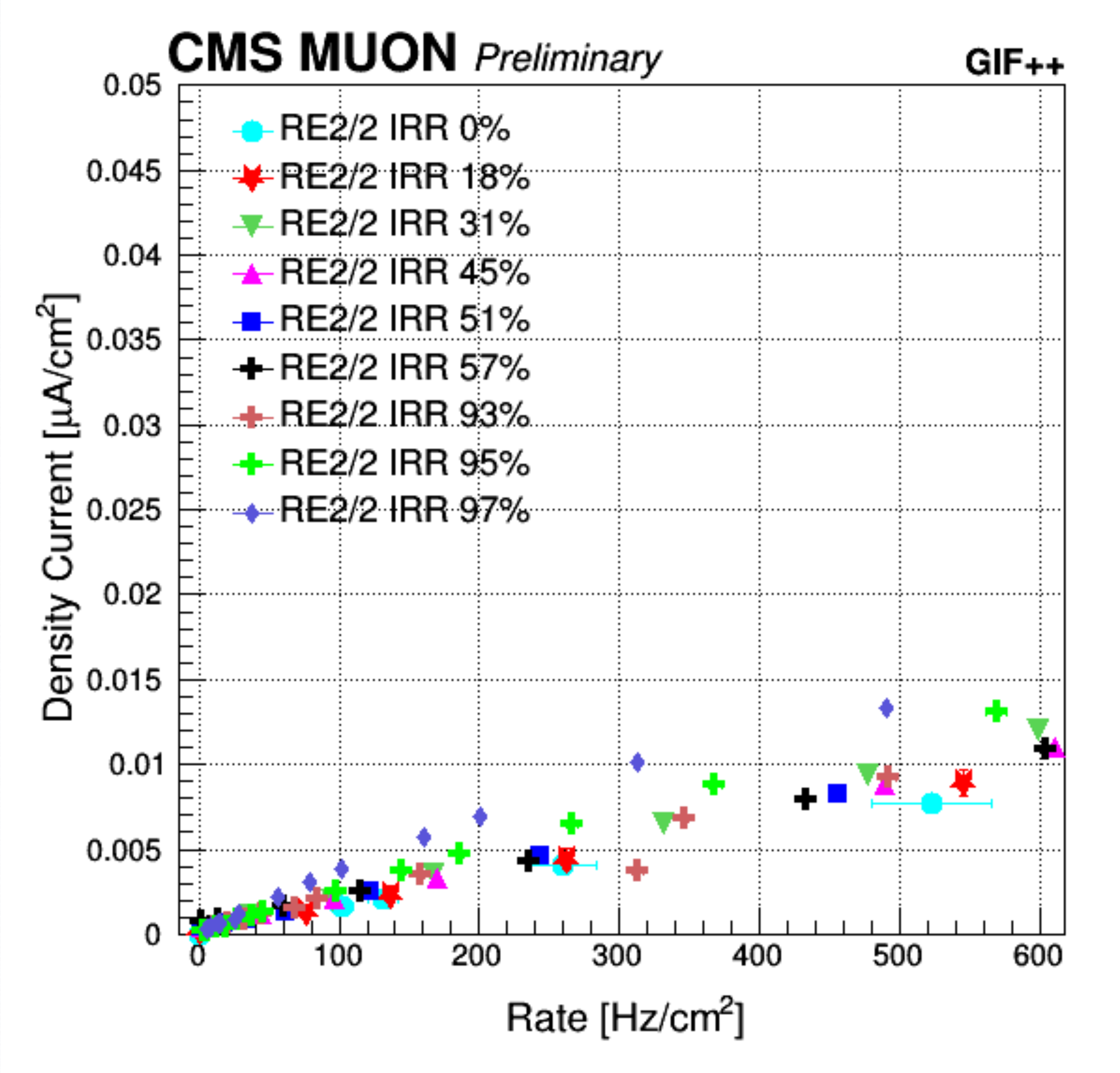


- Performance is measured at the HV working point (WP), defined as the HV at knee + 150V
- Test Beam results with source ON (simulating background rates):
  - efficiency is rather stable at different values of integrated charge (different colours) and background rates (different markers)
  - no significant shifts are observed (HV value for WP is quite stable)

RPCs performance at WP

- **Efficiency** for the defined WP is quite **stable** as a function of the integrated charge (% of irradiation) at the maximum expected rate (600 Hz/cm²)
- **Gain** (density of current) linearly depends from the rate:
  - linearity is rather **stable** increasing the integrated charge (curves overlap, except for deviation in the latest measurement, which is due to a technical issue)

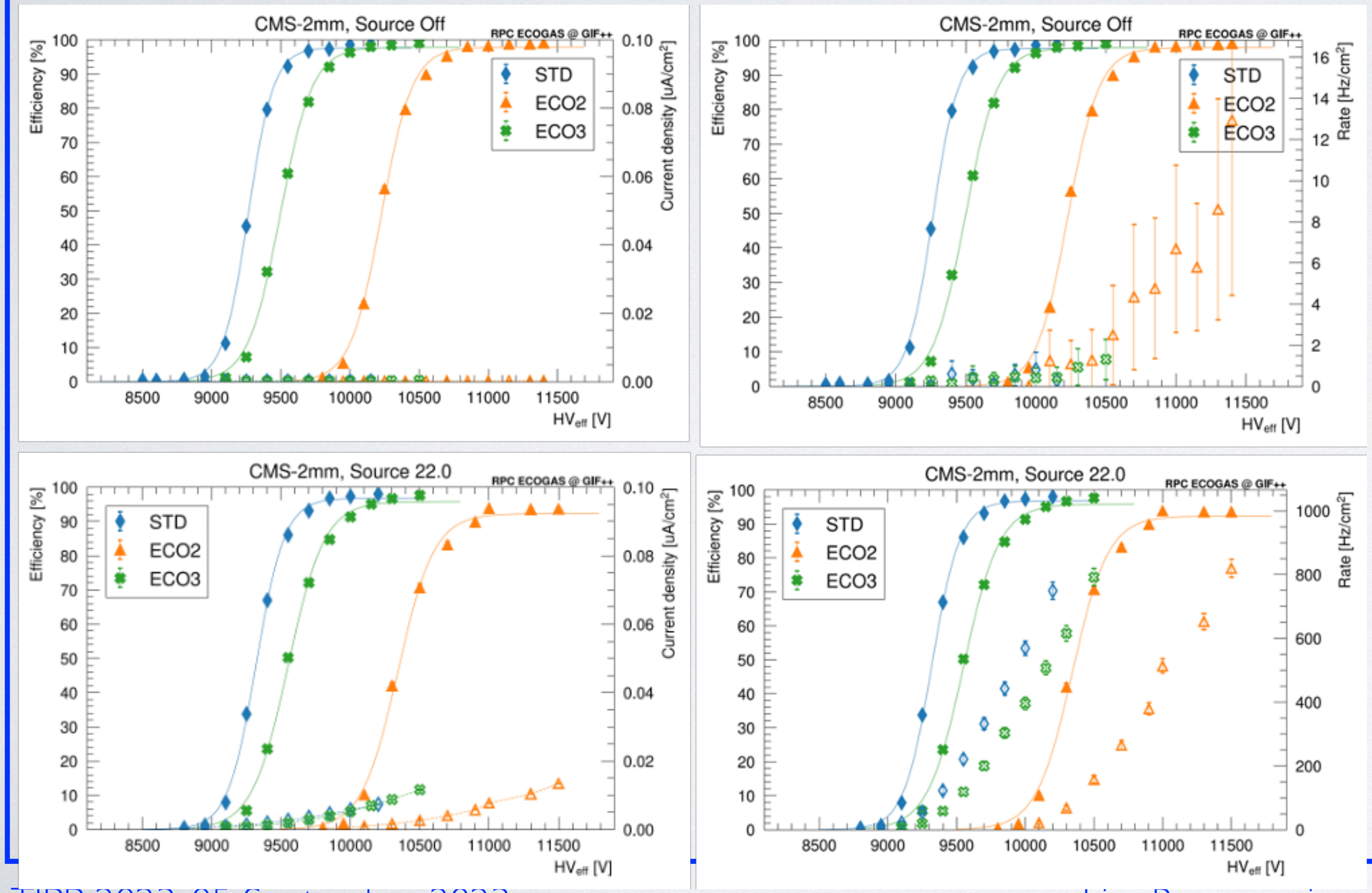




- results obtained during Test Beam with source on (simulating background rates)

RPCs eco-gas

- How to reduce the use of $C_2H_2F_4$:
  - **recuperation**: extensive leak repair campaign has been done during LS2
    - the commissioning of gas recuperation system almost completed and allows up to 80% of recycling efficiency (re-injection of Freon)

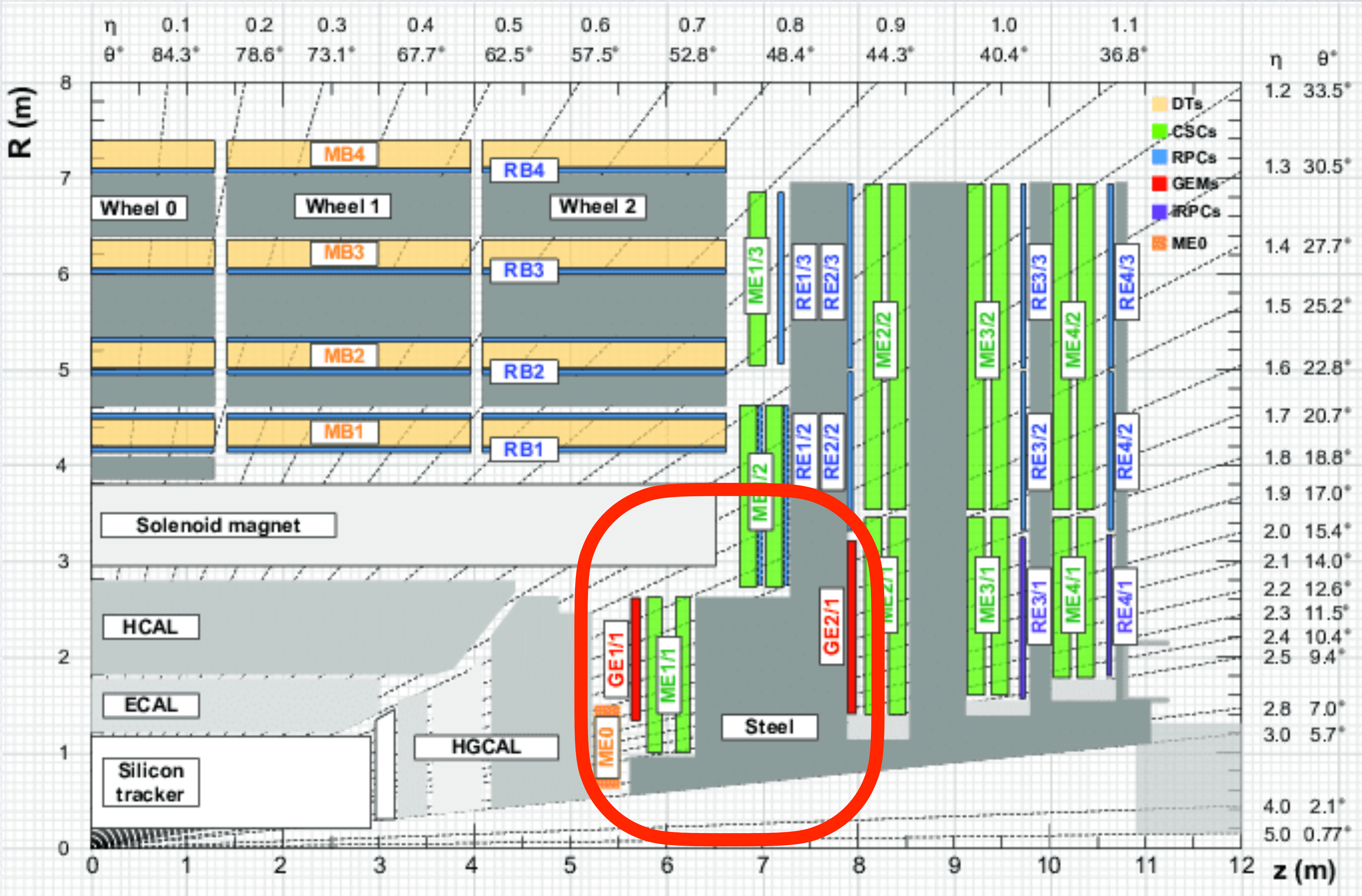


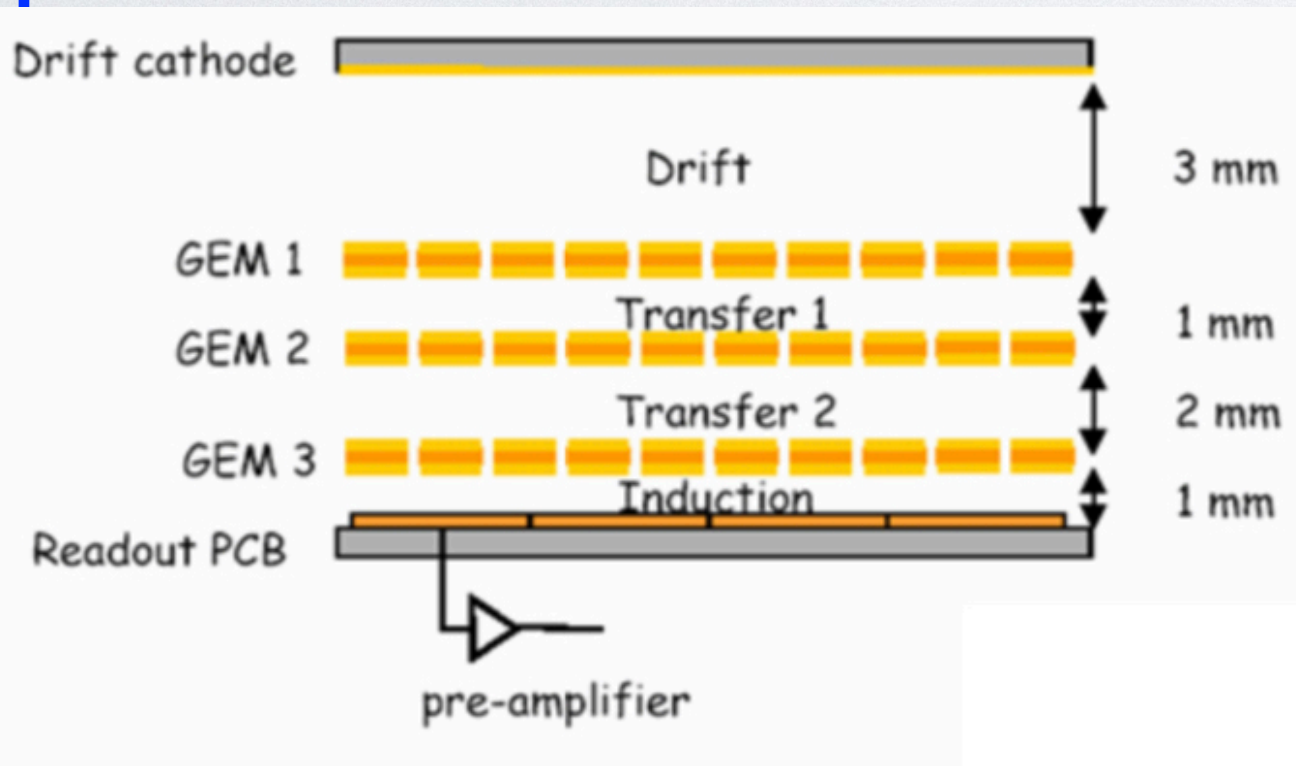
- **substitution**: joint collaboration (ATLAS, CMS, LHCb, CERN, SHIP) currently testing 2 HFO-based alternative mixtures:
  - CMS studies carried out by AIDAinnova Task WP 7.2.3
  - preliminary **results look promising**, but longer term irradiation tests are needed to be conclusive

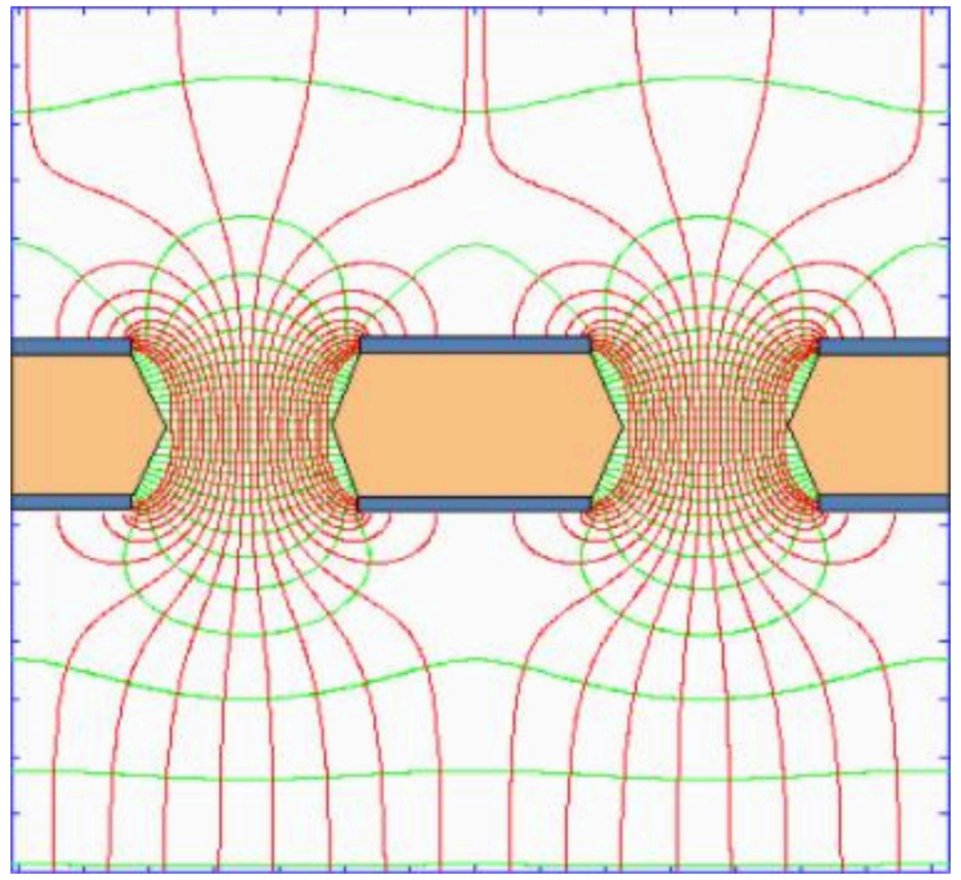
- **standard gas mixture**
- **CO_2 60%, HFO 35 %, iC_4H_{10} 4%, SF_6 1%**
- **CO_2 69%, HFO 25 %, iC_4H_{10} 5%, SF_6 1%**

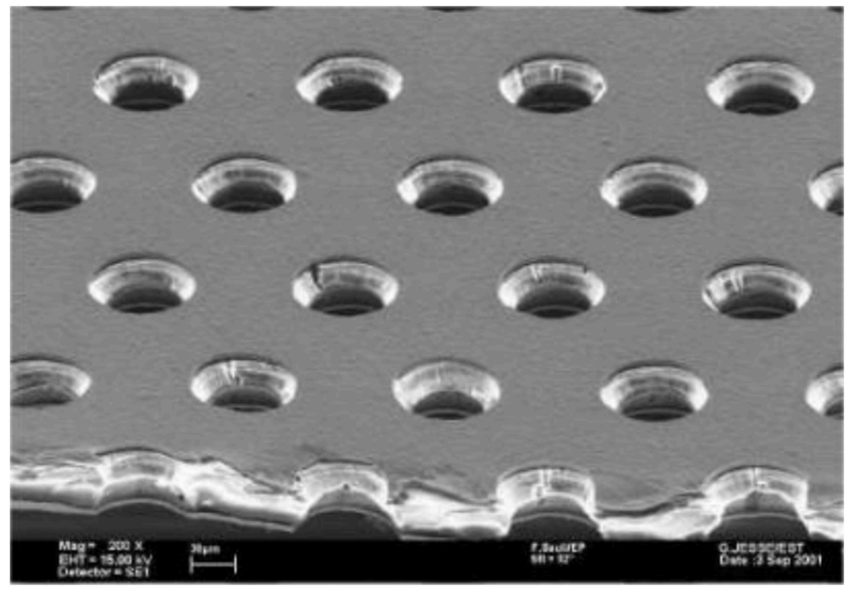
Gaseous Electron Multiplier (GEMs)

- GEMs complement existing detectors in the **forward endcap regions close to the beam pipe**, where large radiation doses and high event rates are critical, and will increase further during HL-LHC
  - the GEM chambers will improve the measurement of the polar muon bending angle, allowing the trigger of the muon system to cope with the high rates, and will further extend the muon system coverage in the very forward regions
- GEM chambers are gaseous detectors consisting of two PCBs, containing the gas volume (Ar/CO_2), and a stack of three GEM foils in between
  - the **GEM foil** consists in a 50 um-thick insulating polymer (polyimide) surrounded on the top and bottom with copper conductors
    - throughout the foil, microscopic holes are etched in a regular hexagonal pattern: a potential difference applied across the foils generates sharp electric fields in the holes





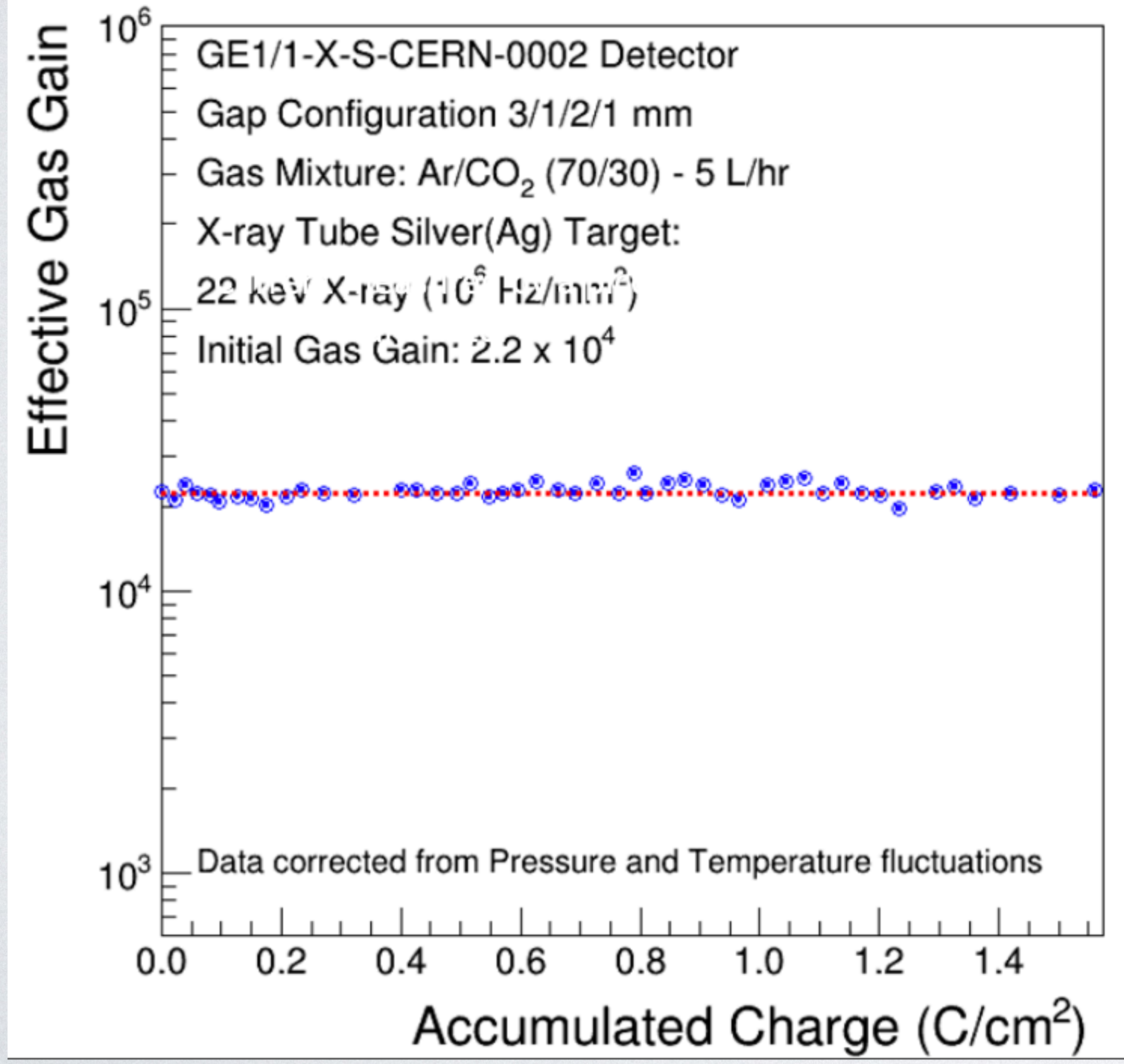


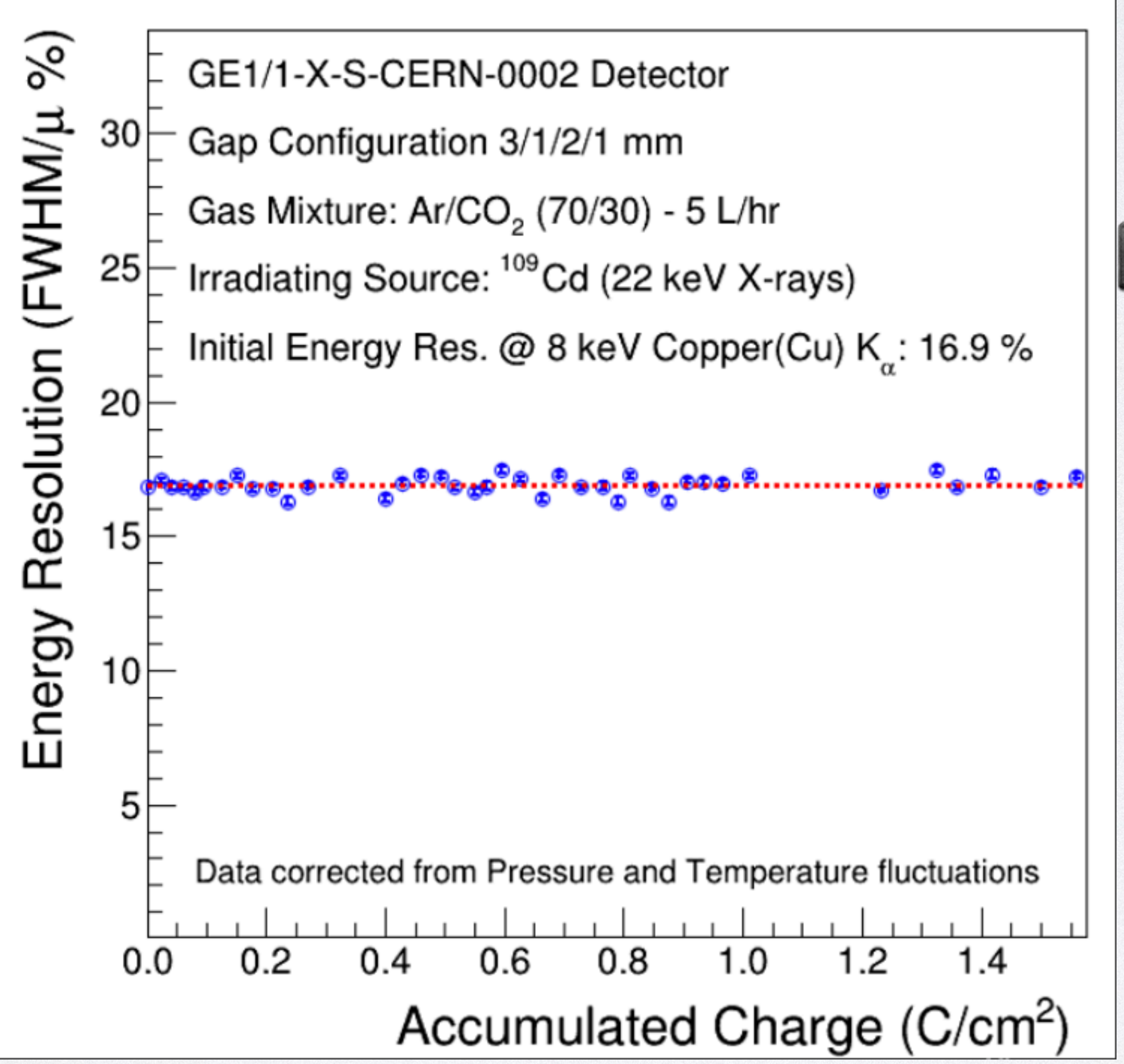


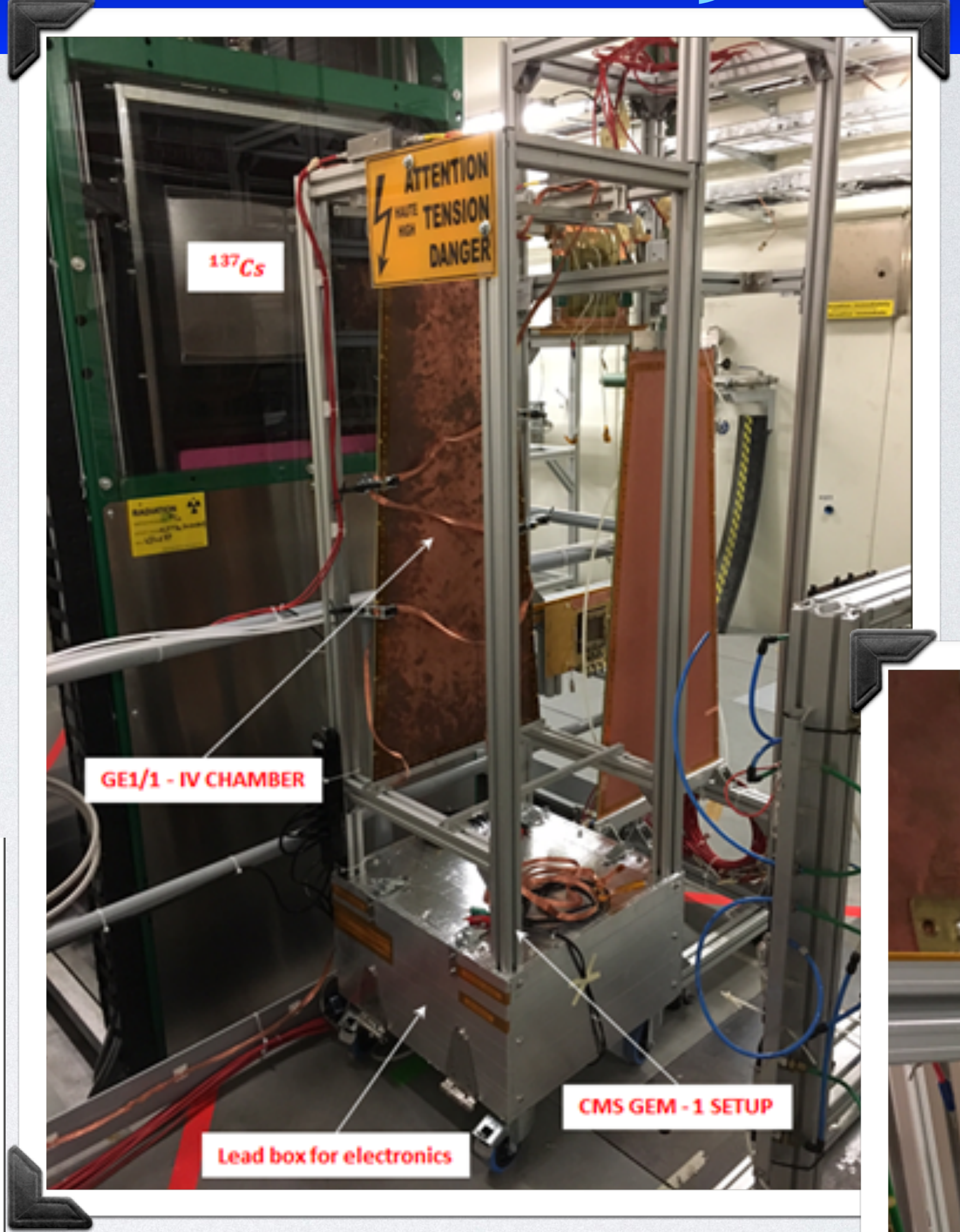
- The CMS GEMs are the first GEM chambers with such a large size (an area of about 0.5 m^2)
  - a first batch of 144 chambers was installed during **LS2** on the first disk of the two endcaps (**GE1/1**)
  - two more disks of GEM chambers will be installed in each endcap during 2024-2026, before **HL-LHC** (**GE2/1 and ME0**)

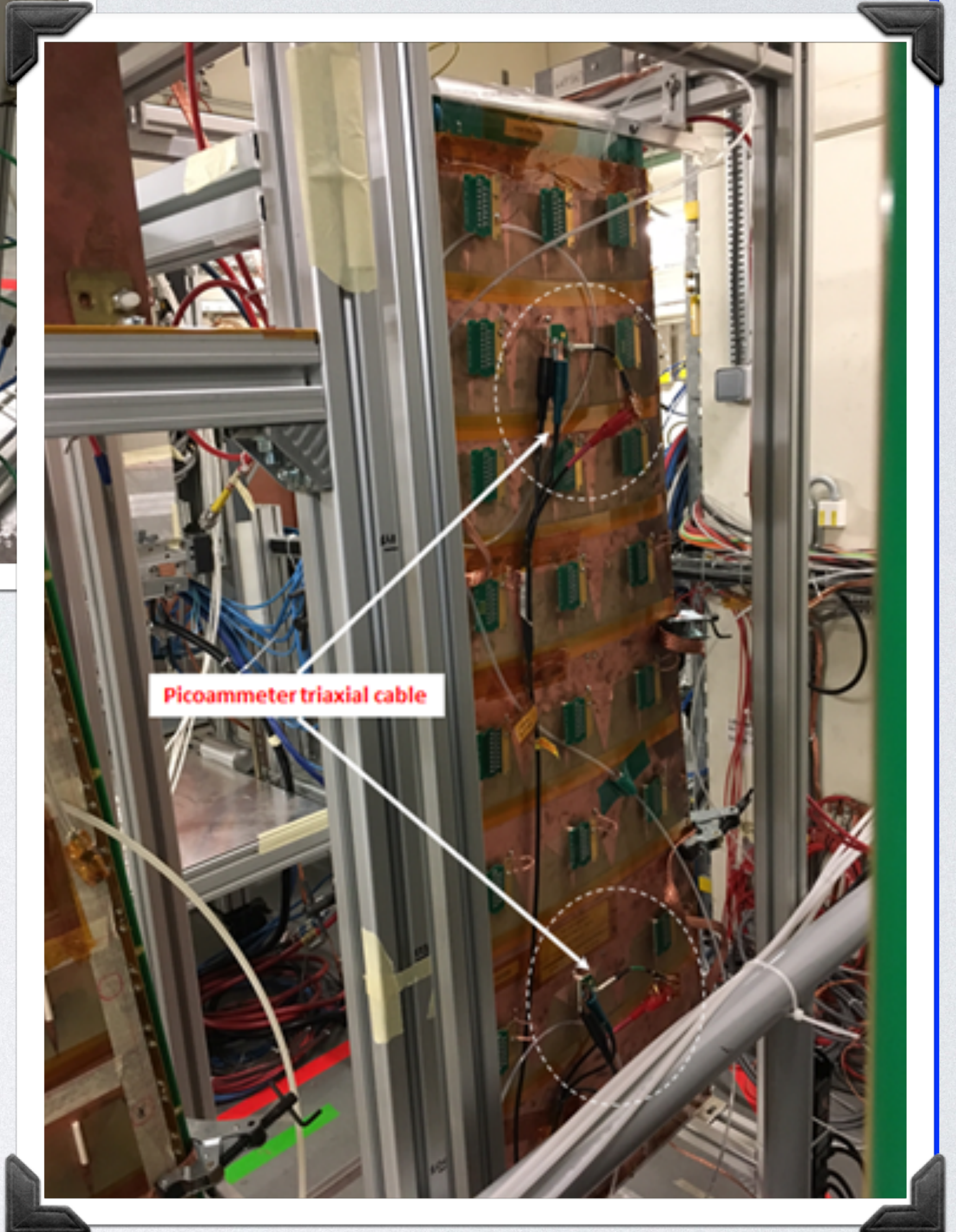
GEMs at GIF++ and 904 Lab: GE1/1, GE2/1

- Studies carried out at GIF++ and in the CERN 904 Lab (**X-ray gun**) to validate GE2/1 and GE1/1 stations
- Expected integrated charge:
    - 60 mC/cm^2 GE1/1 → validated up to 3.6 HL-LHC
    - 30 mC/cm^2 GE2/1 → validated up to 7 HL-LHC





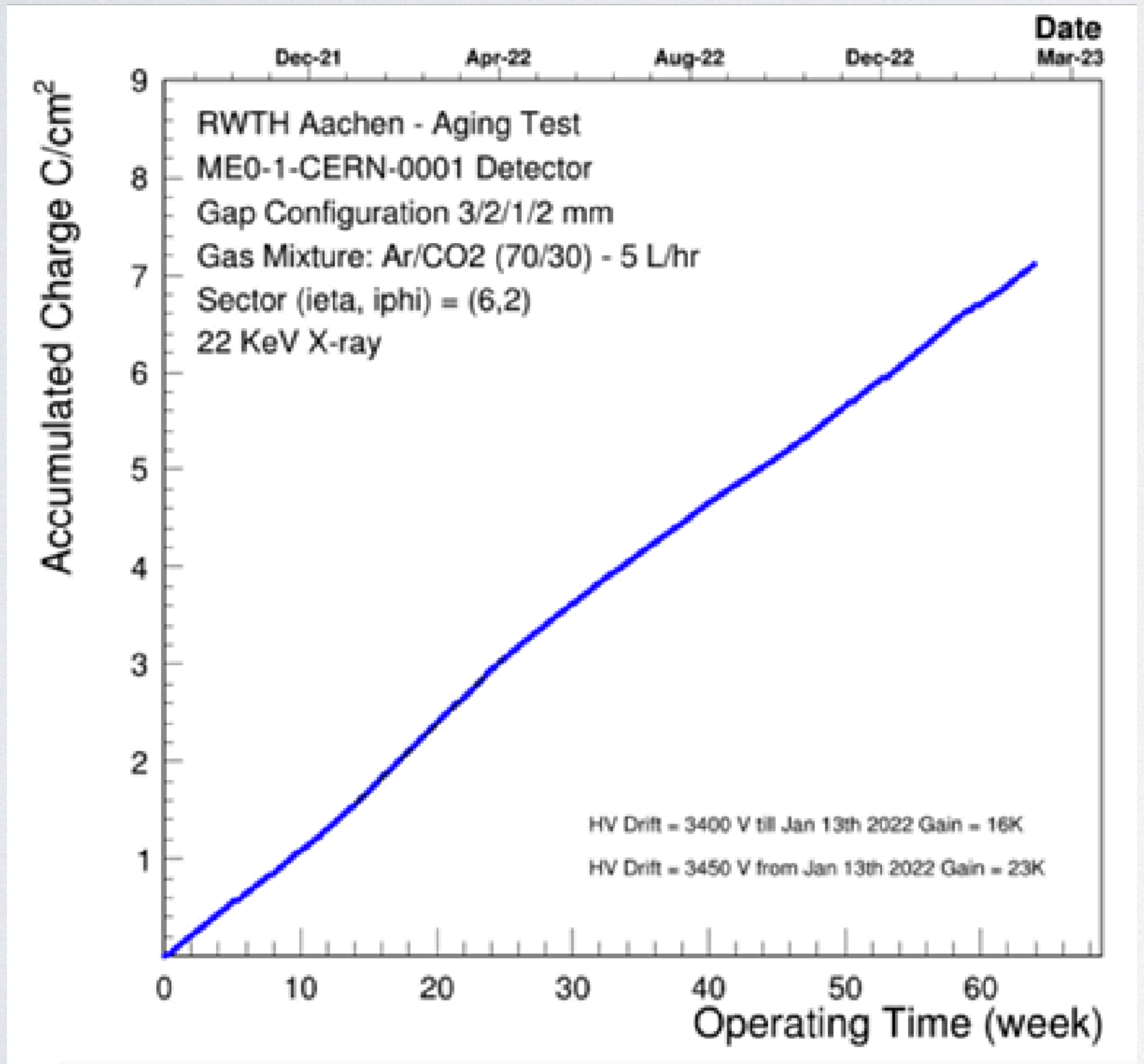


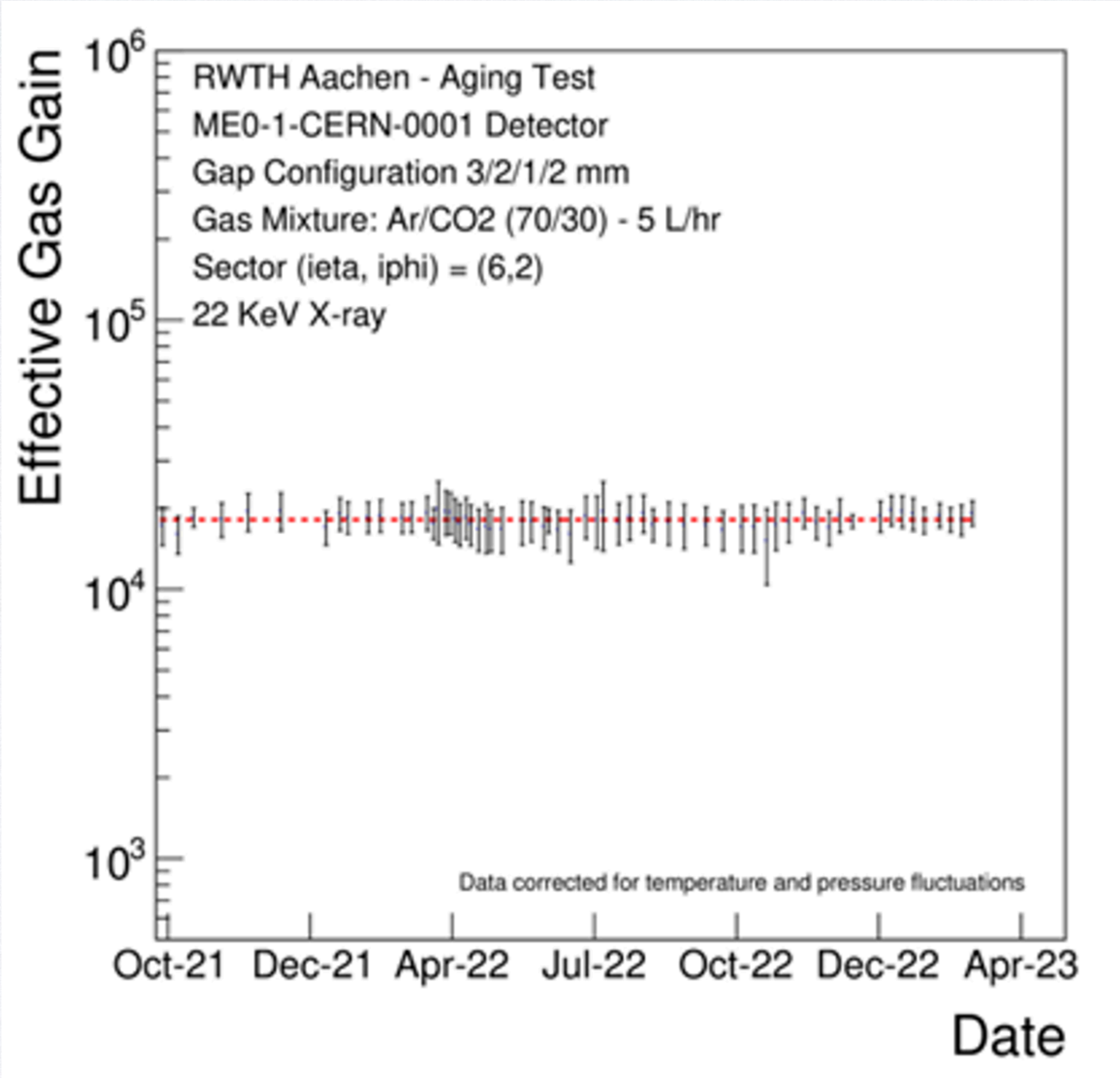


- **no signs of aging** up to 1.5 C/cm^2
    - GE1/1 and GE2/1 fully validated

GEMs at GIF++ and 904 Lab: ME0

- Expected integrated charge:
  - 7900 mC/cm² ME0 → recently validated up to 1 HL-LHC (approved shown plots reach 7100 C/cm²)
  - accelerated irradiation (8 times more than GIF++) is ongoing in X-ray facilities (in Aachen and Seoul)





- ME0 gain is stable
- **no signs of aging up to 1 HL-LHC** for ME0

Conclusions

- Longevity studies have been ongoing since many years **to estimate the performance of the CMS Muon System in the harsh HL-LHC conditions**

- The results obtained for the aging studies carried out at the CERN GIF++ (and in detectors Lab) show that the CMS **muon system can continue to efficiently operate**:

    - **mitigation strategies** are already in place in oder to slow down the possible aging of the **DTs**, that in any case is not expected to compromise the global muon reconstruction and trigger performances in the barrel

    - huge effort ongoing to improve the gas system technology to allow operations with a **reduced consumption of the GHG** for **RPCs** and **CSCs**
        - further studies ongoing to find alternative gas mixtures

    - present results obtained at X-ray facilities confirm that **GEM** detector technology can sustain the HL-LHC operations

Thanks!