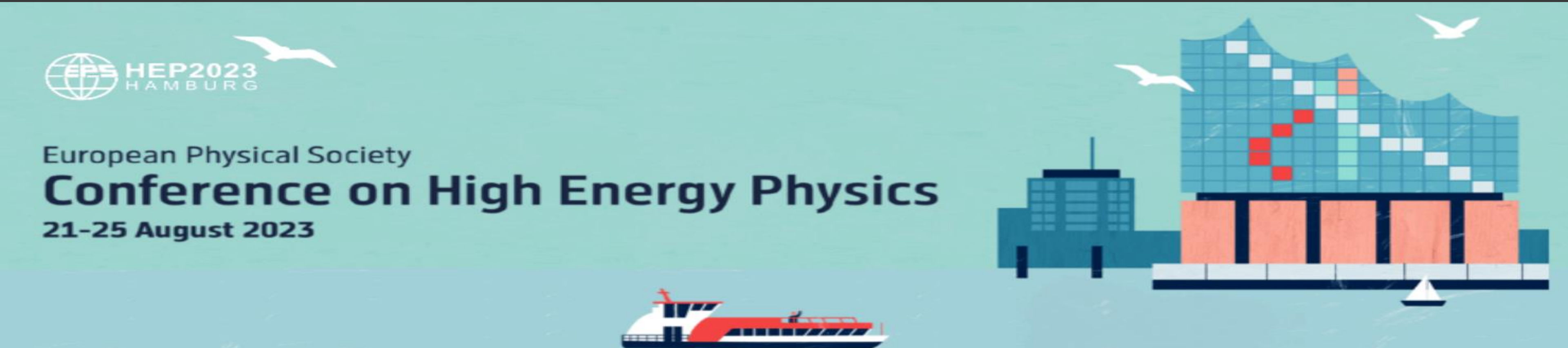
Longevity studies for the CMS Muon System towards HL-LHC

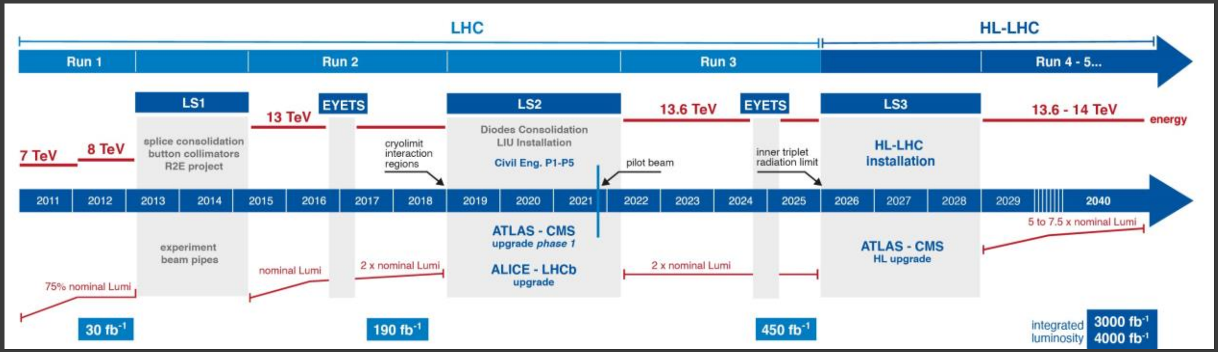
Federica Primavera (Bologna University and INFN)
on behalf of the CMS Collaboration

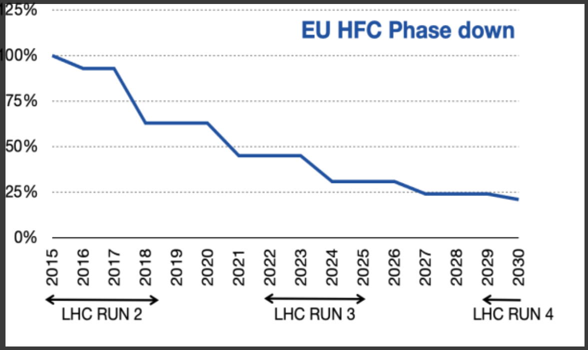


Introduction

The CMS Muon Spectrometer, composed by gaseous detectors, was designed to deal with the LHC conditions

- excellent performance for both efficiency and resolution
- essential for trigger and reconstruction





A major upgrade of the LHC is planned to fully exploit the physics potential of the accelerator (Phase2)

- higher PU environment 140 (up to 200)
- expected instantaneous luminosity of ~5(7)x 10^{34} cm^{-2} sec^{-1} (5 x LHC)
- integrating about a 10 times larger LHC design luminosity (3000 fb^{-1})

CERN, according to the European strategy to phase down of greenhouse gases planned:

- the reduction of the consumption by mid Run3
- the use of alternative gases in longer terms

Worse background conditions will not only accelerate the aging process of the detectors and electronics component, but also result in increased trigger rates, which translate into more demanding requirements on the electronics

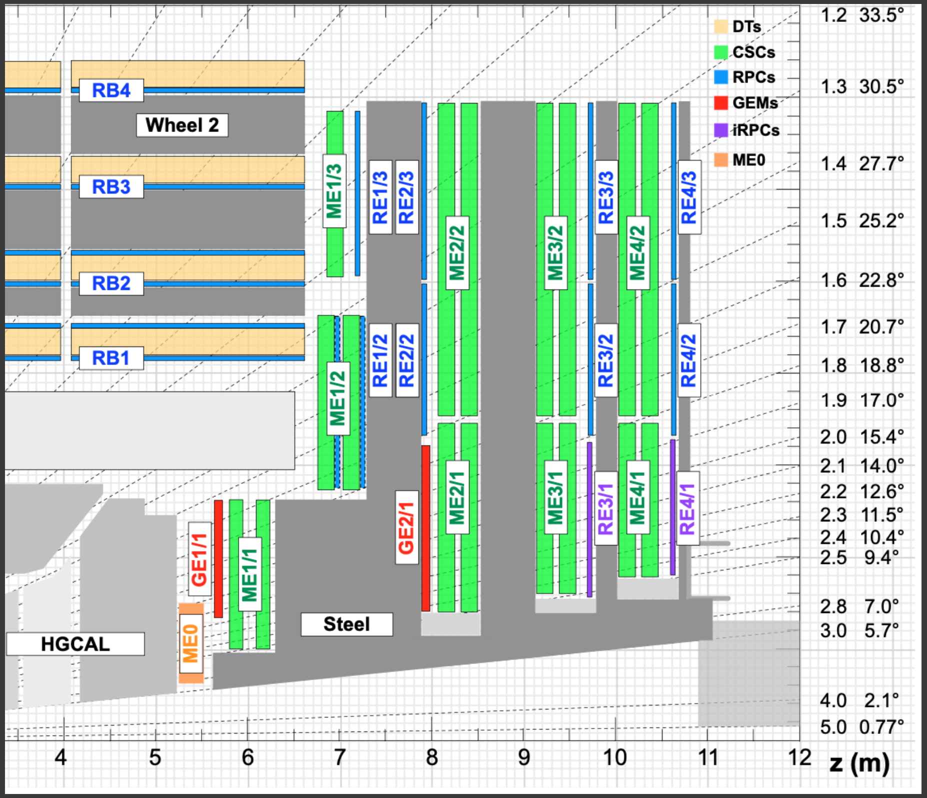
Muon system in Phase2

Challenge: cope with the higher rate, fully profiting from it and maintaining the present excellent performance along the 10 years

Strategy:

- **upgrade of the on-detector electronics** of the existing detectors mainly implemented during the Long Shutdown 3 (LS3) more in the Bilal Kiani's talk:
  - Drift Tubes (DT)
  - Resistive Plate Chambers (RPC)
  - Cathode Strip Chambers (CSC)

- **installation of new muon stations,** already occurring during LS2, adding redundancy to the system, **providing more precise measurements of muon parameters in the forward region (higher background and a lower magnetic field):**
  - Gaseous Electron Multipliers (GEM):
    - GE1/1 (already installed)
    - GE2/1
    - ME/0
  - Improved RPC (iRPC)



- **long-term irradiation tests** to evaluate the muon chambers performance at high value (3 x HL-LHC) of integrated charge

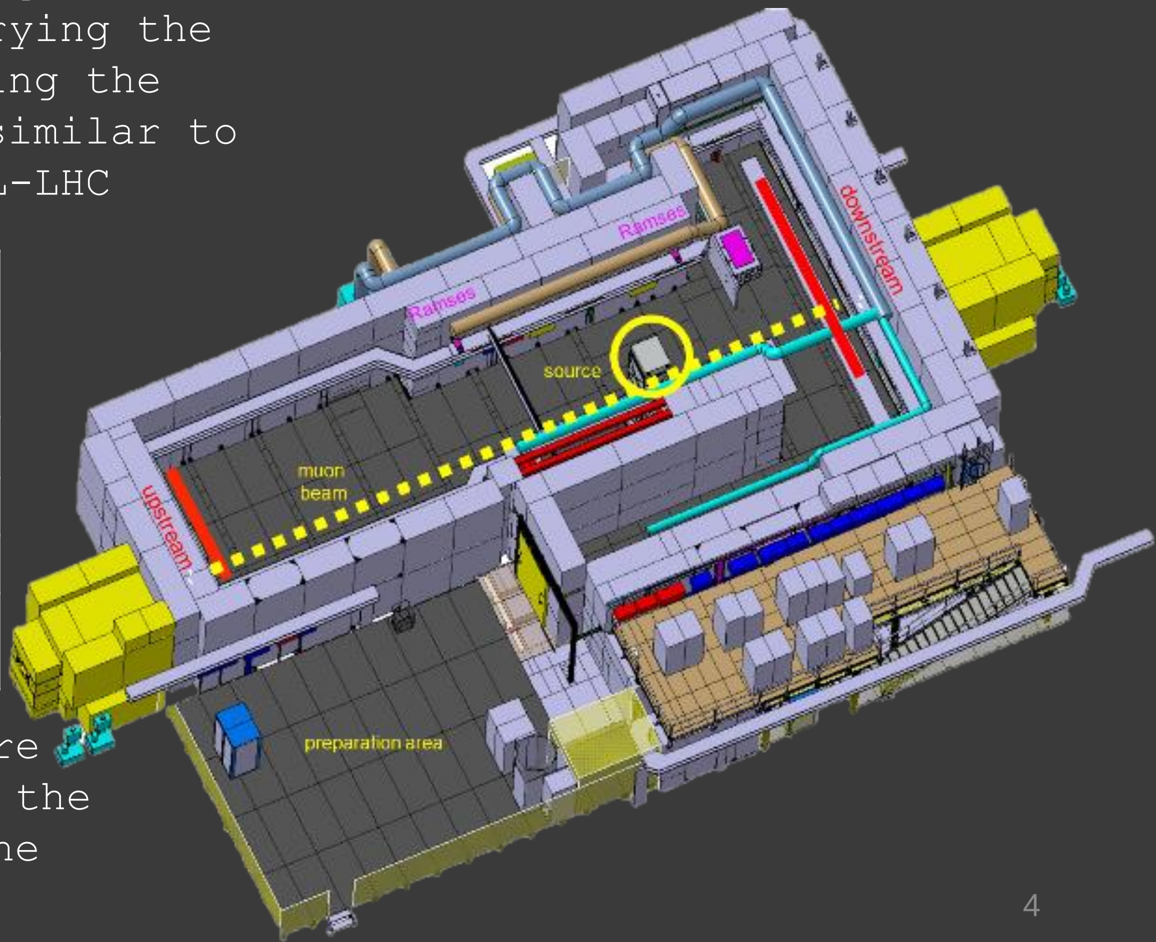
GIF++ irradiation setup

Most of the aging program is carried out at the CERN Gamma Irradiation Facility (GIF++) equipped with:

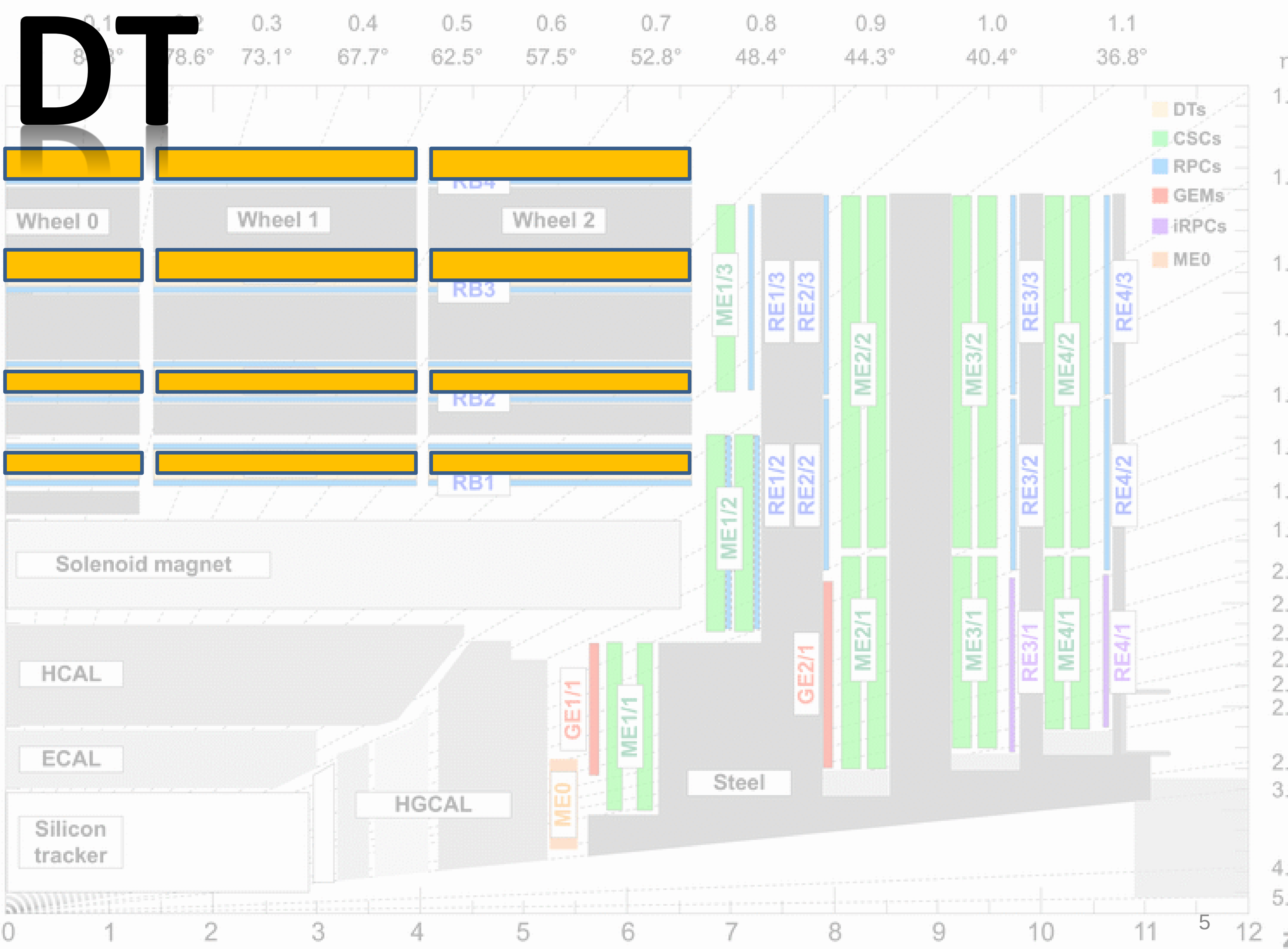
- **a 100 GeV/c muon beam**
- **gamma source (13 TBq Cs-137) to reproduce the expected background**
  - movable filters for varying the gamma flux and generating the background conditions similar to the ones expected at HL-LHC

Detector	irradiation nominal gas	irradiation alternative gas
DT	completed	not needed
CSC	completed	ongoing
RPC	97%	ongoing
GE1/1 and GE2/1	completed	not needed
ME0	30% (at X-ray facilities)	not needed

- main detector parameters are monitored as a function of the integrated charge and of the backgroud rate

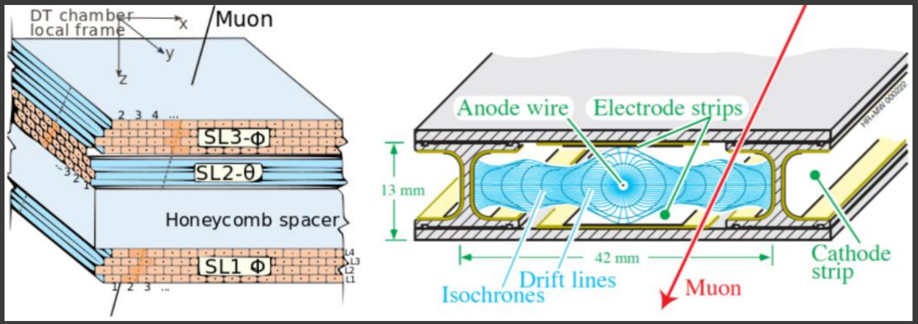


DT



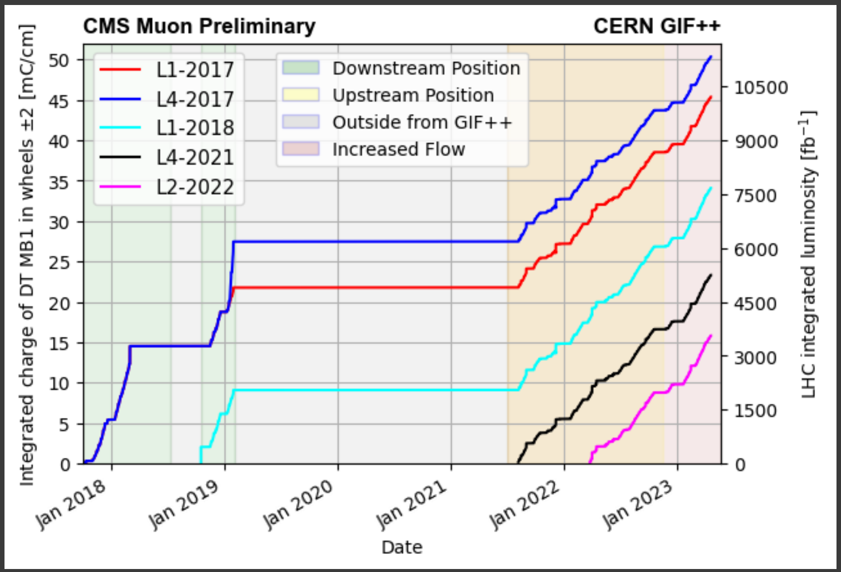
DTs
CSCs
RPCs
GEMs
iRPCs
ME0
Wheel 0
Wheel 1
Wheel 2
RB4
RB3
RB2
RB1
ME1/3
RE1/3
RE2/3
ME2/2
ME3/2
RE3/3
ME4/2
RE4/3
ME1/2
RE1/2
RE2/2
RE3/2
RE4/2
ME2/1
ME3/1
RE3/1
ME4/1
RE4/1
GE2/1
GE1/1
ME1/1
ME0
Solenoid magnet
HCAL
ECAL
HGCAL
Silicon tracker
Steel

DT irradiation



A DT chamber, 2.5m x 2m (2.5m x 4m) consists of 12(8) layers (L) arranged in 3 (2) super layers (SL), each one containing up to hundreds of cells:

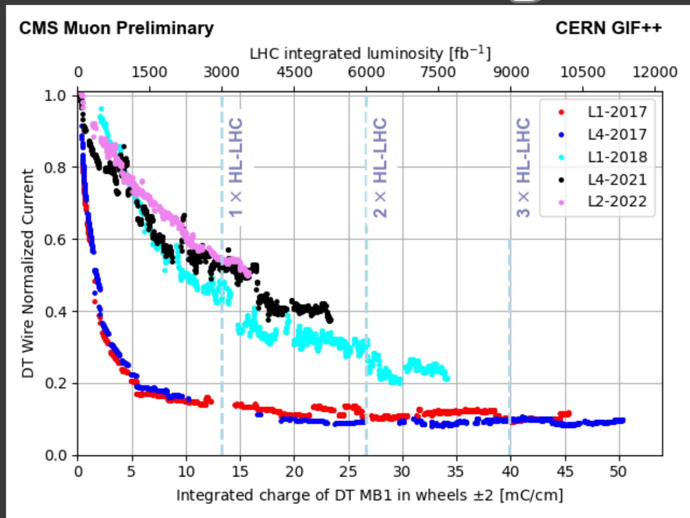
- the basic element is a rectangular 4cm **drift cell filled with Ar/CO2 (85/15%) gas mixture, nominal operating at 3600 V**
- electrons, from muon ionization, drift towards the anode wire, registering a time measurement (hit-position assuming v-drift 55µm/ns)
- **muon segment tracks are built with at least 3 hits in two independent SL**

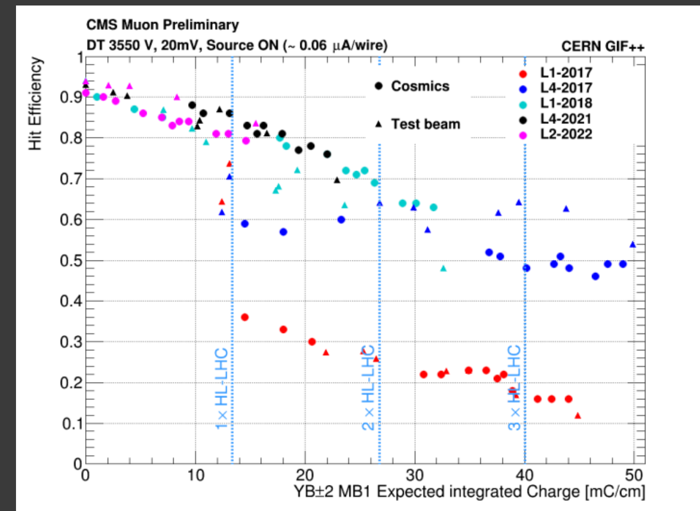


A spare MB2 chamber, with 3 SL, irradiated since the 2017:

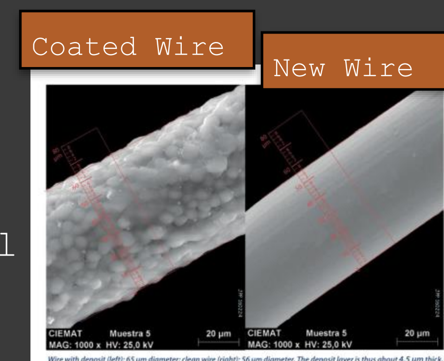
- only L1, L2 and L4 of SL1 are on during the irradiation, while L3 is kept off and used as reference
- SL2 and SL3 are used for internal trigger
- in Summer 2018 8 wires in L1 were extracted, analysed, and replaced with new wires
  - among the new replaced, 1 has been extracted and analysed in the 2020
- the same happened in the 2021 for 5 wires in L4

DT aging studies





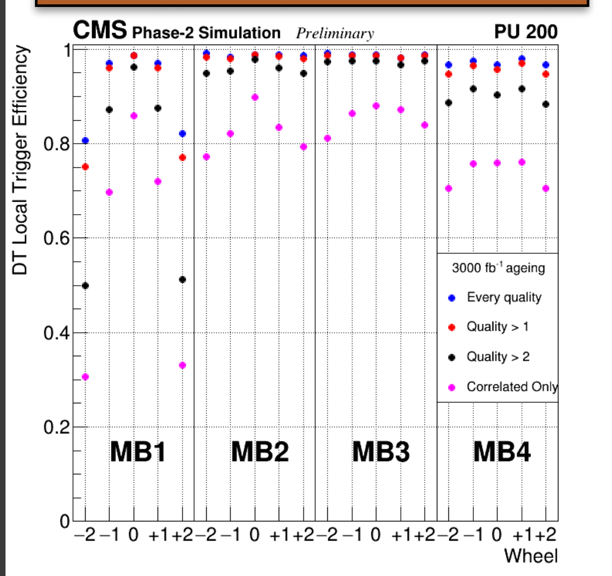
- Analysis of the currents monitored by the HV boards gives an estimation of the gain
- Using cosmic muons (internal trigger) to estimate the hit efficiency is mainly to study the behaviour among the different irradiation periods, than to obtain the absolute expected efficiency:
  - background conditions expected in the MB1 of the external wheels (24/250 chambers)
    - similar in the top sectors of the MB4 (about 30/250)
    - 10 times smaller in the MB2 and negligible in the MB3
- wires irradiated since the beginning show a fast degradation in the performance (red and blue)
- replaced virgin wires (cyan and black) show a slower reduction of gain and smaller loss of efficiency, similarly to what is observed in the most recent irradiated wires in L2
- correlated to the presence of a carbon peak in the spectroscopy analysis (backup)



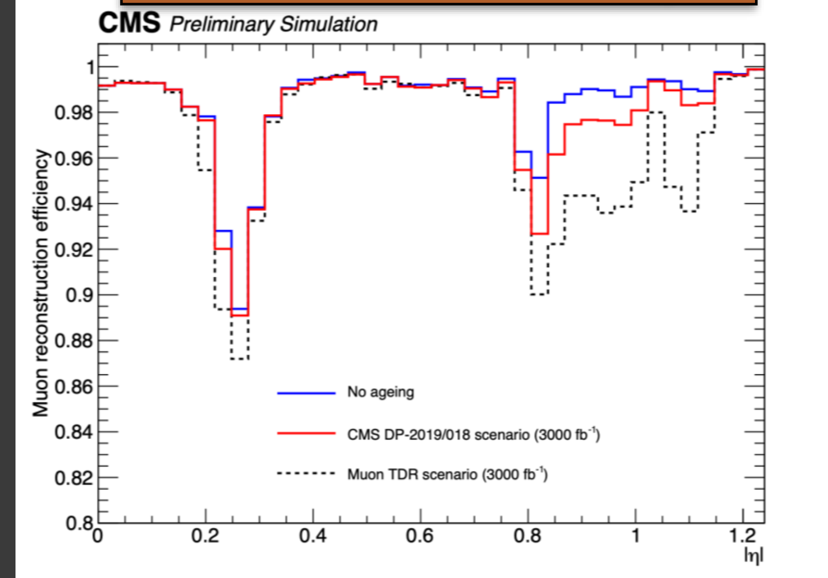
Electron avalanche enable chemical reactions of impurities creating a coating on the wires

DT aging on physics performance

DT trigger segment efficiency



Standalone muon reco efficiency



The expected hit efficiency (worst scenario) has been used to evaluate the final impact at HL-LHC with a safety factor 2:

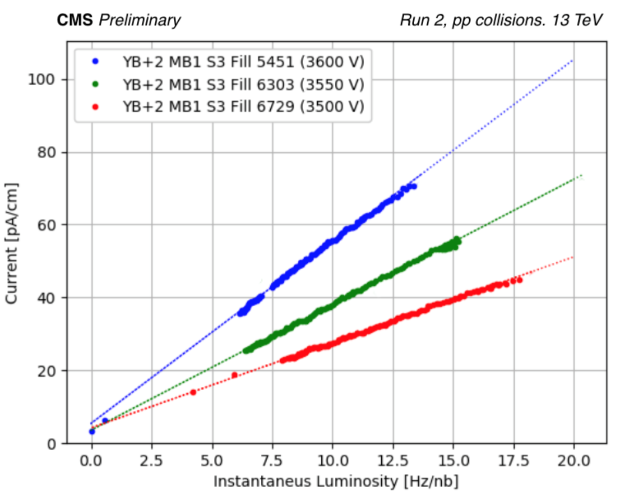
- the major effect seen in the **DT local trigger efficiency** of MB1 is effectively mitigated by:
  - multiple layers per chamber (3 out of 8 are needed)
  - handling of TDC hits in the backend in Phase2
  - redundancy of the CMS muon system
    - the most aged DT region is also covered by 3 CSC stations and 4-5 RPC layers along a prompt muon trajectory

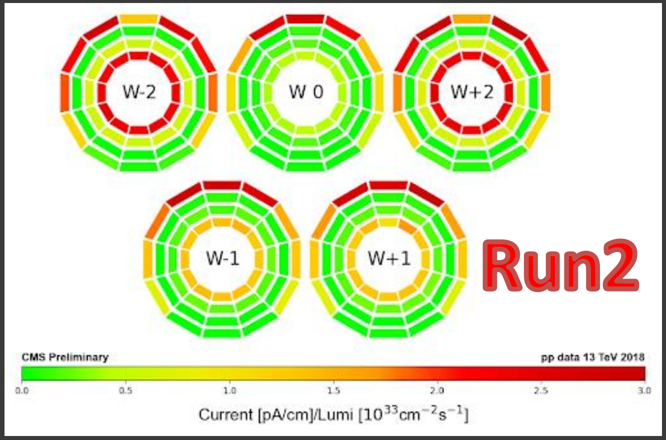
- Minor impact on the overall reconstruction of the standalone muons

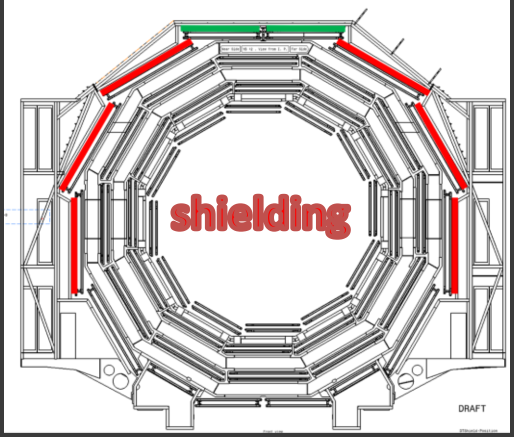
DT mitigation strategy

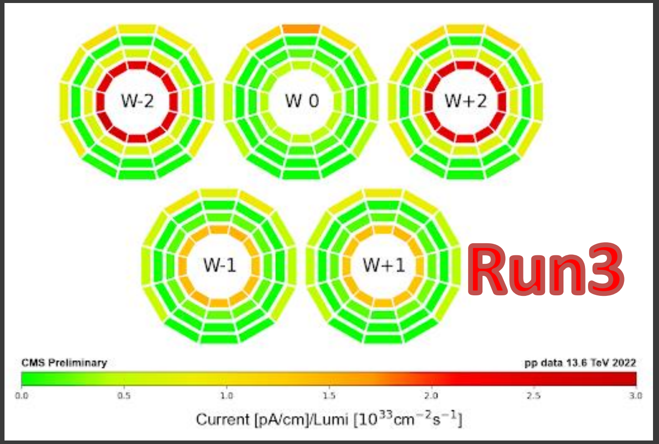
A strategy to mitigate the DT longevity has been adopted:

- since 2016 **voltage** of the wires in the most exposed chambers has been **reduced:**
  - each step of 50 V decreases the integrated charge of the 30%
  - readout thresholds also reduced from 30 to 20 mV
- in 2017 gas system at CMS has been modified to operate in **open loop** to minimize the recirculation of the impurities
- irradiation test operating with a **doubled gas flow shows no significant difference** in the performance



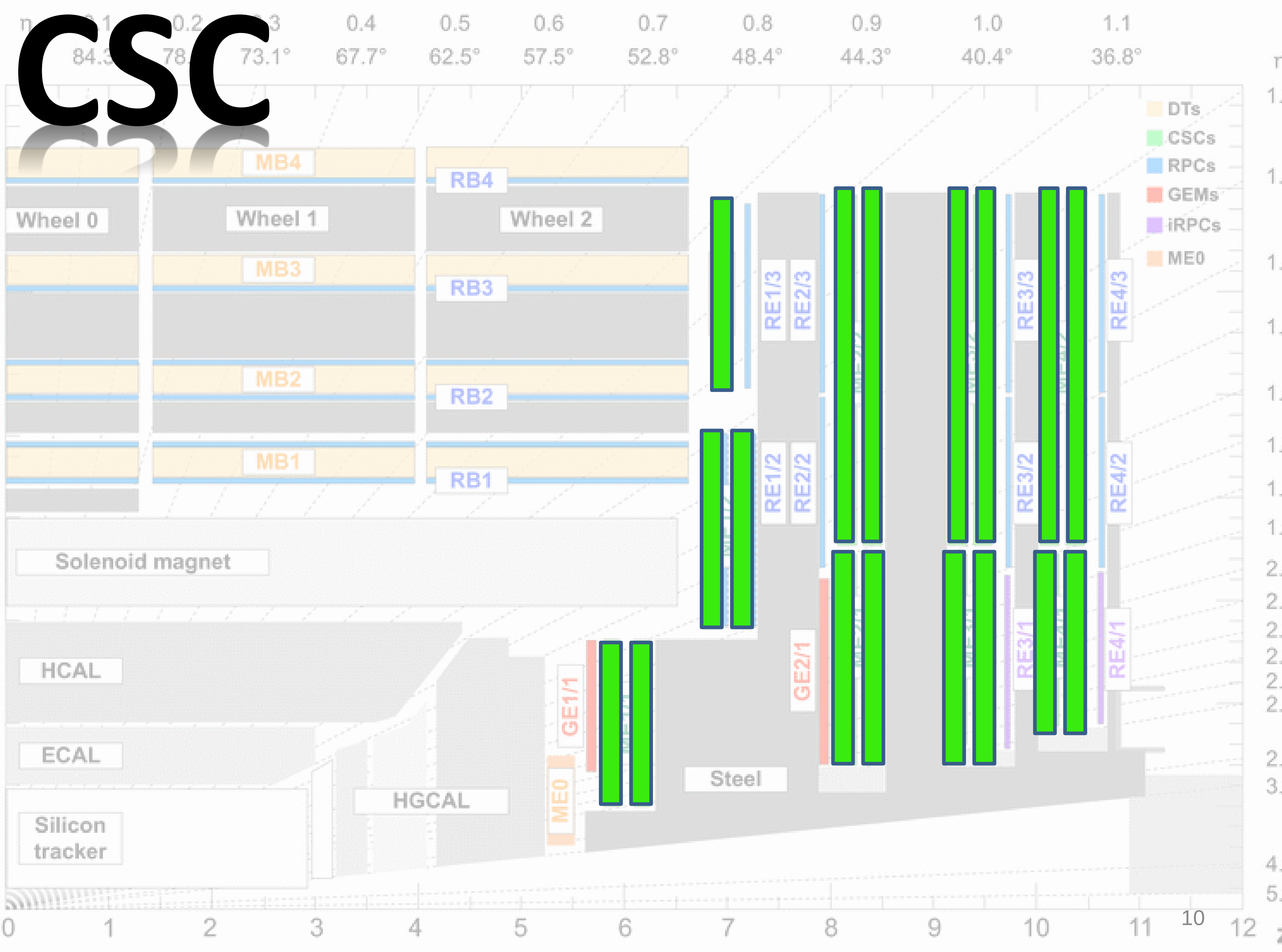






- during LS2 shelding installed for the neutron background reduction in the top sectors
  - 3 cm layer of Borated Polyethylene + 1 cm layer of lead for gamma absorbtion
  - **25% less background in the experimental cavern (top)**
  - **50-70% of background reduction in the MB4 chambers**

CSC

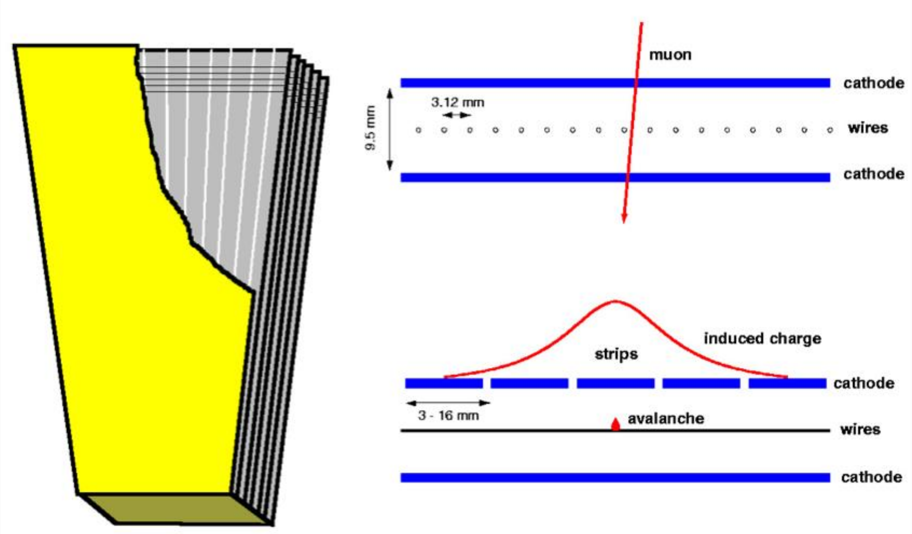


DTs
CSCs
RPCs
GEMs
iRPCs
ME0
MB4
MB3
MB2
MB1
RB4
RB3
RB2
RB1
Wheel 0
Wheel 1
Wheel 2
RE1/3
RE2/3
RE3/3
RE4/3
RE1/2
RE2/2
RE3/2
RE4/2
RE3/1
RE4/1
GE1/1
GE2/1
ME0
Solenoid magnet
HCAL
ECAL
HGCAL
Silicon tracker
Steel
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
73.1°
67.7°
62.5°
57.5°
52.8°
48.4°
44.3°
40.4°
36.8°
0
1
2
3
4
5
6
7
8
9
10
11
12

CSC Aging tests

A CSC is a multi-wire proportional chamber with 6 gas gaps, each with radial cathode strips and perpendicular wire groups:

- using a 40% Ar, 50% CO_2, 10% CF_4 gas mixture
  - CF_4 has a greenhouse warming potential (GWP) 6500 but also protect against anode wire aging caused by Si and Carbon polymers
- both electrons and ions are respectively read giving two coordinates per each detected particle
- segment tracks are reconstructed in 3D



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

There are 3 ways 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

CSC irradiation

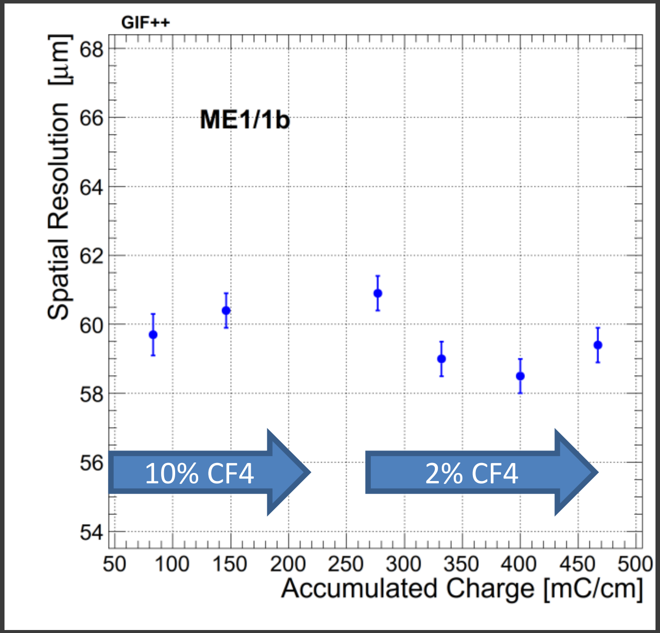
Irradiation setup: 2 **ME1/1** chambers and 1 **ME2/1** chamber respectively with HV-ON on 4 layers and HV-OFF on 2 layers kept as reference.

Amount of **integrated charge expected at 1 HL-LHC** estimated using the Run2 currents scaled with the Fluka simulation (HL-LHC/Run2 ratio):

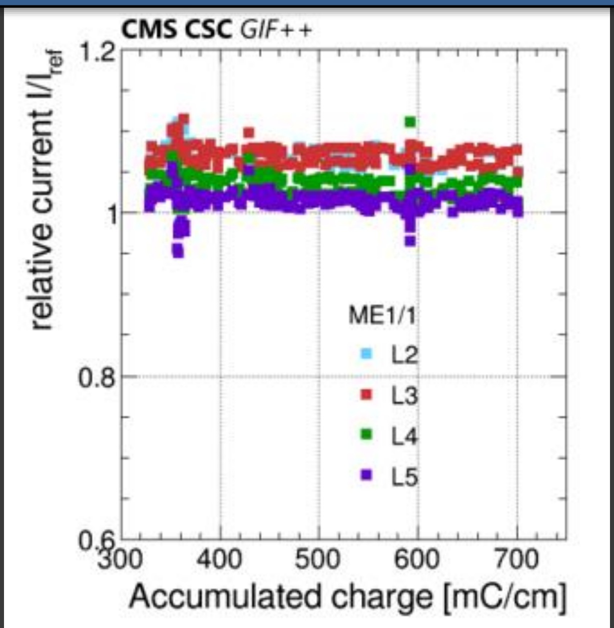
- **ME1/1: 200 mC/cm → 600 with a safety factor 3**
- **ME2/1: 130 mC/cm → 390**

Studies with nominal gas mixture (2016-2021):

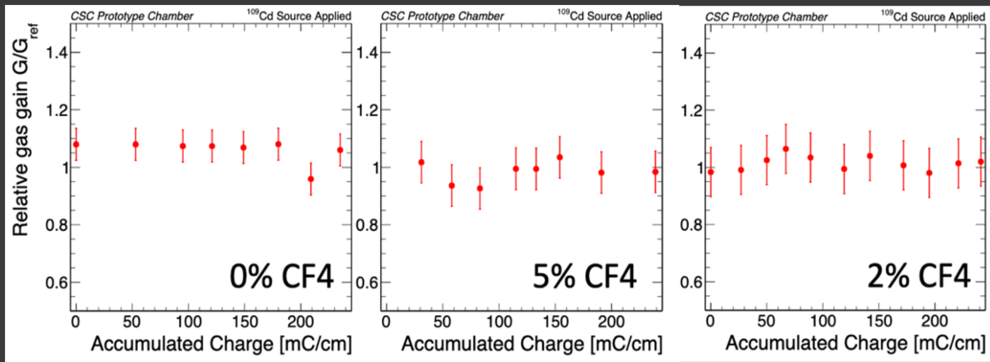
- **ME1/1 and ME2/1** received **330 mC/cm** using 40% Ar, 50% CO_2, **10%** $\mathbf{CF_4}$
- **ME1/1 received further 370** mC/cm using only the **2% of** $\mathbf{CF_4}$
- No significant sign of aging



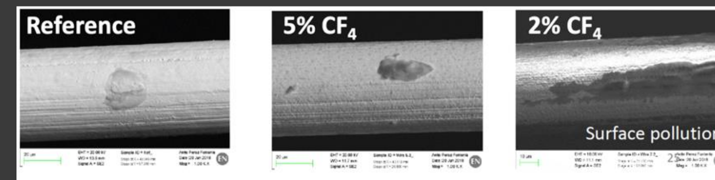
Relative gain with the 2% of CF_4



CSC eco-gas



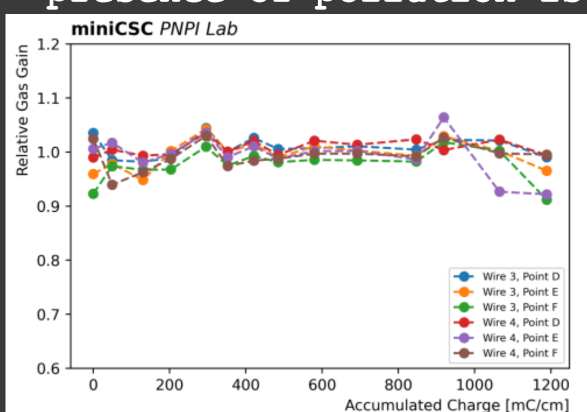
The **reduction of CF_4 doesn't seem to affect the CSC gain, despite an increased pollution is visible on the wire:** validated up to 2 HL-LHC

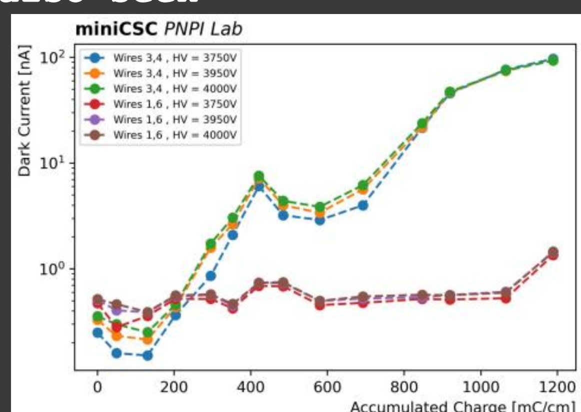


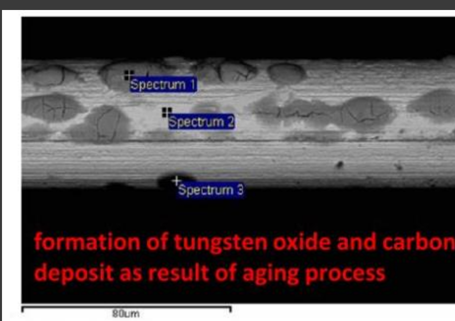
Deposits on the anode wires show that operating with 2% CF_4 might be a risky choice, while running with 5% CF_4 looks more sustainable (irradiation ongoing)

Preliminary study, performed on a 30x30 cm^2 CSC prototype, on the **alternative HFO-1234ze (GWP 7) 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**



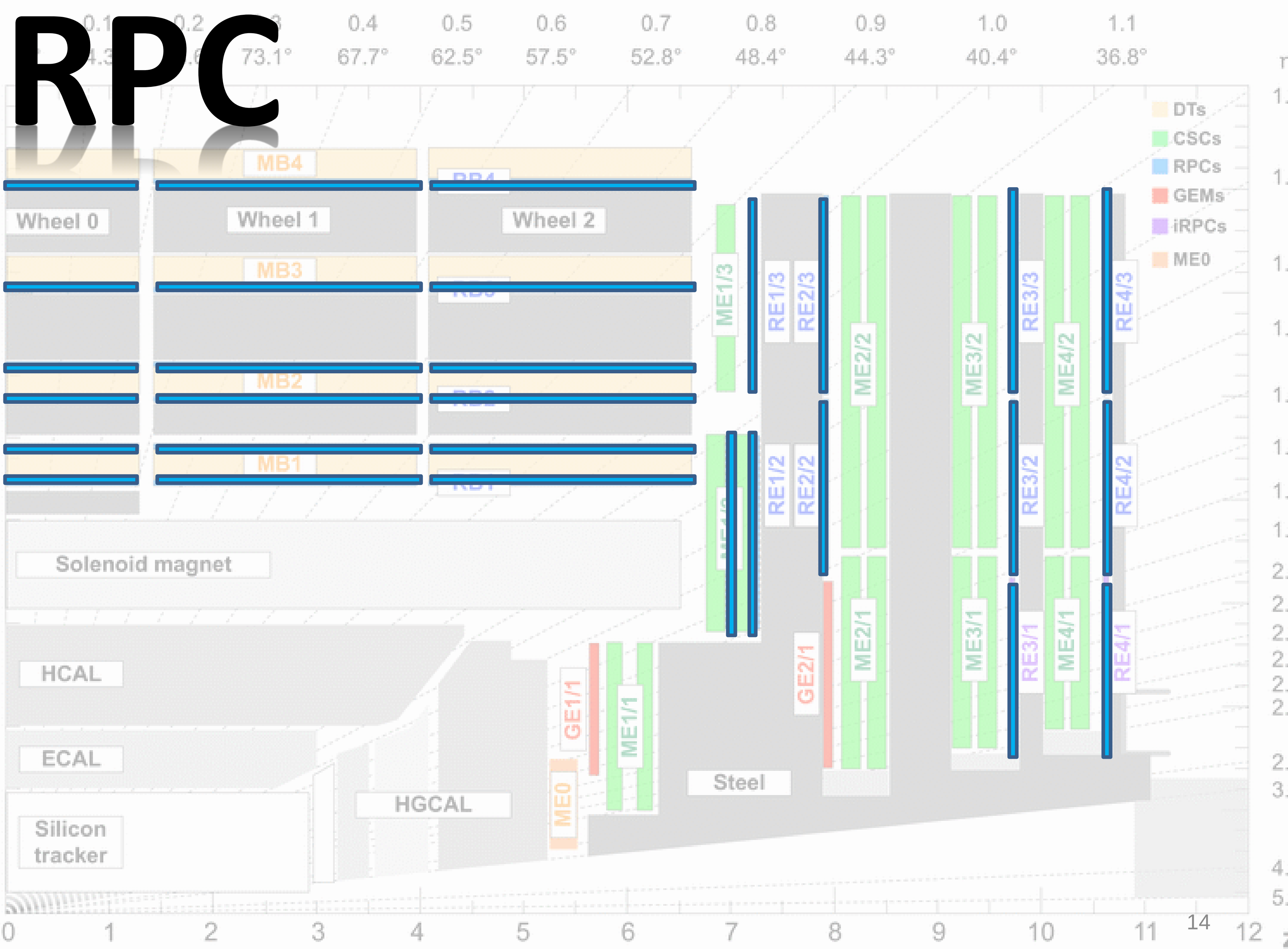




All results in weight%

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

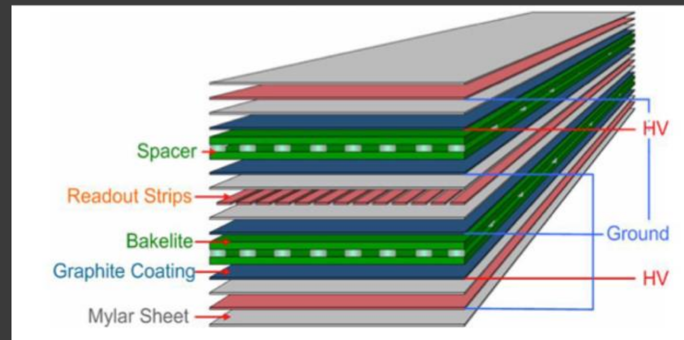
RPC

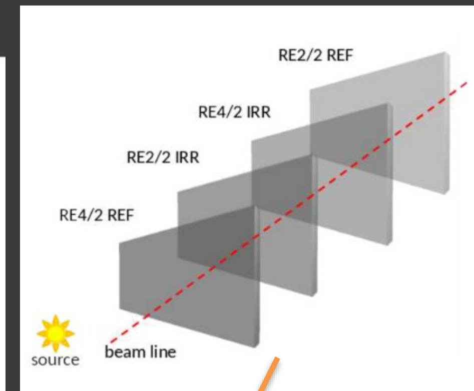

0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
73.1°
67.7°
62.5°
57.5°
52.8°
48.4°
44.3°
40.4°
36.8°
DTs
CSCs
RPCs
GEMs
iRPCs
ME0
MB4
Wheel 0
Wheel 1
Wheel 2
MB3
MB2
MB1
ME1/3
RE1/3
RE2/3
ME2/2
ME3/2
RE3/3
ME4/2
RE4/3
RE1/2
RE2/2
RE3/2
RE4/2
Solenoid magnet
GE2/1
ME2/1
ME3/1
RE3/1
ME4/1
RE4/1
HCAL
GE1/1
ME1/1
ECAL
Steel
HGCAL
ME0
Silicon
tracker
0
1
2
3
4
5
6
7
8
9
10
11
12

RPC irradiation

RPC double gap chambers:

- 2mm gap width filled with the **$C_2H_2F_4$(95.2%)+iso-C_4H_{10}(4.5%)+SF_6 (0.3%)** gas mixture, nominal operating above 9000 V
- bakelite bulk resistivity $\rho=1\sim6 \times 10^{10}\ \Omega cm$
- operate in avalanche mode
- signal is read on strips of width 1-4 cm
- 1 ns time resolution, used for triggering





Setup at GIF++ since July 2016: 2 RE2 chambers and 2 RE4 chambers (one irradiated, one as reference)

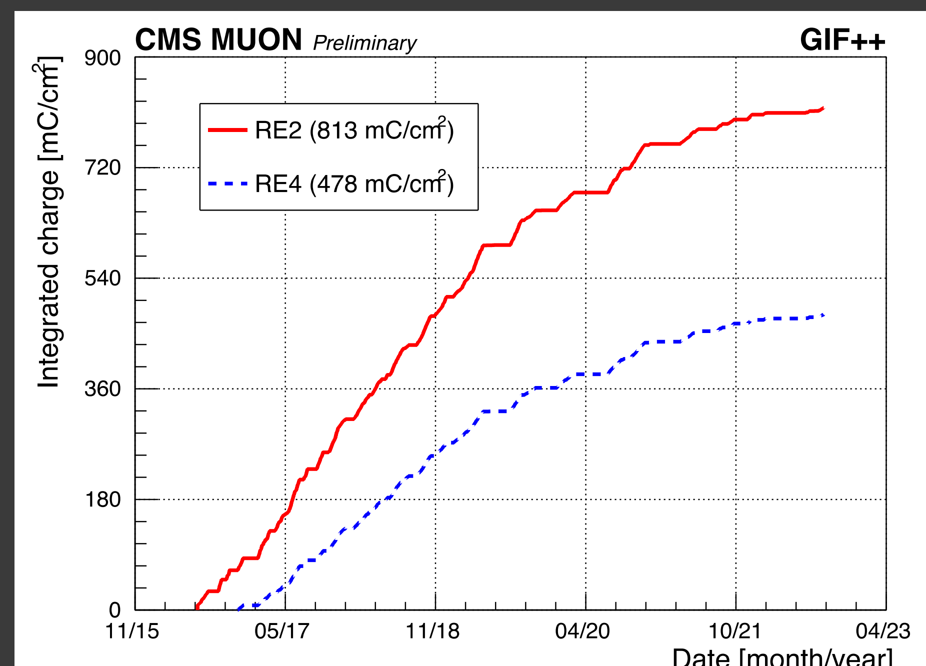
Expected Integrated charge at HL-LHC:

- Max. IC: ~ 280 mC/cm² → **~ 840** mC/cm² (safety factor 3)
- barrel chambers factor 2 less

Expected rate:

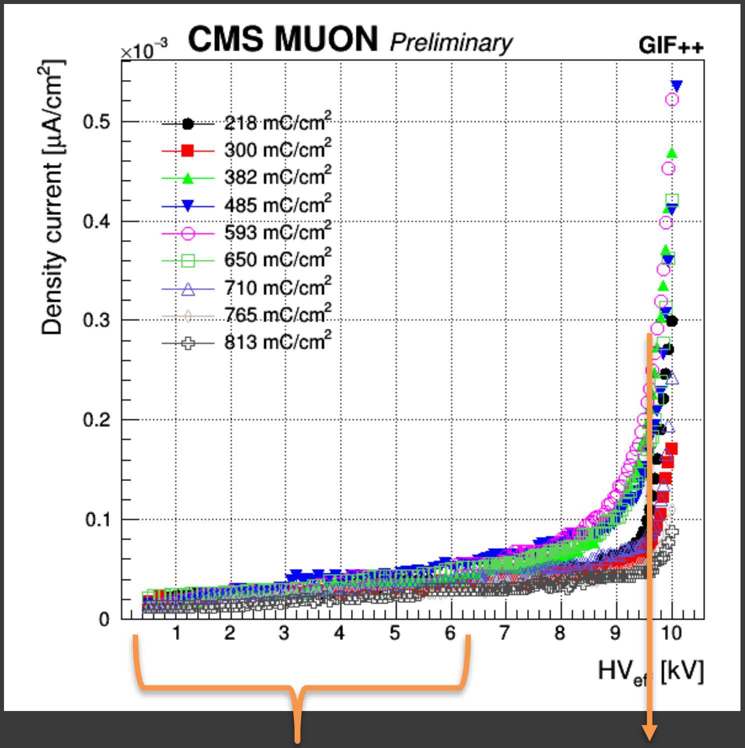
- Max. Rate: ~ 200 HZ/cm² → ~ **600** HZ/cm² (safety factor 3)
- barrel chambers factor 2 less

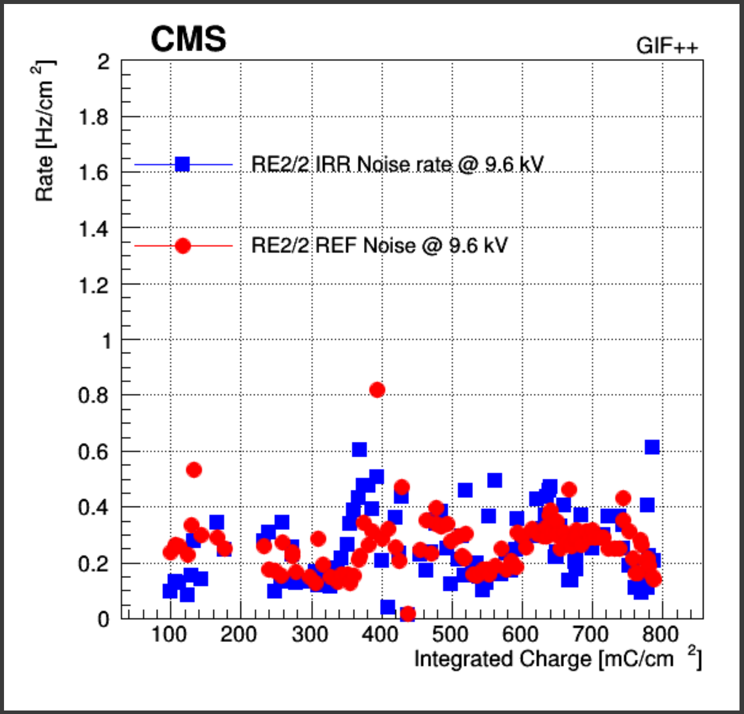
- **Rates measured in the Run3 data confirm the improvements due to the shielding installation**



RPC: current and rate

Results with source OFF:





Ohmic current (up to 6.5 KV) is the most stable

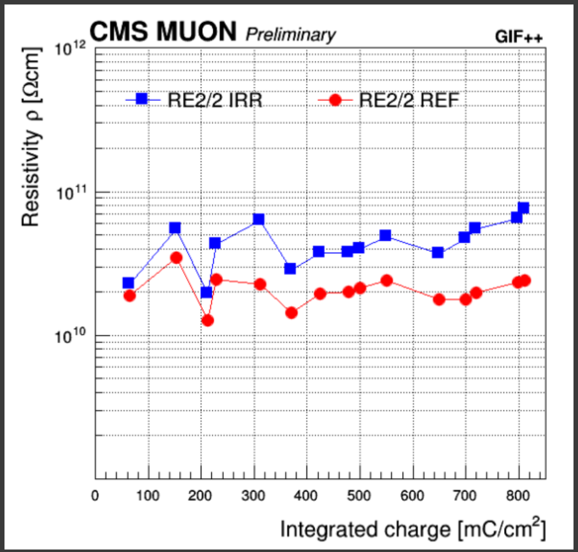
Total current (around 9.5 KV) is also stable with larger fluctuations

Dark current is quite stable up to 3 HL-LHC (different curves)

Noise is quite stable and rather below 1 Hz/cm^2 :

- fluctuations, even large, don't show a stable trend of increase

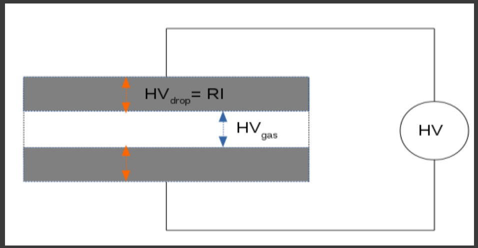
RPC: resistivity



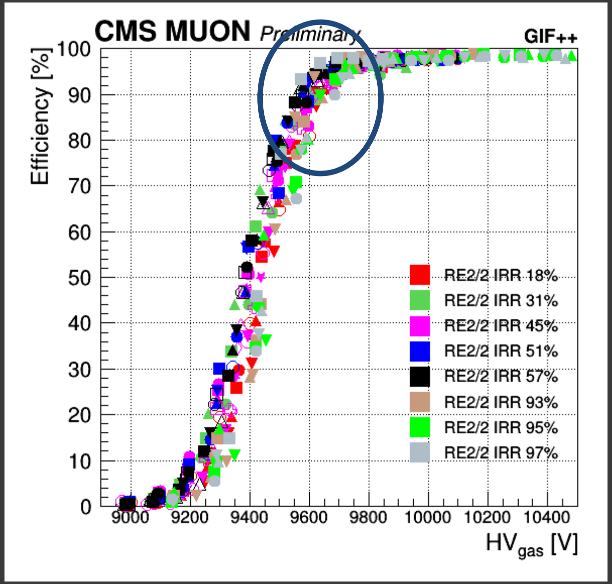
Resistivity is periodically measured running the chambers with pure Argon:

- **trend of rise in the irradiated chamber**
- changes in the resistivity can be compensate by increasing the effective HV

The applied HV = HV_gas + R*I



Performance is measured at the HV working point (WP), defined as the **HV at knee + 150 V**



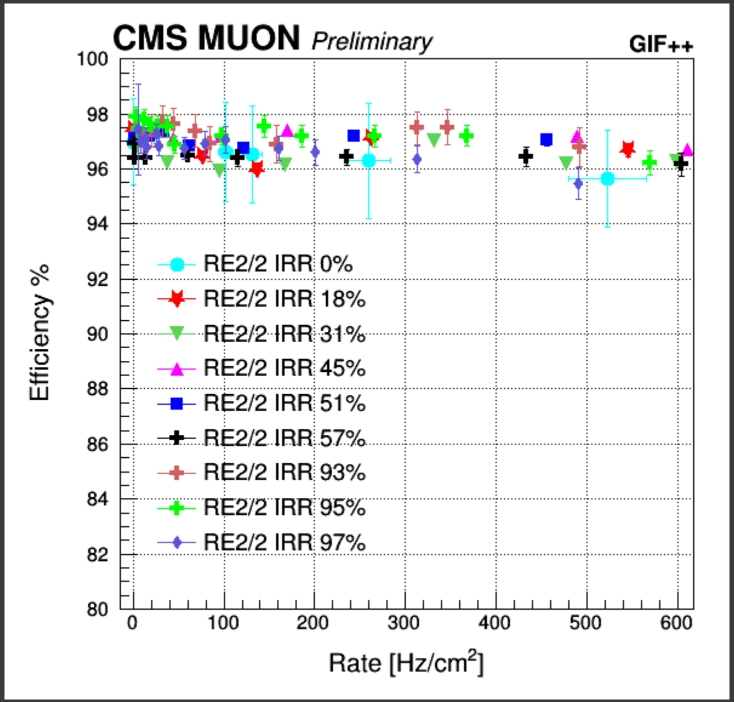
Test Beam results with source ON:

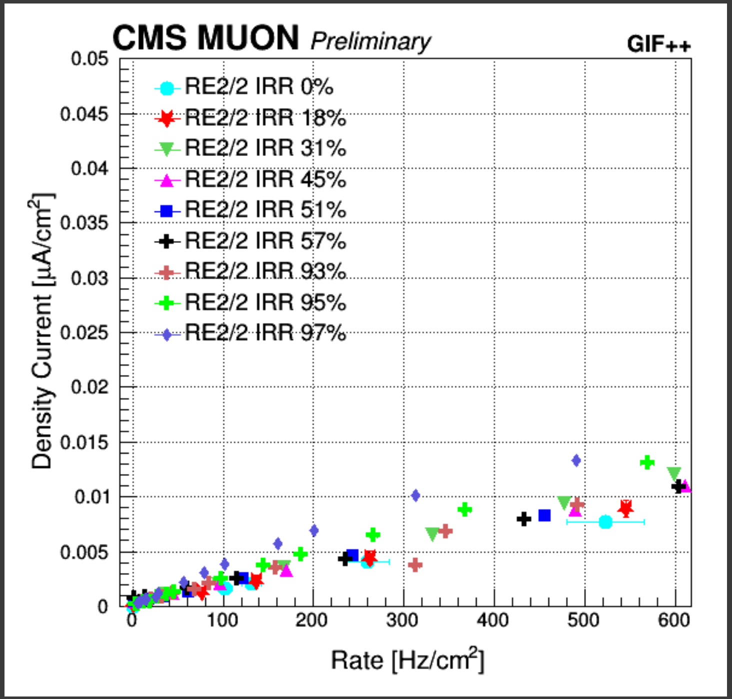
- **efficiency is rather stable at different values of integrated charge (different colours) and background rates (different markers)**

- **no significat shifts are observed (HV value for WP is quite stable)**

RPC performance at WP

Test Beam results with source ON (background):





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)

RPC eco-gas

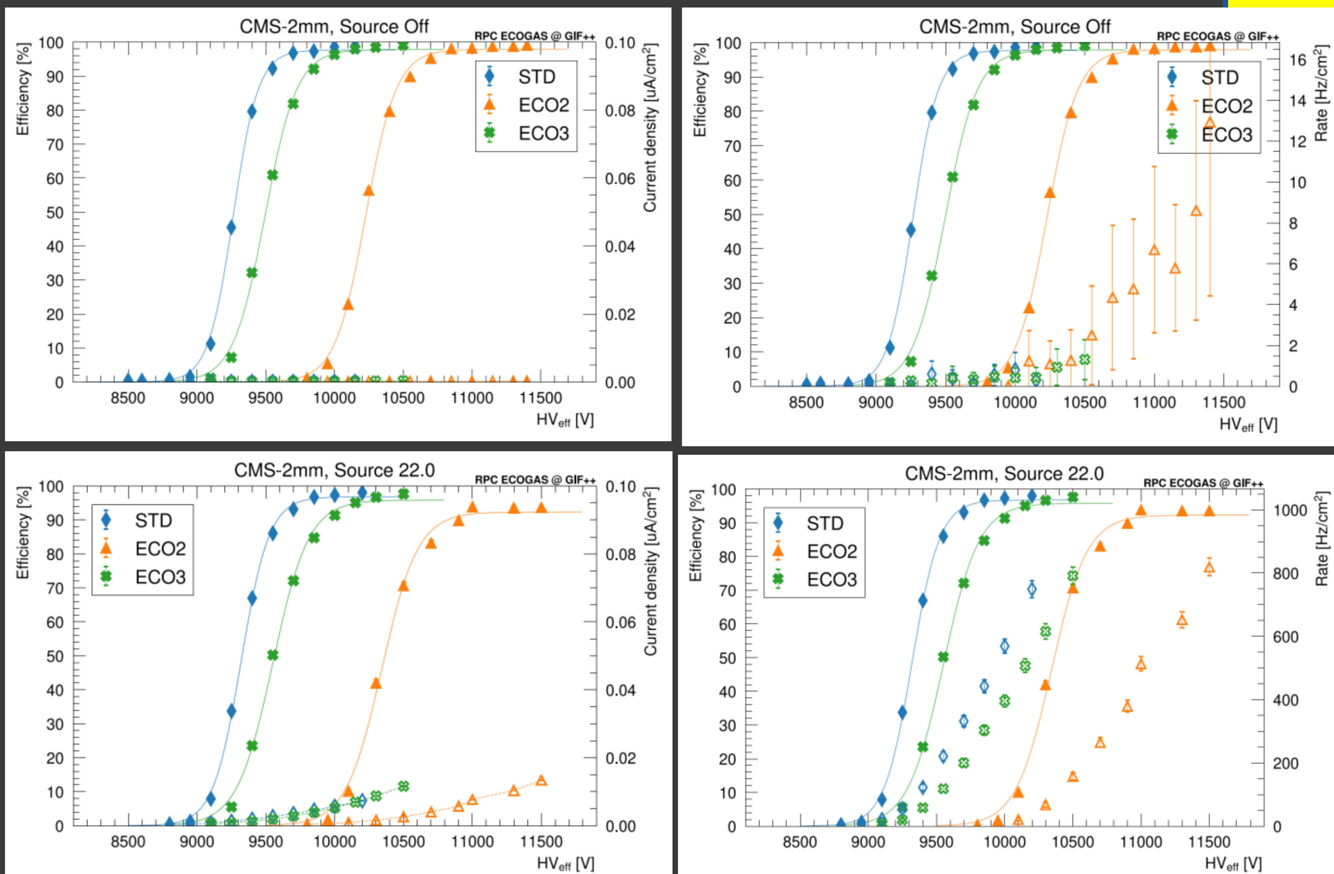
There are 2 ways to reduce the use of $C_2H_2F_4$ (GWP 1430):

- **Recuperation:** extensive leak repair campaign has been done during LS2. Commissioning of gas recuperation system almost completed. It allows up to 80% of recycling efficiency

- **Substitution:** joint collaboration (ATLAS, CMS, LHCb, CERN, SHIP) currently testing 2 HFO-based (GWP 230) alternative mixtures:
- CMS studies carried out by AIDainnova Task WP 7.2.3

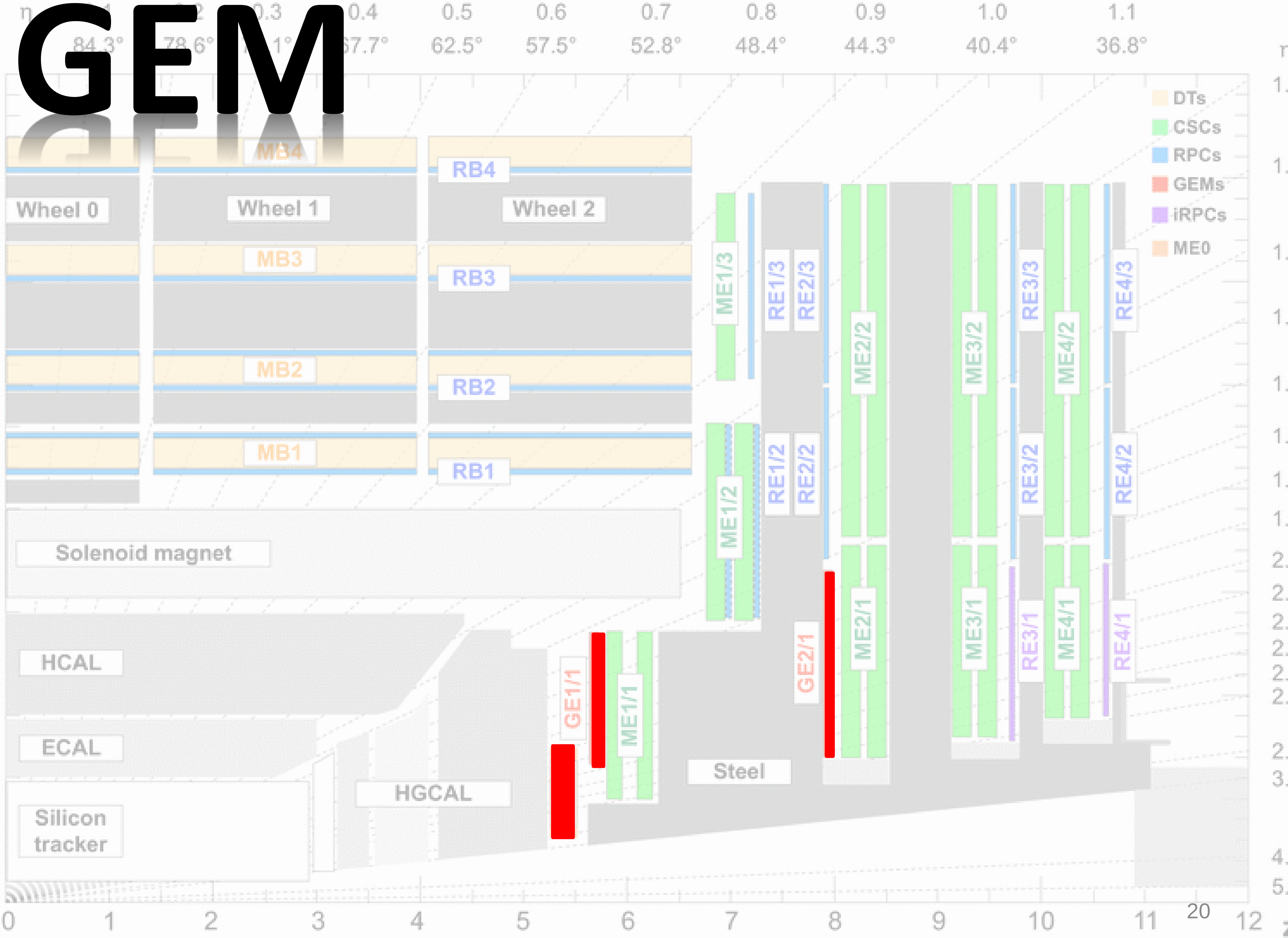
ECO2: CO_2 60%, HFO 35%, iC_4H_{10} 4%, SF_6 1%

ECO3: CO_2 69%, HFO 25%, iC_4H_{10} 5%, SF_6 1%

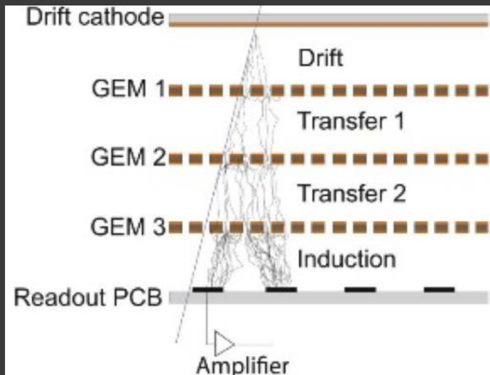


Results look promising, but longer term irradiation tests are needed to be conclusive

GEM

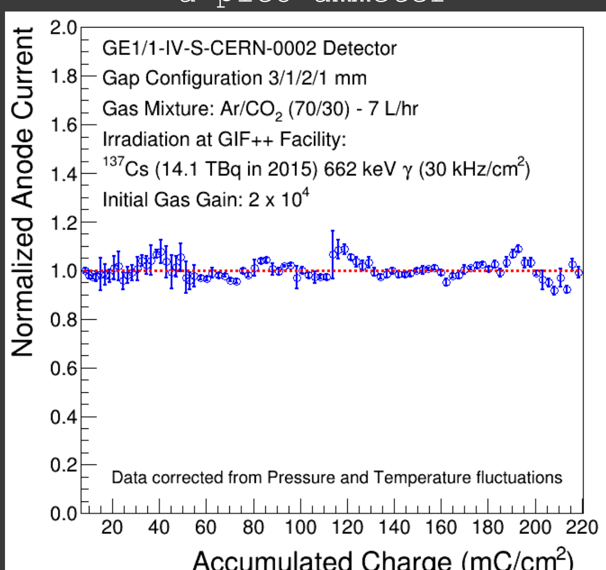

η
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
57.7°
62.5°
57.5°
52.8°
48.4°
44.3°
40.4°
36.8°
DTs
CSCs
RPCs
GEMs
iRPCs
ME0
MB4
MB3
MB2
MB1
RB4
RB3
RB2
RB1
Wheel 0
Wheel 1
Wheel 2
ME1/3
RE1/3
RE2/3
ME2/2
ME3/2
RE3/3
ME4/2
RE4/3
ME1/2
RE1/2
RE2/2
RE3/2
RE4/2
GE1/1
ME1/1
GE2/1
ME2/1
ME3/1
RE3/1
ME4/1
RE4/1
Solenoid magnet
HCAL
ECAL
HGCAL
Steel
Silicon tracker
0
1
2
3
4
5
6
7
8
9
10
11
12

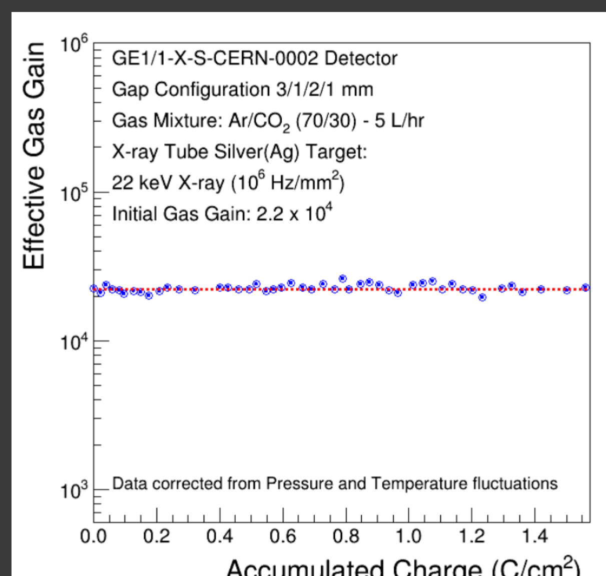
GEM Aging with X-ray:GE1/1

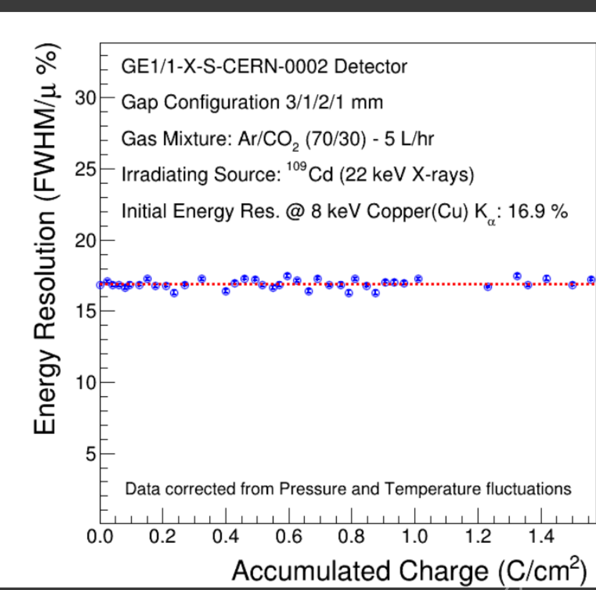


- Triple-GEM are micro-pattern gaseous detectors made of 3 GEM foils in cascade:
- operating with Ar/CO_2 70/30% gas mixture
- instrumenting region with high rate, expected int. charge:
  - **60 mC/cm2 GE1/1** → validated up to 3.6 HL-LHC
  - **30 mC/cm2 GE2/1** → validated up to 7 HL-LHC

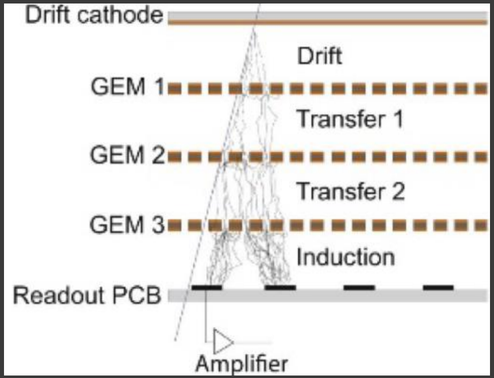
Current measured by
a pico-ammeter



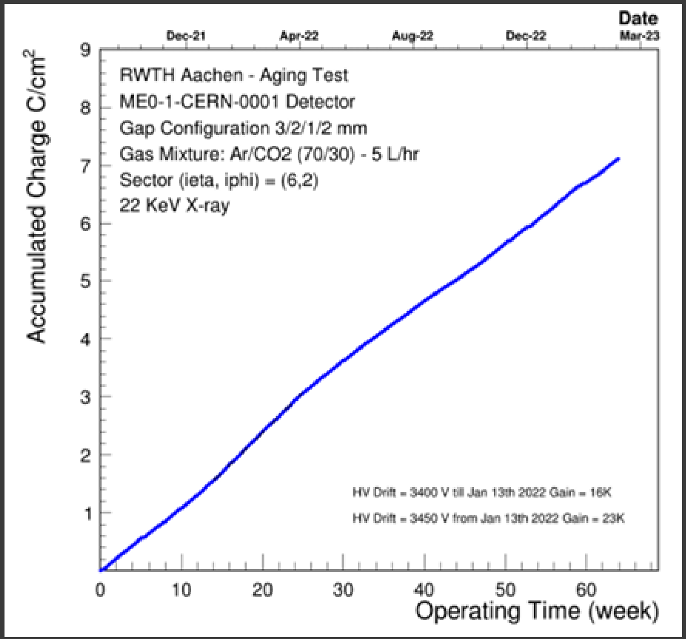


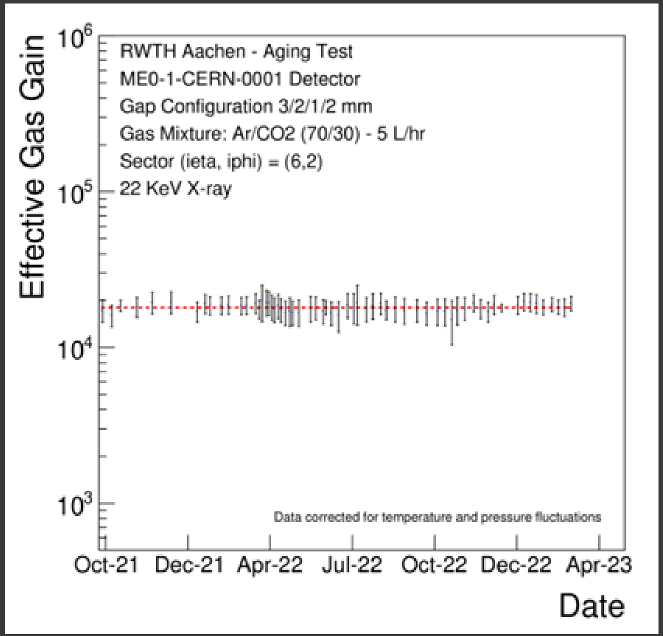


GEM Aging with X-ray: ME0



- Triple-GEM are micro-pattern gaseous detectors made of 3 GEM foils in cascade:
- operating with Ar/CO_2 70/30% gas mixture
- instrumenting region with high rate, expected int. charge:
  - 60 mC/cm2 GE1/1 → validated up to 3.6 HL-LHC
  - 30 mC/cm2 GE2/1 → validated up to 7 HL-LHC
  - **7900 mC/cm2 ME0** → recently validated up to 1 HL-LHC, but approved 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

Corrections for temperature and pressure fluctuations are applied

Summary

Efforts have been going since many years to estimate the performance of the CMS Muon detectors in the harsh HL-LHC conditions

Results obtained at X-ray facilities also confirm that GEM detector technology can sustain the HL-LHC operations

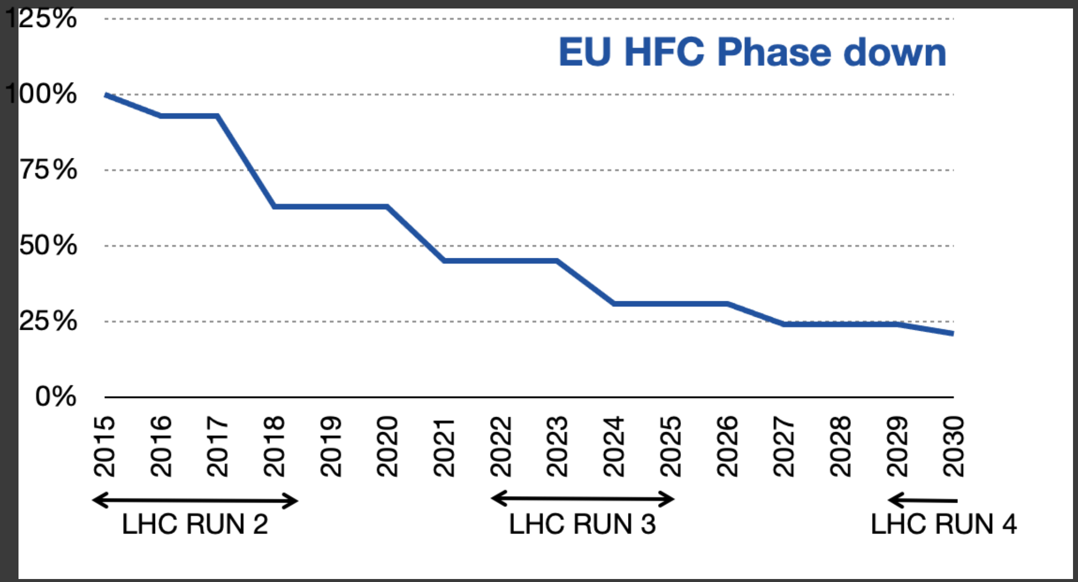
Results obtained at CERN GIF++ show that the CMS Muon System can continue to efficiently operate:

- mitigation strategy is already in place in view of the future operations to slow down the possible aging of the DTs, that in any case is not expected to compromise the global performance in the barrel
- work done to improve the gas system technology allows to operate with a reduced consumption of the GHG for RPCs and CSCs, while further efforts to find alternative gas mixtures are ongoing

Back-up

Greenhous gasses (GHG)

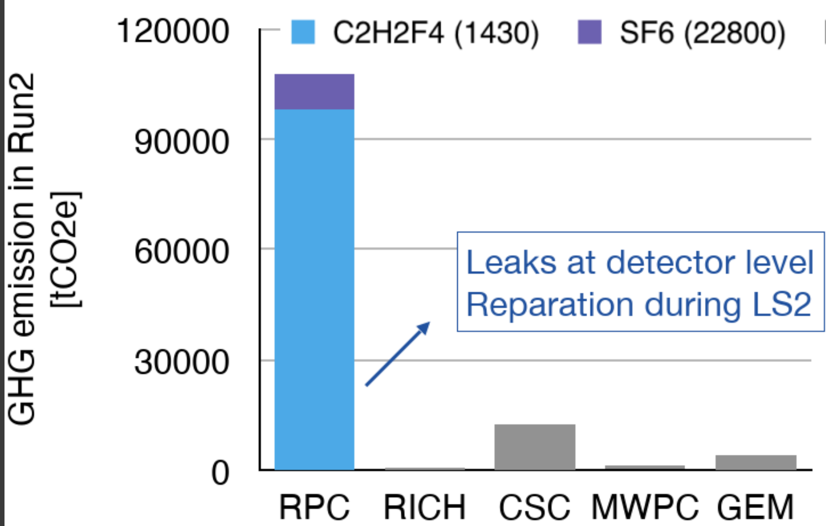
Despite almost no aging effect is seen, both CSCs and RPCs have to deal with the European/CERN strategy to reduce the use of GHG:



- reduction of the consumption up to mid-Run3:
  - Optimization of the current technologies to reuse the gas
    - Done since 2021 for CSCs
    - Onging R&D for the RPCs (prototype installed 2 years ago)
  - Campaign of gas leak repair for RPCs

- use of alternative gasses in the long term

GHG: leak repair campaign



CERN GHG emissions from particle detectors

- **Main contributor is $C_2H_2F_4$** used for ALICE, ATLAS and CMS RPC systems
- **Emissions mainly due to leaks** at detector level (fragile connectors) in ATLAS and CMS.
- **Campaign** for leaks reparation in LS2

RPC gas mixture
~95%$C_2H_2F_4$ - ~5%iC_4H_{10} - 0.3%SF_6

RPC eco-gas

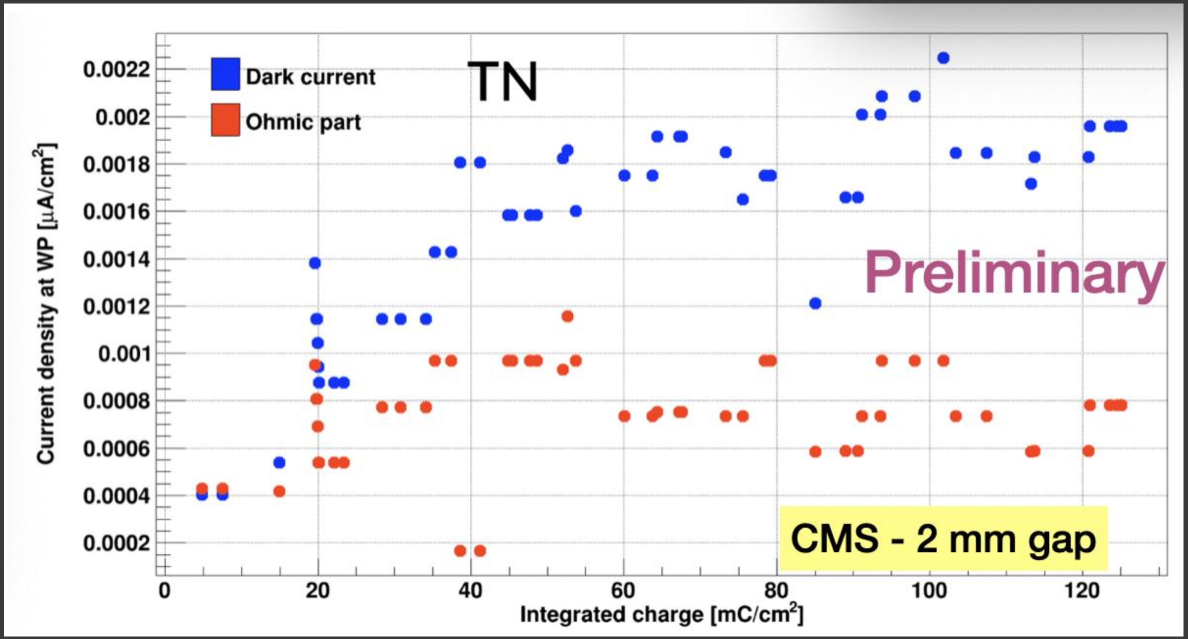
There are 2 ways to reduce the use of **$C_2H_2F_4$** (GWP 1430):

- **Recuperation:** extensive leak repair campaign has been done during LS2. Commissioning of gas recuperation system almost completed. It allows up to 80% of recycling efficiency

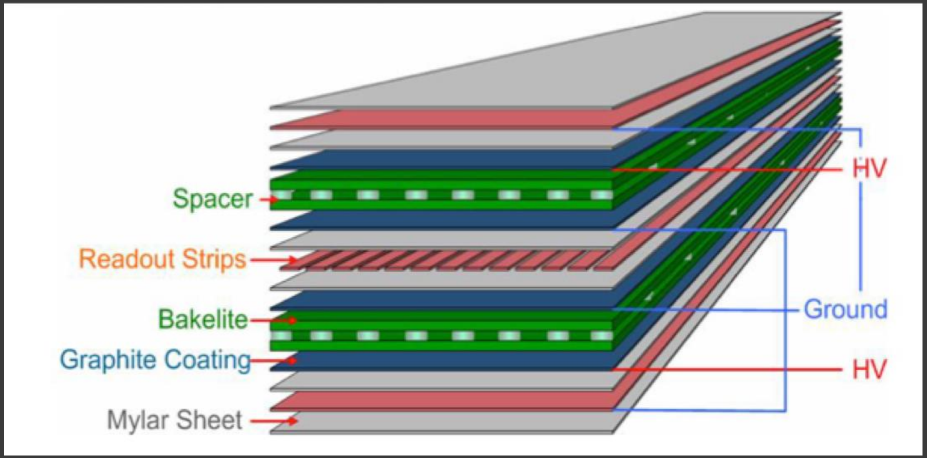
- **Substitution:** joint collaboration (ATLAS, CMS, LHCb, CERN, SHIP) currently testing 2 HFO-based (GWP 230) alternative mixtures:
- CMS studies carried out by AIDainnova Task WP 7.2.3

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%



iRPC



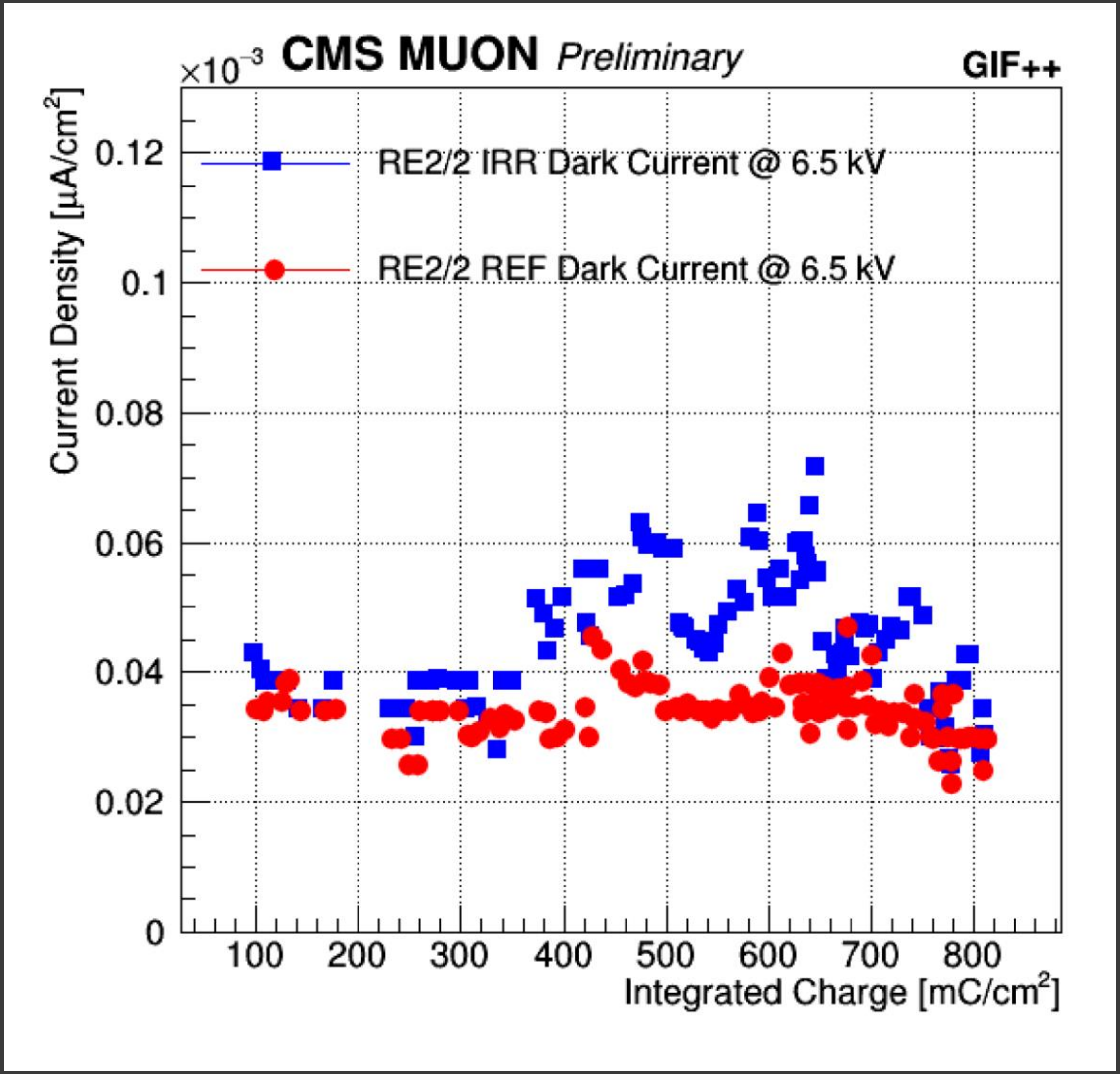
RPC double gap chambers:

- 2mm gap width filled with the $C_2H_2F_4$(95.2%)+iso-C_4H_{10}(4.5%)+SF_6 (0.3%) gas mixture, nominal operating above 9000 V
- bakelite bulk resistivity: $\rho = 1\sim6 \times 10^{10}$ Ωcm
- operated in avalanche mode
- strips of width 1-4 cm

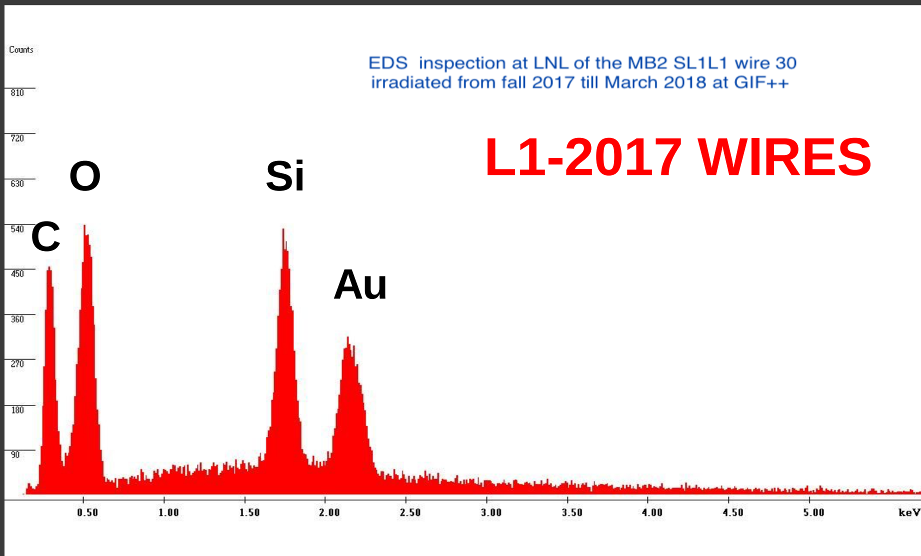
iRPC:

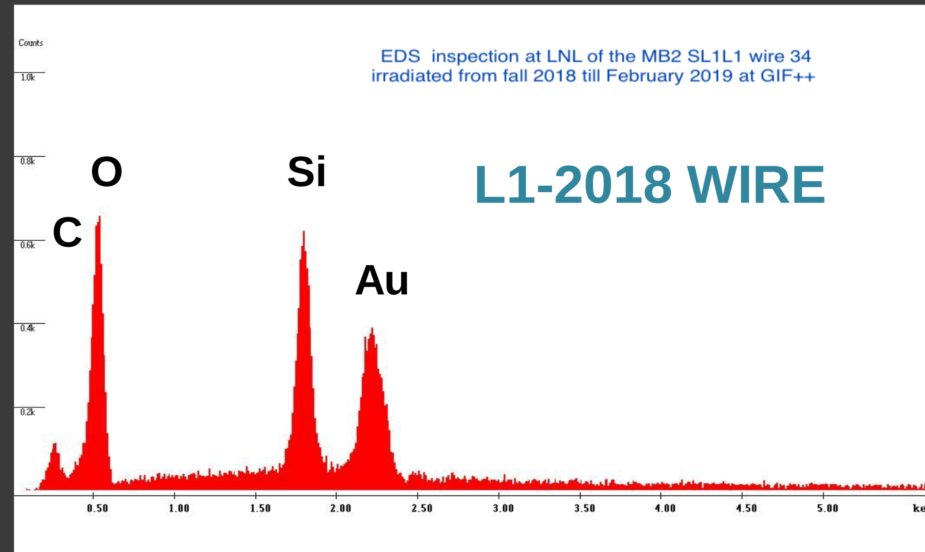
- 1.4mm gas gap
- resistivity: $\rho = 0.9\sim3 \times 10^{10}$ Ωcm operating at ~7000 V
- strips width 0.7-1.2cm

RPC: dark current



DT: spettroscopy analysis

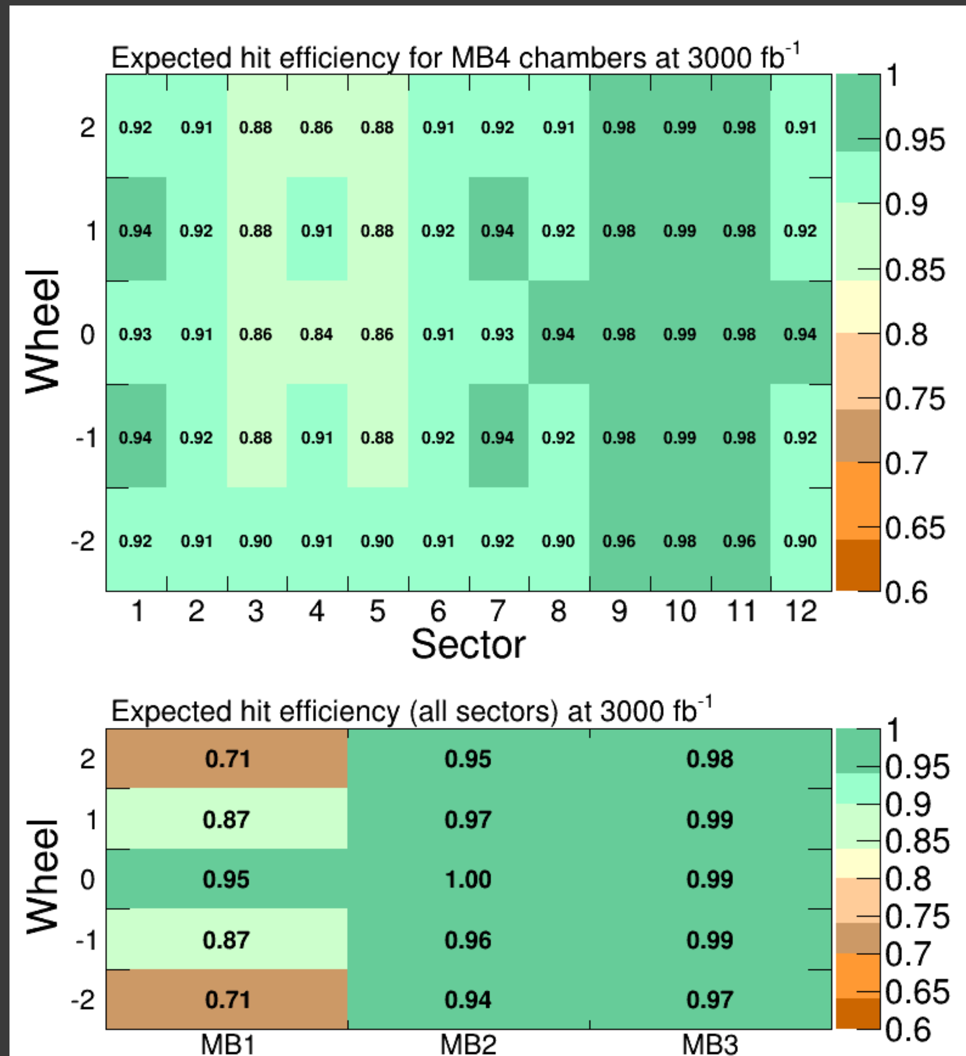




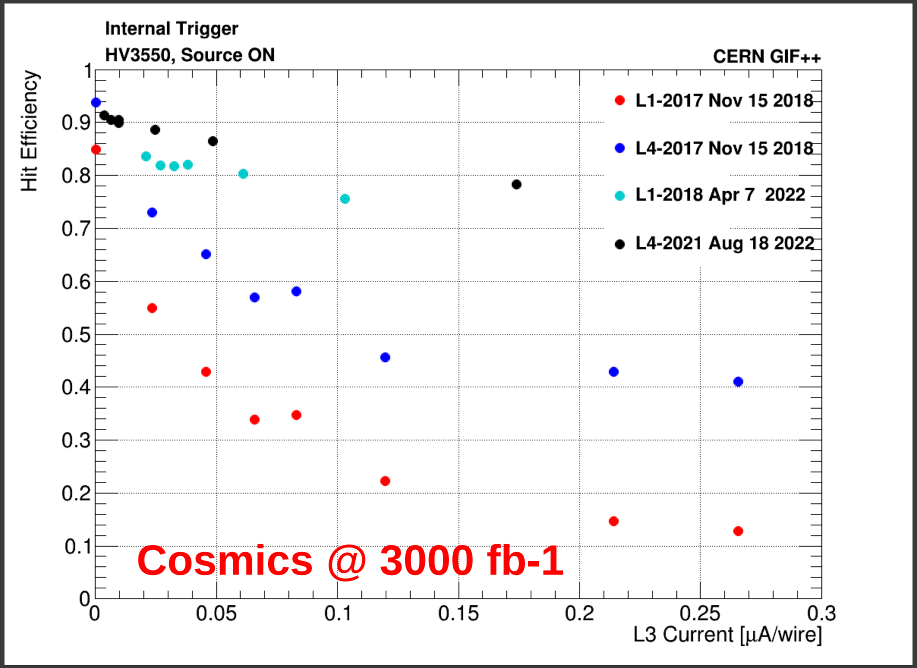
Energy dispersive X-ray spectroscopy (EDS) of a wire of SL1L1 of the MB2 chamber exposed at GIF++ on the first irradiation, 2017-2018 , and extracted after ~1 Hl-Lhc integrated charge (as expected on the most exposed DT chamber, MB1 of wheels +2 and -2).In the x axis the energy of the absorbed gammas of different material are reported. From the left the peaks correspond to carbon (C), oxigen (O), silicon (Si) and aurum (Au).

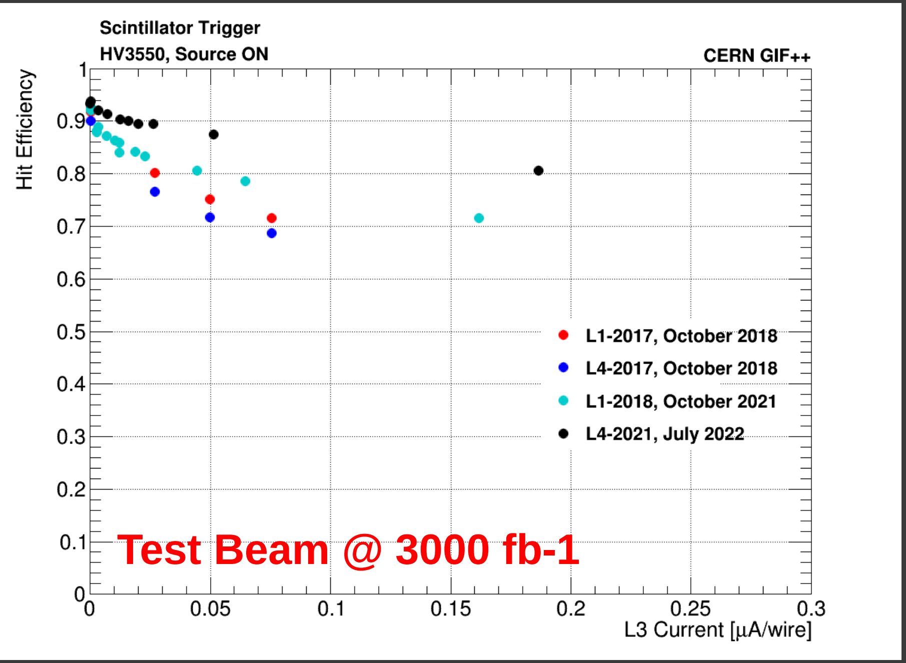
Energy dispersive X-ray spectroscopy (EDS) of a wire of SL1L1 of the MB1 chamber exposed at GIF++ on 2018-2019 after ~0.7 HL-LHC integrated charge (charge expected on the most exposed DT chamber, MB1 of wheels +2 and -2). In the x axis the energy of the absorbed gammas of different material are reported. From the left the peaks correspond to carbon (C), oxigen (O), silicon (Si) and aurum (Au).

DT local efficiency



DT hit efficiency





CSC aging in physics performance