Long-term and aging studies: the example of CMS Muon system

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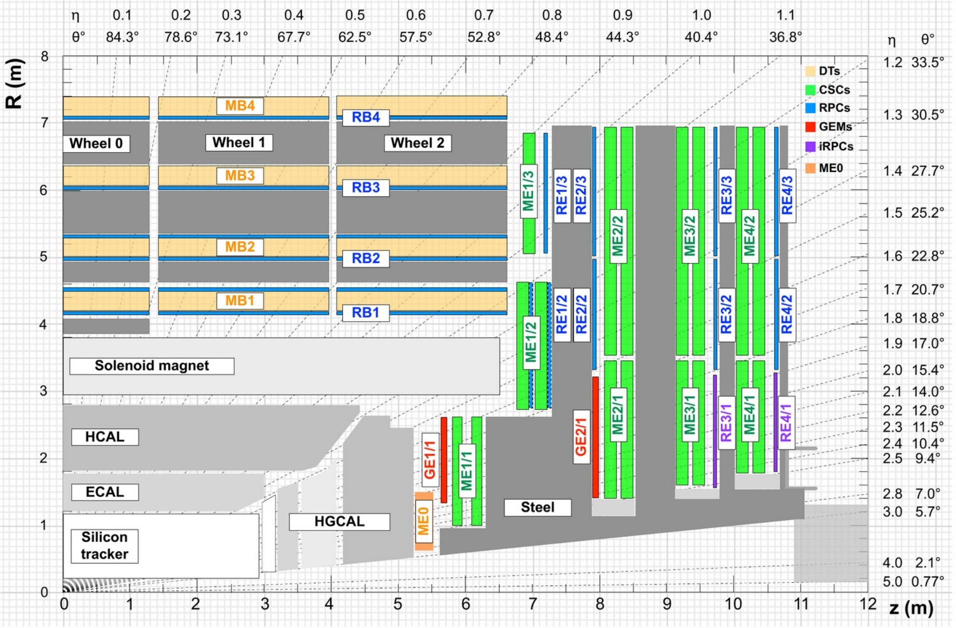
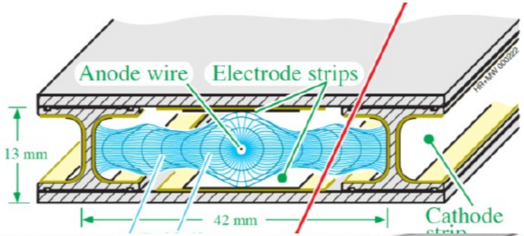
DRD1 February 2024

Barrel: DT+RPC
Endcap: RPC+CSC+GEM

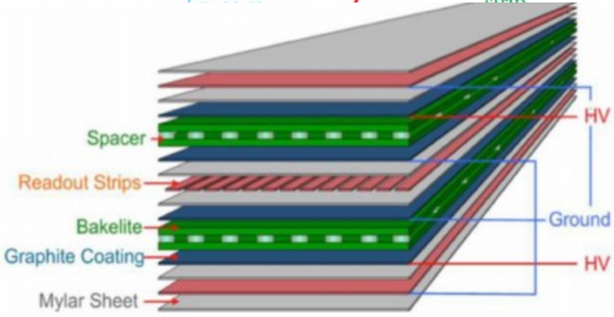
CMS Muon System



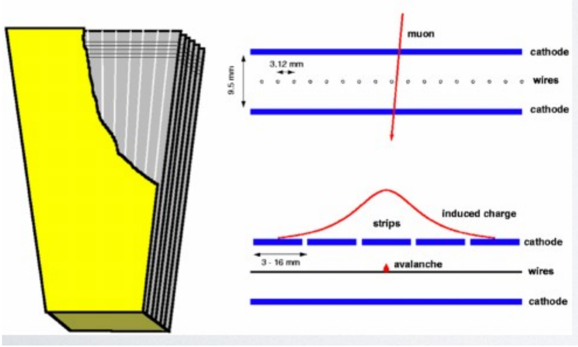
DT: muon trigger and tracking



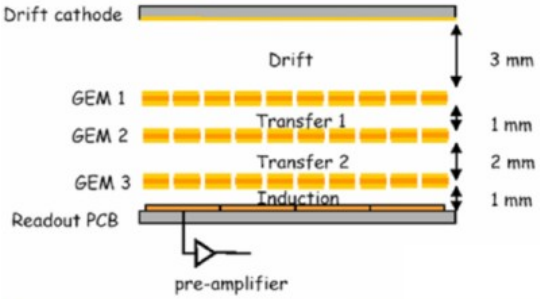
RPC: muon trigger (ns time resolution)



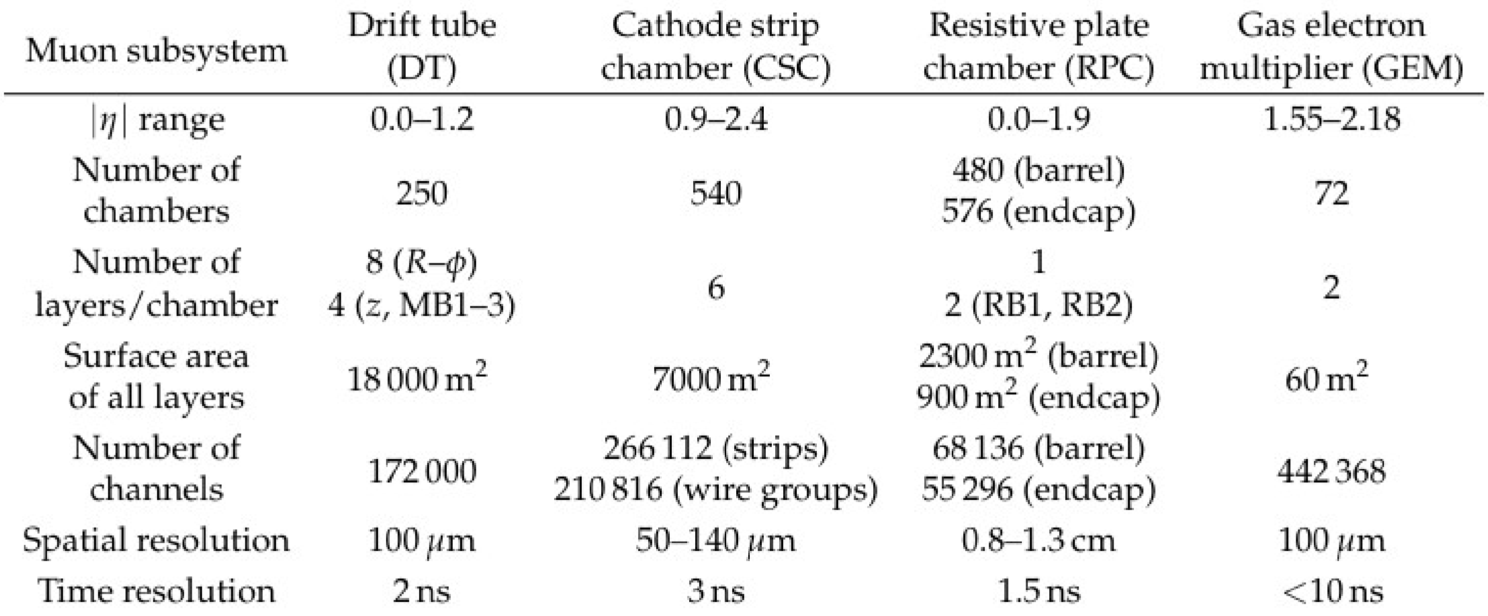
CSC: muon trigger and tracking



GEM: a new subdetector - muon trigger in the high occupancy region + additional coordinate measurements
- GE1/1 installed in LS2
- ME0 and GE2/1: 2024-2026



CMS Muon System



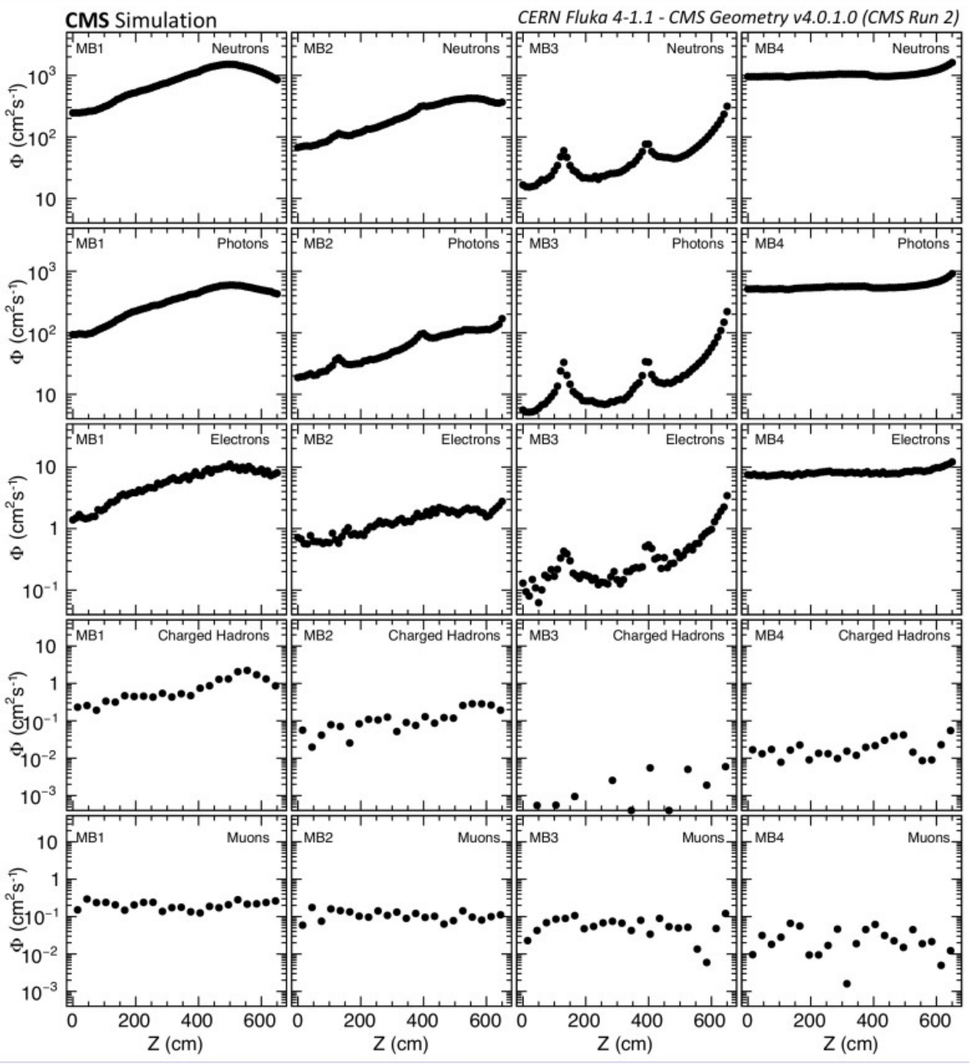
Muon subsystem	Drift tube (DT)	Cathode strip chamber (CSC)	Resistive plate chamber (RPC)	Gas electron multiplier (GEM)
$\|\eta\|$ range	0.0–1.2	0.9–2.4	0.0–1.9	1.55–2.18
Number of chambers	250	540	480 (barrel) 576 (endcap)	72
Number of layers/chamber	8 (R–ϕ) 4 (z, MB1–3)	6	1 2 (RB1, RB2)	2
Surface area of all layers	18 000 m^2	7000 m^2	2300 m^2 (barrel) 900 m^2 (endcap)	60 m^2
Number of channels	172 000	266 112 (strips) 210 816 (wire groups)	68 136 (barrel) 55 296 (endcap)	442 368
Spatial resolution	100 μm	50–140 μm	0.8–1.3 cm	100 μm
Time resolution	2 ns	3 ns	1.5 ns	$<$10 ns

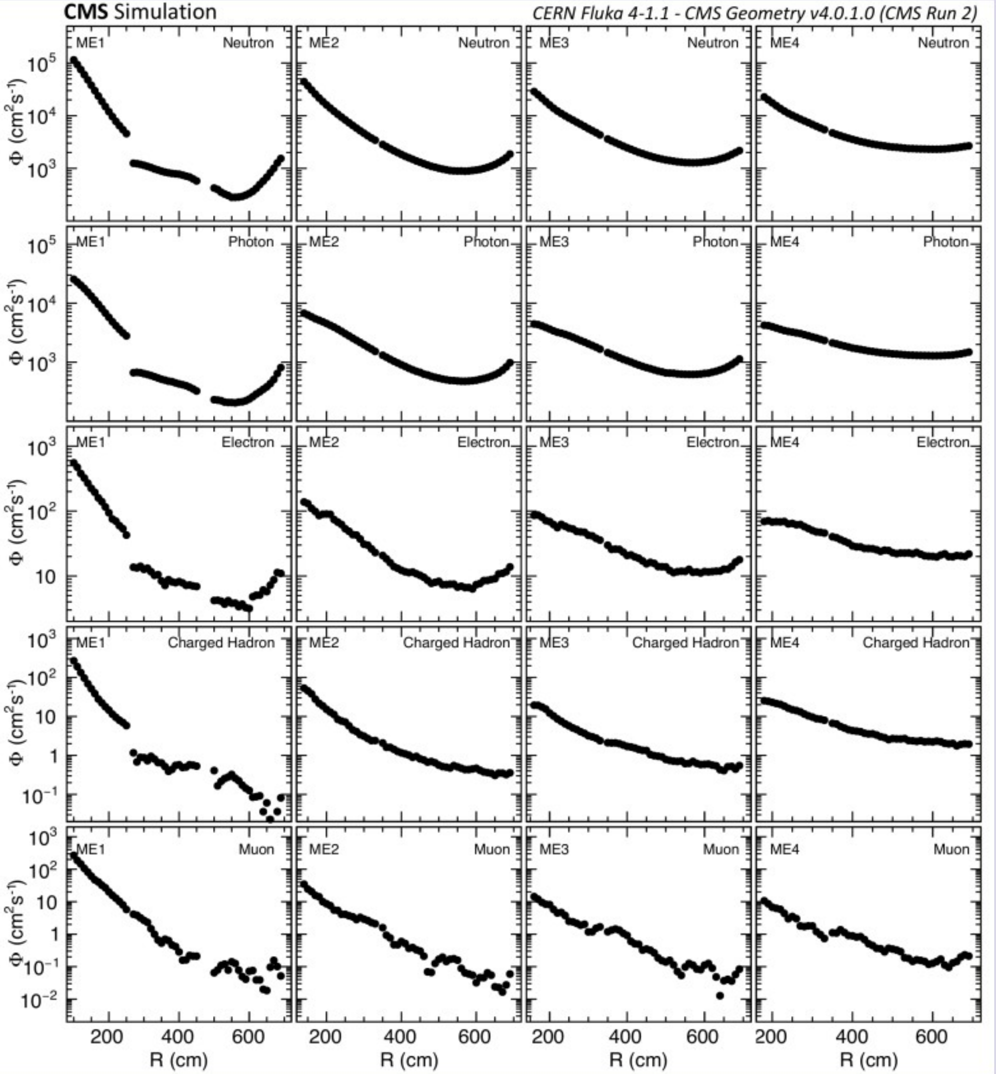
CERN-EP-2023-136
2023/09/12

CMS-PRF-21-001

Development of the CMS detector for the CERN LHC
Run 3

CMS Muon System background (Run2 per 1e34 Hz/cm2)





Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at √s= 13 TeV - CMS MUO-16-001

CMS Muon System performance

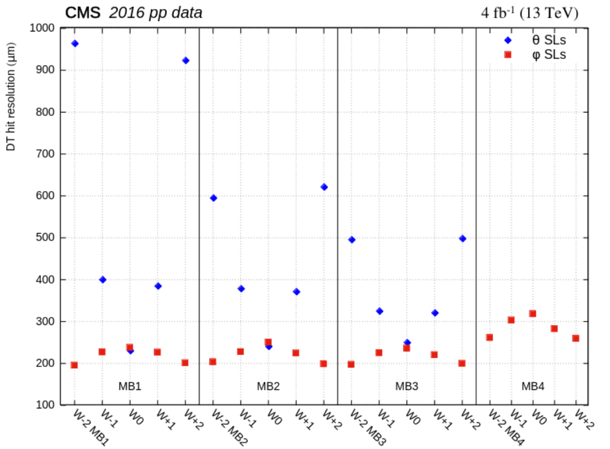


Figure 3: Reconstructed hit resolution for DT ϕ superlayers (squares) and DT θ superlayers (diamonds) measured with the 2016 data, plotted as a function of station and wheel. The uncertainties in these values are smaller than the marker size in the figure.

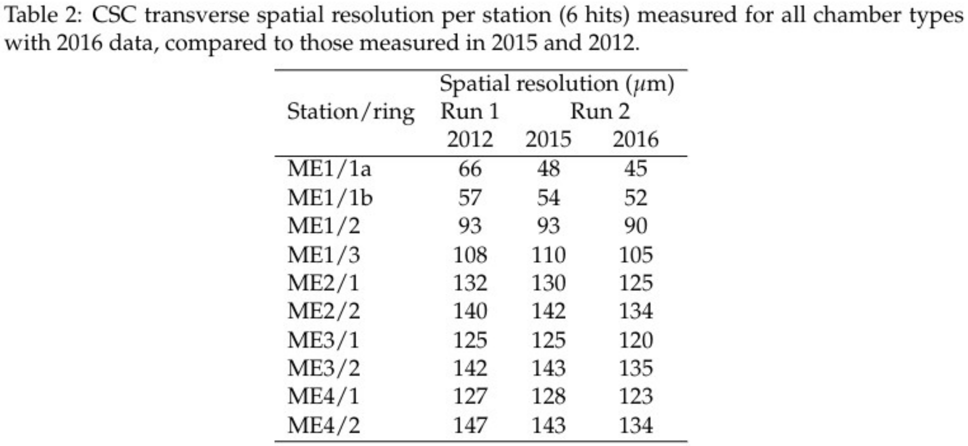
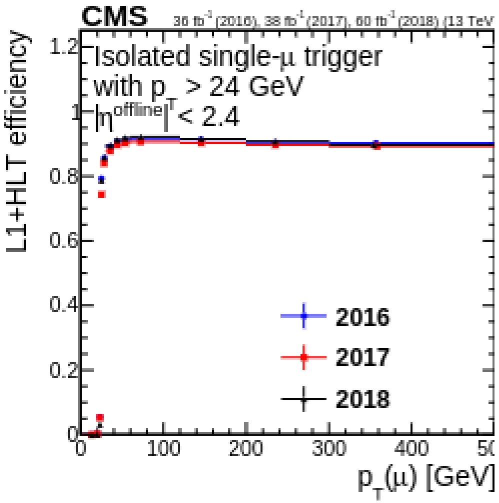
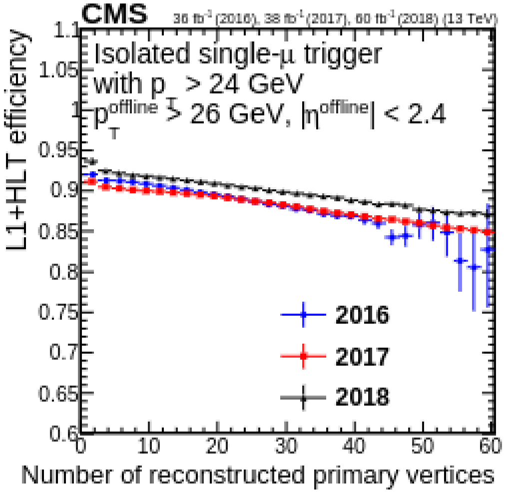


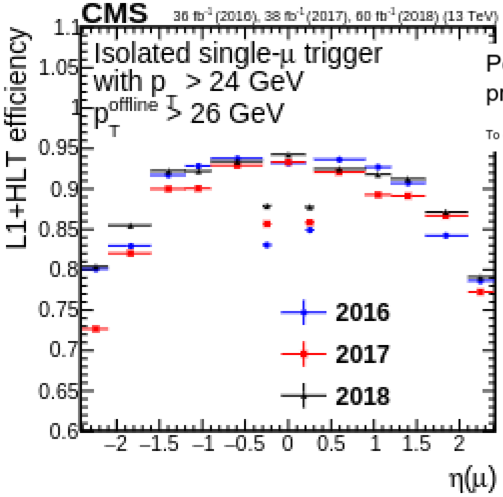
Table 2: CSC transverse spatial resolution per station (6 hits) measured for all chamber types with 2016 data, compared to those measured in 2015 and 2012.

Station/ring	Spatial resolution (μm)		
	Run 1	Run 2	
	2012	2015	2016
ME1/1a	66	48	45
ME1/1b	57	54	52
ME1/2	93	93	90
ME1/3	108	110	105
ME2/1	132	130	125
ME2/2	140	142	134
ME3/1	125	125	120
ME3/2	142	143	135
ME4/1	127	128	123
ME4/2	147	143	134

Perfect performance and redundancy







Performance of the CMS muon trigger system in proton-proton collisions at √(s) = 13

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Longevity for HL-LHC

- **CSC, DT, RPC**:
  - longevity studies performed in 90s-early 2000 for 10 years of **LHC** (1e34 Hz/cm2, 300 fb-1)

- **GEM**: new detectors

- **HL-LHC**: 3000-4000 fb-1 and 5-7.5 e34 Hz/cm2

- modified geometry after LS2, LS3 upgrades (beampipe, HGCAL but also extra-shieldings)

- additional preference for the greenhouse gas use (RPC, CSC)

=> a lot of longevity studies are ongoing from 2015

  - **lab** studies

  - studies at **GIF++**

  - **in situ** monitoring at CMS

=> also a feedback to the operation conditions (HV optimization etc) outline

Longevity prediction for HL-LHC

- DT
- GEM

Ar/CO2 gas mixtures

- RPC $R134a + iC_4H_{10} + SF_6$ $95.2\% + 4.5\% + 0.3\%$
- CSC **40% Ar + 50% CO2 + 10% CF4**

Reduction of the exhaust GWP

- recuperation at CMS

- searches for new mixtures

– Also involve longevity studies

- RPC
- CSC

Evaluation of the HL-LHC accumulated charge:

DT/RPC/CSC:

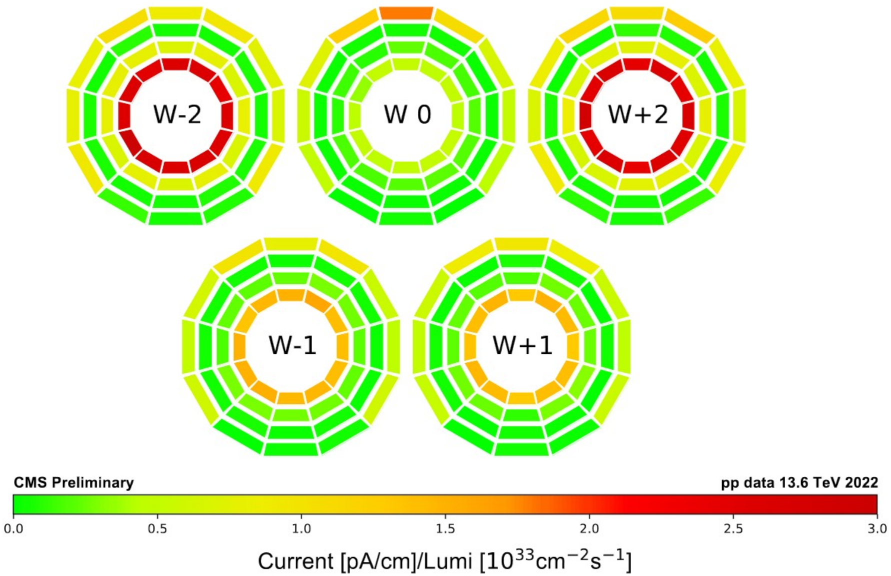
-use CMS data (currents, rates) to extrapolate to the HL-LHC luminosity

-use FLUKA predictions to account for the new geometry

GEM: currently MC based

The final values are taken for the area of the highest BG occupancy and a safety factor of ~3 is considered for longevity test goals

DT *– background at P5 (2022)*



	Chamber	Expected integrated charge at 1 HL-LHC mC/cm	Expected background at HL-LHC (current at 3550 V) μA/wire
🟥	MB1 YB± 2	**9.4**	**0.06**
🟨	MB1 YB±1 MB4 S4 YB0	**4.6**	**0.02**
🟩	MB2 YB± 2 MB4 Upper	**≃2.5**	**≃0.01**
🟩	Rest of the detector	**≲1.0**	**≲0.005**

RPC *– HL-LHC estimation*

HL-LHC conditions:

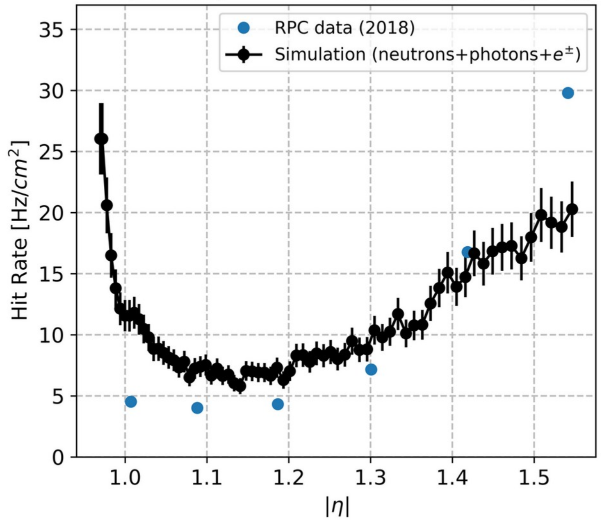
- Expected Integrated charge :

  Maximum: ~ **280** mC/cm2

  Barrel chambers factor 2 less

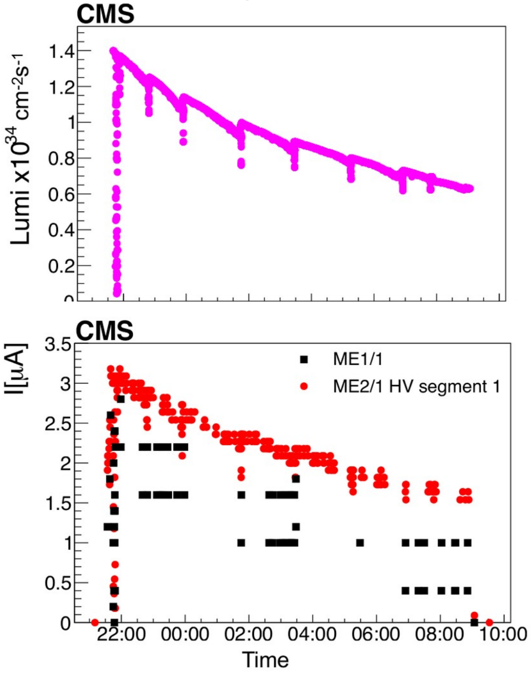
- Expected Max. Rate: ~ 200 Hz/cm2

Run2: good agreement between MC and measurements



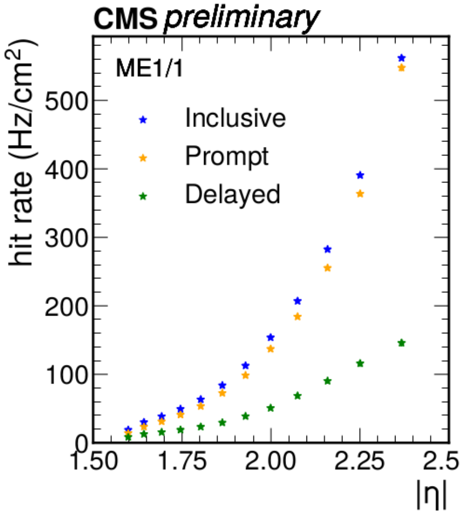
CSC *– background at P5 (Run2)*

Current – total occupancy per chamber (segment)



FLUKA: ratio HL-LHC/Run2 to account for the detector geometry changes

Rate over the area – the highest occupancy spot



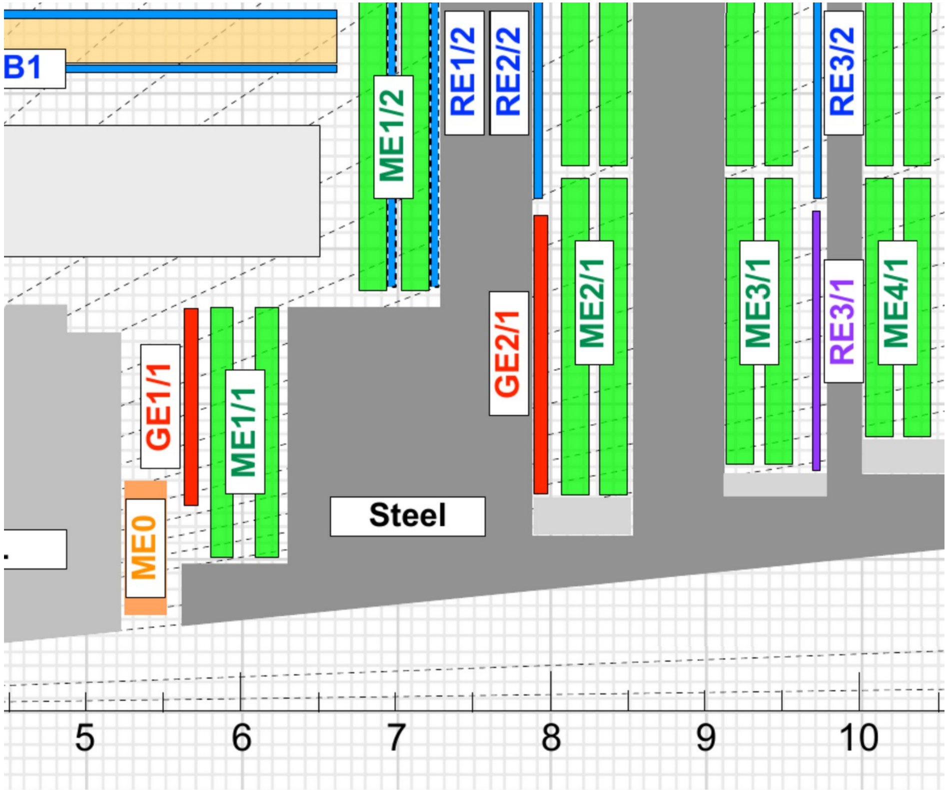
Q [mC/cm]	Expected* Q(HL-LHC)
ME1/1	200
ME2/1	130

GEM*s (MC -based estimates)*

ME0: **8 C/cm2**

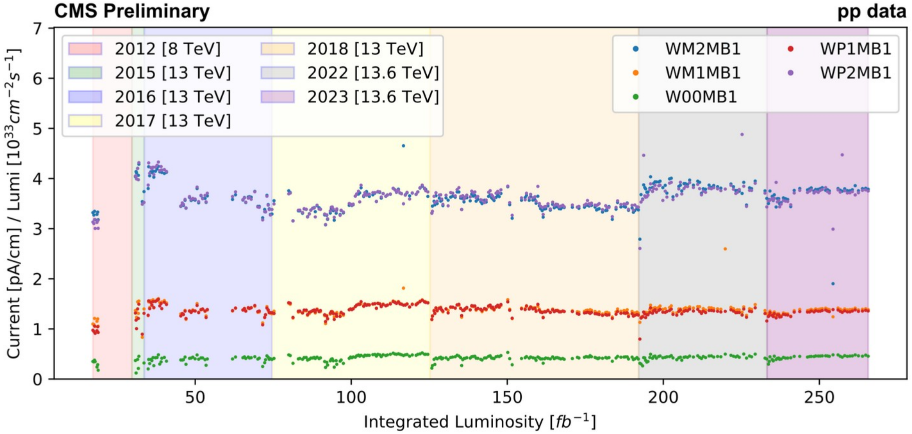
GE1/1: **60 mC/cm2**

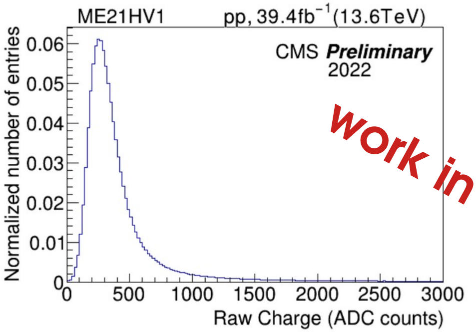
GE2/1: **30 mC/cm2**

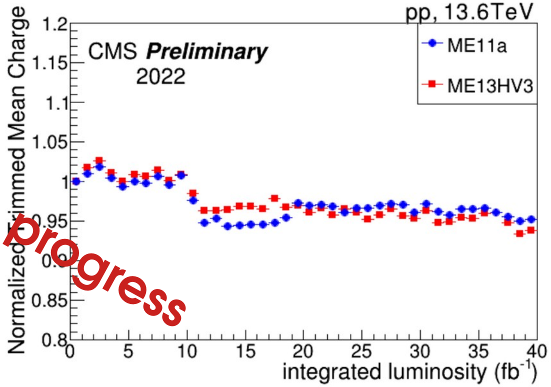


*longevity studies – **monitoring at P5***

- Continuous **current monitoring** at P5 extracting the slope of currents vs luminosity fill by fill.
- DT:
  - Currents: already integrated 0.8 mC/cm in MB1 YB ± 2. Small decreasing trend observed, much slower of what would be expected from the initial tests at GIF++
  - HV scans: changing the setting of one layer in every chamber in dedicated cosmic runs at the beginning and at the end of data taking periods – stable behaviour
- RPC, CSC: current monitoring during LHC beam and dark current monitoring
- CSC muon response monitoring – gas gain stability, spatial resolution monitoring







work in progress

Longevity studies at GIF++, labs and at CMS

GIF++ (see the common facilities talks):

- irradiation, BG intensity test (performance), muon test beam – no BG + BG of different intensity

CMS Muon detector longevity studies:

- CSC, RPC: irradiation at GIF++ ongoing from 2015

- GEM: several tests including early studies at GIF++
  ME0 – not enough intensity for prompt predictions at GIF++ → lab tests
  irradiation with X-ray guns: 904, Aachen, Seoul

- DT: irradiation at GIF++ 2017 – 2023

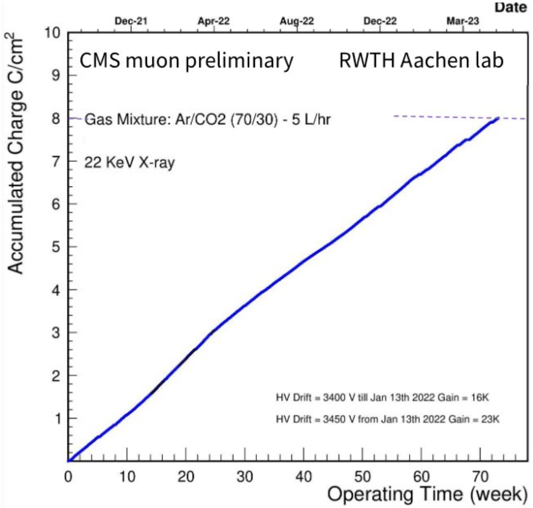
Monitoring as functions of the accumulated charge:

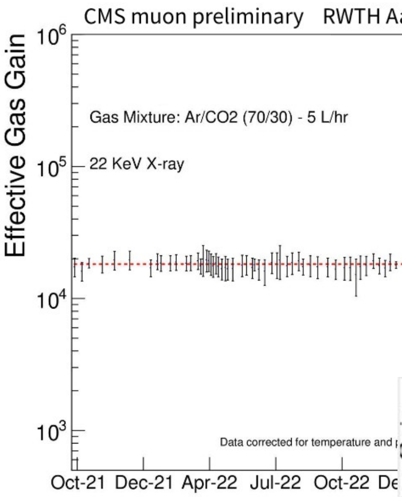
- basic characteristics (lab, GIF++)
- muon detection performance without background (lab, TB, TB @ GIF++)
- muon detection performance with various background levels (**TB @ GIF++ - unique facility**)

GEM *longevity studies (X-ray)*

ME0: now **8 C/cm2 (safety factor 1)**

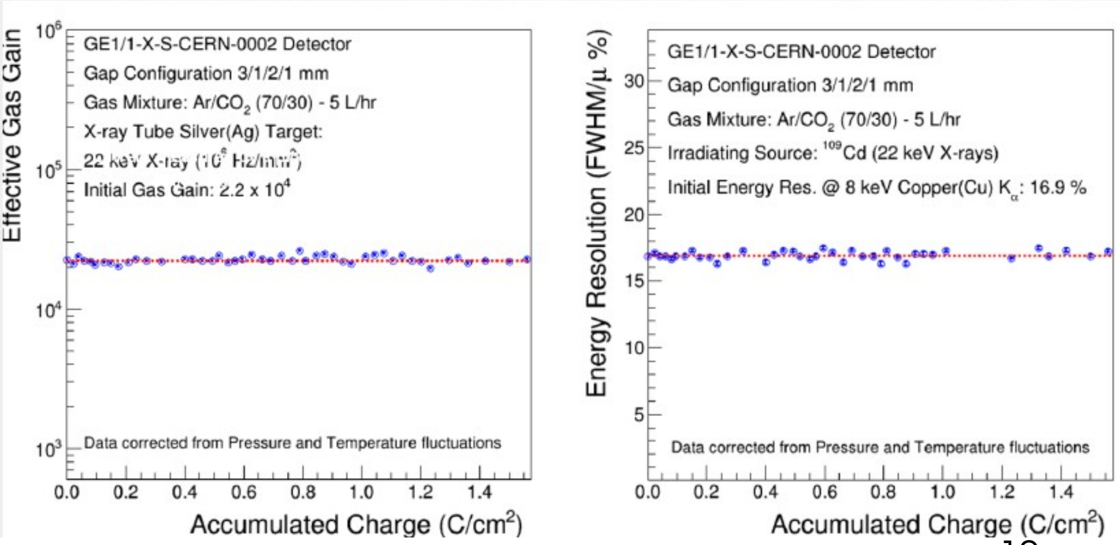
accelerated irradiation (8 times more than GIF++) is **ongoing** in Aachen and Seoul





GE1/1: **60 mC/cm2**
GE2/1: **30 mC/cm2**

No degradation is seen up to 1.5 C/cm2



- Irradiation: 10 W Amptek X-ray source resulting in 15mC/cm2/day from October 2021
- Gas gain calculated from the irradiation current and the evaluated primary charge from the X-ray
- Correction for the temperature and pressure variation is applied
- No decrease of the gas gain is observed up to 8 C/cm2

RPC *longevity studies at* ***GIF++***

HL-LHC conditions:

- Expected Integrated Charge :

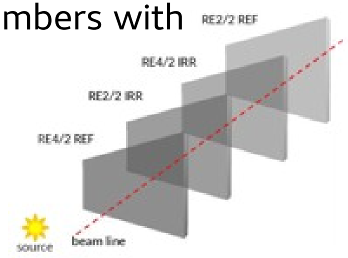
  Max. IC: ~ 280 mC/cm2

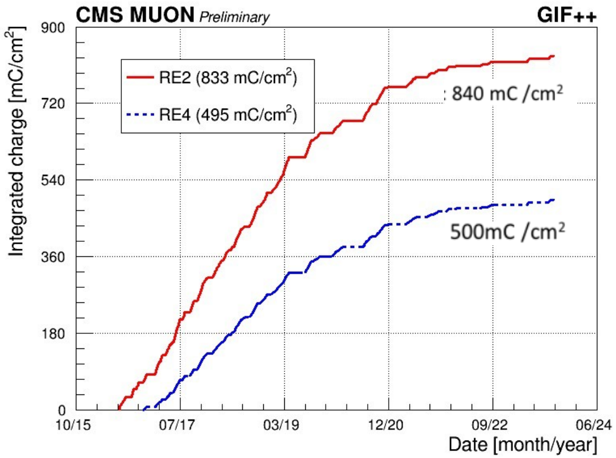
  Barrel chambers factor 2 less

- Irradiation goal ~ **840 mC/cm2** (safety factor 3)
- Expected Max. Rate: ~ 200 Hz/cm2

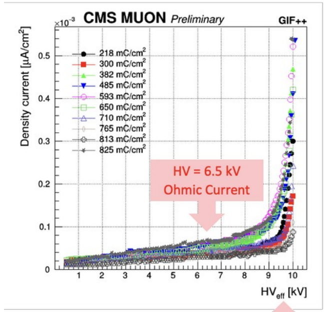
Setup at GIF++:

- RE2 and RE4 chambers since July 2016
- 2mm double gap chambers with standard gas mixture





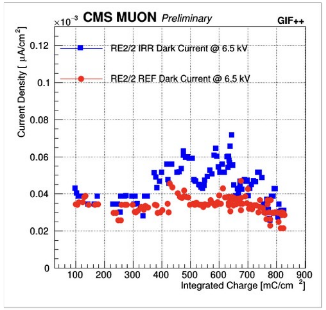
RE2/2 Irradiated dark current



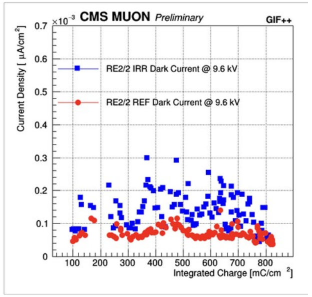
HV = 6.5 kV
Ohmic Current

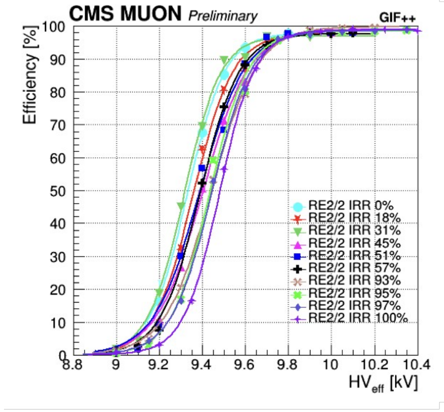
HV = 9.6 kV
total Current

RE2/2 IRR. & REF **ohmic** current

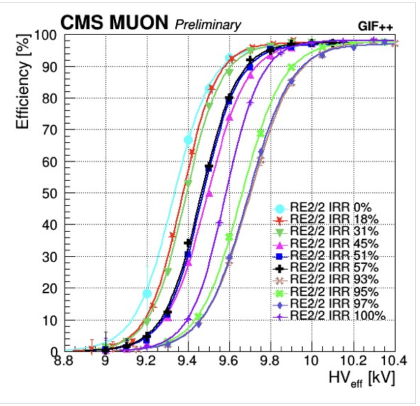


RE2/2 IRR. & REF **total** current





Without Background radiation & With muon beam

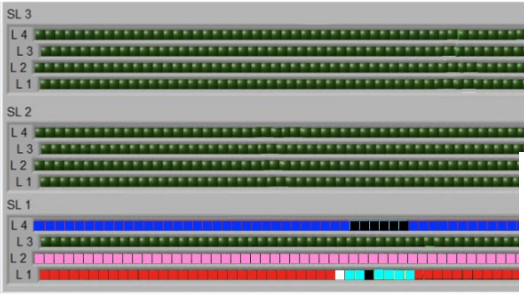


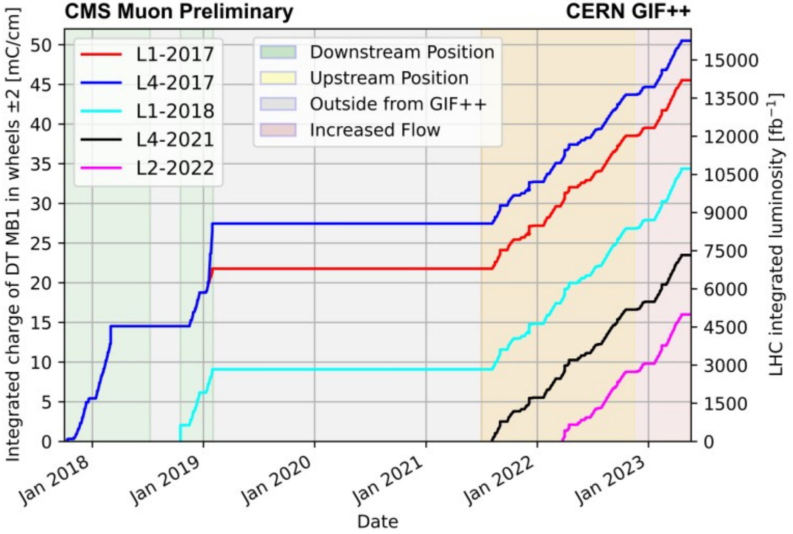
With Background radiation (600 Hz/cm²) & with muon beam

No aging signs were observed for both RE2 and RE4 chambers
Analysis of the RE4 performance with the test beam data ongoing

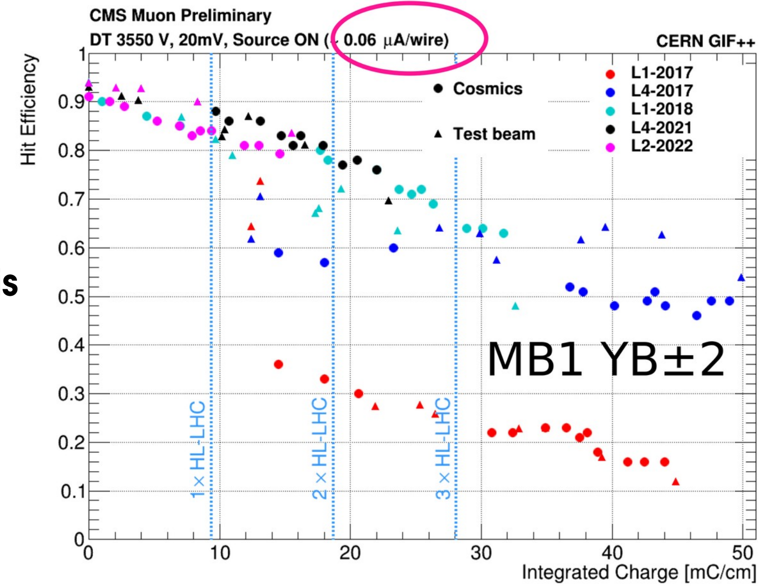
DT** longevity studies at **GIF++** - **gas gain

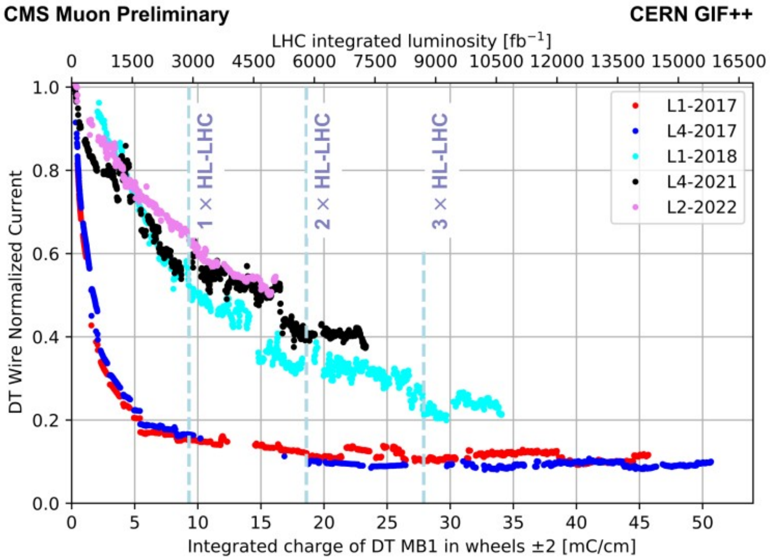
- A spare **MB2 chamber**, with 12 Layers (L), organized in 3 Super Layers (SL), was **irradiated from 2017**: **SL2** and **SL3** reference; **L1**, **L2** and **L4** of **SL1 irradiated**,
- L1-2017 and L4-2017
- 2018: 8 wires were replaced with the L1-2018 wires;
- 2021: 5 wires replaced in L4 with **L4-2021** wires (**black**); L2-2022 wires started the irradiation in the 2022 with the goal of checking the aging effects on a further full layer



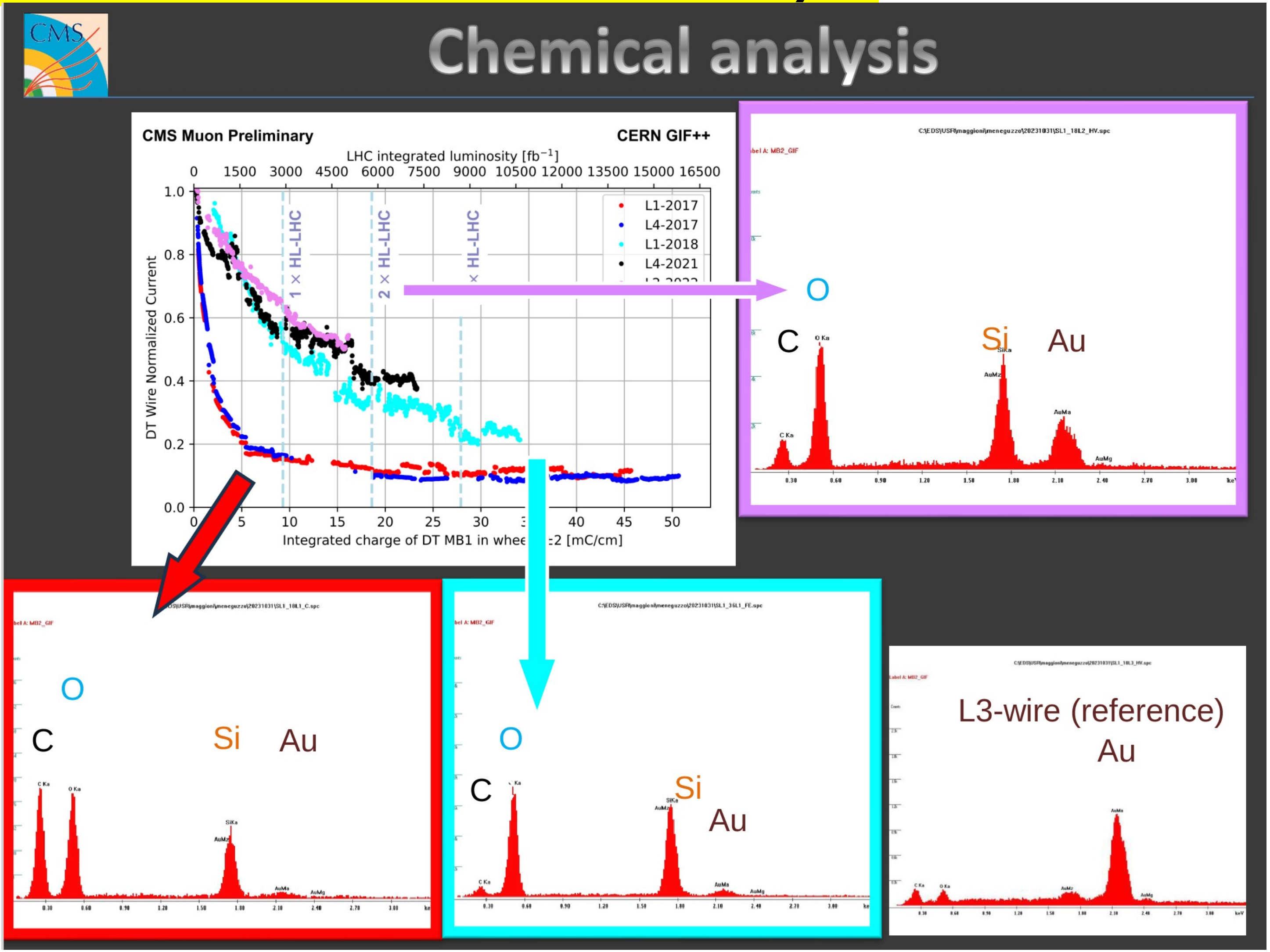


- **Even with gas gain reduction the hit efficiency degradation is small**
- **Prompt feedback to the CMS DT operation – extra-shielding, HV reduction**





DT *longevity studies at* ***GIF++*** *-* ***material analysis***

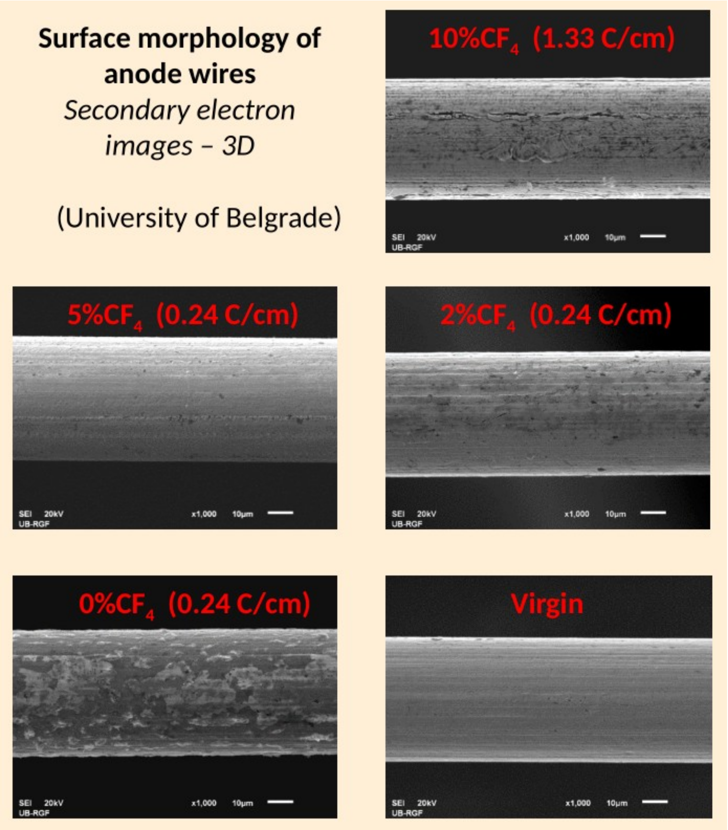


Chemical analysis

CSC: *reduction of CF4 and lab longevity studies*

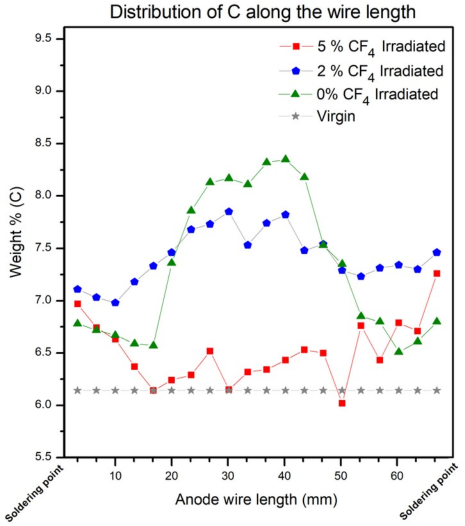
Laboratory longevity studies with reduced CF4 fraction

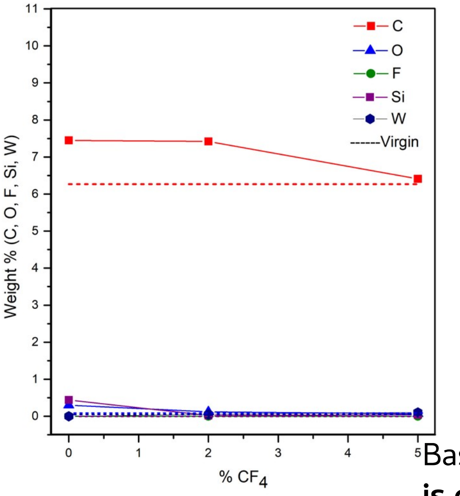
- Lab longevity tests with 0, 2 and 5 %CF4 performed in 2017-2019
  - Open loop, local irradiation, **small prototypes of ME2/1 type**
  - **No performance degradation seen, but anode wire deposition was observed for 0 and 2% CF4 up to 300 mC/cm**
- Dedicated comparative material analysis finalized at the beginning of 2023
  - Methodology for semi-quantitative comparison of the material analysis results has been developed



Surface morphology of anode wires
Secondary electron images – 3D

(University of Belgrade)

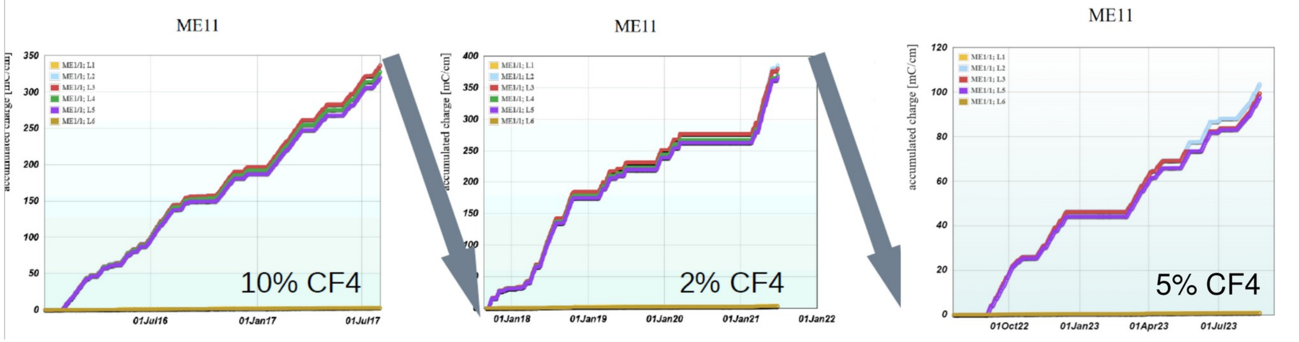




Based on laboratory tests and material analysis **40%Ar+55%CO2+5%CF4 is considered as a potential safe candidate mixture for CSC**

CSC: *longevity studies at* ***GIF++***

- Two production chambers ME1/1 and ME2/1 - of the highest background occupancy at CMS
- Closed loop scaled prototype of the gas system at CMS
- Irradiation ongoing from 2016; current priority – ME2/1 with 5% CF4
- Two of six chamber layers are off during irradiation (reference)
- Regular performance monitoring (currents, dark rates, etc)
- Measurements with muon test beam



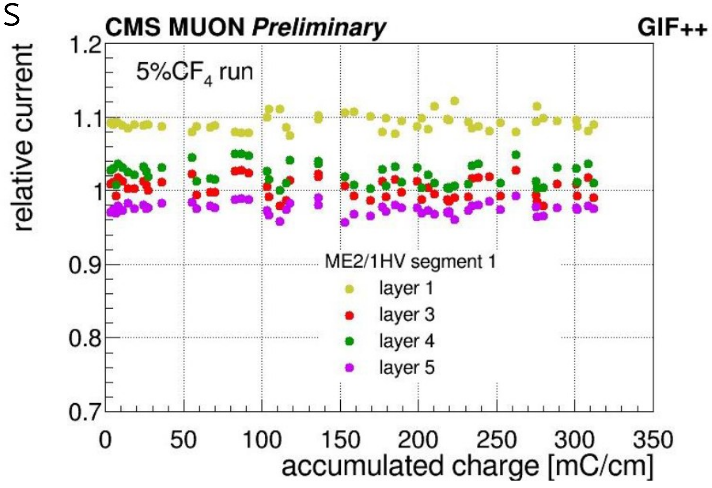
Q [mC/cm]	Expected* Q(HL-LHC)	10%CF4	+ 2%CF4	+ 5%CF4**	Total
ME1/1	200	330	370	100	800
ME2/1	130	330	-	300	630

(*) Dose estimated with Run2 currents and b/g occupancies and then corrected with FLUKA simulation with HGCAL – to be updated with Run3 currents.

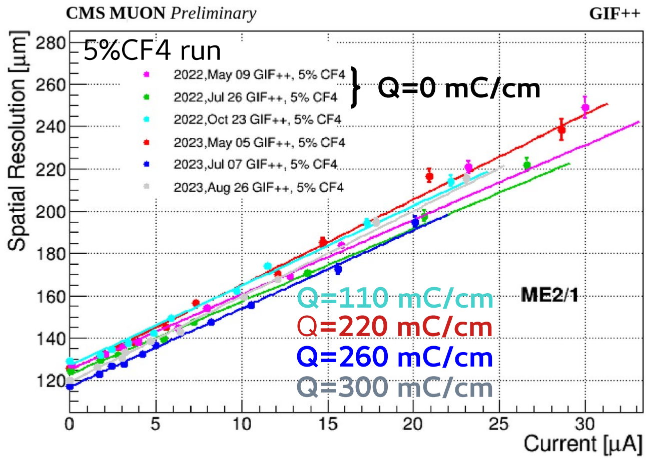
(**) as of today

No significant performance degradation has been seen in any of the irradiation runs
Irradiation with 5% CF4 ongoing till next test beam (~late spring 2024)

Relative gas gain monitoring: I_irr / <I_ref>



Spatial resolution for different background intensity



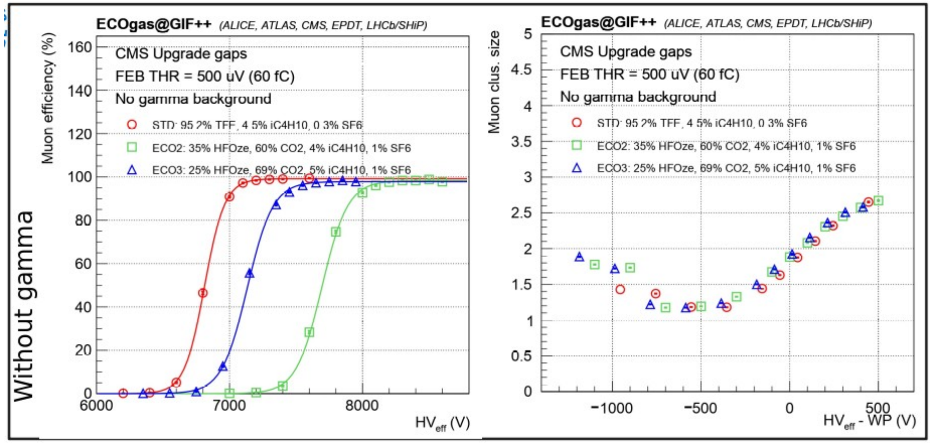
Summary

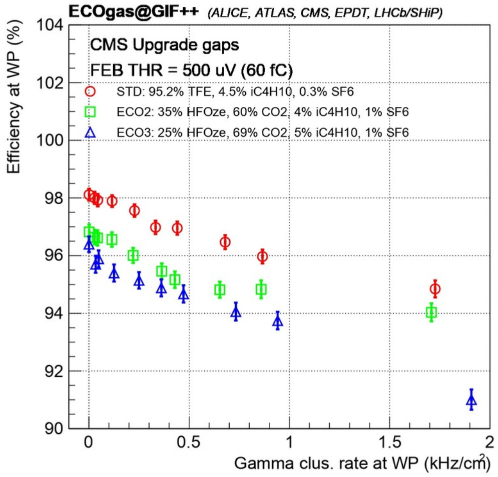
- CMS Muon System: 4 types of the detectors with good performance and high redundancy
- Longevity studies for the HL-LHC are ongoing from 2015 at labs and GIF++
- GIF++ provides a unique opportunity for longevity and performance studies of the muon detectors operating at high background occupancy
- The friendly GIF++ user community within and across LHC experiments is natural environment for expertise exchange
- Despite the difference in the detector technologies there are a lot of common aspects of such studies – a good seed of the DRD1 WP1 longevity and eco-gas tasks

backup

RPC: *searches for alternative mixtures*

STD and HFO based



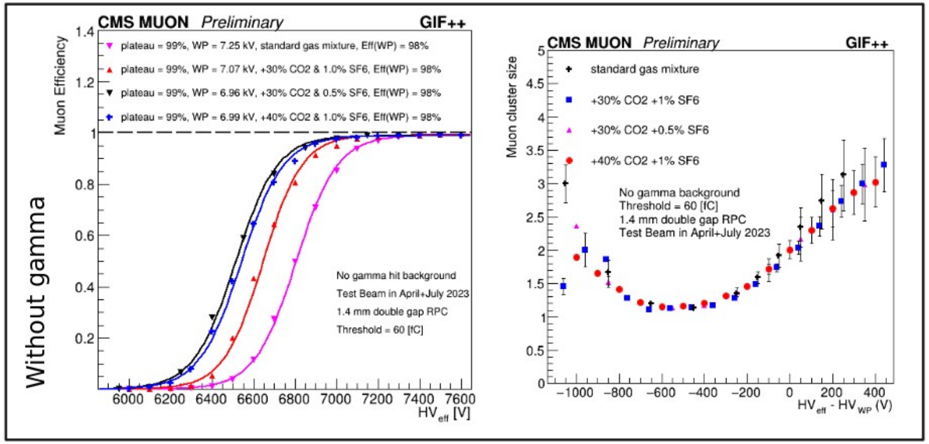


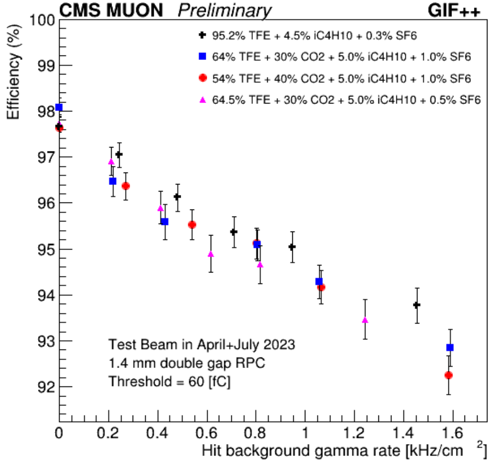
Mixture	WP (kV)	Efficiency (%)
STD	7.16	98.1
ECO2	8.10	96.8
ECO3	7.54	96.4

Longevity studies with **ECO2** :

- Ongoing with RE1/1 (~120 mC/cm2 up to now) – analysis of performance in progress
- Starting irradiation with a KODEL chamber now

TFE+CO2 based

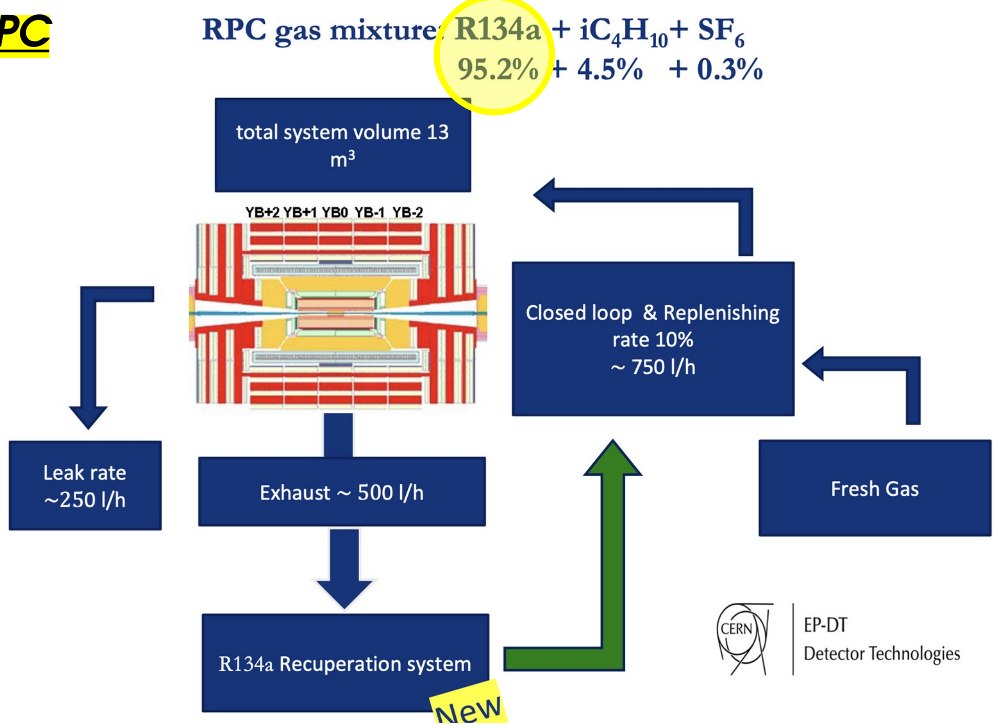




Mixture	WP (kV)	Efficiency (%)
STD	7.25	98
30% CO_2 + 1% SF_6	7.07	98
30% CO_2 + 0.5% SF_6	6.96	98
40% CO_2 + 1% SF_6	6.99	98

R134a and CF4 recuperation at P5

RPC



RPC gas mixture: R134a + iC_4H_{10} + SF_6

95.2% + 4.5% + 0.3%

total system volume 13 m^3

Closed loop & Replenishing rate 10% ~ 750 l/h

Leak rate ~250 l/h

Exhaust ~ 500 l/h

Fresh Gas

R134a Recuperation system

New

EP-DT Detector Technologies

- Commissioning started in June 2023, running since August 2023 in the continuous mode
- As of September 23:

  20% / 80% recuperated / fresh (90 / 360 L/h)
- **Recuperation efficiency ~80%**
- Gas quality inside requirements

CSC

- 6m3/h gas flow but
  - 10% CF4
  - **closed loop** with 10% replenishment
  - **CF4 recuperation**

Current operation

- CF4 recuperation (EP-DT gas group) :
  - Maximal recuperation efficiency ~60-70% depending on CF4%
  - Lab longevity test with recuperated CF4 to be performed soon
- Running **5% CF4 during TS and low luminosity**
- During last years **shortages of the CF4 supply** were experienced twice
  - A stock of CF4 for entire 2024 run was agreed to avoid shortages in the future

CSC: *searches for further CF4 reduction/replacement*

Replacement candidates (F-containing gases)

HFO1234ze (F:C = 4:3) – lab longevity test in 2019

- no gas gain reduction but significant rise of dark current
- to be repeated in more controllable conditions but no great expectations

Other candidates from general considerations:

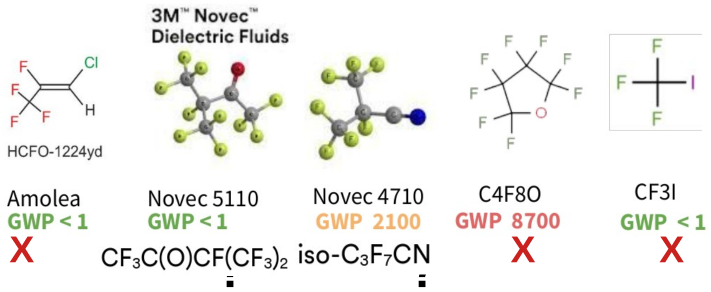
HFO-1336mzz(E) (6:4) GWP~18,

HFE-245fa1 (5:3) and HFE-143m (3:2) GWP~700

Other candidates under study by RPC community : **Novec** gases?

Other way – F containing gases + O2 addition (increasing F-radicals)?

SF6 alternatives research still ongoing in electrical industry



Gianluca Rigoletti

Infrastructure, prototypes and setups

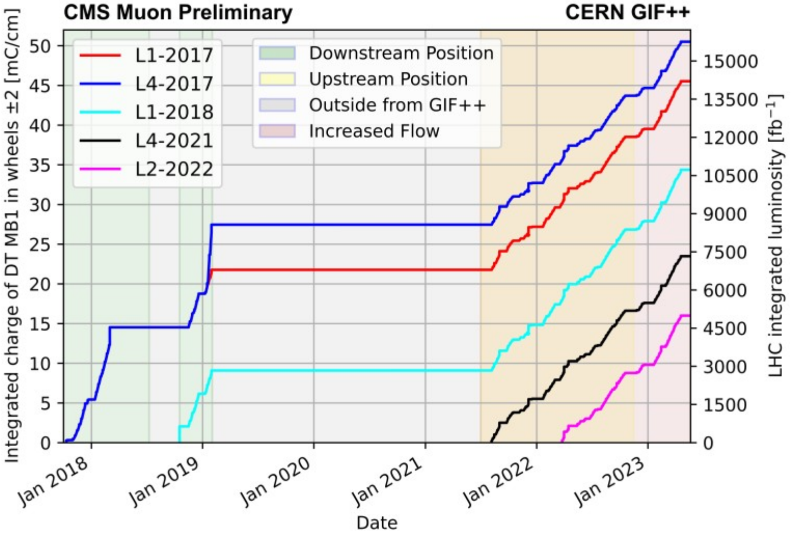
- Development is ongoing in parallel to irradiation activity at GIF++ since 2021
- Performance characterization setup based on CSC DAQ : commissioned
- MiniCSC production – 6 prototypes are produced (30x30 cm2, <1 L gas volume) : commissioning ongoing
- 4-channel dynamic mixing gas system – calibrated for low gas flows (Ar/CO2/CF4/O2, together with EP-DT) -commissioning ongoing
- Two irradiation stands with Sr sources ready
- First irradiation tests to be started at the end of the year/beginning 2024
    - recuperated CF4
    - repeating test with HFO1234ze
- **Close collaboration with the EP-DT gas group and Belgrade chemists team**

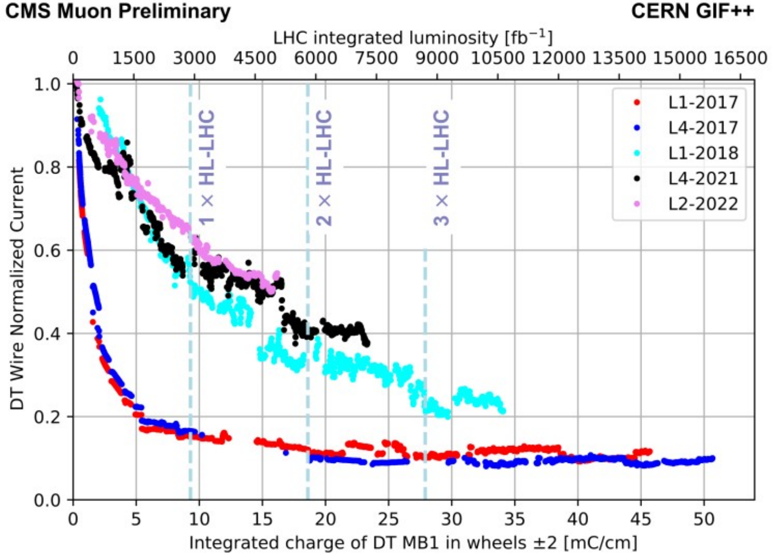
summary

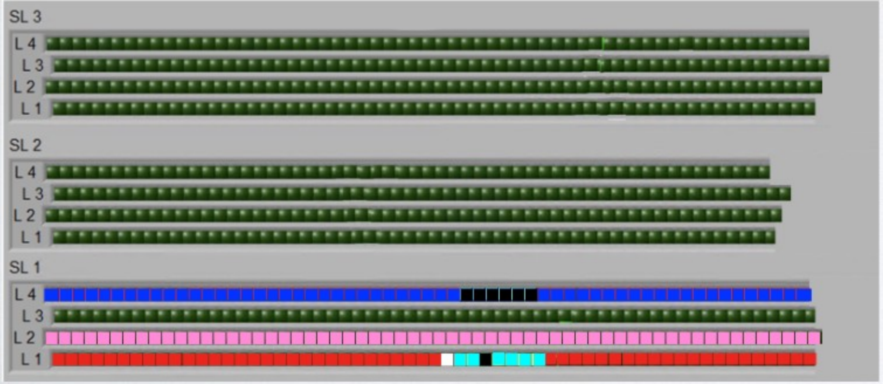
- DT
  - Accumulated charge prediction updated
  - Longevity run at GIF++ is done for more than 3 x HL-LHC expected accumulated charge – optimistic prediction
  - Material analysis of irradiated electrodes ongoing
  - Performance monitoring at CMS – optimistic prediction for HL-LHC as well
- GEM ME0
  - 1 x HL-LHC expected charge accumulated – no gas gain reduction is observed; a longevity test aiming factor 3 is ongoing
- RPC
  - Nominal gas mixture: the charge of 1.8-3.0 of expected for HL-LHC is accumulated– no performance degradation observed so far
  - Alternative gas mixtures – intensive studies together with ECOGAS R&D Collaboration, ATLAS-RPC and EP-DT gas group – promising performance, longevity tests with ECO2 gas mixture are ongoing
- CSC
  - Factor of 3 of the charge predicted for HL-LHC is expected to be accumulated with reduced CF4 content by mid of 2024 for both chambers under the test – no significant performance degradation is seen up to now
  - Laboratory studies of performance and longevity of the CSC prototypes operating with alternative gas mixtures are scheduled to start at the beginning 2024

DT** longevity studies at **GIF++** - **gas gain

- A spare **MB2 chamber**, with 12 Layers (L), organized in 3 Super Layers (SL), was **irradiated from 2017**:
- **SL2** and **SL3** kept off during irradiation and used for internal trigger
- only **L1**, **L2** and **L4** of **SL1** were on during the irradiation, while **L3** was kept off and used as reference
- **L1-2017** and **L4-2017** wires started the irradiation in the 2017 collecting the same dose up to Jan. 2019, after the **L4-2017** was kept at very high HV, collecting more charge
- 2018: 8 wires were replaced with the **L1-2018** wires; 2021: 5 wires replaced in L4 with **L4-2021** wires (**black**); **L2-2022** wires started the irradiation in the 2022 with the goal of checking the aging effects on a further full layer
- **gas test**: increased gas flow from Nov 2022 to April 2023
- **end of the GIF++ operations in June 2023**
- extracted some wires to perform the chemical analysis







DT** longevity studies at **GIF++** - **hit efficiency

- Different efficiency between Cosmics and TB is expected, and mainly due to the intrinsic difference of the two sources

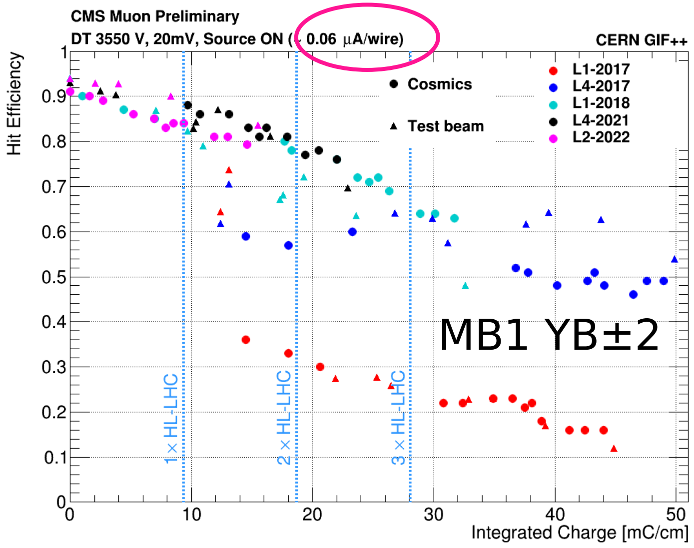
  Measurements done from the Fall 2018 on, in Cosmics and TB, show compatible results also among the wires except for the **L4-2017**

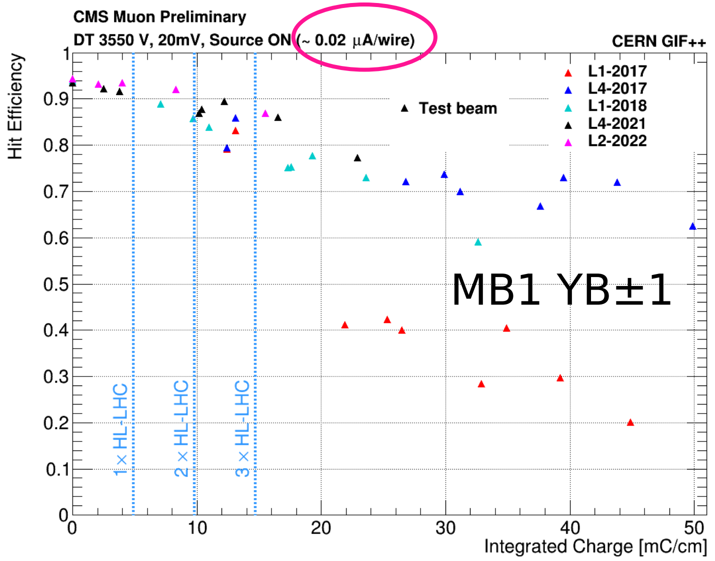
  Behaviour of **L2-2022**, which is a full layer, like **L1-2017** and **L4-2017** were at the beginning, is very consistent with the one of the **L1-2018** and **L4-2021** wires

- Loss of efficiency in less exposed chamber scale also due to lower background, and not only for reduced accumulate integrated charge

- Absolute value of efficiency at P5 is not directly comparable to the one at GIF++

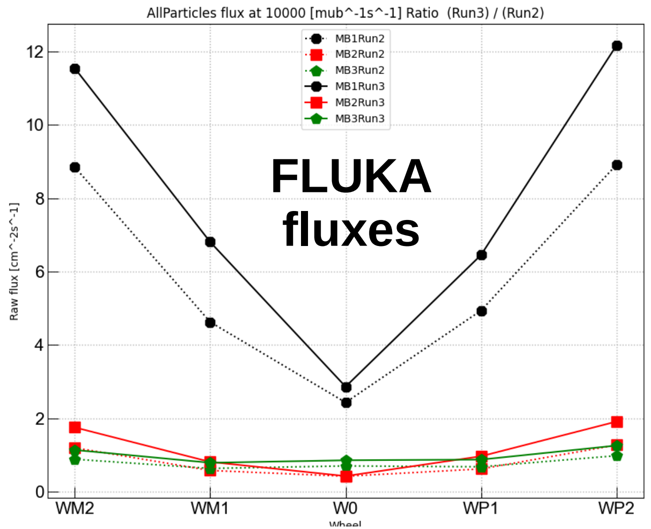
  Corrections need to be applied before giving values as input to Phase 2 reconstruction (work ongoing)



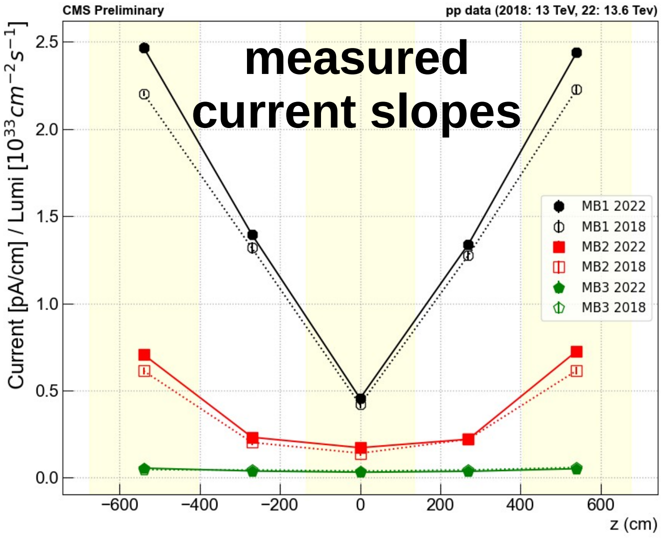


DT - background prediction for HL-LHC

- Direct extrapolation of Run3 condition to HL-LHC does not take into account **changes in CMS with the upgrade program**
- Main effect will come from **HGCAL** different material budget
- Also the new beam pipe will have an effect
- We have checked the prediction of Fluka between Run2 (v4.0.1.0) and Run3 (v5.0.0.0) for MB1 (no shielding is implement in FLUKA to work with MB4)
- **Fluka predicted an increase of flux that we also measured in currents between Run2 and Run3**
- This make us confident on Fluka predictions
- Last **Fluka Phase 2 simulation** (v6.3.0.1) expects **an increase of flux of 20% in MB1 external wheels with respect to Run3**
- This is added to the extrapolation from P5



FLUKA fluxes



measured current slopes

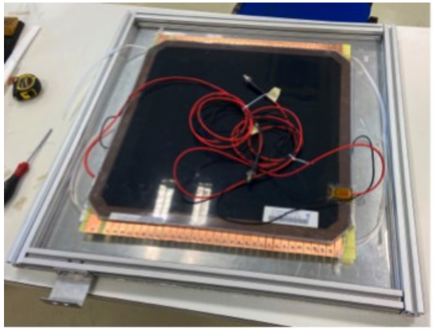
***RPC:** searches for alternative mixtures*

- Requirements: low GWP, low toxicity, not flammable and detector performance comparable with standard one

- ECOGAS collaboration R&D with the full replacement of R134-a by HFO-1234ze adding CO2 to decrease the WP

- Efforts with ATLAS-RPC and EP-DT to study the effects of replacing a small amount of R134-a with CO2, decreasing the CO2e* and the WP
  - The GWP values are mainly driven by SF6 which is increased up to 1% to decrease cluster size and streamer probability (as shown in previous EP-DT studies)
  - First step of the R&D – a short term solution reducing the mixture price (~30%) and CO2e* (15-26 %)
  - Next iterations are expected

* in contrast to GWP, which is a mass-related metric, CO2e = GWP*mass(gas) can be defined for a given exhaust volume



Setup at GIF++

RPC prototype (KODEL):
- 1.4mm double gap
- ~ 1.3 x 10^{10} Ω.cm
- 45.5 x 45.5 cm2

Readout:
- KODEL FE + CAEN multi-hit TDC

	R134-a (%)	HFO-1234ze (%)	CO_2 (%)	i-C_4H_{10} (%)	SF_6 (%)	GWP_{MIX}
GWP	1430	7	1	3	22800	
Density (g/L)	4.68	5.26	1.98	2.69	6.61	
STD	**95.2**			**4.5**	**0.3**	**1486**
ECO2		35	60	4	1	476
ECO3		25	69	5	1	527
30%CO2+1%SF6	64		30	5	1	1529
30%CO2+0.5%SF6	64.5		30	5	0.5	1337
40%CO2+1%SF6	54		40	5	1	1353

monitoring the CSC performance at CMS

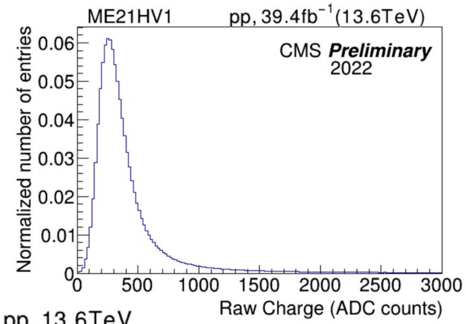
Relative gas gain with the CMS data

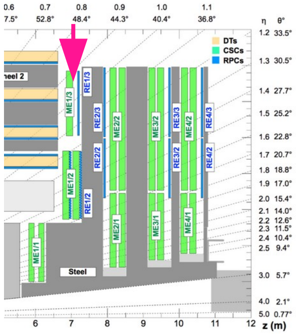
Z->mumu data sample analysis for each of 31 radial segments of CSCs (radial segmentation of CSC chambers – 3 or 5 HV segments, and ME1/1 a and b areas)

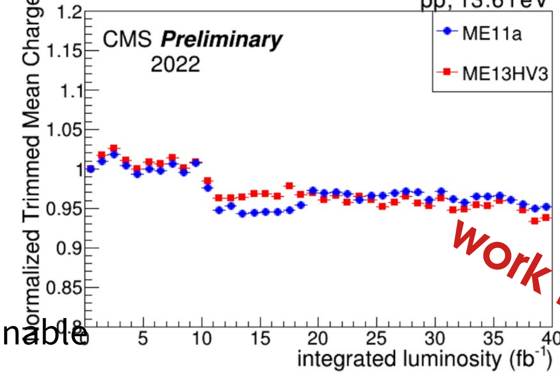
- Trimmed mean of the muon response charge
- Atmospheric pressure correction
- Current results:

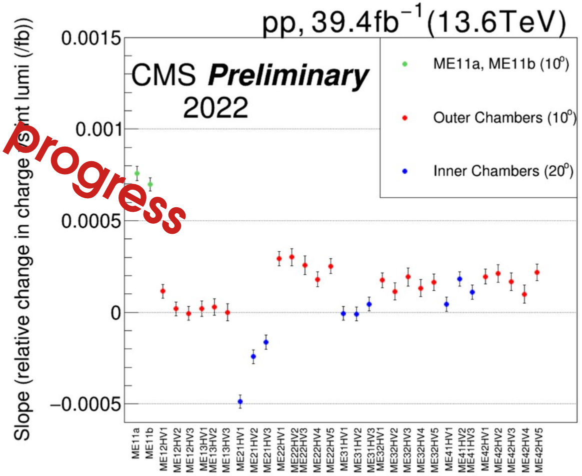
    in comparison to ME1/3 HV segment3

- Next steps
    - further corrections are needed for a reasonable precision
        - Charge vs instantaneous luminosity (voltage drop due to large current)
        - Useful additional cross-check : gas gain monitor (EP-DT data)
    - Run2+Run3 data analysis





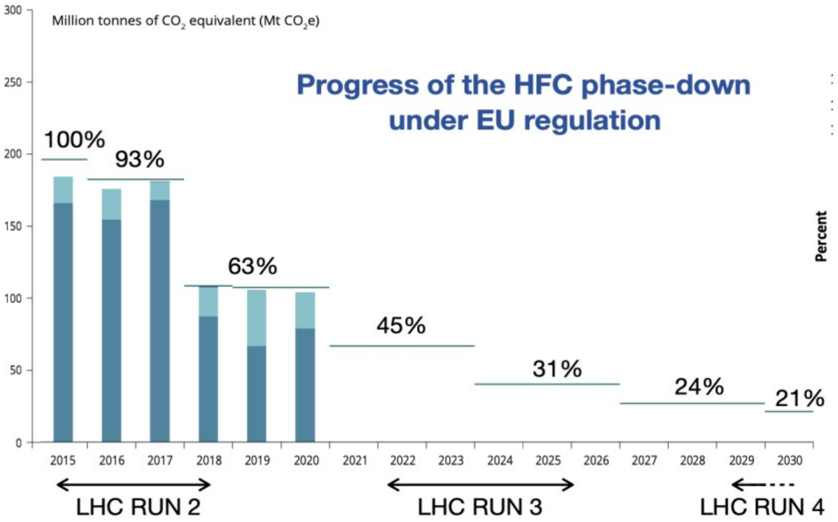




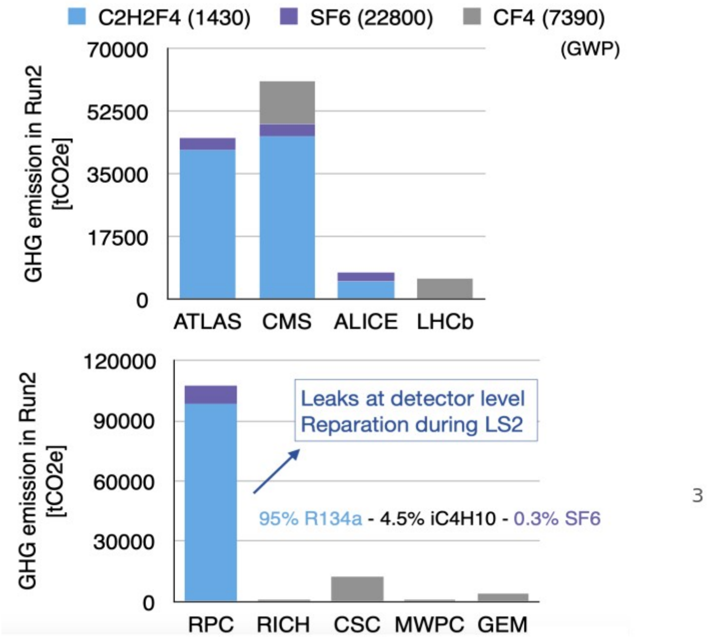
work in progress

F-gases emission at CERN

- Main contributor is $C_2H_2F_4$ user for ALICE, ATLAS and CMS RPC systems.
- Major contribution due to the leaks (reparation campaign in LS2)



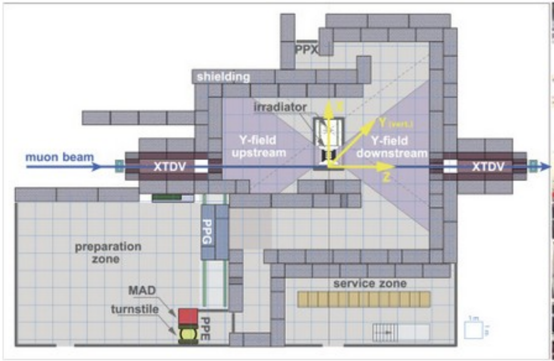
- Prices increased in European Union and availability in the future is not known.
- Reduction of the use of F-gases is fundamental for future particle physics detector applications

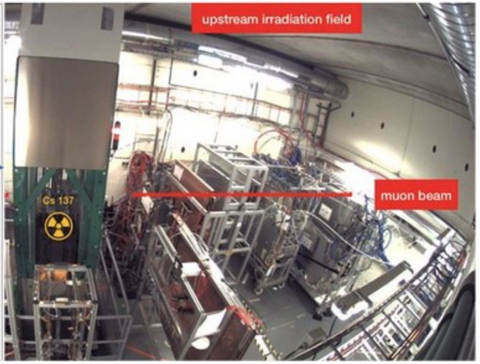


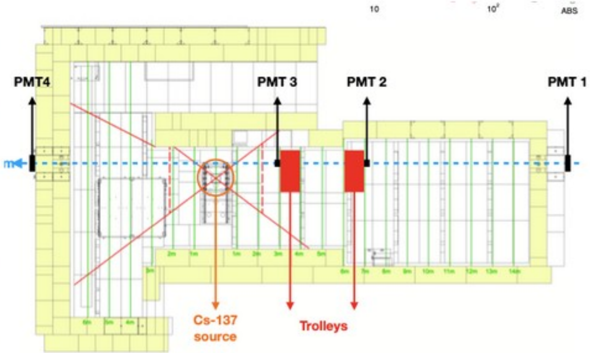
Leaks at detector level
Reparation during LS2

95% R134a - 4.5% iC4H10 - 0.3% SF6

GIF++ R&D with alternatives gas mixtures

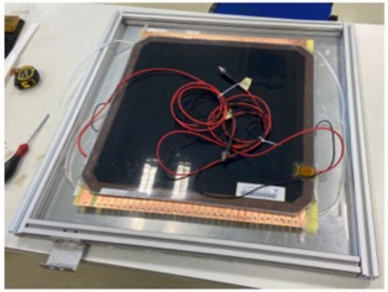






- H4 beam line in EHN1, CERN North Area
- Cs-137 gamma source up to 12 TBq
- Muon Beam 10-450 GeV
- Gamma flux can be set independently to mimic radiation background scenario

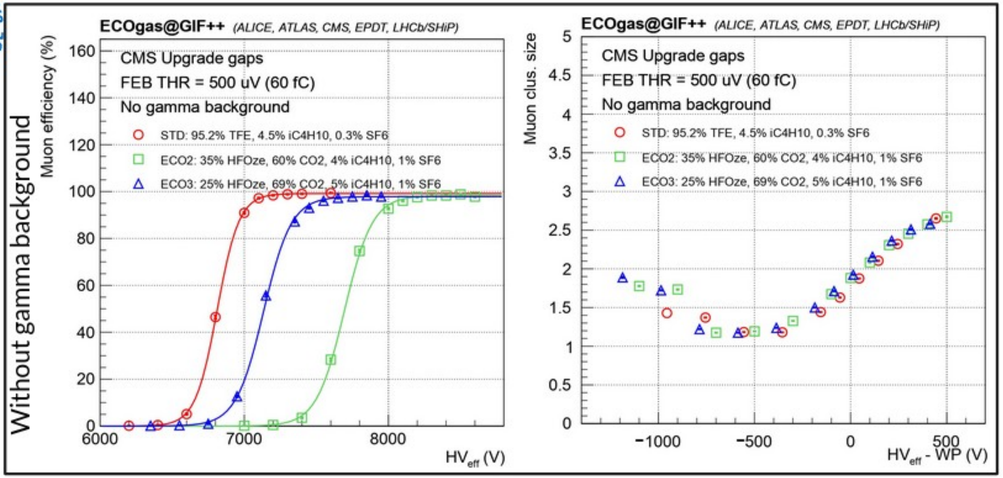
    - RPC prototype (KODEL E and H):
        - 1.4mm double gap
        - $\rho \sim 1.3 \times 10^{10}$ Ω.cm
        - 45.5 x 45.5 cm^2 active area

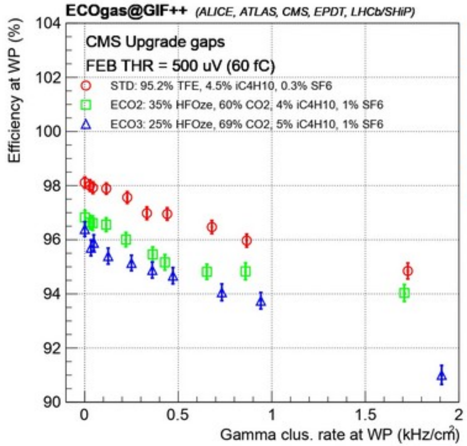


- Readout electronics:
    - Current sensitive mode for input signals
    - Input impedance 20 Ω
    - Threshold 0.5 mV ~60fC

HFO+CO2 based mixtures

ECOGAS@GIF++ Collaboration



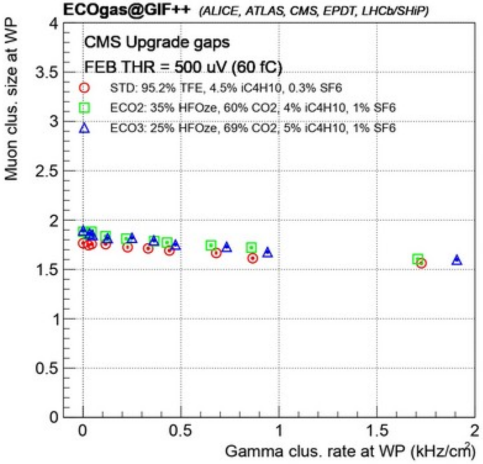


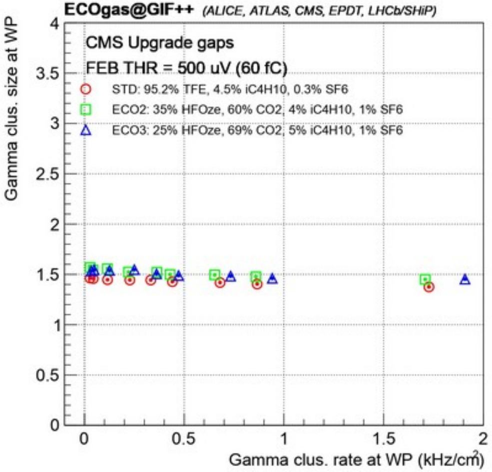
Mixture	WP (kV)	Efficiency (%)
STD	7.16	98.1
ECO2	8.10	96.8
ECO3	7.54	96.4

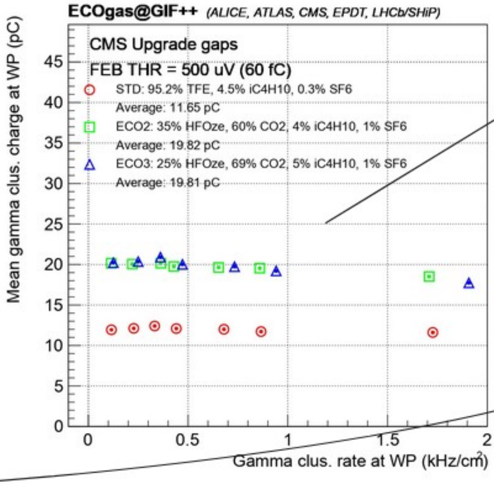
Muon Cluster Size ~1.8 strips for all mixtures at WP without gamma

Shift in WP depending on the gas mixture

Efficiency drop similar between the mixtures **but gap** in the HFO/CO2 ones



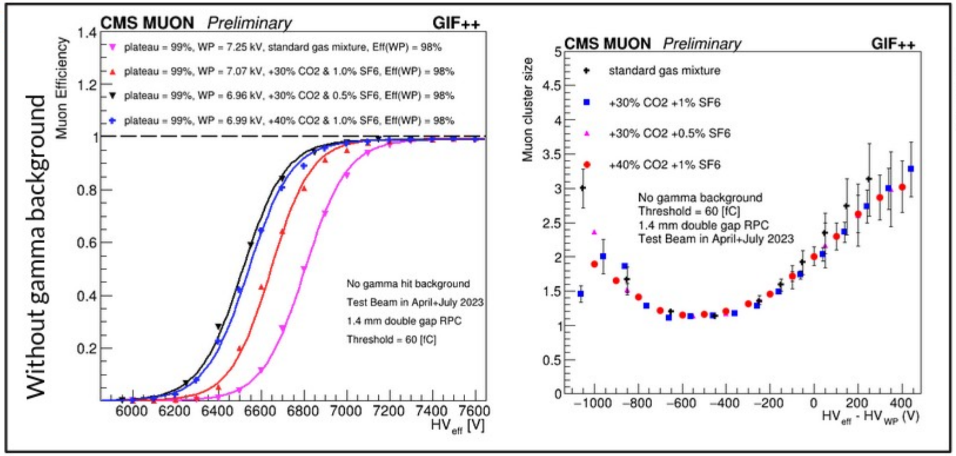


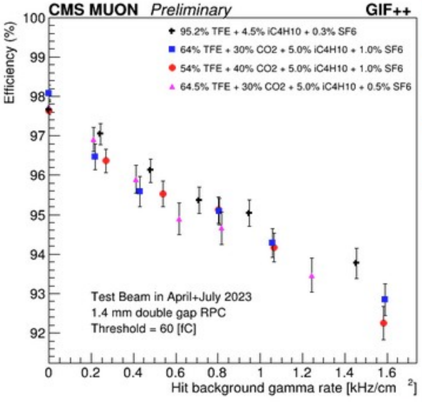


Higher (~1.7x) gamma cluster charge for HFO/CO2 mixtures to be investigate in longevity studies

Similar muon and gamma cluster size for different gas mixtures

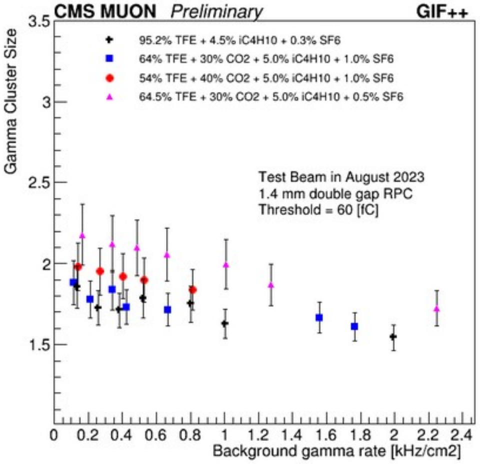
TFE+CO2 based mixtures

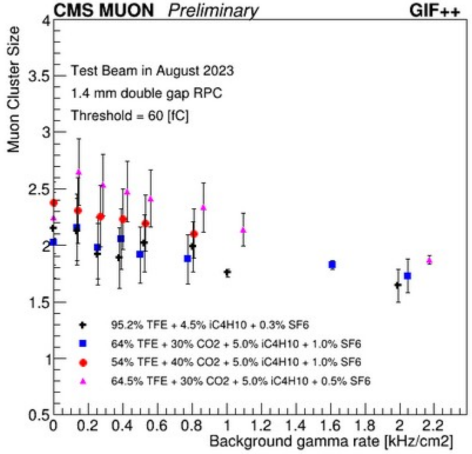


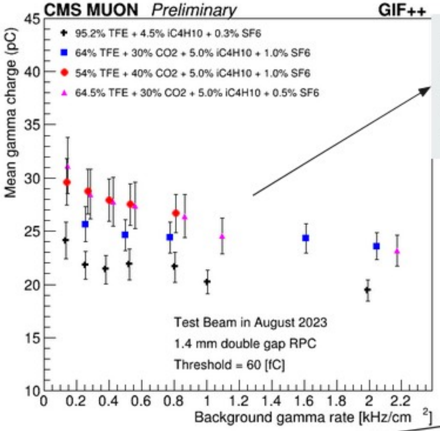


Mixture	WP (kV)	Efficiency (%)
STD	7.25	98
30% CO$_2$ + 1% SF$_6$	7.07	98
30% CO$_2$ + 0.5% SF$_6$	6.96	98
40% CO$_2$ + 1% SF$_6$	6.99	98

- Muon Cluster Size ~ 2 strips for all mixtures at WP without gamma
- Shift in WP depending on the gas mixture
- Efficiency drop similar between the mixtures and no gap..







Higher (20%) gamma cluster charge for TFE/CO2 mixtures to be investigate in longevity studies

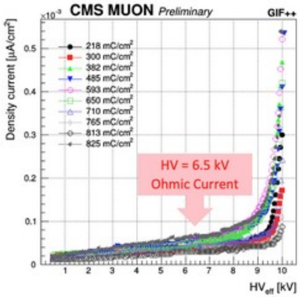
Similar muon and gamma cluster size for different gas mixtures

Longevity studies for current RE2 and RE4 chambers

RE2 Results

RE4 Results

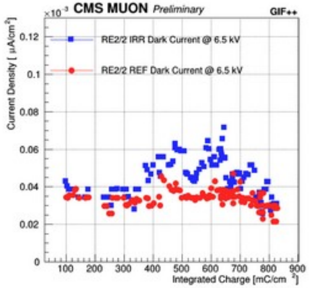
RE2/2 Irradiated dark current



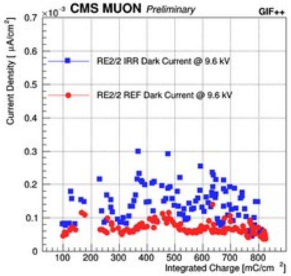
HV = 6.5 kV
Ohmic Current

HV = 9.6 kV
total Current

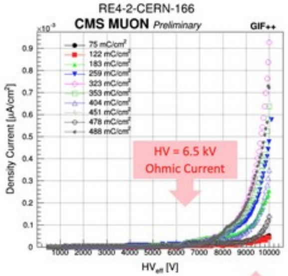
RE2/2 IRR. & REF **ohmic** current



RE2/2 IRR. & REF **total** current



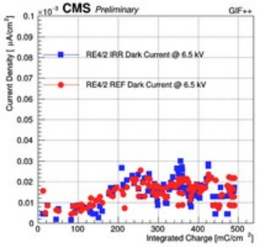
RE4/2 Irradiated dark current



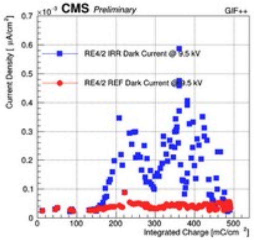
HV = 6.5 kV
Ohmic Current

HV = 9.6 kV
total Current

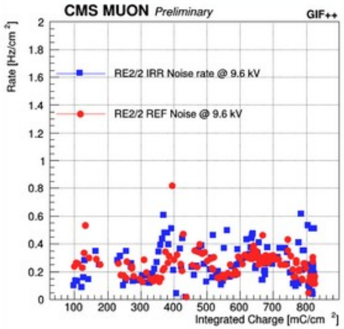
RE4/2 IRR. & REF **ohmic** current



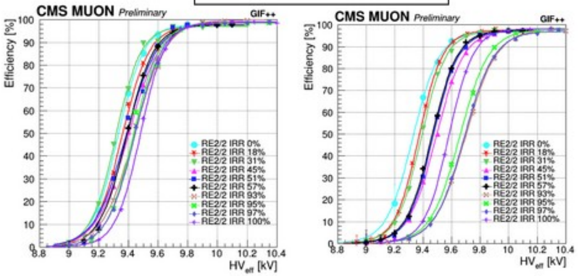
RE4/2 IRR. & REF **total** current



RE2/2 IRR. & REF Noise rate



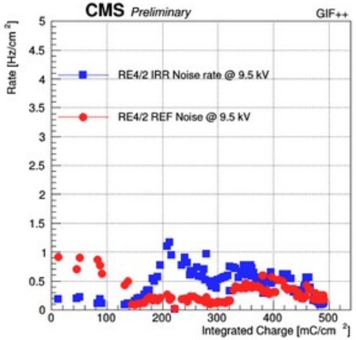
RE2/2 Performance



Without Background radiation & With muon beam

With Background radiation (600 Hz/cm²) & with muon beam

RE4/2 IRR. & REF Noise rate



- **No aging effects have been observed so far!**
- Performance of RE4 still under analysis.

Longevity studies with **ECO2** :

- Ongoing with RE1/1 (~120mC/cm2 up to now) – analysis of performance in progress
- Starting irradiation with a KODEL chamber now