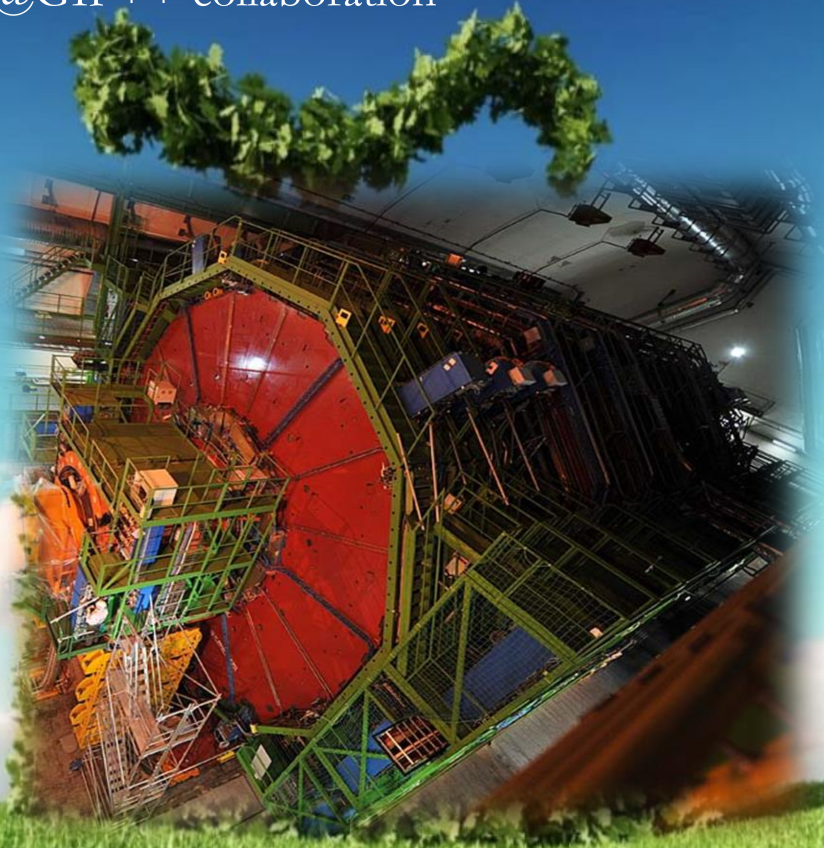
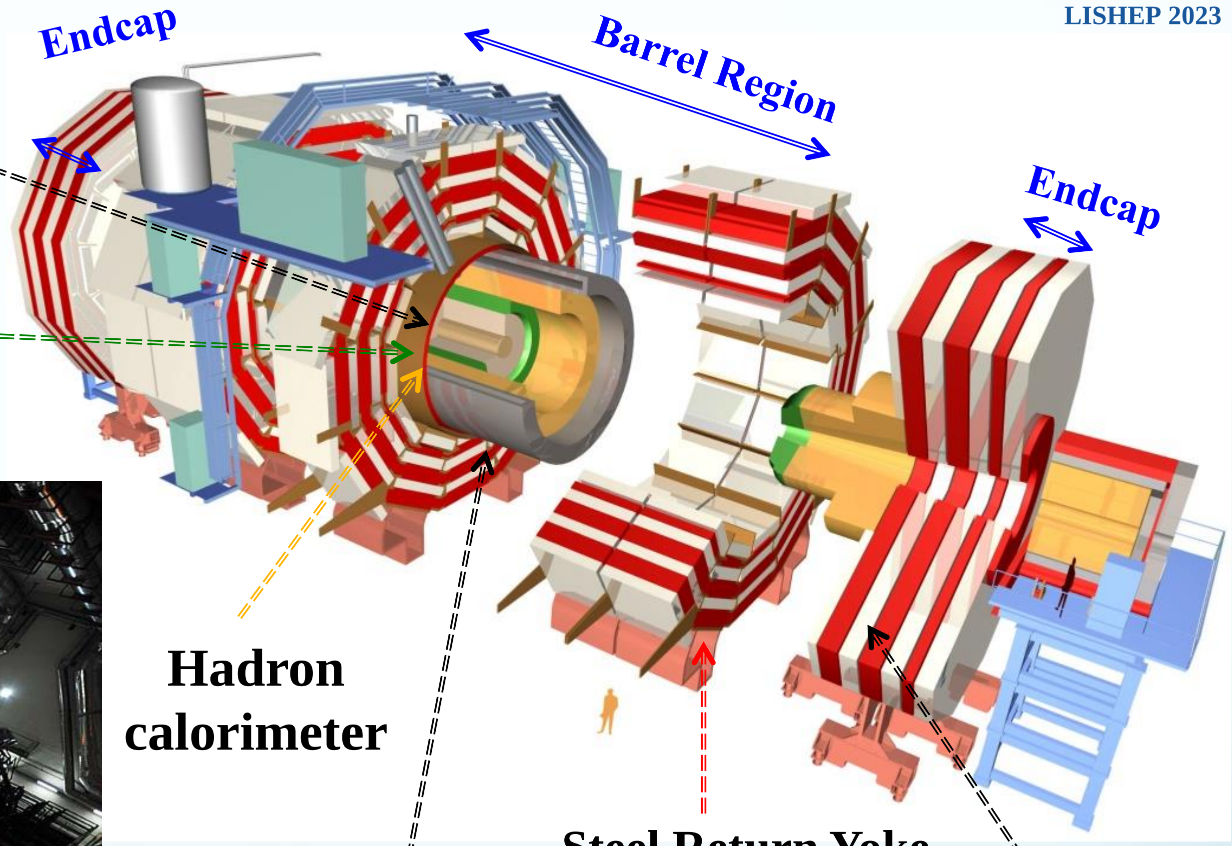
G. Pugliese
INFN & Polytechnic of Bari
On behalf of the CMS Muon Group &
RPC EcoGas@GIF++ collaboration

LISHEP Conference
Rio de Janeiro 5-10 March 2023

Emissions of Fluorinated Gases from the CMS Muon System in RUN3 and perspectives for RUN4 and beyond



CMS detector



Tracker

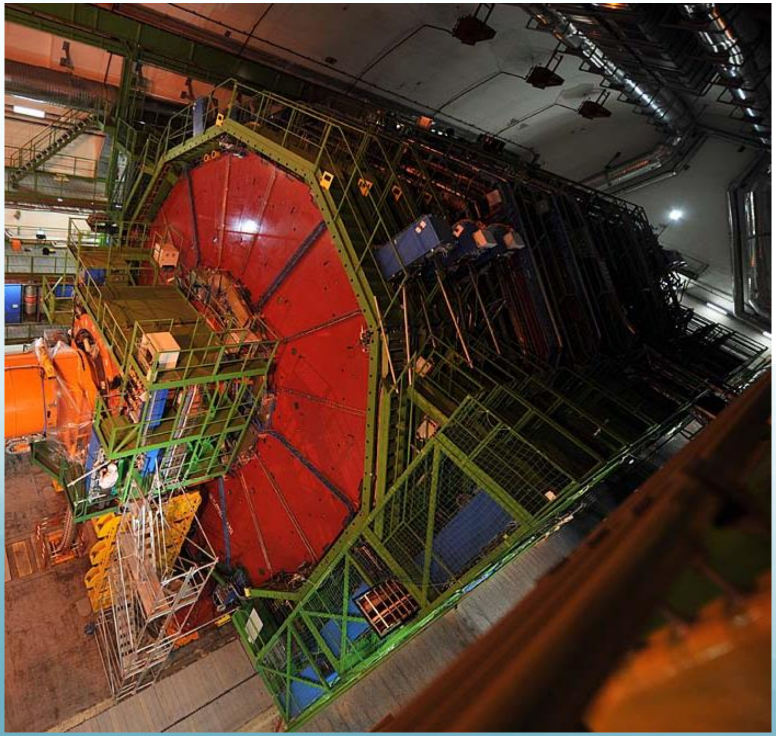
Electromagnetic calorimeter

Hadron calorimeter

Superconducting Solenoid
Niobium titanium coil carrying 18.000 A

Steel Return Yoke

Muon Spectrometer



Weight: 14000 t
Length: 28.7 m **Diameter:** 15 m
Magnetic field: 3.8 T

CMS Muon System

G. Pugliese

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Muon system: ~~three~~ four gaseous technologies for muon identification, timing and momentum measurement

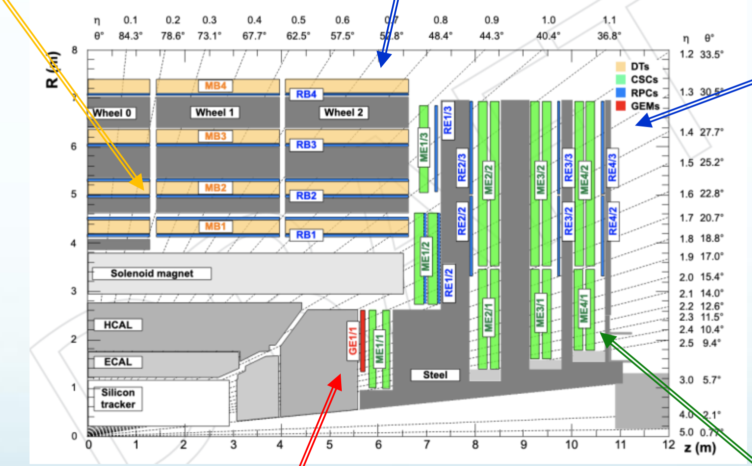
Muon acceptance: |η| < 2.4

Drift Tubes (DT)

- 250 chambers, ≈ 170k channels
- 32 number of hits
- Spatial resolution≈100 μm
- Time resolution ≈ 2 ns

Resistive Plate Chambers (RPC)

- 540 trapezoidal endcap chambers
- 480 rectangular barrel chambers
- ≈ 120k channels
- 6 (4) number of hits
- Spatial resolution ≈1 cm
- Time resolution ≈ 1.5 ns

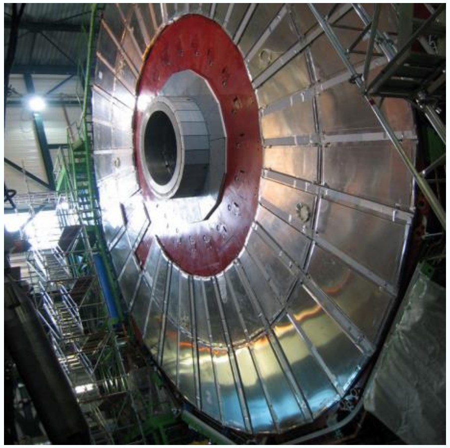


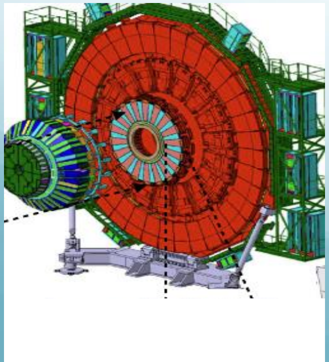
GE1/1 station (since 2021):

- 72 Super-Chambers, consisting of two triple-GEM
- 2 number of hits
- Spatial resolution≈100 mm
- Time resolution ≈ 10 ns

Cathode Strip Chambers (CSC)

- 540 trapezoidal chambers, ≈500k channels
- 24 number of hits
- Spatial resolution≈50 ÷140 μm
- Time resolution ≈ 3 ns





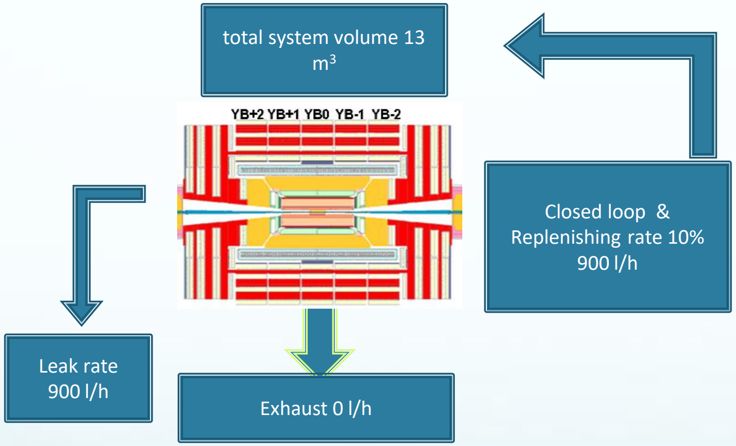
CMS Muon Gas Systems

- **Fluorinated gases** are present in RPC and CSC gas mixtures:

CSC: Ar+CO_2+**CF_4**
40+50+**10%**

RPC: **$C_2H_2F_4$**+iC_4H_{10}+**SF_6**
95.2 +4.5+ **0.3%**

RUN2

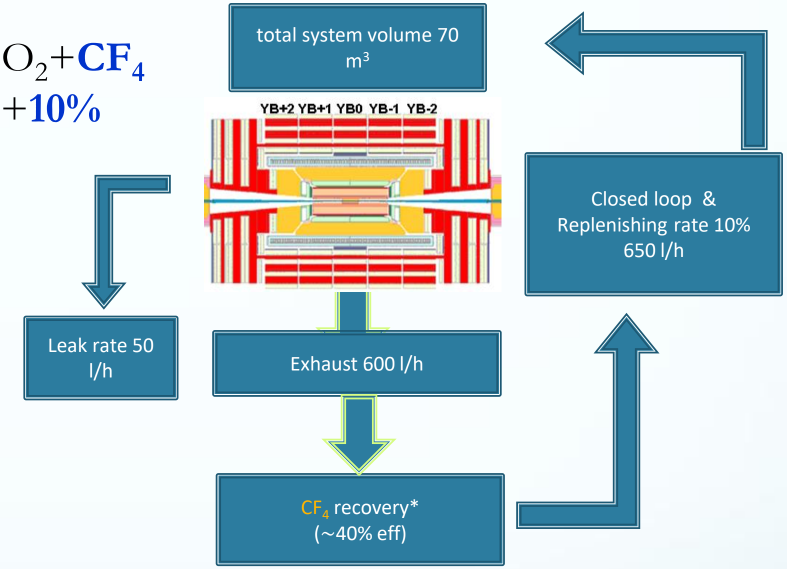


total system volume 13 m^3

Closed loop & Replenishing rate 10% 900 l/h

Leak rate 900 l/h

Exhaust 0 l/h



total system volume 70 m^3

Closed loop & Replenishing rate 10% 650 l/h

Leak rate 50 l/h

Exhaust 600 l/h

CF_4 recovery* (~40% eff)

GEM: Ar+CO_2
70+30%

DT: Ar+CO_2
85+15%

*installed in 2012

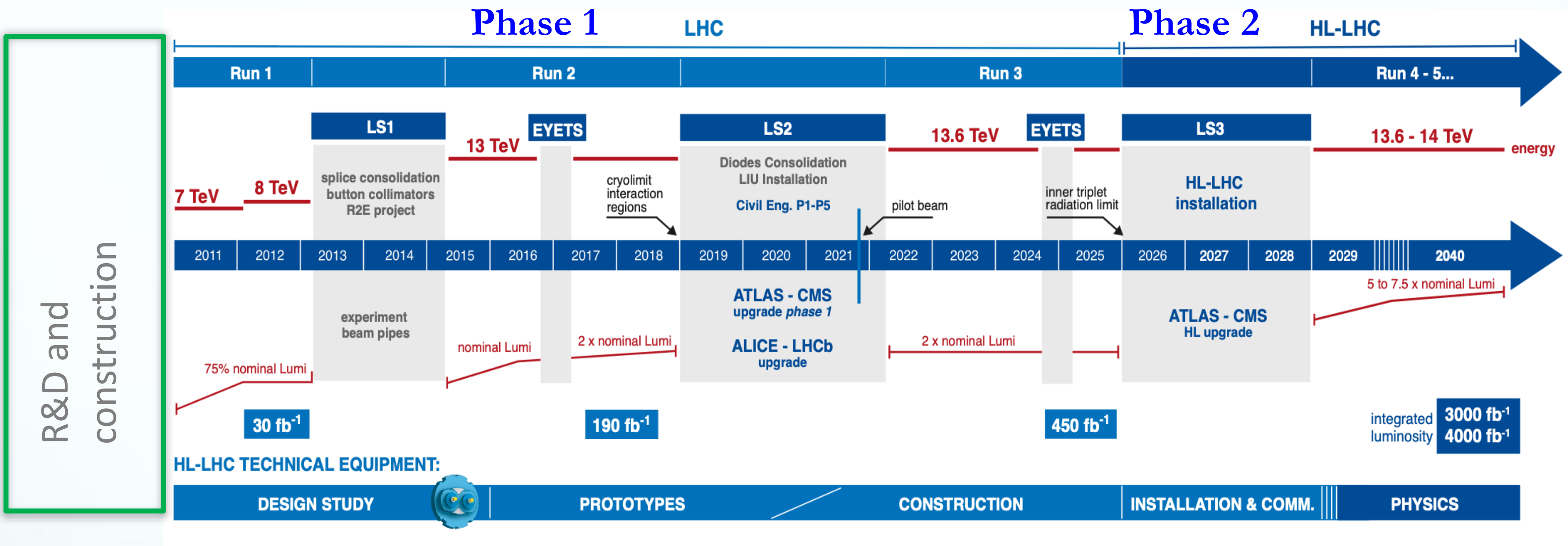
- RPC and CSC systems are working in recirculation mode since LHC beginning and they are operating with ~10% of the fresh gas volume injected to reduce ageing effects [1]

90% of emission reduction

G. Pugliese

LHC and HL-LHC Project

LISHEP 2023



R&D and construction

Phase 1 LHC

Phase 2 HL-LHC

Run 1 | Run 2 | Run 3 | Run 4 - 5...

LS1: splice consolidation button collimators R2E project

EYETS

LS2: Diodes Consolidation LIU Installation Civil Eng. P1-P5

EYETS

LS3: HL-LHC installation

7 TeV – 8 TeV – 13 TeV – 13.6 TeV – 13.6 - 14 TeV energy

cryolimit interaction regions

pilot beam

inner triplet radiation limit

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2040

experiment beam pipes

ATLAS - CMS upgrade *phase 1*

ALICE - LHCb upgrade

ATLAS - CMS HL upgrade

75% nominal Lumi

nominal Lumi

2 x nominal Lumi

2 x nominal Lumi

5 to 7.5 x nominal Lumi

30 fb^{-1}

190 fb^{-1}

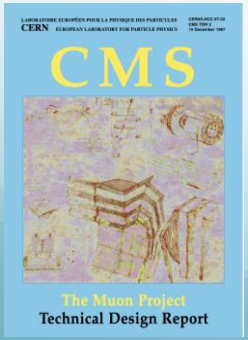
450 fb^{-1}

integrated luminosity 3000 fb^{-1} 4000 fb^{-1}

HL-LHC TECHNICAL EQUIPMENT:

DESIGN STUDY | PROTOTYPES | CONSTRUCTION | INSTALLATION & COMM. | PHYSICS

1997 Muon Project TDR



CMS

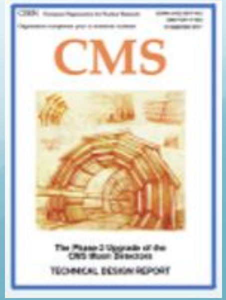
The Muon Project
Technical Design Report

2010 Start of LHC

2012 Higgs Discovery

2013 The EU Strategy Report for High Energy Physics approved the HL-LHC as priority project

2017 The Phase-2 Upgrade of the CMS Muon Detector TDR



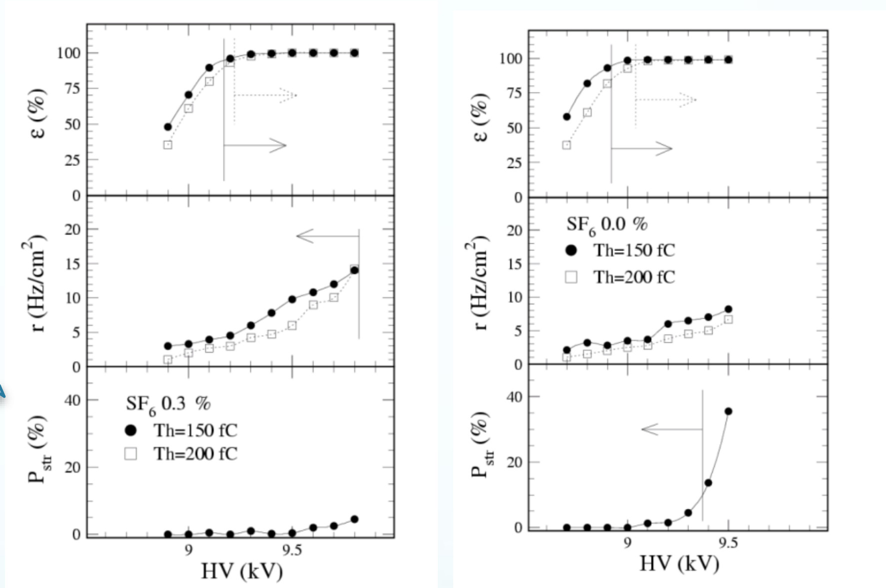
CMS

CMS RPC and CSC gas mixtures

The CMS RPC and CSC gas mixtures were validated in early 2000 years in view of the LHC experiments to sustain the expected background condition at the nominal LHC luminosity of $10^{34}cm^{-2}\,s^{-1}$

- **RPC certified to operate in newly avalanche mode** with a **Freon** based mixture **(95% of $C_2H_2F_4$*)** and **0.3%** of **SF_6** (the latter, strong electronegative gas, added to extend the separation between streamer and avalanche)

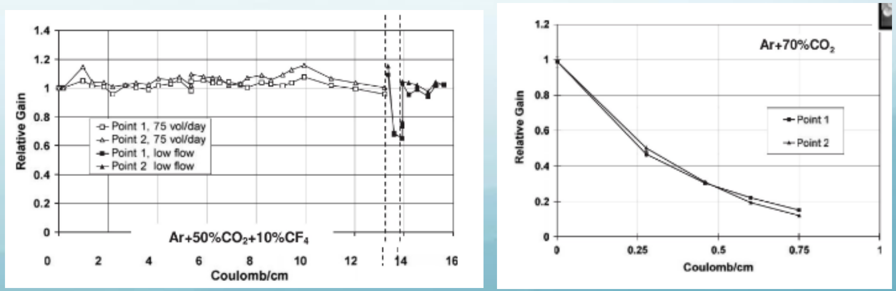
CMS RPC performance requirements:
Time resolution ≈ 1ns **Efficiency** > 96%
Rate Capability ≈ 300-500 Hz/cm^2



Journal of the Korean Physical Society, Vol. 46, No. 5, May 2005, pp. 1090~1095

*Ozone Depletion Potential = 0

- **CSC certified to operate with 10% of CF_4** for its aging preventive properties



NIM A 488 (2002) 240–257

Muon System Performance during Run 2

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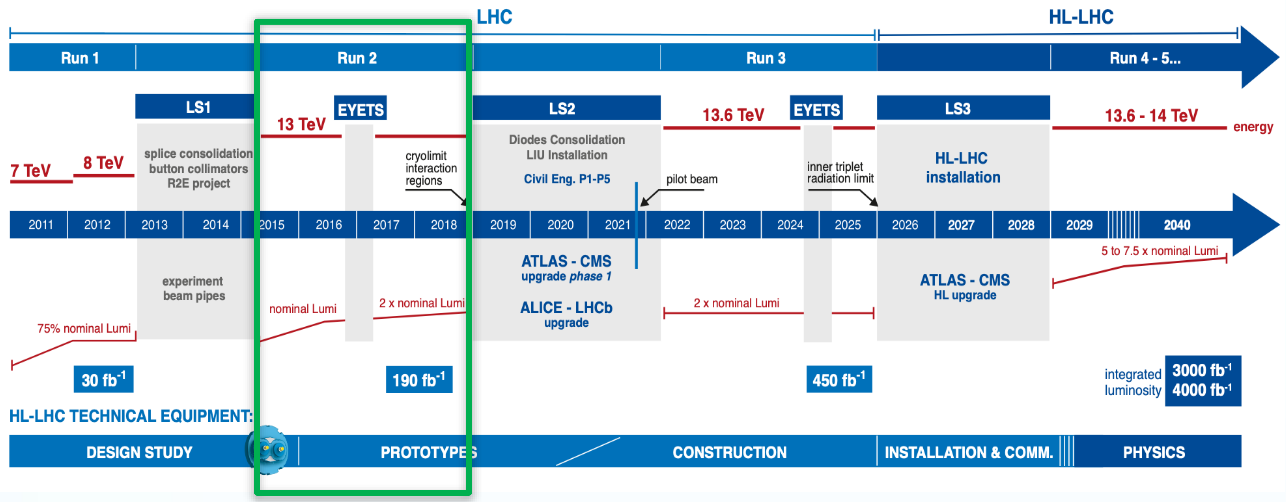
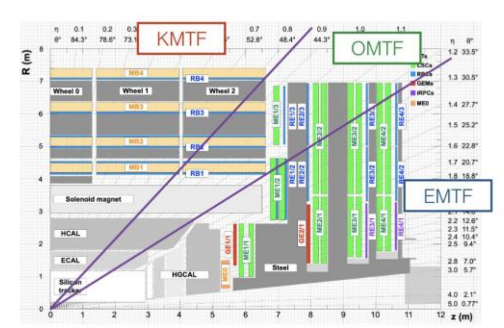
Phase 1

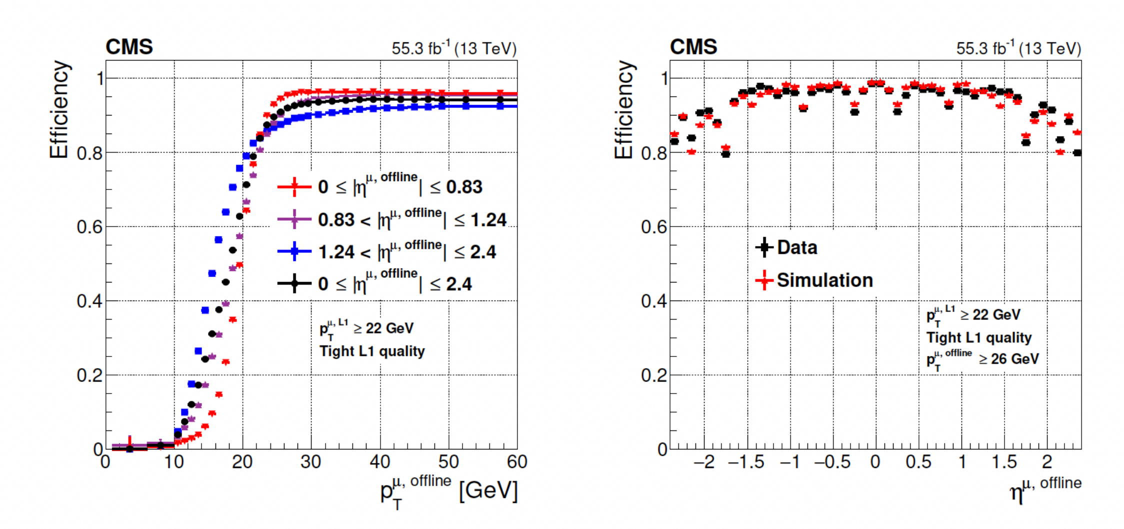
Phase 2



Run2

Muon system guaranteed excellent trigger performance in all eta regions during Run2





Level-1 muon trigger efficiency

RPC and CSC performance during Run 2

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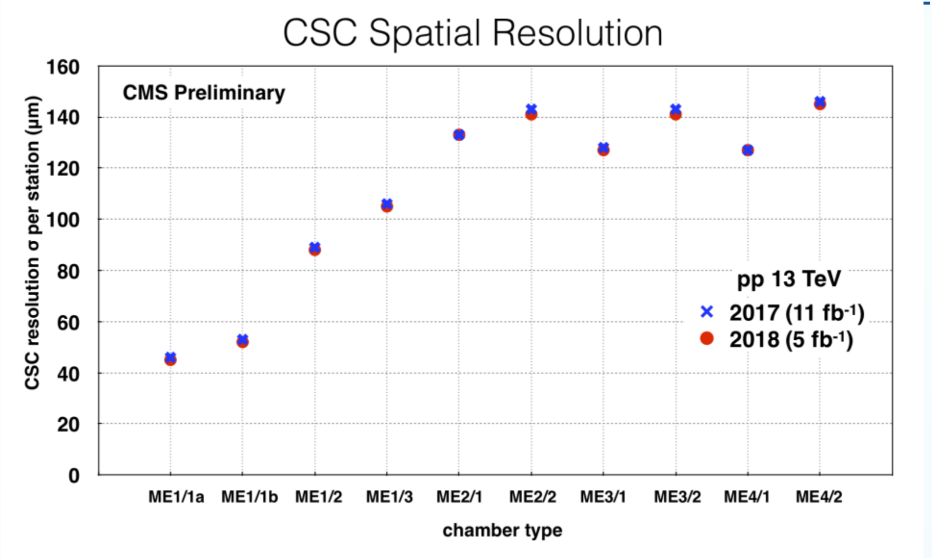
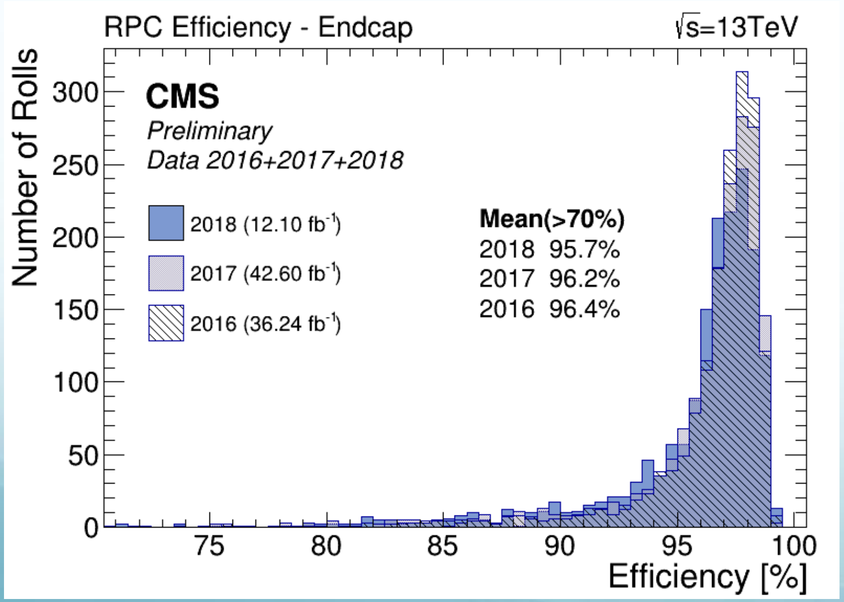
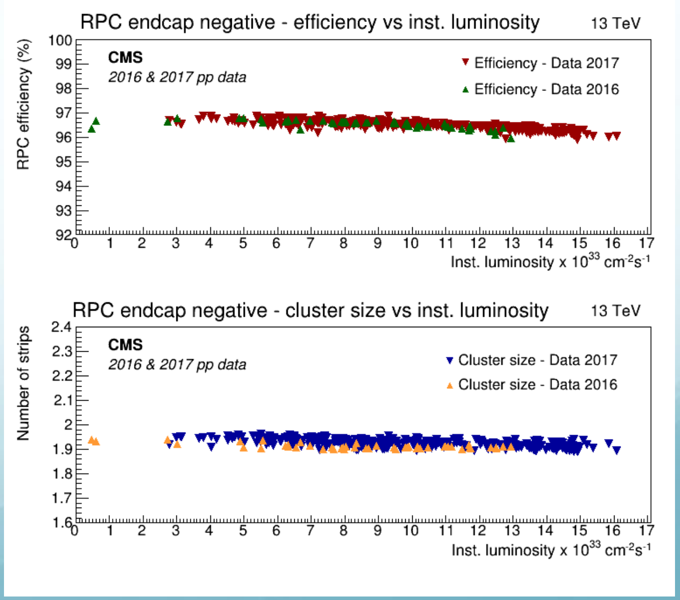
Excellent and stable detector performance in Run2 despite the increase of instantaneous luminosity up to 1.8 10^{34} $cm^{-2}s^{-1}$ (more than the nominal one)







LHC and HL-LHC schedule

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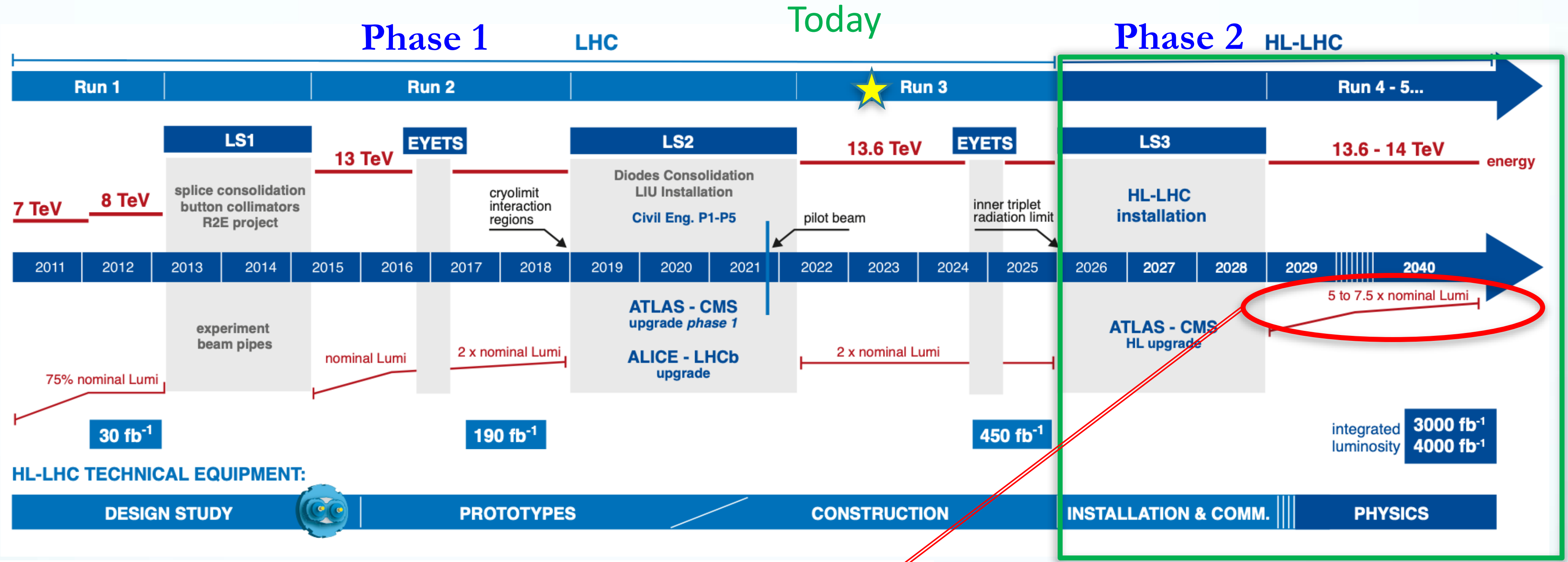
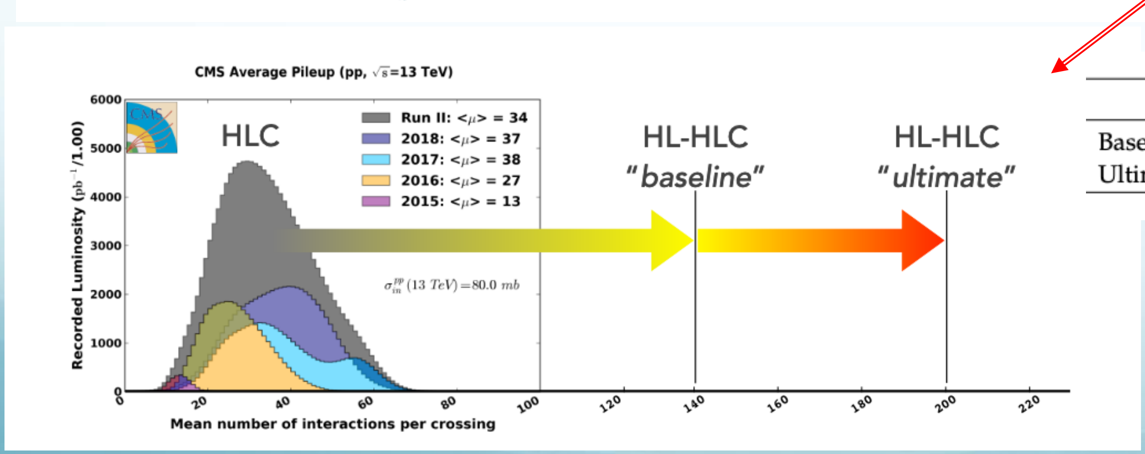




	$\mathcal{L}$	$\langle$ PU $\rangle$	Vertex Density	$\int \mathcal{L}$ / year
Baseline	$5 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	140	0.8/ mm	250 fb^{-1}
Ultimate	$7.5 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	200	1.2/ mm	> 300 fb^{-1}

Muon System Phase 2 Upgrade Project

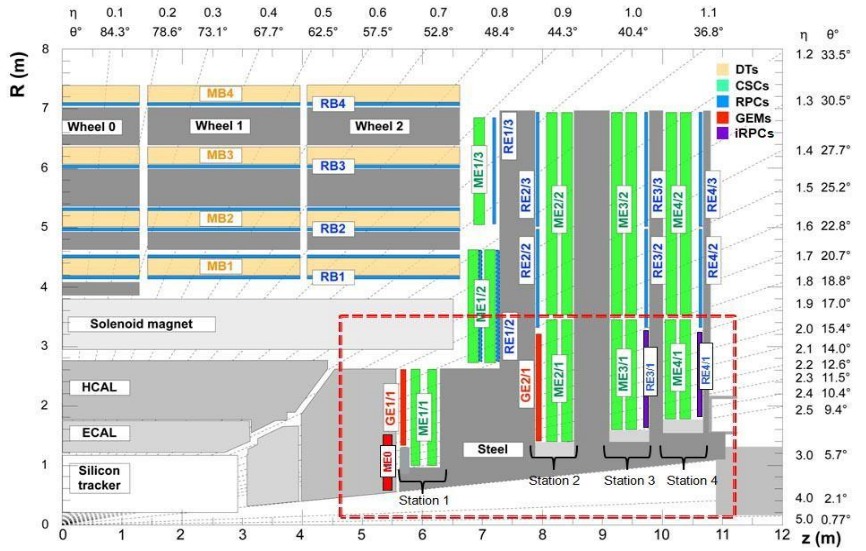
Phase 2 Muon System Upgrade

1. **New longevity tests** needed to certify the performance of the legacy detectors at expected higher rates and radiation doses

2. **New electronics for the legacy detectors:**
   DT: replace all On-Board electronics, BE
   RPC: replace all off-chamber electronics, BE
   CSC: replace selected FE boards, all BE

3. **New detectors (**GEM and improved RPC) in the endcap region to restore redundancy and extend the muon coverage up η = 2.8

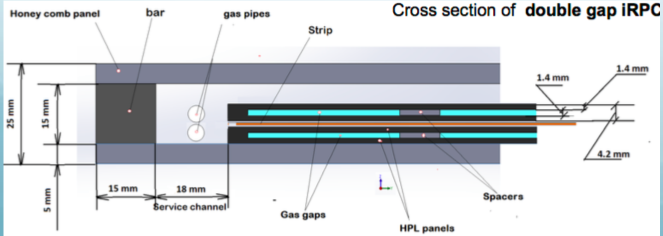
- **Improved RPC vs. legacy RPC**
  - Same electrode material: HPL
  - Thinner gas and electrode thickness 1.4 mm (2mm in the legacy)
  - New on chamber electronics and strip layout (2D readout)




GE2/1


RE3/1


RE4/1


Cross section of **double gap iRPC**

New Longevity test @ the GIF++

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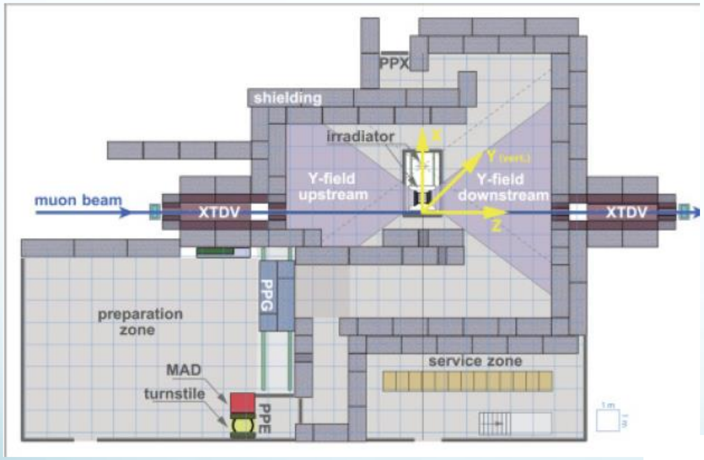
Gamma Irradiation Facility (GIF++) @ CERN

Gamma source

- 137 Cs of 12 TBq → 662 keV gamma
- Lead filter system to provide two large radiation areas (upstream and downstream) and guarantee a uniform and variable photon flux (up to 10^8 $\gamma/cm^2 s$)

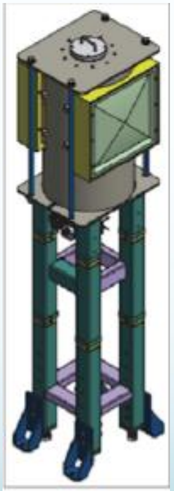
Located at the end of CERN SPS H4 line that provide 150 GeV Muon beam.

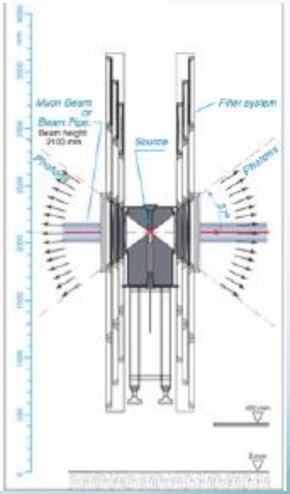


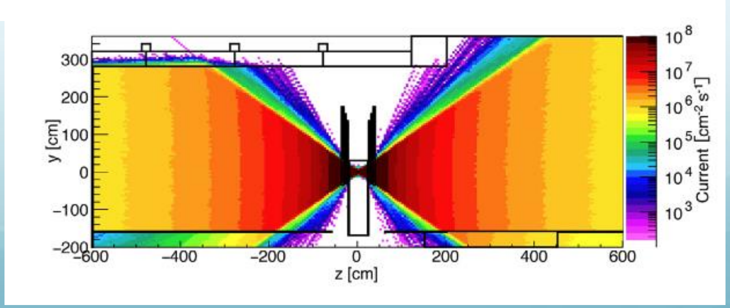
100 m² bunker

Muon Beam

- 150 GeV and 10^4 muons/spill
- (beam size 10 x 10 cm^2)







RPC Longevity results

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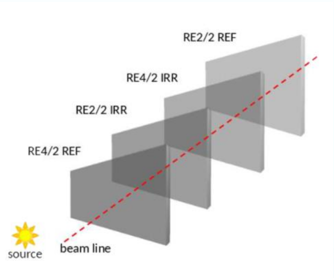
- **Started in July 2016 on:**

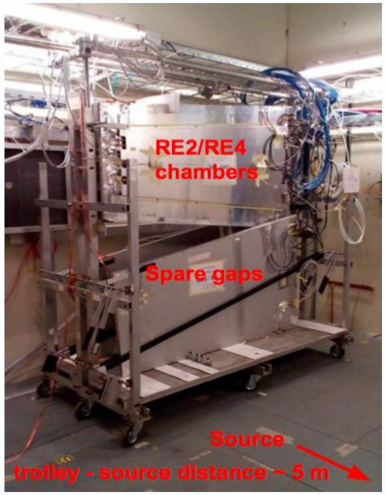
2 RE2 spare chambers (Irrad. & Ref.)

2 RE4 spare chambers (Irrad. & Ref.)

Standard RPC mixture:

95.2% $C_2H_2F_4$ - 4.5 iC_4H_{10} - 0.3% SF_6

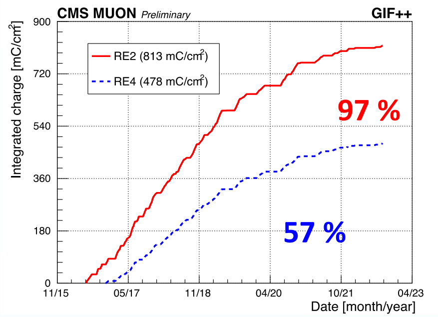


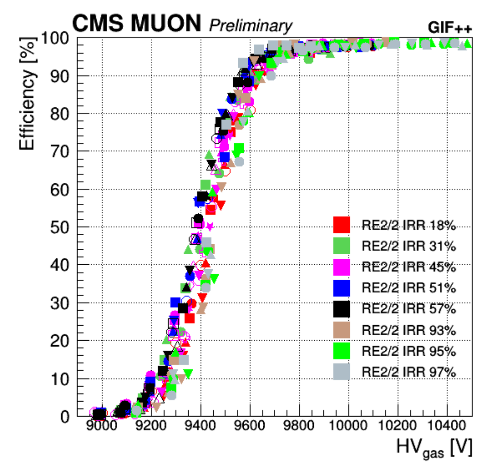


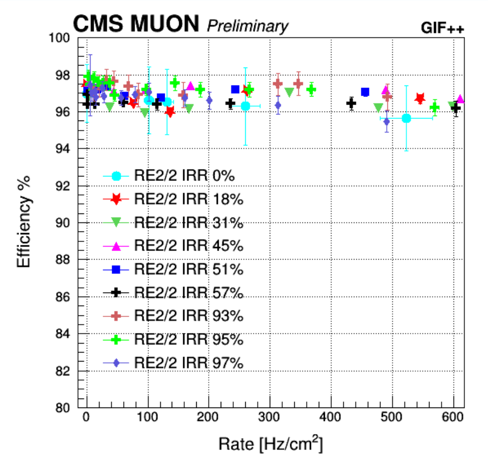
HL-LHC Expectation (including safety factor of 3)

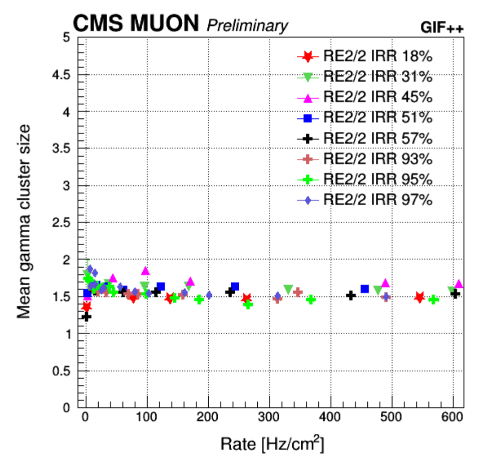
Rate ~ 600 Hz/cm^2

Integrated Charge ~ 840 mC/cm^2







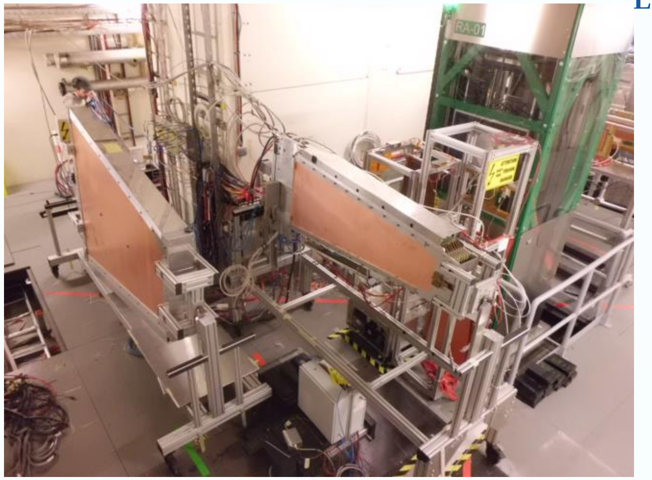


- ✓ Stable performance (efficiency, cluster size) as function of the integrated charge
- ✓ High efficiency (> 95%) up to HL-LHC expected background of 600 Hz/cm^2

✓ No evidence of any aging effect observed

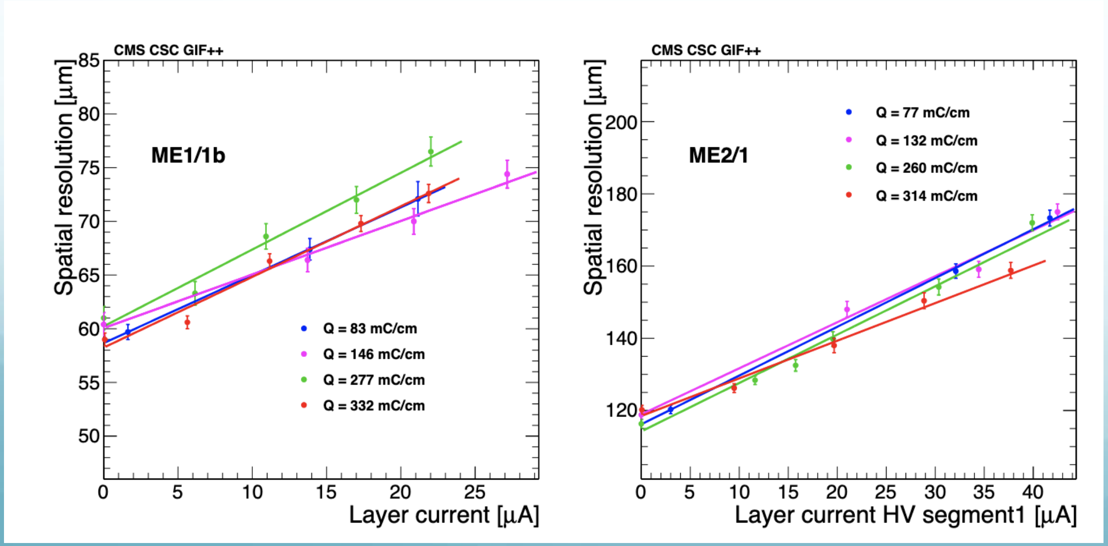
CSC Longevity results

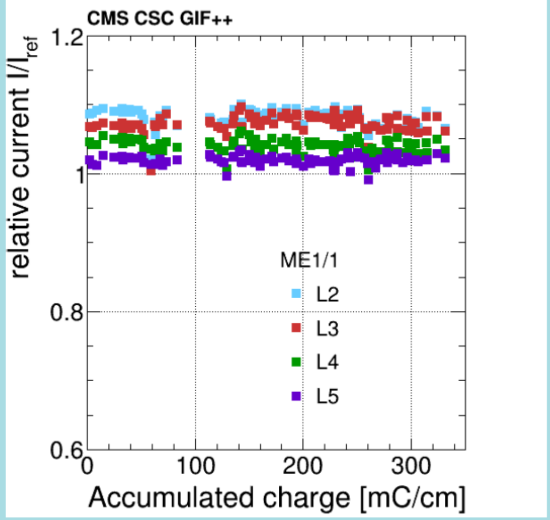
- **Started in 2016** on:
two spare CSC chambers ME1/1 and ME2/1 (~1 mC/cm per day)
Standard CSC mixture:
40% Ar+50% CO_2+10% **CF_4**



- HL-LHC Expectation (including safety factor of 3)
Current: 20 uA for ME1/1 and 15 uA for ME2/1
Integrated Charge: 0.24 C/cm for ME1/1 and 0.13 C/cm for ME2/1

- ✓ **No deterioration of resolution** with different accumulated charge up to 0.33 C/cm and of key chamber parameters such as gas gain, detection efficiency, spurious signal rates, strip to-strip resistance, or dark currents
- ✓ **Modest deterioration** of resolution at higher background rates

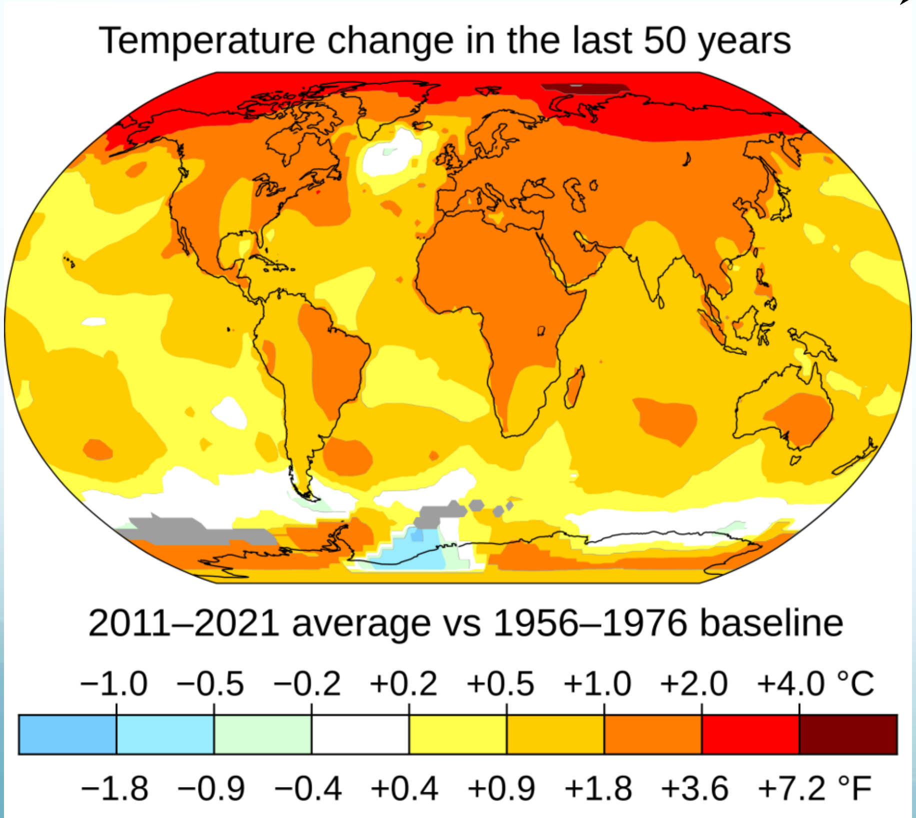




Climate Change

Climate change refers to long-term shifts in temperatures

- Human activities have been the main driver of this change. Energy, industry, transport, buildings, agriculture and land use are among the main emitter of Greenhouse Gas



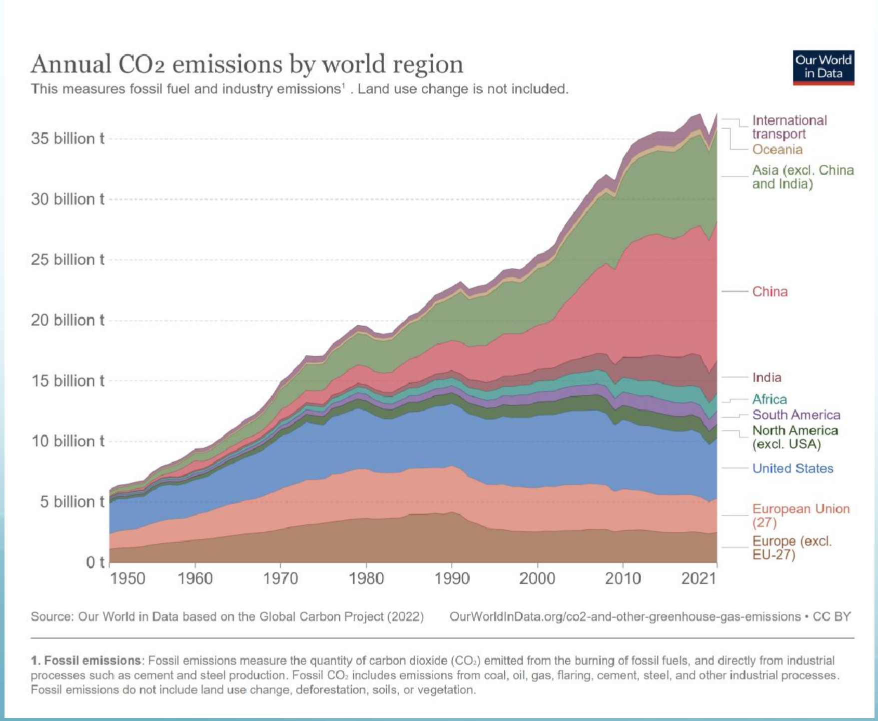
- **Greenhouse gas emissions (GHG)** act like a blanket wrapped around the Earth, trapping the sun's heat and raising temperatures

- To avert the worst impacts of this climate change and preserve our planet, global temperature increase needs **to be limited to 1.5°C** above pre-industrial levels

GHG emission reduction plan

- In 2015, Paris agreement

declared that GHG emissions need to be reduced by **45% by 2030** (compared to 2010 levels) and reach net zero by 2050



Annual CO_2 emissions by world region

This measures fossil fuel and industry emissions[1]. Land use change is not included.

Source: Our World in Data based on the Global Carbon Project (2022) OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

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[1] **Fossil emissions**: Fossil emissions measure the quantity of carbon dioxide (CO_2) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO_2 includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

- In 2022, the Council of the EU

reached a general approach on a ‘Fit for 55’ package, i.e., reducing GHG emissions within the main sectors of the economy by at least **55% by 2030** compared to 1990 levels

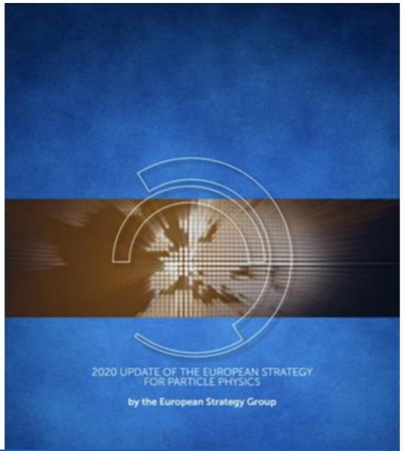
Environmental protection @ CERN

- ➢ Environmental protection is one of the main objectives for the years 2021 – 2025
- ➢ Environment and sustainability are crucial aspects of projects and activities in the HEP field

Highest priority objectives set for:

- ➢ reducing emissions of fluorinated gases from Large Experiments
- ➢ limiting the electrical power consumption
- ➢ limiting the water consumption
- ➢ reducing the impact of effluent water on receiving watercourses

- ➢ CERN fixed the target to reduce direct emissions by **28% by the end of 2024** (baseline year: 2018) and **by 70% by RUN5**



2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

HIGHLIGHTS

CERN AND THE ENVIRONMENT
IN 2019

During the period covered by this report, 2019-2020, CERN's accelerator complex was in its second long shutdown. Due to this shutdown, several environmental indicators show a different pattern from the previous reporting time frame of 2017-2018. These highlights only include 2019 indicators, given that 2020, with the COVID-19 pandemic, was not representative of a normal year.

Energy

428 GWh

In 2019, CERN consumed **428 GWh** of electricity and **68 GWh** of fossil fuel. CERN's electricity consumption during the period was about 64% lower than when the accelerator complex is running.

The Laboratory is committed to **limiting rises in electricity consumption to 5%** up to the end of 2024 (baseline year: 2018), while delivering significantly increased performance of its facilities. CERN is also committed to increase energy re-use.

Waste

57% recycled

In 2019, CERN eliminated 5589 tonnes of non-hazardous waste, of which **57% was recycled**. The Laboratory also eliminated 1868 tonnes of hazardous waste.

CERN's objective is to increase the current recycling rate.

Emissions

78 169 tCO_2e

In 2019, CERN's direct greenhouse gas emissions (scope 1) were **78 169 tonnes of CO_2 equivalent** (tCO_2e), which is less than half of the amount emitted annually over the period 2017-2018 when the accelerators were running.

Indirect emissions arising from electricity consumption (scope 2) were **10 672 tCO_2e**. In addition, indirect emissions from water purification, waste treatment, business travel, personnel commutes and catering (scope 3) were **12 098 tCO_2e.**

CERN's immediate target is to **reduce direct emissions by 28%** by the end of **2024** (baseline year: 2018).

Water

2006 ML

In 2019, CERN drew **2006 megalitres (ML)** of water, mostly from Lake Geneva. This is about 47% less than in operational years.

The Laboratory is committed to **keeping its increase in water consumption below 5%** up to the end of 2024 (baseline year: 2018), despite a growing demand for water cooling of upgraded facilities.

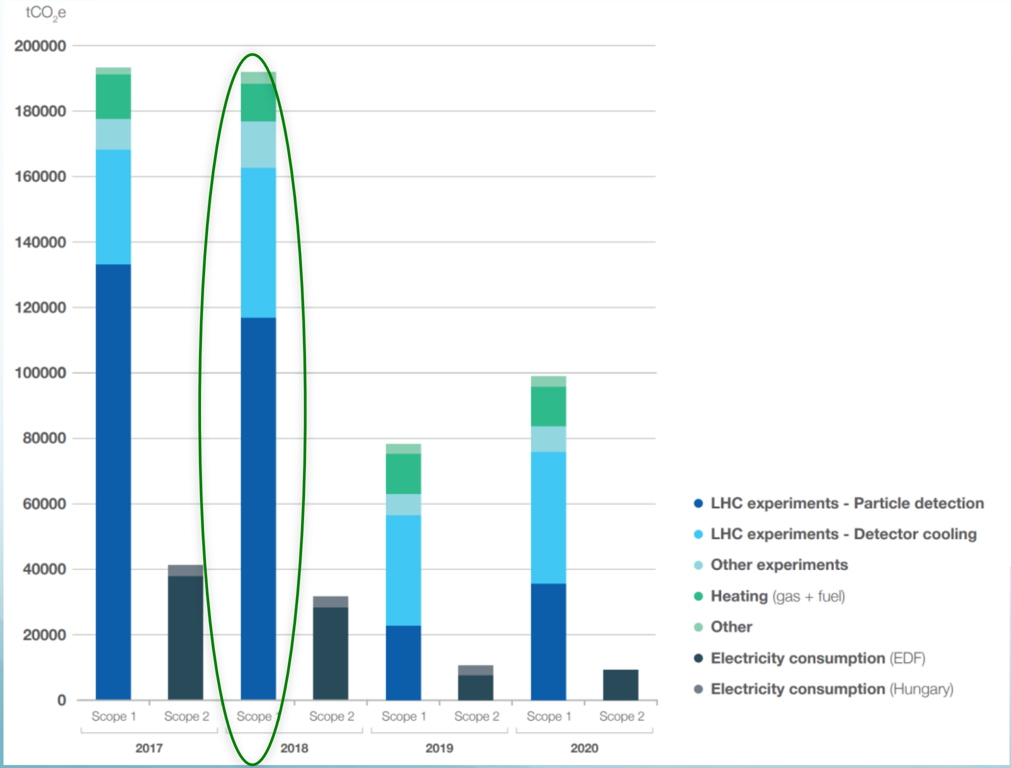
Biodiversity

16 species of orchids

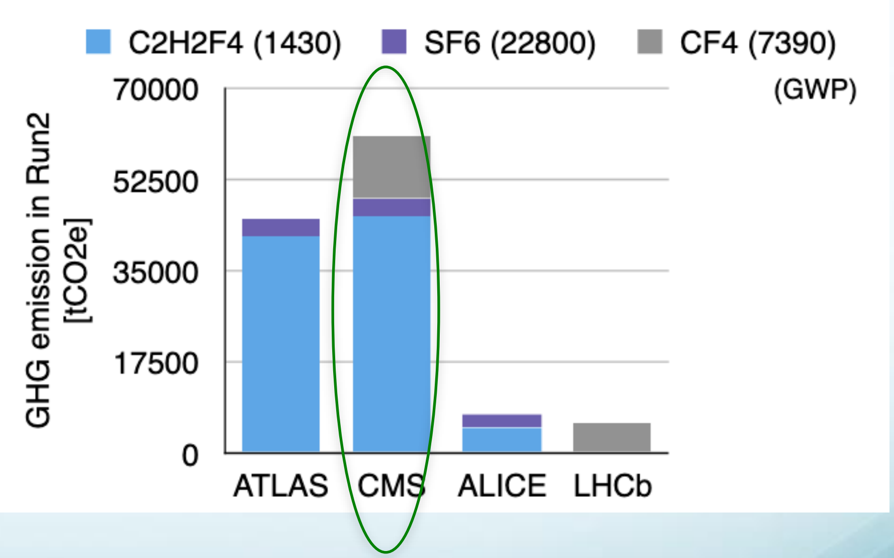
In 2019, a new species of orchid was discovered on CERN's sites, bringing the total to **16 species**. CERN land includes **258 hectares** of cultivated fields and meadows, **136 hectares** of forest and three wetlands.

GHG emission at CERN

- GHG emission : 192k tCO2e (in 2018)
  - 92% of emissions related to large LHC experiments
  - Most emissions from particle detection (CMS and ATLAS)
- CMS emission from Muon system: ~54k tCO_2e (in 2018)
  - It corresponds to about 0.14 % of annual emission in Swiss and 0.01 % in France



Run2 LS2



GWP: Global Warming Potential

It measures how much energy the emissions of 1 ton of a gas will absorb over a given period of time, compared to the emission of the same amount of CO_2.

CMS GHG emission reduction strategy

Benefits

In 2018 CMS defined the following strategy to progressively reduce the GHG emissions from the muon systems:

High priority

1. **Leak repair campaign to re-establish RPC gas flow to exhaust**
   - repair leaks in barrel RPCs (estimate ~50% success rate)
   - disconnect leaky RPCs that cannot be repaired (remaining ~50%)

cost **emission**

2. **Recuperation systems:**
   - Improve CF_4 recuperation efficiency (from 40% to ≥70%)

     cost **emission**
   - Implement $C_2H_2F_4$ recuperation (expected efficiency ~ 80%)

     cost **emission**

Further cost containment

3. Pre-purchase & stockpile GHGs to anticipate price escalation

cost

R&D on alternative gas mixtures

- Search for reduced CF_4% and $C_2H_2F_4$%
- Eco-friendly replacements of GHGs

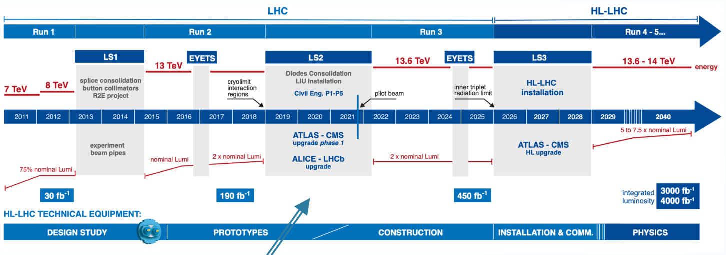
emission

Leak search campaign

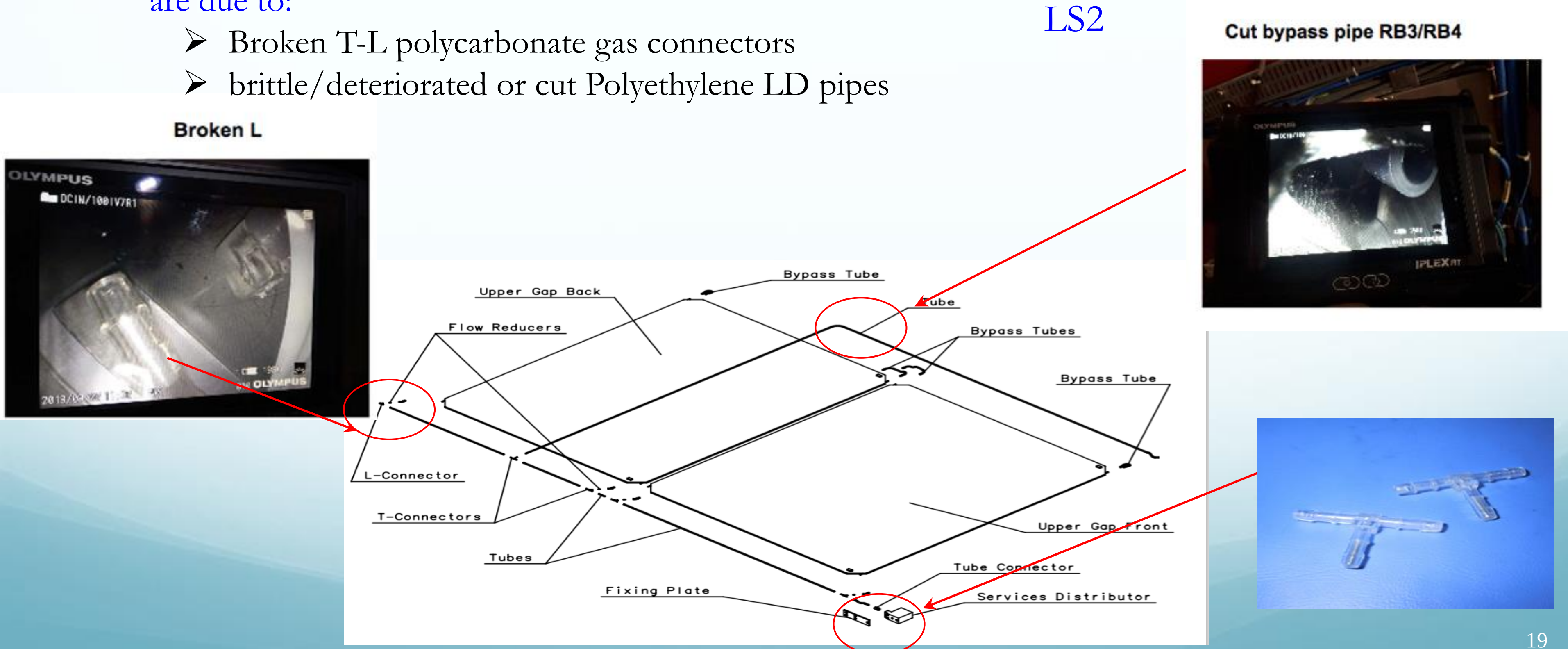
Extensive leak search campaigns were performed during LS1 and LS2 with non-invasive endoscopic technique.

Main conclusions:

- Leaks are mainly localized in the RPC Barrel chambers
- Sources of leaks (identified in most of the cases, 84%) are due to:
  - Broken T-L polycarbonate gas connectors
  - brittle/deteriorated or cut Polyethylene LD pipes



LS2



LS2 Barrel leak repair campaign

Extensive leak repair campaign carried out during LS2

- **Barrel leaking chambers:** special procedure developed to repair them in situ
  It consisted of a partial extraction of the muon station (RPC coupled with DT) for 80 cm from **back** or **front** side (depending by the location of the broken component), then cutting the C illumining profile in order to have access to the gas pipe or T/L connector and repairing/replacing it.

- **Endcap leaky chambers** were replaced with spare chambers or recovered by disconnecting the leaky gap (without effecting the performance)

Back extraction example:

Access to broken component

Repairs

1. Repair done by removing the broken pipe and by-passing the internal circuit and moving externally the parallel connection of two chambers
2. Repair done by gluing the L connector

Closing and validation

RPC status in 2022

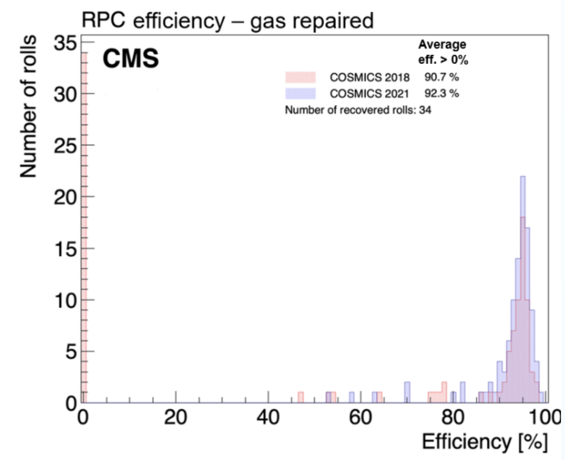
At beginning of RUN3, the RPC gas flow to exhaust **was** successfully re-established (**~400 1/h)**:

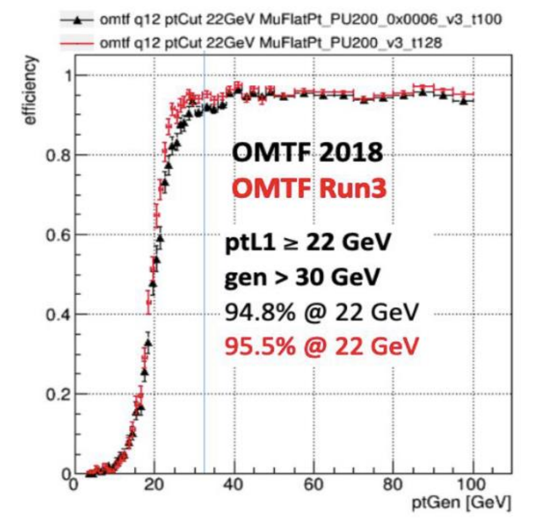
- Out of leaky **126 leaky chambers** (all allocated in the barrel region out of **480 RPCs**), **49** (40%) were repaired and validated with cosmic muons before LHC beginning

- **108** chambers were disconnected at the end of LS2 loosing redundancy without degradation the trigger efficiency

  - Remaining **77 leaky RPC** (63 of them perfectly operational as leak on return line), which could not be repaired during LS2, were temporarily disconnected and gas connection modified in order to re-connect them at any time without opening CMS
  - In addition, **31 chambers,** served by same gas line as the leaky one, were also disconnected. Therefore, in total
  - Almost all these chambers can be repaired during any future access time

- Although with reduced redundancy, Muon Trigger performance in 2022 was comparable with Run2 (in 2018)





CMS GHG emission reduction strategy

In 2018 CMS defined the following strategy to progressively reduce the GHG emissions from the muon systems:

Benefits

High priority

1. **Leak repair campaign to re-establish RPC gas flow to exhaust**
   - repair leaks in barrel RPCs (estimate ~50% success rate)
   - disconnect leaky RPCs that cannot be repaired (remaining ~50%)

cost **emission**

2. **Recuperation systems:**
   - Improve CF_4 recuperation efficiency (from 40% to ≥70%)
   - Implement $C_2H_2F_4$ recuperation (expected efficiency ~ 80%)

cost **emission**

cost **emission**

Further cost containment

3. Pre-purchase & stockpile GHGs to anticipate price escalation

cost

R&D on alternative gas mixtures

- Search for reduced CF_4% and $C_2H_2F_4$%
- Eco-friendly replacements of GHGs

emission

CSC Gas Recuperation System

G. Pugliese

LISHEP 2023

- Since 2012, the CF_4 recuperation system is operational in CMS with an **average efficiency of ~40%** due some technical issue
- Extensive R&D performed during LS2 on:

➢Membrane module

Search and characterization of new membranes

- Membranes used in industry to recuperate CO_2
- For different flow and with different sensitivity

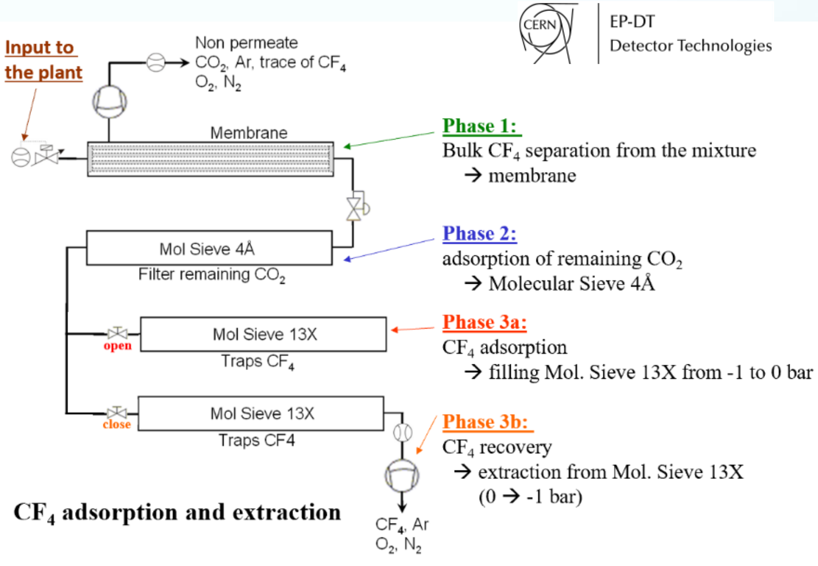
Characterization of existing membranes to improve CF_4 loss

- Impact of different permeate side pressures for Ar, CO_2, O_2, N_2 extraction
- Impact of input flow fluctuations on the membrane efficiency
- Monitoring and fine tuning of membrane parameters

➢CF_4 adsorption module

- Pressure-swing method
- Timing/optimization of run parameters
- Characterization of recuperated gas during full cycle
  - GC analyses for recuperated and exhaust gas

✓ **In 2022, the CF_4 recuperation system operated stable with ≈60% efficiency**



Phase 1:
Bulk CF_4 separation from the mixture
→ membrane

Phase 2:
adsorption of remaining CO_2
→ Molecular Sieve 4Å

Phase 3a:
CF_4 adsorption
→ filling Mol. Sieve 13X from -1 to 0 bar

Phase 3b:
CF_4 recovery
→ extraction from Mol. Sieve 13X
(0 → -1 bar)

CF_4 adsorption and extraction

Schematic View (courtesy of R. Guida and B. Mandelli)

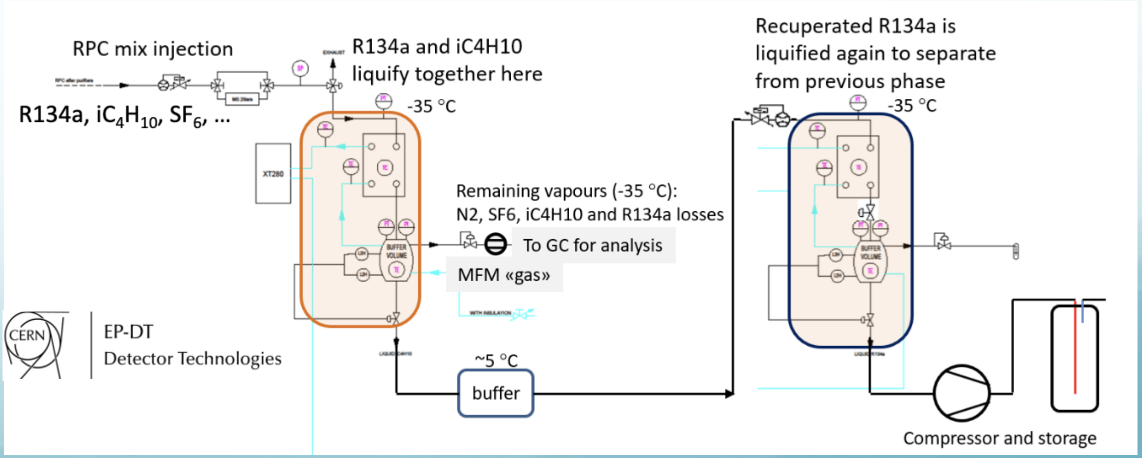
RPC Gas Recuperation System

CERN EP-DT Gas team is developing the first $C_2H_2F_4$ recuperation system:

- Prototype0 installed in CMS in December 2019 and connected to RPC exhaust which became available
- Several tests and studies performed to validate the separation process and the quality of the recuperated gas
- **System validated in 2022:**
  - Good $C_2H_2F_4$ quality with good recuperation efficiency (~80% limit due to azeotrope). Contaminants: air and SF6 (<50 ppm) and iC4H10 (close to detection limit)
  - Integration of compressor unit and storage of recuperated $C_2H_2F_4$ completed
  - Input flow tested up to 600 l/h

Three phases:

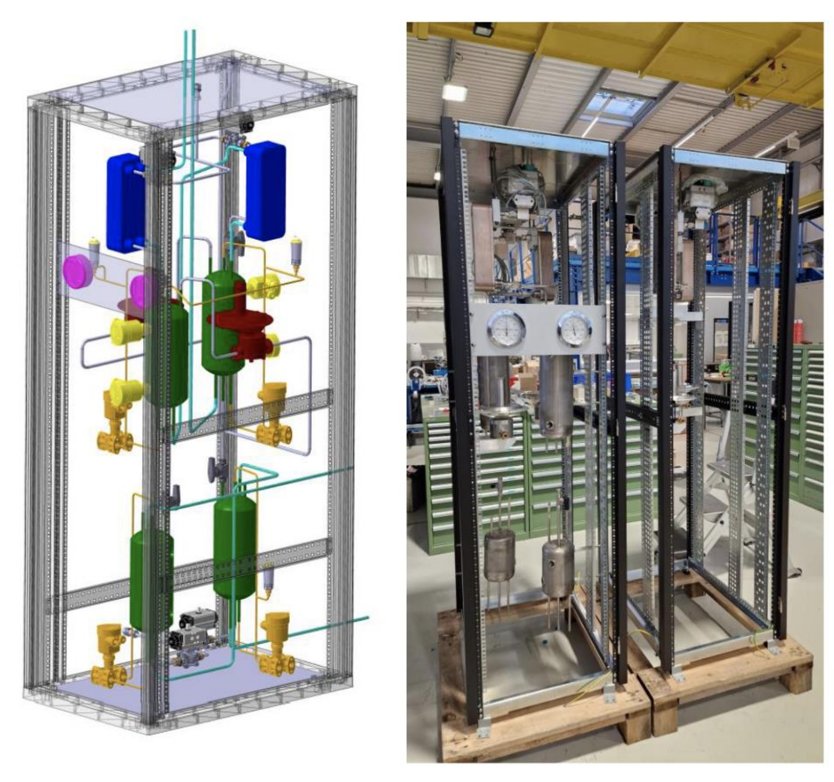
1. **Distillation:** gas mixture is cooled down at -35°C. N_2 and SF_6 exhausted in vapour phase; $C_2H_2F_4$ and iC_4H_{10} form an azeotrope liquid.
2. **Separation of $C_2H_2F_4$ from iC_4H_{10}** The liquid is slowly heated: the vapour of iC4H10 exhaust; $C_2H_2F_4$ in liquid phase goes in next buffer at 5 °C to becomes vapour
3. Compression and storage of vapour $C_2H_2F_4$



Schematic View (courtesy of R. Guida and B. Mandelli)

RPC Gas Recuperation System

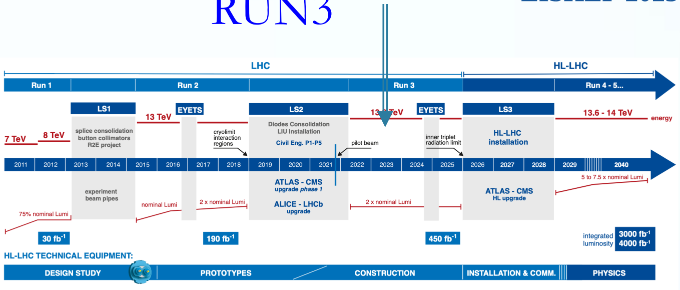
- Construction of the 1st version of $C_2H_2F_4$ recuperation system started end of 2022
- Commissioning of recuperated $C_2H_2F_4$ in mixer: March/April 2023
- Plan to have the recuperation system connected at the CMS exhaust and in full operation at beginning of 2023 LHC data taking (**expected efficiency: ≈ 80%**)



- R&D for possible recuperation of **SF_6** is planned with a timescale of 2-3 years
- Accessibility to the detector for repair intervention, if new leak will appear, is mandatory to maximize the gas flow to the exhaust

GHG emission in Run3

RUN3



Combining all actions performed during LS2:

- ✓ **Improved CSC CF4 recuperation system with ≈60% efficiency**
- ✓ **Optimization (i.e., low-emission mode)** of the gas system operation **outside** LHC collisions (YETS, etc.):
  - ➢ CSC gas mixture with 5% of CF4
  - ➢ RPC fresh gas consumption ≈ 400 l/h
- ✓ **RPC fresh gas consumption** ≈ 840 l/h (~10% less with respect to 2018)

➢ **Emission reduction of 31% achieved in 2022 !**

	2018 Consumption (Kg)	2022 Consumption (Kg)	2022 vs. 2018 % reduction
CF4	1190	875	**26.5**
R134a + SF6	29400 130	20000 90	**32** **31**

CO2e	53,8 kt	37.1 kt	**31% reduction**

➢ The $C_2H_2F_4$ recuperation system should further increase emission reduction (with respect to 2018) to ≈ **40 – 50%**

➢ CERN Target for RUN3 has been achieved

Note: with respect to RUN1, CSC 2022 emission reduced by ≈ 68 %

CMS GHG emission reduction strategy

Benefits

In 2018 CMS defined the following strategy to progressively reduce the GHG emissions from the muon systems:

High priority

1. **Leak repair campaign to re-establish RPC gas flow to exhaust**
   - repair leaks in barrel RPCs (estimate ~50% success rate)
   - disconnect leaky RPCs that cannot be repaired (remaining ~50%)

cost **emission**

2. **Recuperation systems:**
   - Improve CF_4 recuperation efficiency (from 40% to ≥70%)
   - Implement $C_2H_2F_4$ recuperation (expected efficiency ~ 80%)

cost **emission**

cost **emission**

Further cost containment

3. Pre-purchase & stockpile GHGs to anticipate price escalation

cost

R&D on alternative gas mixtures

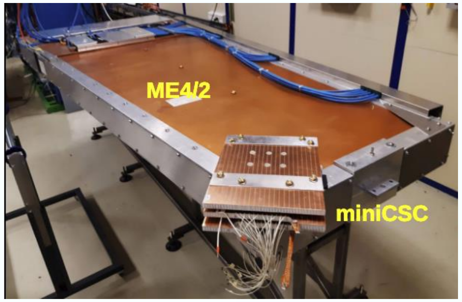
- Search for reduced CF_4% and $C_2H_2F_4$%
- Eco-friendly replacements of GHGs

emission

CSC mixture with reduced CF_4%

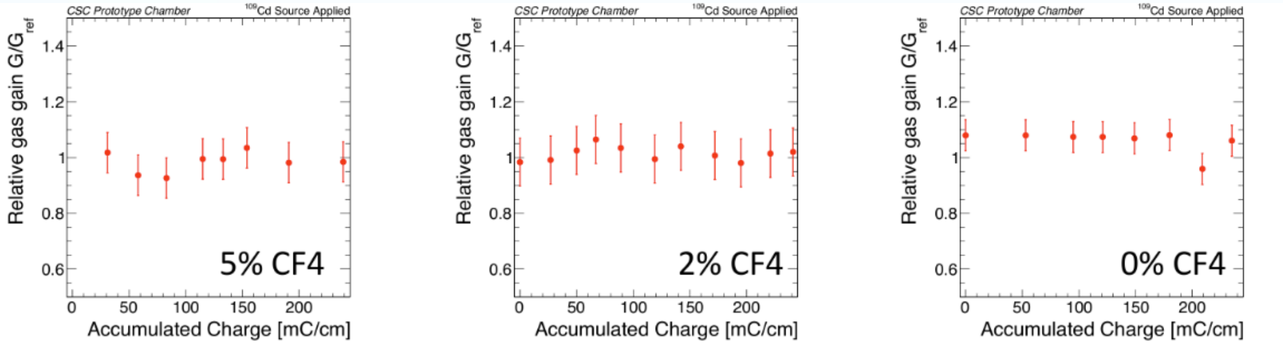
Accelerated irradiation tests with reduced CF_4%:

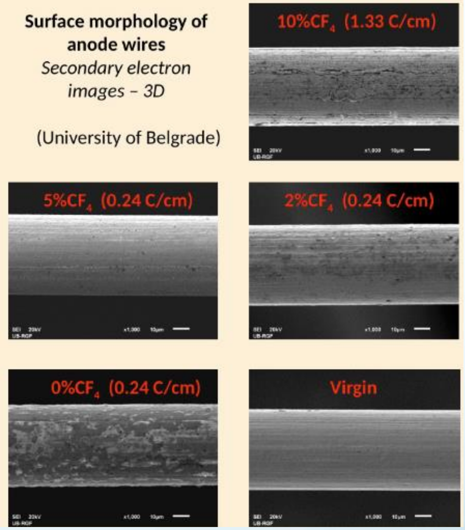
- Performed with small prototypes (‘miniCSC’) in several labs
- Ongoing with full-scale production chamber at GIF++ facility



➢ **Results of tests with miniCSCs and 5,2,0 % of CF_4:**

- no significant performance degradation (gas gain, dark rate and current, interstrip resistance) observed in any tests
- cathode surface modification is seen in all cases
- **anode depositions are clearly seen for 2 and 0% CF_4**




Surface morphology of anode wires
Secondary electron images – 3D
(University of Belgrade)

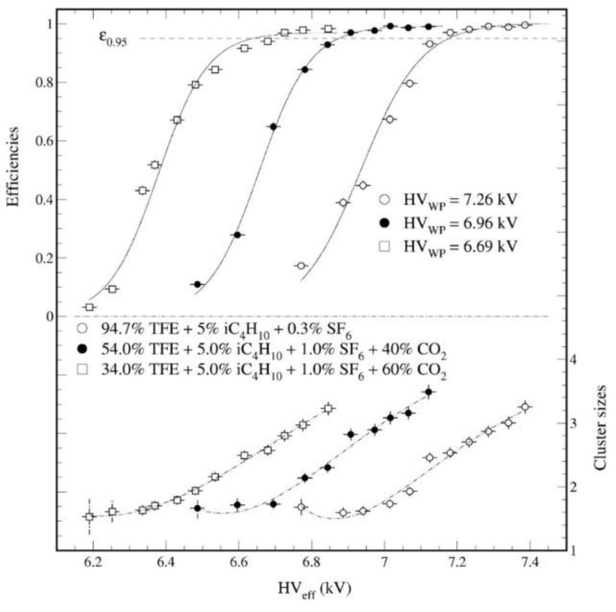
➢ **Full-scale chamber longevity** study of using **5% CF_4** started in GIF++ in September 2022. Though no evidence of performance degradation or aging has been observed so far, the study is to be concluded **in about one year**, in order to accumulate 3 times equivalent HL-LHC charge

Expect CF_4 emission reduction of 50%

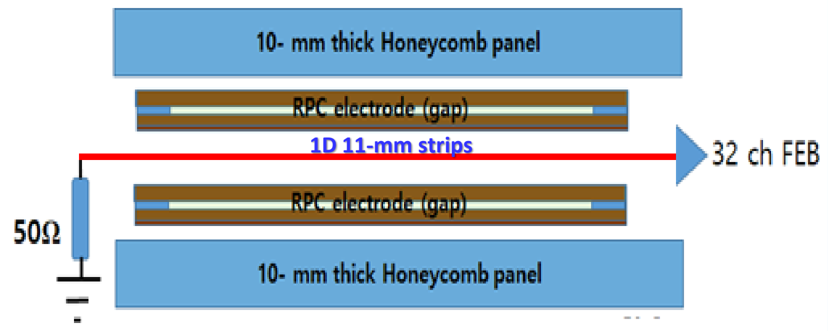
RPC mixture with reduced $C_2H_2F_4$

Performance study with reduced $C_2H_2F_4$ %

- ➢ Investigation ongoing on the possibility of replacing a fraction of $C_2H_2F_4$ with CO_2
- ➢ Tested several mixtures with increasing CO_2 fractions (by Korea Univ. for CMS and EP-DT group at CERN [2])
- ➢ Promising results obtained so far by mixtures containing 30%÷ 60% of CO_2 and increasing the SF6 to 1%



iRPC prototype



Gap thickness = 1.4 mm Bakelite thickness = 1.6 mm
Gap size = 50 cm x 40 cm
32 strips with a 32-ch KODEL FEBs Strip pitch = 11 mm
Th = 0.4 mV ~ 60 fC Digitized pulse width = 30 ns

40% CO_2: HV_{WP} ~ 300 V lower
60% CO_2: HV_{WP} ~ 570 V lower
Cs @WP HV slightly increases with increasing CO_2 ratio

- ➢ **Comparable efficiency plateau,** lower HV working point by adding CO_2 : ~ -150 V/10% CO_2
- ➢ No notable increase in streamer probability or stochastic noise rate or Ohmic current
- ➢ Additional tests ongoing to check the long-term behavior of RPC under gamma radiation with this mixture (in common CMS- ATLAS-Ep-DT group

Expect RPC emission reduction of 26% (40% CO2)

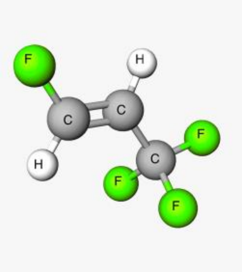
Eco-gas search methodology

Constraints on a new eco-gas mixture:

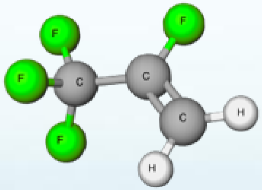
- **Safety:** gases must be non-flammable, not explosive, not toxic and without other environmental hazards
- **Compatible** with the current systems i.e., guarantee same **performance** and **longevity (**CSCs and RPCs must work until the end of CMS) without changing the HV supply systems and Front-End electronics
- **Cheaper (**or similar cost) with respect to the present gases. As consequence new eco-friendly gases must come from industrial applications (i.e., refrigerants and HV insulating medium)

Possible eco-gaseous replacement

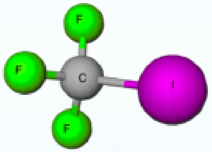
HydroFluoroOlefins (HFOs)



HFO-1234ze
GWP = 6

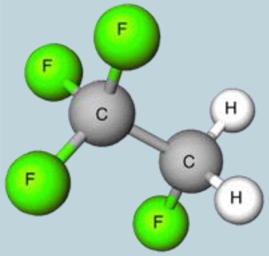


HFO-1234yf
GWP = 4
Discharged due to moderate flammability

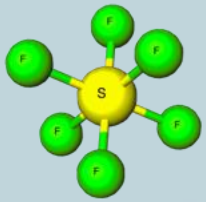


CF_3I
Trifluoroiodomethane
GWP <1
Discharged because too electronegative and expansive

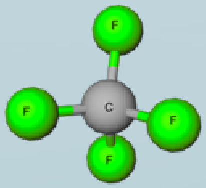
3M Novec 4710
GWP 2100



C2H2F4
GWP = 1430



SF6
GWP = 22800



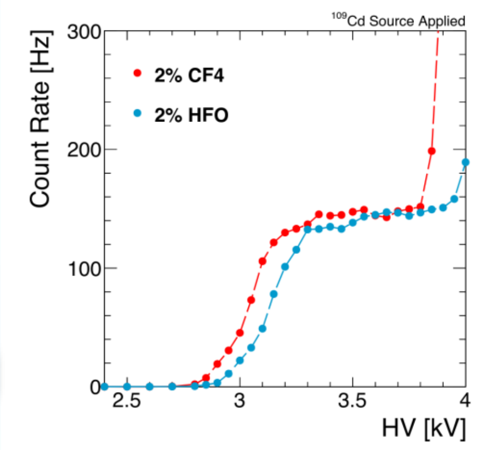
CF4
GWP = 7390

New CSC Gas Mixtures: Search for CF_4 Replacements

A gas mixture containing **2% of HFO** and **Ar-CO_2** was studied on **mini-CSCs** at PNPI (St. Petersburg) and CERN 904 laboratories with following results:

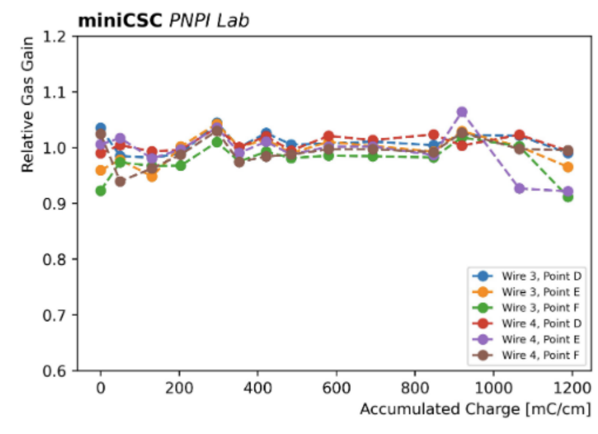
- Detection properties comparable

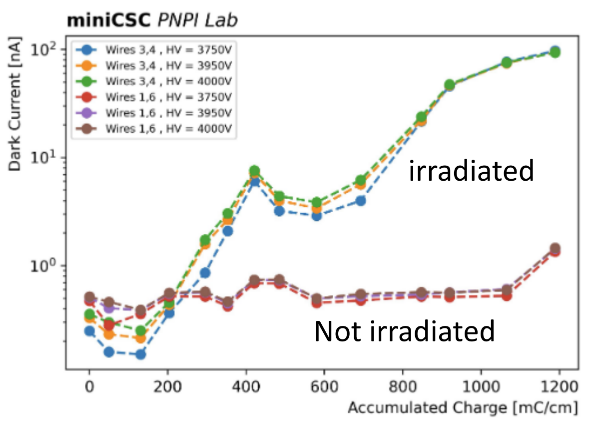
- Significant increase in the dark current after accumulated 0.6 C/cm
- Formation of tungsten oxide on the anode wire, changing its surface

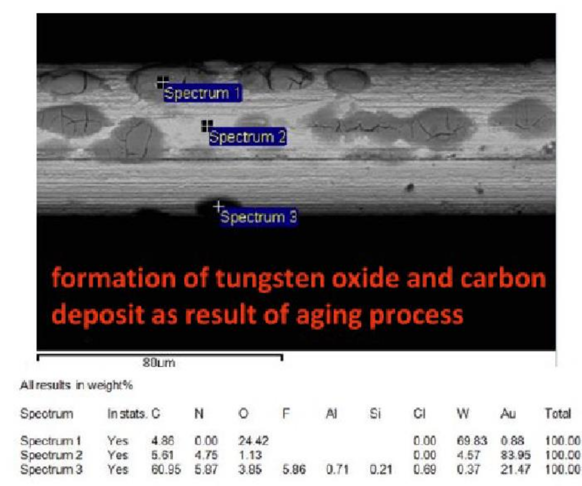


Inacceptable longevity risk !

R&D continuing…







formation of tungsten oxide and carbon deposit as result of aging process

All results in weight%

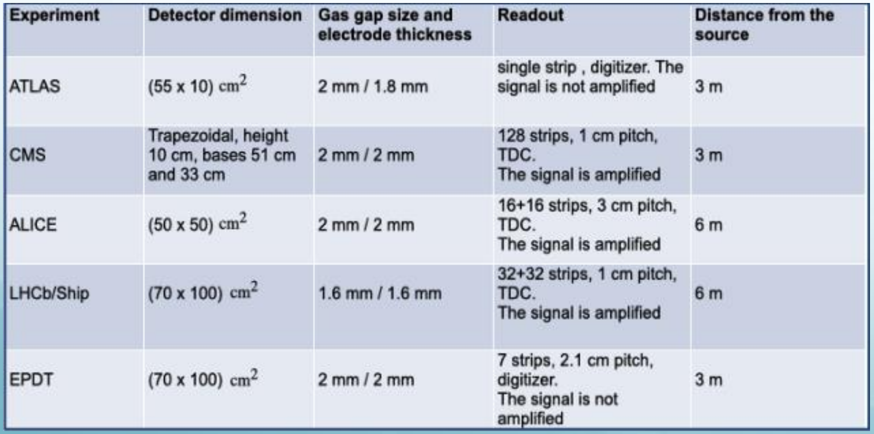
Spectrum	In stats.	C	N	O	F	Al	Si	Cl	W	Au	Total
Spectrum 1	Yes	4.86	0.00	24.42				0.00	69.83	0.88	100.00
Spectrum 2	Yes	5.61	4.75	1.13				0.00	4.57	83.95	100.00
Spectrum 3	Yes	60.95	5.87	3.85	5.86	0.71	0.21	0.69	0.37	21.47	100.00

RPC EcoGas@GIF++ Collaboration

RPC EcoGas@GIF++ collaboration created in 2019 within the ALICE, ATLAS, CERN EP-DT, CMS and LHCb/SHiP experiments to search for an eco-friendly RPC gas mixture and assess the detector performance with muon beam and in background conditions

Benefit of this collaboration:

- Share person-power, instrumentation (power and gas systems, DAQ, DCS), preliminary results obtained in laboratory and… ideas!
- Combine results obtained by detectors with different geometry and readout electronics



Experiment	Detector dimension	Gas gap size and electrode thickness	Readout	Distance from the source
ATLAS	(55 x 10) cm^2	2 mm / 1.8 mm	single strip , digitizer. The signal is not amplified	3 m
CMS	Trapezoidal, height 10 cm, bases 51 cm and 33 cm	2 mm / 2 mm	128 strips, 1 cm pitch, TDC. The signal is amplified	3 m
ALICE	(50 x 50) cm^2	2 mm / 2 mm	16+16 strips, 3 cm pitch, TDC. The signal is amplified	6 m
LHCb/Ship	(70 x 100) cm^2	1.6 mm / 1.6 mm	32+32 strips, 1 cm pitch, TDC. The signal is amplified	6 m
EPDT	(70 x 100) cm^2	2 mm / 2 mm	7 strips, 2.1 cm pitch, digitizer. The signal is not amplified	3 m

R&D founded also by AIDA INNOVA
WP 7 Task 7.2.2 Study of eco-friendly gas mixtures for Resistive Plate Chamber detectors

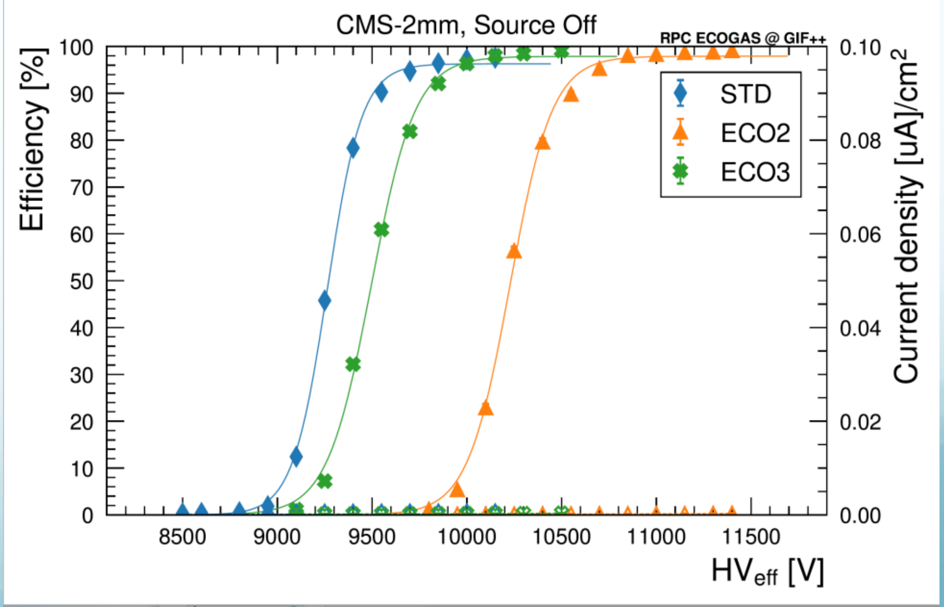
HFO based gas mixture results

Gas mixture	$C_2H_2F_4$	HFO-1234ze	CO_2	$I\text{-}C_4H_{10}$	SF_6
STD	95.2	0	0	4.5	0.3
ECO1	0	45	50	4	1
ECO2	0	35	60	4	1
ECO3	0	25	69	5	1

Gas mixtures under study

- ➢ Addition of a fraction of CO_2 is needed to lower HV working point (WP)

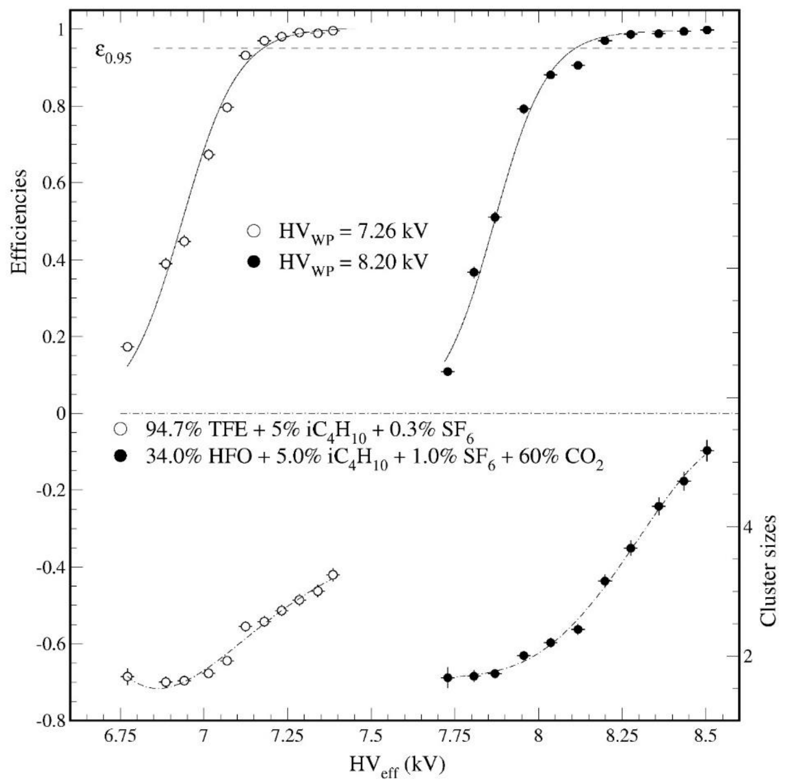
- ➢ Slightly higher WP but inside the limit of 12 kV
- ➢ **Comparable efficiency plateau** between standard and HFO based gas mixtures for the CMS 2mm double gas gap thickness **(without gamma background)**

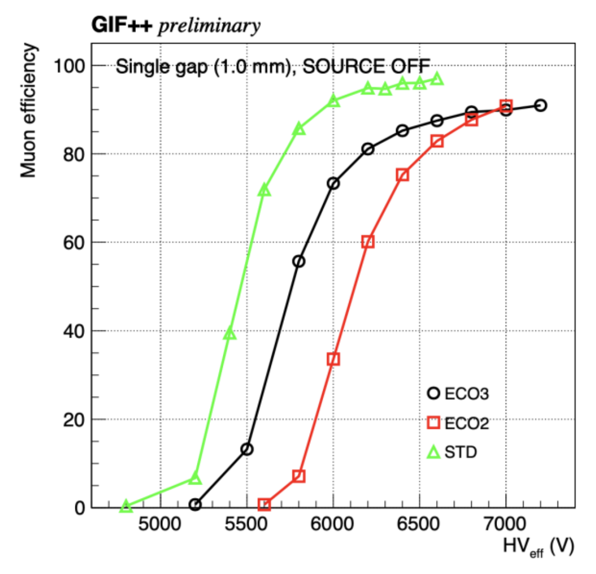


HFO based gas mixture results

Performance with thinner gas gaps:

- **1.4 mm double gap RPC:**
  - Comparable efficiency plateau $HV_{WP}\sim$ 940 V higher (with 60% CO_2 added to HFO)
  - Small increase of cluster size
    - $<C_s>$ for the std. TFE gas = 2.78
    - $<C_s>$ for 60% CO2 + HFO = 3.67
  - Increase factor of Ohmic current and noise (under observation)



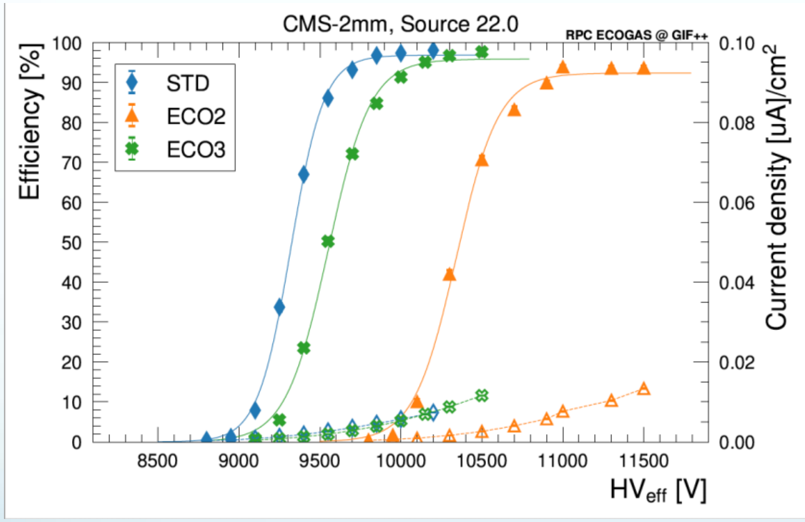


- **1 mm single gas gap RPC**
  - Lower efficiency plateau (~ 5%) for HFO based mixtures (due to low density of the CO_2 that results in a smaller active target available for the primary ionization)

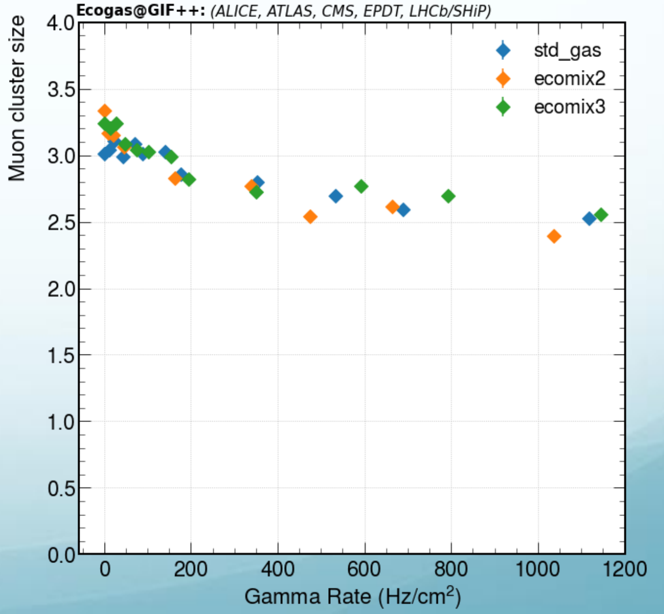
HFO based gas mixture results

Reasonable performance for both ECO2 and ECO3 mixtures for CMS 2 mm gas gap in presence of gamma background:

- Comparable efficiency plateau for ECO3 up to 500 Hz/cm^2, lower **e**fficiency but above 90% for ECO2

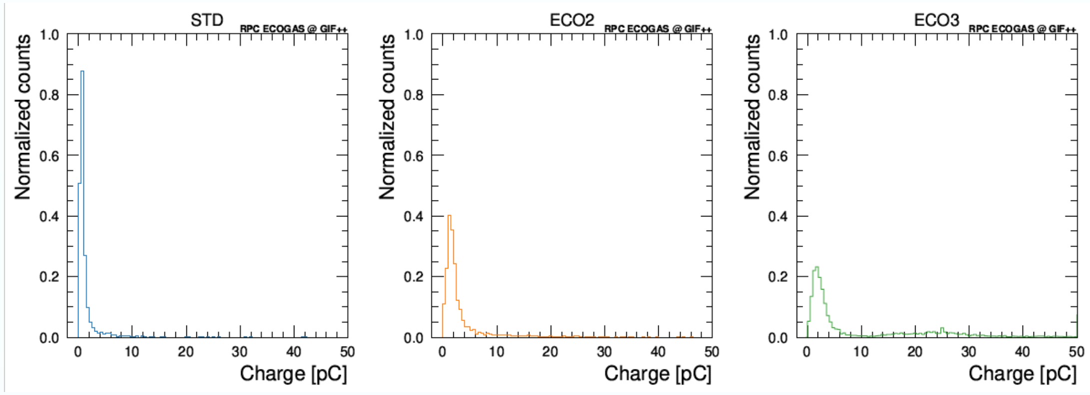


- Cluster size is well controlled for all HFO mixtures at various gamma background conditions



HFO based gas mixture results

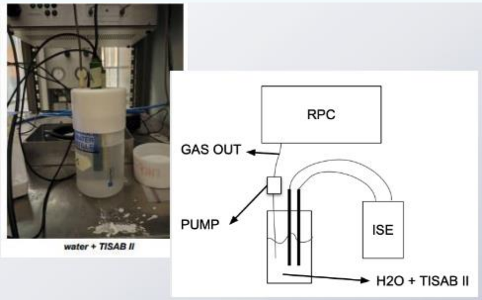
- **Prompt charge** not completely saturated but under control (second peak observed for eco gas mixtures)

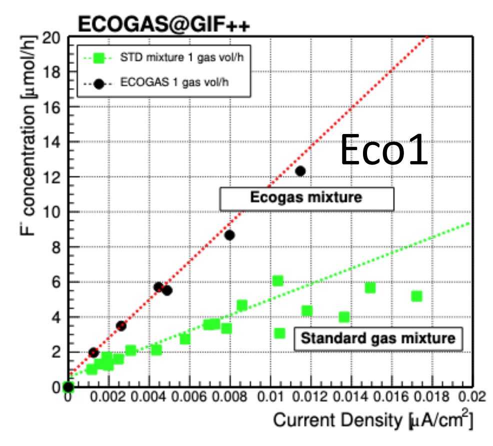


Single Gap
Atlas Chamber (2mm)

- **Higher production** of HF (Fluoridric Acid) for HFO based gas mixture

- F- are produced from the $C_2H_2F_4$ and HFO molecule when operating the detectors under radiation and high electric fields
- HF production was measured using Ion Selective Electrodes (ISE)





→ aging effects to be carefully evaluated. Work is in progress to study long term aging of detectors under irradiation

Conclusions

- It has been proved that the fluorinated **RPC and CSC gas mixtures** are crucial to guarantee high and stable detector performance at LHC & HL-LHC conditions

- However, pollution from those **green-house gases (GHG)** is a concern in view of the potential negative environmental impact and of the related additional costs
- CMS is fully committed to reduce as much as possible the GHG emissions with large investments on the reduction of RPC leaks to restore gas flow to exhaust and on the R&D on recuperation systems and on new low GWP gas mixtures.

  - ✓ **CERN target for RUN3 has been achieved:**
    - ✓ emission has been reduced by **31% in 2022**
    - ✓ further reduce of **emission by 40-50%** from 2023 with $C_2H_2F_4$ recuperation system

  - ✓ **CERN target for RUN5 and beyond:** considering the options being studied (i.e., reduced fraction of CF_4 and $C_2H_2F_4$ and new eco gas mixtures), the 70% reduction should be meet (if results will be positive)

Thanks!

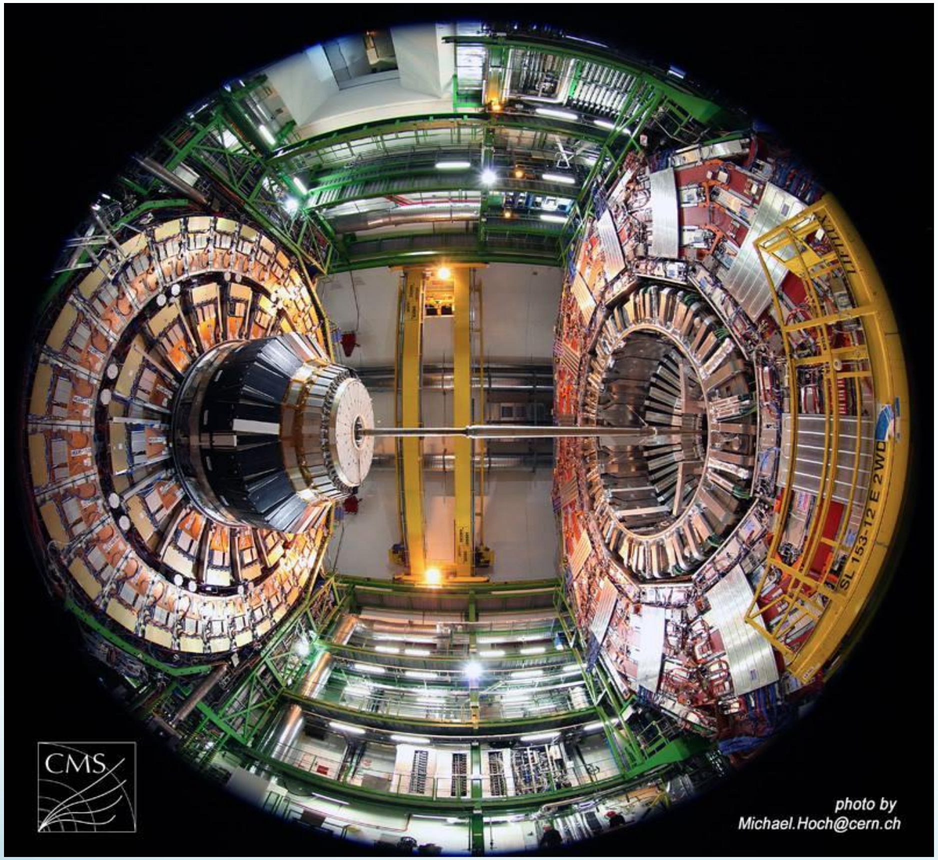
Credits
to the CMS People

and
RPC EcoGas@ GIF++
People and EP-DT CERN team

References

[1] R. Guida et al., “Results from the first operational period of the CF4 recuperation plant for the Cathode Strip Chambers detector at the CERN Compact Muon Solenoid experiment”, in 2012 IEEE Nuclear Science Symposium and Medical Imaging Conference and 19th Workshop on Room-Temperature Semiconductor X-ray and Gamma-ray Detectors, pp. 1141–1145. 2012. doi:10.1109/NSSMIC.2012.6551286.

[2] https://doi.org/10.1016/j.nima.2022.167045

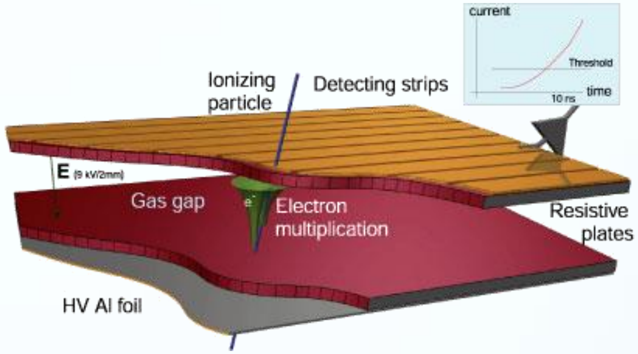


Backup slides

Brief History of the Resistive Plate Chamber

- 1981: **1st generation** R. Santonico published the [paper "Development of Resistive Plate Counters``, Nucl. Instrum. Meth. N.187]

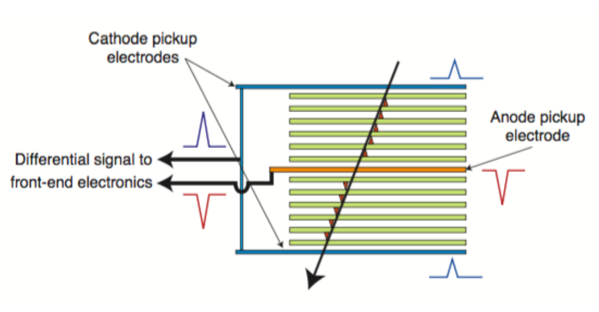
Operated in **streamer mode** with an **Argon** based mixture
Performance: time resolution ≈ 1ns Efficiency > 96%
Rate Capability ≈ 50 Hz/cm2



- 1992: **2nd generation** of RPC detector was developed for LHC experiments (installed in ATLAS, CMS and Alice).

Operated in **avalanche mode** with a **Freon** based mixture
Performance: time resolution ≈ 1ns Efficiency > 96%
Rate Capability ≈ 500 Hz/cm2

- 1995: **Multi-gap RPCs** developed by C. Williams (installed in ALICE).



Operated in **avalanche mode** with a **Freon** based mixture
Performance: time resolution ≈ 60ps Efficiency > 96%

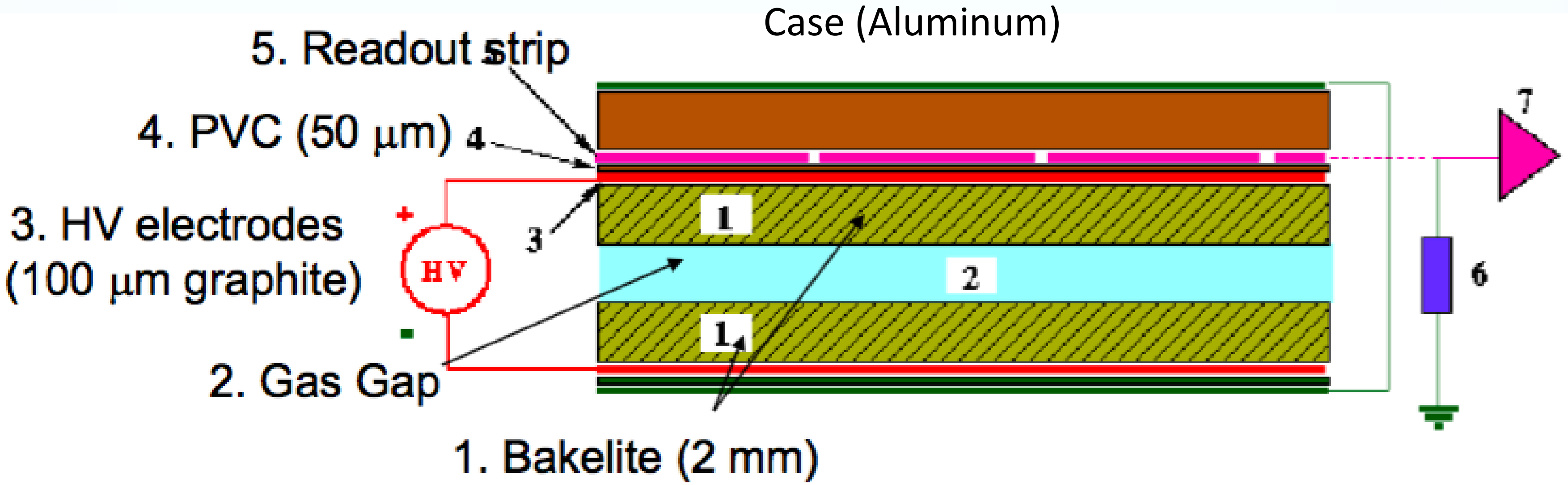
- 2015: **3nd generation of** RPC developed for HL-LHC

RPC basic elements (as in the 1st generation)

Gas mixture:
Argon, Iso-butane and Freon
at P ≈ 1 Atm

High Voltage contact: graphite coating on electrode outer surfaces

Pick up strips are used to collect the signal: **Al/Cu, ~cm**



Resistive Electrodes **($\rho \approx 10^{10}$-10^{12} Ωcm):** **High Pressure Laminates (HPL)** “Bakelite” made by Kraft paper impregnated with melamine/phenol resins.
Internal electrode surface covered with a **thin linseed oil layer (~µm)**

How to improve the rate capability

In the static condition the voltage applied to the chamber ΔV_{gap} is entirely transferred to the gas.

But, in the presence of a ϕ flux of particle, which create a current I, the voltage inside the gas gap is reduced:

$$\Delta V_{gap} = \Delta V_{appl} - RI = \Delta V_{appl} - \Delta V_{el}$$

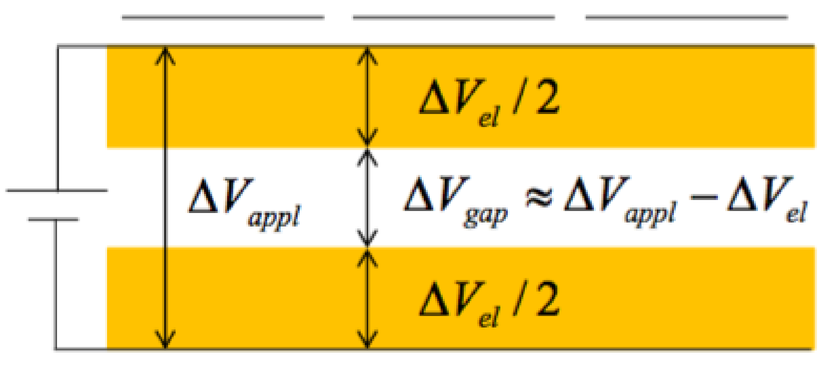
$$\boxed{\Delta V_{el} = \rho\, d\, \Phi \langle Q \rangle}$$

Electrode resistivity

Electrode thickness

Particle flux counts/cm^2

Average charge/hits

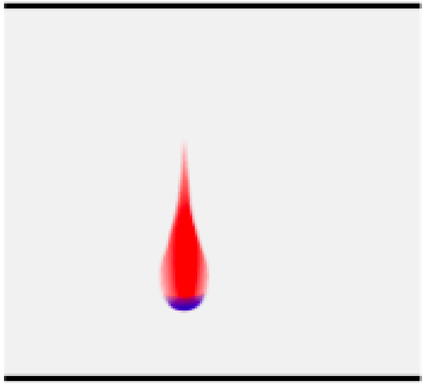


- ➢ To increase the rate capability (i.e the particle flux) we can play with the **average charge, ρ, d**

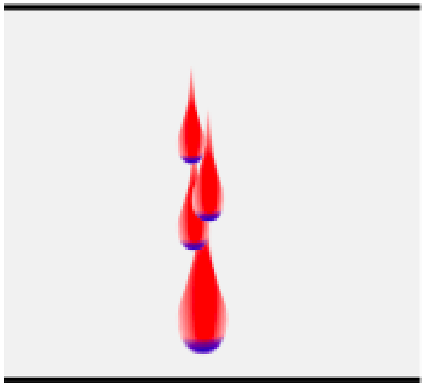
To increase the rate capability: Change of the Operation mode

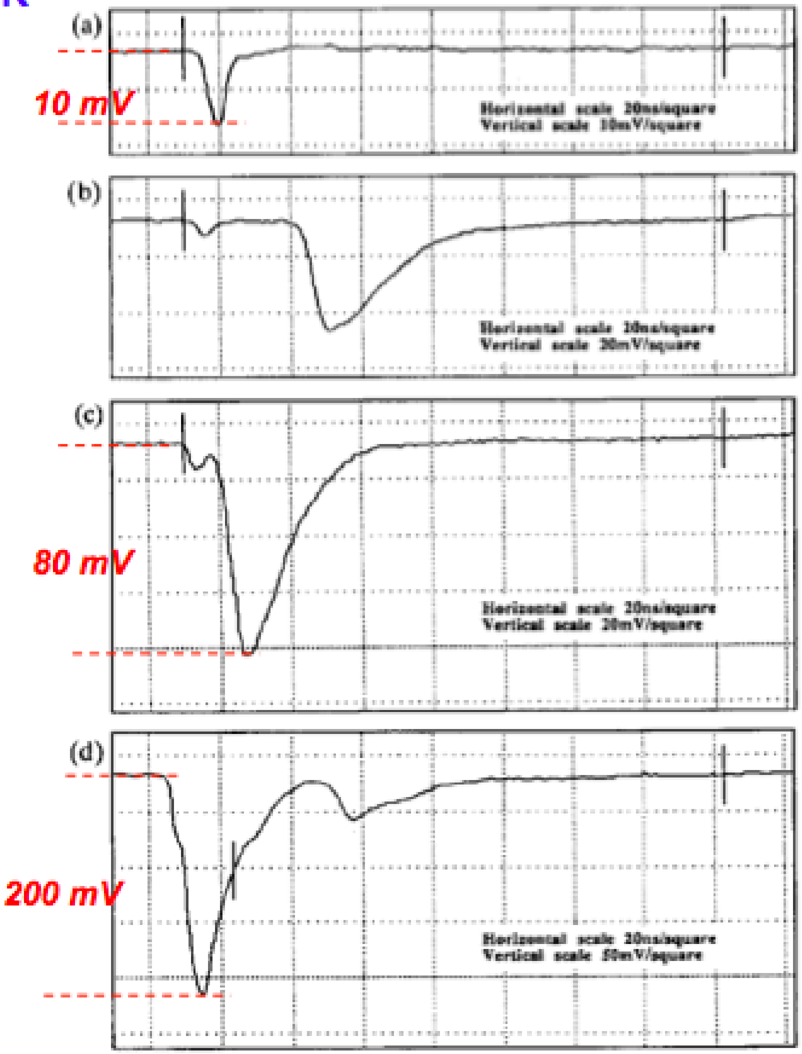
TRANSITION AVALANCHE TO STREAMER

NORMAL AVALANCHE



PHOTON MEDIATED BACKWARD PROPAGATION: STREAMER





A new gas mixture

C2H2F4 (95.4%), Iso-butane = 4.5%, SF6 = 0.3 %

In a streamer mode, the main gas components should provide a robust first ionization signal and a large avalanche multiplication for a low electric field→ **Argon based gas mixture (λ = 2.5 mm^{-1})**

In avalanche mode, the main component must have high primary ionization but with small free path for electron capture. The high electronegative attachment coefficient limits the avalanche electron number → **Freon ($C_2H_2F_4$) based gas mixture (λ = 5 mm^{-1})**

Plus….a “**quenching gas”** like the **iso-butane** which has a high probability for absorbing ultra-violet photons

LHC and HL-LHC schedule

G. Pugliese

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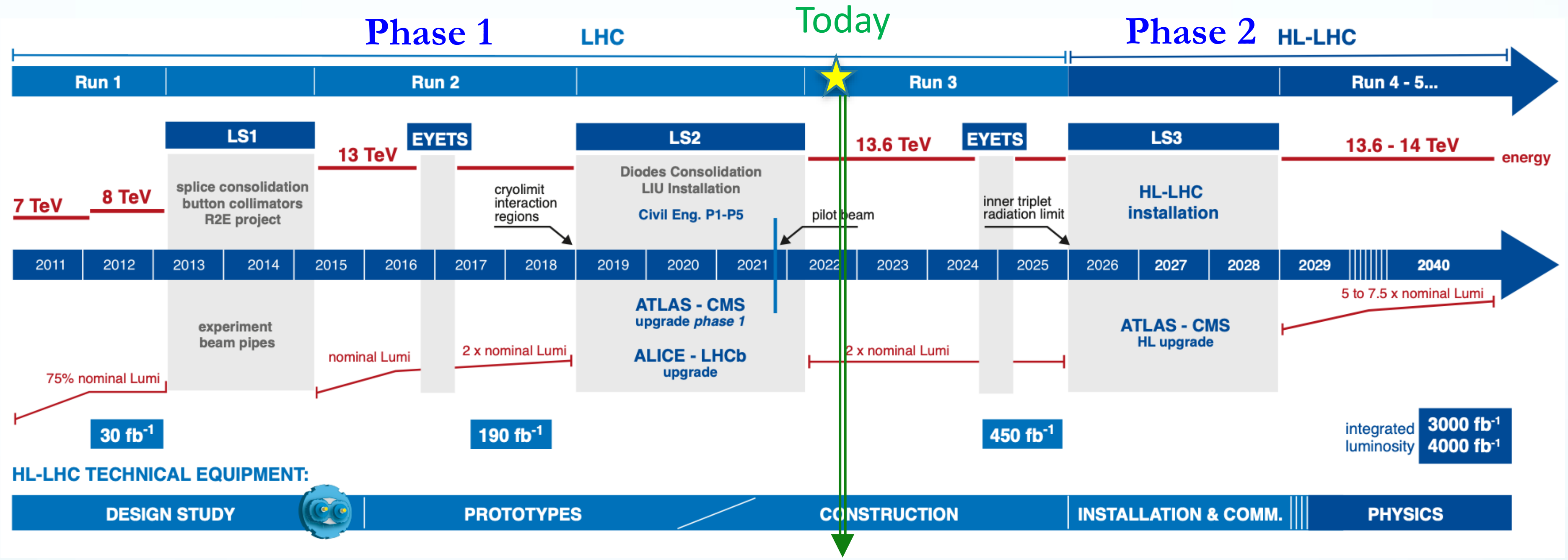
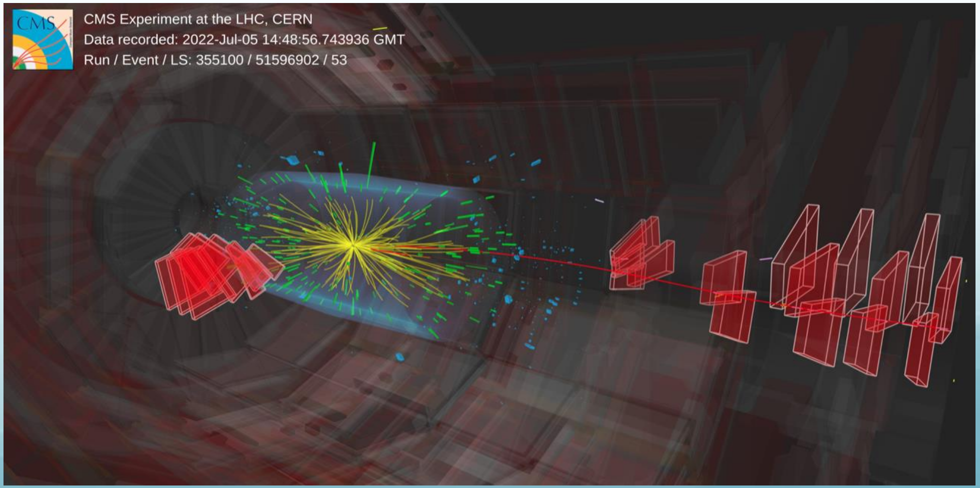




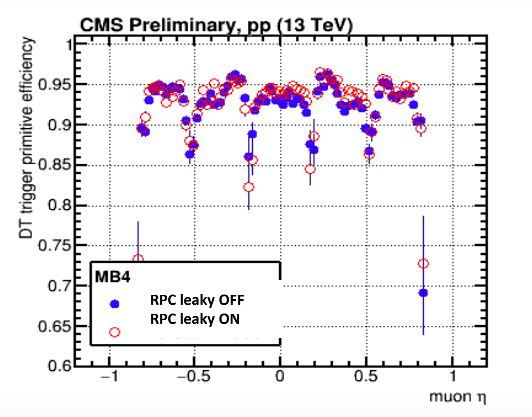
First Stable Beams
energy record 13.6 TeV
on 5th July 2022

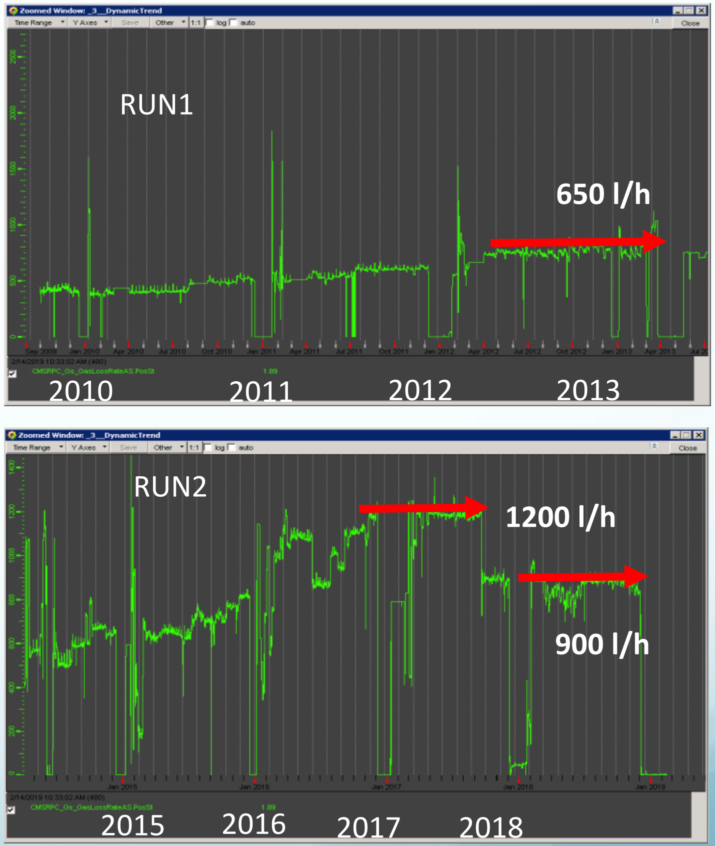
RPC gas system performance

Brief history of the RPC gas system gas leaks :

- The leak is due to the **RPC barrel chambers only**

- **Small increase of the leak rate** in RUN1 (from 450 l/h to 650 l/h)
- Significant **increase of leak rate** from 650 l/h to 1200 l/h in RUN2
- **Stability significantly improved** (improved operation mode and controls system of the UXC ventilation system pressure) up to end of RUN2
- 15 leaky chambers (≈2% of channel) disconnected in Sept 2017, reducing the leak to 900 l/h. Selected RB3 and RB4 stations in order to have less impact in the trigger performance





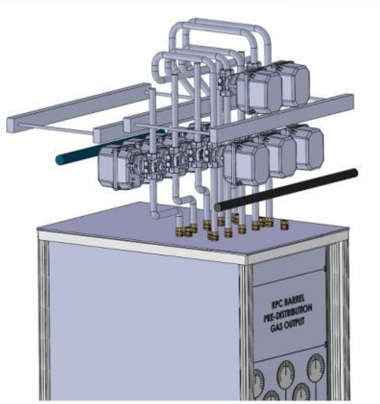
Gas leak monitoring in RUN1 and RUN2

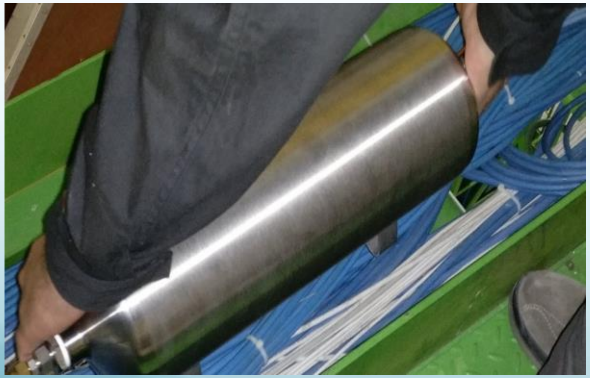
Gas System consolidation in LS2

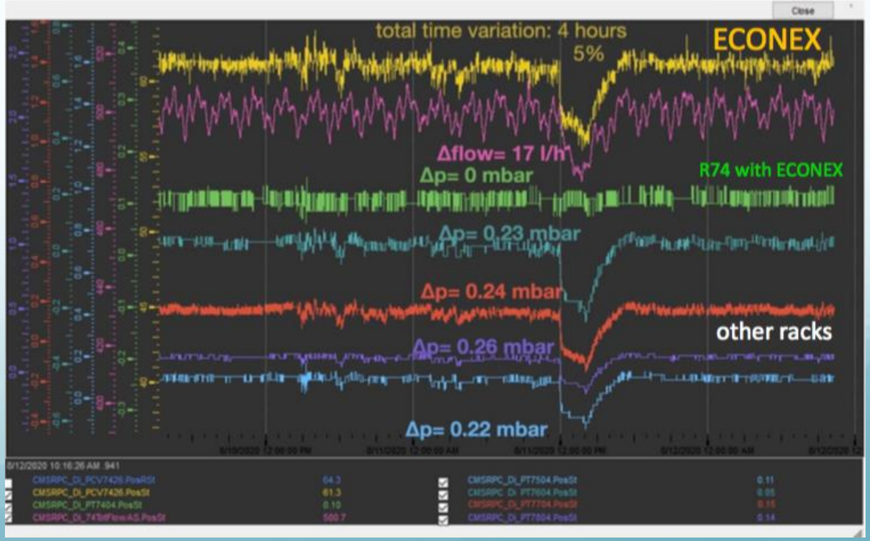
Furthermore to prevent new leaks the gas system was consolidated by:

- Installing new automated regulation valves on the return of each gas distribution module to minimize any pressure fluctuation inside the chambers at level of less than ≤0.1 mbar

- Adding stainless steel reference volumes that simulate detector volume for pressure measurement used as reference to control the new valves







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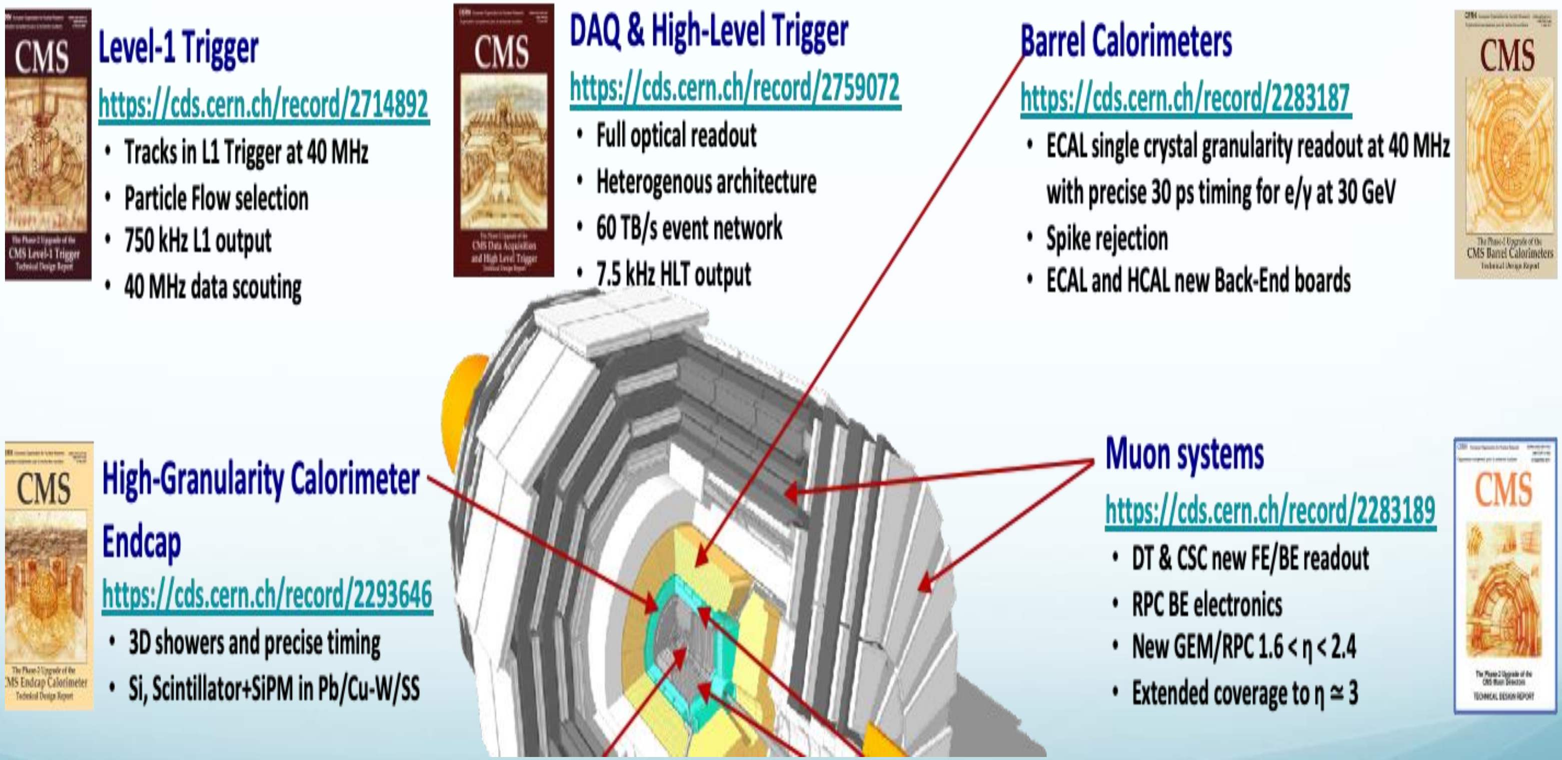
☐ CMSRPC_DI_PCV7426.PosRSt 64.3
☑ CMSRPC_DI_PCV7426.PosSt 61.3
☑ CMSRPC_DI_PT7404.PosSt 0.10
☑ CMSRPC_DI_74TotFlowAS.PosSt 500.7
☑ CMSRPC_DI_PT7504.PosSt 0.11
☑ CMSRPC_DI_PT7604.PosSt 0.05
☑ CMSRPC_DI_PT7704.PosSt 0.15
☑ CMSRPC_DI_PT7804.PosSt 0.14

Courtesy of R. Guida and B. Mandelli by EP-DT group

CMS Upgrade Project

The CMS detector has to be upgraded to cope with expected HL-LHC conditions (highest rate, fluence and pileup ever achieved) for new measurements and new physics searches



Level-1 Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1 Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting

DAQ & High-Level Trigger

https://cds.cern.ch/record/2759072

- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL single crystal granularity readout at 40 MHz with precise 30 ps timing for e/γ at 30 GeV
- Spike rejection
- ECAL and HCAL new Back-End boards

High-Granularity Calorimeter Endcap

https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scintillator+SiPM in Pb/Cu-W/SS

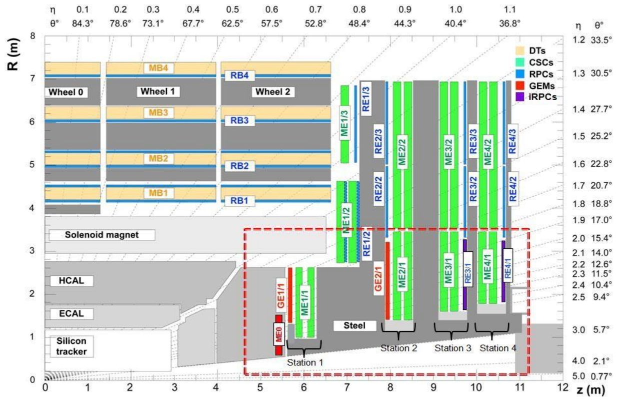
Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC BE electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

The Muon System Upgrade

- **New detectors** in the endcap region, to restore redundancy and extend the muon coverage up η = 2.8, based on GEM and improved RPC

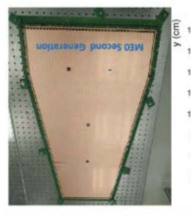


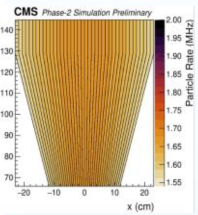
- 72 improved RPC will be installed in the 3rd and 4th stations

- The iRPC consists of:
  - thinner gas gap and electrode thickness
  - New electronics and strip layout

- Four demo-chambers installed in CMS in 2021
- **RE3/1 mass production** started in 2022
- **R&D on an eco-gas mixture ongoing**

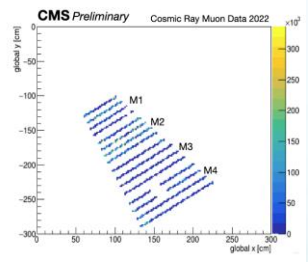
- GEM detectors will be installed in the GE2/1 and ME0 stations
- One demo-chamber installed
- GE2/1 mass production started in 2021



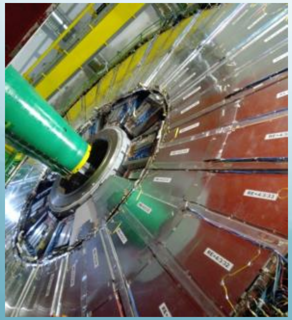


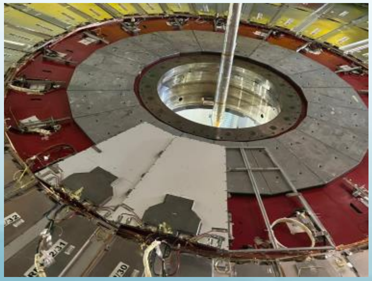
GE2/1

ME0



GE2/1 demonstrator occupancy map





- **New electronics for the legacy detectors:**

  DT: replace all On-Board electronics (OBDT), BE
  RPC: replace all off-chamber electronics, BE
  CSC: replace selected FE boards (**DONE in LS2**), replace all BE

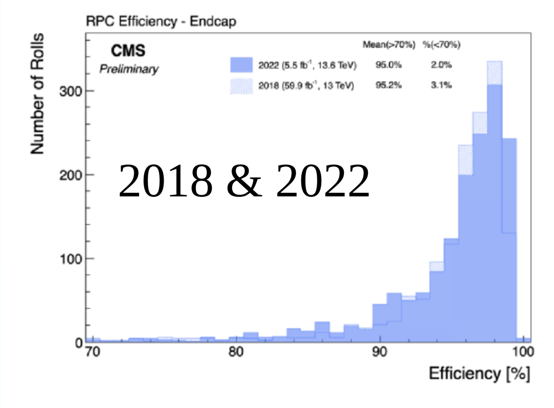
Muon System performance

G. Pugliese

LISHEP 2023

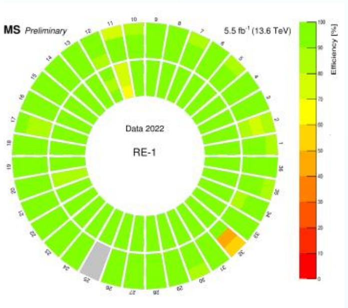
- Muon system successfully commissioned with cosmic muons, LHC Pilot Runs, and calibrations runs (timing, noise, HV, etc.)

- Online and offline analyses on RUN3 data show **detector performance** (efficiency, spatial resolution, etc.) in agreement with RUN2



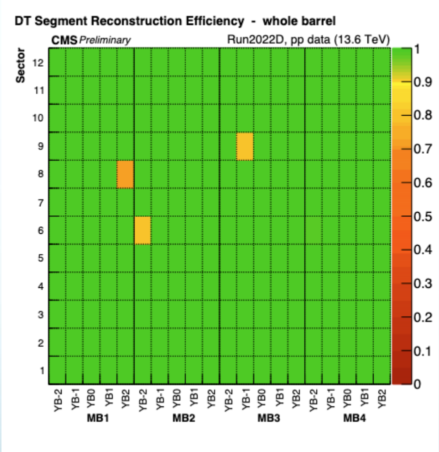
2018 & 2022

2022 collisions



RPC endcap efficiency

2022 collisions



DT Barrel efficiency

Phase 2 project

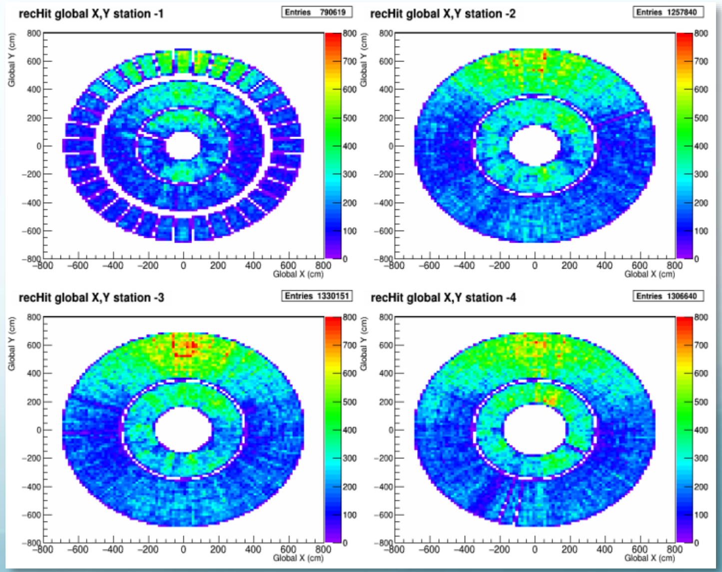
LS2

CATHODE STRIP CHAMBERS (CSC)

Read-out electronics upgraded on all the 180 CSC muon chambers allowing performance to be maintained in HL-LHC conditions.

CMS preliminary

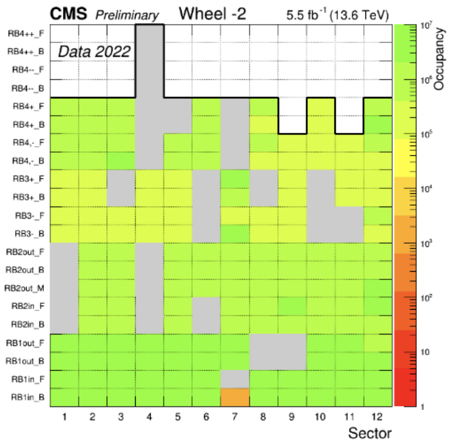
2022 collisions



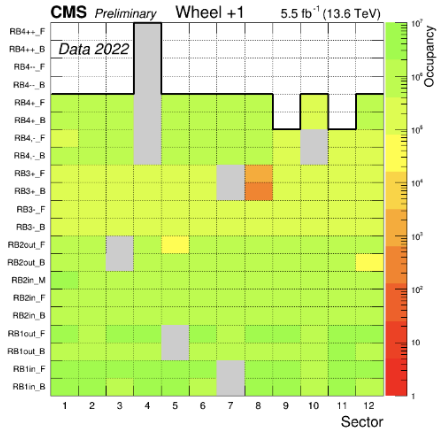
CSC occupancy map in 2022

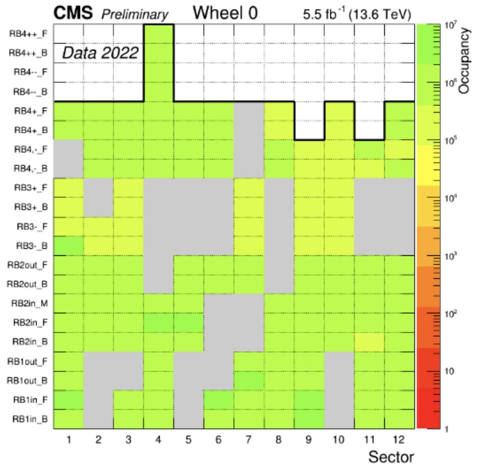
- The **new on-chamber CSC electronics boards** successfully installed and validated. Timing calibration completed by using the first collision data

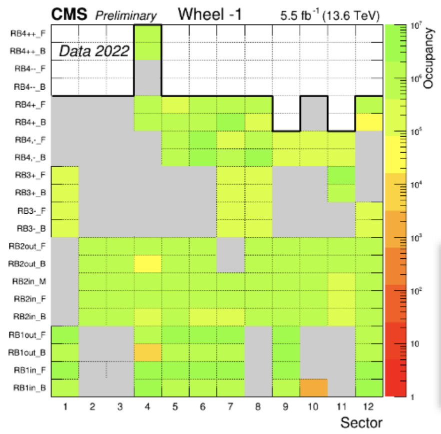
Muon System performance

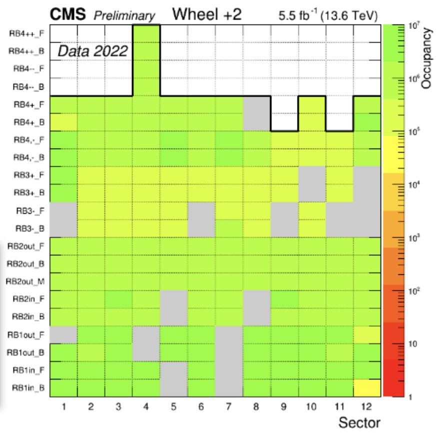


RPC Occupancy (all detected RPC hits), obtained during early 2022 proton-proton collisions, is one of the main parameters to monitor the system performance.









The **grey entries** correspond to the detector units which are switched off due to known hardware problems or to comply with CMS gas leak reduction policy.

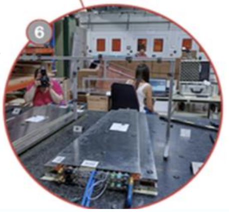
GEM station commissioning

G. Pugliese

LISHEP 2023

LS2

Phase 2 project



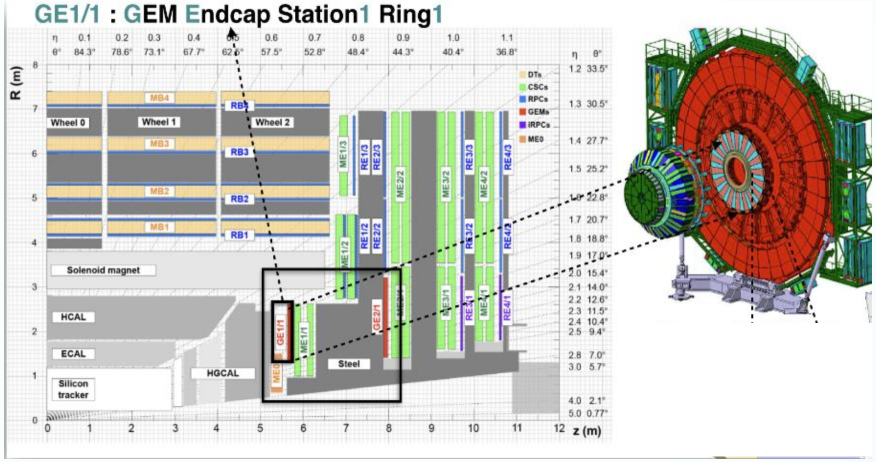
GAS ELECTRON MULTIPLIER (GEM) DETECTORS

An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.

GE1/1 station:

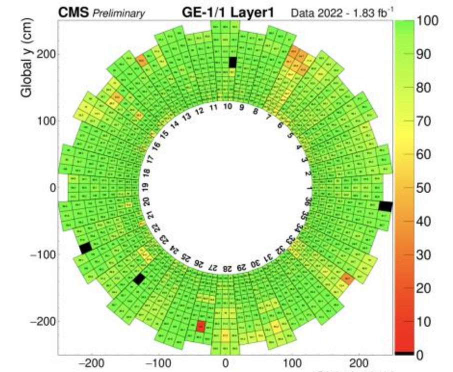
- 72 Super-Chambers (SC), consisting of two triple-GEM detectors
- 3456 VFAT3 chips, 432 GBT and VTRx optical link
- 2 number of hits
- Spatial resolution≈100 mm
- Time resolution ≈ 10 ns

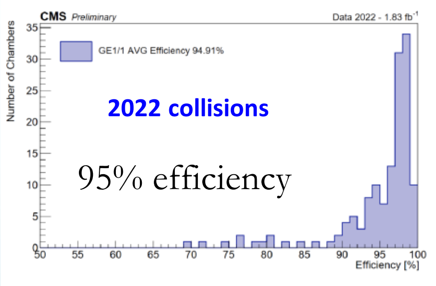
coverage $1.55 < |\eta| < 2.18$



- **HV calibration performed** with promising performance results, further optimization expected

- New back-propagation method for GEM alignment applied: significantly improved accuracy of relative alignment between GEM and CSC chambers

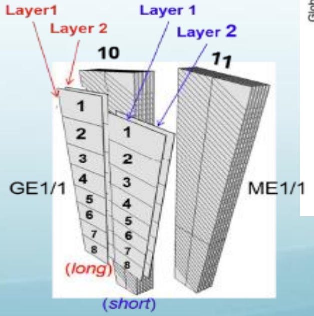


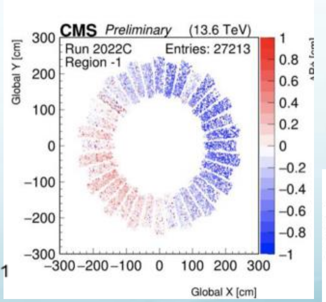


2022 collisions

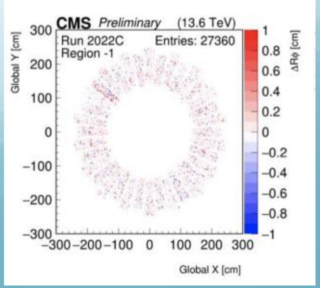
95% efficiency

GEM efficiency in 2022





alignment

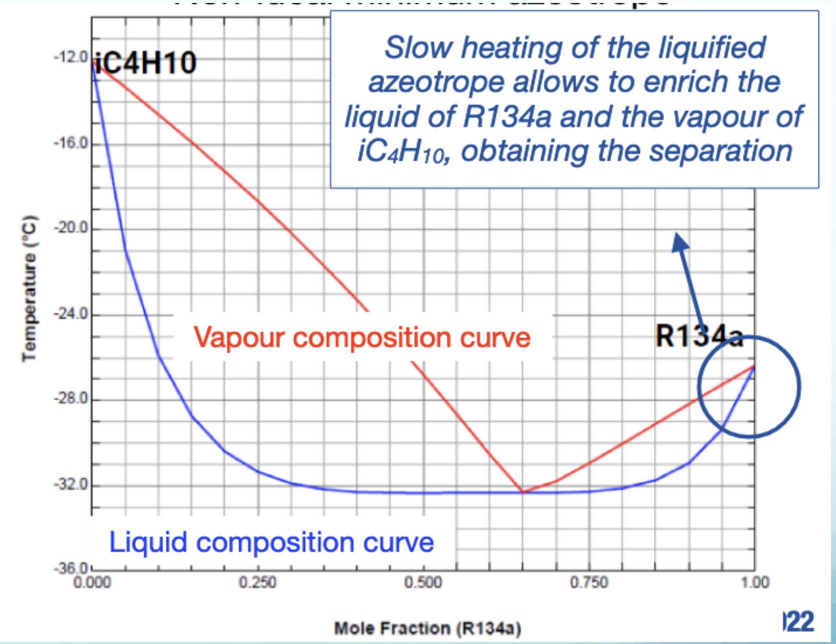


- Novel **GEM-CSC level-1 trigger** extensively verified with cosmic muons. Further tests ongoing to optimize the configuration parameters for LHC collisions. Deployed expected by the end of the year

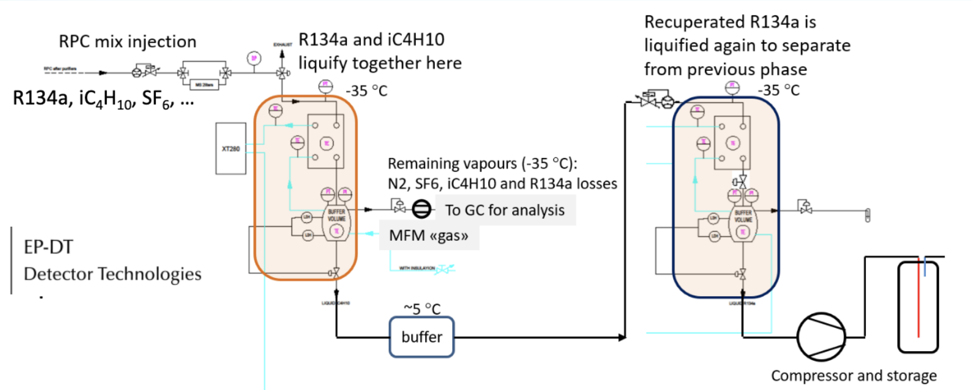
Gas Recuperation – R134a

R134a and iC4H10 form an azeotrope mixture:
- A mixture of liquids whose proportions cannot be altered or changed by simple distillation
- Intramolecular force of same-species is much higher than the reciprocal attraction separation by quasi-static increase of temperature

Courtesy of Beatrice Mandelli (Cern EP-DT)



Slow heating of the liquified azeotrope allows to enrich the liquid of R134a and the vapour of iC_4H_{10}, obtaining the separation



R134a and iC4H10 liquify together here

Remaining vapours (-35 °C): N2, SF6, iC4H10 and R134a losses

To GC for analysis

MFM «gas»

Recuperated R134a is liquified again to separate from previous phase

Longevity Setup & Procedure

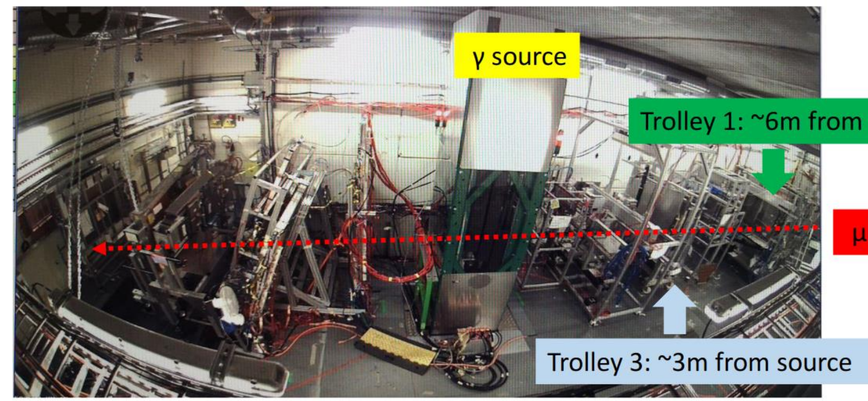
Setup @ GIF++ since July 2016:

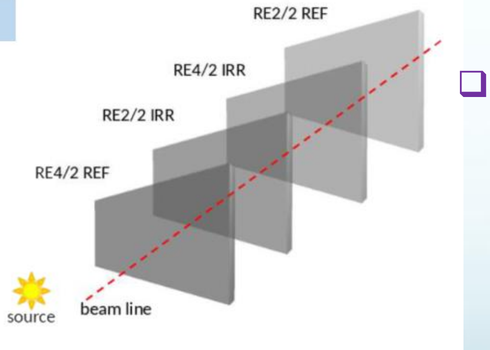
- ❑ 2 RE2 chambers (Irrad. & Ref.)
- ❑ 2 RE4 chambers (Irrad. & Ref.)

- ❑ Two chambers are continuously irradiated & two used as reference.

- ❑ Daily measurements:
  Current & rate with background

- ❑ Weekly measurements:
  Current and rate at different background conditions and without background





- ❑ 3- 4 times per year:
  Argon Resistivity measurements

- ❑ 3- 4 times per year Test beam:
  Detector performance measurements with muon beam at several background conditions

- ❑ The max. background rate expected in endcap region

- ❑ Two different types of chambers from old and new production (RE4 produced in 2012- 2014)

G. Pugliese

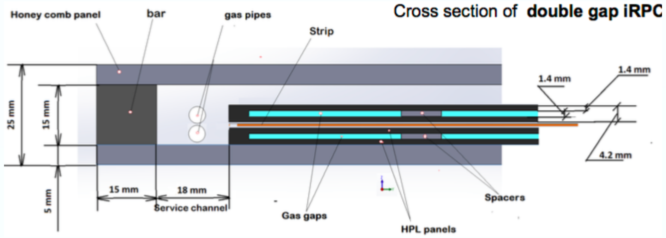
RE3.1 and RE4.1 stations

LISHEP 2023

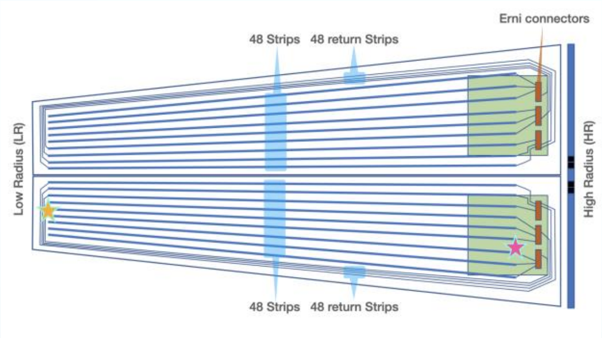
- Detector layout: Improved RPC

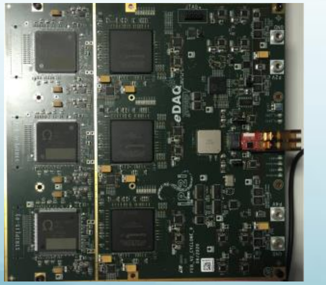
- New Strips layout and Font-End Board electronics (2D readout)

Cross section of **double gap iRPC**

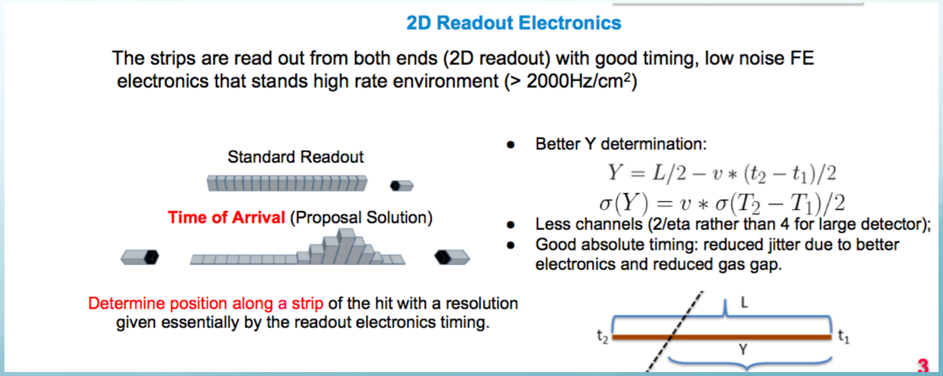


	iRPC	RPC
High Pressure Laminate thickness	1.4 mm	2 mm
Num. of Gas Gap	2	2
Gas Gap width	1.4 mm	2 mm
Resistivity (Ωcm)	0.9 - 3 x 10^{10}	1 - 6 x 10^{10}
Charge threshold	50 fC	150 fC
η segmentation	2D readout	3 η partitions





FEB (v2) is equipped with
6 ASICs PetiROC2C
3 FPGAs CYCLONE V



2D Readout Electronics

The strips are read out from both ends (2D readout) with good timing, low noise FE electronics that stands high rate environment (> 2000Hz/cm^2)

Standard Readout

Time of Arrival (Proposal Solution)

Determine position along a strip of the hit with a resolution given essentially by the readout electronics timing.

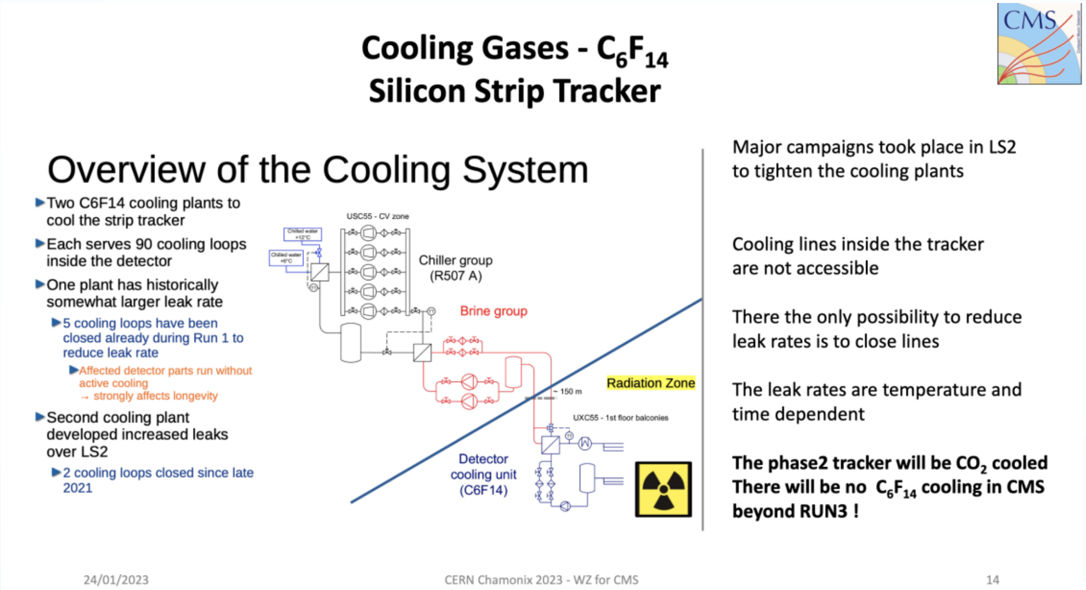
- Better Y determination:

$$Y = L/2 - v * (t_2 - t_1)/2$$
$$\sigma(Y) = v * \sigma(T_2 - T_1)/2$$

- Less channels (2/eta rather than 4 for large detector);
- Good absolute timing: reduced jitter due to better electronics and reduced gas gap.

L
t_2
t_1
Y

CMS Detector Cooling



Cooling Gases - C_6F_{14}
Silicon Strip Tracker

Overview of the Cooling System

- Two C6F14 cooling plants to cool the strip tracker
- Each serves 90 cooling loops inside the detector
- One plant has historically somewhat larger leak rate
  - 5 cooling loops have been closed already during Run 1 to reduce leak rate
    - Affected detector parts run without active cooling → strongly affects longevity
- Second cooling plant developed increased leaks over LS2
  - 2 cooling loops closed since late 2021

Major campaigns took place in LS2 to tighten the cooling plants

Cooling lines inside the tracker are not accessible

There the only possibility to reduce leak rates is to close lines

The leak rates are temperature and time dependent

The phase2 tracker will be CO_2 cooled
There will be no C_6F_{14} cooling in CMS beyond RUN3 !

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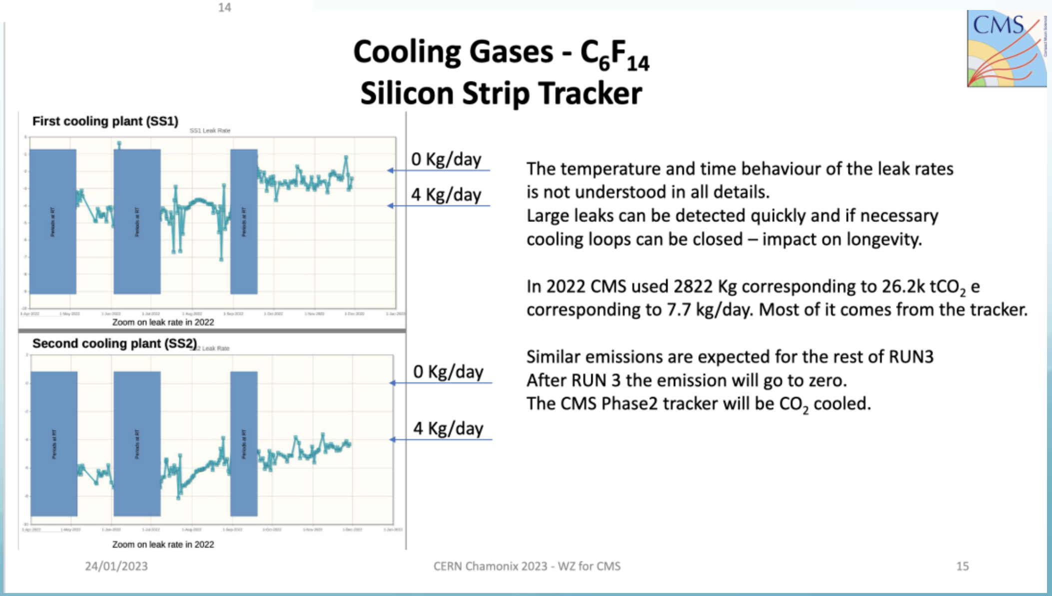

Cooling Gases - C_6F_{14}
Silicon Strip Tracker

The temperature and time behaviour of the leak rates is not understood in all details.
Large leaks can be detected quickly and if necessary cooling loops can be closed – impact on longevity.

In 2022 CMS used 2822 Kg corresponding to 26.2k tCO_2 e corresponding to 7.7 kg/day. Most of it comes from the tracker.

Similar emissions are expected for the rest of RUN3
After RUN 3 the emission will go to zero.
The CMS Phase2 tracker will be CO_2 cooled.

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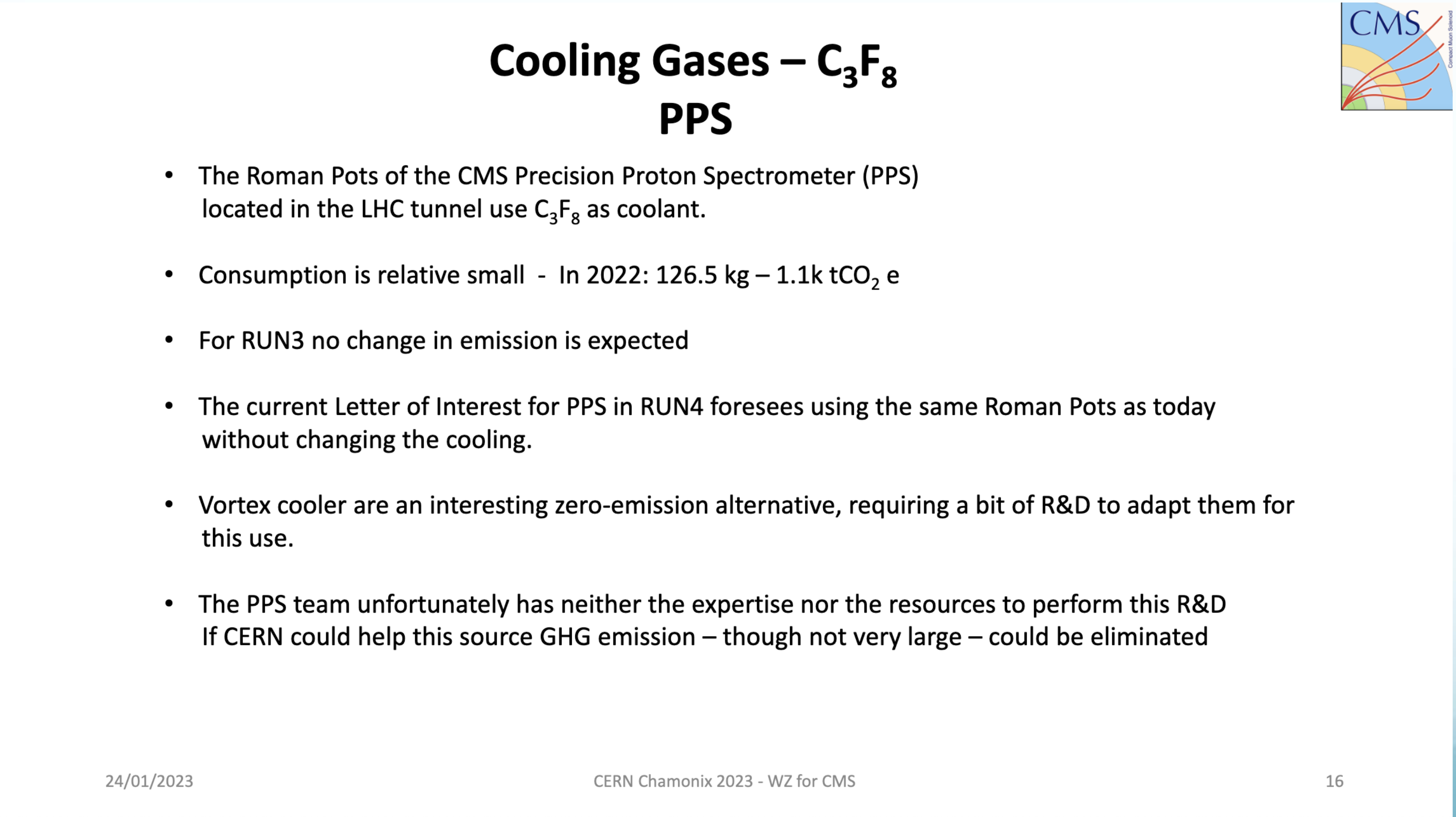
CMS Detector Cooling



Cooling Gases – C_3F_8
PPS

- The Roman Pots of the CMS Precision Proton Spectrometer (PPS) located in the LHC tunnel use C_3F_8 as coolant.
- Consumption is relative small - In 2022: 126.5 kg – 1.1k tCO_2 e
- For RUN3 no change in emission is expected
- The current Letter of Interest for PPS in RUN4 foresees using the same Roman Pots as today without changing the cooling.
- Vortex cooler are an interesting zero-emission alternative, requiring a bit of R&D to adapt them for this use.
- The PPS team unfortunately has neither the expertise nor the resources to perform this R&D
  If CERN could help this source GHG emission – though not very large – could be eliminated