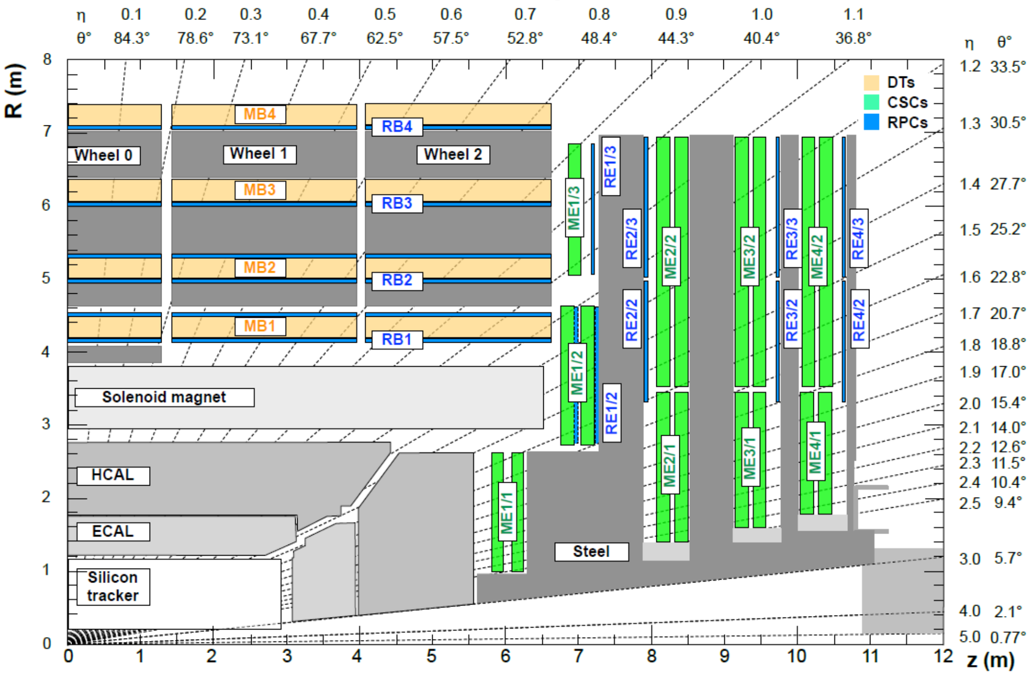
CMS Muon System

V. Perelygin,

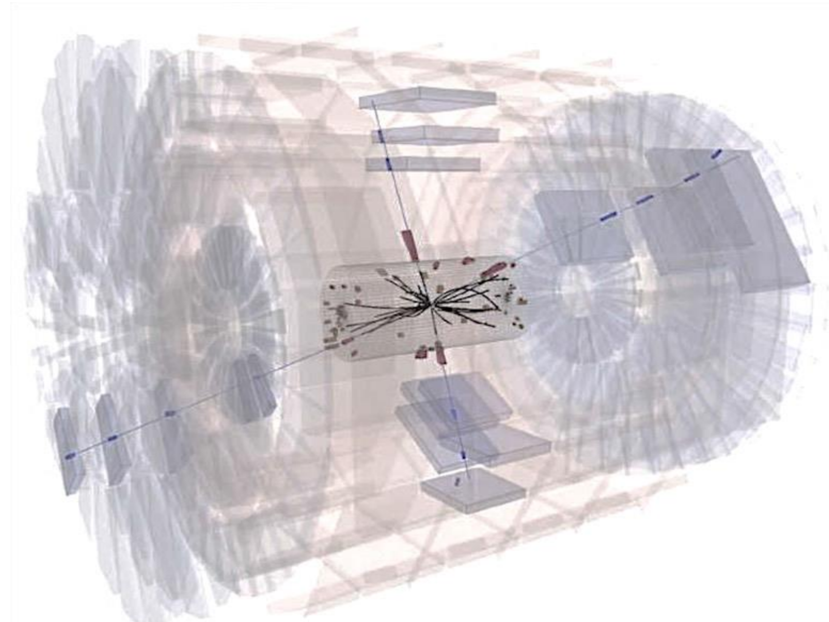
Joint Institute for Nuclear Research

CMS Muon system - types of coordinate detectors

CMS R-z quadrant



4-muon event



1. Drift Tube chambers are used in the **Barrel part** (DT, yellow, 4μ stations) and cover |η| < 1.2

2. Cathode Strip Chambers are used in the **Endcap part** (CSC, green, 4μ stations) and cover 0.9 < |η| < 2.4

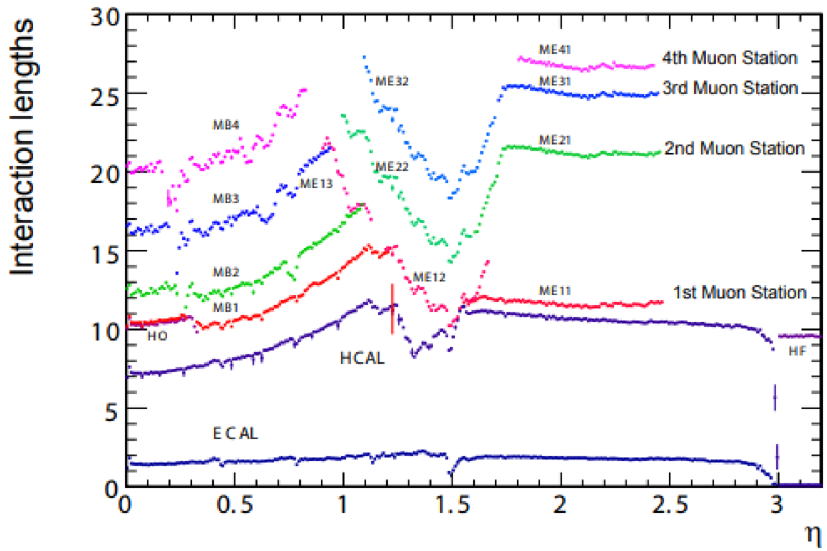
3. Both Barrel and Endcap parts are complemented by a system of Resistive Plate Chambers (RPC) covering the range of |η| < 1.8

Muon system provides:

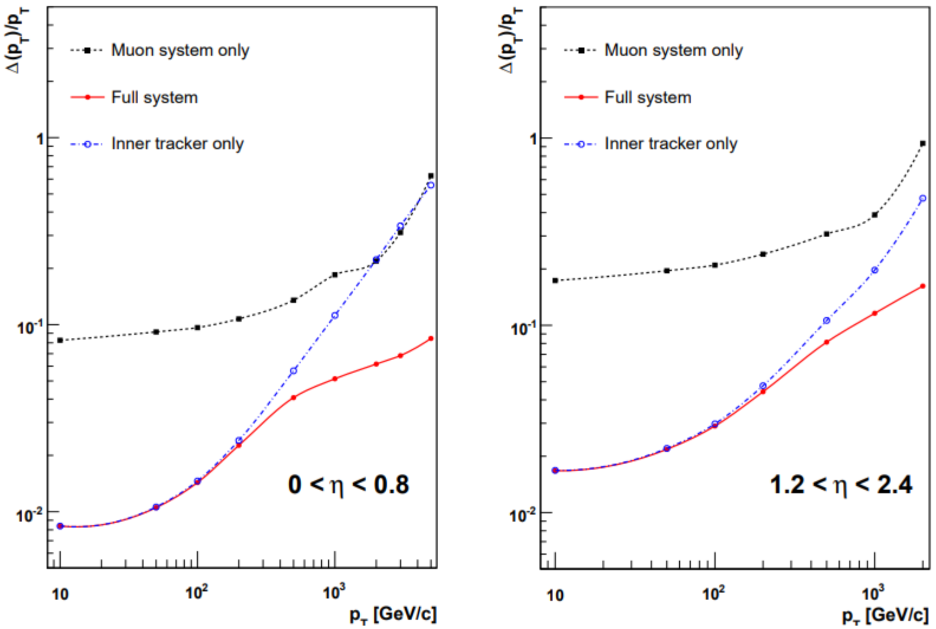
- Muon identification and momentum measurement
- Muon trigger
- Rejection of background by matching of muon tracks with the inner Tracker

Muon detection is a powerful tool to detect Higgs boson decay into ZZ or ZZ∗, which in turn decay into 4 leptons, "gold plated" for the case in which all the leptons are muons.

Muon system in CMS



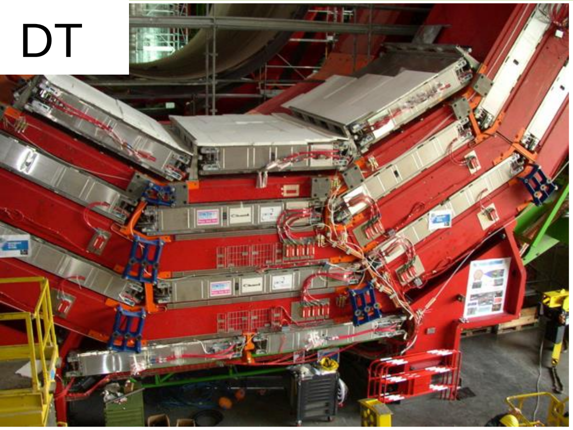
Material thickness in interaction lengths at various depths, as a function of pseudorapidity.

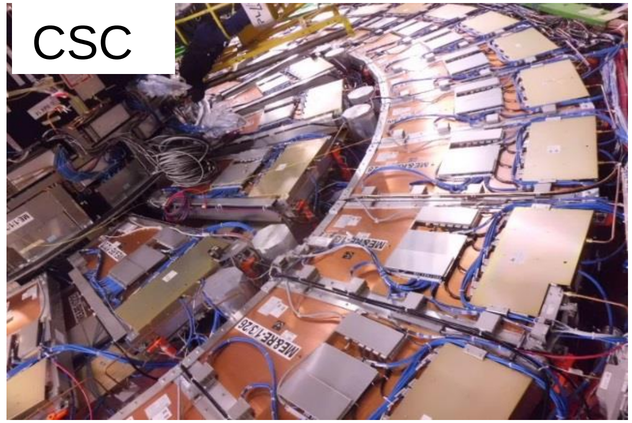


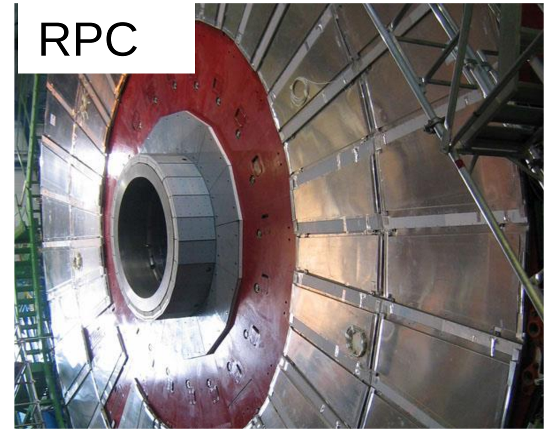
The muon transverse-momentum resolution as a function of the transverse-momentum (pT) using the muon system only, the inner tracking only, and both.

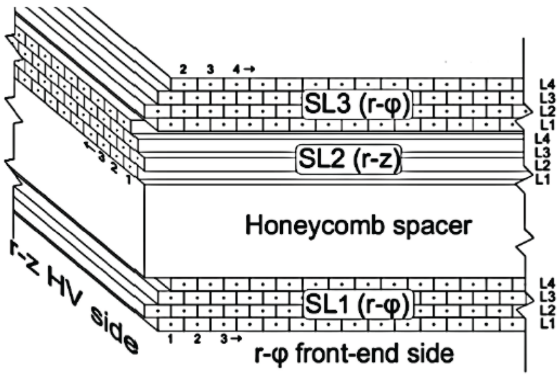
Left: $|\eta| < 0.8$, right: $1.2 < |\eta| < 2.4$.

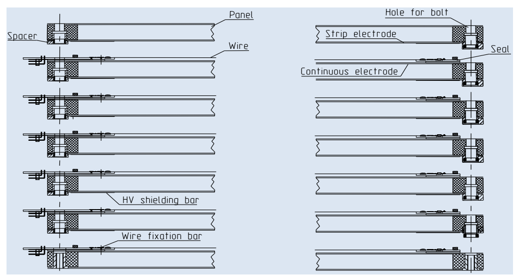
Muon chambers – 3 different technologies

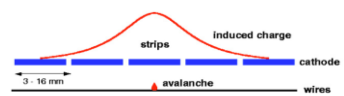


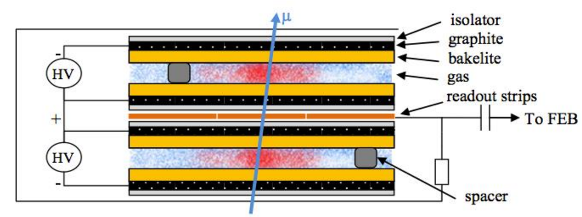












DT chamber consists of 3 super-layers, each composed of 4 layers of drift tube cells

Sensitive area: 18,500 m2
No. of channels: 172K

A CSC consists of 6 layers, and operates as standard multi-wire proportional chamber (MWPC) with cathode readout.

Sensitive area: 6,300 m2
No. of channels: 477K

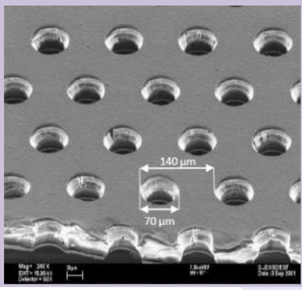
The RPC are double-gap chambers, operated in avalanche mode providing fast and independent trigger signals.

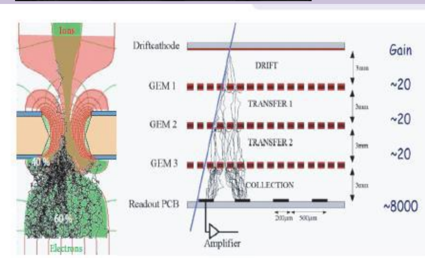
Sensitive area: 4,000 m2
No. of channels: 137K

Muon system upgrade Phase II– new detectors in the forward region

GEM – gas electron multiplier

Avalanches in strong electric field concentrated in thin holes.





Triplet GEM: **gas gain 10^4**

Operate well in **high rate**

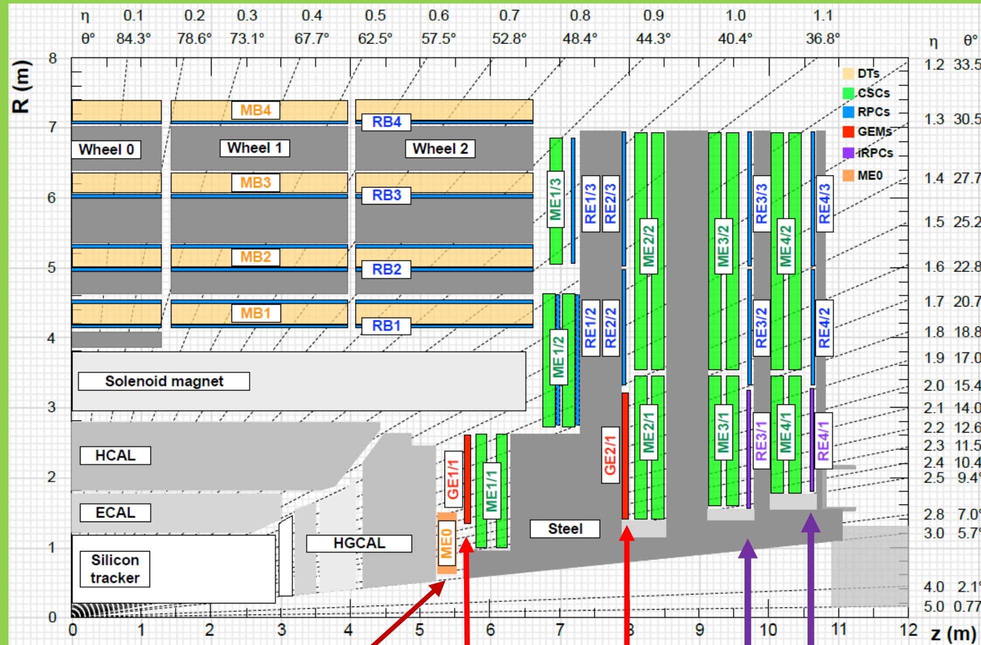
GIF++ Ageing Tests show **excellent longevity**

GE1/1, GE2/1 stations: 2 layers of triplet-GEM units

ME0: 6 layers of triplet-GEM units Extension to cover the far forward region 2.0<|η|<2.8:

Overall area (triplet-GEM): **220 m2**

Number of channels: **1.5M**



iRPC=Improved RPC

Enhancement of the forward region 1.6<|η|<|2.4

Improvements:

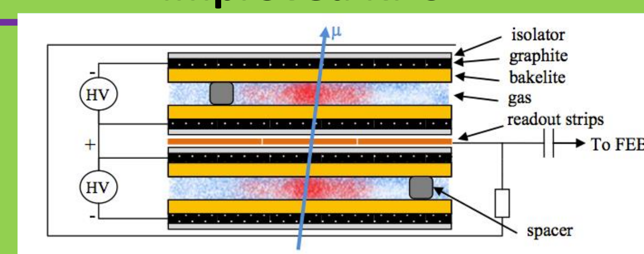
- higher rate capability (Reduced electrode resistivity – 10^{10} Ωcm, smaller gas gain)
- Reduced electrode gas gap thickness
- Low noise FE electronics for high efficiency and low ageing
- two-ended strip readout

RE3/1 and RE4/1 stations: double-layer RPC units

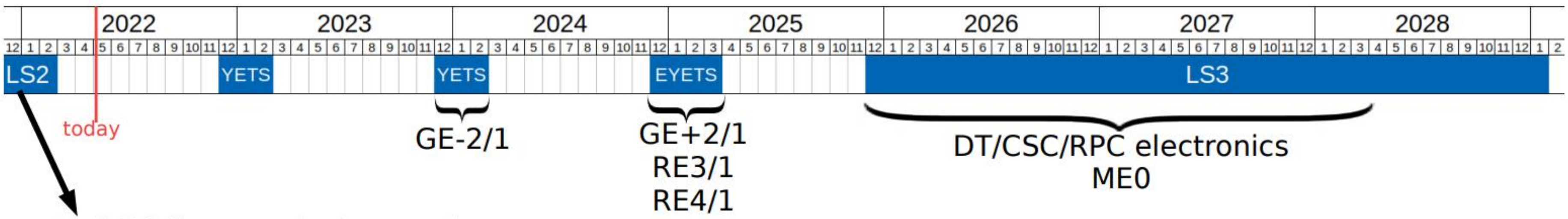
Overall area: **90 m2**

Number of channels: **14K**

Improved RPC

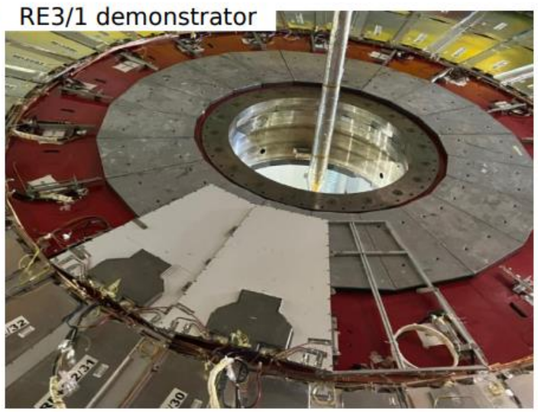


Phase II Upgrade Schedule



- CSC frontend electronics
- GE1/1
- GE2/1 demonstrator
- RE3/1 and RE4/1 demonstrators


GE2/1 demonstrator


RE3/1 demonstrator

Muon Endcap mostly inaccessible in LS3
→ upgrades during LS2, YETS, and LS3

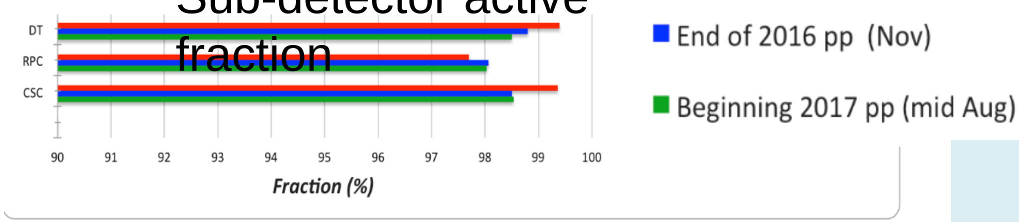
LS2: CSC frontend electronics, GE1/1

YETS: GE2/1, RE3/1, RE4/1

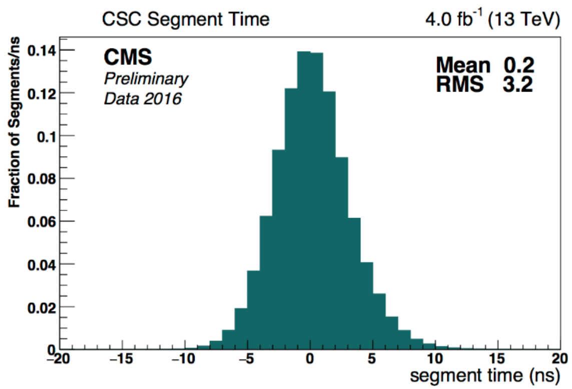
LS3: DT electronics, CSC ODMB5/7 + backend, RPC off-chamber electronics (Link System), ME0

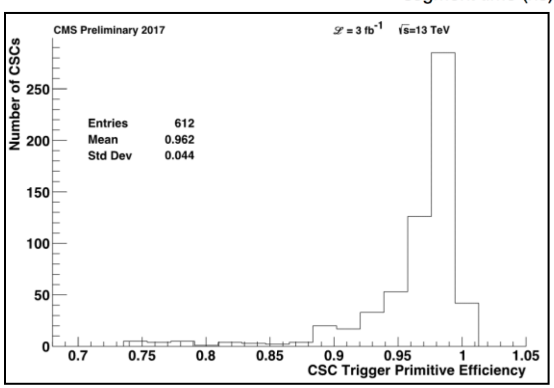
CMS muon system in Run2 (2016-18)

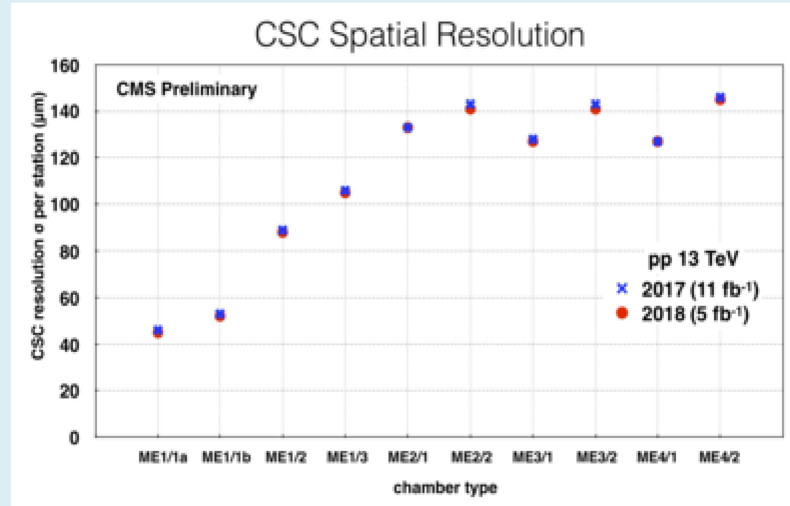
Sub-detector active fraction



Muon system:
>98% availability







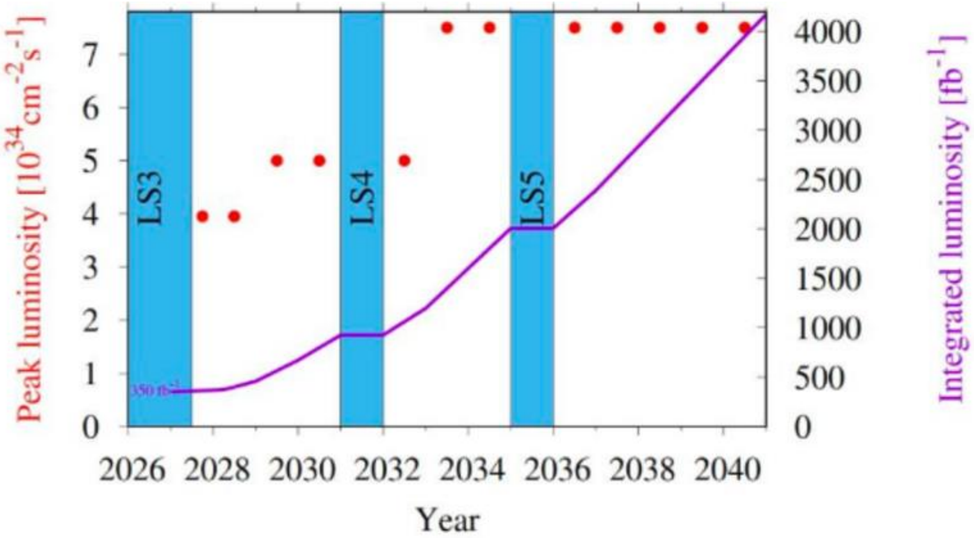
CSC Spatial Resolution (μm)

Station	2017	2018
ME1/1a	46	45
ME1/1b	53	52
ME1/2	89	88
ME1/3	106	105
ME2/1	133	133
ME3/1	128	127
ME4/1	127	127
ME2/2	143	141
ME3/2	143	141
ME4/2	146	145

Muon system:
- Fractions of the operating channels >98%
- High Spatial resolution 45÷300μm (CSC and DT)
- Timing resolution ~ 3 ns or better per chamber for all 3 systems
- Local track efficiency ~ 97%

LHC –> HL-LHC

ultimate HL-LHC performance scenario (max. Lumi)



The increase in luminosity will produce a particle background in the gas-based muon detectors that is an **order of magnitude** higher than under present conditions at the LHC.

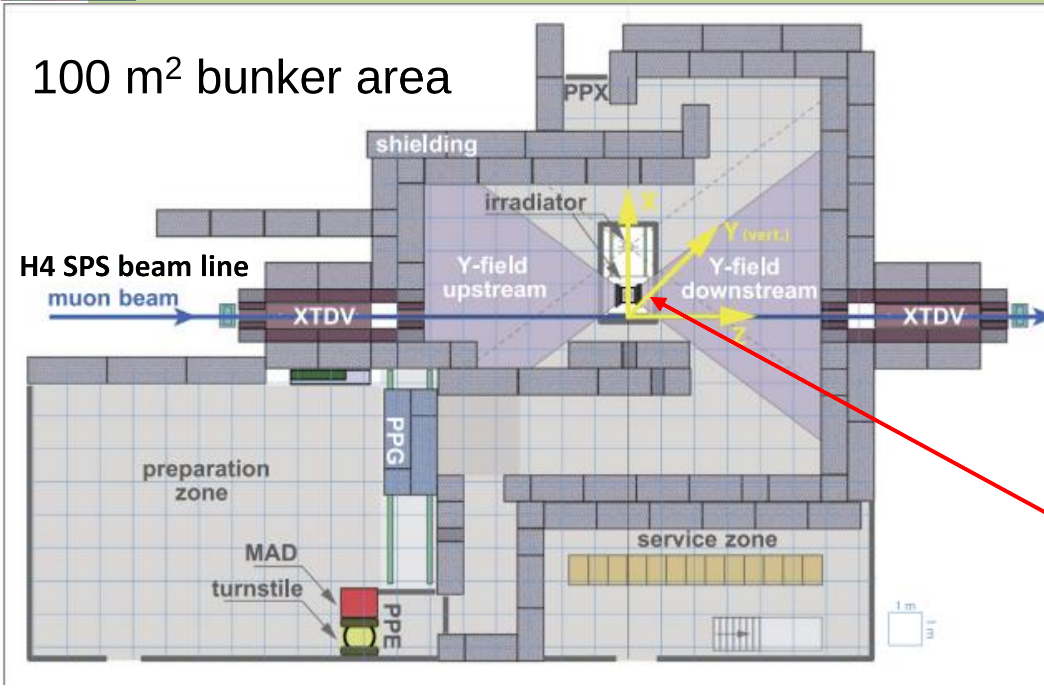
►detector tests at HL-LHC higher rates are required.

To study:

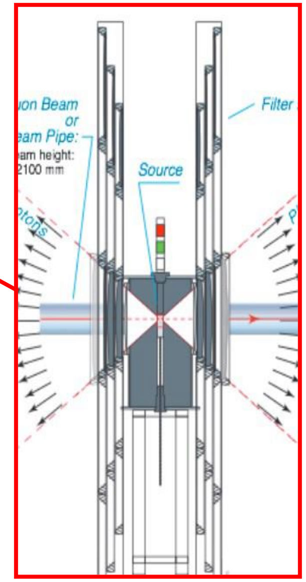
- the detector performance in the presence of HL-LHC background
- possible ageing effects of detector materials and gases.

To cope with these challenging requirements, a new Gamma Irradiation Facility (GIF++) was designed and built in 2015 at the CERN SPS North Area.

GIF++ = Gamma Irradiation Facility at CERN

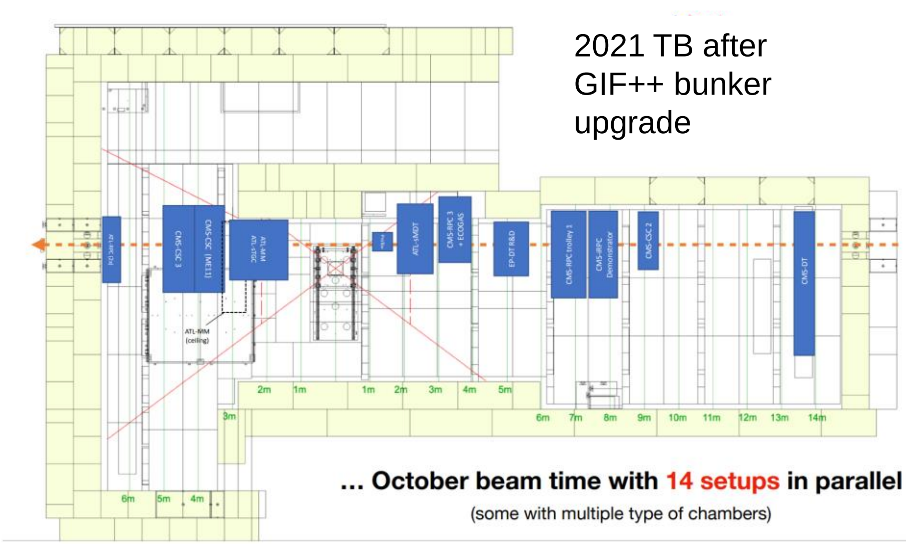


14 TBq Cs^{137} source (Eγ = 662 keV)



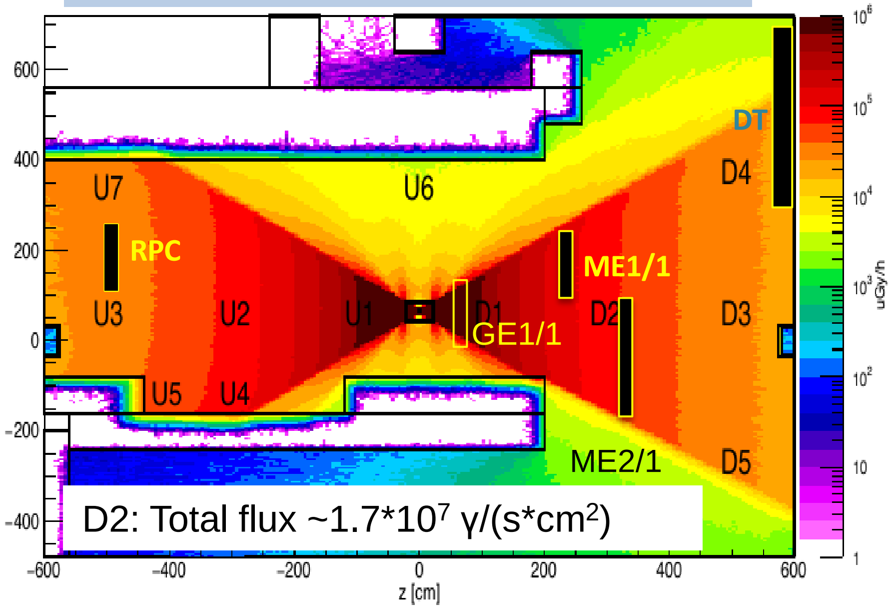
Att.Fact. 1÷46.4k

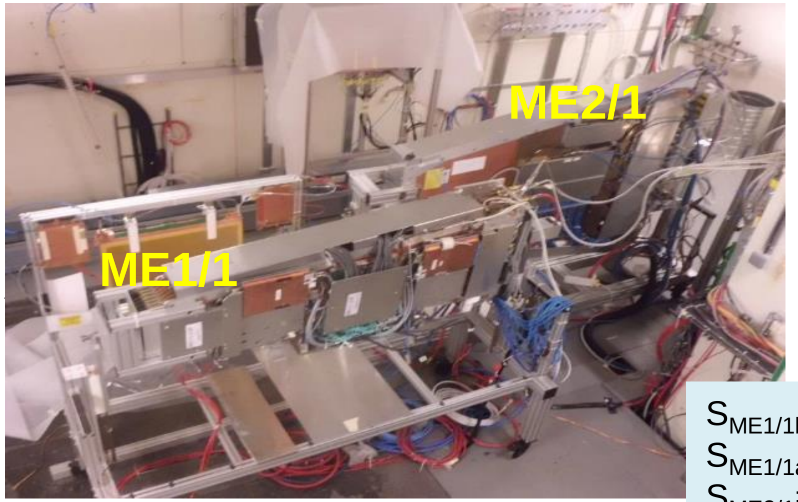
Plane :	A	B	C
Pos. 1	1	1	1
Pos. 2	10	1.47	2.15
Pos. 3	100	100	4.64



GIF++: CSCs longevity tests

GIF++ irradiation intensity map

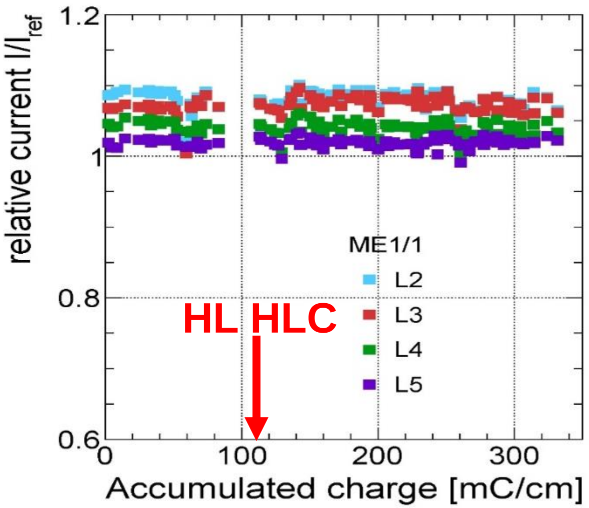




$S_{ME1/1b}$= 0.41m^2
$S_{ME1/1a}$= 0.11m^2
$S_{ME2/1}$= 1.7m^2

CSC at GIF++

ME1/1 and ME2/1 are full scale 6-layer CSCs of different types chosen for ageing tests as most background affected ones.

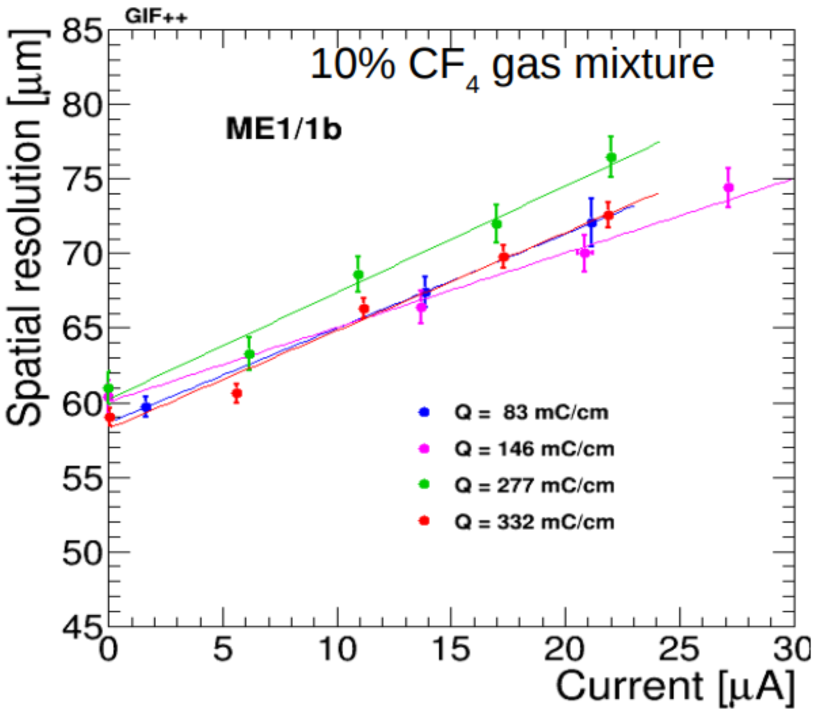


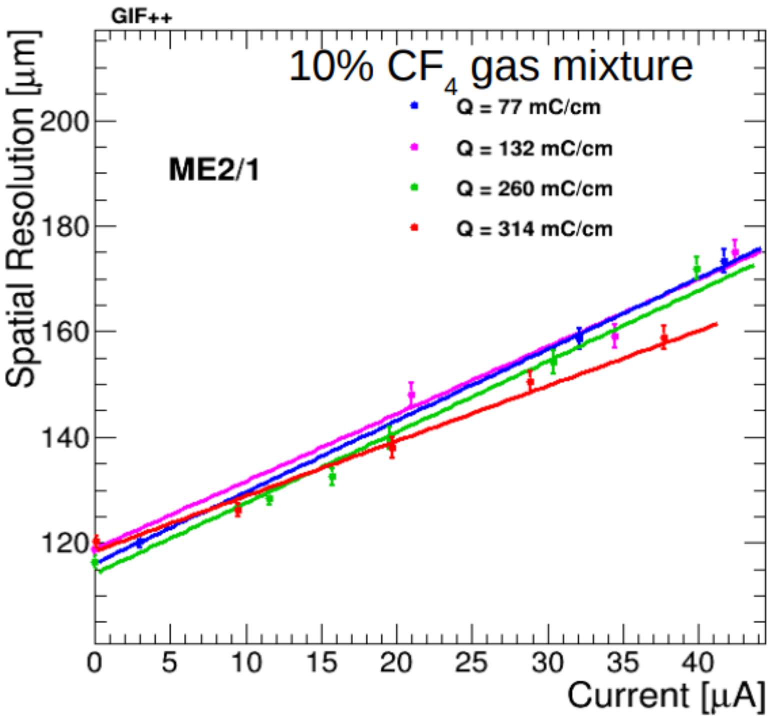
Irradiation: The four inner layers, L2-L5, have HV on while L1 and L6 are reference ones (HV=0)
I per layer (section) ~300μA

Nominal gas mixture Ar+CO2+ CF4 (40/50/10)
Closed loop gas supply,
10% fresh gas injection

Equivalent to 3×HL-LHC of L=3×3000 fb-1 the integrated charge to be:
ME1/1 - 0.33 C/cm
ME2/1(sect.1) - 0.24 C/cm

CSCs spatial resolution as a function of mean Layer current for increasing values of accumulated charge,

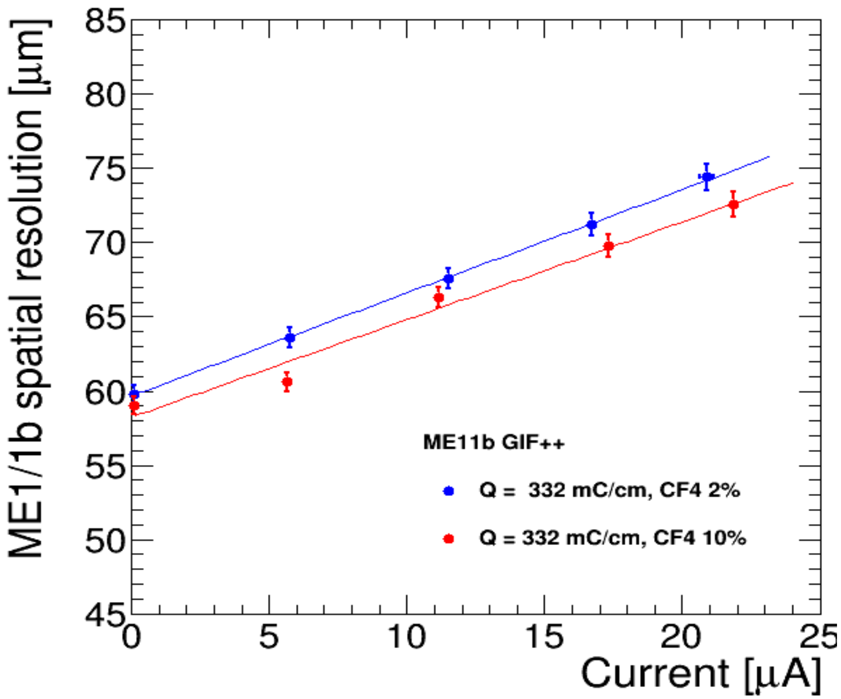


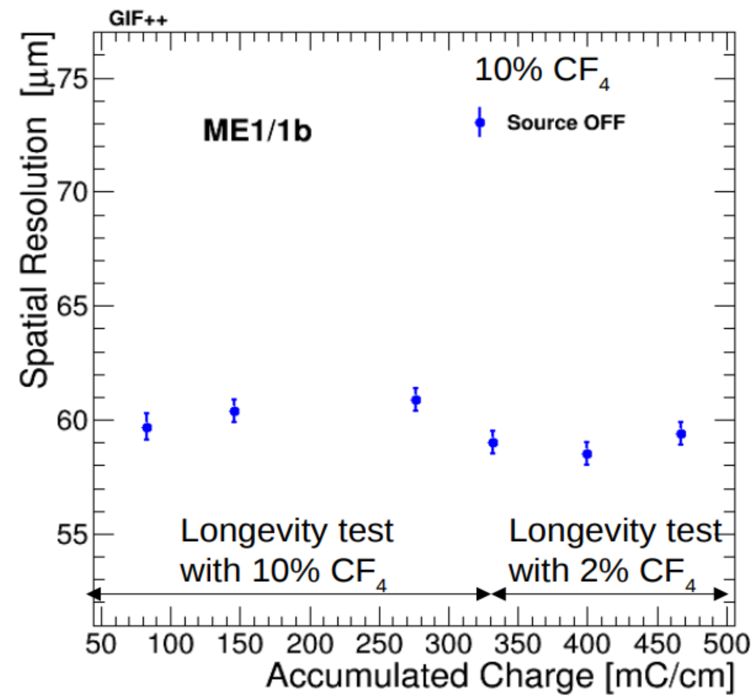


CSCs detect SPS muons. The Layer current is proportional to the background intensity, which can be adjusted using a set of filters.
The results are corrected for atmospheric pressure variation.
The measurements done for different values of the accumulated charge.

The HL-LHC background conditions for L=5 x 10^{34} Hz/cm2 correspond to average currents ~10 uA for ME1/1 and ~18 uA for ME2/1. **With that the spatial resolution degradation of 10% and 16% correspondingly which is not crucial for the muon system.**
No resolution degradation is observed even with accumulated charge exceeding 300 mC/cm

ME1/1 Spatial Resolution with 10% and 2% CF4 gas mixture vs Current and accumulated charge





In 2018 the Longevity test with ME1/1 continued with 2% CF4 gas mixture:
Ar+CO2+ CF4 (40/58/2).
Left plot – Spatial resolution vs layer current – 2 mixtures show the same results.
Right plot - No spatial resolution degradation was observed even with accumulated charge up to 500 mC/cm for ME1/1.

Global Warming Potential coefficient and Greenhouse F-gases limitation

New regulations

In 2014, the European Commission adopted a new regulation limiting the total amount of important ***fluorinated greenhouse gases (F-gases)*** *that can be sold in the EU from 2015 onward and phasing them down in steps to* ***one-fifth of 2014 sales in 2030***

CSC and RPC: F-gas footprints:

- CSCs use **10% CF_4** (GWP=6500): 274 m3/h of CO2 equivalent
- RPCs use **95.2% $C_2H_2F_4$** (GWP=2300): 228 m3/h

and **0.3% SF_6** (GWP=23900): 1440 m3/h of CO2 equivalent

– F-gases used by CSCs and RPCs prevent ageing and ensure reliable operation

Solutions under study:

– **new eco-friendlier gas options** → RPCs explore operation with new gases **CF_3I, $C_3H_2F_4$** (GWP ≈ 0.4)

– **F-gas consumption reduction** → CSCs explore operation with **5% CF_4 or to replace it by HFO-1234ze = $C_3H_2F_4$**

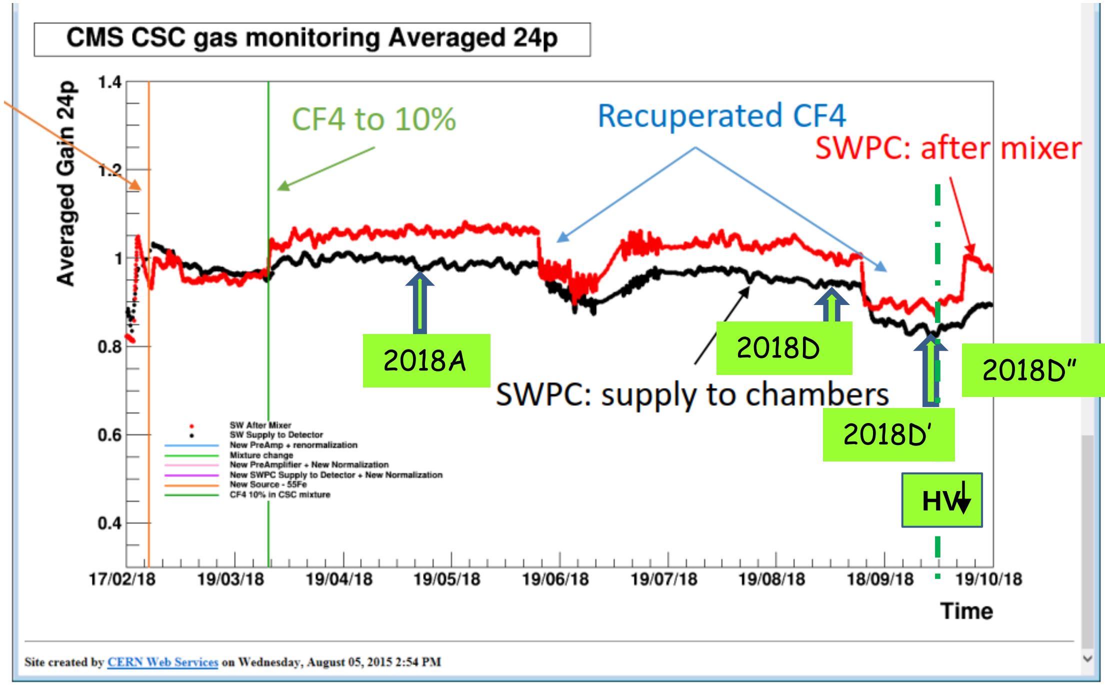
– **Other measures being explored:**

- improved recuperation plant

CSC spatial resolution in Run2 (2018)

Status of CSC gas system in 2018

There were 2 periods of CSC operation with recuperated CF4: [Jun.13÷Jul.05] and [Sept.12÷Oct.10] both show 10% gain drop the in SWPC.

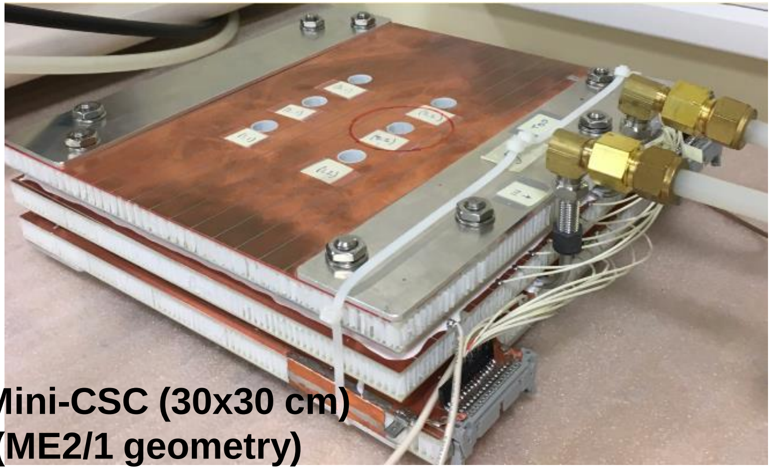


CSC Spatial resolution for datasets.
(V.Palichik Sept.19_2019)

Station/ ring	p-p collision dataset					
	2016H	2017C,F	2018A	2018D	2018D'	2018D''
ME1/1a	46	46	45	46	48	51
ME1/1b	52	53	52	53	55	60
ME1/2	87	89	88	89	93	100
ME1/3	105	106	105	108	115	125
ME2/1	129	133	133	138	146	140
ME2/2	139	143	141	144	156	171
ME3/1	123	128	127	132	140	134
ME3/2	139	143	141	144	157	171
ME4/1	123	127	127	129	139	133
ME4/2	143	146	145	150	159	173

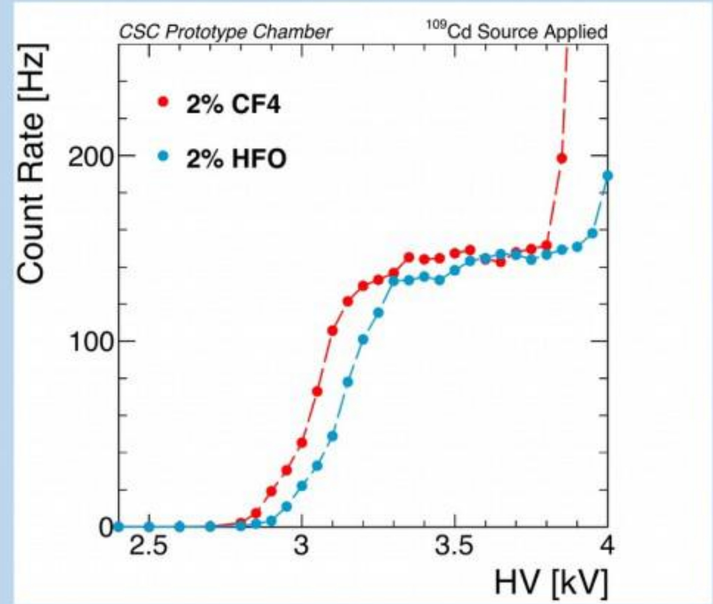
The operation with the gas mixture with recuperated CF_4 shows the spatial resolution deterioration of **2-13 μm** depending on the station/ring (see columns **2018D** and **2018D'**)

Eco-friendly gases investigation at B.904 with mini-CSC



Mini-CSC (30x30 cm)
(ME2/1 geometry)

HFO-1234ze (C3H2F4,GWP < 1 for 100 year)



Magnitude and length of efficiency plateau for 2% HFO mixture is the same as for 2% CF_4

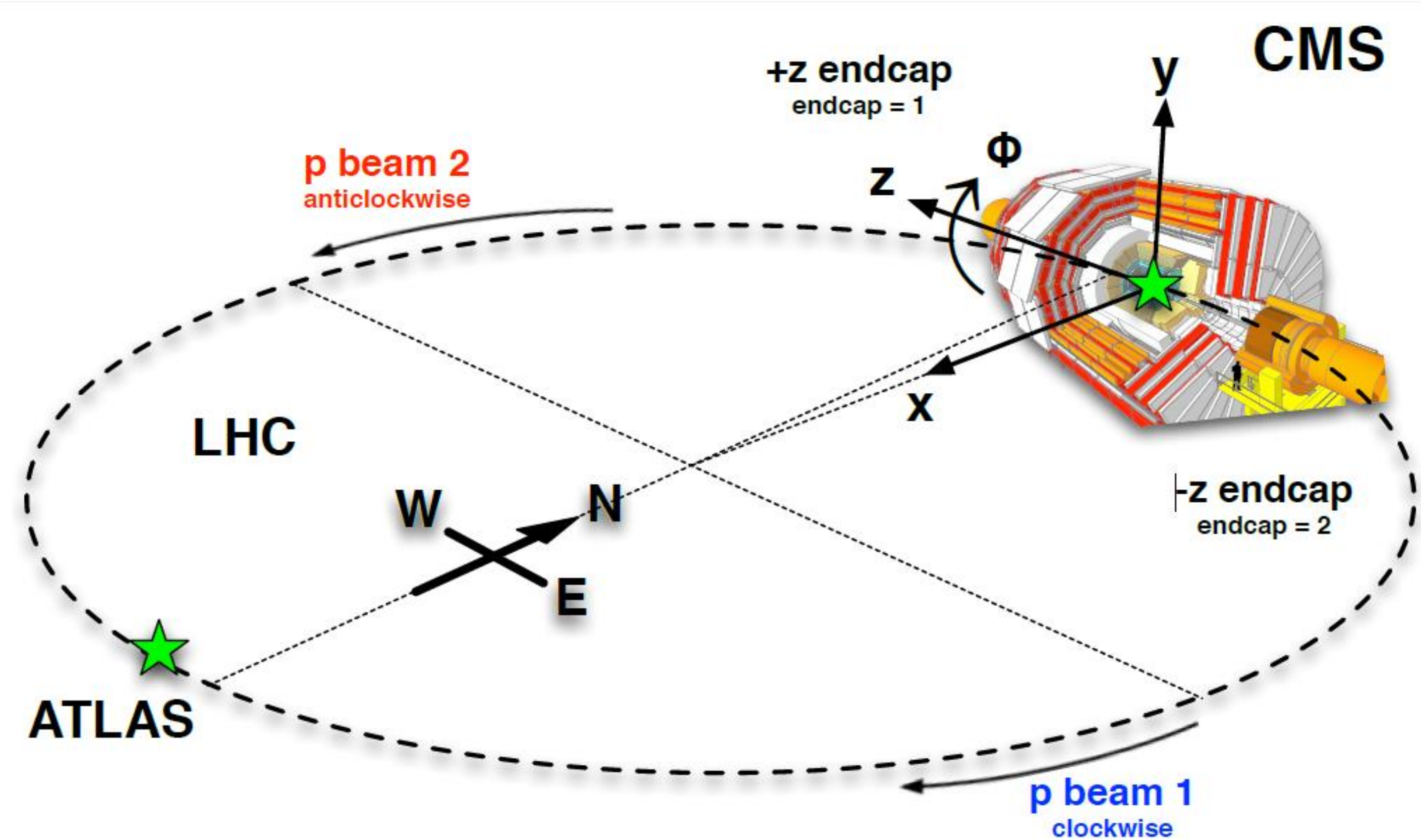
HFO now is the most promising gas to replace CF4.
Non-toxic TrifluoroIodoMethane, CF_3I, having GWP=0.4 was another candidate tested at PNPI but found too electronegative
The work continues.

Conclusions

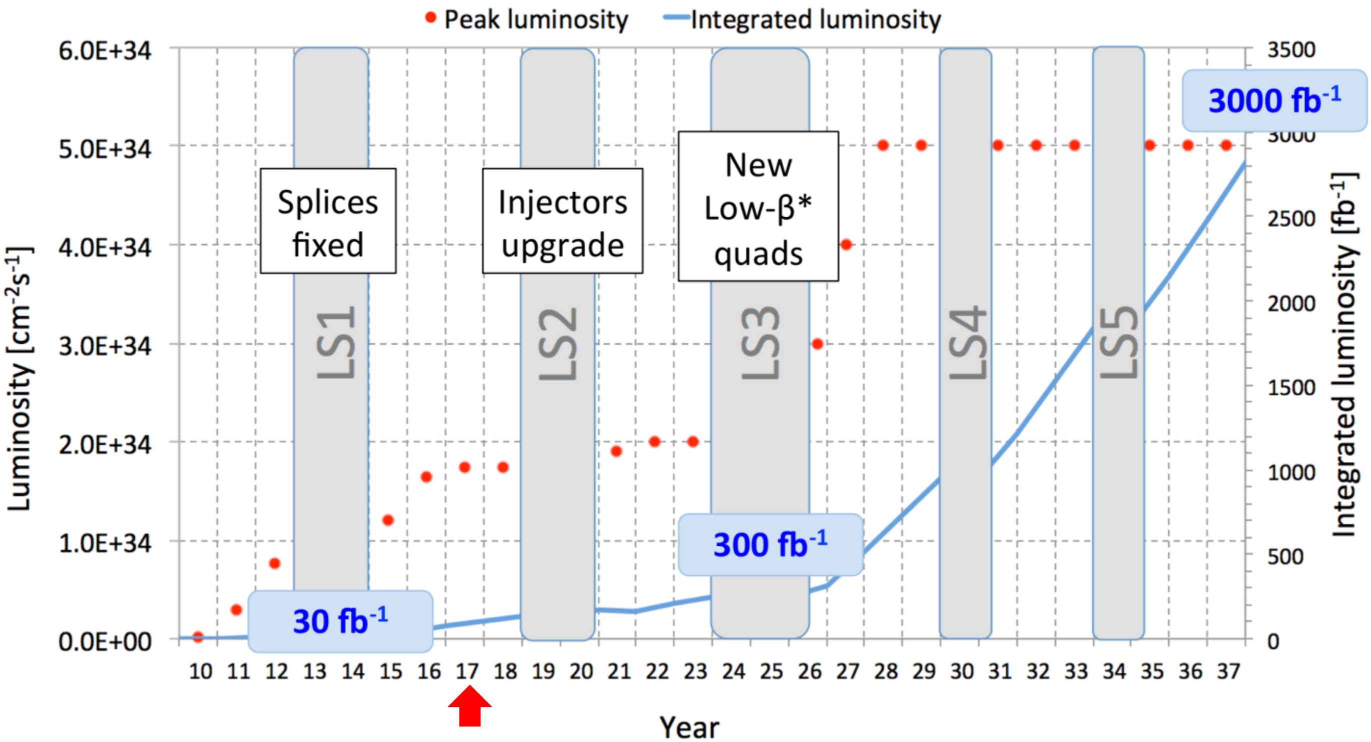
- CSC muon system operates well and ready for data taking in Run3.
- The Phase II upgrade in Muon system is going on and new are installed (GE1/1) or to be installed in YETS 2023-2025 (GE2/1, RE3/1, RE4/1) and ME0 in LS3. There will be 5 types of Muon detectors of 5 different technologies in CMS. Also, the new on-chamber and frontend electronics on all the systems to be installed.
- Ageing tests of muon detectors at GIF++ continue to study the longevity of the muon detectors/electronics for HL-LHC running.
- CSCs and RPCs searching for alternative gas components to find solution to minimize F- gases release.

Backup

CMS – one of two general purpose detectors at LHC



LHC - HL LHC schedule



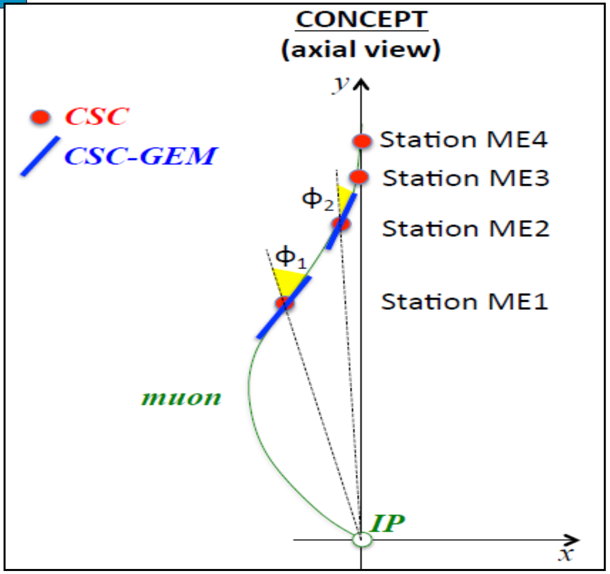
	LHC	HL LHC
Instant. luminosity ($cm^{-2}s^{-1}$)	10^{34}	5×10^{34}
pileup collisions	30	150
integrated luminosity (fb^{-1})	300	3000
CMS L1 trigger rate (KHz)	100	750
CMS L1 trigger latency (μs)	3.6	12.5

New HL LHC parameters require detector upgrade in LS2 and LS3

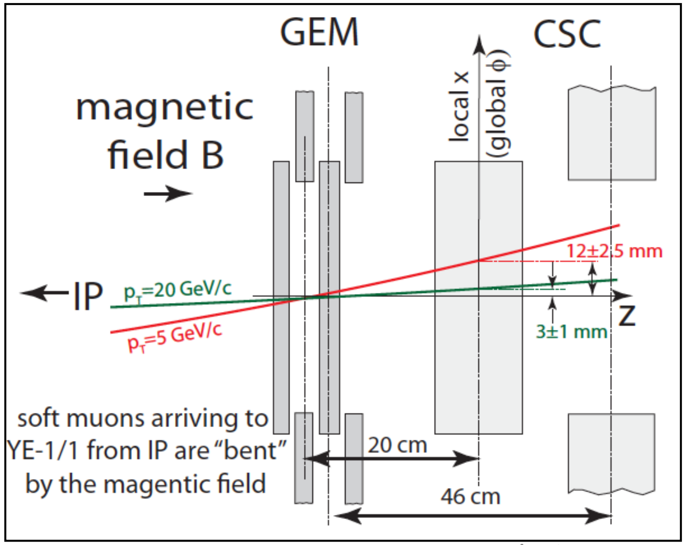
CMS Muon System Upgrade Concept

– Keep the existing muon detectors and DEMONSTRATE the longevity of detectors/electronics for HL-LHC running
– REPLACE some electronics expected to fail HL-LHC requirements (rad. hardness and rate capability)
  - CSC – upgrade of on-chamber and VME cathode and anode r/o electronics for inner ($1.6 < |\eta| < 2.4$) rings to operate with increased data rates at high luminosity and higher L1 trigger latency
  - RPC - new trigger electronics (1.5 ns sampling time, instead of 25 ns)
  - DT – reconfiguration of on-detector electronics readout (mini-crates) architecture
– Add RPC and GEM detectors in the very forward region to improve redundancy on muon ID and L1 triggering

L1 Trigger: p_T measurement and rate



Schematic view of μ trajectory from axial point of view

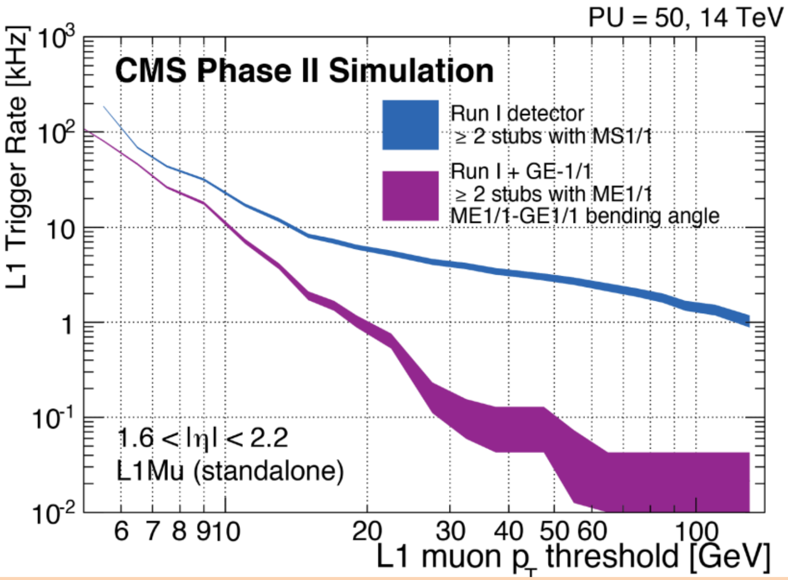


CSCs alone provide short segments with low-precision info on segment direction

GEM-CSC tandems in ME1 and ME2 stations give accurate measurement of muon "local" direction sensitive to muon p_T

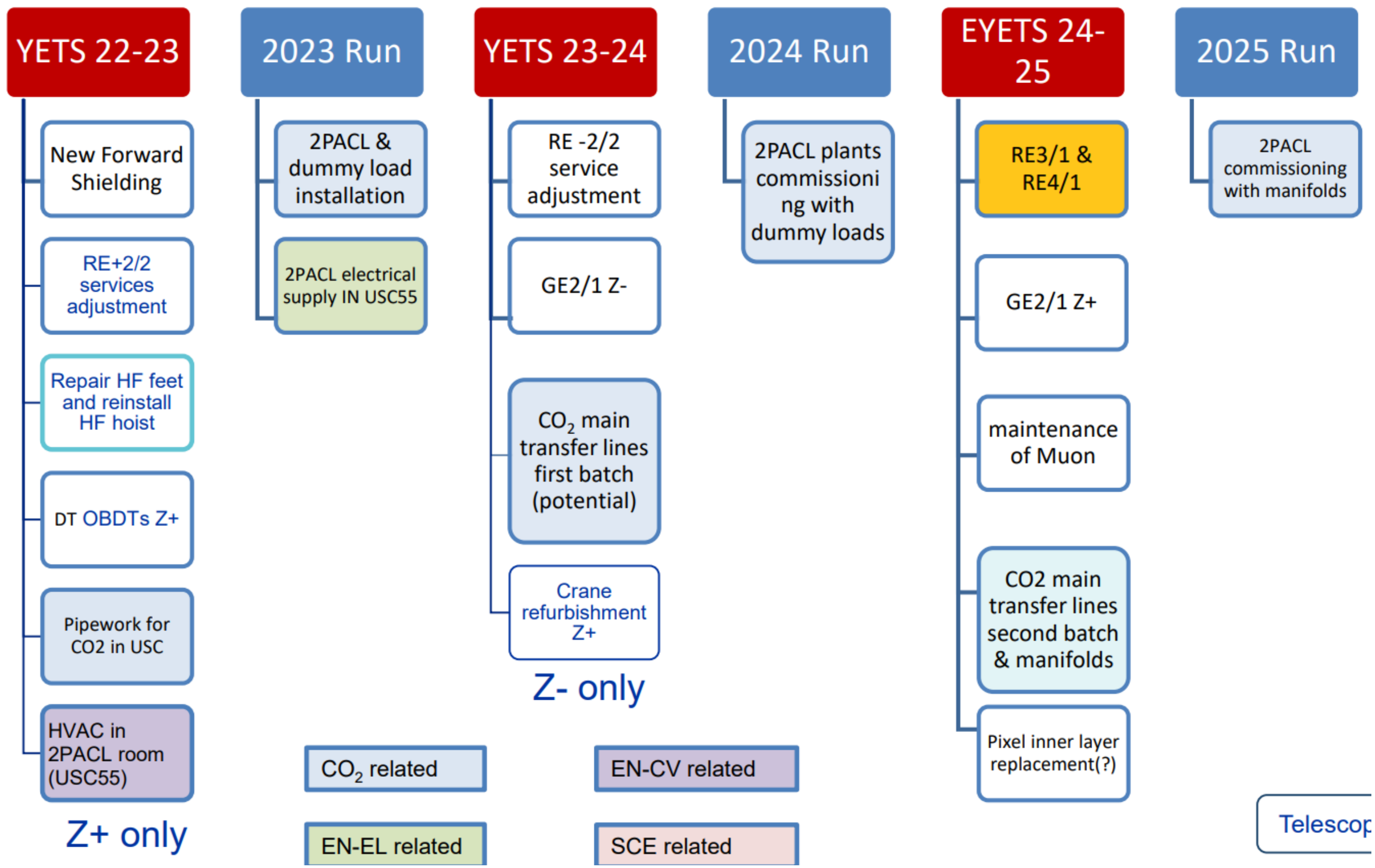
GE1/1 will allow to keep <5 kHz trigger rate without increasing threshold on muon's momentum

10/



GE1/1-ME1/1 super-stab in YE1 provides direction measurement and allows efficient rejection of the muon backgrounds improving p_T resolution → large L1 trigger rate reduction

Overview up to LS3

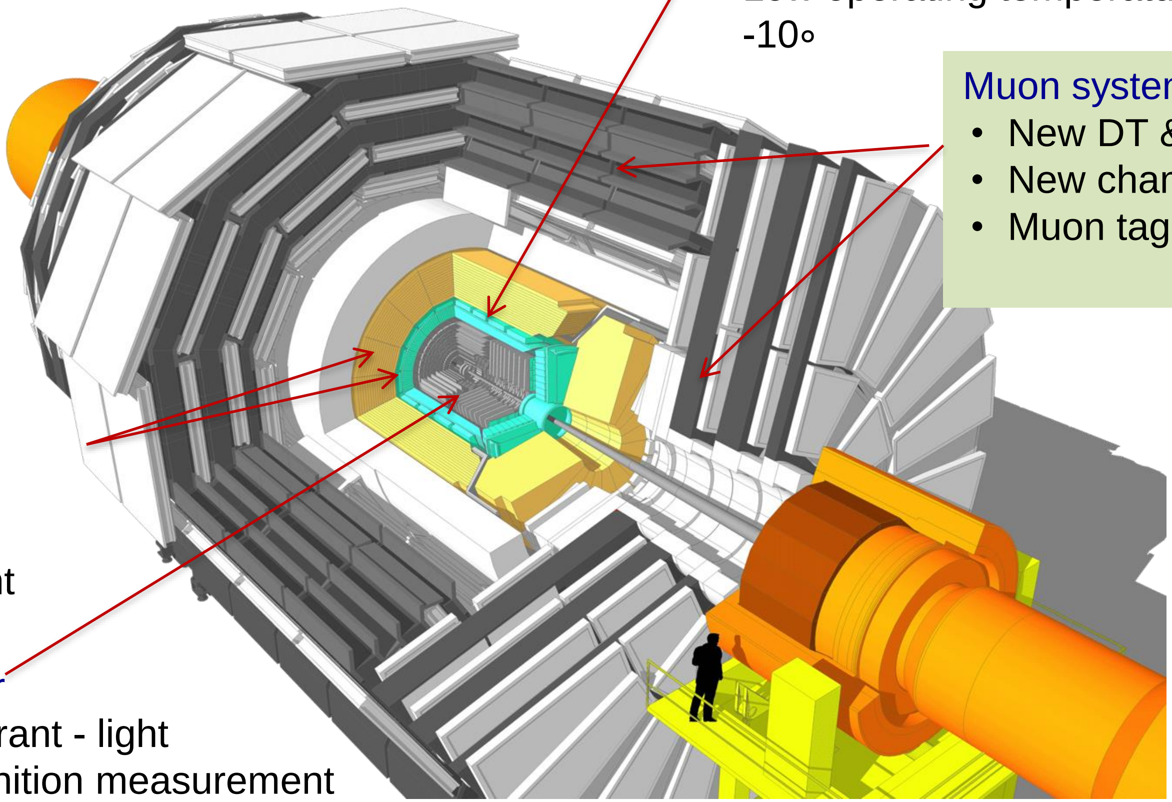


CMS Phase-II upgrades

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature $\simeq$ -10∘

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

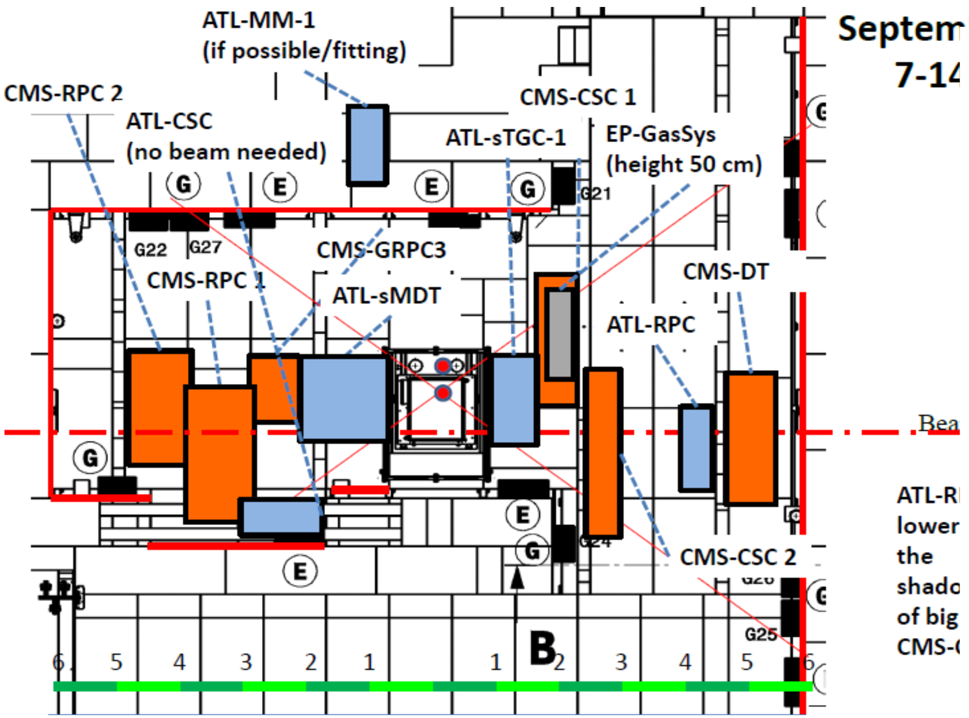


New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \simeq 3.8$

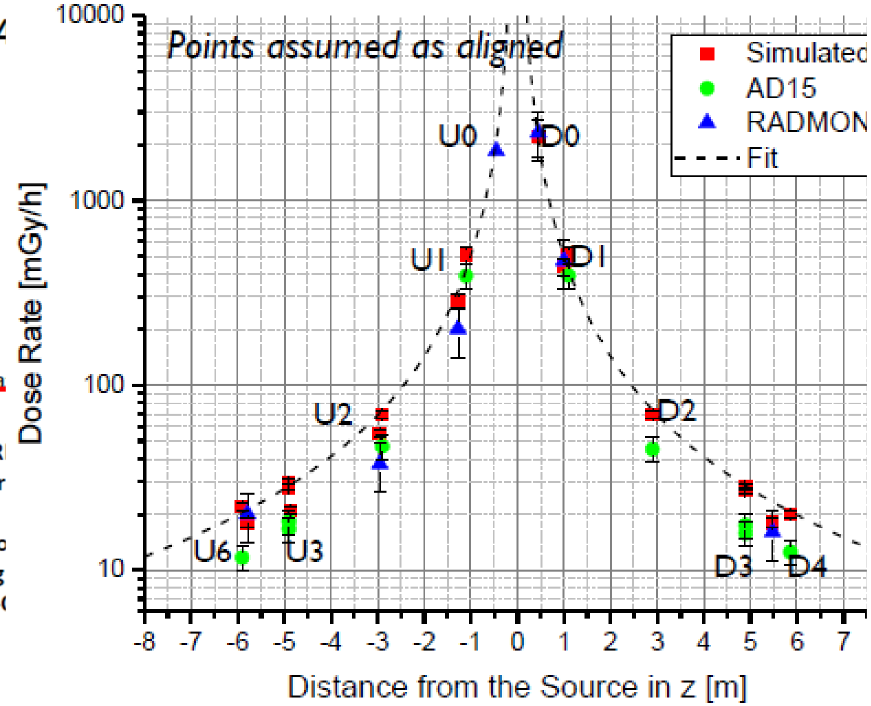
Beam radiation and luminosity
Common systems and infrastructure

Detectors at GIF++



R. Guida. Setups position and schedule for next test beam. https://indico.cern.ch/event/566910/

10 permanent GIF++ users, new requests for longevity tests and RadHardness tests are coming



GIF++ radiation measurements Att. Factor=1 (Dose rate vs distance from the Source)

G. Gorine, GIF++ RADIATION ENVIRONMENT https://indico.cern.ch/event/517100