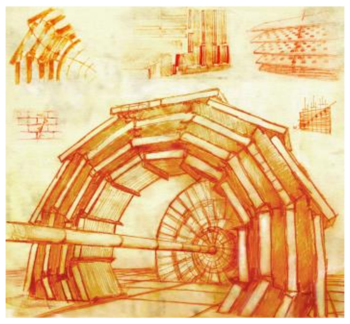
EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE

CMS



Upgrade plans of the CMS Muon System for High Luminosity LHC

Cristina Fernández Bedoya (CIEMAT)

on behalf of the CMS Collaboration

2025 European Physical Society Conference on High Energy Physics

July 7th-11th , 2025. Marseille (France)

Proyecto PID2023-148896NB-I00 financiado por:

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Cofinanciado por la Unión Europea

AGENCIA ESTATAL DE INVESTIGACIÓN

Proyecto PID2020-116262RB-C42 financiado por:

MINISTERIO DE CIENCIA E INNOVACIÓN

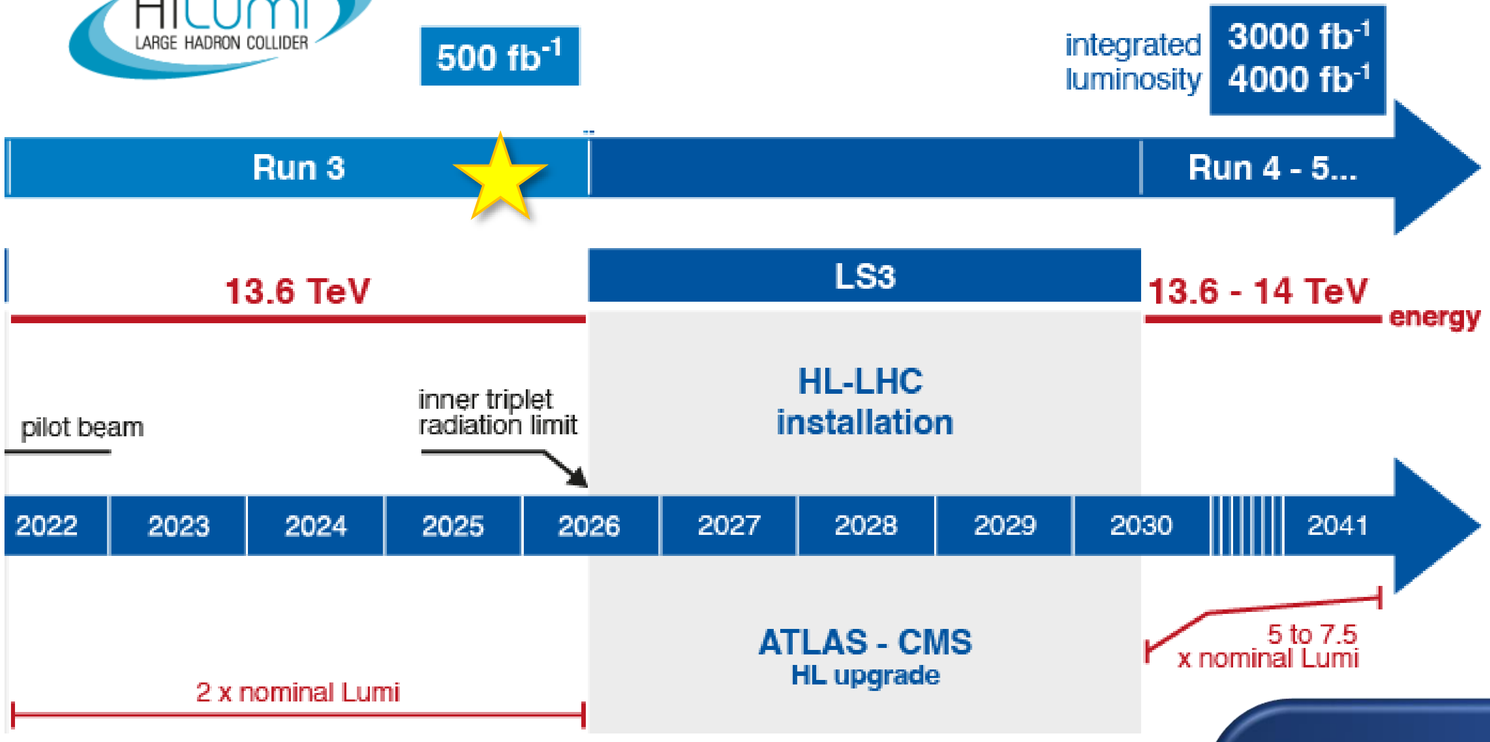
AGENCIA ESTATAL DE INVESTIGACIÓN

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Plan de Recuperación, Transformación y Resiliencia

Funded by the European Union NextGenerationEU

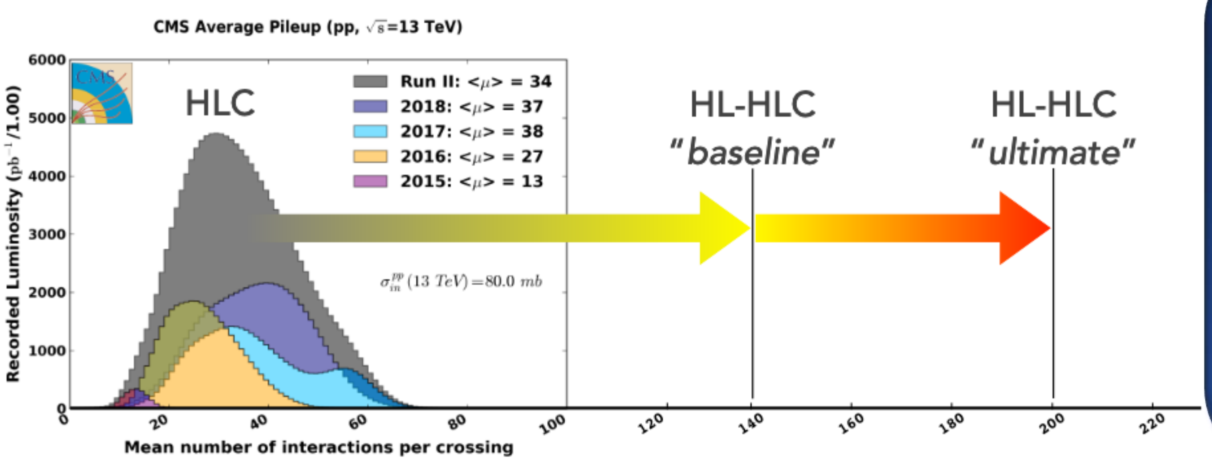
High Luminosity Large Hadron Collider



HL-LHC opens new possibilities for:

- **exploring rare processes**,
- improving **precision** measurements
- discovering **new physics** beyond the Standard Model

Higher **radiation levels, pile-up** and **occupancies** will pose unprecedented **challenges** for the detectors.



Challenge for the detectors:

Maintain performance under harsh data-taking conditions

	LHC	HL-LHC baseline (ultimate)
Instant. Luminosity ($cm^{-2}s^{-1}$)	10^{34}	5 (7.5) 10^{34}
Integrated Luminosity (fb^{-1})	300	3000 (4000)
Pile- Up	30	140 (200)
	CMS Phase 1	**CMS Phase 2**
L1 trigger accept (kHz)	100	750
L1 accept latency (μs)	3.6	12.4

CMS Muon System

Drift Tubes (DT):

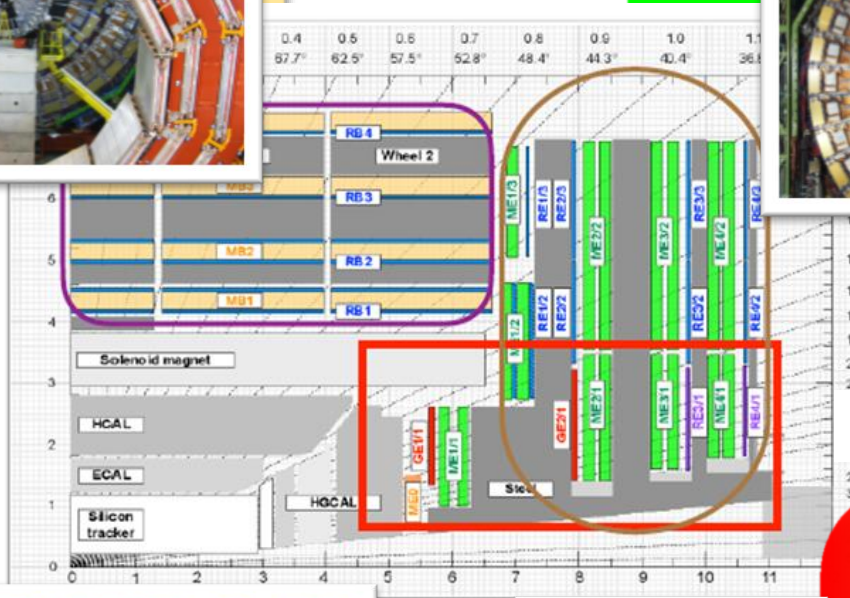
Large rectangular constant drift velocity tubes with anodic wire in the center

- 250 chambers,
- ≈ 170k channels
- 44 hits/track
- Spatial resolution ≈ 100 μm
- Time resolution ≈ 4 ns

Cathode Strip Chambers (CSC):

multi-wire proportional counters with a finely segmented cathode strip readout

- 540 trapezoidal chambers,
- ≈500k channels
- 24 hits/track
- Spatial res. ≈50 ÷140 μm
- Time resolution ≈ 3 ns

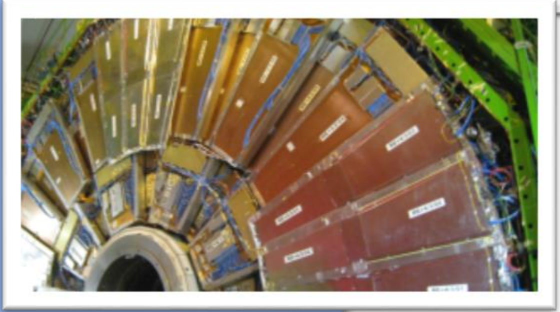


|η| < 2.4

Resistive plate chambers (RPC):

double-gap bakelite electrode chambers operated in avalanche mode

- 480 barrel, 576 endcap chambers
- ≈120k channels
- 6 (4) hits/track
- Spatial resolution ≈ 1 cm
- Time resolution ≈ 1.5 ns



New addition in 2019

Gas Electron Multiplier (GEM):

Micro-pattern gaseous detectors with successive amplification stages using triple-GEM foils

~432 GEMs
~1,2 M channels
2 to 6 hits/track
Spatial res. ~100 μm
Time resolution ~8-10 ns

CMS Muon System Upgrade Plan

Drift Tubes (DT):

Large rectangular constant drift velocity tubes with anodic wi

- 25
- ≈
- 44
- Sp
- Ti

Substitute most of the electronics chain:
- adapt to longer latency, higher data and trigger rates and larger bandwidths

Cathode Strip Chambers (CSC):

multi-wire proportional counters with a finely segmented cathode strip readout

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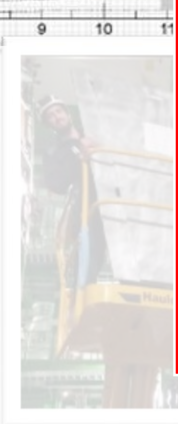


New addition in 2019

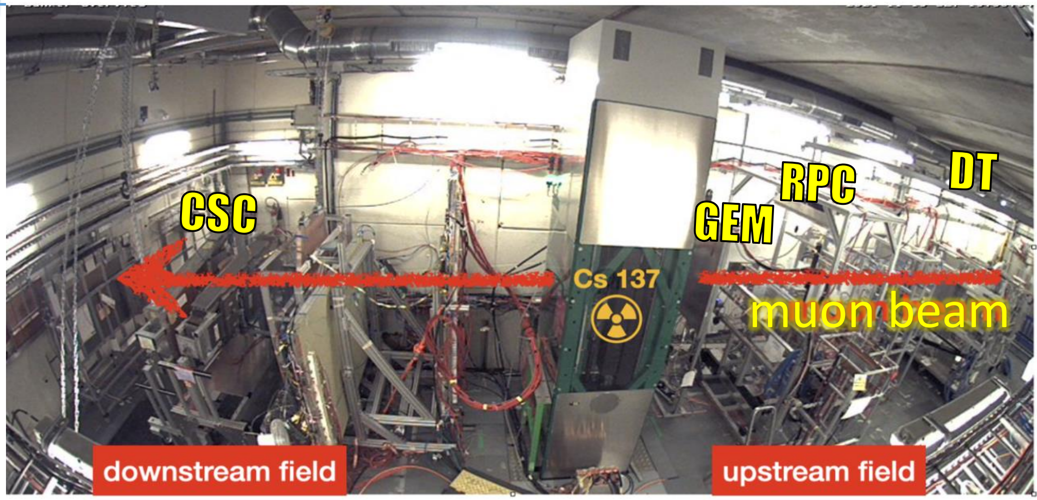
Extend muon id and trigger up to the region of 2.4 <|η| < 2.8

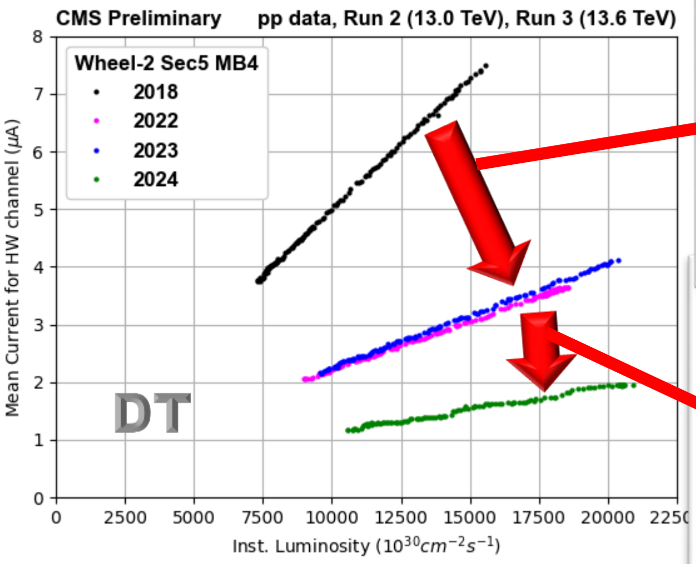
Reinforce and add redundancy in the forward region ~|η| > 1.7

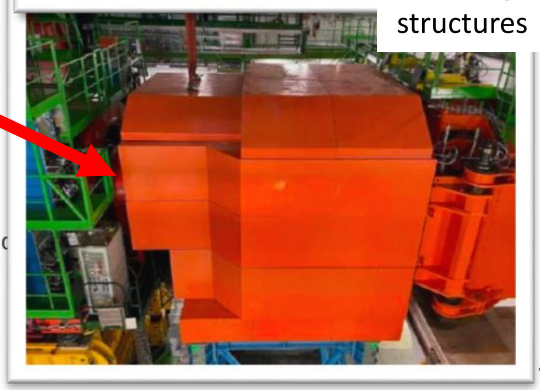
for electron multiplication)

CMS Muon Detector Longevity

- CMS Muon detectors span a surface of **~28000 m^2**, ensuring long term performance is critical => Wide experimental program at **GIF++ at CERN** since 2015
- High intensity Cs^{137} source => replicate HL-LHC integrated dose and particle rates
- DTs are the **most sensitive to integrated dose** (non-fluorinated gas mixture makes them more vulnerable to electrodes degradation)
- Actions: **install additional shielding**: both near focusing magnets and around the entire DT volume
- CSC and RPCs must undergo **validation with alternative gas mixtures** featuring **lower Global Warming Potential (GWP)** to comply with environmental regulations (CSC & RPC recuperation systems operating)





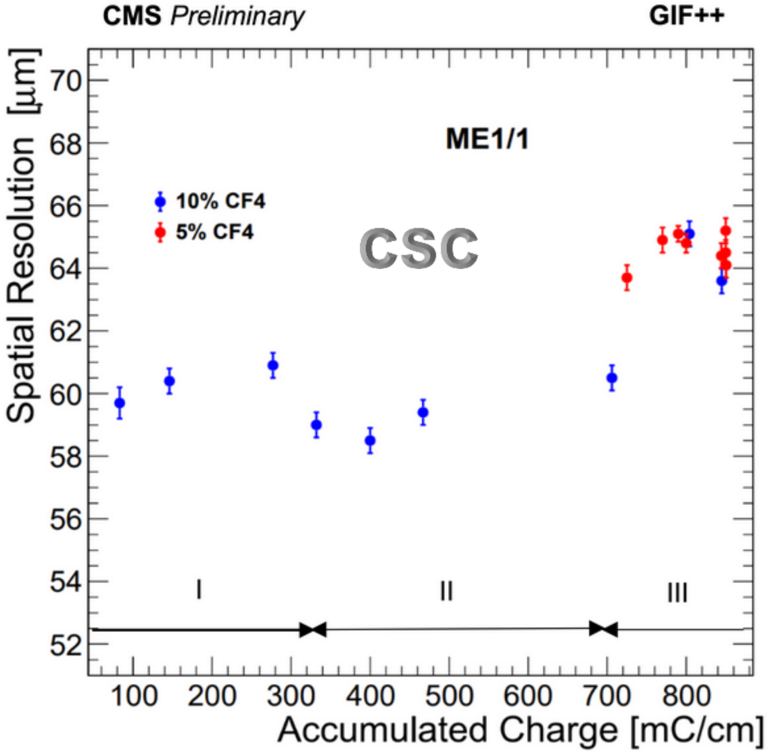


CMS Shielding structures

ME1/1 **spatial resolution** measured with a muon beam

Nominal gas mixture:
40% Ar + 50% CO_2 + 10% CF_4

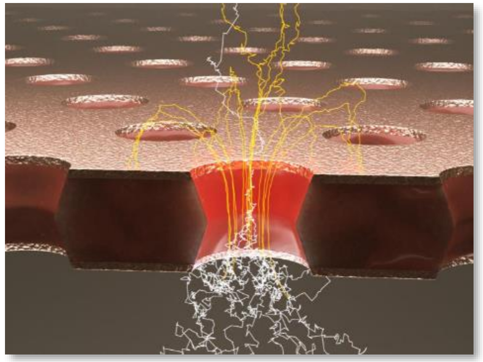
No degradation was observed up to the charge of 840 mC/cm



Reinforce forward region: GEMs

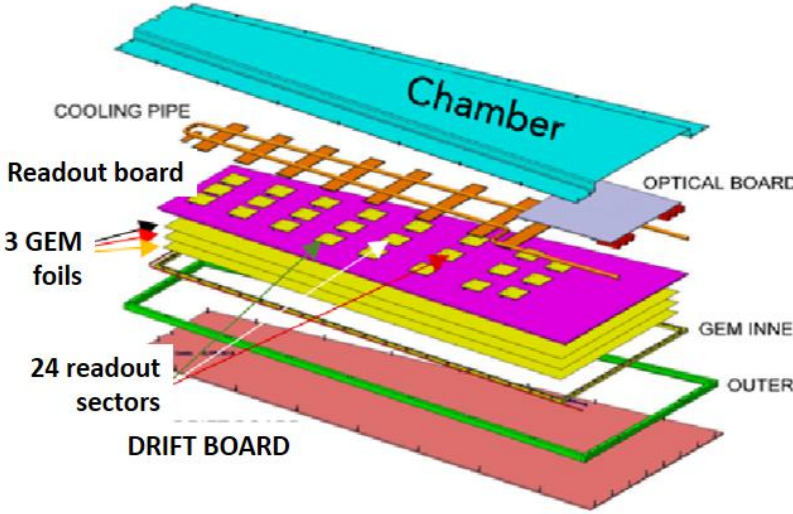
Gas Electron Multiplier (GEM) Technology

	#chambers
COMPASS	20
TOTEM	40
LHCb	~24
CMS GE1/1	144
CMS GE2/1	*72*



GE1/1 and GE2/1:

- TRIPLE GEM DETECTORS
- Polyamide foil: 50 µm
- Copper cladding on both sides: 5 µm
- Data taking: Ar/CO_2 (70/30) (pure CO_2 TS)
- **Very high spatial resolution (~100 µm)**
- **Time resolution ~10 ns**
- **Very high hit rate capability (~MHz/cm²)**

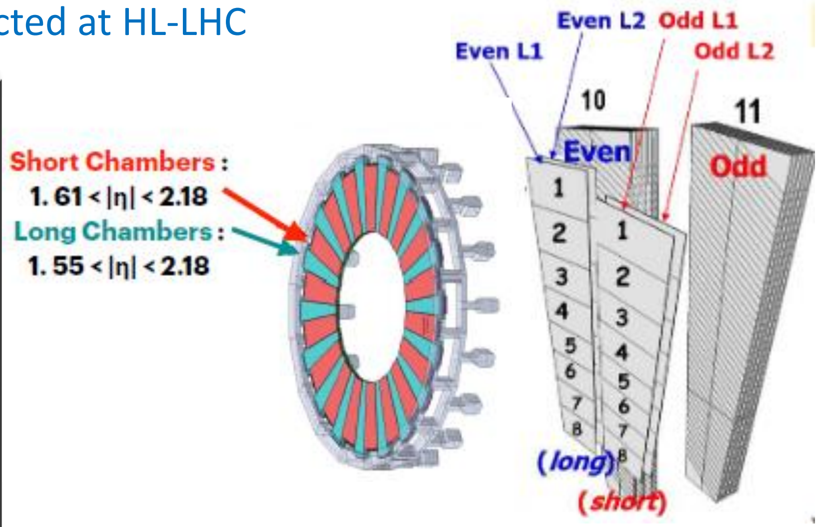


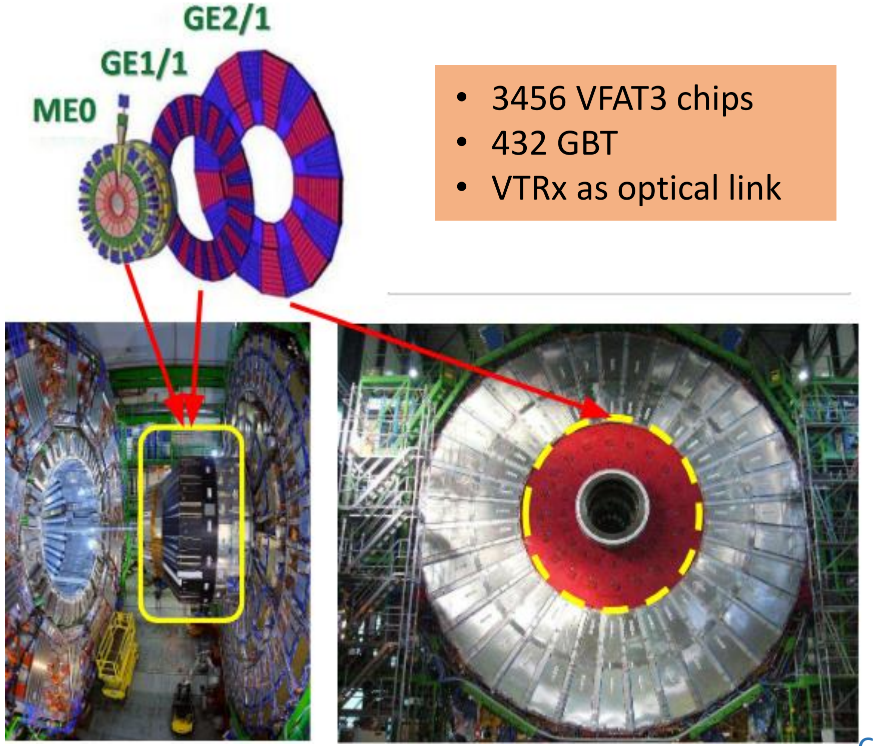
GEMs at CMS, GE1/1, GE2/1:

- complementing CSC in forward region (redundancy)
- improve tracking and trigger efficiency
- avoid large increases in trigger rate expected at HL-LHC

GE1/1 (10° in ϕ):
- Coverage: 1.55 < | η | < 2.18
- 144 detectors installed (72/endcap)

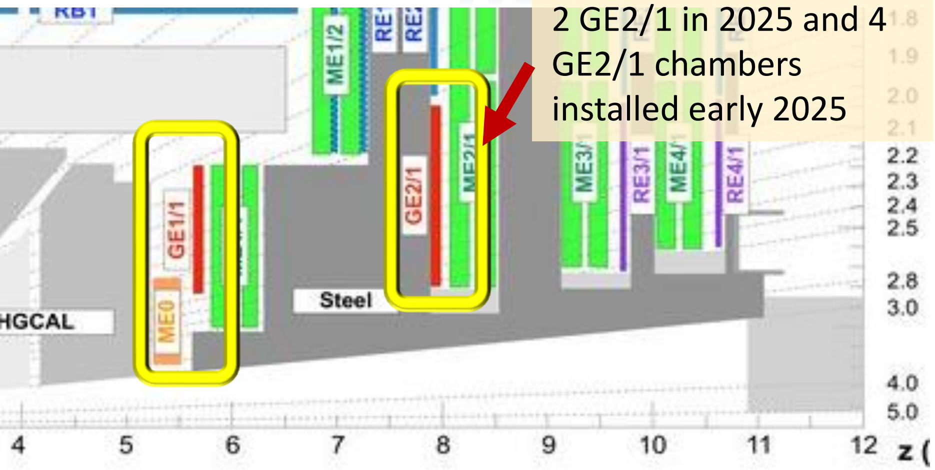
GE2/1 (20° in ϕ):
- Coverage: 1.62 < | η | < 2.43
- 12 modules (out of 72) installed in total
- Full installation postponed after LS3



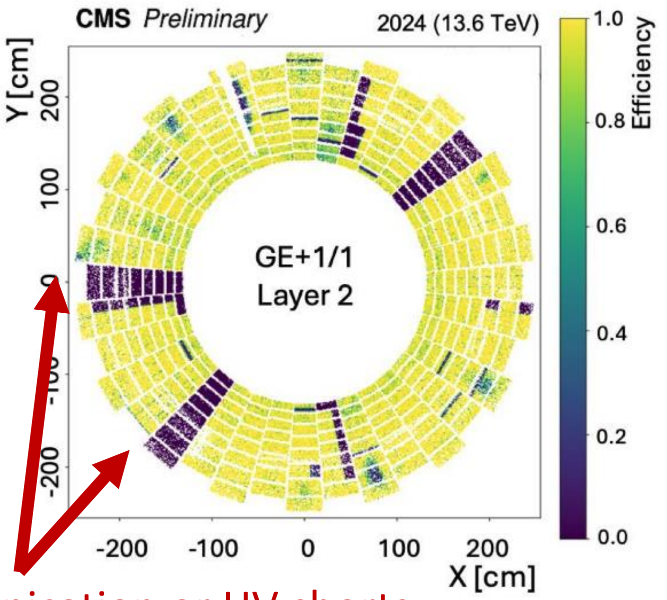


- 3456 VFAT3 chips
- 432 GBT
- VTRx as optical link

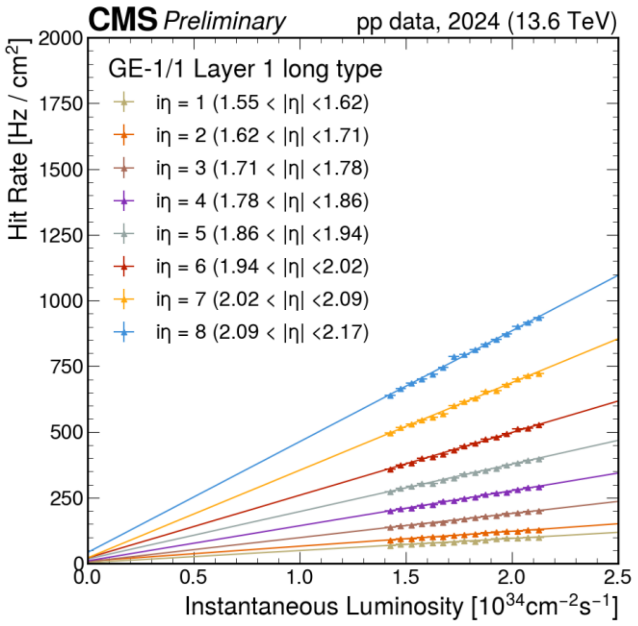
Reinforce forward region: GEMs



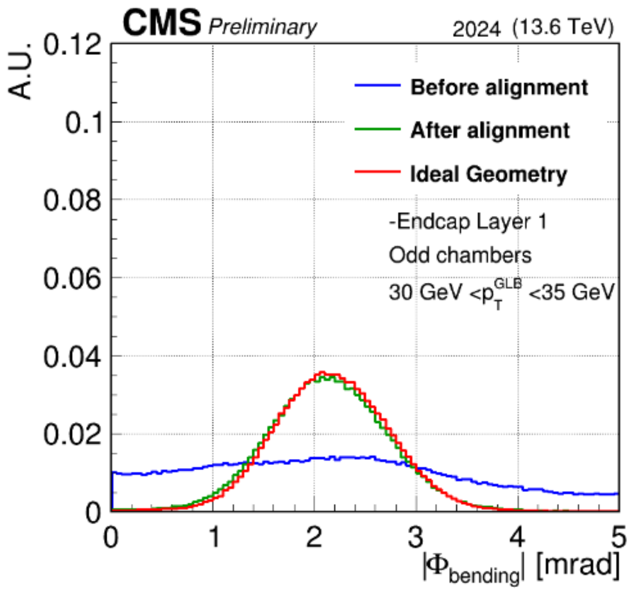
- GE1/1 installed in 2019 and **taking data during all Run 3**
- **Efficiency >95%**
- Operational experience allowed to overcome several problems (discharges, HV shorts, communication issues with VTRX outgassing, PCB issues and bending…



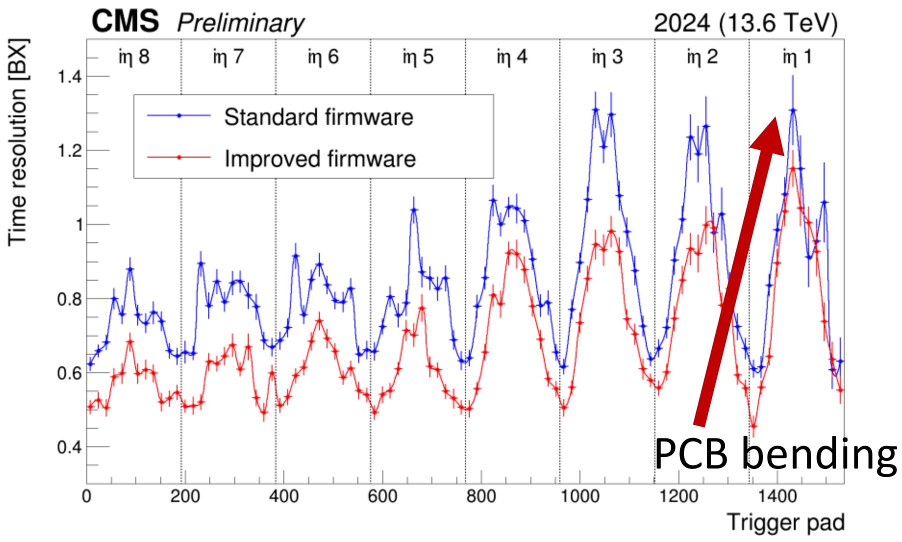
Communication or HV shorts



Good hit rate linearity versus luminosity

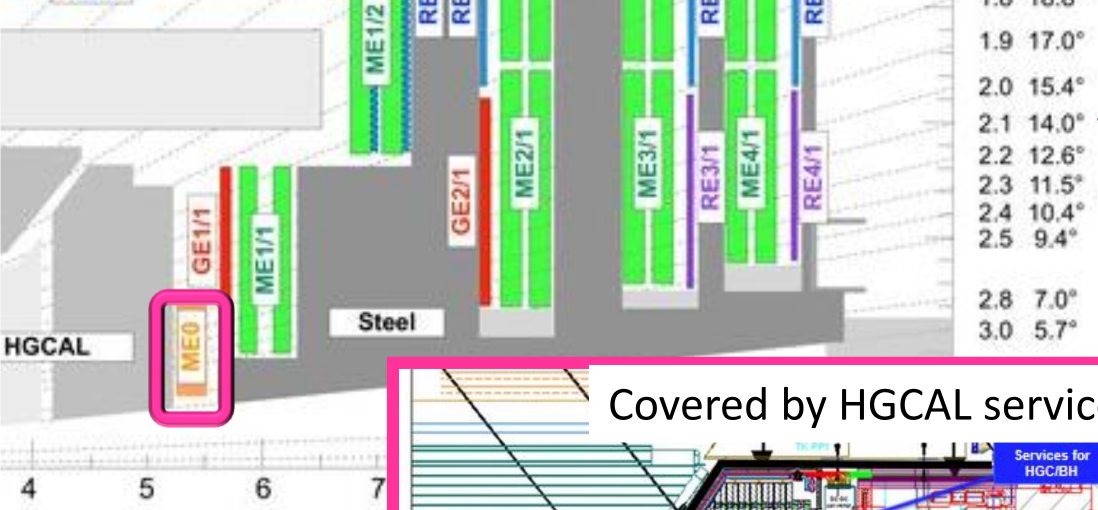


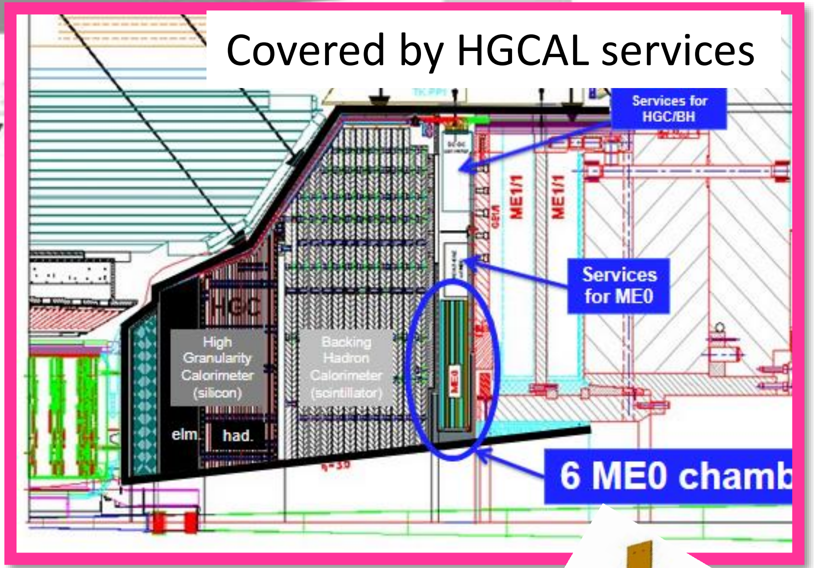
GE1/1-ME1/1 bending angles (phi_ME1/1 – phi_GE1/1_rechit)



Time resolution as a function of the trigger pad (pair of two readout strips) for a long GE1/1 chamber

Extend very forward region: ME0

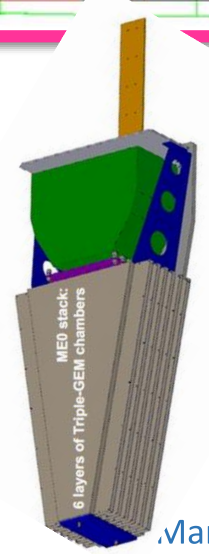




- Extend CMS Muon **acceptance and trigger into the 2.0 < $|\eta|$ < 2.8** region. For example:
  - acceptance increase by 20% in channel H ->ZZ -> 4 μ channel

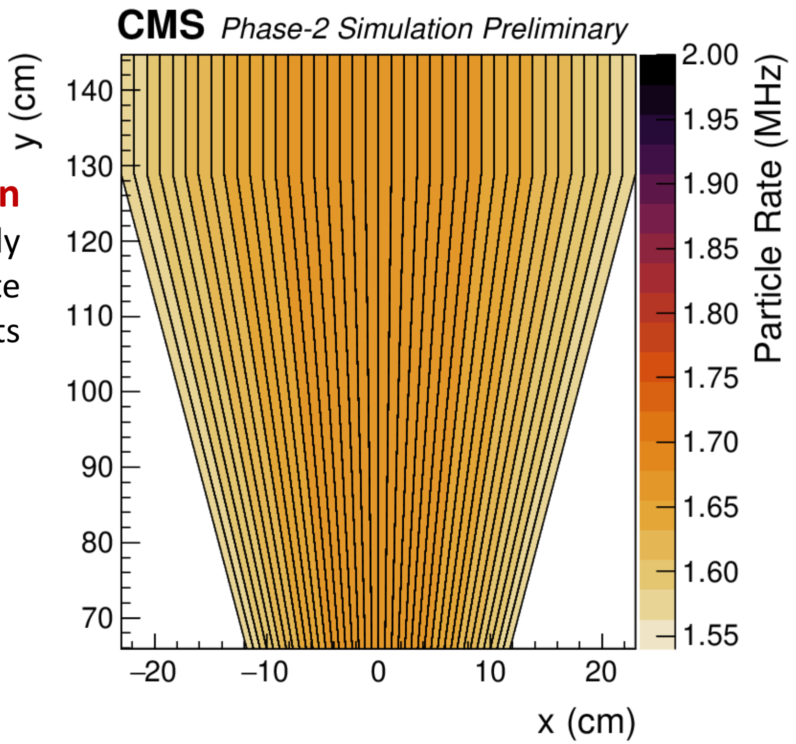
- Based on Triple-GEM technology, 6 layers of GEM foils
- ~2 m² area per station, 20° chambers, 6.5 cm overlap
- 18 stacks per endcap, 36 stacks in total
- 648 GEM foils in total (50% more than GE1/1)
- Located behind the future endcap calorimeter (HGCal)

- Efficiency > 97%/module
- < 500 μrad phi resolution
- ~10 ns time res.
- < 15% gain uniformity
- High rate environment 150 kHz/cm²
- Harsh radiation environment 7.9 C/cm²

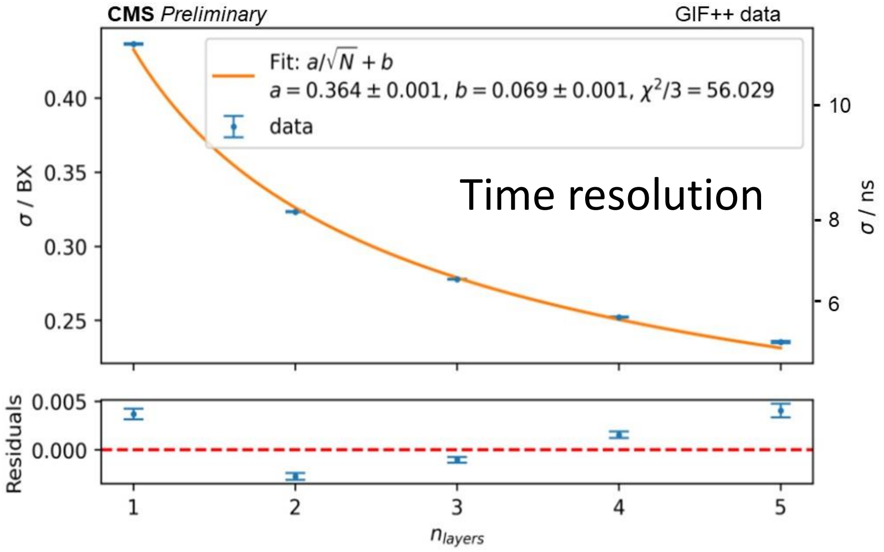


- 24 VFAT3/chamber
- 1 FPGA-less optoh.
- VTRX+

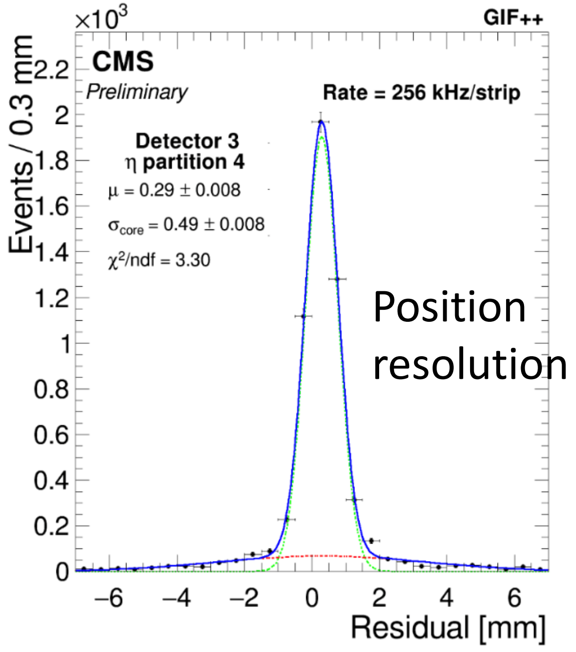
New foil segmentation
oriented azimuthally
equalizes background rate
across all HV segments

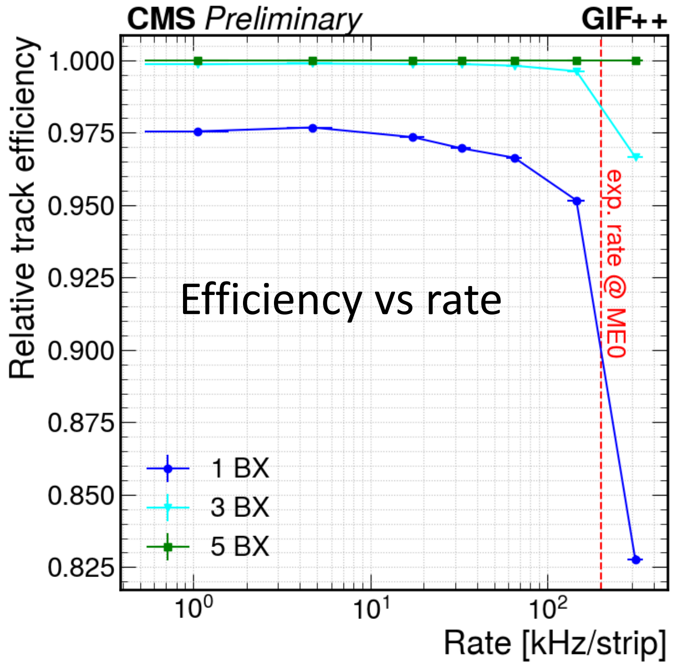


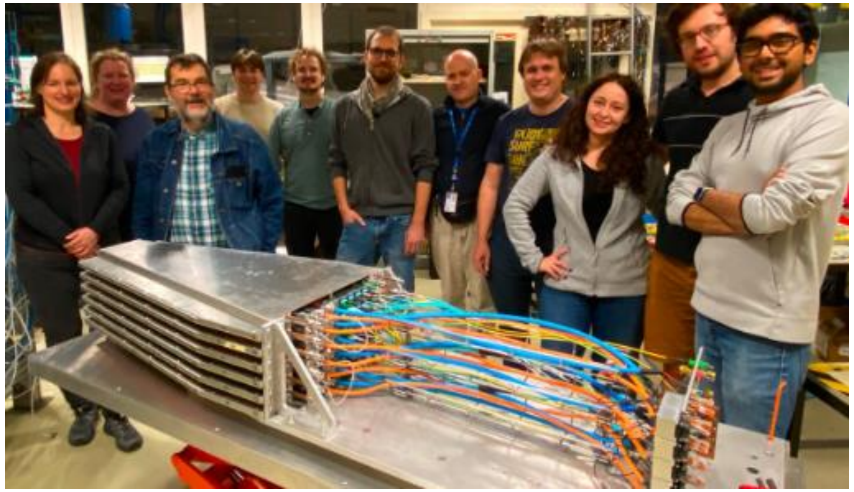
Extend very forward region: ME0



- ME0 will provide precision tracking and timing for muons in forward region
- Performance results from GIF++ provide very promising results







- A total of 8 production sites (CERN, Ghent, Bari, Frascati, Aachen, China, Punjab, Delhi)
- ~30% modules production ready
- The **first stacks are being brought online**

CSC upgrades

Staged replacement of the full electronics chain

Compliant with Trigger/DAQ constrains: occupancy, latency, L1 rate

LS2

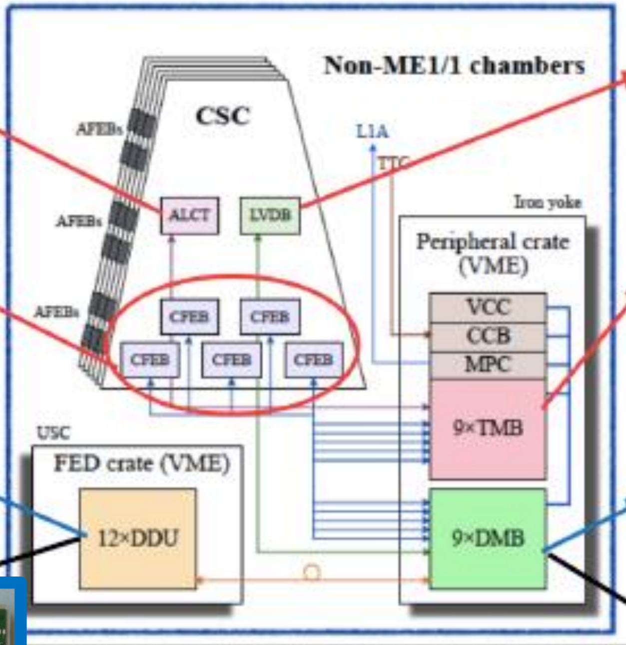
Anode Local Charged Track electronics: replace mezzanine cards to increase latency capability and output bandwidth

LS2

Cathode Front End Boards: replace with Digital Cathode Front End Boards with increased latency and rate capabilities

LS3

Front End Driver: increased data volume, number of links



LS2

Low Voltage Distribution Boards: replace to provide voltages and currents for Digital Cathode Front End Boards

LS2

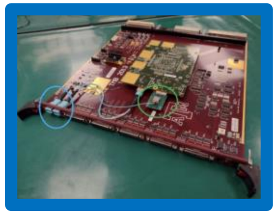
Trigger Motherboard: replace with optical Trigger Motherboard to receive Digital Cathode Front End Board trigger data, increased algorithmic power

LS3

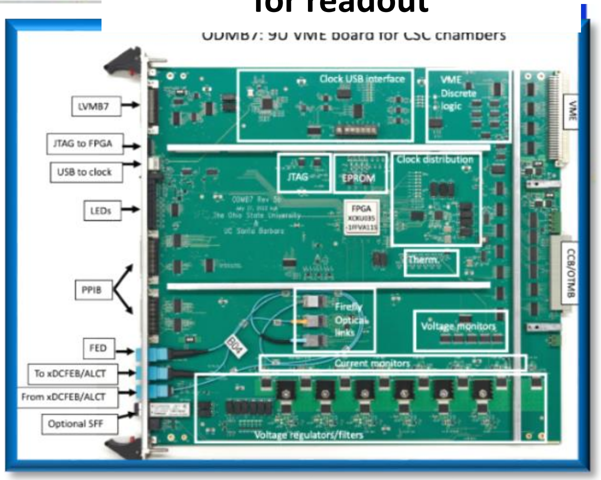
Data Motherboard: replace with optical Data Motherboard to receive Digital Cathode Front End Board data

Backend ATCA based X2O board

OTMB upgrade with new optics and GEMs inputs

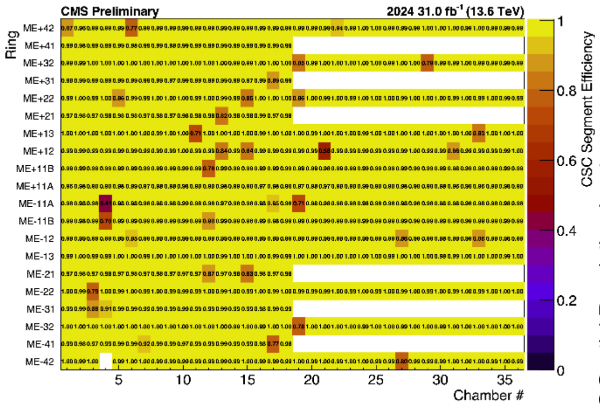


ODMB: Data Motherboard for readout



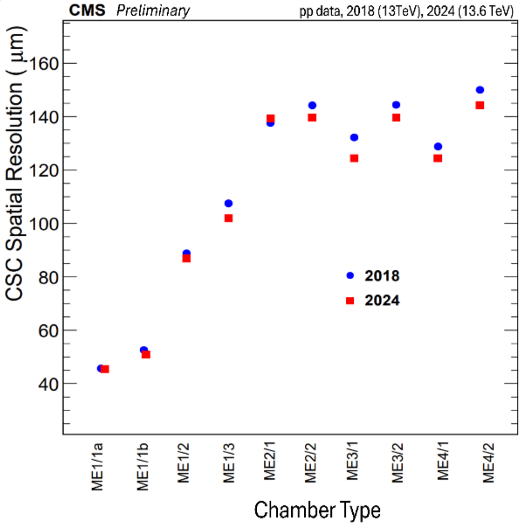
Most of CSC phase 2 upgrade was successfully completed in LS2

Board	Num.	Where	Main reasons for upgrade	
DCFEB	540	ME12/1	Latency and rate, rad-hardness	LS2
ALCT	396	ME1234/12	Latency and rate, rad-hardness	LS2
LVDB5	108	ME234/1	Power levels of DCFEBv2s	LS2
OTMB	108	ME234/1	Receive optical link from DCFEBv2s	LS2
ODMB	180	ME1234/1	Increased DAQ output bandwidth	LS3
HV	40/12	ME1234/1	Increased current due to higher occupancy	LS3
FED	14	USC	Increased data volume, number of links	LS3



Run 3 CSC segment efficiency

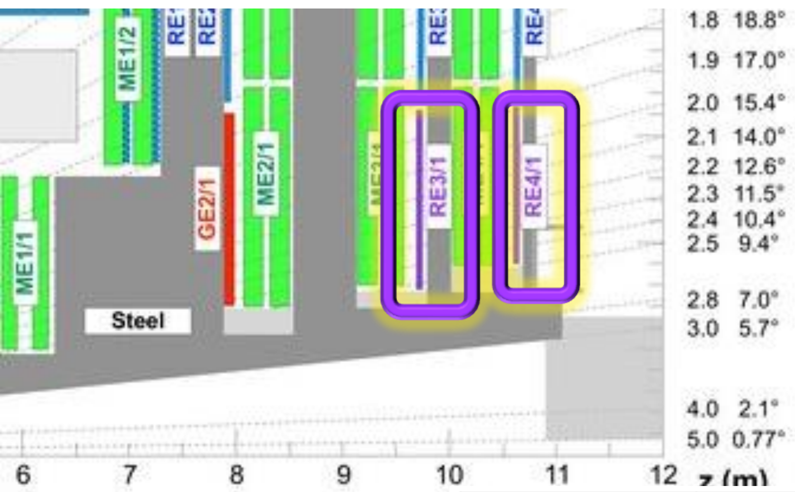
Run 3 CSC spatial resolution



Replace ODMB with new version boards handling higher speed links (up to 12.5 Gbps):

- 72 ODMB7 boards for ME1/1 (100% completed)
- 108 ODMB5 boards for ME234/1 (30% completed, issues with PCB material)

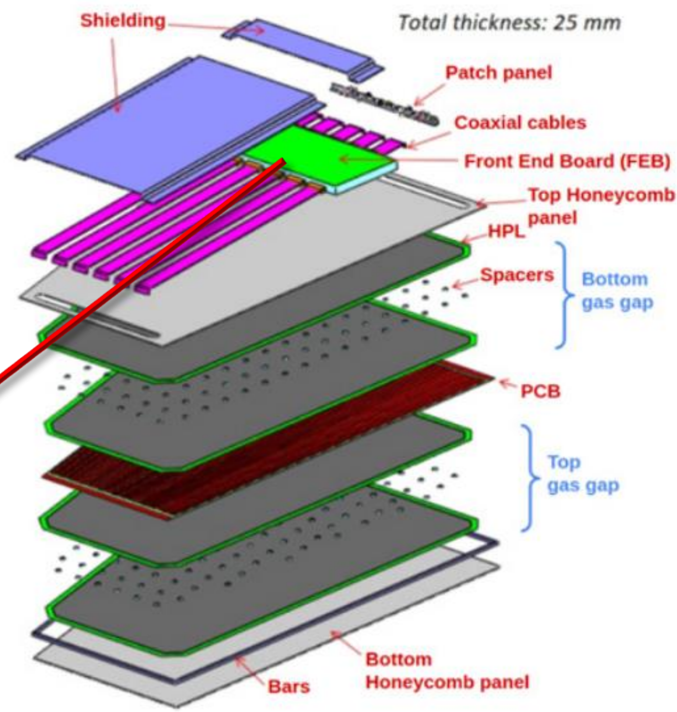
RPC upgrades: iRPC



- **Improved RPC chamber construction**: double gas gap with **1.4 mm** HPL electrodes

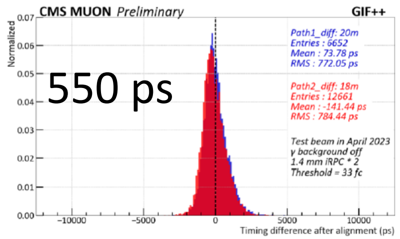
  => allows **lower HV working point (9.5 kV => 7.2 kV)**

- Rate capability up to **2 kHz/cm^2** with hit **efficiency > 95%** at 7.2 kV (max bkg. rate ~700 Hz/cm2)



RE3/1, RE4/1 stations:

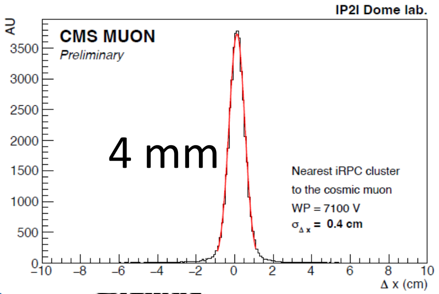
- **Total 72 iRPC**
- **20° chambers**

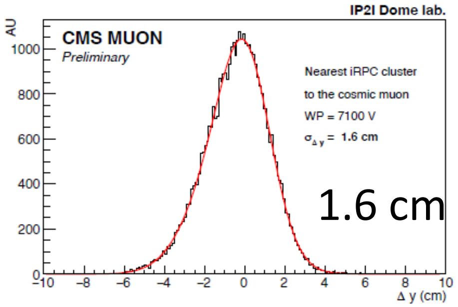


	RPC	iRPC
Gas gap width	2 mm	1.4 mm
HPL thickness	2 mm	1.4 mm
Resistivity	1-6 × 10^{10} Ω·cm	0.9-3 × 10^{10} Ω·cm
Charge threshold	150 fC	50 fC
η space resolution	17 cm (3 η partitions)	2 cm (2D readout)
ϕ strip pitch	0.3 degrees	0.2 degrees
Intrinsic time resolution	1.5 ns	0.5 ns

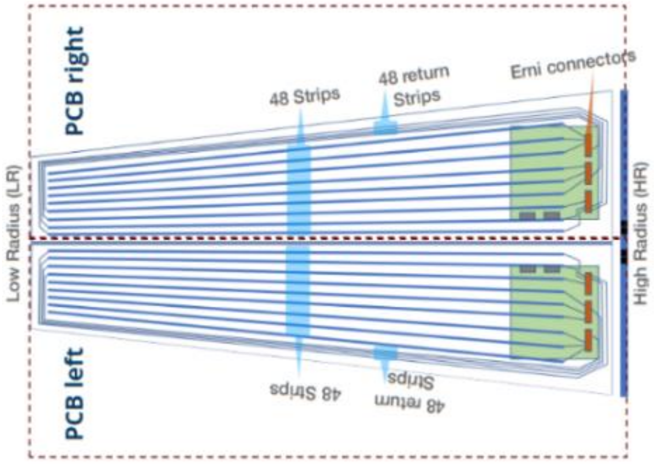
Low noise FEB sensitive to 30 fC

6 PETIROC 2C ASICs
+ 3 Cyclone FPGA
+ GBTx , SCA
+ VTRX



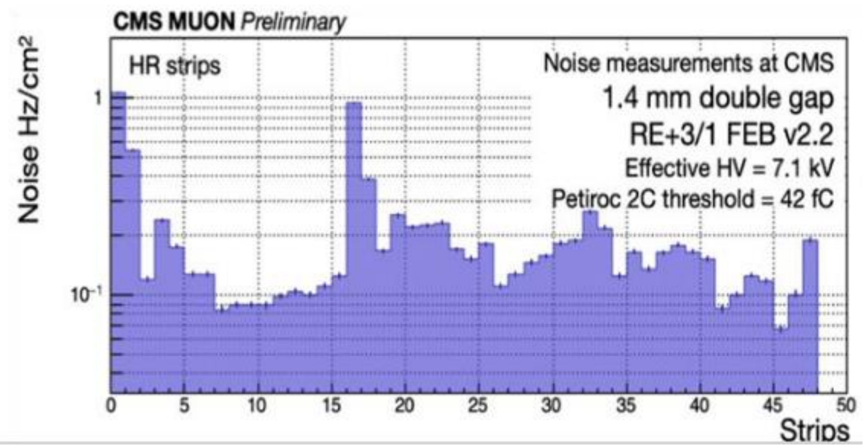


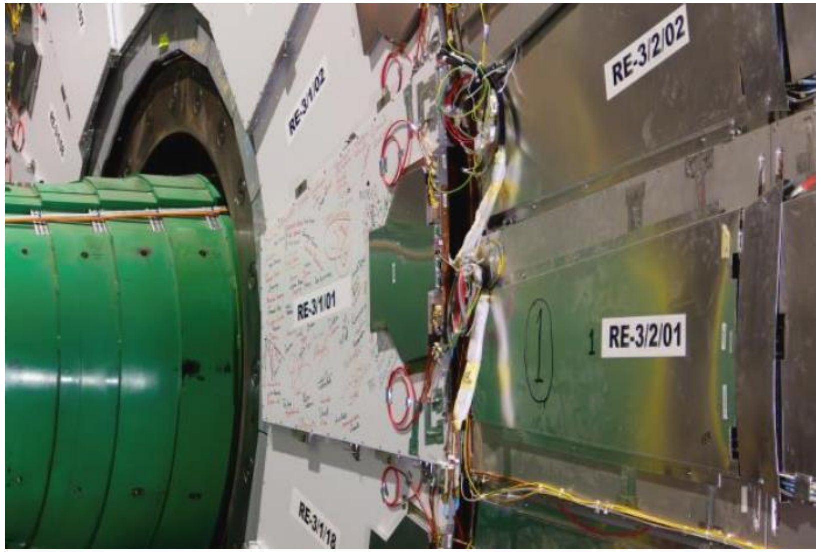
Strip readout:
2D measurement
TDC reading strips
from **both sides**



RPC upgrades

- During Winter Shutdown 2024-2025: **iRPC RE-3/1, RE-4/1 have been successfully installed** in the negative side of the CMS detector (half of the final system)
- Integration with backend electronics is ongoing

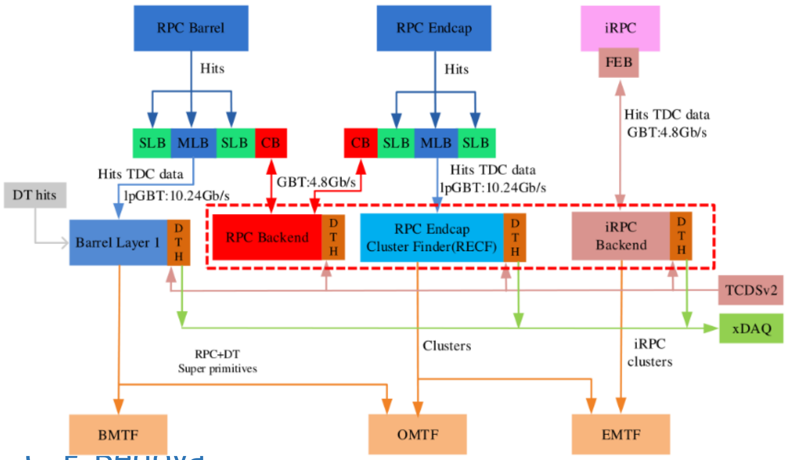


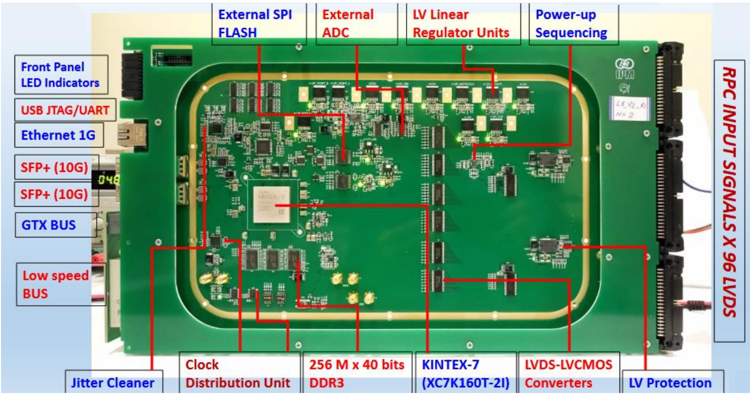


Full RPC system

Upgrade of the **Link boards**

- Data aggregation layer at the Tower Racks in the CMS cavern

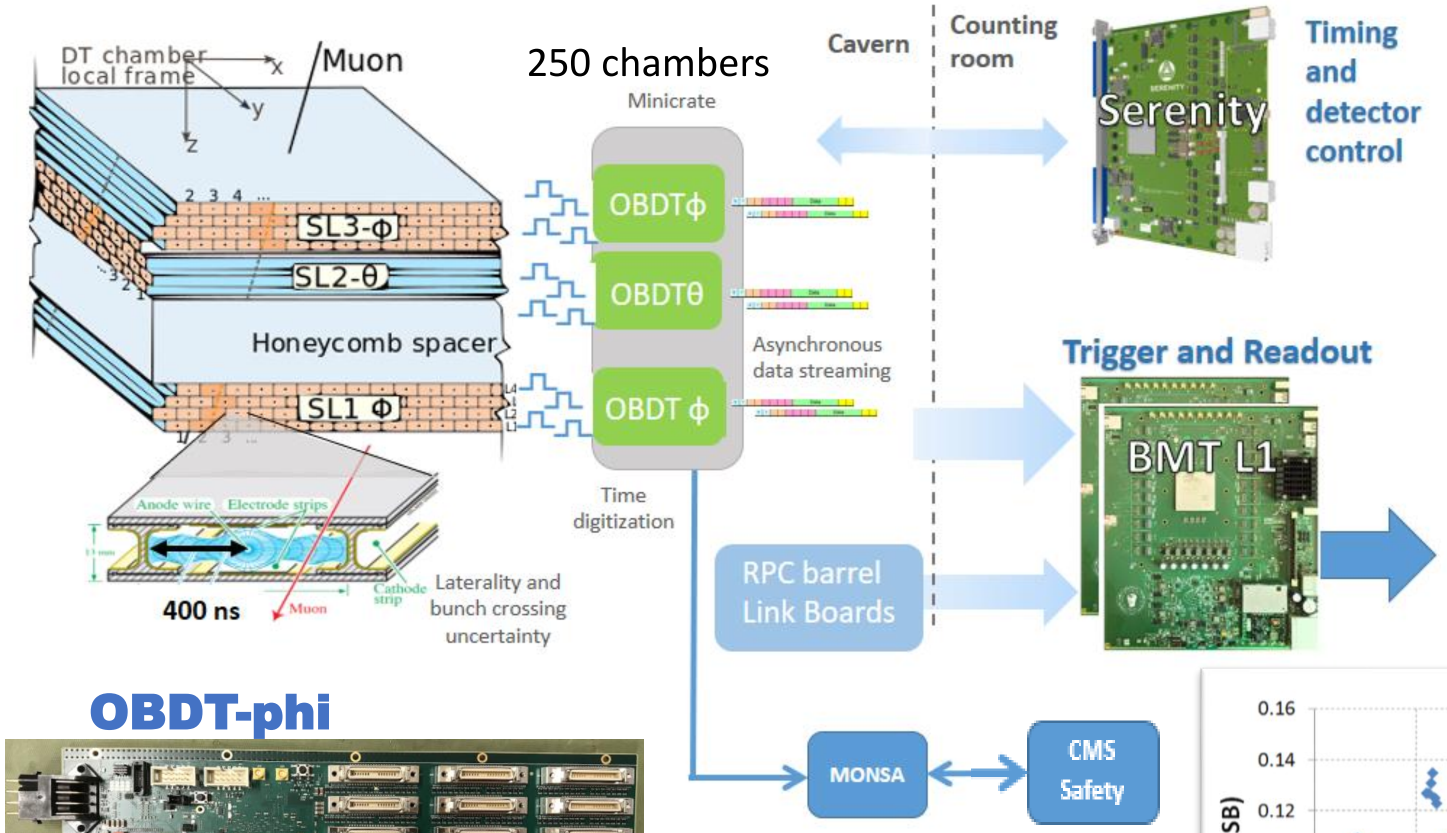




Key Features of new Link System

- 96 RPC channels/Link Board
- 1376 Link Boards (Master and Slave)
- FPGAs are KINTEX-7, XC7K160T implementing lpGBT protocol: 0.14 SEU/min expected, automatic correction implemented
- Muon hit time, TDC timing Resolution : **1.56 ns (previously 25 ns time stamp)**
- Master Link board output data rate : **10.24 Gbps (increased data throughput)**

Drift Tubes upgrades

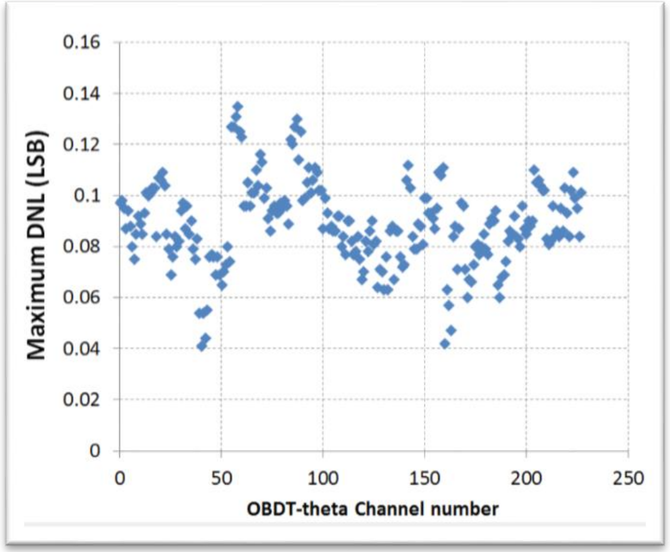


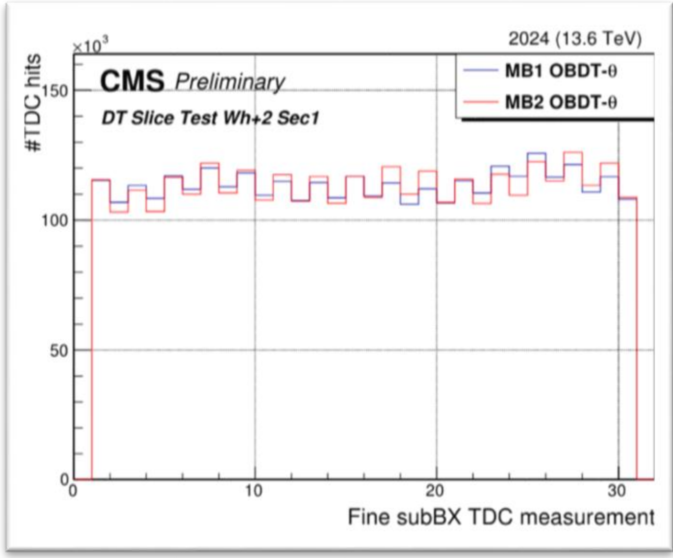
- Replacement of the **full electronics chain**
- Compliant with **Trigger/DAQ** : occupancy, latency, L1 rate
- **Improved performance at Trigger** primitive generation
  - Two OBDT flavors for each coordinate to accommodate to chamber constrains
  - 630 OBDT-phi and 180 OBDT-theta
  - Time digitization (~0.7 ns) by deserialization method inside the OBDT boards

OBDT-phi

OBDT-theta

- Microchip Polarfire FPGA
- + lpGBT
- +2 VTRX+
- + GBT-SCA





Drift Tubes upgrades

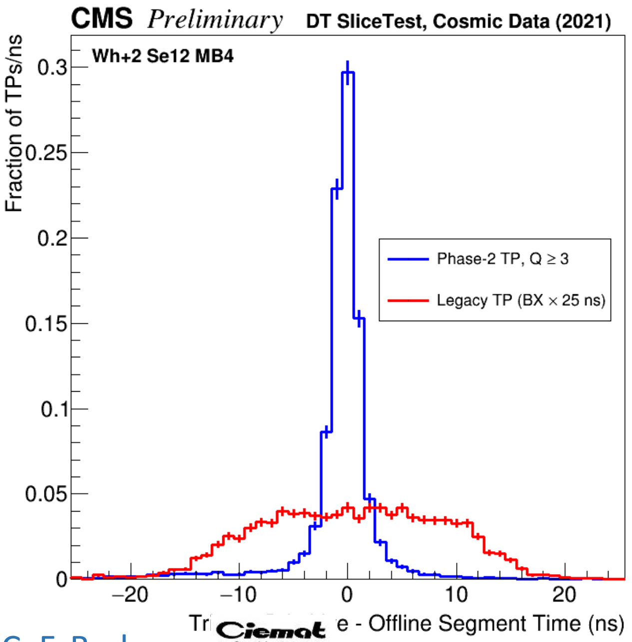
BMTL1

DT "slice-test" demonstrator in two sectors of the CMS detector:

Validation of the new electronics in realistic conditions during LHC Run 3

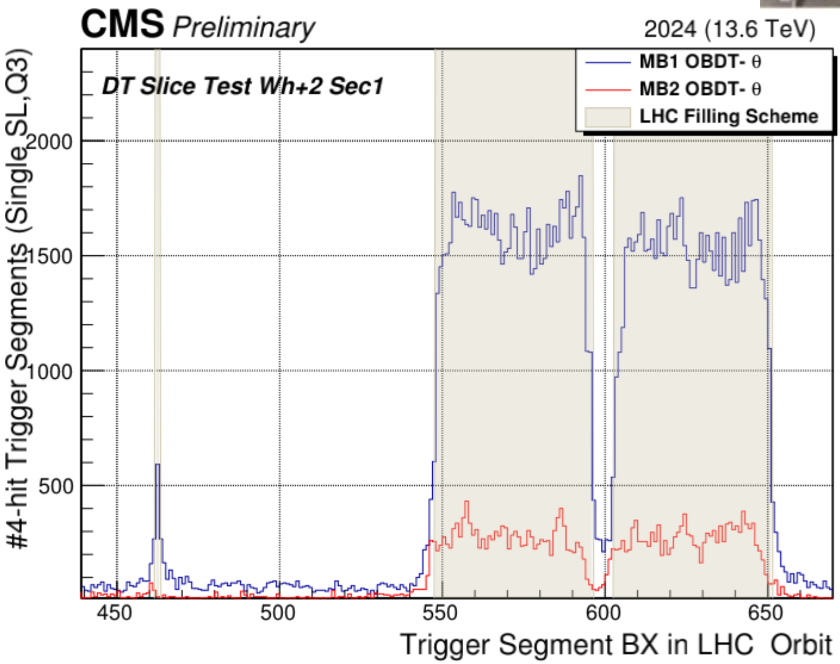
Successful operation of an integrated system:

- Sector 12: OBDTs v1 prototypes + uTCA readout
- Sector 1: OBDTs final prototypes + BMTL1 ATCA backend



Excellent local trigger performance

Trigger resolution comparable to the offline reconstruction!



Reconstruction of DT trigger primitives with the new hardware at Run 3 versus the LHC bunch crossing

Summary and conclusions

- **To ensure the CMS Muon System maintains its performance throughout HL-LHC, a challenging upgrade program will exploit the full potential of the CMS experiment**

- **Upgrades are progressing satisfactorily in all fronts:**

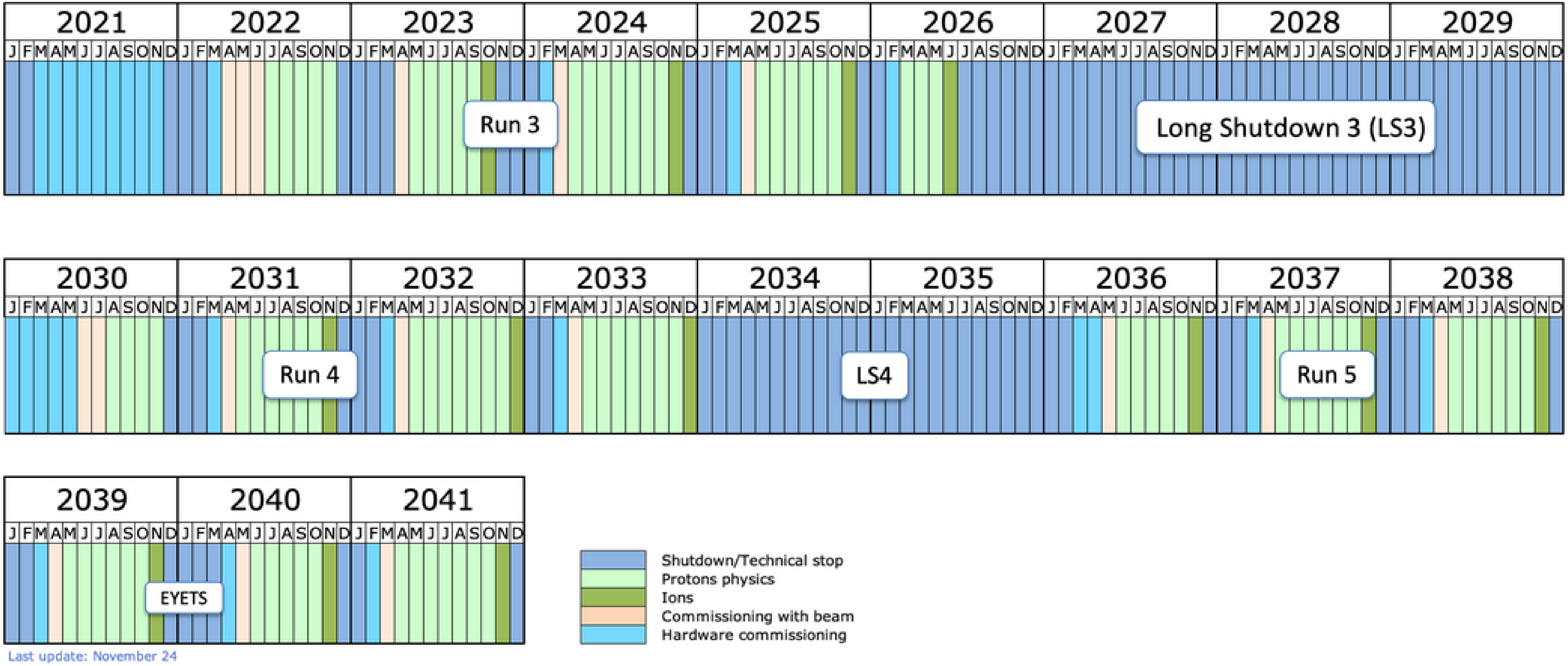
  - **GE1/1 is fully installed and taking data**
  - **CSC upgrade is more than half way already completed and installed**
  - **Half of the iRPCs are already installed and soon the rest will join**
  - **DT production is progressing satisfactorily and performance expected has been measured with real data taking**
  - **ME0 chambers are being built with high priority to ensure installation during LS3**
  - **GE2/1 has been postponed for schedule constrains but detector production is well advanced**
  - **Longevity studies give us confidence in the long term operation**
  - **Environmentally friendly alternatives are giving promising results**

- Integration and commissioning are proceeding in parallel with Run 3, with full readiness targeted for LS3

- Thanks to the electronics upgrades and the installation of new detectors, the **CMS Muon System is well prepared to deliver robust and precise performance under the challenging conditions of the HL-LHC**.

BACK-UP

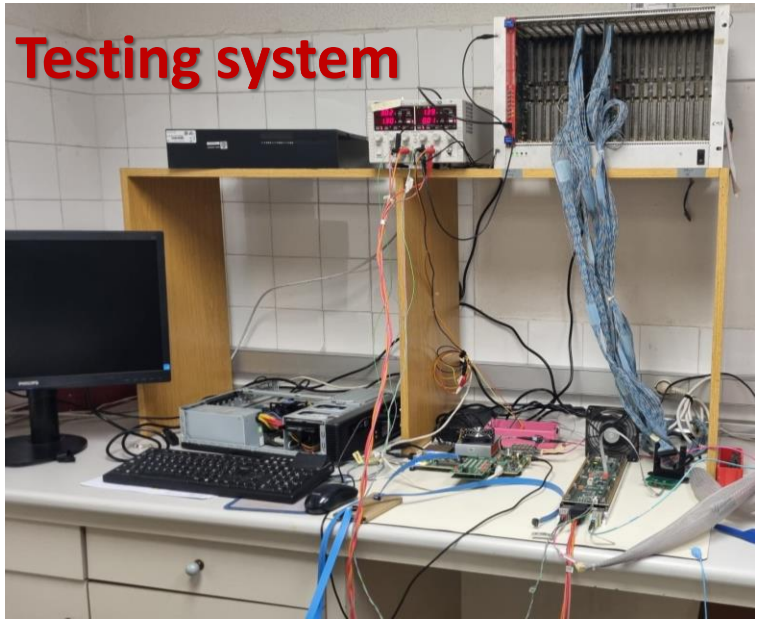
High Luminosity at LHC



OBDT-theta testing

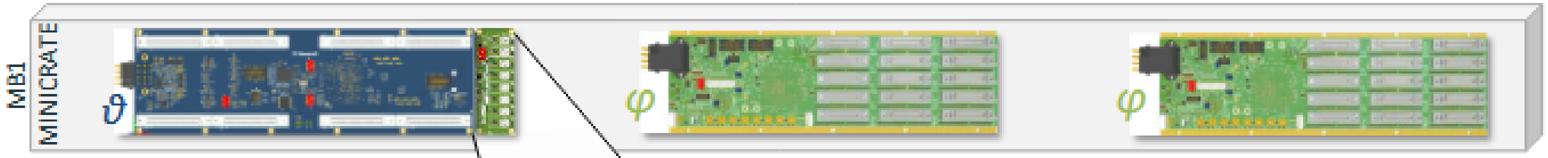
- Testing of the boards performed with a dedicated test stand and a specific software that performs several tests (monitoring of all voltages, currents and temperatures, functional verification of all interfaces and connectors, signal injection, time digitization, link reliability, DNL calculation of all channels, optical power measurement, etc.)

- New issue found: In few boards (4/200) Issue with the Polarfire getting stuck at 0.6 A: required some delay of 1.05V power. Added capacitor in ~all production
- **LPGBT:**
- Agreed with the Company to exercise the lpGBT v1 to v2 replacement. Still not done. In reality only for 4 boards is really mandatory.
- Added more capacitors to delay the 1.2V ramp up to all the boards to minimize the chances that there are issues. It helped to these 4 boards. Now ramp up changed to ~200 ms



OBDT-theta testpulse

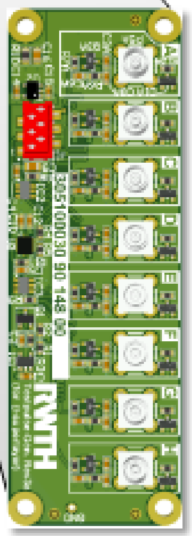
Timing calibration in DT



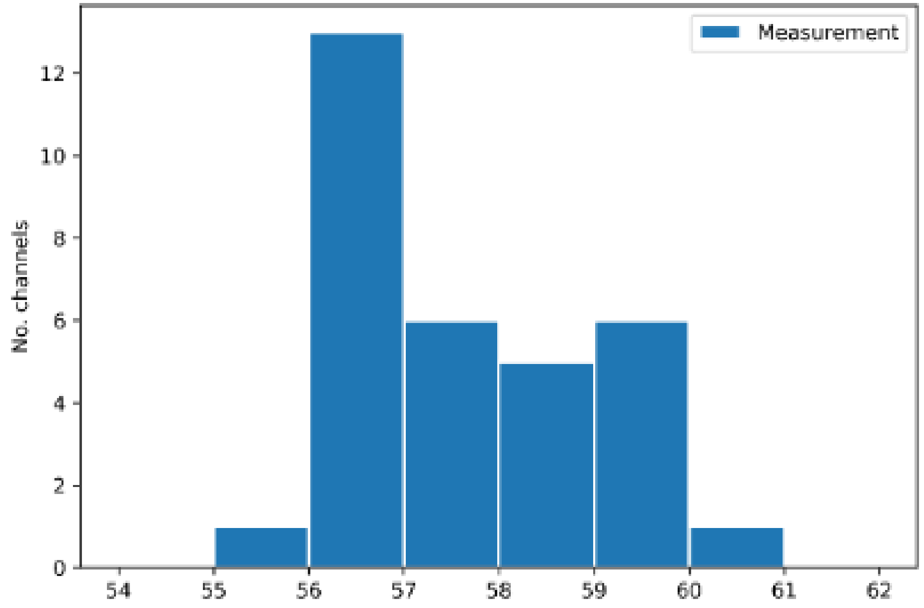
In 2023-2024 I developed the testpulse-board at RWTH, which provides the required functions for the ϑ super-layer:

- Provides eight test-pulses which cover all ϑ super-layer channels,
- Allows for adjustable pulses amplitude,
- On receiving a control pulse from FPGA the board issues pulses at eight outputs, which are cable-connected to the FE-circuits of the DT-chamber,
- The eight Test-Pulses are supposed to be simultaneous.

But how good simultaneous?



Histogram of delays measured for in total 32 channels (with four random boards):



Testing site

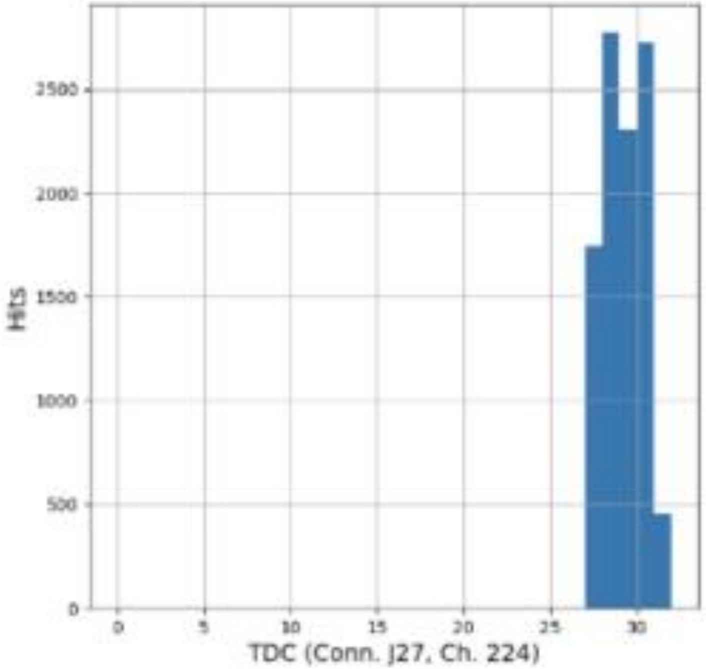
MADRID

LEGNARO

Test of FEPG in Torino

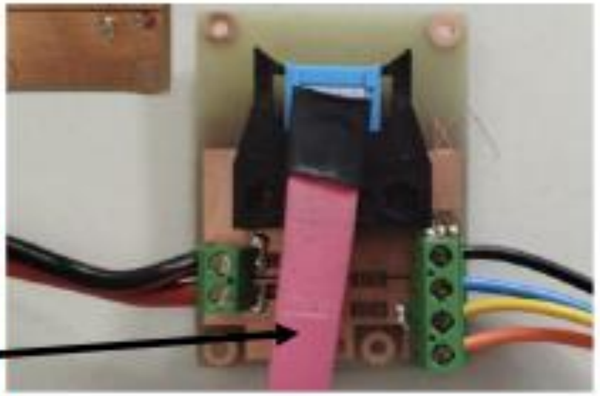
Two prototypes of Front **E**nd **P**attern **G**enerator boards tested:

- I2C, TP and FE connections
- FEPG receiving TP and generating a FE pattern



Received from Bologna:
- 25 FEPG boards
- 26 frames
- 3 bundles LV (9 connettori, 9 connettori, c 8 connettori)
- 3 schedine interfaccia I2C/LV

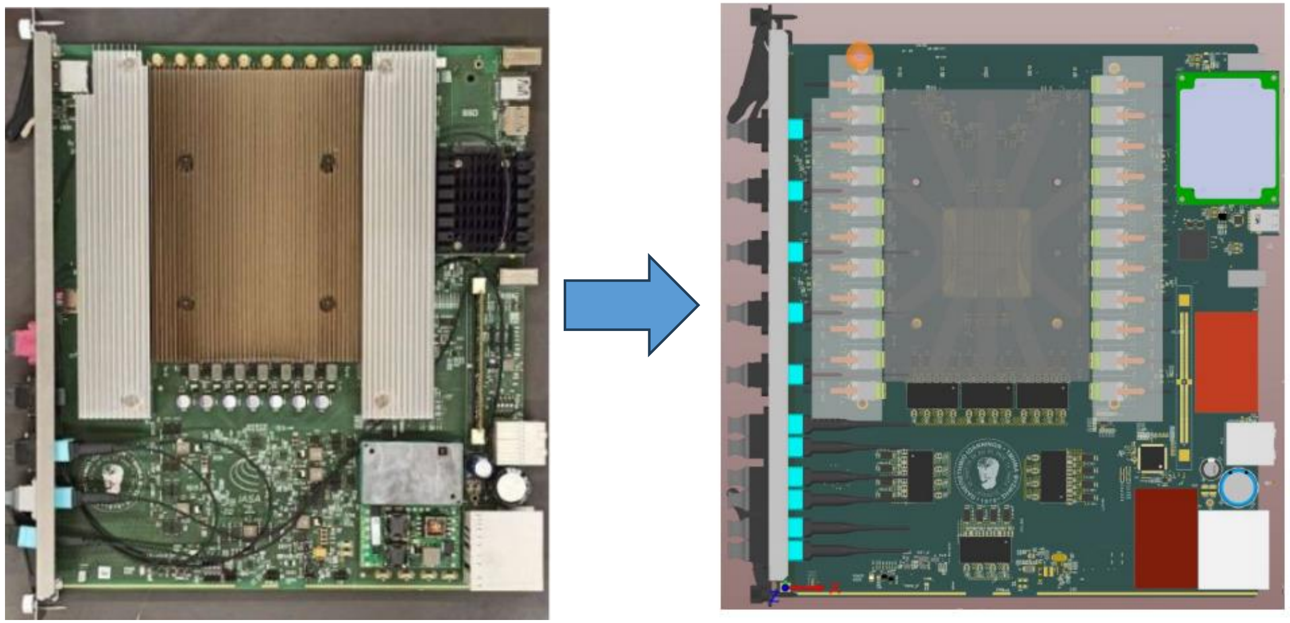
- Missing "rondelle" to mount the FEPG PCB on the frames
- SC Pink cables



DT Upgrade status: Mechanics

BMTL1 Board Revision & Production

BMTL1 board: Ioannis Bestintzanos



Revision2 design underway. *Main specs kept the same*
- Halogen free material, *already* tested with third protoype
- Xilinx Kria SoM K26
- Revised power supply network
- +2 TX fireflies

Expanded PCB into RTM space
- Leaves space for the heatsinks
- Thermal performance improvement
- ~40% area increase for the FPGA heatsink
- Removed obstruction from right heatsink

Design is currently being finalized, expect Rev2 first prototype to be launched in some weeks

➔ Validation after receipt of prototypes not expected very long

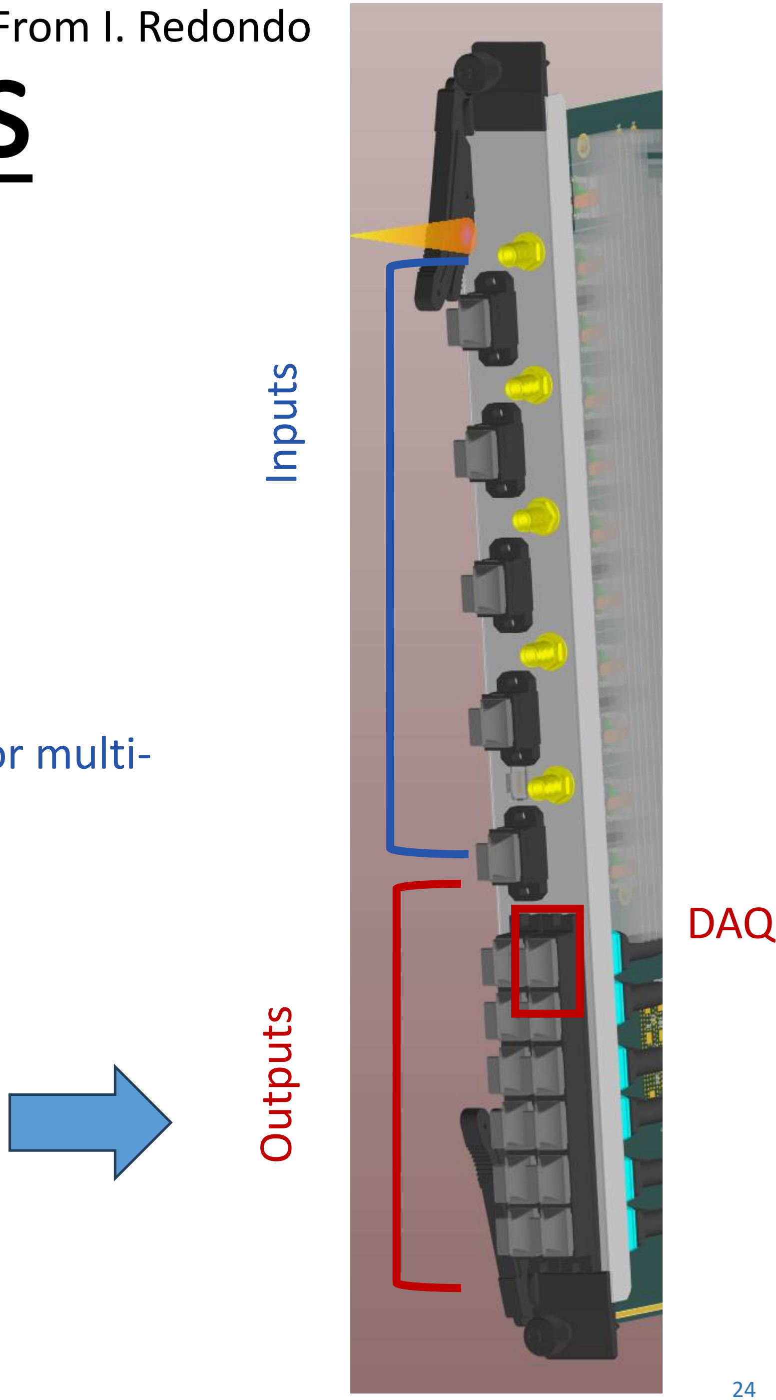
Production plan:
- First half (~25/50 including spares) of the boards produced in 2025
  - PCB production & board fabrication in Spain
- Second half will be produced with Greek funds (first funding instalment arrives in 2025)
  - PCBs by Somacis
  - Possible assembly company in Greece - under testing
- Board production will be validated at CIEMAT and CERN, respectively

From I. Redondo

BMTL1 Integration Status

- DT SXA5 setup not yet operational
  - had to be displaced due to SXA5 building power upgrade
  - Racks are back in place, expect to recover this week (10/03/25)
- Bmtl1-2 protype in 904 cubicle next to X2O since mid February
  - Checked connectivity & verified locking to DTH clock and Bc0
  - Connected to GMT X2O, initial link test show link CRC errors
    - In SXA5 setup bmtl1 is the clock source for the Ocean/GMT
    - FW development (Kosma&Spyros) to change clock distribution ongoing
- Also moved the DTH from our setup to the bottom crate in 904 integration row for multi-crate test when DTH SW/FW is available
- Bmtl1-3 protype mechanics (front panel) to be completed

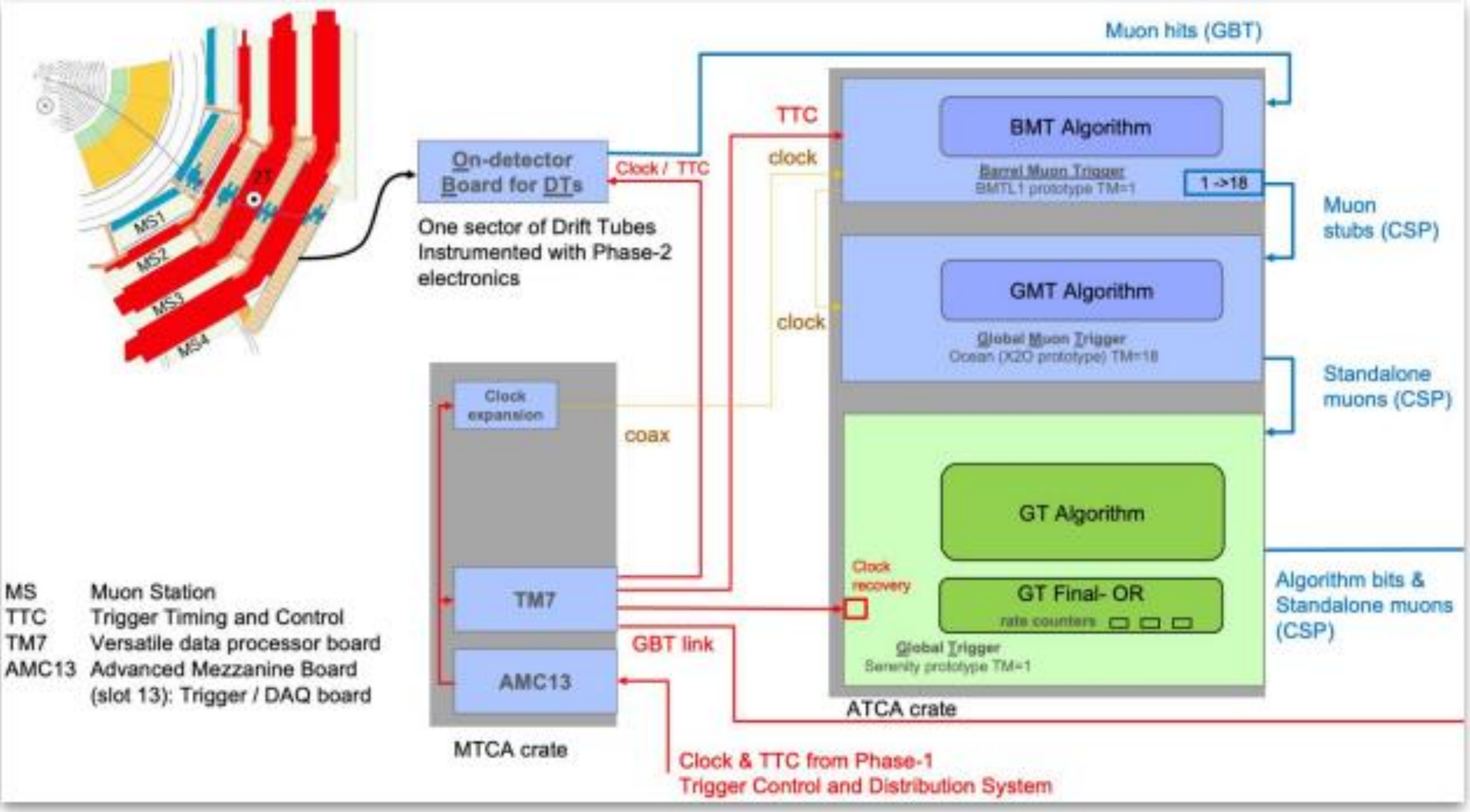
- Update of the Front Panel of rev 2 after cabling Fireflies to frontpanel according to current prototype FW and reasonable frontpanel connections
  - Need at most 12 MTP for BMTL1 or BF, front panel exposes more.
  - Inputs and outputs separated
  - DAQ output is similar location as Serenity.
- Jesus Cuchillo (CIEMAT) used SolidWorks to implement cabling and estimate pigtail length of the different FF modules➔ ready to order B04 and CERN-B FF



From I. Redondo

DT-BMTL1 2025 Integration Plans

- Last year the DT slice test was grown to include :
  - + readout through phase1 HW
  - + GMT, GT (serenity) & scouting instances
- Links and connectivity was successful but trigger primitives not generating tracks at the GMT(Ocean)
  - FW being investigated



➔Plan to reinstall setup early during 2025 collisions, as bmtl1-3 is available, and continue FW debugging

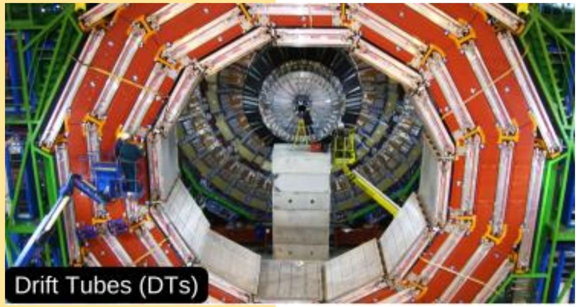
+ RPC Link board test is pending since first unsuccessful tests late 2023.

CMS Muon System

Drift Tubes (DT):

Large rectangular constant drift velocity tubes with anodic wire in the center

- 250 chambers,
- ≈ 170k channels
- 44 hits/track
- Spatial resolution ≈ 100 μm
- Time resolution ≈ 4 ns


Drift Tubes (DTs)

Cathode Strip Chambers (CSC):

multi-wire proportional counters with a finely segmented cathode strip readout

- 540 trapezoidal chambers,
- ≈500k channels
- 24 hits/track
- Spatial res. ≈50 ÷140 μm
- Time resolution ≈ 3 ns

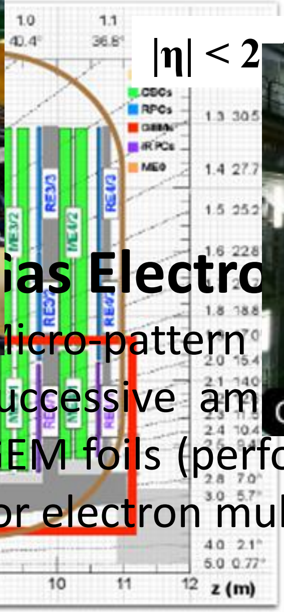

Gas Electron Multipliers (GEMs)

Resistive plate chambers (RPC)

double-gap bakelite electrode chambers operated in avalanche mode

- 480 barrel, 576 endcap chambers
- ≈120k channels
- 6 (4) hits/track
- Spatial resolution ≈ 1 cm
- Time resolution ≈ 1.5 ns


Resistive Plate Chambers (RPCs)



ias Electro

licro-pattern

successive am

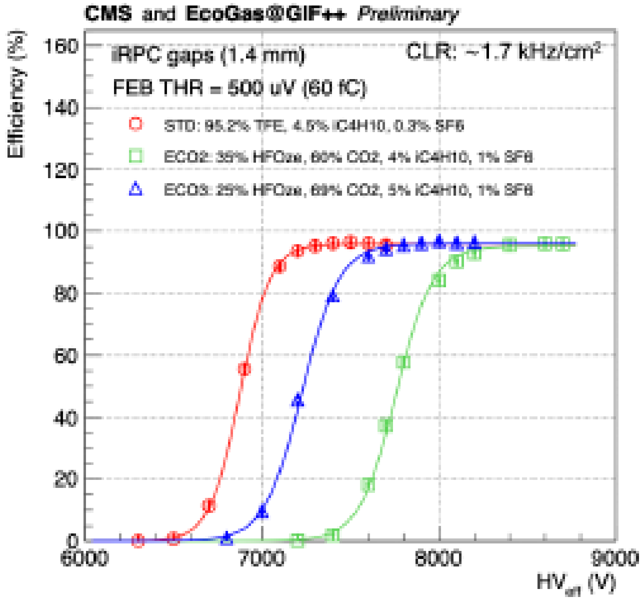
GEM foils (perforated with microscopic holes for electron multiplication)

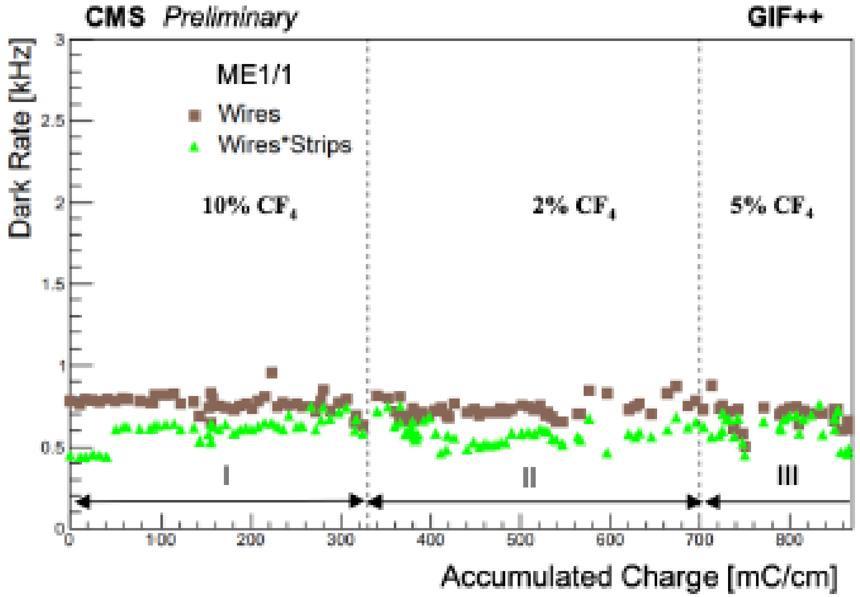
Cathode Strip Chambers (CSCs)

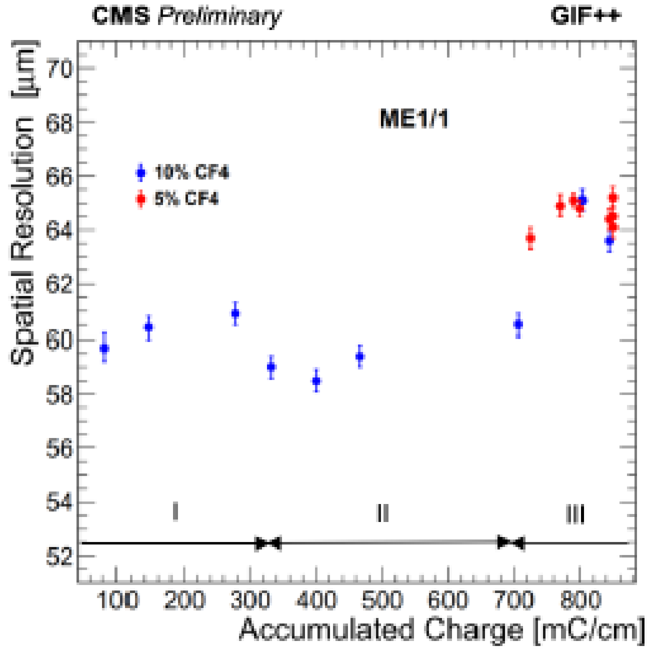
New Gas Mixtures

CSC and RPC gas mixtures contain fluorinated greenhouse gases, (SF_6,$C_2H_2F_4$, CF_4) classified for their Global Warming Potential with respect to CO_2. An extensive R&D program is carried out at Gamma Irradiation Facility (GIF++ CERN) since 2016 on alternative gas mixtures:

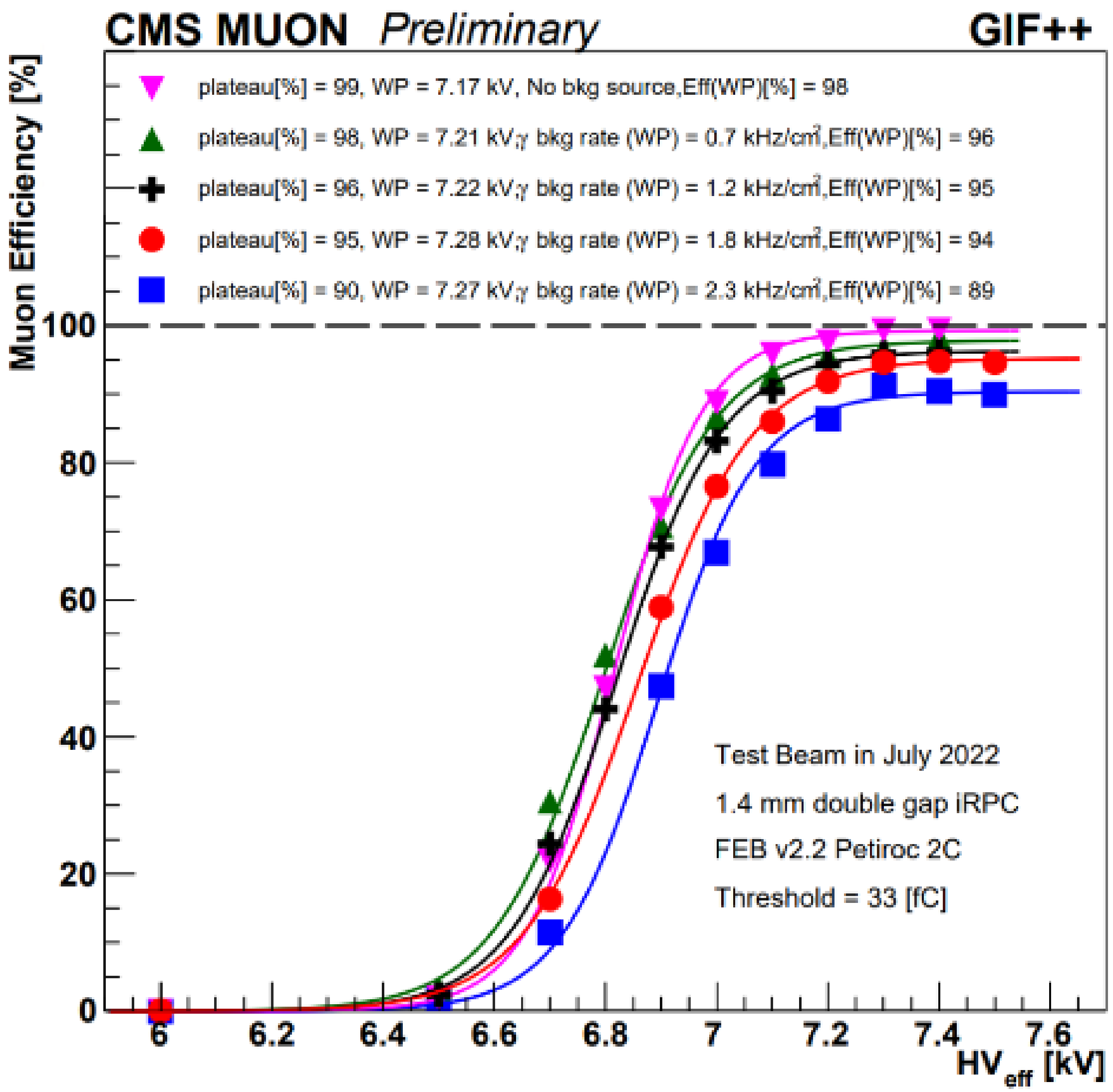
- A full-scale CSC longevity study using 5% CF_4 started in GIF++ in September 2022. No evidence of performance degradation has been observed so far.
- A new gas $C_3H_2F_4$ (HFOze) GWP~6 to replace $C_2H_2F_4$ (TFE)GWP~1430 is studied for the RPCs.







	LHC	HL-LHC baseline (ultimate)
Instant. Luminosity ($cm^{-2}s^{-1}$)	10^{34}	5 (7.5) 10^{34}
Integrated Luminosity (fb^{-1})	300	3000 (4000)
Pile- Up	30	140 (200)
	CMS Phase 1	**CMS Phase 2**
L1 trigger accept (kHz)	100	750
L1 accept latency (µs)	3.6	12.4



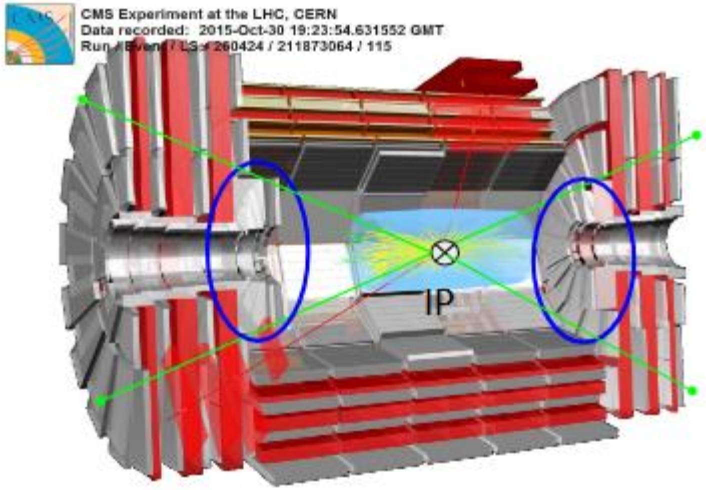
	RPC	iRPC
Gas gap width	2 mm	1.4 mm
HPL thickness	2 mm	1.4 mm
Resistivity	1-6 × 10^{10} Ω·cm	0.9-3 × 10^{10} Ω·cm
Charge threshold	150 fC	50 fC
η space resolution	17 cm (3 η partitions)	2 cm (2D readout)
ϕ strip pitch	0.3 degrees	0.2 degrees
Intrinsic time resolution	1.5 ns	0.5 ns

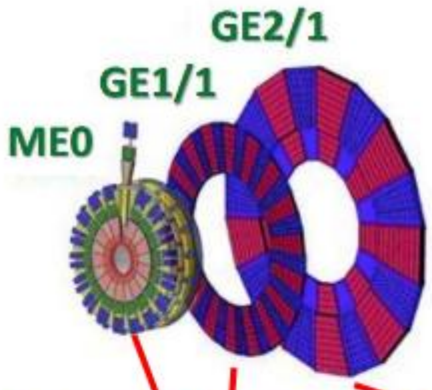
	#chambers
COMPASS	20
TOTEM	40
LHCb	~24
CMS GE1/1	144
CMS GE2/1	*72*

https://www.sciencedirect.com/science/article/pii/S0920563203910188?via%3Dihub

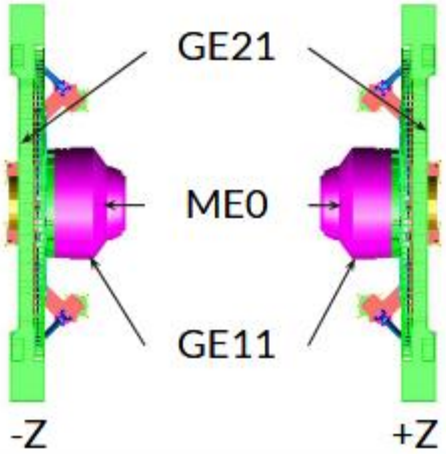
https://linkinghub.elsevier.com/retrieve/pii/S0920563211002544

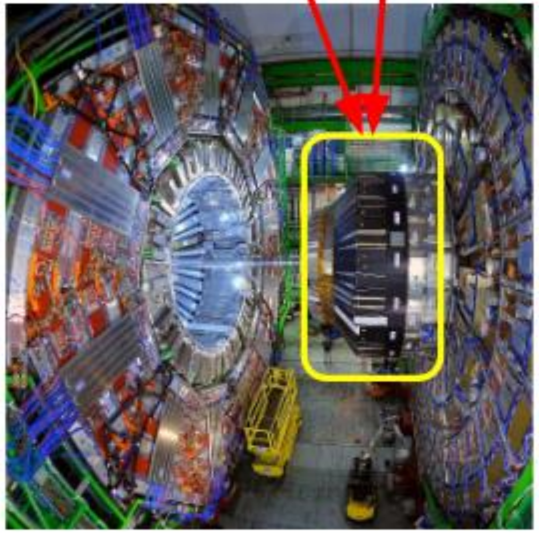
https://cds.cern.ch/record/1495070/files/LHCb-PROC-2012-060.pdf

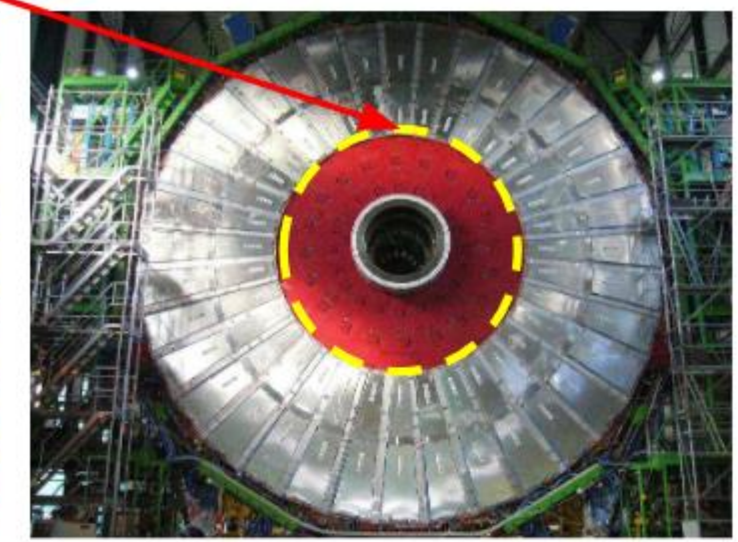




The Muon detector upgrade will preserve and enhance the performance of the CMS muon system in the **Forward** and **High eta** (1.5~2.8) region by installing new forward muon detectors such as GEM (ME0, GE1/1, GE2/1) and iRPC (RE3/1, RE4/1) in the Phase 2.

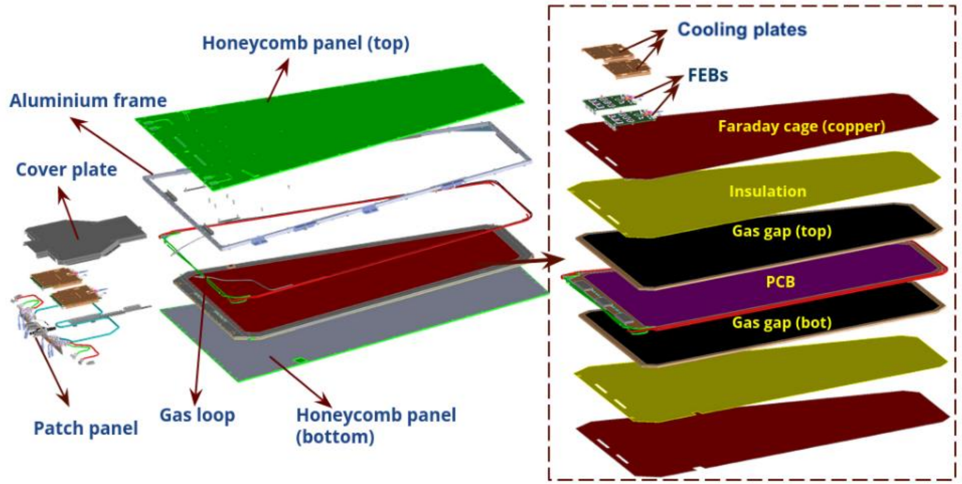


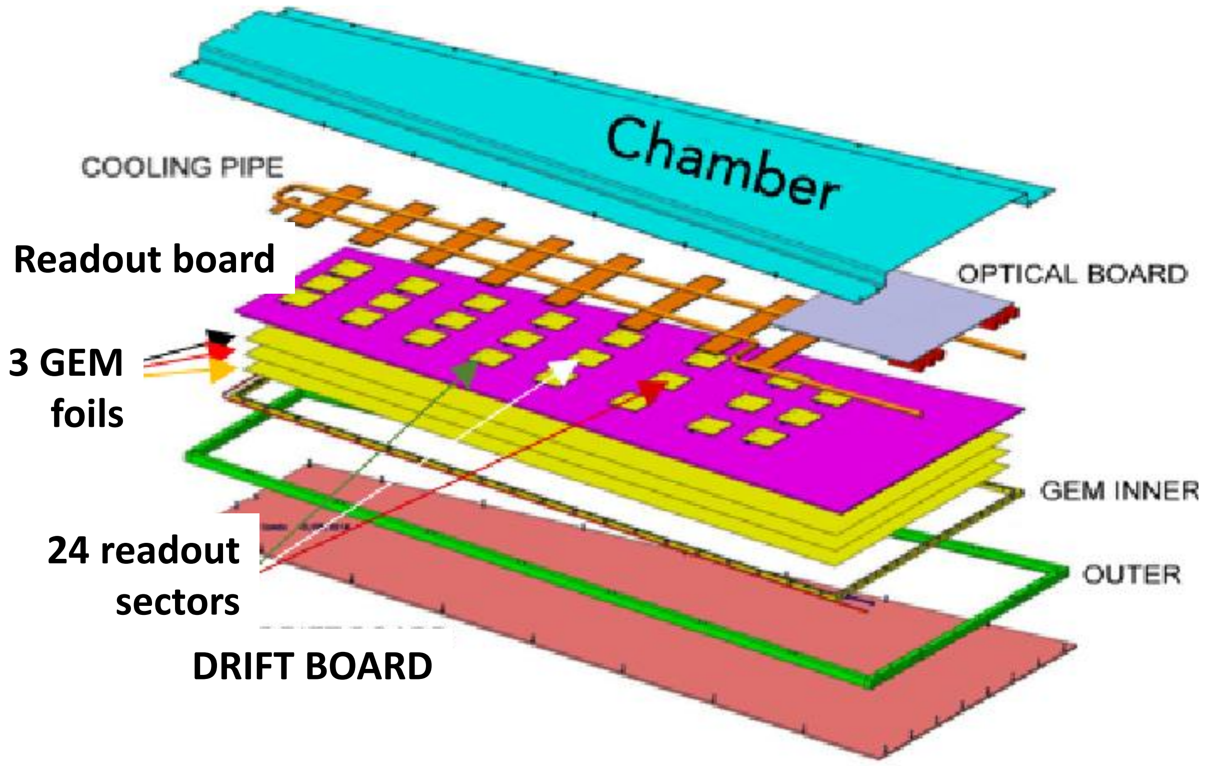




CMS Forward Muon System Upgrade

iRPC https://cds.cern.ch/record/2922533/files/CR2024_343.pdf
https://www.sciencedirect.com/science/article/pii/S0168900224003267?via%3Dihub





https://indico.cern.ch/event/1482887/contributions/6248411/attachments/2977490/5241945/20241209_scalzafe_DRD1_GEMOperations_V2.pdf

https://twiki.cern.ch/twiki/bin/view/CMSPublic/CSCDPGPublic241012A
csc

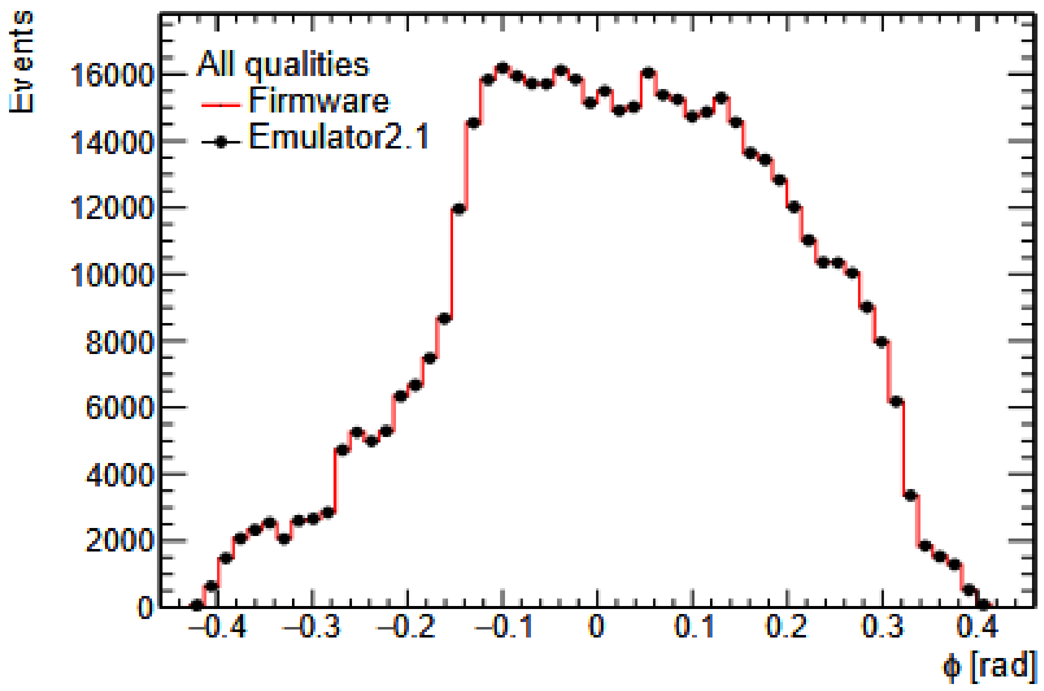
https://cds.cern.ch/record/2916183/files/DP2024_089.pdf

https://twiki.cern.ch/twiki/bin/view/CMSPublic/CSCDPGPublic240701

https://twiki.cern.ch/twiki/bin/view/CMSPublic/GEMDPGPublic

https://www.frontiersin.org/journals/detector-science-and-technology/articles/10.3389/fdest.2025.1517241/full

https://twiki.cern.ch/twiki/bin/view/CMSPublic/DTSliceTestResults20240708ATRUNCOORDINATION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Firmware
Emulator2.1
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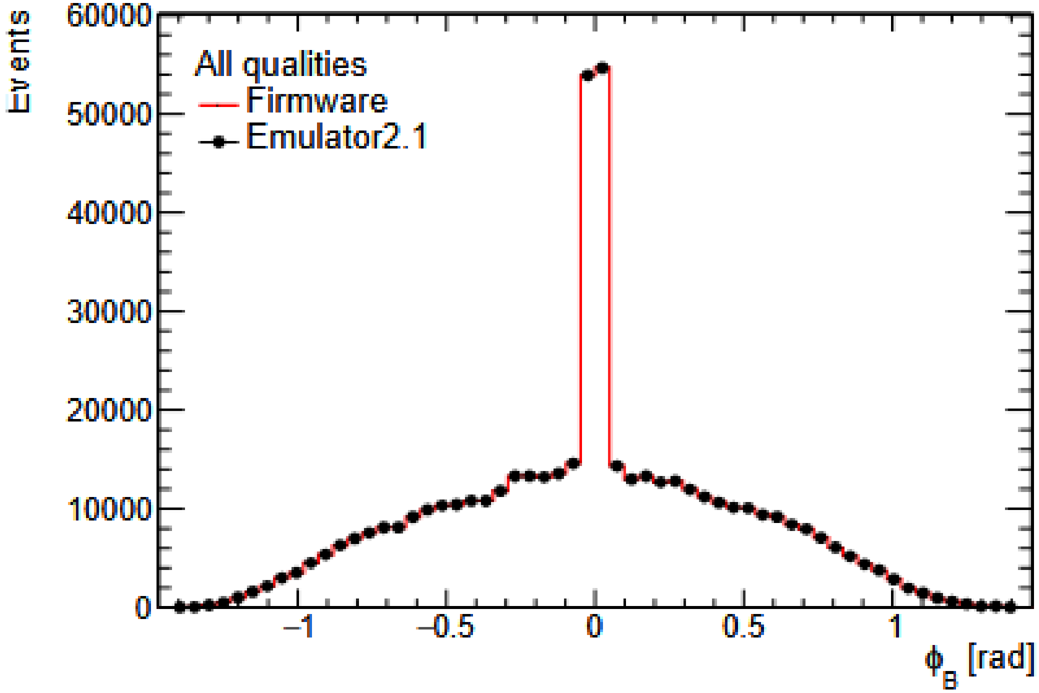
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DT upgrade system