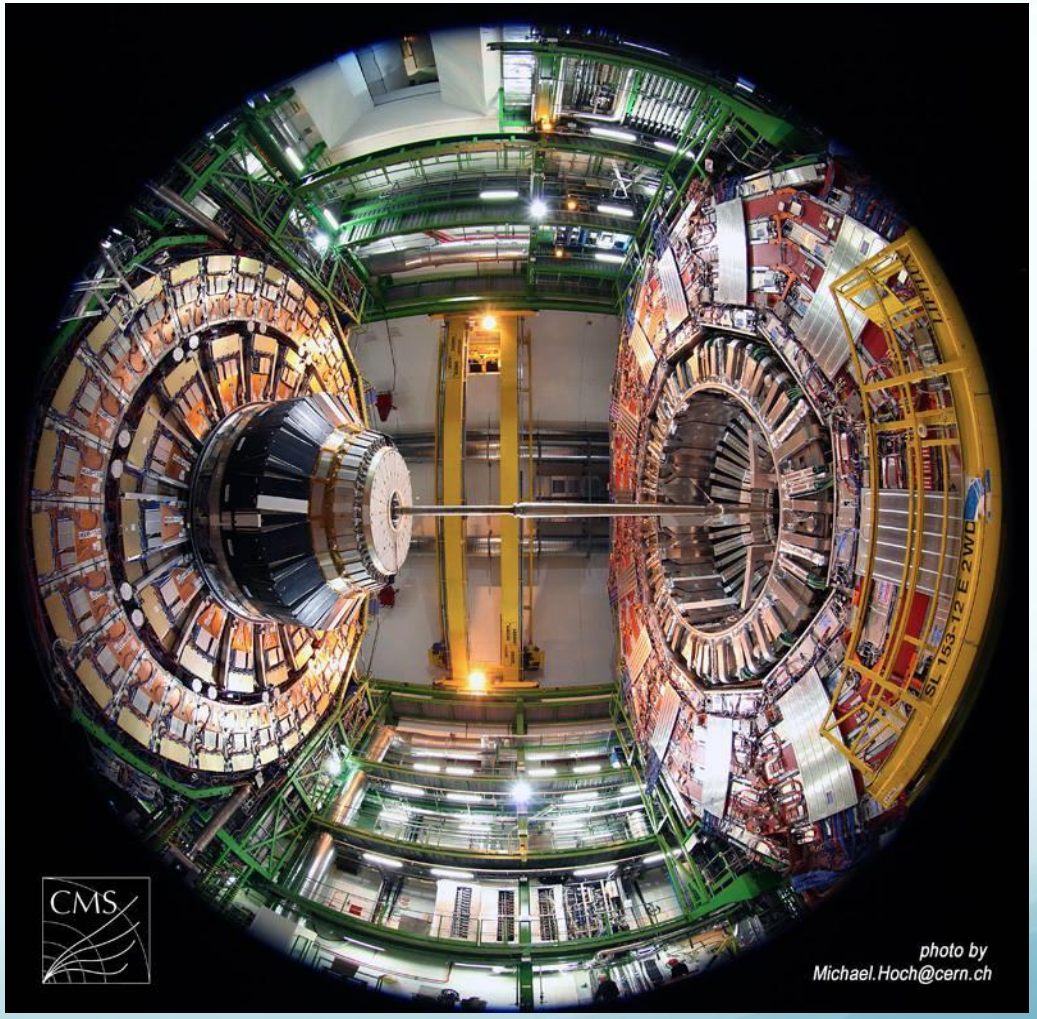
The Muon Detector at CMS

Gabriella Pugliese
INFN and Politecnico of Bari

on behalf of the CMS Experiment



XIII International Conference on New Frontiers in Physics, OAC, Kolymbari, Crete, Greece 26 Aug – 4 Sept 2024

The CMS detector @ LHC

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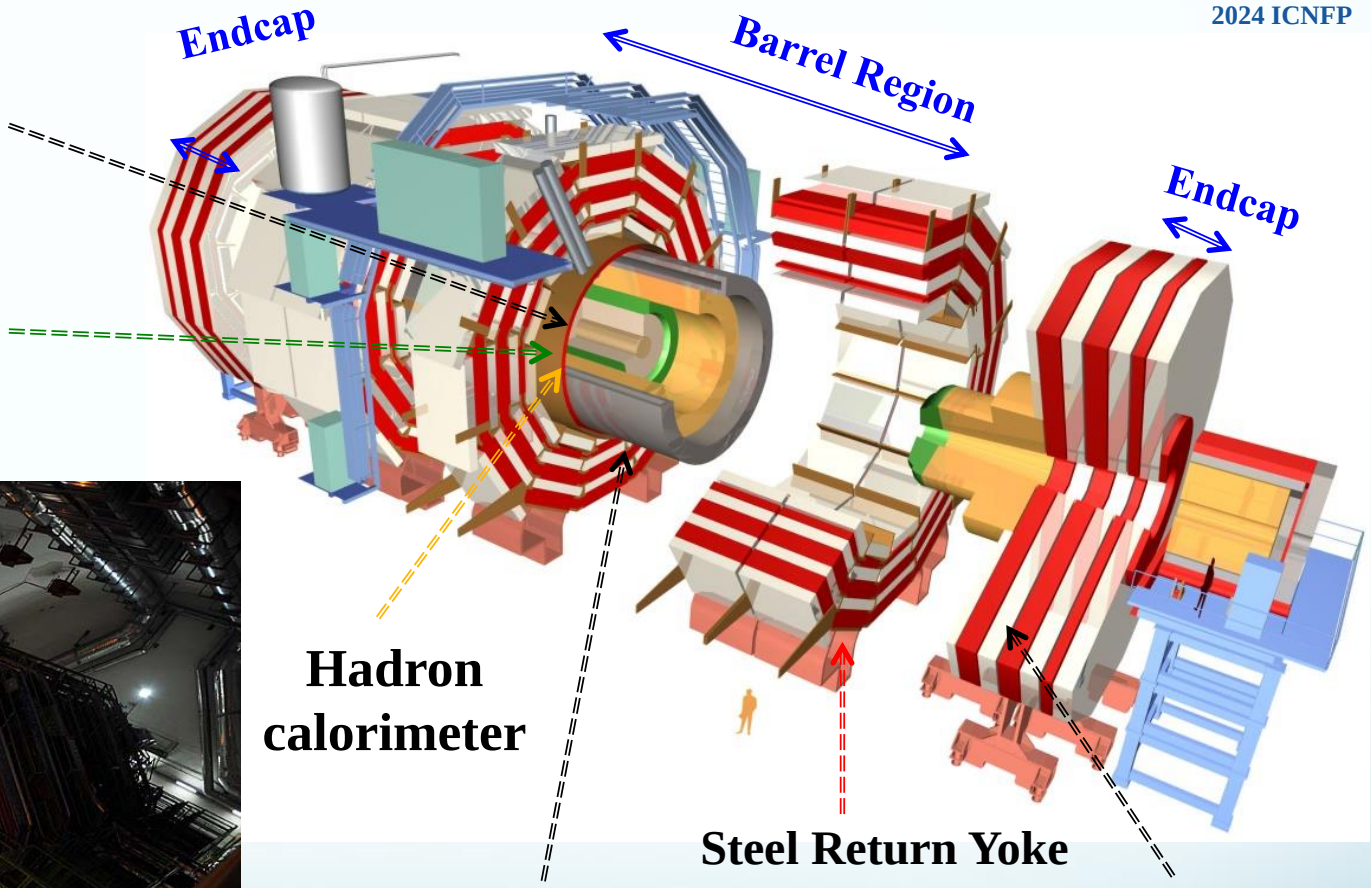

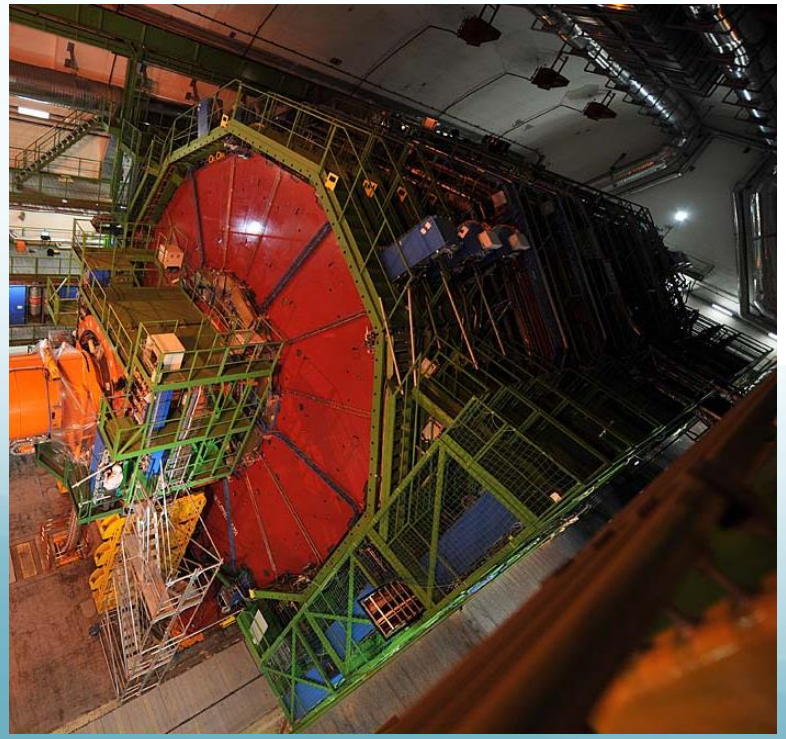

Length: 28.7 m
Diameter: 15 m
Magnetic field: 3.8 T

The CMS Muon Spectrometer

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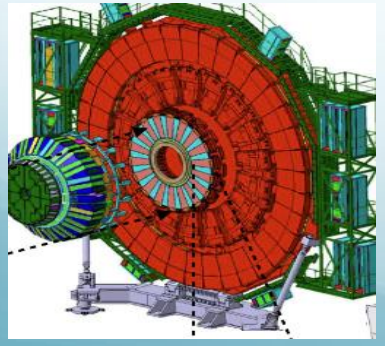
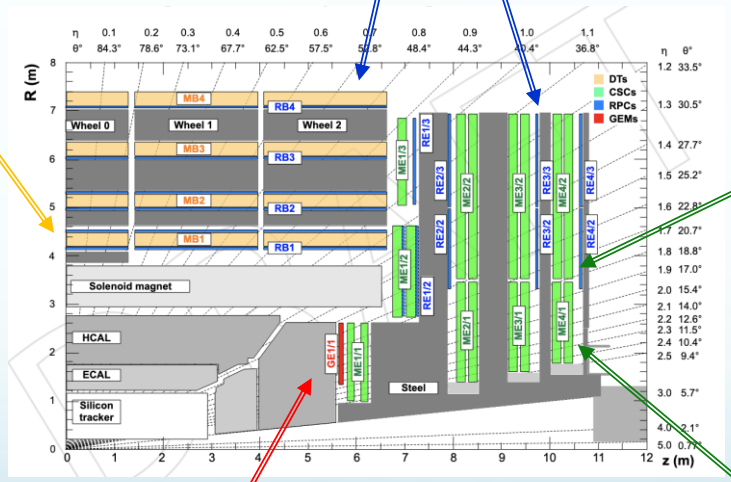
Muon system: ~~three~~ four gaseous technologies for muon identification, timing and momentum measurement

Muon acceptance: |η| < 2.4

Drift Tubes (DT)
- 250 chambers, ≈ 170k channels
- 44 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



Gas Electron Multiplier (GE1.1 installed in 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

The CMS and LHC schedule

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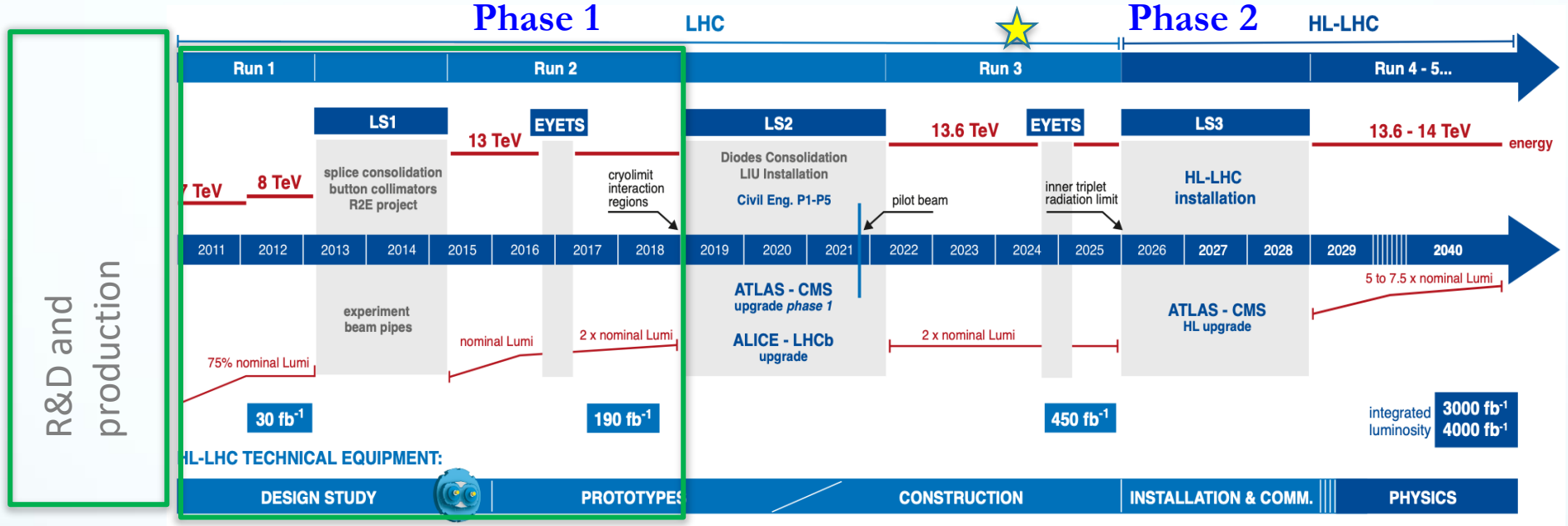
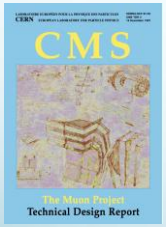
Today

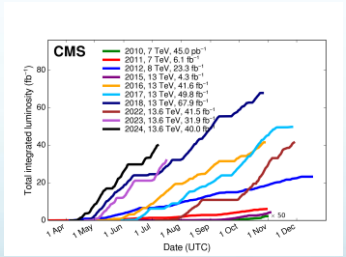


Run 1 & Run 2

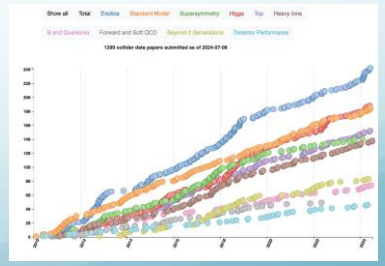
→ Total integrated luminosity



1997 Muon Project TDR



→ 1299 papers published



2005-2008 Muons Chambers produced and installed

2010 Start of LHC

2012 Higgs Discovery

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

LHC and HL-LHC schedule

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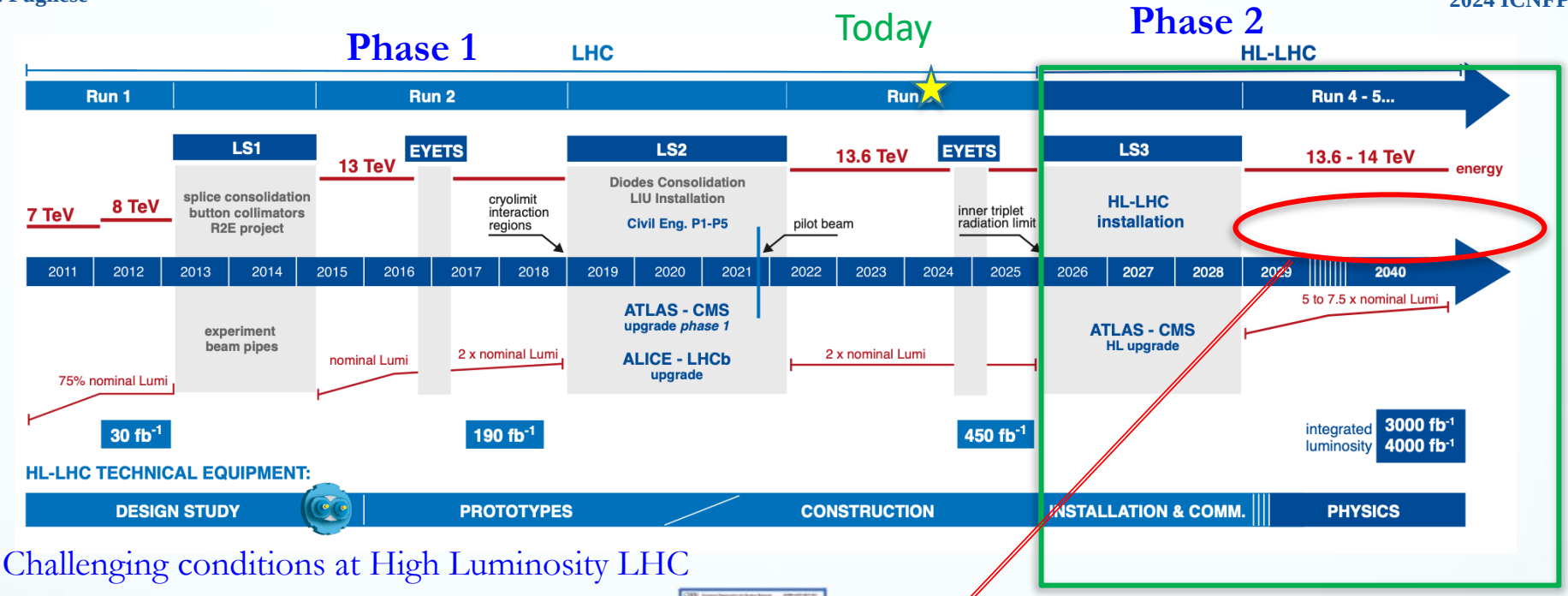
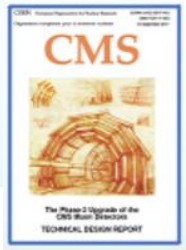
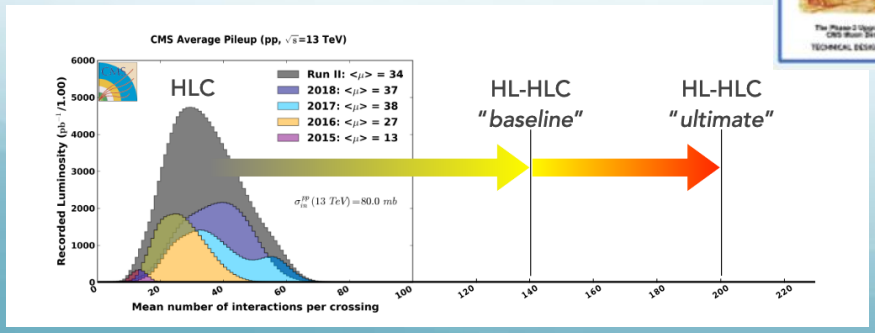


Challenging conditions at High Luminosity LHC

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



	LHC	HL-LHC baseline (ultimate)
Instantaneous lumi ($cm^{-2}s^{-1}$)	10^{34}	**5 (7.5) x 10^{34}**
Integrated Lumi (fb^{-1})	300	**3000 (4000)**
Pile Up	30	**140 (200)**



CMS detector must be upgraded to cope with HL-LHC conditions (see R. Venditti's talk)

LHC and HL-LHC schedule

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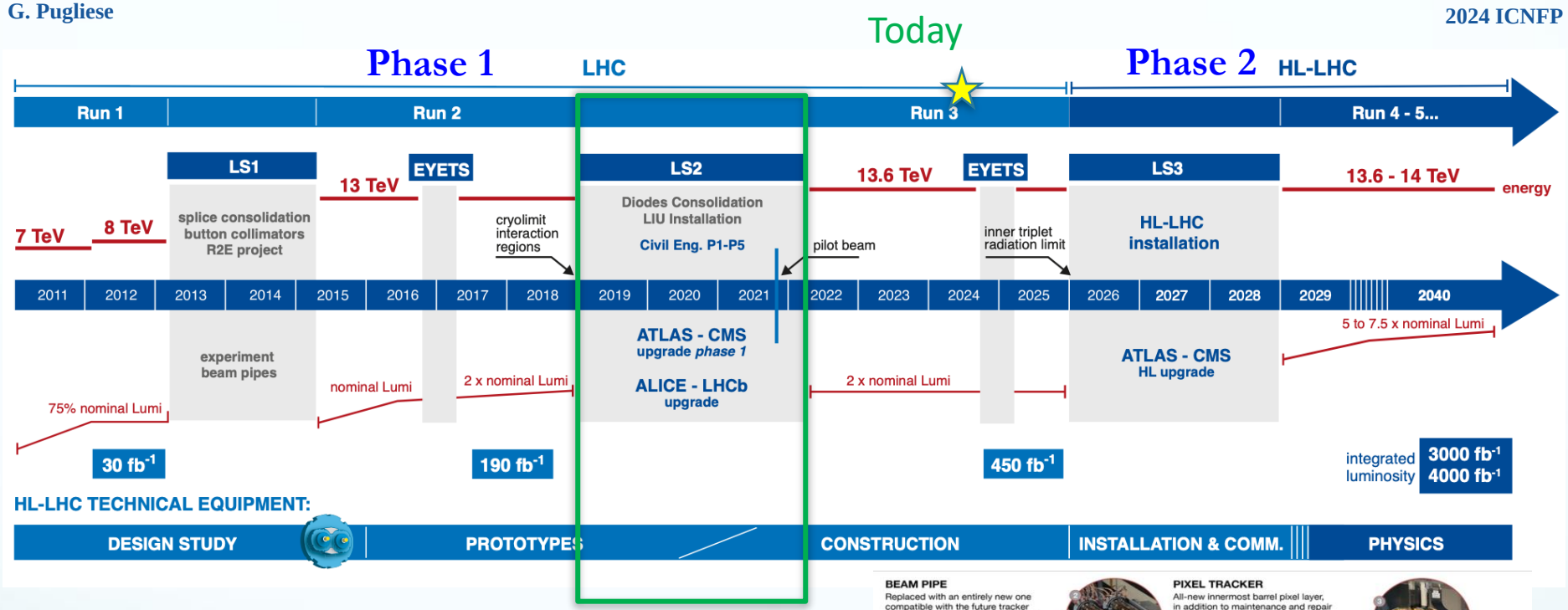
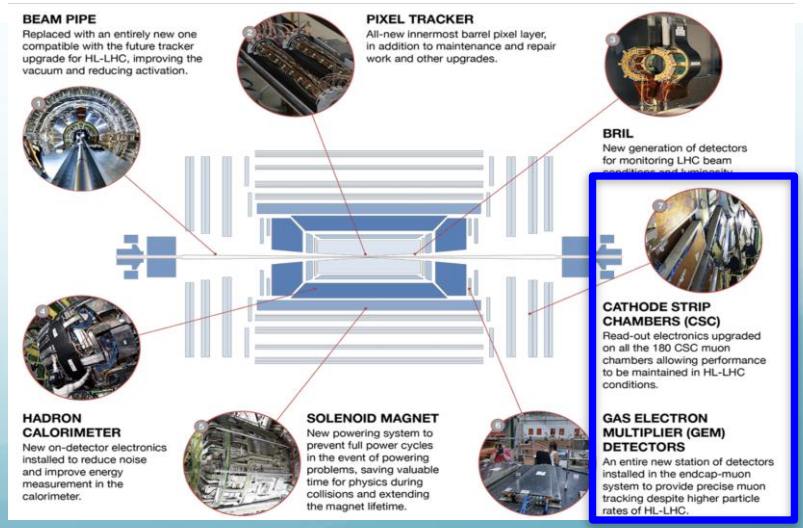


Long Shutdown 2 (2019-2021):

- Extensive work to upgrade the CMS detector because of the increase of energy and luminosity in Run 3 and beyond
- New GEM chambers and CSC electronics in the Muon Spectrometer



https://home.cern/press/2022/CMS-upgrades-LS2

Run 3 operation

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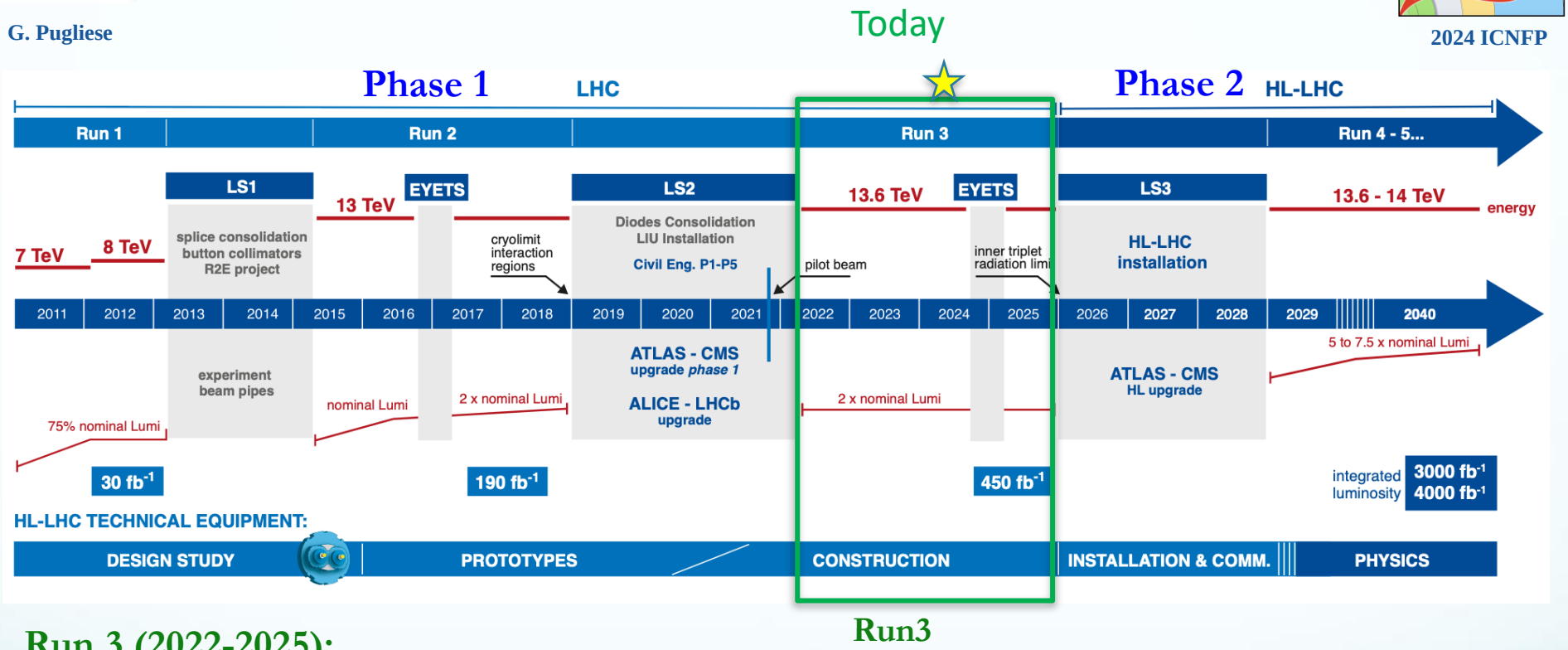
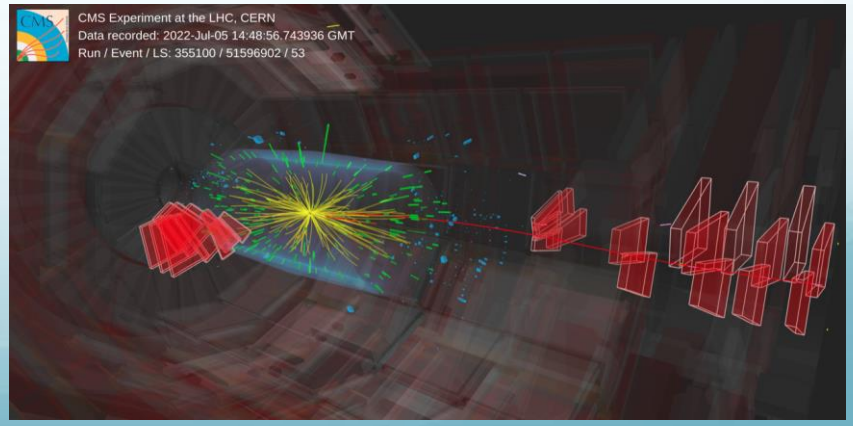


Run3

Run 3 (2022-2025):

- Started on **5th July 2022 with the** first stable beam energy record of 13.6 TeV
- ➢ Excellent CMS data-taking efficiency >92% in RUN3 physics collisions
- ➢ Muon System is running smoothly with a minor contribution to Luminosity loss (~4%)

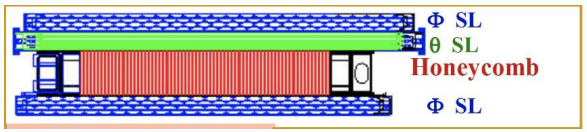


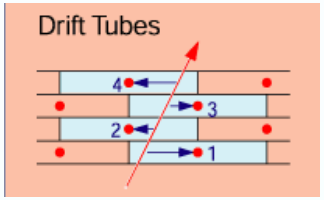
Muon performance in RUN 3

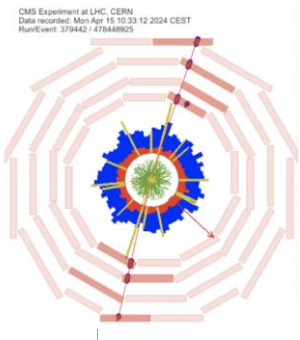
DT Segment Efficiencies in Run 3

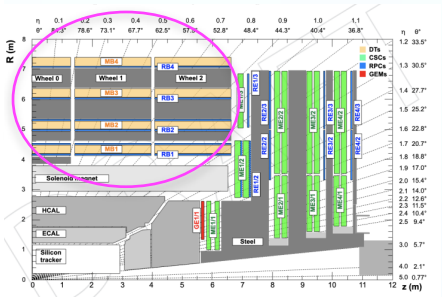
G. Pugliese

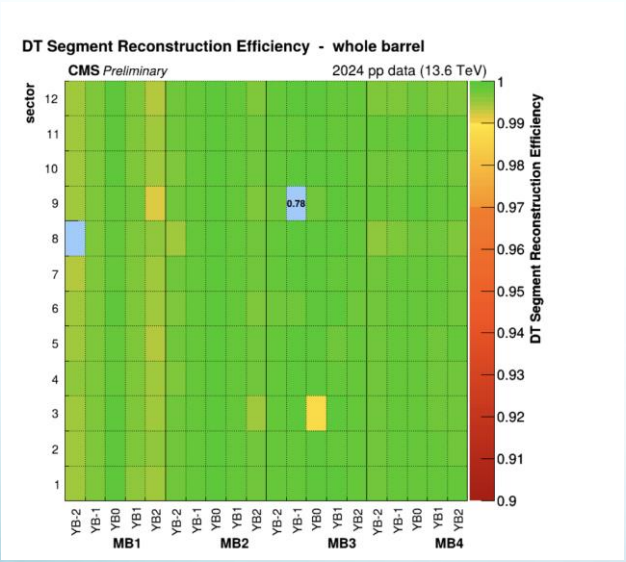
Segment efficiency is studied with Tag &Probe method on di-muons

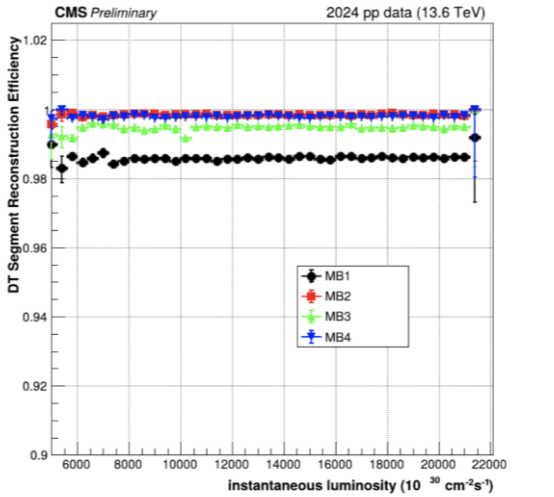




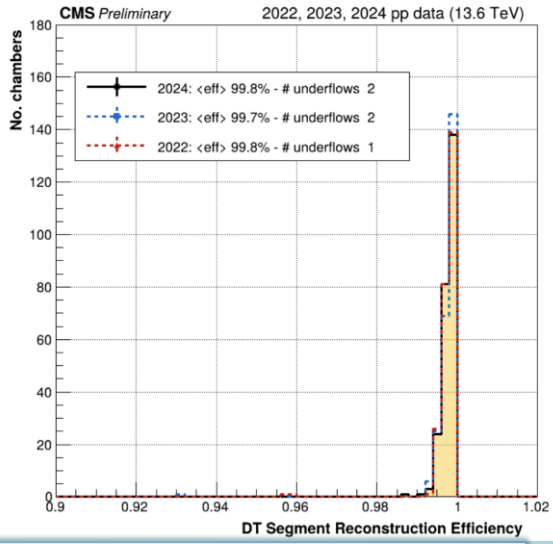








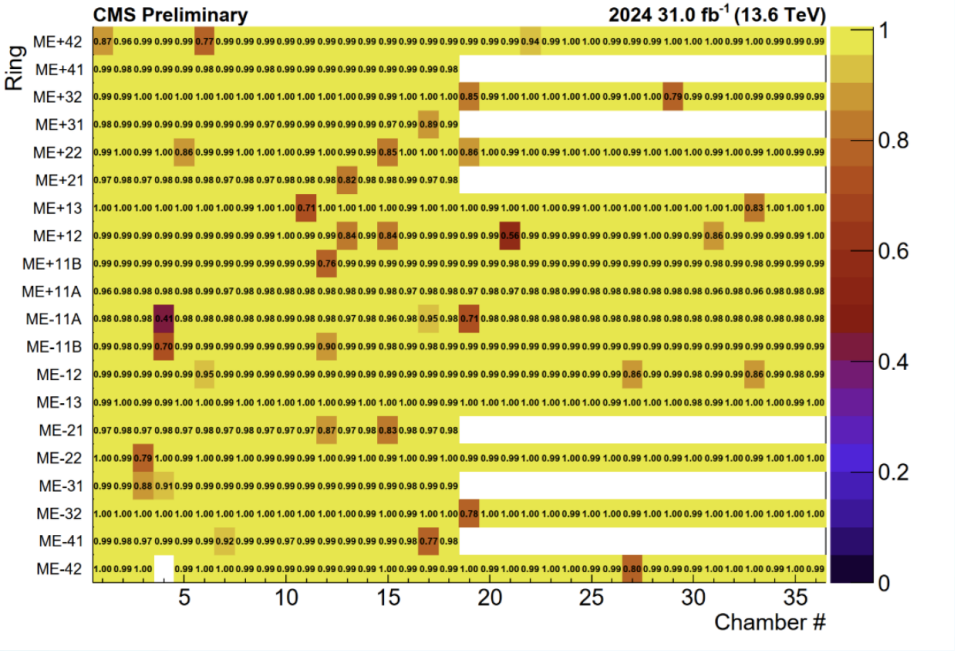
Segment efficiency shown as a function of LHC instantaneous luminosity for the four DT stations

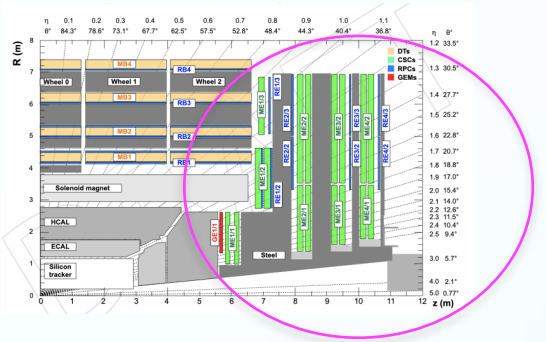


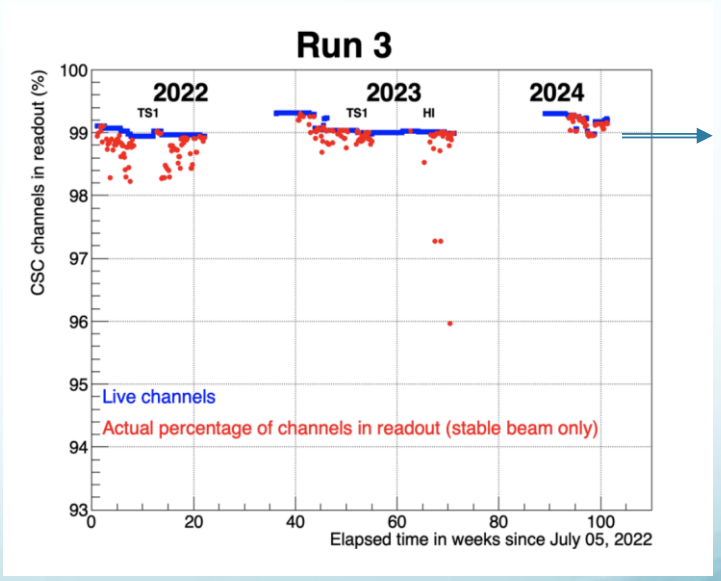
- **DT segment efficiency is more than 99%** with few exceptions due to known hardware problems (one chamber in Wheel -2 Sector 8 MB1 is not working because of a gas connection problem and will be fixed over the coming YETS)
- **Stable in time and with luminosity**

CSC performance in 2024

G. Pugliese







99%

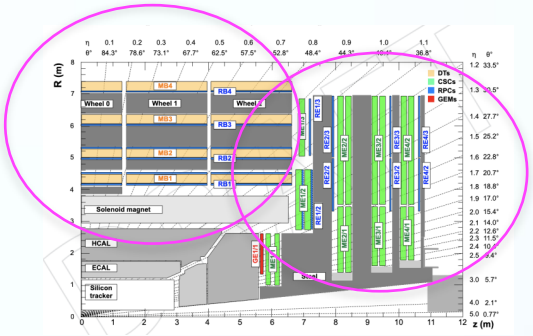
- CSC Segment efficiency: more than 98% of the CSCs is operating at close to 100% efficiency. Few chambers with lower efficiency are due to known reasons (electronics board failures, that cannot be fixed without access to the chambers, or accessional temporary failures

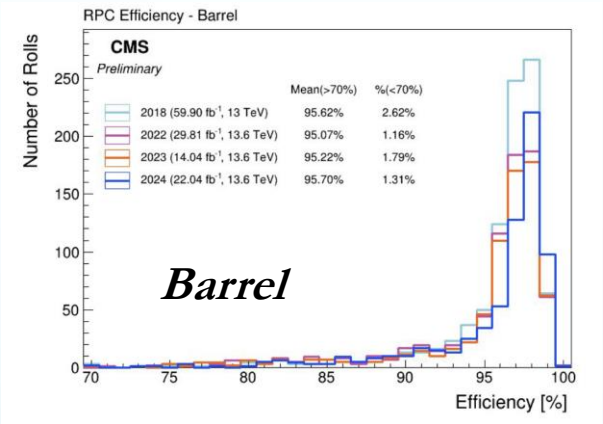
- Stable active channels fraction

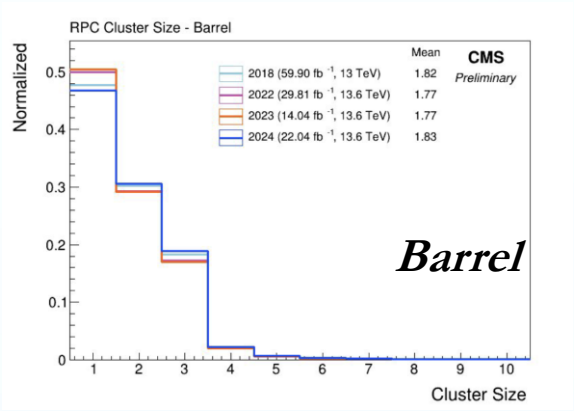
RPC performance in Run 3 (Barrel region)

G. Pugliese

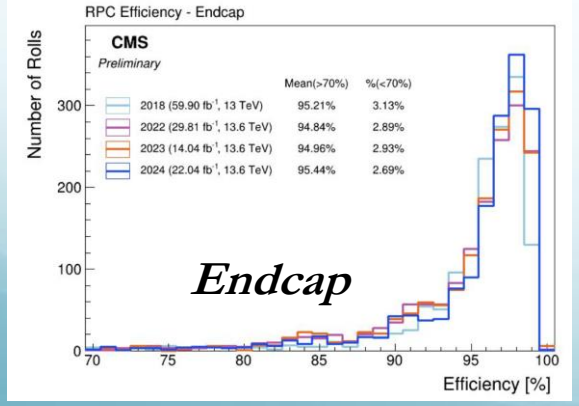
- **RPC performance** is measured using the Segment Extrapolation Method where DT/CSC Segments (in the Barrel/Endcap) that belong to a standalone muon track with timing corresponding to RPC readout BX windows are selected and extrapolated to the plane of a given RPC

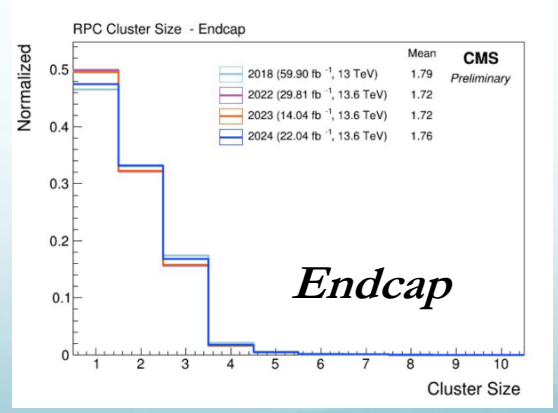






- **Stable RPC performance in RUN 3 and RUN 2**



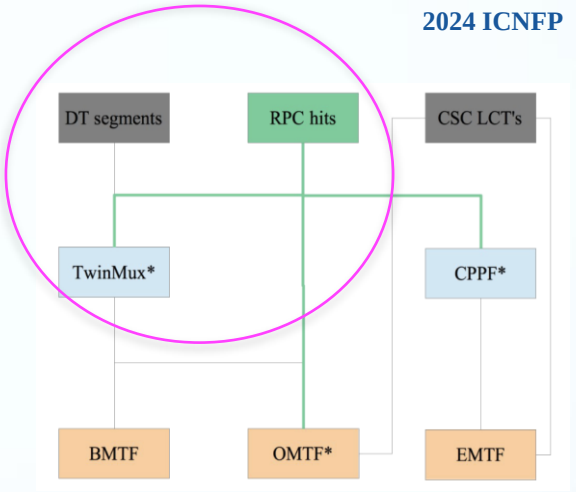


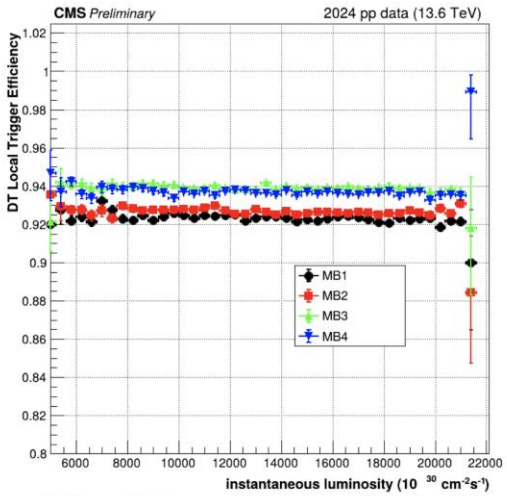
RPC Efficiency distributions ***RPC Cluster size distributions***

Local trigger and TwinMux performance

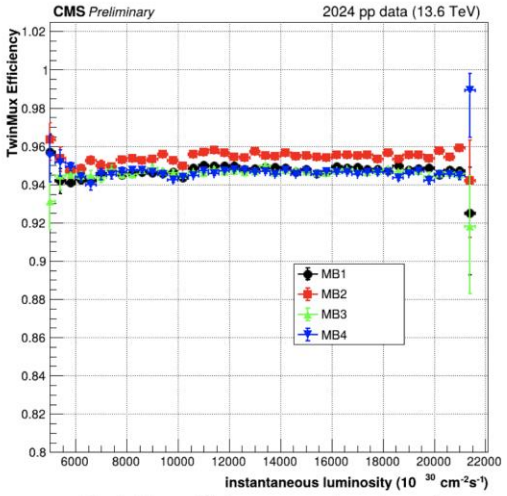
G. Pugliese

- In the Barrel region, DT and RPC information is processed in two stages to provide optimal online reconstruction inputs to Level-1 Muon Trigger Track Finders.
- In the first layer, TwinMux boards match RPC hit clusters with DT Local Trigger segments to:
  - **recover DT inefficiencies** using **RPC-only primitives** (limited to MB1 and MB2 stations)
  - **improve BX identification efficiency** by taking advantage of the RPC's excellent time resolution





DT Local Trigger efficiency as a function of LHC instantaneous luminosity



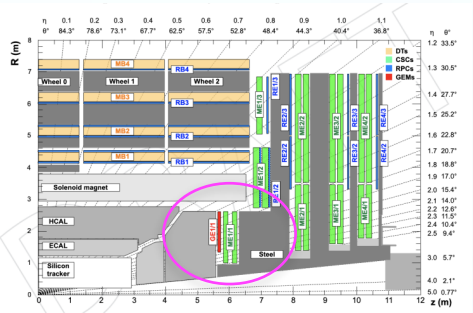
TwinMux efficiency as a function of LHC instantaneous luminosity

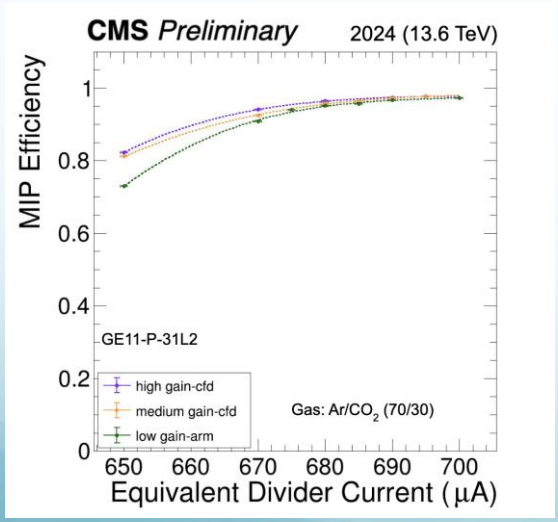
- **DT local trigger and TwinMux efficiency are both stable** as a function of LHC instantaneous luminosity
- **TwinMux efficiency is higher than the DT local trigger efficiency of:**
  - ~3% in the MB1 and MB2
  - ~1.5% in the MB3 and MB4

GE1/1 calibration in 2024

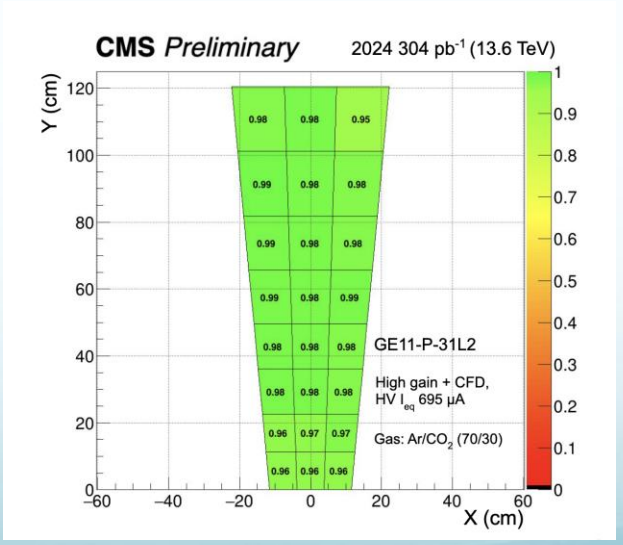
G. Pugliese

- **Calibration runs** were taken in 2024 at different HV settings and Frontend chip (VFAT) configurations:
  - Pre-amplifier [low, medium, high] gain
  - Comparator mode [ARM, CFD].
- GEM analysis done using events with standalone (STA) muons (p_T > 10 GeV, with at least 15 hits in the muon system, and χ_2 < 5) and with hits in the CSC companion station (i.e. accept a track through GE1/1 only if it contains ME1/1 hits)

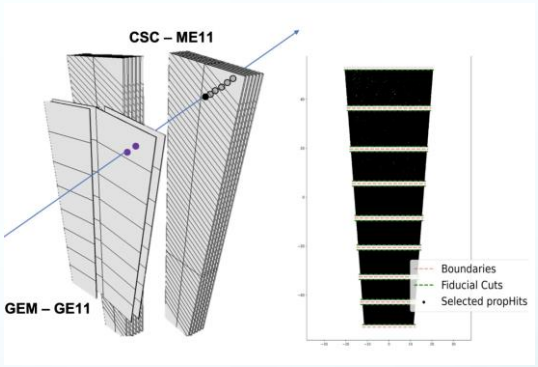




GE1/1 efficiency vs. current



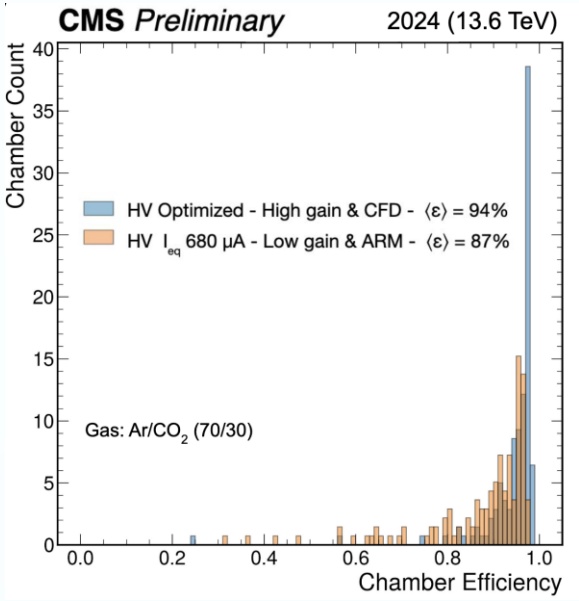
GE1/1 efficiency map



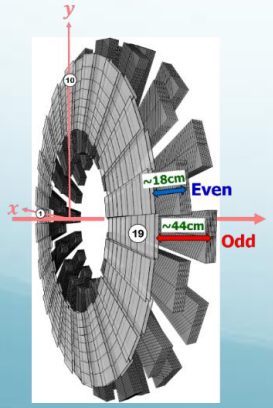
GEM performance in RUN3

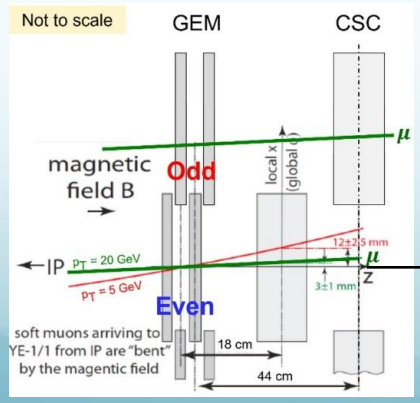
G. Pugliese

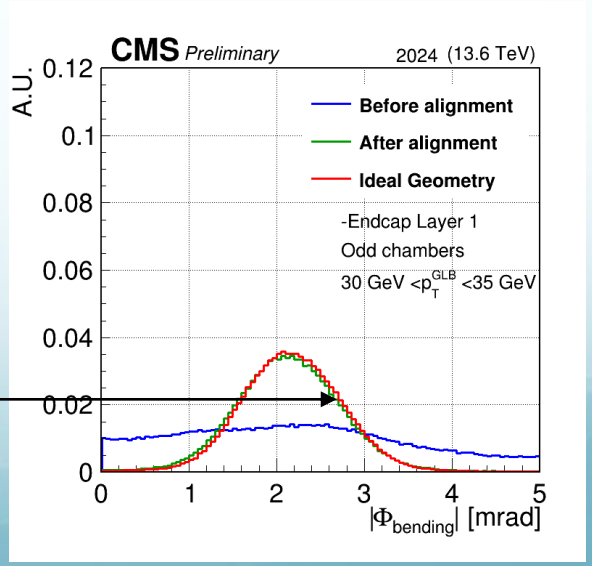
- Based on the 2024 calibration results, a new HV setting was applied in June, increasing significantly the GE1.1 efficiency to 94% (with an HV-optimized and High gain Constant Fraction Discriminator)



- Fully validated the **alignment** for trigger capability: the Banding Angle distributions after the alignments are close to the ideal case







Muon Upgrade project for the HL-LHC period

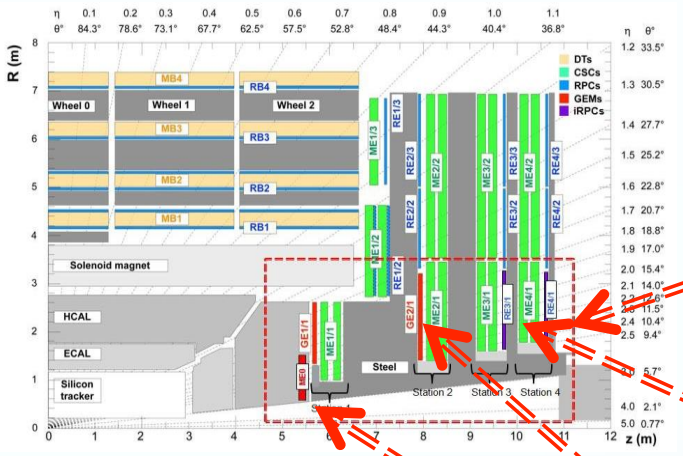
Muon Upgrade Project

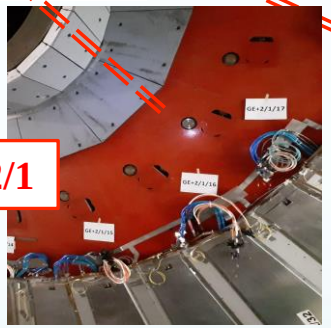
G. Pugliese

2024 ICNFP

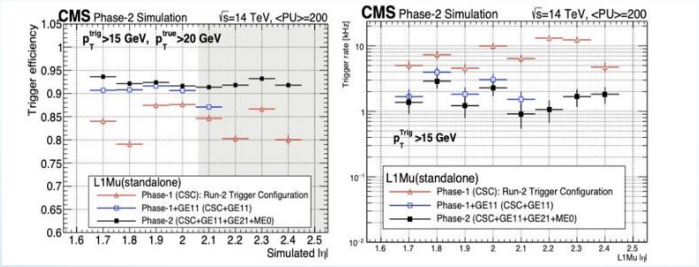
1. New detectors will be installed in the high-eta region to:

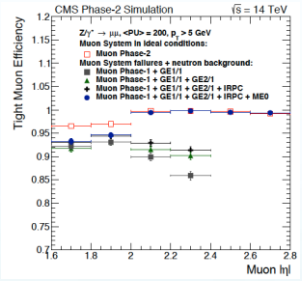
- Restore redundancy
- Extend the muon coverage up $\eta = 2.8$
- Improve Trigger efficiency without increasing the trigger rate
- Improve Muon reconstruction





ME0





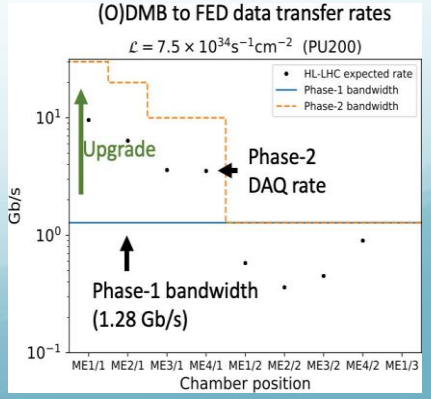
2. New electronics for the legacy detectors:

DT: replace all on-board electronics (OBDT), BE

RPC: replace all off-chamber electronics, BE

CSC: replace selected FE boards, replace all BE

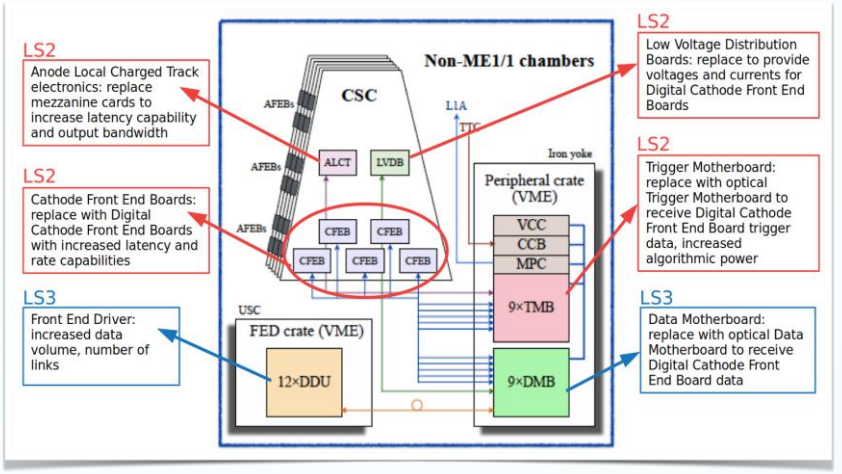
3. Longevity Studies (including the use of ecological gas mixtures, see L. Congedo's talk)



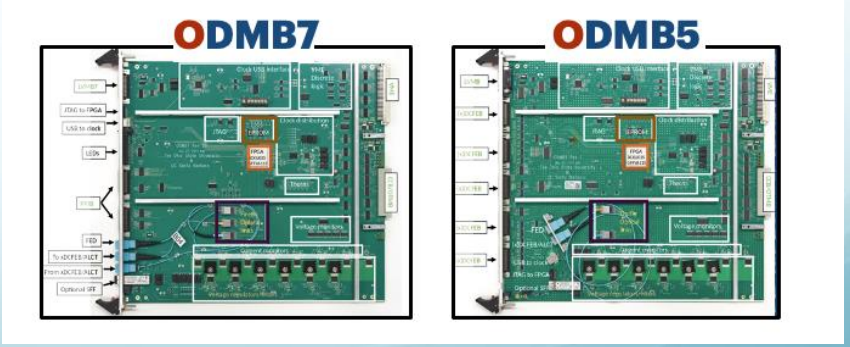
The CSC Upgrade

G. Pugliese

- The majority of the CSC upgrades was completed in LS2 (anticipating some activities originally scheduled for LS3)
- In LS3, the CSC upgrade will focus on off-detector upgrade, including the replacement of the data Motherboard with new version boards (Optical DMB) and the upgrading of the BE
- A total of 72 ODMB7 boards for ME1/1 & 108 ODMB5 boards for ME234/1 need to be produced



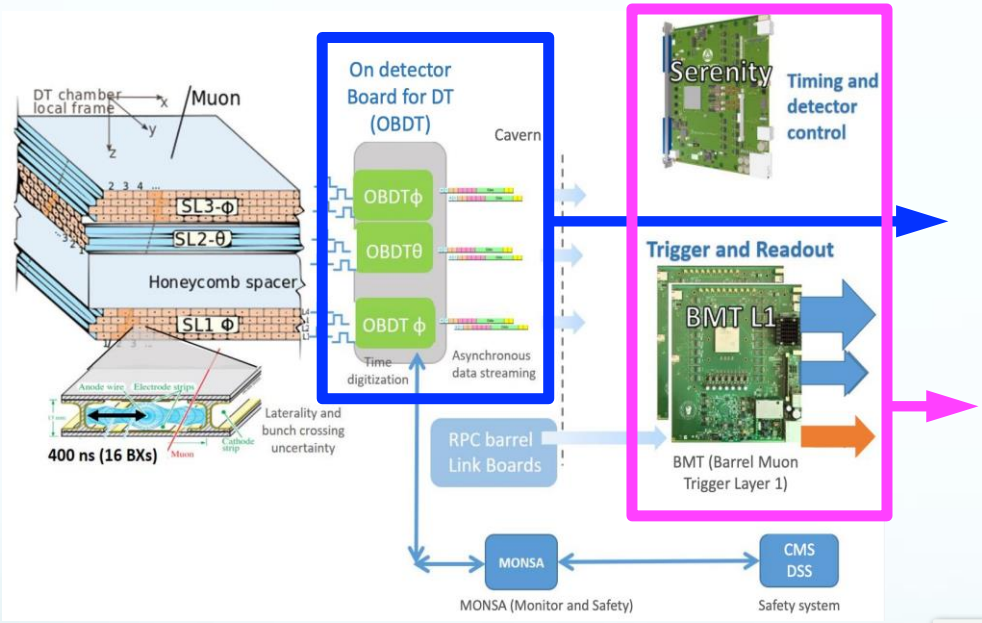
- **ODMB5/7 status:**
  - The pre-production boards were designed, produced, and tested
  - The design was finalized after going through various irradiation tests on different components
  - Production is on schedule: the boards will be tested at UCSB (University of California) and are expected at CERN in early spring 2025



The DT Upgrade

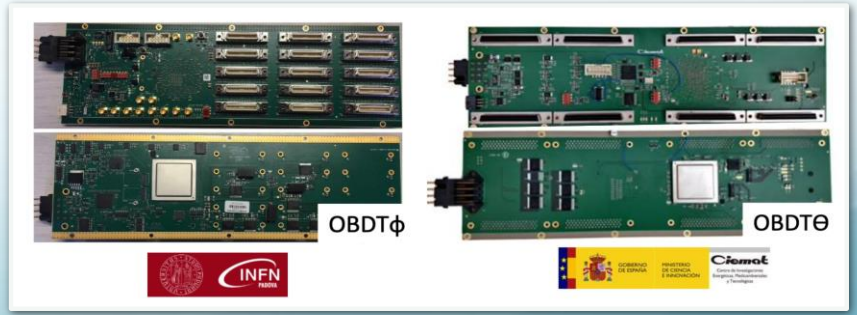
G. Pugliese

- In LS3, the DT upgrade will focus on:



- **New On-Board DT (OBDT) electronics for Theta/Phi chambers:**
  - TDCs implemented in FPGA
  - Improved performance, radiation hardness, and simplified maintenance
  - Comply with HL-LHC requirements
- **The new Trigger logic system moved to the back-end outside of the CMS cavern with the following improvements:**
  - Trigger Primitives are built by exploiting the ultimate DT cell resolution
  - Increased flexibility in combining DT and RPC hits to form TPs
  - Enhanced resilience to detector aging and failures

- The OBDT prototypes have been fully validated (see the next slide)
- The DT Upgrade production has started and is on schedule

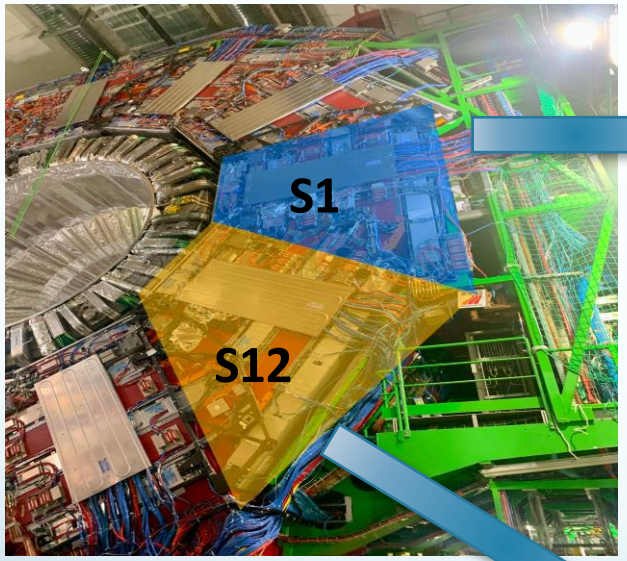


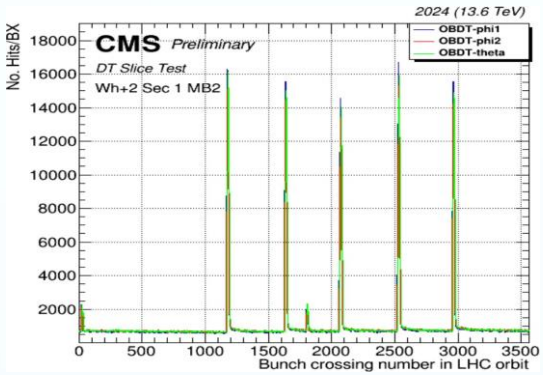
OBDT Prototype v2.0

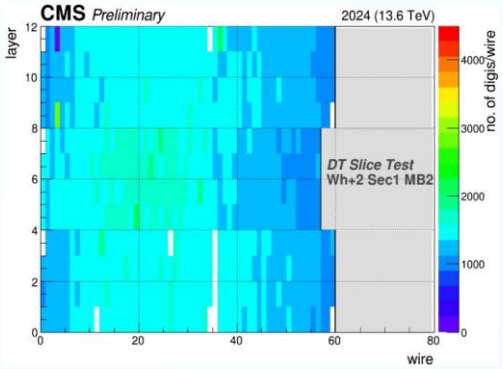
DT Upgrade: slice test

G. Pugliese

To test the new electronics under realistic conditions in the CMS environment, a **DT slice-test demonstrator** has been running since 2019. The data from two sectors have been split and read by both the legacy and new OBDT electronics (initially sector 12 was equipped with OBDTs v1, and later sector 1 with the OBDTs v2)

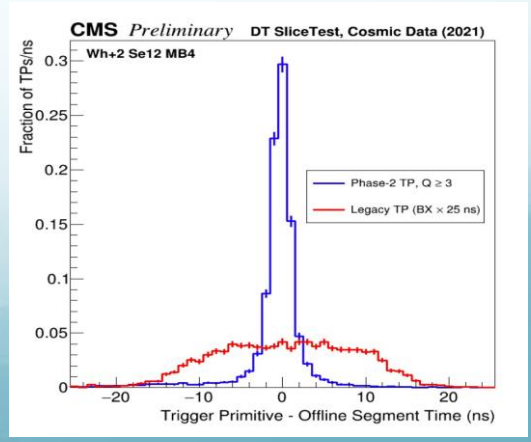






Occupancy map for one chamber is as expected

Time measurement distribution: it is visible the beam structure with 5 bunch trains of 12 colliding bunches each plus two single colliding bunches



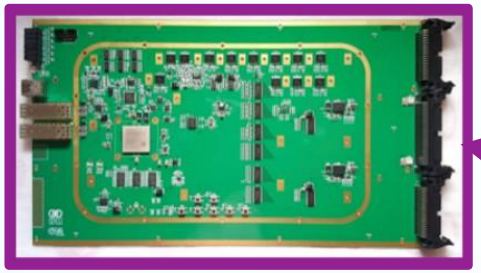
The local trigger performance has a resolution comparable to the offline reconstruction

RPC Upgrade

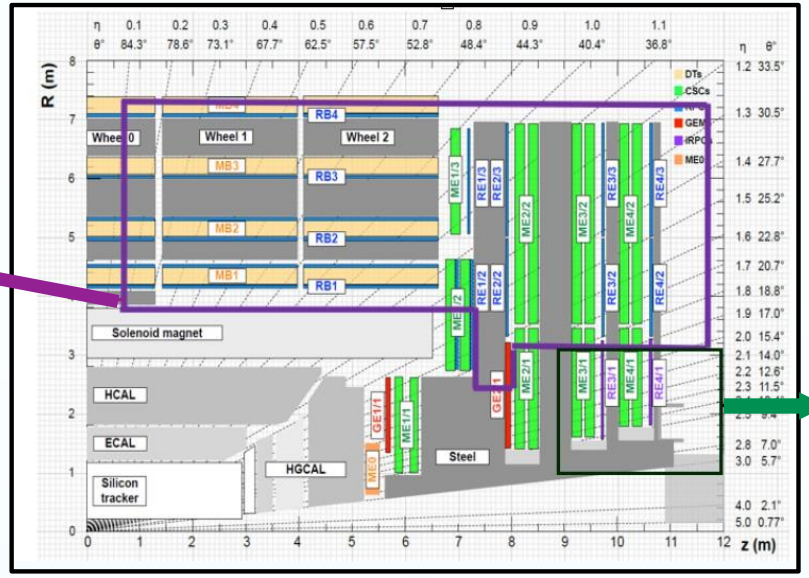
G. Pugliese

2024 ICNFP

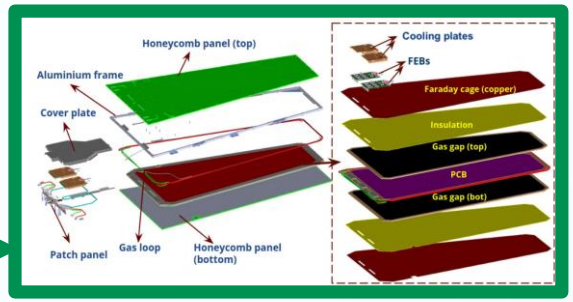
New RPC Link system



- **New Link System:**
  - Improve Trigger hit time resolution from **25 ns to 1.56 ns**
  - Data transmission speeds up to **10.24 Gbps**



New Improved RPCs for Ring 1 of end-cap discs 3/4 (RE3/1, RE4/1)



- 1 chamber =1.6x 1.2 m^2
- Total 72 iRPC (20^0) chambers
- $1.8 < |\eta| < 2.5$

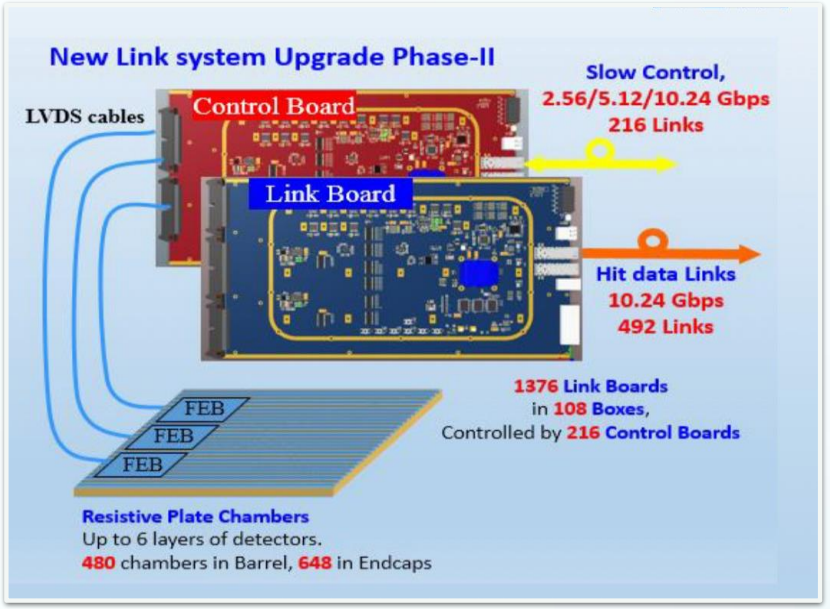
New RPC Link System Upgrade

G. Pugliese

- In LS3 the current RPC Link system will be replaced with a new higher-performance Link System

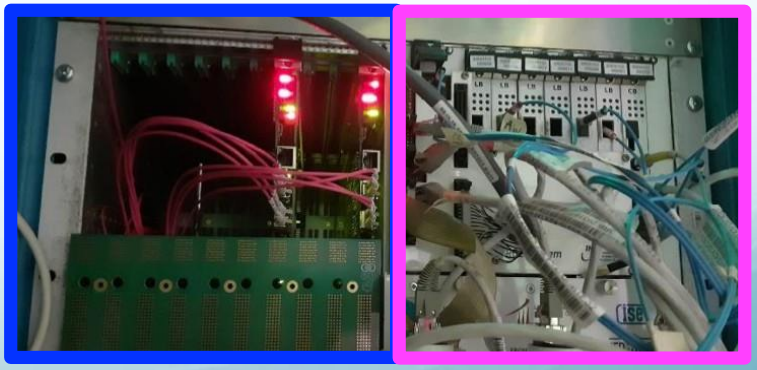
- **Key Features of the new Link System**

- **14 Layer** PCB, 40 × 28 cm2
- FPGAs are KINTEX-7, XC7K160T – Industrial Version
- Muon hit time, TDC timing Resolution: **1.56 ns**
- Master Link board output data rate: **10.24 Gbps**
- Control Board communication with RPC Backend electronics: **4.8 Gbps**



Project status:

- The irradiation tests of various components and FPGAs for the new boards are completed. The electronics meet the HL-LHC radiation requirements with high safety factors
- A demonstrator was installed at the CMS in February 2024 to monitor system behavior under realistic conditions. The system has operated continuously and reliably for five months, with no change in performance or stability
- Pre-production is expected to be delivered to CERN by the **end of 2024**



New Link System (left) and present Link System (right) at CMS experimental cavern (UXC)

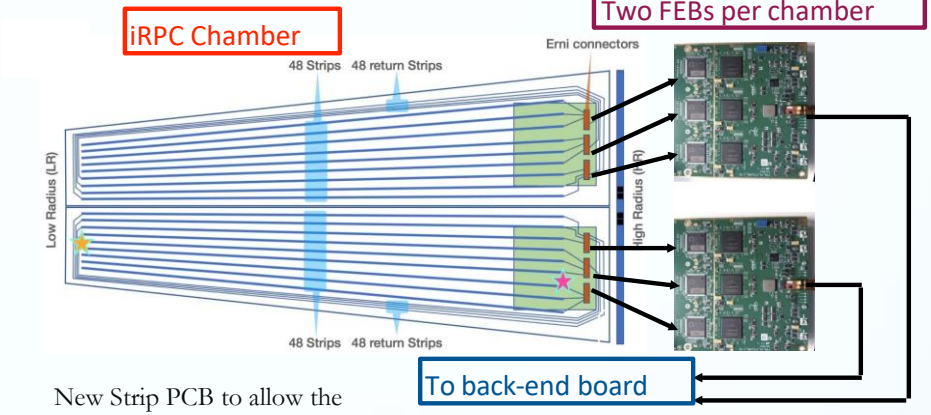
iRPC Design & Performance

G. Pugliese

2024 ICNFP

- New detector geometry, strip layout and Font-End Board electronics (2D readout)

	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

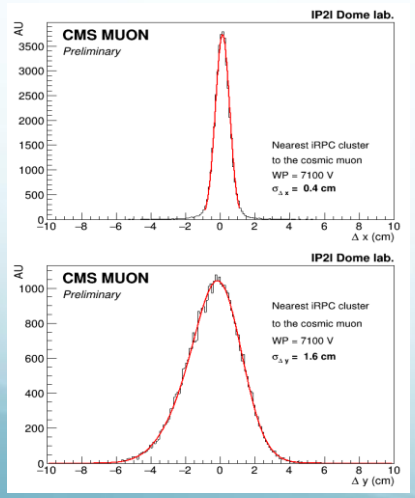


New Strip PCB to allow the return line concept

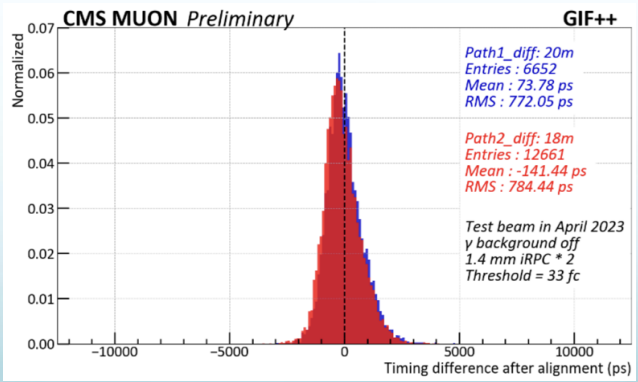
FEB positioned external and @ lowest dose region

- **Requirements:**
  - Space resolution (cm): 1.5 in η and 0.3-0.6 in φ
  - Time resolution (ns): 0.5 ns
  - Rate capability: 2 kHz/cm²

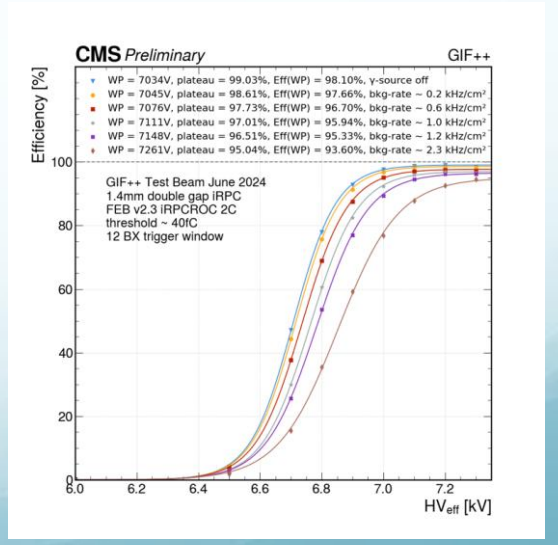
✓ Prototype performance satisfies all requirements



Space resolution: 0.4 cm in φ and 1.6 cm in η



Timing resolution: 780ps/√2= 550 ps



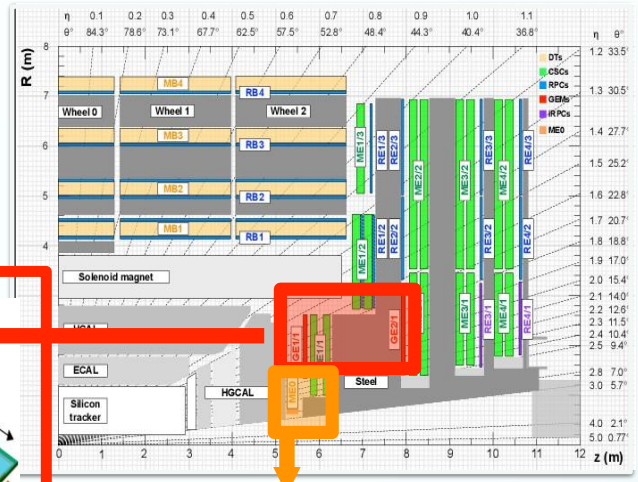
Efficiency @ 2.3 kHz/cm² : 95 %
Working Point = 7.2 kV

GEM Overview Project

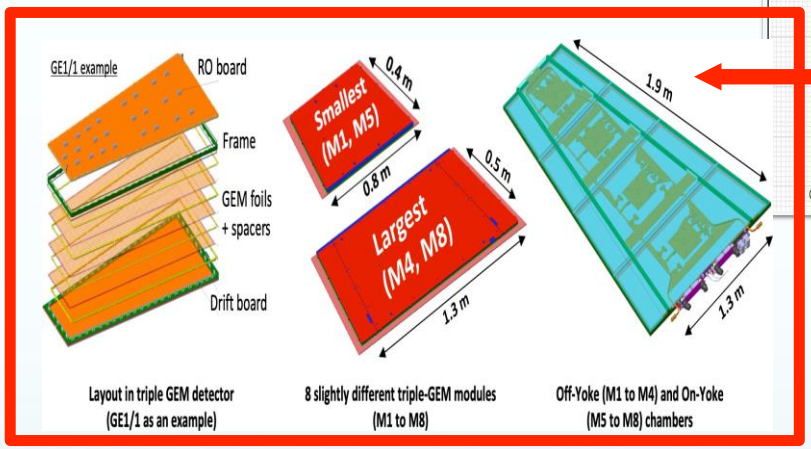
G. Pugliese

2024 ICNFP

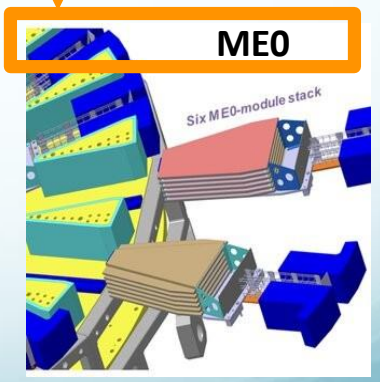
- 3 stations will be equipped with detectors based on **Gas Electron Multiplier (GEM) Technology**
  - **GE1/1, GE2/1 :** complementing CSC in forward region (Station 1 & 2 for Ring 1)



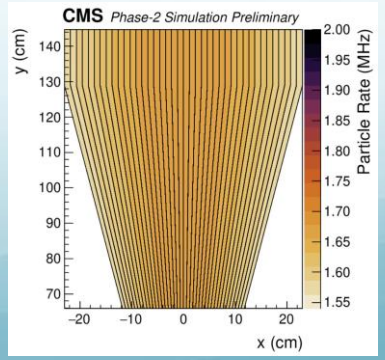
GE1/1 & GE2/1



- Both GE1/1 & GE2/1 are based on the same mechanical design principle: 2 triple GEM detectors per Super-Chamber (SC)
- **GE1/1 :** 72 SC (36 per endcap) 10° in φ from $1.6 < |\eta| < 2.1$
- **GE2/1 :** 36 SC (18 per endcap) 20° in φ from $1.6 < |\eta| < 2.4$



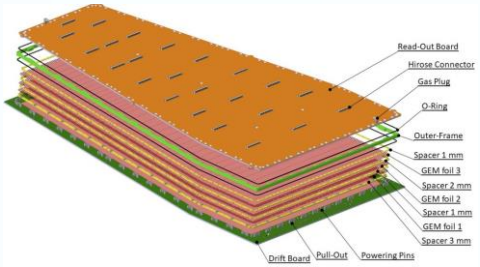
- **ME0:** Extending muon system acceptance in the very forward region up to $|\eta| < 2.8$
  - 18 ME0 stack per endcap, each made of six layers of triple-GEM detector for efficient tagging of muon tracks
  - New Radial GEM foil segmentation w.r. to beamline to equalize the background rate (changed wrt original horizontal design)



ME0 Performance

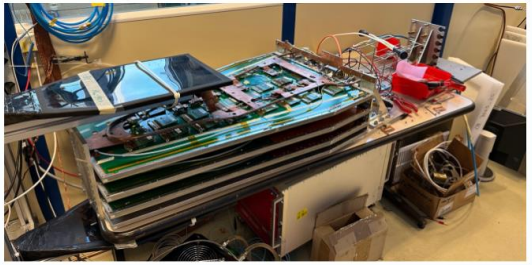
G. Pugliese

2024 ICNFP



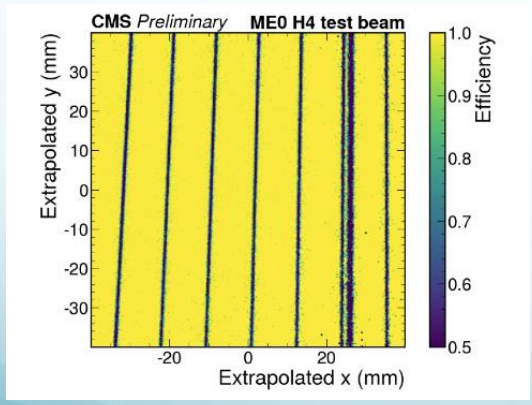
Requirements :

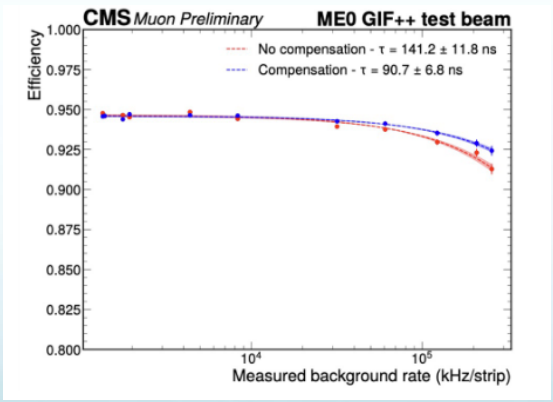
- 97% module efficiency
- < 500 μrad resolution
- 8-10 ns time resolution
- ≤ 15% gain uniformity
- Rate capability: 150 kHz/cm^2
- Radiation hardness: 7.9 C/cm^2

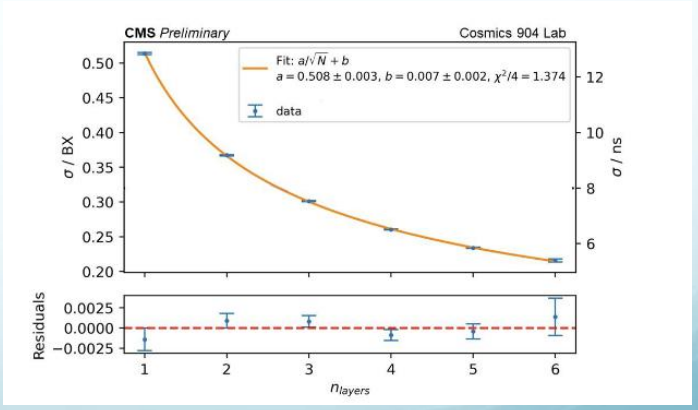


✓ Detector prototype performance satisfies all requirements:

The First ME0 stack prototype was assembled and tested at CERN 904 laboratory and in several test beams







Spatial Resolution: 240 µrad
Efficiency locally > 99%

Rate capability: 2.5% efficiency loss with the highest background (loss in highest eta region) mitigated (1%) by the redundancy

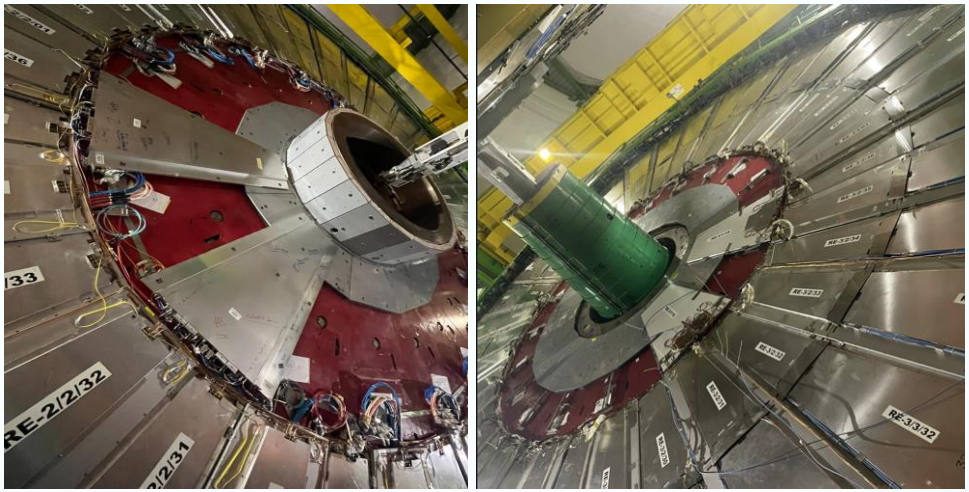
Average time resolution of track segments as a function of the number of ME0 chambers (layers) used to reconstruct the segment.
The time resolution 5.4 ns for 6-layer segments

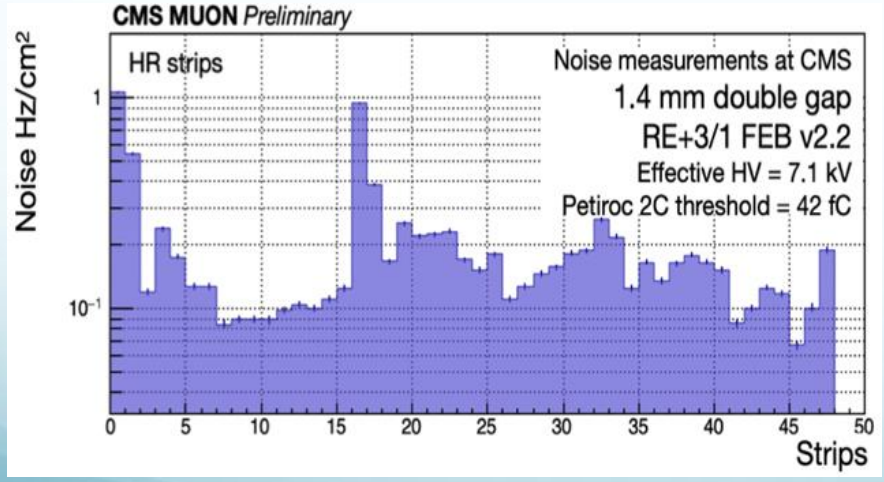
The first iRPC and GE2/1 installed in CMS

G. Pugliese

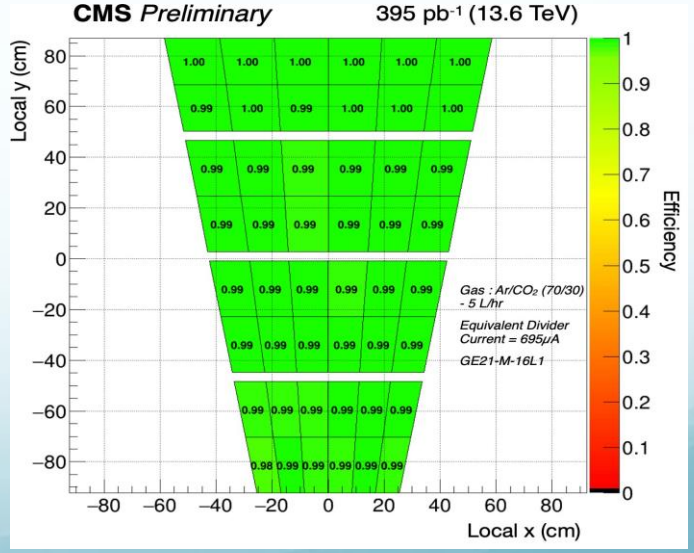
- The first GE2/1 and iRPC chambers were installed in CMS during the last Extended Year End Technical Stop to gain operational experience and perform preliminary measurements of background, noise, performance

- **Preliminary results are satisfactory!**





RPC Average noise ~ 0.2 Hz/cm^2



GE2/1 efficiency map

Conclusions

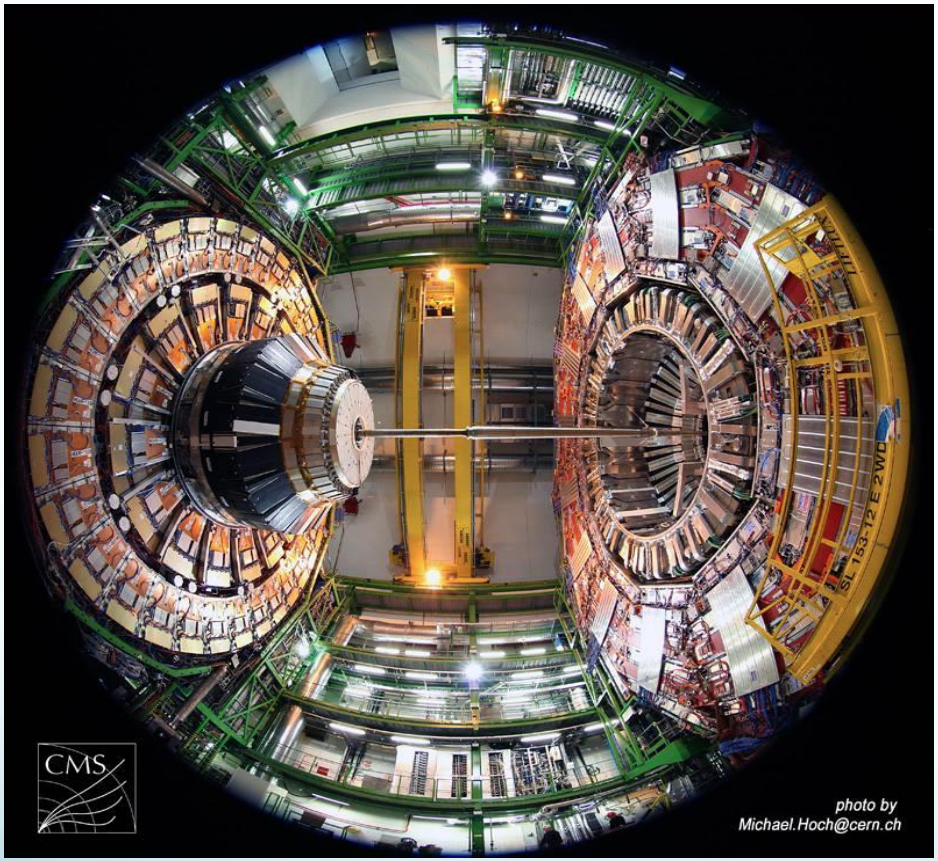
The CMS Muon **system is operating extremely well,** delivering good triggers and data for physics. After 14 years of LHC running with increasing instantaneous luminosity and 20 years since construction, the Muon **detector performance remains** within specifications both as a triggering and as a reconstruction system.

To address the challenges posed by the HL-LHC conditions & maintain high performance of the CMS Muon system, several upgrades have been planned and some have already been successfully implemented for Run 3 (GE1.1 and CSC electronics)

- The present detectors (DT, CSC & RPC), which will continue operating until the end of LHC operations, are undergoing an electronics upgrade to withstand the demanding conditions. The pre-production boars have been fully validated, and production started
- The prototypes of the new muon stations for the high eta region are fully satisfying the requirements, and production has started

Thanks!

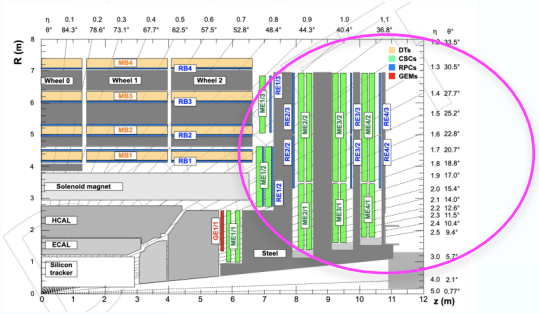
Credits to CMS People

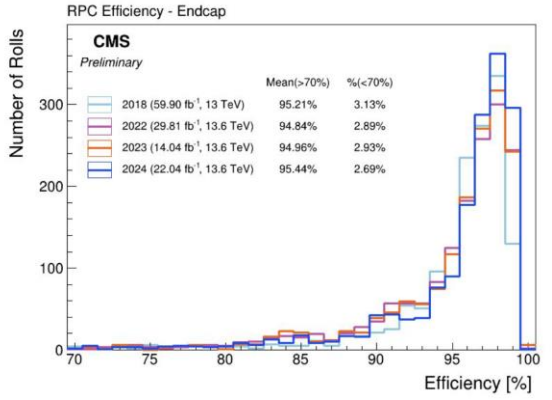


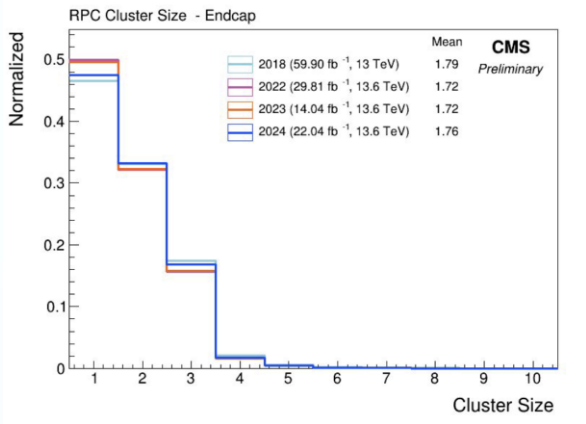
Backup slides

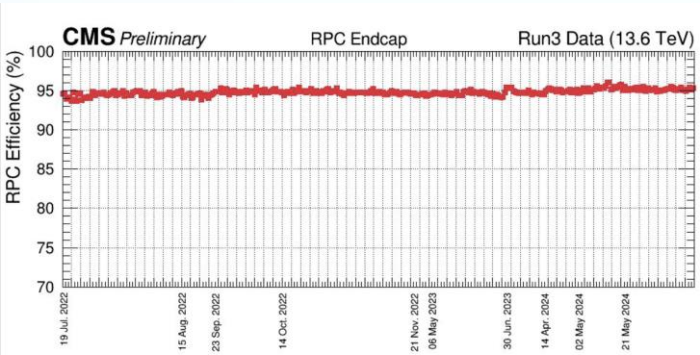
RPC performance in Run 3 (Endcap region)

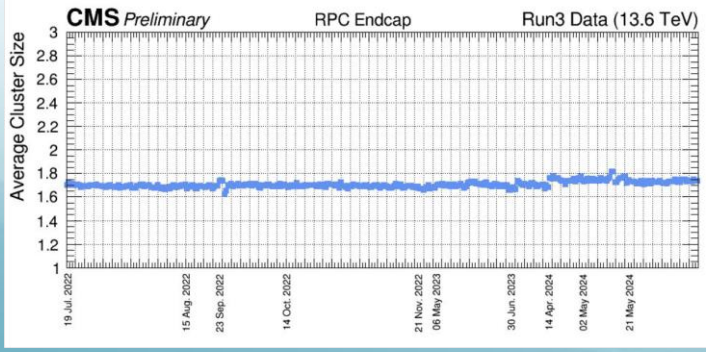
G. Pugliese











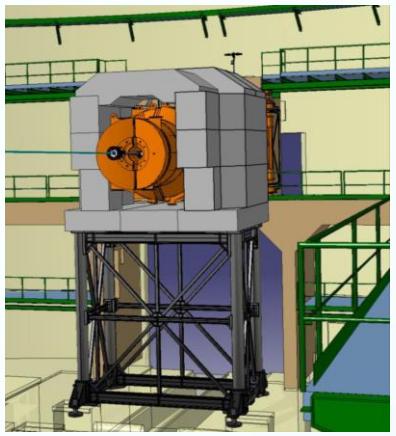
Endcap RPC efficiency and cluster size distribution in Run2 (2018) and Run3 (2022, 2023, and 2024)

- **Stable Endcap RPC performance in RUN 3 and in agreement with previous runs**

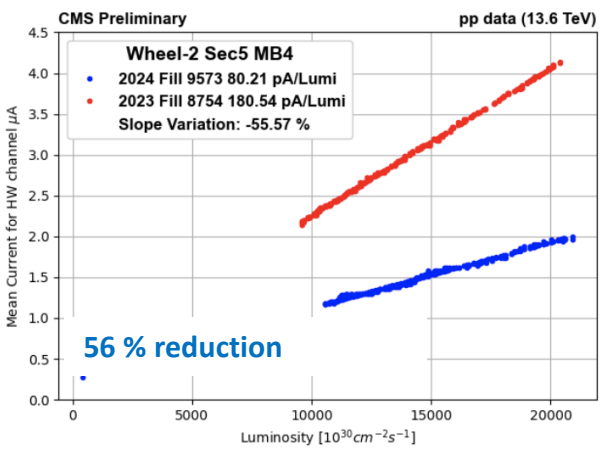
Background reduction in 2024

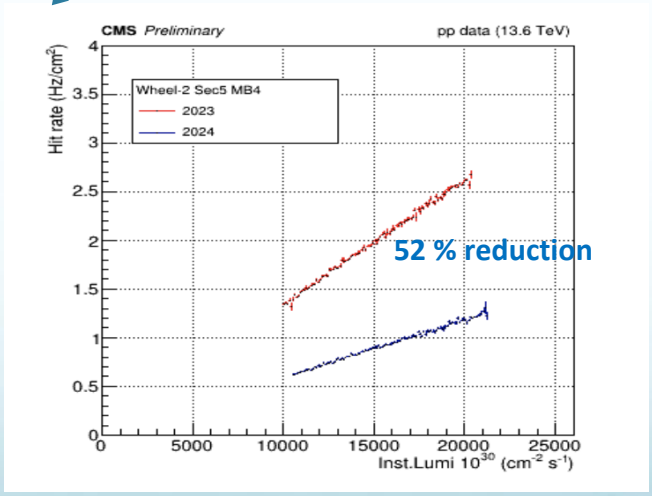
G. Pugliese

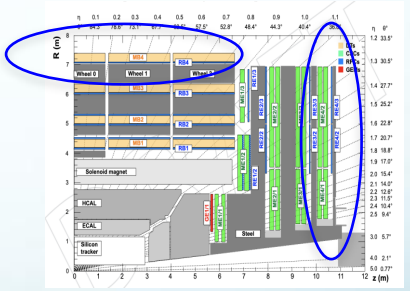
A **New Forward Shielding (NFS)** was designed to reduce background in the cavern detected by the muon detectors. In the last shutdown, it was installed only on the negative side



- Significant reduction of the currents and hit rates observed mostly in the outermost layer of the Muon System (MB4 and ME4)





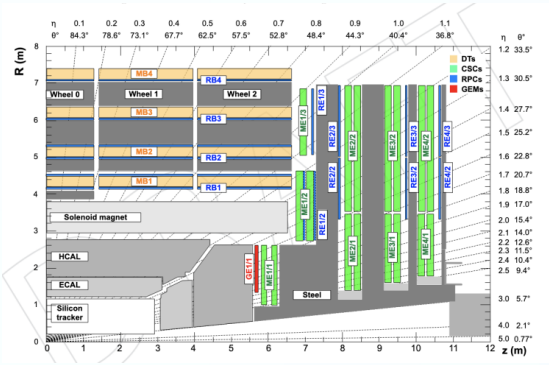


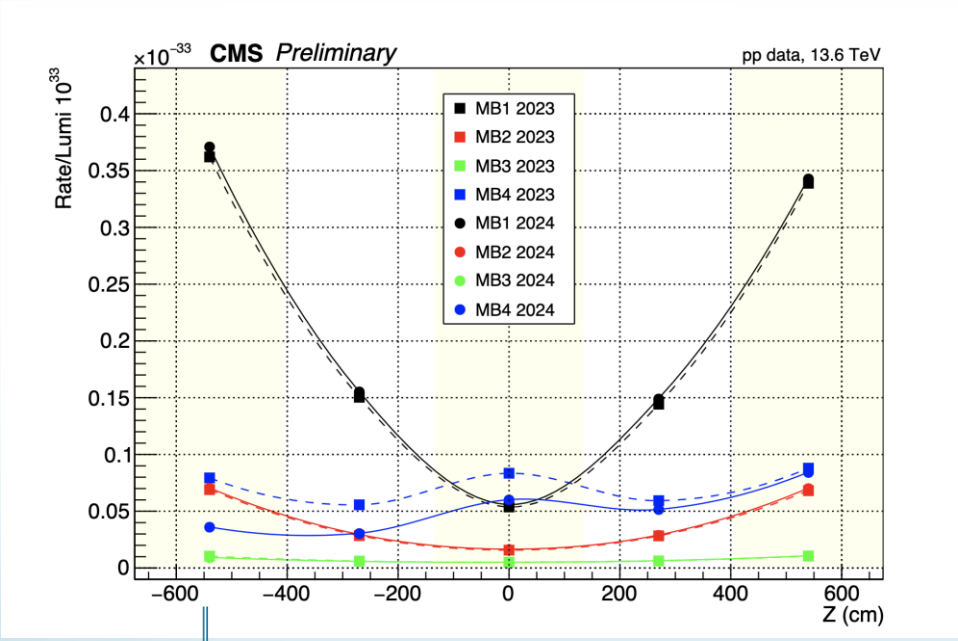
DT Background currents and rates versus instantaneous luminosity in one MB4 sector of W-2 as measured in 2024 and 2023

Background in 2024

G. Pugliese

- The effect gradually decreases going negative side (where the shielding is installed) to the opposite side
- No effect in the internal stations (MB1, MB2 and MB3)





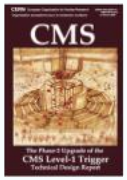
NFS position

- The effect will be fully symmetric after the installation of the NFS on the positive side, thus dramatically reducing the detector aging process

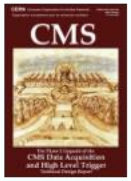
CMS Upgrade Project

G. Pugliese

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

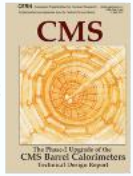


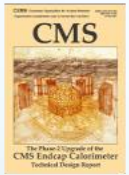
Level-1 Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1 Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



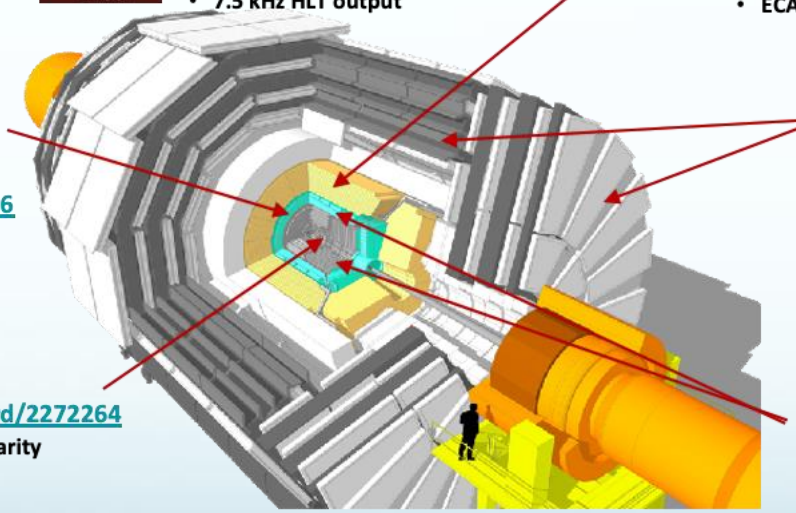
DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

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

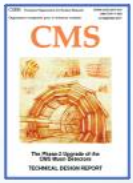


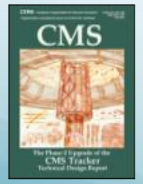


High-Granularity Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scintillator+SiPM in Pb/Cu-W/SS

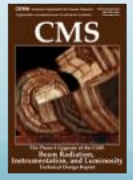


Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC BE electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3



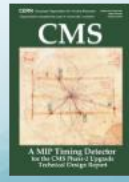


Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Extended coverage to η ≃ 4
- Design for tracking in L1 Trigger



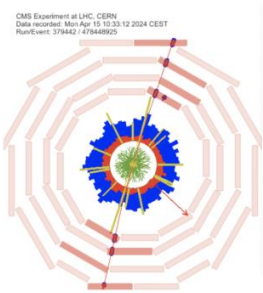
Beam Radiation Instrumentation and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

MIP Timing Detector
https://cds.cern.ch/record/2667167
Precision timing with:
- Full coverage to η ≃ 3
- 30-50 ps time resolution for MIPs
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

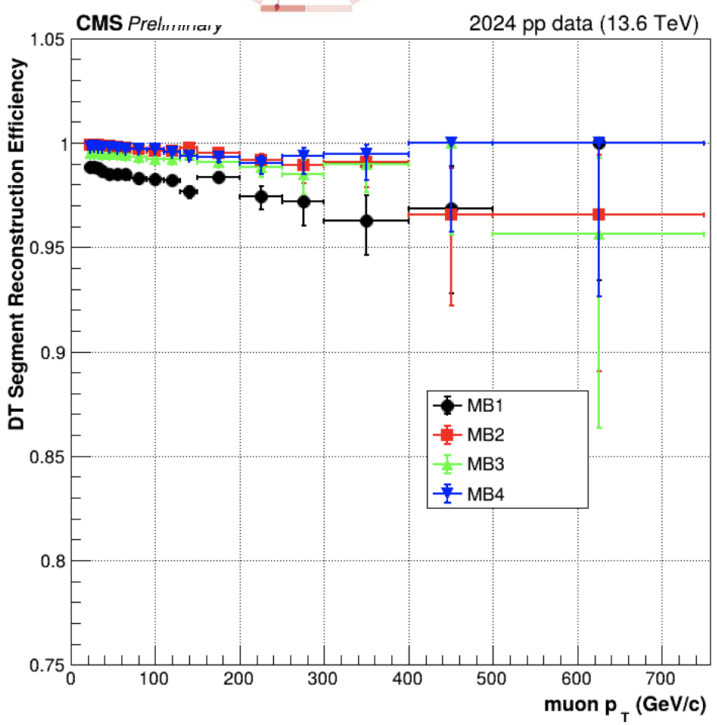


DT Segment Efficiencies in Run 3

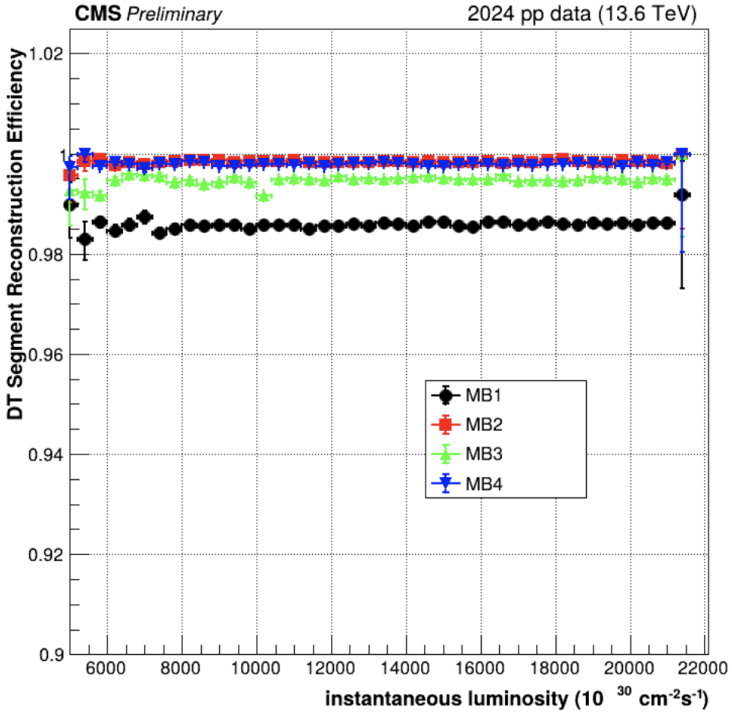
G. Pugliese



- **Excellent DT segment performance up to the maximum LHC instantaneous luminosity (~2.1*10^{33} cm^{-2}s^{-1})**



Segment efficiency shown as a function of muon transverse momentum for the four DT stations



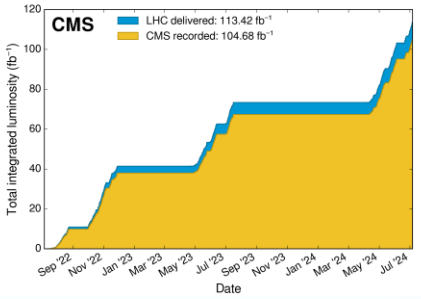
Segment efficiency shown as a function of LHC instantaneous luminosity for the four DT stations

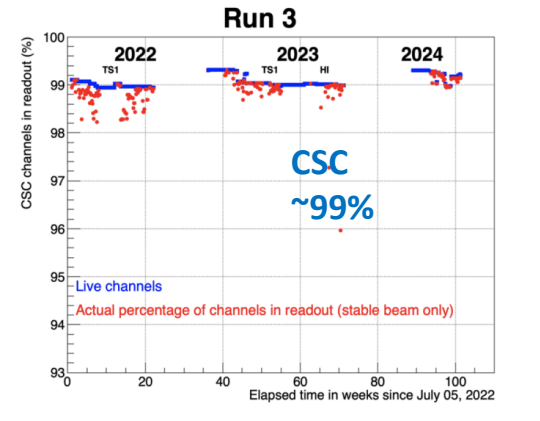
Muon Operation in Run3

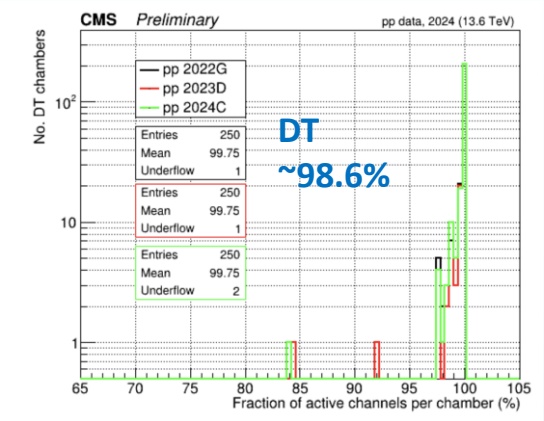
G. Pugliese

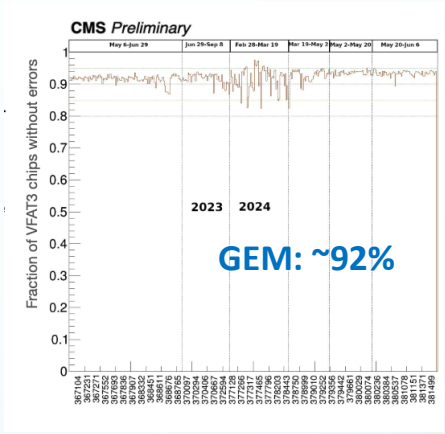
2024 ICNFP

- Excellent CMS data-taking efficiency >92% in RUN3 physics collisions
- Muon System:
  - Smooth operation with a minor contribution to Luminosity loss (4%, due to CSC readout)
  - Stable active channels fraction:









Year	2018	2022	2023	2024
% of RPC active channel	96.5	89.6	87.7	82.6

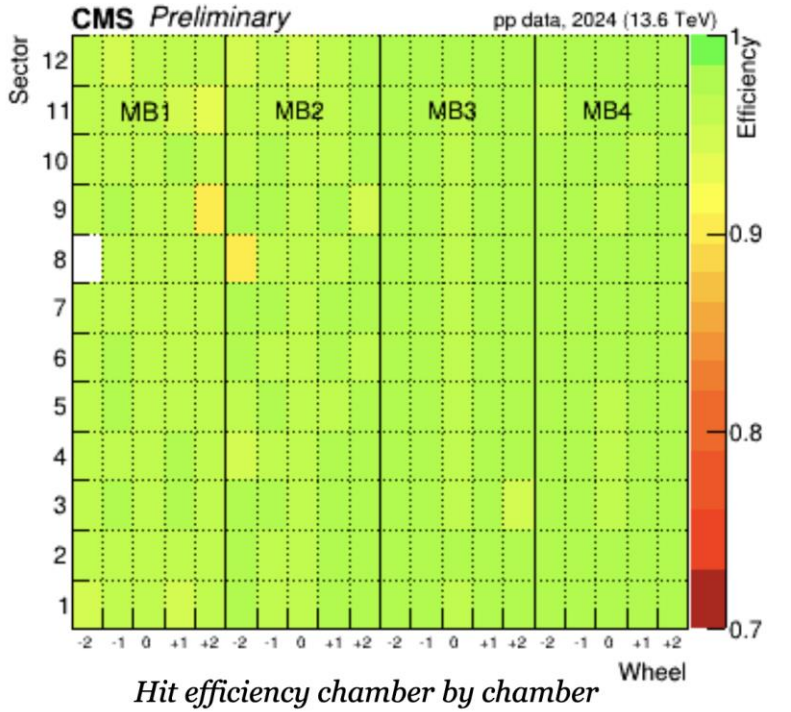
GEM dead channels are mainly due an electronics issue (VTRx outgassing is causing damage in the optical connection) that will be fixed in LS3

Since 2022, all RPC leaky chambers (located only in the Barrel region) have been disconnected to reduce GHG emissions and to use the new RPC recuperation system efficiently

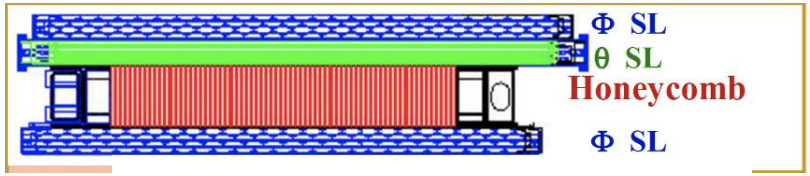
Key to success: prompt intervention of the experts during all beam-off and Technical Access time in case of failure

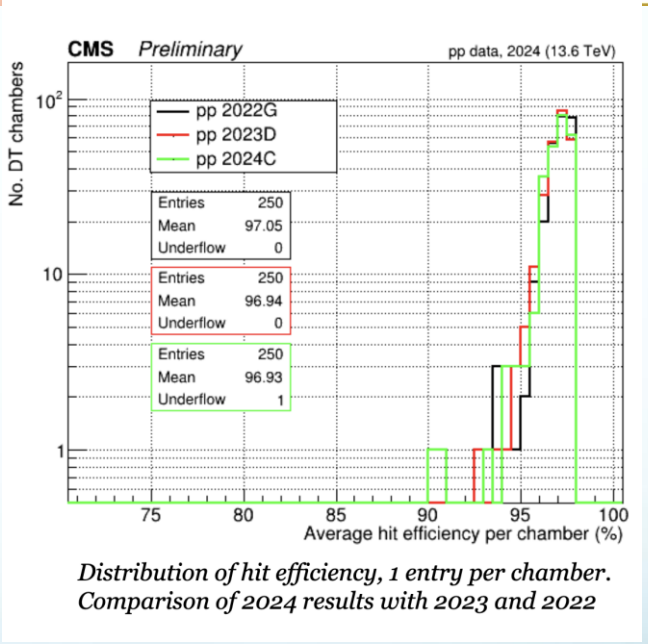
RUN3 DT Hits Efficiencies

G. Pugliese



Hit efficiency chamber by chamber



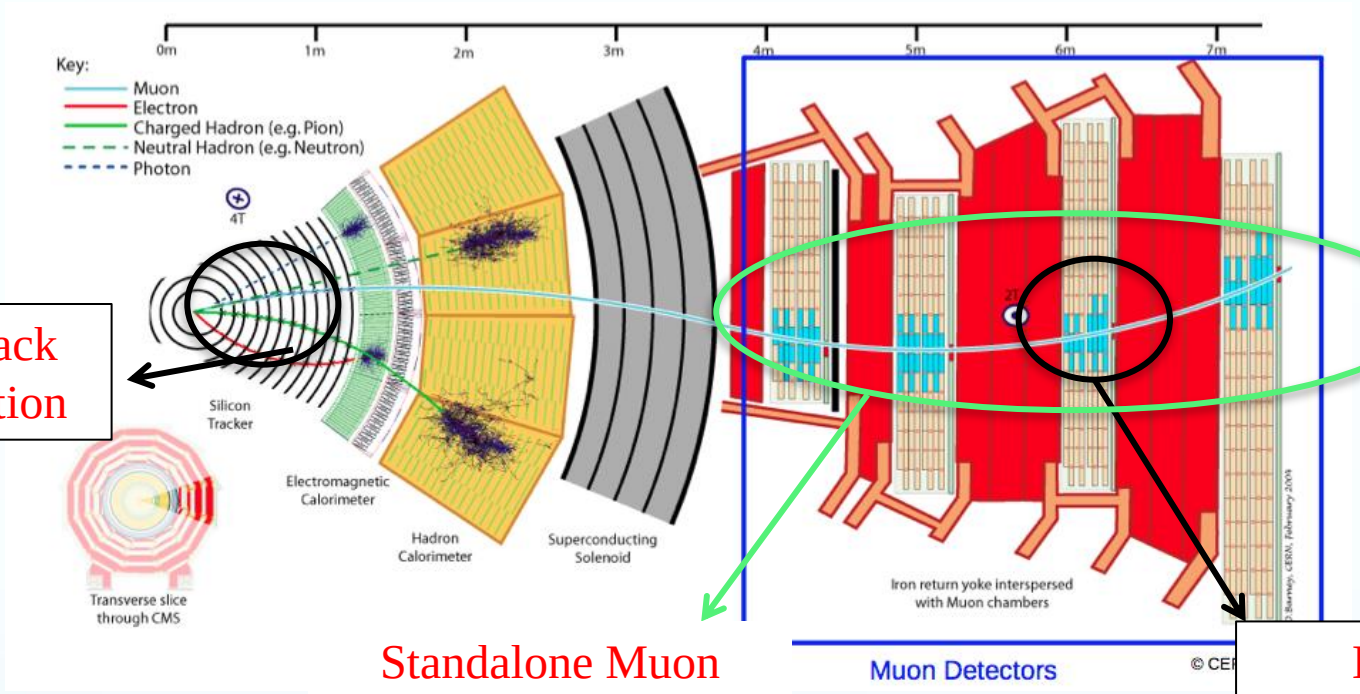


Distribution of hit efficiency, 1 entry per chamber. Comparison of 2024 results with 2023 and 2022

- **DT hits efficiency** exceeds 96.9 % (few exceptions are due to known hardware problems) and it is **stable**
- In 2024, one chamber only in Wheel -2 Sector 8 MB1 is not working because of a gas connection problem: this problem is reported as a light blue bin in the plot and will be fixed over the coming YETS.

Muon Reconstruction

G. Pugliese



Tracker track reconstruction

Standalone Muon reconstruction

Performed using DT/CSC segments & RPC hits

Local reconstruction

Performed within single chamber

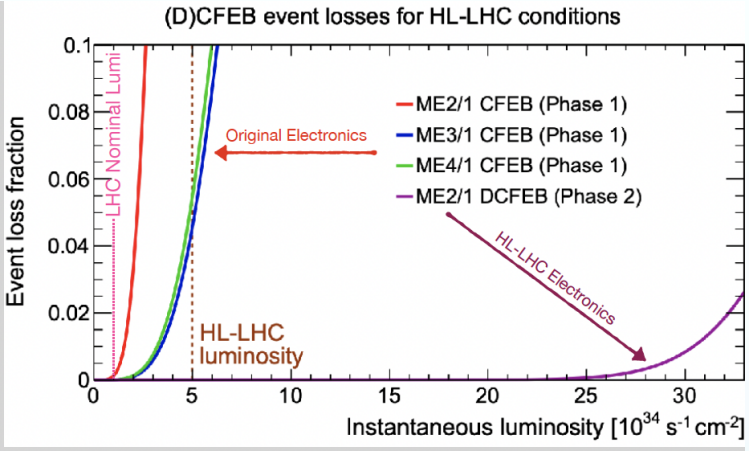
Global muon reconstruction (out side –in): a standalone muon is propagated to match a tracker track. If matching is positive a global fitting is performed.

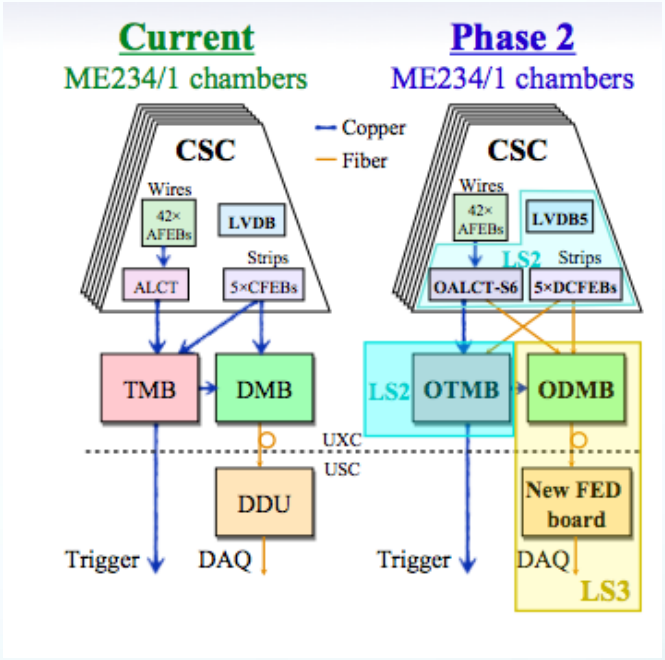
Tracker Muon (inside – outside): a tracker track is propagated to muon system and qualified as muon if matching with standalone or one segment.

CSC Electronics Upgrade motivation

G. Pugliese

On-chamber and off-chamber electronics to be replaced in order to handle the CMS trigger requirements at HL-HC



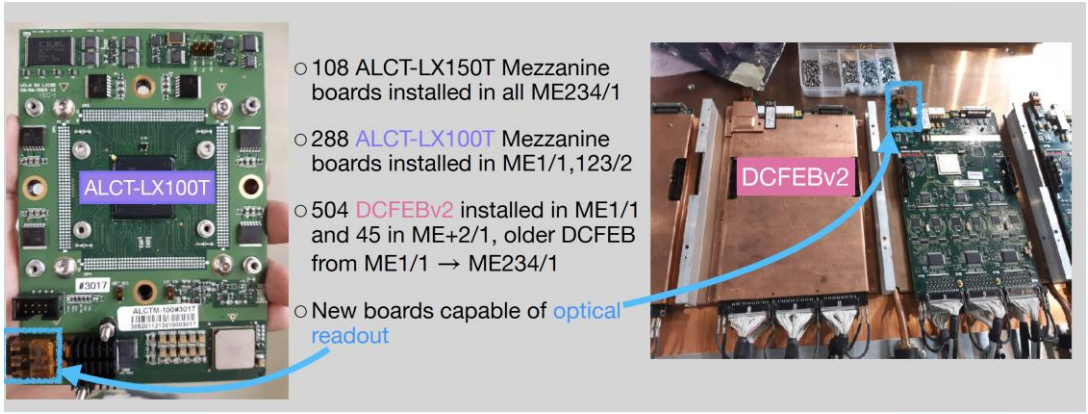


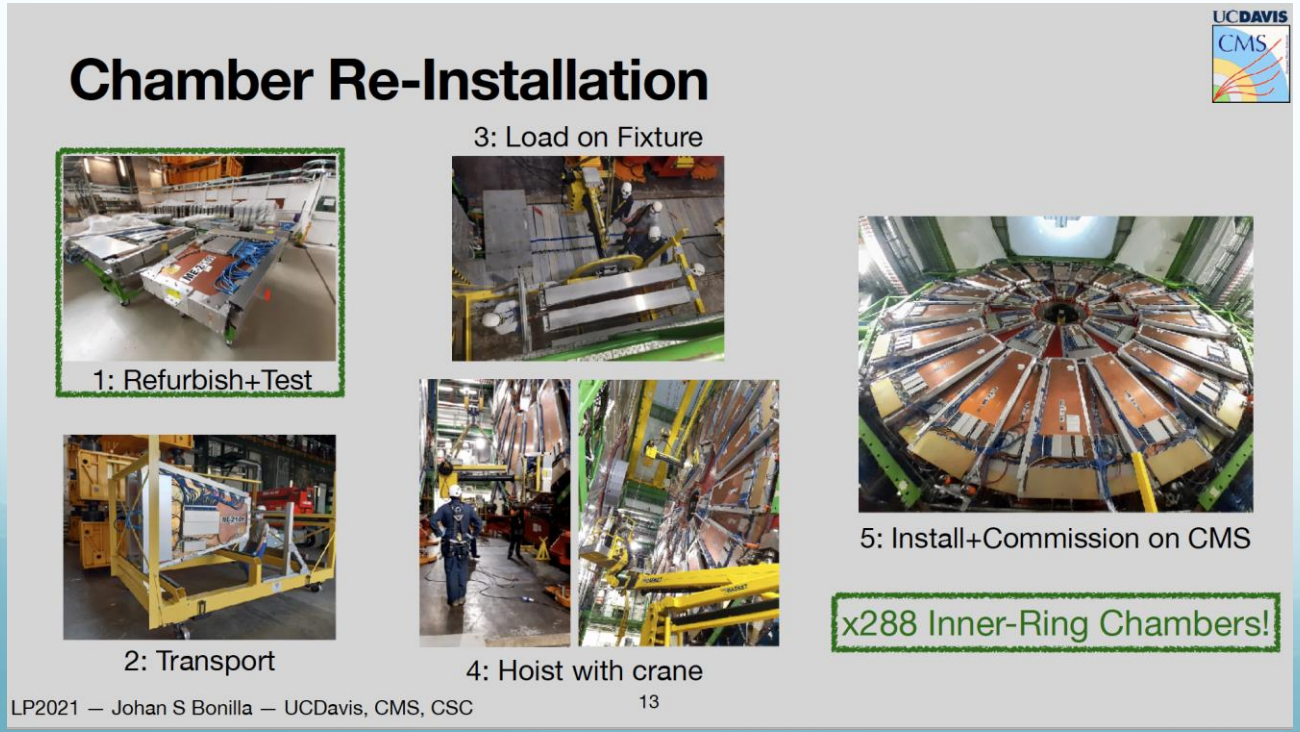
Board	Num.	Where	Main reasons for upgrade	
DCFEB	540	ME12/1	Latency and rate, rad-hardness	LS2
ALCT	396	ME1234/12	Latency and rate, rad-hardness	
LVDB5	108	ME234/1	Power levels of DCFEBv2s	
OTMB	108	ME234/1	Receive optical link from DCFEBv2s	
ODMB	180	ME1234/1	Increased DAQ output bandwidth	LS3
HV	40/12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

LS2 CSC Upgrade activity

G. Pugliese

The on-detector Refurbishment of Electronics in LS2

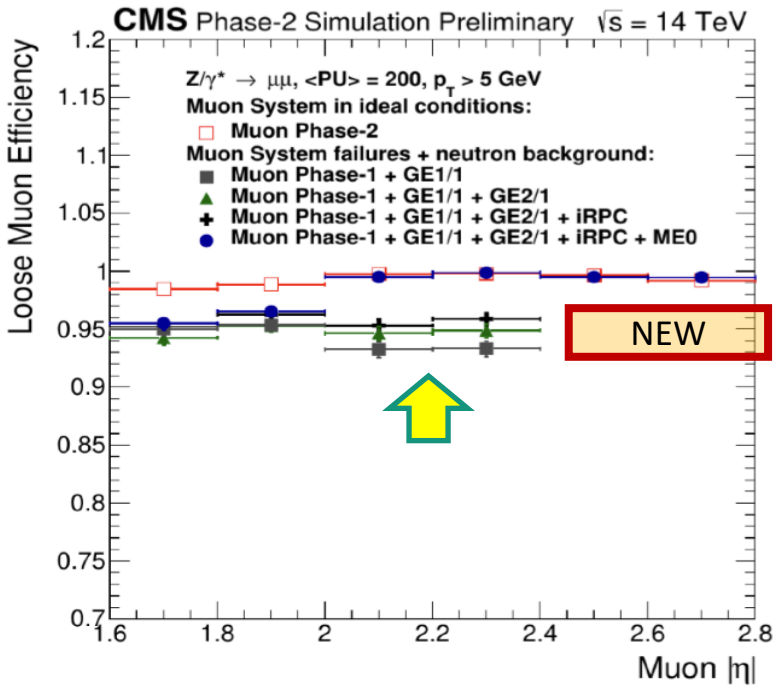




Muon Upgrade

G. Pugliese

New GEM and RPC detectors needed to improve efficiency reconstruction and trigger performance at HL_LHC



- To maintain the high level performance in HL-LHC environment, the CMS muon system is being upgraded
  - to increase the muon spectrometer redundancy, to sustain the high radiation in the endcap region
  - GEM+CSC allow for muon momentum measurement in a single station, which helps reduce considerably L1 trigger rate