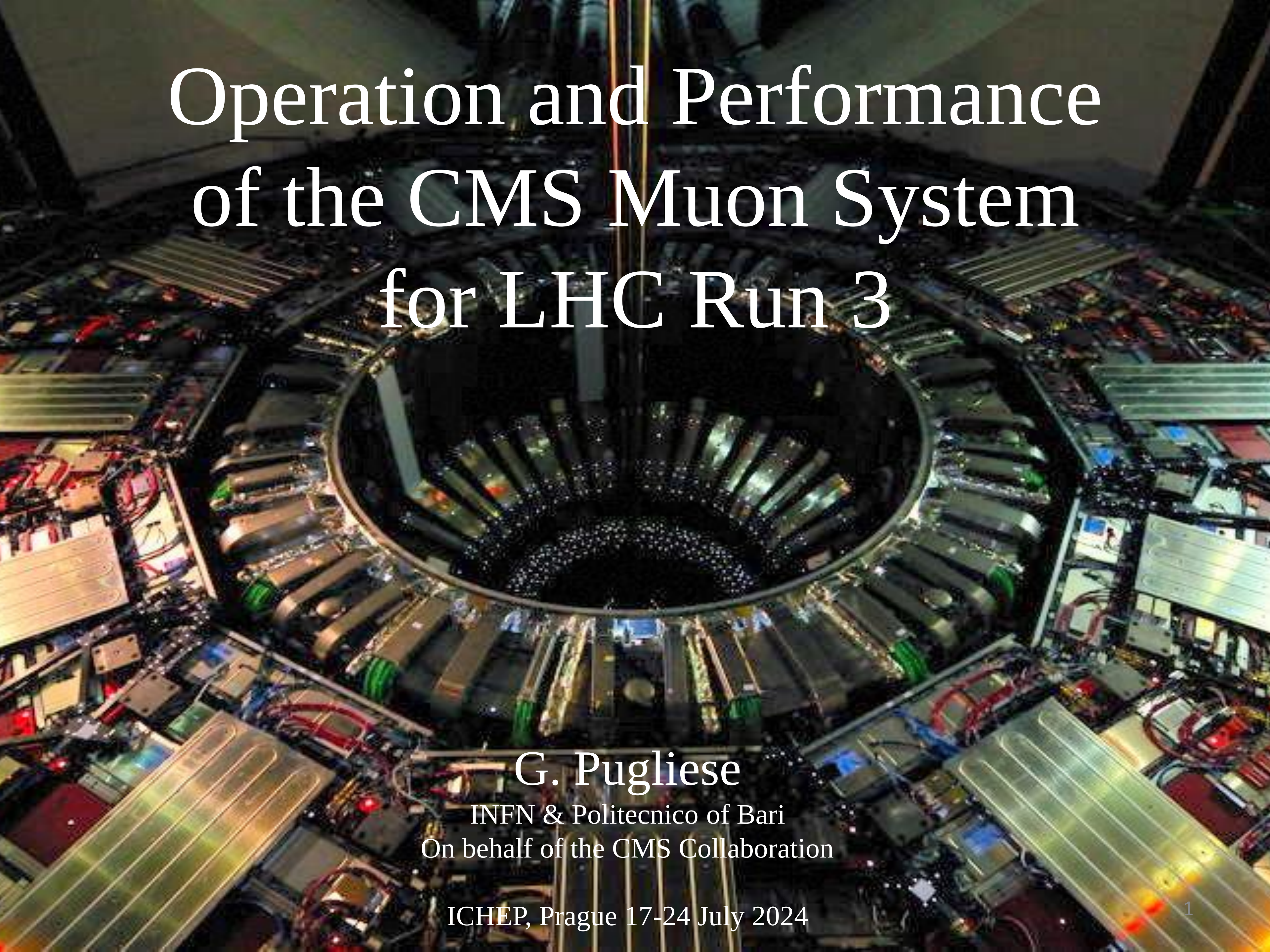
Operation and Performance of the CMS Muon System for LHC Run 3



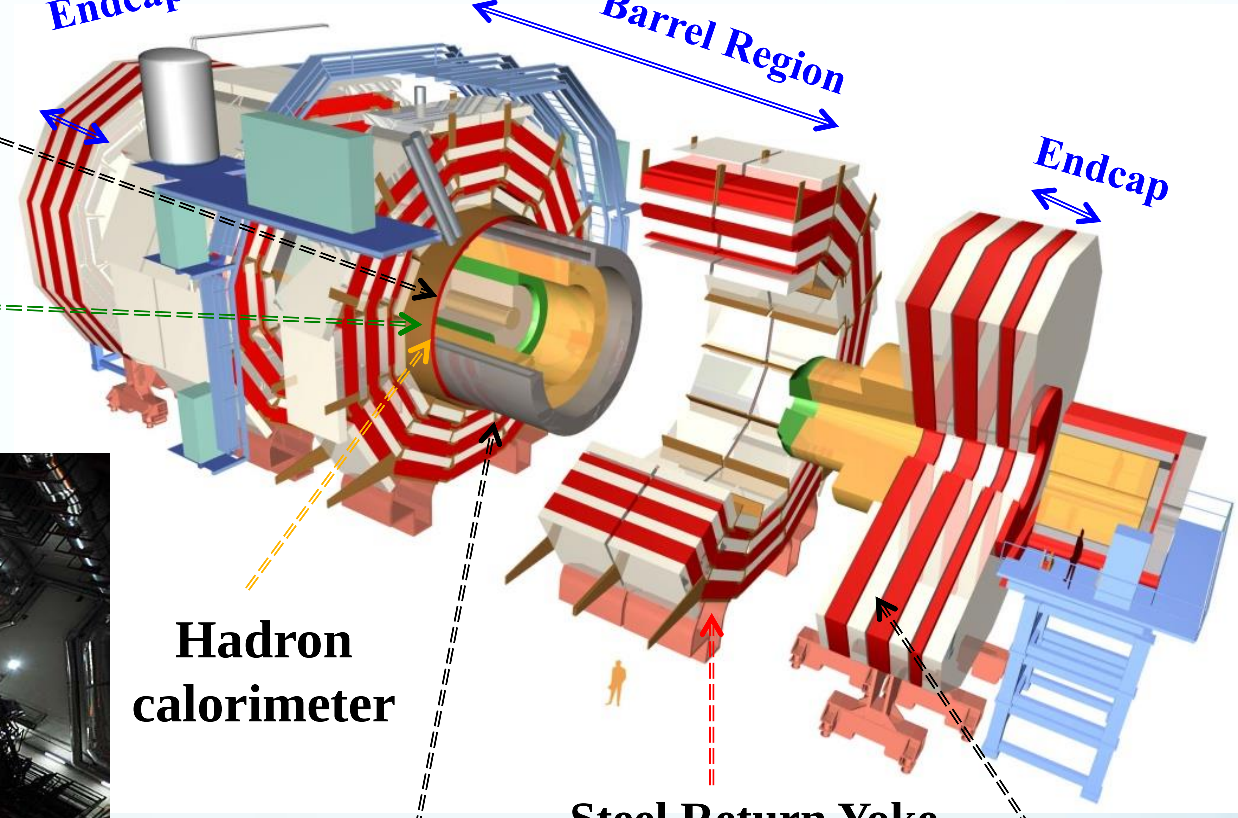
G. Pugliese

INFN & Politecnico of Bari

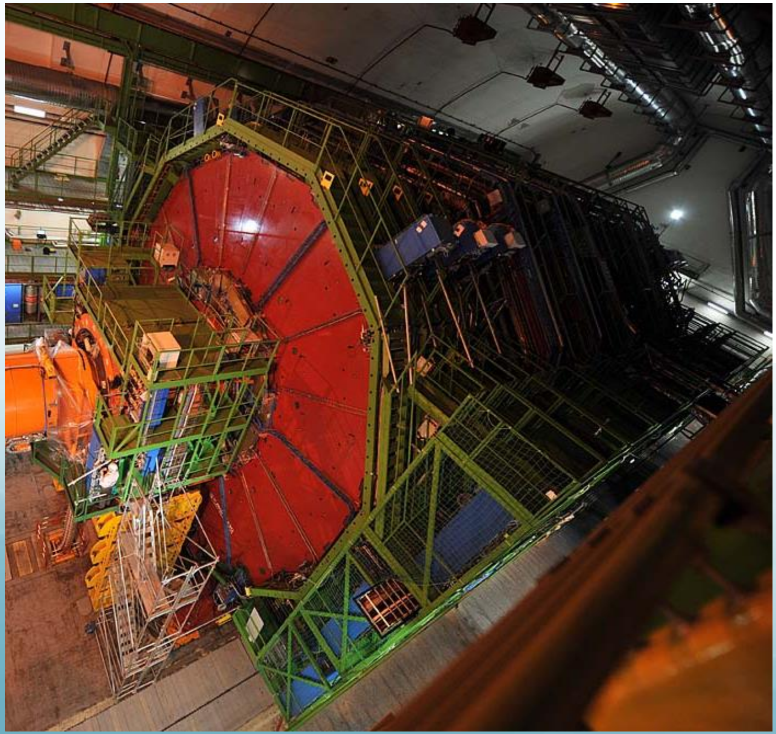
On behalf of the CMS Collaboration

ICHEP, Prague 17-24 July 2024

The CMS detector



Superconducting Solenoid
Niobium titanium coil carrying 18.000 A



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

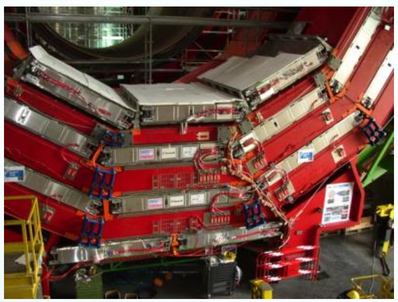
The CMS Muon Spectrometer

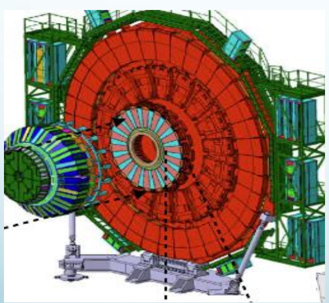
G. Pugliese

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

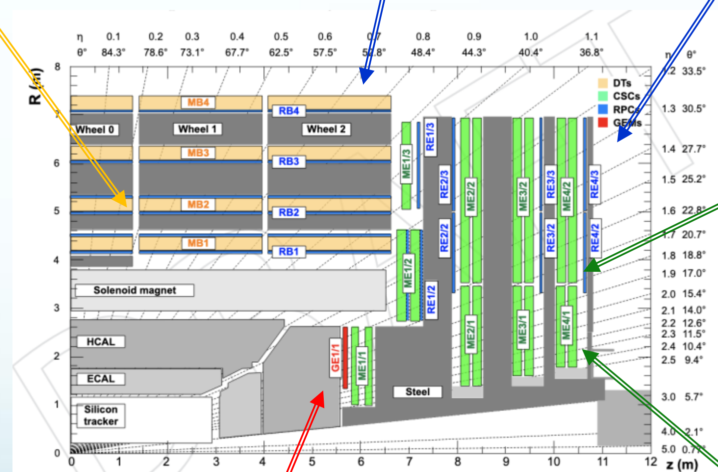
Muon acceptance: |η| < 2.4

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

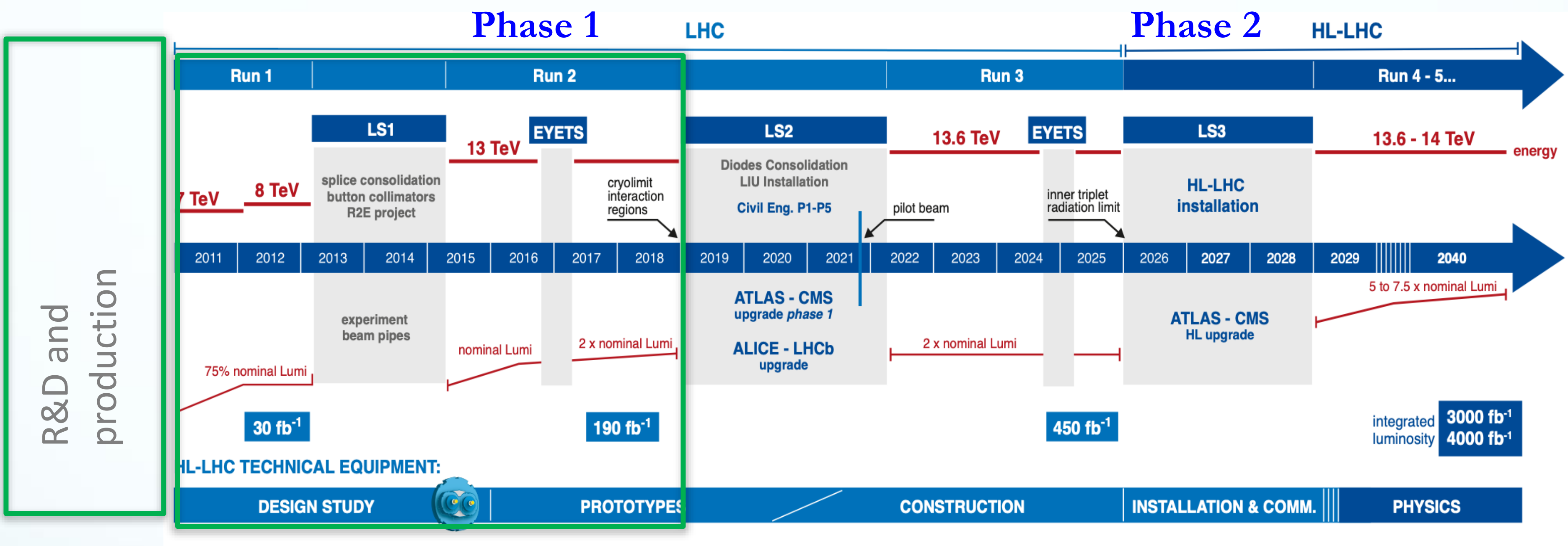
Cathode Strip Chambers (CSC)
- 540 trapezoidal chambers, ≈500k channels
- 24 number of hits
- Spatial resolution≈50 ÷140 μm
- Time resolution ≈ 3 ns

*See more results in **A. Sharma and S. Buontempo's talks***

The CMS and LHC schedule

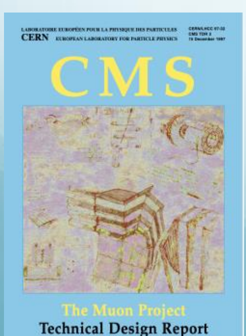
G. Pugliese

2024 ICHEP



Run 1 & Run 2

1997 Muon Project TDR



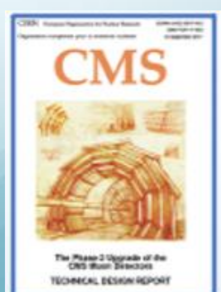
2005-2008 Muons Chambers produced and installed

2010 Start of LHC

2012 Higgs Discovery

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

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



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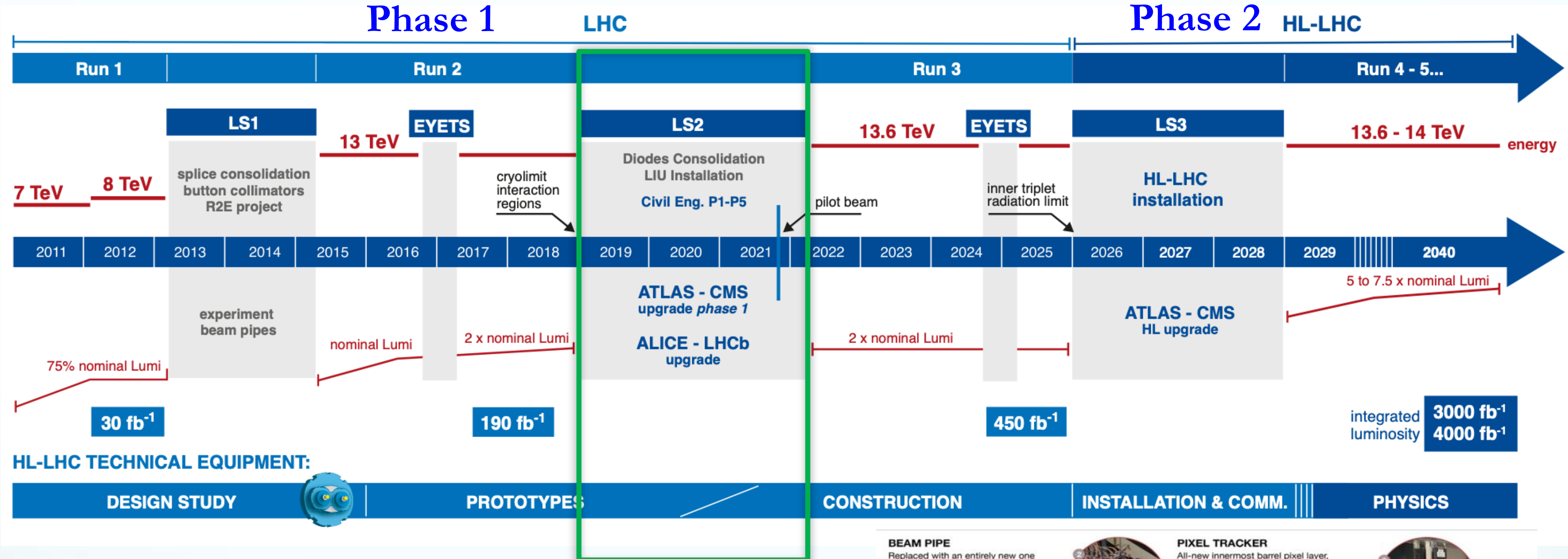
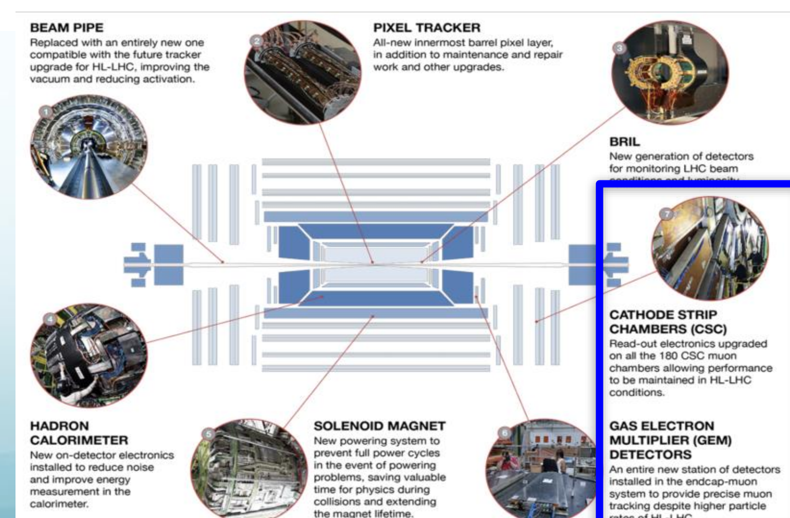
LHC and HL-LHC schedule



Long Shutdown 2 (2019-2021):

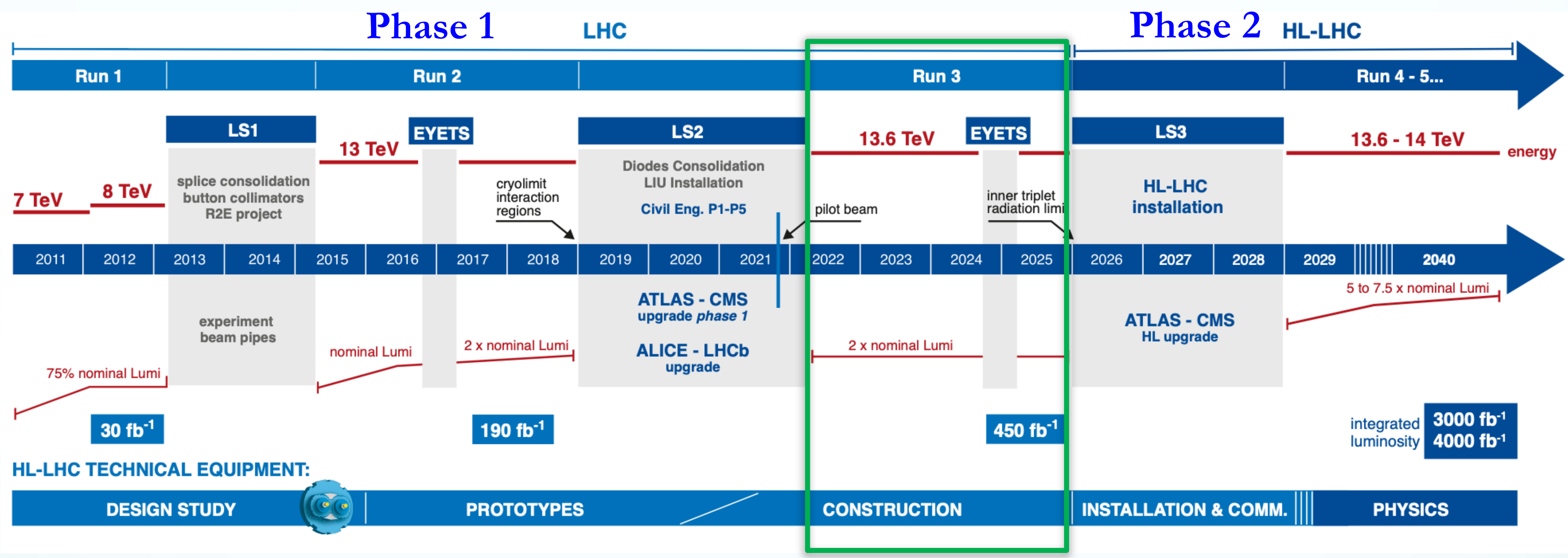
- Extensive work to upgrade the CMS detector because of the increase of energy and luminosity in Run 3 and beyond
- New CSC electronics and GEM chambers in the Muon Spectrometer

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



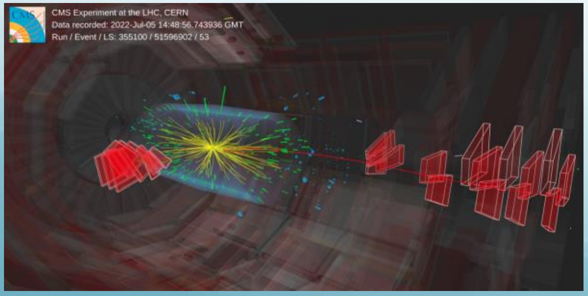
LHC and HL-LHC schedule

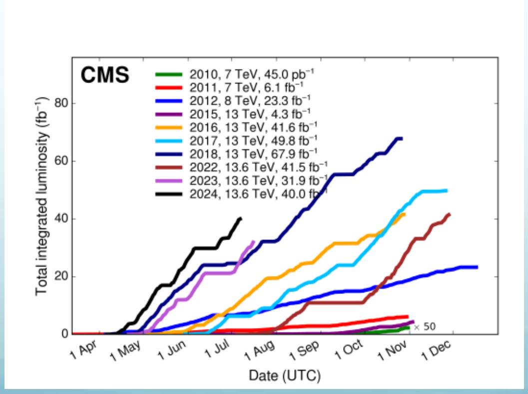
G. Pugliese



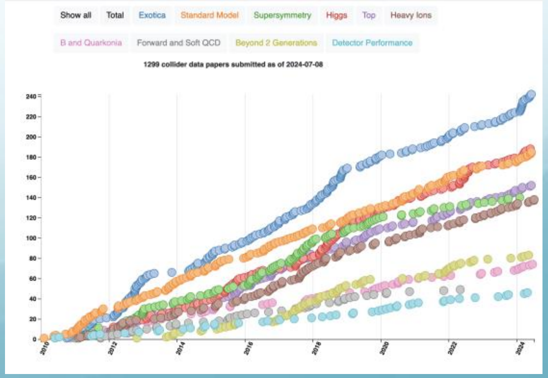
Run3

5th July 2022: start of Run 3 & first stable beam energy record of 13.6 TeV





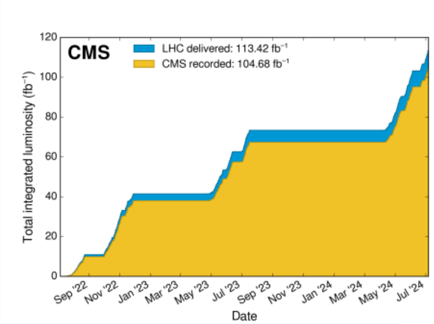
→ 1299 papers published

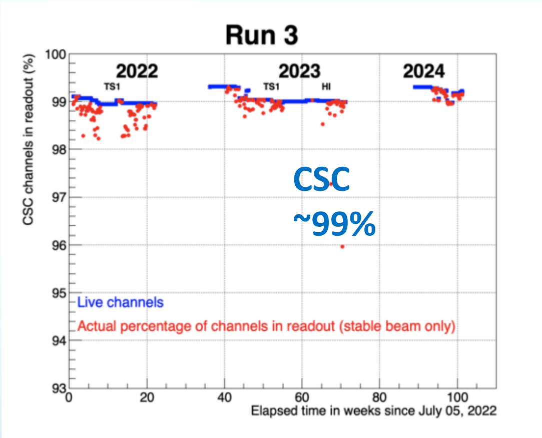


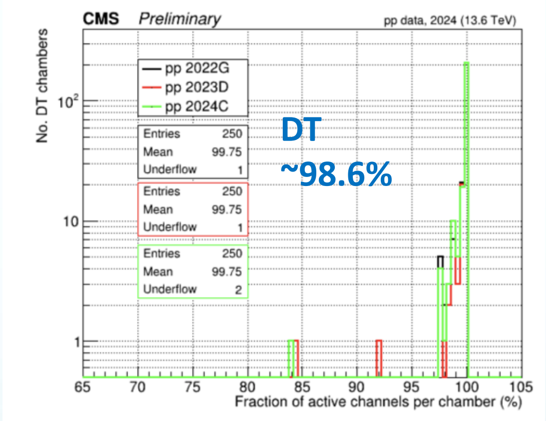
Muon Operation in Run3

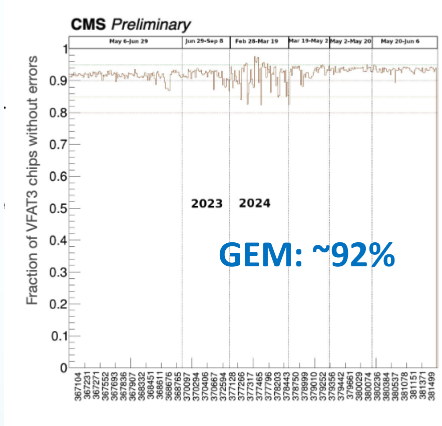
G. Pugliese

- 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

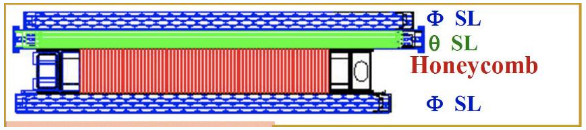
Since 2022, all RPC leaky chambers (located only in the Barrel region) have been disconnected to reduce GHG emissions and to use the new RPC recuperation system efficiently

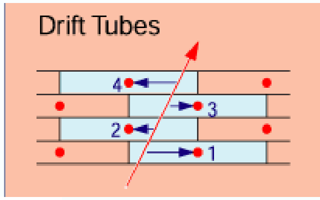
Key to success: prompt intervention of the experts during all beam-off and Technical Access time in case of failure

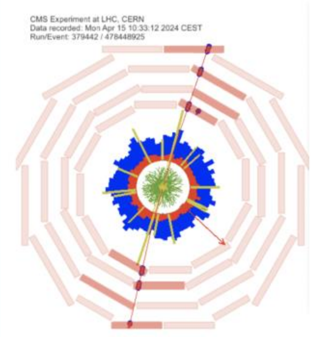
DT Segment Efficiencies in Run 3

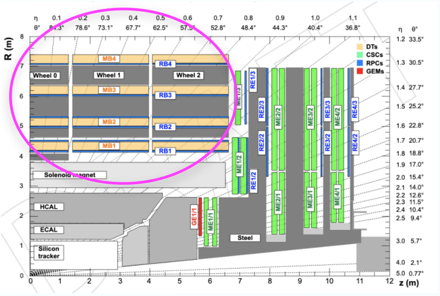
G. Pugliese

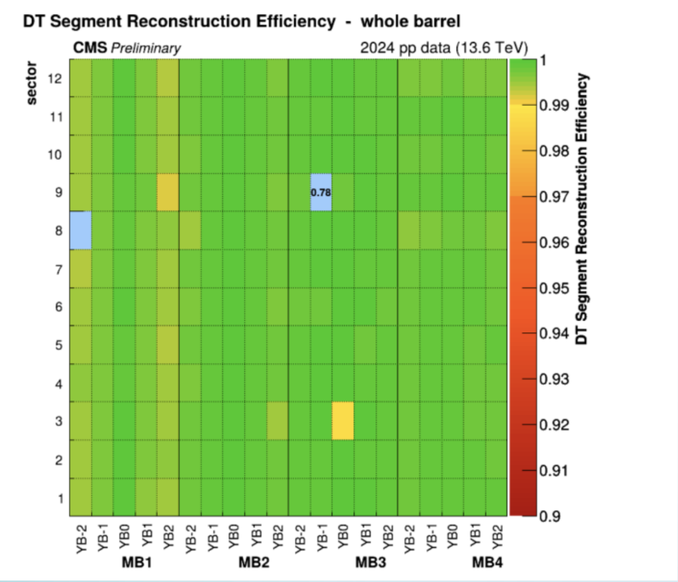
Segment efficiency is studied with Tag &Probe method on di-muons

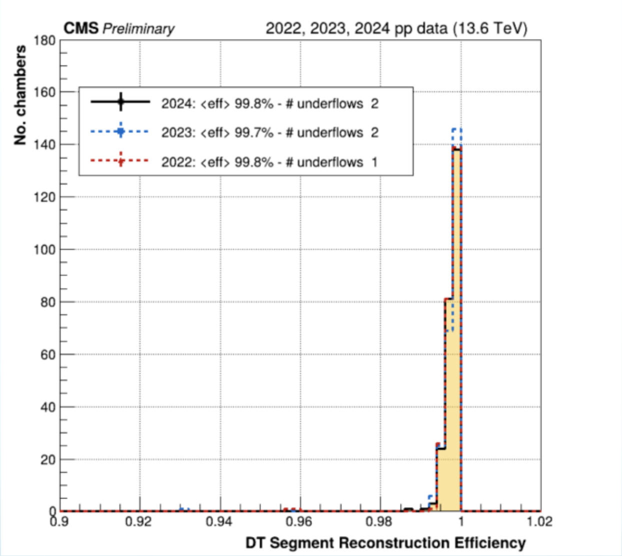








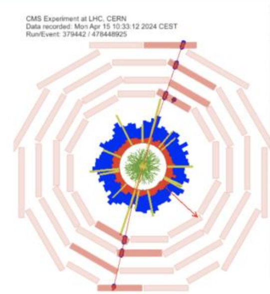




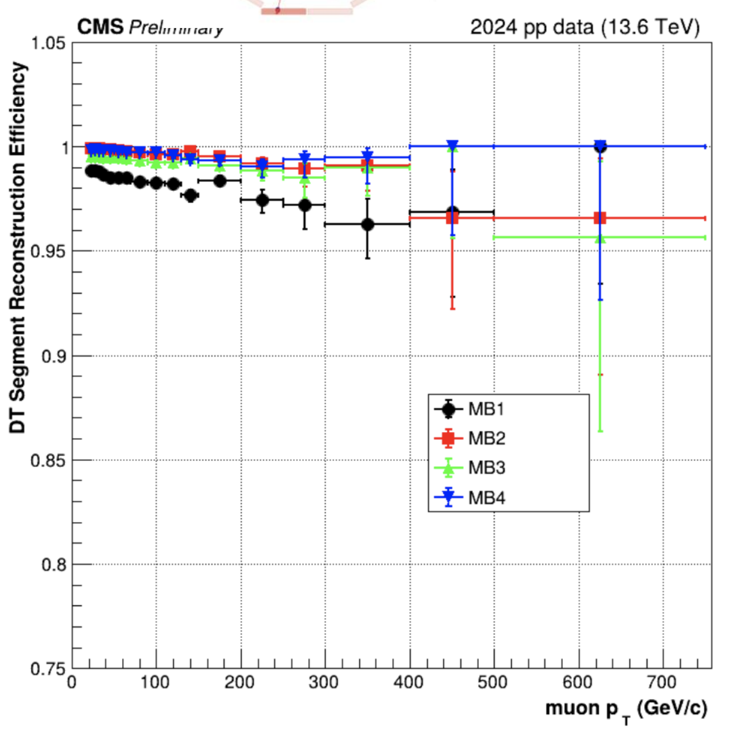
- **DT segment efficiency: stable in time and more than 99%** with few exceptions due to known hardware problems (one chamber in Wheel -2 Sector 8 MB1 is not working because of a gas connection problem and will be fixed over the coming YETS)

DT Segment Efficiencies in Run 3

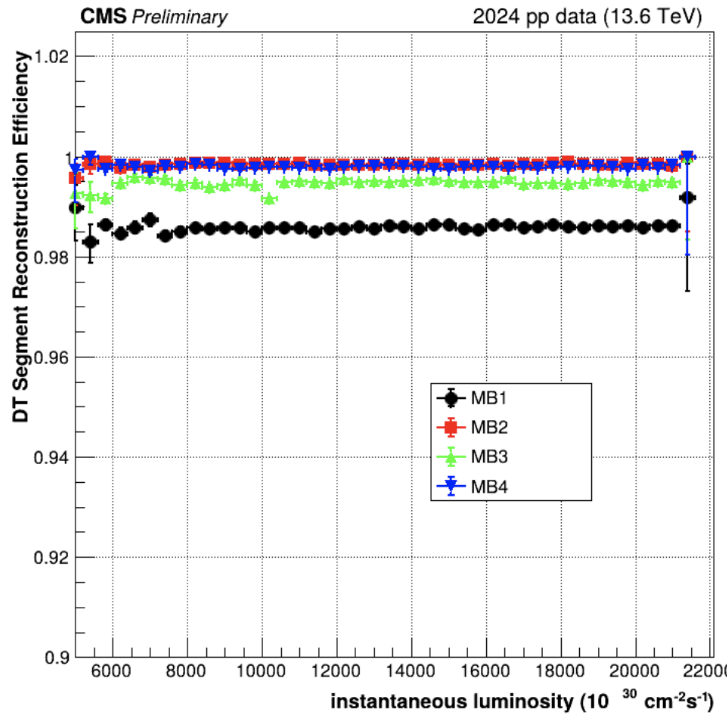
G. Pugliese



- Excellent DT segment performance up to the maximum LHC instantaneous luminosity (~$2.1*10^{30}$ $cm^{-2}s^{-1}$)



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

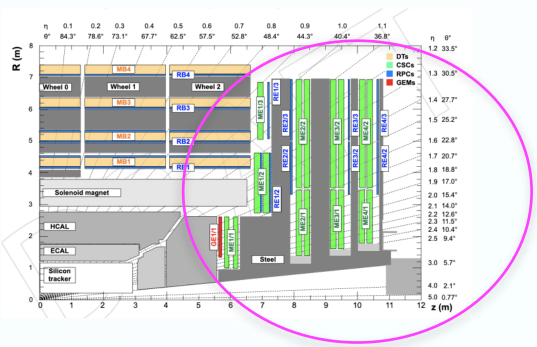


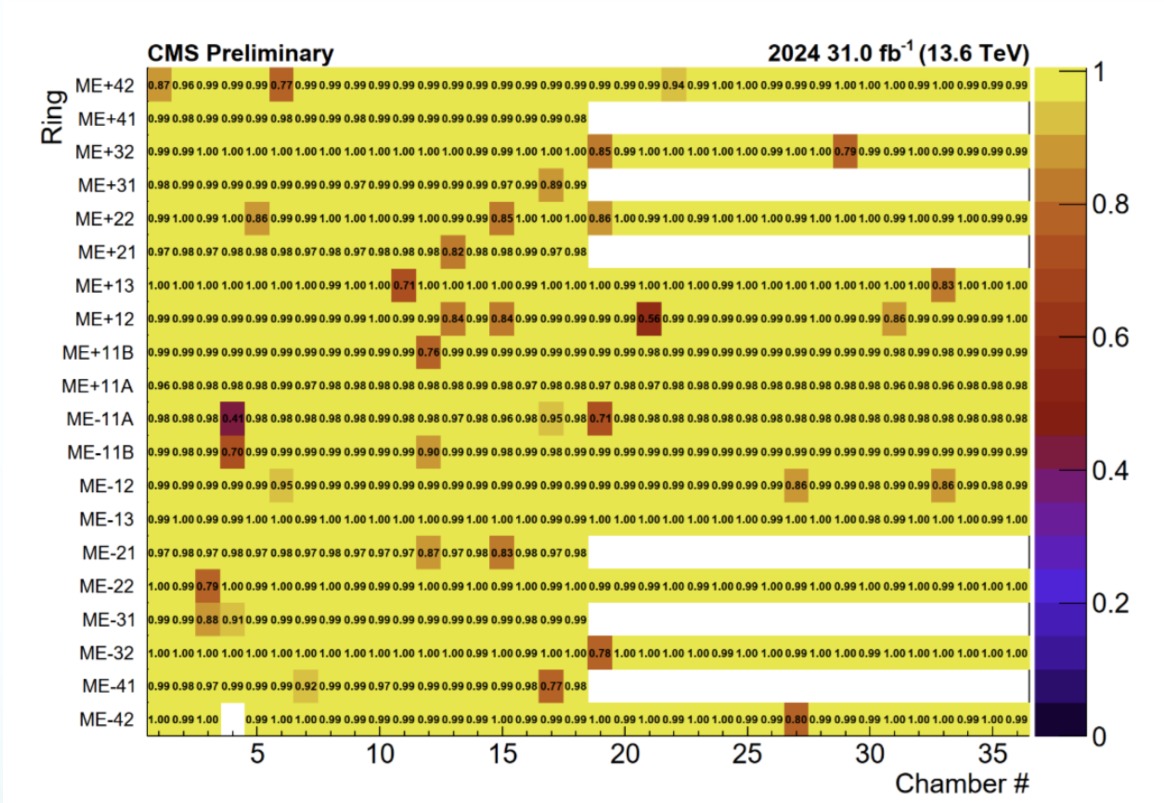
Segment efficiency shown as a function of LHC instantaneous luminosity for the four DT stations

See more results in ***C. Battilana's talk***

CSC Segment Efficiency in 2024

G. Pugliese



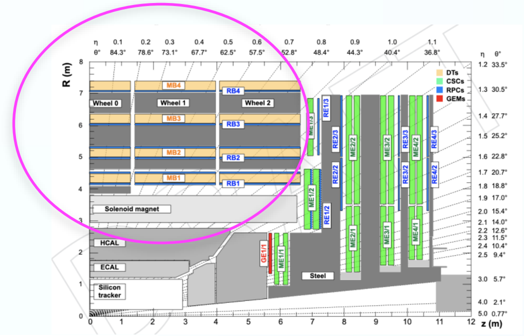


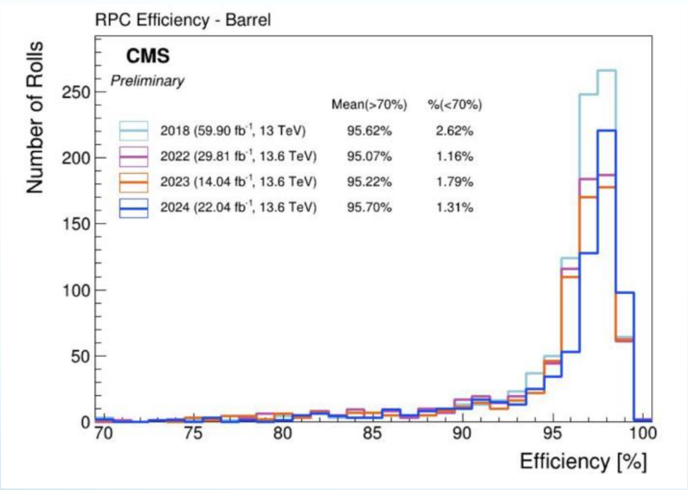
- ➢ CSC Segment efficiency: more than 98% of the CSCs is operating at close to 100% efficiency. Few chambers with lower efficiency are due to known reasons (electronics board failures, that cannot be fixed without access to the chambers, or accessional temporary failures

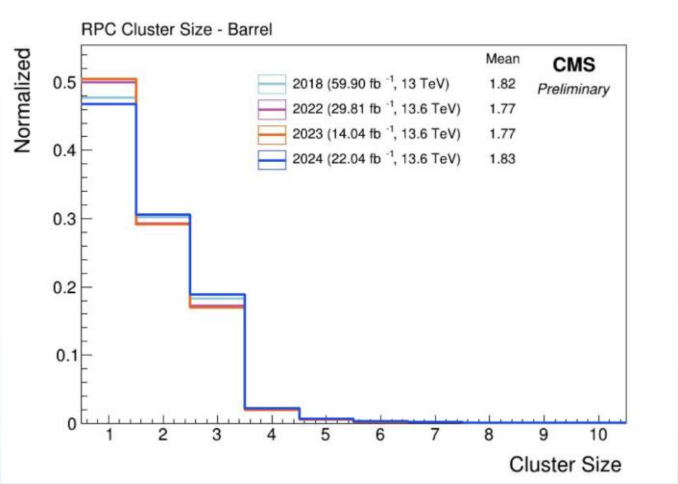
G. Pugliese

RPC performance in Run 3 (Barrel region)

➢ **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







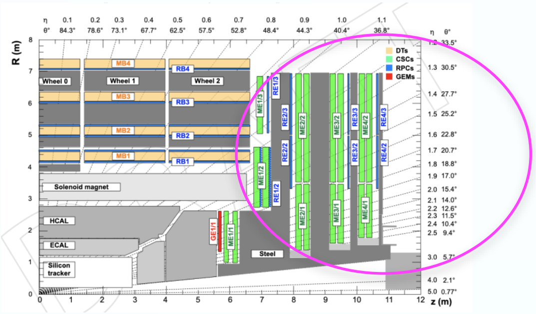
Barrel RPC efficiency and cluster size distributions in Run2 (2018) and Run3 (2022, 2023, and 2024)

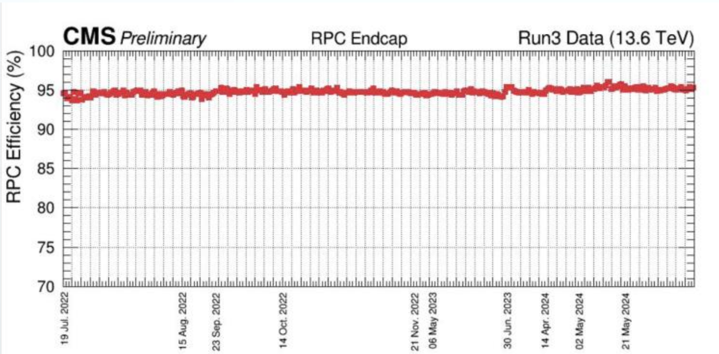
➢ **Stable Barrel RPC performance in RUN 3 and in agreement with previous LHC Runs**

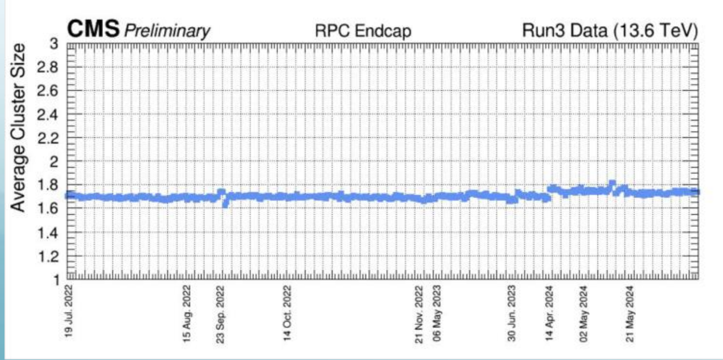
G. Pugliese

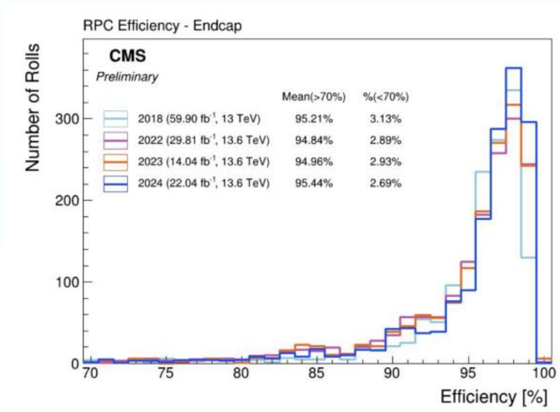
RPC performance in Run 3 (Endcap region)

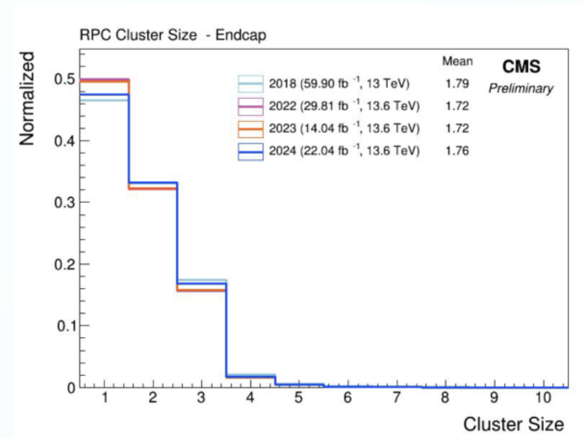
2024 ICHEP









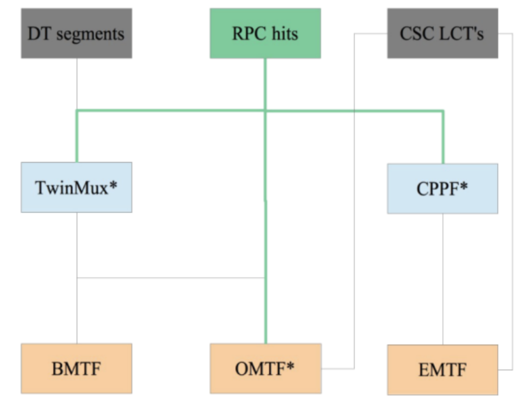


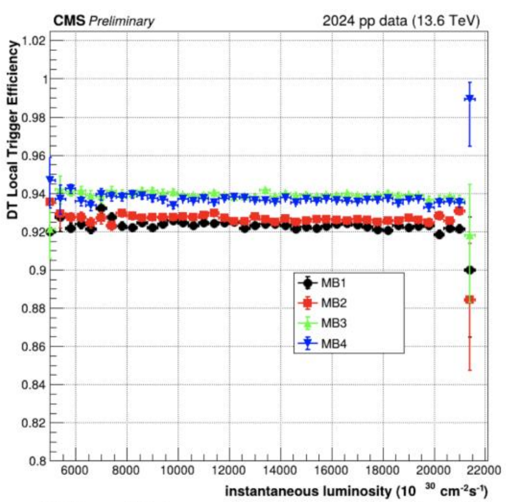
Endcap RPC efficiency and cluster size distribution in Run2 (2018) and Run3 (2022, 2023, and 2024)

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

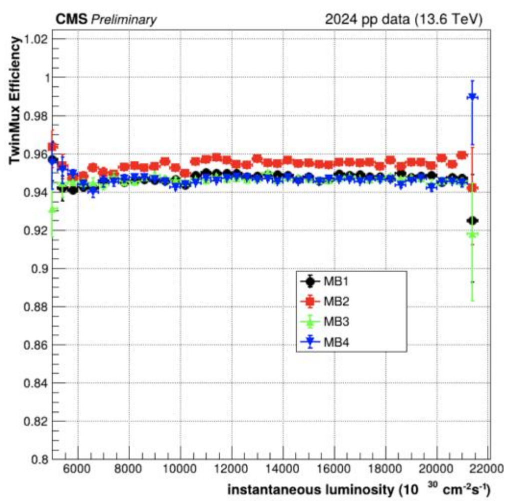
Local trigger and TwinMux performance

- 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 in order to:
  - **recover DT inefficiencies** using **RPC-only primitives** (MB1 and MB2 stations only)
  - **improve BX identification efficiency** by exploiting the RPC's excellent time resolution





DT Local Trigger efficiency as a function of LHC instantaneous luminosity



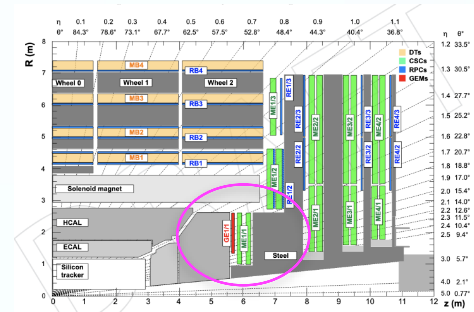
TwinMux efficiency as a function of LHC instantaneous luminosity

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

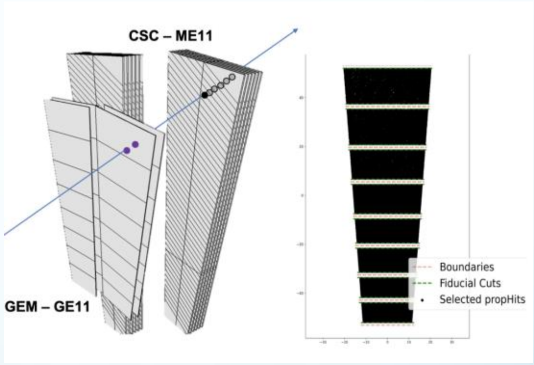
G. Pugliese

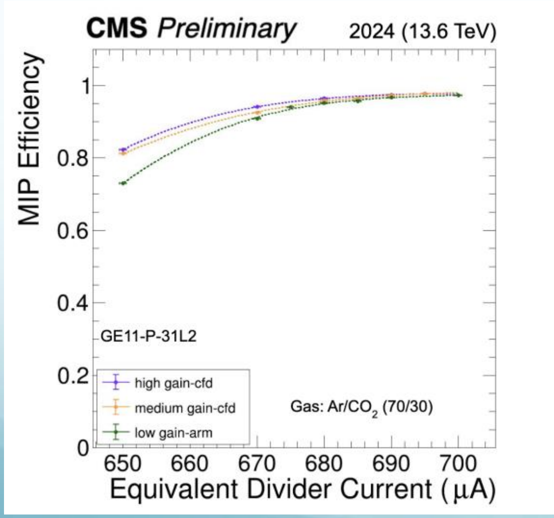
GEM calibration in 2024

- **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].

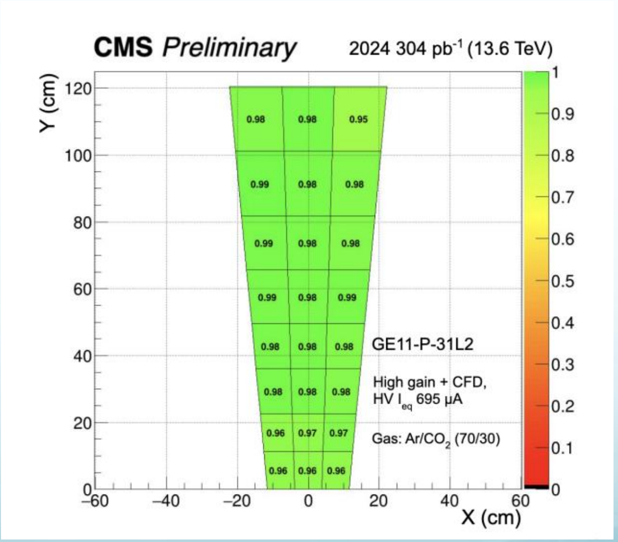


- GEM analysis done using events with standalone (STA) muons (p_T > 10 GeV, with at least 15 hits in the muon system, and χ_2 < 5) and with hits in the CSC companion station (i.e. accept a track through GE1/1 only if it contains ME1/1 hits)





GE1/1 efficiency vs. current



GE1/1 efficiency map

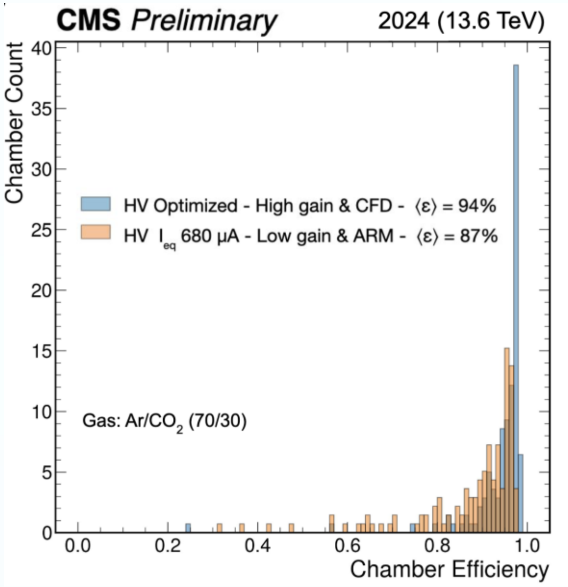
G. Pugliese

GEM performance in RUN3

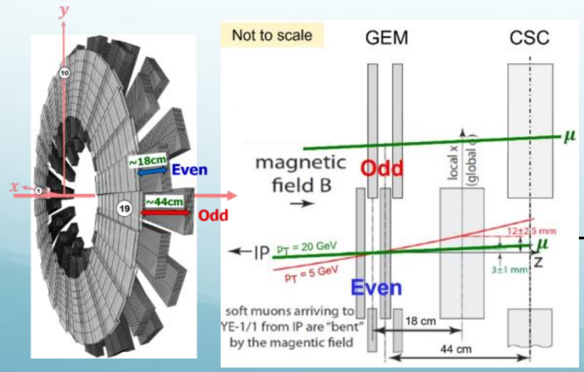
2024 ICHEP

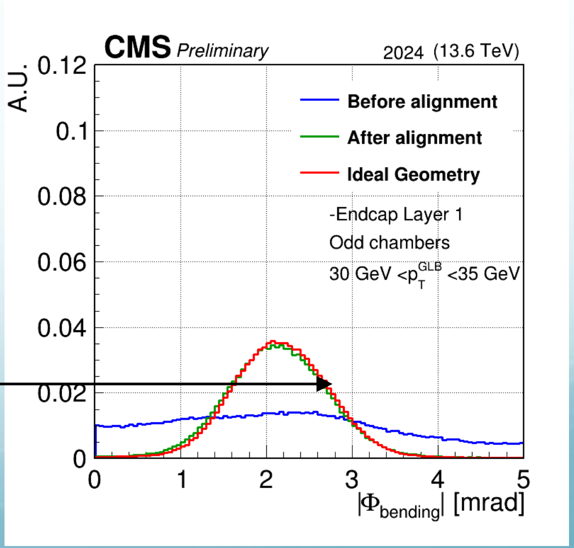
- A new HV setting was applied in the middle of June 2024
- A significant increase in the GE1.1 efficiency has been measured with HV-optimized and High gain Constant Fraction Discriminator

More on GE1.1 operations in ***S. Calzaferri's talk***



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



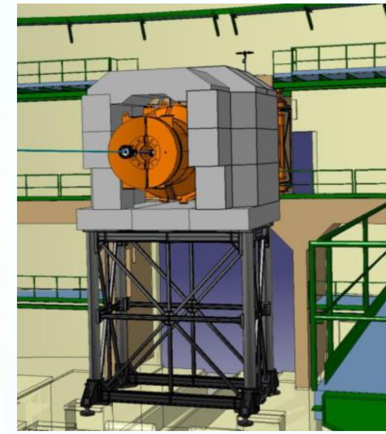


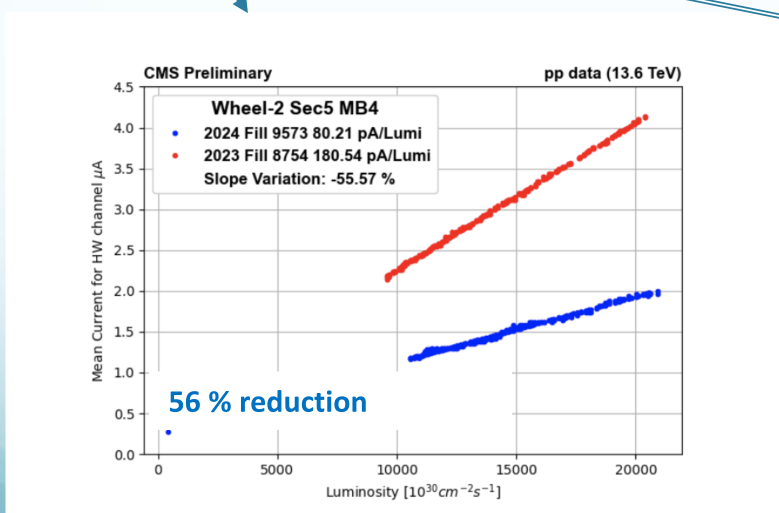
G. Pugliese

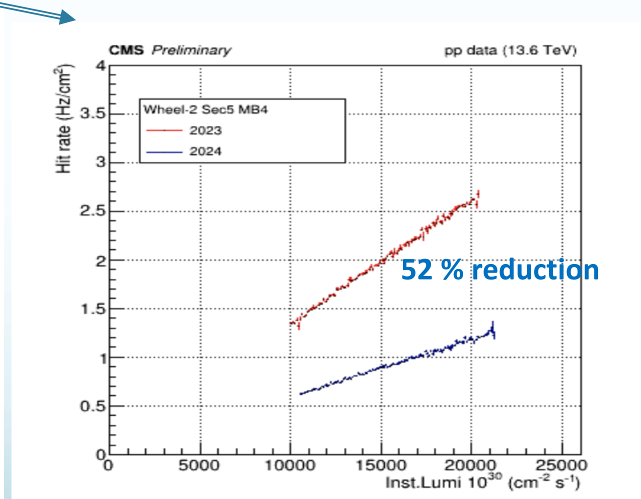
Background in 2024

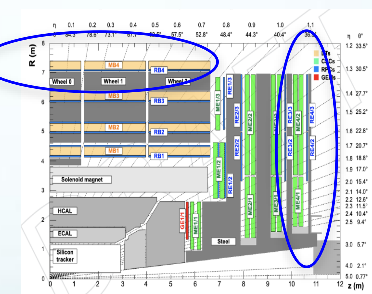
A **New Forward Shielding (NFS)** was designed to reduce background in the cavern detected by the muon detectors. In the last shutdown, it was installed only on the negative side

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





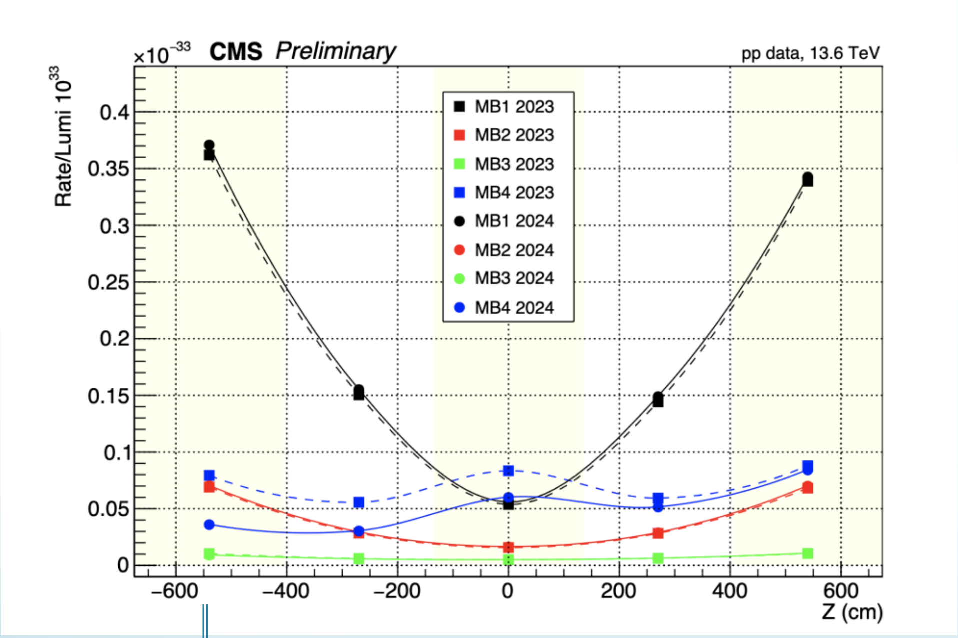


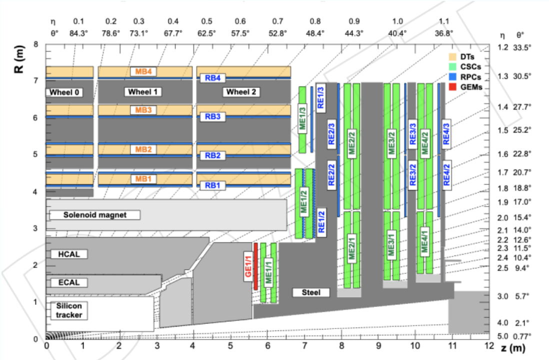


DT Background currents and rates versus instantaneous luminosity in one MB4 sector of W-2 as measured in 2024 and 2023

Background in 2024

- 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

Conclusions

The CMS Muon **system is operating extremely well,** delivering good triggers and data for physics:

- Negligible ~4% contribution to CMS luminosity loss
- Stable fraction of active channels

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:

- Muon chamber performance is stable with no degradation observed
- Excellent and stable DT and CSC Segment and local trigger efficiency
- Excellent efficiency for the new GE1.1 station: 94%

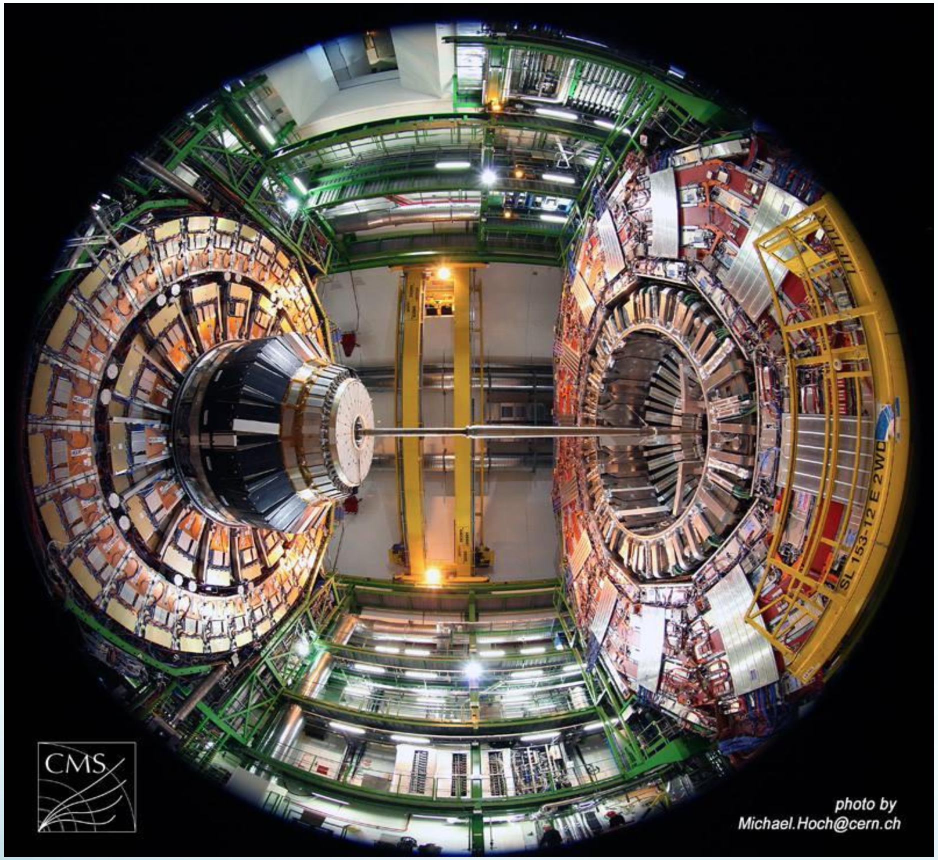
- Significant reduction of the LHC background measured after the installation of the new shielding in early 2024
- NEWS: published the paper **Development of the CMS detector for the CERN LHC Run 3**

G. Pugliese

2024 ICHEP

Thanks!

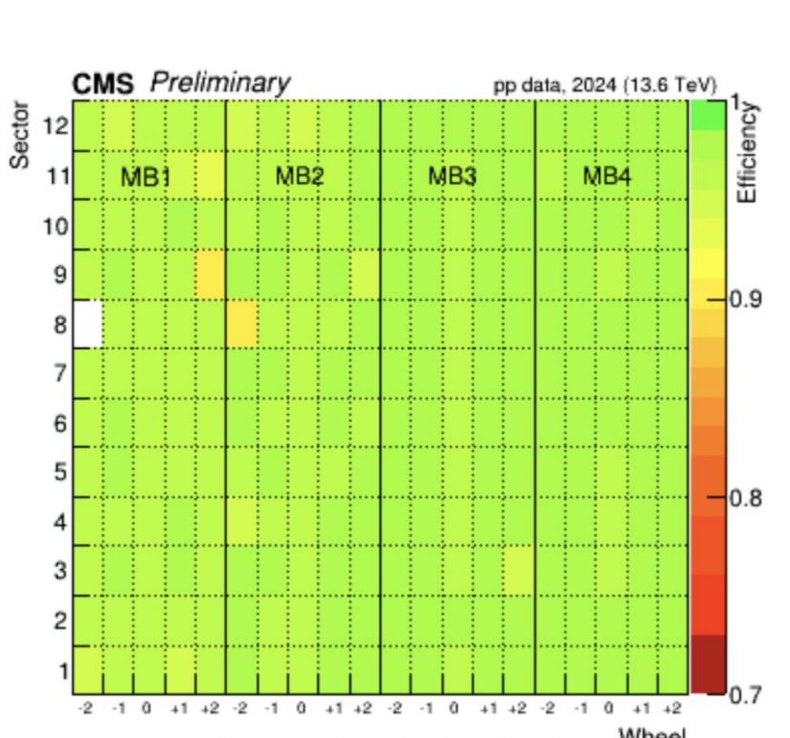
Credits to CMS People



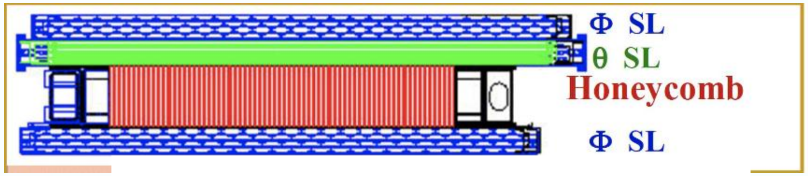
Backup slides

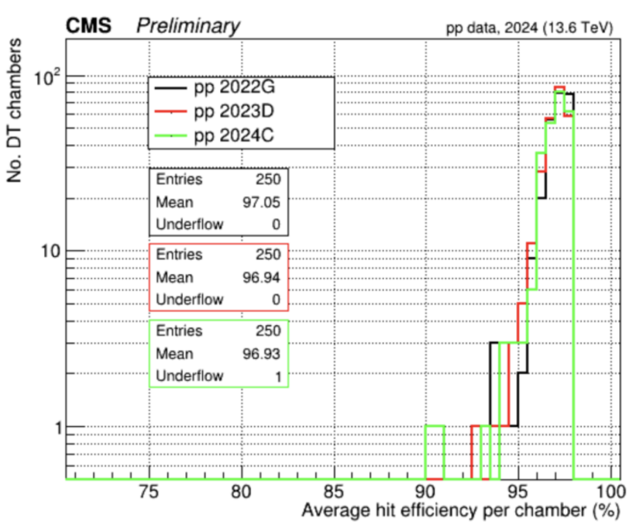
G. Pugliese

RUN3 DT Hits Efficiencies



Hit efficiency chamber by chamber





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

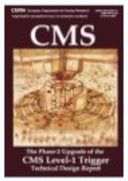
- **DT hits efficiency** exceeds 96.9 % (few exceptions are due to known hardware problems) and it is **stable**
- In 2024, one chamber only in Wheel -2 Sector 8 MB1 is not working because of a gas connection problem: this problem is reported as a light blue bin in the plot and will be fixed over the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

G. Pugliese

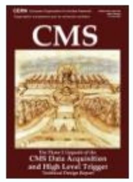
CMS Upgrade Project

2024 ICHEP

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

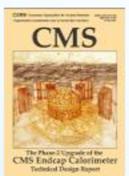


Level-1 Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1 Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting

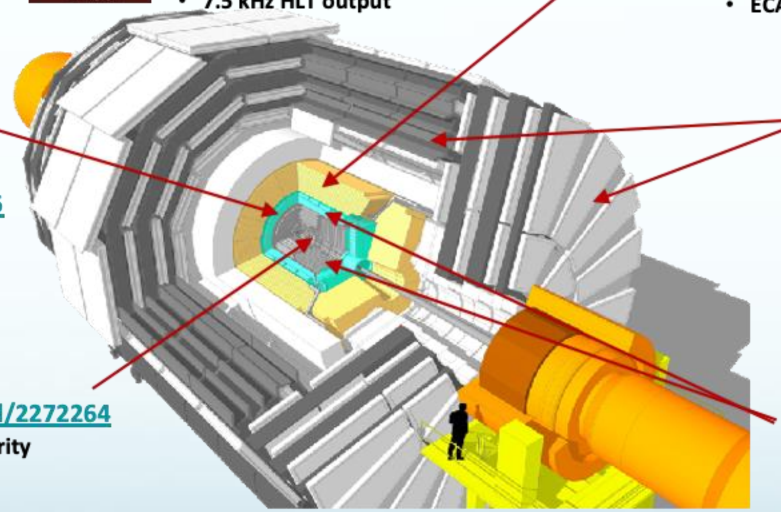


DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

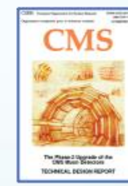
Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL single crystal granularity readout at 40 MHz with precise 30 ps timing for e/γ at 30 GeV
- Spike rejection
- ECAL and HCAL new Back-End boards



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



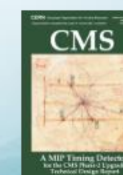
Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC BE electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

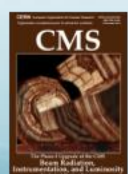


Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Extended coverage to $\eta \simeq 4$
- Design for tracking in L1 Trigger

MIP Timing Detector
https://cds.cern.ch/record/2667167

Precision timing with:
- Full coverage to $\eta \simeq 3$
- 30-50 ps time resolution for MIPs
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes





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

LHC and HL-LHC schedule

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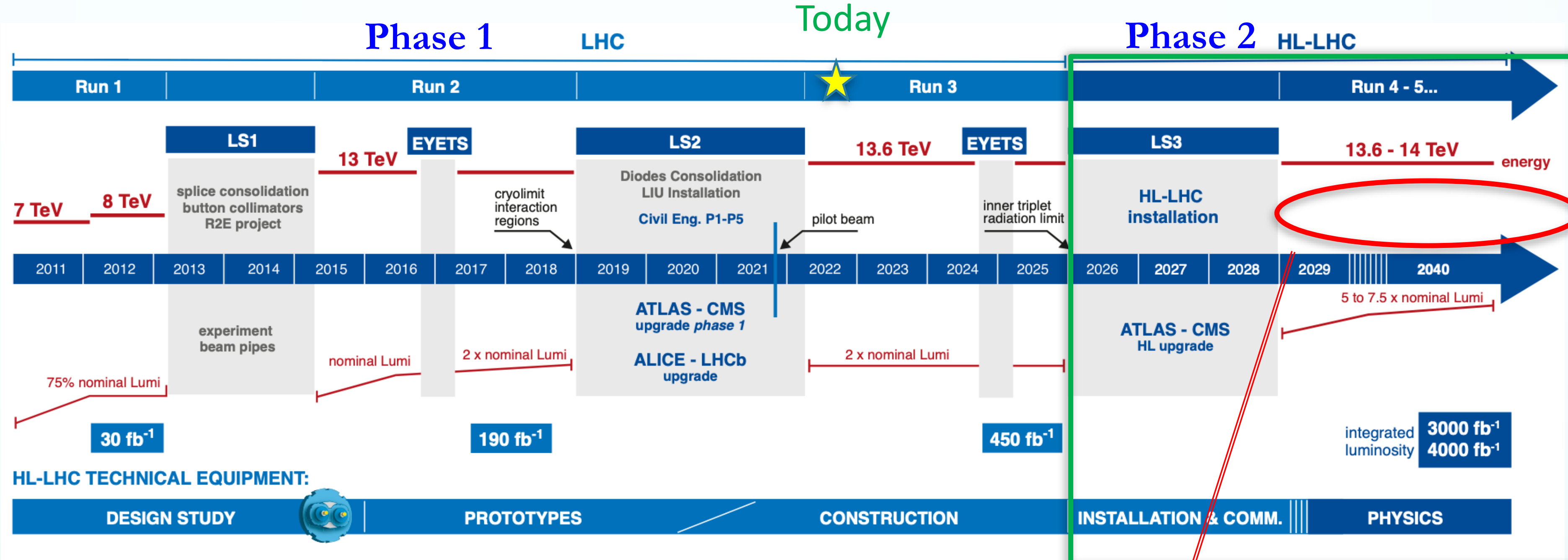
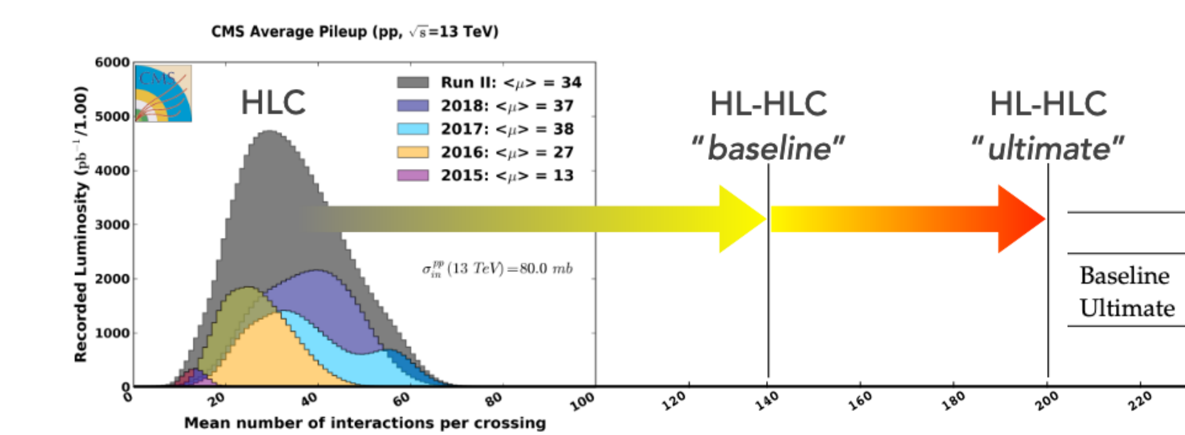
2024 ICHEP





10 years of running at higher rates and radiation doses

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

![INFN logo]

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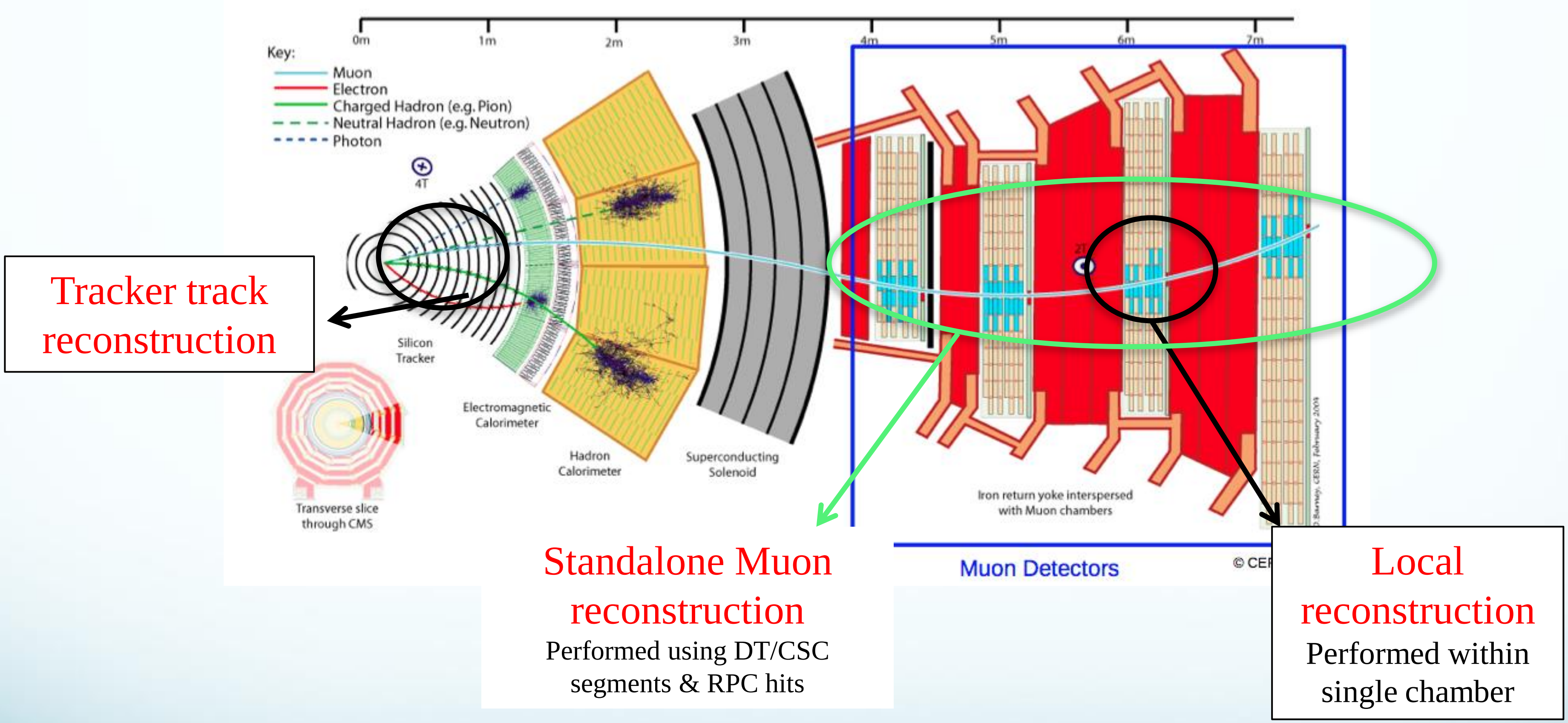
Muon Reconstruction



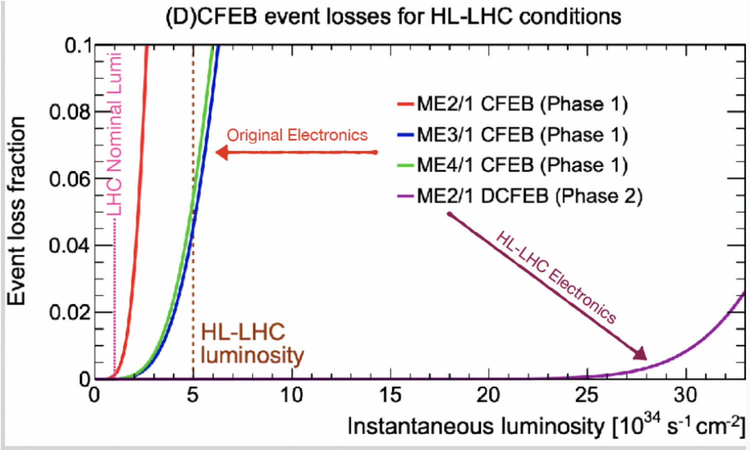
Global muon reconstruction (out side –in): a standalone muon is propagated to match a tracker track. If matching is positive a global fitting is performed.

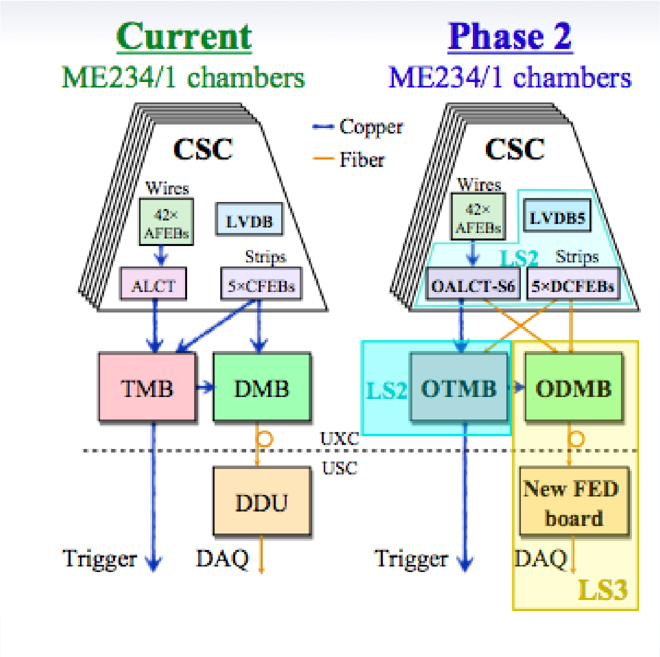
Tracker Muon (inside – outside): a tracker track is propagated to muon system and qualified as muon if matching with standalone or one segment.

G. Pugliese

CSC Electronics Upgrade motivation

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
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
HV	40/12	ME1234/1	Increased current due to higher occupancy
FED	14	USC	Increased data volume, number of links

LS2

LS3

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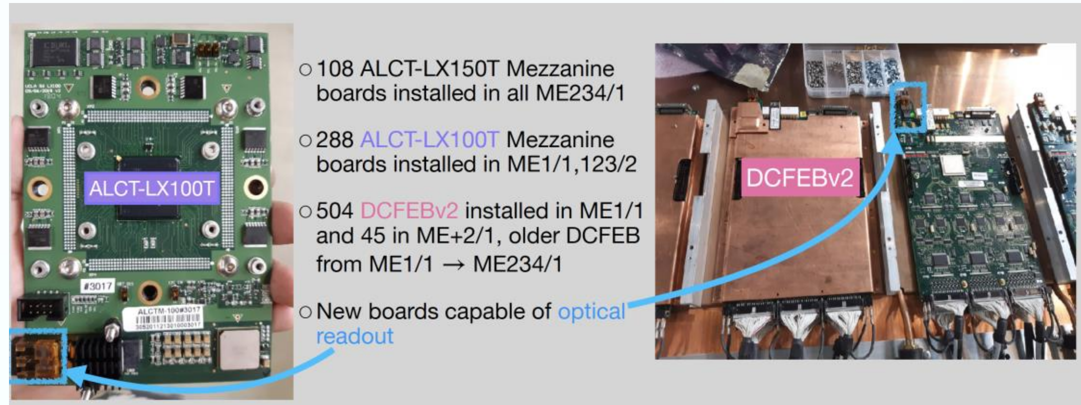
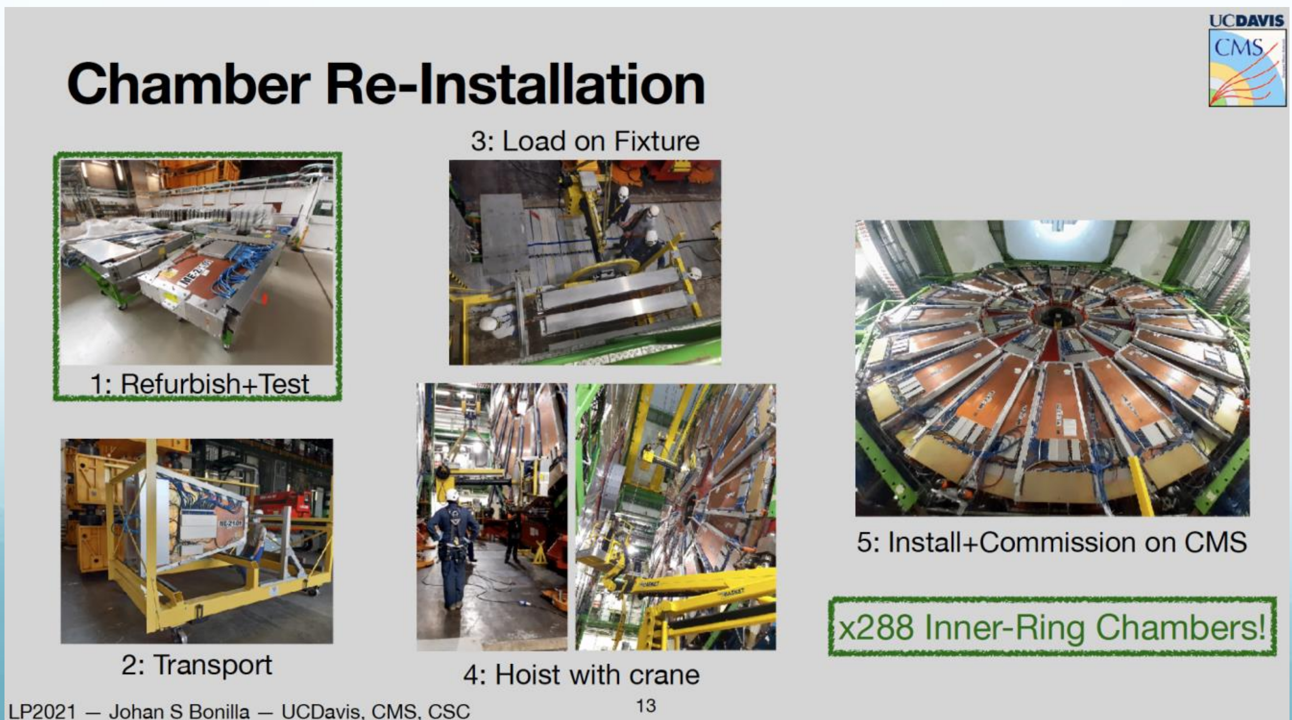
LS2 CSC Upgrade activity

The on-detector Refurbishment of Electronics in LS2





Muon Upgrade

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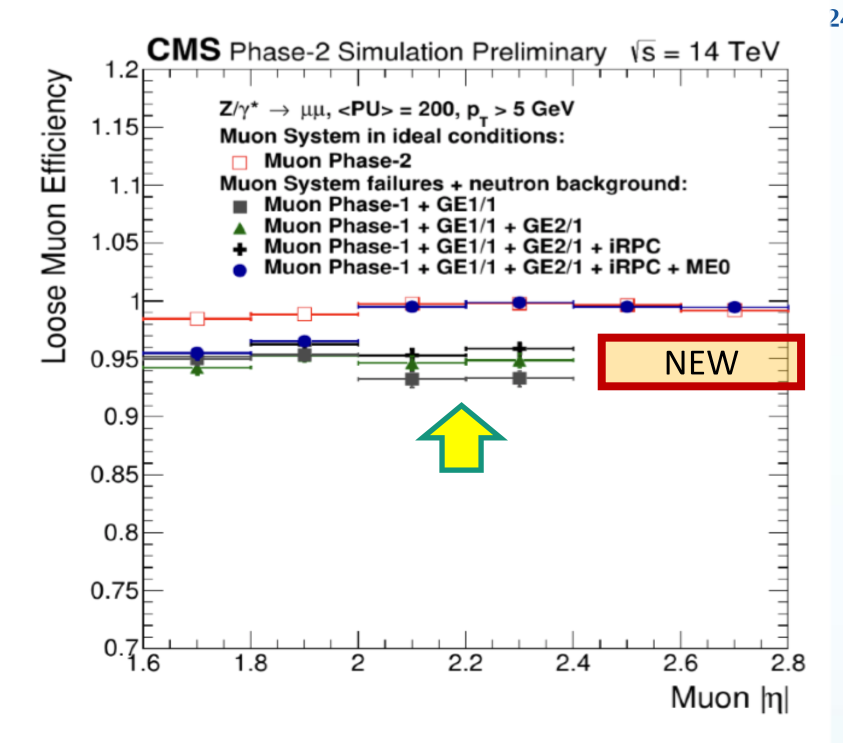
New GEM and RPC detectors needed to improve efficiency reconstruction and trigger performance at HL_LHC



- 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