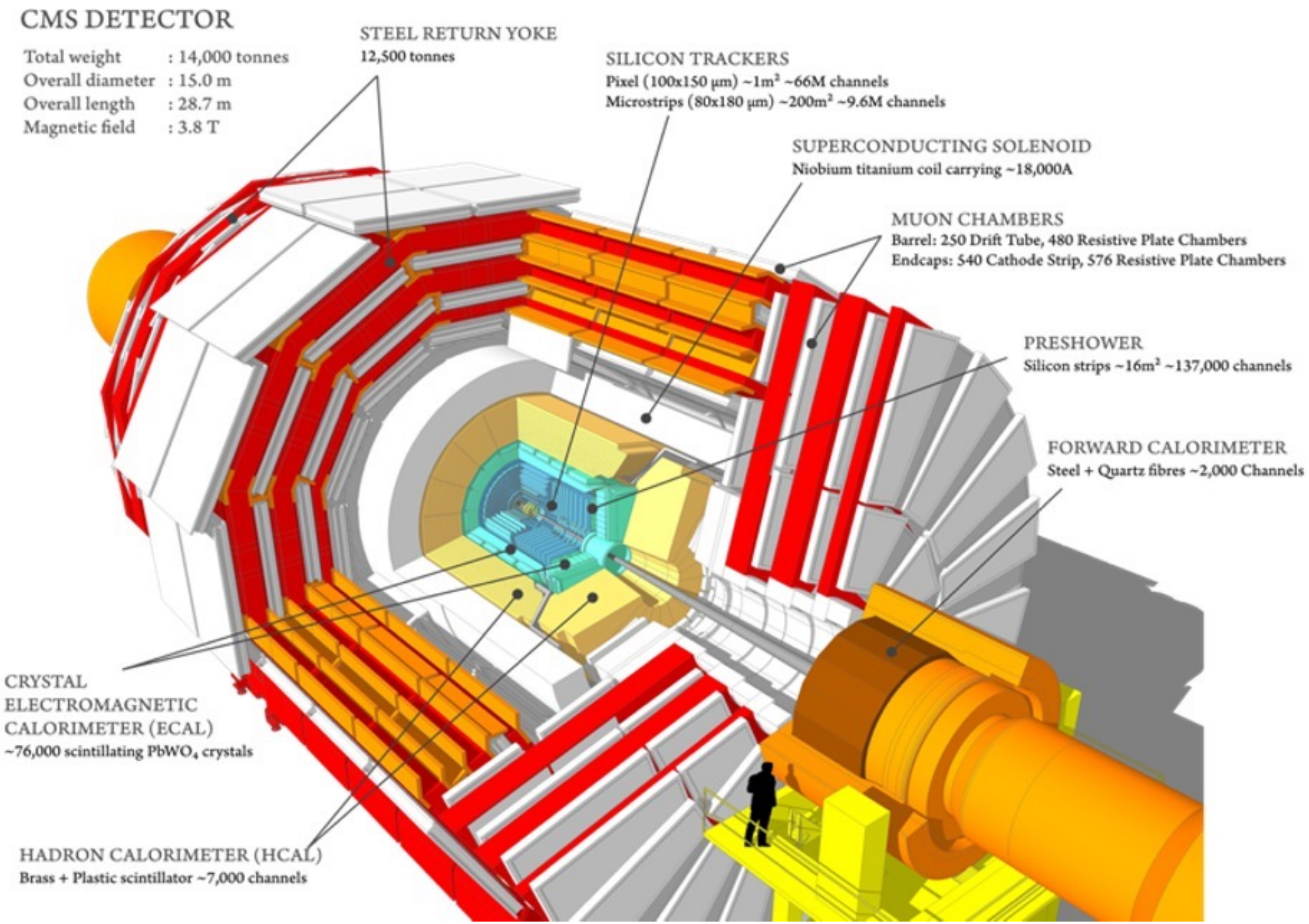
JINR participation in the CMS upgrade for the High Luminosity LHC

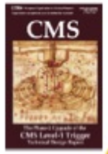


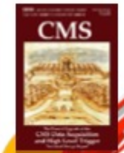
Vladimir Karjavine
Joint Institute for Nuclear Research

CHEP-2023 Yerevan, Armenia
11-14 September 2023

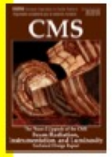
CMS High Luminosity LHC Upgrade (HL-LHC)

L1 Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- L1 40 MHz in/750 kHz out
- Tracking for PF-like selection
- HLT 7.5 kHz out

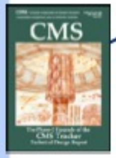




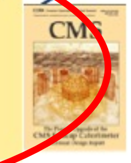
Beam Radiation and Luminosity
https://cds.cern.ch/record/2020886
- Bunch-wise Luminosity
- Beam Monitoring

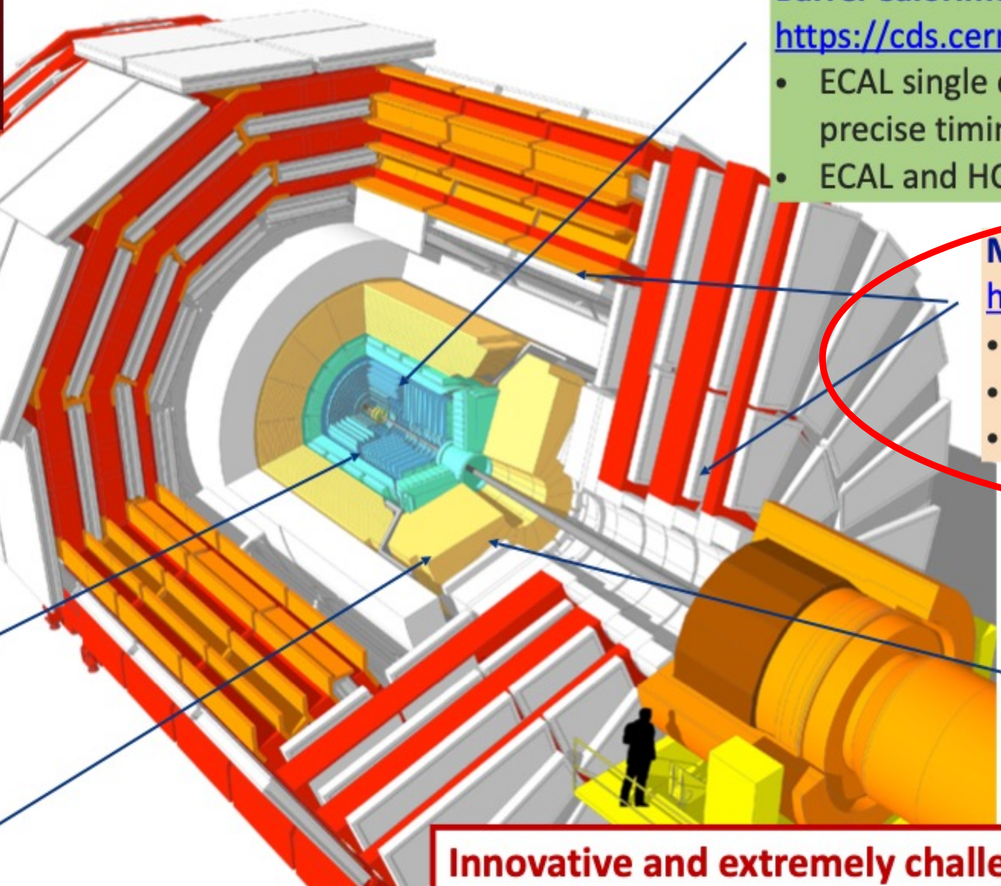


Tracker
https://cds.cern.ch/record/2272264
- Si Strip Outer Tracker designed for L1 Track Trigger
- Pixelated Inner Tracker extends coverage to $|\eta| < 3.8$

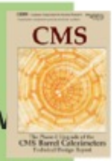


Calorimeter Endcap *Also known as HGCal*
https://cds.cern.ch/record/2293646
- Si, Scint + SiPM in Pb-W-SS
- 3D shower imaging with precise timing



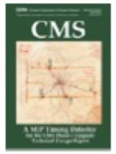


Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL single crystal granularity in L1 Trigger w precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics



Muon Systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| < 3.0$

MIP Timing Detector
https://cds.cern.ch/record/2296612
- < 75 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs



Innovative and extremely challenging new capabilities:
- **Level 1 track trigger**
- **Timing detector**
- **Highly granular endcap calorimeter**

HL-LHC Schedule

High Luminosity LHC program will start by 2029

HL-LHC challenging conditions

	LHC	HL-LHC
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 Phase1	CMS Phase2
L1 trigger (kHz)	100	**750**
L1 latency (μs)	3.6	**12.4**

Goal of the HL-LHC upgrade:

To maintain the excellent performance of the CMS detectors in the High Luminosity LHC operation mode

2022-2023

- Completion of the LS2 upgrade
- CMS Detector commissioning
- Run 3 data taking

Muon System Upgrade Overview

- Goal of Muon system: muon identification, momentum measurement and triggering
- Four detectors based on Gaseous detector technologies:

- Drift Tubes (DT) - Cathode Strip Chambers (CSC) - Resistive Plate Chambers (RPC) - Gas Electron Multiplier (GEM)

- Present DT, CSC, RPC detectors will stay
  - Upgrade Electronics
  - Extensive longevity studies

- **DT: Replace FE/BE electronics**
- **RPC: Replace off-chamber readout/ control system**
- **CSC: Replace selectively FE board and all BE**

- GE1/1: 1.6<|η| < 2.2
- 72 triple-GEM chambers
- Installation done LS2

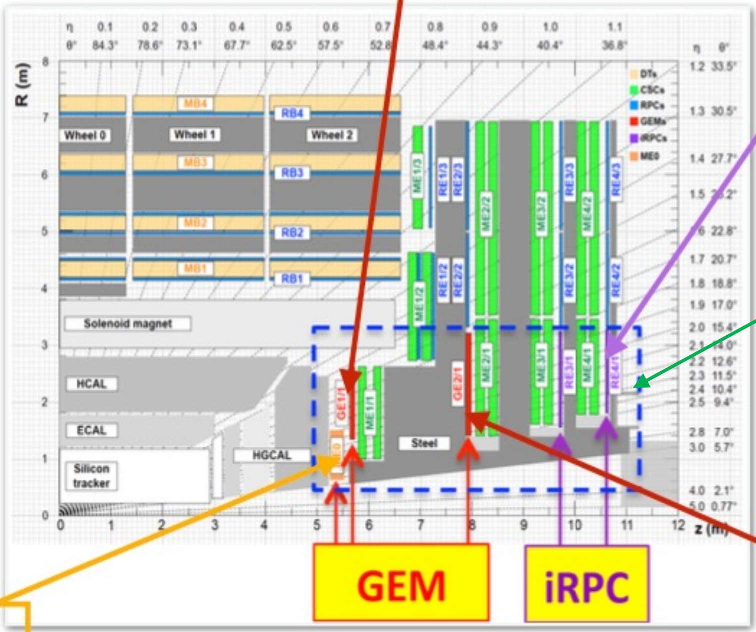
- iRPC: Extends RPC acceptance |η| from 1.9 to 2.4
- RE3/1 and RE4/1

Inner rings MEx/1 stations

ME1/1, ME2/1, ME3/1,ME4/1 Total 180 CSCs

xDCFEBs installed on ME1/1,

old DCFEBs moved on ME234/1



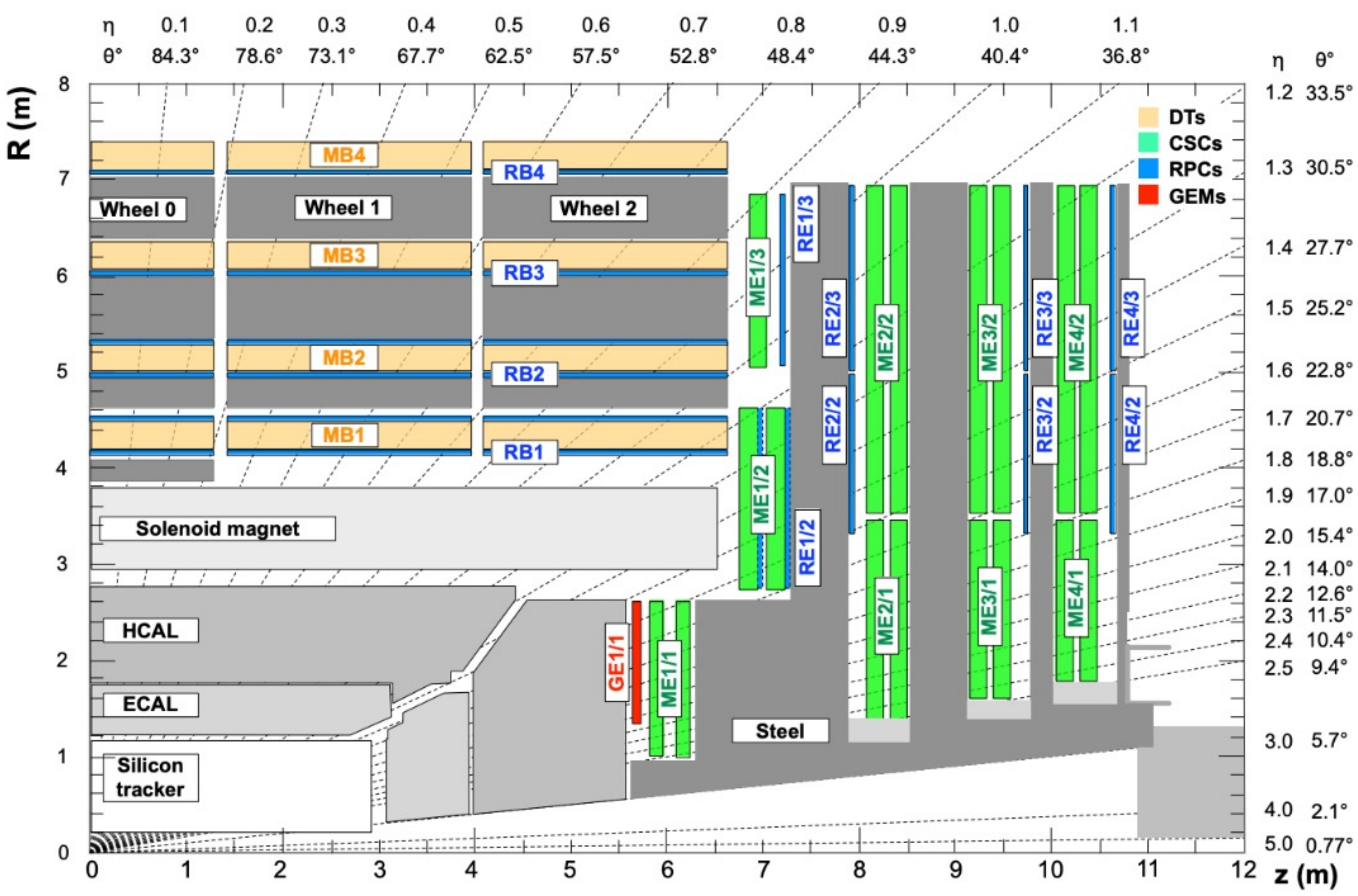
- ME0: extend the acceptance |η|= 2.8
- 6 layers of Triple-GEM

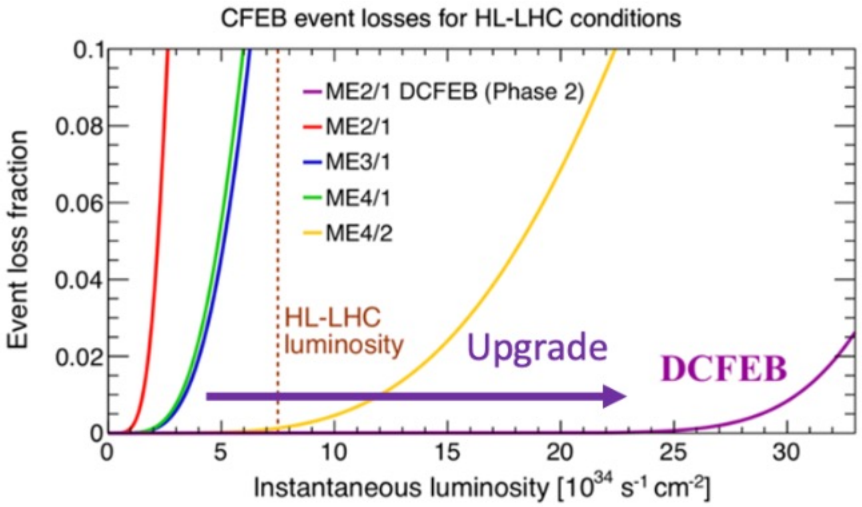
- GE2/1:1.62< |η| < 2.43
- 4 triple GEM modules per chamber

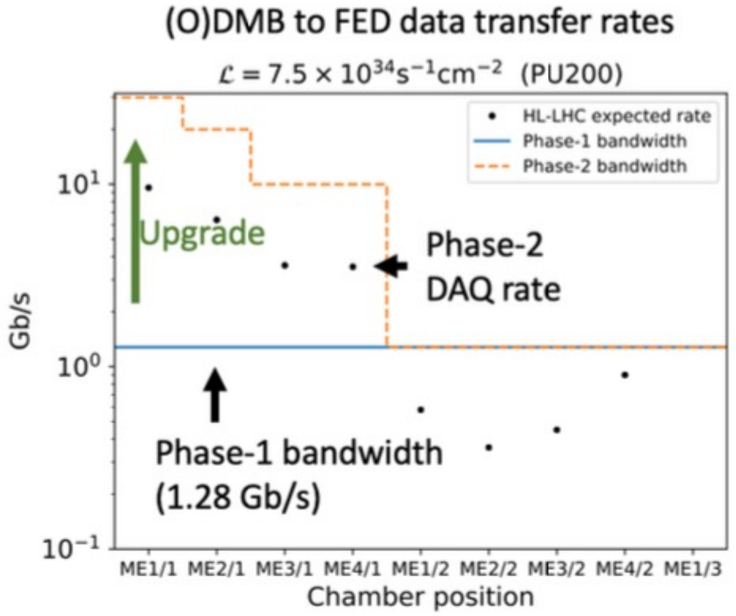
CSC FE Electronics Upgrade

Due to increase of trigger latency and particle rates at HL-LHC

- Memory overflows & readout inefficiencies/event losses are expected
- (O)DMBs for ME1234/1 can't cope with increased data transfer rates in Phase-2





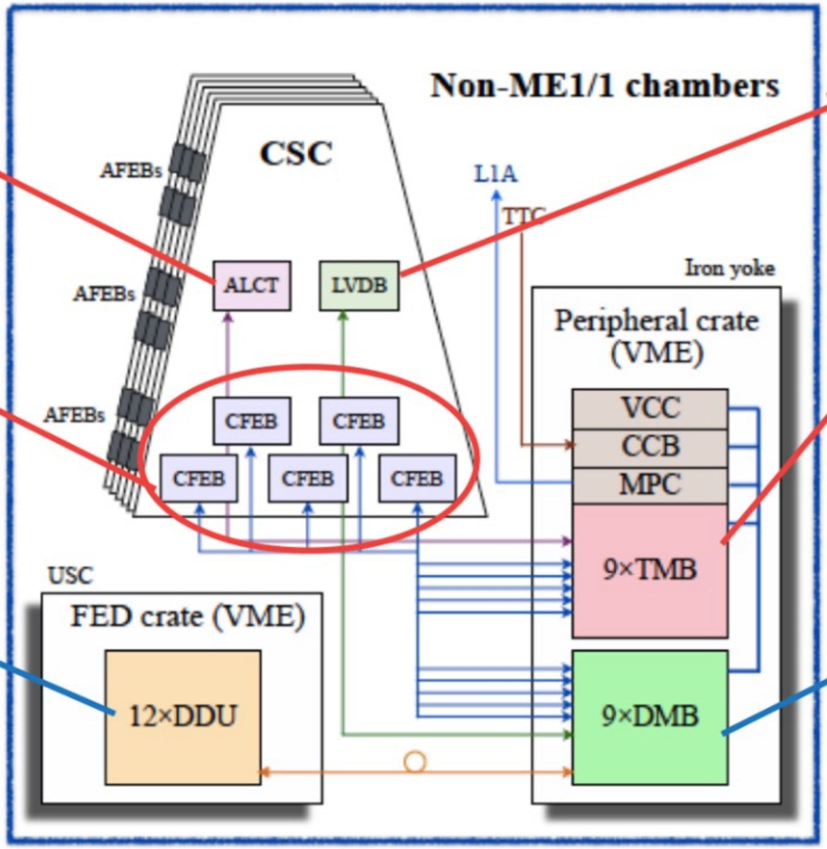


CSC Upgrade Overview

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

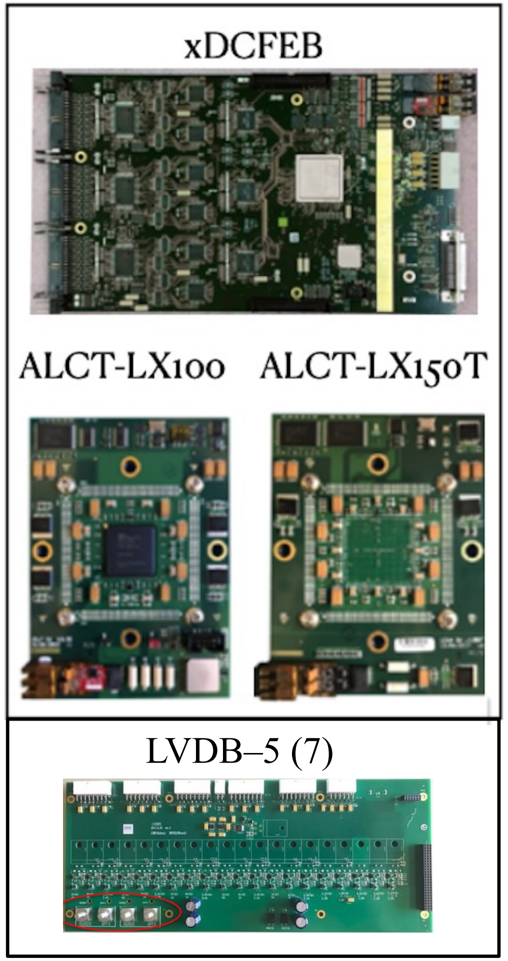
LS3
Front End Driver: increased data volume, number of links



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



LS2 Upgrade

Most of the FE electronics upgrades and LV & HV improvements are done in LS2

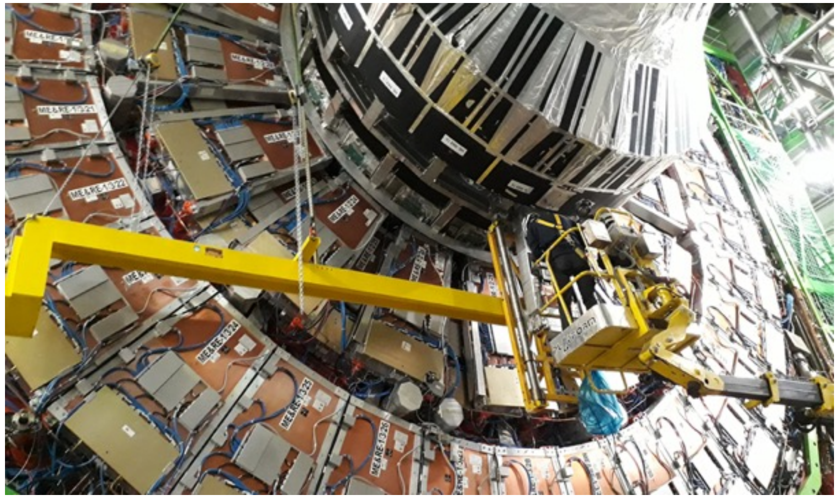
LS3 Upgrade

Replacement of the ODMB7 and ODMB5 and upgrade FED

CSC Upgrade during LS2

180 CSCs of inner rings MEx/1 stations were dismounted from CMS and refurbished with new FE electronics

CSC upgrade infrastructure



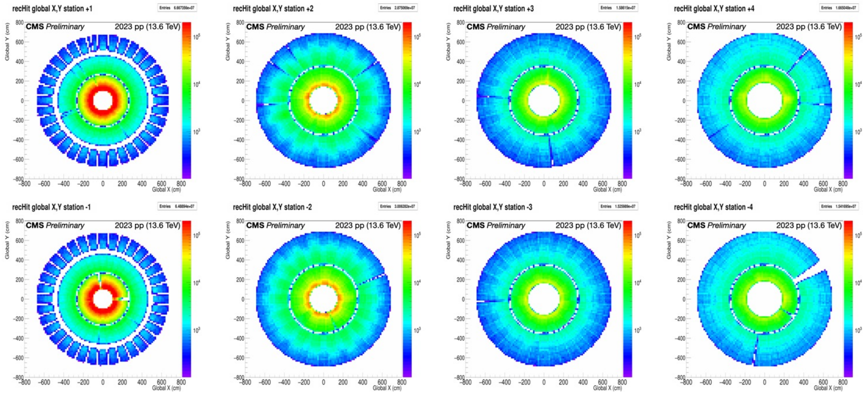
ME1/1 CSC installation

CSC Performance in Run 3

Reconstructed Hit Positions

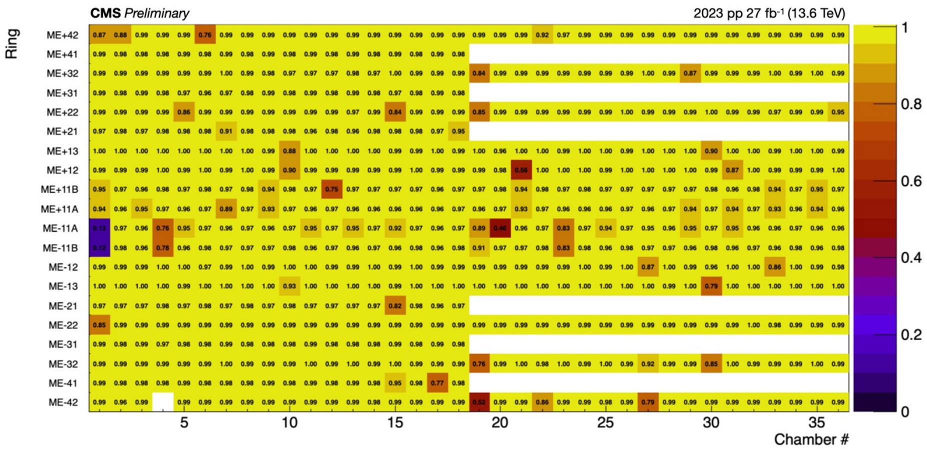
The global x and y position of reconstructed CSC hits in the four stations of the +z and -z endcaps

CSC reconstructed hit positions from one run of a muon-triggered dataset



Trigger Primitive Efficiency

Measured efficiency of each CSC to provide a trigger primitive for the CMS Level-1 trigger



- Neighbouring chambers on Ring 3 of station 1 do not overlap to avoid dead regions – no hits in the gaps between the chambers
- One chamber in ring 2 of station 4 in -z is permanently disabled (no access to failed electronics)
- Few of the empty regions corresponds to failed electronics boards which will be repaired during nearest access
- temporary failures lasting from periods of hours to days, which can be recovered without major intervention

- Excellent CSC Trigger Primitive Efficiency measured in RUN3: more than 98% of CSCs is operating at close to 100% of efficiency
- Few inefficient chambers due to known reasons

HCAL Upgrade

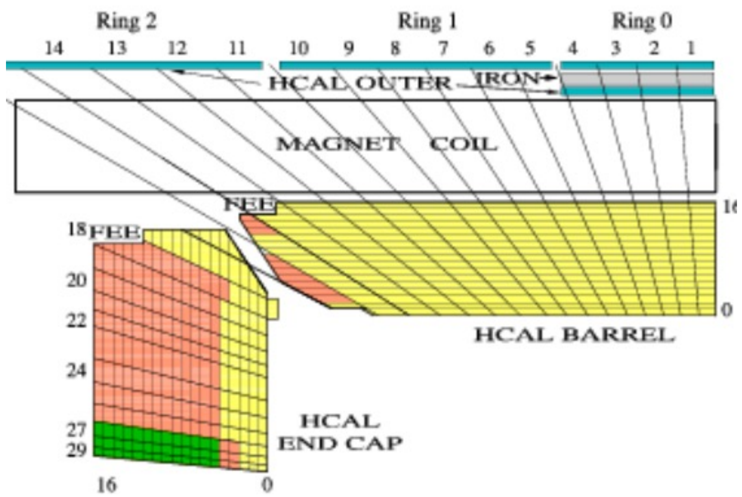
Motivation:

- Mitigate radiation damage to the HB scintillator
- Eliminate a source of high-amplitude noise
- Maintain physics performance for jets and MET

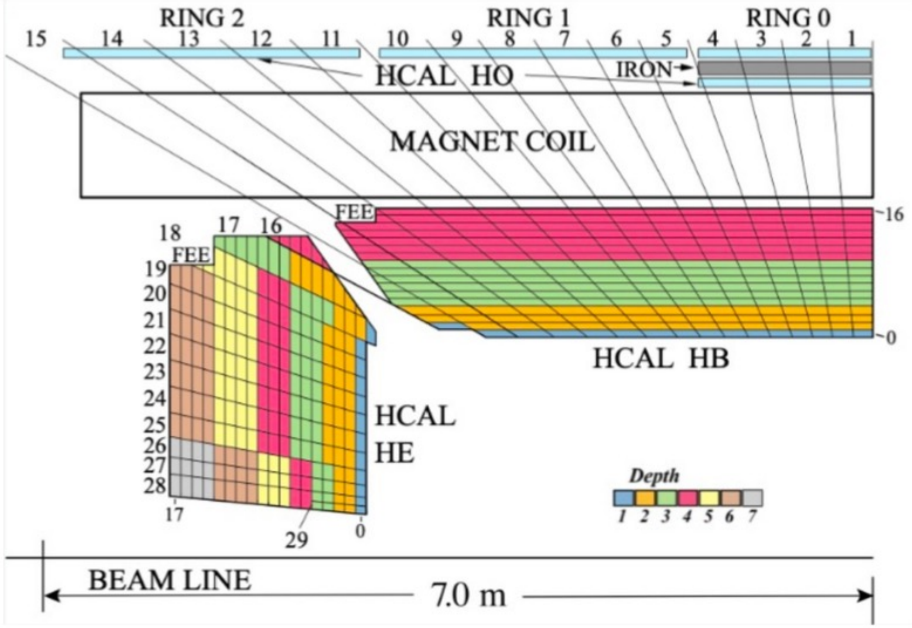
Hybrid photodetectors(HPD) replaced with new silicon multipliers (SiPM)

- ✓ 3 times higher photon detection efficiency, 200 times higher gain
- ✓ Finer depth segmentation 4 in barrel, up to 7 in endcap ==> depth dependent calibration
- ✓ 350% increase in the number of readout channels
- ✓ Added timing information (0.5ns resolution)
- ✓ Enable new triggers (e. g. long lived particles)

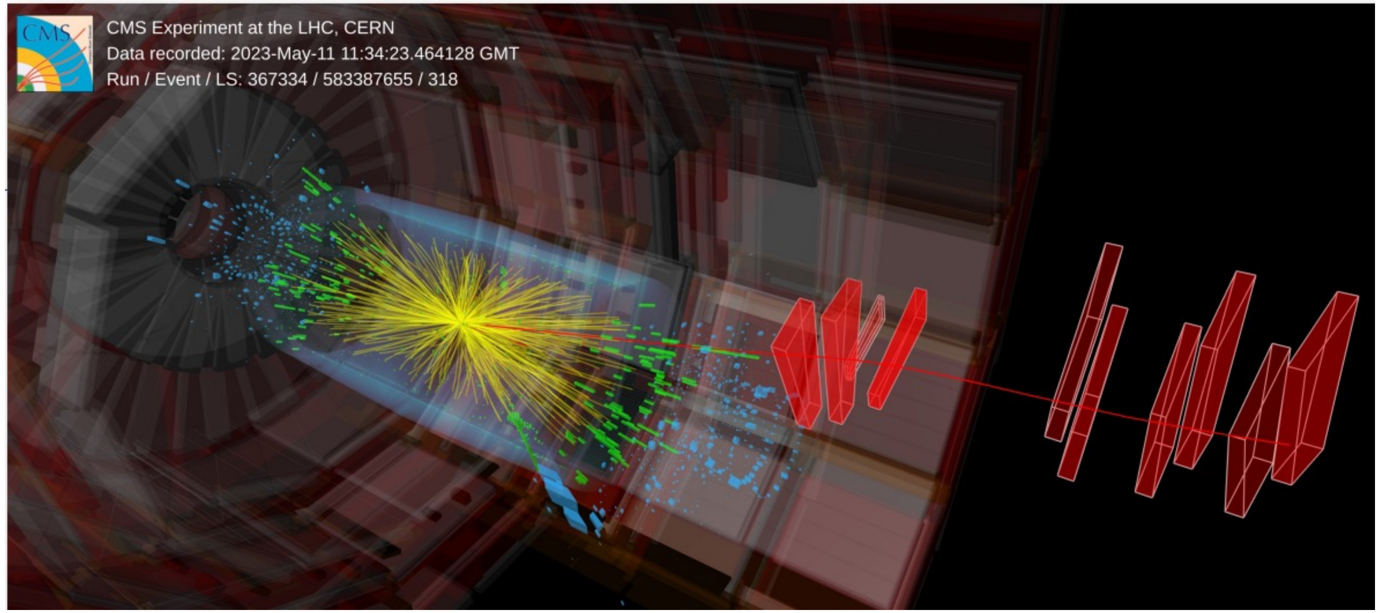
- Endcap upgrade before 2018

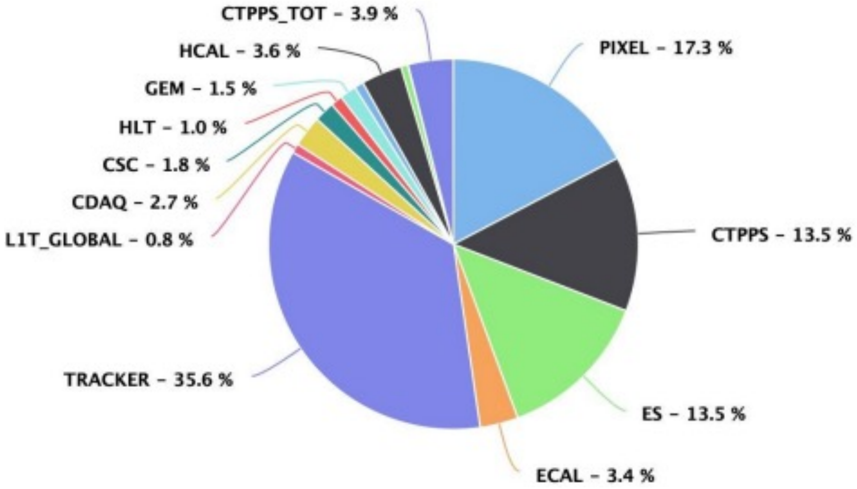


- Barrel upgraded for RUN-3



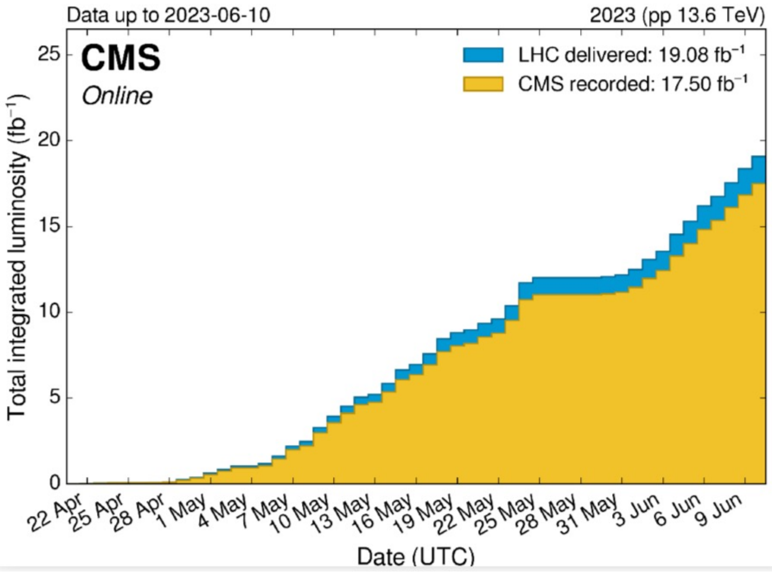
2023 CMS RUN 3 is Underway

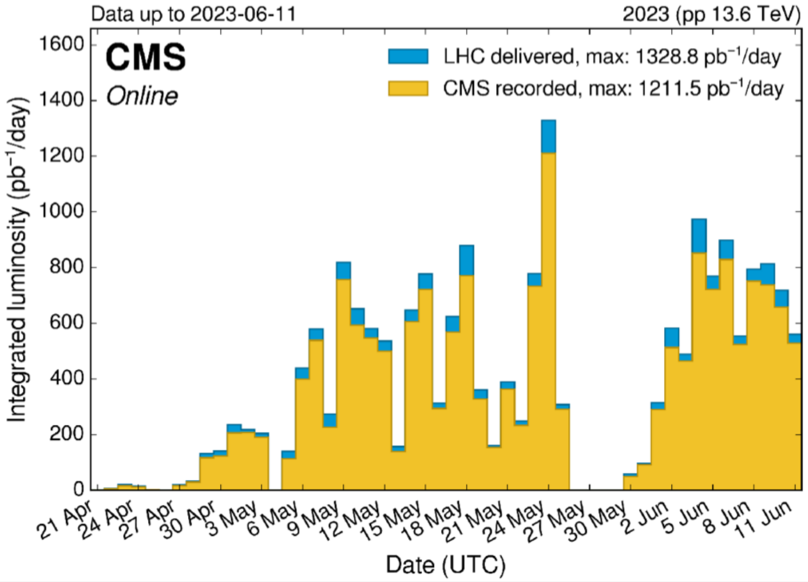


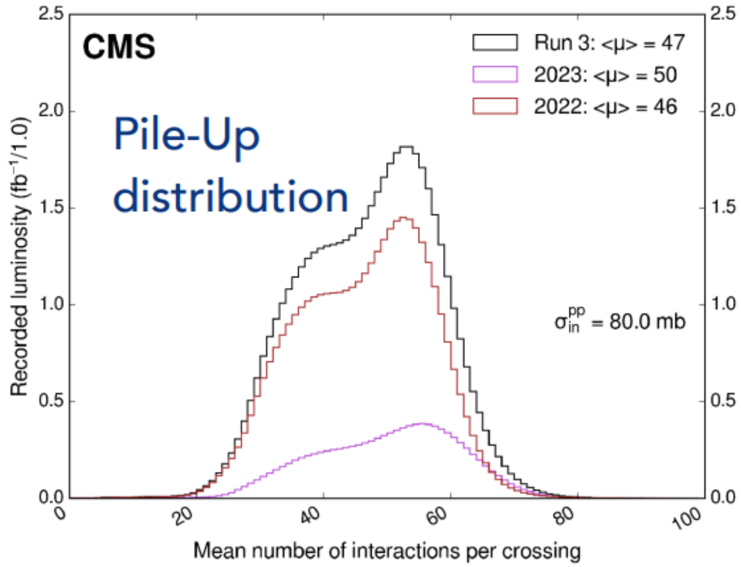


Downtimes are mainly due to automatic procedures to recover blocked channels caused by high lumi and/or high pileup

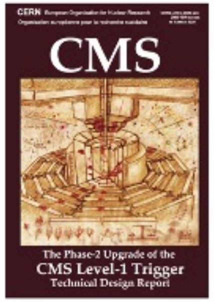
Data taking efficiency: 91.7%







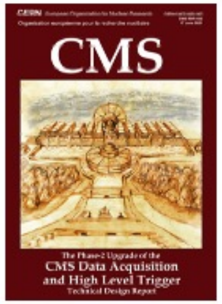
The CMS Phase 2 Upgrade



L1-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

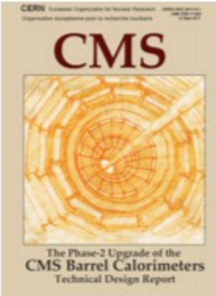
https://cds.cern.ch/record/2759072

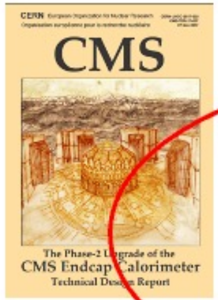
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters

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

- ECAL single crystal granularity at L1 trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

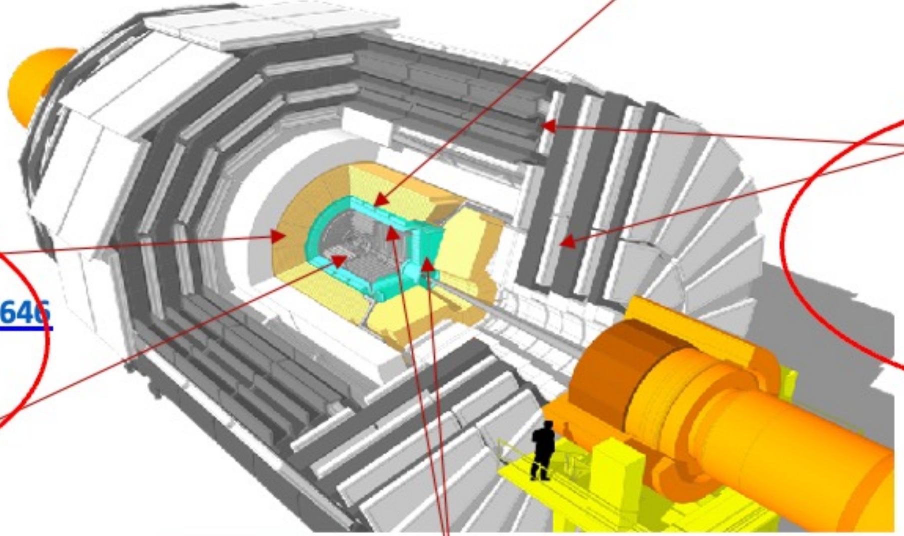




Calorimeter Endcap

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

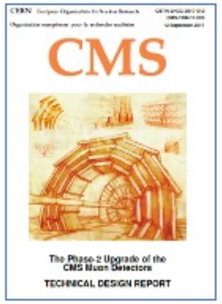
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

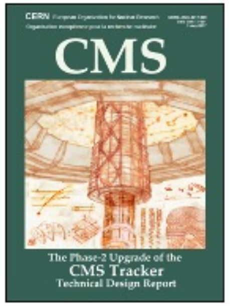


Muon systems

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

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

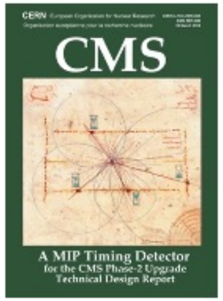




Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



MIP Timing Detector

https://cds.cern.ch/record/2667167

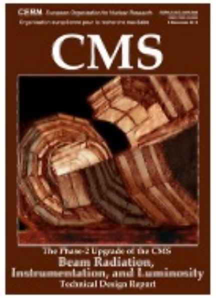
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer:
  Low Gain Avalanche Diodes

Beam Radiation Instr. 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



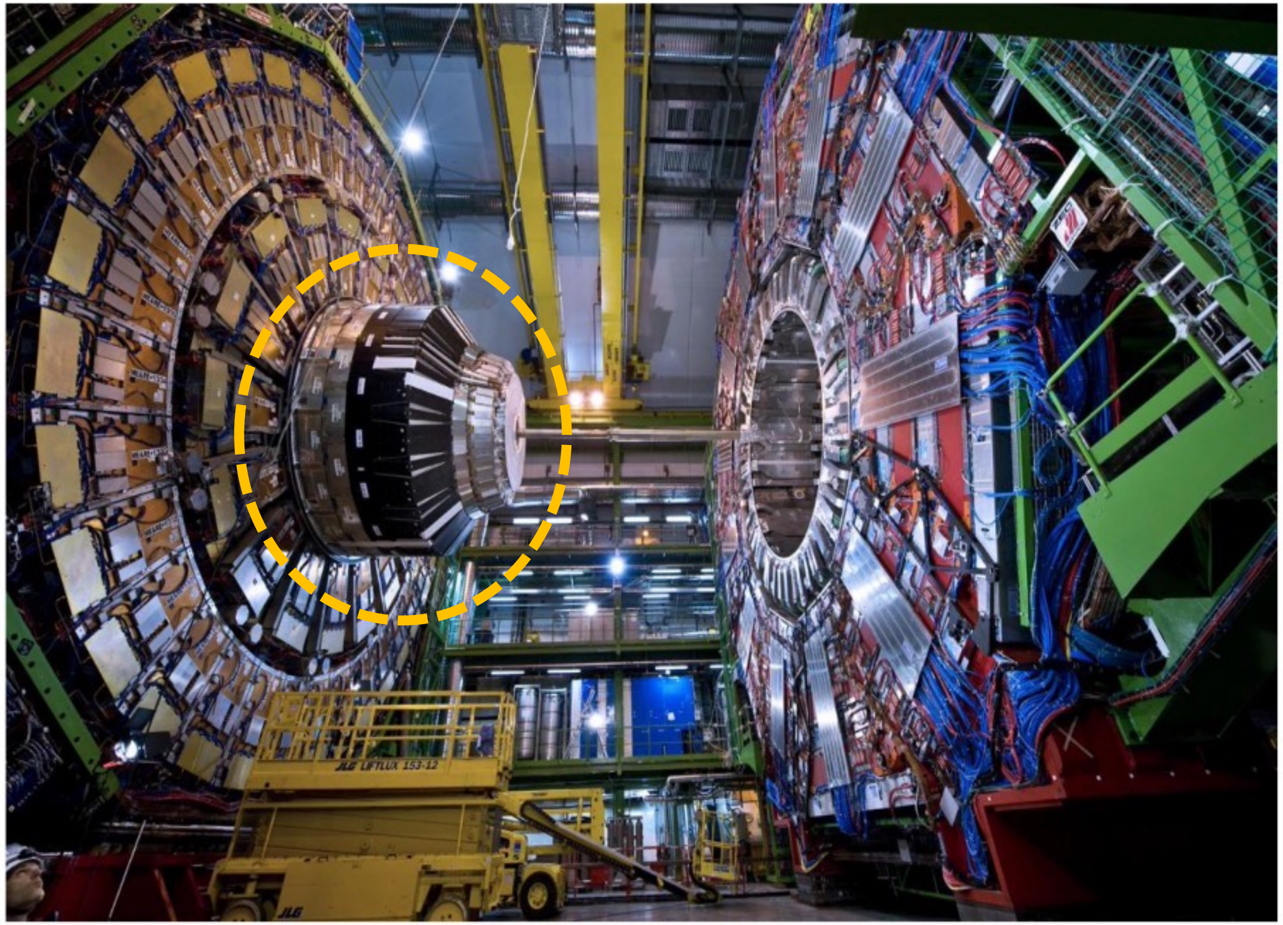
CMS Phase 2 Upgrade

Participation in HGCal Project

- Cooling plate of HGCal cassettes design
- Design and construction of the HGCAL silicon and scintillator cassettes test facilities

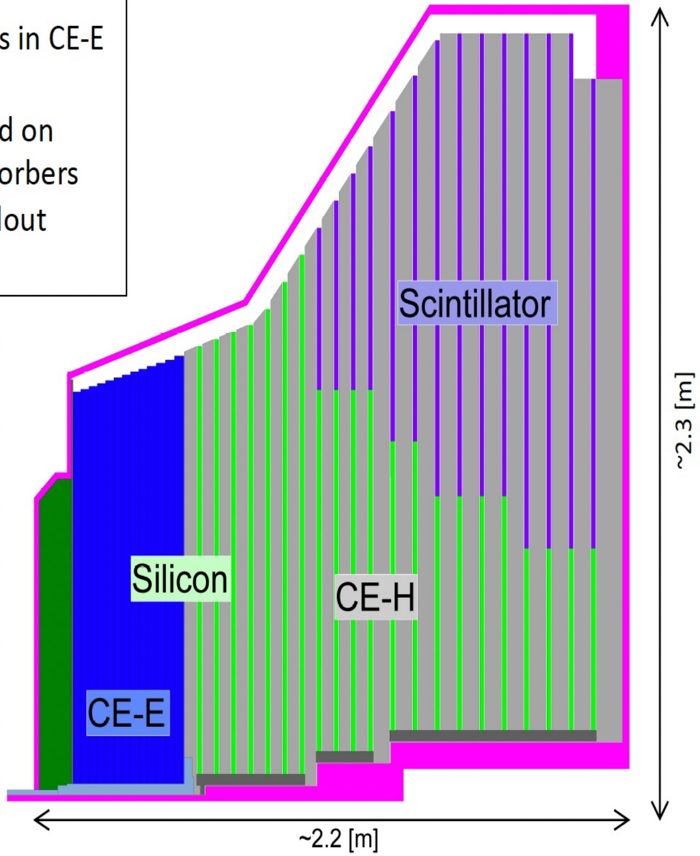
High Granularity Calorimeter - HGCal

- HGCal will replace the present Endcap Calorimeter (ECAL and HCAL) and Preshower sub-systems
- Installation during next Long Shutdown of LHC (lowering Q3 2027)



Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

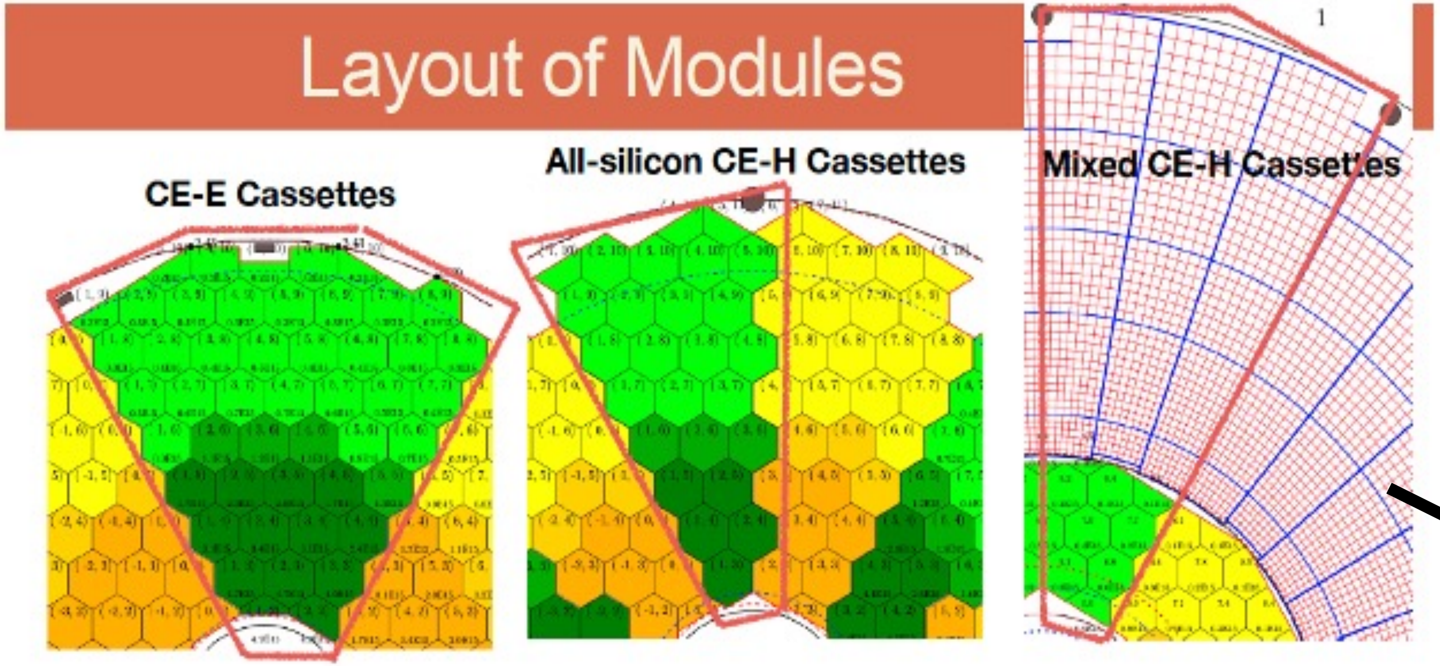
Key Parameters:
Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m^2 Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm^2 cell size
~370m^2 of scintillators in ~3700 boards
~240k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap



Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & ~1.5λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ

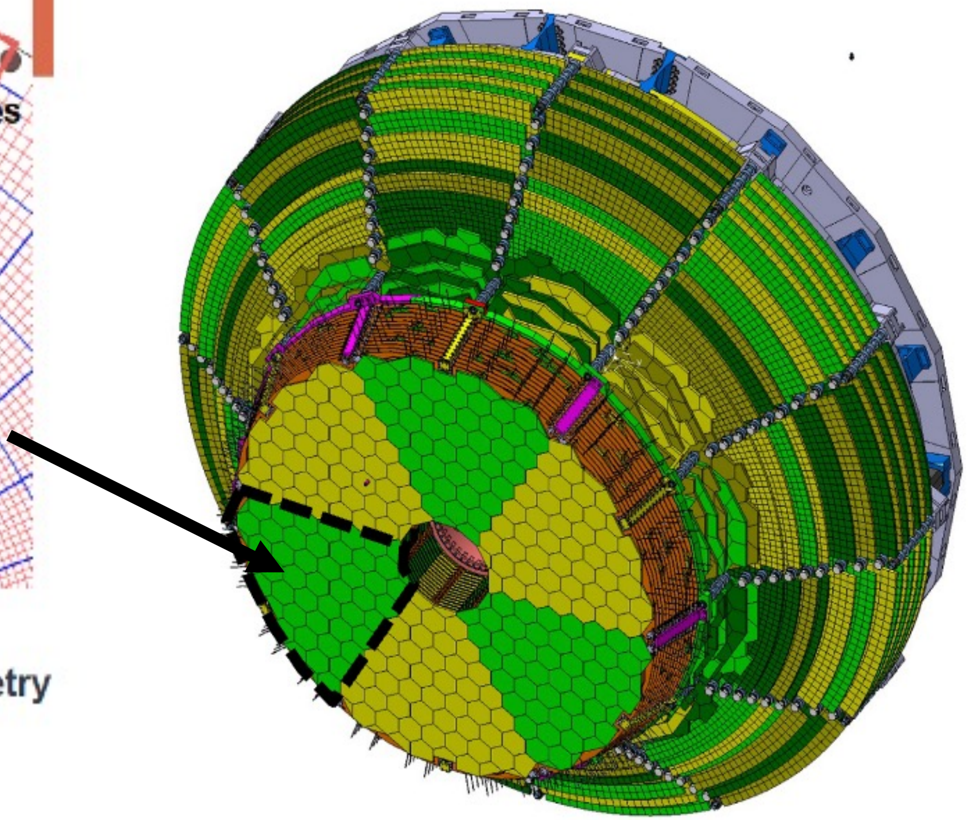
HGCal Main Active Elements – Cassettes

The active detector is formed into cassettes with cooling plate with silicon and scintillation modules



CE-E Cassettes	All-silicon CE-H Cassettes	Mixed CE-H Cassettes

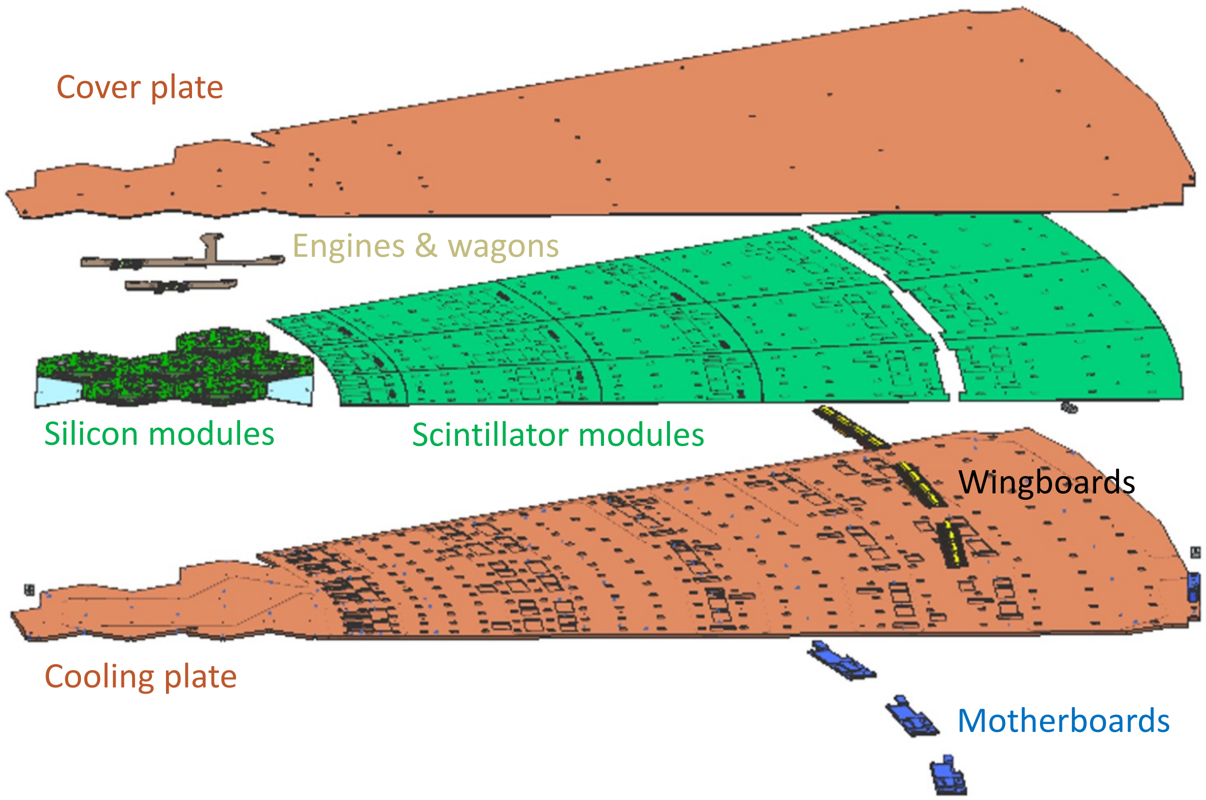
• Wafer-centered geometry
  • 60-degree rotational symmetry
• 60-degree cassettes
• double sided
• 26 layers -> 13 designs
	• Wafer-centered geometry
	  • 60-degree rotational symmetry
	• 30-degree cassettes
	• single sided
	• 7 layers -> 14 designs
		• Corner-centered geometry
		  • 120-degree rotational symmetry
		• 30-degree cassettes
		• single sided
		• 14 layers -> 40 designs



2 Cassette Assembly Facilities being setup (CERN and Fermilab)

Example CE-H Cassette Model

- A cassette is based on a copper cooling plate, up to 2.3m x 1.4m in size
- Silicon and Scintillator modules are attached to cooling plate with screws (not shown)
- Engines and wagons interconnect the silicon modules
- Wingboards and motherboards interconnect the scintillator modules
- Cables and optical fibers connect boards to the edge of cassettes (not shown)
- A cover protects and seals a cassette

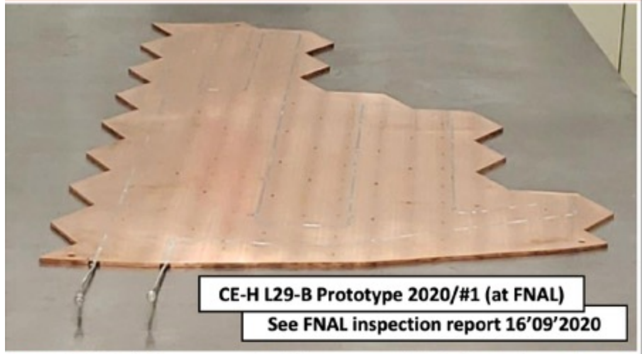


CE-H Cassette Cooling Plate Prototypes

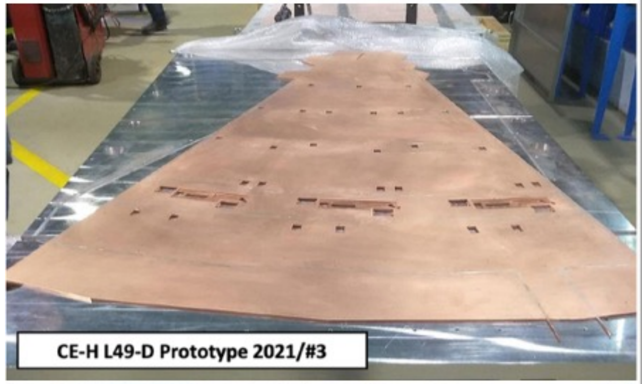
4 prototypes of cooling plates with different sizes were produced in Minsk

Production technologies and tooling were tested :

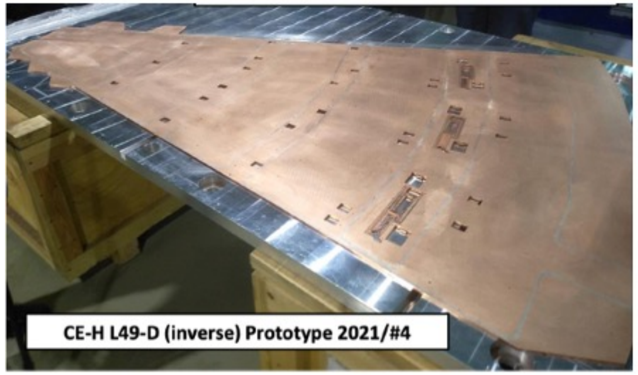
- Automatic soldering using a heating table.
- Copper sheet straightening before and after machining.
- Raw vs. annealed steel tube bending.
- Heat dissipation with press-fitted tube.
- Copper spray coating technique.
- Press fit + glue tube binding technique.
- Soldering the spray-coated tube.



CE-H L29-B Prototype 2020/#1 (at FNAL)
See FNAL inspection report 16'09'2020



CE-H L49-D Prototype 2021/#3



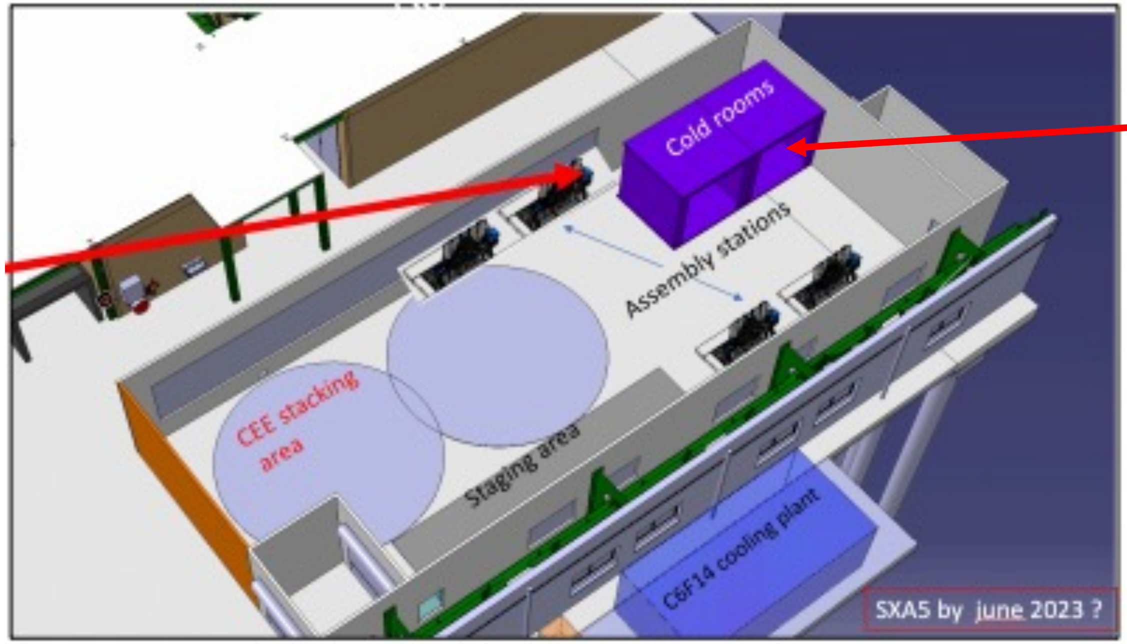
CE-H L49-D (inverse) Prototype 2021/#4

Press-fit + glue

Comprehensive test of prototypes parameters will be done in September this year

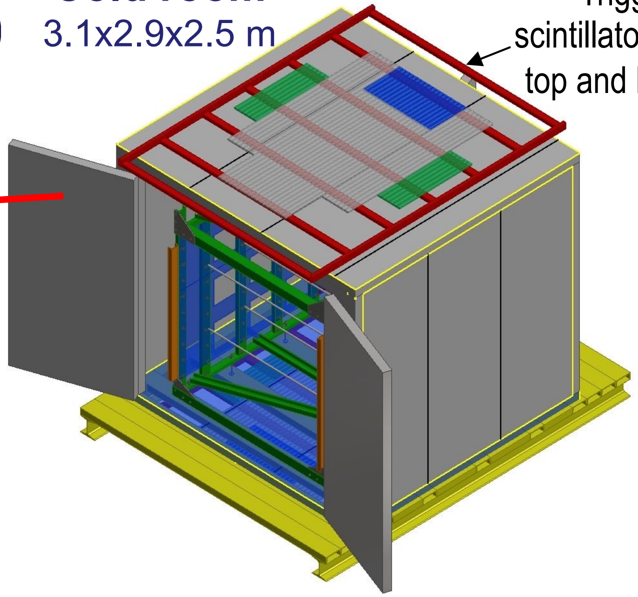
Test Setup for HGCal Cassettes

CE-E Cassette assembly site at CERN (Clean room CR1)

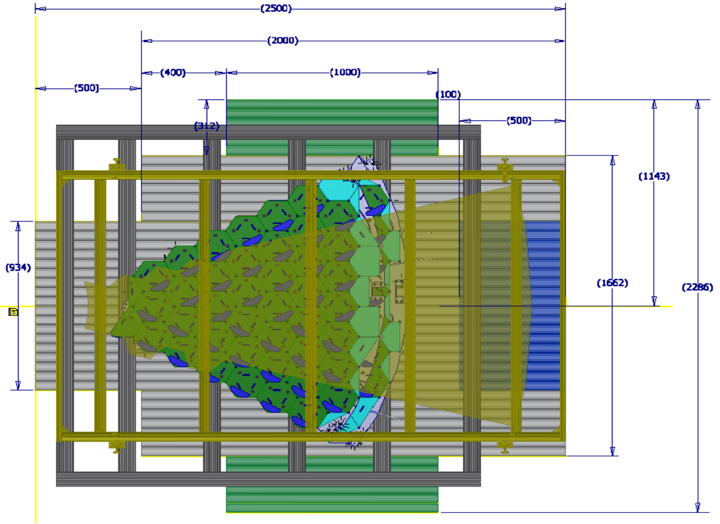


Cold room
3.1x2.9x2.5 m

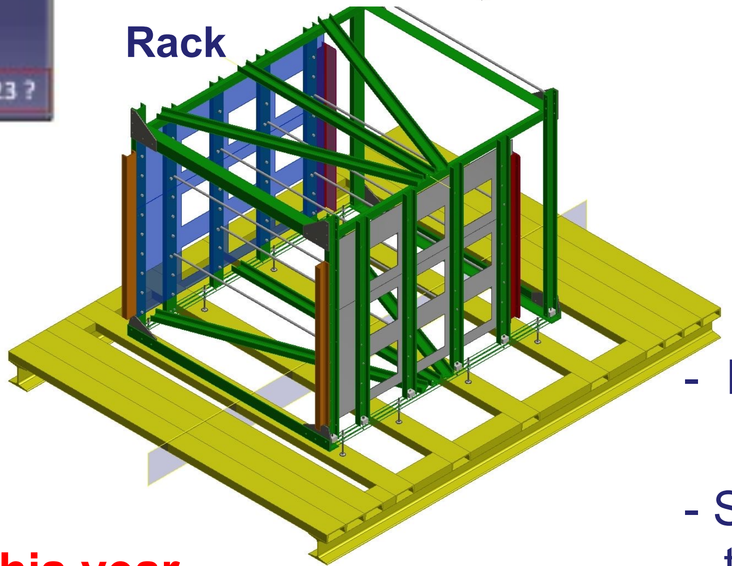
Trigger scintillator plates top and bottom



Supporting frame for cassettes



Rack



Cold rooms delivered to CERN in May 2023

- Assembling planned in Sep. – Oct. 2023
- Rack for cassettes designed - construction in Oct. 2023
- Design and construction of patch panels for cables and services Oct. 2023

Goal is to complete test setup construction this year

Trigger for test setup simulation

- Performance estimations, detector evaluation algorithms tests.
- Scintillator trigger planes of cosmic test setup optimization.

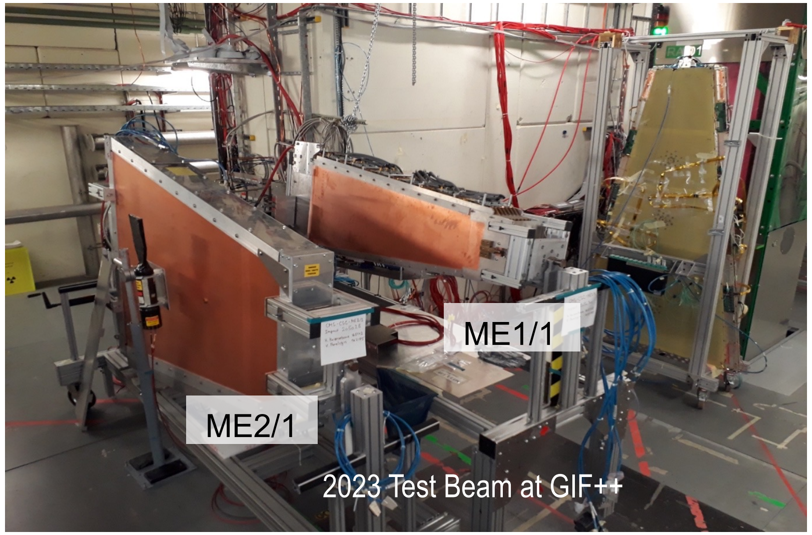
CMS Phase 2 Upgrade

Participation in the Endcap Muon system upgrade

- Cathode Strip Chambers maintenance during LS3 long shutdown period
- CSC longevity study and searches for eco friendly gas mixtures R&D
- Upgrade of the ME1/1 CSCs cables and services layout for the new CMS Endcap detectors configuration
- Design and construction of the new ME1/1 Patch Panel
- Design and construction of new tooling for ME1/1 CSC assembly and installation

Cathode Strip Chamber Longevity Study

Irradiation setup: ME1/1 and ME2/1 CSCs exposed with the 12 TBq Cs-137 gamma source at GIF++ Facility (HV-ON on 4 layers and HV-OFF on 2 layers kept as reference)

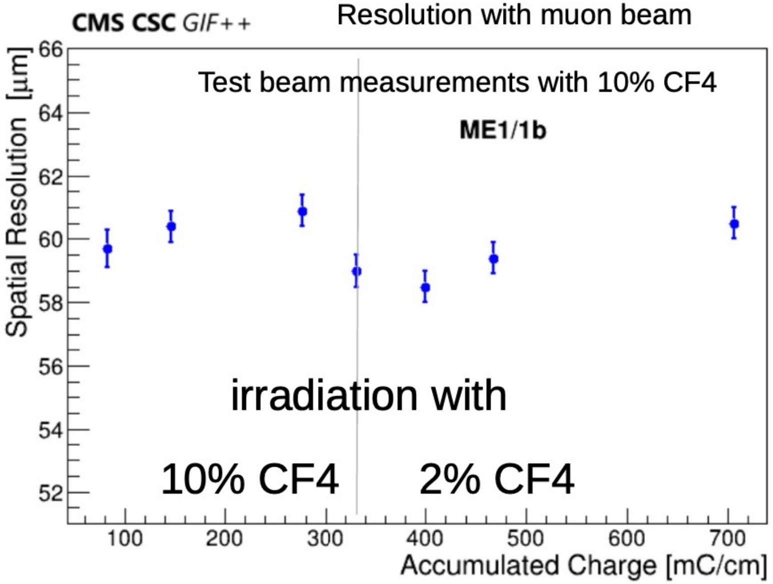


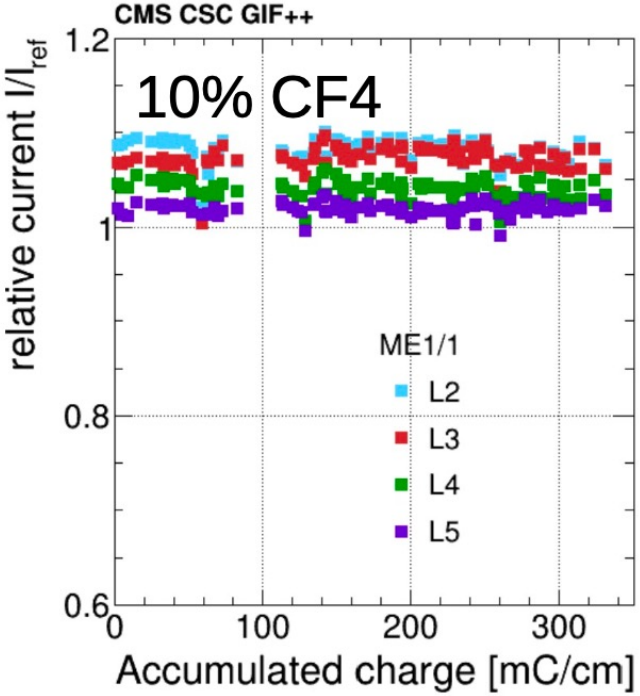
Amount of integrated charge expected at 1 HL-LHC estimated using the Run2 currents scaled with the Fluka simulation (HL-LHC/Run2 ratio):

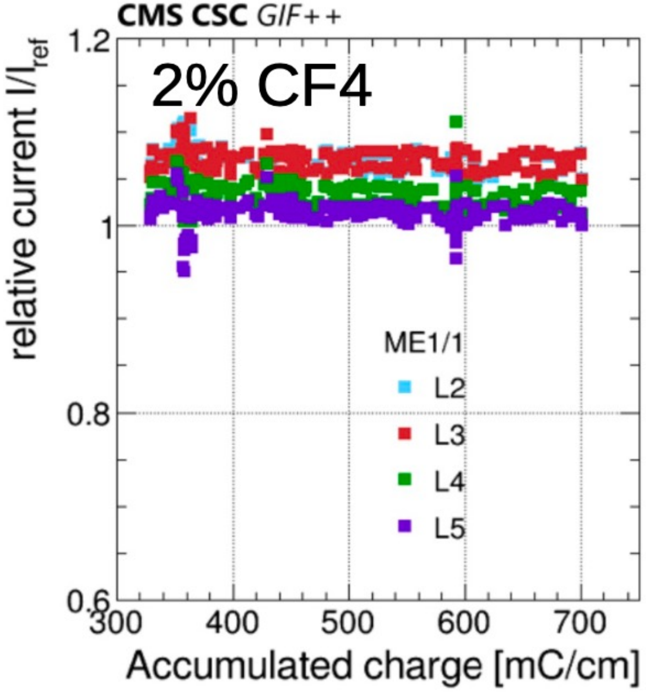
- ME1/1: 200 mC/cm => 600 with a safety factor 3
- ME2/1: 130 mC/cm => 390

Studies with nominal gas mixture and with reduced CF4% ongoing from 2016:

- ME1/1 and ME2/1 received 330 mC/cm using 40% Ar, 50% CO2,10% CF4
- ME1/1 received further 370 mC/cm using 2% of CF4 (test continuing with 5% CF4)
- **No significant performance degradation observed so far**



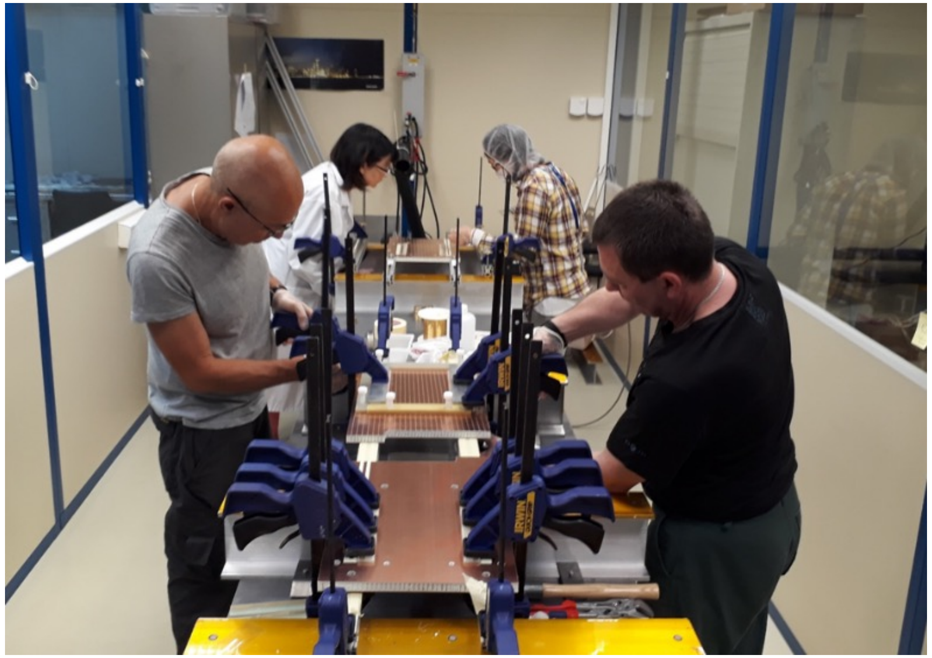




Searches for Eco-friendly Gas Mixtures

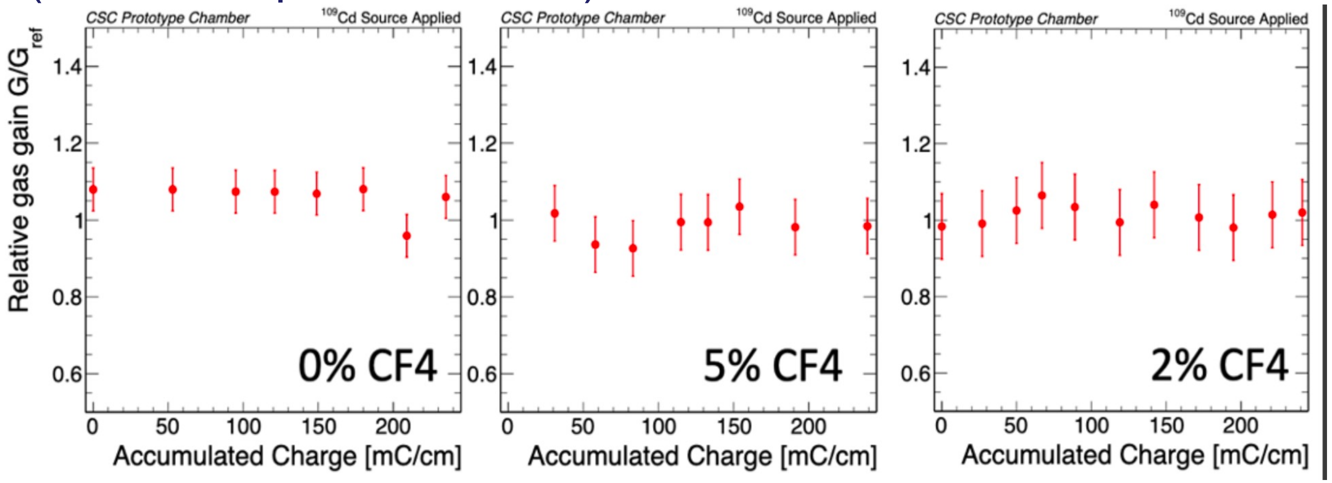
Motivation: CSC use CF4 to protect anode wire from Si deposits and carbon polymers.
But Global Warning Potential (GWP) is too high 7000 x CO_2

- Six 2-layer mini-CSCs with sensitive area (30 x 30 cm^2) were constructed to study the CSC operation with the new gas mixtures

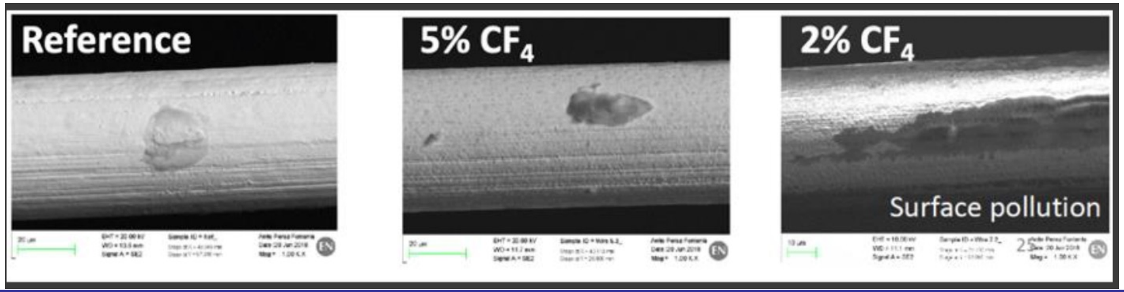


- CSCs prototypes irradiated with and different percentages of CF4 (10%, 5%, 2%, 0%)
- Studies with HFO1234ze and other potential CF4 alternatives are ongoing

- Lab tests shows that reduction of CF4 doesn't affect the CSC longevity however an increased pollution is visible on the wire (validated up to 2 HL-LHC):



- Deposits on the anode wires show that operating with 2% CF4 might be a risky choice, while running with 5% CF4 looks more sustainable (irradiation ongoing)

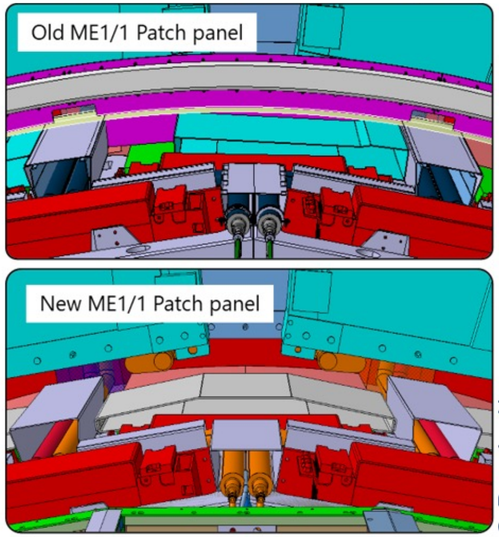


ME1/1 CSC Integration and Tooling Modification

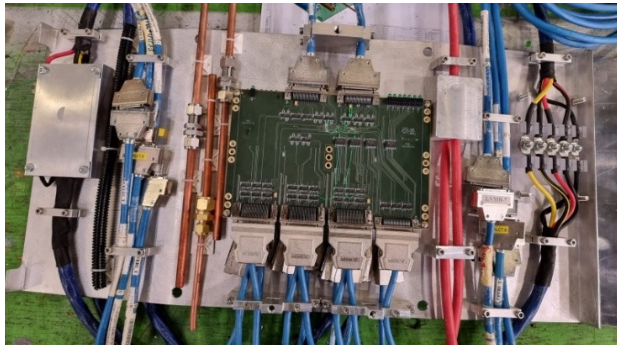
Work in progress

ME1/1 Patch Panel redesign

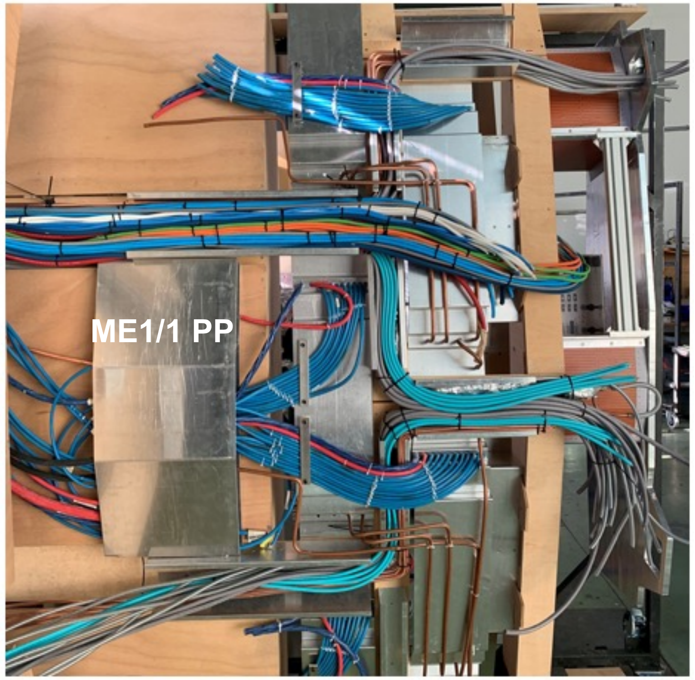
upon HGCAL request to avoid bottlenecks for services routing



New ME1/1 PP became thinner and wider



36 new ME1/1 PP should be constructed before LS3

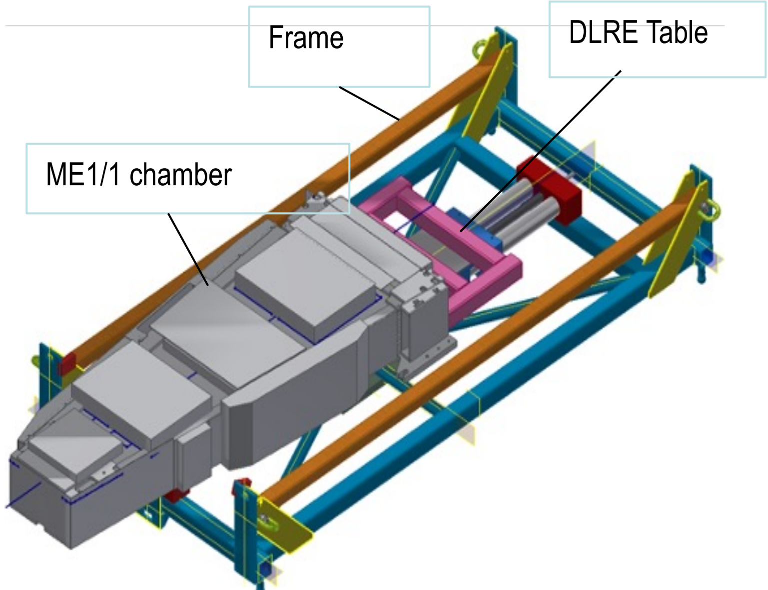


Bottleneck trays with services fitting!

Mockup built to validate design:
off-detector services and cables

ME1/1 Insertion tooling modified

Used for extraction/installation ME1/1 CSC detectors



Summary

- **The CMS had successful LS2 upgrade and commissioning period following YETS 2022**
- **The considerable contribution to the upgrade of the CMS detectors was done by JINR group**
  - CMS Endcap Muon System and Hadron Calorimeter shows a good performance in RUN3
- **CMS Phase-2 HL-LHC upgrade are making good progress**
- **JINR group is actively involved in the HL-LHC upgrade participating in:**

High-Granularity Calorimeter (HGCal) project.

- Cold room delivered to CERN. Rack for HGCal cassettes designed, construction in progress.
- HGCal cassettes test setup assembling will start in September 2023.

Forward muon station (ME1/1) upgrade (major part of CSC Phase 2 upgrade done in LS2)

- CSC patch panel redesigned. ME1/1 loading machine constructed.
- CSC longevity and performance study in progress.
- Continuing study of CSC operation with the new gas mixtures.

Backup slides

LHC / HL-LHC Plan