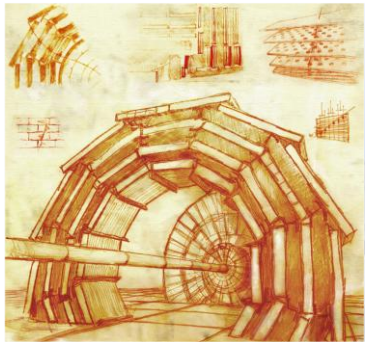
XIV International Conference on New Frontiers in Physics

17-31 July 2025, OAC, Kolymbari, Crete, Greece



CMS Upgrades

Marcello Abbrescia (INFN and University of Bari - Italy)

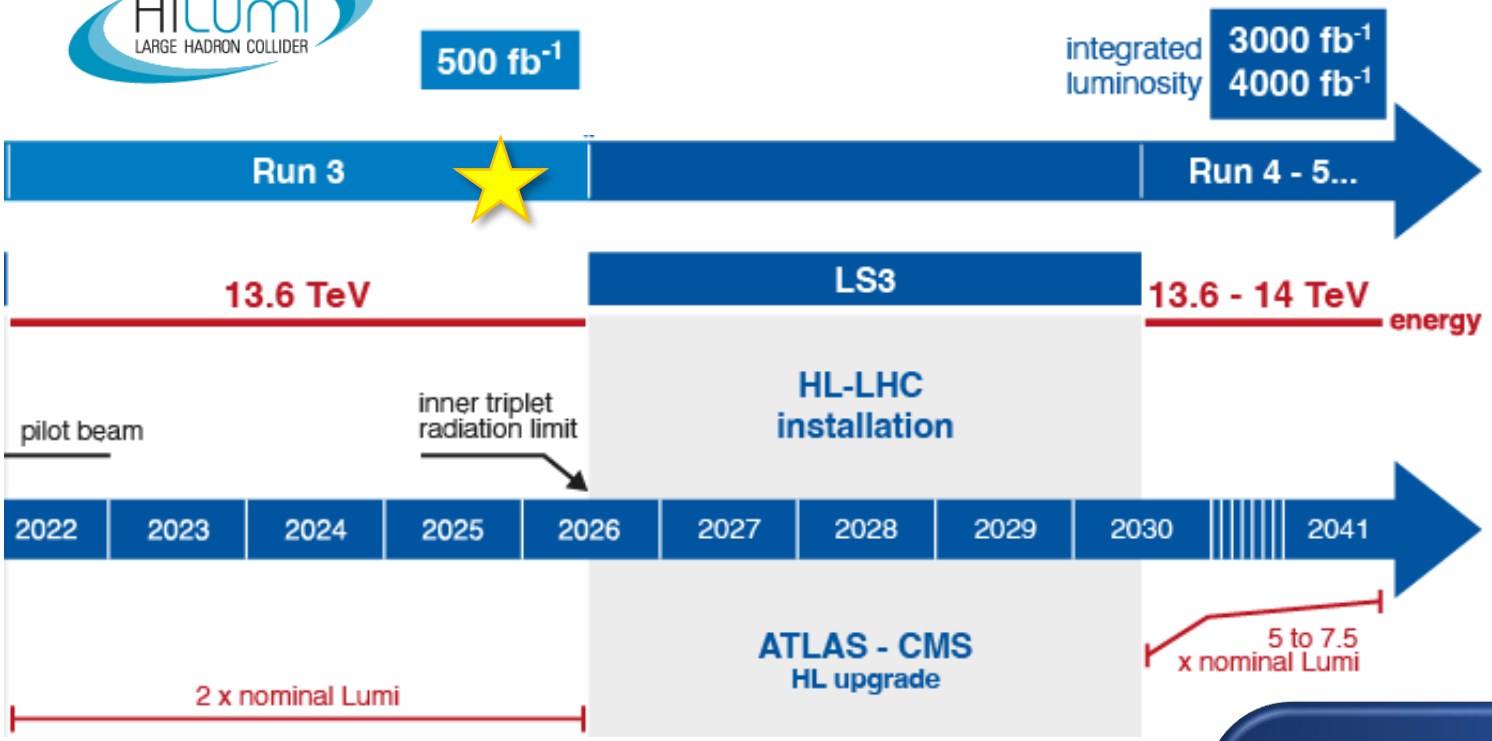
on behalf of the CMS Collaboration

INFN BARI

Istituto Nazionale di Fisica Nucleare

Sezione di Bari

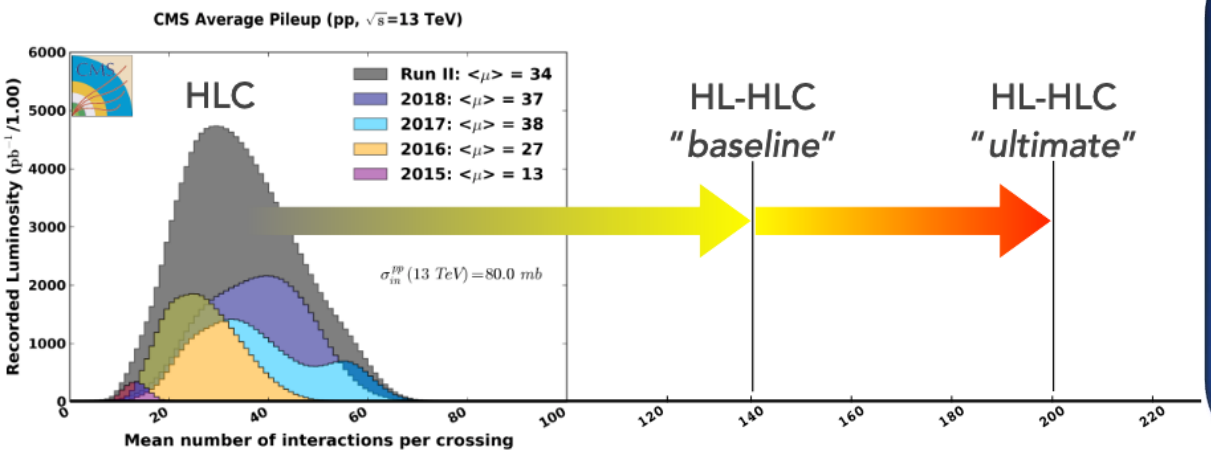
High Luminosity Large Hadron Collider



HL-LHC opens new possibilities for:

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

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

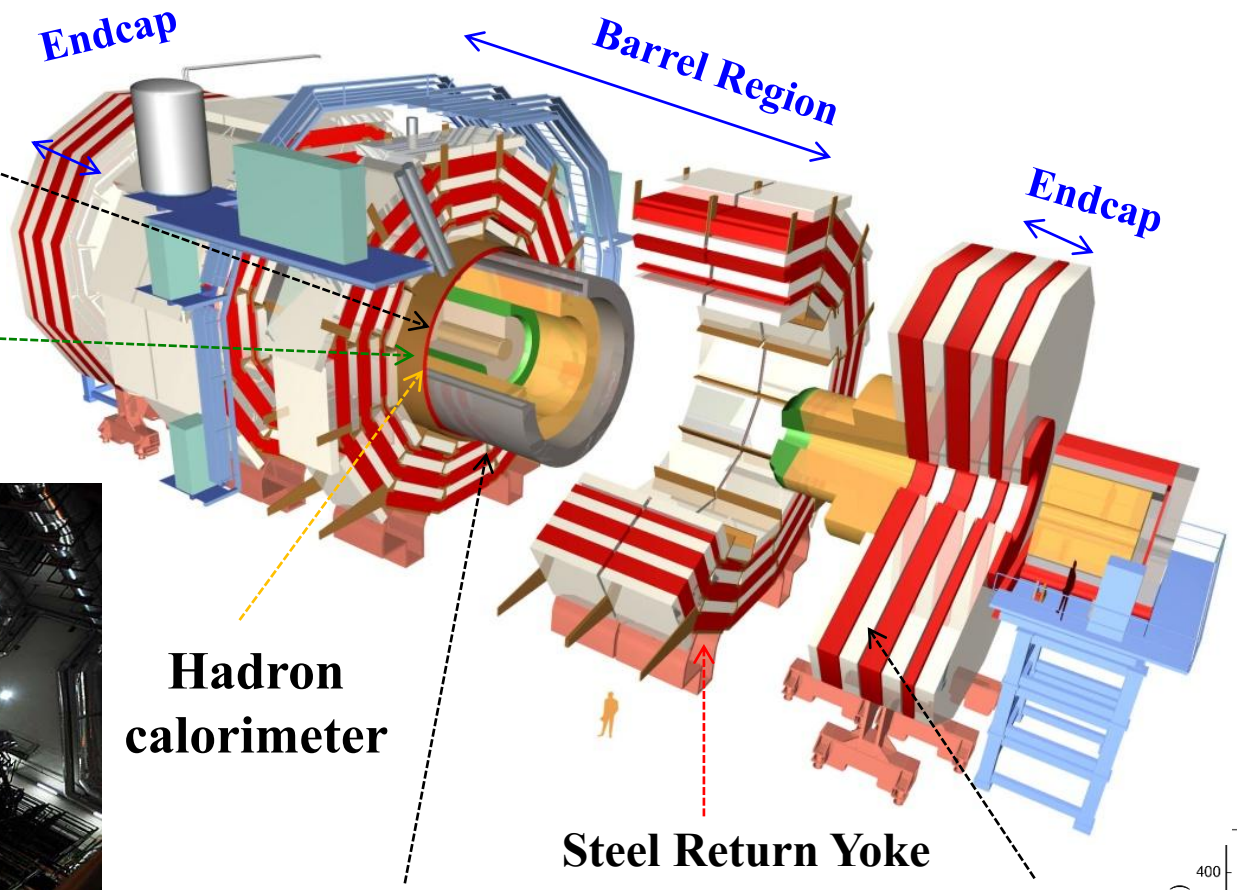


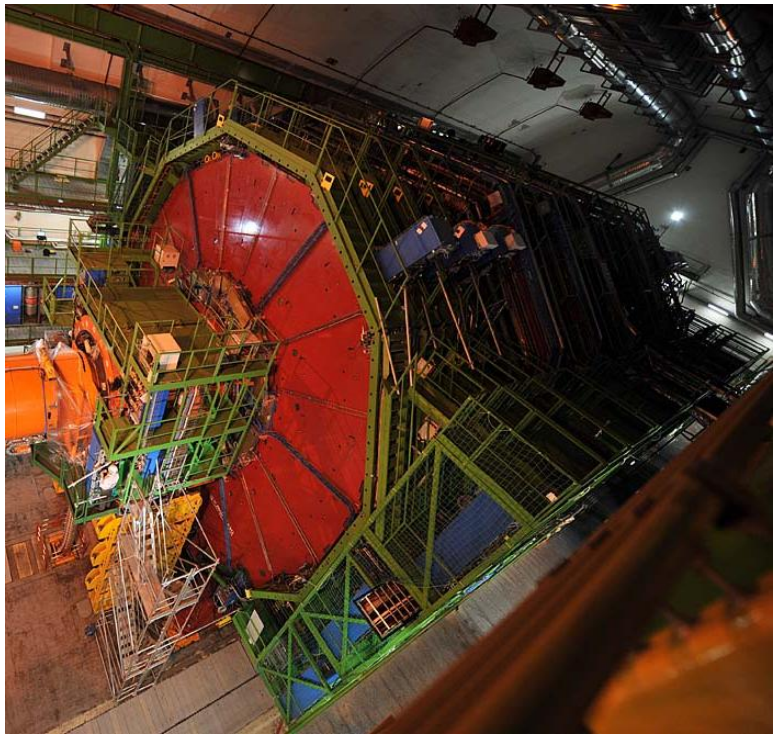
Challenge for the detectors:

Maintain performance under harsh data-taking conditions

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

The CMS detector

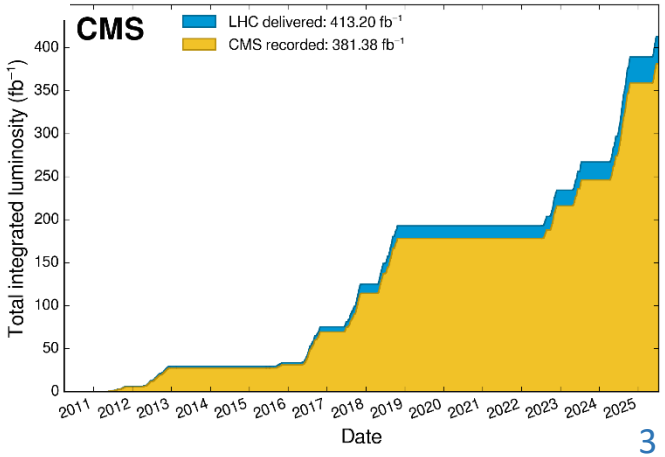




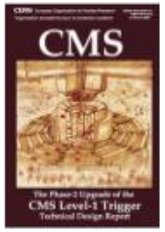
Superconducting Solenoid
Niobium titanium coil carrying 18.000 A

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

Integrated luminosity



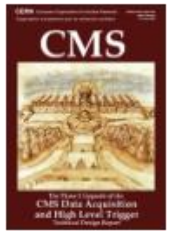
The CMS Phase-2 Upgrade Project(s)



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

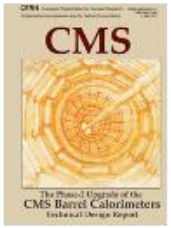
https://cds.cern.ch/record/2759072

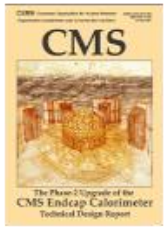
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

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

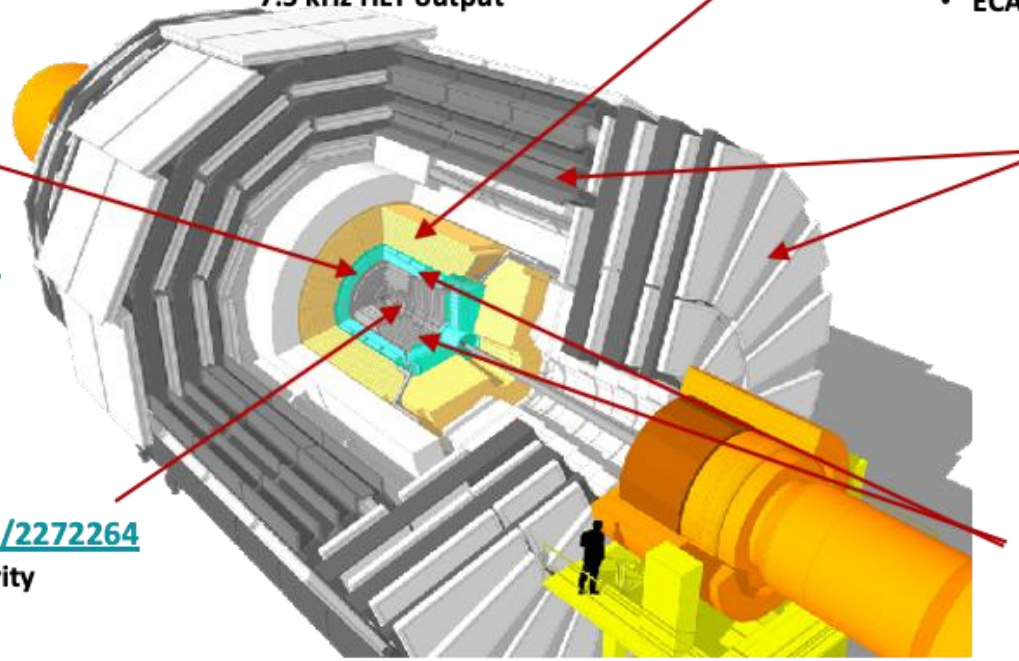




High-Granularity Calorimeter Endcap

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

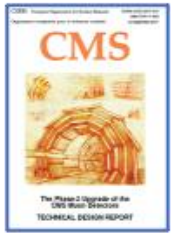
- 3D showers and precise timing
- Si, Scintillator+SiPM in Pb/Cu-W/SS

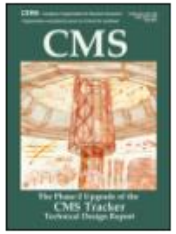


Muon systems

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

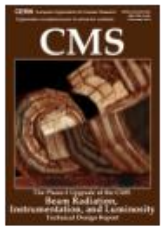
- DT & CSC new FE/BE readout
- RPC BE electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3





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

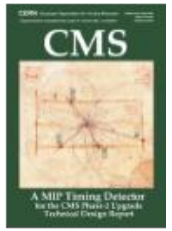
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

MIP Timing Detector

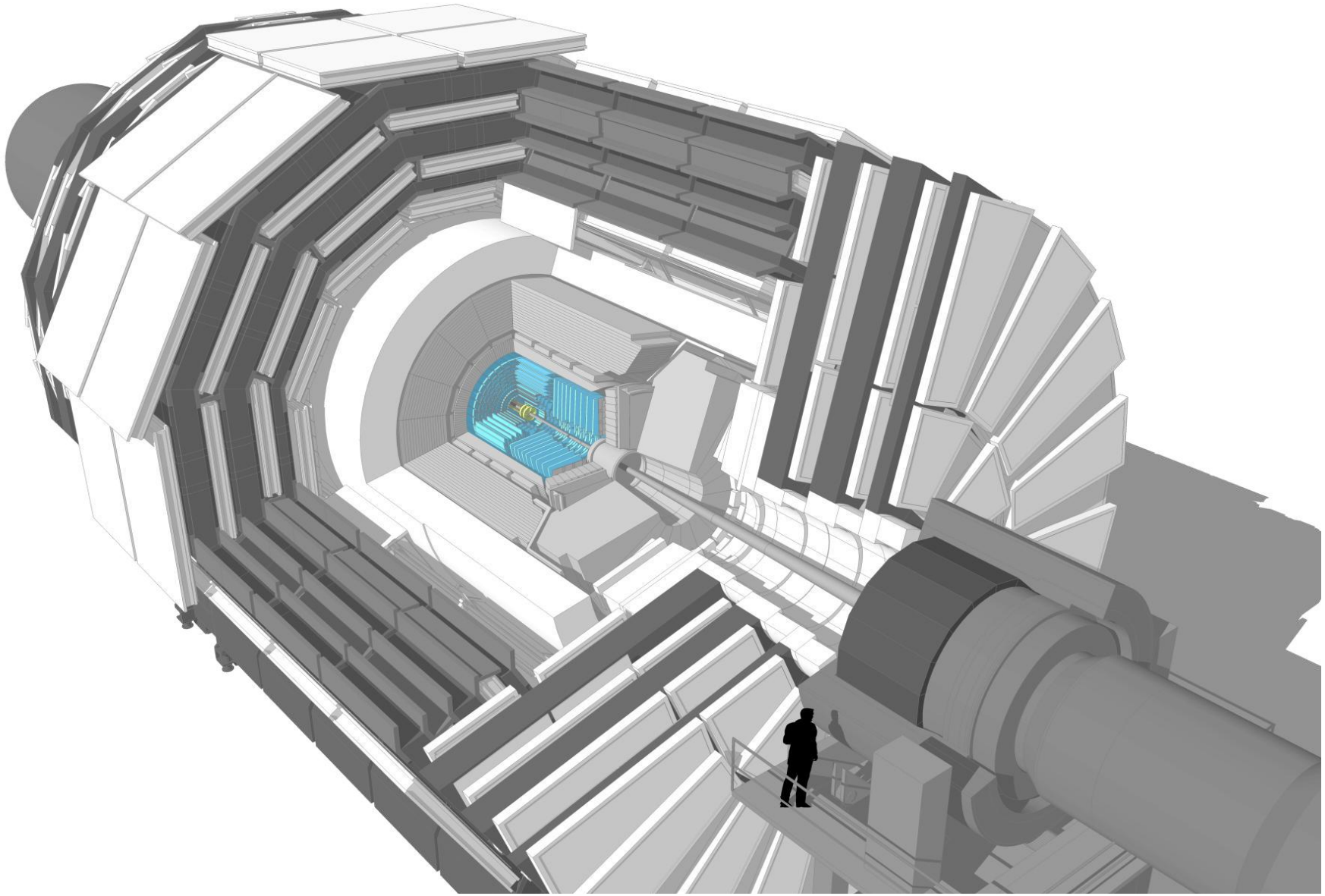
https://cds.cern.ch/record/2667167

Precision timing with:

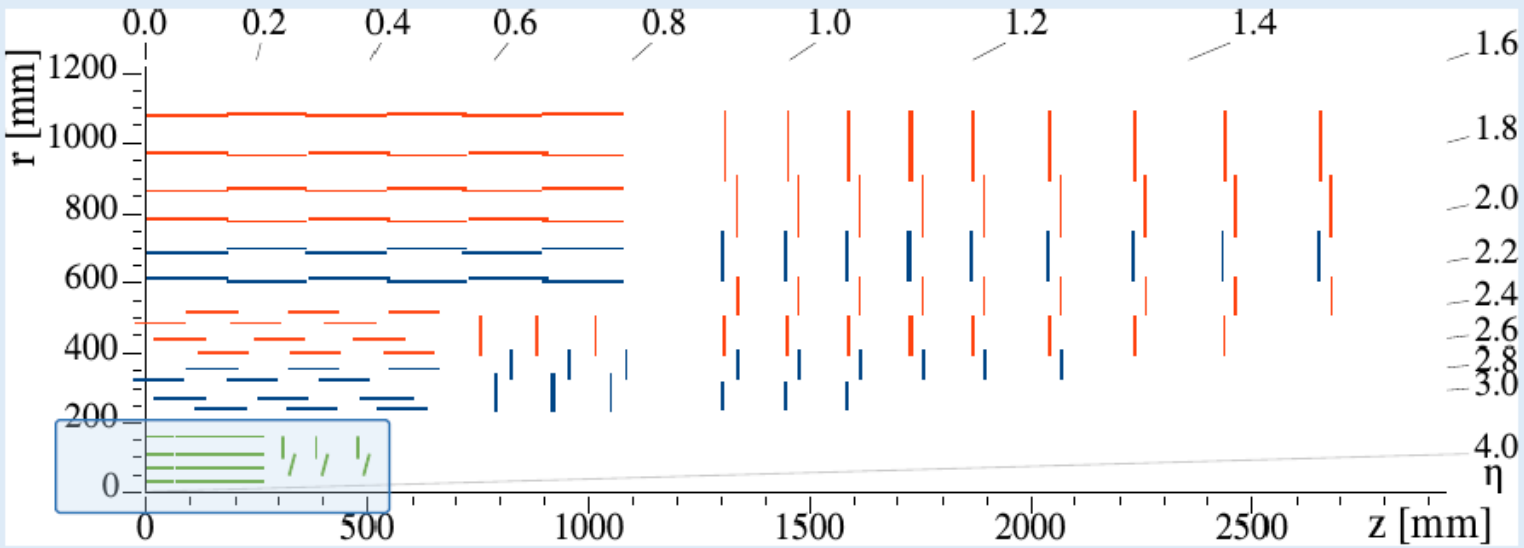
- Full coverage to η ≃ 3
- 30-50 ps time resolution for MIPs
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



CMS Tracker upgrade



CMS Inner (pixel) tracker: phase 1 vs. phase2



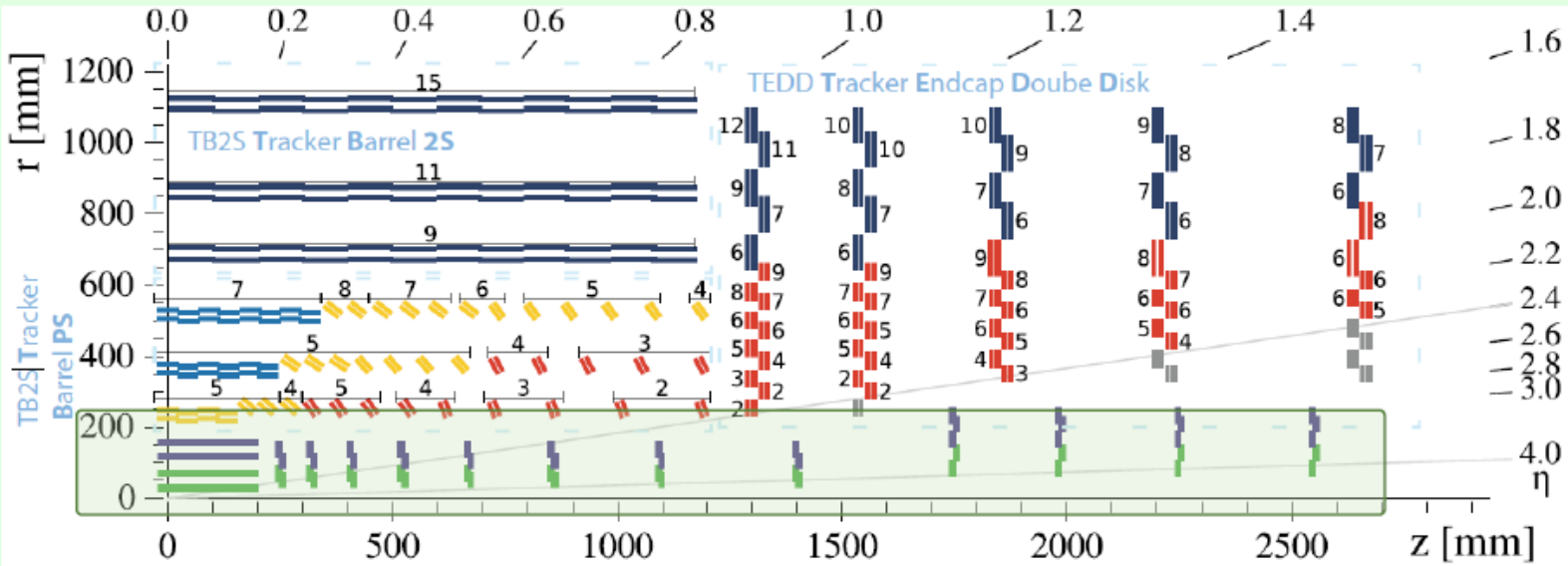
Phase-1

Pixel detector

127 million pixel cells

Cel size: **100 µm × 150 µm** (15000 mµ²)

operated at -20°C degrees



Phase-2

Inner Tracker (Micro-Pixel detector)

Extended to z = 2.5 m – more endcap discs

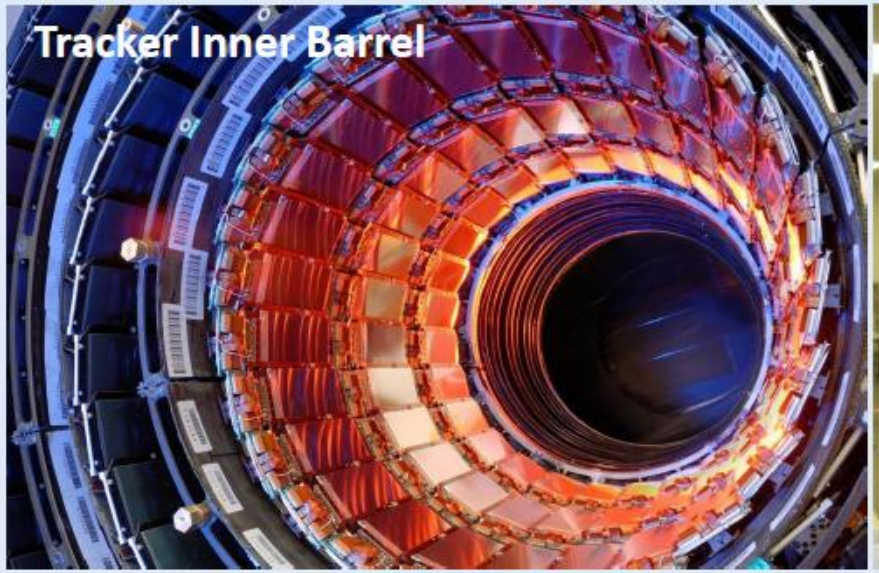
2 billion pixel cells

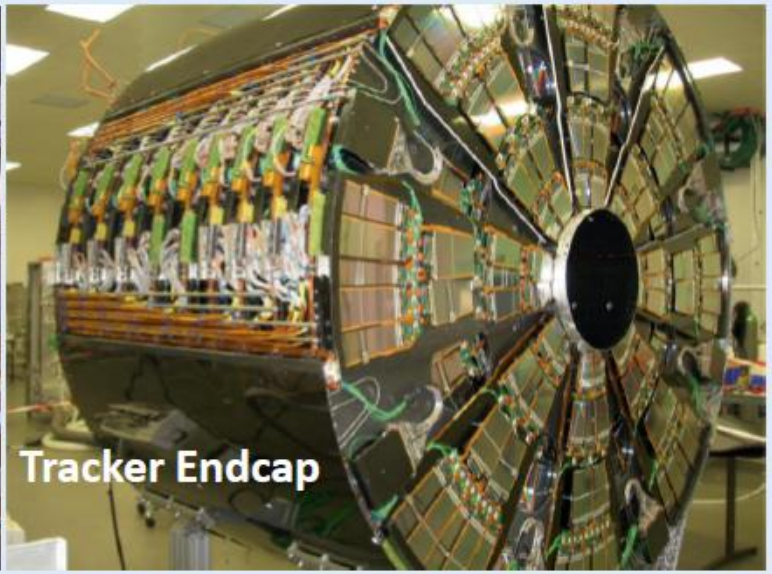
Six time smaller cel surface: 2500 mµ²

25 mµ × 100 mµ or 50 mµ × 50 mµ or

CMS readout chip (CROC) 65 nm CMOS

CMS Outer (strip) tracker: phase 1 vs. phase2





Phase-1

Strip Tracker

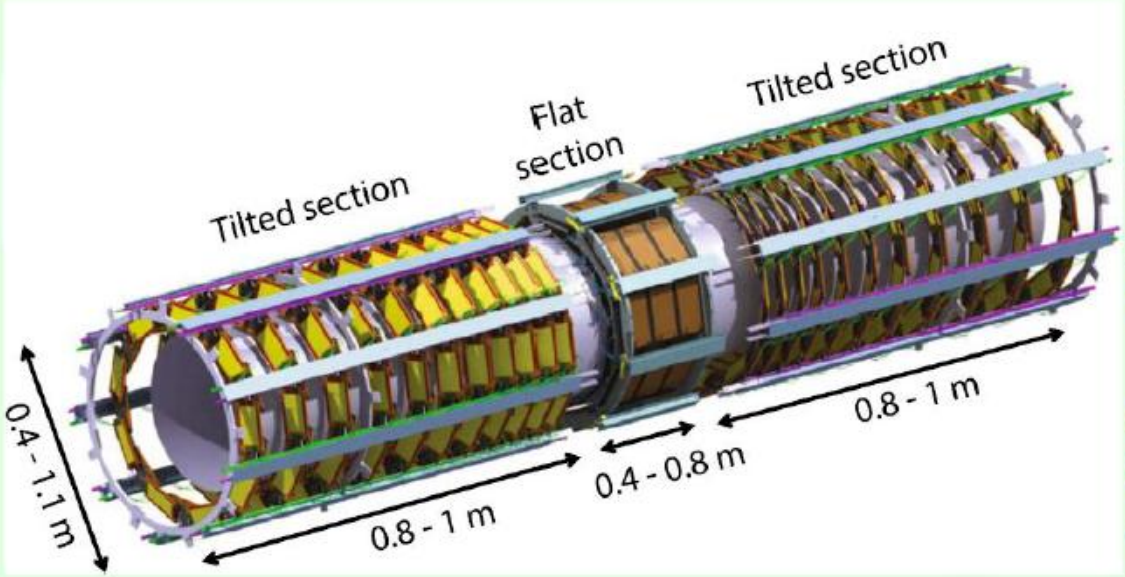
9.3 million detector strips

strip pitch: 80-205 µm

strip lenght: 9-20 cm

thickness: 320 µm or 500 µm

Stereo modules in selected layers for precise z or r measurement



Phase-2

Outer Tracker

172 million macro-pixels

3 inner barrel layers, endcaps rings with r < 650 mm

100 µm × 1.47 mm (precise ϕ and z or r measurement)

42 million micro-strips

90 µm × 5 cm or **100 µm × 2.5 cm**

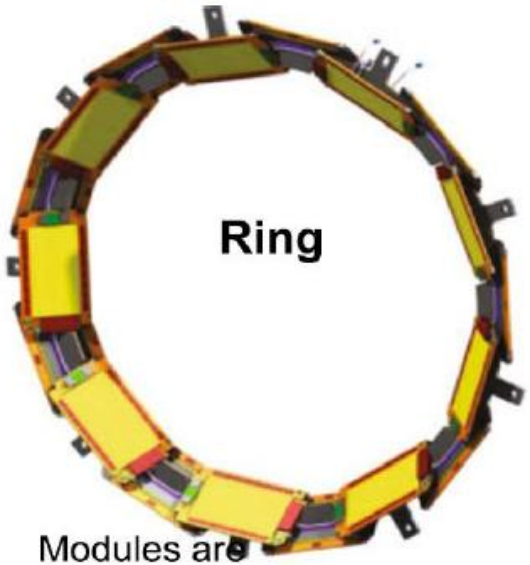
active thickness: 290µm

Karol Buńkowski, UW 17/01/2025 14

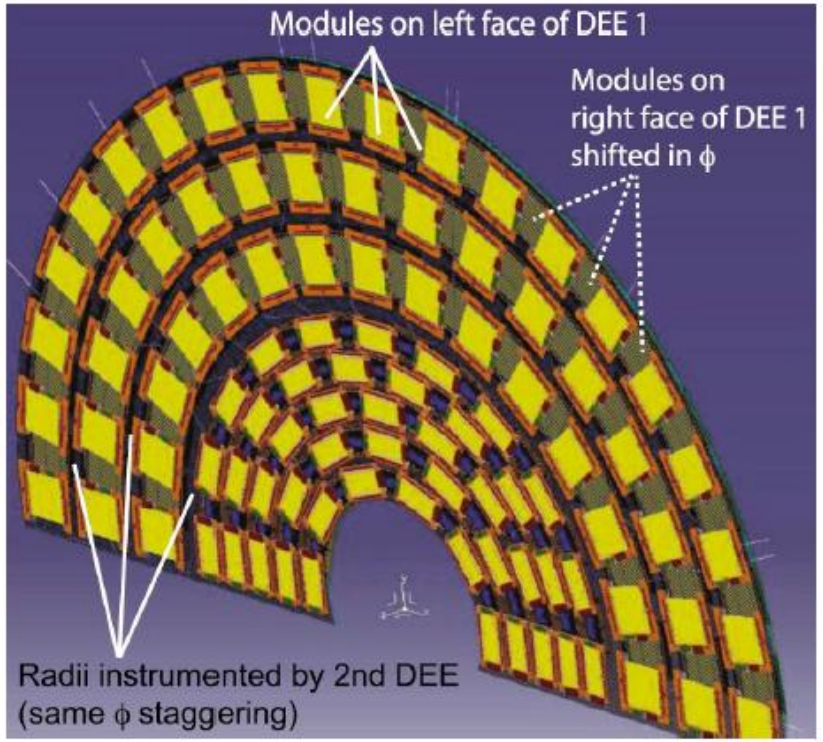
CMS Phase 2 Tracker geometry

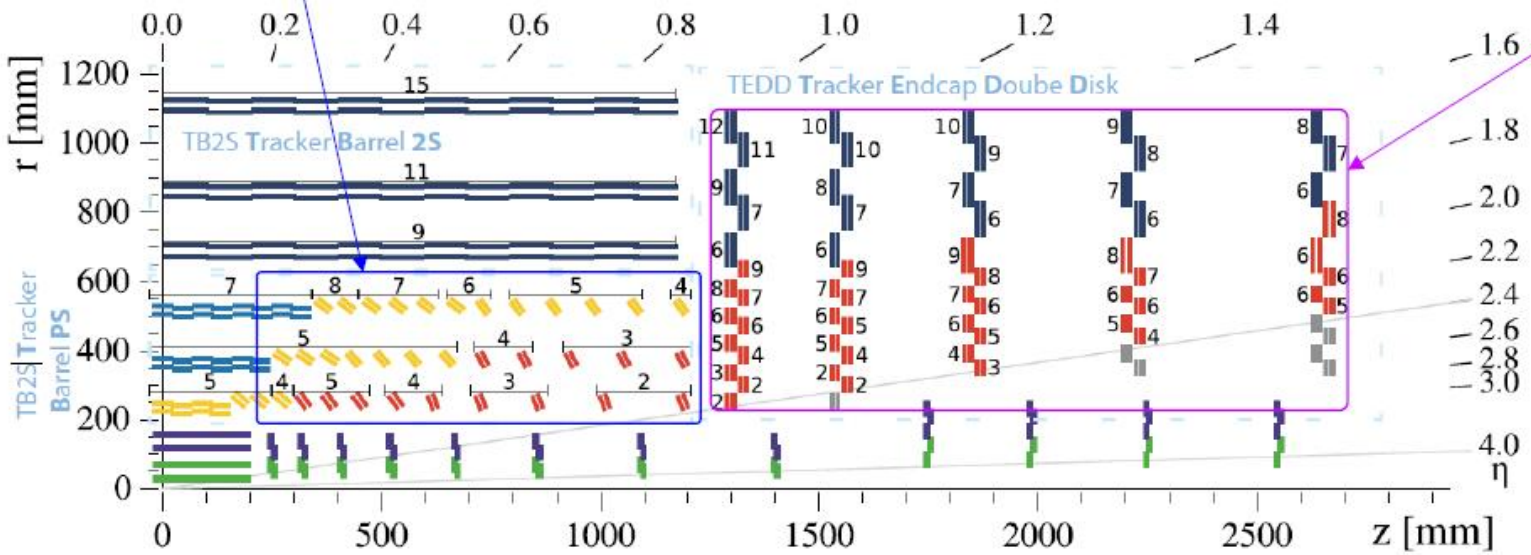
Sensors in the three inner layers **tilted** by 40 – 74°

- significantly reduced material budget and cost (less modules needed)
- much better Level-1 track trigger performance
- closer to ideal spheric geometry



Modules are mounted on plates



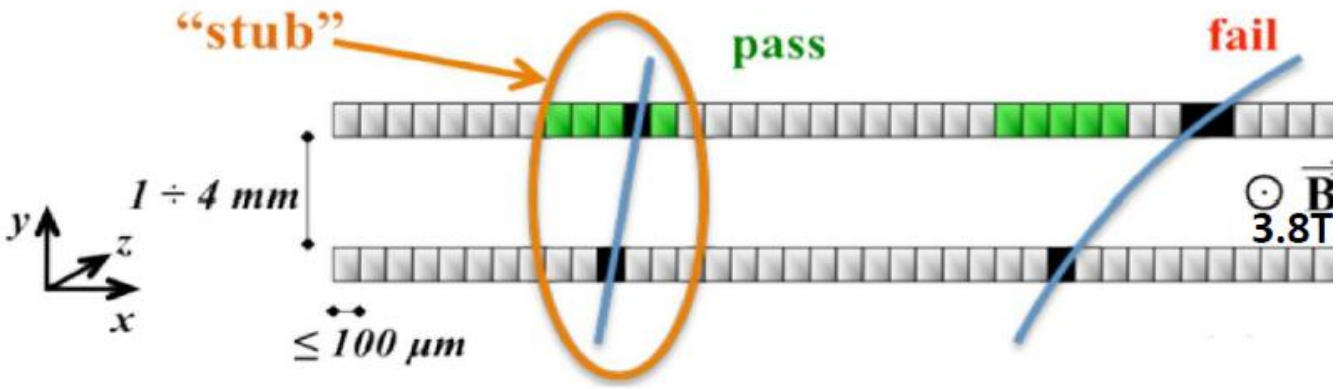


Rectangular instead of wedge-shaped modules in the endcaps

- no significant penalty in material budget and resolution
- but large reduction in system complexity and costs (number of module types)
- no changing pitch size along the radial coordinate

Track trigger at Level-1

HL-LHC pile-up of 140-200 is very challenging for the CMS L1- trigger.
To preserve the physic performance (low thresholds with acceptable rates), ***the Outer Tracker will be added to the L1-Trigger system - one of the main driving factors of the phase-2 Tracker design.***



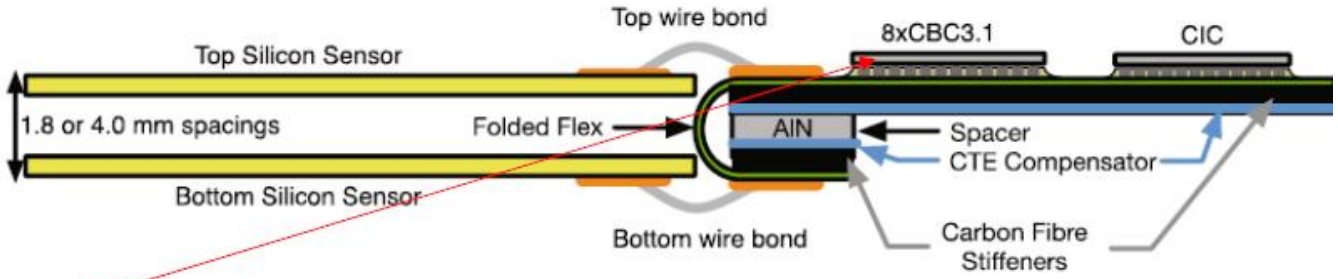
Basic concept:

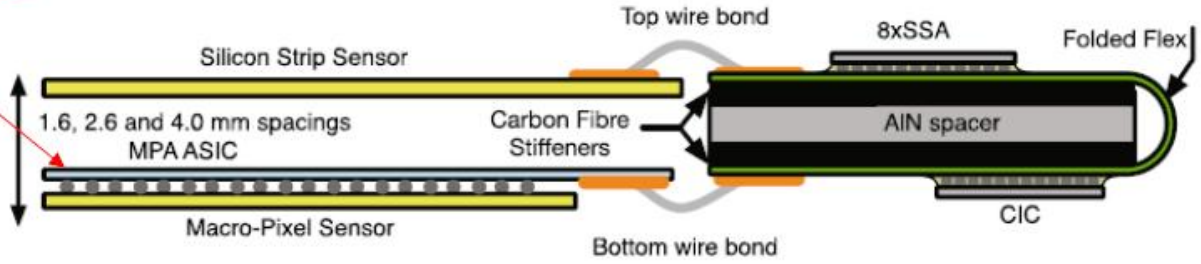
- **reject the data from very low-pt tracks already at the front-end level**, thus limiting the amount of data sent to the Track Finder in the counting room
- each Outer Tracker layer is formed with **"pt-modules" consisting of two closely speared silicon sensors**.
- **front-end ASICs** of each "pt-module" correlate hits from the two sensors, hits that are within a programable window (2 to 15 strips) form "**stubs**"

2 GeV pt threshold was chosen for the stubs

- ~3% of all tracks are above 2 GeV ⇒ ~15 000 stubs per bunch crossing

Stub efficiency: ~98% (measured at test beam)



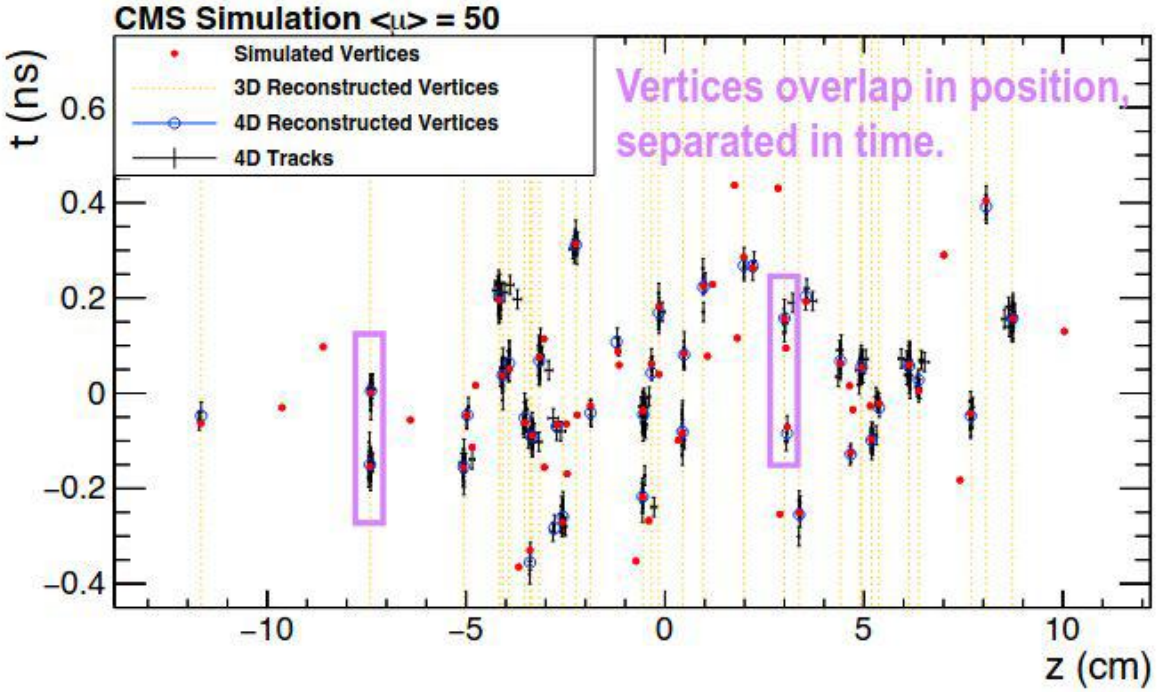


In selected layers, the inner sensor is the macro-pixel version

Mip Timing Detector

MTD motivation

- With PU 200, the track spatial overlapping will degrade the identification of hard interactions
- MTD will allow **associating timing to a track**, restoring vertex reconstruction capabilities
- To do so, it will give MIP timing information with 30-40 ps resolution
  - Expected degradation down to 50-60 ps due to radiation damage end of HL-LHC
- Particle ID based on TOF becomes possible
- Coverage in barrel and endcap (up to |η| = 3)



Detector specifications

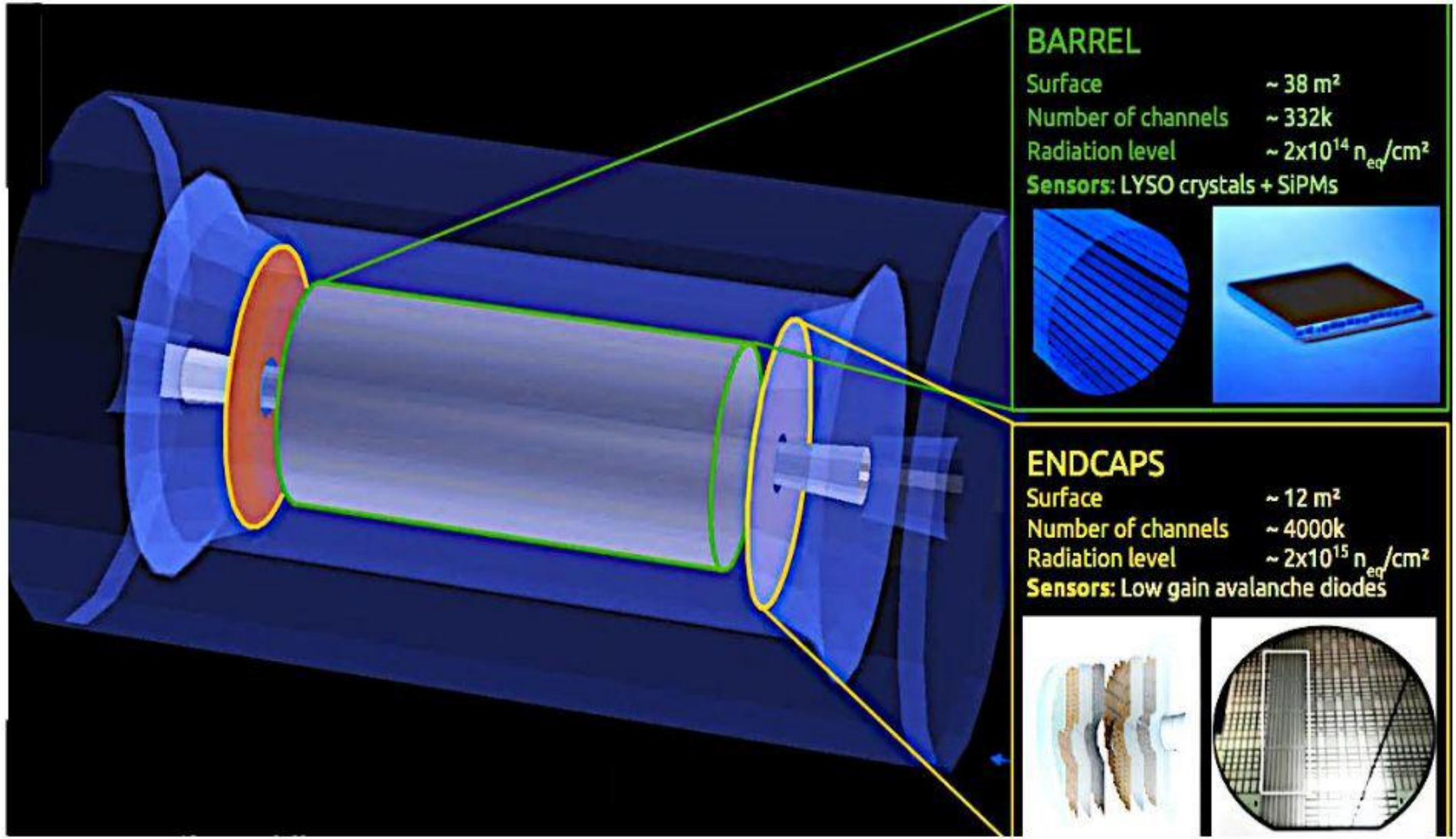
- Coverage in barrel and endcap (up to |η| = 3)
- Technology: LYSO+SiPM (barrel), LGAD (endcap)
- Radiation tolerance up to $1.6 \times 10^{15}\ n_{eq}/cm^2$

A solution to the pile-up problem!

✓ Vertices information can still be useful but it needs to be complemented to untangle the high vertex-density regions

✓ Solution: New layer of detectors in order to discriminate tracks based on their vertex position AND its time information

The Mip Timing Detector (MTD): BTL + ETL



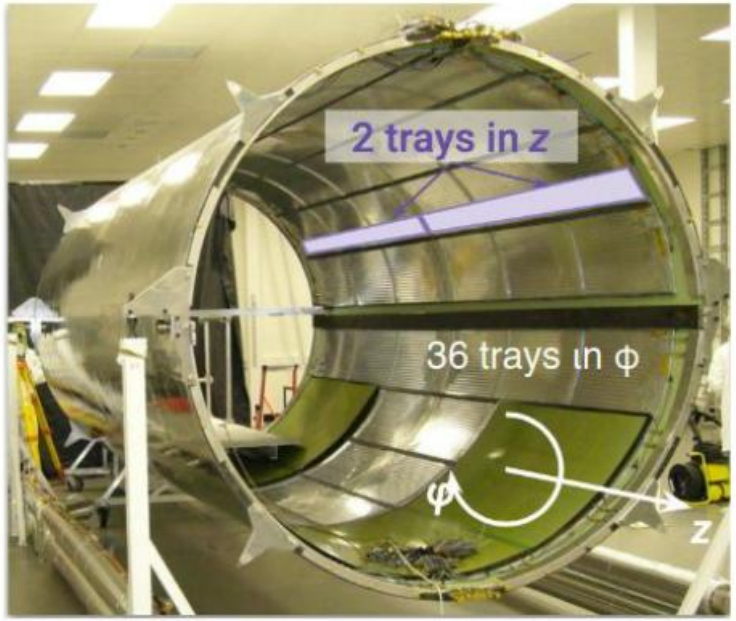
The Mip Timing Detector: BTL + ETL

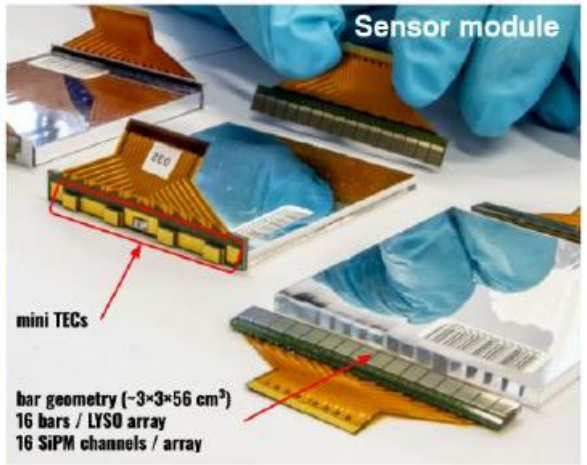
Barrel timing layer (BTL)

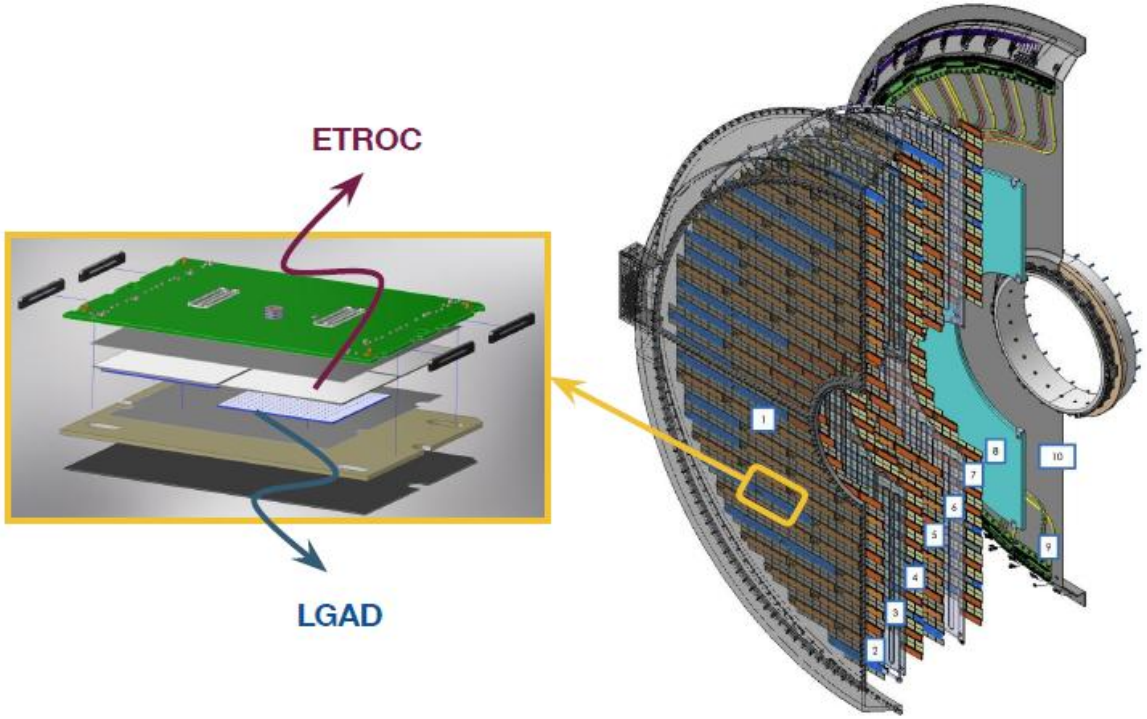
- Covers up to $|\eta| = 1.5$
- Technology: LYSO+SiPM
- Radiation tolerance up to $1.9 \times 10^{14} n_{eq}/cm^2$
- Readout: dual-end for improved position and timing
  - Differential leading-edge discrimination for dark rate cancellation
- Production: sensors completed, modules ongoing

Endcap timing layer (BTL)

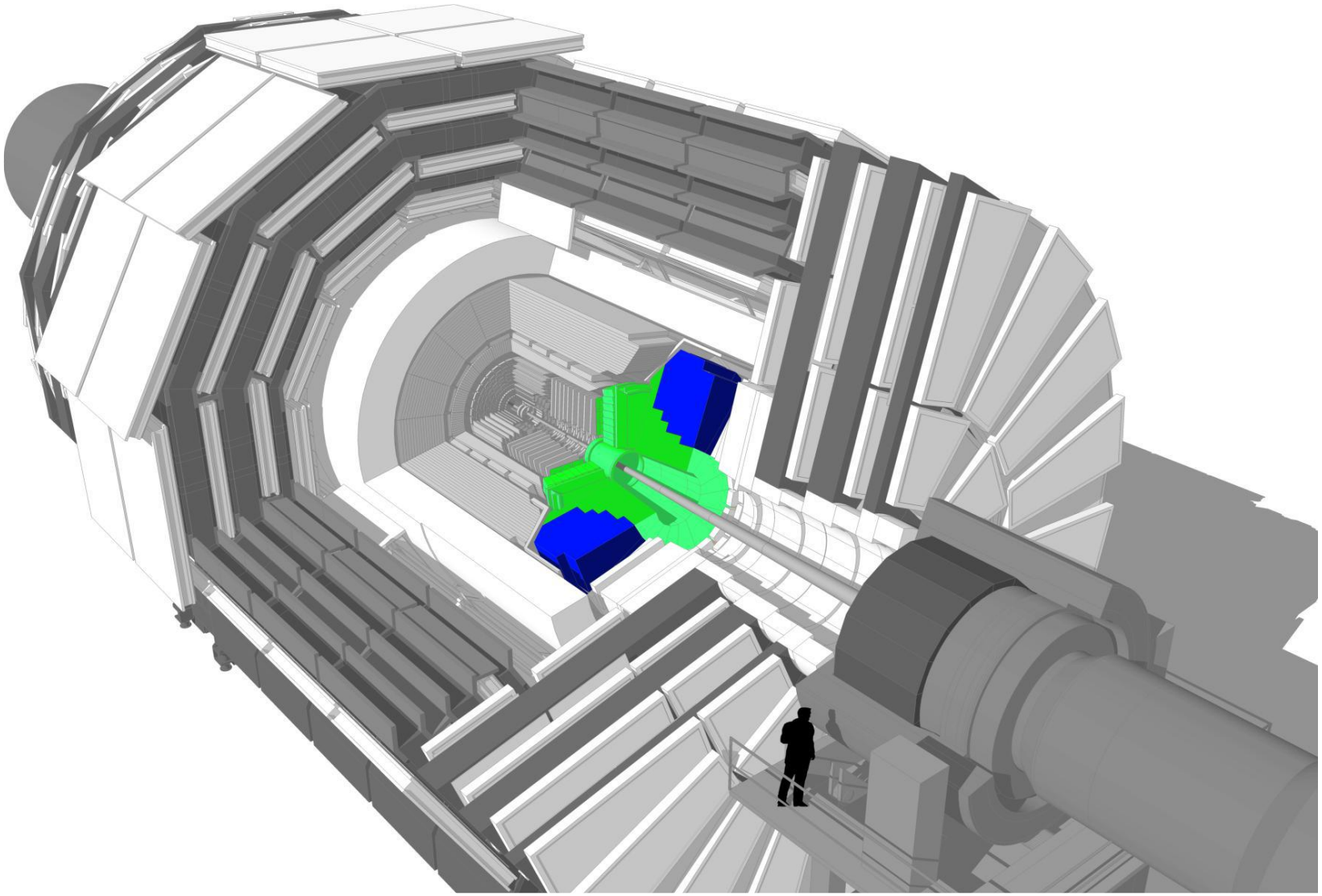
- Covers up to $1.6 < |\eta| < 3$, two disks per endcap in coincidence
- Technology: LGADs
- Radiation tolerance up to $1.6 \times 10^{15} n_{eq}/cm^2$, highly non-uniform with η
- Readout (ETROC3): based on leading-edge discrimination
- Production: sensors in procurement, electronics towards PRR





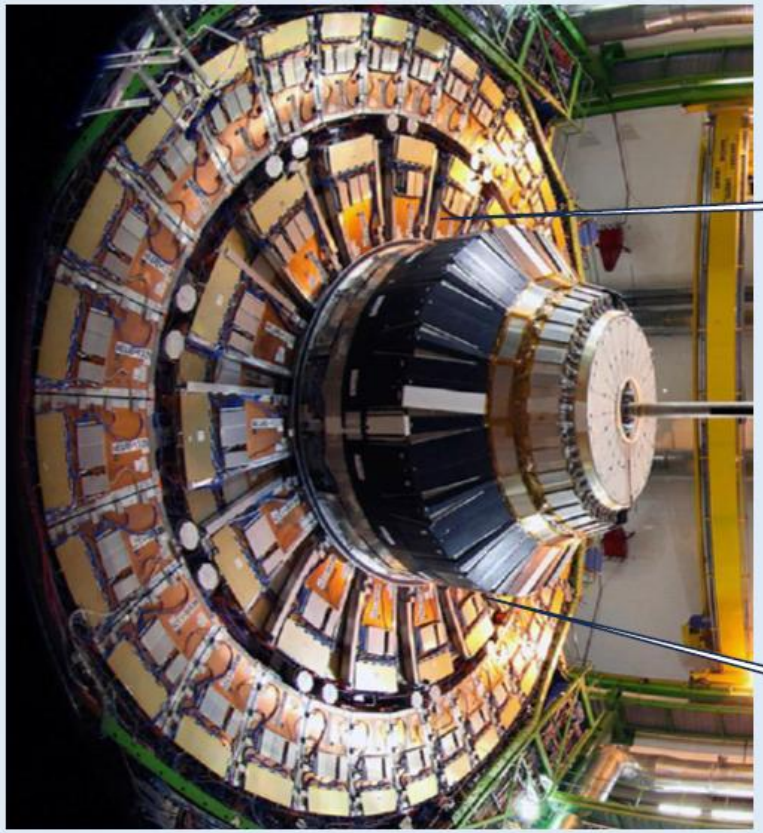


CMS Endcap Calorimeter upgrade: HGCAL (High Granularity CALorimeter)



CMS HGCAL (High Granularity CALorimeter)

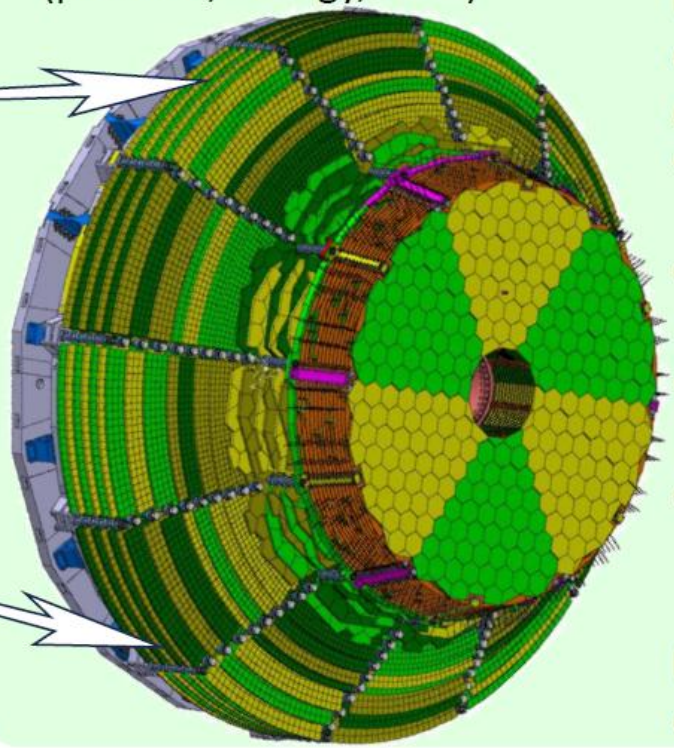
Current endcap calorimeters



PbWO4 electromagnetic calorimeter (ECAL) and **plastic scintillator hadron calorimeter (HCAL)**
- designed for an integrated luminosity of 500 fb^{-1}.
Phase-2 integrated luminosity ⇒ performance degradation
⇒ **unacceptable loss of physics performance**

HGCAL

5D imaging calorimeter
(position, energy, time)



Fine **lateral and longitudinal granularity** to fully exploit CMS Particle Flow reconstruction
Granularity is more important than energy resolution:

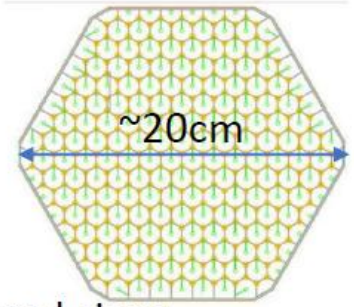
- two-shower separation, narrow jets observation
- minimize pileup contribution to energy measurements
- better electromagnetic energy resolution (e.g. for H →γγ)
- utilize timing (real novelty in calorimetry!)

Expected **timing resolution ~30ps** for clusters from particles with pt > 5 GeV

Barrel ECAL
PbWO4 crystals and APDs stay, but entirely new readout and trigger electronics (160 MHz ADC ASIC, etc.). Timing resolution: 30 ps for energies > 50 GeV. Full granularity Trigger Primitives (single crystal), instead of current 5 x 5 trigger towers
Barrel HCAL – new back-end electronics

HGCAL (High Granularity CALorimeter)

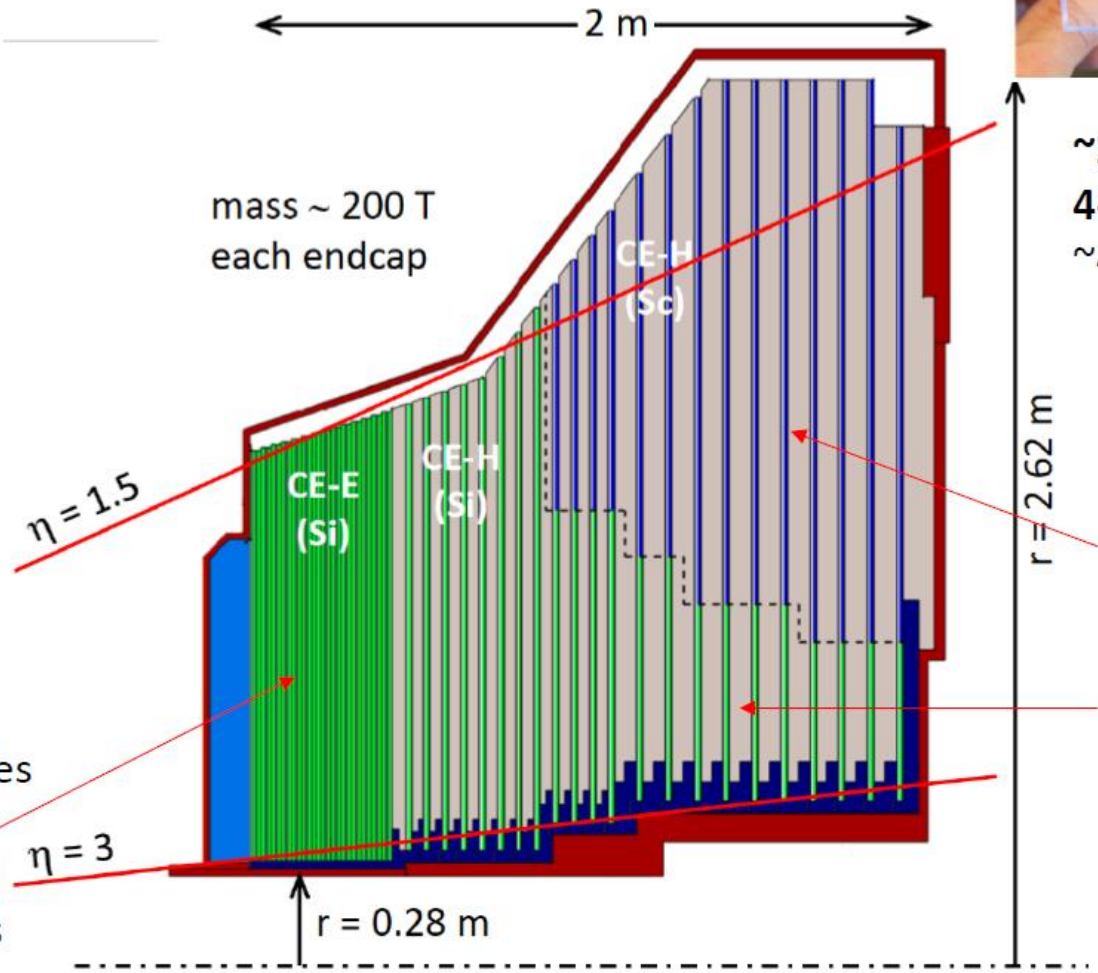
Silicon sensors
hexagonal modules
n-in-p technology

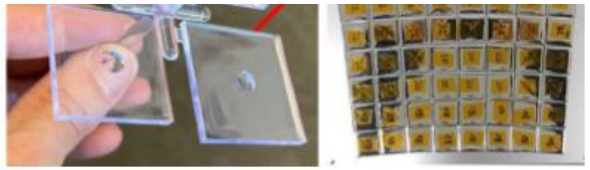


2 different hexagonal pad sizes:

- **~1 cm²** for the Low Density (LD) 300 mμ and 200um thick sensors
- **~0.5 cm²** for the High Density (HD) 120 mμ thick sensors for the inner high radiation and high occupancy region

~ 6 millions Si channels
~620 m² Si sensors in ~27000 silicon modules





~240k scintillating channels
4-10 cm² cell size
~400 m² of scintillators

Hadronic (CE-H)
- steel absorbers
- Low-radiation regions: **scintillation tiles with SiPM readout**
- **High-radiation regions: Si sensors**
- 21 layers
- 9.5 λ (including CE-E)

Electromagnetic (CE-E)
- Cu/CuW/Pb absorbers
- **Si sensors,**
- 26 layers
- 25.5 Xo and 1.7 λ

~125kW per endcap
Cooled to -30°C

The CMS Muon System

Drift Tubes (DT):

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

- 250 chambers,
- ≈ 170k channels
- 44 hits/track
- Spatial resolution ≈ 100 μm
- Time resolution ≈ 2 ns

Cathode Strip Chambers (CSC):

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

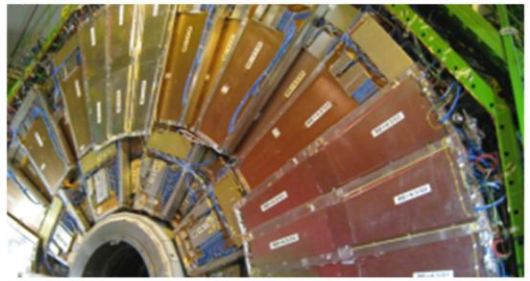
- 540 trapezoidal chambers,
- ≈500k channels
- 24 hits/track
- Spatial res. ≈50 ÷140 μm
- Time resolution ≈ 3 ns

$|\eta| < 2.4$

Resistive plate chambers (RPC):

double-gap bakelite electrode chambers operated in avalanche mode

- 540 trapezoidal chambers,
- ≈120k channels
- 6 (4) hits/track
- Spatial resolution ≈ 1 cm
- Time resolution ≈ 1.5 ns



New addition in 201

Gas Electron Multiplier (GEM):

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

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

CMS Muon System Upgrade Plan

Drift Tubes (DT):

Large rectangular constant drift velocity tubes with anodic wi

- 25
- ≈
- 44
- Sp
- Ti

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

Cathode Strip Chambers (CSC):

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

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

$|\eta| < 2.4$

New addition in 201

Resistive plate chambers (RPC):

double-gap bakelite electrode chambers operated in avalanche mode

- 540 trapezoidal chambers,
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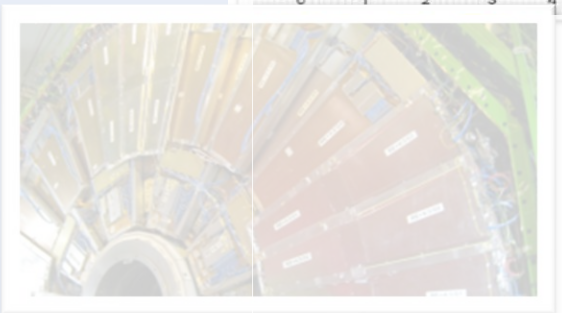
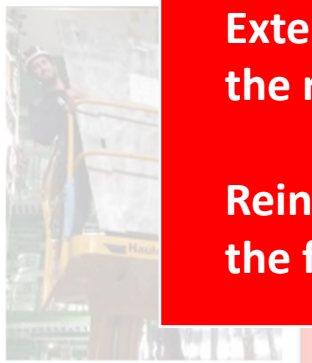


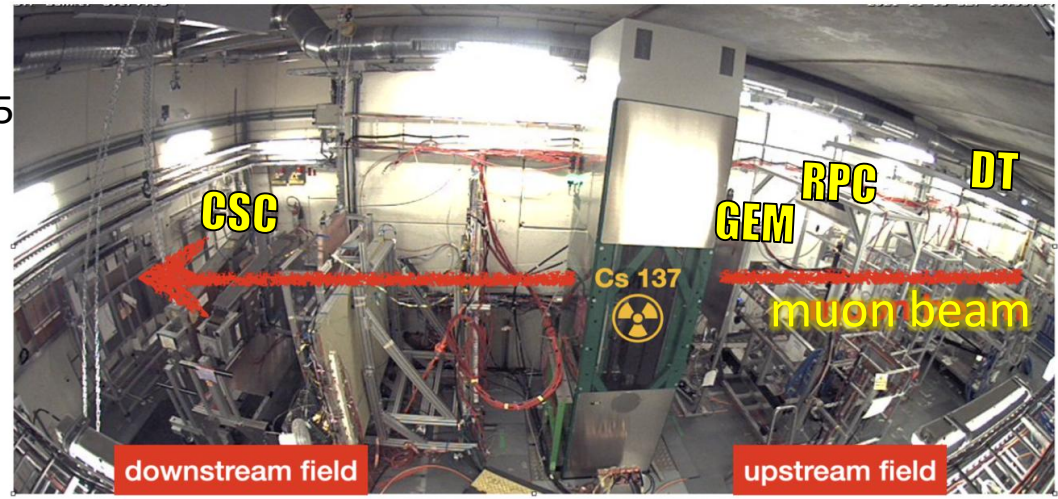


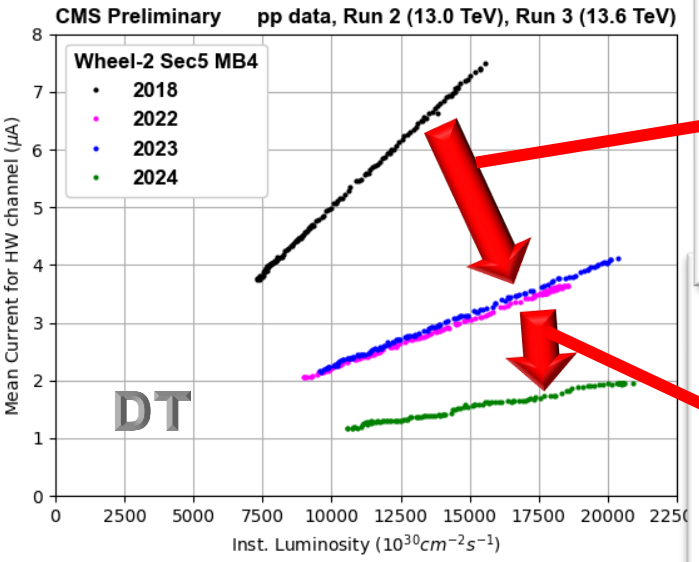
Extend muon id and trigger up to the region of 2.4 <|η| < 2.8

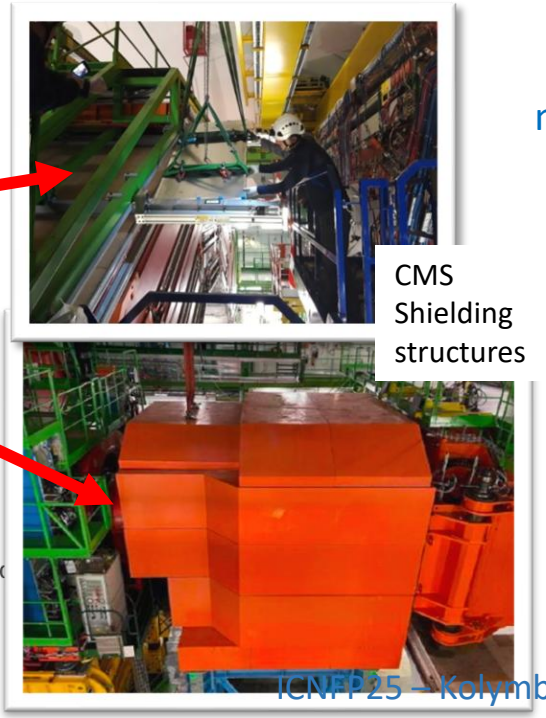
Reinforce and add redundancy in the forward region ~|η| > 1.7

CMS Muon Detector Longevity

- CMS Muon detectors span a surface of **~28000 m²**, ensuring long term performance is critical => Wide experimental program at **GIF++ at CERN** since 2015
- High intensity Cs^{137} source => replicate HL-LHC integrated dose and particle rates
- DTs are the **most sensitive to integrated dose** (non-fluorinated gas mixture makes them more vulnerable to electrodes degradation)
- Actions: **install additional shielding**: both near focusing magnets and around the entire DT volume
- CSC and RPCs must undergo **validation with alternative gas mixtures** featuring **lower Global Warming Potential (GWP)** to comply with environmental regulations (CSC & RPC recuperation systems operating)





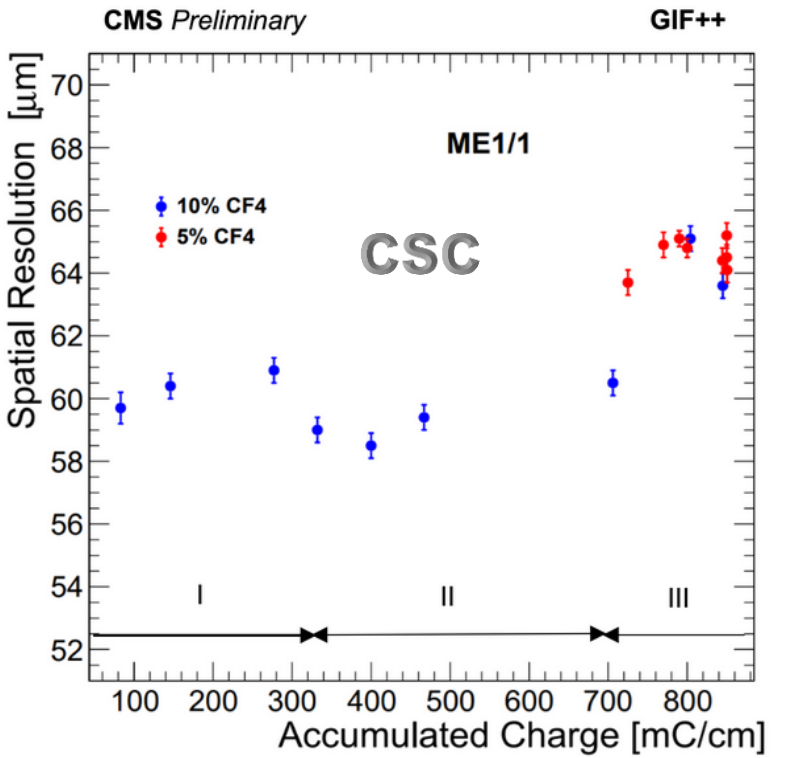


CMS Shielding structures

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

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

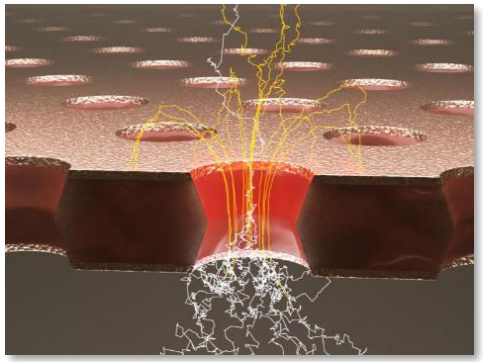
No significant degradation was observed up to the charge of 700 mC/cm



Reinforce forward region: GEMs

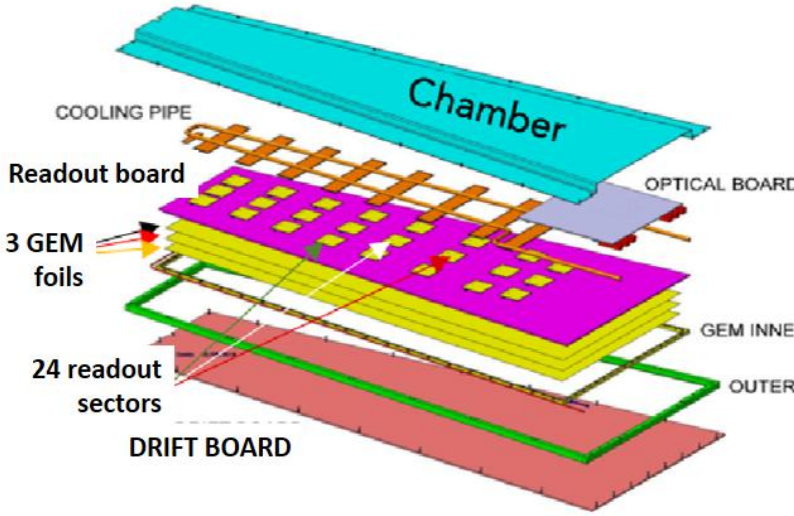
Gas Electron Multiplier (GEM) Technology

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



GE1/1 and GE2/1:

- TRIPLE GEM DETECTORS
- Polyamide foil: 50 µm
- Copper cladding on both sides: 5 µm
- Data taking: Ar/CO_2 (70/30) (pure CO_2 TS)
- **Very high spatial resolution (~100 µm)**
- **Time resolution ~10 ns**
- **Very high hit rate capability (~MHz/cm^2)**



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

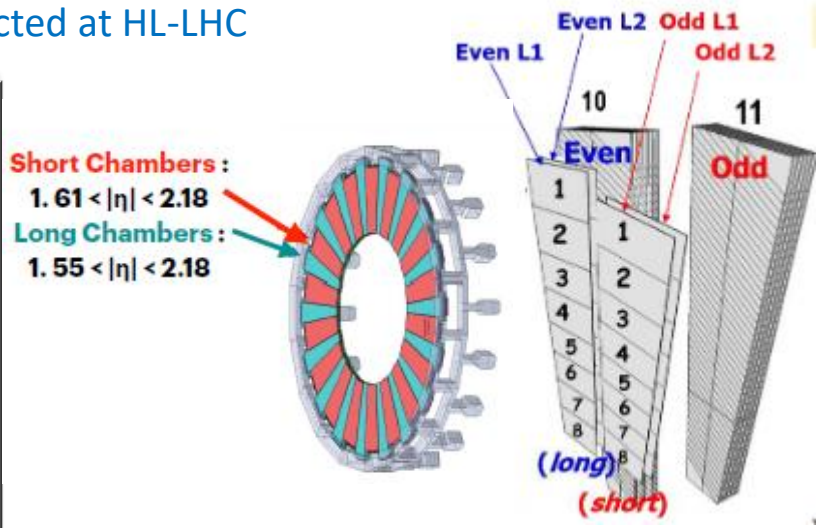
- complementing CSC in forward region (redundancy)
- improve tracking and trigger efficiency
- avoid large increases in trigger rate expected at HL-LHC

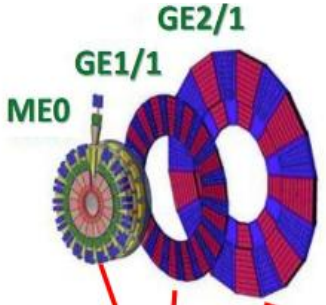
GE1/1 (10° in ϕ):

- Coverage: 1.55 < | η | < 2.18
- 144 detectors installed (72/endcap)

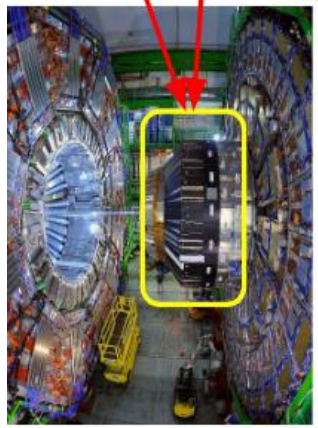
GE2/1 (20° in ϕ):

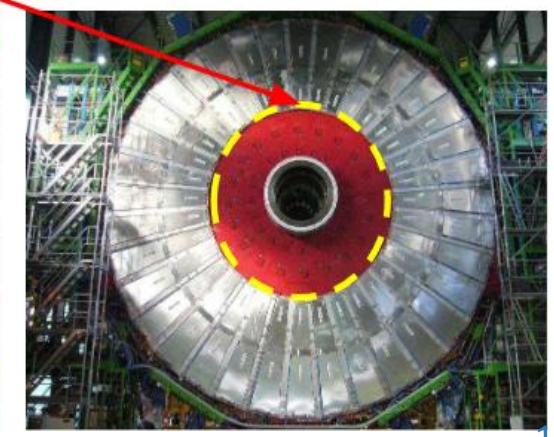
- Coverage: 1.62 < | η | < 2.43
- 12 modules (out of 72) installed in total
- Full installation postponed after LS3



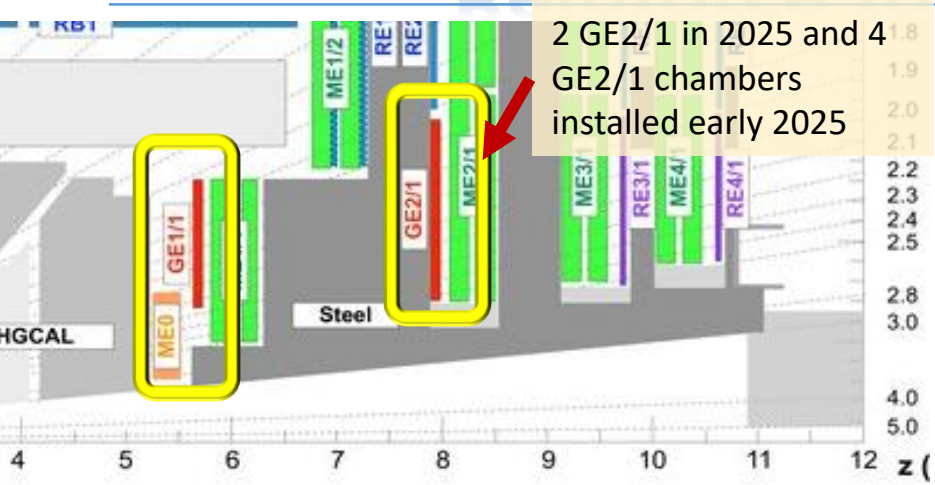


- 3456 VFAT3 chips
- 432 GBT
- VTRx as optical link

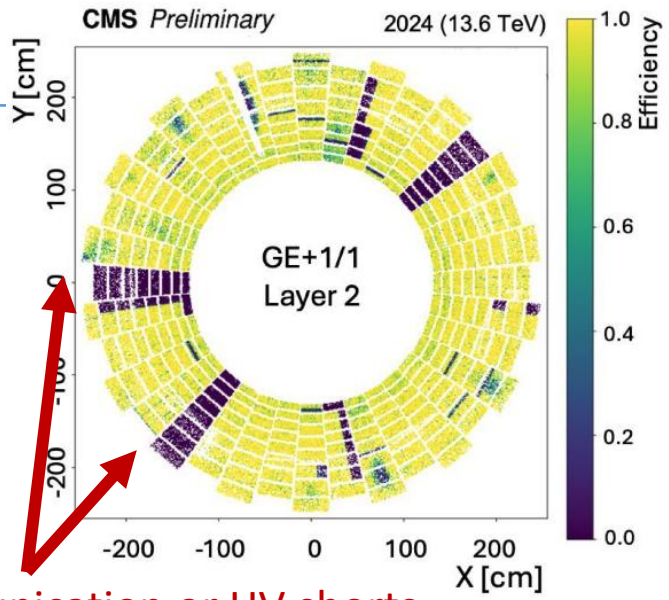




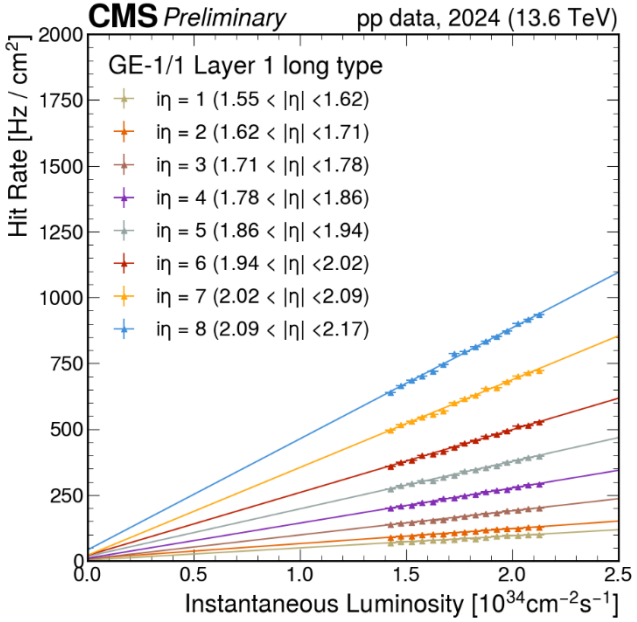
Reinforce forward region: GEMs



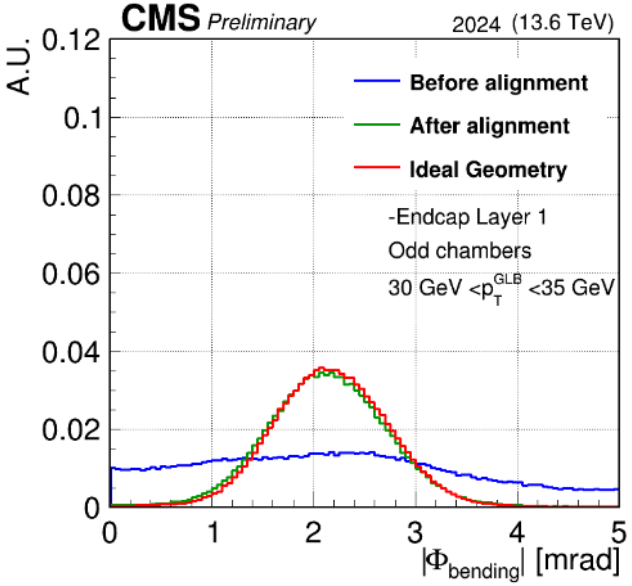
- GE1/1 installed in 2019 and **taking data during all Run 3**
- **Efficiency >95%**
- Operational experience allowed to overcome several problems (discharges, HV shorts, communication issues with VTRX outgassing, PCB issues and bending…



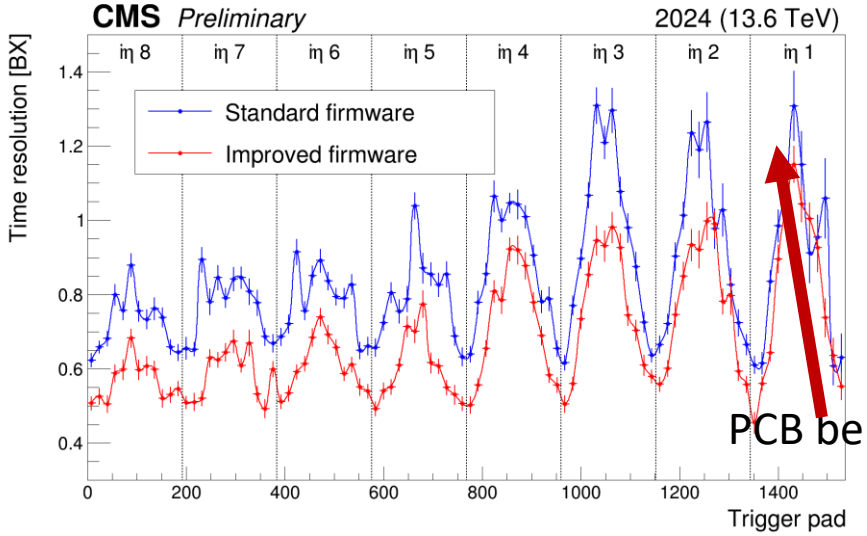
Communication or HV shorts



Good hit rate linearity versus luminosity



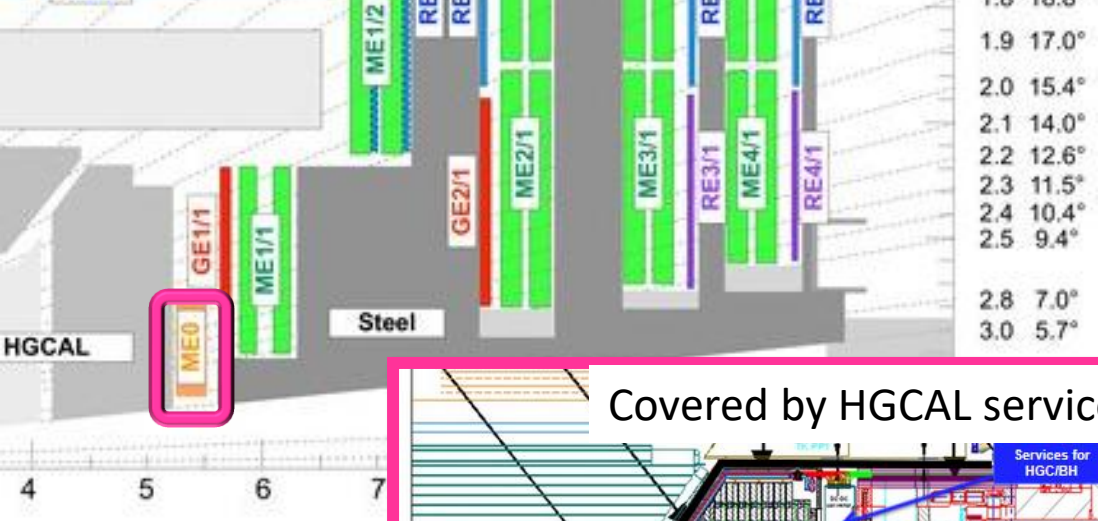
GE1/1-ME1/1 bending angles (phi_ME1/1 – phi_GE1/1_rechit)



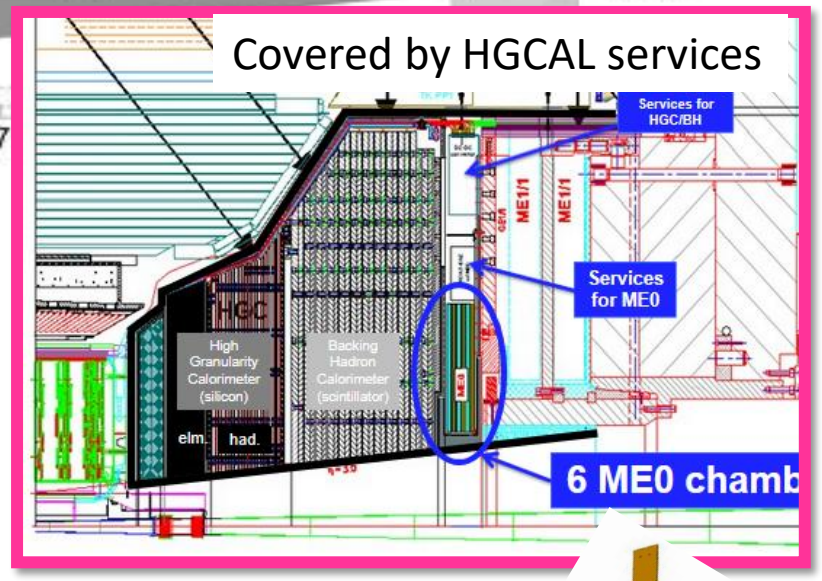
PCB bending

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

Extend very forward region: ME0

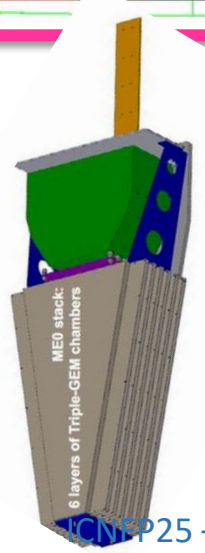


- Extend CMS Muon acceptance and trigger into the $2.0 < |\eta| < 2.8$ region. For example:
  - acceptance increase by 20% in channel H ->ZZ -> 4 u channel



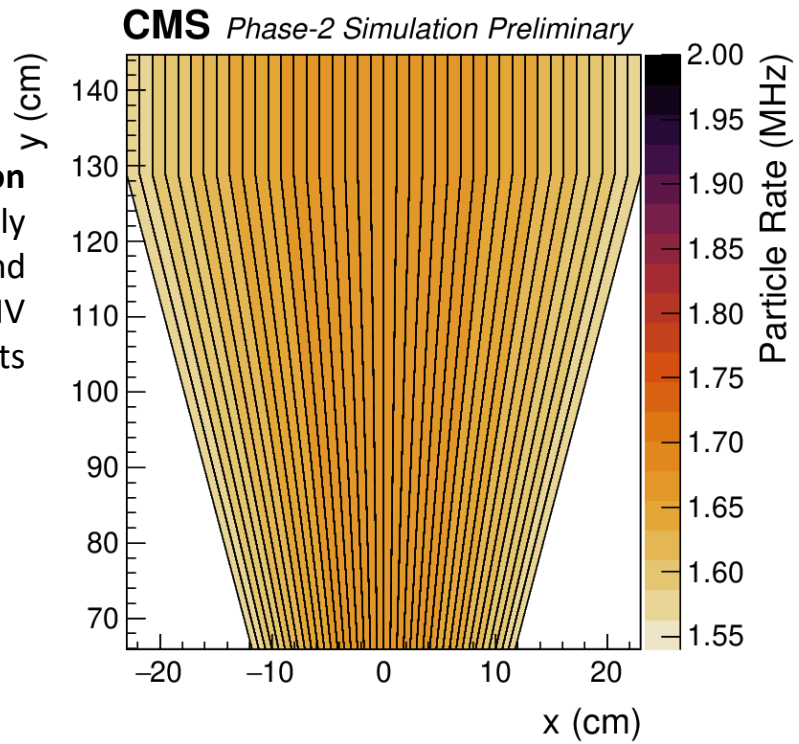
- Based on Triple-GEM technology, 6 layers of GEM foils
- ~2 m² area per station, 20° chambers, 6.5 cm overlap
- 18 stacks per endcap, 36 stacks in total
- 648 GEM foils in total (50% more than GE1/1)
- Located behind the future endcap calorimeter (HGCal)

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

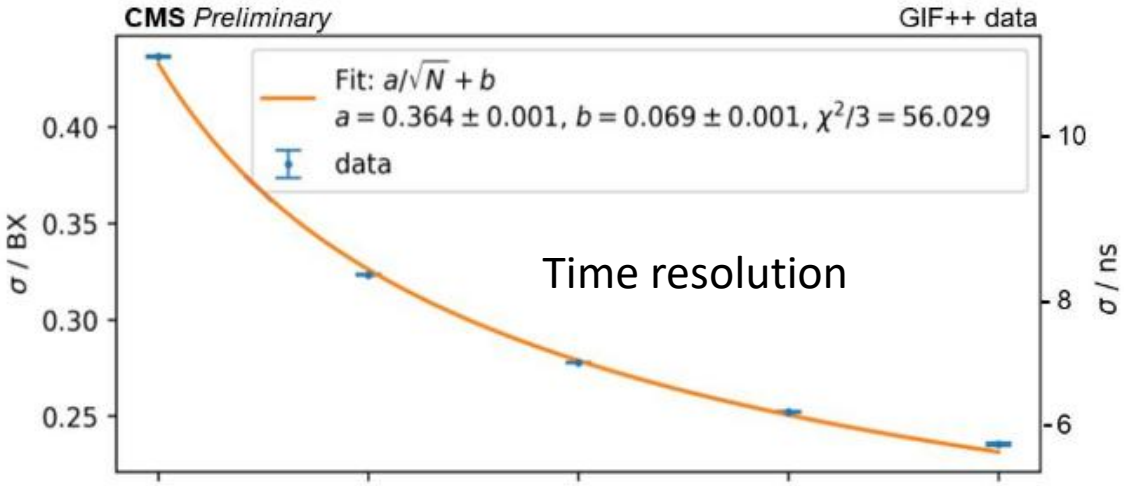


- 24 VFAT3/chamber
- 1 FPGA-less optoh.
- VTRX+

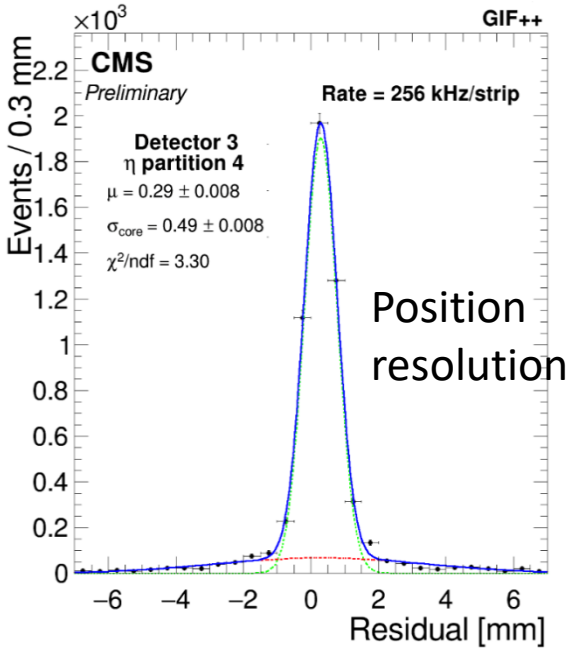
New foil segmentation oriented azimuthally equalizes background rate across all HV segments

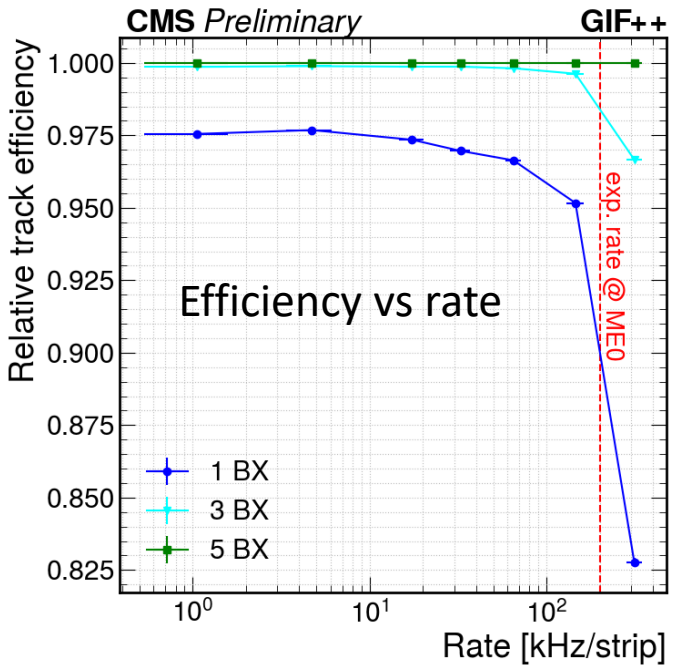


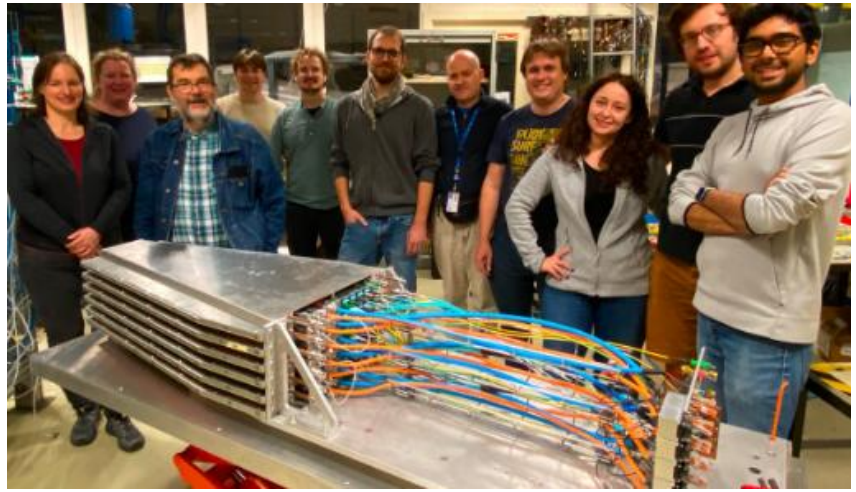
Extend very forward region: ME0



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





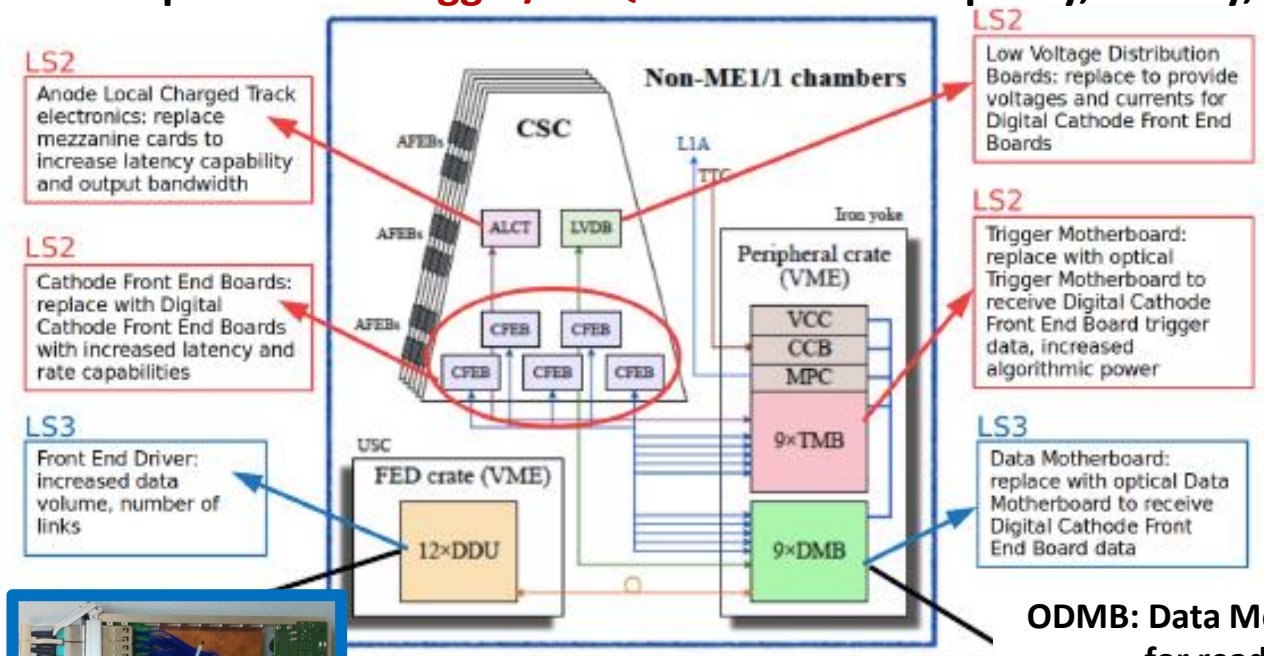


- A total of 8 production sites (CERN, Ghent, Bari, Frascati, Aachen, China, Punjab, Delhi)
- ~30% modules production ready
- The first stacks are being brought online

CSC upgrades

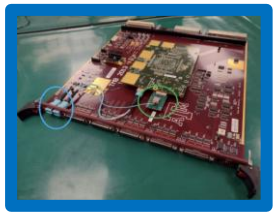
Staged replacement of the full electronics chain

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

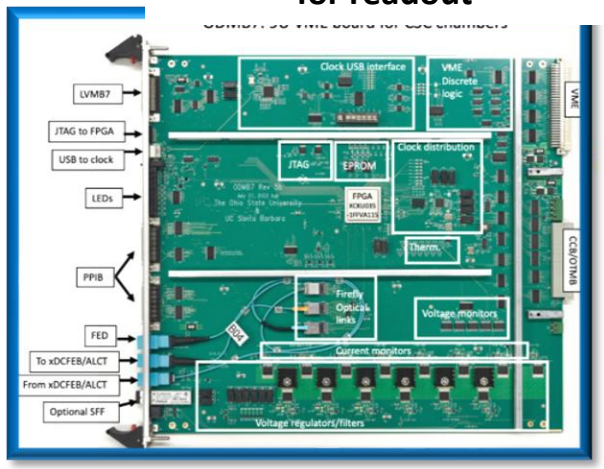


Backend ATCA based X2O board

OTMB upgrade with new optics and GEMs inputs

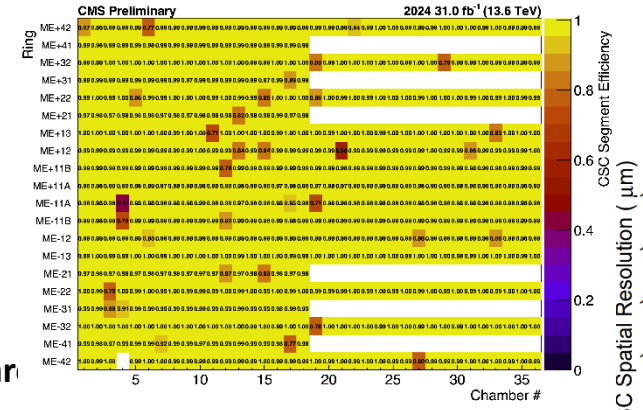


ODMB: Data Motherboard for readout



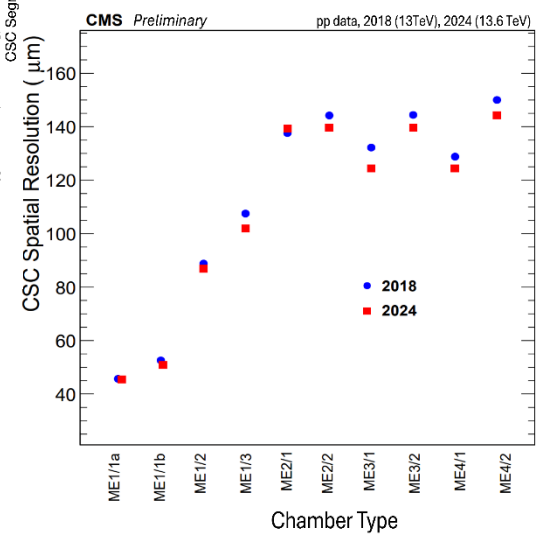
Most of CSC phase 2 upgrade was successfully completed in LS2

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



Run 3 CSC segment efficiency

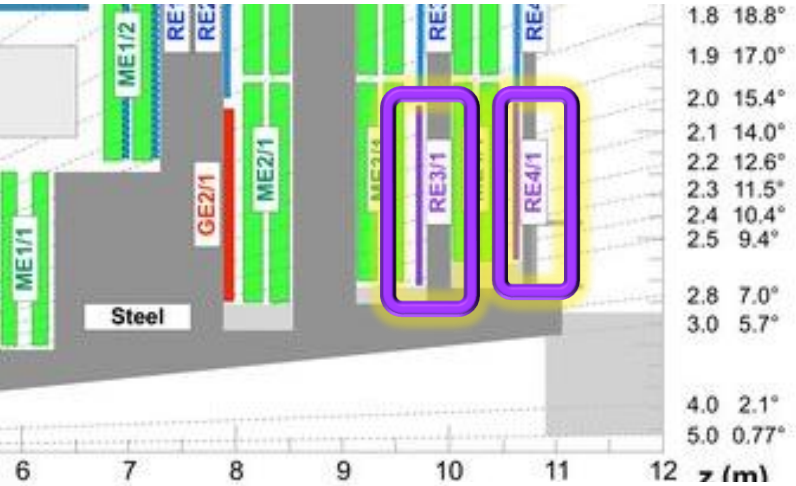
Run 3 CSC spatial resolution



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

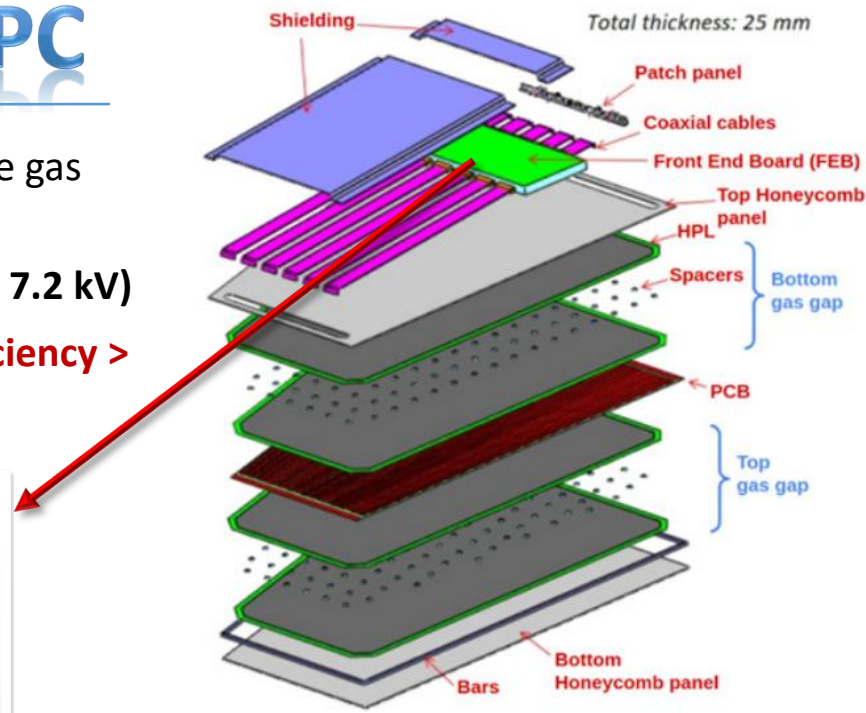
- 72 ODMB7 boards for ME1/1 (100% completed)
- 108 ODMB5 boards for ME234/1 (30% completed, issues with PCB material)

RPC upgrades: iRPC



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

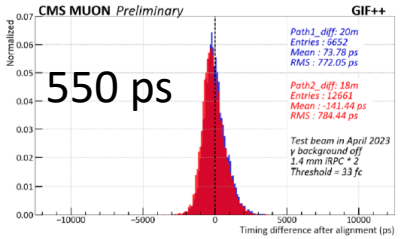
  => allows **lower HV working point (9.5 kV => 7.2 kV)**
- Rate capability up to **2 kHz/cm²** with hit **efficiency > 95%** at 7.2 kV (max bkg. rate ~700 Hz/cm2)

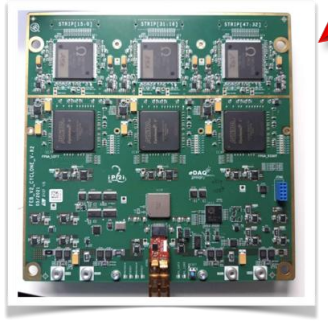


RE3/1, RE4/1 stations:

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

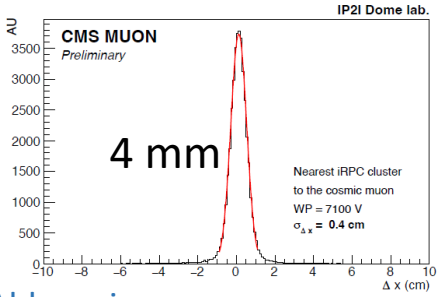
	RPC	iRPC
Gas gap width	2 mm	1.4 mm
HPL thickness	2 mm	1.4 mm
Resistivity	1-6 × 10^{10} Ω·cm	0.9-3 × 10^{10} Ω·cm
Charge threshold	150 fC	50 fC
η space resolution	17 cm (3 η partitions)	2 cm (2D readout)
ϕ strip pitch	0.3 degrees	0.2 degrees
Intrinsic time resolution	1.5 ns	0.5 ns

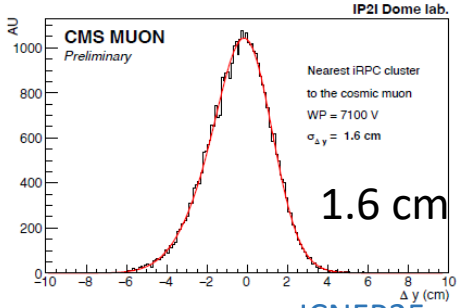




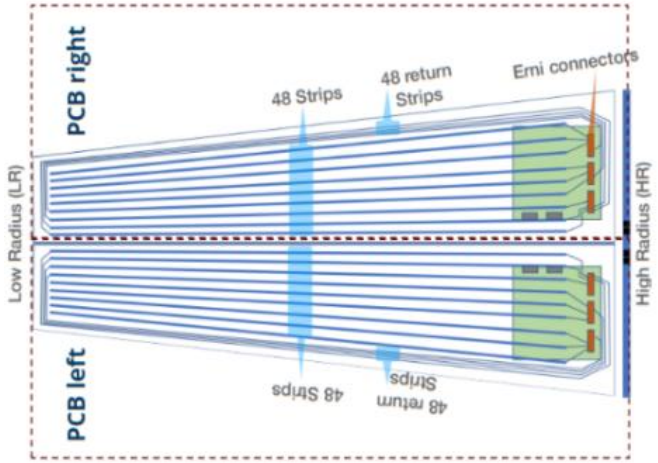
Low noise FEB sensitive to 30 fC

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



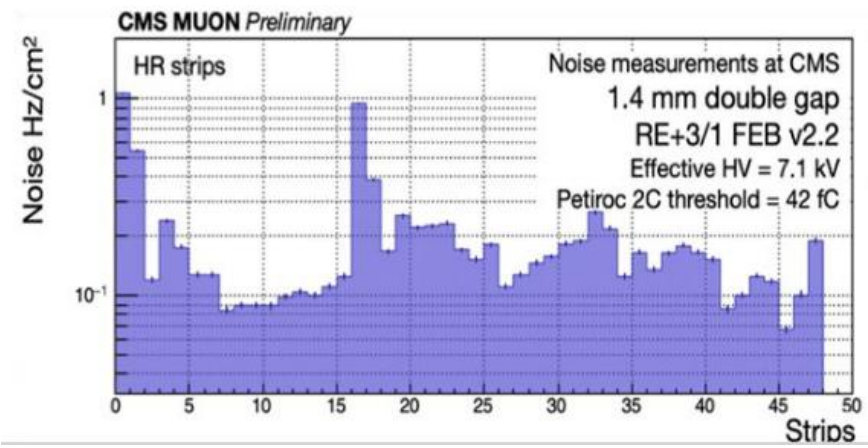


Strip readout:
2D measurement
TDC reading strips
from **both sides**



RPC upgrades

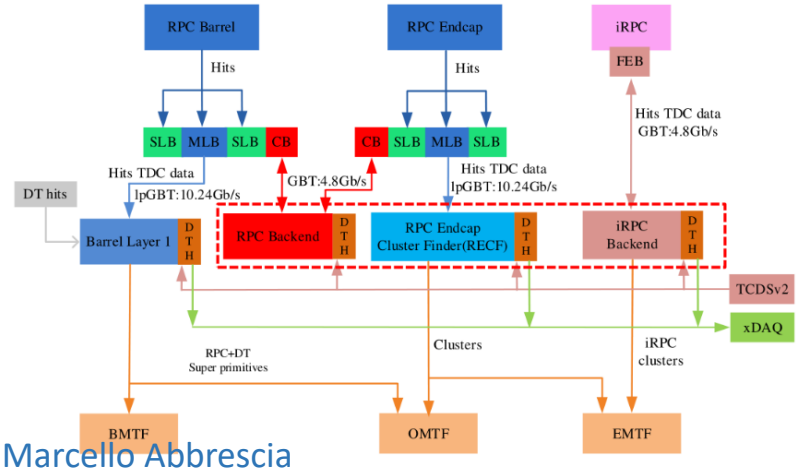
- During Winter Shutdown 2024-2205: **iRPC RE-3/1, RE-4/1 have been successfully installed** in the negative side of the CMS detector (half of the final system)
- Integration with backend electronics is ongoing

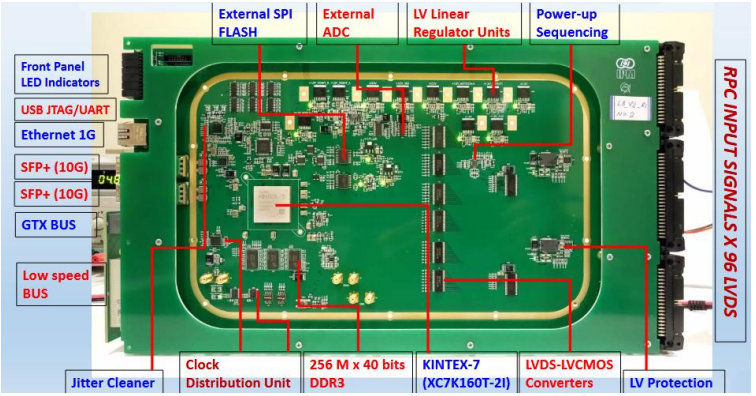


Full RPC system

Upgrade of the **Link boards**

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

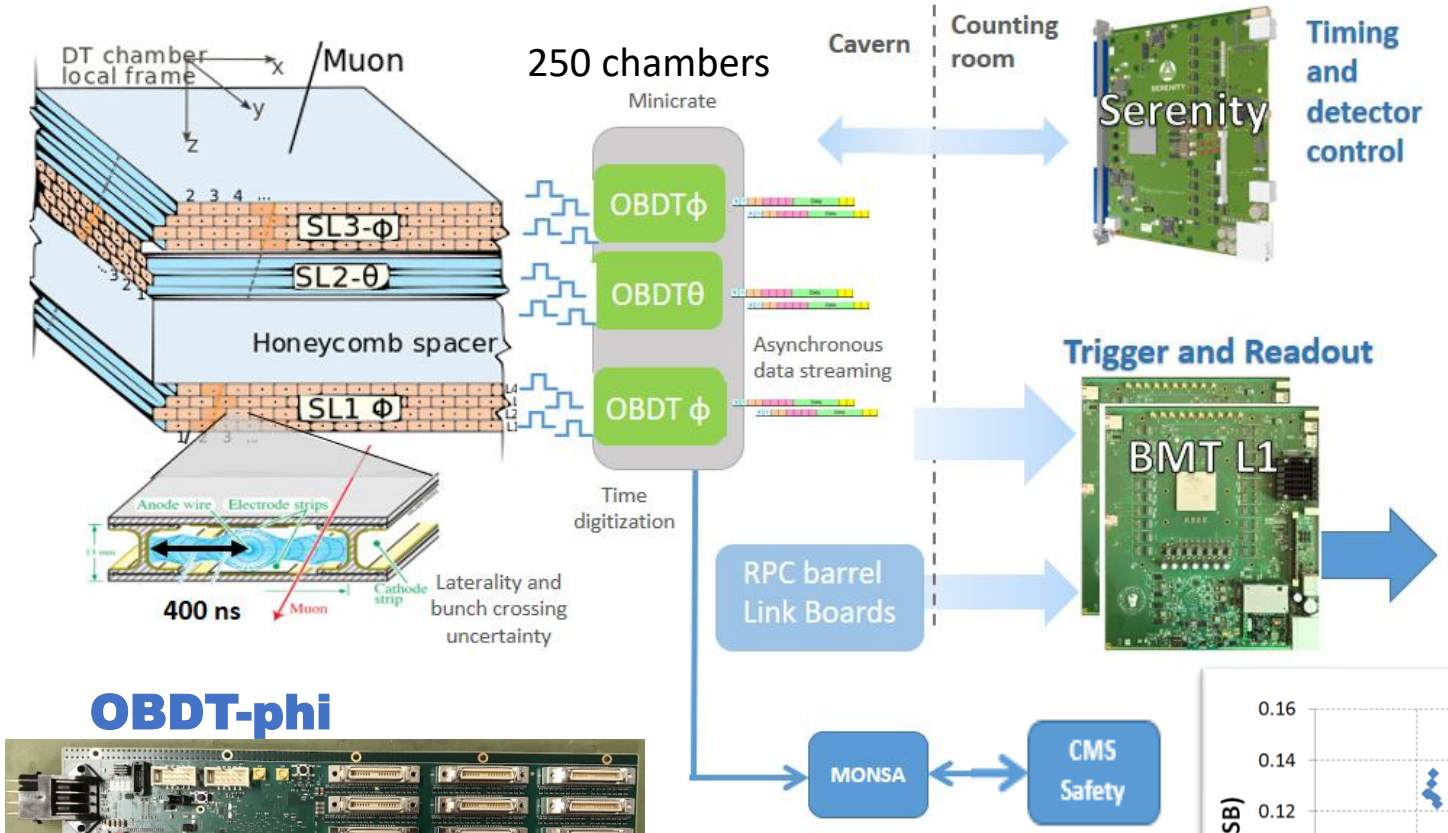




Key Features of new Link System

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

Drift Tubes upgrades



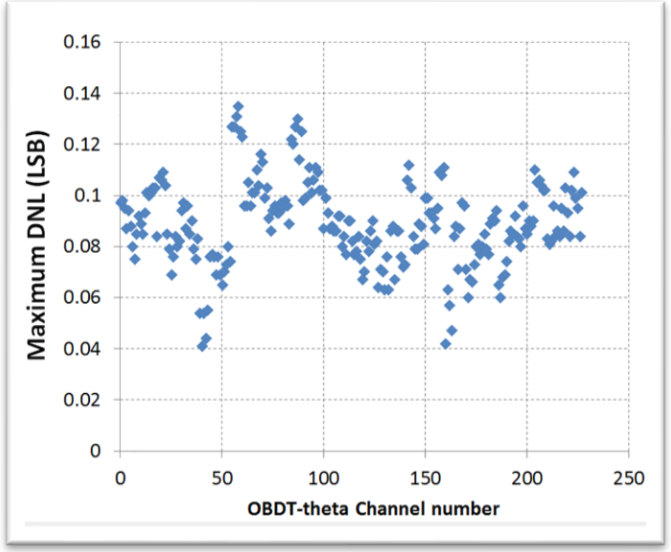
- **Replacement of the full electronics chain**
- **Compliant with Trigger/DAQ : occupancy, latency, L1 rate**
- **Improved performance at Trigger primitive generation**

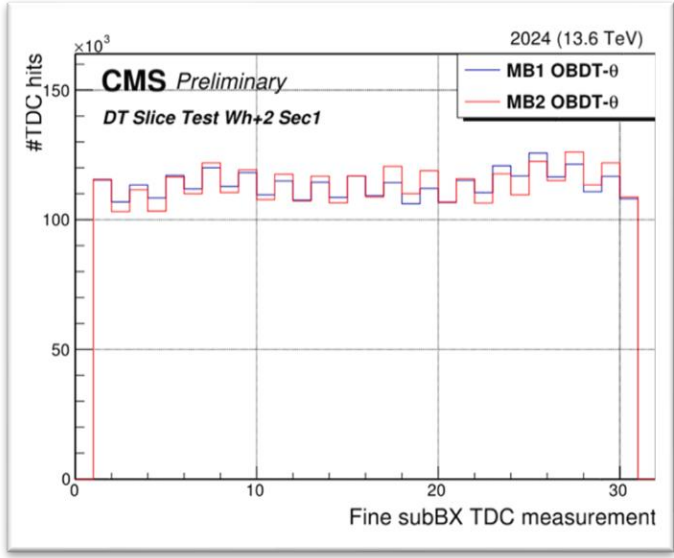
  - Two OBDT flavors for each coordinate to accommodate to chamber constrains
  - 630 OBDT-phi and 180 OBDT-theta
  - Time digitization (~0.7 ns) by deserialization method inside the OBDT boards

OBDT-phi

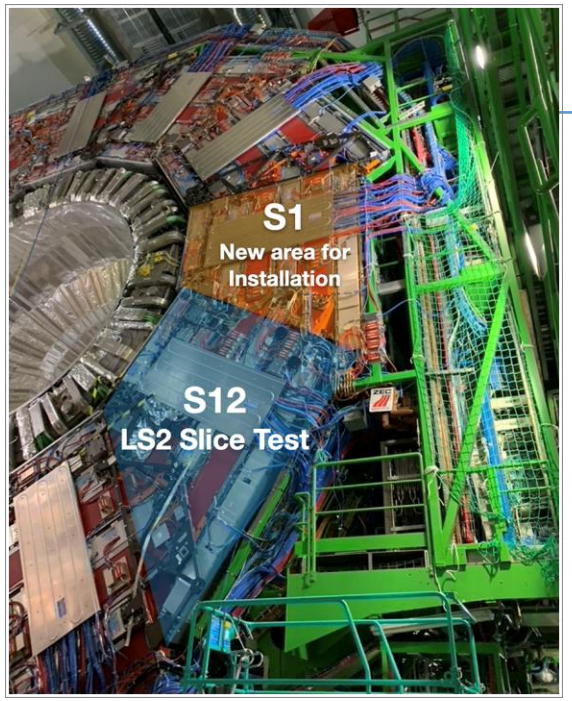
OBDT-theta

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





Drift Tubes upgrades



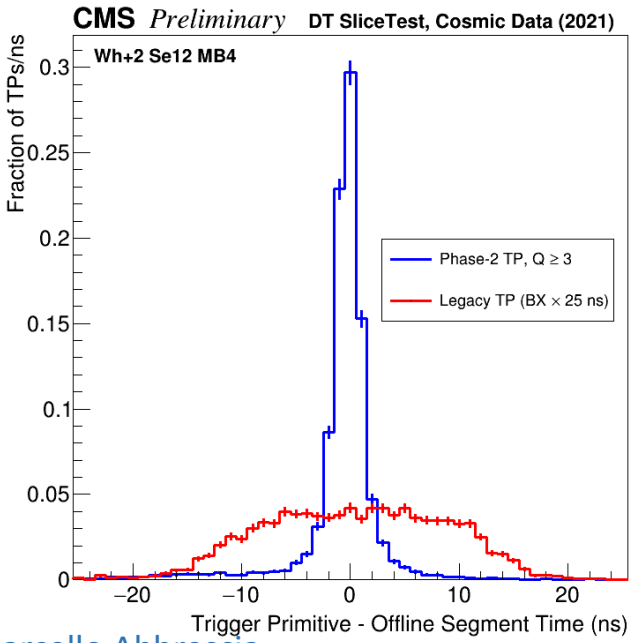
DT "slice-test" demonstrator in two sectors of the CMS detector:

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

Successful operation of an integrated system:

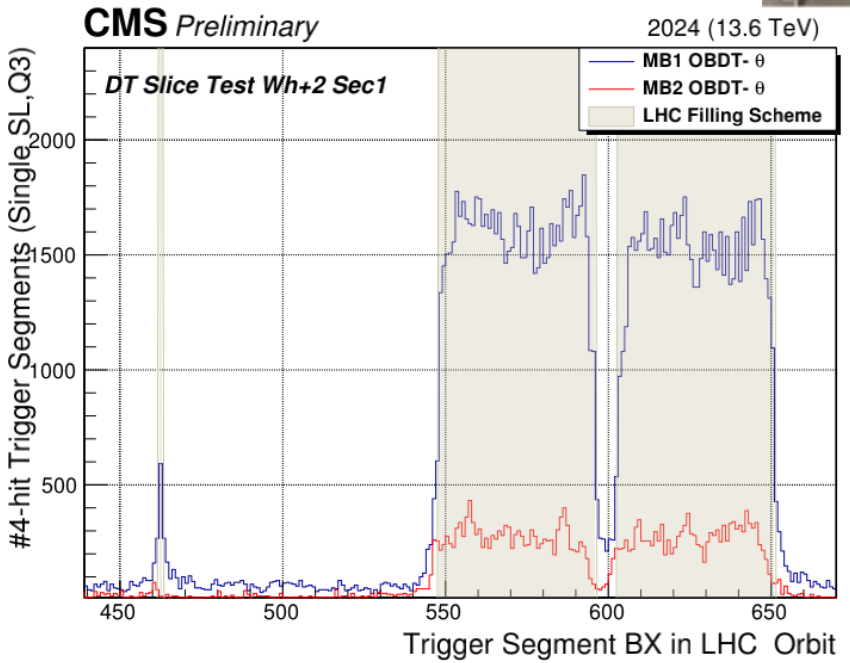
- Sector 12: OBDTs v1 prototypes + uTCA readout
- Sector 1: OBDTs final prototypes + BMTL1 ATCA backend

BMTL1



Excellent local trigger performance

Trigger resolution comparable to the offline reconstruction!



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

Summary and conclusions

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

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

  - **Tracker**: extended acceptance, higher granularity and radiation tolerance
  - **MTD**: new detector providing MIP timing with 30-40 ps resolution for vertexing in high background
  - **HGCAL**: endcap calorimeter for 5D particle flow reconstruction of jets and e/γ
  - **Muon system**: upgraded electronics and new detectors (iRPC, GEM) for improved redundancy and coverage
  - **Level-1 trigger**: including tracker and enabling global reconstruction

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