Upgrade of the CMS detector

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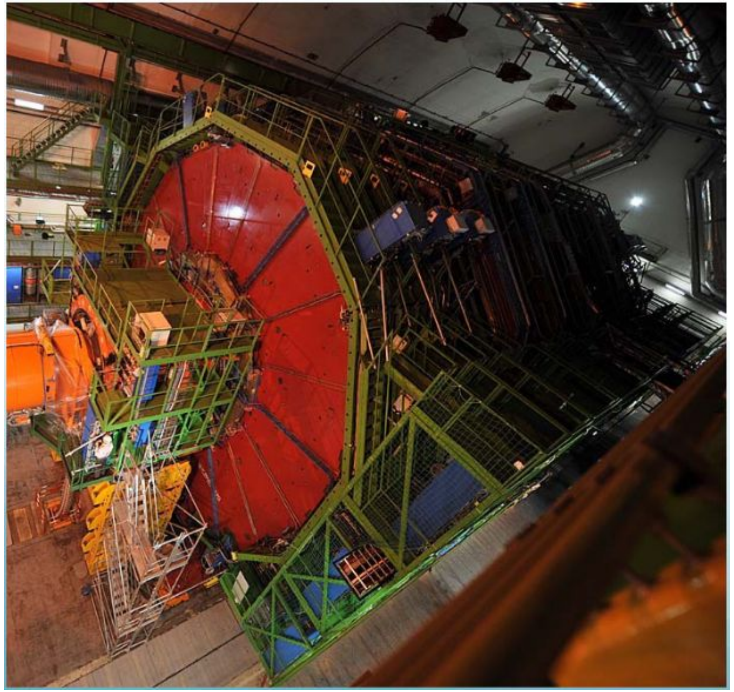
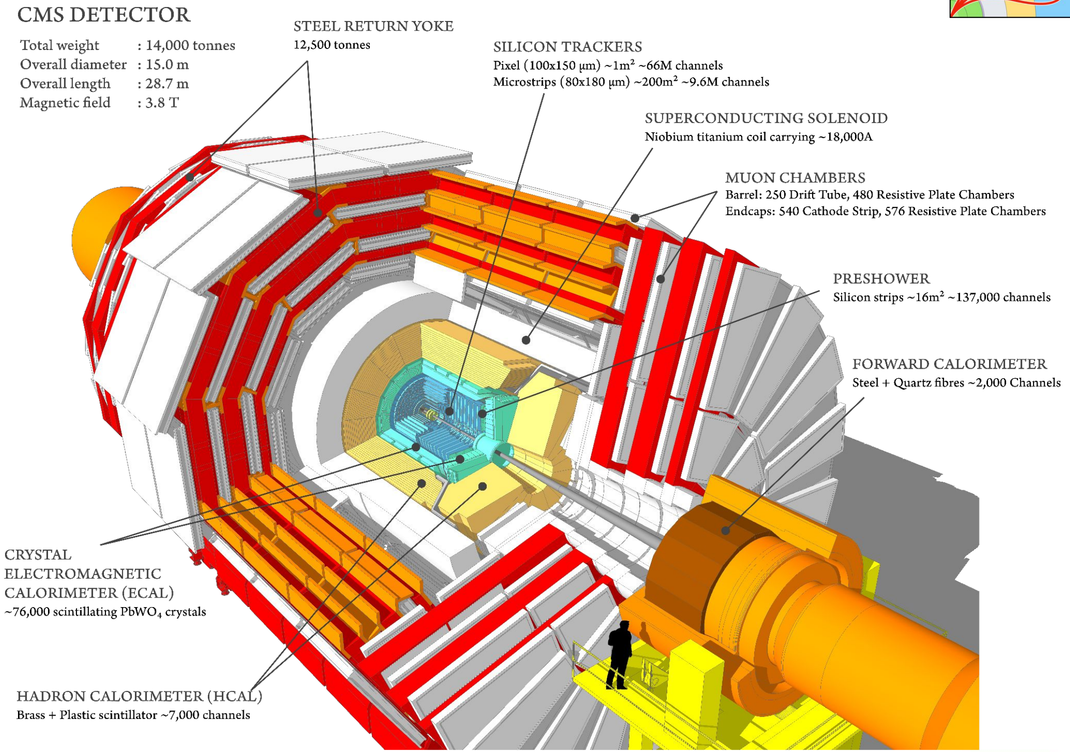
On behalf of the CMS collaboration

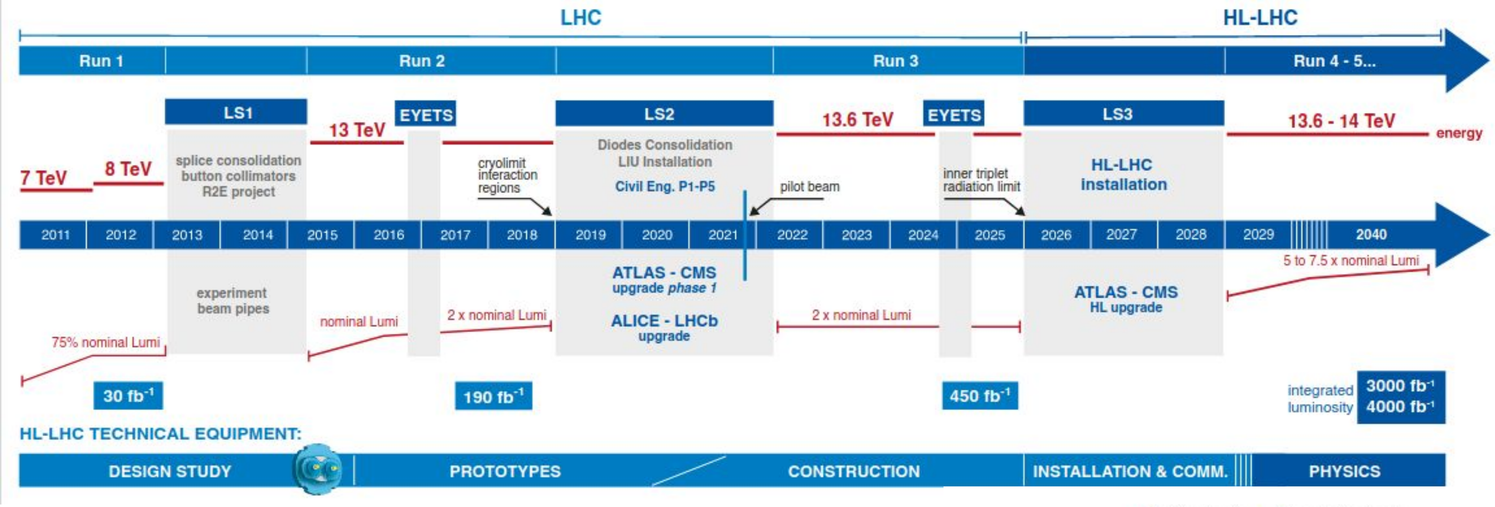
XVIII Mexican Workshop on Particles and Fields

The CMS detector



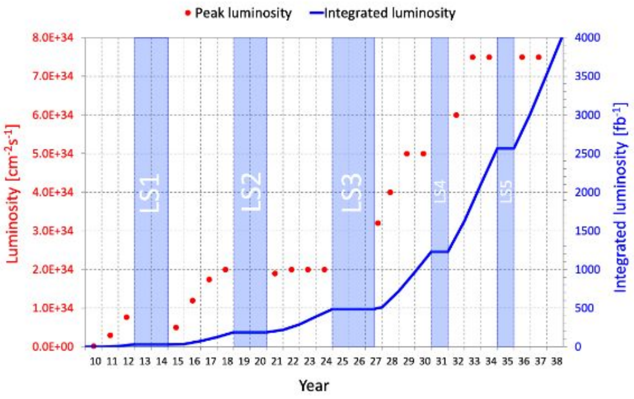


The LHC and HL-LHC schedule



High Luminosity upgrade of LHC

- Up to 7.5 times the nominal instantaneous luminosity.
- Expect to collect up to 4000 fb^{-1} in 10 years.
- 6.5 fb in 24 hrs.

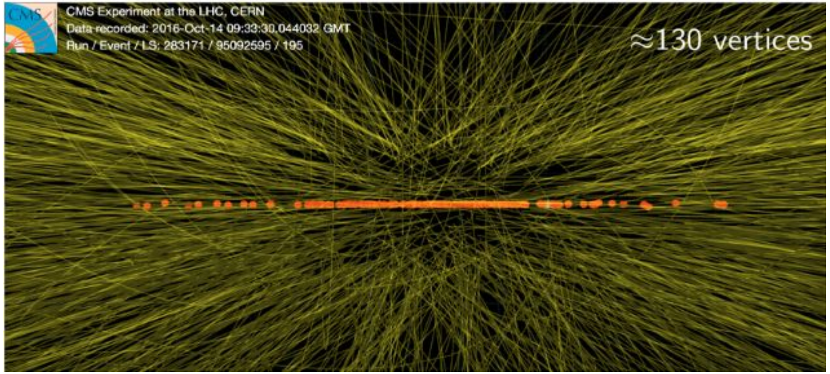


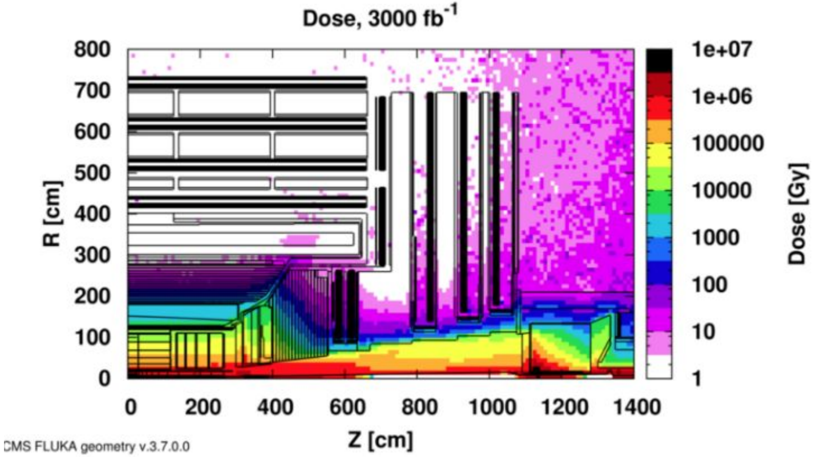
HL-LHC: challenging conditions

- Up to 200 collisions per event (pile up)
  - Very high occupancy on inner detectors.
  - Degradation in resolution, reconstruction efficiency and misid rates are expected.
  - Critical to associate physics objects with correct primary vertex.

- High radiation conditions
  - Doses up to 12 MGy.
  - Fluence up to 2.3 x 10^{16} n_{eq} / cm^2
  - Requires radiation hard materials and electronics.

- Key features to recover CMS performance
  - Higher detector granularity to keep similar occupancy.
  - 4D (space & time) vertex reconstruction.



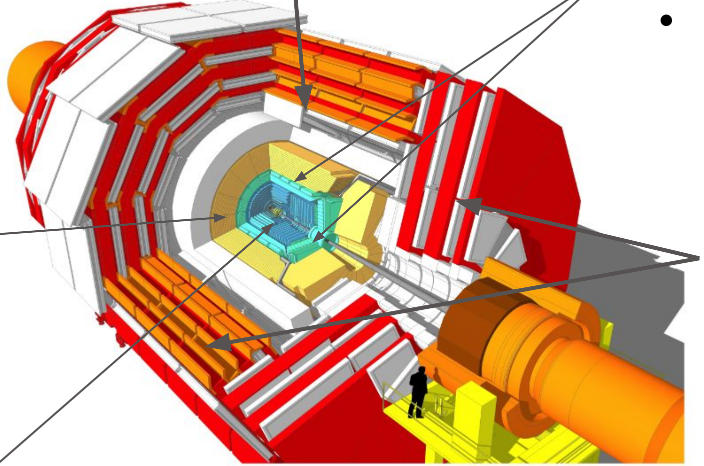


The CMS upgrade for HL-LHC

L1T and HLT/DAQ
- L1 output at 750 kHZ.
- Tracker tracks in L1T.
- L1 latency: from 4 to 12.5 us.
- HLT output at 7.5 kHz.
- 40 MHz Scouting: Real time analysis.

Barrel Calorimeters
- ECAL new front-end boords will exploit single crystal information at L1T.
- New ECAL and HCAL back-end boards.

MIP Timing Detector
- New detector layers.
- 30 ps timing resolution.
- Barrel layer: Crystals + SiPMs
- Endcap: Low gain Avalanche Diodes.



Calorimeter Endcap
- High Granularity Calorimeter (HGCAL).
- Imaging calorimeter.
- 3D showers and precise timing.

Muon System
- DT & CSC new front-end and back-end electronics.
- New RPC back-end electronics
- New GEM/ RPC 1.6 < eta < 2.8

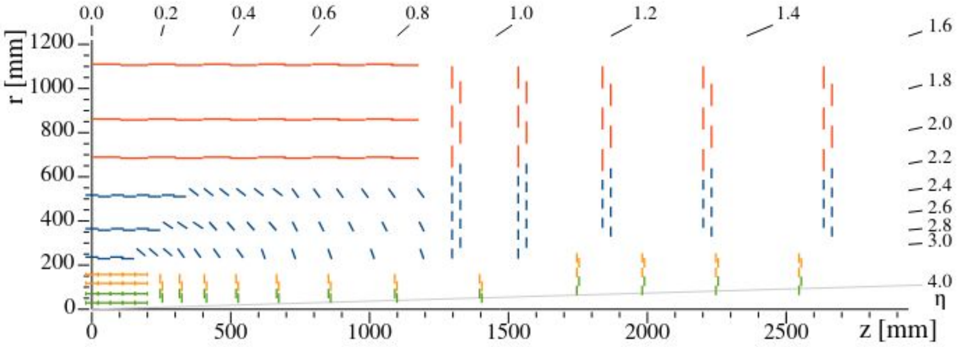
Tracker
- Increased granularity.
- Designed for tracking in L1-trigger.
- Extended coverage to $|\eta| = 4$

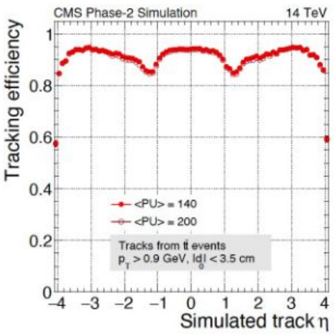
Beam Radiation Instr. and Luminosity
- Bunch-by-bunch luminosity measurement
- 1% offline, 2% online

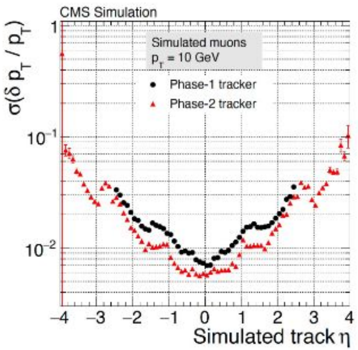
CMS inner and outer tracker

- Completely new silicon tracker
  - Outer tracker (OT) replaces SiStrip tracker.
  - Inner tracker (IT) replaces Pixel Tracker.

- Requirements
  - Radiation hardness.
  - Increased granularity to keep occupancy at the permil level.
  - Reduced material in the tracking volume to improve tracking performance.
  - Improved two-track separation.
  - Robust pattern recognition and contribution to the L1 trigger.
  - Extended pseudorapidity coverage |η|= 4



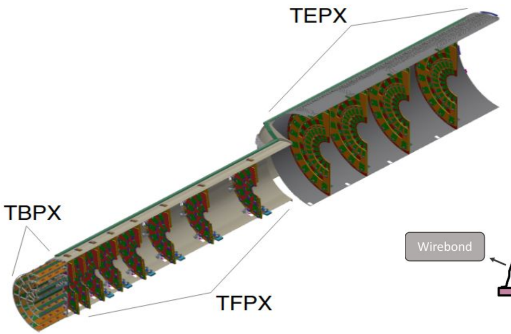


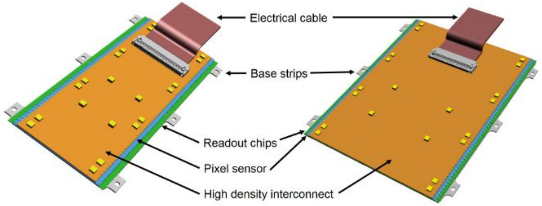


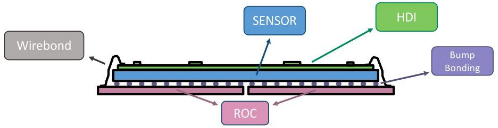
Good trac.king efficiency at 200 PU

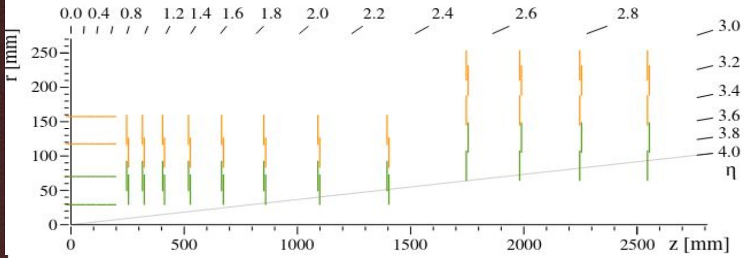
Improved pt resolution wrt to phase-1.

Inner Tracker









- Increased detection coverage
  - 4 barrel layers (TBPX)
  - 8 small disks (TFPX)
  - 4 large disks (TEPX)
- Reduced material budget.
- Lower detection threshold (new ROC).
- Simple installation and removal.

Pixel module:

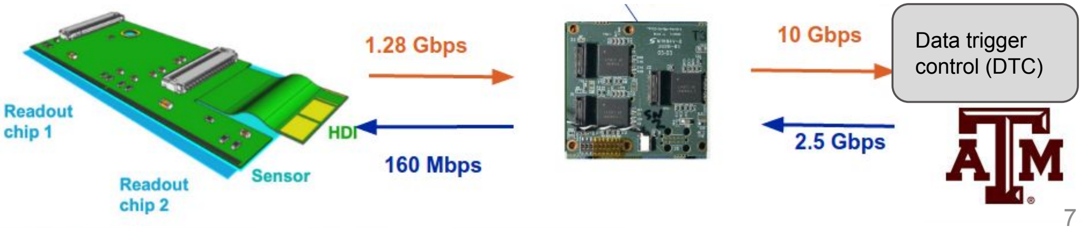
- n-in-p planar **sensors** (150 um thickness),
  - 100x25 um² pixel cells
- ~1.4 x 10^5 pixels per **readout chip**
- Two types of modules
  - 2 x 1 modules in high occ. regions
  - 2 x 2 modules in lower occ. regions.

CMS readout chip (CROC) developed in the RD53 collaboration (ATLAS & CMS)

- 65 nm CMOS tech
- 3 GHz/cm2 hit rate
- Power consumption < 1 W/cm2 at max trigger rate
- Radiation tolerant

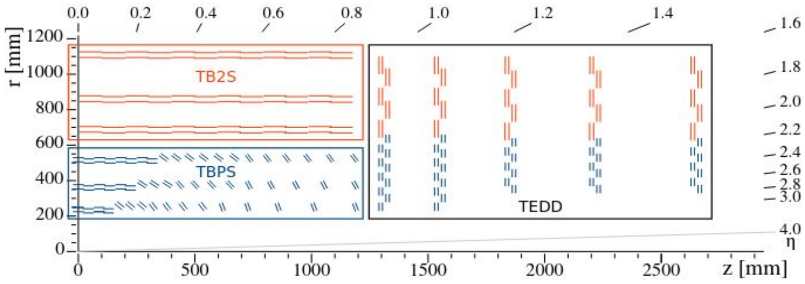
Signal is readout through short electric cables.

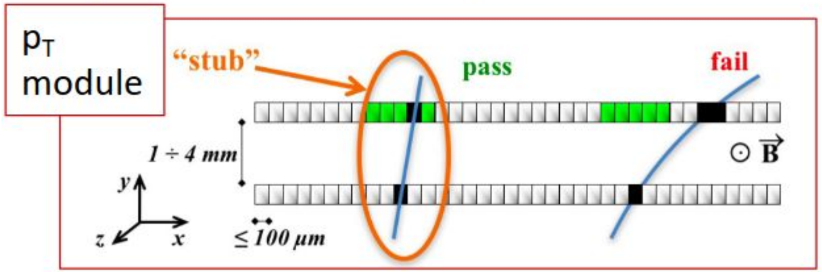
- **Portcard** located in the detector periphery.
- Optical conversion. Data sent to control room through optical links

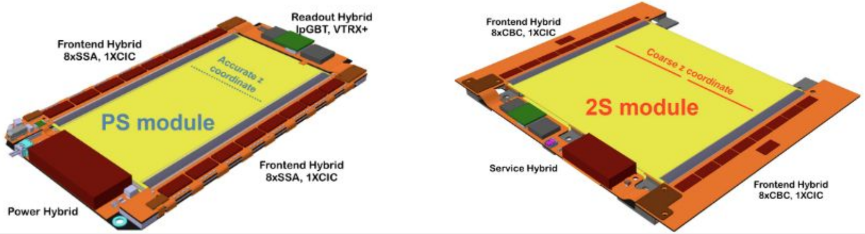


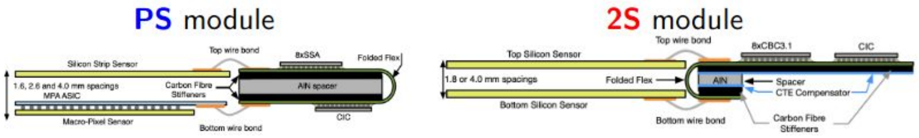
Outer Tracker

- Segmented into three regions and two types of modules:
  - TBPS - PS module for the inner barrel.
  - TB2S - 2S module for outer barrel.
  - TEDD - Endcap 2S and PS modules.
- p_T modules - using two closely spaced sensor (with strong magnetic field), provide p_T discrimination at front-end.

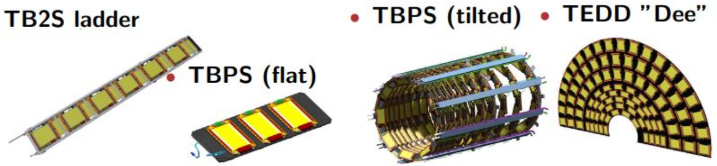






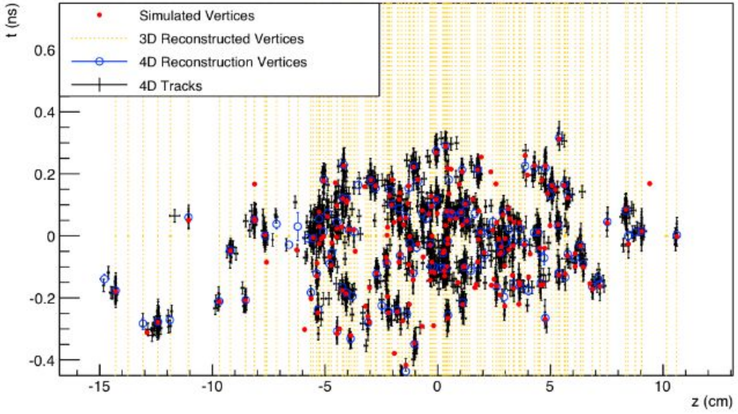


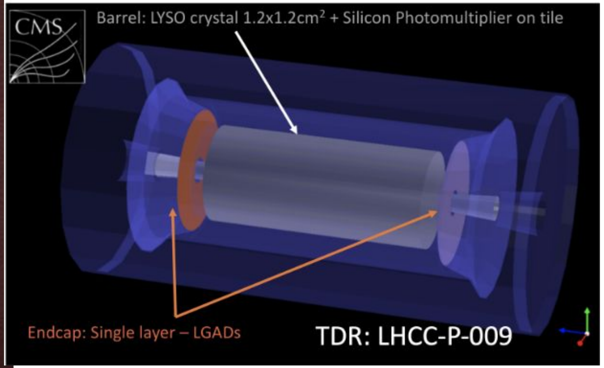
- **Stubs**: correlated pairs of clusters consistent with pt > 2 GeV.
  - Inputs for track finder.
  - Used at L1.



MIP Timing Detectors (MTD)

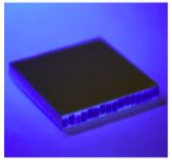
- Vertices overlapping in z might not overlap in time.
- Target resolution: ~30 ps.
- Increase capability to search for Long-lived particles.
- π / K / p identification using TOF measurement.
- Placed between tracker and ECAL
- Two different technologies:
  - Barrel: LYSO:Ce bars + SiPMs.
  - Endcap: Silicon sensors with internal low gain.





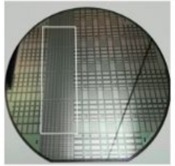
BTL: LYSO bars + SiPM readout:

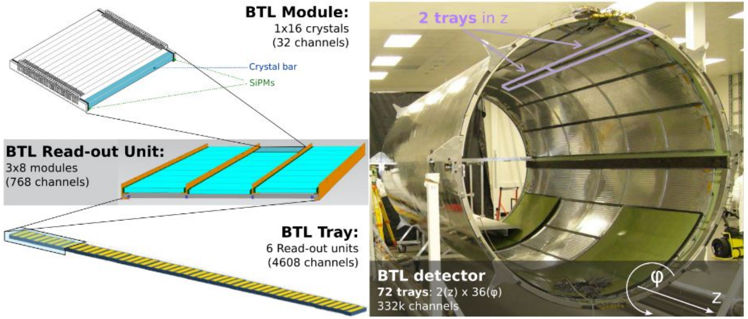
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2x10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD):

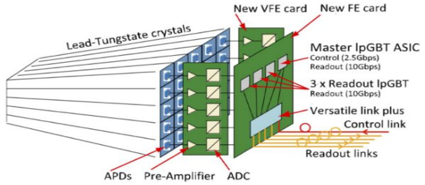
- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2x10^{15} n_{eq}/cm^2

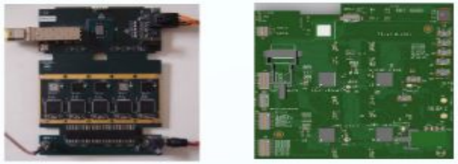


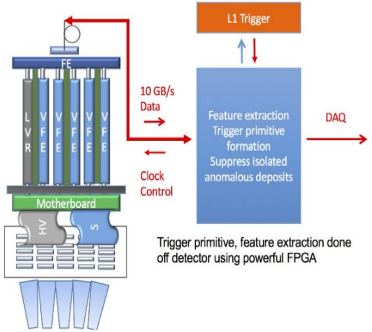


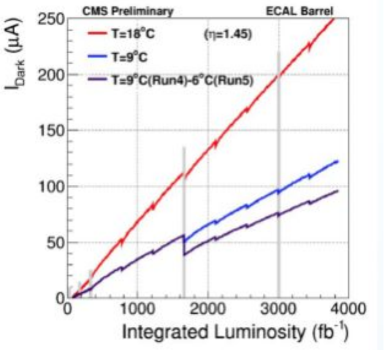
Barrel Calorimeters

- ECAL lead tungstate ($PbWO_4$) crystals and Avalanche Photodiodes (APDs) will be retained.
- Decrease operation temperature from 18 to 9 C to mitigate increase in the leakage current.
- front-end and back-end electronics to be replaced
  - Single crystal information to the Level-1 calorimeter trigger (instead of 5x5)

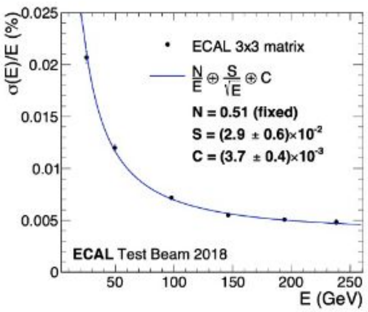


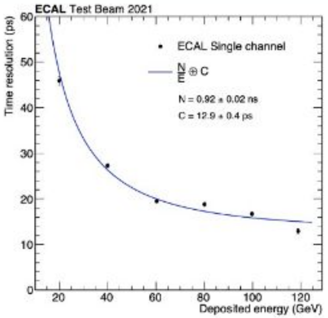






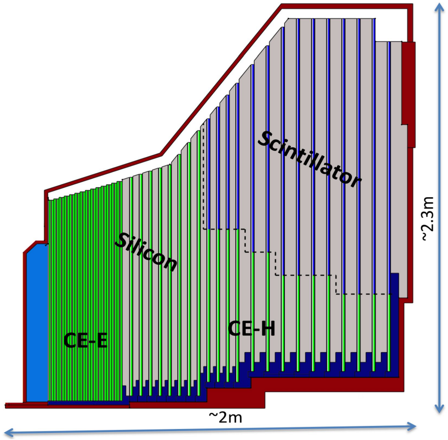
- Test beam results showed new electronics meets the HL-LHC requirements:
  - Time resolution < 30 ps for 30 Gev e/γ
  - Energy resolution in agreement with phase-1 performance.
- HCAL.
  - Plastic scintillator tiles and wavelength-shifting fibers will be kept.
  - front-end electronics with Silicon PhotoMultipliers (SiPM) installed on LS2 will be kept.

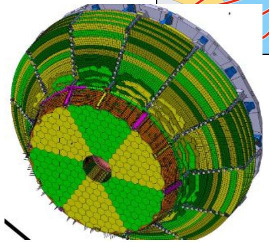


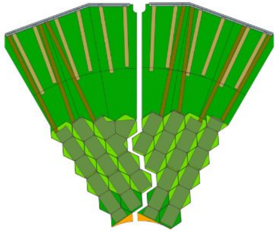


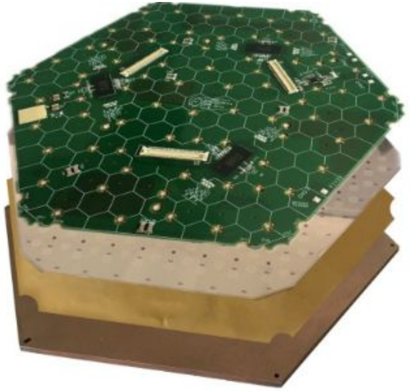
High Granularity endcap Calorimeter (HGCal)

- Highly granular imaging calorimeter
  - particle flow reconstruction.
  - Jet substructure
- More than 6M channels (20k in present detector)
- Electromagnetic calorimeter CE-E
  - Si-sensors (6M channels of 0.5-1 cm^2)
  - 26 layers, 27.7 X_0, ~1.5 λ
  - Cu, CuW and Pb absorbers.
- Hadronic calorimeter CE-H
  - Si-sensors and scintillating tiles (240k channels 4-30 cm)
  - read out with SiPM,
  - 7 all-Si layers, 14 mixed layers, ~8.5 λ
  - steel absorbers.
- CO_2 cooling at -30 C to limit radiation damage of sensors.





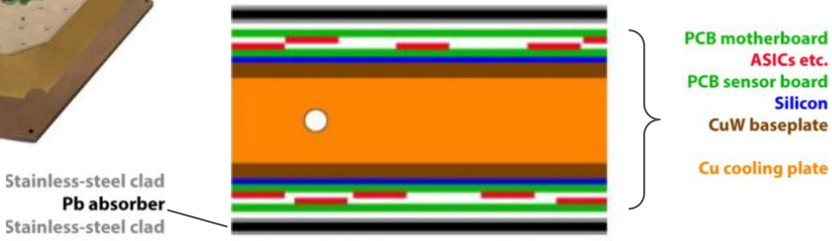


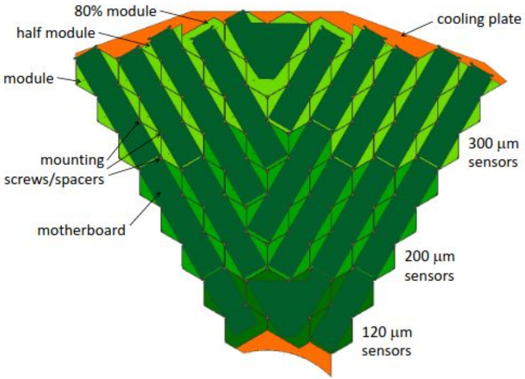


Si modules

- PCB ("Hexaboard"), read-out (HGCROC)
- Si-sensor
- Gold-plated kapton sheet (isolation to baseplate)
- Rigid CuW baseplate

Integrated into "cassettes"--> cooling plate with electronics and absorbers



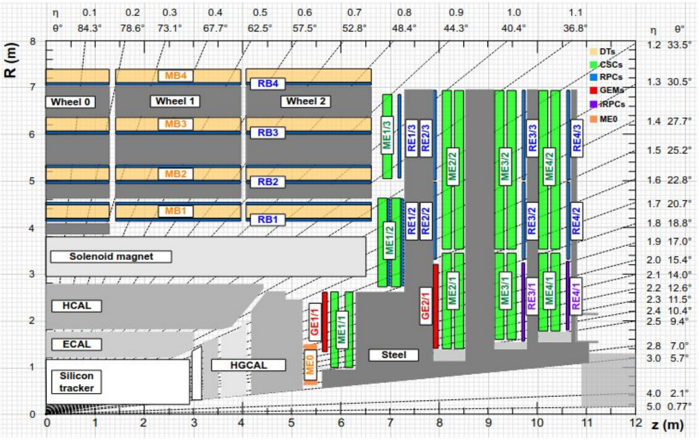


The Muon System Upgrade

Existing DT, CSC and RPC will operate during 10 years at HL-LHC.

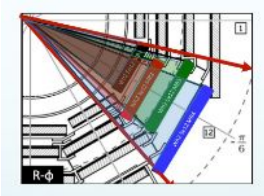
Detectors with upgraded electronics to cope with 10 times higher rates and improve performance.

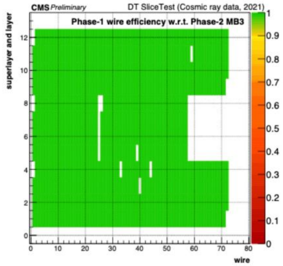
- DT: replace all on-board electronics (OBDT) and back-end.
- RPC: replace all off-chamber electronics and back-end.
- CSC: replace FE boards (LS2), replace back-end.

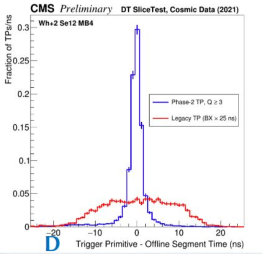


The DT slice test for phase-2:

- A full DT sector/slice is equipped with the phase-2 electronics.
- OBDT prototypes working in parallel with the legacy electronics.



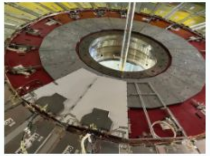




Results from the slice test

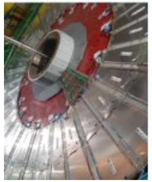
- Measured the phase-1 and phase-2 Hit efficiency: 100% consistent.
- Measured the phase-2 trigger primitive's timing resolution, found it comparable to the offline resolution.

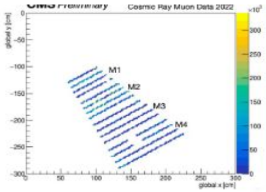
- New detectors in the endcap forward region (high background)
  - Increase redundancy and extend coverage.
  - High radiation hardness of new detectors.
  - Enhance tracking performance.
  - Enable bending angle measurement at trigger level.
- Gas Electron Multipliers
  - GE1/1, installed in LS2
  - GE2/1 to be installed in 2023/24 & 2024/2025 EYETS
  - ME0 in LS3
- Improved RPCs: RE3/1 and RE3/4 (2024/25 EYETS)



- RE3/1 mass production started in 2022
- Four demo chambers installed

- GE21 mass production started in 2021
- One demo chamber in CMS from Nov 2021

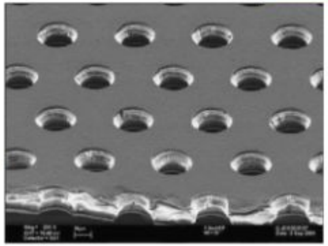


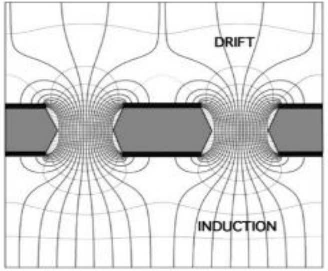


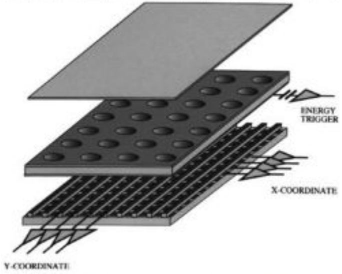
Gas Electron Multiplier

- Introduced by Fabio Sauli in 1996-1997.
- GEM electrode: thin polymer foil, metal coated on both sides and pierced with a high density of holes, 50-100 mm^{-2}.
- Foils are placed between a drift and a charge collection electrode, applying appropriate potentials, field lines and equipotentials are developed near the holes.
- Large difference of potential between the two sides of the foil creates high electric fields in the holes. Electrons released in the the upper region drift towards the holes and acquire energy to ionize the molecules of the gas.
- Sizeable fraction of electrons are transfered into the lower section where they can be collected by an electrode, or injected into a second multiplying region

- Known to operate reliably at high rate (~ Mhz / cm2) and to have excellent longevity.
- Flux in the CMS Endcaps not expected to exceed 50 kHz /cm2

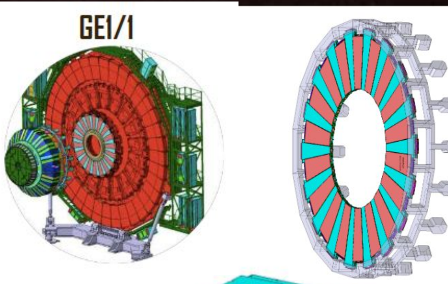


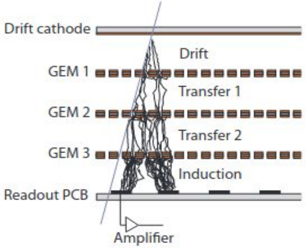


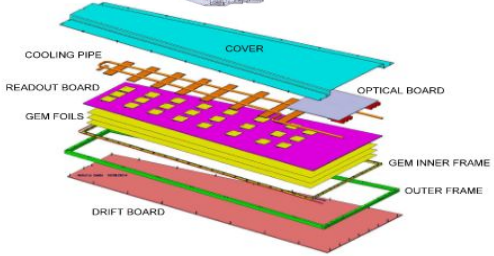


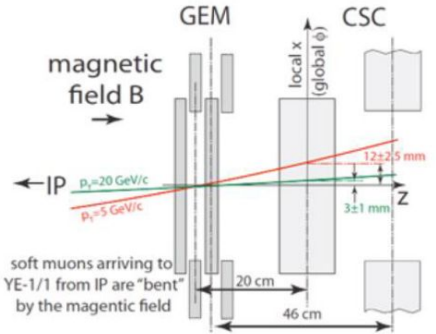
The CMS GE1/1 station

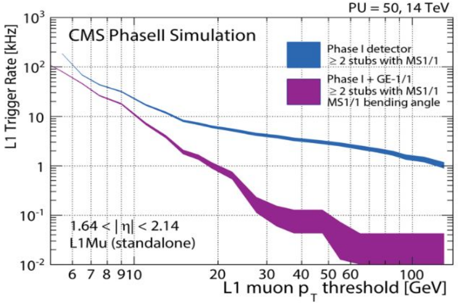
- Triple-GEM detectors (70:30 Ar/CO_2)
- Trapezoidal chambers up to 1.2 m long
- 144 chambers associated in pairs (super chambers) arranged in two disks.
- Installation of all 72 super chambers completed in Sept. 2020.
- Participating in the Run 3 data taking (first phase-2 detector installed and operational)

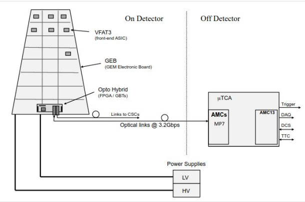










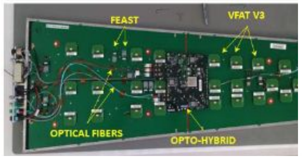


GEM1/1 electronics

Optohybrid
- Communicate between the VFAT and the backend electronics via GigaBits transceivers(GBTs)
- Send slow control commands to the frontend electronics
- Transfers tracking and trigger data to backend and CSCs

VFAT frontend chip
- 24 VFAT3/chamber
- 128 channels/chip
- Binary readout
- Tracking + Trigger data

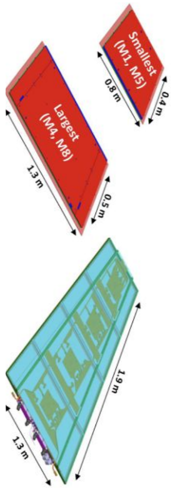
Feast
- DC converter
- LV, VFAT3 &OH

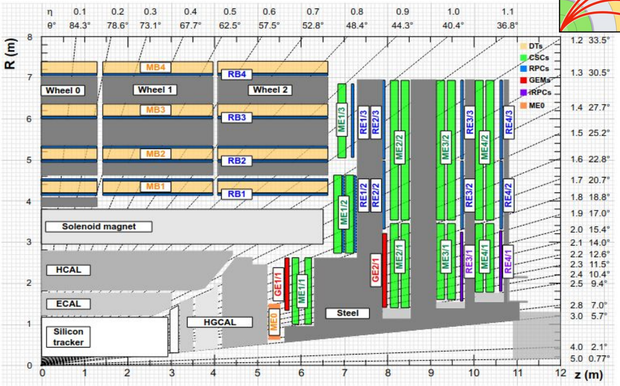


- Before LS2, forward trigger for $|\eta| > 1.6$ relied entirely on the CSCs (ME1/1).
- GEM detector in front of CSC can measure muon bending angle in B field and add redundancy.
- Maintain 15 GeV online threshold, keep < 5 kHz rate, high efficiency.

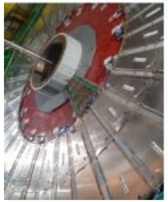
The GE2/1 project

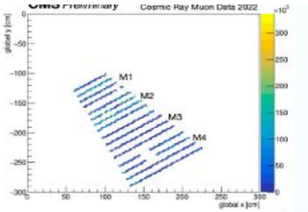
- Triple-GEM technology (same as GE1/1).
- 36 GE2/1 chambers per end cap, organized in two layers of 18 chambers.
- Each chamber consists of 4 GE2/1 modules
- Two different types of chambers to avoid the overlapping of dead ares
  - 8 different modules called M1 to M8
- Installation planned in YETS 2023/24 & 2024/25

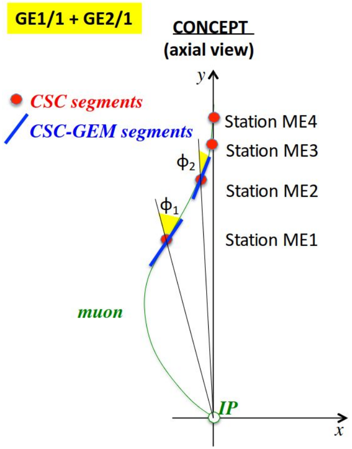


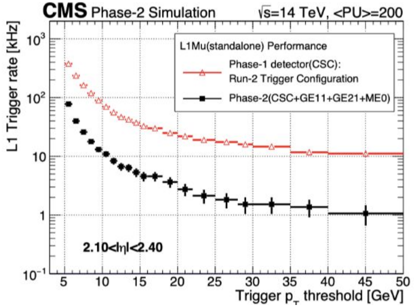


- GE2/1 mass production started in 2021
- 1 Demo chamber was installed in CMS in Nov 2021.
- Using final electronics.





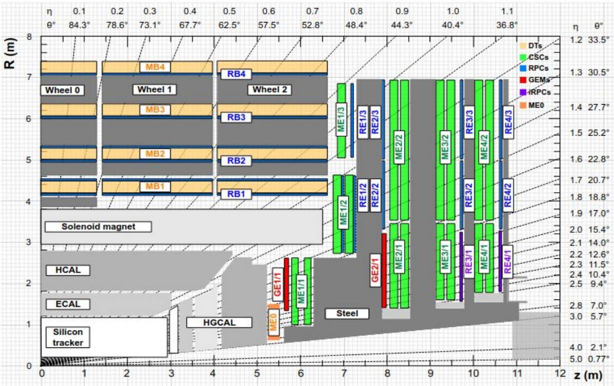


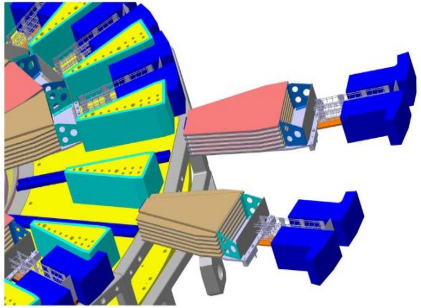


- GEM + CSC in ME1 and ME2 station give accurate measurement of muon "local" direction sensitive to muon $p_{T.}$
- p_T measurement improves, hence the standalone L1-trigger rate drops

The ME0 project

- ME0 detector is a layered stack of 6 triple-GEM detectors
- 18 stacks per endcap (36 total stacks 216 modules)
- Module segmented into 8 readout partitions in η and 3 in ϕ (24 total RO sectors)
- ME0 increases coverage $2.0 < |\eta| < 2.8$
- ME0 will provide muon trigger signal in the very forward region
- ME0 hits will be used in the offline muon reconstruction

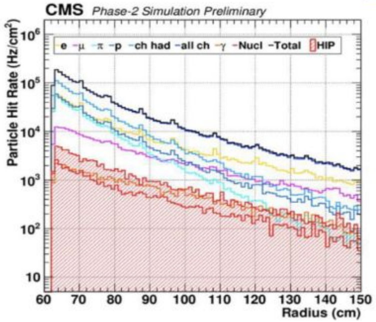


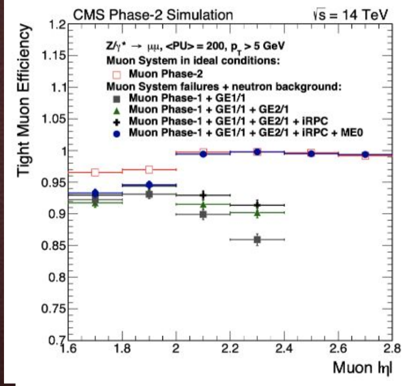


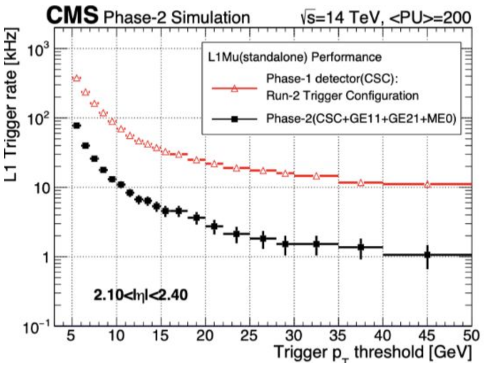
Expected hit rate [2, 144] kHz/cm2

Requirements:

- 97% efficiency
- Rate capability > 150 kHz/cm2
- Radiation hardness
- Angular resolution < 500 urad
- Sufficiently low discharge rate

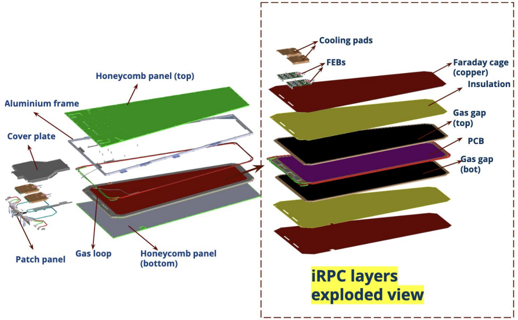


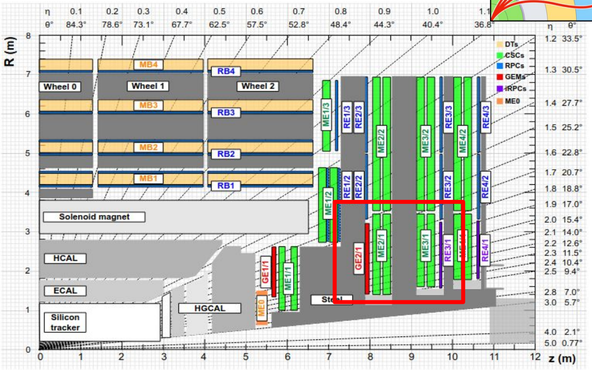


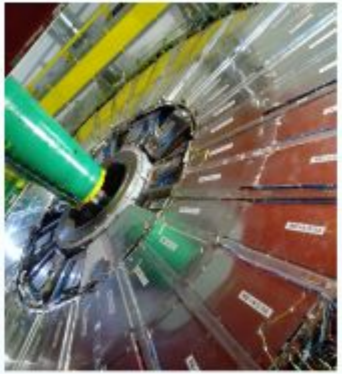


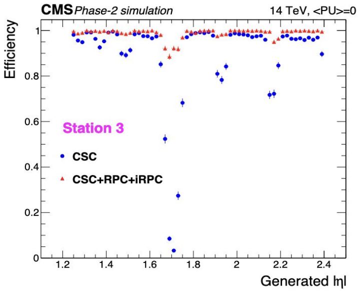
iRPC Upgrade project

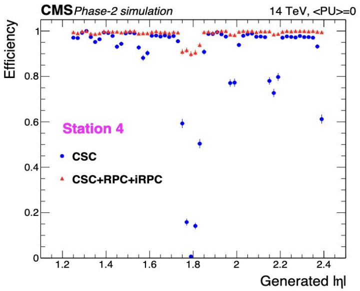
- Extend RPC coverage up to $|\eta| = 2.4$
- Add redundancy in ME3 and ME4
- 72 iRPC chambers in total
- 20 degrees in ϕ
- Chamber: ~ 1.6 x 1.2 m2 trapezoidal shape
- Time resolution 200 ps (RPC ~ 1ns)











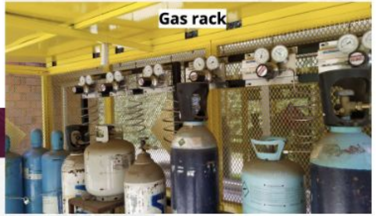
Production sites

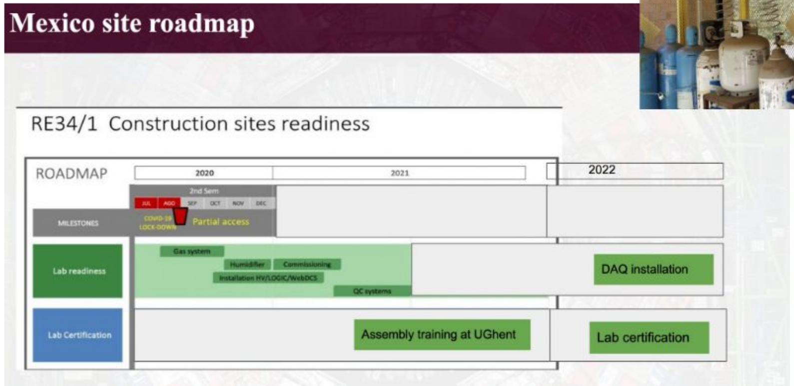
Ghent
- First assembly and initial QC of prototypes in 2020.
- Produced 8 iRPC demonstrator chambers on July 2021.

Mexico
- Near ready

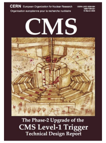
iRPC assembly site at Mexico City (IBERO)

- Mexico's assembly site near ready to assemble and test chambers
- Gas system, HV modules, weather station for QCs are operational.
- Ongoing activities related to the laboratory logistics.
- Team members will be trained at Gent during chamber assembly.
- Team has gained experience in chamber related activities at CERN
- **Final validation of the lab planned for next year.**



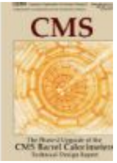


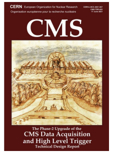
The CMS HL-LHC upgrade documentation



Level-1 trigger
https://cds.cern.ch/record/2714892

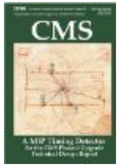
Barrel Calorimeters
https://cds.cern.ch/record/2283187

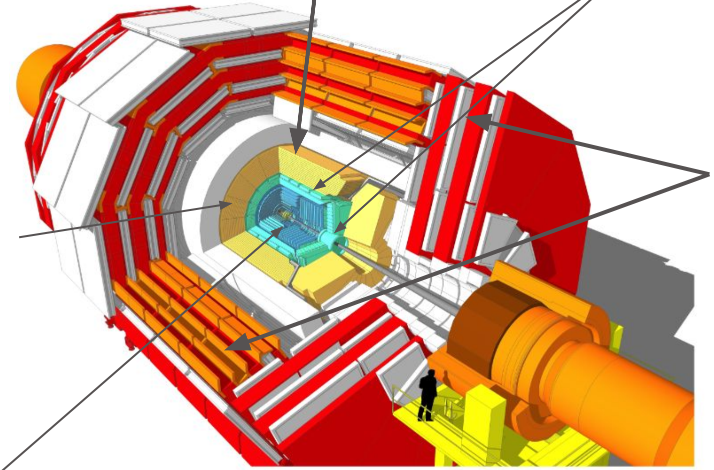


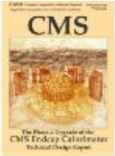


DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072

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

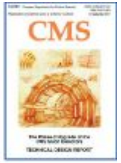


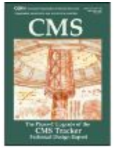




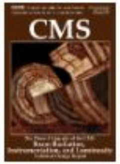
High Granularity Calorimeter Endcap
https://cds.cern.ch/record/2293646

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





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



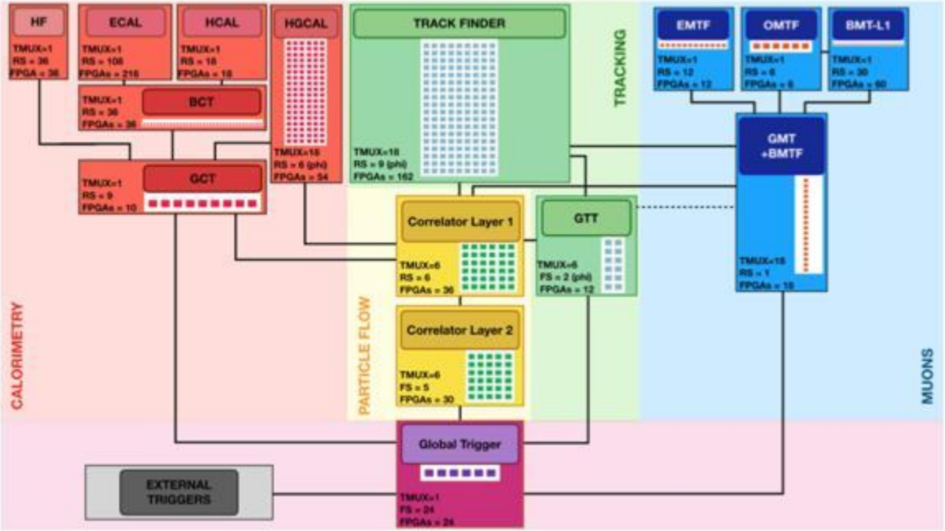
Beam Radiation Instr. and Luminosity
https://cds.cern.ch/record/2759074

Summary

- HL-LHC will deliver up to 4000 fb^{-1}
- CMS will undergone a substantial detector upgrade to cope with the high occupancy and large radiation conditions of the HL-LHC.
- Installed first phase-2 muon detector: GEM GE1/1
- All projects progressing on the transition from prototyping to (pre-) production.

BACKUP

Trigger system design



Provides robust independent triggers for **calorimeter**, **muon** and **tracking** systems separately, and a ***Particle Flow*** trigger, which combines detector information, all feeding into a **global trigger**

Detector inputs

Detector	Object	N bits/object	N objects	N bits/BX	Required BW (Gb/s)
TRK	Track	96	1665	159 840	6 394
EB	Crystal	16	61 200	979 200	39 168
EB	Clusters	40	50	2 000	80
HB	Tower	16	2 304	36 864	1 475
HF	Tower	10	1 440	13 824	553
HGCAL	Cluster	250	416	104 000	4 160
HGCAL	Tower	16	2 600	41 600	1 664
MB DT+RPC (SP)	Stub	64	1 720	110 080	4 400
ME CSC	Stub	32	1 080	34 560	1 382
ME RPC	Cluster	16	2 304	36 864	1 475
ME iRPC	Cluster	24	288	6 912	276
ME GEM	Cluster	14	2 304	32 256	1 290
ME0 GEM	Stub	24	288	6 912	276
Total	-	-	-	-	62 593

System specification and constituents

Increase bandwidth 100 kHz → 750 kHz
Increase latency 3.8 μs → 12.5 μs (9.5 μs target contingency)
Include high-granularity detector and tracker information
Dedicated **scouting system** @ 40 MHz → streaming data

Optical link speeds 16/25 Gb/s as appropriate for application

Use of largest FPGA parts where processing bound e.g. Xilinx Virtex Ultrascale+ (VU9P/VU13P) and smaller parts where processing is less critical e.g. Xilinx Kintex Ultrascale

Overall over 200 FPGAs

Processing partitioned regionally and in time as appropriate

X2O

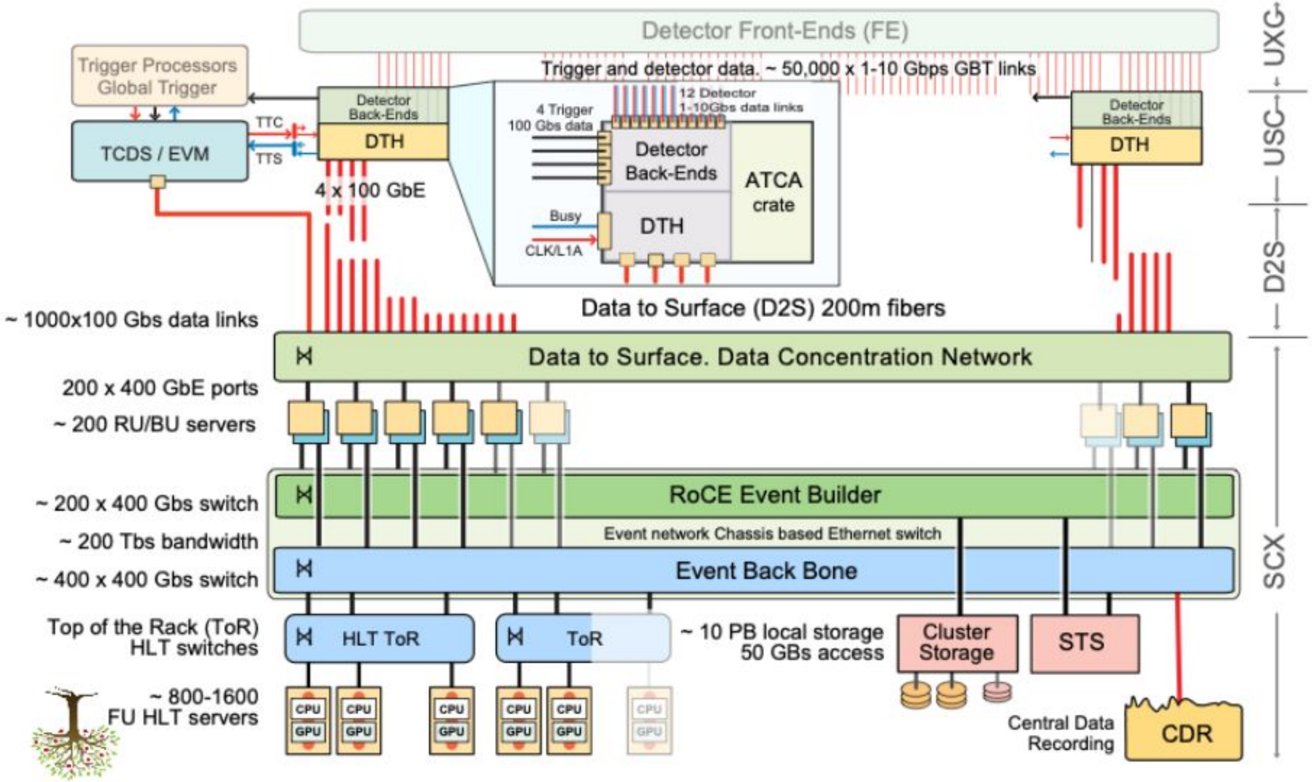
BMT-L1

NEW!

APx-F

Serenity

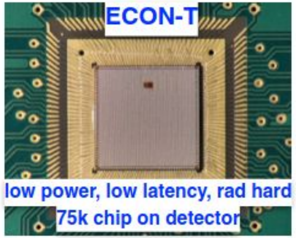
Conceptual DAQ Design (with HLT)

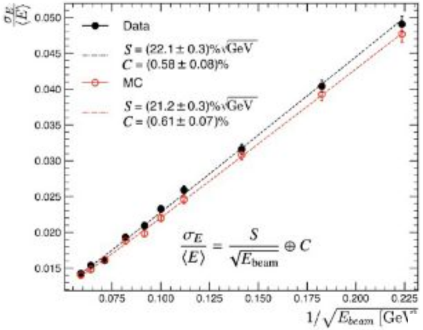


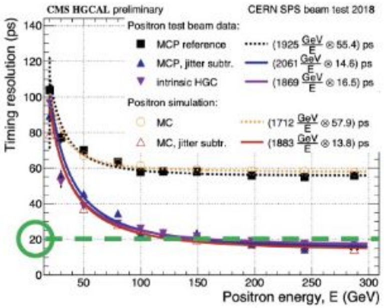
High Granularity endcap Calorimeter (HGCal)

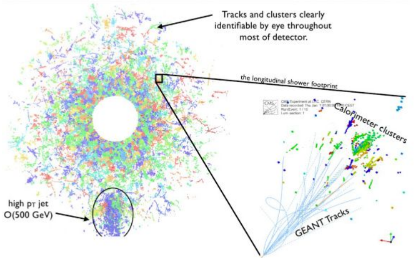
Electronics and data processing

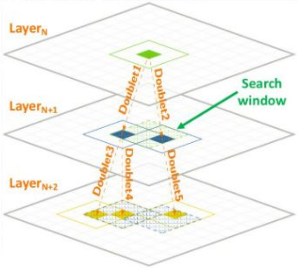
- Signal read out by HGCROC front-end chip
  - Large range from MIPs to high-energy photons
  - Time of Arrival resolution of ~50 ps
  - High radiation resistance (> 1.5 MGy and 10^{16} n_{eq}/cm^2)
- Concentrator chip (ECON)
  - Data compression with autoencoder network:
  - encoding on-detector; decoding off-detector
  - First NN for on-detector data compression
- ECON-D (data) and ECON-T (trigger) concentrator chips.
  - Trigger prototype tested extensively
- Novel reconstruction algorithms
  - including machine learning for PID
  - Tested with beam-test data











TICL:
The iterative clustering alg.