CMS detector upgrade

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on behalf of CMS collaboration

NUCLEUS-2021
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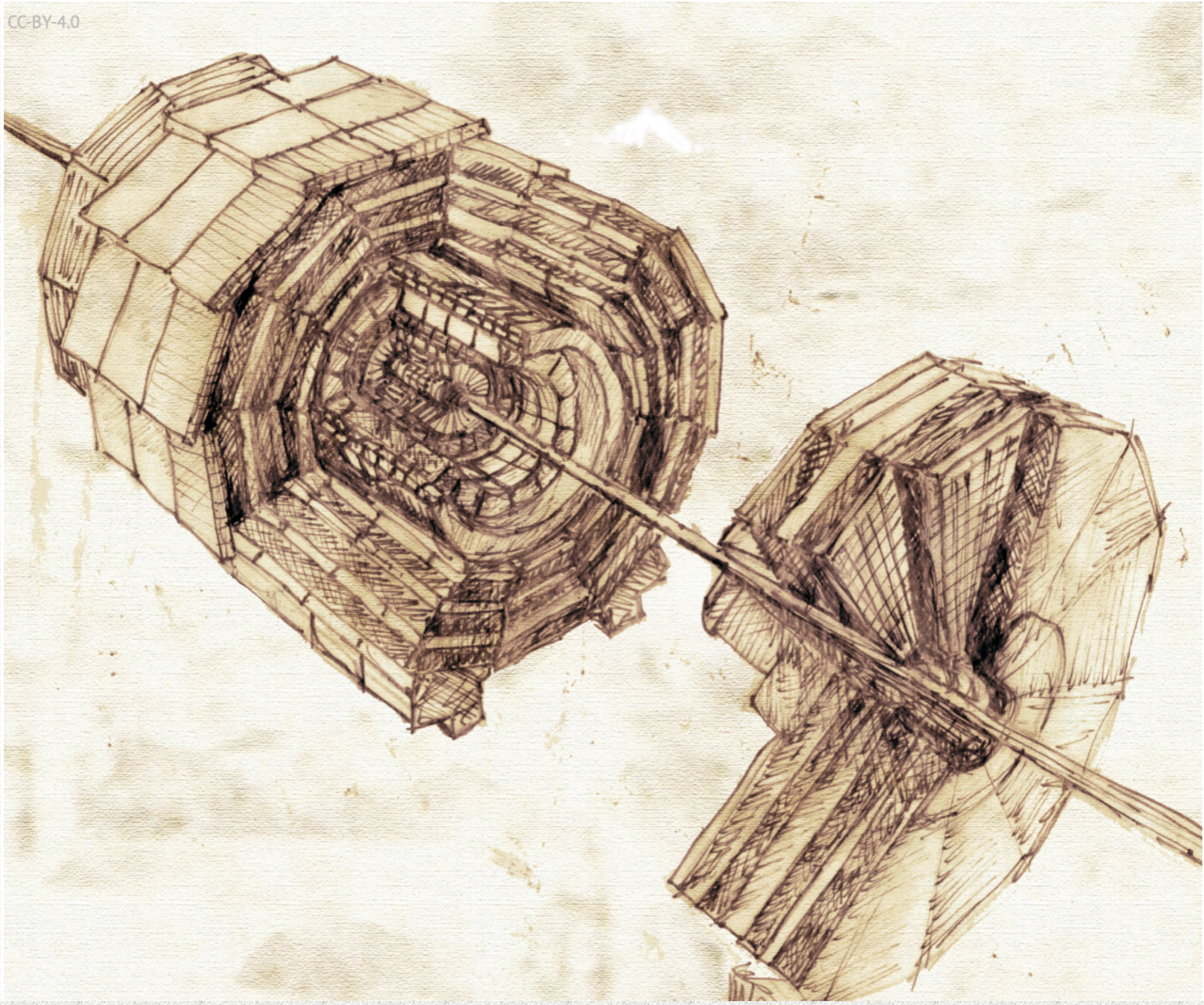
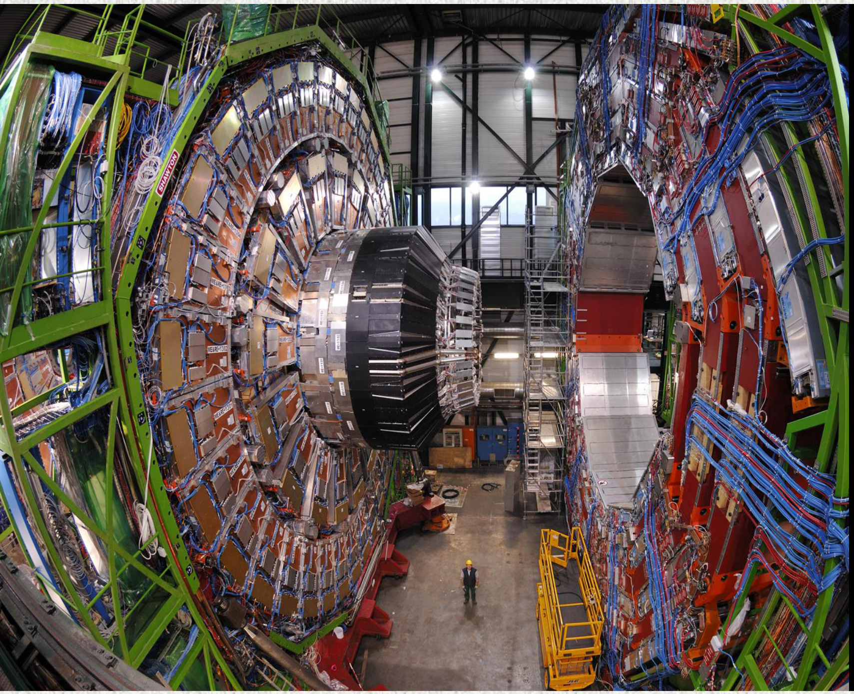


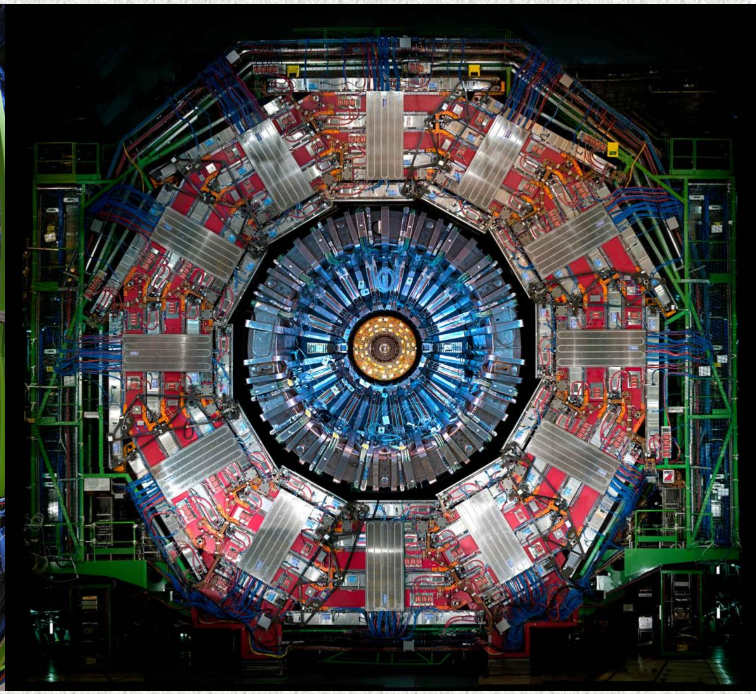
“Compact” detector

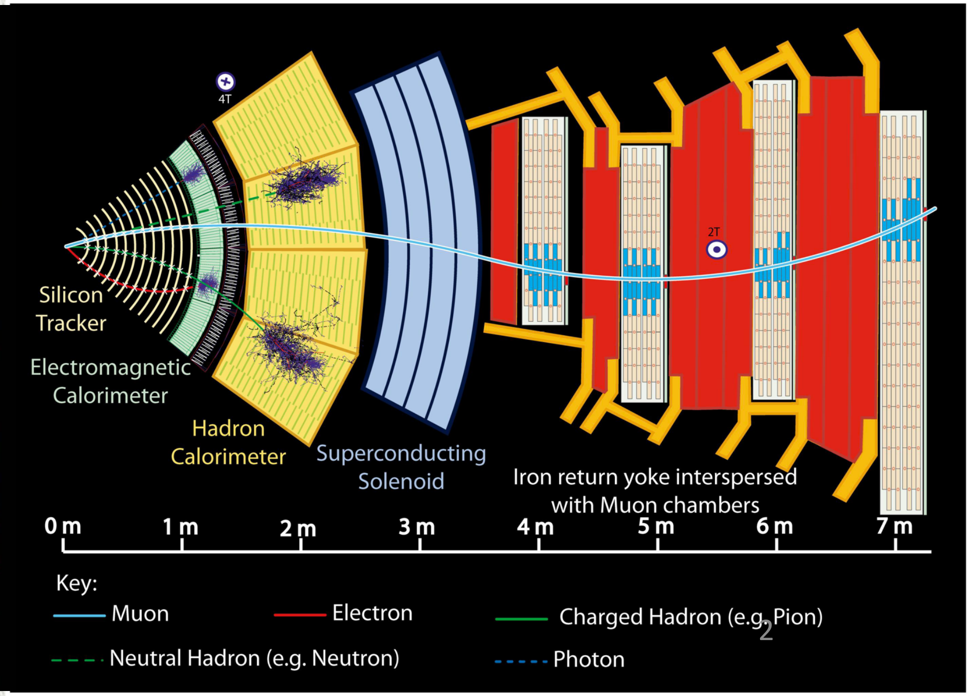
Some statistics:

- CMS is 21.6 meters long, 15 m in diameter, and weighs about 14,000 tonnes *(ATLAS is 46 m long, 25 m in diameter)*
- The solenoid generates a magnetic field of 4 tesla, about 100 000 times that of the Earth
- Consists of 4 layers of the detectors (Tracker, ECAL, HCAL, Muons chambers)
- It really is quite compact for all the detector material it contains and designed to detect particles very accurately

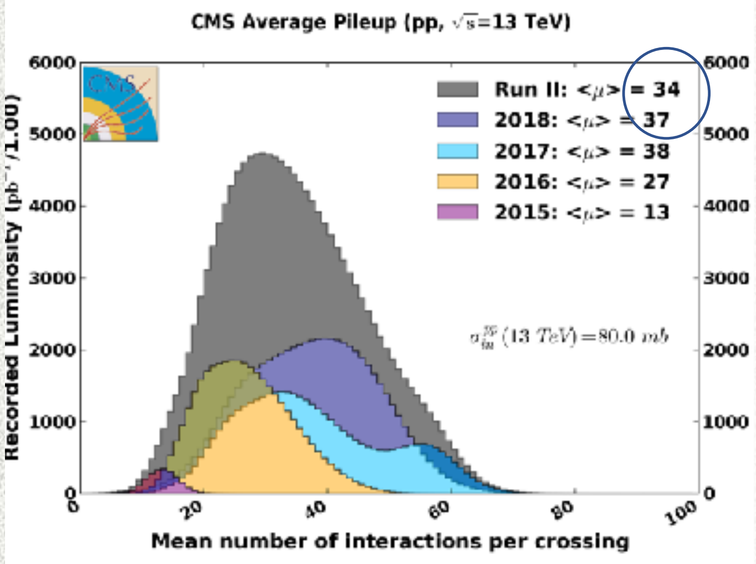
However because of its compactness, CMS cannot be repaired/upgraded on-the-fly. Access to all detectors and to all on-detector electronics is possible only when CMS wheels and discs are opened

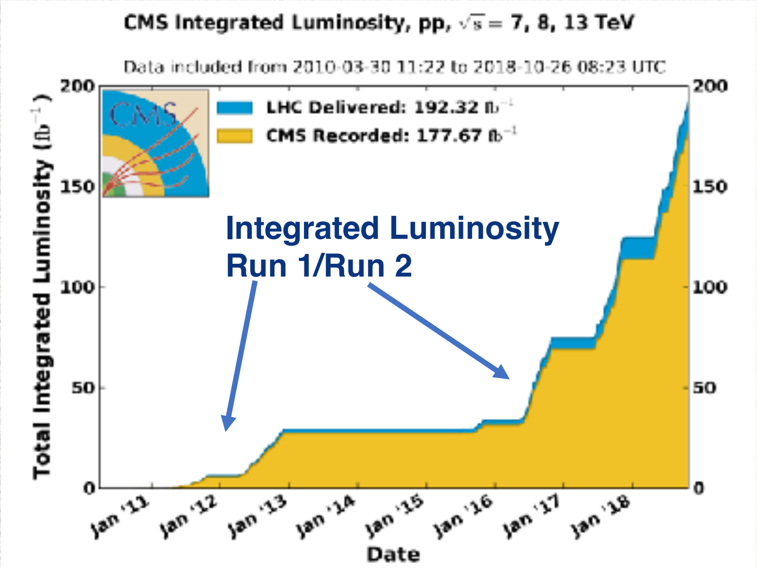






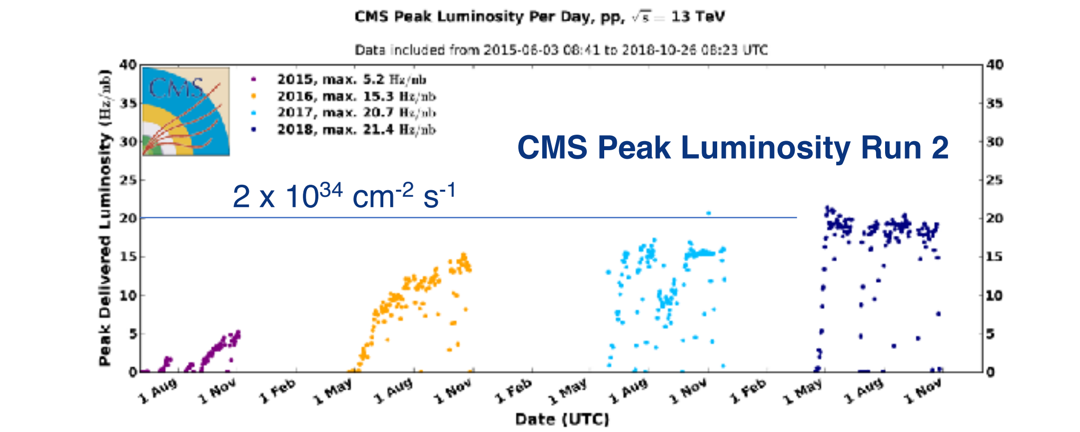
CMS at the LHC in Run 1 and Run 2





Despite of the limited access to the detector electronics, in Run 1 and Run 2 CMS showed solid running, fortunately without major issues and achieved incredible values of PU, peak luminosity and collected more than 160 fb^{-1} physics data.

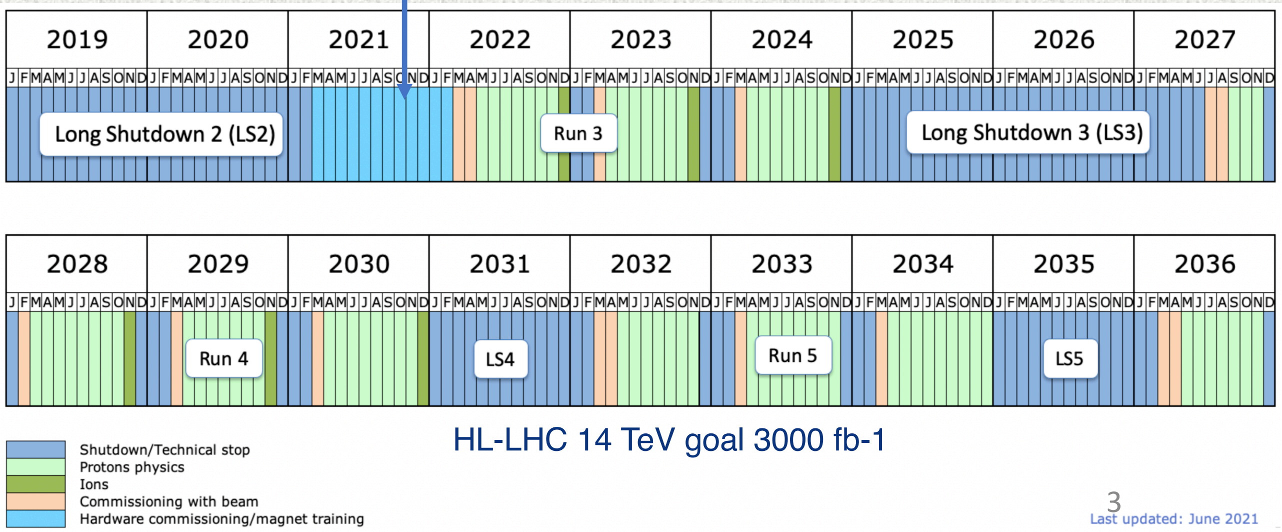
LHC provides shutdown windows (not very wide for year ends) when setups can apply their upgrade program



We are here

LHC Run 3 ~350 fb-1 14 TeV

LHC Run 2 160 fb-1 13 TeV



HL-LHC 14 TeV goal 3000 fb-1

CMS Phase-1 upgrades in Run 2

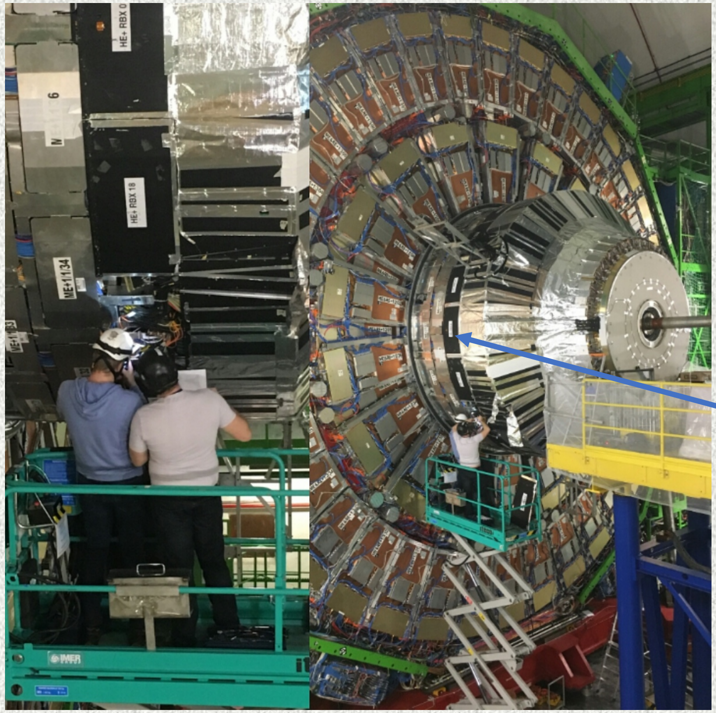
The CMS detector Phase-1 upgrades started during the first Long Shutdown and continued during the Run 2 year end technical stops (YETS and EYETS).

new L1 Trigger system (2016)
L1 hardware ~100kHz
HLT software ~1kHz

Muon system
- GEM GE1/1 demonstrators (2017)
- DT trigger & readout (2016-18)

Pixel (2017)
- sustain high rates
- 4 barrel layers + 3 disks
  innermost at 2.9 cm

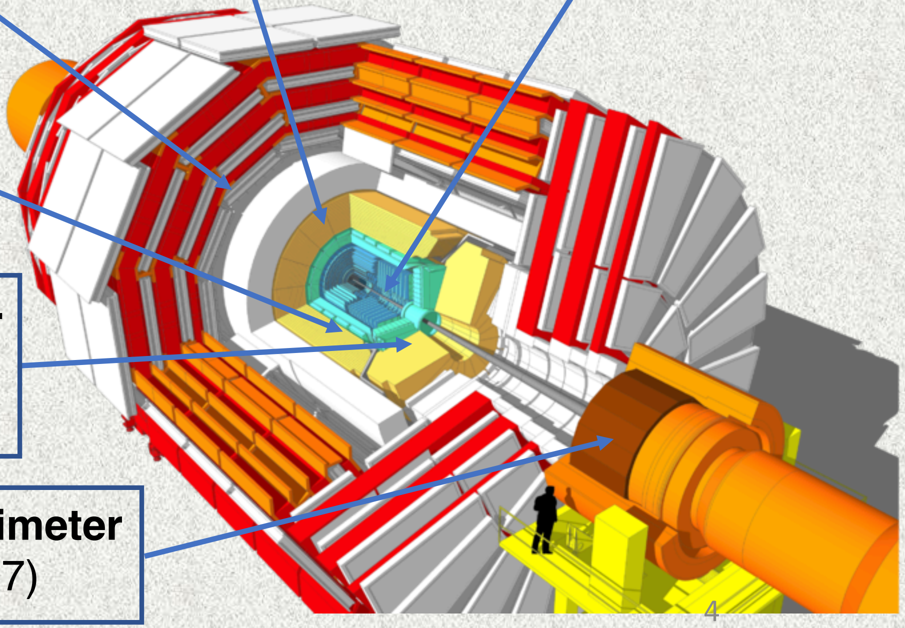
Tracker
running colder
$-15^{o}C$ (2015-2017)
-> $-20^{o}C$ (2018)
-> $-25^{o}C$ (probably) Run 3



Barrel ECAL calorimeter
- new DAQ links (2018)

Phase-1 Hadron Endcap calorimeter
- HPDs -> SiPM readout (2017-2018)
  - better granularity

Phase-1 Hadron Forward calorimeter
- New Front-End electronics (2017)



CMS Phase-1 upgrades in LS2

CMS is performing maintenance of the detector, completing the installation of the Phase-1 upgrades and installing infrastructure for the Phase-2 upgrades for the HL-LHC

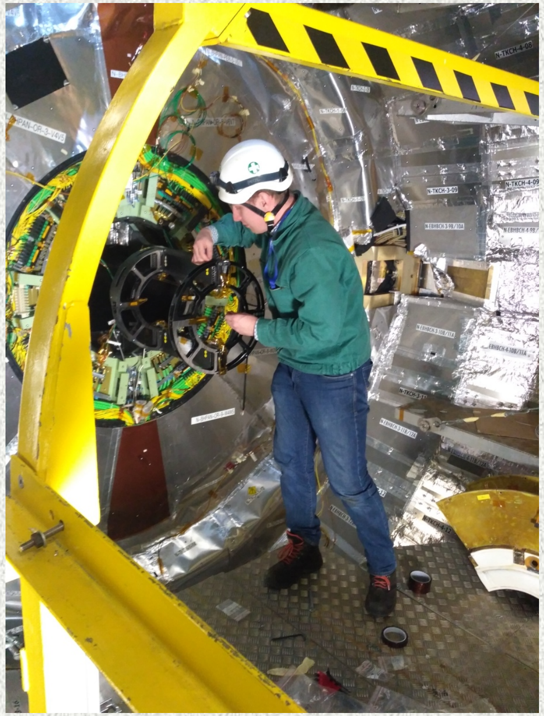
Tracker
- kept cold to avoid reverse annealing, but warmed during beam pipe bake-out

Pixel
- new barrel layer 1 (2021)
- replace all DCDC converters (2019)

new beam pipe (Phase-2) (2021)

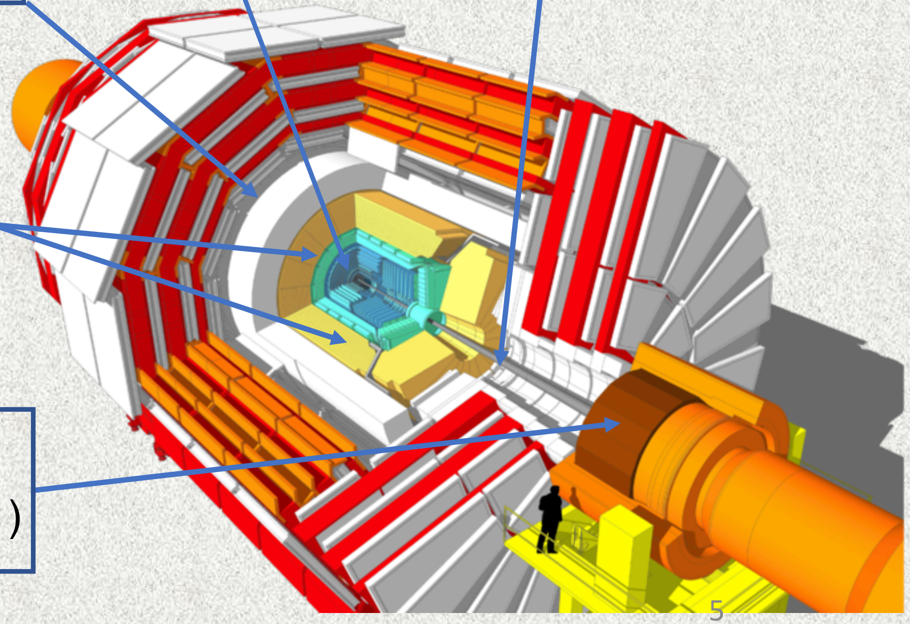
Triggers
- exploring new techniques such as machine learning at L1 or using GPUs for tracking at HLT

Muon system (Phase-2)
- GEM GE1/1 chambers installed
- upgrade CSC FE electronics
- DT slice test
- shielding against neutron background

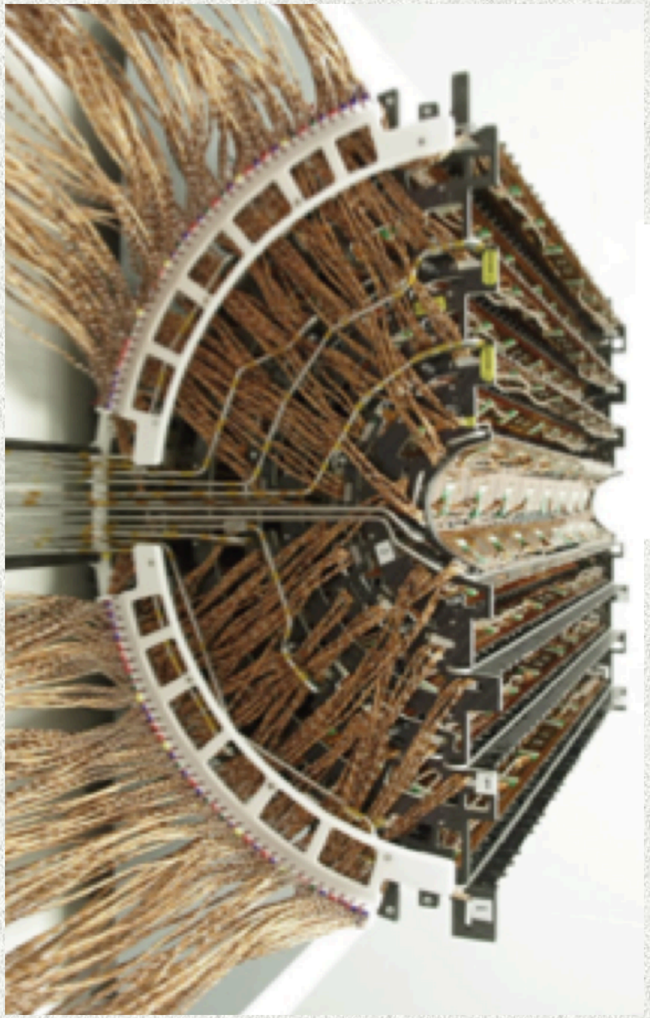


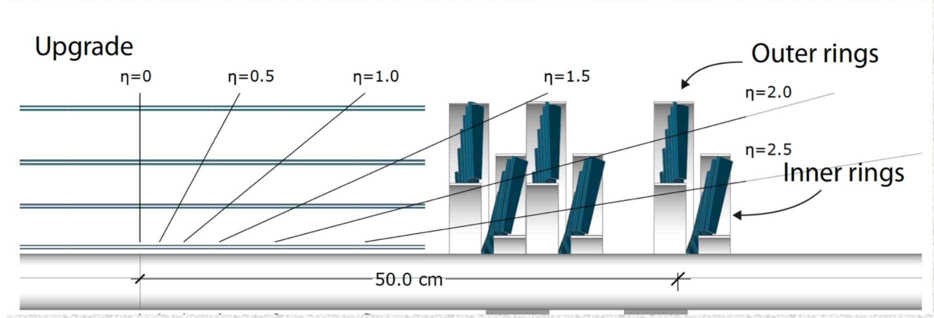
Phase-1 Hadron Calorimeter
- Move all BE electronics to uTCA
- Barrel HPD -> SiPM readout (2019)
  - better granularity
- Endcap ngCCM replacement (2021)

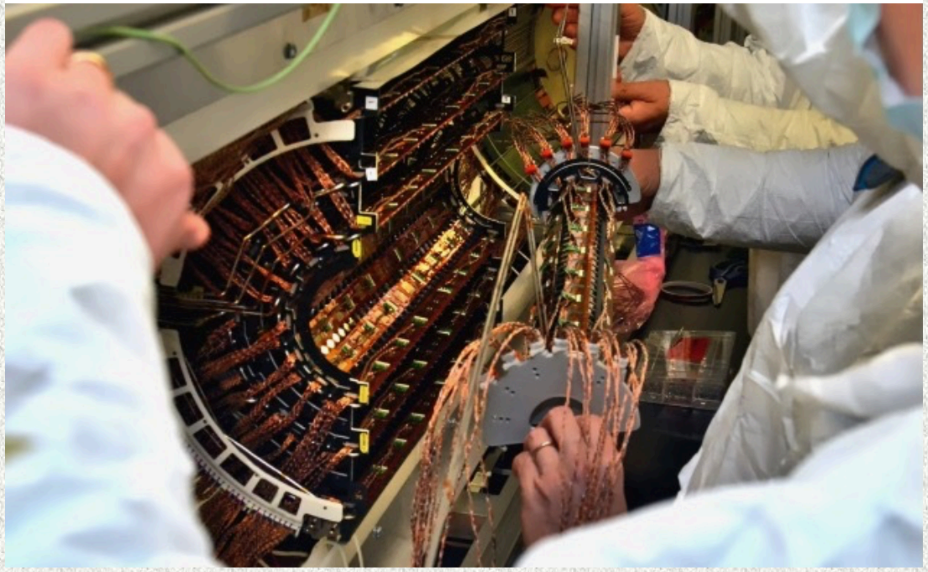
Phase-1 Hadron Forward calorimeter
- Switch from SM to MM control links (2021)



Pixel



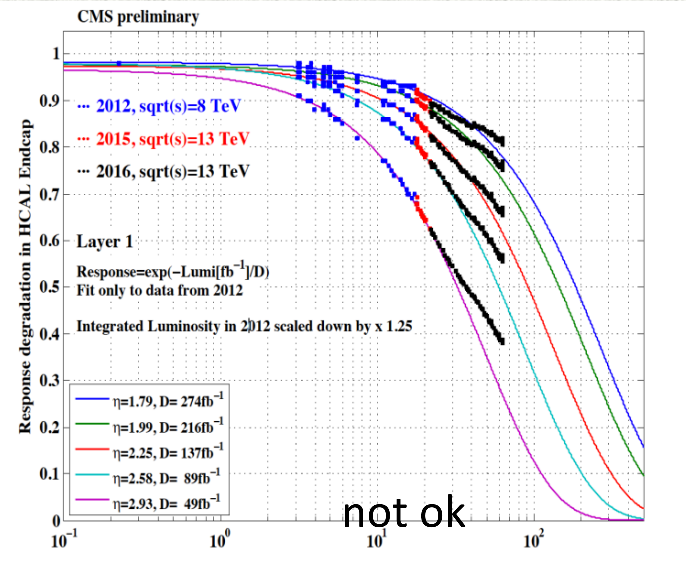




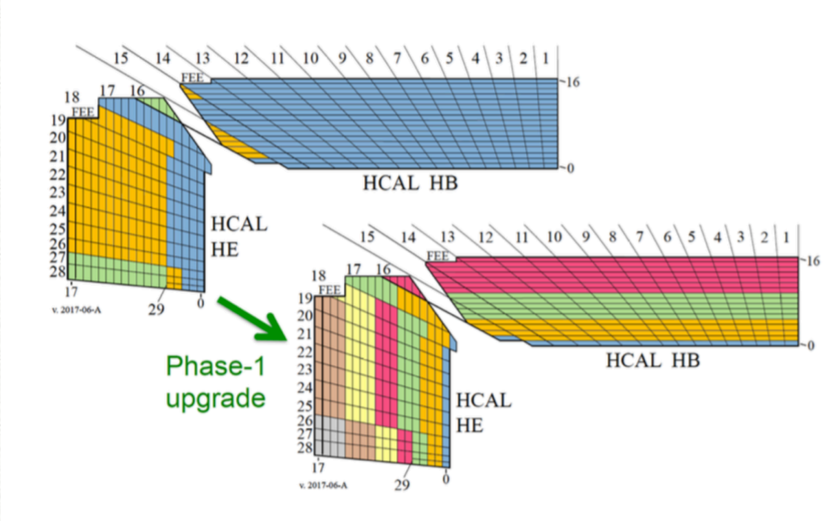
- **extracted in January 2019**
  - readout issues during 2017 had been mitigated, but replace now all DCDC converters
- **improved version of the read-out chips will allow better timing in Layer 1 (closer to beam pipe)**
- **ensure detector longevity during Run 3, despite harder radiation:**
  - replace Barrel Layer 1 (early 2020)
  - ensure the detector can operate with a larger HV bias 600-800 V
- **installed in summer 2021 instead of fall 2020 (COVID-19 changes plans)**

HCAL

Hadron Calorimeter endcap response vs. Luminosity (2010-2017)



HPDs->SiPMs => mitigate noise + increase radiation tolerance + more readout channels (~x3)



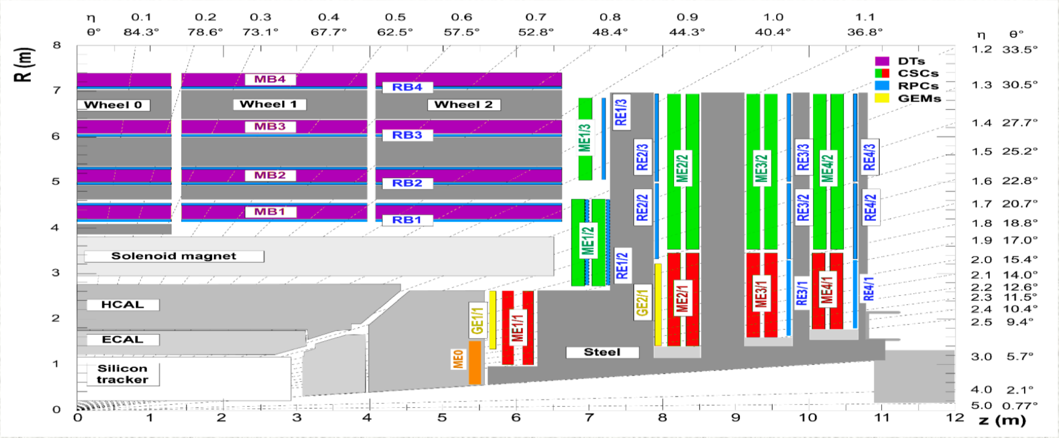
In LS2 HCAL has been focused on replacement of HPDs (Hybrid Photo Detectors) with SiPMs (Silicon Photomultipliers) along with all FE electronics components, it's allow:

- better noise levels, light yield and radiation tolerance
- provide longitudinal segmentation along hadronic showers
- maintain/ improve physics performance for jets and MET

The last Phase-1 upgrade – now focusing on Phase-2 (HE will be cut out)

- HCAL Endcap upgrade completed in 2018
  - replacement of Endcap ngCCMs (2021)
- HCAL Barrel upgrade electronics installed (2019)
- Co60 calibration campaign (light yield measurement in each HCAL cell) as the last step of the new electronics commissioning before the data taking

Muon systems CSC, RPC, DT



In Runs 1-2, the CMS muon system included:

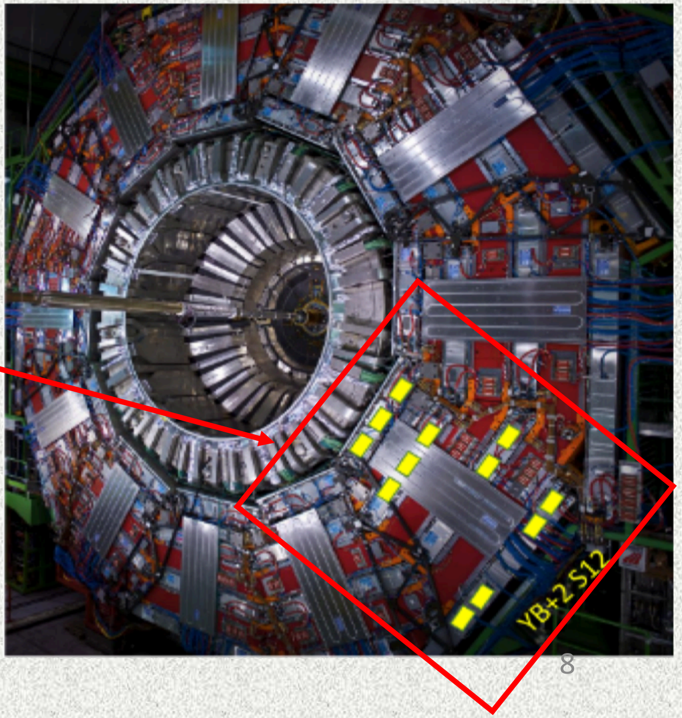
- Drift Tubes: for tracking and triggering in region $|\eta| < 1.2$
- Resistive Plate Chambers: for triggering in region $|\eta| < 1.9$
- Cathode Strip Chambers: for tracking and triggering in endcap $0.9 < |\eta| < 2.4$

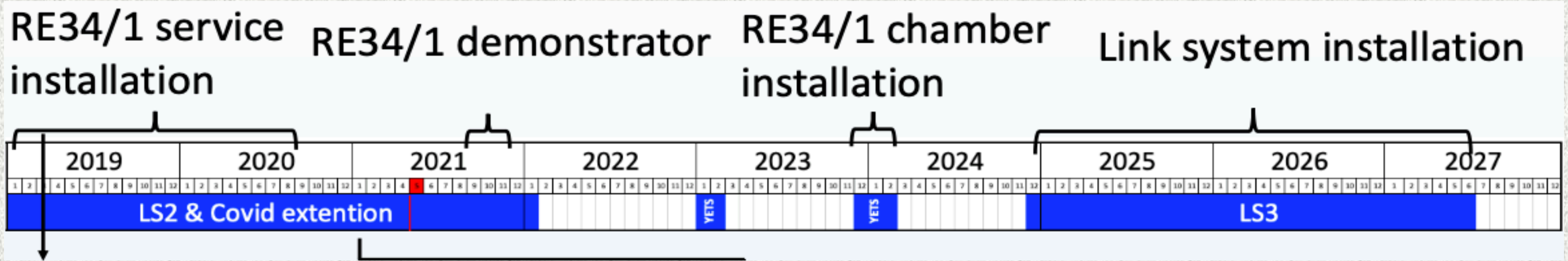
Maintenance work:

- RPC Barrel gas leak repair
- shielding to reduce neutron background on top part of detector

Phase-2 upgrades:

- CSC front-end electronics upgrade: to sustain HL-LHC trigger rates stations have been extracted and brought to surface, then tested and reinstalled back (2021)
- DT slice test of new readout & trigger electronics in LS2 and during Run 3
- RE3/1, RE4/1 chambers preparation (services, demonstrators)

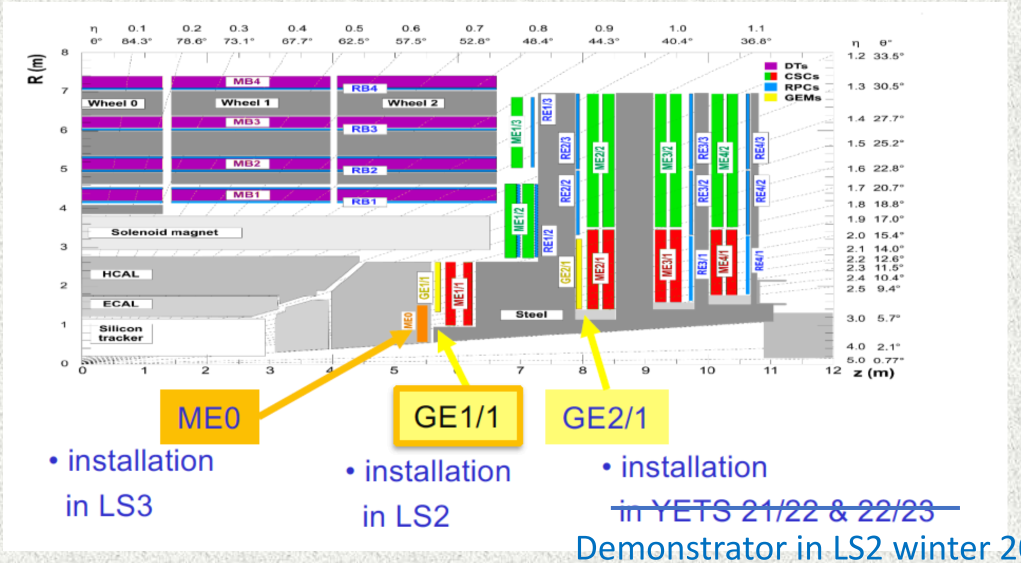




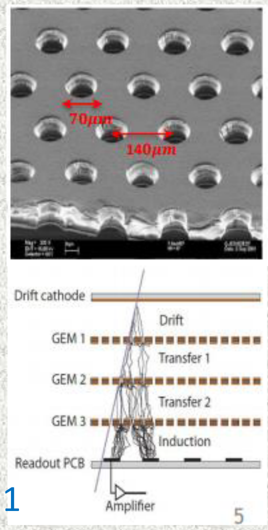
Muon system GEM

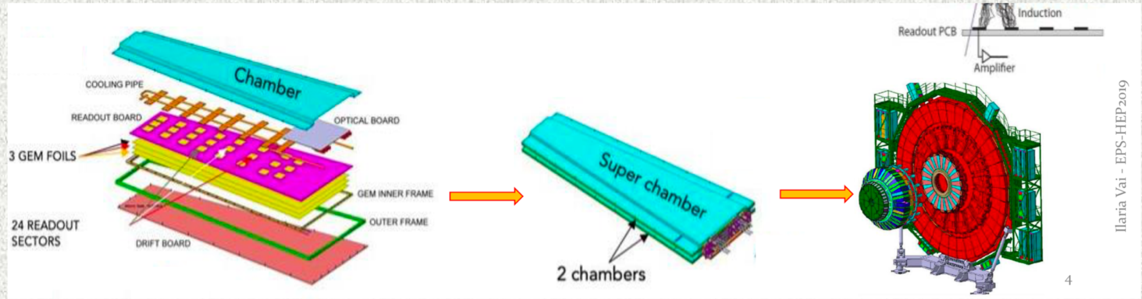
GEM GE1/1chambers: first full Phase-2 detector has been installed and commissioned few months ago!
- to mitigate increased background in the caver (up to 10^6 part/cm^2/s) and increased pileup (up to 140 - 200) at HL-LHC

Providing additional redundancy and measurement points, allowing a better muon track identification and also wider coverage in the very forward region



Demonstrator in LS2 winter 2021

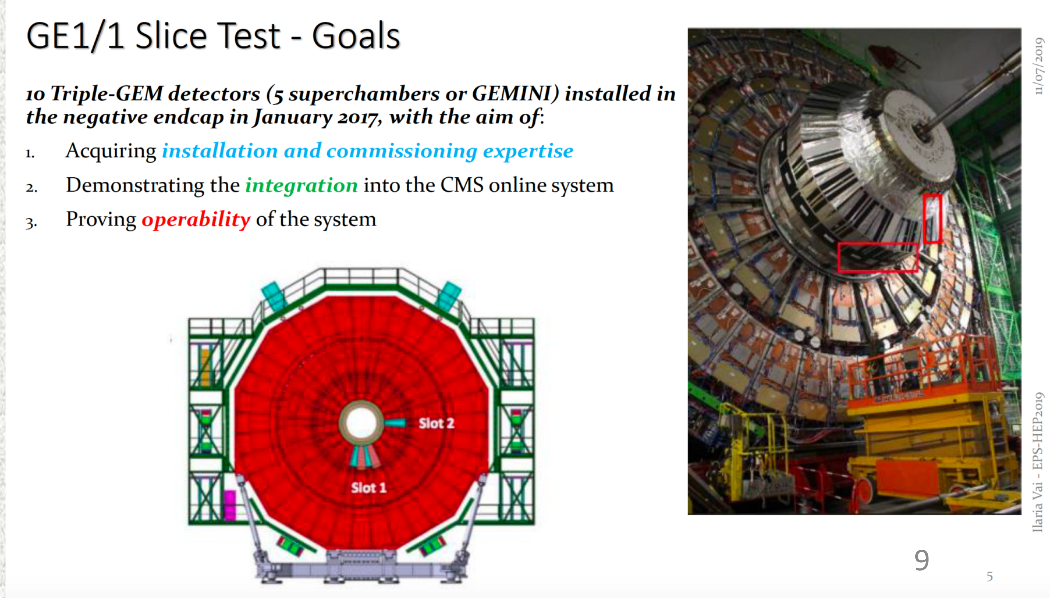




GEM = Gas Electron Multiplier
- 36 Super Chambers (SC) per endcap
- a SC = 2 triple-GEM detectors => 144 triple-GEM in total

GE-1/1 installed in autumn 2019
GE+1/1 in autumn 2020

Muons GEM demonstrator in Run 2 (2017)



Why the HL-LHC?

Strong case to go on exploring the TeV scale:

- Standard Model works very well but does not explain everything
  - low mass of Higgs boson and naturalness hypothesis advocate for the existence of new particles at the TeV scale
  - SM does not provide Dark Matter particle candidate

HL-LHC will deliver 3-4 ab^{-1}, allowing

- detailed studies of the Higgs boson: standard model or BSM?
- precise measurements of standard model, rare processes: indirect evidence for new physics?
- search for new particles and processes at the TeV scale (dark matter candidate)
- investigate properties of any new particle found at Run 3

Goal of HL-LHC was fixed in 2010

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of $L_{peak} = 5x10^{34}$ $cm^{-2}s^{-1}$ with levelling, allowing:

An integrated luminosity of 250 fb^{-1} per year, enabling the goal of $L_{int} = 3000$ fb^{-1} twelve years after the upgrade.

This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

LHC should not be the limit, would Physics require more…

L. Rossi - Chamonix 2018

Physics at the HL-LHC

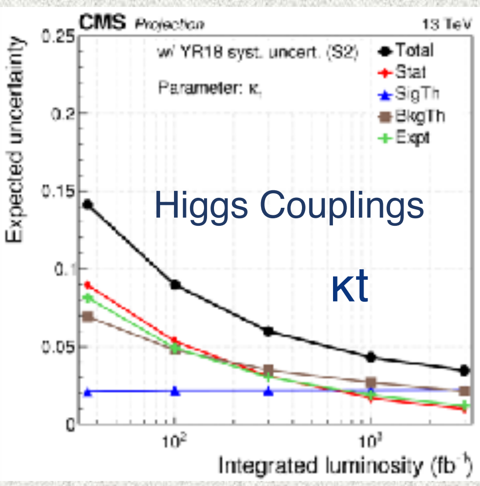
HL-LHC will enable unprecedented precision in measurements of standard model (SM) properties, and expand the discovery reach

"Use the Higgs boson as a new tool for discovery"
- 2-5% on Higgs Couplings (except for $Z\gamma$)
- First evidence of di-Higgs production (Higgs self-couplings) needs full HL-LHC stats ($3ab^{-1}$)

"Identify the new physics of dark matter"
- Access to small cross section SUSY processes
- e.g. Stau discovery with 5σ (not possible with 300 fb^{-1})

"Explore the unknown: new particles, interactions and physics principles"
- Study of rare SM processes and discovery of new heavy particles with small cross sections (Dark Matter, Vector-like-quark, Long-Lived particles…)
- MTD extends the reach for new particle searches

Higgs Couplings



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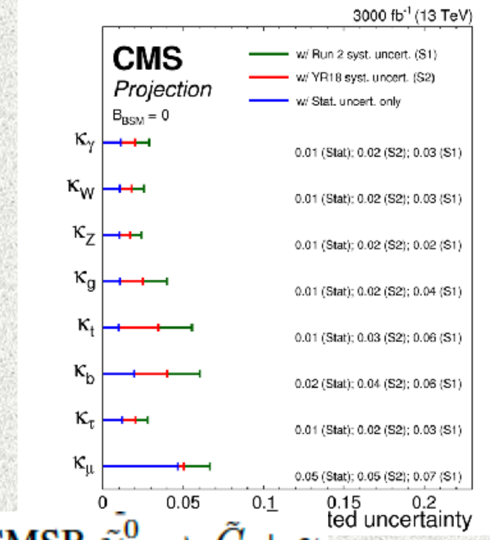
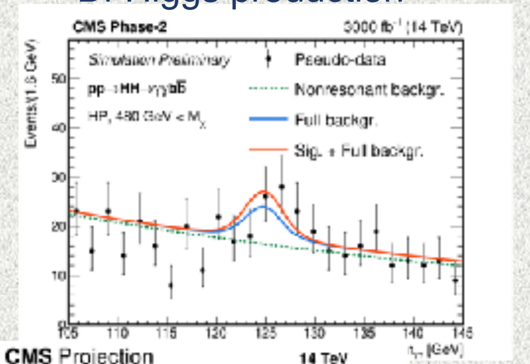
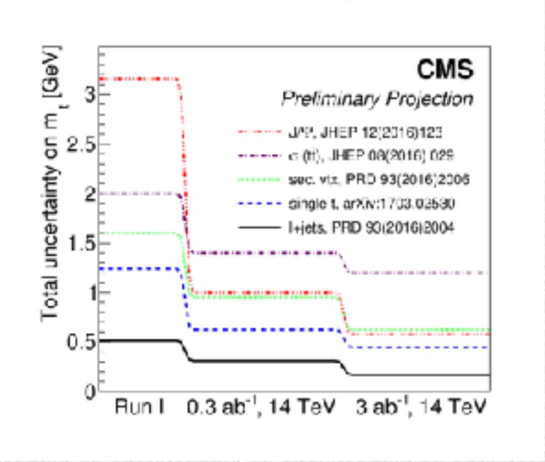
Higgs Couplings



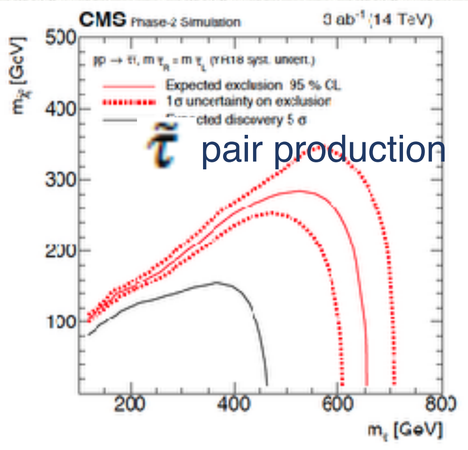
Di-Higgs production



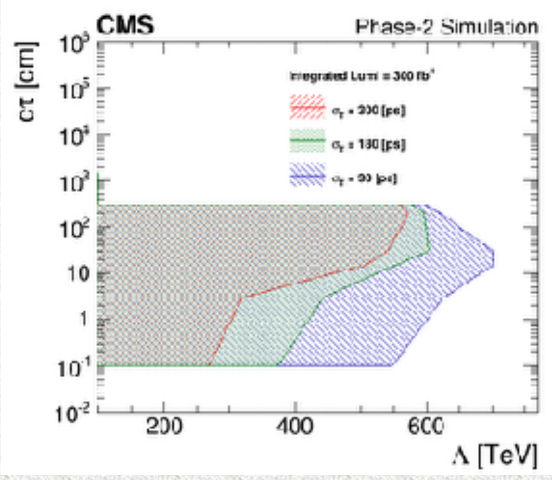
Top Quark mass uncertainty

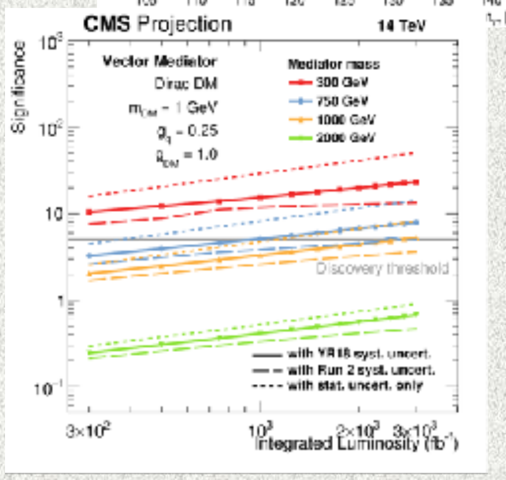


$\tilde{\tau}$ pair production



GMSB $\tilde{\chi}_1^0 \to \tilde{G} + \gamma$

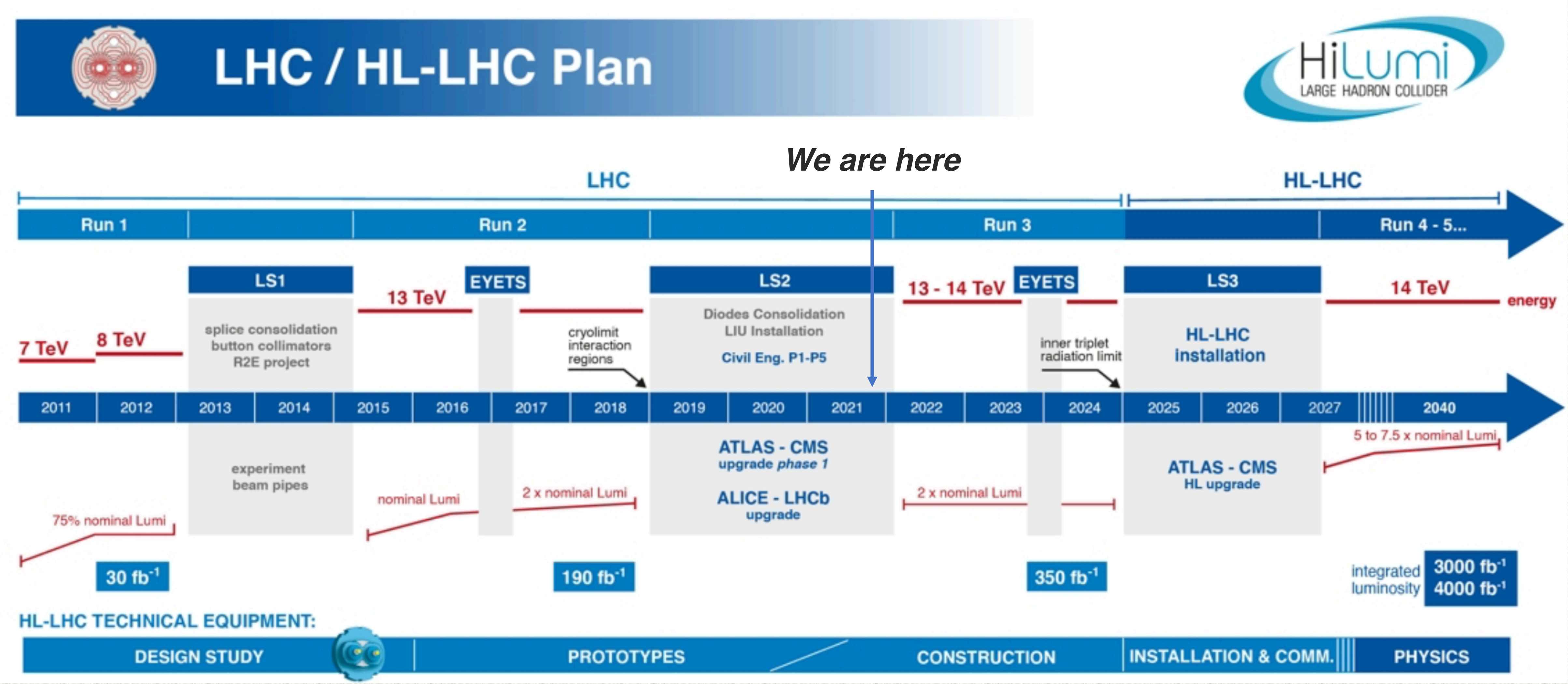




Dark Matter (mono-Z)

And again: LHC should not be the limit, would Physics require more…

LHC/HL-LHC plan

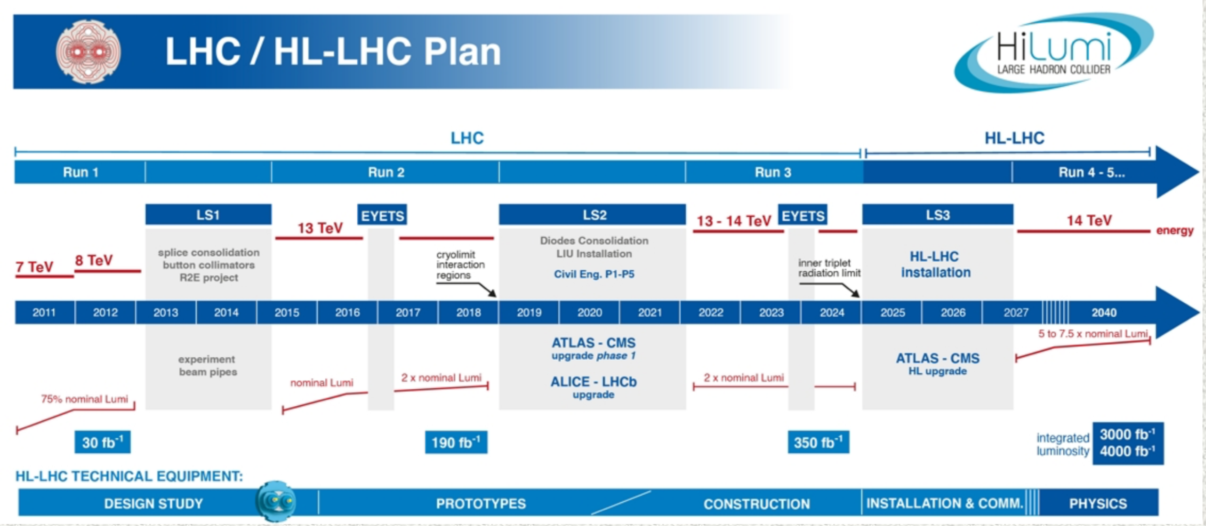


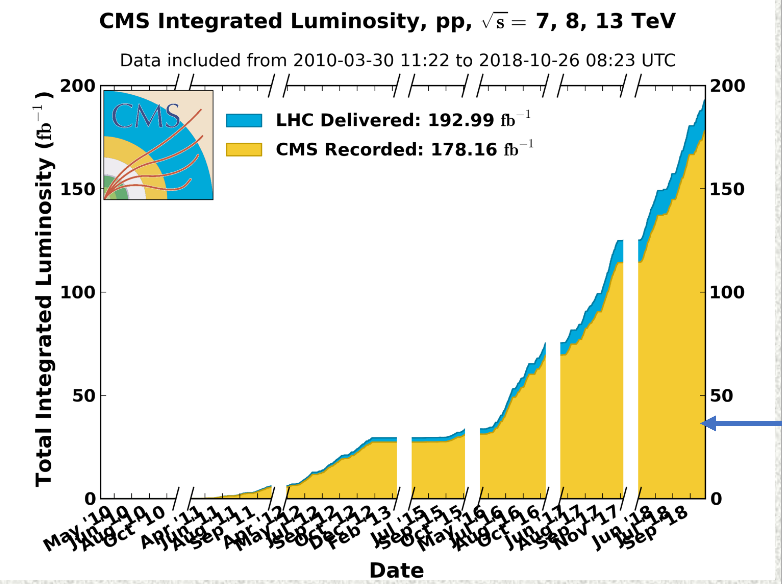
At CERN (not only at CMS), the detector upgrades for the HL-LHC are called the Phase-2 upgrades. The Phase-1 CMS upgrade is complete. The installation of the GE 2/1 and RE demonstrators are coming soon by end of 2021.

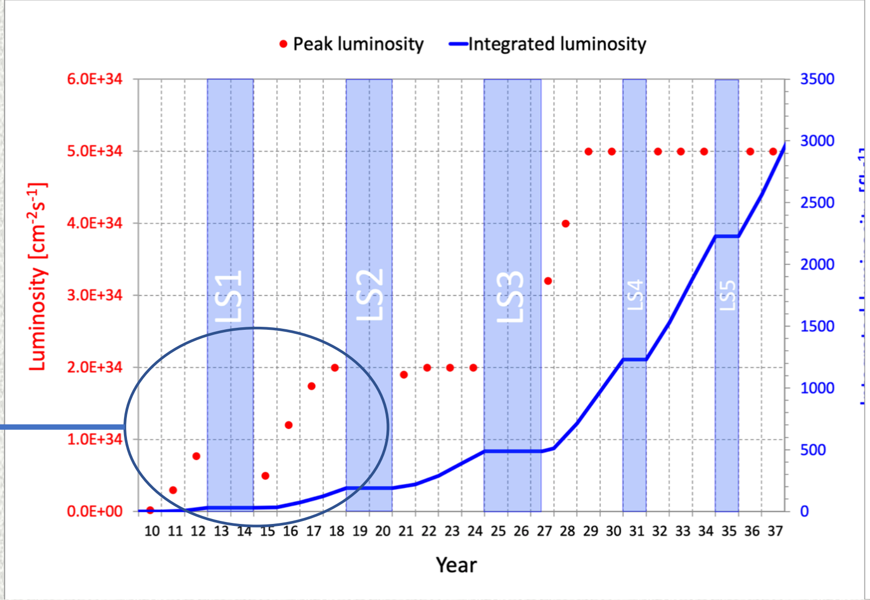
Nominal and Ultimate HL-LHC forecast

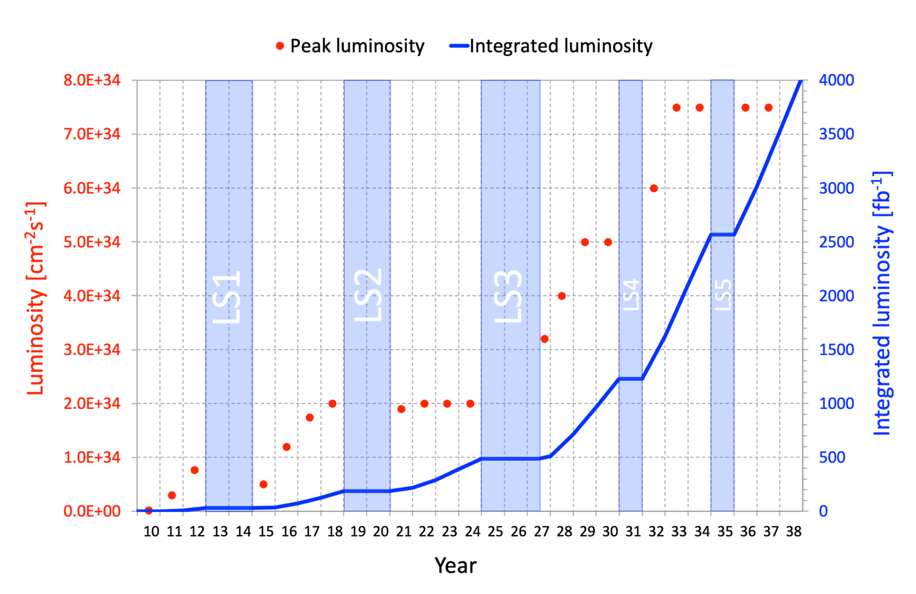
In the Nominal program HL-LHC will produce:
- peak luminosity of 5E34 $cm^{-2}s^{-1}$
- total integrated luminosity 3 ab^{-1}
- or total integrated luminosity 3.5 ab^{-1} (+ ions)

In the **Ultimate** program HL-LHC will produce:
Peak luminosity of 7.5E34 $cm^{-2}s^{-1}$ (75 nb^{-1}/s)
- 6.48 fb^{-1} in 24h = entire 2011 7 TeV dataset (6.1 fb^{-1})
- total integrated luminosity 4 ab^{-1}







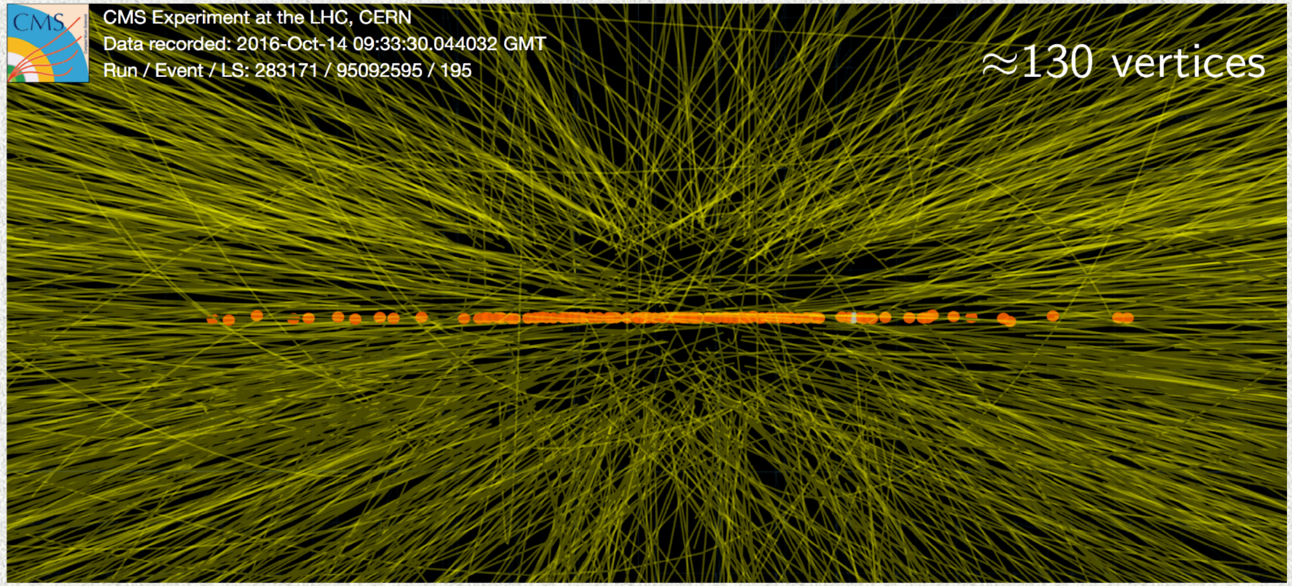


Ultimate performance established in 2015-2016: with same hardware and same beam parameters: use of engineering margins: $L_{peak\ ult} \cong 7.5\times10^{34}\ cm^{-2}s^{-1}$ and Ultimate Integrated $Li_{nt\ ult} \sim 4000\ fb^{-1}$

Challenges of the HL-LHC

HL-LHC and the CMS detector requirements:

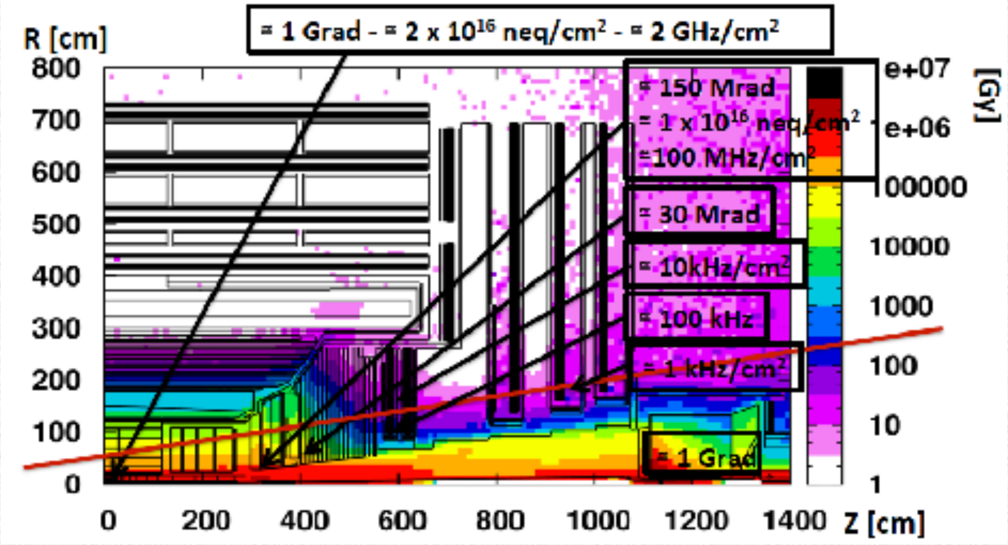
- Be able to trigger, read out and analyze data with high instantaneous luminosity and PU up to 140 (200)
  - Very high occupancy on inner detectors
  - Critical to associate detector hits and physics objects with the correct vertex



CMS should be and will be a high resolution 4D space+time (+ energy) detector

Be able to manage a much higher instantaneous and integrated radiation dose

- Increase in luminosity causes more radiation damage
- Detector will experience fluences up to 2.3E16 n_{eq}/ cm2
- Integrated dose up to 12 MGy
- Requires integration of radiation hard detector materials
- Radiation hard integrated circuits and readout electronic



CMS radiation dose map, neutron equivalent fluence, and particle rates for luminosities of 3000 fb $^{-1}$(integrated) and 5 x10^{34} Hz/cm2 (instantaneous).

below the red line: beyond limit of currently used detector technologies in several systems

HL-LHC Detector Upgrades

- Replacement of the entire tracking detector
- Replace pixel detector with inner tracker
- Replace strip detector with outer tracker
- Add a MIP Timing Layer
- Replace the calorimeter endcaps
- Upgrade barrel calorimeter electronics
- Expand and upgrade the muon system
- Improve trigger and DAQ electronics

L1-Trigger/HLT/DAQ
- Tracks in L1-Trigger at 40 MHz
- HLT input 100 kHz -> 750 kHz
- HLT output 7.5 kHz

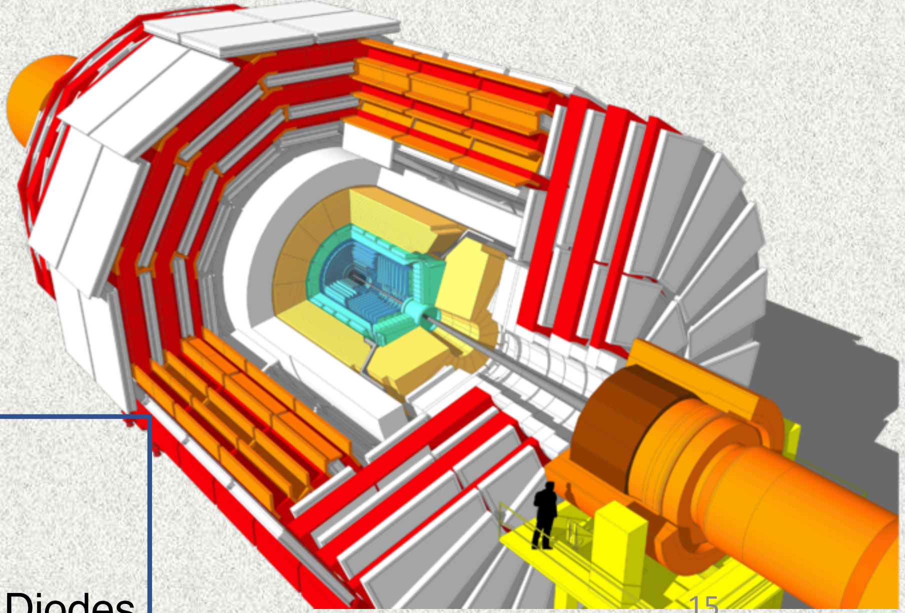
Muon systems
- DT & CSC new FE/BE readout
- RPC link –board
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Calorimeter Endcap
- Si-based and Scint+SiPM high granularity
- 4D shower topology:
    - 30 ps timing resolution

MIP Timing Detector
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

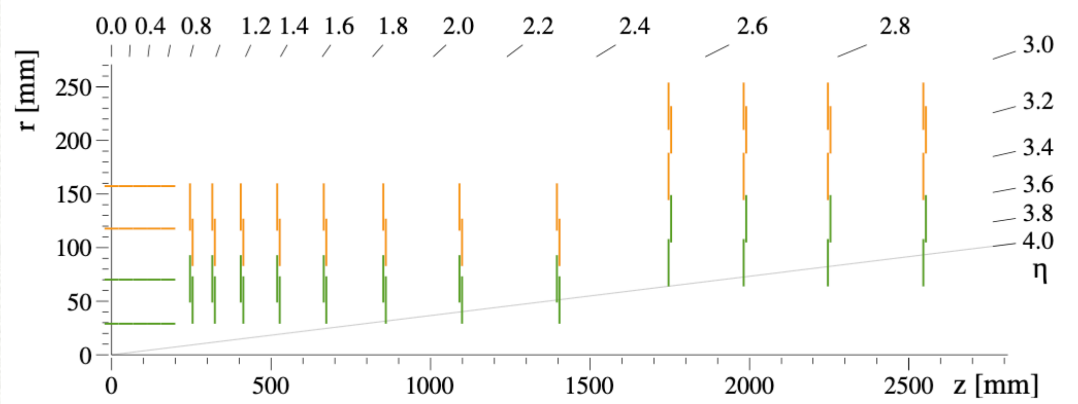
Tracker
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

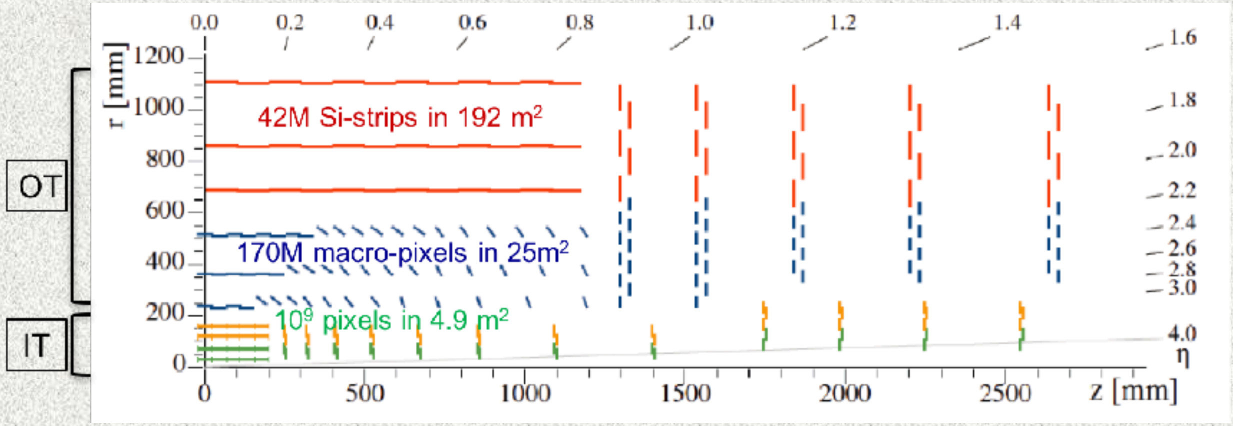
Barrel Calorimeters
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new merged Back-End electronics
- HCAL Front-End improved cooling

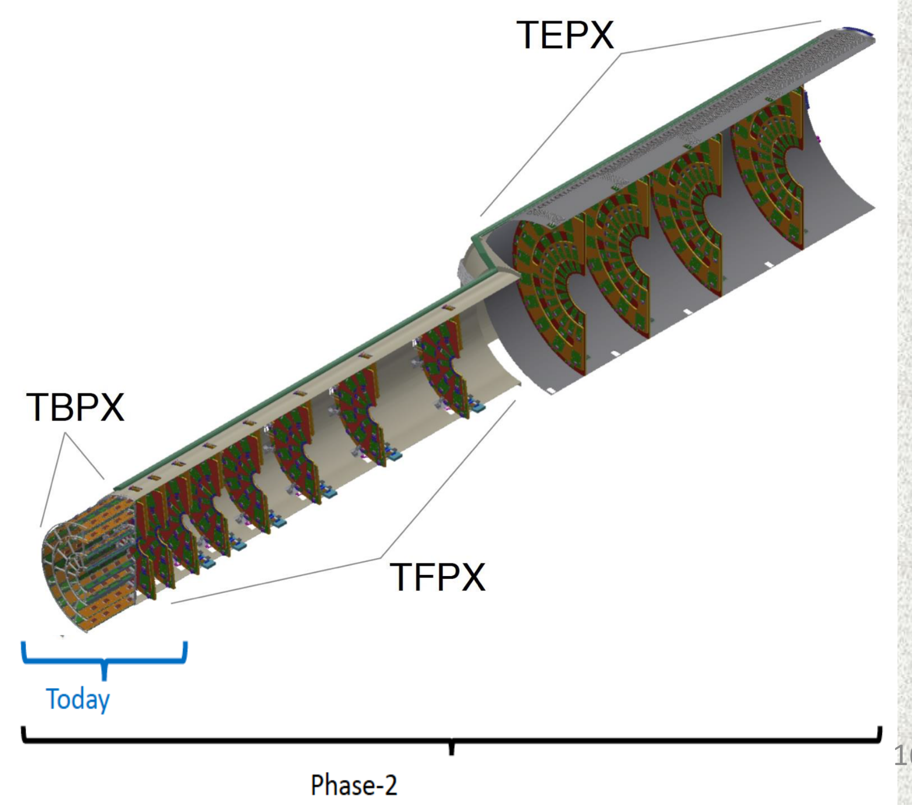


CMS Tracker Upgrade (OT/IT)

- IT maintains or improves on phase-I pixel tracker
  - Creates seeds needed for particle flow (PF)
- Can operate under a fluence of 3 GHz/cm^2
- Narrower pixel pitch than phase-I detector
  - 25x100 pixel-pitch baseline
- Coverage up to IηI < 3.8
- Increased hit capacity and radiation tolerance
- Capable of real-time luminosity measurement
- Carbon fiber support with CO_2 cooling system
  - 50 kW power requirement







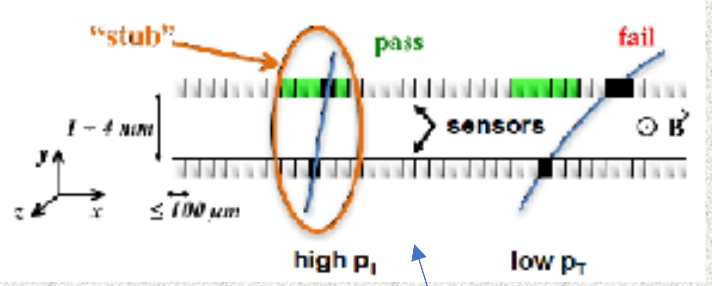
~ 2 billions pixels and strips!

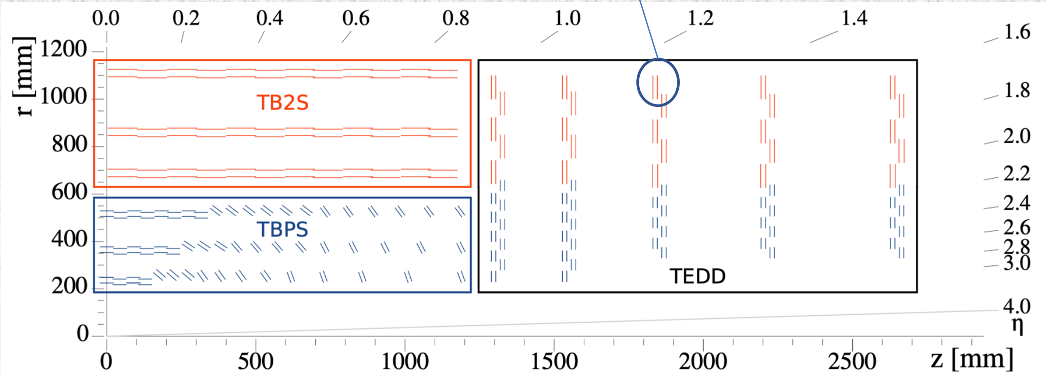
CMS Tracker Upgrade (OT/IT)

- OT maintains or improves physics performance of the original strip tracker
  - Critical for Trigger at HL-LHC Luminosity
- Outer Tracker: design driven to provide tracks (pT > 2-3 GeV) at 40 MHz to the L1 trigger

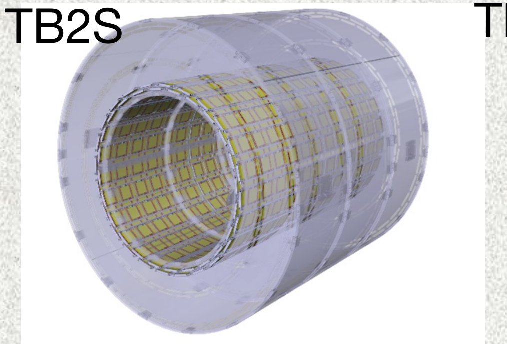
  => each module consists of 2 closely spaced sensors (~mm)
  - pixel-strip (PS) modules: macro-pixel (1.5 mm x 100 µm), strip (2.4 cm x 100 µm) tilted in Barrel (hermetic coverage with less modules and material)
  - strip-strip (2S) modules: strips (5 cm x 90 µm)
  - Gives 'vectors' instead of points
- Completely new carbon fiber and composite structure
- CO2 cooling system
  - 25 kW thermal foot print

2-sensor modules concept for L1 track-trigger

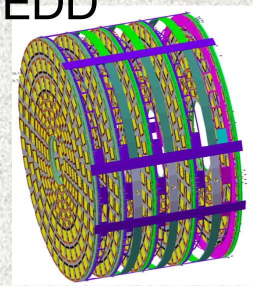




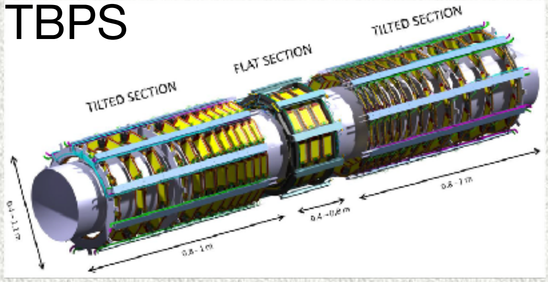
TB2S



TEDD



TBPS



Enhanced radiation tolerance;
- OT longevity up to 4000 fb^{-1}

Improved two track separation in high energy jets huge data rate capability

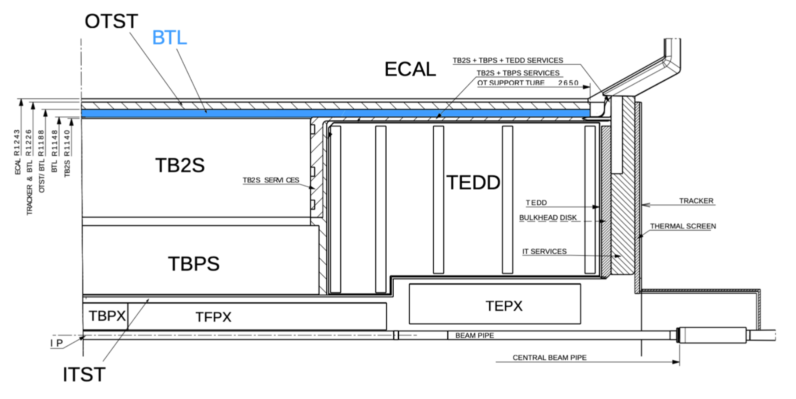
CMS MIP Timing Detector (MTD)

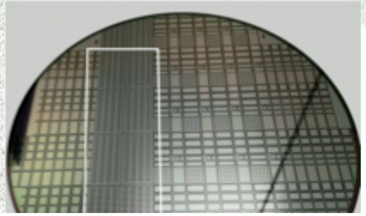
Brand New Detector Layer!

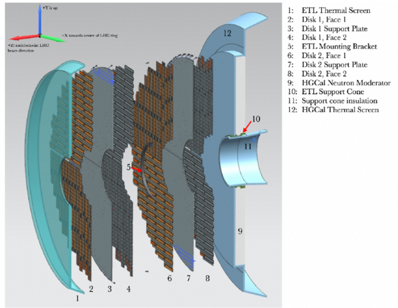
- 30-40 ps time resolution on traversing charged particles
- Assigns charged tracks to proper vertex
- Coverage for particle up to $|\eta| < 3$
- Barrel region covered by scintillator (LYSO) and Silicon Photomultipliers
- The endcap region is covered by Low Gain Avalanche Detectors (LGADs)
    - Active gain silicon detectors

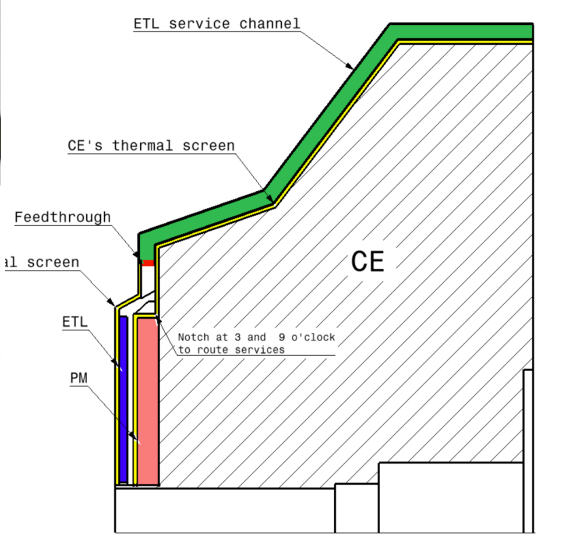
LGAD with internal gain layer

- Covers $1.6 < |\eta| < 3.0$
- Z position of 3.0 m, 45 mm thick, $315 < r < 1200$ mm, surface area of ~14 m^2
- Operates at a fluence of 2E15 n_{eq}/cm^2



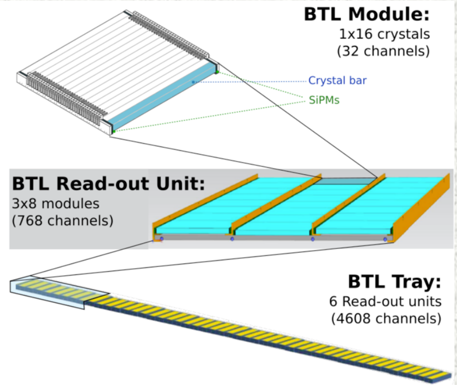


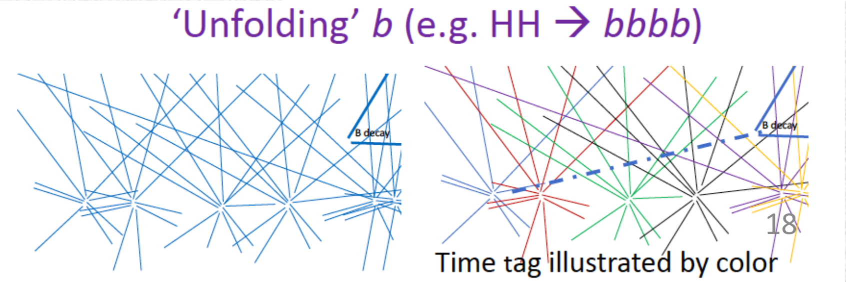




LYSO bars with SiPM Readout

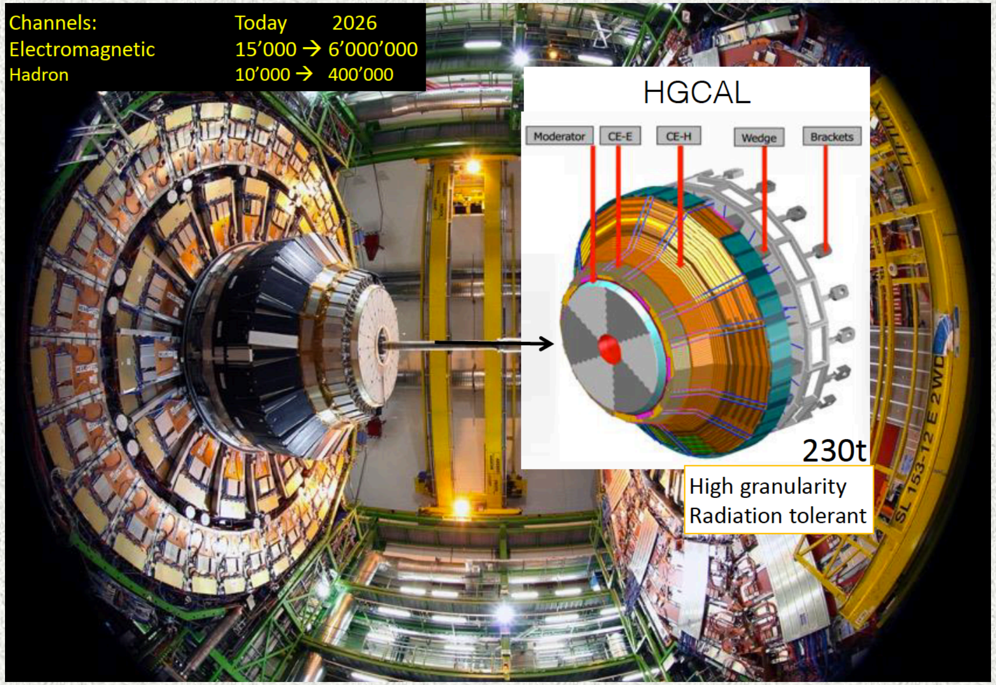
- Covers up to Tracker/ECAL gap at $|\eta| < 1.45$
- Inner radius of 1148 mm (40 mm thick), length 5.2 m along z, surface area of ~38 m^2
- Total of 332k channels
- Operates at fluence of 2E14 n_{eq}/cm^2

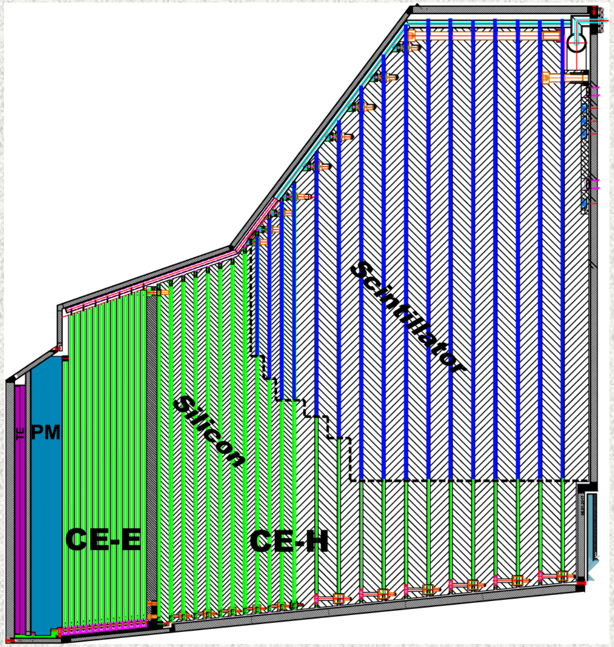




HGCAL Upgrade

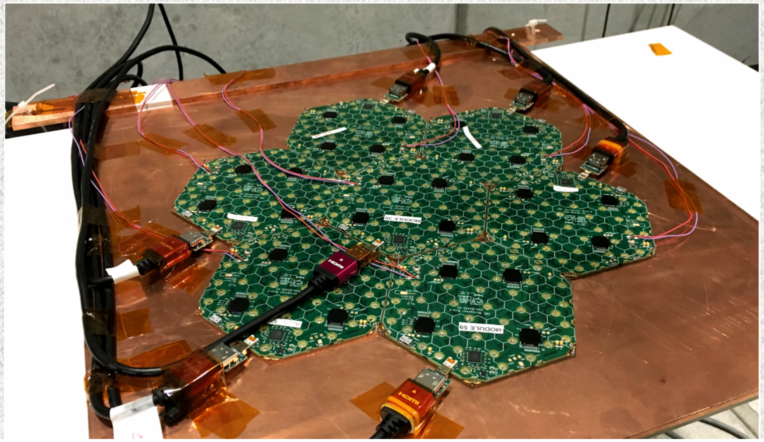
Sampling calorimeter that will replace the ECAL and HCAL endcap
- Layered CuW and stainless steel absorber and silicon sensors or scintillating plastic
- HGCAL covers $1.5 < \eta < 3.0$
- ~600m^2 of silicon sensors
- ~500m^2 of scintillators
- 6M Si channels, 0.5 or 1.1 cm^2 cell size
- 400k scint-tile channels (η–ϕ)
- Data readout from all layers
- Trigger readout from alternate layers in CE-E and all in CE-H
- Full system maintained at -30^{o}C





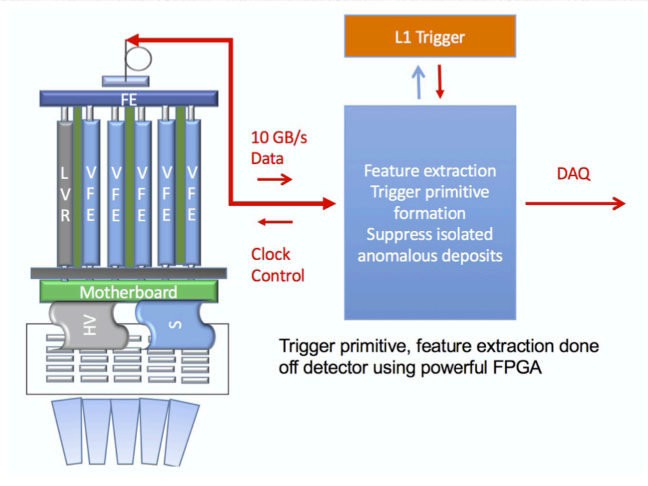
Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

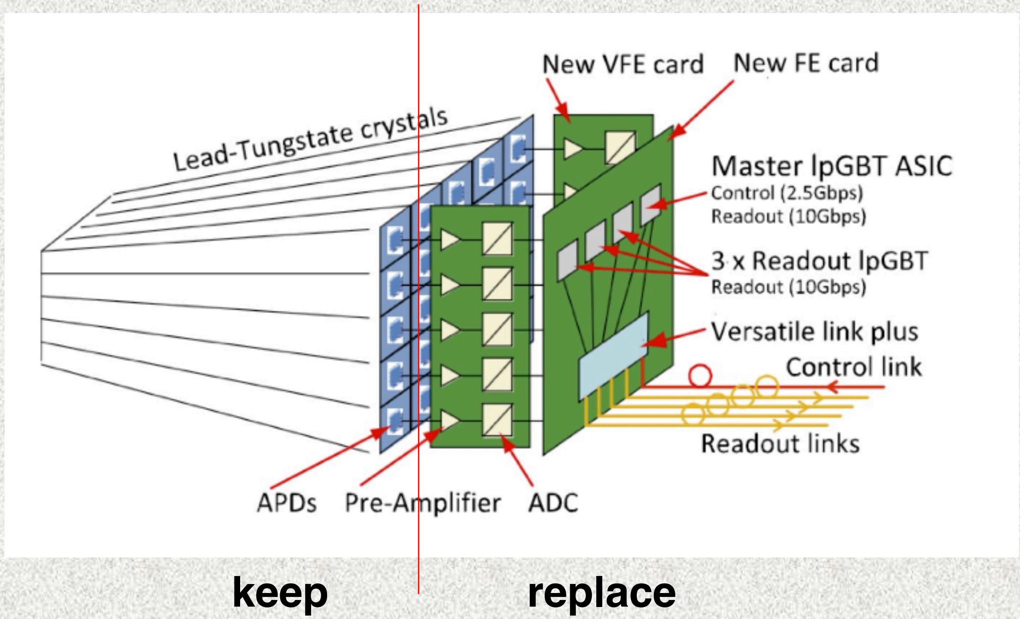
Electromagnetic calorimeter (CE-E):
Si, Cu/CuW/Pb absorbers, 28 layers, 26 X_0 & ~1.7λ
Hadronic calorimeter (CE-H):
Si & scintillator, steel absorbers, 24 layers, ~9.0λ


HGCal Modules on Copper Support/Cooling Plate

ECAL Barrel Upgrade

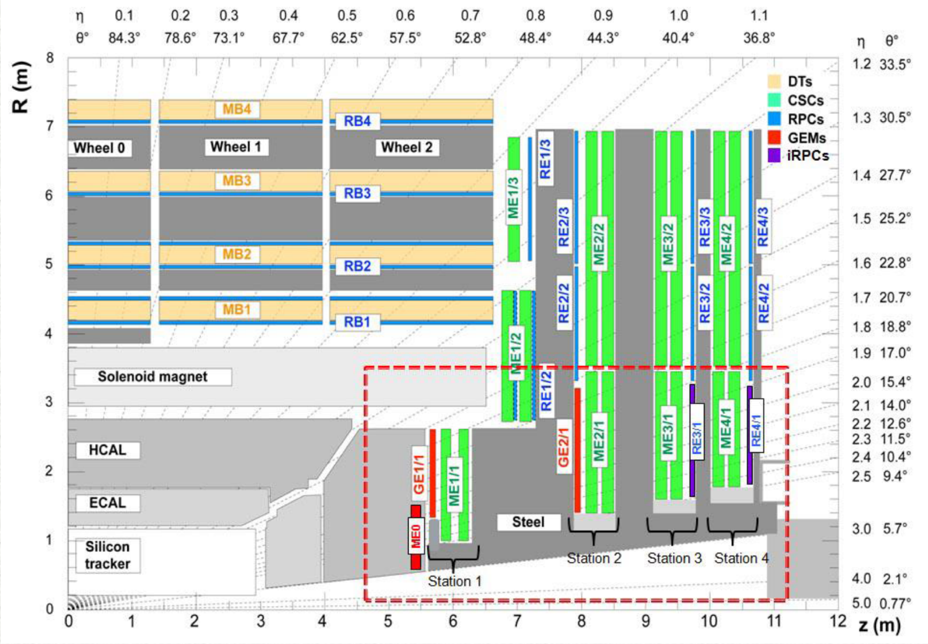
- Upgrade will keep PbWO4 crystals and APDs (Avalanche Photodiodes)
- Replace front-end electronics (new custom ASICs):
  - 30 ps resolution for 30 GeV e/g
  - Accommodate new L1 rate of 750 kHz (from 100 kHz)
  - Will provide single crystal granularity at L1 (better resolution at L1 trigger). Upgraded from 5x5 trigger tower
  - A new very front end (VFE) will remove spikes from the APDs at L1
    - full 40MHz readout (no trigger latency)
- Reduce the operating temperature from 18 to 9 C (to mitigate APD aging)
- new ATCA back-end boards

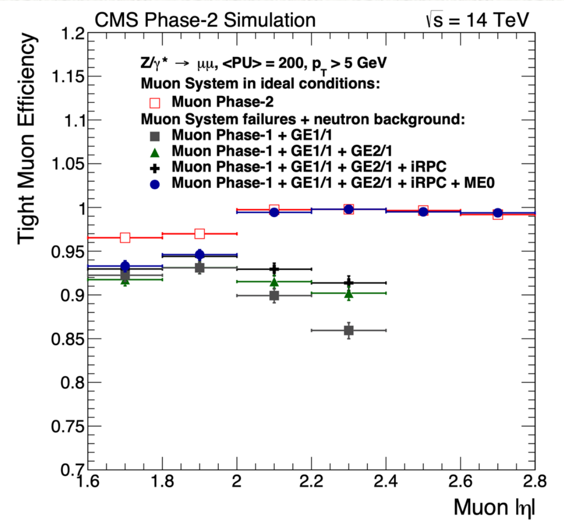


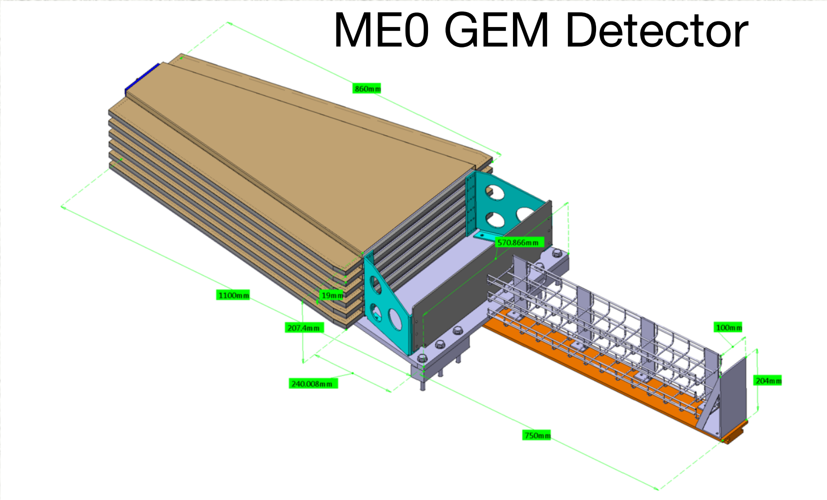


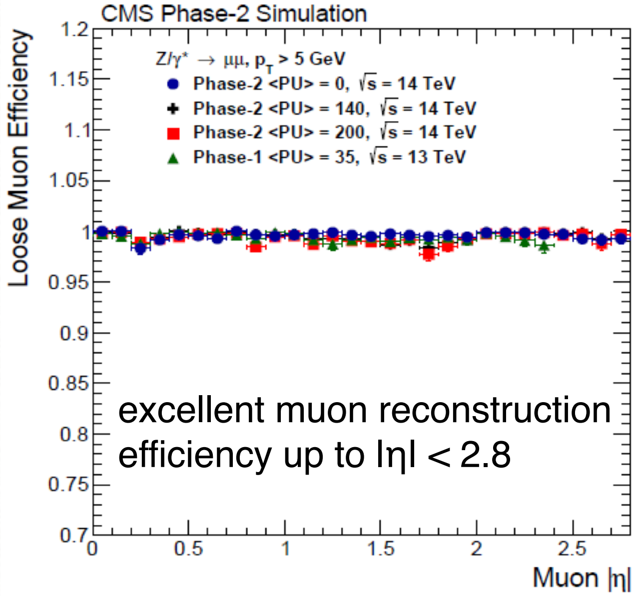
Muon System Upgrade

- **New detectors for high η muons**
  - GEM and RPCs cover $1.6 \leq |\eta| \leq 2.4$
  - ME0 extends muon coverage within $2.4 \leq |\eta| \leq 2.8$
- DT and RPC: new readout with improved z and time precision
- CSC forward: new readout at high bandwidth
- Improved hit coverage
  - Lower background rate at high η
- Upgraded muon system will maintain physics performance in the HL-LHC era
  - Much better resolution
  - Much better rate capability
- Significant improvements in time resolution





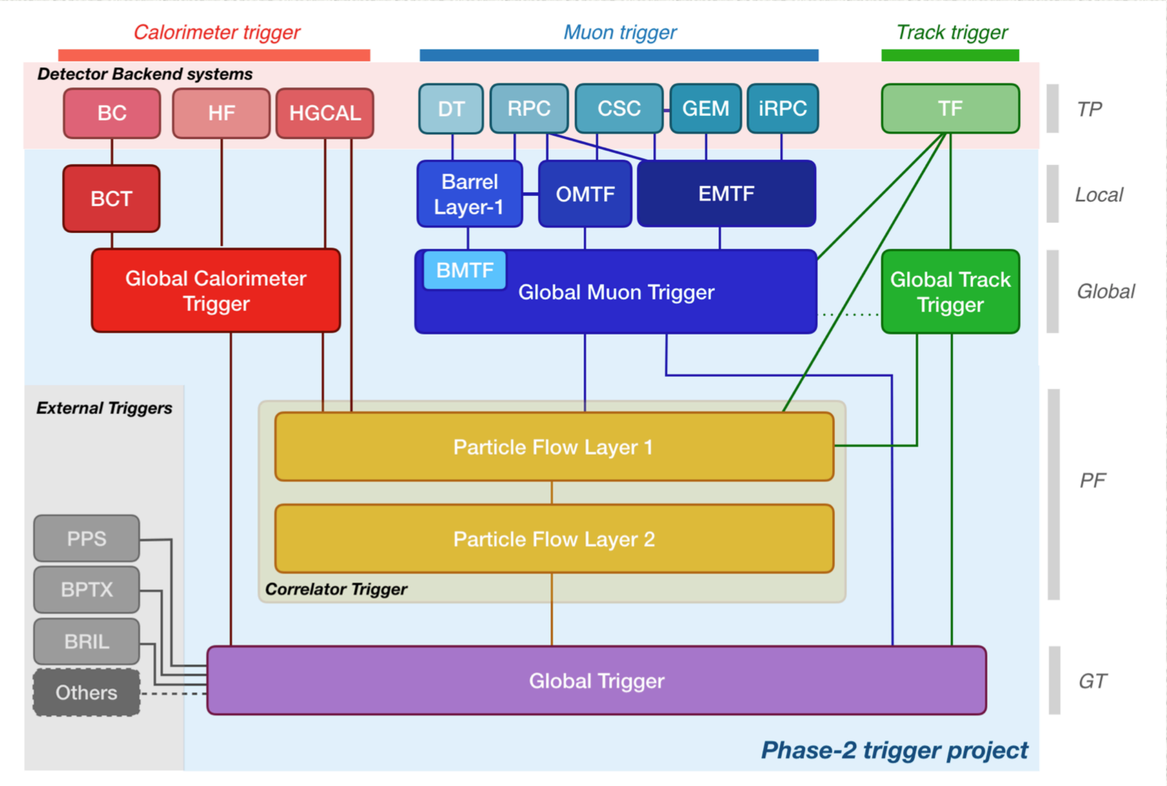


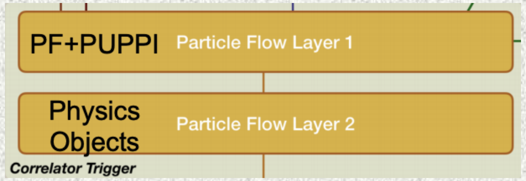


Trigger and DAQ Upgrade

Readout systems and data acquisition system improved to handle the higher trigger rates

- L1 trigger rate increased from 100 kHz to 750 kHz
- Latency increased from 3.8 to 12.5 μs
- HLT rate increased from 1 kHz to 7.5 kHz
- L1 trigger moved to FPGA based system
    - Includes tracking information at L1 : allow matching calorimeter and muon objects to tracks
    - New correlation trigger to combine information of multiple sub-systems at L1
    - Particle flow can now be implemented at L1
- Tracking information: new objects available
- Barrel Calorimeter: 25x resolution improvement
- Endcap Calorimeter: 3D High Granularity





In Phase2 CMS Trigger will be using algorithms much closer to offline:

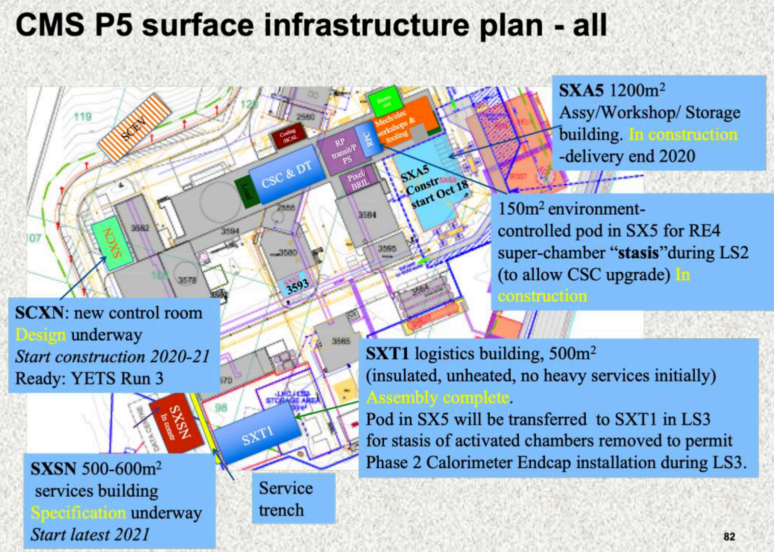
- PUPPI for PU removal (extremely needed with PU 140-200)
- Machine Learning

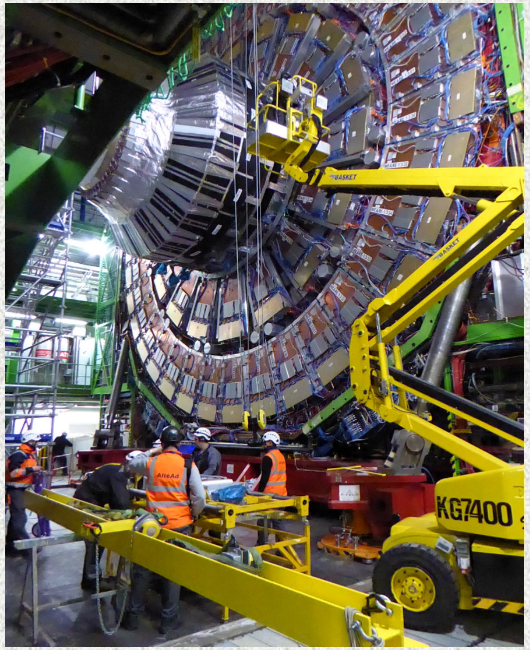
No need to improve resolution of detector without improving resolution at trigger level ~ thresholds

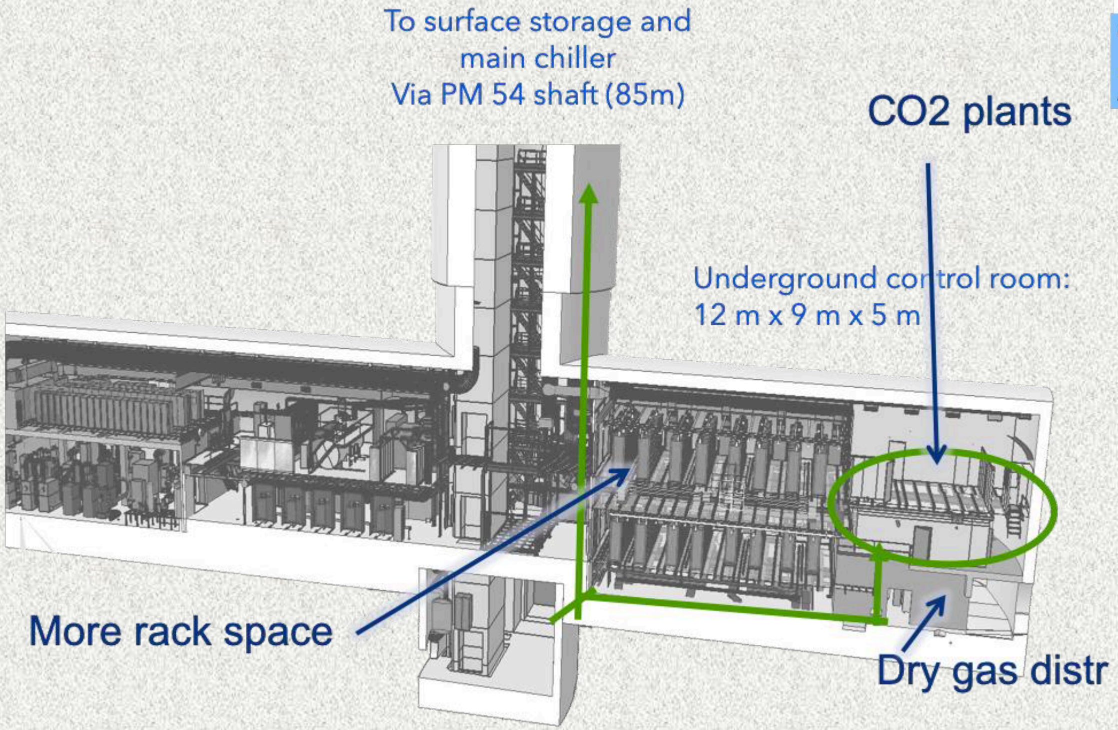
Beside of detector, but not less important

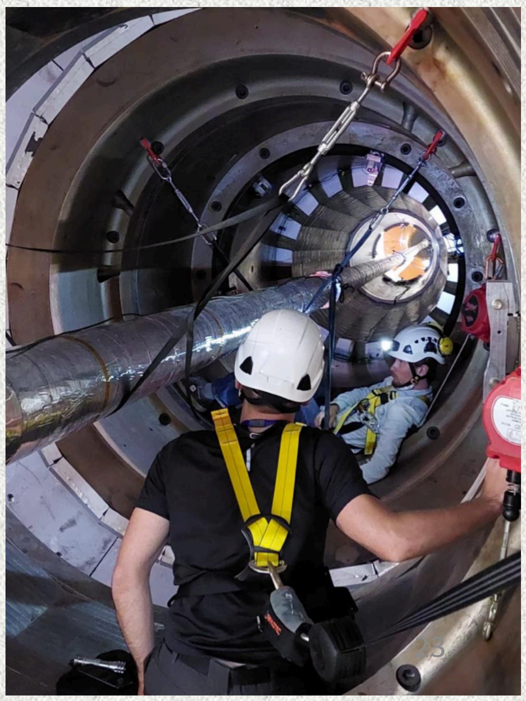
- New buildings, CO_2-cooling plants, gas distribution, power system, safety, databases, service installation (power, fibers, pipes), 3.8T magnet re-commissioning, Data AcQuisition, firmware, control systems, opening and closing 600t-objects, lowering 20t objects, racks system, alignment & survey

- Custom chips, custom electronics boards, custom optical transmitters/receivers
- Computing – neural network, machine learning









Space in the cavern is even more scarce then money

Summary

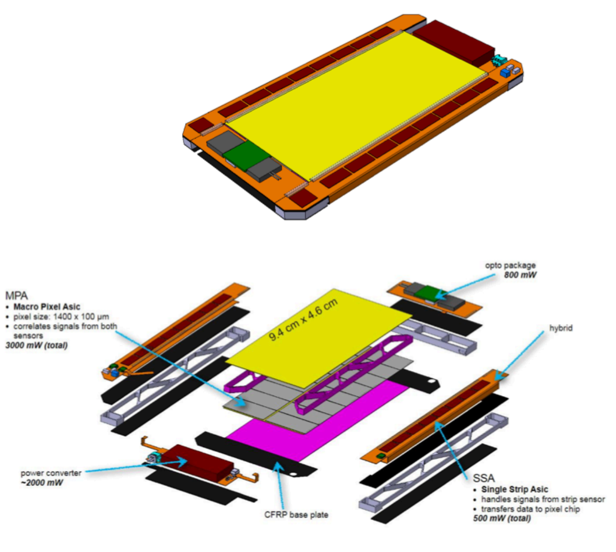
- **CMS upgrades for the HL-LHC are well underway**
- *Preparations have started to prepare the infrastructure during LS2*

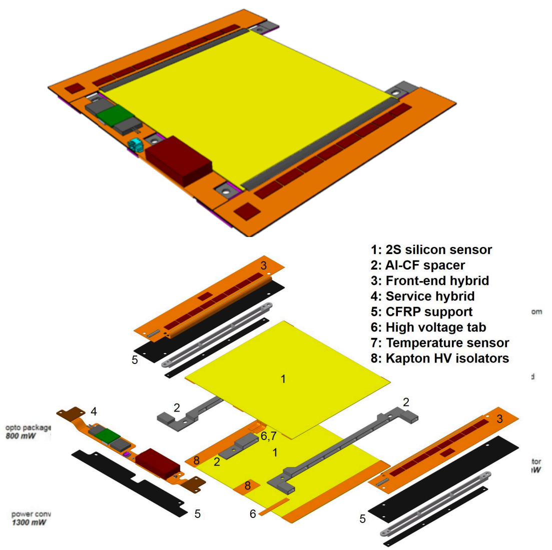
- **HL-LHC will produce up to 4000 fb^{-1}**
  - ~20x more data than currently collected
  - 4x current instantaneous luminosity
- **High-occupancy environment requires substantial detector upgrades**
- **Completely replace tracking detector**
- <60 picoseconds timing resolution used for vertex identification
- **High-granularity endcap replaces current calorimeter endcap**
- **Extend physics object identification for $|\eta| < 4.0$**
- **Significantly increase trigger rates**
  - 7.5x L1 and HLT trigger rate
  - Tracker information and PF included at L1
- **Expect CMS to maintain physics performance in HL-LHC era**

Backup

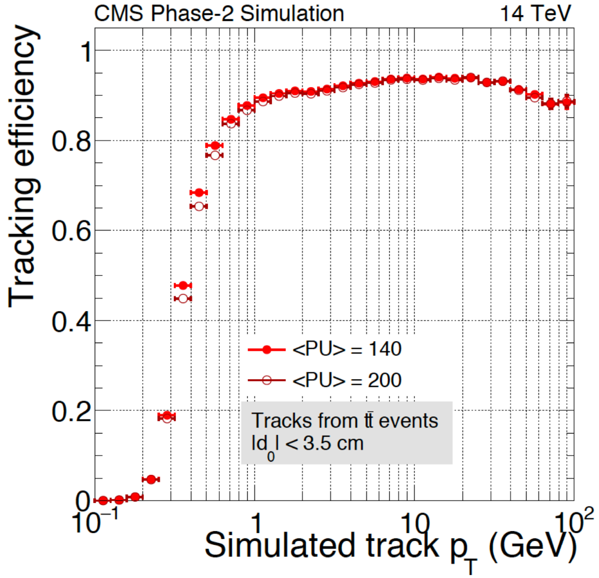
2S and PS modules

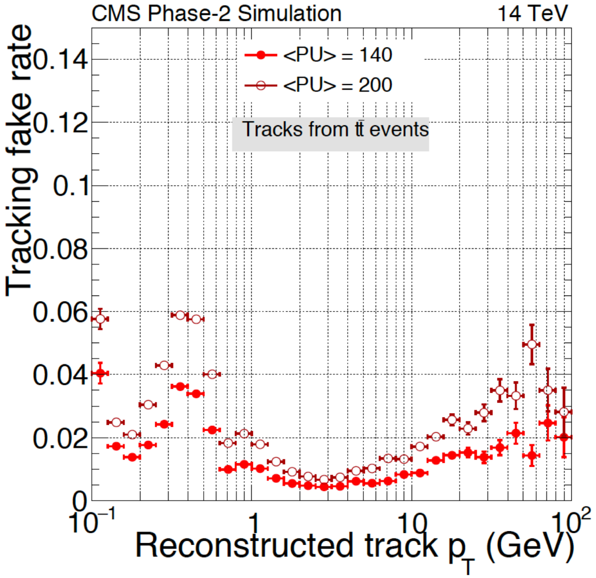
PS module **2S module**



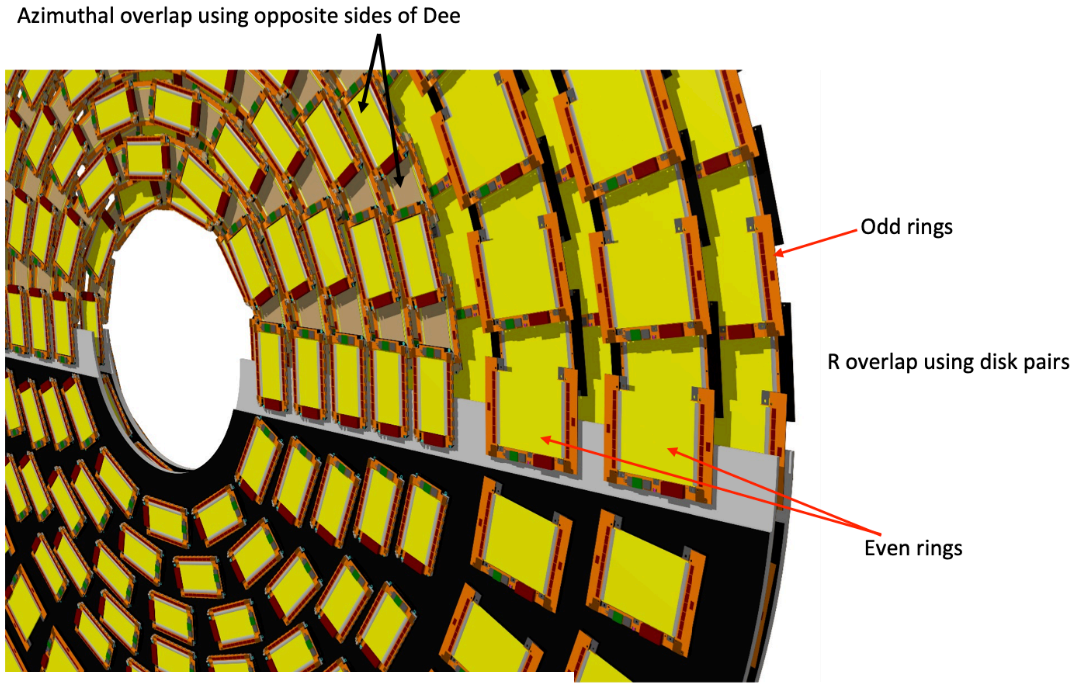


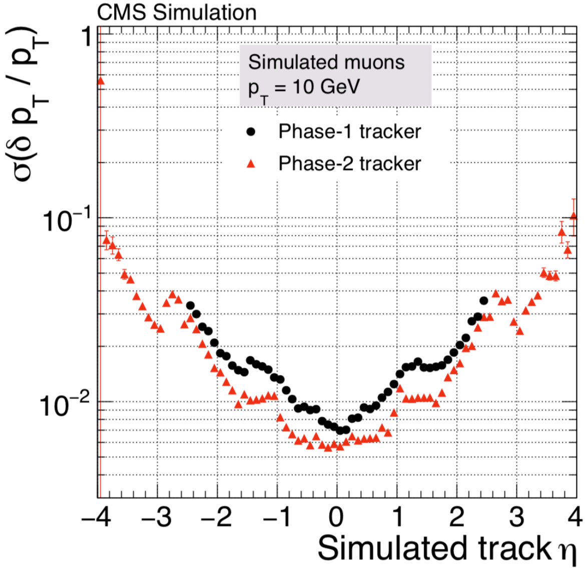
- track reconstruction efficiency > 90% for pT > 1 GeV
- fake rate < 2% (4%) at 140 (200) PU for pT within 1-100 GeV





Double-disks concept: module overlap



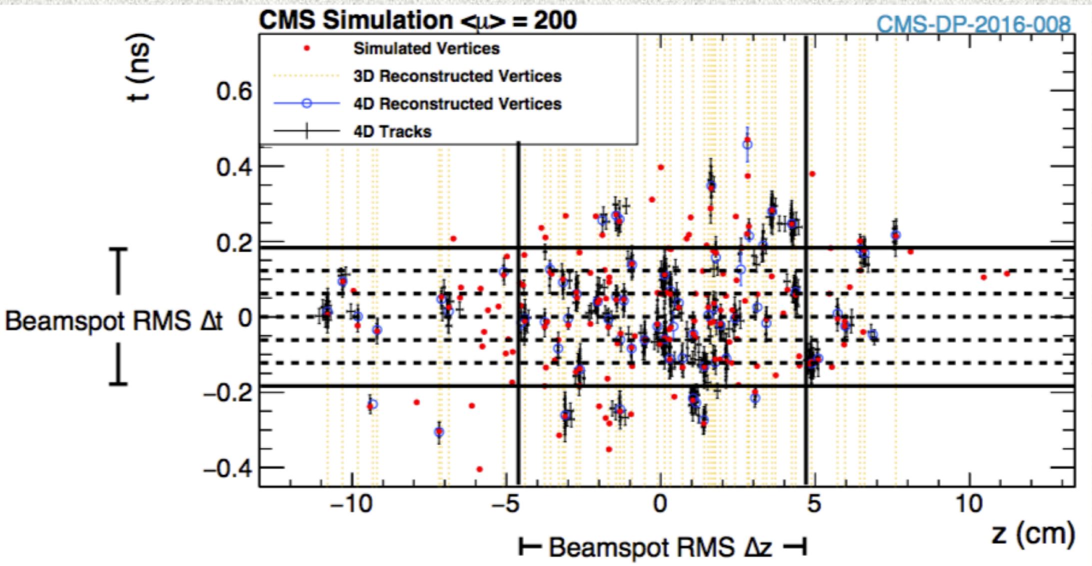


extended η range improves p_T resolution with Phase-2 tracker vs Phase-1

Precision timing at HL-LHC

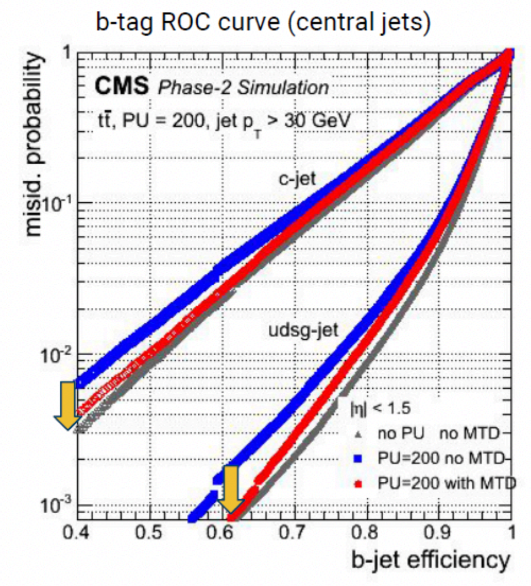
Pileup vertices spread along beam direction and time precision timing for charged and neutral particles will be a key to reduce pileup contamination

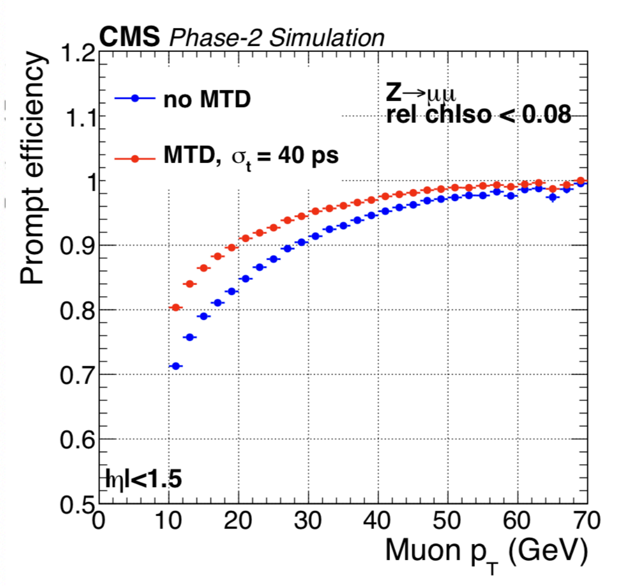
- track timing (~40 ps) will allow 4D (space+time) vertex reconstruction
- will reduce effective pileup to a level similar at current LHC
- will allow to clean tracks and jets from pileup (calorimeters will also have timing capabilities)



Improving particle ID

- improve b-tagging performance
    - increase of photon and lepton reconstruction, identification and isolation efficiencies
- improve missing ET resolution (~15%)



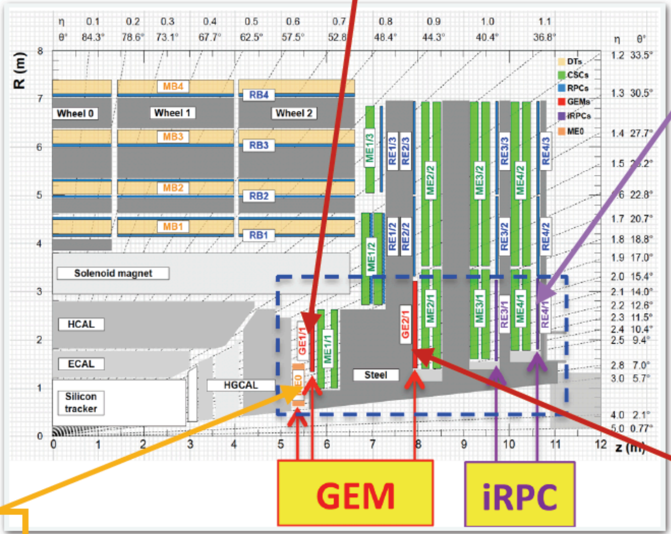


Muon System upgrade overview

- 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

- 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