The upgrades and future plans of the CMS experiment at the Large Hadron Collider

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The LHC and its Experiments
Motivations for a higher Luminosity LHC

- O(1%) precision on SM Higgs couplings
- Extending reach of BSM searches (e.g. Dark Matter candidates)
- Rare Higgs Decays (e.g. $H \rightarrow \mu\mu$) and production (e.g. $HH$)

The High-Luminosity (or phase 2) LHC is an approved project
The Higher Luminosity LHC

- Improved injection system
- Improved focusing in interaction region

The HL-LHC will produce as many Higgs Bosons in one year as the LHC in 10 years

<table>
<thead>
<tr>
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<th>Instantaneous Luminosity (cm(^{-2}) s(^{-1}))</th>
<th>Integrated luminosity fb(^{-1})</th>
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</thead>
<tbody>
<tr>
<td>LHC (2010-2023)</td>
<td>0 to 2 x 10(^{34})</td>
<td>300</td>
</tr>
<tr>
<td>HL-LHC (2036-2036)</td>
<td>5 to 7.5 x 10(^{34})</td>
<td>3000 to 4000</td>
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Challenges of the CMS Upgrade

- High Luminosity means
  - Many collisions (Pileup) (140 to 200 per event)
  - High irradiation (up to 1 GigaRad in forward region or close to collision point)

A top pair event with 140 collisions
Strategies to Deal with the Challenges

- **Increased use of silicon sensors** (high radiation tolerance)
- **More granularity in the silicon** to deal with the high pileup
- **Precision timing** (< 50ps resolution) to separate collisions in time as well as space
- **Faster processing** of data in real time for trigger using modern high speed electronics

Essentially try to maintain or improve the legacy LHC performance in HL-LHC conditions
More than 99.99% of events are discarded in real time by the level1 hardware trigger.

Processing must be done in 12.5µS and reduce rate from 10 GHz to 1 MHz.
All New Silicon Tracker

- More granular
- Lighter (less material)
- Extended coverage to $\eta=3.8$
- Tracking included in L1 Trigger for the first time
Inner plus Outer Tracker

Outer Tracker
- strip-strip (2S)
- pixel-strip (PS)

Inner Tracker
- All Pixel

Hermetic Silicon Coverage to $\eta = 3.8$

Significant reduction in tracker material improves performance of tracker and calorimeters
Outer Tracker – Track Trigger

OT Si-sensors \(\approx 200\mu\text{m} \) thick - 90/100\(\mu\text{m} \) pitch - 2.5/5cm strips - 1.5 mm macro-pixels in inner layers

- Two layer track stubs remove low \(P_T\) tracks in trigger (<2GeV)
- Tilted modules to maintain geometric acceptance for stubs
- Track trigger reduces data rate by x 10
Inner Tracker (Pixels)

Si-Silicon sensors ≤ 150μm thickness 50x50 to 25x100μm²

Radiation tolerant to ~ 1 GigaRad

Very challenging pixel readout chip in joint ATLAS+CMS development
Collision Vertices in the CMS interaction region with 200 Pileup

Precision timing with 30-50ps resolution allows separation of pileup

Requires dedicated timing layer for tracks and modification of readout for Barrel Calorimeter
Precision Timing Layer

Barrel: LYSO crystal 1.2x1.2cm² + Silicon Photomultiplier on tile

Endcap: Single layer – LGADs
Precision Timing Benefits

- Pileup Mitigation
- Effective luminosity gain of O(20%) for some Higgs measurements
- Significantly enhances discovery potential for massive long lived particles (measure decay time)
The CMS Calorimeter: Electromagnetic + Hadronic

Barrel $\eta | < 1.5$

Endcap
To be Replaced with silicon calorimeter for high irradiation tolerance

Legacy front end readout

A $H \rightarrow \gamma \gamma$ candidate event observed in the ECAL

Barrel Electromagnetic Calorimeter electronics replaced for precision timing and better trigger granularity

Hadron Calorimeter electronics replaced for better signal strength and higher trigger rates
Barrel Calorimeter Electronics Upgrade

Electromagnetic Calorimeter on detector

- Faster response pre-amplifier to give 30ps timing for EM showers at 50 GeV
- Higher bandwidth transmission off detector to provide more granularity to trigger
- High speed processor board to deal with Greater spatial and time granularity

Electromagnetic + hadronic Calorimeter off detector

Like turning a 1M pixel camera to 25M pixel camera
Silicon+Scintillator Calorimeter Endcap

- Sampling calorimeter with 28 layers for EM showers
  24 layers for Hadrons
- Silicon in front and inner regions for radiation tolerance
- High granularity in 3d and good time resolution (50ps) for pileup mitigation.
- Scintillator tiles + SiPM’s in lower radiation regions

**CE-E:** 28 sampling layers – $25X_0 + \sim 1.3\lambda$

24 sampling layers – $9\lambda$
Calorimeter Endcap All Silicon layer

A cross-sectional layer of the EM endcap

Each Module subdivided into 0.5 - 1.2 cm² hexagonal cells

Module prior to wirebonding
A simulated high $P_T$ jet in 200 pileup showing the lateral and longitudinal granularity
Calorimeter Endcap Prototype tests

Proof of principal test successful

Expected prototype performance achieved
Muon Detector Upgrade

Muon detection is an essential element of the Compact Muon Solenoid (CMS)

Existing muon chambers most unchanged as they will be performant in HL-LHC

Replace electronics to improve trigger performance (lower $P_T$ thresholds)

Extend coverage to $n=3.0$ in forward region with GEM’s

Upgrades are relatively modest
Trigger/Data Acquisition Upgrade

Adding tracking to the hardware trigger is critical.

More sophisticated algorithms for pattern recognition in general.

The ability to process the increased information from the more segmented detector in a more sophisticated way makes possible the entire upgrade program.

It is due to advances in high speed optical links (10 Gb/s) and GHz FPGA’s.
Now finishing the design phase and moving to prototyping (2018-2021). Production is 2021-2023 and installation 2024-2026.
Summary

• The High Luminosity LHC is an approved project planned to operate 2026+

• The high radiation and multiple collisions make the detector upgrades very challenging

• CMS is harnessing new technology to significantly upgrade the detector and its discovery potential for a new era
ADDITIONAL MATERIAL
LHC era   CMS tracker
HL-LHC Tracker

- OT Si-sensors ≈ 200\(\mu\)m thick - 90/100\(\mu\)m pitch - 2.5/5cm strips - 1.5 mm macro-pixels in inner layers
- IT Si-silicon sensors ≤ 150\(\mu\)m thickness - 50x50 to 25x100\(\mu\)m\(^2\) - large pixels in outer layers?