CMS Upgrade and Future Plans

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On behalf of the CMS collaboration

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Compact Muon Solenoid (CMS)

Emphasis on electron and photon energy measurement, full silicon tracker providing high momentum resolution

**Key features:**
- High $B$-field
- Solenoid containing tracker & both calorimeters

**CALORIMETERS**
- ECAL
  - Scintillating PbWO4 crystals
  - $\sigma_{E/E} \approx 2.9%/\sqrt{E(\text{GeV})} + 0.5%$
- HCAL
  - Plastic scintillator/brass sandwich
  - $\sigma_{E/E} \approx 120%/\sqrt{E(\text{GeV})} + 6.9%$

**SUPERCONDUCTING COIL**

**TRACKER**
- Silicon Microstrips
- Pixels
- Tracking: $\sigma_{p_T/p_T} \approx 1.5 \cdot 10^{-4} p_T(\text{GeV}) + 0.5%$

**MUON BARREL**
- Drift Tube Chambers ($\text{DT}$)
- Resistive Plate Chambers ($\text{RPC}$)

**MUON ENDCAPS**
- Cathode Strip Chambers ($\text{CSC}$)
- Resistive Plate Chambers ($\text{RPC}$)

**Overall length:** 28.7 m
**Overall diameter:** 15.0 m
**Total weight:** 14000 tons
**Magnetic field:** 3.8 T
LHC very successful up to now!
Run-1 provided 30 fb\(^{-1}\) of high quality data
~200 publications

For LHC phase-2 increase luminosity. Consequences for detectors:

- Higher rates would imply increased trigger thresholds w/o upgrade
- Detector ageing
- More bandwidth needed

### E\(_{CM}\) [TeV]
| 8 |

### L [cm\(^{-2}\) s\(^{-1}\)]
| 7 \times 10^{33} |

### PU
| \sim 21 |

### \int L dt [fb\(^{-1}\)]
| \sim 30 |

### Phase-1

| 13 |
| \leq 2 \times 10^{34} |
| \leq 50 |
| \leq 120 |

### HL-LHC

| 13? |
| \approx 5 \times 10^{34} |
| \leq 140 |
| \leq 3000 |

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HL gives access to rare processes and allows precision measurements. Benefit on physics see talks by Susan Gascon-Shotkin and Nikolina Ilic.
LHC very successful up to now! Run-1 provided 30 fb⁻¹ of high quality data ~200 publications

For LHC phase-2 increase luminosity. Consequences for detectors:

- Higher rates would imply increased trigger thresholds w/o upgrade
- Detector ageing
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Higher luminosity results in more pile-up (PU) in detectors.
25 Vertices in 2012 →
140 Vertices in 2025

Radiation six times higher than nominal LHC design

By ~2025 detectors are operational for ~20 years. Built in technology from ~30 years ago (in particular electronics and computing)

→ Redesign electronics, trigger and DAQ
Consequences

Detector will age and performance deteriorate

Many high rate testbeam campaigns, aging projections and simulations
→ Need to replace tracker and forward detectors with radhard material

Higher rates, in particular in the forward

Triggers need to stay efficient (MHz → kHz). Keep trigger thresholds low for Higgs and particles from cascade decays
→ Finer granularity detectors and larger trigger bandwidth
Trigger

Increase L1 Trigger **latency** $3.4 \, \mu s \rightarrow 12.5 \, \mu s$

& L1 Trigger **rate** $100 \, kHz \rightarrow 750 \, kHz$

- New readout electronics, including sub-detectors that will not be replaced (ECAL barrel, muon)

**The trigger challenge:** keep the **thresholds** at 5x higher PU. Sharpen **turn-on** curves and reduce **fake** triggers. Tools:

- **Single ECAL crystal readout** improves track matching, spike rejection (noise) and timing

- Additional muon detectors (GE1/1) enable measurement of bending angle in forward region $\rightarrow$ reduce mis-measurement

- Tracking information at L1 (tracking trigger)
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CMS Si Tracker today

**B=3.8T**

Current & Phase1: Planar pixels

CMS Si Tracker as it could be in 2025

Outer Tracker, new Pt modules
3 more Pixelated layers
5 more Pixelated disks

Strip/Strip modules SS in outer layers

Macro Pixel/Strip modules PS in inner layers (z-measurement)

Pixel modules, new Disks to $\eta=4$
Possible pixel size $\sim 25 \times 100 \mu m^2$

Planar or 3D?
Upgraded Tracker: Lighter, Smarter, Better (acceptance)

**Lighten up** DC-DC powering scheme, CO$_2$ cooling, low mass assemblies, reduced material within tracker volume, thinner sensors

- Physics gain: improved track $p_T$ resolution. Reduced rate of $\gamma$ conversions.

**Larger coverage** extend pixel acceptance to $|\eta| \approx 4.0$.

- Physics gain: Reduces fake jets due to PU for VBF physics. Allows to separate signal jets (primary vertex) from PU jets.

**Smart track trigger** Including tracking information at L1 trigger

- Physics gain: helps controlling the rate, trigger thresholds can stay moderate
Phase-II Tracking Trigger

**Objective:** reconstruct all tracks with $p_T > 2$ GeV at trigger level. Identify primary vertex along beam line with \( \sim 1 \) mm precision.

**Conceptual design:** to implement tracks in hardware trigger (40 MHz)
- Correlate hits in two closely-spaced sensors to provide vector (“stub”) in transverse plane: angle is a measure of $p_T$
- Exploit the strong magnetic field of CMS

**Physics benefit:**
- Threshold can stay roughly at present level
- Sharp trigger turn on
Calorimeters

- At present PbWO$_4$ crystals in ECAL barrel and scintillator-tile HCAL.
- Active detectors can stay in barrel where rad damage is less. Electronics needs replacement to cope with new trigger rates/latency.

Radiation dose strong function of eta. Variation in forward region by 100.
Two Scenarios for Forward Calorimetry

Scenario 1
- Maintain present geometry with ECAL and HCAL stand-alone
- ECAL Endcap in Shashlik design
- HCAL Endcap re-build as radhard

Scenario 2
- New integrated design as a High Granularity Calorimeter (HGC)
- Particle flow imaging calorimeter

Need to replace forward calorimeters after 500/fb due to ageing damage
Scenario 1: Shashlik ECAL

**Sampling** calorimeter w/out depth segmentation, very compact $X_0 \sim 25$
- Radhard inorganic scintillator. Best performance with LYSO and tungsten & brass as absorber
- Light readout with WLS in shashlik configuration
- Readout with GaInP photosensors (radhard due to larger band gap)

- **Good energy resolution** $\Delta E/E = 10%/\sqrt{E}$
- Very compact and highest light yield
- Small Moliere radius (14mm) provides **fine granularity** for pile up mitigation (matching with tracker)
Two Scenarios for Forward Calorimetry

Scenario 1

- Maintain present geometry with EE and HE stand-alone
- EE in Shashlik design
- HE re-build as radhard

Scenario 2

- New integrated design as a High Granularity Calorimeter (HGC)
- Particle flow imaging calorimeter

Need to replace forward calorimeters after 500/fb due to ageing damage
Scenario 2: High-granularity combined calorimeter

High granularity calorimeter (HGCAL) based on ILC/CALICE development. Key point: “visualize” energy flow through fine granularity and longitudinal segmentation.

- Good resolving power for single particles in very dense jets. $\Delta E/E = 10%/\sqrt{E}$

- Planes of Si separated by layers of Pb/Cu or brass
- Exploits developments on Si rad.hardness and price

Structure:
- E-HG: 33 cm, 25 $X_0$, 1$\lambda$, 31 layers. Absorber W/Pb
- H-HG: 66 cm, 3.5$\lambda$, 12 layers, Absorber brass
- B(back)-HG as HE re-build 5 $\lambda$

Opens up possibility to extend to $|\eta| \sim 4$
Forward Muon Challenge

Challenging rates:
- Forward region $|\eta| \geq 2.0$ with rates in 10’s of kHz/cm$^2$ and higher towards higher $\eta$
- Reduced resolution and longevity issues
- New requirements often exceed capabilities of the existing

Interesting physics in the forward:
- One place to gain physics acceptance
- Highest background rates yet least redundancy
- Challenging B-field topology

$H \rightarrow ZZ \rightarrow 4\mu$: acceptance increase
60% $\rightarrow$ 94% if $\eta_{\text{max}} = 2.4 \rightarrow 4.0$
Forward Muon Upgrade

Triple GEM detector (GE1/1): precision chambers to improve trigger momentum selectivity and reconstruction already in late LHC phase-1. Installation in LS2 (2018).

Enhance region without redundancy $1.6 < |\eta| < 2.4$ with **maximum rate**.
Technology = GEM (GE2/1) and improved high-rate RPC (RE3/1 and RE4/1)
**Forward Muon Upgrade**

**Triple GEM detector (GE1/1):**
precision chambers to improve trigger momentum selectivity and reconstruction already in late LHC phase-1. Installtion in LS2 (2018).

**Extended coverage** provides muon tag in forward region \(|\eta|<3\)
Several tens of kHz expected → GEM technology

Enhance region without redundancy 1.6 < |\(\eta\)| < 2.4 with maximum rate.
Technology = GEM (GE2/1) and improved high-rate RPC (RE3/1 and RE4/1)
Additional Detectors: Benefits

Additional detectors yield extra hits $\rightarrow$ Increased efficiency
Summary

It is time to prepare for LHC high-luminosity operation in ≥2025. Expected to record up to 3000/fb of pp data.

Ageing and radiation damage requires to rebuild the inner tracker and forward detectors. New trigger concepts implemented. Larger bandwidth requires upgrade of electronics.

New detectors designed to cope with high rates, high pile-up and radiation.
Summary CMS Phase 2 Upgrades

Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to $\eta \sim 4$

Endcap Calorimeters
- Radiation tolerant - higher granularity
- Investigate coverage up to $\eta \sim 4$

Barrel ECAL
- Replace FE electronics

Muons
- Additional detectors $|\eta| > 1.6$
- Muon-tagging up to $\eta \sim 3$

Trigger/DAQ
- L1 with tracks & up to 1 MHz
- Latency $\geq 10\mu s$
- HLT output up to 10 kHz
BACKUP SLIDES
Upgrades 2013/14 ongoing
- Completes muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD\(\rightarrow\)SiPM)
- DAQ1 \(\rightarrow\) DAQ2

Phase 1 Upgrades 2018/19 (TDRs)
- New Pixels, HCAL electronics and L1-Trigger
- GEM under cost review
- Preparatory work during LS1
  - New beam pipe
  - Install test slices
    - Pixel (cooling), HCAL, L1-trigger
  - Install ECAL optical splitters
    - L1-trigger upgrade, transition to operations

Phase 2: 2023-2025 Now being defined
- Tracker Replacement, Track Trigger
- Forward : Calorimetry and Muons and tracking
- Further Trigger upgrade
- Further DAQ upgrade
- Shielding/beampipe for higher aperture
Performance Degradation of Silicon Tracker
Pixel sensors radiation

Hadron fluence after 3000 fb⁻¹

- $2 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2} \ @ \ r=3 \ \text{cm}$
- $3 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2} \ @ \ r=11 \ \text{cm}$
CMS Upgrade and Future Plans
ICNFP2014 August 2014

**LS1: Detector consolidation**
- Install originally planned ME4/2 + RE4/2
- Partially move DT electronics from detector to cavern and redesign in uTCA technology.
- Upgrade ME1/1 electronics.

**LS2: Anticipated phase-2 upgrades**
- Installation of GE1/1 Combined CSC+GEM trigger

**LS3: HL upgrades**
- Muon trigger: Additional detectors in forward region of all 4 stations
- Rapidity extension of tracker, calorimeter, and muon to $|\eta| \sim 4$
- Redesign of DT on-chamber electronics

Nominal lumi ~14 TeV
2 x lumi ~14 TeV

Phase 1
Phase 2

<\mathcal{L}> = 5 \times 10^{34} \text{ cm}^2\text{s}^{-1} 
3000 \text{ fb}^{-1}