CMS detector performance for HL-LHC

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for the CMS collaboration

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Workshop on the physics of HL-LHC,
and perspectives at HE-LHC
CERN
The Current CMS Detector

- **Silicon Tracker**
  - Pixels (100 x 150 μm²)
  - ~1m², ~66M channels
  - Microstrips (80-180μm)
  - ~200m², ~9.6M channels

- **Crystal Electromagnetic Calorimeter (ECAL)**
  - ~76k scintillating PbWO₄ crystals

- **Forward Calorimeter**
  - Steel + quartz fibres
  - ~2k channels

- **Preshower**
  - Silicon strips
  - ~16m², ~137k channels

- **MUON CHAMBERS**
  - Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
  - Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers

- **Superconducting Solenoid**
  - Niobium-titanium coil carrying ~18000 A

- **Hadron Calorimeter (HCAL)**
  - Brass + plastic scintillator
  - ~7k channels

- **Steel Return Yoke**
  - ~13000 tonnes

- **Total weight**: 14000 tonnes
- **Overall diameter**: 15.0 m
- **Overall length**: 28.7 m
- **Magnetic field**: 3.8 T

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The Current CMS Detector

Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g. Pion)
- Green dashed: Neutral Hadron (e.g. Neutron)
- Cyan: Photon
HL-LHC and Phase II Upgrades

- **HL-LHC**: Significant upgrade of LHC and injectors to increase beam intensity
  - $L_{\text{inst}} > 5 \times 10^{34} \text{ cm}^{-1} \text{ s}^{-1}$, up to **140-200 pileup**
  - Ultimate integrated luminosity target of **3000 fb$^{-1}$** (baseline)

- **Phase II Detector Upgrades**: Significant upgrades of ATLAS and CMS for HL-LHC conditions
  - Radiation hardness
  - Mitigate physics impact of high pileup

- **Physics Goals/Opportunities**:
  - Precision Higgs Measurements
  - Higgs Self Coupling
  - Precision Electroweak Measurements
  - Extend BSM searches to smaller production cross sections
  - Precision measurements of rare $B$ decays
  - Heavy Ion Physics
Real-life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches
CMS Phase II Upgrades

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature $= 10^\circ$

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta = 3.8$

Beam radiation and luminosity
Common systems and infrastructure
Tracker Upgrades

- Upgraded tracking detectors to cope with increased radiation hardness and occupancy demands
- Rapidity coverage of inner tracker (pixel detector) extended to $|\eta| = 4$
- Addition of hardware track trigger capabilities
Substantial reduction of the material budget with respect to present detector
Tracking Performance: Efficiency/Fake Rate

(a) $\epsilon$ (High $p_T$ muons)  
(b) Efficiency  
(c) Fake Rate

- High efficiency maintained across coverage
- Significant, but manageable increase of the fake rate with pileup
Tracking Transverse Momentum/Impact Parameter Resolution

CMS Simulation Preliminary

Simulated muons $p_T = 10$ GeV
- Phase-1 tracker
- Phase-2 tracker

(a) $p_t$

(b) $d_0$

- Significant improvements in resolution with respect to current detector

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L1 Track Trigger

- Outer tracker provides hardware trigger capabilities
- Readout of full detector at 40 MHz is not feasible → $p_T$ modules with two closely spaced sensors provide a **local** $p_T$ measurement, and allow on-detector application of $p_T$ thresholds for hardware trigger
- Hardware trigger receives track stubs with $p_T > 2$ GeV → 10-100x reduction in data-volume
- Coverage up to $|\eta| = 2.4$

![Diagram of track stubs and pass/fail criteria](image.png)

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**Chapter 6. Expected Performance**

**Figure 6.6:** L1 tracking efficiency versus generated particle $p_T$ for $|\eta| < 2.4$ (left) and versus $h$ for $p_T > 3$ GeV (right) for $t\bar{t}$ events in a scenario with 200 pileup events on average. Results for muons (electrons) are shown as filled black (open red) circles.

**Figure 6.7:** Total L1 track rate for $t\bar{t}$ events with an average pileup of zero (black circles), 140 (red triangles), and 200 (blue squares) events. Results are shown for scenarios in which truncation effects are (markers) or are not (dashed lines) considered in the emulation of L1 track processing. In all cases, the expected average track rates are easily accommodated by the downstream L1 trigger.

The resolutions of the $p_T$ and $z_0$ parameters of muons with $p_T > 10$ GeV in $t\bar{t}$ events are shown in Fig. 6.8 for various average pileup scenarios. The resolutions are defined in terms of an interval centred on the residual distribution that contains 68% or 90% of the tracks. As expected, resolutions degrade at forward pseudorapidity due to a corresponding increase in multiple scattering. In general, L1 parameter resolutions are excellent, which will provide for robust trigger object matching and charged particle reconstruction in the L1 trigger.

**6.3.2 Offline tracking performance**

Starting from 2026, the HL-LHC will achieve an instantaneous luminosity of $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, with a bunch spacing of 25 ns, as described in Chapter 1. In each bunch crossing, the CMS CMS Phase-2 Simulation Preliminary

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L1 Track Trigger Performance

- Performance shown for $p_T > 3$ GeV
- Excellent efficiency possible for muons
- Electrons are more challenging due to material interactions (further algorithmic improvements possible)
L1 Track Trigger Performance

- Performance shown for $p_T > 3$ GeV
- $z_0$ resolution sufficient for some level of pileup mitigation
Muon System Upgrades

- Upgrade electronics for radiation hardness and upgraded trigger/readout requirements
- Additional GEM chambers in front of existing forward muon (CSC) system, and additional RPC’s to improve trigger and reconstruction performance in region $1.6 < |\eta| < 2.4$
- ME0: New GEM chambers to extend muon system coverage to $|\eta| = 2.8$ and further improve trigger and reconstruction performance in $2.0 < |\eta| < 2.4$ region
Level 1 Muon Trigger

- Improved measurement of forward muons drastically reduces trigger rate at a given threshold, with increased efficiency.

(a) Trigger Rate

(b) Trigger Eff.

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Level 1 Muon Trigger

- High efficiency maintained over full trigger coverage up to $|\eta| < 2.4$ (further improvement possible with addition of ME0)
- Combination with track trigger dramatically improves momentum resolution

(a) Efficiency  
(b) Turn-on
Level 1 Displaced Muon Trigger

- Improved measurement of forward muons allows efficient triggering on displaced muons with greatly reduced rates (further reduction possible with track trigger veto).
- Improved timing resolution of RPC’s (O(ns)) allows efficient triggering on (slow-moving) Heavy Stable Charged Particles.

(a) Displaced Rate

(b) HSCP Eff.
Extended Muon $\eta$ Coverage

- ME0 extends offline muon reconstruction and identification to $|\eta| < 2.8$, relevant for many searches and measurements
- 17% increase in acceptance for $H \rightarrow ZZ \rightarrow 4\mu$
- Substantial reduction in “lost lepton” background for searches with same-sign dileptons

(a) Reco+ID Efficiency

(b) “Lost lepton” $|\eta|$ from WZ
Barrel Electromagnetic Calorimeter Upgrade

- Lower operating temperature to mitigate additional noise in APD’s due to radiation damage
- Upgrade electronics to accommodate trigger rate and latency requirements
- New electronics will provide full detector granularity to hardware trigger
- Significantly reduced shaping time and increase of sampling rate to 160 MHz for precision timing, improved suppression of anomalous signals and out-of-time pileup
Barrel Photon Energy Resolution

(a) Unconverted (3x3)  
(b) Inclusive

Several contributions to the energy resolution

- Additional noise in APD’s induced by radiation damage
- Constant term degraded by hadron-damage induced longitudinal non-uniformities
- In-time pileup contributes additional energy to clusters
- No containment/multivariate energy corrections tuned for these conditions

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Barrel Photon Energy Resolution

(a) Unconverted (3x3)

- Containment/Multivariate energy corrections not present here, but have large demonstrated gains in Run 1/2
- Expectation that with optimization of clustering, pileup suppression, multivariate energy corrections, performance will be much closer to current detector/conditions

(b) Inclusive

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Timing resolution limited by the APD dark current rather than the crystals themselves

Target resolution of 30 ps achievable for moderate energy photons

Precision timing can help matching of photons to primary vertices for photon id, di-photon invariant mass
Entirely new endcap calorimeter: High granularity silicon detector with tungsten/brass absorber in EE/FH

Plastic scintillator and brass absorber for back hadronic section
Full set of performance studies to come with TDR in the near future

(a) Energy Resolution

Silicon sensors have excellent time resolution for sufficiently large charge deposition → precision timing for ∼ all electromagnetic showers and hadronic showers of sufficiently high energy

(b) Shower Profile
(Central) Jet/b-tagging Performance

(a) Jet Energy Res.

(b) b-tag Efficiency
Pileup Jet Discrimination

- Extension of tracking acceptance leads to greatly improved pileup jet suppression over wider range of phase space for VBF-like processes.
But there are still challenges: Physics Impact of Pileup
(from CMS Phase-2 Scoping Document)

(a) $\mathbb{E}_T$ Tails

(b) Jets from PU

- Contamination of neutrals scales with overall PU to first order
Physics Impact of Pileup (from CMS Phase-2 Scoping Document)

(a) \( \slant E_T \) Tails

(b) EWK SUSY Search

- Significant impact on physics reach
Total amount of pileup and width of luminous region evolve over the course of a fill

Linear pileup density further varies over the luminous region
Primary vertex and tracks from hard interaction can still be reconstructed efficiently, but pileup contamination increases rapidly as a function of pileup density (pure geometric effect, independent of total pileup).

Quantities based on charged particles are currently nearly free of pileup, will not be so at HL-LHC.
Interactions are also distributed in time with a spread of 150-200 ps.

A detector with 10’s of ps timing resolution could meaningfully distinguish between interactions on the basis of timing.
Mitigation with Precision Timing

With sufficient time resolution and coverage for charged particles, traditional three-dimensional vertex fit can be upgraded to a four-dimensional fit.
Calorimeter upgrades can already provide precision timing for high energy photons in the central region, moderate energy photons, and higher energy hadrons in the forward region.

**Additional capabilities: MIP timing to cover large fraction of charged particles in the event**

**Targeting** \( \sigma_t = 30 \text{ ps} \)

**Extension to Phase-II Upgrade: MIP timing layer**

Concept for central region: Thin **LYSO + SiPM** layer built into tracker barrel support tube (in between tracker and ECal Barrel) → precision timing for charged particles and converted photons

Concept for forward region (more stringent radiation hardness requirements): **LGAD** (Silicon with Gain), with baseline location as additional final layer of strip tracker

**TP in preparation**
Effect of Precision Timing on Track-PV Association

- Total # of tracks/hard PV
- $\eta$ Coverage Variation

- $\sim 5x$ reduction in effective pileup in terms of charge multiplicity
Lepton Charged Isolation with Precision Timing

- Significant effect on lepton charged isolation efficiency at fixed working point (≈ constant background rejection)
Conclusions

- Comprehensive set of upgrades in progress for CMS at HL-LHC in order to cope with increased radiation dose and maintain physics performance at high pileup
- Still to come at this workshop: All of the exciting physics which is enabled by this upgraded detector with multiple ab$^{-1}$ of data from HL-LHC