Optimising the performance of the CMS Electromagnetic Calorimeter to measure Higgs properties during Phase I and Phase II of the LHC

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For the CMS Collaboration
Outline

1. The current detector: description and performance during LHC Phase 1
2. The high luminosity LHC (HL-LHC) upgrade
3. ECAL Barrel upgrade and expected performance during LHC Phase 2 (HL-LHC)
Current Detector
**The CMS Detector and the ECAL**

**Electromagnetic calorimeter (ECAL)**

**CMS:**
- Length: 21.5m
- Diameter: 15m
- Weight: 14kT
- Magnetic field: 3.8T

**ECAL:** the main component of CMS to detect and precisely measure the energies of electrons and photons.

**Goal:** excellent diphoton mass resolution (~1%), needed for H→γγ observation
Crystal Barrel & Endcaps (PbWO$_4$) + Lead/Si Preshower

Two crystal producers:
- BTCP (Russia)
- SIC (China)

Barrel (EB)
36 supermodules (1700 crystals)
Total of 61200 PbWO$_4$ crystals
Avalanche PhotoDiode readout coverage: $|\eta|<1.48$

Endcap (EE)
4 half-disks (3662 crystals)
Total of 14648 PbWO$_4$ crystals
Vacuum PhotoTriode readout coverage: $1.48<|\eta|<3.0$

Preshower (ES)
Two Lead/Si planes
137216 Si strips (1.8x61mm$^2$)
coverage: $1.65<|\eta|<2.6$
The excellent resolution and electron/photon ID of the CMS ECAL was crucial in the discovery and subsequent characterisation of the 125 GeV Higgs Boson.

The continued excellent performance of ECAL in the entire pseudorapidity range is a key component of many searches for new Physics.
Challenges during Run 2 (2015-2018)

Higher integrated Luminosity

CMS Integrated Luminosity Delivered, pp

Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC

Larger radiation dose:
increase of loss of light of crystals (transparency degradation), and
of radiation induced ageing of photodetectors and on detector readout

Larger pileup (PU):
from higher bunch intensities, and from 25ns bunch spacing (larger out-of-time PU) \rightarrow \text{impact on ECAL pulse reconstruction}
Significant response changes (crystal+photodetector) due to LHC irradiation. Monitoring of each channel via a dedicated laser system, is performed every 40 minutes and corrections are provided within 48 hours. These are crucial to maintain stable ECAL energy scale and resolution over time.
ECAL Energy reconstruction

Crucial to mitigate out-of-time pileup

Regular updates of pulse templates and baseline pedestals are performed to mitigate ageing effects on crystals and on-detector readout.
ECAL energy calibration updates

Crucial to maintain optimum resolution

Regular recalibrations using several in-situ methods

Equalise response of all channels to physics signals

Precision of better than 0.5% obtained in the central barrel (|\eta|<1.)

Regular recalibrations using W and Z electrons achieve the time stability of the di-electron invariant mass distribution

\[ \frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} + B + C \]
Excellent energy resolution maintained during run 2 as a result of improved energy reconstruction and regular recalibration.

Excellent Run 1 ECAL energy scale stability and resolution has been maintained in Run 2 despite significantly larger pileup and larger radiation-induced detector ageing.

For Run 3 (2021-2023) regular recalibration and optimized energy clustering are planned in order to mitigate the same effects (PU and ageing) and retain the excellent ECAL performance.

Di-electron invariant mass distribution using $Z\to ee$ low-bremsstrahlung electrons recalibrated data (green) shows improved performance.

Unfolded single electron fractional resolution vs $|\eta|$, from $Z\to ee$ events recalibrated data (blue) shows improved performance.
The High Luminosity LHC upgrade (HL-LHC)
HL-LHC: accelerator upgrade in Long Shutdown 3 (LS3) to provide x10 larger dataset for physics, focus on new physics searches, Higgs coupling and precision SM measurements.

Large increases in peak lumi, integrated dose relative to LHC:

<table>
<thead>
<tr>
<th></th>
<th>Inst. lumi (cm(^{-2})s(^{-1}))</th>
<th>peak pileup</th>
<th>integ. lumi (fb(^{-1})/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 2 (2018)</td>
<td>2.0(\times)10(^{34})</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Run 3 (2021-2023)</td>
<td>2.0(\times)10(^{34})</td>
<td>53</td>
<td>100</td>
</tr>
<tr>
<td>HL-LHC (baseline)</td>
<td>5(\times)10(^{34})</td>
<td>140</td>
<td>250</td>
</tr>
<tr>
<td>HL-LHC (stretch)</td>
<td>7.5(\times)10(^{34})</td>
<td>200</td>
<td>320</td>
</tr>
</tbody>
</table>

R. Tomas presentation at Chamonix 2017
γ dose and hadron fluences are higher closer to the beam pipe (Endcaps)—Caveat: this is the current geometry

Expected up to ~6 times higher hadron fluence level during High Luminosity LHC (HL-LHC) CMS-TDR-015

Barrel crystals will perform well during HL-LHC: will retain ~40% of light after 3000 fb⁻¹ (end of HL-LHC) with limited degradation of energy resolution

Endcaps will suffer large light output losses and a large degradation of the resolution

For HL-LHC, ECAL Endcaps will be replaced with High Granularity Calorimeter (HGCal)
ECAL Barrel Upgrade and performance
Plan to Refurbish ECAL Barrel Supermodules during LS3:2024-2026

1. **Crystals + APDs will be kept** and are expected to maintain performance throughout Phase 2
2. **Replace Front-End (FE) and Very-Front-End (VFE) readout to**
   1. Maintain performance in more challenging HL-LHC conditions (noise(x10), pileup(200/currently 60), APD spikes).
   2. Achieve precise (~30ps) timing measurements for high energy photons.
3. **New off-detector (OD) readout** to be compatible with increased CMS Phase 2 trigger requirements: higher output bandwidth(rate:750/currently100kHz; latency: 12.5/currently 4μs)
4. **Operate at lower temperature 9°C (now 18°C)** to mitigate the increase in noise due to radiation induced APD dark current and minimize its impact on resolution
Precise timing in Phase 2

needed to maintain the reconstruction performance at 140-200 pileup

-at 140-200 pileup the primary vertex efficiency is reduced (from 80% to 40% (at PU=140) and to 30% at PU=200) for $H \rightarrow \gamma\gamma$ decays

- the vertex localisation efficiency can be improved with precise (30ps) timing: 10% improvement in the fiducial cross-section sensitivity and $H \rightarrow \gamma\gamma$ resolution compared to no precise timing case

$H \rightarrow \gamma\gamma$ mass resolution with different assumptions on vertex efficiency:

- no precise timing
- adding precise timing in calorimeter
- adding precise MIP timing (timing layer (see N. Minafra talk in this conference))
-30ps timing resolution has been achieved in test beam evaluations of Phase 2 ECAL prototype electronics

2016: Trans Impedance Amplifier (TIA) discrete components @5GHz (5GS/s))

2018: first prototype ASIC TIA chip + commercial ADC @ 160MHz

The emulated sampling at 160MS/s shows a time resolution similar to that of 5GS/s

Test results with ADC sampling at 160MS/s show a time resolution that matches the 30ps target

Excellent Phase 1 Energy resolution retained

Phase 2 object reconstruction

Aim for the upgraded ECAL to preserve the current performance in the challenging HL-LHC conditions

Photon reconstruction efficiency

Photon energy resolution

Small impact of ageing

2.5-4% resolution for $E_T=50\text{GeV}$
Higgs Physics in Phase 2 with ECAL

Full details in Barrel Calorimeter Phase 2 TDR and the Physics at HL-LHC Report

HL-LHC will provide x10 larger dataset for physics

H→γγ resolution

Slow degradation with ageing

- With full optimisation, H→γγ resolutions expected to be achieved for Phase 2, up to 1000/fb are similar to run 2 and a slow degradation is expected beyond

- Couplings are expected to be determined with less than 5% uncertainties

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Higgs Physics in Phase 2 with ECAL

Full details in Barrel Calorimeter Phase 2 TDR and upcoming HL-LHC Yellow Report

**HH→b¯bγγ signal**

- Combined HH signal significance of 2.6σ (with HH→b¯bγγ as the best sensitivity channel)

- The Higgs self-coupling λ is expected to be in the interval $[0.35,1.9]*\lambda_{SM}$ at the 68% CL and in $[-0.18,3.6]*\lambda_{SM}$ at the 95% CL
Summary

- **Run 2**: Excellent ECAL energy resolution maintained
- **Run 3**: ECAL performance is also expected to be maintained with improved PU and ageing effects mitigation and optimised energy clustering

- **Phase 2**: Upgrade of ECAL barrel supermodules planned for LS3
- With Phase 2 upgrades CMS ECAL will continue to provide excellent photon/electron/jet performance for Higgs Physics, and meet the challenges of HL-LHC
Backup slides
ECAL Longevity

<table>
<thead>
<tr>
<th></th>
<th>LHC design</th>
<th>HL-LHC prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity [cm(^{-2})s(^{-1})]</td>
<td>1 \times 10^{34}</td>
<td>5 \times 10^{34}</td>
</tr>
<tr>
<td>Int. Luminosity [fb(^{-1})]</td>
<td>500</td>
<td>3000</td>
</tr>
<tr>
<td>(\gamma) dose rate (EB</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>[Gy/h] (EE</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>hadron fluence (EB</td>
<td>12 \times 10^{11}</td>
<td>7.6 \times 10^{12}</td>
</tr>
<tr>
<td>[cm(^{-2})] (EE</td>
<td>3 \times 10^{13}</td>
<td>2.0 \times 10^{14}</td>
</tr>
</tbody>
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Expected up to ~ 6 times higher radiation during High Luminosity LHC (HL-LHC).

Radiation is higher closer to the beam pipe (Endcaps) - Caveat: this is the current geometry.

Ionizing radiation damage:
- It recovers at room temperature
- Light transmission of crystals is constantly monitored in ECAL using laser light
- Evolution of the response is in agreement with expectations

Hadron damage:
- No recovery at room temperature
- Shift of transmission band edge
- Dominant losses at HL-LHC
- Measured correlation between the hadron fluence to which the crystals were exposed and the corresponding induced absorption coefficient.

- Measured loss of light output of proton-irradiated PbWO₄ crystals as a function of induced absorption, compared with simulation predictions.
ECAL energy calibration updates

Crucial to maintain optimum resolution

Regular recalibrations using several in-situ methods

Equalise response of all channels to physics signals

Precision of better than 0.5% obtained in the central barrel (|η|<1.)

Regular recalibrations using W and Z electrons

achieve the time stability of the di-electron invariant mass distribution
EB Phase II architecture

1. **TIA (Trans Impedance Amplifier) preamp:**
   1. Two gain ranges (G1, G10). 2 TeV dynamic range with 50 MeV LSB (= Least Significant Bit)

2. **ADC**
   1. 12 bit, 160 MHz sampling, dual channel with gain selection logic
   2. Data Transmission Unit (DTU) implements data compression before FE

3. **FE**
   1. lpGBT (4x10.24 Gb/s data links, 1x2.56 Gb/s control link)
   2. eLink serial interface to ADC, clock and i2C interface

4. **Low voltage regulator (LVR):**
   1. needed voltages (1.2, 2.5V) supplied by point-of-load FEAST DC/DC converters
ECAL trigger upgrade

1. **ECAL upgrade will replace on-detector and off-detector electronics**

2. **This will provide improved information to the Level-1 trigger**
   1. Full ECAL granularity available to L1 trigger (improved by factor of 25)
   2. Advanced clustering algorithms possible in new off-detector electronics with matching to Level-1 tracks—implement particle flow algorithms at L1
   3. Much improved rejection of spikes in the EB photodetectors
   4. due to new on-detector electronics with shorter pulse shaping

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### Current vs. Upgrade

**Current**
- Towers

**Upgrade**
- Crystals

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**25x better trigger granularity**

**Much better “spike” rejection**
Prediction of the ECAL Barrel Spike mitigation

Spike rate vs $E_T$ threshold at HL-LHC

Pulse shape discriminant

These upgrades are necessary to maintain good spike mitigation during HL-LHC running.

Shorter pulse shape
Schedule and planning

Overall schedule

---|---|---|---|---|---|---|---|---|---|---|---
LS2

Design/Prototyping | TDR | Engineering/Prototype testing | EDR | Pre-prod | Production | FLOAT

Supermodule refurbishment in LS3

Enfourneur installation (2wk)
Remove first SM of EB+, EB- (2wk)
Remove 17 SM of EB+, EB- (2wk)
Remove enfourneurs (2wk)
Electronics refurbishment (60wk)
Enfourneur installation (2wk)
Install 36 SM (3wk)
Remove enfourneurs (1wk)

Week during Long Shutdown 3

TDR submitted to LHCC this month