Performance of the CMS precision electromagnetic calorimeter at the LHC Run II and prospects for high-luminosity LHC

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on behalf of the CMS Collaboration

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ECAL is crucial in CMS physics analysis

- Excellent e/γ energy resolution
- Position measurement
CMS electromagnetic calorimeter (ECAL)

- Homogeneous and hermetic calorimeter
- Lead tungstate (PbWO$_4$) as scintillating crystals (61200 in EB, 7324 x 2 in EE)
  - Density: 8.28 g/cm$^3$
  - X$_0$ = 0.89 cm
  - Molière radius (R$_M$) = 2.2 cm
  - Size: 2.2 x 2.2 x 23 cm (EB), 2.86 x 2.86 x 22 cm (EE)
  - Granularity (EB): 360 in $\phi$ and 2 x 85 in $\eta$ (0.0174 x 0.0174)
- APDs/VPTs as photodetector
- 1% - 5% energy resolution for e/$\gamma$ from Z/H boson
e/\gamma energy reconstruction

- e/\gamma energy is reconstructed by the sum over all crystals in the supercluster (SC)

\[ E_{e,\gamma} = F_{e,\gamma} \cdot G \cdot \sum_i S_i(t) \cdot C_i \cdot A_i \]

- Dynamic clustering algorithm:
  - Crystal size \( R_M \rightarrow \) EM showers spread in several crystals
  - Basic clusters are extended in \( \phi \) direction to form supercluster to recover further energy spread due to magnetic field + conversion of photons / bremsstrahlung from electrons
pulse amplitude - $A_i$

CMS simulation, $\sqrt{s}=13$ TeV

PU=20/BX, 25 ns

- Observed signal
- Total pulse
- In-time pulse
- Out-of-time pulses

Each pulse from APD/VPT is digitized into 10 samples

$$
\chi^2 = \sum_{i=1}^{10} \frac{\sum_{j=1}^M A_j \times p_{ij} - S_i)^2}{\sigma_{S_i}^2}
$$

Weight method (Run I)

- Amplitude is a weighted sum of all 10 samples

Multifit (Run II)

- Contamination from out-of-time (OOT) pulses becomes more severe
- **Multifit**: pulse shape is modeled as in time pulse plus several OOT pulses (up to 9)
- Minimizing $\chi^2$ to get best in-time pulse amplitude
- Resolution improved w.r.t. Run I for $e/\gamma$ reconstruction (substantial for low $p_T$ ones)
response changes - $S_i(t)$

- Crystal transparency changes under radiation damage, and recovers through self-annealing during shutdowns.
- A laser monitoring (LM) system is used to measure such response change.
- Scan over all crystals in about 40 mins, and then the corrections are delivered in less than 48h for prompt reconstruction.

$$E_{e,\gamma} = F_{e,\gamma} \cdot G \cdot \sum_i S_i(t) \cdot C_i \cdot A_i$$
laser monitoring validation - $S_i(t)$

$E_{e,\gamma} = F_{e,\gamma} \cdot G \cdot \sum_i S_i(t) \cdot C_i \cdot A_i$

- **$\pi^0$ mass**
  - Huge amount of data for fast feedback (every few mins)
  - A dedicated trigger with high rate (~ 10 kHz) and small data size
  - RMS after LM correction (in 2017): 0.19% (EB)
laser monitoring validation - $S_i(t)$

- Ratio of energy $E$ (measure by ECAL) to the momentum $p$ (measured by tracker) to provide energy scale
- RMS after LM correction (in 2015): 0.15% (EB)
single channel intercalibration - $C_i$

**Intercalibration**
- Relative calibration between channels; equalize their crystal+APD/VPT responses

**Methods**
- **$\phi$-symmetry**: equalize the average transverse energy in crystals at constant $\eta$
- **$\pi^0/\eta$ mass**: iterative procedure to update the $C_i$ which corrects the diphoton mass (one photon centered on crystal i)
- **$E/p$**: iterative method based on ECAL energy and tracker momentum for isolated electrons from Z/W decays

$$E_{e,\gamma} = F_{e,\gamma} \cdot G \cdot \sum_i S_i(t) \cdot C_i \cdot A_i$$
single channel intercalibration - $C_i$

- Combination is weighted (by precision) mean of each method
- Precision (contributes to the constant term of final resolution):
  - Run I: 0.3-0.5% in EB
  - Run II: 0.5-1% in EB

$E_{e,\gamma} = F_{e,\gamma} \cdot G \cdot \sum_i S_i(t) \cdot C_i \cdot A_i$
supercluster energy correction - $F_{e,\gamma}$

**MVA technique**

- Supercluster energy containment:
  - Material budget before ECAL
  - Shower containment in supercluster: gaps, cracks between crystals ...
- MVA training with MC simulation
  - Gen level energy known
  - Crystal coordinates and shower shapes as input
  - Electrons and photons are tuned separately due to their different behaviors (conversion, bremsstrahlung)

**validation with Z->ee**

- Improvement on Z mass is demonstrated by using supercluster (vs. 5 x 5 cluster) and the MVA correction (vs. raw SC energy)
The absolute energy scale calibration $G$ is adjusted such that the fitted $Z\rightarrow ee$ peak in data agrees with that of the MC simulation.

$Z\rightarrow ee$ events are also used to calibrate the $\eta$ ring dependence of the energy reconstruction.

\[ E_{e,\gamma} = F_{e,\gamma} \cdot G \cdot \sum_i S_i(t) \cdot C_i \cdot A_i \]
energy resolution

- Single electron energy resolutions are measured by relating them to di-electron mass resolution of Z->ee events
  - Recalibration gives us significant improvement
  - Precision at the level of Run I in low $\eta$ region
- Higgs mass resolution is a combination of the resolutions of photon energies and the opening angle
challenges for HL-LHC

VBF $H \rightarrow \gamma \gamma$ with 200 PU
Energy resolution of irradiated crystals have been measured in test beam data with high energy electrons (10-150 GeV). Radiation damage affects all three terms:

- **Stochastic**: crystal light yield
- **Noise**: the noise term is amplified by the light output loss
- **Constant**: non-uniformity of the light collection

\[
\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c
\]

- Energy resolution of irradiated PbWO₄ crystals have been measured in test beam data with high energy electrons (10-150 GeV)
- Radiation damage affects all three terms:
  - **Stochastic**: crystal light yield
  - **Noise**: the noise term is amplified by the light output loss
  - **Constant**: non-uniformity of the light collection
EB upgrade strategies for HL-LHC

- Everything before motherboard remain unchanged
  - APD colder (from 18°C to 8°C) to mitigate radiation induced noise
- VFE: similar, optimize shaping time & sampling, to reduce OOT pile-up, spikes, noise and improve timing
- FE card becomes streaming readout, most processing off-detector
- Trigger: single crystal trigger primitive vs current 5x5 for spike rejection and improved trigger performance

See talks from Gianni Mazza, Alexander Ledovskoy


**timing performance: Run I vs. HL-LHC**

- Upgrades for timing improvement
  - VFE with Trans-impedance Amplifier (TIA)
  - Faster ADC sampling rates: 40MHZ to 160MHZ
- Promising intrinsic timing performance measured in test beam: 30ps resolution at $A/\sigma = 250$
  - HL-LHC start: $\sigma \sim 100$ MeV => 25 GeV photon
  - HL-LHC end: $\sigma \sim 240$ MeV => 60 GeV photon

See talk from Andrea Massironi

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$\sigma(t_1 - t_2) = \frac{N}{A_{\text{eff}}/\sigma_n} \oplus \sqrt{2\ C}$

$N = 35.1 \pm 0.2$ ns

$C = 0.020 \pm 0.004$ ns

$\chi^2 / \text{ndf} = 173 / 169$
energy resolution w/ vs. w/o upgrades

With the proposed upgrades, the energy resolution during HL-LHC will be maintained at the similar level of current Run II.
Summary

- Excellent ECAL performance is achieved in Run II in a similar level as in Run I.
- Upgrades are needed to maintain the performance in HL-LHC.
BACKUP