Performance of the CMS Electromagnetic Calorimeter

And the Challenge of the Calibration

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Physics with High Energy Photons

Low mass Higgs decays into $b, \tau, \gamma$
$
\gamma$ background well known
Relevant when looking for a small bump

SM Higgs: narrow resonance at low mass
Photon energy resolution drives discovery capability
The Compact Muon Solenoid at the Large Hadron Collider

**Large Hadron Collider (LHC)**
- Proton-proton collisions at $\sqrt{s} = 7$ TeV
- Achieved Luminosity $>2 \cdot 10^{33}$ cm$^{-2}$ s$^{-1}$ (1380 bunches)
- More than 1 fb$^{-1}$ data delivered

**Compact Muon Solenoid (CMS) Experiment**
The Electromagnetic Calorimeter (ECAL)

ECAL Features

- Homogeneous Calorimeter (>75000 PbWO₄ crystals)
- High density (8.3 g/cm³),
- Short Radiation Length (0.89 cm)
- Small Moliere Radius (2.2 cm)

Compact
Fine Granularity

Barrel
Preshower
Endcap

η=0

η=3

η=∞

pseudorapidity
ECAL Photodetectors

**Barrel:**
Avalanche PhotoDiodes (APD)
- two 5x5 mm² sensors
- high QE: ~75%
- Temp. Sensitivity -2.4%/°C

**Endcaps:**
Vacuum PhotoTriodes (VPT)
- 280 mm² sensor
- QE: ~20%
- More radiation tolerant than APDs

~4.5 photoelectrons/MeV @ 18 °C both in APD and VPT
Energy Measurement of Electromagnetic Objects

\[ E_{e,\gamma} = F_{e,\gamma}(\eta) \ G(\text{GeV}/\text{ADC}) \sum_i S_i(T, t) \times c_i \times A_i \]

1) \( A_i \): Measured Amplitude in each channel (ADC counts)
2) \( C_i \): Inter-Calibration Constants
3) \( S_i(T, t) \): Corrections for Transparency Loss (\( T = \) crystal transparency, \( t = \) time)
4) \( G \): ECAL Energy Scale: ADC to GeV Conversion Factor
5) \( F(\eta) \): Object Dependent Correction Factor \( \rightarrow \) Factorises Geometry and Material Effects

Design Energy Resolution

\[
\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{12\%}{E(\text{GeV})} \oplus 0.3\% 
\]

- stochastic
- noise
- constant
\[ E_{e,\gamma} = F_{e,\gamma}(\eta) \ G(GeV/ADC) \ \sum_i S_i(T, t) \times C_i \times A_i \]
Inter-Calibration Methods

Calibration Strategies:

❖ \(\phi\)-symmetry calibration: exploit the energy flow invariance around the beam axis
  ❖ Fast method. Calibration precision limited to \(\sim 1.4\%\)

❖ \(\pi^0\) calibration: photon pairs selected as \(\pi^0 \rightarrow \gamma\gamma\) candidates
  ❖ High statistics available (dedicated data stream in data acquisition flow)
  ❖ Allows both crystal inter-calibration and absolute scale calibration

❖ Isolated electrons from \(W\rightarrow e^+\nu\) and \(Z \rightarrow e^+e^-\): compare the energy measured in ECAL to
  the track momentum
  ❖ Several \(fb^{-1}\) needed to perform single crystal inter-calibration:
    integrated luminosity accumulated is not yet sufficient

❖ Di-electron resonances such as \(J/\psi \rightarrow e^+e^-\) and \(Z \rightarrow e^+e^-\): standard candles to define
  the ECAL energy scale.
  ❖ Larger data sample is needed. So far \(Z\) used to compute only global scale
Inter-Calibration Results

- Inter-Calibration precision combining all the methods
- Barrel: $|\eta| \sim 1$ rapid increase of material budget in front of ECAL
- Endcap: $(|\eta| < 1.6) \cup (|\eta| > 2.5)$ No Preshower Coverage
\[ E_{e,\gamma} = F_{e,\gamma}(\eta) \ G(\text{GeV}/\text{ADC}) \sum_i S_i(T, t) \times c_i \times A_i \]
Crystal Radiation Damage

- ECAL crystals have to withstand huge radiation levels

Radiation dose (in Gy) absorbed by ECAL. Corresponding integrated luminosity: 500 fb$^{-1}$

- Radiation $\rightarrow$ Wavelength-dependent loss of light transmission (w/o changes in scintillation)

- Crystal Transparency *drops* within a run by a few percent and *recovers* in the inter-fill periods
Correction for Crystal Transparency Loss: Method

- Inject fixed amount of light (laser) to monitor transparency loss
- **Blue Laser**: check transparency at scintillation wavelength
- **I-Red Laser**: check response stability (blind to color centers)
- Transparency Loss of ~1% in EB (~3% in EE) during 2010

**APD**: Avalanche Photodiode (EB)
**VPT**: Vacuum Phototriode (EE)
**PN**: Reference diode

Strongly correlated with LHC instantaneous luminosity

![Graph showing normalized APD/PN over time from March 2010 to December 2010]
Correction for Crystal Transparency Loss: Results

- Normalized $\pi^0$ invariant mass history from di-photon events
- Data before/after laser energy corrections
- In Barrel 1% drop if not accounting for crystal transparency loss
- Energy/Momentum Ratio for high energy electrons
- Electrons selected from $W\to e\nu$ decays
- $\pi^0$ and $e$ histories are not directly comparable (different rapidity reconstruction efficiency)
\[ E_{e,\gamma} = F_{e,\gamma}(\eta) \cdot G(\text{GeV/ADC}) \sum_i S_i(T, t) \times c_i \times A_i \]
Energy Scale Using $Z \rightarrow e^+e^-$ Decay

Energy scale measured at **test beam** for EB and EE separately

- Goal: equalizing energy sum of 5x5 crystal matrix to the electron beam energy

**In-situ** determination: reconstructing di-electron invariant mass of $Z$

- Requiring electrons emitting very low Bremsstrahlung

**Method**: matching reconstructed invariant mass peak position in data with MonteCarlo position (G-independent)

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**BARREL**

No scale adjustment

0.6% syst uncert

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**ENDCAP**

1% adjustment needed

1.5% syst uncert
Energy Resolution Using Z Width

- Fit to the Z shape using convolution of Breit-Wigner and Crystal-Ball (CB)
- $\Delta m_{CB}$: difference between CB mean and true Z mass. $\sigma_{CB}$: width of CB function
- Energy scale of data distribution scaled to match the mean of the MC distribution

Resolution measured on data matches MC expectation ($\sigma_{CB} \sim 1$ GeV for non-showering $e^{\pm}$)
Outcome of ECAL Performance: $H \rightarrow \gamma \gamma$ Results

- Search for $H \rightarrow \gamma \gamma$ performed with $1.09 \text{ fb}^{-1}$ (CMS PAS HIG-11-010)
- Excluded $x2 \div x6$ Standard Model Cross Section in $110 \text{ GeV} < m(H) < 135 \text{ GeV}$
- Observed limit within $2\sigma$ from expected value

![Graph showing CMS preliminary results for $\sigma \times BR(H \rightarrow \gamma \gamma)$ vs. $m_H$ (GeV/c^2) with observed CLs limit, observed Bayesian limit, median expected CLs limit, and expected CLs limits at $\pm 1\sigma$ and $\pm 2\sigma$. Almost there... annotation.]
Conclusions

- ECAL is facing a big challenge to keep energy resolution below 1% at $E(\gamma) \sim 100$ GeV with increasing machine luminosity.

- Inter-calibration, laser corrections and absolute scale proved to be well tuned to achieve design parameters during 2010 (and begin of 2011) data taking.

- $H \rightarrow \gamma \gamma$ is the main Physics channel profiting by ECAL performance, and it is now reaching the sensitivity to discover/exclude Standard Model Higgs.

- Inter-calibration and laser corrections have to keep improving to fully exploit ECAL potential and increase Higgs discovery reach.