The CMS Electromagnetic Calorimeter Calibration strategy

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On behalf of CMS ECAL Collaboration

CALOR04 - Perugia
01/04/2004
The performance of the CMS electromagnetic calorimeter (e.g. the discovery potential for a low mass Higgs Boson decaying into 2 photons) depends on its excellent energy resolution.

\[
\frac{\sigma}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.5\% \oplus \frac{150\ MeV}{E}
\]

**Constant term:** intercalibration precision goes directly into the constant term with very little scaling (due to the fact that most of the energy is in a single crystal)
Global calibration strategy

Before ECAL installation
- Calibration with an electron beam
- Calibration from laboratory measurements

After ECAL installation
- In situ calibration with physics events
- Laser monitoring system
  - Follow short time response variation of the detector
Calibration before installation

- It is anyhow important to have a starting point for the calorimeter calibration for the trigger threshold settings and to guarantee a reasonable initial resolution.

- Due to the tight CMS schedule few Super-Modules will be calibrated with high energy electrons at the 0.5% level.

- Most of the crystals will have calibration coming only from the laboratory measurements.
Source of Cobalt $^{60}$ ($2\gamma, \approx 1.2$ MeV)
- One measurement per cm along the crystal axis
- Typical LY is around 4-5 pe
- Precision of LY measurement: 4%

Extrapolation from 1.2 MeV to O(10-100) GeV !!!
Crystal LY is correlated with the position of the LT edge.

- LT is easier to measure than LY for PWO (more stable)

- LY can be predicted from LTO

\[
LY_{LTO} = 4.62 + 0.129 \cdot T_{360}
\]
Results from 2003 Test Beam

Using the average of direct LY and LY predicted from LTO

Using only direct LY
\[ \sigma = 4.63\% \]

\[ \chi^2/\text{ndf} = 15.98/10, \quad 7.625 \]

\[ \text{Mean} = 0.1149E-02, \quad 0.4046E-01 \]

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In-situ calibration

In-situ calibration with physics events is the main tool to reduce the constant term to the design goal of 0.5%.

• At the beginning of detector operation -> fast intercalibration method based on the $\phi$ symmetry in minimum bias events.

• Energetic electrons from $Z \rightarrow e^+ e^-$ decay -> intercalibration of different regions and absolute energy scale setting.

• Once the Tracker fully functional and aligned -> intercalibration of individual crystals with E/p measurement ($W \rightarrow e\nu$ events).

TRACKER MATERIAL:
the amount of material between interaction point and ECAL is the main difficulty in performing in situ calibration.
Tracker Material

- More than one rad. length in front of endcaps and part of the barrel
- High probability for Bremsstrahlung and photon conversion

The size of the tail is eta depending!

intrinsic ECAL resolution: 0.8%
Bremsstrahlung spoils the energy resolution.

SuperCluster from dynamic clustering algorithms

• It’s necessary to use electrons “with not too much Bremsstrahlung” (on going systematic studies finalized for the Physics TDR end 2005)

• Variables such as $E_{3x3}/E_{SC}$ and $E_{5x5}/E_{SC}$ allow to select good electrons mostly using only ECAL infos
Assumption: the total transverse energy deposited from a large number of events should be the same for all crystals at fixed $\eta$.

Aim: reduce the number of intercalibration constants at the startup: from 61200 (crystals) to 170 (rings) in the barrel.

Events used: 18M minimum bias crossings (few hours at $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ assuming 1 kHz of Level1 bandwidth for calibration) or jet events.
In-situ Calibration: $\phi$ symmetry (2)

$\phi$ symmetry is not exact
(tracker material not homogeneous)

Precision in case of limited knowledge of $\phi$ inhomogeneity:
1.3% - 3.5%

Results on fully simulated samples
In-situ Calibration: $Z \to e^+e^-$

- The rings can be rapidly intercalibrated using $Z \to e^+e^-$ without tracker momentum measurements, using reconstruction of the invariant mass.
- A large fraction of events allows to intercalibrate the endcaps with respect to the barrel.
- The $Z \to e^+e^-$ rate is $\approx 1$ Hz (almost flat in $\eta$).

\[
\sigma_{\text{cal}} \approx 2 \cdot \left( \frac{\sigma_Z}{M_Z} \frac{1}{\sqrt{N_{\text{electrons}}}} \right)
\]

100 electrons per $\eta$ ring are enough to calibrate at 0.5% level.
17000 selected $Z \to e^+e^-$ can be collected in less than one day at the startup.
In-situ Calibration: $Z \rightarrow e^+e^-$ (2)

Method: L3 iterative algorithm

$$C_n(\eta_j) = C_{n-1}(\eta_j) \cdot \frac{\sum_{i=1}^{\infty} \left( \frac{M_{Z_i}}{M_{\text{inv}_i}} \right)^\alpha}{\sum_{i=1}^{\infty} W_{i,j}}$$

Precision obtained on calibration coefficients ($C_{\text{OPT}}$) using the L3 method in less than one day at “low lumi” (with fully simulated sample of $Z \rightarrow e^+e^-$ starting with “miscalibrations” coefficients $C_{\text{MIS}}$)

$C_{\text{OPT}} \times C_{\text{MIS}}$ should be 1 (MC correct calibration) x average energy scale correction (due to clustering non containment varying with eta)

RMS 0.7 %
Type 1 Module

$0 < \gamma < 0.4$

RMS 0.9 %
Type 4 Module

$1.1 < \gamma < 1.5$
In-situ Calibration: $W \rightarrow e\nu$

Use of tracker measurements of electron momentum to obtain calibration coefficients for individual crystals. The electron shower involves many crystals, like in $Z \rightarrow e^+e^-$ calibration, therefore it needs to unscramble individually the calibration constants.

\[
\sigma_{\text{cal}} \approx \frac{\sigma(E/p)}{\sqrt{N_{\text{electrons}}}}
\]

Selection:
- optimize $E/p$ resolution over efficiency cutting out electrons with Bremsstrahlung

Assuming $E/p$ resolution at 2-3% 40-50 events per crystal to have the desired resolution (6-7 weeks at $2 \times 10^{33}$)

**L3 method**

\[
C_j^n = C_j^{n-1} \cdot \frac{\sum_{i=1}^{N_j} \left( \frac{E_{\text{track}}}{E_{5x5}} \right)_i \cdot w_{i,j}}{\sum_{i=1}^{N_j} w_{i,j}}
\]

Method not yet tested on full simulation. Ongoing work
High luminosity simulation at $\eta=0$, based on data taken in test beam

- PWO crystal transparency is reduced by radiation damage
- Damage level reaches an equilibrium after a small administered dose
- Partial damage recovery in few hours
- Loss in extracted light of few % is tolerable and can be followed by a laser monitor system between two adjacent calibration with physics events

See talk of Adolf Bornheim
The goal of ECAL calibration is to achieve a level of 0.5% for the constant term in energy resolution (dominated by intercalibration).

LY laboratory measurements allows an initial intercalibration at the level of $\approx 4\%$.

The amount of material in front of ECAL is a big hurdle in the calibration procedures.

At the startup it will be possible to intercalibrate at level of $\approx 1\text{-}2\%$ in a few of days using the $\phi$ symmetry method together with $Z \rightarrow e^+ e^-$ events.

$\sim 2$ months at $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, exploiting the full tracker information, the high statistics $W \rightarrow e\nu$ decays will allow to reach 0.5% resolution.
Backup
LY vs Transmission

\[ LY_{LTO} = 4.62 + 0.129 \cdot T_{360} \]

\[ s(LY_{MEAS}) = 0.65 \text{ pe/MeV} \]

\[ s(LY_{LTO} - LY_{MEAS}) = 0.44 \text{ pe/MeV} \]

mainly due to the LY experimental error
Results from 2003 Test Beam

LY from LTO(360nm) info only
LY=P1+P2*LTO(360nm)

N.B. almost the same resolution, so we decide to average LY and LY_LTO
Reconstruction vs eta

Containment vs eta (5x5)

- unconverted photon
- electron: no tracker
- electron: B=0
- electron: full

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Intermodule Gap

Figure 4: Illustration of the effect of the presence of inter-module gaps. The incident photon travels in a straight line from the interaction point. Due to the 3-dimensional pointing arrangement, such a particle can enter crystals on one side of an inter-module gap from a side face as well as from the front face. Such crystals therefore receive more hits than other crystals.
Laser monitoring (2)

- The relation between XL response to e \( (S/S_0) \) and response to laser \( (R/R_0) \) varies in the same way during recovery and irradiation phases.

- Crystals irradiated 2-3 times produce the same slope \( \alpha \)

- Light monitoring system operational and stable during the test beam

\[
\frac{S}{S_0} = \left( \frac{R}{R_0} \right)^\alpha
\]

\( \alpha = 1.6 \)

\( \sigma/\mu = 6.1\% \)
Calibration @ H4

- Cancel out the dependency of reconstructed energy on impact position looking for maximum response: IV order polynomial fit

selections: events in a $4 \times 10 \, \text{mm}^2$ region for polynomial fit, then events in a central $7 \times 7 \, \text{mm}^2$ region for the $E$ distribution (retains $\sim 25\%$ of events)

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No correction for the position

After the correction for the position
Calibration @ H4 (2)

- Estimate of channel response:
  
  Signal corrected for the position
  Composed fit (gaussian + exponential left tail) → Position of the peak

Relative calibration:

$$\alpha_i = \frac{M_i}{M_{\text{Ref}}}$$
Calibration @ H4 (3)

\[ \left( \frac{M_i}{M_0} \right)_{\text{First data set}} - \left( \frac{M_i}{M_0} \right)_{\text{Second data set}} \]

120 GeV, free gain - gain 9

RMS :\(\sim 0.3\%\)

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RMS :\(\sim 0.3\%\)