Calibration of the electromagnetic calorimeter of the CMS experiment

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Abstract. The calibration of the relative response of the individual channels, or intercalibration, and of the energy scale for electrons and photons are severe technical challenges for the operation of the electromagnetic calorimeter of the CMS experiment. The channel response uniformity within ECAL and stability in time will directly contribute to the overall energy resolution. Intercalibrations performed during the commissioning phase of the detector provide an acceptable performance at startup and a handle for validation of in situ calibration procedures based on the use of events collected during LHC operation. A laser monitoring system will be used to track response variations with time, as in the case of changes in crystal transparency caused by irradiation. Triggers, selections and reconstruction procedures of in situ calibration signals and their projected performance are reviewed. The interplay with reconstruction algorithms of electrons and photons is also discussed. Calibration procedures offer sufficient redundancy and flexibility to fast improve on startup conditions, intercalibrate the response of the individual channels towards a target precision of 0.5% and calibrate the energy scale of electrons and photons.

1. Introduction

The Compact Muon Solenoid (CMS) detector [1] is a general purpose detector installed at the new CERN proton collider (LHC). The Electromagnetic Calorimeter (ECAL) of CMS is a hermetic homogeneous calorimeter made of lead-tungstate (PbWO$_4$) crystals, equipped with avalanche photodiodes (APDs) in the central “barrel” part and vacuum phototriodes (VPT) in the end-caps for the light collection. The barrel calorimeter is organised into 36 supermodules, each containing 1,700 crystals arranged in four modules. It is closed at each end by an end-cap calorimeter consisting of two dees, each with 3662 crystals. The design of the calorimeter has been optimised for the detection of the Higgs boson through its electromagnetic decay ($H \rightarrow \gamma \gamma$). This requires an excellent energy resolution and fine granularity. The performance of the components of the calorimeter has been extensively tested with electron beams. The stochastic and electronic noise contributions to the energy resolution of ECAL have been demonstrated to match the design requirements [2, 3, 4].

An essential issue in CMS will be the channel response uniformity within ECAL, as this will contribute directly to the overall energy resolution. This uniformity is determined by the accuracy of the calibration of the relative response, or intercalibration, between different

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1 On behalf of the CMS Electromagnetic Calorimeter Group
channels across the detector. *In situ* calibrations with events collected during LHC operation are the main tool to achieve the target intercalibration precision of 0.5% required for detection of the $H \rightarrow \gamma \gamma$ decay. In addition, for optimal detector performance, the energy scale and linearity of the response to electromagnetic particles must be precisely calibrated. In CMS, electrons may lose energy through bremsstrahlung and photons may be converted into electron pairs in the Tracker material in front of ECAL. This will affect the energy measurement and resolution in ECAL and dedicated reconstruction algorithms have been developed to cope with the different cases [6]. These effects will also need to be calibrated *in situ*.

2. Intercalibration

The relative channel response spread affects the constant term of the energy resolution of ECAL in CMS with little dilution, as electromagnetic showers involve only a small number of crystals: unconverted photons deposit on average about 70% of their energy in a single crystal. The main sources of channel-to-channel response variation are the crystal light yield variation in the barrel, about 13% at construction, and the gain spread of the photodetectors in the endcaps, about 25%.

To reduce this spread and provide an acceptable performance of the detector at startup, different calibration procedures have been adopted during the construction and commissioning phase of ECAL. In particular, an intercalibration accuracy of 0.3% will be available at startup for nine ECAL barrel supermodules exposed to electron test beams. In addition, all the supermodules of the ECAL barrel have been commissioned in turn on a cosmic rays stand for a period of about one week. From these data, intercalibration coefficients with an accuracy better than 1.5% over most of the volume of a supermodule, raising to above 2% at the outer end (corresponding to $|\eta| \sim 1.5$) have been derived [7]. Due to tight construction constraints, the ECAL endcaps could not be intercalibrated with the same accuracy. Intercalibration coefficients at startup will be available with an accuracy of about 10-15%, derived from laboratory measurements of crystal light yield and photodetector response.

The pre-calibration accuracy of the ECAL barrel is adequate for LHC startup physics and for physics channels involving the measurements of electrons. For example, the impact of intercalibrations on the $Z$ mass resolution in $Z \rightarrow ee$ decays is marginal for intercalibration accuracies better than 2%: other effects, including the impact of the electron reconstruction, also contribute to the mass resolution. On the other hand, the intercalibration precision in the endcaps should be quickly reduced to a few percent by means of *in situ* calibration procedures exploiting LHC data. Improvements in the intercalibration accuracy will be monitored from the width of known resonances, including the $Z$ mass peak. *In situ* data must also be exploited to achieve the ultimate intercalibration precision over the entire detector.

With very first data, the invariance around the beam axis of the energy flow in minimum bias events (so-called $\phi$-invariance) can be exploited to rapidly confirm, and possibly improve on, the startup intercalibrations within fixed pseudorapidity regions [8]. An external input, for example provided by intercalibrations performed prior to installation or by other physics events, must be used to intercalibrate these regions to one another. According to Monte Carlo studies, this method is expected to provide an accuracy of a few percent with of about $20 \times 10^6$ minimum bias events. This accuracy represents the systematic limit of the procedure assuming ignorance of the distribution of the material in front of ECAL, which is a source of $\phi$-invariance violation. For fast calibration purposes at startup, a dedicated calibration trigger has been deployed: upon L1 minimum bias trigger, the High Level Trigger (HLT) module will unpack ECAL data, select and log only those crystals (about 20 per event on the average) above a tunable threshold. This will enable for logging data at 1 kHz rate, with minimum use of the bandwidth, and reach the systematic limit of the procedure within one day of data taking. Comparisons to pre-calibrations in the ECAL barrel, having a similar precision, will be used to validate the procedure. In the long
term this procedure could be refined with corrections for tracker and geometry effects derived through comparisons to other calibration data.

A promising channel for intercalibrations exploits the \( \pi^0 \) mass constraint on the energy of the two photons from the \( \pi^0 \to \gamma\gamma \) decay [9]. According to simulation, a clean sample of unconverted photons from \( \pi^0 \)'s decays can be selected by restricting the search of photon pairs within a few crystals (few degrees). Due to the magnetic field of CMS, converted photons of low energy are swept away or produce energy depositions well separated in ECAL. The use of unconverted photons reconstructed in \( 3 \times 3 \) fixed arrays of crystals prevents the intercalibration procedure from being complicated by the effects of energy radiation in the tracker. Thus, this calibration method is only indirectly affected by tracker material, through an efficiency loss and a worsening of the signal to background ratio in the detector regions where the tracker is thicker. An iterative procedure is used to unfold the individual crystal constants. According to simulation, an intercalibration accuracy of 0.5% can be achieved in the barrel with about 2000 photons per crystal from \( \pi^0 \) decays, for a typical signal to background ratio of about two. This event sample can be collected in a few days of data taking, if \( \pi^0 \) can be logged at 1 kHz rate. To this end, a dedicated calibration trigger has been developed, which unpacks ECAL data only in restricted regions around L1 electromagnetic candidates in QCD events. In the HLT filter, \( \pi^0 \) candidates are selected upon simple shower-shape, kinematics and isolation cuts. Bandwidth constraints are satisfied by logging only a minimal information around the candidates and dropping all the rest of the event. Detailed studies for the endcaps, including the use of the pre-shower in front of ECAL, are ongoing.

In the medium and long term, when the tracker will be precisely aligned and understood, isolated electrons, mainly from W decays, can be used to derive intercalibration coefficients. In this procedure the energy measured in ECAL is required to match the momentum measured in the tracker [10]. Isolated electrons with negligible radiation in the tracker are selected by means of shower shape variables and tracker information. These electrons, similarly to unconverted photons, are well reconstructed in \( 5 \times 5 \) fixed arrays of crystals. Thus the derivation of intercalibration constants is cleanly separated from reconstruction effects. The main drawback of this approach is a limited selection efficiency, of around 10%, in the regions at the end of the barrel and in the endcaps, due to the large amount of tracker material in front of ECAL. Yet, results of the full simulation shows that the target precision of 0.5% can be achieved after 5-10 fb\(^{-1}\), depending on the pseudorapidity.

3. Time stability of the channel response
An important part of the calibration procedure is the time stability of the calorimeter response. During LHC cycles, the ECAL response will vary depending on irradiation conditions, which modify the transparency of the PbWO\(_4\) crystals. These effects take place on a time scale of hours and cause transparency changes of a few percent at the design luminosity. The changes in crystal transparency will be monitored at 20 min intervals by means of laser light injected into each crystal through optical fibres. The capability of this system to allow correction for transparency changes was proved with test beam data [5].

4. Energy reconstruction of electrons and photons
The final goal of calibration is to achieve the best energy measurement for electrons and photons. Electromagnetic particles deposit their energy over several crystals and the energy estimate implies a sum over the corresponding channels. In addition to the intercalibration coefficients, a correction factor is also needed to relate the energy contained in these crystals to the energy of the incoming particle. This correction is particle, energy and position dependent: different reconstruction procedures are used for electrons, unconverted and converted photons. This is a consequence of the different interaction processes of these particles, of the significant variation
of the thickness of tracker material as a function of the pseudorapidity, of the small continuous variation of the ECAL geometry along the length of the barrel and of the variation of the structure of ECAL between the barrel and the endcaps.

The best energy estimate for unconverted photons, reaching ECAL without interactions in the material in front of it, is obtained by summing the energy deposited in fixed arrays of crystals, like \(5 \times 5\) crystal matrices. In this case, containment corrections are precisely known from test beam measurements, where electrons were targeted on the calorimeter without any material in front of it.

For electrons and converted photons, more sophisticated “clustering” algorithms [6] are used to collect the energy radiated in the tracker material by bremsstrahlung or photon conversions and spread azimuthally by the intense magnetic field of CMS. Not all the energy is collected, due to algorithm inefficiencies, and part of the energy, lost in the tracker and swept by the magnetic field, never reaches ECAL. Thus, algorithmic corrections based on Monte Carlo simulations of the CMS detector must be applied. Due to unavoidable imperfections of the Monte Carlo model, in particular in the description of the material budget in front of the calorimeter, these corrections must be tested and tuned on data, using events collected during LHC operation.

\[ Z \rightarrow ee \] events are the primary data sample to set the energy scale and test the algorithmic corrections for electrons, by using the \(Z\) mass constraint [11]. This procedure is largely independent of the tracker performance, which could be not optimal at startup. While a clean sample of \(Z \rightarrow ee\) can be selected, the event rate is insufficient for calibration of the individual channels. Still, these events are valuable to test and tune the \(\eta\) dependency of the algorithmic corrections. In addition, most methods of intercalibrations are local to a region of ECAL and \(Z \rightarrow ee\) events are useful to intercalibrate these regions to one another.

Another sample under consideration is the \(Z \rightarrow \mu\mu\gamma\) decay, where the photon comes from final state radiation. In these events, the \(Z\) mass constraint can be exploited to set the energy scale and tune the algorithmic corrections for converted photons. According to simulation, a large reduction of the major background, due to Drell-Yan events where one jet is mistaken for a photon, is possible by exploiting the \(\mu - \gamma\) collinearity. An event rate of about 1 photon per crystal per 1 fb\(^{-1}\) is anticipated.

5. Summary and conclusions

Precise calibration of the ECAL detector in CMS is a severe technical challenge and several effects need to be carefully controlled to achieve the per mil precision. Calibration performed during the commissioning phase of the detector provide an acceptable performance of the ECAL barrel of CMS for startup physics and also a valuable handle for validation of in situ calibration procedures. The ultimate calibration accuracy, including precise intercalibrations and calibration of the electron and photon energy scales, will be achieved in situ by exploiting the redundancy of independent data sets.

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