Performance of calorimeters at the LHC

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Abstract. The LHC is the new CERN hadron accelerator that has recently started to collide proton beams at 7 TeV center of mass energy. It features two general purpose experiments ATLAS and CMS and two specific experiments: LHCb to study b-quark physics and Alice to study heavy ions collisions. Electromagnetic and hadron calorimeters play a crucial role in the ATLAS and CMS experiments. High energy electrons and photons and missing transverse energy are used in most new particle searches. Calorimeters are also used in the experiment trigger.

This paper reviews the design of the various electromagnetic and hadronic calorimeters employed in the LHC experiments, their commissioning and the first results on the performance with beam.

1. Introduction

The LHC is the new CERN hadron accelerator that has recently started to collide proton beams at 7 TeV center of mass energy and may in the future reach energies up to 14 TeV. The design luminosity is $10^{34} \text{cm}^{-2}\text{s}^{-1}$ and the bunch crossing rate is 40 MHz.

It features two general purpose experiments: ATLAS and CMS and two dedicated experiments: LHCb that will study b-quark physics in the forward direction and Alice for heavy ion collisions.

The LHC is primarily a discovery machine to explore an unprecedented range of energies. Its main goal is to search for the Higgs boson and to study the physics beyond the Standard Model. In addition standard particles like top and beauty quarks can be produced and studied with large statistics.

The Higgs boson search will be performed exploiting the $H \rightarrow \gamma\gamma$ decay channel in the low Higgs mass range and the $H \rightarrow ZZ \rightarrow 4l$ decay to cover up to 1 TeV Higgs mass. These channels have electrons or photons in the final state and require an excellent energy and position resolutions for electrons and photons. The ATLAS and CMS electromagnetic calorimeters were optimized with these channels as bench-marks.

Supersymmetric particle searches will study channels with leptons, jets and neutralinos in the final state. Good jet energy and position resolution and good missing transverse energy reconstruction are important for these studies. The hadronic calorimeters of ATLAS and CMS have been optimized to have the best possible jet energy resolution and missing transverse energy ($E_T^{\text{miss}}$) resolution compatible with the space constraint of the experiment.

At the LHC the inelastic cross-section is about 70 mb while the new physics channels have a small cross-section. Only a few 100 Hz event rate can be recorded on tape so the trigger system is crucial. The calorimeter signals are integrated in the trigger logic.
The detectors were installed in the experimental cavern few years ago and at the beginning they were commissioned using cosmic rays. Then the LHC beams started to circulate in the accelerator and several beam splash events were recorded where single bunches of $10^9$ protons were sent on purpose on the closed collimators 150 metres upstream of the experiments. These events have proved to be important for timing and calibration studies. At the end of 2009 proton collisions were recorded at the injection energy (450 GeV per beam) and in the course of 2010 an energy of 3.5 TeV per beam was reached.

This paper describes the ATLAS and CMS electromagnetic and hadronic calorimeters design, commissioning and performance with first beams. Section 2 reviews the design principles for the LHC electromagnetic and hadronic calorimeters while section 3 and 4 describe the general experiment layout. The following sections describe in detail the ATLAS and CMS electromagnetic and hadronic calorimeters and review the status and performance of the detectors as it has been studied with cosmic rays, beam splashes and collision events.

Section 7 and 8 briefly outline the LHCb and Alice calorimeters.

2. Electromagnetic and hadronic calorimeters requirements

The ATLAS and CMS electromagnetic calorimeters were optimized for the Higgs boson search. In the $H \rightarrow \gamma \gamma$ channel, the typical photon energy is in the range above 50 GeV. This channel requires a very good energy and position resolution in order to reconstruct the Higgs invariant mass with a resolution of 1% and detect the Higgs mass peak over the large continuous background. The $H \rightarrow ZZ \rightarrow 4 \text{ electrons}$ decay requires a full $\eta \phi$ coverage up to $|\eta| = 3$ in order to detect the four electrons. The calorimeter energy range must be able to reach up to 1.5 TeV in order to detect electrons from possible $Z'$ bosons. The detectors must be fast to cope with the LHC bunch crossing rate of 40 MHz and give an input to the trigger. Radiation hardness has also been taken into account in the calorimeter project because of the unprecedented LHC design luminosity.

The energy resolution of a calorimeter can be parametrized as:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + \frac{b}{E} + c$$

where $a$ is the stochastic term, $b$ is the electronic noise term and $c$ is a constant term that includes effects of detector instabilities and mis-calibration. The stochastic term takes into account the statistical fluctuations in the shower detection and it is small for homogeneous calorimeters and larger for sampling calorimeters, but its effect decreases with growing energy.

Physics channels with jets require good energy and position resolution for high energy jets up to about 1 TeV. Simulations show that such energetic jets require at least 11 interaction lengths to be contained. New physics channels require good energy measurement for jets, hermeticity and a good resolution on missing transverse energy. Jets are made of an electromagnetic component as well, so good combined hadronic and electromagnetic energy resolution is required.

The space available for the ATLAS hadronic calorimeter is larger than for CMS due to the limited volume available inside the CMS solenoid. So the CMS hadronic calorimeter design was limited by space constraint.

Both ATLAS and CMS have installed forward calorimeters to tag forward jets and cover the solid angle up to $\eta = 5$. The radiation levels in the forward region are so high that the detector design was limited to very radiation hard materials. Nevertheless forward calorimeters have a reasonable forward energy measurement for missing $E_T$ resolution and are also employed for luminosity measurement.
3. The ATLAS experiment
ATLAS [1] is the largest of the four LHC experiments. It is 40 metres long and 22 metres high. It has a muon spectrometer embedded in a system of three toroidal magnets, a highly segmented lead-liquid argon electromagnetic calorimeter and a tile calorimeter for hadronic activity. A smaller 2 T solenoid surrounds the tracker, which has tracking and particle identification capability. The volume inside the muon spectrometer that is available for the calorimeters has a diameter of 8.5 metres.

4. The CMS experiment
The CMS experiment [2] is smaller in size than ATLAS. It is made of a superconducting solenoid that contains a full silicon tracker and the calorimeters. Muon chambers are embedded in the magnet iron return yoke. The electromagnetic calorimeter is a homogeneous crystal calorimeter. The hadron calorimeter is a compact tile calorimeter. The volume inside the solenoid that is available for the calorimeters has a diameter of 6 metres.

5. Electromagnetic calorimeters
5.1. The ATLAS electro-magnetic calorimeter
The ATLAS electromagnetic calorimeter is a sampling calorimeter made of accordion-shaped lead absorbers and liquid argon operated at a temperature of 87 K. The signal is given by the particle ionization in the liquid argon gap that is collected on the electrodes. The signal level is high, stable and radiation hard.

The calorimeter has a barrel and two endcap parts housed in three cryostats. The barrel covers $|\eta| < 1.475$ while the endcaps extend the coverage up to $|\eta| = 3.2$. The barrel readout is segmented in depth in three sections: a front, a middle and a back section. The central section cells are subdivided in $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. The front section has a more granular $\eta$ segmentation.

The design energy resolution is parametrized by:

$$\frac{\sigma(E)}{E} = \frac{10}{\sqrt{E}} \oplus \frac{170 \text{ MeV}}{E} \oplus 0.7\%.$$ \hspace{1cm} (2)

During the construction one of the challenges for this calorimeter was the high mechanical precision required in the thickness of the lead absorber. It had to be machined to 2 mm with a precision of 10 $\mu$m. Indeed a variation of 1% of the lead thickness would cause a 0.6% signal drop.

Another point of concern is the temperature stability in the cryostat due to a signal dependence on the temperature of -2 %/K. The calorimeter is equipped with 500 temperature probes. During the 2009 run it was shown that a temperature stability of 1.6 mK (maximum 5 mK) of each probe over a period of 10 days was achieved and the uniformity of the temperature across the calorimeter was between 50 and 70 mK for the barrel and endcaps, well below the required level of 100 mK.

The liquid argon signal is shaped, amplified and sampled by the front-end electronics. The energy calculation relies on the accurate knowledge of the electronics response. Regular calibration runs measure the electronics stability: the pedestal and noise levels, the electronic gains and the pulse shape with a test-pulse. During the 2009-2010 data-taking the pedestals, noise levels, gains and pulse shapes have been measured and proven to be stable. Figure 1 shows the pulse shape for the barrel middle layer of the calorimeter and the comparison with the predicted values.

The total number of channels is about 180 thousands and 98.5% of the channels are operational. Most of the faulty channels are due to non-functioning optical transmitters on the front-end electronics. This failure is expected to be repaired during the next LHC shutdown.
For what concerns the timing, the calorimeter has been preliminarily timed in using splash events.

The LAr calorimeter is used in the trigger. Figure 2 shows the trigger efficiency turn-on curve, produced using the collisions data at 7 TeV. This curve is given by the probability that an event with an offline reconstructed cluster of a given transverse energy has fired the Level1 trigger selecting electromagnetic clusters above 5 counts (approximately 5 GeV). As the figure shows, this trigger is fully efficient above 7-8 GeV.

Figure 3 shows the comparison between the LAr signal in Monte Carlo simulation and in 900 GeV collisions data. The excellent level of understanding of the calorimeter gives a superb agreement between data and simulation over several orders of magnitude.

Figure 1. Pulse shape of the ATLAS LAr Barrel calorimeter acquired with cosmic muons. The detector signal is shown superimposed with the expected signal. The acquired and predicted pulse shape are shown to agree at the percent level.

Figure 2. ATLAS LAr calorimeter trigger efficiency turn-on curve: it represents the probability that an event with an offline reconstructed cluster of a given transverse energy has fired the 5 GeV Level1 trigger.

Figure 3. The cell energy distribution for the ATLAS electromagnetic endcap calorimeter acquired during the 2009 data-taking. The data and Monte Carlo simulation are superimposed.

5.2. The CMS electro-magnetic calorimeter

The CMS electro-magnetic calorimeter (ECAL) is a homogeneous crystal calorimeter made of 75648 lead tungstate crystals (PbWO$_4$). The crystals are arranged in a barrel and two endcap sections. The barrel covers $|\eta|$ up to 1.47 while the endcaps extend the coverage up to $|\eta| = 3$. The barrel crystals cover $\Delta \eta \times \Delta \phi = 0.0174 \times 0.0174$. 


The lead tungstate crystals were specially developed through a 10 year R&D project by SIC (China) and BTCP (Russia). PbWO$_4$ is a very dense material, its radiation length is 0.89 cm and it has a Molière radius of 2.2 cm. This property has allowed to build a very compact calorimeter of 25 X$_0$ in only 23 cm. The scintillation light is low compared to other scintillating materials, and it is peaked around 420 nm. So photo-detectors with internal amplification were chosen: Avalanche Photo-Diodes (APD) in the barrel and Vacuum Photo-Triodes (VPT) in the endcaps.

A lead-silicon strip pre-shower is installed in front of the endcap crystals. The ECAL target energy resolution is below 0.5% for high energy unconverted photons. The resolution measured in test-beams with electrons is:

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{120\,MeV}{E} \oplus 0.3\%.$$  

(3)

Since it is a homogeneous calorimeter, the effect of the very small stochastic and noise term become negligible at 50 GeV. The real challenge for the ECAL energy resolution at high energy is the constant term.

During the construction special care was devoted to making sure that the crystal light collection was uniform along the crystal depth. In fact there can be large fluctuations in the position of the first interaction of electrons and photons. Thus the shower maximum position can vary considerably from event to event. If the crystal light yield is not uniform along its depth, the energy resolution is sensitive to these fluctuations. Thanks to the crystal quality control, the contribution to the constant term due to this effect is limited to 0.3%.

Both the crystal light yield and APD gain have a strong temperature dependence, which give a signal variation of -4%/°C. Measurements taken during the 2009 data-taking show that the calorimeter cooling apparatus stabilizes the temperature at the level of 0.03°C.

Another point of concern is the crystal radiation hardness. Under irradiation lead tungstate crystals tend to lose transparency and consequently the signal deteriorates. A very sophisticated monitoring system based on blue laser light monitors the crystal transparency constantly. Figure 4 shows a typical crystal laser signal acquired for a period of 350 hours during 2010 collisions. A stability of 0.1% is observed. This shows both that the calorimeter environment variables (temperature, high voltage, low voltage,...) are stabilized at the permill level and that the signal from the monitoring system is under control at the same level.

The total number of channels is 75648 and more than 99% are operational.

The calorimeter has been preliminarily timed in using splash events and collisions at the 0.3 ns level.

The calorimeter is used in the Level1 trigger and preliminary efficiency turn-on curves have been produced with cosmics in 2008 and with collisions in 2009-2010.

During the 2009-2010 data-taking, anomalous crystal signals were observed in the barrel. These signals appear as isolated single crystal high energy deposits. This effect is under investigation and it seems to be due to low energy neutron interactions in the APDs. Algorithms have been studied to reject these signals based on timing and shower shape variables. After this selection, the agreement between data and Monte Carlo is superb (see Figure 5).

5.3. Detector commissioning and performance
In this section few common points are discussed and compared for ATLAS and CMS. In particular the calibration and the material budget in front of the calorimeters.

5.3.1. Calibration The ATLAS LAr calorimeter is by construction mechanically very uniform. The electronics calibration system measures the gain and response of each signal with an electronics path that is almost identical to the ionization signal one. Ten percent of the
calorimeter modules were exposed to test-beam. The uniformity of response was verified in the test-beams and measured at the level of 0.45% within one module. The long range non-uniformity will be measured using physics events (like \( Z \rightarrow e^+e^- \) or \( W \rightarrow e\nu \)) and is expected to limit this effect at the level of 0.7%.

The CMS ECAL crystals and photon sensors were measured during construction and provide a starting calibration at the 4% level. All barrel modules were calibrated with cosmic rays at the 1-2% level. Twenty-five percent of the ECAL barrel modules were calibrated with high energy electron beams at the 0.4%. This calibration allows to set a preliminary absolute scale. Various physics channels are exploited to improve the inter-calibrations and to check the energy scale, in particular \( \pi^0 \rightarrow \gamma\gamma \), \( Z \rightarrow e^+e^- \) or \( W \rightarrow e\nu \) and \( \phi \) symmetry in minimum bias events.

### 5.3.2. Material budget

A common problem that the ATLAS and CMS calorimeters have faced, compared with previous collider calorimeters, is the material budget in front of them. The ATLAS and CMS trackers constitute 0.5-1.5 \( X_0 \) of material depending on \( \eta \). In front of the ATLAS LAr calorimeter there is also the solenoid coil that brings the material to 2 \( X_0 \) at \( \eta = 0 \).

This amount of material is such that a large fraction of photons convert in electron-positron pairs before reaching the calorimeters. Figure 6 and Figure 7 shows the conversion vertex for photons measured in 2009-2010 collision data by ATLAS and CMS. The position of these vertices can be attributed to the various pixel and tracker layers.

For what concerns the electrons, the combined effect of a heavy tracker and a strong magnetic field is such that the radiated Bremsstrahlung photons may hit the calorimeter at a considerable distance from the impact position of the electron shower. In particular in CMS, where the magnetic field is 3.8 T in the tracker volume, 50% of the electrons give a non negligible radiation. A special electron tracking algorithm has been studied to reconstruct tracks with big kinks, and a special clustering algorithm has been developed to recover radiated photons in the direction of the track curvature. Figure 8 shows the fraction of radiated energy for electrons in 2009 collisions data. This variable is calculated as the difference between the track momentum measured by the innermost track hits \( P_{in} \) and the outer ones \( P_{out} \) divided by \( P_{in} \). Data and Monte Carlo events show a good agreement on this complex effect.
5.4. Performance
During the 2009-2010 LHC run both the ATLAS and CMS electromagnetic calorimeters have proven to be ready for data-taking: the detectors are well timed in, they are used in the trigger, the design stability on the environment parameters is reached and there is a superb level of accuracy in the Monte Carlo description of the detector.

Both experiments have started to analyze beam collision data and have produced preliminary photon pairs invariant mass plots in minimum bias events that show a clear sign of the $\pi^0$ peak. Photons are selected with a transverse energy above 300 MeV for ATLAS and 400 MeV for CMS. The calorimeters are not designed for optimal resolution at these low energies. In fact electronics noise levels and channel readout in zero-suppression mode have a non negligible effect not allowing an optimal shower reconstruction. Nevertheless the peak position is well centered on the real $\pi^0$ mass. The resolution for the $\pi^0$ mass is 19 MeV for ATLAS and 14 MeV for CMS and it is well described by Monte Carlo simulation.

6. Hadronic calorimeters
6.1. The ATLAS hadronic calorimeter
The ATLAS hadronic calorimeter is made of several parts:

- a sampling calorimeter made of steel and plastic scintillator tiles covers the barrel part up to $|\eta| = 1.7$. The tiles are arranged perpendicular to the beam axis. Wavelength shifting fibers carry the light to photo-multiplier tubes located at the back of the calorimeter modules.

Figure 6. Location of the conversion vertex for converted photon events in ATLAS (2009 collision data).

Figure 7. Location of the conversion vertex for converted photon events in CMS (2010 collision data).

Figure 8. Fraction of radiated energy for electrons in 2009 collisions data. This variable is defined as the difference between the track momentum measured by the innermost track hits $P_{in}$ and the outer ones $P_{out}$ divided by $P_{in}$.
• an endcap part made of copper and liquid argon is embedded in the endcap e.m. calorimeter cryostat.

• a forward calorimeter (FCal) installed in the cryostat extends the coverage up to $|\eta| = 5$. It is made of copper and liquid argon (for the electromagnetic section) and tungsten and liquid argon (for the hadronic section).

The standalone tile calorimeter energy resolution obtained in test-beams for single pions is:

$$\frac{\sigma(E)}{E} = \frac{52.9\%}{\sqrt{E}} \oplus 5.7\%.$$  \hspace{1cm} (4)

The electronic noise is negligible and so it is not used in the fit.

The detector is installed and taking data since long. It amounts to 9800 channels, out of which 97.3% are operational. The detector signal is used in the trigger to detect events with high energy jets.

The endcap liquid argon hadronic calorimeter and forward calorimeter constitute respectively 5600 and 3500 channels and are fully efficient.

6.2. The CMS hadronic calorimeter

The CMS hadronic calorimeter (HCAL) is a sampling calorimeter made of brass and plastic scintillator tiles. The tiles are arranged parallel to the beam axis in the barrel. The scintillation light is shifted in the visible region via wavelength shifting fibers and detected with HPD (hybrid photodiodes). One HPD can read multiple channels. The Barrel section covers $|\eta| < 1.2$, the endcaps extend the coverage up to $|\eta| < 3$. A forward calorimeter (HF) made of steel and quartz fiber covers $|\eta| < 5.2$.

The barrel and endcap parts have about 5000 channels in total and are fully operational. The HF has 1700 channels and is fully operational.

The detector was well timed using splash events and is used in the jet trigger.

The CMS HCAL is taking data since the beginning and is already starting to see some very high energy jet events, as the one represented in Figure 9.

![Figure 9. A very high energetic di-jet event recorded by the CMS experiment during 2010 collisions at 7 TeV.](image)

6.3. Detector performance

Two effects limit the hadron calorimeter resolution: non containment and non compensation.

The ATLAS calorimeter reaches $10 \lambda_I$ at $\eta = 0$ and more than $12 \lambda_I$ in the endcaps.
Due to the limited space available in the experiment design inside the magnet coil, the CMS ECAL and HCAL reach $7 \lambda_I$ at $\eta = 0$. Data collected during beam tests have shown that 5% of the energy deposited by a 300 GeV pion escape detection. The installation of an additional layer of scintillator outside the magnet coil (called HO) improves the energy resolution for high energy pions and recovers linearity.

Non compensation is a common problem for the calorimeter system of both experiments. Indeed both hadronic calorimeters have an electron over hadron ratio of approximately 1.4 and the electromagnetic part in front is non compensating, so the combined energy measurement of the hadronic and electromagnetic section is highly non compensating. This causes intrinsic sensitivity to fluctuations in the electromagnetic component of the shower and of the jets, and non linearity. In general the non linearity can be corrected, but the sensitivity to the fluctuation remains and causes a poor resolution. Indeed test-beam analysis shows that before and after non-linearity correction the combined energy resolution of the CMS HCAL+ECAL for pions is:

$$\sigma(E) = 110.7\% \pm 7.3\% \text{ (before correction)} \text{ and } \sigma(E) = 84.7\% \pm 7.4\% \text{ (after correction)}.$$ (5)

In conclusion the choices made for the hadronic central section by ATLAS and CMS are similar: sampling calorimeters with scintillator as active material. In both cases the dominant factor on resolution and linearity is the non compensation. CMS HCAL space limitation have conditioned the design and performance ATLAS higher segmentation and containment gives a better total resolution.

6.4. Particle flow analysis technique

The particle flow technique principle is to follow the particle signals through the experiment and measure their energy with the most performant detector for each particle type and energy. This technique identifies each energy deposit in the calorimeters and matches it to tracks. The energy of matched objects is evaluated using track momentum. Unmatched energy deposits are attributed to neutral hadronic or electromagnetic objects, depending where they occur and measured by the calorimeters.

Normally this technique requires highly segmented calorimeters (to disentangle overlapping showers) and powerful tracker detectors. However an attempt has been done to use it also in CMS, which has a very powerful tracker, a fine grain electromagnetic calorimeter, but a hadron calorimeter with poor granularity. The results of this analysis are encouraging. The power of the particle flow technique is best seen in the calculation of the missing transverse energy and of the total transverse energy and it will be shown in Section 6.5.

6.5. Missing transverse energy and total energy measurements

The measurement of the missing transverse energy is a key ingredient of many important analyses: W bosons, top quark events and supersymmetric particle searches.

Normally the missing transverse energy and the total energy measurements are calculated using the calorimeter cells only. These quantities are particularly sensitive to noise levels in the detectors. Using higher level objects like clusters, rather than single calorimetric energy deposits, helps to reduce the sensitivity to noise.

At colliders the missing transverse energy is defined as minus the vector sum of the transverse energy deposits

$$E_T^{miss} = -\sum_i \vec{E}_T^i.$$ (6)

Also its components along the x and y axes are often used $(E_T^{miss})_{x,y}$. Another important quantity that is often referred to is the total transverse energy, which is the scalar sum of the transverse energy deposits:

$$\Sigma E_T = \Sigma_i E_T^i.$$ (7)
This last quantity is very challenging because the calorimeter noise adds up in the sum.

The missing transverse energy components along the x and y axes are very useful because their distribution allows to obtain the missing transverse energy resolution from data directly. This helps considerably in the understanding of subtle detector effects that may enter the computation. However it should be stressed that the resolution in $(E_{T}^{\text{miss}})_{x,y}$ should always be quoted as a function of the total transverse energy defined above. Indeed a strong cut on the minimum cluster energy considered in the calculation may falsely improve the resolution on $(E_{T}^{\text{miss}})_{x,y}$, while reducing the total transverse energy.

Among the subtle effects that were cleared during this analysis, it is worth mentioning for CMS the anomalous ECAL signals and HF noise, and for ATLAS the misalignment of the forward calorimeter.

CMS particle flow studies have shown that the resolution in the total transverse energy is more gaussian than for the standard calorimetric cells computation.

Figure 10 and 11 compares the $(E_{T}^{\text{miss}})_{x,y}$ distribution for data and simulated events at $\sqrt{s} = 7$ TeV in ATLAS and CMS. The ATLAS analysis is based on topological clusters where a basic noise suppression is used in the clustering algorithm. The CMS data are based on the particle flow technique discussed in Section 6.4. Figure 12 and 13 shows the $(E_{T}^{\text{miss}})_{x,y}$ resolution as a function of the total transverse energy. A fit to the points gives:

$$\sigma((E_{T}^{\text{miss}})_{x,y}) = 37\% \sqrt{\Sigma E_{T}} \text{ for ATLAS and } \sigma((E_{T}^{\text{miss}})_{x,y}) = 45\% \sqrt{\Sigma E_{T}} \text{ for CMS.}$$

However the ATLAS hadron calorimeter is calibrated at the electro-magnetic energy scale, and, since the calorimeter is non compensating, the $\Sigma E_{T}$ horizontal scale cannot be directly compared with the CMS plot.

**Figure 10.** Distribution of the missing transverse energy in the x direction in ATLAS calculated with topological clusters.

**Figure 11.** Distribution of the missing transverse energy in the x,y direction in CMS calculated using the particle flow technique.

7. The LHCb experiment

The LHCb experiment [3] uses high production rate of b-quarks at small angle at the LHC to perform a thorough study of the CP-simmetry violation in the neutral B meson systems. It is a single arm spectrometer that covers an angle from the beam of 10-300 mrad. The
Figure 12. Resolution on the missing transverse energy in the x,y direction as a function of the total transverse energy in ATLAS. The calorimeter energy is calibrated at the e.m. scale.

Figure 13. Resolution on the missing transverse energy in the x,y direction as a function of the total transverse energy in CMS using the particle flow technique.

The detector is well timed in (at the level of 1 ns) and 99.8% of the channels are operational. A hadron calorimeter made of iron and scintillator tiles completes the calorimeter system of the experiment. It constitutes 5.6 $\lambda_f$.

There are high radiation levels at small angle. A monitoring system based on LED light is installed to monitor the calorimeter stability. The detector was not calibrated with cosmics underground due to the small statistics of cosmic rays that match the horizontal geometry of the LHCb experiment. The calibration is being performed using collision events and in particular with the energy flow method (equalizing the detector signals in symmetric regions) and with $\pi^0 \rightarrow \gamma\gamma$ decay. Simulation shows that the detector can be calibrated at the 1% level with 50 million events. Figure 14 shows the $\pi^0$ peak reconstructed by LHCb. The reconstructed mass is in good agreement with expectations and the resolution is of 10 MeV.

8. The Alice experiment
Alice [4] is an experiment dedicated to heavy ion collisions. Its purpose is to study strongly interacting matter at high densities where the formation of quark-gluon plasma is expected. In order to do this, Alice needs to study and measure the spectra of hadrons, electrons, photons and muons produced in the collisions.

The Alice experiment is installed inside a large magnet that provides an axial field of 0.5 T. In order to measure the spectra of photons, $\pi^0$ and $\eta$ in the range of 0.5-10 GeV it has installed a precise electromagnetic calorimeter that covers a limited region in $\eta$ and $\phi$ at 4.6 metres from
the interaction point. It is made of 18000 lead tungstate crystals read by avalanche photodiodes. Three of the five modules were installed for the 2009-2010 data-taking. The crystals measure 18 cm in length (20 \textit{X}_0) and they are operated at -25 °C in order to increase the light yield and improve the signal to noise ratio. The crystals were not calibrated prior to installation.

The energy resolution measured in test-beams is:

$$\frac{\sigma(E)}{E} = \frac{3.3\%}{\sqrt{E}} \oplus \frac{18 \, \text{MeV}}{E} \oplus 1.1\%.$$  \hspace{1cm} (10)

9. Conclusions

It was a challenging adventure to build calorimeters with this unprecedented number of channels and the required level of stability and reliability for 10 years or more in the LHC environment. It took almost 20 years from design to construction and operation. All calorimeters are in good shape, they are well timed in and are used in the first level trigger algorithms.

They are well understood detectors with spectacular agreement between data and Monte Carlo simulation on basic and complex observables.

They are precious instruments for a new era in high energy physics going to explore a completely new range of energies.

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