Calorimeters: key detectors for LHC physics

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Abstract. The calorimeters designed for the LHC experiments are reviewed. Their expected performance is compared with the requirements set at the beginning of the project.

1. Introduction

Two decades after the launch of the projects, the LHC experiments are now almost completely installed and ready to take data at the start of LHC. Calorimeters are crucial detectors for this physics program. From the first edition to the present one, the CALOR Conference series were a privileged observatory to follow the design, development and construction of the LHC calorimeters. Today is probably the right moment for an assessment on the achievements of the different projects and on the perspectives of their exploitation.

2. Requirements for hadron collider calorimeters

Since the first concept of LHC, a hadron collider aiming to complete the exploration of the Standard Model, the physics goal was clearly set to the study of the origin of the electroweak symmetry breaking, whose mass scale is expected below 1 TeV. In this respect, a crucial benchmark is the discovery of the Higgs boson, whose small cross section demands high luminosity in the machine and high resolution in the detectors to fight backgrounds: in its search, calorimeters are needed for the detection of electrons, photons and jets. Later on, supersymmetry gained more and more favour as the simplest Standard Model extension providing natural mechanisms to avoid an implausible fine tuning of the parameters. For SUSY signals, missing energy is the key signature, enhancing once more the relevance of calorimetric measurements.

It is of some interest to look back at the CALOR91 edition in Capri, where for the first time a large fraction of the program was devoted to the calorimeters for hadron colliders. In the paper by D. Green [1] a list of requirements for calorimeters was given and discussed. The main items and their arguments are summarized here:

- hermiticity and speed were obvious requirements; the angular coverage was set to $\eta = 3$ for electrons and $\eta = 5$ for hadrons;
- trigger capability was a natural bonus of the fast and granular signals provided by the calorimeters;
- the containment of the upstream material was considered a must to many respects: a limit at less than $1X_0$ for the coil material and less than $0.1X_0$ for the more dangerous tracking material was set;
the depth of the hadronic section was set to 10 absorption lengths by the requirement to reconstruct dijet masses up to 10 TeV;

• a transverse segmentation of 0.05-0.1 rad for the hadron section and 0.05 rad or better for the e.m. section was set to detect showers coming from isolated electrons and match them with their tracks;

• longitudinal segmentation was required for both sections, but the emphasis in the e.m. part was to give a handle, on an event by event basis, to correct for longitudinal inhomogeneities in the shower response, due to an expected severe damage by radiation;

• finally, the resolution: the e.m. one was clearly driven by the \( H \rightarrow \gamma\gamma \) benchmark signal, but thanks to the \( E^{-1/2} \) stochastic term, improving with energy, the key figure was identified in the constant term, with a better-than-1% goal; the hadronic stochastic term was set around 0.7%, with a strong requirement for compensation (\( |e/h - 1| \) better than 30%) to provide the linearity needed to detect possible deviations of jet cross-sections with respect to QCD predictions: "linearity is more important than precision".

Even though some points of view changed with time, these requirements remain valid and can be used to benchmark the performance of the calorimeters as they have been built.

3. LHC experiments
The CERN Large Hadron Collider is coming into operation and should give first proton-proton collisions at \( \sqrt{s} = 10 \) TeV in the second half of 2008, moving on to the design energy of \( \sqrt{s} = 14 \) TeV in 2009. Four big experiments will take data at LHC: two of them, ATLAS and CMS, are general purpose detectors, aiming at discovering the Higgs boson and exploring the physics beyond the Standard Model; the other two are dedicated to specific physics: LHCb to the study of \( b \) physics and ALICE to heavy ion collisions.

General purpose experiments have to measure electrons, photons and jets: calorimeters play a key role not only to reconstruct with good precision invariant masses from two photons and two or four electrons in the Higgs decay chains, but also to identify complex decay chains (as the ones expected from the decay of supersymmetric particles) by reconstructing and measuring electrons, jets and missing transverse energy, as shown in figure 1.

Different choices in the magnetic field configuration lead to quite different general schemes for ATLAS and CMS:

• ATLAS [2] has an air muon spectrometer with three huge toroidal magnets. The tracker is inserted in a 2 T solenoid, while an highly segmented lead/liquid-Argon (LAr) e.m. calorimeter is placed behind it. Hadronic activity is measured by an iron/scintillating-tile sandwich in the barrel and LAr in the end-caps. In the very forward region (\( 3.2 < \eta < 4.9 \)) a tubular structure with very narrow LAr gaps integrates the e.m. section (LAR/Cu) with the hadron section (LAr/W).

• CMS [3] has a compact solenoidal magnet (4 T) containing the calorimeters and the silicon tracker, while muon chambers are embedded in the iron return yoke. The e.m. calorimeter is made by homogeneous PbWO\(_4\) scintillating crystals, while the hadron calorimeter employs the scintillating tile technique everywhere but in the forward region (\( 3 < \eta < 5 \)), where an iron/quartz-fiber structure, sampling the Čerenkov light, is installed. In the barrel region, a tail catcher is placed behind the coil to detect the tails of the hadronic showers.

4. Triggering with calorimeters
As said before, calorimeters play a very important role in the trigger of the experiments, as they provide fast and granular signals able to identify the electromagnetic clusters, to detect the presence of jets, to tag both events with large transverse energy and those with high transverse
missing energy, and to determine the isolation for all the leptons and photons candidates. In practically all the cases, the calorimetric information is available already at the first level of trigger (L1), and can obviously be refined at higher trigger levels and in the off-line analysis.

An example is the CMS "regional calo trigger", which provides at L1 isolated electron or photon candidates not only by comparing the deposit in the electromagnetic trigger tower with the one in the hadronic towers (both with a granularity of $\Delta \phi \Delta \eta = 0.087 \times 0.087$), but also looking at the so called ”fine grain profiles”, namely dominos of $2 \times 5$ crystals in $\eta, \phi$ allowing to identify narrow shower profiles in $\eta$ compatible with electromagnetic showers (being the spread in $\phi$ larger due to bremsstrahlung in high magnetic field), as shown in figure 2.

5. Electromagnetic calorimeters

5.1. Requirements for electromagnetic calorimeters

The requirements for the LHC electromagnetic calorimeters are direct consequences of the general requirements and experimental environment of LHC: they must provide large acceptance, good energy and position resolution for high energy em showers up to $|\eta| < 2.5$, they must be fast, compact and granular to cope with the expected high event rates, they have to be radiation tolerant, to provide a large dynamic range, from MIP to the TeV scale, they have to be linear and finally they must provide particle identification, in particular to separate electrons from jets and photons from $\pi^0$s.

Both calorimeters fulfill these requirements:

- the ATLAS LAr-Pb sampling calorimeter with the novel technique of the "accordion" shape of the layers gives a special emphasis on high granularity, both longitudinal and transverse. As a consequence it can provide a good $\gamma/\pi^0$ separation.
- the CMS calorimeter focuses more on an excellent energy resolution given by the choice of homogeneous PbWO$_4$ crystals as shower detectors, relaxing the requirements on $\gamma/\pi^0$ separation.
5.2. The ATLAS e.m. calorimeter

The Atlas electromagnetic calorimeter is made by layers of lead and liquid-argon, shaped in an accordion structure to allow an easy read-out of the longitudinal towers, as schematically shown in figure 3.

The length is 22 $X_0$ (47 cm) at $\eta = 0$, increasing with $\eta$. It is subdivided in 3 longitudinal layers with a pre-sampler just outside the superconducting coil. The first 4 $X_0$ are finely segmented in $\eta$ by use of cathode strips, $\Delta \eta = 0.0031$ wide, to provide a good $\gamma/\pi^0$ rejection. The following 16 $X_0$ are read in towers of $\Delta \phi \times \Delta \eta = 0.0245 \times 0.025$ and measure the shower core. The last 2 $X_0$, with larger granularity, are to evaluate late showers. In total, there are 170000 readout channels.

One of the challenges of this design is the control of the mechanical uniformities. As an example, a 1% variation of the lead thickness would correspond to a 6 per mill change in the response. The measured spread on the absorber thickness has a $\sigma$ of 9 $\mu$m around the average value of 2.2 mm. Other parameters to be controlled are the variation of the accordion slant angle and the sagging of the layer structure.

The resolution measured with an electron beam at $\eta = 0.687$ [4] can be represented as

$$\sigma(E)/E = (10.1 \pm 0.1)%/\sqrt{E(\text{GeV})} \oplus (0.17 \pm 0.04)%$$

after noise subtraction. The linearity is within 1% from 15 to 180 GeV. The uniformity of the response was measured scanning in $\eta$ the modules with 245.6 GeV monochromatic electrons, showing a variation within 0.44% in the barrel. At this energy, the resolution goes from 0.7% at $\eta = 0$ to 0.9% at $\eta = 1.5$. From these figures a global constant term of 0.6% can be evaluated.
5.3. The CMS e.m. calorimeter

The overall structure of the calorimeter is shown in figure 4.

The main features of PbWO$_4$ scintillating crystals are the extremely short radiation length and Molière radius ($X_0 = 0.89$ cm, $R_M = 2.2$ cm), allowing the realization of a compact calorimeter ($\Delta \phi \times \Delta \eta = 0.0245 \times 0.0245$ in the barrel), with fast light emission (80% in 25 ns) but a reduced light yield (100 photons per MeV). An intensive R&D program has been developed since the selection of these particular crystals to ensure the mass production of optically clear, fast and radiation resistant crystals [8]. Ionizing radiation produces a loss of light transmission without changes to the scintillation mechanism. The damage can be tracked and corrected for by monitoring the optical transparency with injected laser light. To ensure an adequate performance throughout the duration of the experiment, production crystals were required to exhibit radiation hardness properties quantified as an induced light attenuation length greater than approximately 3 times the crystal length when the damage is saturated.

The light is read in the barrel by Avalanche PhotoDiodes (two for each crystal), insensitive to the 4T magnetic field, especially developed by Hamamatsu for CMS (operated at gain 50) and Vacuum Photo-Triodes in the end-caps, insensitive to the expected high radiation level and able to operate in a magnetic field almost parallel to their axis.

The resolution of CMS ECAL can be parametrized as [5]

$$\sigma(E)/E = 2.8%/\sqrt{E(\text{GeV})} \oplus 0.12/E(\text{GeV}) \oplus 0.3\%$$

for central impact electrons.
Figure 4. The structure of the CMS ECAL: Barrel crystals ($|\eta| < 1.48$) are grouped in 36 Supermodules containing 1700 crystals each, for a total of 61200 crystals. End-caps are divided into four "Dees" made by "supercrystals" ($5 \times 5$ crystals each), for a total of 14648 crystals, covering $1.48 < |\eta| < 3$. A Pb/Si pre-shower is placed in front of the Endcaps.

5.4. Calibration of e.m. calorimeters
One of the main problems of a precision calorimeter is the calibration of the channels. The associated uncertainty directly contributes to the constant term, which tend to be dominant at high energies, where the stochastic term is naturally dumped. The conversion of the individual channel response to the incident particle energy requires several steps, each introducing some conversion factor. As an example, in the CMS energy reconstruction, first the digitized signals have to be multiplied by intercalibration constants and then a cluster algorithm selects the channels to be summed up. At this stage, an overall correction factor must be applied to the sum of energies, depending on the cluster algorithm and including containment corrections, but also the dependence of the response on the impact position, particle type and other possible parameters. Finally, an overall scale factor must provide the right absolute energy scale.

ATLAS will start data taking with channels intercalibrated at better than 1%, thanks to the mechanical uniformity in the modules construction and to an electronic calibration system. Checks of the calibration were performed on 10% of the modules in test beams. In the long term, precise in situ absolute calibrations will be provided by electron decays of $W$ and $Z$: 50 $Z \rightarrow e^+e^-$ events, corresponding to 0.1 fb$^{-1}$ integrated luminosity will provide a global constant term better than 0.7%.

CMS calibrated one quarter of the calorimeter at an electron beam, reaching an intercalibration of 0.3%. All Supermodules were calibrated with cosmic rays prior to installation, with a precision better than 2%, as shown by comparison with test beam calibrations. In situ fast equalization at 1.5 to 2% can be reached exploiting the $\phi$ symmetry of the detector in the energy deposition of minimum-bias events. In the long term, intercalibration can be obtained by comparing the energy and the momentum of the electrons from $W$ decays, while absolute calibration can be obtained by looking at the reconstructed invariant mass of $Z \rightarrow e^+e^-$ events. From $W$ alone, 5 fb$^{-1}$ are required to get better than 5 per mill intercalibrations in the center of the barrel, but Monte Carlo studies show that faster calibration is possible by $\pi^0$ mass reconstruction.
5.5. Material budget in front of e.m. calorimeters

Material budget from the tracker and other services (including the coil for the ATLAS solenoidal magnet) has always been a big concern, often increasing with an improved definition of the central detector parameters. Because of the tracker material, electrons loose energy via bremsstrahlung, while photons convert in $e^+e^-$ pairs. Moreover, the high solenoidal magnetic field bends electrons, so that the radiated energy is spread in $\phi$. So, the effects of the material are different for photons and electrons, while the strategies for in situ calibrations rely on electrons but the results have to be applied to photons as well. The material of the tracker maximizes these effects, but in principle a detailed track reconstruction could help at least to identify more affected events. On the contrary, material immediately in front of the calorimeter can be considered as an additional sampling, less contributing to the energy spread in $\phi$.

In CMS, the tracker material goes from $0.4X_0$ at $\eta = 0$ up to $1.4X_0$ (of which $0.4X_0$ is the material outside the sensitive area) around $\eta = 1.7$, then decreasing to $0.8X_0$ at $\eta = 2.5$. 50% of electrons undergo non negligible bremsstrahlung. Most of the energy spread can be recuperated by means of dynamic cluster algorithms, summing adjacent clusters in extended $\phi$ windows. In ATLAS, a constant amount of $2X_0$ is due to the coil everywhere, and the maximum amount of material, in the region of transition from barrel to endcap, reaches $6X_0$.

6. Hadron calorimeters

6.1. Role of hadron calorimeters at LHC

Hadron calorimeters are crucial in all the physics channels with jets, requiring good energy and position resolution for energies up to the TeV scale. This sets to $10\lambda_{int}$ the minimum depth required. All the new particles searches demand hermeticity in jet measurement to provide good resolution in missing energy. Jets are made of an e.m. component as well, so good combined hadronic and e.m. resolution is required. In addition, forward calorimeters are also requested to tag forward jets in the "combined production channels" and must maintain a good jet energy measurement to preserve the missing $E_T$ resolution.

6.2. ATLAS hadron calorimeters

The barrel ATLAS HCAL is a sandwich of iron and plastic scintillator tiles perpendicular to the beam axis, grouped in towers with granularity $\Delta\phi \times \Delta\eta = (0.1 - 0.2) \times 0.1$. Each tower is segmented in three longitudinal samplings, for a total of 9852 channels. Wavelength shifting fibers carry the light to photomultipliers (mounted on the back of the towers). The barrel covers $|\eta| < 1.7$ and surrounds both the EM barrel and the forward calorimeters, with a depth of 10 to $13\lambda_{int}$. The energy resolution for pions at $\eta = 0.35$ is

$$\sigma(E)/E = 56.4\%/\sqrt{E(\text{GeV})} \oplus 5.5\%.$$ 

The End-cap HCAL is made of copper/Liquid argon layers mounted in two wheels for each side (behind the e.m. section), has a depth of 10 to $12.5\lambda_{int}$ and a granularity $\Delta\phi \times \Delta\eta = (0.1 - 0.2) \times (0.1 - 0.2)$ in four longitudinal samplings, resulting in 5632 channels.

The forward calorimeter covers $3.2 < |\eta| < 4.9$ and integrates the e.m. and the hadronic section. Both have a tubular structure with very narrow LAr gaps. The absorber is copper for the $27.6 X_0$ of the e.m. section and tungsten for the $7.48 \lambda_{int}$ of the hadronic section, divided into two samplings. There are 3524 channels in total.

6.3. CMS hadron calorimeters

CMS hadron barrel calorimeter is made by brass/plastic-scintillator tiles, parallel to the beam axis. Wave-length shifting fibers are coupled to clear fibers leading the light to pixel Hybrid
Photo-Diodes mounted at the end-side of the barrel. There are 2593 towers without longitudinal segmentation. The HCAL is $7\lambda_{int}$ deep at $\eta = 0$. The energy resolution is

$$\sigma(E)/E = 100%/\sqrt{E(\text{GeV})} \oplus 8\%.$$ 

To improve the energy resolution and the linearity, an additional layer is placed outside the coil, adding $3\lambda_{int}$ and improving by 10% the energy resolution for 300 GeV pions.

The forward region, $3 < |\eta| < 5$, is covered by a radiation resistant iron/quartz fiber structure, detecting the Čerenkov light emitted in the quartz. Fibers are of two different lengths, the longer ones starting from the front face, the shorter ones after 22 cm. With this arrangement, the energy deposited in the first section, corresponding to the e.m. showers, can be determined by subtraction of the signals from the two kinds of fibers. In total, there are 1728 towers, with a segmentation $\Delta \phi \times \Delta \eta = 0.175 \times 0.175$.

6.4. Missing $E_T$ resolution

The differences in the hadron calorimeter resolutions reflect in the resolution on the sum of $E_T$, corresponding to the missing $E_T$ resolution. This is $0.48/\sqrt{\sum E_T}$ for ATLAS and $0.97/\sqrt{\sum E_T}$ for CMS. However, both experiments show similar performance in the search for SUSY particles in inclusive channels with jets and missing $E_T$ [6, 7]. The reason for that is that what really matters in these searches is the hermeticity of the detector (and, obviously, its correct description in the Monte Carlo simulations) rather than the missing $E_T$ resolution.

7. Combined energy measurements

In the past years, a big effort was put in the test-beam measurements of the combined performances of the e.m. and the hadron calorimeters of both experiments. ATLAS launched this work since 1996, developing a “cell weighting” technique, where a different weight, varying with the energy, is applied separately to each e.m or hadronic cell. The result [9] is a linearity within $\pm 2\%$ from 20 to 300 GeV and a resolution represented by

$$\sigma(E)/E = 52%/\sqrt{E(\text{GeV})} \oplus 1.6/E(\text{GeV}) \oplus 3\%.$$ 

The combined test of ECAL and HCAL in CMS is more recent, and some results are reported at this Conference [10]. The main result is that adopting an ”optimized” sum of the energies, a linearity better than $2\%$ from 5 to 300 GeV is obtained.

8. 1991 requirements revisited

If we confront the actual parameters of the calorimeters and their measured performance with the general requirements outlined in sect. 2, we see that most of them are fulfilled: hermeticity, angular coverage, speed and trigger capability are satisfied in both experiments. The same is true for the expected resolutions, which are even beyond expectation for CMS e.m. and ATLAS hadronic sections respectively. The transverse segmentation of the e.m. sections is a factor two below the 1991 figures. The hadronic transverse segmentation is not as good, but this is not considered a big deal. ATLAS also provides extended longitudinal segmentation in all sections, though the main purpose of this solution, the handle against radiation damage, is no more expected to be necessary because of the detector choices. The HCAL depth is above $10\lambda_{int}$ for ATLAS only, though also CMS reaches this limit taking into account also the tail catcher.

None of the two experiments aimed at an intrinsic e.m./hadron compensation. However, both are hardly working to recuperate the required linearity by means of some kind of software compensation, based on a refined weighting of the different energy deposits, well performing on test beam data.
The only item where some concern remains, is then the material in front of both electromagnetic calorimeters. This material is much larger for ATLAS than for CMS, but due to the better nominal resolution, the effect could be important for the latter too, also because of the higher magnetic field, which is spreading the energy for electrons over a larger azimuthal region. The degradation of the resolution has been studied extensively in both experiments and tools for taking it into account have been developed. The effect is already included in all the simulations leading to the estimations of signal-to-noise ratios in all the main physics cases. However, everything relies for the moment on the Monte Carlo description of the inner material: in particular the different behaviour of photons, where we seek the best resolution, and electrons, which will be mainly used to get the best calibration of the response.

9. LHCb Calorimeters

The LHCb Collaboration [11] exploits the high production rate of $B$ particles at small angle to study the CP-symmetry violation in the neutral $B$ meson systems. The experiment is a single arm spectrometer, covering angles from 10 to 300 mrad.

The purpose of the calorimeters in LHCb is twofold: to provide electron/hadron separation at the trigger level and in off-line analysis; to measure the position and energy for electrons/photons and hadrons. The calorimetric section is placed at more than 12 meters from the interaction point and is organized in four layers:

- a scintillating pad detector (SPD), made of 6016 cells, whose light is transmitted through WLS fibers to photomultiplier tubes;
- a preshower (PS) with a 2.5 $X_0$ lead sheet followed by a second scintillating pad with the same structure of SPD;
- an e.m. calorimeter (ECAL) made of a Pb/scintillator sandwich in the "shashlick" configuration, with WLS fibers read by photomultipliers; the lateral size is $7.8 \times 6.3$ m$^2$ with three tower granularities going from the center to the side;
- a hadron calorimeter (HCAL) made by 16 cm iron layers and 4 mm scintillating tiles, with a total depth of $5.6 \lambda_{int}$; it has a surface of $8.4 \times 6.8$ m$^2$.

At the trigger level, the calorimeters alone can identify and measure electrons, photons and hadrons: the SPD tags the charged particles, the PS identifies the electromagnetic nature of the shower, the two calorimeters provide the estimate of the transverse energy.

The resolution of the ECAL is

$$\sigma(E)/E = 10\%/\sqrt{E(\text{GeV})} \pm 1\%$$

up to 100 GeV. The ECAL will be calibrated in situ by energy flow, by comparing the energy of the electrons with their momentum measured in the spectrometer and from the $\pi^0$ mass reconstruction. The HCAL has been precalibrated by means of a Cs source and its response will be followed in situ by a LED system.

10. ALICE Calorimeters

ALICE Collaboration [12] is building a dedicated heavy-ion experiment for nucleus-nucleus interactions, to study strongly interacting matter at high densities where the formation of quark-gluon plasma is expected. To investigate the nature of this process, they have to detect and measure hadrons, electrons, muons and photons produced at LHC in the collisions of lead nuclei at 5.5 TeV/nucleon-pair.

One of the key detectors is the photon spectrometer, PHOS, acting as a quark-gluon plasma thermometer: the spectrum of the emitted photons is related to the temperature of the source.
To measure this spectrum, a large coverage is not required, so the solution adopted was a limited-coverage high-resolution calorimeter.

A wider angle electromagnetic calorimeter, EMCAL, has been recently approved and funded. It will be a projective Pb-scintillator sampling calorimeter, installed back to back with PHOS. The details of this project will be presented at this Conference [13].

10.1. The PHOS calorimeter

The purpose of PHOS is to measure photons, $\pi^0$, and $\eta$ in the energy range from 0.5 to 100 GeV. It covers $|\eta| < 0.12$ and $\Phi < 100^\circ$ with a granularity $\Delta\phi \times \Delta\eta = 0.004 \times 0.004$. It is made of 18000 PbWO$_4$ scintillating crystals, $22 \times 22 \times 180$ mm$^3$ each, positioned at 4.6 meters from the interaction point. The crystals are operated at -25 C$^\circ$ and read out by a single APD of the same type of the CMS ones. One out of five modules is already installed and the whole detector will be completed in 2010.

The resolution measured at electron test-beams can be parametrised as

$$\sigma(E)/E = 3.3%/\sqrt{E(\text{GeV})} \oplus 0.18/E(\text{GeV}) \oplus 1.1\%$$

and is consistent with ALICE requirements.

11. Conclusions

The calorimeters for LHC experiments are almost ready to take data. Their design and construction gave a big contribution to the development of calorimetric techniques. In spite of the tight requirements, some of them at the limit of the available technologies, these detectors passed extended tests demonstrating the ability to meet the design specification. In a few months, a new, unexplored physics domain will hopefully be reached and will try out their performance.

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