Effects of Calorimeter Peculiarities on the Jet Energy Scale

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Abstract. It is well known that non-compensating calorimeters, such as the ones used in the general purpose experiments at the Tevatron and the LHC, offer particular problems for correctly reconstructing the energy deposited by single hadrons and jets. In this talk, I will review these problems, discuss the remedies usually employed, and possible alternatives. I also briefly review the options for hadron calorimetry at a future Lepton Collider, where jet spectroscopy is expected to become a major experimental tool.

1. Introduction

The question of the jet energy scale (JES) in modern particle physics experiments is crucially linked to the interpretation of the signals provided by the calorimeter system. The fact that a special workshop is organized to discuss this issue indicates that this interpretation is far from trivial indeed, especially if the experiments use non-compensating calorimeters, which is true for all general-purpose experiments at the Tevatron and the Large Hadron Collider. The non-triviality mainly concerns the calibration of longitudinally segmented calorimeter systems. In this talk, I will first describe some general consequences of non-compensation that affect the JES. Most of my time will be spend on describing different methods that are used to intercalibrate the sections of longitudinally segmented calorimeter systems, and their (adverse) consequences. At the end, I will briefly discuss new developments that may affect the future of hadron calorimetry in particle physics experiments.

2. General aspects of hadron calorimetry relevant for the jet energy scale

The absorption of a high-energy hadron in dense matter is characterized by two components, which we will call the electromagnetic (em) and non-electromagnetic shower component. The em component is initiated by $\pi^0$s and other electromagnetically decaying hadrons, while the non-em component encompasses everything else that occurs in the absorption process. The latter component is dominated by nuclear processes: release of protons, neutrons and nucleon aggregates from the nuclear environment in which they are bound. The nuclear binding energy that has to be provided to make these processes possible does itself not contribute to the measurable calorimeter signals. It is usually referred to as invisible energy, and may comprise on average up to 40% of the energy carried by the non-em shower component. Mainly as a result of this invisible energy, the calorimeter response, i.e., the average signal per unit deposited energy, to the non-em shower component is typically considerably smaller than the em response. Because of the large variety in possible nuclear reactions (and associated binding energy...
losses), the width of the non-em response function is also larger than that of the em one, where invisible energy plays no role. Both effects are schematically illustrated in Figure 1. The ratio of the mean values of these distributions, i.e., the ratio of the em and non-em responses, is known as the e/h value of the calorimeter. In this example, $e/h = 1.8$, which means that on average $1 - 1/1.8 = 44\%$ of the non-em energy does not contribute to the calorimeter signals. Calorimeters with $e/h \neq 1$ are usually called non-compensating.

A shower induced by a high-energy pion has both an em and a non-em component. The response function of the calorimeter for such pions thus centers around a mean value in between those for the em ($e$) and non-em ($h$) components, at a value determined by the average energy sharing between these components at that energy ($\langle f_{\text{em}} \rangle$). As can be seen in Figures 2 and 3, the characteristics of $f_{\text{em}}$ and its fluctuations have direct and defining consequences for the hadron calorimeter performance. These characteristics, some of which are illustrated in Figure 2, include:

- The fact that $\langle f_{\text{em}} \rangle$ increases with energy (Figure 2a). As a result, non-compensating calorimeters are intrinsically non-linear for hadron detection (Figure 3a).
- Event-to-event fluctuations in $f_{\text{em}}$ are non-Poissonian (Figure 2b). The hadronic response function (line shape) mimics these fluctuations as well (Figure 3b).
- As a result of the non-Poissonian nature of the $f_{\text{em}}$ fluctuations, their rms width does not scale with $E^{-1/2}$ (Figure 2c). The same holds for the hadronic energy resolution (Figure 3c).
- The fluctuations in $f_{\text{em}}$ depend also on the type of hadron that initiates the shower. For example, in showers induced by high-energy protons, $\langle f_{\text{em}} \rangle$ is smaller than for pion showers of the same energy. Also, the event-to-event fluctuations are smaller and more symmetric in the proton case. As a result, the calorimeter response to protons is smaller, the resolution better and the line shape more symmetric than for pions [2].
- The production of em shower components is not limited to the early part of the shower, but may take place over the entire absorbing volume.

The latter effect, which is illustrated in Figure 4, greatly complicates the intercalibration of the different segments of a longitudinally segmented calorimeter system. Since em shower components are sampled more efficiently than non-em ones, the calibration constant of every sampling layer thus depends on the type of particle and on details of its shower development.
Figure 2. Effects of non-compensation on relevant hadronic calorimeter properties. Shown are the energy dependence of the average fraction of the hadron energy carried by the em shower component, $\langle f_{em} \rangle$ (a), the event-to-event fluctuations in $f_{em}$ (b), and the measured energy dependence of the rms width of the $f_{em}$ distribution (c).

Figure 3. Experimental characteristics of a hadron calorimeter with $e/h = 1.5$. Shown are the hadronic signal non-linearity (a), the response function to 140 GeV/c pions (b) and the hadronic energy resolution as a function of energy (c). Data from [1].
Figure 4. Longitudinal energy deposit profiles for 270 GeV $\pi^-$ showers in a lead/iron/plastic-scintillator calorimeter. The 90 sampling layers, which cover a total depth of 6 nuclear interaction lengths, were read out individually in this experiment [3].

3. Calibration of longitudinally segmented calorimeter systems

Calibration problems of longitudinally segmented calorimeters are not limited to non-compensating hadron detectors. In fact, the earliest reports about this issue concern electron detection [4]. Let us, to illustrate the problem, consider a simple em calorimeter based on the detection of Čerenkov light, e.g., a block of lead glass (Figure 5). When high-energy electrons or $\gamma$s are absorbed, this detector produces, for example, 10 photoelectrons (p.e.) per GeV deposited energy. Therefore, 20 GeV electrons give a signal of 200 p.e., 100 GeV $\gamma$s a signal of 1000 p.e., etc. Shower particles with energies below 0.3 MeV are not sufficiently relativistic to produce Čerenkov light and thus do not contribute to the signals. The relative contribution of such soft shower particles increases of course with the age of the shower, i.e., with the depth inside the calorimeter. When this device is cut into three segments (I,II,III, see Figure 5), the number of photoelectrons produced per unit deposited energy is thus different for these segments.

Figure 5. A high-energy electron shower developing in a lead glass calorimeter.
three segments, e.g., 15, 10 and 5 p.e./GeV for the early (I), middle (II) and late (III) parts of a 100 GeV shower, which deposits typically 30, 40 and 30% of its energy in these 3 segments. As before, this yields a total signal of $100\% \times (0.3 \times 15 + 0.4 \times 10 + 0.3 \times 5) = 1000$ photoelectrons. In this detector, the number of photoelectrons per GeV constitutes the calibration constant, which relates the measured signal to the deposited energy. However, when these calibration constants (15 p.e./GeV etc.) are used for a 10 GeV electron, which deposits a larger fraction of its energy in segment I, the energy of this particle is systematically overestimated. On the other hand, the energy of a $\pi^0$ produced in segment III (calibration constant 5 p.e./GeV) by a hadron is systematically underestimated. The only way to avoid these problems is to use the calibration constant found for the unsegmented detector (10 p.e./GeV) for all three segments. However, in that case the energies deposited in these individual segments are not correctly determined from the measured signals. We conclude that by cutting this calorimeter into longitudinal segments, problems are created that did not exist for the unsegmented detector.

This example illustrates two of the major problems encountered when calibrating a longitudinally segmented calorimeter system: 1) Signal non-linearity, and 2) Dependence of the reconstructed energy on the starting point of the shower. The phenomenon that led to these problems in the example given above also plays an important role in all sampling calorimeters. The reason is that the composition of a developing shower changes and that the sampling fraction of the different shower particles contributing to the signal is not the same. As an example we mention em showers developing in a typical sampling calorimeter consisting of lead absorber and plastic scintillator active material (Figure 6). In such a structure, the abundantly produced soft $\gamma$ s ($E < 1$ MeV) are much less efficiently sampled than mips, because of the $Z$ dependence of the photoelectric effect. As the shower develops, it changes gradually from a collection of particles dominated by mips to a collection of particles dominated by soft $\gamma$s. The relationship between deposited energy and resulting signal decreases accordingly, by as much as 30%. This effect has caused major calibration problems for longitudinally segmented em calorimeters in ATLAS [5] and AMS [6]. These problems could only be resolved thanks to the availability of Monte Carlo simulations with which the mentioned issues and their consequences could be studied in great detail.

![Figure 6](image-url). The sampling fraction as a function of the shower depth, or age, for 1 GeV electrons in a Pb/plastic scintillator calorimeter, normalized to the sampling fraction for a mip in this structure. Results from EGS4 Monte Carlo simulations.
For hadron showers, the intercalibration problems are even more complicated than for em ones, because 1) em shower components may start at any point in the absorber structure, 2) the sampling fraction of the particles constituting the non-em shower component also changes with depth, 3) the calorimeter responses to the em and non-em components are not the same and 4) the energy sharing between these components varies wildly from event to event (Figure 4). Unfortunately, unlike for em showers, Monte Carlo simulations of hadron showers are not reliable enough to provide meaningful help for solving these problems. Just as in the case of em showers, where most of the energy carried by GeV-type particles is ultimately deposited in the last stages of the absorption process, through very soft electrons produced in photoelectric effect (with consequences for calorimetry shown in Figure 6), most of the energy carried by the non-em component is also deposited in the last stages of the absorption process, in this case through nuclear reactions. And as long as that part of the shower simulations is not correctly and completely implemented in the simulations, no reliable help in solving the complicated calibration problems should be expected. Experimental evidence for the strongly dominating contribution of soft protons to the non-em energy deposit is provided by

(i) The observation that calorimeters that are blind to such protons have very large $e/h$ values. For example, in the DREAM Čerenkov calorimeter, an $e/h$ value of 4.7 was measured, which means that only $\sim 20\%$ of the non-em energy was deposited by relativistic particles [7].

(ii) The absence of correlations between the signals from neighboring active layers in the fine-sampling ZEUS calorimeter. This proves that a typical shower particle contributing to the hadronic signals traveled less than the $0.06\lambda_{\text{int}}$ separating the active layers [8].

Because of the absence of guidance from Monte Carlo simulations, and the emphasis in the design on the em energy resolution, the calorimeter systems of the LHC experiments face serious calibration challenges. This is particularly true for CMS, where the em and hadronic sections of the calorimeter have very different $e/h$ values. The hadronic performance of this calorimeter system was systematically studied with various types of particles ($e, \pi, K, p, \bar{p}$), covering a momentum range from 1 - 300 GeV/c. Figure 7 shows some results from this study [9]. Both sections were calibrated with 50 GeV electrons.

![Figure 7: The response to electrons and pions as a function of energy, for the CMS barrel calorimeter. The pion events are subdivided into two samples according to the starting point of the shower, and the pion response is also shown separately for these two samples [9].](image-url)
The figure shows that the calorimeter is very linear for electrons. The response to pions, represented by the black dots, indicates that the calorimeter is extremely non-linear for these particles. This non-linearity is especially evident below 10 GeV, which is important since pions in this energy range carry a large fraction of the energy of typical LHC jets, even in the TeV domain. More troublesome is the fact that the response strongly depends on the starting point of the showers. The figure shows results for two event samples, selected on that basis: showers starting in the em section (red) or in the hadronic section (blue). At low energies, the response is about 50% larger for the latter (penetrating) events. In practice in an experiment, it is often hard/impossible to determine where the shower starts, especially if these pions are traveling in close proximity to other jet fragments (e.g., photons from $\pi^0$ decay) which develop showers in the em section.

Fortunately, the effects for jets are not as dramatic as Figure 7 may seem to suggest. This is because a jet consists typically of a large number of fragments, whose shower starting points fluctuate independently of each other. CMS have studied the jet response based on the very large database of events obtained in test beams of a variety of particles at a large number of energies, covering the range from 1 - 300 GeV. The response of the combined ECAL+HCAL system to electrons, pions, kaons, protons, antiprotons and muons is shown as a function of “available” energy\(^1\) in Figure 8a. Differences between these particles observed in the for the jet response important energy range below 10 GeV are caused by differences in cross section, which affect the energy sharing between the two calorimeter sections. From the perspective of calorimetry, a jet is just a collection of particles, mainly pions and photons, which hit the calorimeter in the same region and develop simultaneous showers in it. The database summarized in Figure 8a can thus be used to reconstruct the response to a given jet in a semi-infinite number of ways. This is done in Figure 8b, which shows the response function to one particular 100 GeV jet, reconstructed 1000 times using measured events for the fragments of which it consisted, properly weighted to account for small differences in energy\(^2\). This procedure can be repeated for many different 100 GeV jets, and in

\(^1\) Available energy denotes the energy that is available for producing a calorimeter signal. For protons, it is the kinetic energy, for mesons the kinetic energy plus the rest mass, and for antiprotons the kinetic energy plus twice the rest mass.\n
\(^2\) For example, a 11.6 GeV $\pi^+$ generated in the fragmentation process was represented by an event from a 10 GeV $\pi^+$ run, and all calorimeter signals for this event were multiplied by a factor 1.16. Etcetera.
Figure 9. The CMS response to single π− and to jets, as derived from the response functions of the constituting fragments (a).

The reconstructed jet energy (normalized to the generated jet energy) after the inverse of the jet response is used as a correction factor (b). See text for details [9].

this way, the overall response function can be found for jets at this energy, or at any other energy. This is illustrated in Figure 9a, where the jet response obtained this way is given as a function of energy. For comparison, the response to single pions is shown as well. The fact that the jet response is generally smaller than the one to single pions of the same energy reflects the fact that the average hadronic jet fragment carries only a small fraction of the jet energy. The steeply decreasing response to low-energy pions apparently beats the fact that the response to the em jet fragments is larger (namely 1.0). Since the response is normalized to 1 for em showers, which were used to set the energy scale in both calorimeter sections in this analysis, the inverse of the jet response obtained in this way is the overall calibration constant with which the signals have to be multiplied in order to obtain the correct jet energy (Figure 9b). Figure 8b indicates that the energy resolution obtained for jets in this way is considerably better than the 14.8% measured for 100 GeV single pions.

Not all experiments set the scale in the different calorimeter sections in the same way, as in the example given above. In some experiments, more weight is given to the signals from the em section, in other methods the signals from the hadronic section are given a larger weight. The (lack of) merit of such methods has been extensively discussed elsewhere [10, 11, 12, 13]. Let me just comment that

(i) Such methods introduce unnecessary non-linearities and dependence on the starting point of the showers, and

(ii) Since the energy resolution is determined by event-to-event fluctuations and not by overall weighting factors, such methods offer no benefit whatsoever in this respect.

Ultimately, the merits of the calibration procedures used by an experiment will be judged by how well a precisely known energy deposit is reproduced in practice. In em calorimetry, one can rely on abundantly produced resonances (Z, Y, J/ψ → e+e−) for that purpose. Unfortunately, the situation is not that simple for the hadron calorimetry. Hadronically decaying intermediate vector bosons are an obvious candidate, but since UA2 no experiment has seen a W, Z bump in the minimum-bias jet-jet invariant mass distributions [14]. QCD background is blamed for that. However, given the larger cross sections, and the strongly improved b-tagging, one would expect the major experiments to have adequate samples of Z → bb events, in which QCD background should be much less of a problem, for this purpose. Alternatively, one could possibly use samples of hadronically decaying W's from t-quark...
decay or from diboson events. However, in all these cases integrated luminosities of several fb$^{-1}$ would probably be needed for a meaningful check of the calibration procedures.

Of course, all calibration procedures of non-compensating hadron calorimeters are designed for “average” events. Jets of a specific type, e.g., jets with a leading $\pi^0$, are likely to be reconstructed with an energy that is systematically wrong (too high in this case). Various methods are being employed to recognize such events and avoid this problem. Such methods are either based on the additional use of tracker information (“particle flow analysis”), or on the energy deposit pattern in the calorimeter itself (“offline compensation”), and are discussed in several other talks at this workshop.

Personally, I am in favor of longitudinally unsegmented calorimeters, for the following reasons:

(i) Calibration is trivial in that case, electrons in each tower and you are done. If there are no longitudinal segments, one is also not tempted to do the intercalibration wrongly.

(ii) As illustrated by the recent “spike” problem in the CMS ECAL, it is dangerous to place readout elements in the path of developing showers. As described in Section 2, most of the energy in the non-em component of hadron showers is deposited through nuclear reactions such as the one shown in figure 10. The nuclear fragments have $dE/dx$ values that are typically 100-1000 times larger

\[ \text{Figure 10. A typical nuclear reaction, through which non-em shower energy is deposited.} \]

than for a mip. When traversing the APD that detects the scintillation light from the PbWO$_4$ crystals constituting the CMS ECAL, such (MeV type) particles may generate signals that are 100,000 times larger that that from a scintillation photon, and thus fake energy deposits of tens of GeV.

(iii) And finally, there is not a single issue for which longitudinal segmentation is essential. In particular, electron identification can be accomplished in several excellent ways without the need for a separate em calorimeter section [15].

4. The future of calorimetry

It is expected that jet spectroscopy will become a major, if not the main, experimental technique at a future Lepton Collider. Separating hadronically decaying $W$ and $Z$ bosons is the benchmark for experiments at such a machine. The calorimeter systems currently operating at the high-energy frontier are not capable of this, as illustrated in Figure 11a, which shows the invariant jet-jet mass distribution for $W$s and $Z$s reconstructed from jets in CMS as described in Section 3. The different approaches that are followed to develop calorimeter systems that are up to this task include:

- Compensating calorimeters. The reasons for the poor performance of non-compensating calorimeters, as well as the mechanisms to achieve compensation ($e/h = 1$), are completely
Figure 11. Reconstruction of the mass of hadronically decaying $W$, $Z$ bosons from jets detected in the CMS calorimeters, using the method described in Section 3 (a). The compensating WA80 calorimeter as a high-resolution spectrometer (b) [16]. Note that the mass resolution needed to separate hadronically decaying $W$, $Z$ bosons, $\Delta M/M \sim 0.11$

understood since 25 years. All performance records for hadron calorimeters are held by the SPACAL [17] and ZEUS [18] calorimeters, which were designed based on this understanding. Figure 11b shows that the resolution obtained with such compensating calorimeters ($\sim 30\% / \sqrt{E}$) is good enough to turn them into high-precision jet spectrometers, with a resolving power that is adequate to separate hadronically decaying $W$ and $Z$ bosons. The compensation mechanism relies crucially on the detection of neutrons, which are abundantly produced in the nuclear reactions that take place in the hadronic absorption process. In order to boost the signal contribution of these neutrons to the required level, the sampling fraction has to have a very precise, small value (e.g., 2.4\% in the case of Pb/plastic-scintillator), which limits the em energy resolution that can be achieved with such calorimeters, to $\sim 13\% / \sqrt{E}$ in SPACAL. In addition, the signals have to be integrated over a rather large volume and time ($\sim 50$ ns).

- **Dual-readout** calorimeters were invented to further improve on the excellent results obtained with compensating calorimeters, by avoiding the mentioned drawbacks of the latter. They are based on the idea that if the em fraction of hadronic showers ($f_{em}$) can be measured event by event, the effects of fluctuations in this variable can be eliminated. The DREAM Collaboration has shown that this can be achieved by simultaneously measuring both the visible deposited energy and the Čerenkov light generated in the shower absorption process [7], exploring the fact that the latter is for all practical purposes only produced in the absorption of the em shower component. They have demonstrated that calorimeters based on this principle are linear for single hadrons and jets, have a Gaussian response function, and provide an energy resolution that scales with $E^{-1/2}$. The limitations of intrinsically compensating calorimeters do not apply to such devices, and excellent em energy resolution is not at all precluded, since one can even use the dual-readout principle for homogeneous crystals. Of course, it is in that case necessary to separate the light signals generated by such crystals into scintillation and Čerenkov components. The DREAM Collaboration has developed four different ways to achieve this [19, 20].

- **Systems using Particle Flow Analysis** are based on the combined use of a precision tracker and a
highly-granular calorimeter. The idea is that the charged jet particles can be precisely measured with the tracker, while the energy of the neutral particles is measured with the calorimeter. Such methods have indeed successfully been used to improve the mass resolution of hadronically decaying $Z^0$s at LEP, to $\sim 7$ GeV/$c^2$ [21]. However, no one has ever come close to achieving the 3 - 3.5 GeV/$c^2$ resolution needed to separate $W$ and $Z$ bosons in this way. The problem that limits the success of this method is of course that the calorimeter does not know or care whether the particles it absorbs are electrically charged. Therefore, one will have to correct the calorimeter signals for the contributions of the charged jet particles. Proponents of this method have advocated a fine granularity as the key to the solution of this “double-counting” problem [22]. However, it has been argued by others that this, for practical geometries, is an illusion [23]. Especially in jets with leading charged particles, the overlap between the showers from individual jet particles makes the fine granularity largely irrelevant. In the absence of reliable Monte Carlo simulations, the only way to prove or disprove the advocated merits of the proposed methods is by means of dedicated experiments in realistic prototype studies. The CALICE Collaboration, which is building and testing detectors based on this principle, will hopefully make a significant contribution in this respect.

5. Concluding remarks

Interpretation of the calorimeter signals is crucially important for the jet energy scale. The need to (inter)calibrate the various segments of a longitudinally subdivided calorimeter system makes this a very complicated issue, especially when the segments have different $e/h$ values. Naively, one would think that the additional information provided by longitudinal segmentation would allow one to make more precise measurements. However, I think this is an illusion. There is in that respect an analogy with the calorimetry practiced in thermodynamical experiments. Just as it does not help to know the 4-vectors of all the molecules when one wants to measure the specific heat of a certain substance, the additional information provided by the longitudinal calorimeter segments mainly complicates and confuses the measurement of the energy deposited in the absorption of jets.

The absence of reliable Monte Carlo simulations is becoming more and more problematic as the need for high-precision jet spectroscopy increases. In Section 3, we saw how simulations were crucial for resolving complicated calibration problems encountered with the electromagnetic calorimeters of ATLAS and AMS. I think that the lack of equivalently useful tools for hadron absorption in matter has actually led to a decrease of the quality of hadron calorimetry in the experiments developed in the last 20 years. Unfortunately, as long as those who could make a difference in that respect are not aware or, worse, in denial of the existing problems, this is unlikely to change.

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