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On the limits of the hadronic energy resolution of calorimeters

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This paper is dedicated to the memory of our long-time friend and collaborator Guido Ciapetti

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ABSTRACT

In particle physics experiments, the quality of calorimetric particle detection is typically considerably worse for hadrons than for electromagnetic showers. In this paper, we investigate the root causes of this problem and evaluate two different methods that have been exploited to remedy this situation: compensation and dual readout. It turns out that the latter approach is more promising, as evidenced by experimental results.

1. Introduction

In the past half-century, calorimeters have become very important components of the detector system at almost every experiment in high-energy particle physics. This is especially true for 4π experiments at high-energy particle colliders, such as LEP and the Large Hadron Collider at CERN, the Tevatron at Fermilab and RHIC at Brookhaven. Experiments at proposed future colliders such as the FCC (CERN), CEPC (China) and ILC (Japan) will be designed around a powerful central calorimeter system.

A calorimeter is a detector in which the particles to be detected are completely absorbed. The detector provides a signal that is a measure for the energy deposited in the absorption process. In *homogeneous* calorimeters, the entire detector volume may contribute to the signals. In *sampling* calorimeters, the functions of particle absorption and signal generation are exercised by different materials, called the *passive* and the *active* medium, respectively. Almost all calorimeters operating in the mentioned experiments are of the latter type. The passive medium is usually a high-density material, such as iron, copper, lead or uranium. The active medium generates the light or charge that forms the basis for the signals from such a calorimeter.

Among the reasons for the increased emphasis on calorimetric particle detection in modern experiments, we mention

- The fact that calorimeters can provide important information on the particle collisions, in particular information on the *energy flow* in the events (transverse energy, missing energy, jet production, *etc.*)
- Calorimeters can provide this information *very fast*, almost instantaneously. In modern experiments, *e.g.,* at the LHC, it has become possible to decide whether an event is worth retaining for offline inspection on a time scale of the order of 10^{-8} s. Since the LHC experiments have to handle event rates at the level of 10^9 each second, this triggering possibility is a crucial property in these experiments.
- Calorimeter data can be very helpful for *particle identification*.
- Important aspects of the calorimeter performance, such as the energy and position resolutions, tend to *improve with energy*.

Calorimetric detection of γ's and electrons has a long tradition, which goes back to the early days of nuclear spectroscopy, when scintillating crystals such as NaI(Tl) were the detectors of choice. In high-energy physics, detection of electromagnetic showers is nowadays routinely performed with a resolution at the 1% level, both in homogeneous [1] and sampling [2] calorimeters.

The success of experiments at a future high-energy e^+e^- Collider will also depend critically on the quality of the hadron calorimetry. Unfortunately, the performance of hadron calorimeters leaves much to be desired.

In this paper, we describe first the reasons for the generally poor performance of calorimeters intended to detect hadrons and jets (Section 2). In Sections 2 and 3. In Section 4, two methods that have been developed as a remedy for these problems are presented, and the performance improvement achieved with these methods is compared in Section 5. Conclusions are given in Section 6.

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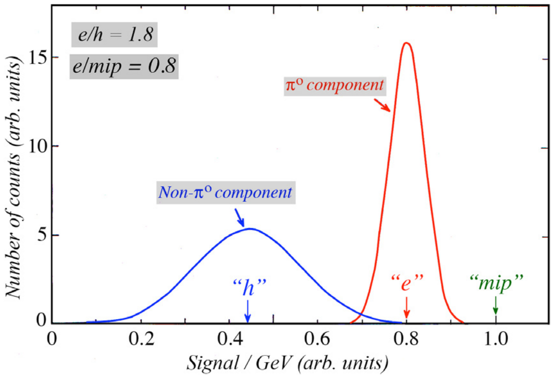

Fig. 1. Illustration of the meaning of the e/h and e/mip values of a calorimeter. Shown are distributions of the signal per unit deposited energy for the electromagnetic and non-em components of hadron showers. These distributions are normalized to the response for minimum ionizing particles ("mip"). The average values of the em and non-em distributions are the em response ("e") and non-em response ("h"), respectively.

2. The problems of hadron calorimetry

The development of hadronic cascades in dense matter differs in essential ways from that of electromagnetic ones, with important consequences for calorimetry. Hadronic showers consist of two distinctly different components:

1. An *electromagnetic* component; π^0s and ηs generated in the absorption process decay into γ's which develop em showers.
2. A *non-electromagnetic* component, which combines essentially everything else that takes place in the absorption process.

For the purpose of calorimetry, the main difference between these components is that some fraction of the energy contained in the non-em component does *not* contribute to the signals. This *invisible energy*, which mainly consists of the binding energy of nucleons released in the numerous nuclear reactions, may represent up to 40% of the total non-em energy, with large event-to-event fluctuations.

Let us define the calorimeter *response* as the conversion efficiency from deposited energy to generated signal, and normalize it to electrons. The responses of a given calorimeter to the em and non-em hadronic shower components, e and h, are usually not the same, as a result of invisible energy and a variety of other effects. We will call the distribution of the signal per unit deposited energy around the mean value (e or h) the *response function*.

Fig. 1 illustrates the different aspects of the calorimeter response schematically. The em response is larger than the non-em one, and the non-em response function is broader than the em one, because of event-to-event fluctuations in the invisible energy fraction. Both e and h are smaller than the calorimeter response for minimum ionizing particles, because of inefficiencies in the shower sampling process [3]. The calorimeter is characterized by the e/h and e/mip ratios, which in this example have values of 1.8 and 0.8, respectively. Calorimeters for which $e/h \neq 1$ are called *non-compensating*.

The properties of the em shower component have important consequences for the hadronic *energy resolution*, signal *linearity* and *response function*. The average fraction of the total shower energy contained in the em component, $\langle f_{\rm em}\rangle$, was measured to increase with energy following a power law [4,5], confirming an induction argument made to that effect [6]:

$$\langle f_{\rm em}\rangle \;=\; 1-\left[\left(\frac{E}{E_0}\right)^{k-1}\right] \qquad (1)$$

where E_0 is a material-dependent constant related to the average multiplicity in hadronic interactions (varying from 0.7 GeV to 1.3 GeV for π-induced reactions on Cu and Pb, respectively), and $k \sim 0.82$ (Fig. 2a). For proton-induced reactions, $\langle f_{\rm em}\rangle$ is typically considerably smaller, as a result of baryon number conservation in the shower development [7]. A direct consequence of the energy dependence of $\langle f_{\rm em}\rangle$ is that calorimeters for which $e/h \neq 1$ are by definition *non-linear* for hadron detection, since the response to hadrons is given by $\langle f_{\rm em}\rangle + \left[1-\langle f_{\rm em}\rangle\right]h/e$. This is confirmed by many sets of experimental data, for example the ones reported for CMS [8] shown in Fig. 3a.

Event-to-event fluctuations in $f_{\rm em}$ are large and non-Poissonian [4], as illustrated in Fig. 2b. If $e/h \neq 1$, these fluctuations tend to dominate the hadronic energy resolution and their asymmetric characteristics are reflected in the response function [3]. It is often assumed that the effect of non-compensation on the energy resolution is energy independent ("constant term"). This is incorrect, since it implies that the effect is insignificant at low energies, *e.g.,* 10 GeV, which is by no means the case. The measured effects of *fluctuations* in $f_{\rm em}$ can be described by a term that is very similar to the one used for its energy dependence (1). This term should be added in quadrature to the $E^{-1/2}$ scaling term which accounts for all Poissonian fluctuations:

$$\frac{\sigma}{E} \;=\; \frac{a_1}{\sqrt{E}} \oplus a_2\left[\left(\frac{E}{E_0}\right)^{l-1}\right] \qquad (2)$$

where the parameter $a_2 = |1-h/e|$ is determined by the degree of non-compensation [9], and $l \sim 0.72$. It turns out that in the energy range covered by the current generation of test beams, *i.e.,* up to 400 GeV, Eq. (2) leads to results that are very similar to those from an expression of the type

$$\frac{\sigma}{E} \;=\; \frac{c_1}{\sqrt{E}} + c_2 \qquad (3)$$

i.e., a *linear sum* of a stochastic term and a constant term. Many sets of experimental hadronic energy resolution data exhibit exactly this characteristic, for example the results reported for ATLAS [10] shown in Fig. 3b. In this figure, the energy resolution is plotted on a scale linear in $E^{-1/2}$, inverted to increase from right to left.[1] Scaling with $E^{-1/2}$ is thus represented by a straight line through the bottom right corner in this plot. The experimental ATLAS data are located on a line that runs parallel to such a line, indicating that the stochastic term (c_1) is ≈80% and the constant term (c_2) is ≈5% in this case.

The root cause of the poor performance of hadron calorimeters is thus the invisible energy. Because some fraction of the energy carried by the hadrons and released in the absorption process does not contribute to the signal, the response to the non-em shower component is typically smaller than that to the em shower component. And the characteristic features of the energy sharing between these two components lead to hadronic signal non-linearity, a poor energy resolution and a non-Gaussian response function.

To mitigate these effects, one thus needs a measurable quantity that is correlated to the invisible energy. The stronger that correlation, the better the hadronic calorimeter performance may become. In the next two sections, two such measurable quantities are discussed: the kinetic energy released by neutrons in the absorption process (Section 3) and the total non-em energy (Section 4).

3. Compensation

The first successful attempt to mitigate the effects described in the previous section involved a calorimeter that used depleted uranium as absorber material. The underlying idea was that the fission energy released in the absorption process would compensate for the invisible energy losses. By boosting the non-em calorimeter response in this way, the e/h ratio would increase and, as a matter of good fortune, reach the (ideal) value of 1.0. This is the reason why calorimeters with $e/h = 1.0$ have become known as *compensating* calorimeters.

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[1] This convention is used for all energy resolution plots in this paper.