Nuclear Instruments and Methods in Physics Research A 705 (2013) 24–31

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Degradation of resolution in a homogeneous dual-readout hadronic calorimeter

Donald E. Groom *

Lawrence Berkeley National Laboratory, 50R6008, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 5 October 2012
Received in revised form
6 December 2012
Accepted 11 December 2012
Available online 20 December 2012

Keywords:
Hadronic calorimetry
Hadron cascades
Sampling calorimetry

ABSTRACT

If the scintillator response to a hadronic shower in a semi-infinite uniform calorimeter structure is S relative to the electronic response, then $S/E=[f_{em}+(1-f_{em})(h/e)]$, where E is the incident hadron energy, f_{em} is the electronic shower fraction, and h/e is the hadron/electron response ratio. If there is also a simultaneous readout with a different h/e, say a Cherenkov signal C, then a linear combination of the two signals provides an estimator of E that is proportional to the incident energy and whose distribution is nearly Gaussian—even though the S and C distributions are non-linear in E, wide, and skewed. Since an estimator of f_{em} is also obtained, it is no longer a stochastic variable. Much of the remaining resolution variance is due to sampling fluctuations. These can be avoided in a homogeneous calorimeter. The energy resolution depends upon the contrast in h/e between the two channels. h/e is small in the Cherenkov channel. *Mechanisms that increase h/e in sampling calorimeters with organic scintillator readout are not available in a homogeneous inorganic scintillator calorimeter.* The h/e contrast is very likely too small to provide the needed energy resolution.

1. Introduction

A homogeneous dual-readout hadron calorimeter has been suggested for possible use at a future linear collider [1]. The machine will probably be an e^+e^- collider and in some concepts will have a long bunch spacing ($\mathcal{O}$(100 ns)), so that detectors with time constants in this range might be used. Discrimination between the Cherenkov signal (C) and scintillator (S) optical signals is expected to use a combination of timing, color, and, possibly, Cherenkov light direction and polarization.

In practice corrections must be made for cracks, leakage, and light collection variations, and the structure usually varies with depth. For the purposes of this analysis we shall assume that the corrections have been made properly, and consider a semi-infinite calorimeter with uniform structure that is either fine-sampling or homogeneous.

In each high-energy interaction in a hadronic cascade an average of 1/4 of the energy is carried away by π^0's [2]. These immediately decay to γ's which initiate electromagnetic (EM) showers. This occurs many times, with the result that a large fraction f_{em} of the incident energy joins the EM shower. The mean, $\langle f_{em}\rangle$, is ≈ 0.5 for 100–150 GeV incident pions. It increases slowly with incident energy E, asymptotically approaching unity.

The hadronic response S to an incident hadron with energy E (calibrated to electron response) is

$$S=E[f_{em}+(1-f_{em})(h/e)]. \quad (1)$$

The EM energy deposit is detected with relative efficiency e, and the hadronic signal with relative efficiency h. Both vary from event to event. In part because of low multiplicities in the initial hadronic interactions, the variance of h is much larger than the variance of e. It makes sense to treat h/e as a stochastic variable. To the extent that the variance of h dominates, the distribution of the conventional e/h is not useful. In Section 5 we treat the distribution of h/e as Gaussian.

Most energy deposit is by very low-energy electrons and charged hadrons. Because so many generations are involved in a high-energy cascade, the hadron spectra are essentially independent of the cascade's origin except for overall normalization. This "universal spectrum" concept is discussed in detail in Ref. [2]. It is because of this feature that $\langle h/e\rangle$ is a robust quantity, independent of energy and incident hadron species.

The energy-independent $\langle h/e\rangle$ does depend upon calorimeter composition and structure, as well as the readout—for example, an organic scintillator readout is sensitive to the otherwise-invisible neutron content of the cascade while a Cherenkov readout is relatively blind to the hadronic content. $\langle f_{em}\rangle$ can

* Tel.: +1 5104866788; fax: +1 5104864799.
E-mail address: degroom@lbl.gov

0168-9002/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2012.12.080

be found by fitting the average π^-/e response as a function of test-beam energy with an appropriate $\langle f_{em}\rangle$ parameterization such as a power law in energy [2].[1]

Usually $\langle h/e\rangle$ is less than unity, since the EM contribution is detected with greater efficiency than the hadronic energy deposition. If $\langle h/e\rangle$ is not unity, then the broad, skewed f_{em} probability distribution function (p.d.f.) significantly degrades and skews the energy resolution, resulting in the familiar wide, non-Gaussian energy distributions. The response is not linear with energy because of the energy dependence of $\langle f_{em}\rangle$. If f_{em} could be measured for each event, then the response as given in Eq. (1) could be corrected to the actual energy with a nearly Gaussian distribution and a mean proportional to the energy.

The importance of measuring the EM content on an event-by-event basis was realized as early as 1980, although how to use the information was not so clear. There was even a (stillborn) dual readout test by A. Erwin (BNL) using scintillator and radiator plates [3].

EM showers result in large local energy deposit; with sufficient readout segmentation this "lumpiness" provides a measure of f_{em}. Weighting this part differently than the remaining signal might improve resolution. This approach was used with some success by the WA1 collaboration [4], but has been less successful elsewhere, e.g., for the ATLAS central barrel calorimeter [5].

In a 1983 summer school review of high-energy calorimetry, P. Mockett stressed the importance of measuring the fractional EM content of the shower. He speculated that one could use two sampling media, an electron-sensitive detector (Cherenkov) and an ionization sensitive detector (scintillator). He also imagined taking advantage of the fast Cherenkov pulse and slow scintillation signal in a heavy inorganic scintillator. Both suggestions were prophetic [6].

Such a separation was actually made by Theodosiou et al. [7] in 1984, using the time structure of pulses observed in scintillating glass. He thought the technique might permit electron/hadron separation or even help with particle identification. Winn [8] later suggested using color in addition to timing to make the separation. There must have been considerable speculation about dual-readout calorimetry, but only Theodosiou et al. took this speculation into the laboratory.

Part of the problem was that the physics of energy deposition had not yet been elucidated, or at least widely understood. This came in the late 1980s with the work of Fabjan et al. [9], Wigmans [10], Brückmann et al. [11], Drews et al. [12], and others, but a key element was the energy deposition inventories produced by the very detailed simulations of Gabriel and his collaborators at Oak Ridge as early as 1974 [9,13].

Much of the hadronic energy resolution problem was related to the large fraction of missing energy in the hadronic sector, due to nuclear dissociation, nuclear recoil, residual nuclear excitation, μ and ν escape, and (unobserved) neutrons. Scintillator response to highly ionizing charged particles is non-linear, resulting in significantly more lost signal. For a time it was thought that ionization by U fission products could make up some of the lost energy [9,10,14], but non-linear scintillator response to the highly ionizing fragments negated most of the gains.

In a sampling calorimeter, only a small fraction of the energy is deposited in the sensors (quartz or scintillator), and fluctuations in this fraction are more important than intrinsic fluctuations in the hadronic signal. These dominate, once f_{em} is removed. The sampling fluctuations are avoided in a homogeneous calorimeter. The possibly long bunch spacing at a future linear collider opens the door to a homogeneous dual-readout dense crystal or glass calorimeter, where a fast, blue, Cherenkov pulse might be separated from a slower, redder scintillation signal. Crystal studies are being successfully explored by Akchurin et al. [15–22], but with only speculative mention of dual-readout hadron calorimeters. A feasibility study is part of a new proposal [23].

Akchurin et al. have demonstrated signal separation that would be adequate for recovering energy estimators that are linear in the corrected energy and have a nearly Gaussian distribution. However, I am concerned that the energy *resolution* would not be adequate. In this paper I explore the likely resolution as a function of energy and $\langle h/e|_S\rangle$ using resolution contributions based on published crystal, glass, and sampling calorimeter performance. Simple, transparent Monte Carlo simulations (MCs) are used by choice, to make the physics more transparent than if a sophisticated MC such as GEANT4 were used. The p.d.f. of f_{em} is approximated with some care, while other resolution contributions are taken to be Gaussian.

2. $\langle h/e\rangle$ in a high-density crystal or glass scintillator

In an EM cascade the electrons are relativistic until their energies fall well below the critical energy, so that almost all of the energy is deposited by near-minimum ionizing electrons. No appreciable energy exits from the EM cascade via photonuclear interactions. The result is a response very nearly linear in the incident electron or photon energy.

Hadronic interactions deposit energy in a variety of ways. (An inventory is given in Table 1 [by Gabriel and Schmidt] in Ref. [9], and detailed discussions can be found in Refs. [24–26] and other recent reviews). A large fraction of the hadronic energy ($\approx 20\%$ for Fe/scintillator and $\approx 40\%$ for U/scintillator sampling calorimeters) goes to nuclear dissociation and recoil, and is "invisible." Neutrinos and most muons escape. Some fraction of the neutrons can be detected via n–p scattering in hydrogeneous materials such as organic scintillator, but much or most of the neutron energy is also lost. Low-energy protons and charged fission fragments produce saturated signals in scintillator. (This occurs in inorganic [27] as well as organic scintillators [28].) All of these factors result in low visible response to the hadronic component of the cascade relative to response to the EM component.

Detection of recoil protons in neutron scattering in hydrogenous detectors increases h [29]. In a sampling calorimeter a disproportionate fraction of the EM energy is deposited in the higher-Z absorber; the absorber/active region thickness ratio can be "tuned" to decrease e. Both of these effects increase h/e. In practical sampling calorimeters $\langle h/e\rangle$ is typically 0.7, and can be made to approach unity with careful design.

Neither mechanism for increasing h/e is available to a high-density homogenous calorimeter.

As we shall see, the resolution is dependent on the "h/e contrast," the difference between $\langle h/e\rangle$ for the Cherenkov ($\langle h/e|_C\rangle$) and scintillation($\langle h/e|_S\rangle$) readouts. Based on the experience with quartz-fiber readout calorimeters [30–32], $\langle h/e|_C\rangle = 0.20$–$0.25$.[2] There are few data concerning $\langle h/e|_S\rangle$ in a homogeneous calorimeter, but there is no way to hide EM energy in the absorber and there is very little neutron sensitivity. We might expect as much as 30% of the hadron energy to be expended on nuclear dissociation and therefore invisible, and 15-20% to be carried by neutrons. These alone would result in $\langle h/e|_S\rangle \approx 0.5$. There are other effects, such as incomplete

[1] Technically, a power-law fit finds $a = (1-\langle h/e\rangle)E_0^{1-m}$. Since $1-m$ is small and the scale energy E_0 is close to 1 GeV for pion-induced cascades, the distinction is minor: $\langle h/e\rangle \approx 1-a$. A similar distinction occurs when other parameterizations are used. $\langle h/e\rangle$ itself cannot be isolated.

[2] From the data shown in Table 3 of Ref. [30] I obtain $h/e|_c = 0.247$ [35].