Energy measurement at the TeV scale

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Abstract. In this paper, our current understanding of calorimetry is discussed, in view of the challenges offered by future applications in experiments at the LHC and the ILC/CLIC. Calorimetry is likely to become an even more crucial component of the detector complex than in the present generation of experiments. And the demands on performance will increase, in particular concerning the detection of fragmenting quarks and gluons. The (underlying reasons for the) obstacles one faces in trying to meet these demands are discussed in some detail, emphasizing the difficulties encountered in calibrating a longitudinally segmented calorimeter system. Generic R&D efforts that are being carried out in this context are described, and recent results of these projects are presented.

Contents

1. Introduction 2
2. Calorimetry: possibilities and limitations at the TeV scale 2
   2.1. Hadronic energy resolution .............................................. 2
   2.2. Calibration problems ...................................................... 7
3. New approaches 11
   3.1. Particle flow analysis (PFA) ............................................ 11
   3.2. Dual-readout calorimetry ................................................. 14
4. Concluding remarks 20
References 21
1. Introduction

The history of the quest for a better understanding of the innermost structure of matter and of the forces that govern its behavior shows that extending the energy domain in which experiments could be performed has often led to quantum leaps in this process. These quantum leaps were made possible by subsequent generations of ever more powerful particle accelerators. However, they also typically required the development of new, increasingly sophisticated and precise instruments and measurement techniques in order to take full advantage of the new opportunities. This will not be any different when the tera-electron-volt (TeV) domain opens up for experiments in the LHC and Linear ($e^+e^-$) Collider eras. The quality of the scientific information that can be obtained will, to a very large extent, be determined (and limited) by the quality of the detectors with which experiments at these machines will be performed. In these experiments, that quality concerns the precision with which the four-vectors of the scattered objects produced in the collisions can be measured. At the TeV scale, these objects are leptons, photons and fragmenting quarks, di-quarks and gluons, commonly referred to as jets. Achieving the best possible precision for the momentum and energy measurements of these objects is usually a very (if not the most) important design goal of the proposed experiments.

One example that illustrates the advantages of excellent resolution for spectroscopic measurements at high energy was given by the heavy-ion experiments WA80 and HELIOS at CERN. Figure 1(b) shows the total energy distribution measured by the WA80 Collaboration when the 6.4 TeV $^{32}$S beam from the CERN SPS was dumped in their detector [1]. It turned out that $^{32}$S nuclei were not the only particles present in this beam. A few percent of the nuclei apparently dissociated on the way and those with the proper $A/Z = 2$ ratio made it through the acceleration process. The good energy resolution of this experiment allowed a detailed study of these contaminating lower-mass nuclei. Similar results (figure 1(a)) were reported by HELIOS [2].

The detectors for which results are shown above are calorimeters. Originally developed as crude, cheap instruments for some specialized applications in particle physics experiments (e.g. detection of neutrino interactions), calorimeters have in the past 30 years evolved to become the heart and soul of many modern experiments. They fulfill a number of crucial tasks, ranging from event selection and triggering to precision measurements of the four-vectors of individual particles and jets and of the energy flow in the events (missing energy, etc). In this paper, we discuss the prospects for calorimetry at colliders that will open up the TeV domain. The discussion focuses on hadron calorimetry, where the challenges will be greatest, although the detection of electromagnetic (em) showers also faces problems, especially in finely segmented instruments.

2. Calorimetry: possibilities and limitations at the TeV scale

Calorimeter quality is often considered synonymous with energy resolution. However, in the TeV domain other aspects, in particular signal linearity, are equally, if not more important. We will come back to that in section 2.2. First, we discuss the hadronic energy resolution.

2.1. Hadronic energy resolution

It is important to realize that the resolutions shown in the examples from figure 1 are misleading. In the heavy-ion scattering experiments from which these data were obtained, a convolution of
either 16 or 32 independent 200 GeV nucleon showers was measured. Hence, strictly speaking, these results only say something about the precision of the energy measurement for a 200 GeV nucleon shower. If 16 signals from such showers are convoluted, then the resulting signal has a resolution $\sigma/E$ that is $4 (= \sqrt{16})$ times smaller than the resolution for the individual signals from 200 GeV nucleons. In other words, if the resolution for 200 GeV protons (or neutrons) was 7.6%, then a resolution of 1.9% should be expected for $^{16}$O ions with an energy of 3.2 TeV.

In the TeV domain, it is incorrect to express calorimetric energy resolutions in terms of $a/\sqrt{E}$, as is often done. Deviations from $E^{-1/2}$ scaling are the result of non-Poissonian fluctuations. These manifest themselves typically predominantly at high energies, where the contribution from the Poissonian component becomes very small. Since the contribution of the $E^{-1/2}$ scaling term to the resolution of the 200 GeV nucleons in these experiments was less than 4%, the contribution of non-Poissonian fluctuations must have been at least as large. Depending on the precise origin of these fluctuations, their contribution at 3 TeV may have been several percent as well, and thus dwarf the contribution of the $E^{-1/2}$ scaling term. The measured resolution for heavy ions at multi-TeV energies is thus by no means indicative for the resolution that may be expected for the detection of single hadrons or jets carrying such energies.

The most important source of non-Poissonian fluctuations is a consequence of non-compensation. Hadronic showers consist of two distinctly different components.

1. An em component; $\pi^0$s and $\eta$s generated in the absorption process decay into $\gamma$s which develop em showers.
2. A non-em 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.
The numerous nuclear reactions that take place in the absorption process are responsible for the overwhelming majority of this invisible energy. The nuclear binding energy of the released protons, neutrons and heavier aggregates has to be supplied by the shower particles that induce the reactions, and does not contribute to the signals. Other, relatively minute contributions to the invisible energy come from neutrinos and muons that escape the calorimeter.

The invisible energy may represent a considerable fraction of the total shower energy. If we define the response as the average calorimeter signal per unit of energy, and the responses to the em and non-em shower components as $e$ and $h$, respectively, then the $e/h$ ratio quantifies the importance of invisible energy effects for a given calorimeter. For example, in some crystal calorimeters (e.g. PbWO$_4$) $e/h > 2$, which means that, on average, more than half of the non-em energy is invisible.

Let $f_{em}$ be the fraction of the total shower energy contained in the em shower component. Among the characteristics of this component that have profound implications for the performance of hadron calorimeters, we mention:

1. The fact that $\langle f_{em} \rangle$ increases with energy. This effect, which is illustrated in figure 2(a), is directly responsible for the intrinsic hadronic signal nonlinearity exhibited by all non-compensating hadronic calorimeters (i.e. calorimeters with $e/h \neq 1$). The figure shows that the em shower component typically represents about half of the total energy, and that $\langle f_{em} \rangle$ not only depends on the energy, but also on the type of absorber material.

2. Event-to-event fluctuations in $f_{em}$ are large and non-Poissonian. Figure 2(b) shows a measurement of these fluctuations for showers initiated by 150 GeV $\pi^-$ in a lead-based hadron calorimeter. The observed asymmetry in this distribution is a consequence of the fact that $\pi^0$ production is a ‘one-way street’, i.e. energetic charged pions produced in the interactions may transfer (part of) their energy into $\pi^0$s in subsequent reactions, but

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1 Nuclear binding energy losses are not the only cause of the reduced non-em response in this case. Signal saturation (for nuclear protons) and escaping neutrons are responsible for 20–30% of the effect.

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Figure 3. Energy dependence of the fractional width of the $f_{em}$ distribution. Shown are the results of measurements [4] and the expected dependence for fluctuations governed by Poisson statistics (a). The hadronic energy resolution calculated for a typical non-compensating calorimeter in the energy regime up to 400 GeV (the solid line), and calculated with a sole stochastic term with a slightly larger scaling constant (b) [6].

the reverse process does not take place because of the extremely short $\pi^0$ lifetime. This effect is responsible for the asymmetric response function (line shape) observed for pions in non-compensating calorimeters.

Another consequence of the non-Poissonian nature of the fluctuations in $f_{em}$ is the fact that the width of distributions such as the one shown in figure 2(b) does not scale with the square root of the shower energy. Measurements of the energy dependence of the fractional width ($\sigma_{rms}$/mean) are shown in figure 3(a), for pion-induced showers in a copper-based calorimeter [4]. For comparison, the $E^{-1/2}$ behavior expected for fluctuations governed by Poisson statistics (such as sampling fluctuations) is shown as well. This deviation from $E^{-1/2}$ scaling determines the energy dependence of the energy resolution, and dominates the resolution at very high energies.

It is often assumed that the effect of non-compensation on the energy resolution is energy independent (‘constant term’). Figure 3(a) illustrates that this is incorrect. It has been demonstrated [6] that the effects of fluctuations in $f_{em}$ are correctly described by a term that is very similar to the one used to describe the energy dependence of $\langle f_{em} \rangle$ (see figure 2(a)). This term should be added in quadrature to the $E^{-1/2}$ scaling term which accounts for the Poissonian fluctuations:

$$\sigma_E = \frac{a_1}{\sqrt{E}} + a_2 \left[ \frac{E}{E_0} \right]^{l-1}. \quad (1)$$

Here, $E_0$ is a material dependent constant related to the average multiplicity in the hadronic interactions and $l$ is determined by the energy dependence of $f_{em}$ [5]. The parameter $a_2$ is determined by the degree of non-compensation. It varies between 0 (for compensating calorimeters) and 1 (for extremely non-compensating calorimeters). Following Groom [7], we will assume a linear relationship for intermediate $e/h$ values:

$$a_2 = |1 - h/e|. \quad (2)$$
Figure 4. Hadronic energy resolution in the TeV domain, calculated with equation (1).

Figure 3(b) shows a graphical representation of equation (1), for parameter values that are fairly typical for many calorimeters. The horizontal scale is linear in $E^{-1/2}$, so that $E^{-1/2}$ scaling is represented by a straight line through the bottom right corner of this plot. Equation (1) is represented by the solid curve. It is interesting that this curve (in the energy range covered by the current generation of test beams, i.e. up to 400 GeV), runs almost parallel to the dotted line, which represents a single stochastic term with a somewhat larger coefficient ($a_1 = 0.55$ versus 0.50). This solves an old mystery, since it means that experimental data following the solid curve might also be described by an expression of the type

$$\frac{\sigma}{E} = \frac{a_1}{\sqrt{E}} + a_2,$$

i.e. a linear sum of a stochastic term and a constant term. Such an expression suggests that there is perfect correlation between the fluctuations that contribute to the two different terms, which is of course nonsense. Yet, many sets of experimental hadronic energy resolution data exhibit exactly this characteristic \[8\], which may now be understood in terms of equation (1).

Interestingly, the similarity between the two types of expressions disappears when the energy range is extended into the TeV domain. This is illustrated in figure 4. The curves in these graphs represent equation (1) for the energy range from 0.2–10 TeV. Figure 4(a) shows the contributions of the stochastic and the non-compensation term as a function of energy, as well as the total energy resolution, for a calorimeter with $e/h = 1.3$ and a stochastic term of $60\% / \sqrt{E}$. It is clear that, even for an $e/h$ value that is usually considered quite good, the effects of fluctuations in $f_{em}$ dominate the hadronic energy resolution in the TeV regime. Figure 4(b) shows the total energy resolution for calorimeters with different $e/h$ values. Especially for large $e/h$ values, the energy dependence of the resolution is no longer well described by a straight line in this plot (thus invalidating equation (3)). Figure 4(b) also shows the effects that may be expected as a result of material dependence. They derive from the value of $E_0$ in equation (1), which is almost a factor of two larger in high-$Z$ absorber materials such as lead, compared to copper or iron.
2.2. Calibration problems

The energy resolution of calorimeters is usually determined from the width of the signal distribution for monoenergetic beam particles. However, this is only correct if the mean value of that distribution reproduces the beam energy, for all energies. Meeting this requirement, which is the purpose of the calibration procedure, is highly non-trivial. As we enter the TeV domain and expect resolutions at the level of a few percent, meeting this requirement is correspondingly harder to achieve. Calibration problems are often grossly underestimated [9]. In this paper, we only highlight some aspects using examples taken from practice. The problems become rapidly worse as the calorimeter is subdivided into more and more longitudinal segments. However, unsegmented calorimeters are not without calibration problems either.

2.2.1. Unsegmented calorimeters. One of the advantages of such a calorimeter system is that there is only one way to calibrate it, so one is not tempted to do it in a wrong way, as in longitudinally segmented systems. The energy scale is set with electrons. Measurements with pions of different, known energies, covering preferably as large an energy range as possible, make it possible to determine $\frac{e}{h}$ and $\langle f_{em} \rangle (E)$. With this information, the signal from an arbitrary pion ($E_{em}$) can be converted into its, on average correct, energy ($E_\pi$):

$$E_\pi = E_{em} \left[ \frac{h}{e} + \langle f_{em} \rangle (E)(1 - h/e) \right]^{-1},$$

in a few iterations in which $\langle f_{em} \rangle (E)$ is adjusted.

A similar procedure can provide the tools for reconstructing jet energies. In the absence of ‘jet test beams’ of known energy, the only way to determine $\langle f_{em} \rangle (E)$ for jets is by means of a suitable fragmentation function (which gives the fraction of the jet energy carried by photons and other fragments developing em showers) and the $\langle f_{em} \rangle (E)$ of the charged fragments.

A fundamental problem arises from the fact that not all hadrons have the same $\langle f_{em} \rangle (E)$ values. For example, in highly non-compensating calorimeters, differences in excess of 10% have been measured between the $\langle f_{em} \rangle (E)$ values for 0.3 TeV proton and pion-induced showers. Unless one has another way to establish the particle type, this phenomenon will inevitably lead to systematic energy mismeasurements. Fortunately, the importance of such effects rapidly decreases as the $\frac{e}{h}$ value gets less extreme, and the jet multiplicity increases.

2.2.2. Segmented calorimeters. Most calorimeters consist of a separate em and hadronic section. Previous studies have indicated the importance of calibrating both sections in the same way [9, 10]. However, even in that case, problems arise when the two sections have different $\frac{e}{h}$ values. This became very clear in studies of the hadronic performance of the CMS barrel calorimeter, which consists of an em section made of PbWO$_4$ crystals ($\frac{e}{h} \approx 2.4$), and a brass/plastic-scintillator hadronic section ($\frac{e}{h} \approx 1.3$).

The hadronic performance of this calorimeter system was recently systematically studied with various types of particles (e, $\pi$, K, p, $\bar{p}$), covering a momentum range from 1 to 300 GeV c$^{-1}$. Figure 5 shows some results from this study [11]. Both sections were calibrated with 50 GeV electrons. The figure shows that the calorimeter is very linear for these particles. 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 more than 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.

2.2.3. Calibration and hadronic signal linearity. Hadronic signal non-linearities and starting point dependence of the response are a general characteristic of non-compensating calorimeter systems, although the effects are usually not as spectacularly large as shown in figure 5. Many calibration schemes used in practice set the energy scale of the em calorimeter section with electrons, while the hadronic section is calibrated with pions that penetrate the em section without a nuclear interaction and deposit their (almost) entire energy in the hadronic section. Other schemes choose the calibration constants for the hadronic section on the basis of a minimization of the width of the total signal distribution. It has been shown repeatedly that both types of schemes are fundamentally flawed [10, 12]. It has been demonstrated experimentally that one of the consequences of these schemes is an increase in the hadronic signal non-linearity, over and above the non-linearity that would result from a correct calibration scheme [10].

Hadronic signal non-linearity is bad, especially when it comes to jet detection. It is bad because it makes the reconstructed energy dependent on the jet topology: a jet with a leading particle that carries a large fraction of the energy of the fragmenting object will be reconstructed with a different energy than a jet whose energy is more evenly divided among the different constituent particles. This phenomenon will, for example, lead to different calorimeter responses to gluon and quark jets of the same energy, because of the different composition of such jets. Calibration schemes that increase such differences should be avoided, but in practice this is not the case since one is usually completely focused on ‘resolution’. However, it should be realized...
that the width of a distribution is only an indication of the resolution (i.e. the precision with which the energy of an event can be determined) if the central value of the distribution has the correct energy. The effects of signal non-linearity invalidate this presumption.

2.2.4. Em showers in segmented calorimeters. Response non-uniformity is not only a problem for hadron showers, it also affects electrons and photons that develop showers in a longitudinally segmented em (sampling) calorimeter. The basic reason is that the sampling fraction of a given calorimeter structure depends on the stage of the developing showers. For example, in calorimeters consisting of high-$Z$ absorber material (e.g. lead) and low-$Z$ active material (plastic, liquid argon), the sampling fraction may vary by as much as 25–30% over the volume in which the absorption takes place. In the early stage of its development, the shower still resembles a collection of mips, but especially beyond the shower maximum, the energy is predominantly deposited by soft ($<1\text{ MeV}$) $\gamma$s. The latter are much less efficiently sampled than mips in this type of structure, where dominant processes such as photo-electric effect and Compton scattering strongly favor the high-$Z$ absorber material [6].

The fact that the em shower sampling fraction decreases as the shower develops may have very important practical consequences. These include:

1. systematic mismeasurement of energy [13],
2. em signal non-linearity [2], and
3. differences in response to showers induced by electrons, photons and $\pi^0$s [14].

These issues are especially relevant in longitudinally segmented calorimeters, where one has to decide which calibration constants to assign to the different segments. This intercalibration is more often than not done incorrectly, resulting in the consequences mentioned above.

A recent example of an experiment that has to deal with this intercalibration issue is ATLAS, whose Pb/LAr ECAL consists of three longitudinal segments. Figure 6 shows how the sampling fraction evolves as a function of depth, in an energy dependent way. Elaborate Monte Carlo simulations played a crucial role in ATLAS’ solution of the intercalibration problems, for which they developed a very sophisticated procedure, based on a variety of energy-dependent parameters. This procedure was tested in great detail with Monte Carlo events and yielded both excellent signal linearity and good energy resolution [15]. Typically, in more empirical
2.2.5. More sections, more problems. As illustrated by the examples in the previous subsections, the (inter)calibration problems get rapidly more complicated as the number of longitudinal calorimeter segments increases. Figure 7 shows data from the Alpha Magnetic Spectrometer (AMS) em calorimeter, which consists of 18 Pb layers (each $\sim 1X_0$ thick), interleaved with plastic scintillating fibers. All 18 longitudinal segments of this detector are thus identical in structure. They are also calibrated in exactly the same way, with minimum-ionizing particles (mips), which deposit on average 11.7 MeV in each layer. Figure 7(a) shows the average signals from 100 GeV electron showers developing in this calorimeter. These signals were translated into energy deposits based on the described calibration. The measured data were fitted to a $\Gamma$-function and at high energies, where the showers were not fully contained, the average leakage was estimated by extrapolating this fit to infinity. As shown in figure 7(b), this procedure systematically underestimated this leakage fraction, more so as the energy (and thus the leakage) increased. The reason for this is clear (see section 2.2.4). Since the sampling fraction decreases as the shower develops, a procedure in which the relationship between measured signals and the corresponding deposited energy is the same for each segment will cause the energy leakage to be systematically underestimated, more so if that leakage increases. What is not so clear is how to solve this very complicated problem.

Figure 7. Average signals for 100 GeV electrons in the 18 longitudinal sections of the AMS lead/scintillating fiber calorimeter (a). Average difference between the measured energy and the beam energy, after leakage corrections based on extrapolation of the fitted shower profile (b). Data from [13].
3. New approaches

It has become customary to express the energy resolution of calorimeters as the quadratic sum of a scaling term and an energy independent (‘constant’) term:

\[ \frac{\sigma}{E} = a_1 \sqrt{E} \oplus a_2, \]  

and often the performance of actual devices is referred to in terms of the value of \( a_1 \). As we have seen in section 2.1, this parameterization is fundamentally incorrect, especially for hadronic showers in non-compensating calorimeters. Therefore, I will quote the resolution in terms of a fraction at a given energy, or in terms of the value of \( \sigma \) at that energy. And, of course, \( \sigma \) should represent the \( \text{rms} \) value of the signal distribution, not the result of a Gaussian fit or some other procedure that ignores the non-Gaussian tails characteristic of the signals from non-compensating calorimeters.

An often mentioned design criterion for calorimeters at a future high-energy linear \( e^+e^- \) collider is the need to distinguish between hadronically decaying W and Z bosons\(^2\). The requirement that the di-jet masses of \( W \to q\bar{q} \) and \( Z \to q\bar{q} \) events are separable by at least one Rayleigh criterion implies that one should be able to detect 80–90 GeV jets with a resolution of 3–3.5 GeV. This goal can be, and has been achieved with compensating calorimeters [16, 17]. However, because of the small sampling fraction required for compensation, the em energy resolution is somewhat limited in such devices. Also, because of the crucial role of neutrons produced in the shower development, the signals would have to be integrated over relatively large volumes and time intervals to achieve this resolution, which is not always possible in practice. In the following, we discuss some other methods that are currently being pursued to circumvent these limitations.

3.1. Particle flow analysis (PFA)

One method that has been proposed in this context, the so-called PFA, is 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 \( \sim 7 \text{ GeV} c^{-2} \) [18]. Several detector concepts studied in the context of the ILC experimental program are based on this method as well\(^3\).

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 [19]. However, it has been argued by others that this, for practical geometries, is an illusion [20]. Especially in jets with leading charged particles, the overlap between the showers from individual jet particles makes the fine granularity largely irrelevant.

\(^2\) An important reaction to be studied is \( e^+e^- \to H^0Z^0 \). By using the hadronic decay modes of the \( Z^0 \) (in addition to \( \mu^+\mu^- \) decay), an important gain in event rates can be obtained. However, more abundant processes such as \( e^+e^- \to W^+W^- \) will obscure the signal unless the calorimeter is able to distinguish efficiently between hadronic decay of W and Z bosons.

\(^3\) http://physics.uoregon.edu/lc/wwstudy/concepts/
Figure 8. Distributions of the calibration constants (a) and the rms noise (b) for 6471 channels of the em section of the CALICE calorimeter.

In order to increase the spatial separation between showers induced by the various jet particles, and thus alleviate the double-counting problem, all concept detectors for the ILC that are based on the PFA principle count on strong solenoidal magnetic fields (4–5 T). Such fields may indeed improve the validity of PFA algorithms, especially at large distances from the vertex, since they open up a collimated beam of particles. It is important to be quantitative in these matters. After having traveled a typical distance of 1 m in a 4 T magnetic field, the trajectory of a 10 GeV pion deviates 6 cm from that of a straight line, i.e. less than one third of a nuclear interaction length (the characteristic length scale for lateral hadronic shower development) in typical calorimeters. The field is not always beneficial, since it may also have the effect of bending some jet particles with a relatively large transverse momentum with respect to jet axis into the jet core.

Of course, in the absence of reliable Monte Carlo simulations the only way to prove or disprove the advocated merits of the proposed PFA methods is by means of dedicated experiments in realistic prototype studies.

A large collaboration, called CALICE, has set out to test the viability of these ideas. They have constructed a large calorimeter system, containing about 14 000 readout channels. For the em section, silicon pads are used, while the hadronic section is equipped with plastic scintillator tiles or resistive plate chambers. The em section uses tungsten as absorber material, which limits the radial size of em showers. Iron, the absorber material used in the hadronic section, has a Moliere radius that is twice that of tungsten, and a radiation length that is five times larger, which means that the detector volume occupied by an em shower component differs by a factor of twenty in these two sections. This calorimeter has been tested extensively since 2005 in testbeams of electrons, muons and pions. Publicly available documents on this project [22] mainly elaborate on technical issues, but information on the performance of the instrument, and in particular in measuring hadronic energies, is very scarce. Figure 8 shows a distribution of 6471 calibration constants derived from an exposure to muons. However, the real calibration issue is of course how to translate these data into particle, energy and position

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Concern about the absence of reliable Monte Carlo simulations for hadronic shower development was the main reason for a special workshop held at Fermilab in 2006 [21]. To my knowledge, the fundamental problems addressed at this workshop, e.g. with regard to the for PFA crucial hadronic shower widths, still exist.

New Journal of Physics 10 (2008) 025003 (http://www.njp.org/)
dependent numbers needed for determining the energy of showers developing in this structure. Given the complications described in section 2.2, this will be a daunting task.

But even if this was successfully accomplished, one would still be faced with an even more challenging problem, namely how to avoid double counting, i.e. how to eliminate from the measured calorimetric energy deposit pattern the contributions from charged hadrons, whose momenta have been measured by the tracking system. The fundamental problem here is that there is no such thing as a ‘typical hadronic shower profile’ that could be used for this purpose. This may be concluded from detailed measurements of the energy deposit profiles in a finely segmented lead/iron/plastic-scintillator calorimeter [23]. Figure 9 shows the longitudinal profiles of 12 randomly selected events. The peaks in these profiles, which characterize the large event-to-event differences, are caused by em shower components. The figure demonstrates that such components are abundantly produced beyond the first nuclear interaction length, i.e. in the hadronic section of typical calorimeter systems. This feature is also the origin of calibration problems in segmented non-compensating calorimeters (see section 2.2).

The mentioned CALICE report [22] also illustrates my earlier statement on the reliability of simulations. Its figure 2-1 displays 50% variations in hadronic shower widths among 15 different simulation codes, an issue crucial to PFA algorithms.

The resolution of calorimeters is determined by fluctuations. Therefore, successful elimination of double counting depends on how this can be achieved event by event, not on average. In a theoretical study of this problem [20], it was concluded that in the absence of energy constraints, such as the ones used at LEP, the proposed method may improve the performance of a poor calorimeter system in a realistic geometry by ~30%, but the resolution
gets nowhere near the performance one may expect from a dedicated stand-alone calorimeter system [20]. Time will show if these conclusions were too pessimistic.

One of the concept ILC detectors that plan to use PFA (GLD) does not gamble entirely on the advocated PFA merits, but has chosen a compensating lead/plastic-scintillator hadronic calorimeter section. Measurements of hadronic showers developing in prototypes of this detector gave a resolution of $\sim 4.5$ GeV in the most relevant 80–90 GeV region [24], in good agreement with earlier measurements for a similar structure [16].

### 3.2. Dual-readout calorimetry

A completely different approach is followed by the DREAM Collaboration, which tries to meet the mentioned performance requirements by developing a calorimeter that can measure the jet energy sufficiently precisely by itself, i.e. without momentum information from the tracking system. Since the resolution is determined by fluctuations, eliminating or reducing the (effects of the) dominant fluctuations is the key to improving it. In non-compensating calorimeters, the hadronic energy resolution is dominated by fluctuations in $f_{em}$. DREAM has shown that (the effects of) these fluctuations can be eliminated by simultaneously measuring both the visible deposited energy ($dE/dx$) and the Čerenkov light generated in the shower absorption process.

Calorimeters that use Čerenkov light as signal source are, for all practical purposes, only responding to the em fraction of hadronic showers [4]. This is because the electrons/positrons through which the energy is deposited in the em shower component are relativistic down to energies of only 200 keV. On the other hand, most of the non-em energy in hadron showers is deposited by non-relativistic protons generated in nuclear reactions [6]. Such protons do generate signals in other types of active media (scintillator, LAr). By comparing the relative strengths of the two signals, the em shower fraction can be determined and the total shower energy can be reconstructed using the known $e/h$ value(s) of the calorimeter.

#### 3.2.1. Fiber-based detectors

This principle was first demonstrated with a calorimeter that uses two active media, hence the name DREAM (Dual REAdout Method): scintillating fibers measure the visible shower energy ($S$), while clear fibers measure the generated Čerenkov light ($Q$). Using the ratio of the two signals, the value of $f_{em}$ could be determined event-by-event, since

$$\frac{Q}{S} = \frac{f_{em} + 0.21(1 - f_{em})}{f_{em} + 0.77(1 - f_{em})},$$

where 0.21 and 0.77 represent the $h/e$ ratios of the Čerenkov and scintillator calorimeter structures, respectively.

The merits of this method are clearly illustrated in figure 10, which shows the overall Čerenkov signal distribution for 100 GeV $\pi^-$ (a), as well as distributions for subsamples selected on the basis of their $f_{em}$ value (b) [25], determined by equation (6). Each $f_{em}$ bin probes a certain region of the overall signal distribution, and the average value of the subsample distribution increases with $f_{em}$.

Once the value of $f_{em}$ was determined, the signals could be corrected in a straightforward way for the effects of non-compensation. In this process, the energy resolution improved, the
signal distribution became much more Gaussian and, most importantly, the hadronic energy was correctly reproduced. This was true both for single pions as well as for jets.\(^5\)

The results for 200 GeV ‘jets’ are shown in figures 10(c)–(e). These ‘jets’ were in fact not fragmenting quarks or gluons, but multivariate events created by pions interacting in a target placed upstream of the calorimeter. Using only the ratio of the two signals produced by this calorimeter, the resolution for these ‘jets’ was improved from 14 to 5\%, in the Čerenkov channel. It was shown that this 5\% resolution was in fact dominated by fluctuations in side leakage in this (small, only 1030 kg instrumented volume) detector. Eliminating such fluctuations led to a further considerable improvement (figure 10(e)).

Also the jet energy was well reconstructed as a result of this procedure. Whereas the raw data gave a mean value of 133.1 GeV for these 200 GeV jets, the described procedure led to hadronic energies that were within a few percent correct, \textit{in an instrument calibrated with electrons}. In the process, hadronic signal linearity (a notorious problem for non-compensating calorimeters, see section 2.2.2) was more or less restored as well. Any remaining effects can be ascribed to side leakage and would most likely be eliminated in a larger detector.

\(^5\) It has been pointed out by Groom \cite{7}, that the measured scintillator and Čerenkov signals may also be directly used to determine the shower energy \((E)\), since

\[
E = \frac{S - \chi C}{1 - \chi}, \quad \text{with} \quad \chi = \frac{1 - (h/e)_{S}}{1 - (h/e)_{C}} \sim 0.3 \text{ for this calorimeter.}
\]
Simultaneous detection of the scintillation and Čerenkov light produced in the shower development turned out to have other, unforeseen beneficial aspects as well. One such effect is illustrated in figure 11, which shows the signals from muons traversing the DREAM calorimeter along the fiber direction [26]. The gradual increase of the response with the muon energy is a result of the increased contribution of radiative energy loss (Bremsstrahlung) to the signals. The Čerenkov fibers are only sensitive to this energy loss component, since the primary Čerenkov radiation emitted by the muons falls outside the numerical aperture of the fibers. The constant (energy-independent) difference between the total signals observed in the scintillating and Čerenkov fibers represents the non-radiative component of the muon’s energy loss. Since both types of fibers were calibrated with em showers, their response to the radiative component is equal. This is the only example I know of a detector that separates the energy loss by muons into radiative and non-radiative components.

3.2.2. Homogeneous DREAM calorimeters. Once the effects of the dominant source of fluctuations are eliminated, the resolution is determined and limited by other types of fluctuations. In the case of the DREAM detector, these fluctuations include, apart from fluctuations in side leakage which can be eliminated by making the detector larger (see figure 10(e)), sampling fluctuations and fluctuations in the Čerenkov light yield. The latter effect alone (8 Čerenkov photoelectrons per GeV) contributed $35\%/\sqrt{E}$ to the measured resolution. Both effects could be greatly reduced by using crystals for dual-readout purposes. Certain dense high-Z crystals (PbWO$_4$, BGO) produce significant amounts of Čerenkov light, which may be separated from the scintillation light by exploiting differences in time structure, spectral properties and directionality.
Figure 12. Average time structure of the signals measured with the PMT reading out one end (L) of a PbWO$_4$ crystal traversed by 10 GeV electrons, for two different orientations of the crystal, and the difference between these two time distributions. At $\theta = -30^\circ$, Čerenkov light contributes to the signals, at $\theta = 30^\circ$, it does not [27, 28]. When the crystal was read out from the other side, the prompt excess signal was detected for $\theta = 30^\circ$, and was absent for $\theta = -30^\circ$.

This is illustrated in figure 12, which shows the time structure of the (L) signals from a lead tungstate (PbWO$_4$) crystal traversed by a beam of 10 GeV electrons. The scintillation process in PbWO$_4$ has a decay constant of $\sim 10$ ns, whereas the Čerenkov component of the signals is prompt. The figure clearly shows the additional prompt signal component that appears when the crystal is rotated from a position in which Čerenkov light does not contribute to the signals ($\theta = 30^\circ$) to a position where it does ($\theta = -30^\circ$). The trailing edge of the PMT signals is not affected by this rotation and is indeed in great detail (including the effects of reflections in the signal cables) identical for these two pulse shapes [27, 28].

Even more interesting features were observed in bismuth germanate (Bi$_4$Ge$_3$O$_{12}$, or BGO) crystals. Even though Čerenkov radiation represents a much smaller fraction of the light produced by these crystals, it is easier to separate and extract it from the signals. The much longer scintillation time constant and the spectral difference are responsible for this [26]. Figure 13 shows recent results obtained by the DREAM Collaboration. The different spectra for the scintillation and Čerenkov light are evident from figures 13(a) and (b), which show the time structures of signals recorded with two different filters. The 'prompt' component observed in the ultraviolet signal is due to Čerenkov light. This can be concluded from figure 13(c), which shows the ratio of both signals as a function of the angle of incidence of the beam electrons. This ratio peaks when the photons emitted at the Čerenkov angle ($\theta_C = \arccos 1/n \approx 63^\circ$) travel along the longitudinal crystal axis: $\theta = 27^\circ$. Figure 13(a) shows that also a small fraction of the scintillation light passes through the UV filter. This offers the possibility to obtain all needed information from that one signal. An external trigger opens two gates: one narrow (10 ns) gate covers the prompt component, the second gate (delayed by 30 and 50 ns wide) only contains

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6 The BGO scintillation spectrum peaks at 480 nm, while Čerenkov light exhibits a $\lambda^{-2}$ spectrum.
Figure 13. Average signals produced by 50 GeV electrons traversing a BGO crystal at angles of incidence ($\theta$) of $\pm 30^\circ$, as measured with a UV filter (a), or with a yellow filter (b). The ratio of these two signals, as a function of the angle of incidence of the beam electrons (c). Preliminary results. See text for details.

scintillation light. The latter signal can also be used to determine the contribution of scintillation to the light collected in the narrow gate. In this way, the Čerenkov/scintillation ratio can be measured event-by-event on the basis of one signal only.

3.2.3. Further improvements. The features described above offer the possibility to improve the already impressive DREAM results significantly. Should one succeed in eliminating, or at least greatly reducing the contributions of sampling fluctuations and photoelectron statistics to hadronic energy resolution this way, then the last hurdle toward ultimate performance is formed by the fluctuations in visible energy, i.e. fluctuations in the energy fraction used to break up atomic nuclei\(^7\). It has been demonstrated that the kinetic energy carried by the neutrons produced in the shower development process is correlated to this invisible energy loss [6].

\(^7\) The elimination of fluctuations in $f_{em}$ takes care of the effects of the average contribution of invisible energy. However, for a given value of $f_{em}$, the invisible energy fluctuates around this average.
Efficient neutron detection, a key ingredient for compensating calorimeters, not only brings $e/h$ to 1.0, but also greatly reduces the contribution of fluctuations in invisible energy to the hadronic energy resolution. It has been demonstrated that this reduces the ultimate limit on this resolution to $\sim 13%/\sqrt{E}$ [29], in compensating lead/plastic-scintillator calorimeters. This would translate into mass resolutions of $\sim 1.5%$ for hadronically decaying $W$ and $Z$ bosons, much better than the requirements of a Linear $e^+e^-$ Collider experiment.

Detailed measurements of the time structure of the calorimeter signals, examples of which are given in figures 12 and 13, make it also possible to measure the contribution of neutrons to the shower signals. Figure 14 illustrates this with data taken from a recent paper by the DREAM Collaboration [30]. The figure shows the average time structure of Čerenkov and scintillator signals measured for 100 GeV $\pi^+$ showers developing in their fiber calorimeter. The scintillator signals exhibit an exponential tail which a time constant of $\sim 20$ ns. This tail has all the characteristics expected of a (nonrelativistic) neutron signal and is thus absent in the time structure of the Čerenkov signals. If the contribution of this tail could be accurately measured event by event, just like $f_{\text{em}}$, then the ultimate hadronic energy resolution mentioned above would be within reach.

3.2.4. Challenges. Many years of experience have shown that detectors based on light as the source of experimental information have their own characteristic problems. Among these, we mention the effects of light attenuation, short-term instabilities arising from temperature and other environmental effects, and long-term effects of radiation damage and other aging phenomena. Perhaps the most daunting challenges should be expected from light attenuation. The scale for fluctuations in hadronic shower development is set by the nuclear interaction
length, typically \( \sim 20 \text{ cm} \) in realistic detector structures. A typical characteristic of a dual-readout calorimeter is its longitudinally \textit{unsegmented} structure, chosen deliberately to avoid the problems discussed in section 2. If one wants to limit the effects of spatial shower fluctuations on the signals in such an unsegmented calorimeter to 1\%, then the light attenuation length of the readout elements thus has to be \( \sim 20 \text{ m} \). This requirement will be extremely hard to achieve with active media other than optical fibers. On the other hand, it may be very hard to make a 4\( \pi \) detector structure with longitudinal optical fibers.

A second set of problems for light-based calorimeters arises from the need to operate in a magnetic field. Not only does this field affect the light production characteristics of some media, it also impedes the choice of light detectors. New types of light detectors developed to deal with these problems (APD, SiPM) exhibit encouraging, but certainly by no means ideal characteristics.

4. Concluding remarks

High-quality energy measurements will be an important tool for accelerator-based experiments at the TeV scale. There are no fundamental reasons why the four-vectors of all elementary particles could not be measured with a precision of 1\% or better at these energies. However, reaching this goal is far from trivial, especially for the hadronic constituents of matter. Unfortunately, little or no guidance is provided by hadronic Monte Carlo shower simulations in this respect. In the past 30 years, all progress in this domain therefore has been achieved through dedicated R&D projects, and this is still the way to go today.

Several major R&D efforts are underway to further improve the quality of hadronic energy measurements. These efforts are characterized by very different styles. R&D in the framework of the PFA concept is to a large extent concentrated on the technicalities of detector design, whereas very fundamental questions concerning crucial aspects of the applicability of this concept (e.g. calibration) tend to be ignored. On the other hand, the dual-readout R&D project concentrates strongly on experimental tests of the validity of the principles on which improvement of the hadronic calorimeter performance is based, and tends to ignore issues concerning the incorporation of this type of detector into a 4\( \pi \) experiment, and simulations in general.

Until now, the dual-readout approach has been remarkably successful. It combines the advantages of compensating calorimetry with a reasonable amount of design flexibility. Since there is no limitation on the sampling fraction, the factors that limited the energy resolution of compensating calorimeters (SPACAL, ZEUS) to \( \sim 30\% / \sqrt{E} \) can be eliminated, and the theoretical resolution limit of \( \sim 15\% / \sqrt{E} \) seems to be within reach. Dual-readout detectors thus hold the promise of high-quality calorimetry for all types of particles, with an instrument that can be calibrated with electrons.

In any case, I am confident that if a high-energy Linear \( e^+e^- \) Collider is ever built, the knowledge of how to build, calibrate and operate an instrument that can measure the objects of interest with the required level of precision will be available.

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8 This number applies to single hadrons. The requirements are much less stringent for the detection of jets, since the depth fluctuations in light production decrease considerably for a number of particles that simultaneously develop showers in the same structure [17, 25].

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