Quartz Fibers and the Prospects for Hadron Calorimetry at the 1% Resolution Level[1]

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1 Introduction

In previous talks at this conference, we have heard a lot about quartz fiber calorimeters. These detectors have many interesting properties indeed. However, excellent energy resolution does not seem to be one of those properties. Yet, I will try to convince you that the application of quartz fibers may bring substantial improvements to a variety of aspects of hadron calorimetry, including measurement of the energy of hadron showers with unprecedented accuracy.

Before elaborating on this point, I will first briefly review the various factors contributing to and limiting the performance of calorimeters.

2 The electromagnetic resolution of calorimeters

The factors contributing to and limiting the electromagnetic (em) energy resolution of calorimeters are all well understood and documented:

- Fluctuations in the number of quanta constituting the calorimeter signals, frequently refered to as *(photo-)electron statistics*. Such fluctuations form the limiting factor for the resolution of semiconductor crystals for the detection of γ rays. They also determine the energy resolution for em shower detection in the quartz fiber calorimeter discussed at this conference by Akchurin [1].
- *Sampling fluctuations*. These fluctuations dominate the energy resolution of almost all em sampling calorimeters. They are the result of the fact that only a fraction of the shower energy is deposited in the active calorimeter layers. This fraction varies from one event to the next. The contribution of sampling

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fluctuations to the em energy resolution of calorimeters is well described by the following expression [2]:

$$\frac{\sigma}{E} = \sqrt{d/f_{\rm samp}} \cdot \frac{1}{\sqrt{E}} \tag{1}$$

in which $f_{\rm samp}$ denotes the sampling fraction of the calorimeter and d the thickness of the active calorimeter layers, while the shower energy E is given in units of GeV.

- *Instrumental effects*. These effects, which are very specific for the type of calori-meter, all have in common that their contribution to the energy resolution does not scale as $E^{-1/2}$. For example, the contribution of electronics noise in liquid-argon calorimeters scales as $1/E$. The contribution of optical effects to the resolution of scintillation calorimeters is sometimes energy independent (*e.g.,* light attenuation in fibers), in other cases it may scale as $E^{-1/4}$ (*e.g.,* fluctuations in the light collection efficiency in some crystals).

3 The hadronic energy resolution of calorimeters

The factors mentioned in the previous section also contribute to the hadronic calorimeter resolution. However, in this case, there is one additional contributing factor, which usually dominates the resolution and determines all aspects of the hadronic calorimeter performance: fluctuations in *visible energy*.

While in em showers all energy carried by the showering particle is deposited by ionizing or exciting the atoms or molecules of the absorbing medium, this is not the case for hadron showers. The reasons for this include:

1. The fact that some particles produced in hadronic shower development may *escape* the detector. The energy carried by such particles (*e.g.,* muons, neutrinos or neutrons) is lost for detection. In typical hadron calorimeters used in particle physics experiments these effects are certainly present, but their contribution to the resolution is usually negligibly small. Much more important are

2. *Nuclear binding energy losses*. These losses occur in the non-em component of the hadron induced shower. When a shower particle interact with a nucleus of the absorber medium and nucleons are released in this process, the binding energy, ΔB, of these nucleons (which has to be provided by the interacting particle) is lost for detection. These losses may be very substantial. Typically, ΔB amounts to 300 - 400 MeV per GeV of energy deposited in non-em form. Since nuclear reactions do not play a significant role in the em component of

the hadron showers, *i.e.* the component initiated by π^0's and η's produced in the shower development, the calorimeter *response* to this shower components is larger than the response to the non-em component: $e/h > 1$.

In practice, fluctuations in visible energy tend to be dominated by fluctuations in the energy sharing between the em and non-em components of hadron showers. Such fluctuations in the em shower fraction, $f_{\rm em}$, are not Gaussian. The production of π^0's in shower development is a one-way street, which may lead to asymmetries in the hadronic lineshape. In some nuclear reactions (*e.g.*, charge-exchange reactions), almost all available energy is transfered to a single π^0. For events in which this happens, $f_{\rm em}$ is very large. However, similar reactions in which a large fraction of the available energy is transfered to a charged pion do not necessary lead to a *small* $f_{\rm em}$ value, since this charged pion may produce one or more energetic π^0's in a later stage of the shower development.

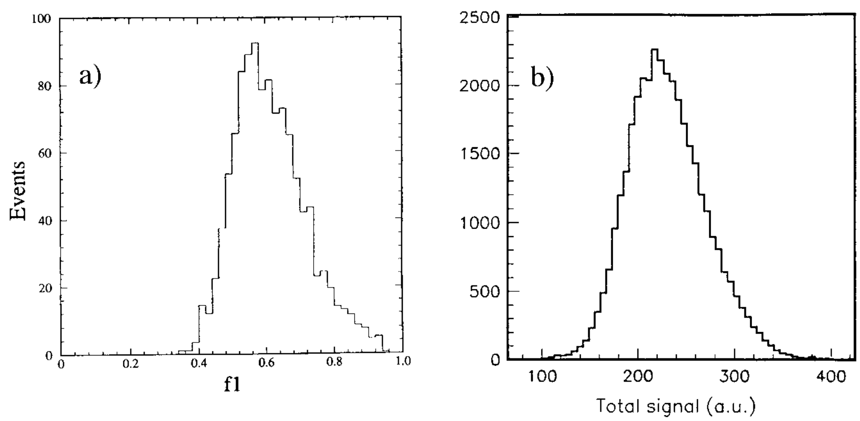

Figure 1: The distribution of $f_{\rm em}$, measured by SPACAL for 150 GeV pions [3] (left) and the distribution of the *total* calorimeter signal for 300 GeV pions, measured with the Quartz Fiber calorimeter [1] (right).

This is illustrated in fig. 1. The left diagram shows the $f_{\rm em}$ distribution for showers induced by 150 GeV π^- in the SPACAL detector [3]. The right diagram shows the signal distribution of the Quartz Fiber calorimeter for 300 GeV π^- [1]. Both distributions are remarkable similar, skewed to the high-energy side.

The fluctuations in $f_{\rm em}$ become relatively smaller as the energy increases, but this improvement proceeds much more slowly than the $1/\sqrt{E}$ scaling characteristic for Gaussian fluctuations. Measurements by the SPACAL and QFCAL groups quoted above indicate that the improvement scales rather with the logarithm of the energy.

This may be understood from the fact that, as the energy increases, more generations of particle interactions occur in the shower development and, therefore, the number of different π^0's contributing to the em shower component increases. This number of generations is exponentially related to the energy of the showering particle [4].

The hadronic energy resolution of almost all calorimeters (*i.e.* the *non-compensating* ones) is dominated by these fluctuations, especially at high energies ($>$ 100 GeV). This is particularly true for homogeneous devices, which are in practice not capable of achieving hadronic resolutions better than $\sim 10\%$.

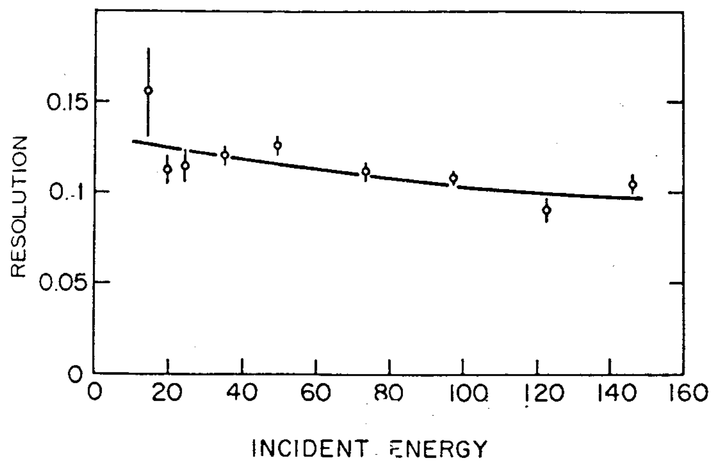

Figure 2: The hadronic response (a) and energy resolution (b) as a function of energy, measured with a homogeneous calorimeter consisting of 60 tonnes of liquid scintillator [5]

Figure 2b shows the hadronic energy resolution measured by Benvenuti and coworkers [5] for a very large homogeneous calorimeter consisting of sixty tonnes of liquid scintillator. This resolution improved only very slowly with energy. Figure 2a illustrates another consequence of non-compensation, measured with the same instrument. Since the average value of $f_{\rm em}$ increases with energy, so does the hadronic calorimeter response (the average signal per unit energy). As a result, the calorimeter is *intrinsically non-linear* for hadron showers.

3.1 Compensating calorimeters

In compensating calorimeters, the average calorimeter responses to the em and non-em shower components are equal ($e/h = 1$). Therefore, the contribution of fluctuations in $f_{\rm em}$, which dominate the hadronic resolution of non-compensating devices, is eliminated. However, this does not mean that fluctuations in visible energy don't contribute to the hadronic energy resolution any more.

The relative importance of such fluctuations depends on the way in which compensation is achieved in the calorimeter. For example, in plastic-scintillator calorimeters, compensation may be achieved by proper amplification of the signal from neutrons released in the shower development [9]. The number of neutrons and the total kinetic energy they carry, which is proportional to that signal, are correlated to the amount of nuclear binding energy lost. As a result, the effect of fluctuations in ΔB on the hadronic energy is reduced, and the resolutions achievable with such compensating calorimeters are considerably better than the ones shown in fig. 2.

The remaining fluctuations in ΔB, which we will call the *intrinsic* fluctuations σ_I, obey Poisson statistics. Together with the fluctuations in the number of signal quanta (σ_P) and the sampling fluctuations (σ_S), they determine the total hadronic resolution of the calorimeter:

$$\frac{\sigma_h}{E} = \frac{\sigma_P \oplus \sigma_S \oplus \sigma_I}{E} = \frac{c}{\sqrt{E}} \tag{2}$$

In Table 1, the hadronic energy resolution and the various factors contributing to it are listed for three different calorimeters with $e/h \approx 1$: The ^{238}U/plastic-scintillator calorimeter used in the ZEUS experiment [6], the compensating Pb/plastic-scintillator module built by ZEUS as part of their prototype studies [7] and the SPACAL Pb/fiber calorimeter [8].

Table 1: Hadronic resolution and the factors contributing to it, for three (approximately) compensating calorimeters.

	ZEUS ^{238}U [6]	ZEUS Pb [7]	SPACAL [8]
σ_P	$6\%/\sqrt{E}$	$10\%/\sqrt{E}$	$5\%/\sqrt{E}$
σ_S	$31\%/\sqrt{E}$	$42\%/\sqrt{E}$	$27\%/\sqrt{E}$
σ_I	$19\%/\sqrt{E}$	$11\%/\sqrt{E}$	$11\%/\sqrt{E}$
$\sigma_{\rm had}$	$37\%/\sqrt{E}$	$44\%/\sqrt{E}$	$30\%/\sqrt{E}$

The contributions from the various sources of fluctuations mentioned above to the measured total energy resolutions were determined as follows.

The contribution from photoelectron statistics was experimentally obtained by reducing the light yield by a known factor, by means of filters placed in front of the photomultiplier tubes, and by measuring the resulting degradation of the total energy resolution. These measurements are best done with low-energy electron showers, where the resolution is most sensitive to this effect [10].

The contribution from sampling fluctuations was measured in a similar way, by reading out only every second sampling layer [6]. When σ_P, σ_S and the total hadron resolution have been measured, the contribution from intrinsic fluctuations can be determined from eq. 2.

It is interesting that the intrinsic fluctuations in the uranium calorimeter are significantly larger than in the lead-based detectors. This can be understood from the fact that most of the neutrons produced by showers developing in uranium are caused by nuclear fission, and thus unrelated to ΔB.

In all three calorimeters, the hadronic energy resolution is dominated by sampling fluctuations. This is a direct consequence of the fact that the condition $e/h = 1$ requires a small sampling fraction, 2.3% for showers developing in lead/plastic detectors, 5.1% for the uranium/plastic calorimeter. The large contribution of sampling fluctuations in lead (42%/$\sqrt{E}$) was a major factor in ZEUS' decision to choose uranium as abosrber material. SPACAL reduced this term to 27%/$\sqrt{E}$ by increasing the sampling *frequency*, *i.e.* by reducing d in eq. 1, keeping $f_{\rm samp}$ at the required value of 2.3%. This detector achieved hadronic energy resolutions better than 3% for 150 GeV "jets" (reaction products from an interaction by a 150 GeV pion in an upstream target).

Since a further increase of the sampling frequency is impractical, the only way to reduce the sampling fluctuations further is by increasing the sampling fraction, $f_{\rm samp}$. For example, if the fiber packing fraction of SPACAL was increased to the level of the KLOE calorimeter [11], the contribution from sampling fluctuations to the hadronic energy resolution would reduce to $13\%/\sqrt{E}$, giving a total resolution of $17\%/\sqrt{E}$, provided that the detector remained compensating.

The latter condition is of course not fulfilled in this scenario, and the resolution would actually deteriorate quite rapidly as a result of an increase of $f_{\rm samp}$, to reach ultimately the values for homogeneous detectors (fig. 2).

As discussed in the next section, this problem might be circumvented by exploiting the wonderful properties of quartz fibers.

4 The benefits of quartz fibers

As discussed in the previous section, the hadronic resolution of non-compensating calorimeters is dominated by fluctuations in the em shower content. An alternative road to compensation, or at least to the practical advantages offered by compensating calorimeters, consists of measuring the value of $f_{\rm em}$ *event-by-event*.

This idea was pioneered by the WA1 Collaboration [12], who tried to measure $f_{\rm em}$ by disentangling the threedimensional energy deposit profile of the showers, exploiting the different shower development characteristics of the em and non-em shower

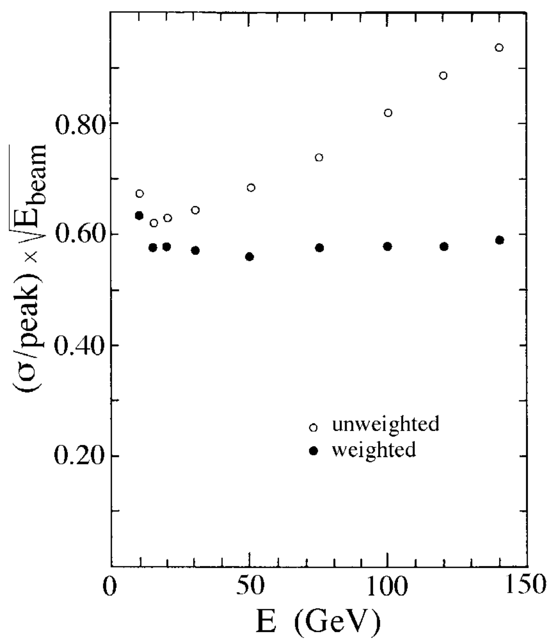

Figure 3: The hadronic energy resolution of the WA1 calorimeter as a function of energy, before and after application of a weighting procedure based on an event-by-event determination of the fraction of shower energy carried by the em component, f_{em} [12]

components in their detector.

This method led to significant improvements in the hadronic energy resolution, especially at the highest energies (fig. 3). However, below 30 GeV the improvements were marginal at best, because of the vanishing differences between the spatial characteristics of the em and non-em shower components for low-energy hadron showers developing in relatively low-Z materials (in this case iron).

The application of quartz fibers adds a completely new dimension to this idea. Quartz fibers are, for all practical purposes, only sensitive to the em components of hadronic showers [1]. Therefore, the installation of a quartz fiber structure, in *addition* to the regular type of active material based on ionization or scintillation, offers the possibility to measure f_{em} event-by-event.

For example, one could envisage a fiber calorimeter with a very high packing fraction (à la KLOE), in which half of the fibers are made of scintillating plastic and the other half of quartz. Every plastic fiber is surrounded by quartz ones and every quartz fiber is surrounded by plastic ones. The showers developing in this structure produce signals in both the scintillating and the quartz fibers, which are read out separately. The signal in the scintillating fibers is a measure for the *visible energy* $E_{\rm vis}$ deposited in the event, while the signal produced in the quartz fibers measures the em energy $E_{\rm em}$ deposited in the same event. By combining both signals, it is then possible to determine both the energy E of the showering hadron and the em energy fraction $f_{\rm em}$ of the event, provided the e/h value of the calorimeter (in the scintillator readout mode) is known:

$$E \;=\; \frac{e}{h}\, E_{\rm vis} \;+\; E_{\rm em}\,(1 - \frac{e}{h}) \qquad\qquad f_{\rm em} \;=\; E_{\rm em}/E \tag{3}$$

How well would such a *dual readout system* work? The answer to that question depends on the correlation between the values of $f_{\rm em}$ measured in this way and the nuclear binding energy losses ΔB, since this correlation will determine the value of σ_I in eq. 2.

We have started a program of simulations to study this question. Initial results indicate that it might be possible to limit σ_I/E to values below $15\%/\sqrt{E}$, *i.e.* at a level comparable to the contribution of sampling fluctuations in a very-fine-sampling detector such as KLOE. In that case, hadronic resolutions near $20\%/\sqrt{E}$ could become within reach.

Assuming that the measurement of $f_{\rm em}$ with this method can be made sufficiently precise, the value of σ_I/E is determined by the irreducible fluctuations in ΔB for a fixed value of the non-em energy. These fluctuations are determined by the large variety of nuclear reactions that may occur in the shower development.

We developed a dedicated Monte Carlo program to study these fluctuations. The cross sections for the various nuclear reactions were derived from a parameterization given by Rudstam [13]. This parameterization gives a satisfactory description of spallation cross sections, and is valid within broad limits either of energies (> 50 MeV) or of atomic mass ($A > 20$). When a particle of energy E hits a target with atomic mass A_T, the relative cross sections σ for producing spallation products (Z_f, A_f) are given by the relation

$$\sigma(Z_f, A_f) \sim \exp\left[-P(A_T - A_f)\right] \;\times\; \exp\left[-R|Z_f - SA_f + TA_f^2|^{3/2}\right] \tag{4}$$

in which E is expressed in MeV and the parameters P, R, S and T have the following values:
$P = 20E^{-0.77}$ for $E < 2100$ MeV, $P = 0.056$ for $E > 2100$ MeV,
$R = 11.8A_f^{-0.45}$, $S = 0.486$, $T = 0.00038$.

We applied this program to study the effects of nuclear binding energy losses on hadronic shower development in ^{63}Cu.

When a 1 GeV pion interacts with a ^{63}Cu nucleus, many different spallation reactions may occur. We found 86 different spallation reactions that have a probability

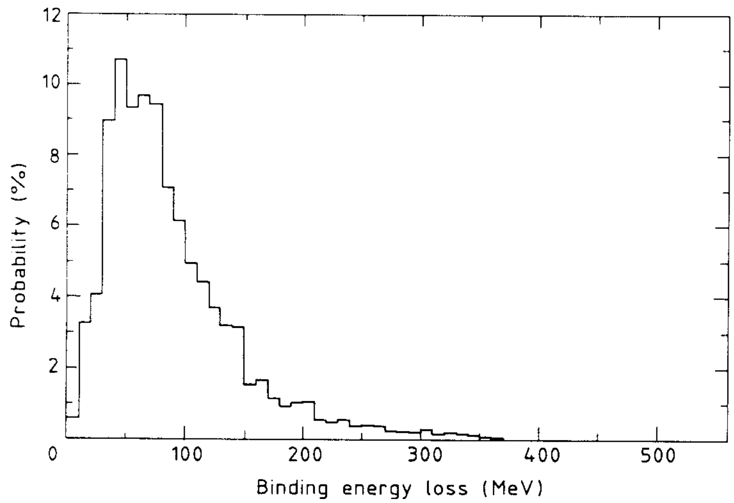

Figure 4: The nuclear binding energy lost in spallation reactions induced by 1 GeV pions on ^{63}Cu nuclei.

in excess of 10^{-3}. The most probable exclusive reaction (1 GeV π^- + ^{63}Cu $\rightarrow$ ^{61}Ni + n +p + pions) occurs with a relative probability of only 5.7%. The distribution of nuclear binding energy losses associated with the different spallation reactions and their relative probabilities of occurring is shown in fig. 4.

Similar distributions can also be obtained for incident hadrons of any other energy. The total ΔB incurred in a certain hadronic shower development is the result of a large number of different nuclear reactions that take place over the entire detector volume in which the shower develops.

The asymmetry in the ΔB distribution observed for reactions initiated by one particylar type of hadrons (*e.g.,* 1 GeV π^-, see fig. 4), rapidly disappears when many such contributions are convoluted. This is illustrated in fig. 5, which shows the ΔB distribution for events in which 50 pions with an average energy of 200 MeV initiate nuclear reactions in ^{63}Cu.

The figure shows that a combined nuclear binding energy loss of about 1.15 GeV exhibits event-to-event fluctuations at the level of $\sim 15\%$. Since the e/h value of neutron insensitive Cu calorimeters is typically ~ 1.6, one may conclude that the total binding energy loss constitutes, on average, 0.6/1.6 $\sim 35\%$ of the non-em energy component. The observed fluctuations in nuclear binding energy loss ($\sigma = 178$ MeV) thus apply to an average non-em energy of ~ 3.3 GeV [14].

They represent the irreducible fluctuations that limit the precision of the measure-

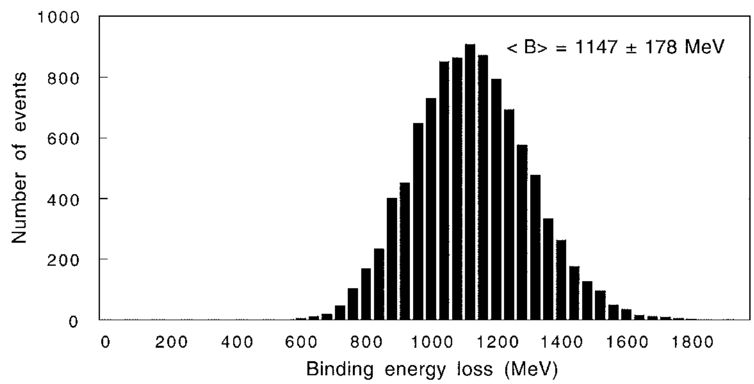

Figure 5: Distribution of the total nuclear binding energy lost in spallation reactions induced in ^{63}Cu nuclei by 50 pions with an average energy of 200 MeV

ment of the hadronic energy, even if the energy sharing between the em and the non-em shower component is measured with the best possible precision. Expressed as a fraction of the energy, they correspond to $\sim 10/\%/\sqrt{E}$. A more detailed evaluation, in which a number of higher-order corrections were taken into account, increased this estimate to $\sim 13\%/\sqrt{E}$.

5 Possible applications of dual-readout schemes

The possibility of measuring hadronic energies with better precision than is possible with current technology is only one, and possibly not even the most important, application of the dual-readout calorimetry discussed here. A very appealing prospect is the possibility to improve the precision of hadronic energy measurements in situations where these measurements have to be performed in a very limited calorimeter volume.

Ultimate precision, as achievable in the compensating calorimeters discussed in section 3.1, requires the shower signals to be integrated over a very large detector volume. For example, SPACAL's $30\%/\sqrt{E}$ hadronic resolution was only achieved when the signals were integrated over a cylinder with a radius of 50 cm around the shower axis, containing some 15 tonnes of detector material. When the signals were restricted to a smaller calorimeter volume, the resolution rapidly degraded, more so at high energies (fig. 6)

The reason for this lies in the fact that the neutrons, which are crucial for achieving compensation in this calorimeter, require a large volume to get rid of their kinetic

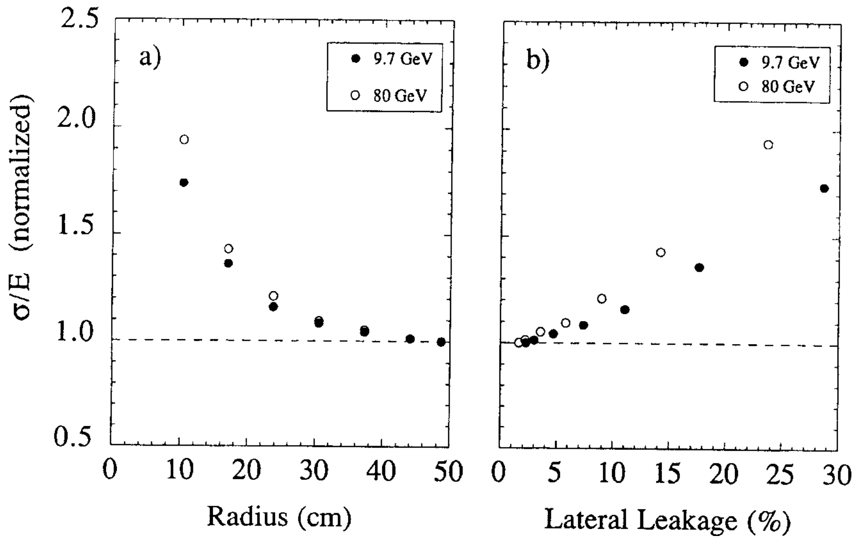

Figure 6: The hadronic energy resolution of SPACAL as a function of the effective radius of the area over which the calorimeter signals are integrated (a) and as a function of the average lateral shower leakage fraction [8].

energy. The mean free path between elastic neutron-proton collisions is about 20 cm and each neutron needs several such collisions to deposit enough of its kinetic energy in the calorimeter structure.

In many experiments, one cannot afford to integrate the calorimeter signals over such large volumes. For example, in the high-η region of proton-proton collider experiments, the particle density is so high that one would include a large number of other, probably unrelated, particle showers if the signals were integrated over a 15-tonne detector volume. In such experiments, one would really have to limit the signal integration over a small cone around the shower axis. Therefore, a calorimeter with $e/h = 1$ would be of little practical use in such experiments.

Similar considerations apply to calorimetry in space-based experiments, where the total mass of the detector is a severely limiting factor. The challenge in such experiments is to measure the energy as precisely as possible, within these imposed limitations.

In these practical situations, the dual-readout systems discussed here might well offer a major improvement compared to classical calorimeters. The signal contributions of neutrons are of little importance in this case. The dual-readout system provides a measurement of the energy *and of the nature of this energy* in the (small) volume available for the measurement. Because of this additional information, the precision of the results obtained in this way is very likely to rival that obtainable with one type of readout in a considerably larger detector volume.

I am convinced that resources for a dedicated R&D program to investigate these possibilities may turn out to be extremely well spent.

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[14] The energy of 3.3 GeV may seem to contradict the fact that the distribution in fig. 5 was generated by hadrons carrying a total energy of 10 GeV (50 $\times$ 200 MeV). However, many of the nucleons generated in these spallation processes in turn initiate nuclear reactions, in which additional binding energy is lost. This important effect was not taken into account and is responsible for this apparent discrepancy.