# Hadron Calorimetry -
## *what have we learned since CALOR 1?*

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**Abstract.** In this talk, I review what has been learned about hadron calorimetry since the CALOR conference series started (1990) and I will give my view on how further progress can be made. I will also discuss some developments that may prevent further progress.

### 1. Introduction - the status quo in 1990

In this talk, I will review what has been learned about hadron calorimetry since the CALOR conference series started, twenty years ago. I will also give my view on how further progress can be made, and discuss developments that may prevent further progress.

Around 1990, the mysteries that had surrounded the issue of compensation in hadron calorimetry for a number of years had been solved. The reasons for the poor performance of non-compensating calorimeters were fully understood, and the same was true for the details of the compensation mechanism. One had come to realize that the use of uranium absorber was neither needed nor sufficient to achieve equal response to the em and non-em shower components, and that nuclear fission played no essential role in this matter. This was experimentally demonstrated with lead/plastic scintillator calorimeters,

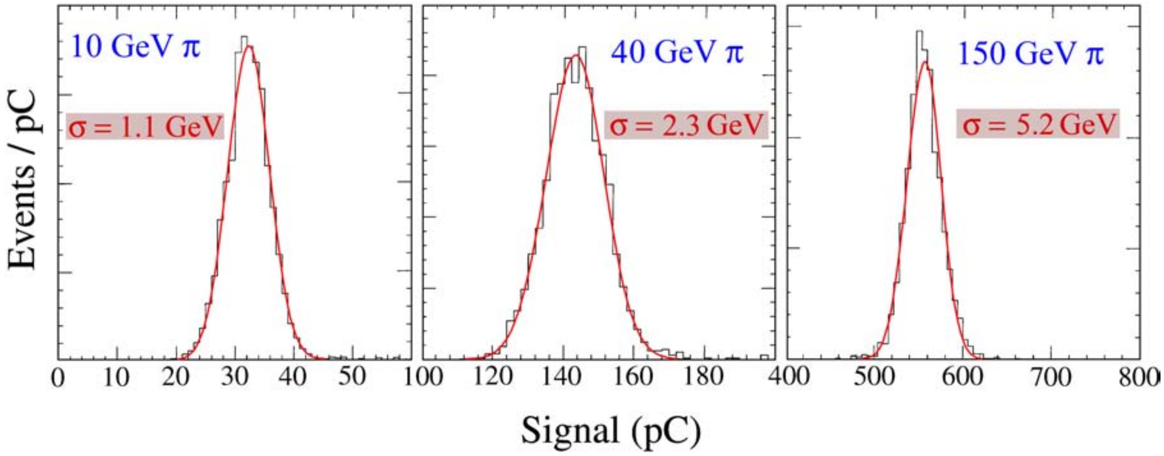

**Figure 1.** Signal distributions for pions of 10, 40 and 150 GeV measured with the SPACAL lead/scintillating-fiber calorimeter

independently by the ZEUS [1] and SPACAL [2] collaborations. The latter calorimeter holds until today the hadronic energy resolution record of about $30\%/\sqrt{E}$. Some of its results are shown in Figure 1. Apart from the excellent energy resolution, the figure also shows that the signal distributions were well described with Gaussian fits. In addition, the calorimeter was linear for hadron detection, with a response that was almost equal to that for the electrons with which it was calibrated. At 80 GeV, the resolution of this instrument (pictured in Figure 2) was measured to be about 3.3 GeV, sufficient to distinguish hadronically decaying $W$s from $Z$ bosons. This separation is the main goal that drives the design of calorimeters for a future high-energy electron-positron collider.

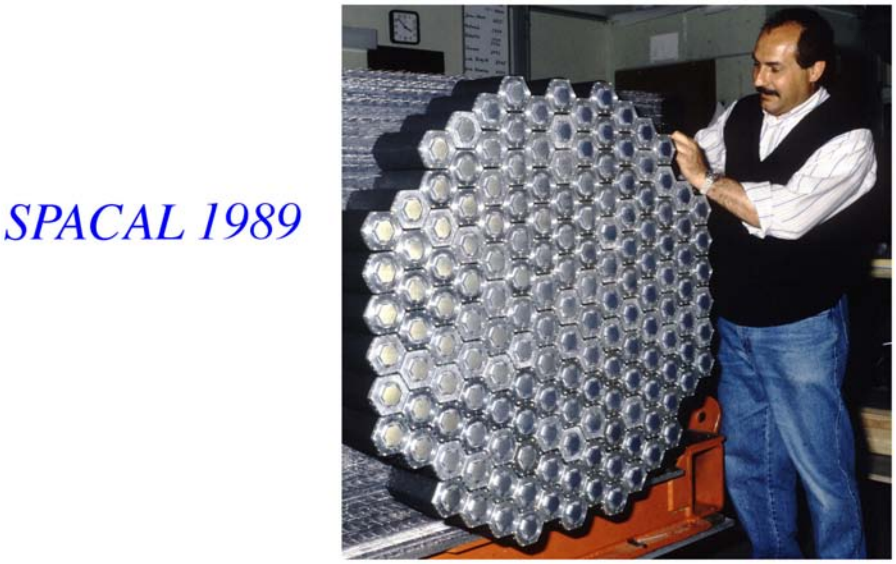

**Figure 2.** The SPACAL lead/scintillating-fiber calorimeter.

The advantages of high-resolution hadron calorimetry are also clear from Figure 3, which shows the total energy measured with the compensating calorimeter of the WA80 experiment for a momentum-selected beam of heavy ions accelerated in the CERN SPS. This beam, nominally consisting of $^{32}$S ions, contained at the fraction-of-1% level essentially all lower-mass ions with the same $Z/A$ ratio. Because of the excellent energy resolution, this instrument acted in this case as a high-resolution spectrometer [3]. Note the excellent separation between the $^{14}$N and $^{16}$O components, where the mass resolution is comparable to that needed for separating the mentioned vector bosons.

In non-compensating calorimeters, $W/Z$ separation has never been achieved, not even approximately. Figure 4 shows the jet-jet invariant mass distribution measured by the UA2 experiment, before ($a$) and after ($b$) subtracting the QCD background [4, 5].

Despite the obvious advantages of compensating calorimeters (signal linearity, energy resolution, response function, calibration), there are also some drawbacks. Compensation relies on amplification of the signal from neutrons produced in the shower development, such as to overcome (*i.e.,* compensate for) the effects of nuclear binding energy losses. The required amplification factor determines the sampling fraction, which is typically rather small, *e.g.,* 2.4% for Pb/plastic-scintillator. As a result, the em resolution that can be achieved with such calorimeters is limited, *e.g.,* $13\%/\sqrt{E}$ for SPACAL, $18\%/\sqrt{E}$ for ZEUS. Also, since the neutron signal results from elastic neutron-proton scattering, the signals have to be integrated over a rather large volume ($> 100\lambda_{\rm int}^3$) and a relatively long time ($\sim 50$ ns). In practice, this is not always possible, especially in experiments at high-luminosity hadron colliders. The main aim of the DREAM project, discussed in the following, is to eliminate these drawbacks and thus improve the already impressive results shown in Figures 1 and 3.

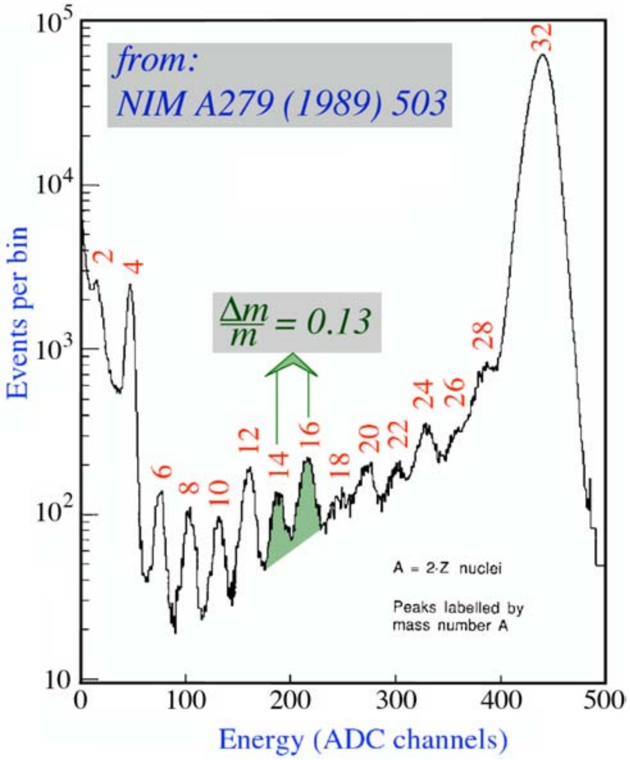

**Figure 3.** The WA80 calorimeter as a high-resolution spectrometer.

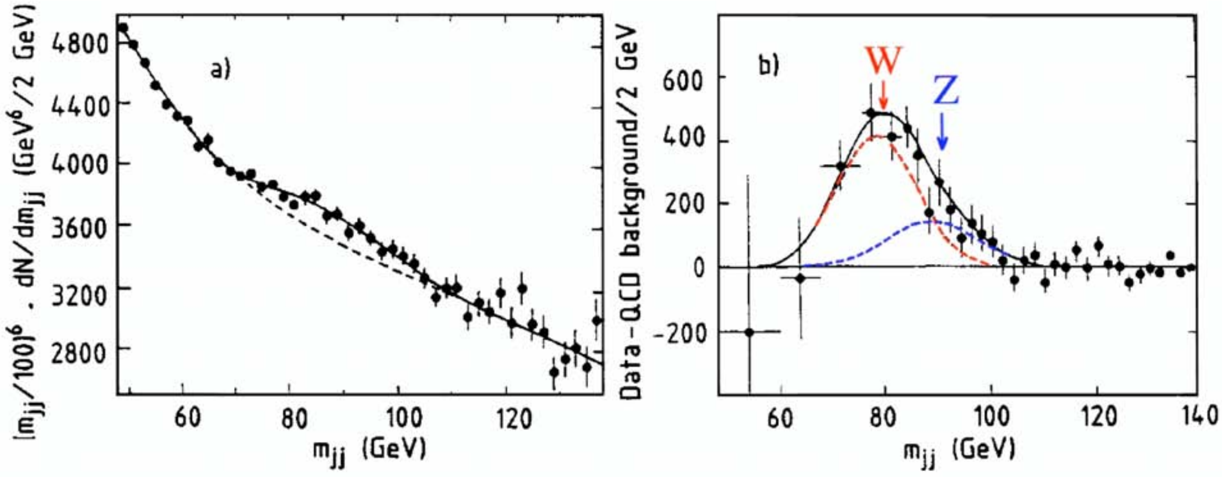

**Figure 4.** Two-jet invariant mass distributions from the UA2 experiment [4], before ($a$) and after ($b$) subtracting the QCD background, indicated by the dashed line in diagram $a$. The data in $b$ are compatible with peaks at $m_W$ =80 GeV and $m_Z$ =90 GeV. The standard deviation of the mass distribution was 8 GeV, of which 5 GeV could be attributed to non-ideal calorimeter performance [5].

Even though the unraveling of the compensation puzzle was primarily achieved by building and testing generic calorimeters, some credit should also be given to Gabriel and coworkers [6], whose simulations had shown the importance of nuclear reactions in the absorption process of hadrons, and who correctly predicted the suppression of the em response of sampling calorimeters. This effect, often referred to to as $e/mip < 1$, is an important ingredient for compensation in calorimeters with high-$Z$

absorber material. The absence of this effect makes homogeneous detectors (*e.g.,* crystals) particularly poor hadron calorimeters. It also plays an important role in the calibration problems of segmented calorimeters, which is discussed in the next section.

## 2. What has been learned since 1990?

In order to appreciate the developments in hadron calorimetry since 1990, it is useful to briefly summarize the relevant aspects of hadronic shower development. In the absorption process, the energy is deposited by two components, which I will call the em and non-em one (Figure 5).

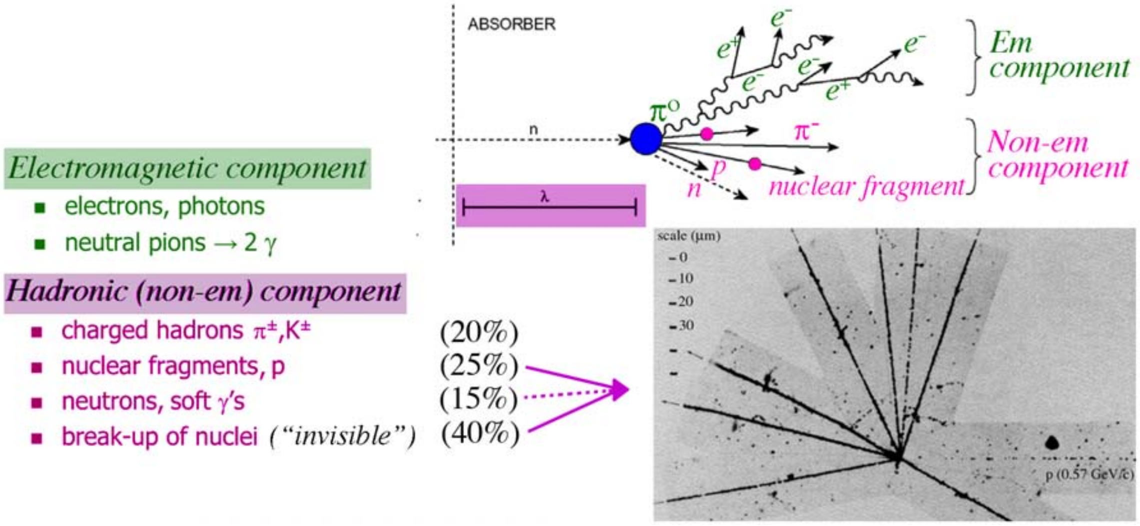

**Figure 5.** Schematic description of hadronic shower development, and an emulsion picture of a nuclear reaction which occur in large numbers in this process.

The calorimeter's response functions for these two components are schematically shown in Figure 6, for a generic noncompensating calorimeter. The $e/h$ value, which represents the ratio of the average signals per unit of deposited energy for these components, has a value of 1.8 in this example. The signal from a particular hadron shower is a combination of the signals from these two components.

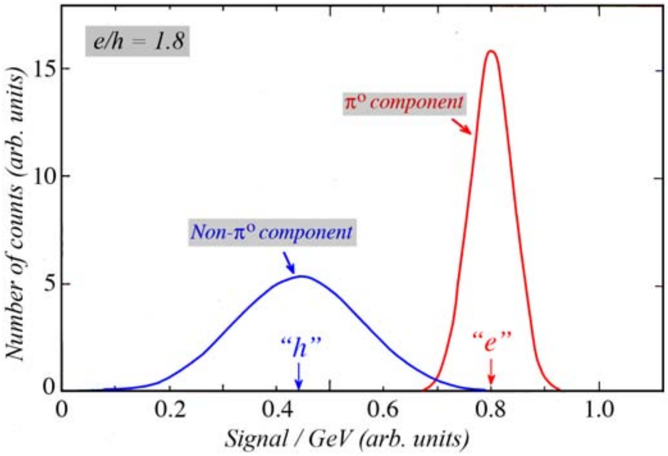

**Figure 6.** The response functions of a noncompensating calorimeter for the em and non-em components of hadron showers.

Event-to-event fluctuations in the energy sharing between these two components are large and non-Poissonian. These fluctuations in the em shower fraction (to be called $f_{\mathrm{em}}$ in the following) form the main contribution to the hadronic energy resolution of non-compensating calorimeters, and are also responsible for deviations from $E^{-1/2}$ scaling. In compensating calorimeters, this source of fluctuations is eliminated and the resolution is usually determined by the width of the non-em response function, which is ultimately dominated by fluctuations in nuclear binding energy losses. The latter fluctuations (in so-called *invisible energy*) can also be affected by the design of the calorimeter. Since the binding energy losses are correlated to the total kinetic energy of the numerous neutrons released in the nuclear reactions, the presence of hydrogen in the active calorimeter layers may reduce their effect significantly. The difference between the energy resolutions for 100 GeV pions measured by the ZEUS (3.5%) and D0 (7%) calorimeter systems, which both had $e/h$ values close to 1.0, is most likely due to the absence of hydrogen in the latter.

An issue that in practice is possibly even more important than the energy resolution is the non-linearity that is typical for noncompensating hadron calorimeters. This nonlinearity is a consequence of the fact that he average value of $f_{\mathrm{em}}$ increases with the shower energy. This phenomenon may lead to systematic mismeasurement of jet energies.

After this brief summary, I now discuss the developments in our understanding of hadron calorimetry that have taken place since 1990. It is a sad truth that, despite the enormous efforts that have gone into the development of GEANT-4 in the past 20 years, the contributions of Monte Carlo simulations in this domain have been negligible.

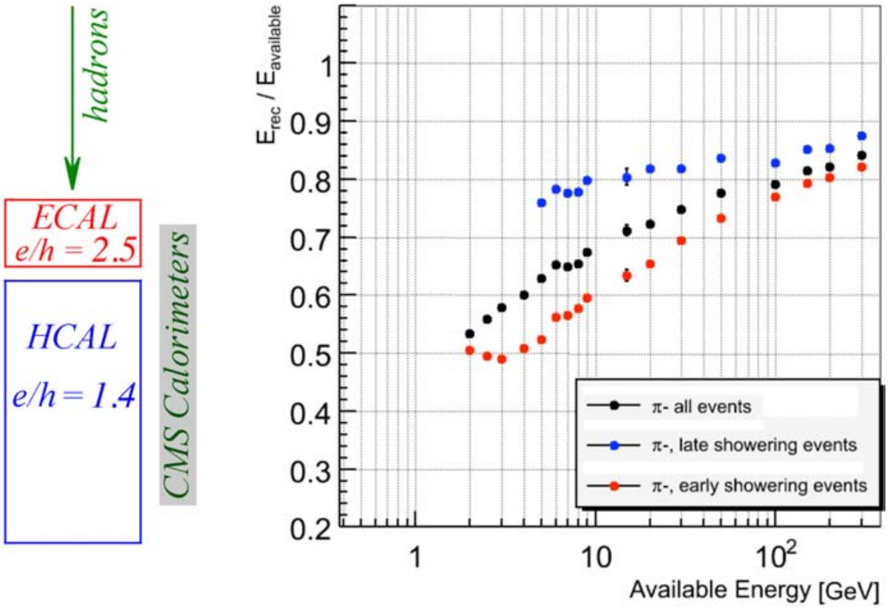

**Figure 7.** The response to electrons pions as a function of energy, for the CMS barrel calorimeter. The pion events are subdivided into two samples according to the starting point of the shower, and the pion response is also shown separately for these two samples [7].

I want to point out the contrast with em calorimetry, where Monte Carlo simulations turned out to be of crucial importance, for example for solving the complicated calibration problems of the ATLAS LAr calorimeter [8] and the calorimeter of the AMS experiment [9]. The absence of similarly reliable simulations for hadronic shower development meant, for example, that the “spikes” observed in the crystal calorimeter of the CMS experiment, which are caused by nuclear reactions close to the APDs which detect the light signals from these crystals, were not at all foreseen. Important calorimeter features such as the hadronic response and the energy resolution [10], as well as the hadronic shower profiles [11], are in general also poorly reproduced by GEANT based simulations. Such simulations are therefore most definitely not suitable for making meaningful predictions, on the basis of which calorimeter systems can be designed. The development of hadron calorimetry for the LHC experiments thus had to take place without meaningful guidance from such simulations. This has resulted in a number of unpleasant surprises, an example of which was mentioned above.

When the calorimeters were built, it turned out that the CMS experiment had to pay a high price for its complete focus on em energy resolution. Its calorimeter system consists of a crystal em section, backed up by a bronze/plastic-scintillator hadronic section. The hadronic performance of this calorimeter system was systematically studied with various types of particles ($e, \pi, K, p, \bar{p}$), covering a momentum range from 1 - 300 GeV/$c$. Figure 7 shows some results from this study [7]. Both sections were calibrated with 50 GeV electrons. The response to pions, represented by the black dots, indicates that the calorimeter is extremely non-linear for these particles. This non-linearity is especially evident below 10 GeV, which is important since pions in this energy range carry a large fraction of the energy of typical LHC jets, even in the TeV domain. More troublesome is the fact that the response strongly depends on the starting point of the showers. This is a direct result of the very different $e/h$ values of the em (2.5) and hadronic (1.4) calorimeter sections. The figure shows results for two event samples, selected on that basis: showers starting in the em section or in the hadronic one. 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.

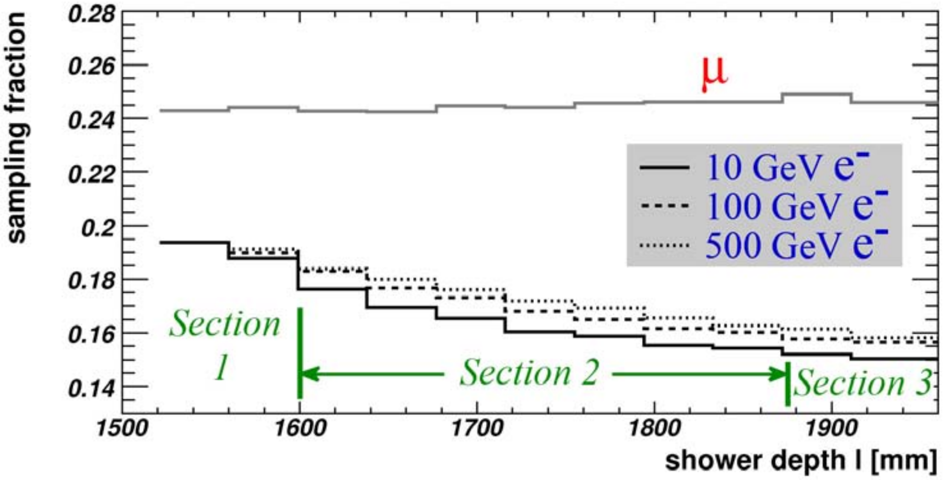

**Figure 8.** Evolution of the sampling fraction for electron showers of different energies in the three longitudinal segments of the ATLAS em calorimeter [8].

Another issue on which some new light has been shed since 1990 concerns the enormous complications that may arise in the process of (inter-)calibrating the different sections of a longitudinally segmented sampling calorimeter. These complications are a consequence of the fact that the sampling fraction is typically different for the different shower particles that contribute to the signals, and the fact that the shower composition changes as it develops. As a result, the relationship between measured signal and deposited energy, *i.e.,* the *calibration constant*, varies with depth and with the energy of the showering particle, and is especially for hadrons in a given longitudinal detector segment different for each event.

Unfortunately, in the absence of high-resolution longitudinally segmented hadron calorimeter systems, detailed information on the extent of these problems for hadron detection is still lacking. However, the fact that these issues already cause major problems in longitudinally segmented em calorimeters does not bode well in that regard, since the problems for hadronic showers are most likely considerably worse. Figure 8 shows how the em sampling fraction decreases with depth in the ATLAS Pb/LAr calorimeter, in an energy dependent way. The (inter)calibration of the three longitudinal segments of this calorimeter was extremely non-trivial. Signal linearity, combined with good energy resolution, was only achieved after very detailed Monte Carlo simulations, which resulted in a very complicated procedure involving a variety of energy dependent calibration parameters. Similar problems were reported by the AMS Collaboration, whose em calorimeter is longitudinally subdivided into 18 independent segments [9].

Avoiding (inter)calibration problems is one of the reasons why the DREAM project concentrates on longitudinally *unsegmented* calorimeters. The DREAM project was started to improve the already excellent hadronic performance of the compensating ZEUS and SPACAL calorimeters, and avoid the disadvantages that made these instruments less than ideal for em shower detection. In practice this implies

(i) Reducing the contribution of sampling fluctuations tot the energy resolution (*the* dominating factor for ZEUS and SPACAL).

(ii) Reducing the effects of fluctuations in invisible energy. This means that the calorimeter has to be sensitive to the “nuclear” fraction of the non-em shower component. This requirement puts homogeneous detectors consisting of high-$Z$ crystals at a clear disadvantage.

(iii) Eliminating the effects of fluctuations in $f_{\rm em}$ in such a way that the previous two points are not prevented.

The latter turned out to be possible by measuring simultaneously the signals from Čerenkov light and scintillation light produced in the shower development (hence the term dual-redaout). By comparing these two signals, it turned out to be possible to measure the em shower fraction event by event, and thus eliminate the effects of the large fluctuations in this variable. This was demonstrated both for showers induced by single hadrons and for jets, as illustrated in Figure 9 [12]. This figure shows that the signal distribution of a non-compensating calorimeter is a superposition of distributions with different $f_{\rm em}$

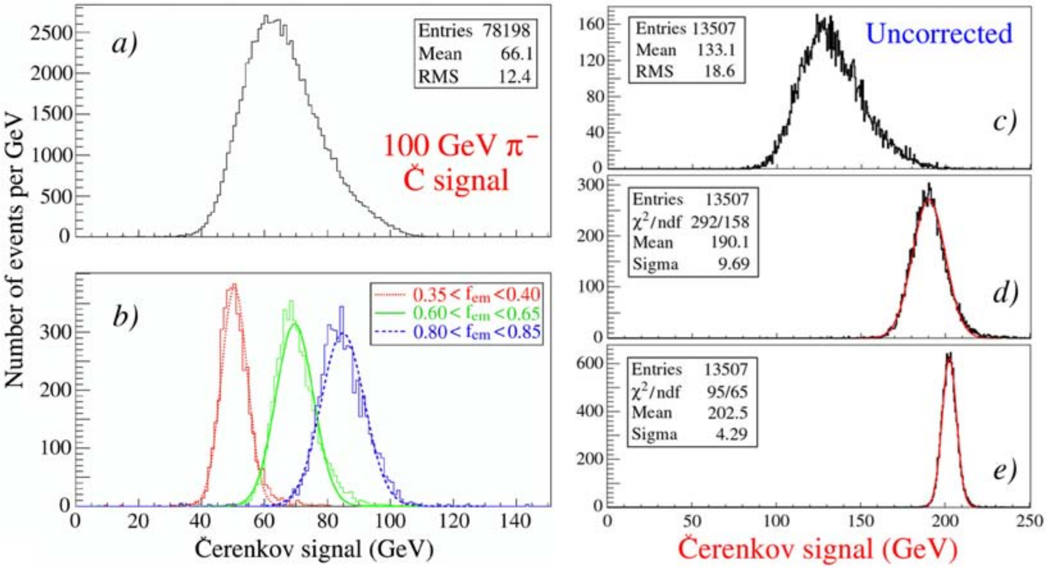

**Figure 9.** Čerenkov signal distribution for 100 GeV $\pi^-$ ($a$) and distributions for subsamples of events selected on the basis of the measured $f_{\rm em}$ value ($b$). Signal distributions for high-multiplicity 200 GeV “jets” in the DREAM calorimeter before ($c$) and after ($d$) corrections as described in the text were applied. In diagram $e$, energy constraints were used, which eliminated the effects of lateral shower leakage fluctuations that dominate the resolution in $d$.

values (and thus different response values). Once the $f_{\rm em}$ value of a particular event has been measured, the signal can be scaled to $f_{\rm em} = 1$ (*i.e.,* the value for em showers). In doing so, the effects resulting from $f_{\rm em}$ fluctuations are eliminated. This results in improved energy resolution, a Gaussian response function and, most importantly, a correctly reproduced hadronic energy. This was true both for single pions as well as for jets.

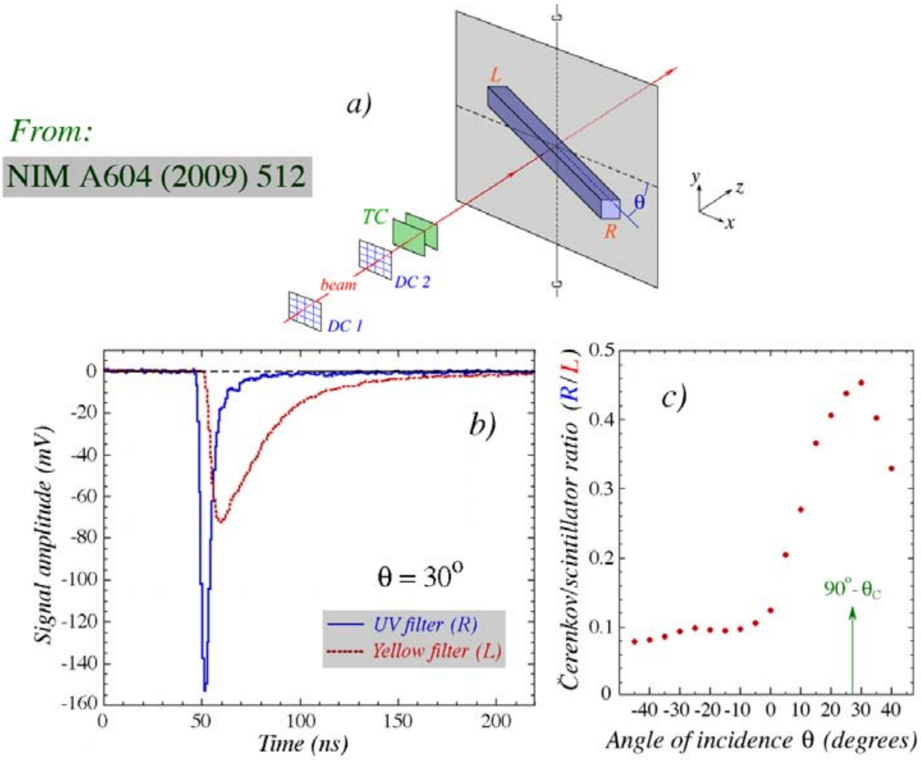

**Figure 10.** Unraveling of the signals from a Mo-doped $\mathrm{PbWO_4}$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram $a$. the two sides of the crystal were equipped with a UV filter (side $R$) and a yellow filter (side $L$), respectively. The signals from 50 GeV electrons traversing the crystal are shown in diagram $b$ and the angular dependence of the ratio of these two signals is shown in diagram $c$ [13].

We have shown that similar results can also be obtained with high-$Z$ crystal calorimeters ($\mathrm{PbWO_4}$, BGO), whose signals can be separated into scintillation and Čerenkov components [14, 15]. This has been achieved by making use of differences in the spectral characteristics, the time structure of the signals and/or the angular distribution of the light. Figure 10 shows that application of a suitable filter led to almost pure scintillation or Čerenkov signals from a Mo-doped $\mathrm{PbWO_4}$ crystal. The Čerenkov nature of the UV signal is underscored by its characteristic angular distribution [13].

The DREAM Collaboration has also demonstrated the importance of measuring the "nuclear" fraction of the non-em shower component event by event. The time structure of the hadronic shower signals provided crucial information in this respect, since the contribution of neutrons was easily recognizable as a tail with a time constant of about 20 ns. This tail, caused by elastic $n - p$ scattering in the scintillating fibers, was absent in the signals from the clear fibers and also in all signals from em showers. We found that the strength of the neutron signal was rather strongly anti-correlated to $f_{\rm em}$, but did provide additional information which allowed for further improvement of the energy resolution [16].

Further improvement of the energy resolution can only be achieved by addressing the factors that have become dominant after elimination of the effects of fluctuations in $f_{\rm em}$ was successfully accomplished. Most prominent among these are fluctuations in (lateral) shower leakage. By making the detector about five times larger, we expect to improve the resolution for 200 GeV jets to $\sim 2\%$ (see Figure 9d,e). We are currently building a new instrument that is not only sufficiently large to achieve this goal, but in which also a number of other improvements are being implemented, which should make it an excellent em calorimeter as well (em resolution better than $10\%/\sqrt{E}$). Details can be found in [17].

## 3. How to make further progress?

Just like in the past 30 years, further progress in the field of hadron calorimetry will entirely have to depend on *experimental verification of new ideas*, given the absence of reliable Monte Carlo simulations which otherwise might provide guidance.

Apart from the DREAM project, which will continue to explore the virtues of dual-readout techniques (see Section 2), two other ideas are currently being pursued:

(i) *Homogeneous dual-readout calorimetry.* Compared to the sampling structures developed in the framework of the DREAM project, homogeneous calorimeters have the advantage of eliminating sampling fluctuations entirely, which results in excellent energy resolution for em showers. On the other hand, such calorimeters have no handle on the "nuclear" fluctuations in the non-em component of hadron showers, a clear disadvantage compared to the fiber-based sampling detectors. Other potential disadvantages include the problems that will undoubtedly arise from attenuation of the Čerenkov light, and the complications associated with the readout of such a (longitudinally segmented) detector, not to mention the very high cost of crystal-based calorimeters.

(ii) *Particle Flow Analysis (PFA).* In this approach, the additional information provided by an upstream tracker is used to measure jet energies. 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 [18]. However, it has been argued by others that this, for practical geometries, is an illusion [19]. Especially in jets with leading charged particles, the overlap between the showers from individual jet particles makes the fine granularity largely irrelevant. It should also be mentioned that calibrating a fine-grained calorimeter would also be a daunting task (see section 2). Of course, in the absence of reliable Monte Carlo simulations[1] 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.

Since progress will entirely depend on experimental tests, it is very important that new devices be tested in conditions that approach the applications fro which they are designed *as closely as possible.* Since modern experiments in particle physics are strongly focussed on jet detection, this implies that one should attempt to assess the jet performance of the instruments, rather than just measuring the performance in beams of mono-energetic particles, where one has many possibilities to make results look good that are not applicable for jets (*e.g.,* weighing schemes commonly referred to as "off-line compensation").

From a calorimetric perspective, a jet is a collection of particles which are simultaneously absorbed in the same area of the calorimeter. Jet performance can be assessed experimentally with multiparticle events, in which one measures the reaction products created by a beam particle in a target placed upstream of the calorimeter. One may also generate jets by means of a suitable fragmentation function and reconstruct the jet response from a database of single-particle events with different energies measured in the calorimeter under study. This method was, for example, used to assess the jet response of the CMS calorimeter system [7].

[1] 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 [20]. To our knowledge, the fundamental problems addressed at this workshop, *e.g.,* with regard to the for PFA crucial hadronic shower widths, still exist.

## 4. How NOT to make further progress

### *4.1. Avoid repeating mistakes from the past*

Since progress in the field of hadron calorimetry depends entirely on experimental trial-and-error exercises, it is very important that people or groups engaged in this effort are aware of the history, if only to avoid repeating mistakes from the past. Unfortunately, this is not always the case, as I will illustrate with two well documented examples.

(i) One should avoid placing readout elements that may produce HUGE signals for one particular type of shower particle in the path of a developing shower. This may lead to a phenomenon that has become known as the "Texas Tower effect" , first observed in the forward calorimeter of the CDF experiment [21, 22, 23]. In this device, recoil protons from elastic neutron scattering may deposit $\sim 1$ MeV in an active (gas) layer, which because of the very small sampling fraction ($\sim 10^{-5}$) looks as an energy deposit of 100 GeV in a single calorimeter cell. Such "hot spots" were recently also observed in the ECAL of the CMS experiment. The culprits are in that case densely ionizing particles from a nuclear reaction, such as depicted in Figure 5. Such nuclear fragments are have $dE/dx$ values that are typically 100-1000 times larger than for a mip. When traversing the APD which detects the scintillation light from the $\mathrm{PbWO_4}$ crystals constituting the ECAL, such (MeV type) particles may generate signals that are 100 000 times larger that that from a scintillation photon, and thus fake energy deposits of tens of GeV.

(ii) "Digital calorimetry was tried and abandoned for good reasons. Figure 11 shows the average signals from em showers in a calorimeter that was read out with wire chambers operating in a "saturated avalanche mode [24]. The response is strongly non-linear, as a result of the increasing *density* of shower particles, combined with the fact that the signal from a calorimeter cell is the same regardless of the number of particles crossing it. This calorimeter was longitudinally subdivided in five sections. In Figure 11b, the average signals recorded in these separate sections are shown as a function of the total energy deposited in the calorimeter. It illustrates that the observed saturation effect is clearly determined by the *density* of shower particles. The degree of non-linearity, given

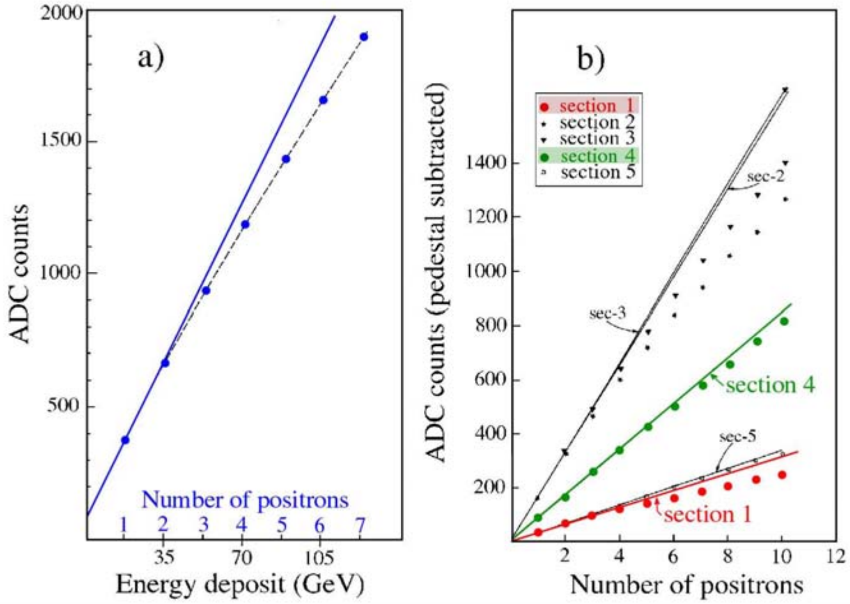

**Figure 11.** Average em shower signal from a calorimeter read out with wire chambers operating in the "saturated avalanche" mode, as a function of energy [24].

by the deviation from the straight line, was more than a factor of six larger in section 1 (where the shower starts) than in section 4 (located beyond the shower maximum), despite the fact that the energy deposit in section 1 was less than half of that in section 4.
Despite this clearly documented example, the CALICE Collaboration is apparently spending a major effort reviving this technique. Not surprisingly, test results reported at this conference exhibit very substantial response non-linearities [25].

### *4.2. Dishonesty in reporting results*

If one wants to make real progress in this field, it is imperative that scientific integrity be the guiding principle. Of course, it is disappointing when an instrument on which a lot of effort (and money) has been spent does not perform as hoped/expected. However, by misrepresenting the measured performance, one does a serious disservice to our discipline. I want to illustrate these statements with two recent, well-documented examples.

(i) The term *linearity* has a precisely defined meaning. A calorimeter is said to be linear if the measured signal is proportional to the deposited energy. The best way to present experimental test results of signal linearity is by means of the residuals: $(E_{\mathrm{meas}} - E_{\mathrm{dep}})/E_{\mathrm{dep}}$ as a function of the deposited energy $E_{\mathrm{dep}}$. Figure 12 shows linearity results recently published by the CALICE Collaboration for their W/Si em calorimeter [26]. The black squares around the line at zero represent the experimental data, and the authors conclude that "the response of their calorimeter is linear to within approximately 1%". However, upon careful reading of the paper one sees that the authors have fitted the measured mean values of their signal distributions to an expression of the type: $E_{\mathrm{mean}} = \beta \cdot E_{\mathrm{beam}} - 360$ MeV, and subsequently redefined the *measured* energy as $E_{\mathrm{meas}} = E_{\mathrm{mean}} + 360$ MeV. If one just takes the measured signals at face value, then the result, represented by the red dots in Figure 12 looks all of a sudden very different. The correct conclusion from the measured data is that this calorimeter exhibited a signal non-linearity for em showers of about 5% in the energy range of 6 - 45 GeV, manifesting itself in the form of a 360 MeV offset .

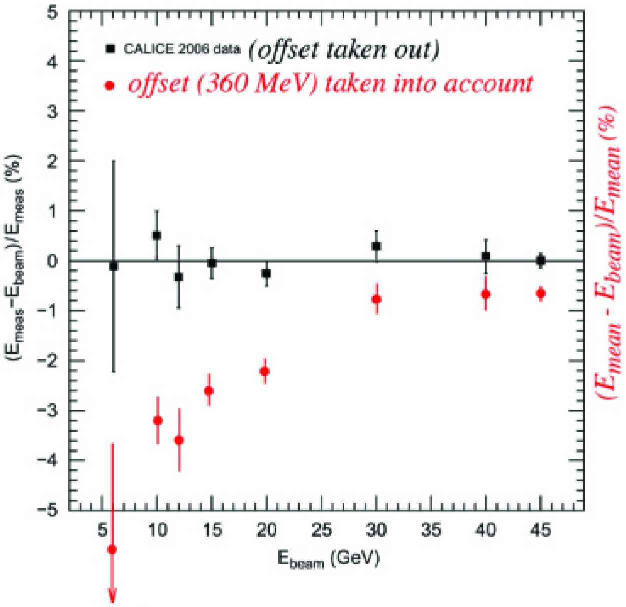

**Figure 12.** The response of the CALICE W/Si em calorimeter to electrons, as a function of energy. Shown is the relative difference between the average measured signal and the beam energy, as a function of energy. Results are given with and without correcting for a 360 MeV offset observed in the measured signals [26].

(ii) The term *energy resolution* has a very precisely defined meaning in calorimetry. It represents the precision with which the energy deposited by a particle absorbed in the calorimeter can be measured. It is usually determined from the signal distribution for mono-energetic particles sent into the calorimeter. In general, the energy resolution is defined as the rms value of this distribution. Only when the signal distribution is well described by a Gaussian function is this rms value equal to the sigma of the Gaussian fit, in all other cases $\sigma_{\rm rms} > \sigma_{\rm Gauss}$.
The CALICE Collaboration has found that the signal distributions resulting from their Monte Carlo simulations of PFA performance have substantial tails. They don't like these tails, since they spoil the energy resolution. Therefore, they have invented a new variable, called rms90, defined as the $\sigma_{\rm rms}$ of the events in the smallest reconstructed energy interval that contains 90% of the events [27]. As an aside, we mention that even for a perfectly Gaussian signal distribution, rms90 is more than 20% smaller than $\sigma_{\rm Gauss}$; for non-Gaussian response functions the discrepancy is correspondingly larger. Of course, everyone is free to use whatever phony statistics fits their purpose. However, the claims subsequently made by the CALICE Collaboration about the energy resolution achievable with their PFA methods are grossly misleading, since *rms90* has now taken on the meaning of *energy resolution* in their vocabulary.

My criticism of CALICE may sound very harsh. However, it is only the academic dishonesty of which I have given some examples above that bothers me. I believe that the CALICE project offers wonderful opportunities to investigate the experimental possibilities and impossibilities of the PFA approach. This should be done on the basis of *experimental data*, and it is very straightforward how to do that, given the enormous data base of events collected by CALICE in several years of test beam campaigns. In calorimetric terms, a jet is simply a collection of particles, mainly pions and photons (from $\pi^0$ decay). An event generator, *e.g.,* PYTHIA, tells you everything you need to know about these particles, their energies and the $p_T$ with respect to the jet axis (the direction of the fragmenting quark). One can then place the calorimeter at a large distance from the vertex, 10 meters or so. This distance defines the impact points of the different jet fragments. Next, one can generate a jet event in the calorimeter, using the extensive database have built up over the years. Of course, one does not have data at the precise energies of all the jet fragments, but things change rather slowly with energy, so it is OK to interpolate. So if the jet calls for an 11.6 GeV $\pi^+$, one takes an event from a 10 GeV pion runs, and multiplies the signals in all the cells that contributed in that event by 1.16. For a photon with energy 4.2 GeV, one takes an event from a 5 GeV electron run and multiplies the signals in all contributing cells by 0.84. Etcetera. In doing so, a hit pattern for this particular jet event in the calorimeter system is generated. Of course, this procedure can be repeated for the same jet event as many times as desired, using other events from the database to reconstruct event patterns. All for the same jet. For each event pattern, the measured energy can be determined as the sum of the exactly known energies of the charged jet fragments plus the calorimeter energy measured after removing hits from the event pattern using the favorite PFA algorithm. In this way, a total measured energy distribution for the particular jet event in question is obtained. This entire procedure can be repeated for other jet events. One can study differences between jet events with leading charged hadrons and leading $\pi^0$s. One can study differences between events with a fragmenting $u$ or $d$ quark and fragmenting heavier quarks. In the latter case, leading $K^0$s may be expected.

At a distance of 10 meters, the whole scheme will probably work pretty well, I guess. Subsequently, the calorimeter can be moved to 9 meters, 8 meters, etcetera. At some point, the confusion will kick in. One can study where that happens, for what type of events, and one could try out the effectiveness of various remedies in practice. The effects of a magnetic field could also be implemented in a rather straightforward way.

A procedure as described above would be a great contribution to the fundamental study of hadron calorimetry, it would offer countless opportunities for students to make their mark with individual contributions. In CMS, a similar approach was followed to investigate the effects of the very different $e/h$ values of the ECAL and HCAL on the jet response of the combined calorimeter system [7], and in the process many things were learned that no MC simulation would have been able to tell us.

## 5. Summary

- It is, and has been for 20 years, possible to build calorimeters that can separate hadronically decaying $W$'s from $Z$'s.
- Calibrating a longitudinally segmented calorimeter continues to be a very complicated and usually grossly underestimated job.
- The DREAM approach combines the advantages of compensating calorimetry with a reasonable amount of design flexibility.
- The dominating factors that limited the hadronic energy resolution of compensating calorimeters such as ZEUS and SPACAL to $30 - 35\%/\sqrt{E}$ can be eliminated, and the theoretical resolution limit for hadron calorimeters ($15\%/\sqrt{E}$) seems to be within reach.
- The DREAM project holds the promise of high quality calorimetry for **all** types of particles, with an instrument that can be calibrated with electrons.
- Rhetoric, combined with academic dishonesty is *not* helpful for further progress in this field.

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