Dual-Readout Calorimetry for High-Quality Energy Measurements

Proposal
in the context of the
Advanced Detector Research Program

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Principal Investigators:

Dr. Nural Akchurin and Dr. Richard Wigmans[1]
Texas Tech University

Dr. Hans P. Paar
University of California at San Diego

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[1]Contact person. Tel. [806] 742 3779, FAX [806] 742 1182, E-mail: wigmans@ttu.edu

1 Introduction

Calorimeters were originally developed as crude, cheap instruments for some specialized applications in particle physics experiments, such as detection of neutrino interactions. However, in the past 25 years, their role has changed considerably. In modern colliders, calorimeters form the heart and the soul of the experiments. They fulfill a number of crucial tasks, ranging from event selection and triggering to precision measurements of the fourvectors of individual particles and jets and of the energy flow in the events (missing energy, *etc.*). This development has benefitted in no small part from the improved understanding of the working of these, in many respects somewhat mysterious, instruments.

The contribution of calorimeter information to the data analysis focuses in many experiments primarily on particle identification (electrons, γs, muons) and on the energy measurement of particles that develop electromagnetic (em) showers (e, γ, π^0). Especially in ep and $p\bar{p}$ experiments, calorimetric energy measurement of hadrons and jets is also important. The importance of hadron calorimetry is expected to increase considerably as the collision energy is further increased:

- Jets become highly collimated collections of particles. The precision with which jet energies can be measured will thus increasingly be determined by the quality of the detector and no longer by jet-defining algorithms. This is illustrated in Figure 1, which shows the contribution of such algorithms to the jet energy resolution. For comparison, the hadronic energy resolutions of the ATLAS and CMS experiments are shown, as well as the hadronic energy resolution of the current world-record holder, SPACAL.

- Multi-jet spectroscopy becomes an important new tool in the search for new physics phenomena, and the quality of the jet measurements will become a limiting factor in that respect. As an example, we mention that the experimental uncertainty on the mass of the top quark is currently already dominated by the hadronic energy resolution of the calorimeters of the Tevatron experiments.

- The possibilities of studying new physics phenomena of interest are directly determined by the quality of the hadron calorimetry. For example, the achievable limits on the mass of the Lightest Supersymmetric Particle are completely determined by the hermeticity and the energy resolution of the calorimeter system.

The techniques that have been used until now in calorimetry make high-resolution em and hadron shower detection mutually exclusive propositions [2]. High-resolution hadronic shower measurements require compensating calorimeters. And compensation (*i.e.* equal calorimeter response to the em and non-em components of hadron showers, $e/h = 1.0$) is only achieved in sampling calorimeters with a very small sampling fraction, *e.g.* 2.3% in lead/plastic-scintillator structures. On the other hand, high-resolution em shower detection requires an instrument with a large sampling fraction, *e.g.* 100% in crystals or $> 20\%$ in LAr devices such as the ATLAS em calorimeter. The ZEUS Collaboration, which operates the highest-resolution hadron calorimeter in the world, pays a price for that in the form of a rather mediocre performance for em shower

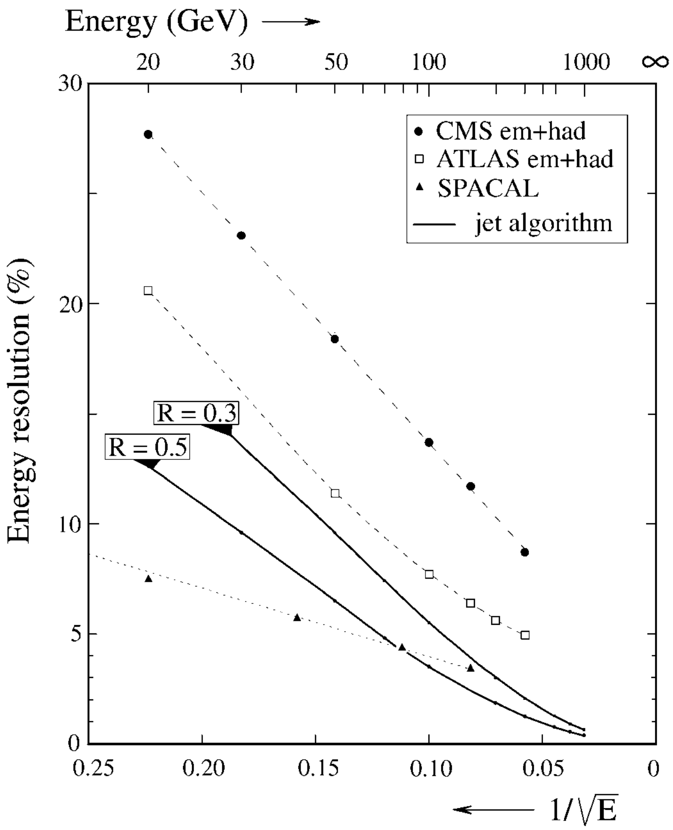

Figure 1: The hadronic energy resolution of three calorimeter systems and the contribution of a jet-defining cone with R = 0.3 or 0.5 to the jet energy resolution, as a function of energy [1].

detection: $\sigma/E = 18\%/\sqrt{E}$. If one focuses on excellent em resolution, one pays a heavy price when it comes to hadronic shower detection. One experiment in which this has become very clear is CMS. Figure 2 shows experimental results for pion detection in a prototype of the CMS calorimeter system, consisting of a $1.3\lambda_{\rm int}$ deep em section made of lead-tungstate crystals, followed by a copper/plastic-scintillator hadronic section [3]. The full dots represent the experimental results for events in which the starting point of the showers was located in the hadronic section and are thus in fact equivalent to a stand-alone test of this calorimeter section. The figure shows considerably deterioration when all events, *i.e.* including those in which the shower started in the em section, were taken into account (the open squares). The energy resolution (Figure 2b) is in this case completely determined by fluctuations in the energy sharing between the em and hadronic calorimeter sections, which have very different e/h values. Even the most sophisticated compensating hadronic section would not have altered these results. *Once the choice is made for a crystal em section, it does not matter what you install behind it.*

When non-compensating calorimeters are being discussed, one usually focuses on the adverse effects of $e/h \neq 1$ on the hadronic energy resolution, especially at high energies. However, non-compensation has several other disadvantageous consequences, which may in practice prove even more of a problem than the poor energy resolution. For example, all non-compensating calorimeters are *intrinsically non-linear for hadron detection,* as a result of the energy dependence

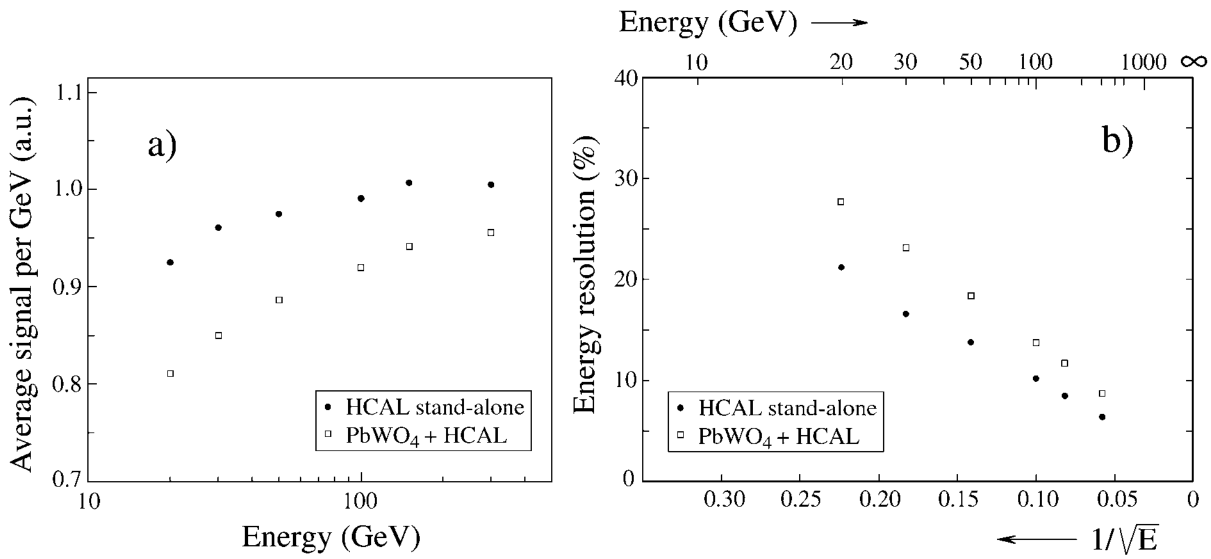

Figure 2: Experimental results for pion detection in a prototype of the CMS calorimeter system. Shown are the response (a) and the energy resolution (b), as a function of the pion energy. See text for details.

of the average em shower fraction, $\langle f_{\rm em}\rangle$. This is illustrated in Figure 2a, which shows that the large e/h value of the CMS crystal calorimeter also has the effect of deteriorating the hadronic signal linearity further. Another adverse effect concerns the *shape of the hadronic response function*. Non-Gaussian fluctuations in $f_{\rm em}$ tend to make the lineshape asymmetric. This may have serious consequences for the triggering function of the detector, in the sense that biases are introduced in the selected event samples.

All problems described above, and some more, are avoided or solved with the calorimeter technique that we propose to develop in the framework of this program. Moreover, if our technique does indeed work as well as we hope and expect, it will offer options to improve the hadronic performance of calorimeter systems such as the one used by CMS. In Section 2, the ideas on which our proposal is based are presented, as well as the evidence in support of these ideas. In Section 3, we describe the proposed R&D program. Section 4 contains concluding remarks.

2 Dual-readout calorimetry

The idea for this proposal originated from prototype studies we have performed for the Forward Calorimeter of the CMS experiment. This calorimeter uses quartz fibers as its active medium. Therefore, the calorimeter signals are generated by Čerenkov light. It turns out that hadrons showering in this detector register, for all practical purposes, only through their em shower component, *i.e.* π^0s and ηs produced in the shower development completely dominate the signals. The non-em shower component is suppressed by a factor of about 5 for what concerns its contribution to the calorimeter signals: $e/h \approx 5$, which makes it by far the most non-compensating calorimeter ever reported on [4].

This result, which was predicted in great detail [5], illustrates that the signals from the non-em component of hadron showers are strongly dominated by spallation protons produced in the nuclear reactions. These particles typically carry kinetic energies of several hundred MeV and are thus not sufficiently relativistic to produce Čerenkov light. The electrons and positrons through which the energy of the em shower component is deposited are relativistic down to a fraction of 1 MeV and thus dominate the production of Čerenkov light in hadron showers [2].

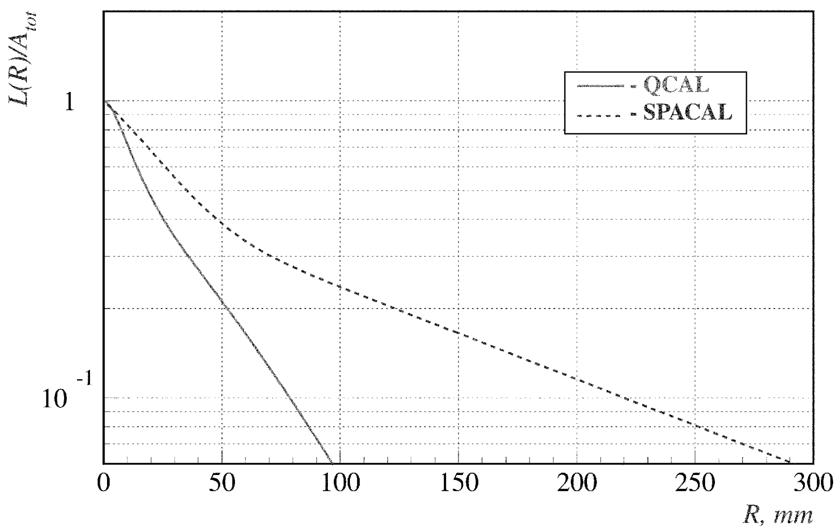

Figure 3: A comparison of the transverse profiles of 80 GeV π^- showers measured with a scintillation calorimeter [6] and with a Čerenkov calorimeter [4]. Shown is the fraction of the signal recorded outside a cylinder with a radius R around the shower axis, as a function of R.

Figure 3 shows an experimental consequence of this phenomenon. It compares the lateral shower profiles for 80 GeV pions in a calorimeter equipped with scintillating fibers (SPACAL [6]) and in a quartz-fiber calorimeter [4]. The latter profile is considerably narrower. The tails detected by SPACAL are mainly composed of soft, non-relativistic shower particles (spallation protons and recoil protons from neutron interactions in the plastic fibers) which do not produce Čerenkov light. The quartz-fibers only detected the narrow em core of the hadron showers.

This example shows that the quartz fibers and the scintillating fibers measure different characteristics of the shower development. The scintillating fibers produce light for every charged particle that crosses them. The amount of scintillation light is, in first approximation, proportional to dE/dx, the energy deposited by the shower particles in these fibers. On the other hand, the quartz fibers only produce light when they are traversed by charged particles traveling faster than c/n, the speed of light in quartz. Because of the dominating role of soft shower electrons, the amount of light produced by the quartz fibers is a measure of the energy carried by π^0s produced in the shower development.

We propose to build a detector that generates both signals. This detector is equipped with scintillating and quartz fibers. Hadron showers developing in this detector generate signals in both types of fibers and these signals provide *complementary information* about these showers. By measuring the signals from both types of fibers simultaneously, we learn $a)$ how much energy was deposited in the calorimeter and $b)$ what fraction of that energy was carried by π^0s. With this method, the dominating source of fluctuations contributing to the hadronic energy resolution can be eliminated, since it allows us to measure the em energy fraction, f_{em}, **event by event**.

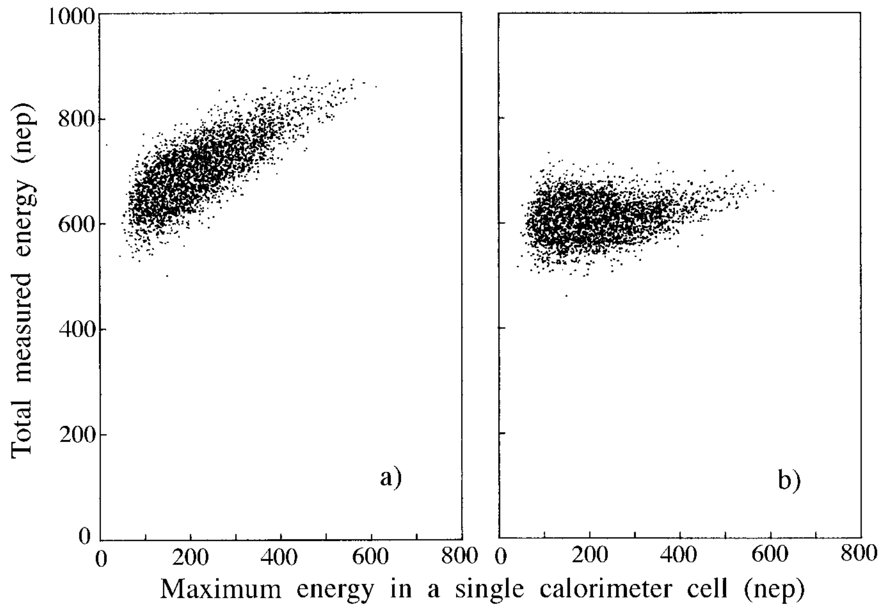

Figure 4: WA1 results on offline compensation, showing the correlation between the total measured signal and the maximum signal observed in one individual calorimeter segment. Results are given for 140 GeV pions before (a) and after (b) applying a weighting factor, based on the signals observed in the individual calorimeter segments.

Measurement of the f_{em} value event by event is **the** key element to improving the hadronic energy resolution of an intrinsically non-compensating calorimeter. Global weighting factors are useless in that respect. The idea of measuring f_{em} event by event and use the information to improve the hadronic energy resolution is not new. It was earlier applied by the WA1 Collaboration [7], who used differences in the energy deposit profiles in their fine-grained calorimeter to determine f_{em}. Some of their results are shown in Figure 4, which depicts a scatter plot in which the total calorimeter signal is plotted versus the maximum signal observed in an individual calorimeter segment. Their calorimeter had an e/h value of about 1.6. Therefore, events with a large value of f_{em} produced large signals. However, since the em shower core was highly localized, such events were also characterized by large energy deposits in individual scintillator planes. This was the basis of the observed correlation in Figure 4a.

The authors then used the observed correlation to reduce the effects of the fluctuations in the em shower fraction on the energy resolution. They assumed that the value plotted on the horizontal axis was a measure of the em shower fraction and reduced the signal observed in each individual scintillator plane by a factor determined by the signal value in that plane:

$$S_i' = S_i\left[1 - \frac{C}{\sqrt{E}}S_i\right] \qquad (1)$$

The optimum value for the constant C was determined empirically from data at a wide range of energies. The result of this procedure is shown for the 140 GeV pions in Figure 4b. In Figure 5a,

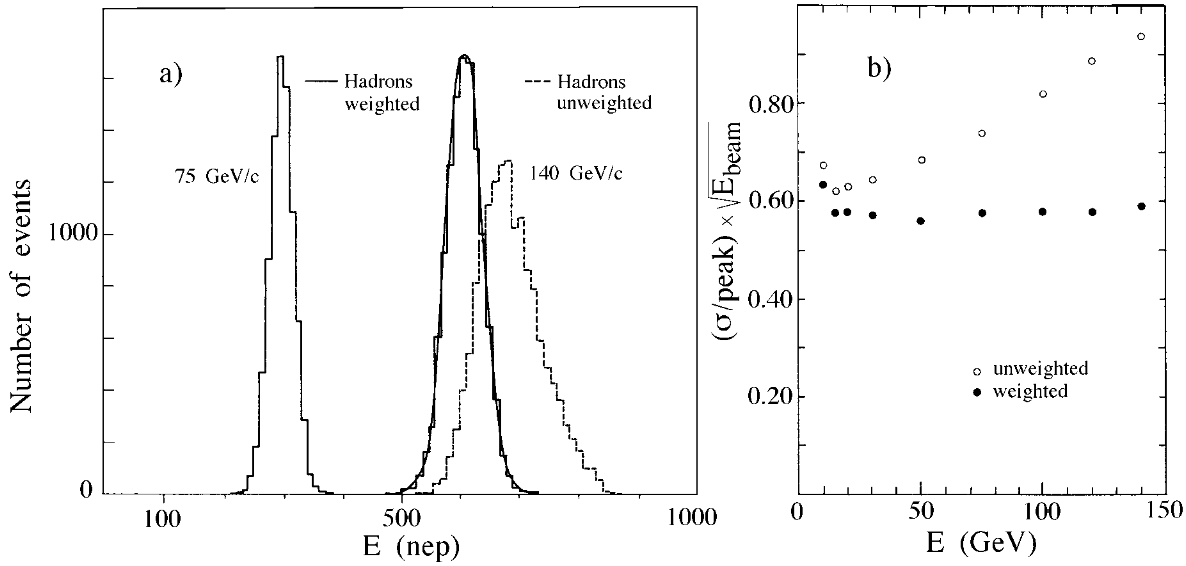

Figure 5: WA1 results on offline compensation. The signal distribution for 140 GeV pions (a) and the hadronic energy resolution as a function of energy (b), before and after the weighting procedure described in the text was applied to the experimental data.

the projections of the scatter plots from Figure 4 on the vertical axis are shown. The described event-by-event corrections clearly made this signal distribution considerably narrower. Also, the signal distribution became much more symmetric as a result of this procedure.

The hadronic energy resolution is shown in Figure 5b, before and after the described corrections were applied. The resolution improved considerably, especially at high energies. Before the corrections, the measured energy resolution leveled off at about 7%. After the corrections, the energy resolution was observed to scale as $\sigma/E = 58\%/\sqrt{E}$.

We described the WA1 technique in some detail since it illustrates how knowledge about $f_{\rm em}$ may be used to improve the performance of an intrinsically non-compensating calorimeter. However, the technique we want to use has several major advantages over the one described above. First, methods based on the energy deposit profile do not work well at low energy. Figure 5b shows that the improvement for energies below 20 GeV was marginal. A second, and more important drawback is that these methods break down for jets. Jets consist of a collection of particles (mainly γs and charged pions) that enter the calorimeter spread out over a certain area. Therefore, the spatial energy deposit profile is not only determined by the em energy fraction in the shower development of the particles constituting the jet, but also by the (unknown) spatial distribution of the particles as they enter the calorimeter.

Our method is based on the comparison of the relative amounts of Čerenkov and scintillation light and should thus work as well for jets as for single hadrons. Our method offers also several crucial advantages over calorimeters that are intrinsically compensating:

- The sampling fraction of detectors based on our method can be chosen as desired. It is not limited to the (small) value needed to achieve compensation. As a result, excellent em energy resolution is by no means precluded.

- The Čerenkov light is limited to a narrow core around the shower axis (see also Figure 3). Also, most of the scintillation light is produced in a relatively narrow cylinder around this axis. Therefore, our method to determine $f_{\rm em}$ from a comparison of these two signals probably works already very well with signals from a very limited detector area. This is very different in intrinsically compensating calorimeters. These rely on the (properly boosted) contribution of neutrons to the calorimeter signals. These neutrons behave like a gas and, therefore, the calorimeter signals have to be integrated over a large detector volume in order to meet the compensation condition. For example, in SPACAL, we had to include all signals from all 155 cells located within 50 cm from the shower axis to achieve $e/h = 1$. In practical experiments, one can almost never afford to integrate over such large detector areas, if only because of the problems of underlying events.

The dual-readout technique thus offers a powerful alternative way to achieve the advantages of compensation, while avoiding the disadvantages. The idea to use the complementary information from scintillating fibers and quartz fibers was first applied in a prototype study for ACCESS, a high-energy cosmic ray experiment planned for the International Space Station. These prototype tests are described in Reference [8]. Because of the very severe restrictions on the mass of the instruments, the ACCESS calorimeter has to be very thin, at maximum 2 $\lambda_{\rm int}$. It is therefore imperative to maximize the amount of information obtained per unit detector mass.

When high-energy hadrons develop showers in such a thin calorimeter, the response function is completely determined by leakage fluctuations. These fluctuations are very likely correlated with the fraction of energy spent on π^0 production inside the detector. In general, π^0s produced in the first nuclear interaction develop em showers that are contained in the detector, while charged pions typically escape. Therefore, events in which a large fraction of the initial energy is converted into π^0s in the first interaction will exhibit little leakage (a large detector signal), while events in which a small fraction of the energy has been transferred to π^0s will be characterized by large leakage (small detector signals). A dual-readout calorimeter that measures both the ionization losses (dE/dx) and the production of Čerenkov light might distinguish between events with relatively small and large shower leakage, since the ratio of the two signals would be different in these two cases: A relatively large Čerenkov signal would indicate relatively little shower leakage, while a small Čerenkov signal (compared to the dE/dx signal) would suggest that a large fraction of the shower energy escaped from the detector.

Figure 6 shows some results of the tests of the 1.4 $\lambda_{\rm int}$ deep dual-readout prototype built for ACCESS. These tests were carried out at CERN with a beam of 375 GeV pions. In Figure 6a, the signals recorded by the quartz fibers are plotted versus those from the scintillating fibers. The non-linear correlation between these signals indicates that they indeed measure different characteristics of the showers.

The scintillator signal distribution, *i.e.* the projection of the scatter plot on the horizontal axis, is shown in Figure 6b. The fact that this distribution is skewed to the low-energy side may be expected as a result of shower leakage. The *ratio of the signals from the quartz fibers and from the scintillating fibers (Q/S)* corresponds to the slope of a line through the bottom left corner of Figure 6a. The two lines drawn in this figure represent $Q/S = 1$ and $Q/S = 0.5$, respectively.

In Figure 6c, the signal distribution is given for events with a small Q/S value ($Q/S < 0.45$).

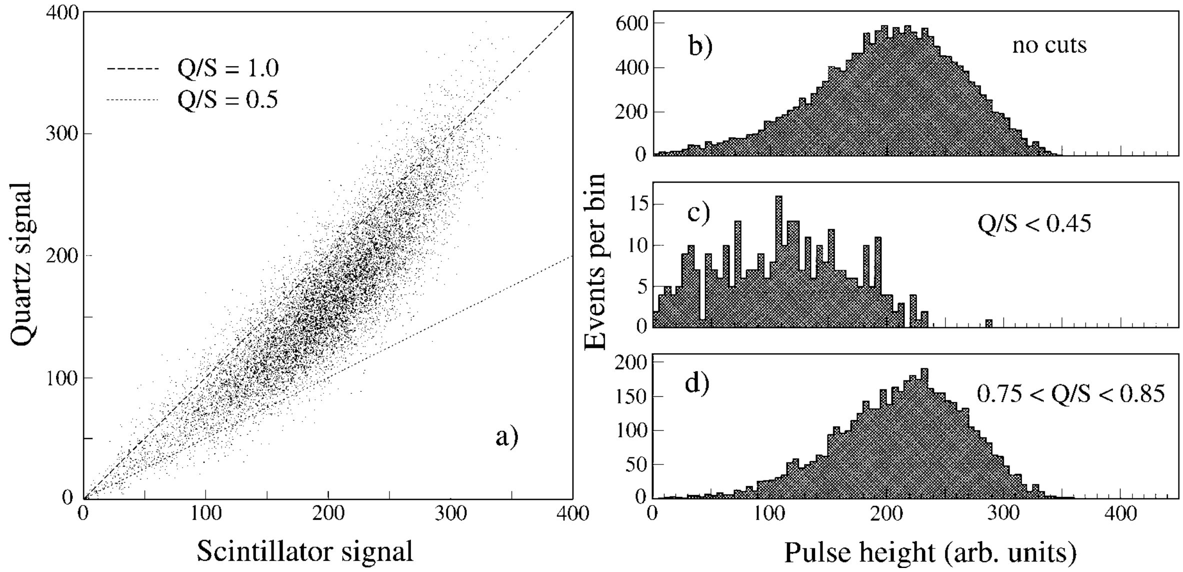

Figure 6: Results of tests of the dual-readout ACCESS calorimeter with 375 GeV pions. Scatter plot of the signals recorded in the quartz fibers *vs.* those in the scintillating fibers (a). The signal distributions from the scintillating fibers for all events (b) and for subsets of events with a small (c) or average (d) fraction of Čerenkov light [**?**].

These events indeed populate the left-side tail of the calorimeter's response function (Figure 6b). This distribution is very different from the one obtained for events with Q/S ratios near the most probable value, shown in Figure 6d. The average values of the scintillator signal distributions in Figures 6c and 6d differ by about a factor of two.

These results demonstrate that events from the tails of the Q/S distribution correspond to events from the tails of the (dE/dx) response function. Therefore, the ratio of the signals from the quartz and the scintillating fibers does indeed provide information on the energy containment and may thus be used to reduce the fluctuations that dominate the response function of this very thin calorimeter.

It turned out that the improvement of the energy resolution that could be achieved on the basis of this information was primarily limited by the light yield of the quartz fibers, 0.5 photoelectrons per GeV in this detector. Fluctuations in the number of Čerenkov photoelectrons determined the width of the "banana" in Figure 6a and thus the selectivity of Q/S cuts. Therefore, the relative improvement in the energy resolution also increased with the hadron energy (see Figure 7b).

Figure 7a shows the fractional width of the distribution of the ratio of the signals from the quartz and the scintillating fibers, represented by the black triangles, as a function of the energy of the incoming pions. This energy is plotted on a scale linear in $E^{-1/2}$, so that scaling with $[\sqrt{E}]^{-1}$ corresponds to a straight line through the bottom right corner of this plot. The experimental data, which cover an energy range of 100 – 375 GeV, are well described by such a line. This means that the width of the Q/S distribution in this energy range is completely determined by fluctuations governed by Poisson statistics, *i.e.* fluctuations in the number of photoelectrons produced by Čerenkov light from the quartz fibers.

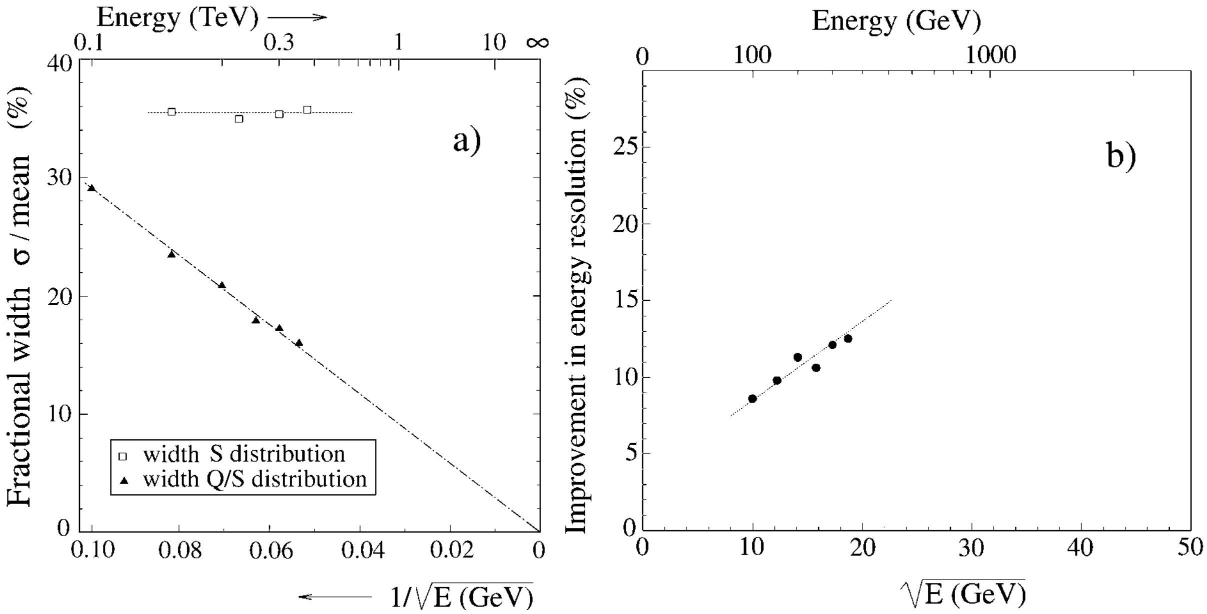

Figure 7: The fractional width of the distributions of the signals from the scintillating fibers (S) and of the ratio of the signals from the quartz and the scintillating fibers (Q/S) as a function of the energy(a). Improvement in the energy resolution achieved on the basis of the Q/S signal ratio (b).

It is remarkable that our technique already works so well in this very thin calorimeter. After all, in this detector one is looking only at the very first generation of shower particles and the non-em shower component has barely had a chance to develop. The overwhelming majority of the non-relativistic shower particles, in particular the spallation and recoil protons, are produced in later stages of the hadronic shower development. The signals from these non-relativistic shower particles are crucial for the success of our method, since they are the ones that do produce scintillation light and no Čerenkov light. The fact that our technique already appears to work so well in this very thin calorimeter therefore holds the promise that excellent results may be expected for detectors that fully contain the showers.

3 R&D program

Although the ACCESS results, described in the previous section, were extremely encouraging, one should realize that these represent no more than a proof of principle., *i.e.* the principle that simulataneous detection of scintillation light and Čerenkov light provides a handle on the fluctuations in the em content of developing hadronic showers. In the ACCESS study, we assumed that these fluctuations were correlated to those in shower leakage, which dominated the resolution of that very thin instrument. The improvement in energy resolution that we obtained by exploiting this correlation was very modest, $< 15\%$ in the energy range where the instrument was tested. In the proposed study, we plan to concentrate on the following issues:

1. The benefits of our technique are expected to be much larger in detectors that contain most of the showers developing in them. However, this remains to be experimentally proven

and that is precisely the purpose of the first stage of the project.

2. If our technique works as well as envisaged, new possibilities for high-resolution hadron calorimetry open up, without the restrictions on em resolution that apply to compensating devices. These possibilities are not limited to detectors in which the scintillation and the Čerenkov light are recorded by different active media. One may try to separate these two types of light with only one light producing medium. This can be studied with the equipment at hand and will require fast analyses of signals reminescent of pulse-shape discrimination (PSD) techniques.

3. If such tests prove successful, one could use techniques of this type to improve existing detectors. In the third stage of this study, we would want to explore the possibilities in this respect. One obvious candidate is the CMS calorimeter, which might be turned into a high-resolution jet detector.

The funding requested at this time only concerns the first stage of this study.

3.1 The proposed detector

The consequences of non-compensation on the hadronic energy resolution are most apparent at high energies. Figure 2 shows a resolution for pions in the combined CMS em + hadronic calorimeter of about 8% at 300 GeV. We believe that we can do at least a factor of three better, with an instrument that requires integration of the signals over an area with a radius of less than 15 cm.

Our ACCESS experience has taught us that it is crucial that the light yield of the quartz fibers be adequate. Therefore, the quartz sampling fraction is the most important (and most costly) element of the prototype design. If we want a resolution better than $40\%/\sqrt{E}$, which should be easily achievable once the effects of fluctuations in $f_{\rm em}$ on the resolution are eliminated, the quartz should produce at least 10 photoelectrons per GeV. Based on our CMS measurements, this translates into a packing fraction of about 20% by volume.

The other element that contributes to the energy resolution is sampling fluctuations. In SPACAL, which had a scintillating-fiber packing fraction of 20% by volume, these fluctuations amounted to $\sim 25\%/\sqrt{E}$ for hadrons ($13\%/\sqrt{E}$ for electrons). Figure 8 shows the em energy resolution and the contributions of these two main factors to the hadronic energy resolution, as a function of the packing fraction.

The detector we would like to construct has about 23% quartz fibers and 17% scintillating fibers by volume. The expected resolution amounts to $\sim 40\%/\sqrt{E}$ for jets and $14\%/\sqrt{E}$ for electrons and γs. Iron will be used as absorber material, because it is cheap and easily machinable. Several options to embed the fibers in the iron structure are being studied. Because of the large packing fraction, the tolerances and the associated amount of air in the absorber structure are of critical importance. One promising option is extrusion of the base element, a hexagonal iron tube (5 mm apex-to-apex) with a circular hole (2.5 mm diameter) in it. In this hole, we insert 7 fibers with a diameter of 0.8 mm each (4 quartz, 3 scintillating). If this technique is chosen, some 8000 of these base elements will be needed for the total detector. They can be glued, welded or strapped together.

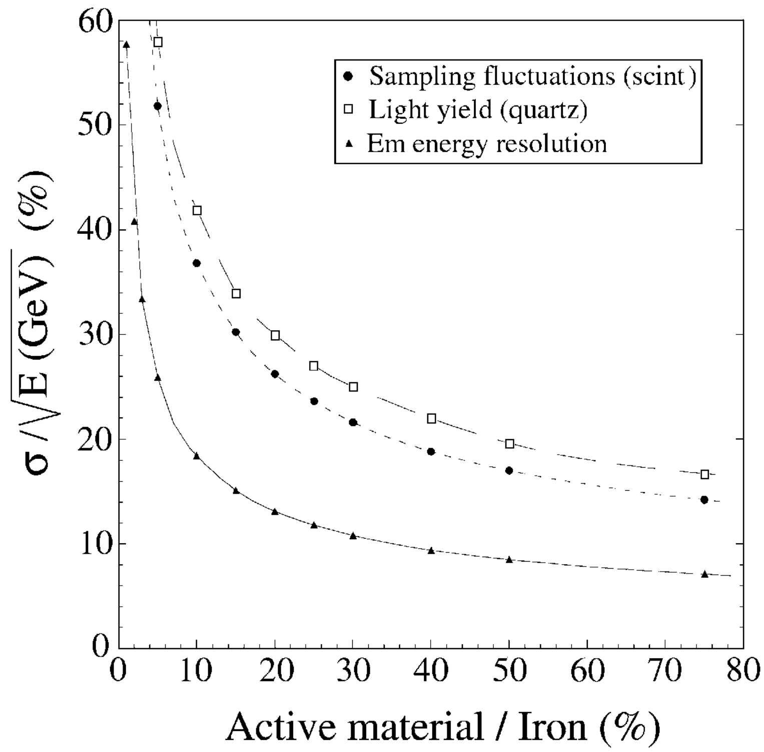

Figure 8: The contribution of sampling fluctuations and light yield to the hadronic energy resolution of the dual-readout calorimeter, and the electromagnetic energy resolution of this device, as a function of the relative amounts of active material.

In another option that is being studied, the base element is a 1 mm thick iron plate with the required pattern of holes stamped into it. If this technique is chosen, some 2500 plates will be stacked on top of each other (total thickness 2.5 m, which for a total filling fraction of 40% corresponds to about 9 nuclear interaction lengths). The plates will be aligned and kept in position with tie rods, and the fibers are inserted in the channnels that are formed this way. We have used this technique earlier with lead plates in the construction of the SPAKEBAB calorimeter [9]. Tests carried out with iron plates for the CMS HF calorimeter showed that this method works provided that adequate tolerances are maintained.

The instrumented volume will have a radius of 15 cm (*i.e.* $0.5\lambda_{\rm int}$ or $5\rho_M$), enough to contain more than 70% of the scintillation light and more than 95% of the Čerenkov light generated in high-energy hadron showers. The detector will be longitudinally unsegmented, laterally it will be subdivided into towers, a central tower surrounded by two concentric rings. Each of the towers represents a calorimeter surface of ~ 35 cm^2 and contains about 1200 scintillating fibers and 1600 quartz fibers. In total, 60 km of scintillating fiber and 80 km of quartz fiber will be needed for this instrument. The signals will be read out with PMTs. In total, ~ 40 PMTs will be needed, with a photocathode surface of 7 cm^2 each.

3.2 Test program

The detector is being designed by physicists from TTU and UCSD. It will be assembled at TTU and then shipped to CERN, to be tested in high-energy particle beams. If our proposal is approved, we will request beam time at CERN. Physicists from TTU and UCSD will go to CERN to prepare the testbeam and adapt the teststand and Data Acquisition Systems to the requirements of the detector. TTU and UCSD have collaborated successfully in the past in projects of this type (SPACAL [6], SPAKEBAB [9]). Based upon that experience, we expect we need a team of 5 people for a periods of 3 weeks. If our proposal is approved, we expect to be able to do the first tests in the summer of 2002. Analysis of the testbeam data will take place in real time using the on-line DAQ systems and later at the TTU and UCSD home institutions. We will make use of existing computer systems for this purpose.

Based on our experience, it is a good idea to foresee a second test period one year later. Based on the results of the first tests, the detector may be modified and/or additional tests may be carried out in that case. If the results of the first tests are encouraging, we would also like to start the second stage of the project, *i.e.* bench tests of PSD techniques, at that time.

3.3 Collaborators

We have discussed the ideas on which this proposal is based with a number of colleagues and have encountered a lot of interest. It is very likely that if and when DoE approves this project, other groups would like to join. We welcome this, and are willing to share whatever resources DoE would make available for this project with others. Based on our experience with previous projects of this type, there will be plenty of work. In particular, we would also welcome students who could work on the analysis of the test beam data or on other parts of the project as part of their graduate training. It is our experience that projects of this type are ideally suited for this purpose and are among the best tools to generate interest for our field in the next generation of researchers.

3.4 Budget

Based on offers received so far, we estimate the cost of the detector components as follows:

- Absorber + miscellaneous mechanics $ 45,000
- Quartz fibers ($ 2.50/m) $ 200,000
- Scintillating fibers ($ 0.70/m) $ 42,000
- PMTs $ 15,000

To this, workshop charges have to be added. We estimate these at $10,000. This brings the cost of the total detector to $ 312,000.

The costs of testing the detectors in particle beams are also substantial. For two testbeam periods, as mentioned above, these costs are estimated at $ 42,000:

- Shipping detector (2 roundtrips TTU - CERN) $12,000
- Travel expenses crew (5 people, 2×3 weeks) $30,000

This brings the total cost of the project to $ 354,000, not counting salaries of the people involved in it. If this project is approved, one TTU postdoc and one UCSD postdoc will work half-time on it. We expect to involve a large number of undergraduate students, who will help with the construction of the detector (more than 50,000 fibers have to be handled!). One TTU graduate student will work on the data analysis, as part of a PhD thesis.

We have managed to obtain substantial funds from sources other than DOE for this project. The State of Texas is contributing $ 150,000 and TTU has committed $ 30,000 in matching funds (contingent upon DOE approval). In addition, workshop charges will be waived. By using materials that can be recycled from other projects to the extent possible, we believe that these additional resources will allow us to build the described detector, if DOE contributes modestly to this project.

It is crucial that this project receive some DOE support. Not only do we need it to balance the books, but such support would also give the project the "official" status needed for obtaining dedicated beam time at CERN.

We request specific DOE support, $ 215,775 in total ($ 161,775 for TTU, $ 54,000 for UCSD), for the described detector test program and some salary support for the postdocs and students who will work on this project. The submitted budget has been prepared for a period of two years, FY02 - FY03.

4 Concluding remarks

Calorimeters are non-trivial devices, especially when it comes to hadron detection. Unfortunately, the Monte Carlo packages describing hadronic shower development in calorimeters, especially those incorporated in the GEANT structure, are all seriously flawed. Yet, in the past 20 years tremendous progress has been made in understanding the tricky aspects of calorimetry. This progress has been driven by dedicated detector R&D efforts, such as the one proposed here. The authors of this proposal have played a leading role in this development. Among the projects they led should be mentioned:

- The SPACAL project. In this project, compensating lead/scintillating-fiber calorimetry was developed. A collaboration of 50 physicists from 10 institutes built and tested a 20-ton prototype at CERN. This detector still holds the world record for hadronic energy resolution. This project was initiated and led by Dr. Wigmans. The UCSD group led by Dr. Paar also played a crucial role. The SPACAL project resulted in 10 publications in NIM (*e.g.* [6]).
- The RD1 project. In this project, the merits of the compensating lead/scintillating-fiber calorimetry for high-luminosity 4π geometries were investigated. Among the issues that were studied were the effects of sampling *frequency* on the em energy resolution of a compensating calorimeter, various options to make projective fiber detector structures,

etc. Dr. Wigmans was the initiator and first spokesman of this project (until his relocation to the USA in 1992). The RD1 results are described in 2 NIM papers [10, **?**].

- The SPAKEBAB project. In this project, we studied the possibilities of combining a high-resolution em calorimeter with a reasonably small e/h value and a compensating hadronic section. This project was also a collaborative effort between Texas Tech University and the University of California at San Diego (Professor Hans Paar's group). The results are described in Reference [9].
- The QFCAL project. In this project, the 0° quartz fiber calorimeter technology was developed from an idea to the technology of choice for the CMS HF calorimeter [4, **?**].
- The dual-readout ACCESS calorimeter project, in which the ideas on which this proposal is based were first tried out [**?**].

This list may also serve as our track record on bringing detector R&D projects to a successful conclusion, including publication of the results. Our expertise may also be illustrated by the fact that Dr. Akchurin is the project leader for the Forward Calorimeter of the CMS experiment. Dr. Wigmans is the author of the standard reference book on calorimetry [2]. We strongly believe that the proposed project could be the next big thing in detector development for experiments in particle physics. If and when approved, we will give it our very best efforts.

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