Ultimate Hadron Calorimetry

Classification (subsystem)

Calorimeter

Personnel and Institution(s) requesting funding

Texas Tech University: N. Akchurin, H. Kim and R. Wigmans

Collaborators

University of California at San Diego: H.P. Paar
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Collaborating personnel will work on the project but are not requesting funding here.

Project Leader

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Project Overview

High-precision measurement of the 4-vectors of hadrons and jets is an essential requirement for experiments at the ILC, and one of the main goals in developing a detector for such an experiment.

Thirty years of experience have taught us that hadron calorimetry is extremely non-trivial. Unfortunately, Monte Carlo simulations of the type available in the GEANT package have little predictive value for the performance of hadron calorimeters. Progress in our understanding of hadron calorimetry has been entirely due to generic detector R&D projects of the type proposed here.

In most hadron calorimeters, the performance is dominated (and spoiled) by the fact that the response to the electromagnetic (em) shower component is different from that to the non-em shower component: $e/h \neq 1$. Fluctuations in the energy fraction carried by the em component ($f_{\rm em}$), dominate the energy resolution and the (non-Gaussian) lineshape, while the energy dependence of the average value of $f_{\rm em}$ causes (a usually substantial) non-linearity.

There are two proven ways to eliminate these problems and improve the calorimeter performance.

1. Make the calorimeter compensating ($e/h = 1$)
2. Measure the value of $f_{\rm em}$ event by event and correct for the response differences mentioned above.

The compensation mechanism is now well understood. It can be achieved by designing the calorimeter in such a way that the signals from neutrons, abundantly produced in the non-em shower component, are boosted to such an extent that they, on average, compensate for the "invisible" energy resulting from nuclear breakup. In practice, this can be achieved with a sampling calorimeter with a hydrogenous active medium. The sampling fraction has to be small, *e.g.* 2.4% in lead/plastic-scintillator structures, $\sim$ 10% in uranium/plastic-scintillator.

Such calorimeters work very well, and they hold all world records for hadronic performance. However, they have a few disadvantages. Because of the crucial contribution of neutrons, one has to integrate the signals over a large detector volume (1 m^3) and a considerable time (100 ns) to achieve this performance. Also, because of the small sampling fraction, the resolution for em shower detection is limited. The best em resolutions reported for compensating calorimeters are $\sim 10\%/\sqrt{E}$.

The DREAM (Dual-REAdout Module) calorimeter was developed as a device that would make it possible to perform high-precision measurements of hadrons and jets, while *not* subject to these limitations. It is based on the second principle mentioned above, measuring $f_{\rm em}$ event by event. The detector is based on a copper absorber structure, equipped with two types of active media which measure complementary characteristics of the shower development. Scintillating fibers measure the total energy deposited by the shower particles, while Čerenkov light is only produced by the charged relativistic shower particles. Since the latter are almost exclusively found in the electromagnetic shower component (dominated by π^0s produced in hadronic showers), a comparison of the two signals makes it possible to measure the energy fraction carried by this component event by event.

The idea to combine the complementary information from dE/dx and from the production of Čerenkov light has been proven to be a very powerful tool for improving the hadronic calorimeter performance (see the section "Results of Prior Research" for details). Based on the successes achieved so far, we believe that we can take this approach one step further, in an attempt to obtain the ultimate hadron calorimeter.

The ultimate limitation on the resolution that can be achieved with a hadron calorimeter is determined by fluctuations in (in-)visible energy, *i.e.* fluctuations in the energy fraction that is used to break up atomic nuclei and thus does not contribute to the measured signals. Fortunately, this fraction is correlated to the total kinetic energy of the neutrons liberated in this process, especially in high-Z absorber materials such as lead. Therefore, efficient detection of these neutrons is key to obtaining the best possible energy resolution.

We propose to modify the existing DREAM calorimeter in such a way that a separate measurement of the kinetic energy carried by shower neutrons, $E(n)$, becomes possible. We believe that the combined information from dE/dx, Čerenkov light and $E(n)$ will maximize the relevant knowledge about the developing showers and, therefore, will provide the ultimate hadron calorimetry. We propose two avenues to achieve this goal:

1. Replace every second plastic scintillating fiber by a non-hydrogenous scintillating fiber, *e.g.* quartz doped with a scintillating agent. A comparison of the signals from these two types of fibers will provide $E(n)$, since the only difference between these two signals comes from the neutrons.
2. Replace one or several fibers in each copper tube with fibers that are made specifically sensitive to MeV-type neutrons, *e.g.* using boron.

The first method will almost certainly work, but since quartz fibers are very expensive, the second method has a better potential to provide a cost-effective solution. That's why we want to investigate both options.

In Year 1, we want to dedicate ourselves to the purely generic part of this project, *i.e.* investigate the advantages and disadvantages of all different options. In Year 2, we want to implement the chosen solution in our DREAM calorimeter and perform high-energy beam tests at CERN or Fermilab. We realize that the existing prototype detector (1030 kg) is too small to achieve the ultimate performance allowed by this triple-readout approach. However, we expect that the improvement of the performance compared to the dual-readout version will allow us to fully assess the possibilities of this new technique.

Broader Impact

This proposal, if funded, will contribute to the knowledge base in our respective Physics Departments. The beneficiaries of that will be postdocs, graduate students, and undergraduate students participating in the research funded in this proposal.

One of our collaborators (Hans P. Paar) is co-director of NSF's REU (Research Experience for Undergraduates) program located in UCSD's Physics Department. Through this program, we will recruit undergraduates, generally from disadvantaged backgrounds, to participate in our research program. This includes taking them with us to an accelerator laboratory such as FermiLab or CERN where they can experience first hand the atmosphere of forefront research.

As in the case of the DREAM project, we will involve TTU Quarknet treachers and their highschool students in construction, tests and analyses, where possible.

Faculty will recruit junior and senior undergraduates to participate in our laboratory based research. There they will use the state-of-the-art equipment to which this Grant has contributed.

Undergraduates working in our labs will often present their research at an Undergraduate Research Conference, attended by their peers and faculty supervisors. Here they learn what it means to stand up and present your results and answer questions "on your feet".

Results of Prior Research

The DREAM project was started in 2001, with a grant ($150K) received by the project leader in the context of the Advanced Research Program of the State of Texas. In 2002, this grant was supplemented by funds from DOE's Advanced Detector Research program. Since then, the proponents have received a total amount of $340K from the latter source, in four installments.

We have used these funds to construct and test a generic prototype, which was intended to test the dual-readout principles and measure the extent to which the performance of hadron calorimeters could be improved by making use of these principles. The detector is based on a copper absorber structure, equipped with two types of active media which measure complementary characteristics of the shower development. Scintillating fibers measure the total energy deposited by the shower particles, while Čerenkov light is only produced by the charged, relativistic shower particles. The total instrumented mass is 1030 kg (depth 10 $\lambda_{\rm int}$), and the 36,000 fibers are read out by 38 PMT's.

This detector was built in the Physics department of Texas Tech University and then shipped to CERN, where it was tested with high-energy pions, electrons and muons in the H4 beam of the Super Proton Synchrotron. CERN allocated three testbeam periods to this project, during the summers of 2003 and 2004.

The results of these tests are described in a number of papers. Three papers have already appeared in the scientific literature:

- N. Akchurin *et al., Muon Detection with a Dual-Readout Calorimeter*,
  Nucl. Instr. and Meth. **A533** (2004) 305–321.

- N. Akchurin *et al., Electron Detection with a Dual-Readout Calorimeter*, Nucl. Instr. and Meth. **A536** (2005) 29–51.
- N. Akchurin *et al., Hadron and Jet Detection with a Dual-Readout Calorimeter*, Nucl. Instr. and Meth. **A537** (2005) 537–561.

A fourth paper has been accepted for publication:

- N. Akchurin *et al., Comparison of High-Energy Electromagnetic Shower Profiles Measured with Scintillation and Čerenkov Light*, Accepted for publication in Nucl. Instr. and Meth.

Two other papers are in an advanced state of preparation. The DREAM project was also presented in two talks at the XIth International Conference on Calorimetry in High Energy Physics (Perugia, Italy, 2004). In his summary talk, the speaker called DREAM the most significant new development in calorimetry in recent history. All papers can also be found at the website of the DREAM project: http://www.phys.ttu.edu/dream/

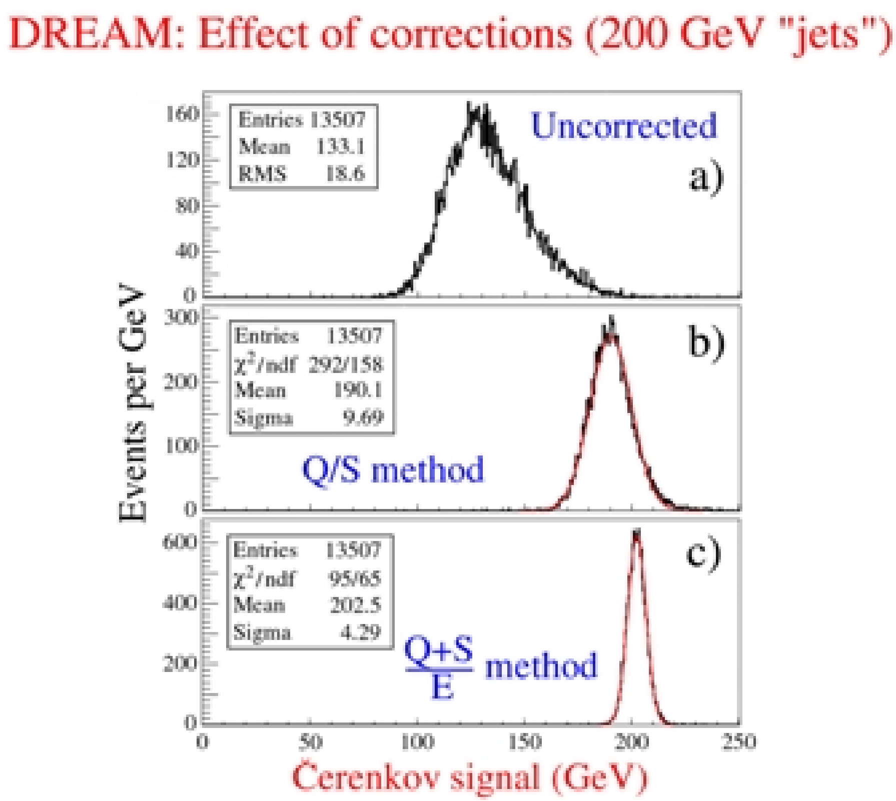

Figure 1: Scintillator signal distributions for 100 GeV π^- in the DREAM calorimeter before any corrections were made(a), after the corrections based on the observed Q/S signal ratio were applied (b) and after, in addition, leakage fluctuations were eliminated (c). See text for details.

The idea to combine the complementary information from dE/dx and from the production of Čerenkov light has been proven to be a very powerful tool for improving the hadronic calorimeter performance (Figure 1). The performance of our detector is considerably superior to what is commonly achieved with hadron calorimeters used in particle physics experiments. For example, high-energy (200 GeV) jets were measured with a resolution better than 4%

(Figure 1b). Because of the limited size (the total instrumented mass of the test module was only 1030 kg), fluctuations in (lateral) shower leakage contributed significantly to the measured resolution. We have shown that if we made use of the fact that the jet energy was known (thus effectively eliminating the contributions of shower leakage to the results), the mentioned resolution could be further improved by a factor of two (Figure 1c). Similar improvements may thus be expected for a detector with a larger instrumented mass than the device tested in this study.

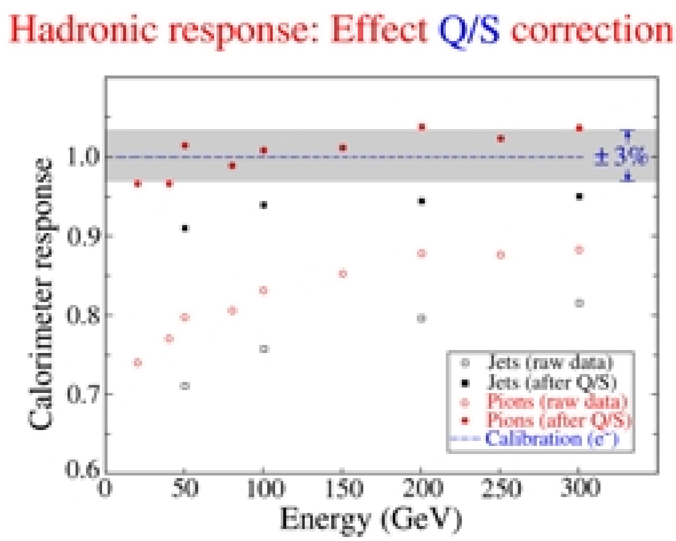

Figure 2: The calorimeter response (average signal per GeV) for single pions and high-multiplicity jets, as a function of energy, before and after corrections made on the basis of the measured Q/S signal ratio. The response is normalized to electrons.

Perhaps even more important is the fact that the (simple) procedure we developed to correct event by event for differences in the electromagnetic shower fraction automatically led to a correct reconstruction of the shower energy, both for jets and for single hadrons, *in an instrument calibrated with electrons*, over the full energy range at which the detector was tested. Anyone who has ever worked with a hadron calorimeter in an experiment will appreciate this very important feature, which is illustrated in Figure 2.

Facilities, Equipment and Other Resources

The TTU HEP labs are equipped with generic NIM, CAMAC and VME electronics. Several specialized tools were designed and manufactured for fiber cleaving, polishing and termination during the DREAM project. Some funds for modification and upgrade of this equipment are requested.

Our computer facilities are well-equipped for Monte Carlo calculations and data analyses with the newest versions of the common simulation packages. For bench test measurements, we have adequate data acquisitions systems and electronics as well.

We anticipate using different types of spectrometers for the analyses of light from a variety of active media (scintillation and Čerenkov radiation). We may have to augment our existing spectrometers with different gratings to gain enhanced sensitivity to various wavelength regions.

The TTU HEP lab operates a 2-MeV electron Van de Graaff that we used extensively in the early stages of fiber selection for the DREAM project. We anticipate using this versatile accelerator in the initial phases of these studies.

It is necessary to study the light generation mechanism of doped quartz (or glass) fibers using neutrons. There are a number of neutron sources available on campus (TTU Health Sciences Center).

It is important to note that this proposal builds on a recent successful R&D program (DREAM). This has several positive implications:

- The absorber, standard scintillating and Čerenkov (quartz and clear plastic) fibers, and photomultipliers already exist.
- The proponents of this proposal have invested many years developing new calorimeter techniques and have been very effectively working as a single team.
- The two proposals (*Dual-Readout Calorimetry for ILC* and *Ultimate Hadron Calorimetry*) we submit in this context for consideration are tightly coupled in all kinds of resources.

All of the above provide a unique and proven synergy.

FY2005 Project Activities and Deliverables

The proposed work calls for investigation of two types of fibers: one is a non-hydrogenous scintillating fiber, and the second one is a specifically designed fiber sensitive to a few MeV neutrons.

In the first year of this program, we anticipate researching doped quartz (or glass) and other types of fibers in collaboration with fiber industry. Over the years we have developed productive working relationships with several fiber producers. We plan to investigate prototype fibers in 2005 and engage a MS graduate student in this project. By the end of 2005, we will have chosen the best possible fiber for neutron detection, and simulated the signals expected from a calorimeter equipped with three different types of fibers.

FY2006 Project Activities and Deliverables

The second phase of the program calls for production of these optical fibers and construction and/or modification of a calorimeter prototype. We assume that a beam test of the constructed prototype will be possible either at FNAL or CERN in 2006. We analyse the test results for publication and prepare for improvements and needed modifications for the following year.

FY2007 Project Activities and Deliverables

If the objectives outlined above are met by the beginning of 2007, we expect this year to be more of an analyses and simulation period. If however, new ideas emerge and/or modifications become necessary, we are prepared to carry through those activities and beam tests in 2007.

Budget justification:

Texas Tech University will be the lead institution in this project. For the first two years, we plan to use professional expert assistance in scintillator doping and in specialty design of optical fibers (∼6K$). This research is well-suited for an MS thesis and we expect to pay part of a graduate student salary (two months out of a year, ∼10.5K$). The fringe benefits rate is assumed to be 25% on salaries.

The largest fraction of the project cost concerns the investigation and production of specialty optical fibers (∼84K$ over three years). This estimate is based on our experience with polymer-clad fused-silica (quartz) and clear plastic fibers for the DREAM project. Note that there is considerable savings in producing a prototype with these novel features: The copper absorber, standard scintillating fibers, undoped quartz fibers along with photodetectors already exist at no cost to this project.

We assumed no overhead charge on equipment and travel. A similar agreement was reached with TTU for previous grants of this type. TTU will charge overhead on salaries at the off-campus rate (26.5%).

Three-year budget, in then-year K$

Institution: Texas Tech University

Item	FY2005	FY2006	FY2007	Total
Other Professionals	3.0	3.0	0	6.0
Graduate Students	3.5	3.5	3.5	10.5
Undergraduate Students	0	0	0	0
Total Salaries and Wages	6.5	6.5	3.5	16.5
Fringe Benefits	1.6	1.6	0.9	4.1
Total Salaries, Wages and Fringe Benefits	8.1	8.1	4.4	20.6
Equipment	3.0	3.0	0	6.0
Travel	5.0	5.0	4.0	14.0
Materials and Supplies	31.7	31.7	20.5	83.9
Other direct costs	0	0	0	0
Total direct costs	47.8	47.8	28.8	124.5
Indirect costs	2.2	2.2	1.2	5.5
Total direct and indirect costs	50.0	50.0	30.0	130.0