The DREAM Project – Results and Plans

Request for SPS Beam Time

The DREAM Collaboration

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1 Introduction

DREAM started in 2002 as a generic detector R&D project, intended to explore (and, if possible, eliminate) the obstacles that prevent calorimetric detection of hadrons with a comparable level of precision as we have grown accustomed to for electrons and photons. The initial collaboration, consisting of fewer than 10 physicists, built a prototype detector (DREAM = Dual REAdout Module) that was successfully tested at the SPS in 2003 and 2004. The excellent results obtained in these tests generated a lot of interest, and the collaboration has now expanded to 7 institutions, 3 from the USA, 4 from Italy.

After the initial studies, in which the effects of the dominating source of fluctuations on the calorimeter performance were successfully eliminated, the collaboration is now focusing on the remaining effects, which have risen to prominence as a result: Sampling fluctuations, signal quantum statistics and nuclear breakup effects. By reducing these effects as much as possible in a systematic, sequential manner, we expect to be able to approach the theoretical limits for hadronic calorimeter performance (*e.g.,* energy resolution $15\%/\sqrt{E}$).

Even though DREAM is in essence still a generic R&D project, some of the new collaboration members have of course practical applications in mind. These applications include a detector for an experiment at a future Linear e^+e^- Collider in the TeV energy range, and an upgrade of the CMS calorimeter system.

The physics program of a Linear e^+e^- Collider requires excellent hadronic energy resolution. It has been estimated that to distinguish between hadronically decaying W and Z bosons, a resolution better than 4% will be needed. This requires detectors that are considerably better than the ones used in experiments at LEP, the Tevatron and the LHC. One of the proto-detectors studied for the ILC (the so-called 4th Concept) is based on the DREAM approach to calorimetry. Several proponents of this concept are also members of the DREAM collaboration.

2 The DREAM approach to ultimate calorimetry

The energy resolution of calorimeters is determined by fluctuations. If one wants to improve that resolution significantly, then one has to address the dominating source of these fluctuations. In almost all calorimeters (*i.e.* the ones with $e/h \neq 1.0$), fluctuations in the electromagnetic shower fraction ($f_{\rm em}$) dominate the energy resolution for hadrons and jets. These fluctuations, and their energy-dependent characteristics, are also responsible for other undesirable calorimeter characteristics, in particular hadronic signal non-linearity and a non-Gaussian response function. There are two possible approaches to eliminate (the effects of) these fluctuations [1]: By designing the calorimeter such that the response to em and non-em energy deposit is the same (compensation, $e/h = 1.0$), or by measuring f_{em} event by event. The DREAM project follows the latter approach.

Calorimeters based on Čerenkov light as the signal source are, for all practical purposes, only responding to the em fraction of hadronic showers [2]. This is because the electrons/positrons through which the energy is deposited in the em shower component are relativistic down to energies of only 200 keV. On the other hand, most of the non-em energy in hadron showers is deposited by non-relativistic protons generated in nuclear reactions [1]. However, in other types of active media (scintillator, LAr) such protons do generate signals. The DREAM detector uses two active media, hence the name (dual-readout): Scintillating fibers measure dE/dx, while clear fibers measure the Čerenkov light generated in the shower development. By comparing the two signals, f_{em} can be measured event by event, and the total shower energy can be reconstructed using the known e/h value(s) of the calorimeter.

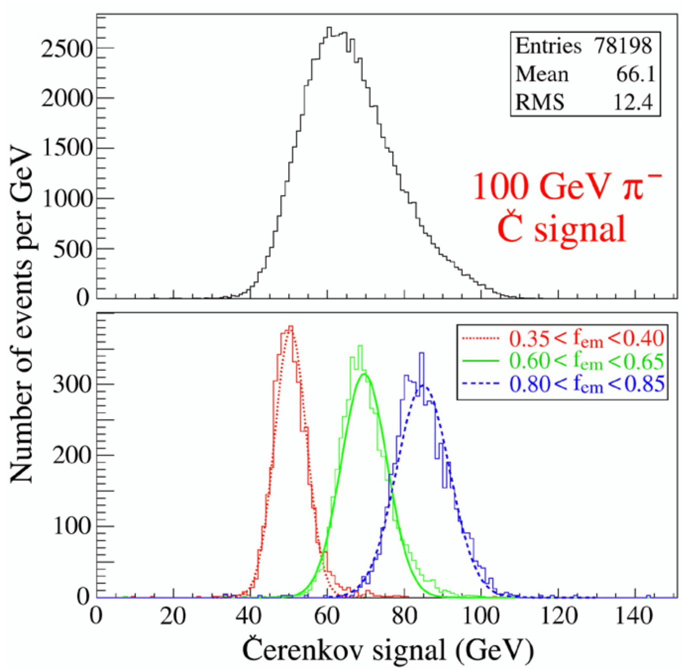

Figure 1: Čerenkov signal distributions for 100 GeV π^-. Shown are all events (top) and samples selected on the basis of their electromagnetic shower content (bottom).

The DREAM calorimeter, as well as many results obtained in beam tests of this device, have been described in detail in a number of papers [3]. In the following, we only illustrate that this principle works very well. Figure 1 shows the Čerenkov signal distribution for 100 GeV π^- showers (top diagram), as well as the signal distributions for event samples selected for 3 bins of the em shower fraction (bottom diagram). The larger the value of $f_{\rm em}$, the larger the calorimeter signal. The overall signal distribution (top) is evidently a superposition of many narrow distributions such as the ones in the bottom diagram. By using the measured value of $f_{\rm em}$, the total signal distribution can be transformed into a narrow one, with the correct central value, *i.e.* the signal one would find for pure em showers of the nominal energy. This is illustrated in Figure 2, which concerns the signal distri-

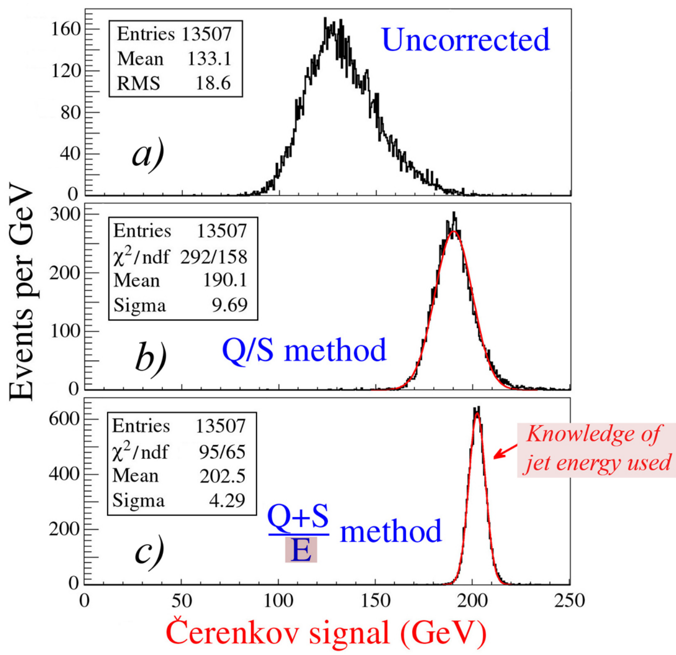

Figure 2: Čerenkov signal distributions for 200 GeV multi-particle events. Shown are the raw data (a), and the signal distributions obtained after application of the corrections based on the measured em shower content, with (c) or without (b) using knowledge about the total "jet" energy.

butions from 200 GeV multiparticle events (reaction products from an upstream target, intended to mimick jets). The raw Čerenkov signal distribution (Figure 2a) shows the usual characteristics: Asymmetric, broad and a central value that is much too small (133 GeV). After applying the correction method based on event-by-event measurements of $f_{\rm em}$, this distribution is transformed into the one shown in Figure 2b, which is almost perfectly symmetric, much more narrow, and centered around approximately the correct energy value (190 GeV). It should be emphasized that the value of $f_{\rm em}$ was uniquely determined on the basis of the *ratio* of the two measured signals (the so-called Q/S method[1]), no other information was used. Because of the relatively small detector size (1200 kg), this result is dominated by fluctuations in (lateral) leakage. We have demonstrated that, by using knowledge of the total shower energy, this effect could be eliminated and the signal distribution improved to the one shown in Figure 2c.

3 Current activities for further improvement

The beam tests of the DREAM detector have shown that, simply by using the ratio of the Čerenkov and scintillation signals, all detrimental effects of fluctuations in the em shower fraction could be eliminated: Hadronic signal linearity was restored, deviations from $E^{-1/2}$ scaling in the hadronic energy resolution were eliminated, a Gaussian response function was obtained and, most importantly, the hadronic energy scale was the same as the electromagnetic one, so that the entire instrument could be calibrated with electrons [3].

The elimination of (the effects of) this dominant source of fluctuations means that other types of fluctuations now dominate the detector performance. Further improvements may be obtained by concentrating on these. Three types of fluctuations currently dominate and limit the energy resolution of the DREAM calorimeter:

- Leakage fluctuations
- Fluctuations in Čerenkov light yield
- Sampling fluctuations

The first source can be eliminated by making the detector sufficiently large. The tested instrument had an effective radius of only 0.8 $\lambda_{\rm int}$. Side leakage amounted, on average, to about 10% of the shower energy, and fluctuations in this fraction played a dominant role (Figure 2). The small Čerenkov light yield (8 photoelectrons per GeV) contributed more than $35\%/\sqrt{E}$ to the measured hadronic energy resolution. Sampling fluctuations were measured to contribute $\sim 15\%/\sqrt{E}$ to the

[1]The symbol Q refers to the quartz fibers that measured the Čerenkov light.

electromagnetic resolution of the detector, and may thus be estimated to contribute about twice as much to the hadronic energy resolution.

There is absolutely no reason why the DREAM principles should be limited to fiber calorimeters. In particular, they could be applied to *homogeneous* detectors, provided that a way is found to distinguish the Čerenkov and scintillation light produced by such a detector. If successful, this approach could eliminate at once both the effects of sampling fluctuations and the effects of fluctuations in the Čerenkov light yield to the hadronic energy resolution.

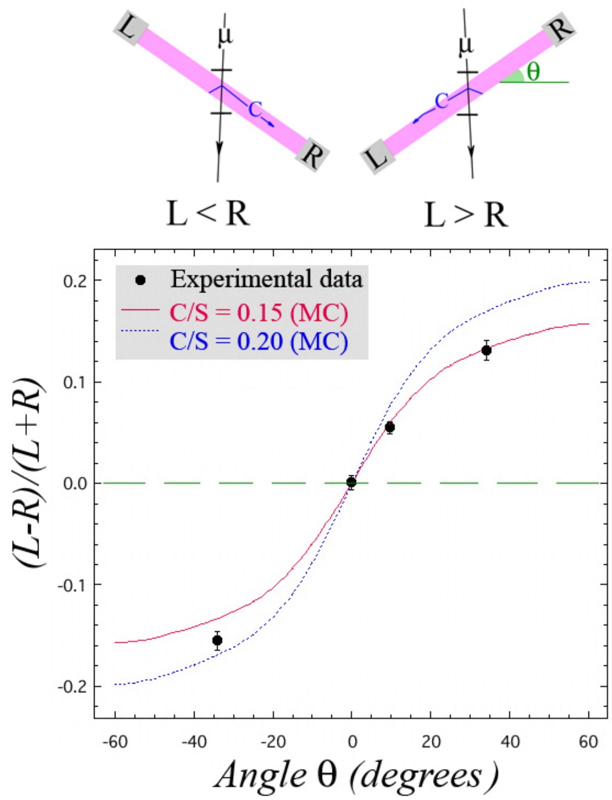

Figure 3: Left-right asymmetry measured for cosmic rays traversing a $PbWO_4$ crystal, as a function of the orientation of this crystal. The curves represent the results of calculations for a fixed ratio of the numbers of Čerenkov and scintillation photons produced in this process.

To that end, we have started a series of studies with crystals, and in particular $PbWO_4$. This material has the advantage of producing relatively little scintillation light, while the high effective Z value promises a substantial Čerenkov light yield. Moreover, it has the great advantage of being readily available. Both CMS and

ALICE are using large numbers of $PbWO_4$ crystals for their em calorimeters. The measurements described below were carried out with crystals generously made available to us by ALICE.

We have measured the ratios of the two types of signals for cosmic rays, which traversed a crystal that was read out from both ends. By changing the orientation of the crystal, the acceptance for (directional) Čerenkov light was varied, and by measuring the left/right asymmetry of the total signal as a function of the angle θ, we were able to establish that 15-20% of the photons were actually generated by the Čerenkov mechanism (Figure 3). This result was corroborated by measuring the time structure of the signals. The signals from the PMT that "saw" the

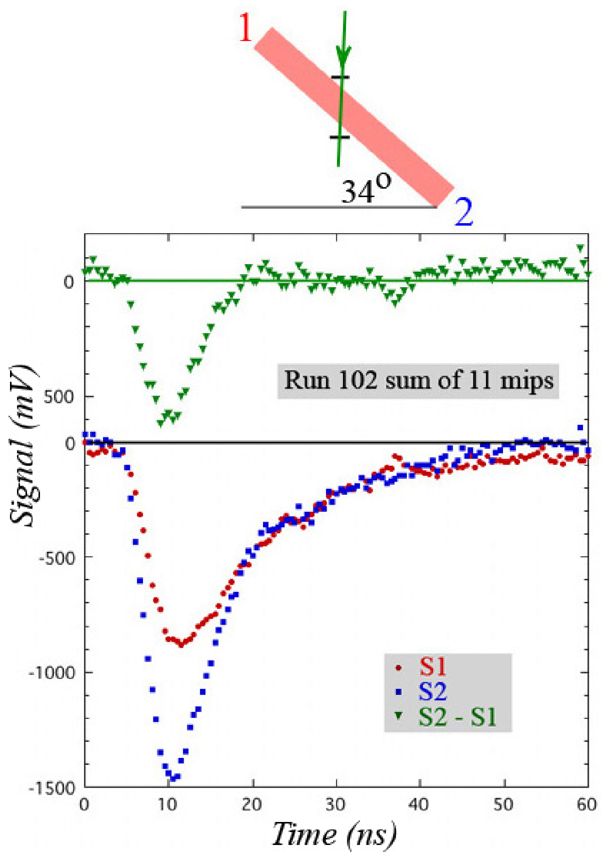

Figure 4: Time structure of cosmic ray events. Shown are the pulse shapes for the signals measured in the 2 PMTs reading out the $PbWO_4$ crystal, as well as the difference between these two pulse shapes. The pulses represent the sum of 11 randomly chosen events that generated signals in the most probable region of the Landau distribution. The crystal is oriented as shown.

Čerenkov component exhibited a clear fast component that was absent in the signals from the other PMT which, because of the crystal orientation, only detected scintillation light (Figure 4).

In a recent beam test[2], we have studied $PbWO_4$ crystals with high energy particle beams. Preliminary results confirm the cosmic ray results described above. We have also studied hadronic shower development in a calorimeter system consisting of an em section made of $PbWO_4$ crystals, backed up by the DREAM module. The purpose of this test was to see if and to what extent it is possible to measure the em shower fraction event by event on the basis of the crystal signals, and if this information can be used to improve the calorimeter performance for hadron detection, in the same way as with DREAM in stand-alone mode. Analysis of these data has just started, and no results are available at the present time.

It would be a major achievement if the $PbWO_4$ signals could indeed be used for the purpose described above. This is because this crystal is in many ways far from ideal. An ideal crystal would generate similar fractions of scintillation and Čerenkov light, would scintillate primarily in the $\lambda > 500$ nm region, and the decay time of the scintillation light would be sufficiently long to distinguish it easily from the prompt Čerenkov component. None of these conditions were met in the $PbWO_4$ crystals used for our studies. As mentioned above, the most attractive feature of these crystals was that they existed and were available for our tests. Any success obtained with these crystals could be strongly improved with dedicated crystals specifically developed for this type of application. Developing such dedicated new types of crystals is one of the projects we have undertaken in the context of DREAM.

4 Toward ultimate calorimetry

If we assume that the dual-readout principles can be as efficiently applied in homogeneous detectors as in the original DREAM calorimeter, then the contributions of signal quantum fluctuations and sampling fluctuations to the hadronic energy resolution can be made negligibly small. In that case, the resolution of a sufficiently large detector will become dominated by *nuclear breakup* effects. Fluctuations in the fraction of the total energy needed to release protons, neutrons and heavier nuclear fragments in the nuclear reactions initiated by the shower particles lead to fluctuations in *visible energy*, and thus to fluctuations in the calorimeter response.

[2]CERN SPS, October 29 - November 4, 2006

It has been demonstrated that measurement of the total kinetic energy carried by neutrons generated in the shower development is a powerful tool for reducing the effects of these fluctuations, especially in high-Z absorber materials where most of the nucleons released in the nuclear reactions are indeed neutrons [1].

Measuring the signal contributions from shower neutrons event by event is another important objective of the DREAM Collaboration. Two different approaches are considered to achieve this:

1. By equipping the DREAM detector with a *third* type of fibers, which is specifically intended for this purpose. One could either use a material that is specifically sensitive to neutrons, or a hydrogen-free scintillating fiber. In the latter case, the neutron contribution could be deduced from the difference between the signals from the plastic and the hydrogen-free scintillating fibers.

2. By measuring the time structure of the scintillator signals. The neutron contribution should manifest itself as a tail with a characteristic time constant. This tail is more dominant in the calorimeter towers that detect the shower halo than in the tower located on the shower axis.

In our recent beam tests, exploratory measurements of the time structure and possible differences between on-axis and off-axis towers have been performed. The results of these measurements will determine our strategy in this respect.

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

5 Test beam requests

As indicated above, the DREAM project is at present primarily a generic detector R&D project. The next steps to be taken will depend on the outcome of the tests that were recently performed. It is therefore too early to describe our plans for the 2007 test beam campaign in great detail. However, the road map is clear: We want to gain a detailed understanding of the various factors that limit the hadronic calorimeter performance, and of the possibilities for reducing/eliminating the effects of these factors. Once this understanding is complete, we will want to build a full-scale calorimeter to put it to the test. Such a full-scale model will no doubt be a prototype for a Linear Collider experiment.

We would like to request two weeks of SPS test beam in 2007. The program currently foreseen for these tests includes:

- Measurements of the scintillation/Čerenkov characteristics of new types of crystals that are currently being developed
- Measurements of hadronic shower development in a calorimeter system consisting of a crystal em section backed up by the DREAM hadronic calorimeter
- Detailed measurements of the time structure of hadronic signals in *all* 19 DREAM scintillator channels, in an effort to determine the contribution of neutrons to these signals event by event. As demonstrated in our recent tests, modern FADCs allow nanosecond sampling of this time structure.

In the past years, we have built the infrastructure needed for these tests in the H4A beam area (remotely controlled support table, cables/cable trays, tracking hodoscopes, *etc.*) Given the increased emphasis on measurement of the time structure of the signals, we may decide to digitize the signals at the front end, rather than transporting them through special air-core cables to the counting room, as was done up to now. This would require a few days of additional installation time.

The beams available in the H4 area, and the existing auxiliary equipment for measuring the beam characteristics, are adequate for our purpose. We are planning to use electrons in the momentum range 10 - 200 GeV/c, and hadrons in the momentum range 20 - 300 GeV/c. The purity of the beams will be determined with our own equipment.

We would also like to say that, once we move to the stage of full-scale prototyping, we will want to reconsider the experimental area. H4A is in several ways not very practical, for example in terms of accessibility. However, for our 2007 program it is adequate.

References

[1] R. Wigmans, *Calorimetry, Energy Measurement in Particle Physics*, International Series of Monographs on Physics, Vol. 107, Oxford University Press (2000).

[2] N. Akchurin *et al.* , Nucl. Instr. and Meth. **A399** (1997) 202.

[3] N.Akchurin *et al.* , Nucl. Instr. and Meth. **A533** (2004) 305; **A536** (2005) 29; **A537** (2005) 537; **A548** (2005) 336; **A550** (2005) 185.