New Results from the DREAM project

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Dual-Readout calorimetry is a promising new technique for high precision measurements of hadronic showers and jets. The DREAM Collaboration is exploiting the possibilities offered by this technique, a key aspect of which is the simultaneous measurement of the scintillation light and the Cerenkov light generated in the shower development process. By comparing these two signals, the electromagnetic shower fraction can be measured event by event, eliminating the effects of its fluctuations, that are the dominant contribution to the hadronic energy resolution. In the first detector of this type the two signals were provided by two independent active media: scintillating fibers and quartz fibers. In follow-up studies, we have explored the possibilities of heavy crystals such as BGO and $PbWO_4$. The use of homogeneous detectors has the advantage that it eliminates the effects of fluctuations that limit the resolution of the fiber calorimeter: sampling fluctuations and quantum fluctuations in the Cerenkov signals. A very important tool turnes out to be a detailed measurement of the time structure of the signals. In this paper, the latest results of this project will be presented.

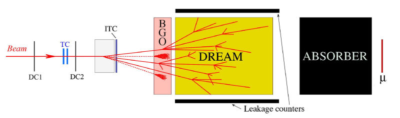

Figure 1. Setup showing the fiber (DREAM) and the electromagnetic (BGO) calorimeters.

1. Introduction

The measurements were performed in the H4 beam line of the SPS at CERN. We present the latest results on the fiber calorimeter tests in section 2, on single $PbWO_4$ crystals in section 3 and on a hybrid calorimeter in section 4.

2. The Fiber Calorimeter

The basic element of the hadronic DREAM calorimeter ([1–3]) was an extruded copper rod, 2 m long and 4×4 mm^2 in cross section. This rod was hollow, and the central cylinder had a diameter of 2.5 mm. Seven optical fibers were inserted in this hole. Three of these were plastic scintillating fibers, the other four fibers were undoped, intended for detecting Cerenkov light. The instrumented volume had a length of 2.0 m (10 λ_{int}) and an effective radius of 16.2 cm. The fibers were grouped to form 19 hexagonal towers. The fibers sticking out at the rear end of this structure were separated into 38 bunches: 19 bunches of scintillating fibers and 19 bunches of Cerenkov fibers. Each bunch was coupled through a 2 mm air gap to a PMT[1]. Despite its mass of more than one metric ton, hadronic showers developing in this structure were not fully contained. On average, $\sim$ 10% of the energy carried by a 100 GeV hadron leaks out, most of it sideways ([4]). We surrounded the calorimeter with large scintillator paddles to account for the energy leakage. We used eight scintillator paddles, with lengths up to 2 m, a thickness of 1 cm, and widths varying from 15 to 30 cm, which formed a cylinder surrounding the calorimeter. Fig. 2 shows that adding the leakage signals led to an improvement of the energy resolution typically $\sim$ 10%.

[1]The PMTs were Hamamatsu R580. The charge measurements of the signals from the towers were performed with two CAEN V792AC QADC.

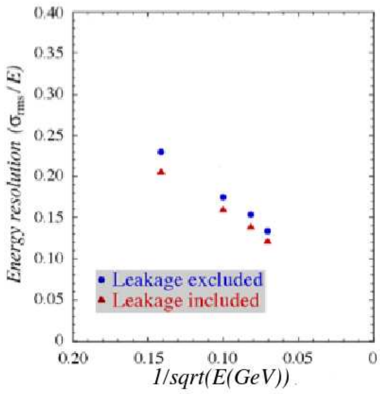

Figure 2. Energy resolution for single pions measured with the scintillation signals alone, with and without taking into account the signals from the leakage counters.

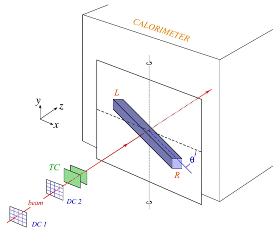

Figure 3. Experimental setup of the tests performed on single crystals. The angle θ is negative when the crystal is oriented as drawn here.

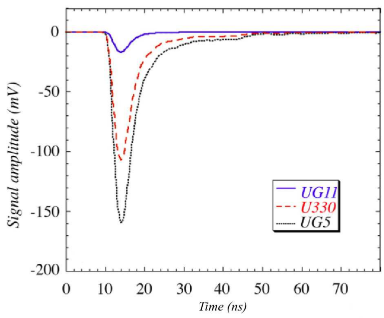

Figure 4. Average time structure from 50 GeV electrons traversing a $PbWO_4$: Mo(0.3%) crystal at an angle $\theta = 30°$, such as to maximize the detection efficiency of Cherenkov light.

3. Single crystals

In earlier papers ([5,6]), we have demonstrated that a significant fraction of the signal from $PbWO_4$ crystals is due to Cherenkov radiation. However the precision with which the contribution of this component could be determined event by event was found to be poor, since the scintillation process in $PbWO_4$ is very fast and has a blue dominated spectrum. Studies with a BGO crystal, a much brighter scintillator, showed that it was possible to separate the two types of light effectively by means of filters. On the basis of this experience, we performed a systematic study of $PbWO_4$ crystals doped with a small fraction of molybdenum (between 0.1% and 5%). Radioluminescence measurements indicated that the maximum of the emission shifted from 420 to 480nm as a result of this doping. All crystals had a length of 20 cm and a cross-section of 2×2 cm^2. The transverse dimension corresponded to 2.25 radiation lengths (X_0). The signal were read out by two PMTs located at opposite ends[2]. We used different types of optical transmission filters to study the crystal signals. Three different filters, known as UG11, U330 and UG5, were intended to increase the relative fraction of Cherenkov light, since they only transmitted short wavelengths. A yellow filter (GG495), which transmitted wavelengths longer than the 495 nm cutoff value, was used to generate essentially pure scintillation signals. The setup is illustrated in Fig. 3 . Fig.4 shows the average time structure of the signals [3] from 50GeV electrons traversing a $PbWO_4$ crystal doped with 0.3% Mo, for three different filters used to select Cherenkov light. The Cherenkov

[2]Hamamatsu R8900U tubes, with 10 multiplication stages and equipped with a borosilicate window and a Super Bi-Alkali photocathode.

[3]The time structures were recorded by means of a Tektronix TDS 7254B digital oscilloscope.

signals measured with the UG11 filter are on average smaller than those measured with the UG330 and UG5 filters. This is due to the fact that the transmission curve of the UG11 filter was located very close to the UV absorption edge of the crystal. We observed other two undesirable consequences of a small effective bandwidth for the Cherenkov signal: the strong attenuation of the detected light and the related reduction in Cherenkov light yield. Both could be significantly alleviated by using these less restrictive filters. Any $PbWO_4$ crystal with a molybdenum concentration from 0.1% to 1.0% seems adequate for dual-readout applications for what concerns signal purity, light yield and light attenuation of the Cherenkov component.

4. The hybrid calorimeter

After encouraging results on single BGO crystals, we tested an hybrid calorimeter consisting of two sections. The electromagnetic section(ECAL) consisted of 100 crystals of BGO and the hadronic section was the DREAM calorimeter. The crystals were 24 cm long and tapered. One end face had a cross-section of 2.4 $\times$2.4 cm^2, the other one measured 3.2$\times$ 3.2 cm^2. For particles entering the calorimeter in its geometrical center,the ECAL thus had an effective thickness of 25 X_0. Four PMTs were facing the small face of the crystals[4]. Our goal in this test was to demonstrate that the dual-readout principles also work in a hybrid calorimeter system when, on average, a large fraction of the energy is deposited in the homogeneous detector section. The crucial aspect of the DREAM method is measurement of the ratio between these the scintillation and Cherenkov signals (C/S), that is a measure for the electromagnetic shower fraction of the hadronic shower ([3]). Fig. 5a shows the distribution of the total Cherenkov signal for jets of 200 GeV in the hybrid calorimeter. This signal is broad, asymmetric and centered around a value of only 110GeV. Fig. 5b shows three different subsets of events, selected on the basis of the measured C/S signal ratio. These three distributions are narrower,well described by Gaussian fits and centered at a value that increases roughly proportionally with the C/S value of the selected event sample. This is precisely what was observed for the fiber calorimeter in stand-alone mode, and what allowed us to eliminate the effects of fluctuations of the electromagnetic fraction in that calorimeter. Further tests with an improved readout system have been developed, the analysis of the data is still on going, but the preliminary results confirm the conclusion of this first test.

[4]XP4362B PMTS manifactured by Photonis, France.

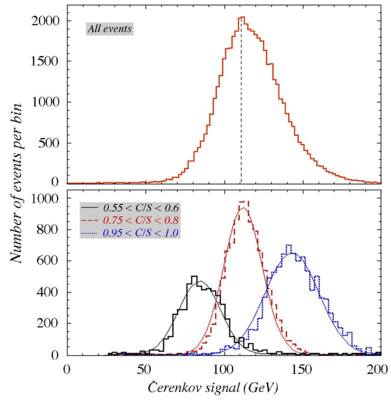

Figure 5. The Cherenkov signal distribution for 200GeV jet in the hybrid calorimeter (a), the distributions for subsets of events selected on the basis of the ratio of the total Cherenkov and scintillation signals(b).

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