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HADRON CALORIMETER TOWERS WITH A HIGH SPACE RESOLUTION

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ABSTRACT

The performances of a set of hadron calorimeter towers for measuring the hadron impact point are described. It is shown that an accuracy of 1-2 cm can be achieved with a proper treatment of the data.

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INTRODUCTION

In the design of a solenoid detector for a large particle collider one inevitably finds that the problem of an accurate measurement of direction and energy of forward-produced hadrons becomes increasingly difficult with decreasing production angle. The bending power of the magnetic field decreases in the forward direction, and at the same time the tracking capability of most central detectors is reduced because of the reduced number of available information bits and because of the increasing flux of particles and background. This is even more true if particles are produced in jets, which are harder to disentangle with tracking detectors. An increasing demand of space -- as well as of energy -- resolution is correspondingly transferred to the forward hadron calorimeters that are generally enclosing the detector. During the design of such forward calorimeters for the Fermilab antiproton-proton collider, we have studied whether small-size towers of scintillator/iron sandwiches, where the light is read out with BBQ sheets on the tower sides [1], and whose geometry is well suited for optimum energy resolution at high energy and small angles, could also measure the hadron direction. The idea was to see whether the method used successfully by Davidson et al. [2], who reconstructed the shower centroid by studying the pulse-height transverse distribution in sandwiches of x-y scintillation hodoscopes, could be extended to a matrix of towers pointing at a source and from which the light was collected from the sides via thin wavelength shifters [3]. We have found that a resolution of the order of a few centimetres on the impact point of single hadrons in the direction normal to the BBQ sheets can readily be obtained for high-energy hadrons. The method can provide both projections of the impact point without the need of accommodating BBQ readouts on all sides of the towers. Finally, the method would still be applicable if particles are produced in jets and one wants to determine the overall vector momentum of the jet.

1. PROTOTYPE DETECTOR

The geometry of our prototype three towers (called HCAL in the following) is illustrated in fig. 1. In each tower, 16 iron plates, 5 cm thick, are interleaved

with 15 plates of 8 mm thick acrylic scintillator. The four sides of the towers are tapered to an angle of 5 degrees and point at a source which is about 3 m away. The front tower plate is $18 \times 18 \text{ cm}^2$ and the rear plate $26 \times 26 \text{ cm}^2$. The length of the towers is about 100 cm (with 80 cm of iron), corresponding to an overall thickness of about $4.8\lambda_\pi$. Each tower is viewed from the left and the right by 3 mm thick BBQ sheets (90 mg/l BBQ) that are carefully shaped to match the calorimeter side. Each sheet terminates in a light-pipe and is glued to an XP2008 photomultiplier. The acrylic scintillator (Polypop, produced by Polivar, Italy) was doped with 1% BUTIL-PBD, 0.01% POPOP, and with a variable percentage of naphthalene. By varying this percentage, different light outputs are obtained. This property allows us to compensate for differences in the average response of plates at different depths in the tapered towers. This difference is caused by the different path lengths of light, both in the scintillators and in the BBQ sheets. To compensate qualitatively for these effects, the naphthalene concentrations were chosen to be 8%, 7%, and 6% for plates 1 to 5, 6 to 10, and 11 to 15 (from front to back), respectively. A uniform energy response to within 5% throughout the tower volume was expected. The energy resolution of the towers, the discussion of which is outside the scope of this work, was indeed found to be quite good $[\Delta E/E \approx 65\%/\sqrt{E(\text{GeV})}]$.

2. DATA COLLECTION

The towers were calibrated at CERN on the H4/E4 beam of the SPS, which was tuned to provide negative pions of 300 GeV/c. The attainable space resolution is expected to deteriorate slowly with decreasing beam energy. The momentum spread was less than 0.5%. The towers were placed at the beam focus, where the beam section was $\lesssim 1 \text{ cm}^2$. Typical beam intensity was 10^4 ppp, with a 1.2 s burst length. In such clean conditions a good trigger was provided simply by signalling an incident beam particle with three counters in coincidence along the beam. Each photomultiplier was fed to a linear ADC whose 80 ns gate was opened by the trigger. The relative gains of the six readout channels were equalized with a relative precision better than 5%, with the beam at the centre of each tower. The data were

collected at a distance of 10 cm behind an electromagnetic calorimeter (Pb/scintillator sandwich, called EMCAL in the following), whose thickness was ~ 35 cm and $\sim 1\lambda_\pi$ ($20 X_0$).

3. DATA ANALYSIS AND RESULTS

To determine the position resolution of the tower assembly, data were collected moving HCAL in 6 mm steps in front of the beam. The systematic error of the position measurement was negligible (of the order of 1 mm). The first and the last measurement corresponded to the beam hitting the centre and the edge of the central tower, respectively. EMCAL was used as an active absorber. The response of HCAL was studied separately for interacting and non-interacting pions in EMCAL.

The hadron impact point can be derived from the relative pulse heights of the various counters in a number of ways. First of all, we exploited the pulse-height ratio between the left (PH3) and the right (PH4) counters viewing the central tower. Preliminarily, the PH3/PH4 pulse-height ratio was fitted for the effective attenuation length in the scintillator, obtaining $\lambda = 30$ cm. For this calibration, only impact points not more than 6 cm distant from the tower centre were used. The impact point was then reconstructed as:

$$x = (\lambda/2) \ln (PH3/PH4) . \quad (1)$$

The results are shown in fig. 2 for events interacting in EMCAL. For $x \leq 6$ cm, the x -distribution is found to be nicely Gaussian, with resolution of about ± 1 cm. The resolution rapidly deteriorates at larger x . In addition, one observes that the method has a large systematic error when one approaches the tower edge. This should be attributed to Čerenkov light produced in the BBQ sheet of counter 4 ("hot spot"). This problem can be cured by exploiting the information provided by counters which are distant from the beam. We show, in the following, how this can be done using the pulse-heights of counters 3 and 6.

In a hadronic cascade, the average longitudinally integrated energy release $E(x)$ as a function of the transverse distance x from the cascade axis can be described by a double exponential

$$E(x) = A \exp (-x/b_1) + B \exp (-x/b_2) . \quad (2)$$

One finds $b_1 = 2.2$ cm, and $b_2 = 7.0$ cm, for a 1 cm iron sampling [2].

The first term in eq. (2) represents the "hard core" and the second the "soft core" of the hadronic cascade. This characteristic shape can be used to measure the impact point of the hadron in the cell, provided the cell size is comparable to the cascade size. Given the size of our towers, we expect them to be sensitive only to the soft core. This is even more true since our sampling thickness is 5 cm of iron, and therefore the cascades are more compact than in the case of ref. [2].

Preliminarily, we have determined an effective lateral profile of the hadronic cascade using the ratio of pulse heights in photomultipliers 3 and 6. This measurement is reported in figs. 3a and 3b, where the events are divided into two groups: those which did and those which did not interact in EMCAL. The data can be fitted by a single exponential. As expected, the size of the cascade is found to be slightly larger for events interacting in EMCAL ($b = 4.2$ cm rather than 3.9 cm).

For an exponential profile of the cascade, one can easily derive the distance of the cascade axis from the tower centre in terms of the ratio between the energy released in the tower (monitored by PH3) and the energy released in an adjacent one (monitored by PH6). One finds:

$$x = \Delta - b \ln \frac{1}{2} (1 + \text{PH3/PH6}), \quad (3)$$

where 2Δ is the effective cell size. Figures 4a and 4b show the calculated positions as a function of the incident beam positions, for the two categories of events. One sees that the method is subject to a larger systematic error for interacting pions in EMCAL and at $x \approx 5$ cm, but that in all cases this error is $\lesssim 0.5$ cm. Therefore for large x ($x \gtrsim 7$ cm) this method is superior to that based on algorithm (1).

The slope b and the effective tower half-width Δ entering in eq. (3) (see fig. 4) were obtained in a best-fit procedure, by minimizing the over-all χ^2 . As expected, the b -values practically coincide with those fitting the lateral profiles of figs. 3a and 3b. One should observe that in an experiment these parameters may depend slowly on energy. This is true in particular for Δ , because of the pyramidal tower shape and because the maximum of the cascade moves deeper into the tower with increasing energy. Using algorithm (3), the resolution in the sample of pions interacting in EMCAL was found to vary between ± 2 cm at the tower edge and ± 3.5 cm at

the centre. We note that using the results of ref. [2], a more modest resolution of about ± 4 cm would be expected for a rectangular tower of 20 cm full width, which is similar to our towers. Indeed, this is the resolution that we find for pions not interacting in EMCAL. The method therefore gives better results for wider jets, as is naturally expected. This also shows that the method would still be applicable to the determination of the centroid of a narrow incoming jet.

We conclude that in a region about two centimetres wide around the tower edge ($x \geq 7$ cm) the method based on eq. (3) can be used rather than the one based on eq. (1), thus limiting the systematic error to $\lesssim 0.5$ cm at any x . Correspondingly, a resolution of about ± 1 cm at the tower centre and of ± 2 cm at the edge can be obtained. We show in fig. 5 the dependence of the r.m.s. resolution of the position measurement on x , both for method (1) and for method (3). We observe that in an actual experiment, even assuming that the direction of the incoming hadron is totally unknown (e.g. for neutral hadrons), one could use both methods and determine both $x_{(1)}$ and $x_{(3)}$. One would then adopt $x_{(1)}$ as the best measurement if $x_{(1)} \lesssim 7$ cm, and $x_{(3)}$ otherwise.

The energy resolution of a tower assembly such as ours is excellent provided the counters showing hot-spots are not used in the energy determination. For single incoming hadrons, or for narrow jets, this can be done once the impact position has been determined and on the basis of suitable calibrations of the response of the photomultipliers as a function of the position of the incoming hadron.

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Figure captions

- Fig. 1 : Sketch of the three towers arrangement. The towers are tapered to a 5° angle on the four sides and point at a 3 m distant source. Left and right of each tower, two 4 mm thick BBQ sheets collect the light and bring it to the back of the towers. Each tower is viewed by two photomultipliers.
- Fig. 2 : Reconstructed average hadron position (x) versus beam position (x_{beam}), using the left/right pulse-height ratio of the two counters viewing the tower hit by the beam. The data are for 300 GeV/c pions interacting in EMCAL.
- Fig. 3 : Dependence of the ratio of the average pulse heights in counters 3 and 6 on the transverse beam position for interacting (3a) and non-interacting (3b) pions in EMCAL. The beam is moved from the centre of the middle tower towards counters 4 and 5 (see fig. 1). The data can be well fitted by single exponentials with slopes $b = 4.2$ and 3.9 cm, respectively.
- Fig. 4 : Reconstructed average hadron position (x) versus beam position (x_{beam}) using the pulse heights of counters 3 and 6, for interacting (a) and non-interacting (b) pions in EMCAL.
- Fig. 5 : Dependence of r.m.s. resolution on the distance of the hadron impact point from the tower centre for methods based on formulas (1) and (3). The bands are twice as large as the systematic error.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5