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COORDINATE MEASUREMENTS WITH A HODOSCOPE HADRON CALORIMETER
AT ENERGIES UP TO 300 GeV

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ABSTRACT

The possibilities offered by a novel experimental technique - the hodoscope hadron calorimeter - to determine coordinates of high energy hadrons accurately by measuring the transverse spread of their associated showers have been studied. This accuracy is shown to improve with energy as $(\ln^4 E + q_1 E)^{1/2}/E$ and at $E = 300$ GeV it reaches $\sigma_y = 3$ mm. The shrinkage of the hadron shower and the growth of its central component with increasing energy have been measured. As for energy resolution, the hodoscope calorimeter does not yield to conventional calorimeters.

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1. INTRODUCTION

It has been shown in a previous work [1] that hadron calorimeters with a hodoscope structure allow to measure not only the energy of hadrons but also their impact coordinates by measuring the transverse spread of the showers [2]. With the first detector of this type a coordinate accuracy of ~ 1 cm has been obtained for π^- , K^- and $\bar{p}$ between 25 and 40 GeV [1,3].

The present work is devoted to the study of the resolution of the hodoscope hadrons calorimeter at higher energies, $E = 100 - 300$ GeV. The energy resolution of a calorimeter improves like $1/\sqrt{E}$ with increasing energy (see review [4] for experimental data). According to [5], approximately the same energy dependence is expected for the accuracy of hadron coordinates measurements with a hodoscope calorimeter. One of the aims of the experiments described below was to verify this statement.

2. CHARACTERISTICS AND CALIBRATION OF THE CALORIMETER

The calorimeter, installed on the H8 beam line of the CERN SPS, has been irradiated with π^- of 100 GeV, 200 GeV and 300 GeV. The K^- and $\bar{p}$ contamination of the beam is low: 6%, 4% and 1%, respectively [6]. The impact point of the particles on the calorimeter has been determined with a precision of ± 0.5 mm with auxiliary x-y scintillation hodoscopes.

A detailed description of the hodoscope hadron calorimeter has been given in the preceeding paper [1]. In short, it is a total absorption detector of sandwich type in which hodoscope planes made of scintillator strips of width $d = 5$ cm (perpendicularly to the beam direction) alternate with 2.5 cm thick iron converter planes. The detector has an aperture 70×70 cm². It is divided in three identical blocks (25 cm of iron in each block) which allow to follow the longitudinal development of the hadron shower. Combinations of signals from the last dynode of the PM's are used for triggering purposes, namely the sum of corresponding channels in the three blocks and the sum of all 84 counters in the calorimeter. This makes it possible to tune the detector with a parasitic beam, using this last summation as a trigger for muons.

The adjustment and the calibration of the 84 calorimeter counters have been made, as before [1], by irradiating the detector with muons. Nevertheless, the procedure becomes much more involved at higher energies. At 300 GeV, the amplitude of the global signal due to a hadron is 200 times larger than that due to a muon. This difference is even 2 or 3 times bigger for a single counter of the calorimeter at the maximum of the shower.

The photomultipliers FEU-84-3 used in the detector are linear over such a dynamical range. Nevertheless, in order to cover such a wide range, it is necessary to carry out the calibration in a few steps, comparing each time the signals from muons with those from reference light pulses delivered by the light emitting diodes (LED) of the calorimeter light calibration system [1,7].

At first, the gain of each counter is tuned so that the average converted amplitude for muons $\langle A_{\mu}(k) \rangle$ is about 50 units of 12-bit ADC system and the LED signal $\langle A_{LED}^{(1)}(k) \rangle$ is about 1000 units on the same scale^(*). This measurement fixes the scale between muon signals and the signals of the LED system. After, the gain of the PMs is reduced several times changing the high voltage and the new value $\langle A_{LED}^{(2)}(k) \rangle$ is measured. Then, the amplitude of LED signals is increased and a new value $\langle A_{LED}^{(3)}(k) \rangle$ is obtained. This procedure is repeated n (3 to 4) times until the amplitude of the signal due to pions in each counter $A_{\pi}(k)$ stays within the range of conversion of the ADC's.

The calibration coefficient β_k for each calorimeter counter is then simply the product of measured ratios:

$$\beta_k = \frac{\text{const}}{\langle A_{\mu}(k) \rangle} \cdot \frac{\langle A_{LED}^{(1)}(k) \rangle}{\langle A_{LED}^{(2)}(k) \rangle} \cdots \frac{\langle A_{LED}^{(n-1)}(k) \rangle}{\langle A_{LED}^{(n)}(k) \rangle} \quad (1)$$

All the quantities entering (1) have been measured with a statistical accuracy better than 1%. The error on the value of the calibration coefficients has been estimated to be less than 4% from the symmetry deviation and from the smoothness of the $\beta_k \langle A_{\pi}(k) \rangle$ distribution.

(*) Here and below brackets $\langle \rangle$ around a value, or a bar above it, stand for its average value taken over a set of events.

3. RESULTS OF THE MEASUREMENTS

3.1 Hadron shower profile

The possibility to measure hadron coordinates with the hodoscope calorimeter depends on a basic characteristic of the showers namely their profile, i.e. the energy distribution of the showers in the transverse direction. The shower profiles measured in the present work (fig. 1) as well as those measured at lower energies [1], are described by two exponential functions:

$$d\langle A_{\pi}(y) \rangle / dy = a_1 \exp(-|y|/b_1) + a_2 \exp(-|y|/b_2). \quad (2)$$

The values of the parameters appearing in expression (2) are shown on fig. 2. b_1 and b_2 decrease slowly with increasing energy, according to the following power laws^(*):

$$b_1 = (3.9 \pm 0.2) E^{-0.17 \pm 0.02} \text{ cm}, \quad (3)$$

$$b_2 = (7.5 \pm 0.3) E^{-0.06 \pm 0.01} \text{ cm} \quad (4)$$

(here and below E is expressed in GeV). The decrease of the peripheral part of the shower (a_2) seems to slow down above 100 GeV.

Contrary to electromagnetic showers [5], hadron showers shrink with rising energy. This is explained by the growth of π^0 contribution and the corresponding increase of the electromagnetic component in the hadron shower (see e.g. [8]).

It can be seen on fig. 2 that the hadron shower must keep shrinking in the TeV energy region (fig. 1). The shrinkage of the shower with increasing energy, and also the diminution of the relative fluctuations of the energy release, lead to a better localisation of showers in the hodoscope calorimeter and to a more effective spatial separation of showers from adjacent hadrons.

(*) In the 10 GeV to 1 TeV region, the energy dependence of b_1 and b_2 may also be described with logarithmic functions:
 $b_1 = (3.0 \pm 0.2) - (0.27 \pm 0.04) \ln E \text{ cm},$
 $b_2 = (7.3 \pm 0.4) - (0.35 \pm 0.03) \ln E \text{ cm},$ which practically coincide with (3), (4).

3.2 Measurement of hadron coordinates

The coordinate of a hadron is obtained from the center of gravity of its associated shower $y_0 = d \sum_k k B_k A_\pi(k) / \sum_k B_k A_\pi(k)$ after a small bias correction [1] due to the exponential form of the shower (2). The measured coordinate $\bar{y}_f$ corresponds to the true coordinate y_c with a high accuracy (fig. 3). This procedure eliminates systematic errors for wider cells also^(*), where the non-linearity of $\bar{y}_0$ towards y_c increases.

The accuracy σ_y of the reconstructed hadron coordinates, which as shown in ref. [1] is independent of the nature of the particle, varies with the location of the impact point on the calorimeter cell. The closer to the cell boundary the impact is, the better the accuracy is (fig. 4). The amplitude of this variation is larger in wider cells [9,10] as a consequence of the exponential profile of the shower. It depends also on the algorithm chosen to determine the coordinates (for more details, see [3,9]).

The spatial resolution of the hodoscope calorimeter is well described by a Gaussian distribution (fig. 5). At 300 GeV the accuracy of the coordinate determination for hadrons, averaged over the calorimeter cell, reaches

$$\bar{\sigma}_y = 2.9 \text{ mm},$$

i.e. it is improved by a factor 3 for the energy increase by an order of magnitude.

The dependence of the coordinate accuracy on energy is shown on fig. 6. As expected [5], it follows the relationship

$$\bar{\sigma}_y = q_0 (\ln^4 E + q_1 E)^{1/2} / E. \quad (5)$$

Extrapolation of these data into the TeV energy region shows that a hodoscope hadron calorimeter should provide a one millimeter coordinate accuracy at UNK energies (3 TeV).

(*) The summation of signals from adjacent cells allows to get also results for calorimeters with wider cells: $d = 10, 15$ and 20 cm.

3.3 Dependence of the coordinate accuracy on the cell width

The error on reconstructed hadron coordinates grows rapidly with the calorimeter cell dimension. For the central part of the cell ($y_c \approx d/2$) the growth is exponential [5]:

$$\sigma_y(y_c = d/2) = \sigma_0 \exp(d/d_0) \quad (6)$$

as follows from the shower profile (2). In this case $d_0 \sim 2b_2$, if $d > 2b_1$. Expression (6) describes well the experimental numbers (fig. 7). The quantity d_0 is constant within the limits of errors of measurement in the energy interval 25 - 300 GeV and is equal to (11.8 ± 1.5) cm, which is close to the value of $2b_2$ (see fig. 2). It follows that (fig. 8):

$$\sigma_0 = (3.6 \pm 0.2)/\sqrt{E} \text{ cm.} \quad (7)$$

The coordinate accuracy averaged over the cell, $\bar{\sigma}_y$, is given in the table. Its dependence on the cell width is more complex than (6), specially for small d and large E values. This results from the dependence of the coordinate resolution on the impact point on the cell (fig. 4). The variation of $\bar{\sigma}_y$ with hadron energy for various cell widths is analogous to (5).

3.4 Energy resolution of the calorimeter

The main goal of the present work was to study the possibility to measure precisely the coordinates of high energy hadrons with a hodoscope calorimeter. As an energy measuring instrument, the hodoscope calorimeter is nevertheless similar to conventional calorimeters whose energy resolution has been studied in detail [4,11]. It has not been attempted in this work to reach the best attainable energy resolution.

The spectrum of the sum of the signals from all cells of the calorimeter, A_{tot} , irradiated with 100 GeV π^- is shown on fig. 9. As in the previous work [1], events in which the shower is starting to develop in the first calorimeter block have been selected. The spectra look the same for $E = 200$ and 300 GeV.

The total thickness of iron in the calorimeter cells is $\ell = 80$ cm. This ensures practically full absorption ($>95\%$) of $E \sim 30$ GeV hadron showers, the thickness needed for 95% absorption being equal to [5]:

$$\ell_{0.95}(\text{cm of iron}) = 4 + 9 \ln E. \quad (8)$$

At 300 GeV, the thickness of the present calorimeter is already insufficient to ensure a large enough absorption (according to (8), it should have $\ell > 90$ cm of iron). This entails a broadening of the resolution curve by $\sim 30\%$ [4,11]. Also, the shower leakage (7% at 100 GeV, 10% at 300 GeV) gives rise to a tail on the left side of the spectrum (fig. 9) (it is absent when the shower is fully absorbed [8]).

The relative energy resolution σ_E/E of the hodoscope calorimeter at various π^- energies appears on fig. 10 together with results from other works. In comparing various calorimeters one must not forget that the energy resolution changes with the thickness t of the converter: $\sigma_E \sim t^{1/3}$ corresponding to calculations [4] and measurements [1,8]. Taking this factor into account, the data on fig. 10 show a behaviour close to:

$$\sigma_E/E = 0.65/\sqrt{E} \quad (9)$$

as expected for iron-scintillator sandwich counters.

The resolution of the hodoscope calorimeter depends also on the calibration inaccuracies (to measure A_{tot} , signals from a few tens of counters are summed), whose contribution increases with the growth of the energy. The comparison of measured σ_E/E values with formula (9) shows that the broadening of the resolution curve on account of the calibration errors is less than 3%.

It is to be noticed that the hodoscope calorimeter used in the present work at energies up to 300 GeV does not yield to usual hadron calorimeters in so far as the accuracy of energy measurement is concerned. Adding one more block should allow, according to (8), to cover the energy region up to 1 TeV without a loss of energy resolution.

4. CONCLUSION

It has been shown that for energies of hundreds of GeV a hodoscope calorimeter allows to localise hadron showers with a high spatial accuracy. This accuracy improves with energy like $(\ln^*E + q_1E)^{1/2}/E$ and is equal to 3 mm at 300 GeV for 5 cm wide detector elements. This dependence has been checked in a broad energy interval, 25 to 300 GeV, which allows to extrapolate safely into the TeV energy region where an accuracy of one millimeter should be reached.

The prospects of the hodoscope hadron calorimeter method are particularly promising in the case of detectors with a cellular structure allowing to measure at high energy a large number of hadrons, neutral as well as charged, at the same time [5]. Large detectors may be built on this principle (e.g. the 50 ton cellular hadron calorimeter of experiment NA12 now in the course of installation in the H8 beam-line of the CERN SPS).

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TABLE

Coordinate accuracy $\bar{\sigma}_y$, averaged over the cell,
versus the cell width d for various π^- energies E.

E[GeV]	$\bar{\sigma}_y$ [mm]			
	d = 5 cm	10 cm	15 cm	20 cm
25	10.4 $\pm$ 0.4	17.0 $\pm$ 0.9	22.7 $\pm$ 1.1	35.9 $\pm$ 1.3
40	8.6 $\pm$ 0.3	14.5 $\pm$ 0.7	20.0 $\pm$ 1.0	32.0 $\pm$ 1.2
100	5.1 $\pm$ 0.2	9.0 $\pm$ 0.5	14.4 $\pm$ 0.7	19.0 $\pm$ 0.8
200	3.6 $\pm$ 0.2	7.3 $\pm$ 0.2	11.0 $\pm$ 0.6	15.0 $\pm$ 0.7
300	2.9 $\pm$ 0.2	6.2 $\pm$ 0.4	9.4 $\pm$ 0.5	12.5 $\pm$ 0.6

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FIGURE CAPTIONS

- Fig. 1 Differential distribution of average amplitude (shower profile) versus the distance to the impact point on the cell, measured with the hodoscope calorimeter and π^- of 25 [1] and 300 GeV. The full curve is the weighted sum of two exponentials (2). The profile of 3 TeV showers (dashed curve) deduced from the extrapolated parameters on fig. 2 is used to illustrate the prospects of the method. Normalization is $d \langle A_\pi(0) \rangle / dy = 1$.
- Fig. 2 Variation of the shower profile with increasing π^- energy. The points on the figure are measured values of the parameters appearing in expression (2) in the energy region $25 \div 300$ GeV. The straight lines correspond to the power functions (3) and (4). The lower curve is a guide for the eye only. $a_1 = 1 - a_2$.
- Fig. 3 Dependence of the measured coordinates of a shower $\bar{y}_f$ on the π^- impact point in the cell y_c at $E = 200$ GeV. The error bars shown are σ_y . $y = 0$ corresponds to the border of the cell and $y = d/2$ to its center. Results shown on the left correspond to a cell width $d = 5$ cm, while those on the right correspond to $d = 10$ cm.
- Fig. 4 Dependence of the coordinate accuracy σ_y on the impact point in the calorimeter of $E = 100, 200$ and 300 GeV π^- .
- Fig. 5 Distribution of the difference between measured (y_f) and real (y_c) π^- coordinates obtained with a $d = 5$ cm wide cell uniformly irradiated with 300 GeV π^- . The dashed curve is a Gaussian distribution with $\bar{\sigma}_y = 3$ mm.
- Fig. 6 Dependence of the coordinate accuracy $\bar{\sigma}_y$ on π^- energy. The cell of the calorimeter is uniformly irradiated. Data in the range 25 to 40 GeV are taken from [1], data between 100 and 300 GeV are results obtained in the present work. The curve shows the dependence (5), normalized at $E = 25$ GeV with $q_0 = 1.8$ cm and $q_1 = 4$ GeV $^{-1}$ [5].

Fig. 7 Coordinate accuracy at the center of the cells $\sigma_y (y_c = d/2)$ versus cell width d for several π^- energies. The curves represent relation (6).

Fig. 8 Variation of the parameter σ_0 in formula (6) with π^- energy. The straight line is relation (7).

Fig. 9 Spectrum of the sum of the signals from all cells in the calorimeter irradiated with 100 GeV π^- . $A_{tot} = \sum_k \beta_k A_{\pi}(k)$. Dashed curve is a Gaussian distribution with $\sigma_E/E = 6.7\%$.

Fig.10 Accuracy of π^- energy measurements with various calorimeters. ● are data obtained in the present work and in previous measurements [1] with the hodoscope hadron calorimeter, o are data taken from ref.[8] ($t = 2.5$ cm of iron), Δ are data from ref.[12] ($t = 1.25$ cm of iron). Other points : see ref.[5] (∇ , $\square$ and $+$ correspond to $t = 4, 5$ and 10 cm of iron, respectively). The straight line is function (9), the dashed curve is the resolution expected for the described calorimeter taking into account the shower leakage.

Fig. 1

Fig. 2

Fig. 3

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Fig. 9

Fig. 10