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HADRON ENERGY RECONSTRUCTION FOR **ATLAS** BARREL COMBINED CALORIMETER USING NON-PARAMETRICAL METHOD

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1 Introduction

The key question for calorimetry in general, and hadronic calorimetry in particular, is that of energy reconstruction. This question becomes especially important when a hadronic calorimeter has a complex structure incorporating electromagnetic and hadronic compartments includes different technologies. Here we describe a non-parametrical method of energy reconstruction for a combined calorimeter, known as the e/h method, and demonstrate its performance utilizing the test beam data from the ATLAS [1] combined calorimeter.

This work has been performed using the 1996 combined test beam data taken in the H8 beam line of the CERN SPS with pions of energies from 10 to 300 GeV. Detailed information about the test beam setup one can find in [2]. Information about ATLAS LAr and Tile calorimeters are presented in [3, 4].

2 Method of Energy Reconstruction

An hadronic shower in a calorimeter can be seen as an overlap of a pure electromagnetic and a pure hadronic component. The calorimeter response to these two components is usually different [5] and can be written as: $R = e\cdot E_e + h\cdot E_h$, where e (h) is a coefficient to rescale the electromagnetic (hadronic) energy content to the calorimeter response. From this

$$E = (1/e)\cdot(e/\pi)\cdot R\,, \tag{1}$$

$$\frac{e}{\pi} = \frac{e/h}{1+(e/h-1)\cdot f_{\pi^0}}\,, \tag{2}$$

where f_{π^0} is the fraction of electromagnetic energy of the shower whose dependence on the incident hadron energy can be parameterized as $f_{\pi^0} = E_e/E = k\cdot\ln E$ [6]. In the case of the combined setup the total energy is reconstructed as the sum of the energy deposit in the electromagnetic compartment (E_{LAr}), the deposit in the hadronic calorimeter (E_{Tile}), and that in the passive material between the calorimeters (E_{dm}). Expression (1) can then be rewritten as:

$$E = E_{LAr} + E_{dm} + E_{Tile} = \left[\frac{1}{e}\left(\frac{e}{\pi}\right)R\right]_{LAr} + E_{dm} + \left[\frac{1}{e}\left(\frac{e}{\pi}\right)R\right]_{Tile}\,, \tag{3}$$

where R_{LAr} (R_{Tile}) is the measured response of the LAr (Tile) calorimeter compartment and $1/e_{LAr}$ ($1/e_{Tile}$) is energy calibration constant for the LAr (Tile) calorimeter.

Similarly to the procedure in [2], the E_{dm} term is taken to be proportional to the geometrical mean of the energy released in the third depth of the electromagnetic compartment and the first depth of the hadronic compartment: $E_{dm} = \alpha \sqrt{E_{LAr,3}\ E_{Tile,1}})$. The validity of this approximation has been tested using a Monte Carlo simulation along with a study of the correlation between the energy released in the midsampler and the E_{dm}.

The ratio $(e/h)_{Tile} = 1.3$ has been measured in a stand-alone test beam run [4] and is used to determine the $(e/\pi)_{Tile}$ term in equation 3. To determine the value of the $1/e_{Tile}$ constant we selected events which started showering only in the hadronic compartment, requiring that the energy deposited in each sampling of the LAr calorimeter and in the midsampler is compatible with that of a single minimum ionization particle: $1/e_{Tile} = 0.145$. The response of the LAr calorimeter has already been calibrated to the electromagnetic scale [2].

The value of $(e/h)_{LAr}$ has been evaluated using the data from this beam test, selecting events with well developed hadronic showers in the electromagnetic calorimeter. The $(e/\pi)_{LAr}$ ratio can be written as:

$$\left(\frac{e}{\pi}\right)_{LAr} = \frac{E_{beam} - E_{dm} - E_{Tile}}{R_{LAr}/e_{LAr}} \ . \qquad (4)$$

The mean values of these $(e/\pi)_{LAr}$ distributions are plotted in Fig. 1 as a function of the beam energy. From a fit using expression (2) to this values we obtain $(e/h)_{LAr} = 1.74 \pm 0.04$ and $k = 0.108 \pm 0.004$. For a fixed parameter $k = 0.11$ [6], the result is $(e/h)_{LAr} = 1.77 \pm 0.02$. The systematic error on the $(e/h)_{LAr}$ ratio, which is a consequence of the uncertainties in the input constants used in the equation (4) as well as of the shower development selection criteria, is estimated to be ± 0.04.

In Ref. [6], it was demonstrated that the e/h ratio for non-uranium calorimeters with high-Z absorber material is satisfactorily described by the formula: $e/h = (e/mip)/(0.41 + f_n\ n/mip)$, where f_n is a constant determined by the Z of the absorber (for lead $f_n = 0.12$), and e/mip and n/mip represent the calorimeter response to electromagnetic showers and to MeV-type neutrons, respectively. These responses are normalized to the one for minimum ionizing particles. The Monte Carlo calculated e/mip and n/mip values [5] for the lead-liquid-argon electromagnetic calorimeter [7]

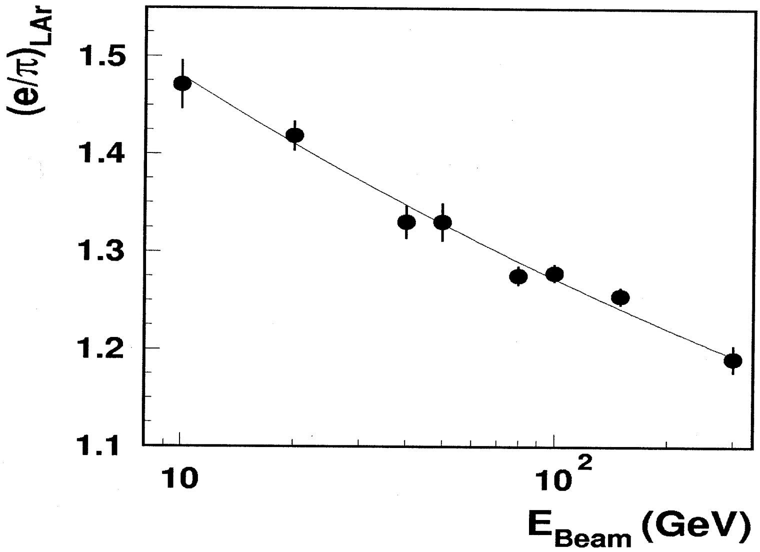

Figure 1: *The mean value of the* $(e/\pi)_{LAr}$ *ratio as a function of the beam energy.*

are $e/mip = 0.78$, $n/mip < 0.5$ and leading to $e/h > 1.66$. The measured value of the $(e/h)_{em}$ ratio agrees with this prediction. Using this expression and our value of e/h we can find that $n/mip \simeq 0.3$.

To use expression (3) for reconstructing incident hadron energies, it is necessary to know the $(e/\pi)_{Tile}$ and $(e/\pi)_{LAr}$ ratios, which themselves depend on the hadron energy. For this purpose, a two cycle iteration procedure has been developed. In the first cycle, the $(e/\pi)_{Tile}$ ratio is iteratively evaluated using the expression (2). To start this procedure a value of 1.13 (corresponding to $f_\pi^0 = 0.11 \ln(100)$) has been used. In the second cycle, the first approximation of the energy is calculated using the equation (3) with the $(e/\pi)_{Tile}$ ratio obtained in the first cycle and the $(e/\pi)_{LAr}$ ratio from equation (2). Again, to initiate the iteration $f_{\pi^0} = 0.11 \ln(100)$ has been used. In both of the cycles the iterated values are arguments of a logarithmic function, thus the iteration procedure will be very fast. The suggested algorithm of the energy reconstruction can be used for the fast energy reconstruction in a first level trigger.

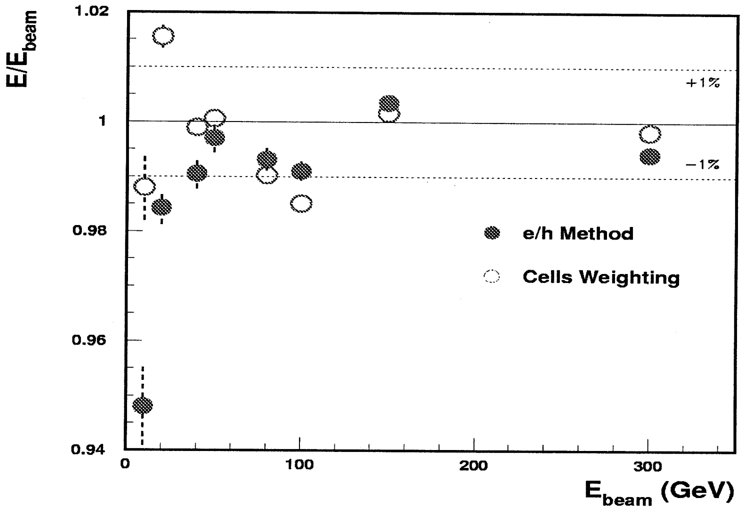

Figure 2: *Energy linearity as a function of the beam energy for the e/h method (black circles) and the cells weighting method (open circles).*

Fig. 2 demonstrates the correctness of the mean energy reconstruction. The mean value of E/E_{beam} is equal to $(99.5 \pm 0.3)\%$ and the spread is $\pm 1\%$, except for the point at 10 GeV. However, as noted in [2], result for 10 GeV is strongly dependent on the effective capability to remove events with interactions in the dead material upstream and to separate the real pion contribution from the muon contamination. Also shown is the comparison of the linearity as a function of the beam energy for the e/h method and for the cells weighting method [2]. Comparable quality of the linearity is observed for these two methods. Fig. 3 shows the fractional energy resolutions (σ/E) as a function of $1/\sqrt{E}$ obtained by three methods. The energy resolutions for the e/h method are comparable with the benchmark method and 30% worse than for the cells weighting method. A fit to the data points gives the fractional energy resolution for the e/h method

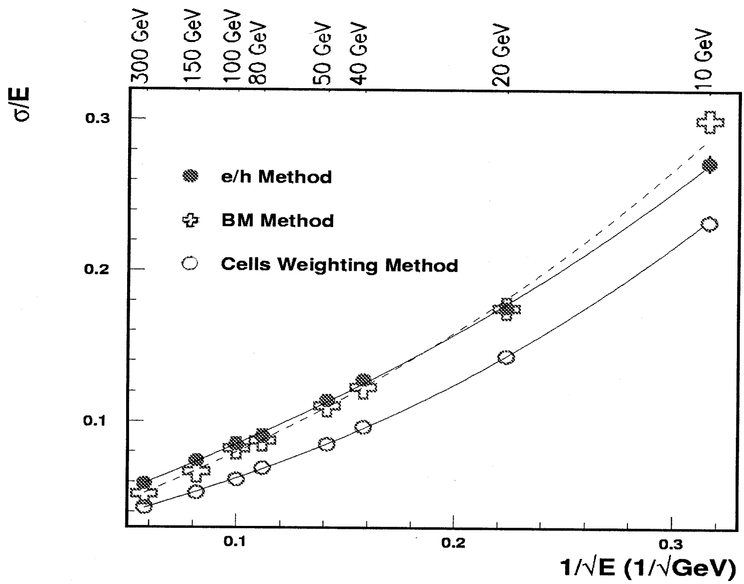

Figure 3: *The energy resolutions obtained with the e/h method (black circles), the benchmark method (crosses) and the cells weighting method (circles).*

obtained using the iteration procedure with $\epsilon = 0.1\%$: $\sigma/E = [(58 \pm 3)\%\sqrt{GeV}/\sqrt{E} + (2.5 \pm 0.3)\%] \oplus (1.7 \pm 0.2)\ GeV/E$.

3 Hadronic Shower Development

The e/h method for energy reconstruction has been used to study the energy depositions in each longitudinal calorimeter sampling. Fig. 4 shows the differential energy depositions as a function of the longitudinal coordinate Z for energy from 10 to 300 GeV.

An analytical representation of the hadronic shower longitudinal development from the calorimeter face has been used [9]:

$$\frac{dE(Z)}{dZ} = N\left\{ \frac{wX_0}{a}\left(\frac{Z}{X_0}\right)^a e^{-b\frac{Z}{X_0}} {}_1F_1\left(1, a+1, \left(b - \frac{X_0}{\lambda_I}\right)\frac{Z}{X_0}\right)\right.$$

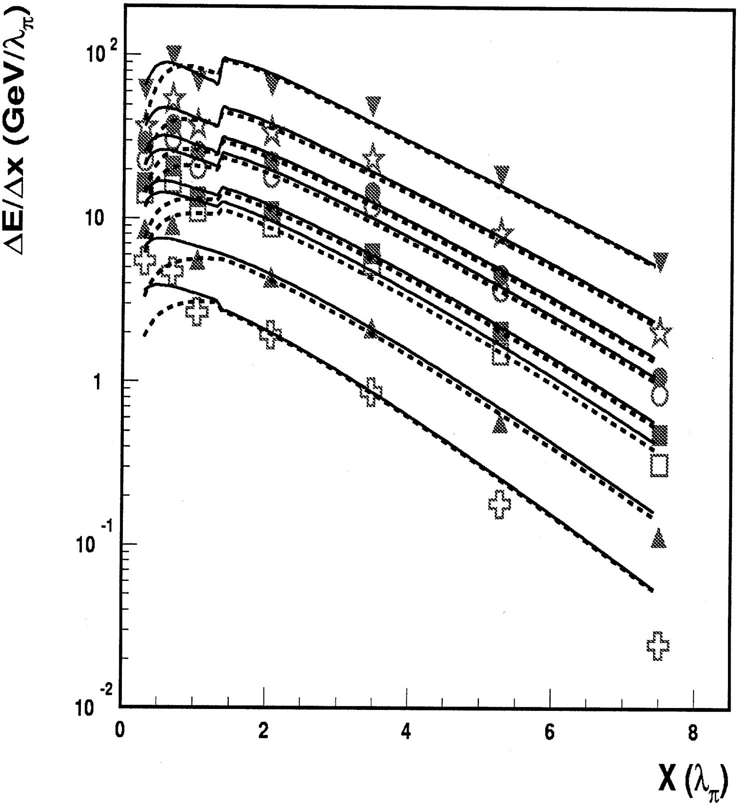

Figure 4: *The differential longitudinal energy depositions at 10 (crosses), 20 (black top triangles), 40 (open squares), 50 (black squares), 80 (open circles), 100 (black circles), 150 (stars), 300 (black bottom triangles) GeV as a function of the longitudinal coordinate Z and the results of the description by the Bock et al. [8] (dashed lines) and modified (solid lines) parameterizations.*

$$+\frac{(1-w)\lambda_I}{a}\left(\frac{Z}{\lambda_I}\right)^a e^{-d\frac{Z}{\lambda_I}}\,{}_1F_1\left(1,a+1,(d-1)\frac{Z}{\lambda_I}\right)\Bigg\}, \quad (5)$$

where ${}_1F_1(\alpha,\beta,Z)$ is the confluent hypergeometric function and a, b, d, w are parameters. Note that the formula (5) is given for a calorimeter characterized by its X_0 and λ_I. In the combined setup the values of X_0, λ_I and the e/h ratios are different for electromagnetic and hadronic compartments. So, the use of formula (5) is not straightforward for the description of the hadronic shower longitudinal profiles. To overcome this problem, Ref. [10] suggests an algorithm to combine the electromagnetic and hadronic calorimeter curves of the differential longitudinal energy deposition. Fig. 4 shows comparison of the differential longitudinal energy deposition with the combined curves for the longitudinal hadronic shower profiles (dashed lines). A significant disagreement has been observed between the experimental data and the combined curves in the region of the LAr calorimeter, especially at low energies. We attempted to improve the description and to include such essential feature of a calorimeter as the e/h ratio. Several modifications and adjustments of some parameters of this parameterization have been tried. The conclusion is that replacing the two parameters in the formula (5) with $b = 0.22 \cdot (e/h)_{cal}/(e/h)'_{cal}$ and $w = 0.6 \cdot (e/\pi)_{cal}/(e/\pi)'_{cal}$. Here the values of the $(e/h)'_{cal}$ ratios are $(e/h)'_{em} \approx 1.1$ and $(e/h)'_{had} \approx 1.3$ which correspond to the data used for the Bock et al. parameterization [8]. The $(e/\pi)'_{cal}$ are calculated using formula (2). In Fig. 4 the experimental differential longitudinal energy depositions and the results of the description by the modified parameterization (solid lines) are compared. There is a reasonable agreement between the experimental data and the curves. Fig. 5 shows the measured and calculated relative values of the energy deposition in the LAr and Tile calorimeters. The relative energy deposition in the LAr calorimeter decreases from about 50% at 10 *GeV* to 30% at 300 *GeV*. Conversely, the fraction in the Tile calorimeter increases as the energy increases.

4 Conclusions

Hadron energy reconstruction for the ATLAS barrel prototype combined calorimeter has been carried out in the framework of the non-parametrical method. The non-parametrical method of the energy reconstruction for a combined calorimeter uses only the known e/h ratios and the electron

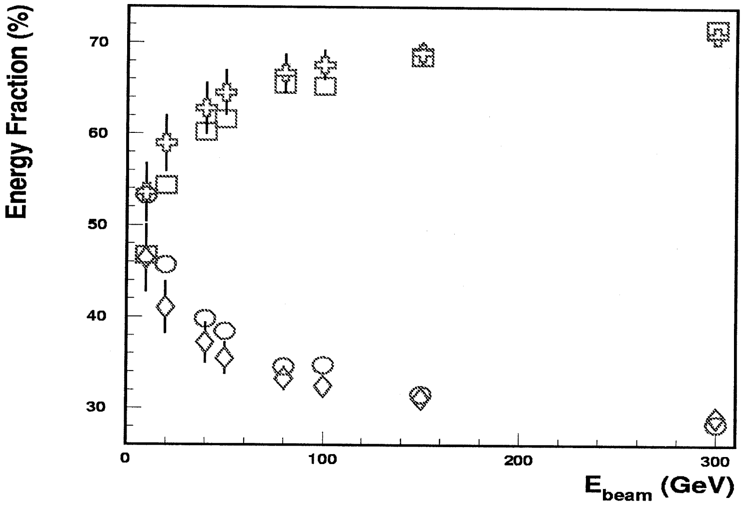

Figure 5: *Energy depositions in the LAr (circles) and Tile (squares) calorimeters at different beam energies. The diamonds (crosses) are the calculated energy depositions in the LAr (Tile).*

calibration constants, without requiring the determination of any parameters by a minimization technique. Thus, it can be used for the fast energy reconstruction in a first level rigger. The value of the e/h ratio obtained for the electromagnetic compartment of the combined calorimeter is 1.74 ± 0.04. The results of the study of the longitudinal hadronic shower development have also been presented.

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Измерение энергии адронов
в комбинированном калориметре установки АТЛАС
с использованием беспараметрического метода

Приведены результаты измерения энергии адронов в прототипе комбинированного калориметра установки АТЛАС в рамках беспараметрического метода. В предложенном методе используются измеренные величины нескомпенсированности калориметров, составляющих комбинированный калориметр, а также калибровочные величины. При этом не требуется определения каких-либо параметров с использованием минимизационной процедуры. Данный метод может быть применен при измерении энергии в триггере первого уровня. Показано, что определенная таким методом энергия не отклоняется более чем на $\pm 1\%$ от номинальной, и энергетическое разрешение составляет $[(58 \pm 3)\% \sqrt{\text{ГэВ}} / \sqrt{E} + (2{,}5 \pm 0{,}3)\%] \oplus (1{,}7 \pm 0{,}2)$ ГэВ/E. Измерена величина нескомпенсированности для электромагнитного калориметра, как составной части комбинированного калориметра, которая составляет $e/h = 1{,}74 \pm 0{,}04$. Приведены результаты исследования продольного профиля адронного ливня в комбинированном калориметре.

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Hadron Energy Reconstruction
for ATLAS Barrel Combined Calorimeter
Using Non-Parametrical Method

Hadron energy reconstruction for the ATLAS barrel prototype combined calorimeter in the framework of the non-parametrical method is discussed. The non-parametrical method utilizes only the known e/h ratios and the electron calibration constants and does not require the determination of any parameters by a minimization technique. Thus, this technique lends itself to fast energy reconstruction in a first level trigger. The reconstructed mean values of the hadron energies are within $\pm 1\%$ of the true values and the fractional energy resolution is $[(58 \pm 3)\% \sqrt{\text{GeV}} / \sqrt{E} + (2.5 \pm 0.3)\%] \oplus (1.7 \pm 0.2)$ GeV/E. The value of the e/h ratio obtained for the electromagnetic compartment of the combined calorimeter is 1.74 ± 0.04. Results of a study of the longitudinal hadronic shower development are also presented.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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