CERN-EP/82-08
21 January 1982

THE RESPONSE AND RESOLUTION OF A FINE-GRAIN MARBLE CALORIMETER
FOR HADRONIC AND ELECTROMAGNETIC SHOWERS

CHARM Collaboration

M. Jonker, J. Panman¹⁾ and F. Udo
NIKHEF, Amsterdam, Netherlands

J.V. Allaby, U. Amaldi, G. Barbiellini²⁾, A. Baroncelli, V. Blobel³⁾,
W. Flegel, W. Kozanecki, K.H. Mess, M. Metcalf, J. Meyer,
R.S. Orr, F. Schneider, A.M. Wetherell and K. Winter
CERN, Geneva, Switzerland

J. Aspiazu, F.W. Büsler, P.D. Gall, H. Grote, B. Kröger, E. Metz,
F. Niebergall, K.H. Ranitzsch and P. Stähelin
II. Institut für Experimentalphysik, Universität Hamburg,
Hamburg, Germany

P. Gorbunov, E. Grigoriev, V. Kaftanov, V. Khovansky and A. Rozanov
Institute of Theoretical and Experimental Physics, Moscow, USSR
B. Borgia⁴⁾, C. Bosio⁵⁾, A. Capone⁴⁾, F. Ferroni⁴⁾, E. Longo⁴⁾,
P. Monacelli⁴⁾, F. de Notaristefani⁴⁾, P. Pistilli⁴⁾,
C. Santoni⁵⁾ and V. Valente⁶⁾
Istituto Nazionale di Fisica Nucleare, Roma, Italy

(Submitted to Nuclear Instrum. Methods)

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- 1) Now at CERN, Geneva, Switzerland.
 - 2) On leave of absence from the Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy.
 - 3) On leave of absence from II. Institut für Experimentalphysik, Universität Hamburg, Germany.
 - 4) Istituto di Fisica, Università di Roma, and INFN, Sezione di Roma, Italy.
 - 5) INFN Sezione di Sanità and Istituto Superiore di Sanità, Roma, Italy.
 - 6) Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy.

ABSTRACT

The response of the fine-grained CHARM target calorimeter built to detect ν interactions has been studied in π^- and e^- beams of 15-140 GeV. The development of hadronic and electromagnetic showers was studied and the precision of energy measurements determined. Methods used to measure the direction of particle showers and to distinguish electromagnetic from hadronic showers have been developed and the results are given.

1. INTRODUCTION

The neutrino detector built by a CERN-Hamburg-Amsterdam-Rome-Moscow Collaboration (the CHARM Collaboration) consists of a fine-grain target-calorimeter composed of 78 equal subunits, each surrounded by a frame of magnetized iron for muon identification, and of a muon spectrometer. It has been described elsewhere [1]. The detector was designed for the study of a variety of reactions induced by high-energy neutrinos, in particular for the comparison of inclusive semileptonic scattering of neutrinos and antineutrinos by weak neutral- and charged-current interactions. It has also been used to study the scattering of neutrinos and antineutrinos on electrons.

The kinetic energy of hadrons produced in these reactions and of recoiling electrons is determined from the ionization loss in the calorimeter sampled by plastic scintillation counters and proportional tubes between the target plates. In order to discriminate between hadron- and electron-induced showers, a detailed knowledge is required of the response of the calorimeter to hadrons and electrons over a wide energy range and of the distinct properties of the showers induced by these particles.

We describe here measurements of the response of the calorimeter to pion and electron beams in the energy range 15-140 GeV, of the energy resolution, and of the spatial resolution of the interaction vertex, the power of discrimination between pion- and electron-induced showers, and the accuracy in determining the direction of showers.

This paper is intended to help in the understanding of physics results which are currently being obtained using this calorimeter [2].

2. THE TARGET CALORIMETER

The set-up used for calibration consisted of 30 of the 78 identical subunits of the target calorimeter. A partial view is shown in fig. 1. Each subunit is composed of the following elements:

- A marble plate, with $3 \times 3 \text{ m}^2$ surface area and 8 cm in thickness, surrounded by an iron frame of the same thickness and of 45 cm width, which is magnetized in a toroidal configuration by two coils on the vertical parts of each frame. During the calibration runs the frame was not magnetized.
- An array of 20 scintillation counters of 3 m length, 15 cm width, and 3 cm thickness, covering the target plate.
- An array of 128 proportional drift tubes of $3 \times 3 \text{ cm}^2$ cross-section and 4 m length, covering the target plate and the surrounding iron frame. They are oriented at 90° with respect to the scintillation counters; both scintillators and proportional counters alternate in the horizontal and vertical directions.

The scintillation counters and proportional drift tubes are used to sample the particle shower as it develops in the target plates, and to measure the shower energy and direction. Proportional drift tubes also measure the direction of muons, and sample that part of hadron showers which may escape from the target-calorimeter into the iron frame.

The response of this calorimeter to pion-induced and electron-induced showers was measured relative to the energy loss of cosmic-ray muons.

The response of the scintillation counters and of the proportional tubes to cosmic muons was constantly monitored to control variations in gain to a statistical error of $\pm 3\%$ for individual scintillation counters, resulting in an estimated uncertainty of $\pm 1\%$ in the energy of a shower involving a larger number of scintillators. The light attenuation of each scintillator was measured by using the information on location of cosmic muons provided by the hodoscopes of scintillators and proportional drift tubes. These data were subsequently used to correct the response of each scintillator with respect to the position of the detected particles. The constant revision of the scintillator parameters was found to be essential, as the light transmission of the material deteriorated continuously at a rate of about 1.5% per month. The response of the proportional tubes is found to be uniform within $\pm 5\%$ over 98 layers of $4 \times 4 \text{ m}^2$ surface area and to vary less than $\pm 1\%$ over periods of months.

3. THE BEAM

Negative particles produced by the interaction of 200 GeV protons from the CERN SPS were selected and focused in a beam with less than 1% momentum spread and a central momentum, in the range of 15 to 140 GeV, known to $\pm 1\%$. Figure 2 shows the beam layout in the experimental hall. A bending magnet was used to deflect the beam horizontally to hit different points of the calorimeter. Table 1 gives details of the impact points chosen and of the beam direction in the horizontal and vertical planes at these points.

A 10 m long threshold Čerenkov counter filled with helium was used to identify electrons with momenta of 15 and 20 GeV/c. At 50 GeV/c electrons were identified by the width of the shower profile (see Section 6). The electron content of the beam varied from 50% at 15 GeV/c (using a 150 mm long Cu target) to about 1% at 50 GeV/c (using a 50 mm long Be target).

The beam was centered onto a two-dimensional hodoscope array (H) of two times eight scintillation counters, each 6 cm wide, covering the entrance aperture of the bending magnet. A two-dimensional array (S) of two times sixteen streamer tubes [3], each 8.8 mm wide, was mounted in front of the calorimeter to determine the horizontal and the vertical position of incoming particles. A beam of incident particles was defined by a coincidence between three scintillation counters (T), located at the entrance and exit apertures of the bending magnet, and in front of the calorimeter. Signals from the Čerenkov counter in coincidence with incident particles were registered and their pulse height analysed. Signals from a veto counter (V) of $1 \times 1 \text{ m}^2$ surface area with a hole of $4 \times 4 \text{ cm}^2$ for the beam, and the time-of-flight over the distance to counter T_3 were recorded to discriminate against beam halo without rejecting particles going backwards from the albedo of showers in the calorimeter.

In the analysis, events were selected if each hodoscope of streamer tubes and scintillators had registered only one incoming beam particle and if no veto count with beam particle timing was registered.

The calorimeter was read out if at least four scintillator planes were hit. Events induced by pions were required to have only one hit in the first two scintillator planes and in the first plane of proportional drift tubes to avoid beam halo.

4. CALIBRATION OF THE SCINTILLATOR RESPONSE

Figure 3 shows the scintillator response, $E_{\text{vis}}/E_{\text{beam}}$, as a function of the kinetic energy of incident pions and electrons. The response of the calorimeter is measured relative to the energy loss of cosmic-ray muons in the scintillators. The value of E_{vis} is calculated assuming that muons penetrating at least eight calorimeter subunits deposit on average 2.2 MeV per cm of scintillator material traversed. This auxiliary standard serves to apply this beam calibration to neutrino-induced showers.

Owing to the limited length of the test set-up of 30 subunits, equivalent to 783 g/cm of aluminium or 6.45 absorption lengths, some of the pion-induced showers are not fully contained. Figure 4 shows the spectrum of E_{vis} observed for 140 GeV pions and the low-energy tail caused by leakage if no condition on the pion interaction point is imposed. To extrapolate the response for an infinitely long calorimeter, the longitudinal distribution of the average shower was parametrized by the expression

$$F(x) = A \left(1 - e^{-x^2/\alpha} \right) e^{-x/\Lambda} . \quad (1)$$

The values of the parameters were determined for each energy by the best fit to the data (see fig. 12). The largest correction was 10% at 140 GeV. The same result and an estimate of the r.m.s. resolution was obtained in a different way by fitting the E_{vis} distribution with a Gaussian distribution representing the response function of the infinite detector convoluted with the lower half of a Cauchy distribution representing the longitudinal containment correction:

$$F(E_{\text{vis}}) = A \int_{E_{\text{vis}}}^{\infty} \frac{1}{1 + [(E' - E_{\text{vis}})^2/a]} \exp \left[- \frac{(E' - E_0)^2}{2\sigma^2} \right] dE' . \quad (2)$$

The parameters of the fit, the Cauchy parameter α , the mean visible energy E_0 and the energy resolution σ have been determined using a maximum-likelihood method. The result of the fit is shown in fig. 4 (solid line) together with the response function of an infinitely long detector (broken line). The assumptions made in this method have been checked by determining the containment correction using neutrino-induced hadron showers in the complete calorimeter and in the limited volume used for these calibration measurements. Another check was performed by selecting events with the incident pion interacting in one of the first two plates and repeating the unfolding procedure described before. Good agreement is found for all three methods.

Figure 5 shows the r.m.s. energy resolutions thus obtained for incident pions and electrons as a function of $E_{\text{beam}}^{-1/2}$. The error bars indicate the estimate of systematic uncertainties of the containment correction. The resolution is well described by a simple dependence on $E^{-1/2}$, as shown in fig. 5; for hadrons we find

$$\frac{\sigma(E_h)}{E_h} = \frac{0.53}{\sqrt{E/\text{GeV}}}$$

and for electrons

$$\frac{\sigma(E_e)}{E_e} = \frac{0.20}{\sqrt{E/\text{GeV}}}.$$

We note that the hadron energy resolution, $\sim 5\%$ at 100 GeV, is rather good for a sampling calorimeter and is a result of the small sampling step. Comparison with the calculated resolution of 4% for Monte Carlo generated showers shows that fluctuations due to errors in the light attenuation corrections for the scintillators and to gain variations of the photomultipliers are small.

The response shown in fig. 3 has been obtained with the beam incident on point T (see Table 1) near to the centre of the calorimeter. We have also investigated, using data obtained at the other impact points (A, B, C, etc., see Table 1), how much the response and the resolution of the calorimeter is affected for neutrino-induced events in a fiducial volume extending laterally to vertex

points of 120 cm off axis. The measured response for incident pions of 20 GeV as a function of the distance d from the beam axis is shown in fig. 6. At the limit of the fiducial volume, $d = 120$ cm, the lateral leakage reaches 15%. Adding the energy detected in the proportional tubes covering the 8 cm thick iron frame surrounding the target plates, multiplied by an experimentally determined calibration factor, gives a corrected response as shown in fig. 6 and allows, therefore, to extend the fiducial volume to $d = 120$ cm.

The energy resolution is strongly affected by leakage into the frame owing to the coarse sampling step of the iron plates (16 cm), to the large fluctuations of the ionization loss in proportional counters (see section 5), and to the coarse approximation of a constant correction factor. Figure 7 shows how the energy resolution for 50 GeV pion-induced showers deteriorates near the edge of our fiducial volume. This effect is taken into account when energy distributions of neutrino-induced showers are unfolded.

For exposures to the narrow-band beam of the West Area Neutrino Facility at the 400 GeV CERN Super Proton Synchrotron we extend the fiducial volume of the target-calorimeter to plane 60, leaving only 18 planes for calorimetric measurements of the hadron energy for events starting in plane 60. The fractional energy leakage as a function of the number of calorimeter plates, determined from neutrino events with vertices in the first plates of the calorimeter, is shown in fig. 8. For 18 calorimeter planes the fractional leakage is 12% at 100 GeV and 17% at 140 GeV; in the range of interest the fractional leakage α_L can be approximated by

$$\alpha_L = e^{0.015 E_h/\text{GeV}} \cdot e^{-0.2014 N}, \quad (3)$$

where N is the number of marble plates available. Adding the energy detected in the proportional tubes inserted between 10 cm thick iron plates in the end calorimeter (see ref. 1), multiplied by an experimentally determined calibration factor, gives a corrected response.

The resolution of this coarse iron calorimeter has been measured in a separate test for 5-17 GeV pions with the result (see section 5) (valid for $E < 50$ GeV)

$$\frac{\sigma^{\text{Fe}}(E_h)}{E_h} = \frac{1.39}{\sqrt{E/\text{GeV}}}.$$

The ratio of the resolutions in the combined marble-iron calorimeter and in the marble calorimeter only can be parametrized in terms of the fractional leakage α_L

$$r = \frac{\sigma(E_h)_{\text{marble+Fe}}}{\sigma(E_h)_{\text{marble}}} = (1 + 5.83 \alpha_L)^{\frac{1}{2}}, \quad (4)$$

with the dependence of α_L on N and E_h as given before. For a neutrino event originating in plane 60, corresponding to $N = 18$ and for $E = 50$ GeV, the resolution is worse by a factor of 1.26 than in marble alone. The expression for r is used for unfolding measured energy distributions.

5. CALIBRATION OF THE PROPORTIONAL TUBE RESPONSE

The response of the proportional tubes of the marble calorimeter, $E_{\text{vis}}/E_{\text{beam}}$, as a function of the beam energy for pions and electrons is shown in fig. 9. The values of E_{vis} have been deduced relative to an assumed energy loss of 2.52 keV per cm of traversed counter gas of cosmic-ray muons traversing a tube at an angle of 67.5° with respect to the wire. Because of space-charge effects which are larger for tracks near 90° and because of the limited range of the amplitude digitizer, we cannot expect a linear response. Because of their denser core the response to electron-induced showers is more strongly affected than that to pion-induced showers. At the lowest energies, where this saturation effect is negligible, the energy response to electron-induced showers should be higher than to pion-induced showers. Figure 9 indicates a cross-over near 15 GeV.

The energy dependence of the energy resolution, shown in fig. 10, deviates from the $E^{-\frac{1}{2}}$ law found for the scintillator response, because of the non-linearity of response.

Shower energy leaking laterally and longitudinally from the marble calorimeter is detected by layers of proportional tubes inserted between the plates of the iron frames and of the end calorimeter. This energy is then used to correct the response of the marble target-calorimeter for neutrino events occurring in a certain fiducial volume. Figure 11 shows the response of the proportional tubes to hadron showers induced by 17 GeV/c π^- in a calorimeter, with sampling every 10 cm of Fe as in the end calorimeter. We observe a mean pulse height corresponding to 7.7 equivalent minimum ionizing particles per GeV of kinetic energy and an r.m.s. width of 33.7%. The visible energy is found to increase linearly with the kinetic energy in the range 6 to 22 GeV and to scale with the density of the calorimeter. The energy resolution is well described by the following expression

$$\frac{\sigma(E_h)}{E_h} = 1.39/\sqrt{E/\text{GeV}} . \quad (5)$$

The corrected response and energy resolution of the target-calorimeter have been described in section 4.

6. SHOWER DEVELOPMENT IN THE CALORIMETER

The longitudinal and lateral development of showers in the calorimeter induced by pions and electrons has been studied to develop methods of discriminating between them and to measure their direction.

The target-calorimeter plate material has been chosen for approximately equal lengths of hadronic and electromagnetic showers so as to minimize fluctuations of the length of showers induced by semileptonic neutrino interactions. This leads to the requirement of a material with

$$\Lambda \approx 4X_0 ,$$

where X_0 is the radiation length and Λ the absorption length. The solution adopted consists of a modular construction with 8 cm thick marble plates of density $\rho = 2.75 \text{ g/cm}^3$. The average density is 1.3 g/cm^3 , the average radiation length 20 cm, and the average absorption length for pions is 93 cm.

As a result, electromagnetic showers originating, for instance, from $\nu_\mu e^-$ elastic scattering cannot be separated from hadronic showers originating from semileptonic neutrino scattering, for example in $\nu_\mu + N \rightarrow \nu'_\mu + \text{hadrons}$ on the basis of the longitudinal energy distribution.

Figure 12 shows the average longitudinal distribution of energy loss by hadronic showers of different energies in the scintillator plane and fig. 13 shows the distributions induced by electrons. As expected these distributions are very similar. However, the lateral profiles of hadronic and electromagnetic showers are distinctly different. A Cauchy distribution fitted to the profiles measured by the scintillation counters gives the distribution of half width Γ for 20 GeV electron- and pion-induced showers shown in fig. 14. A second separation, more sensitive to the tails of the distributions, is obtained by the r.m.s. width σ of the profiles measured by the proportional counters as shown in fig. 15. A selection of events with $\Gamma < 1.6$ cm and $\sigma < 9$ cm gives a rejection factor of approximately 100 for pion-induced showers and an efficiency of $(85 \pm 5)\%$ for electrons. A comparison of this method of separation of e and π with the one given by the pulse height registered in the Čerenkov counter at 20 GeV/c, shown in fig. 16, shows two distinct groups of events. At 50 GeV the Čerenkov counter was too short to identify electrons, and the separation of e and π was therefore made using the lateral shower width. This method of separation has been used by us in a recent measurement of the cross-section of $\bar{\nu}_\mu e^-$ elastic scattering [4].

7. MEASUREMENT OF THE SHOWER VERTEX AND DIRECTION

A two-step method is used to measure the direction of particle showers. First the vertex position of the shower is determined in both projections; next a line is determined, starting from the vertex, which divides the projected energy deposition into two equal parts. This line represents an estimate of the shower direction in each projection.

The longitudinal position of the vertex is defined as the centre of the first marble plate behind which an energy loss corresponding to more than four equivalent minimum ionizing particles has been detected in two contiguous scintillator planes. If this search fails to find a vertex the energy loss threshold is lowered by a factor of two. In the case of hadronic showers, the lateral coordinates of the vertex are estimated from the hit pattern weighted by the energy loss in the proportional tubes and scintillators in the following eight detector planes. All possible straight line fits combining tube clusters and scintillator barycentres are formed after elimination of spurious tube hits from the tails of the shower. The intersection of the line with the best fit with the vertex plane determines the lateral shower vertex position.

In the case of electron-induced showers, events with only one tube hit in the first plane are selected (with efficiency $\epsilon = 71 \pm 10\%$) and the coordinate is determined from the drift time. For drift distances larger than 4 mm the left-right ambiguity can be solved by visual inspection. In the second, orthogonal projection, the barycentre of the pulse height recorded in the proportional tubes is used as the vertex position.

The line joining the vertex and the barycentre of the energy deposition distribution measured by the scintillators gives one estimate of the shower direction. It can be improved by using the shower profile detected in the proportional tube planes (see fig. 17). An iterative method has been developed, to find a straight line starting at the vertex which subdivides the energy deposition in each projection into two equal parts. Tube hits far from the shower axis are given less weight in this procedure than tube hits near the axis. The vertex resolution and the angular resolution thus obtained for hadron showers is shown in figs. 18 and 19. The energy dependence of $\sigma(\theta_h)$ shows an approximate $E_h^{-1/2}$ dependence, suggesting the use of $u = \theta_h \cdot E_h^{1/2}$ as a kinematical variable for unfolding resolution effects from measured distributions.

The angular resolutions for electron showers are given in Table 2.

8. RECOGNITION OF ELECTROMAGNETIC SHOWERS EMBEDDED
IN HADRONIC CASCADES

In the case of charged-current interactions of electron-neutrinos or electron-antineutrinos with nuclei, the shower created in the calorimeter consists of two components, an electromagnetic part from the final state electron and a hadronic part from the recoiling hadronic system. In most of the cases these two components are not separated in space.

To recognize the electron shower and to measure its energy and the hadron energy separately, we make use of the fact that electromagnetic showers, in contrast to hadronic showers, are extremely narrow (typically 2.5 cm FWHM, see also fig. 14), and very regular in their longitudinal energy profile. To search for an electromagnetic component in a muonless neutrino event we define a band of the width of the scintillator elements (15 cm) which starts at the interaction vertex. The length of the band is restricted to 10 radiation lengths (10 target plates). In the central part of the band, over a range of 8 planes, the energy loss in each scintillator must be larger than the equivalent of three minimum ionizing particles and the maximum of the pulse height must lie within a limited distance from the vertex.

In such a band we define four estimators of the total energy of the electromagnetic shower candidate: the maximum pulse height in a single scintillator, the pulse height measured in three longitudinally adjacent scintillators around the maximum, and the total pulse height for each of the two orientations of scintillator elements. These estimators have been calibrated in electron test beams for energies from 3 to 50 GeV. The combined resolution was found to be $\sigma(E)/E = 0.25/\sqrt{E/\text{GeV}}$, comparable to the one obtained without spatial restrictions (see fig. 5).

The four estimators are submitted to a test of whether they measure the same energy, and the band with the lowest χ^2 is retained as the best candidate for containing an electromagnetic shower. We define the quantity η to measure the fractional energy of the hadronic part of the shower:

$$\eta = (E_{\text{shower}} - E_{\text{em}})/E_{\text{shower}} .$$

In the case of charged-current ν_e ($\bar{\nu}_e$) interactions η measures the inelasticity y .

Figure 20 shows the result of the method applied to a 50 GeV π^- beam, which was contaminated with electrons. Applying a cut in η , which retains 95% of the electrons, one obtains a contamination from π 's of about 2.5%.

To test the method we used charged-current ν_μ interactions, obtained in the wide-band neutrino beam, and replaced the μ track by a Monte Carlo generated electromagnetic shower of the same energy and direction. The y distribution of these events is approximately flat. Restricting the analysis to events with $y < 0.6$ yields the energy resolution shown in fig. 21 as averaged over the electron spectrum of fig. 22.

9. CONCLUSION

We have measured the response and the energy resolution of a fine-grained marble-scintillator calorimeter. For incident pions the response is linear between 15 and 140 GeV; the energy resolution, $\sim 53\%/\sqrt{E/\text{GeV}}$, is very good for a sampling calorimeter. The response to electrons is about 16% higher than to pions. The energy resolution for electrons is $\sim 20\%/\sqrt{E/\text{GeV}}$. Leakage corrections for the fiducial volume used in neutrino beams have been determined and parametrized.

The development of showers has been studied and methods have been developed to distinguish showers induced by pions and by electrons by the width of their lateral shower profiles.

A two-step procedure was found to determine the direction of hadron and of electron showers with a resolution of ~ 10 mrad for 15 GeV electrons and ~ 18 mrad for 100 GeV pions. Electron showers embedded in hadron showers, induced by electron-neutrinos can be recognized owing to their narrow lateral profile and their energy can be measured with a resolution of about $25\%/\sqrt{E/\text{GeV}}$.

Acknowledgements

We would like to thank our numerous technical collaborators for their skilled and dedicated contributions to the realization of the detector. In particular, we wish to thank W. Albrecht, G. Petrucci, G. Pozzo and U. Ubaldi for their contributions to the magnet design and assembly; G. Basti, R. Donnet, A. King, L. Sokolov and P. Veneroni for their contributions to the design and installation of scintillators and proportional drift tubes; G. Fremont, B. Friend, K. Geske, H. Riege, J. Schütt, Y. Semenov, J.C. Tarlé and H. Verweij for their contributions to the design and installation of electronics for proportional drift tubes; F. Cesaroni, M. Ferrat, S. Guerra, G. Lunadei and A. Tusi for their contributions to the construction and installation of ADCs and photomultiplier electronics; E. Gygi and M. Jimenez for the gas system of the proportional drift tubes; Y. Perrin, E. Rimmer, P. Scharff-Hansen for on-line computing; J. Audier and C. Busi for off-line analysis. V. Gemanov has contributed with technical assistance. The assistance of E. Chiaveri for setting up and operating the beam, and of the SPS experimental area group, in particular M. Glaser, who provided and installed the Čerenkov counter, is gratefully acknowledged.

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Table 1

Beam impact points and directions for calibration measurements

Code	Impact points ^{a)} (cm)		Impact angles ^{a)} (mrad)	
	H	V	θ_H	θ_V
T	32.95	5.33	-37.6	8.7
Y	94.7		- 7.9	
Z	106.7		- 2.1	
A	114.2		+ 1.6	
B	131.7		+10.1	
C	141.7		+15.0	

a) Defined with respect to the central line of the calorimeter.

Table 2

Angular resolution for electron showers

E_{electron} (GeV)	15	20	50
$\sigma(\theta_1)$ a) (mrad)	10	10	6
$\sigma(\theta_2)$ a) (mrad)	14	12	8

a) θ_1, θ_2 are the angles in the projections starting in the first or second plane behind the vertex, respectively.

Figure captions

- Fig. 1 : Partial view of the fine-grain calorimeter. Each subunit is composed of a marble plate of $3 \times 3 \text{ m}^2$ surface area and 8 cm thickness, a layer of 20 scintillators 15 cm wide and 3 m long, and a layer of 128 proportional drift tubes 3 cm wide and 4 m long. Each marble plate is surrounded by a frame of magnetized steel.
- Fig. 2 : Layout of the particle beam and the calorimeter. A bending magnet allows to deflect the beam horizontally to hit different points of the calorimeter. A 10 m long threshold Čerenkov counter (C) is used to identify electrons. Beam hodoscopes (H, S) and trigger counters (T) are also shown. A veto counter (V) rejects incoming particles accompanied by halo particles.
- Fig. 3 : Response of the scintillation counters of the fine-grain calorimeter to beams of pions and electrons. The error bars indicate the estimated systematic uncertainties.
- Fig. 4 : Spectrum of E_{vis} observed for 140 GeV pions using the scintillation counters of 30 modules without imposing a condition on the longitudinal vertex position. The low-energy tail is due to leakage out of the end of the set-up. A Gaussian folded with the expected leakage was fitted to the data (solid line). The broken line represents the same but unfolded Gaussian used in calculating the response and the resolution of the entire calorimeter.
- Fig. 5 : Energy resolution (r.m.s.) of scintillators for hadron and for electron showers after containment corrections. The lines represent the parametrizations $\sigma(E_h)/E_h = 0.53/\sqrt{E/\text{GeV}}$ and $\sigma(E_e)/E_e = 0.20/\sqrt{E/\text{GeV}}$.
- Fig. 6 : Response of the calorimeter to pions of 20 GeV as a function of the distance of the vertex from the centre of the calorimeter. Adding the leakage detected by the proportional tubes covering the Fe frames surrounding the target plates gives the corrected response.

- Fig. 7 : Energy resolution for 50 GeV pions as a function of the distance of the vertex from the centre of the calorimeter, after leakage.
- Fig. 8 : Measured fraction of energy α_L leaking out of the marble calorimeter, N plates beyond the vertex position.
- Fig. 9 : Response of the proportional tubes in the target-calorimeter to beams of pions and electrons.
- Fig. 10 : Energy resolution of the proportional tubes for pion and electron showers in the target-calorimeter. The deviation from an $E^{-1/2}$ dependence is due to the non-linear response.
- Fig. 11 : Response of the proportional tubes in a calorimeter with sampling every 10 cm Fe, as in the end calorimeter, to 17 GeV/c π^- in units of equivalent minimum ionizing particles. The r.m.s. resolution is 33.7%.
- Fig. 12 : Longitudinal distribution of energy loss by pion-induced showers in the scintillator planes of the target-calorimeter.
- Fig. 13 : Longitudinal distribution of energy loss by electron-induced showers in the scintillator planes of the target-calorimeter.
- Fig. 14 : Distribution of the half width Γ of electron- and pion-induced showers as measured by the energy deposition profile in scintillators.
- Fig. 15 : Distribution of the r.m.s. width σ of electron- and pion-induced showers as measured by the energy deposition profile in the proportional tubes.
- Fig. 16 : Scatter plot of pulse height recorded in the beam γ Cerenkov counter and of the shower width Γ observed in the calorimeter. Electron-pion separation is clearly visible.
- Fig. 17 : Lateral energy deposition profile of 10 GeV pion showers as measured in the proportional tube planes. The shower direction is determined by a line starting at the vertex and dividing the energy flow into two equal parts.

- Fig. 18 : Shower vertex resolution in one projection as a function of the incident pion energy.
- Fig. 19 : Angular resolution of hadron shower direction in one projection as a function of shower energy. At 100 GeV the r.m.s. resolution is ~ 18 mrad.
- Fig. 20 : Distribution of η , the fractional energy of the hadronic part of showers, induced by a 50 GeV pion beam contaminated with electrons.
- Fig. 21 : Energy resolution for electrons from charged-current ν_e events with $\eta \leq 0.6$.
- Fig. 22 : Energy distribution of simulated electron showers for charged current ν_e events derived from charged-current ν_μ events of wide-band beam data.

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