

THE RESPONSE AND RESOLUTION OF AN IRON-SCINTILLATOR
CALORIMETER FOR HADRONIC AND ELECTROMAGNETIC SHOWERS
BETWEEN 10 GeV AND 140 GeV

H. Abramowicz^{*}, J.G.H. de Groot, J. Knobloch, J. May,
P. Palazzi, A. Para^{*}, F. Ranjard, J. Rothberg^{**},
W. von Rüden, W.D. Schlatter, J. Steinberger,
H. Taureg, H. Wahl and J. Wotschack

CERN
Geneva, Switzerland

F. Eisele, H.P. Klasen, K. Kleinknecht,
B. Pszola, B. Renk and H.J. Willutzki
Institut für Physik der Universität Dortmund^{***}
Dortmund, Germany

F. Dydak, T. Flottmann, C. Geweniger,
J. Królikowski^{*} and K. Tittel^{***}
Institut für Hochenergiephysik^{***}
Universität Heidelberg
Heidelberg, Germany

C. Guyot, J.P. Merlo, B. Peyaud, J. Rander,
J.P. Schuller and R. Turlay
D.Ph.P.E.
CEN-Saclay, France

J.T. He, T.Z. Ruan and W.M. Wu
Institute of High Energy Physics
Peking, China

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- * On leave of absence from Institute of Experimental Physics, Warsaw University, Warsaw, Poland.
** On leave of absence from University of Washington, Seattle, Washington.
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ABSTRACT

The energy resolution and response of a segmented iron-scintillator total absorption calorimeter has been measured for pion energies from 10 to 140 GeV and for electron energies up to 50 GeV. A procedure has been found to weight individual counter responses for hadron showers which results in improved energy resolution at high energies and a nearly linear dependence of response on hadron energy above 30 GeV. There is evidence in the data that this weighting procedure compensates for fluctuations in energy deposition due to the electromagnetic component of the hadronic shower. For an iron sampling thickness of 2.5 cm the hadron energy resolution follows a $0.58/\sqrt{E}$ law, while the resolution for electromagnetic showers is $0.23/\sqrt{E}$.

1. INTRODUCTION

The energy resolution and response of an iron-scintillator total absorption calorimeter has been measured for pion energies between 10 and 140 GeV and for electron energies between 10 and 50 GeV. The purpose of this measurement was to evaluate the design of the improved calorimeter for the CDHS neutrino experiment, WA1, at CERN¹⁾. The model calorimeter that was used for these measurements had the same longitudinal structure as the new WA1 detector, but smaller lateral dimensions. Compared with the existing WA1 detector²⁾, the new apparatus has finer sampling and substantially improved spatial resolution in the transverse directions.

The same pion beam has also been used to calibrate the presently installed WA1 detector. Results on resolution from this measurement for 5, 10, and 15 cm iron sampling will be compared with the results obtained with the 2.5 cm sampling of the new modules.

2. DESCRIPTION OF THE MODEL CALORIMETER

A module of the calorimeter (Fig. 1) consisted of five $60 \times 60 \text{ cm}^2$ sheets of 2.5 cm thick iron, each followed by 0.5 cm of scintillator material^{*)} divided into four 15 cm wide strips. The five scintillators along the beam direction were viewed by a single 3 inch photomultiplier tube^{**)} by an adiabatic 10-strip light guide. Scintillators in successive modules were arranged in vertical and horizontal strips, alternately. The entire test calorimeter consisted of 16 such modules, corresponding to a total length of 200 cm of iron and 40 cm of scintillator.

Data were taken at the CERN SPS at negative pion momenta of 10, 15, 20, 30, 50, 75, 100, 120, and 140 GeV/c. For momenta of 50 GeV/c and below, the electrons present in this beam could be tagged with a helium threshold Čerenkov counter. Above 50 GeV/c the electron component of the beam was less than 1%. A pure pion beam could be obtained by placing a lead filter in the beam line. Typical beam intensities were 50 particles per pulse in a 30 msec spill with a fractional momentum spread of 0.75%.

*) Plexipop 1922, Röhm GmbH, Darmstadt, Germany.

***) SRC L75B07 (SRC Laboratories, Fairfield, Connecticut, USA).

Event triggers were based on a coincidence of two $4 \times 4 \text{ cm}^2$ scintillators in the beam. The signals from the 64 photomultipliers were digitized using analogue to digital converters (ADC) with a parabolic characteristic. In order to extend the dynamic range of the system, each photomultiplier signal was also attenuated by a factor of eight, mixed with similarly attenuated signals from three other counters, and separately digitized. The groups of four channels were chosen so that the occurrence of more than one overflow among the four was extremely unlikely. The attenuation factors for the mixed channels and the ADC characteristics were established periodically with a mercury pulser calibration system. The digitized information from each of the 80 ADC's (64 photomultipliers and 16 mixed channels) was converted to input charge and to energy deposition.

3. MUON CALIBRATION

To establish the response of the 64 elements of the test calorimeter we took advantage of the presence of muons produced in beam lines upstream of the calorimeter during the long (1-2 sec) 200 GeV proton extraction of the SPS. A pair of hodoscope arrays just upstream of the calorimeter and a second pair beyond a 1.5 m block of iron downstream of the calorimeter (see Fig. 1) provided muon triggers. The 3.5 m of iron between the hodoscope arrays ensured a minimum muon energy of about 5 GeV. Muon data were taken concurrently with hadron data during each beam spill cycle, but within a separate time gate. An amplifier was switched on during this gate, its gain (~ 30) having been chosen to provide input charges to the ADC's comparable in magnitude to those obtained from hadron showers.

In the analysis of the muon data it was required that only a single photomultiplier in each calorimeter module receive a signal from the muon track. In addition, the track had to intercept each counter within 15 cm on either side of the center, the region in which most of the hadron shower energy was deposited.

The muon pulse-height spectra for each of the 64 counters were fitted individually by a Landau distribution convoluted with a gaussian

(see Fig. 2). This function is not a precise representation of the observed spectra, but it was found that fits of good quality were obtained if the tails of the distributions were excluded. The fitted peak values, corresponding to the most probable energy loss, are insensitive to the cut on the tails and to the width of the gaussian smearing function. These peak values, which are expected to be insensitive to the details of the muon energy spectrum, define the pulse height of an "equivalent particle" (ep). The widths of the muon distributions correspond to approximately 80 photoelectrons per minimum ionizing particle traversing five scintillator sheets. The photomultipliers have been balanced to give muon pulse heights agreeing to within about 20%. Muon pulse heights measured at different times during the data taking run show variations of the order of 1-2%.

4. RESULTS FROM THE TEST CALORIMETER

4.1 Calorimeter response and energy resolution

The criteria for accepting a hadron or electron event for the final data sample are:

- a) An interaction takes place in the first 37.5 cm of iron, in order to assure adequate longitudinal containment of the shower.
- b) None of the scintillators in the front hodoscope gave a signal (the hodoscope had a 4×4 cm² hole along the beam axis). This requirement eliminates events with additional particles originating upstream and also removes events for which backscattered particles were detected in the hodoscope.
- c) No signal in the downstream hodoscope. This requirement serves to eliminate beam muons from the sample.

After applying these criteria, 5000 to 10000 events survive for each beam energy. The data from each ADC are converted to energy units [numbers of equivalent particles (nep)] and summed to give the total measured energy. Typical energy distributions for pions and electrons are shown in Fig. 3. Mean energies and the widths of the distributions in terms of equivalent particles are given in Table 1a and Fig. 4a and b (open symbols). The errors given in Table 1 are statistical

only. Systematic uncertainties for the unweighted response come from an uncertainty in the definition of an "equivalent particle", derived from the muon peak and are of the order of several percent. Uncertainties due to the beam energies are estimated to be less than 1% at high energies and less than 2% at low energies. To study possible non-linearities in the electronic response of the calorimeter, data were taken at 140 and 50 GeV with two different photomultiplier high voltage settings. The photomultipliers have been operated at 1510 and 1600 V, thus changing the relative charge output by a factor of ~ 1.6 . The energy response for the two high voltage settings agrees to better than 1% for both the 50 and the 140 GeV data (see Table 2).

The longitudinal development of the shower is given in Table 3. We have investigated the effect of inadequate longitudinal containment of the shower on the response and energy resolution, see Table 4. The detected energy was summed over a variable number of modules, starting from the origin of the shower. For 140 GeV pions, reducing the number of modules from 14 to 12, corresponding to 175 and 150 cm of iron, diminishes the detected energy by on average 0.2%; the width increases by a factor of 1.02. Furthermore, only 0.1% of the shower energy is detected in the fourteenth module. We conclude that the measurements presented here are not significantly affected by the finite length of the test calorimeter.

The transverse containment of the showers was studied by displacing the calorimeter sideways with respect to the beam. We estimate that no more than 2% of the energy escaped our 60 cm wide calorimeter when the beam was centered. Although we were unable to determine the effect of this leakage on the energy resolution, we believe it to be small.

4.2 Calorimeter response to electrons and hadrons

Comparing the response to electrons with the response to hadrons we find that 10 GeV electrons deposit $\sim 30\%$ more visible energy than 10 GeV hadrons. This difference between electromagnetic and hadronic showers decreases with energy, and at 140 GeV hadronic showers are deficient in visible energy by only 10-15%. This observation supports the picture of an increasingly important role being played by the electromagnetic components of the shower at higher energies, see e.g.

Monte Carlo calculations in Refs 3 and 4. Similar results on calorimeter response to electrons and hadrons have been found by several experiments⁵⁻⁹⁾ with comparable calorimeters (see Fig. 5).

4.3 Improved resolution by weighting

At higher pion energies the pulse height distributions have a non-gaussian shape characterized by excess events on the high side (see Fig. 3). A study of individual events with an unusually high pulse height showed that the showers contributing to this part of the distribution had very large energy depositions in typically one or two calorimeter elements.

Figure 6a is a scatter plot of maximum energy deposition in any single counter against the total shower energy for 140 GeV incident pions. An important feature of Fig. 6a is that the total energy distribution becomes narrower for large localized energy depositions. These observations are consistent with the interpretation that the high energy tail of the distributions is due to showers with an unusually large electromagnetic component. The electromagnetic component, mostly due to π^0 decay, produces high concentrations of ionization, since the radiation length is shorter than the nuclear mean free path. The relative amount of light produced in the scintillator by the electromagnetic showers is larger than for hadrons, since there are no losses to nuclear excitation and binding, and smaller saturation losses associated with very slow, highly ionizing particles.

This picture is confirmed by a Monte Carlo calculation¹⁰⁾ simulating the response of 140 GeV hadrons for the geometry of the test calorimeter. The total energy distribution obtained this way shows the same qualitative features as the data, see Fig. 7.

*We have been able to improve the energy resolution for hadrons by weighting individual counter responses so as to reduce the fluctuation due to the electromagnetic component described above. A simple algorithm which works rather well reduces the response of individual counters by a fraction proportional to the unweighted response (E)¹¹⁾:

$$E'_i = E_i(1 - C'E_i) .$$

In this expression, $C'E_i$, the reduction in response, was not permitted to be larger than 30%. Since it was found that the optimum value for C' was dependent on the incoming pion energy, C' was parametrized to make this procedure useful when the hadron energy is not known a priori. A simple expression that works moderately well over our energy range is

$$C' = C/\sqrt{E_{\text{tot}}} ,$$

where E_{tot} is the total unweighted energy in nep and $C = 0.03(\text{nep})^{-\frac{1}{2}}$. A variation of C changes the energy resolution for 140 GeV data as shown in Fig. 8. It should be noted that this parametrization optimizes the resolution for a particular energy range, and cannot be expected to be very good in other energy domains.

This weighting procedure reduces the correlation between maximum energy deposition and total energy as shown in Fig. 6b. The energy distributions have become narrower and more symmetric in shape. The weighted energy distributions were fit with a gaussian to determine the peak position and the width in terms of equivalent particles (nep), see Table 1b. The full symbols in Fig. 4a and b show the response and the obtained resolution as a function of incident beam energy.

The resolution for hadronic showers improves by 30% at 140 GeV and by 10% at 10 GeV compared to the unweighted results. The energy dependence is well described by

$$\frac{\sigma}{\text{mean}} = 0.58/\sqrt{E_{\text{beam}}} .$$

For electrons one obtains

$$\frac{\sigma}{\text{mean}} = 0.23/\sqrt{E_{\text{beam}}} .$$

As expected no improvement was found compared to the unweighted distributions in the case of electrons.

The response of the calorimeter to hadrons becomes more linear with energy after the weighting procedure.

5. RESULTS FROM THE WA1 5 cm MODULES

In addition to the test calorimeter, three of the 5 cm iron sampling modules of the existing CDHS detector²⁾ have been calibrated in the same beam and at the same energies as described above. Each of these modules consists of 15 iron plates, 5 cm thick, each followed by a plane of eight scintillators^{*)}, 0.6 cm thick and 45 cm wide (see Fig. 9). The scintillators are viewed by photomultipliers^{**)} at each end. The three modules provide a total length of 2.25 m of iron; their diameter is ~ 3.75 m.

Apart from the photomultipliers the same electronics as in the test calorimeter have been used. The procedure to extract the calorimeter response is the same as has been described above. However, in this case, the mean pulse height, instead of the most probable pulse height, of cosmic muons was used to establish the reference charge of an "equivalent particle" and we have not attempted to make an absolute comparison of the calorimeter responses.

The same weighting technique as in Section 4.3 has been applied to improve the resolution. The parameter which gives the optimal results is $C' = 0.02/\sqrt{E_{\text{tot}}}$. As before, significant improvement in energy resolution at high energies and more linear response with energy are obtained.

For 5 cm sampling thickness the resolution as a function of energy is well described by

$$\frac{\sigma}{\text{mean}} \approx 0.70/\sqrt{E_{\text{beam}}} .$$

6. RESOLUTION AS A FUNCTION OF SAMPLING THICKNESS

Coarser sampling for the 5 cm modules has been simulated by summing the energy deposited in every second and third scintillator plane. The resolution for 10 cm sampling is

$$\frac{\sigma}{\text{mean}} \approx 0.98/\sqrt{E_{\text{beam}}} ,$$

*) NE110, Nuclear Enterprise Ltd., Scotland.

***) 150 AVP, Philips, France.

and for 15 cm sampling it is

$$\frac{\sigma}{\text{mean}} \approx 1.35/\sqrt{E_{\text{beam}}} .$$

The resolutions obtained with the 5, 10, and 15 cm sampling modules can be compared with the 2.5 cm sampling data from the test calorimeter.

To be independent of the details of the weighting procedure (as e.g. the choice of the optimal weighting parameter C) a comparison has been made on the basis of the unweighted results.

Figure 10 shows the hadron energy resolution as a function of \sqrt{t} , where t is the sampling thickness in cm of iron. Results are given for 15, 50, 100 and 140 GeV beam energy.

The improvement in resolution with decreasing sampling thickness between 15 and 5 cm is consistent with a \sqrt{t} behaviour. Going to smaller sampling thicknesses the gain in resolution seems to become smaller.

7. CONCLUSION

We have measured the response and the resolution of an iron-scintillator test calorimeter with 2.5 cm iron and in the 5 cm sampling WAl modules. Compared to the 5 cm modules a $\sim 20\%$ gain in resolution could be achieved for 2.5 cm sampling thickness. At 10 GeV the calorimeter response to electrons is about 30% higher than to hadrons. We have observed a tail on the high side of the pulse height distribution for high energy hadrons which we believe to be due to an unusually large electromagnetic component in some of the showers.

A weighting procedure was found to compensate for this effect, which results in gaussian response curves, nearly linear dependence of response on hadron energy above 30 GeV, and improved energy resolution following a $0.58/\sqrt{E}$ law. The energy resolution for electrons is approximated by a $0.23/\sqrt{E}$ behaviour.

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	beam energy [GeV]	pions			electrons		
		mean [nep]	σ [nep]	$\frac{\sigma}{\text{mean}}$	mean [nep]	σ [nep]	$\frac{\sigma}{\text{mean}}$
a) unweighted	10	40.9±1.2	8.7±1.2	0.213	55.8±0.3	4.5±0.3	0.080
	14.8	64.3±0.2	10.4±0.1	0.161	83.9±0.1	5.3±0.1	0.063
	19.85	89.3±0.2	12.6±0.1	0.141	114.1±0.2	6.3±0.2	0.055
	29.5	137.2±0.2	16.3±0.1	0.119	169 ±0.5	7.4±0.4	0.044
	49.35	234.8±0.2	22.9±0.2	0.097	281 ±1.0	7.9±0.9	0.028
	74.1	354 ±0.4	30.5±0.3	0.086			
	98.8	482 ±0.5	40 ±0.5	0.083			
	117.3	586 ±0.5	48 ±0.5	0.082			
137.8	692.7±0.7	55 ±1.0	0.080				
b) weighted	10	38.8±1.2	8.0±0.2	0.203	49.6±0.3	4.2±0.2	0.084
	14.8	60.3±0.2	9.2±0.1	0.151	74.1±0.1	4.6±0.1	0.062
	19.85	83.8±0.2	10.9±0.1	0.130	99.3±0.2	5.5±0.1	0.055
	29.5	127.8±0.2	13.4±0.1	0.105	144.3±0.5	6.6±0.4	0.046
	49.35	216.6±0.2	17.3±0.1	0.079			
	74.1	323 ±0.4	21.5±0.2	0.067			
	98.8	432 ±0.5	24.9±0.3	0.058			
	117.3	521 ±0.5	27.8±0.4	0.053			
137.8	611.5±0.5	30.5±0.5	0.050				

TABLE 1

Energy response and resolution for pions and electrons in nep.

a) unweighted and b) after the weighting has been applied.

The errors are statistical only.

	photomultiplier HV		difference
	1510 v	1600 v	
muon peak (amplified)	~ 70 pC	~ 110 pC	~ 60%
50 GeV π^- unweighted	235.8 nep	233.8 nep	1%
140 GeV π^- unweighted	692.4 nep	693.0 nep	0.1%
50 GeV π^- weighted	216.7 nep	216.5 nep	0.1%
140 GeV π^- weighted	610.0 nep	613.0 nep	0.5%

TABLE 2

Calorimeter response to 50 GeV and 140 GeV pions at two different photomultiplier high voltage settings. Also given are the typical charge outputs (amplified) for a muon for the two voltages.

beam energy (GeV)	Modules of 12.5 cm iron													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
10.0	0.51	0.34	0.09	0.03	0.014	0.008	0.002							
14.8	0.39	0.36	0.13	0.05	0.028	0.014	0.007	0.003						
19.85	0.34	0.37	0.15	0.07	0.04	0.020	0.010	0.005	0.002					
29.5	0.28	0.36	0.17	0.08	0.05	0.03	0.014	0.008	0.004	0.002				
49.35	0.22	0.35	0.19	0.10	0.06	0.04	0.02	0.012	0.007	0.004	0.002			
74.1	0.18	0.34	0.19	0.11	0.07	0.04	0.03	0.016	0.009	0.005	0.003	0.002		
98.8	0.16	0.33	0.20	0.12	0.08	0.05	0.03	0.02	0.011	0.007	0.004	0.002	0.001	
117.3	0.15	0.32	0.20	0.12	0.08	0.05	0.03	0.02	0.012	0.008	0.005	0.003	0.002	0.001
137.8	0.13	0.31	0.20	0.12	0.08	0.06	0.04	0.02	0.015	0.009	0.005	0.003	0.002	0.001

TABLE 3

Longitudinal shower development in iron. Given is the fraction of the total shower energy detected per module of 12.5 cm iron. Module 1 is the module in which the shower originates.

	beam energy (GeV)	Modules of 12.5 cm iron															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14		
a)	10.0	0.50	0.80	0.89	0.93	0.95	0.96	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00
	19.85	0.69	0.83	0.91	0.95	0.97	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00
	49.35	0.56	0.74	0.84	0.91	0.94	0.97	0.98	0.98	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00
	98.8	0.48	0.68	0.80	0.87	0.92	0.95	0.97	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00
	137.8	0.44	0.65	0.77	0.85	0.90	0.94	0.96	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00
b)	10.0	1.09	1.11	1.11	1.09	1.08	1.06	1.05	1.05	1.05	1.05	1.04	1.03	1.02	1.00	1.00	1.00
	19.85	1.63	1.55	1.36	1.22	1.13	1.08	1.06	1.06	1.04	1.04	1.03	1.02	1.02	1.01	1.00	1.00
	49.35	2.5	2.4	2.1	1.78	1.52	1.32	1.18	1.09	1.09	1.05	1.03	1.02	1.02	1.01	1.00	1.00
	98.8	2.9	2.9	2.6	2.2	1.82	1.53	1.34	1.19	1.09	1.09	1.04	1.01	1.00	1.00	1.00	1.00
	137.8	3.3	3.5	3.2	2.7	2.2	1.84	1.54	1.31	1.14	1.04	1.02	1.00	1.00	1.00	1.00	1.00

r.m.s.

TABLE 4

The calorimeter response and resolution as a function of the number of modules over which the shower energy is summed. Given are a) the mean pulse height and b) the width of the pulse height distribution normalized to the case of summing over 14 modules.

FIGURE CAPTIONS

- Figure 1 : The test calorimeter and the detailed structure of a module.
- Figure 2 : Muon pulse height distribution for a track traversing the five scintillator sheets of a single module. The fitted smeared Landau distribution function is also shown.
- Figure 3 : Total energy distributions for pions of 140 GeV and for electrons of 15 GeV. Also shown is the energy distribution for 75 GeV and 140 GeV pions after the weighting procedure, described in the text, has been applied to individual counter responses. The curve is a Gaussian fit to the 140 GeV energy response after weighting.
- Figure 4 : a) The calorimeter response to hadrons and electrons in terms of numbers of equivalent particles (nep) per incident energy (GeV) against the energy of the incident particle, E_{beam} in GeV.
 b) The width of the energy distributions. $(\sigma/\text{peak}) \cdot \sqrt{E_{\text{beam}}}$ against incident energy, E_{beam} in GeV.
- Figure 5 : Difference between the calorimeter response to hadrons and electrons:
 ● hadron response divided by measured electron response;
 ○ hadron response divided by extrapolated electron response.
 The other data points are from:
 × Ref. 5, 5 cm iron sampling (39.4 g/cm²);
 △ Ref. 6, 2 cm iron sampling (15.7 g/cm²);
 □ Ref. 7, 13 and 26.3 g/cm² tungsten scintillator sampling;
 ◇ Ref. 8, 1.5 mm iron sampling (1.2 g/cm²).
- Figure 6 : a) A scatter plot of maximum energy deposition in a single counter against total energy of the shower for 140 GeV incident pions.
 b) Also shown is the same scatter plot after the weighting procedure has been applied.

- Figure 7 : Total energy distribution for 140 GeV hadrons. Data and Monte Carlo events have been normalized to the same number of events.
- Figure 8 : The width of the hadronic total energy distribution as a function of C , the parameter which determines the weighting factor applied to each counter.
- Figure 9 : a) Front and side view of one of the 5 cm sampling WA1 modules. The pion beam hits the modules in the area indicated by the arrow.
b) Layout of one scintillator plane.
- Figure 10 : The effect of sampling thickness on the resolution. The resolution (unweighted) in terms of $(\sigma/\text{peak}) \cdot \sqrt{E}$ is given for four iron scintillator thicknesses, $t = 2.5, 5, 10$ and 15 cm, as a function of \sqrt{t} .

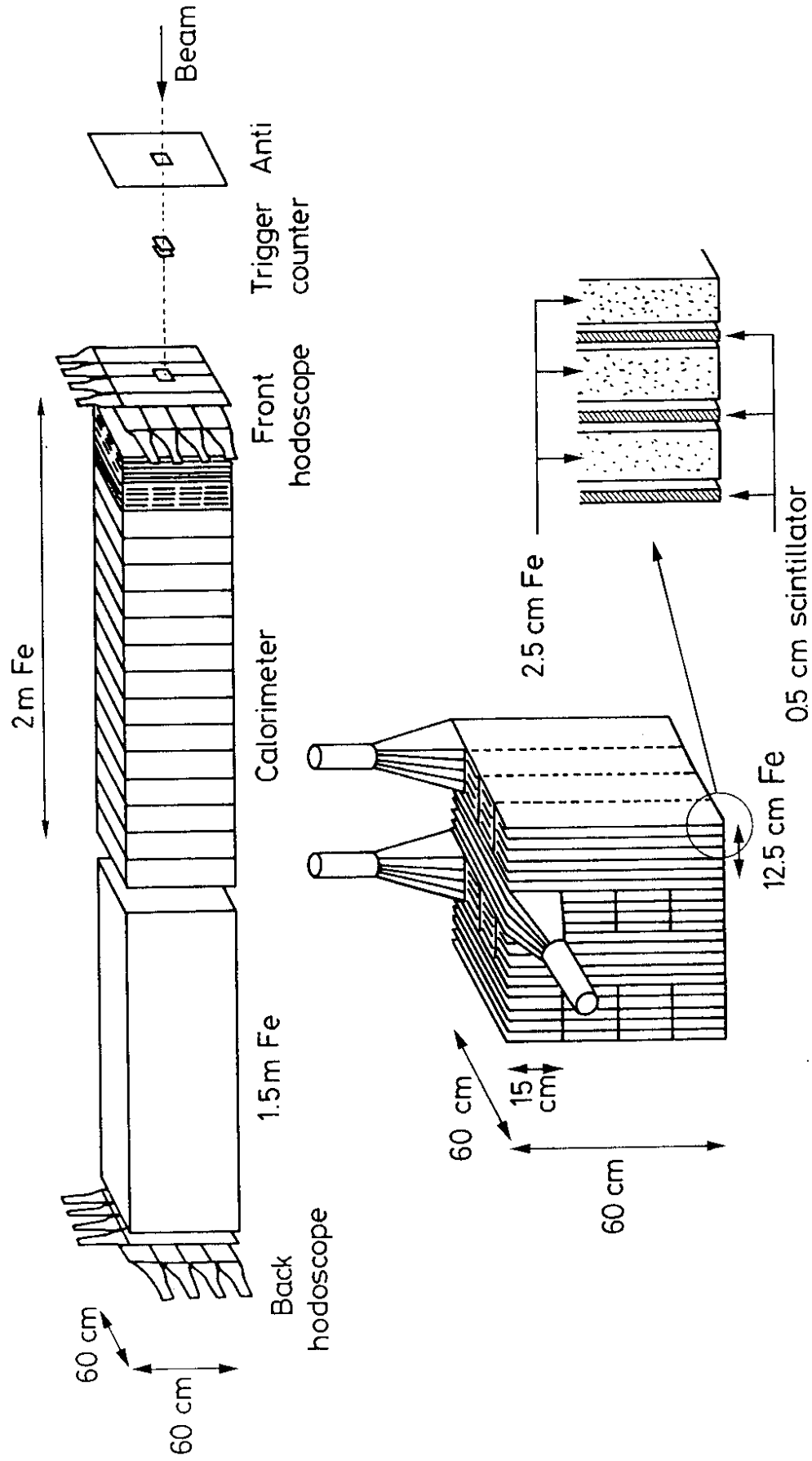


FIG.1

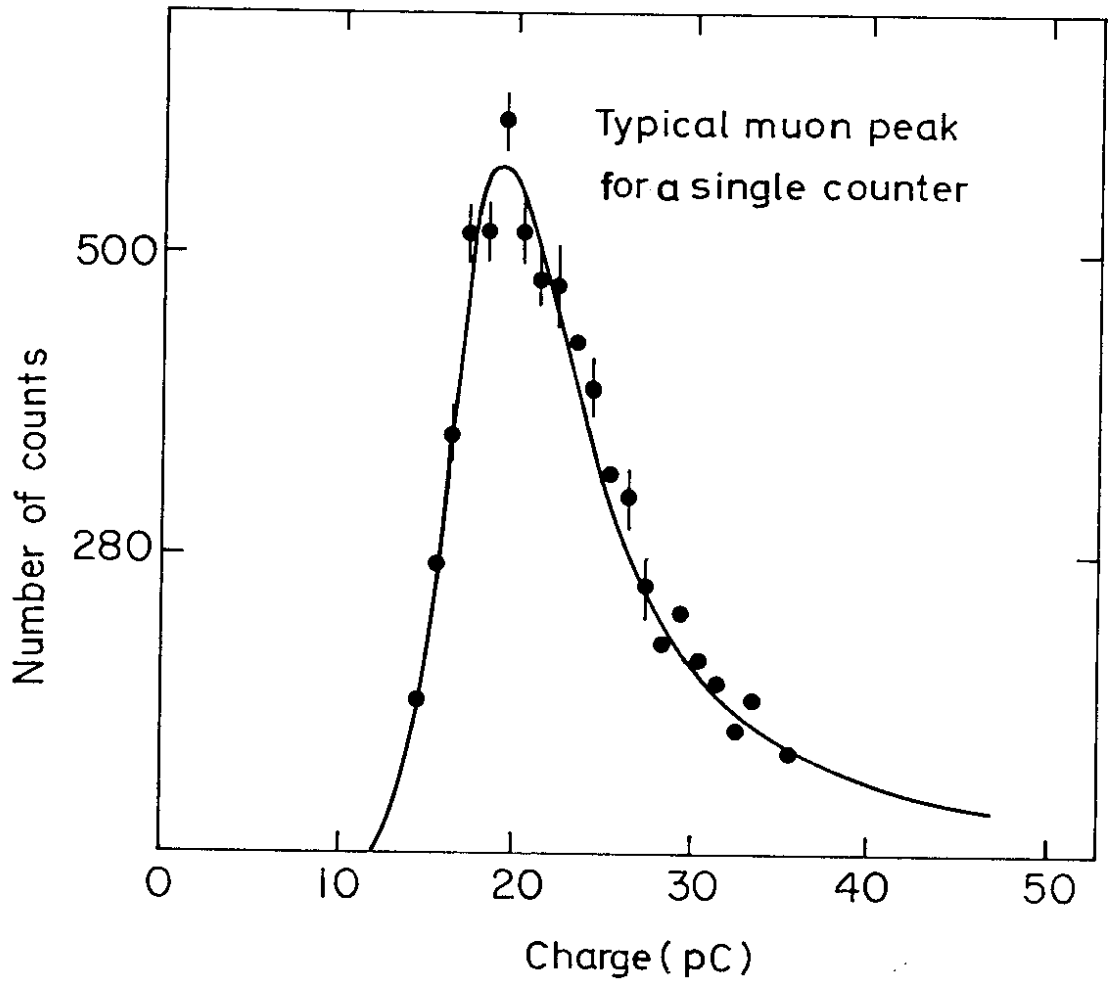


FIG. 2

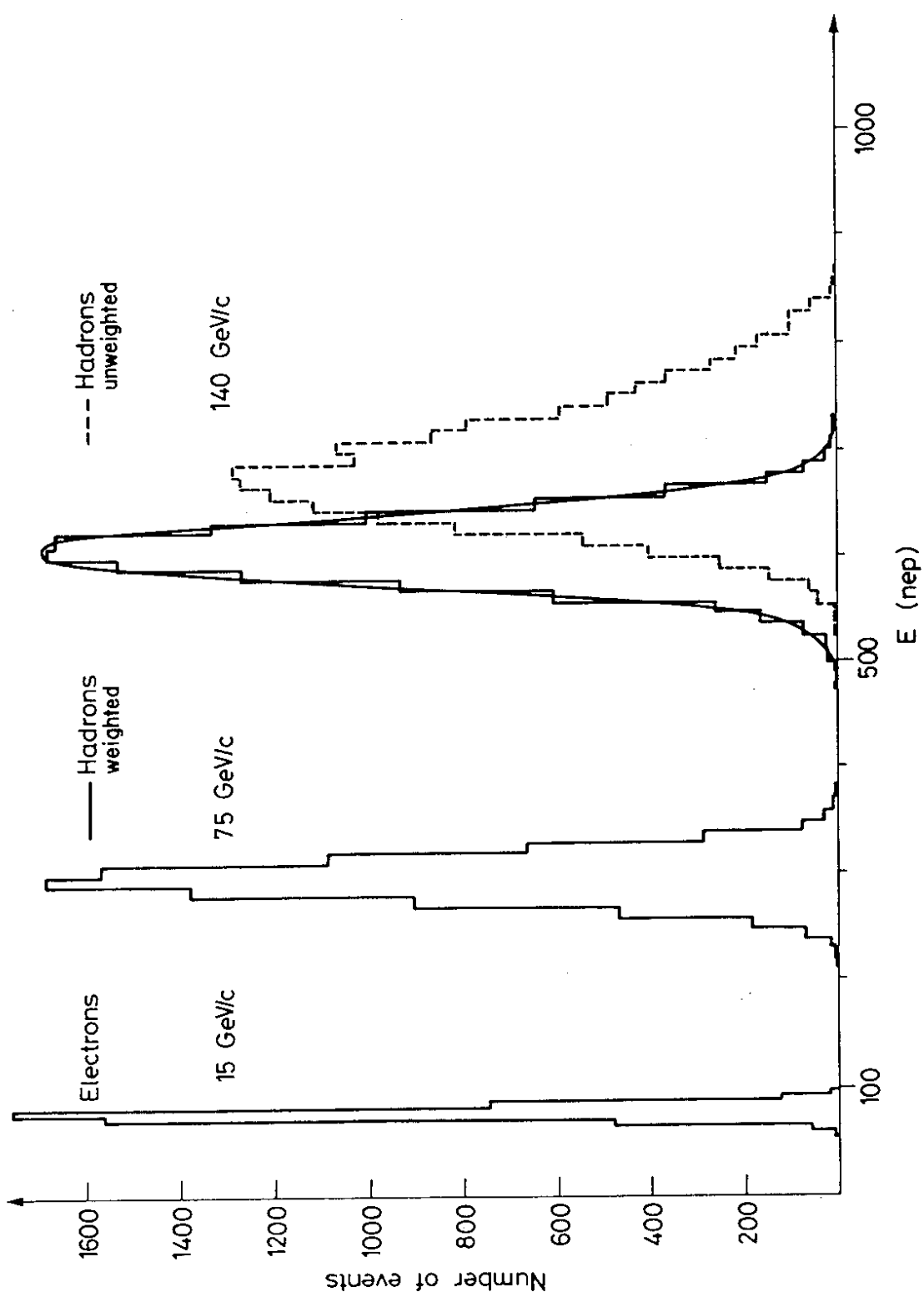


FIG. 3

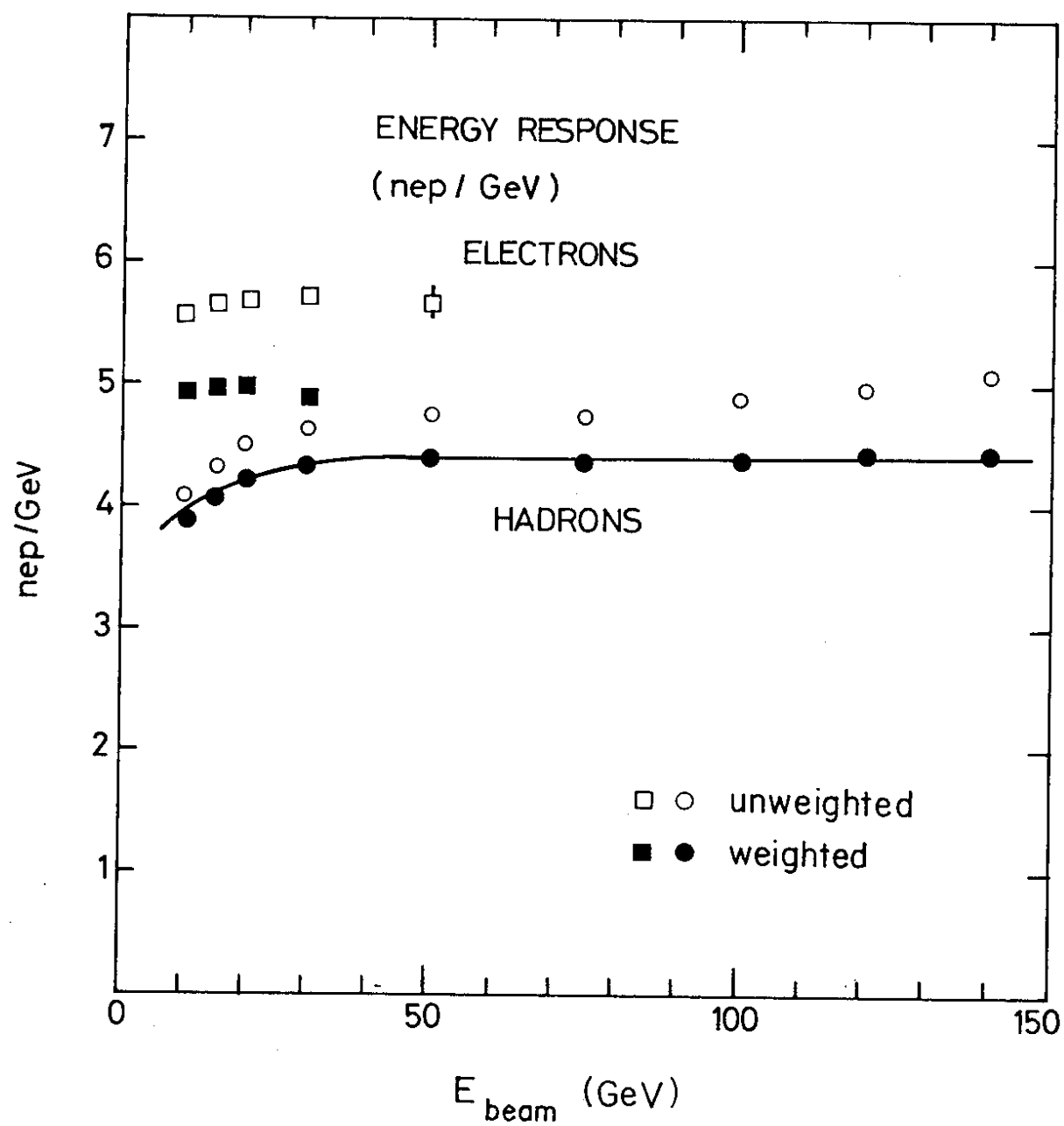


FIG. 4 a

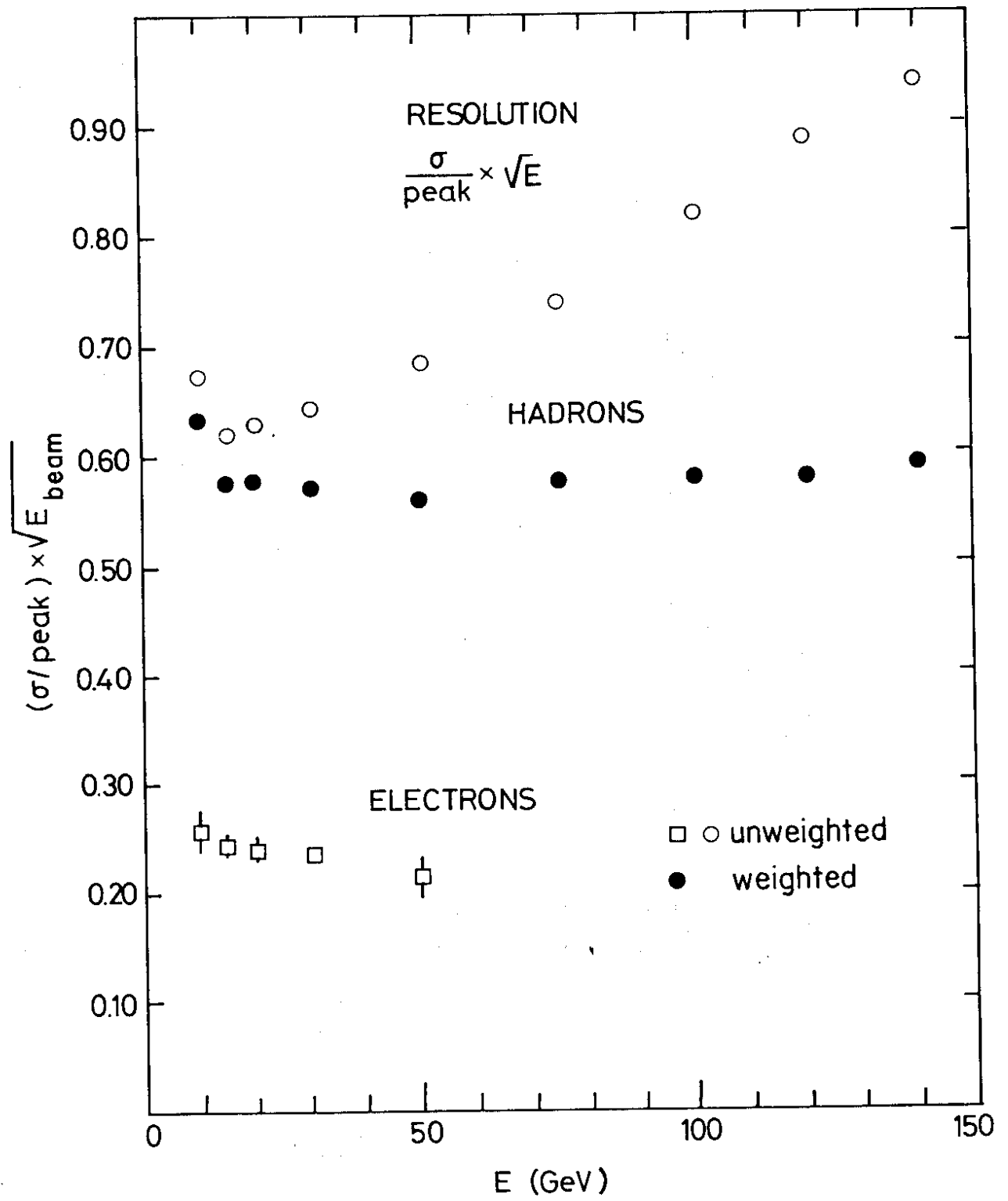


FIG. 4 b

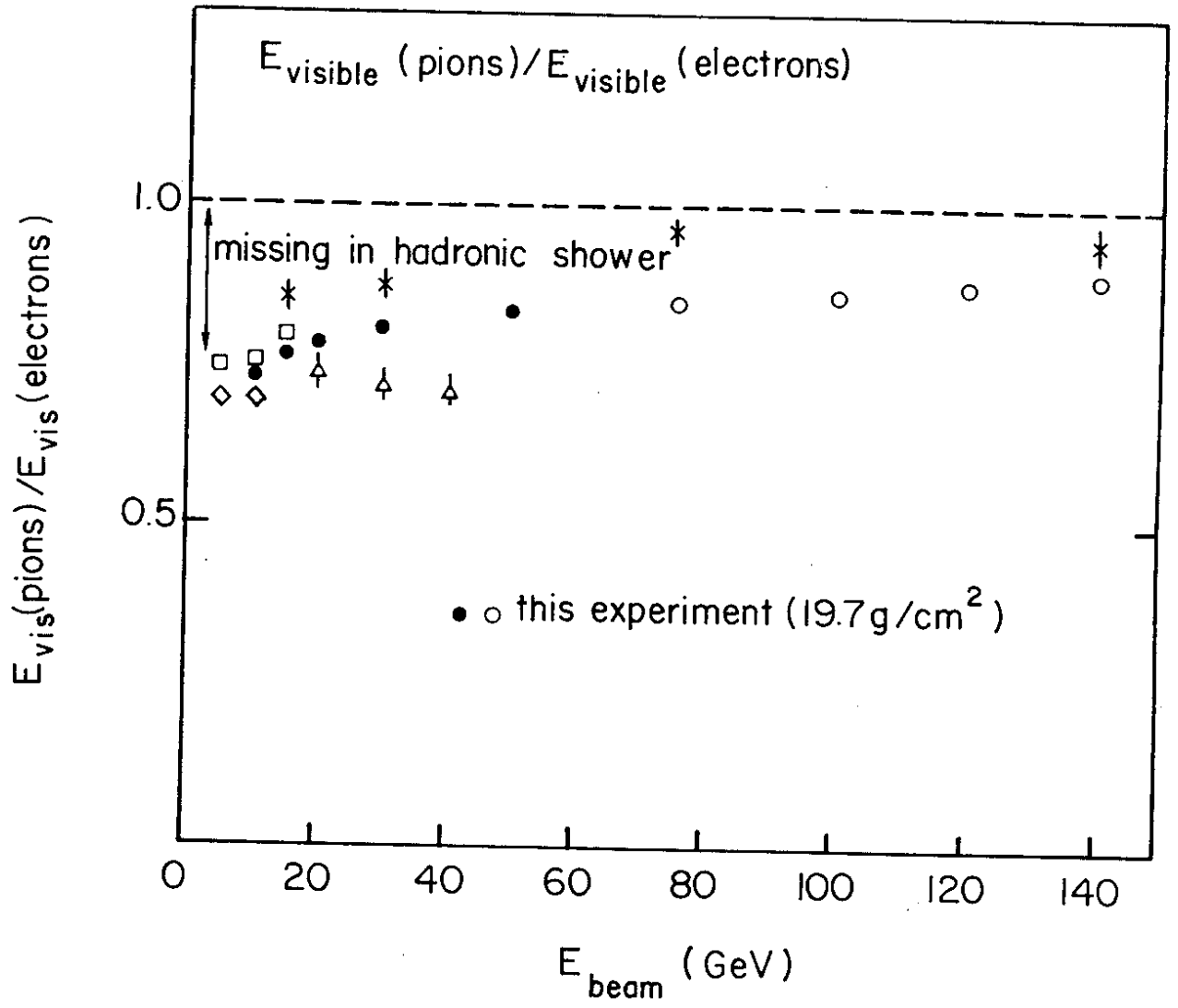


FIG. 5

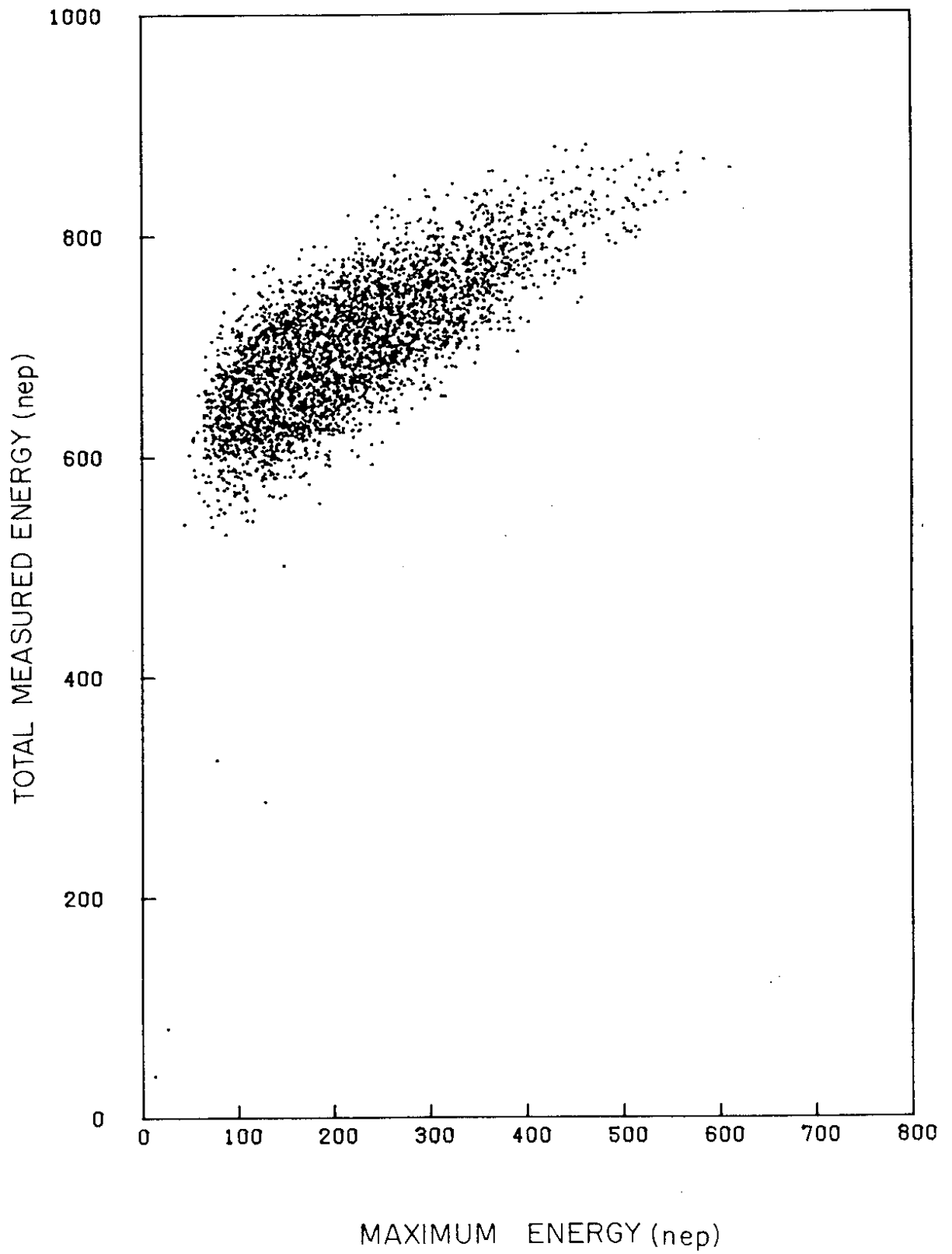


FIG. 6 a

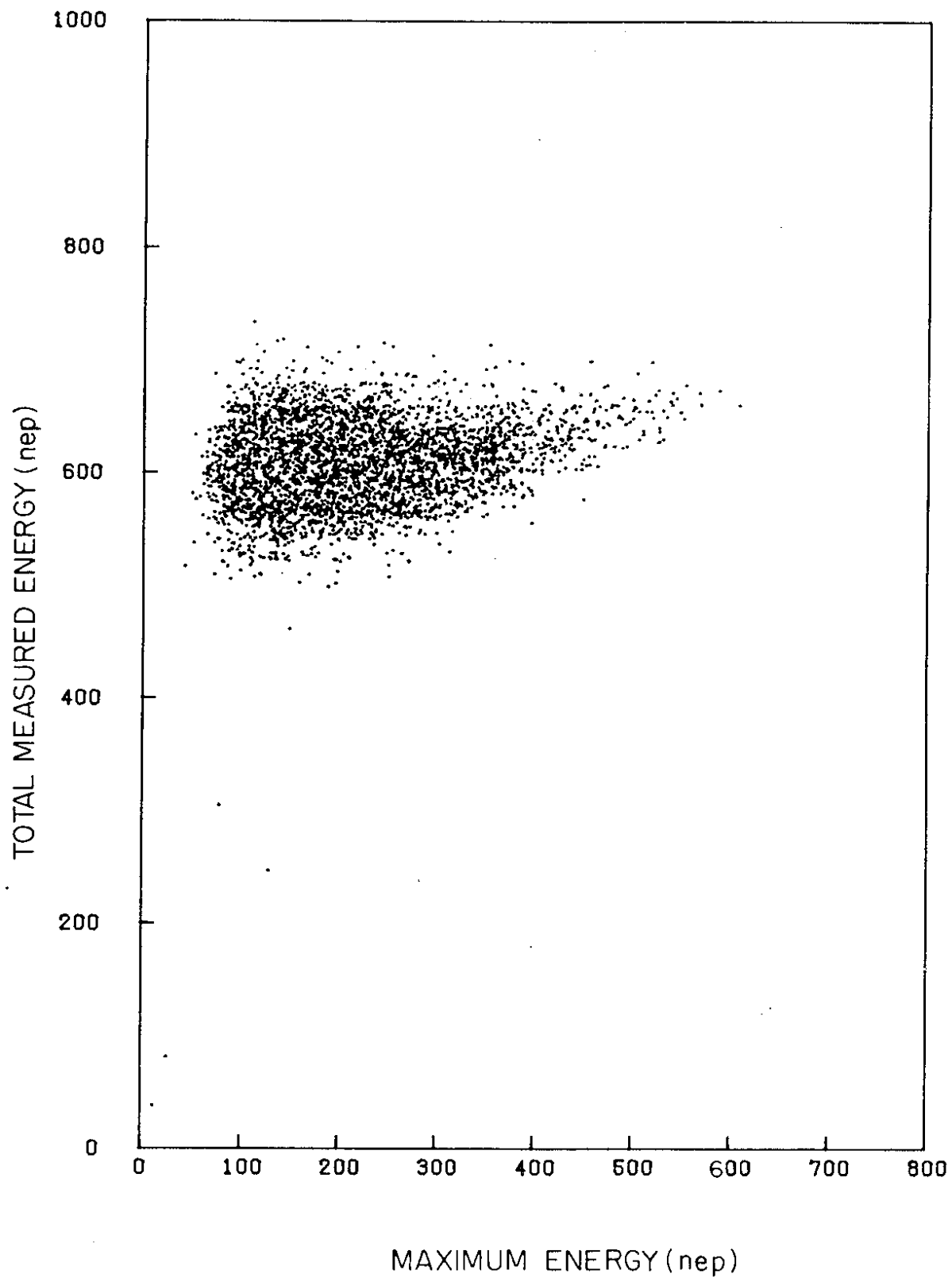


FIG. 6 b

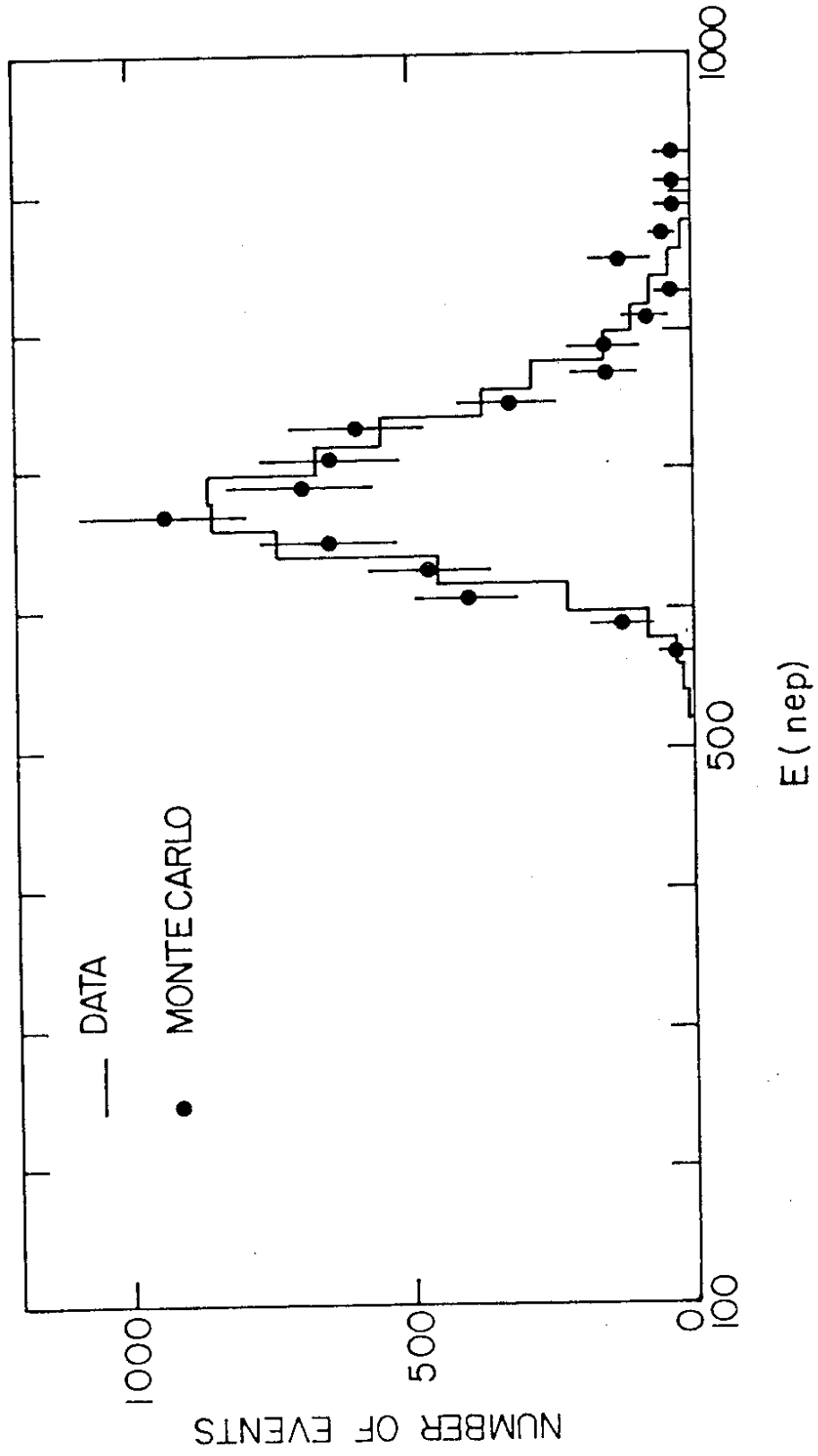


FIG. 7

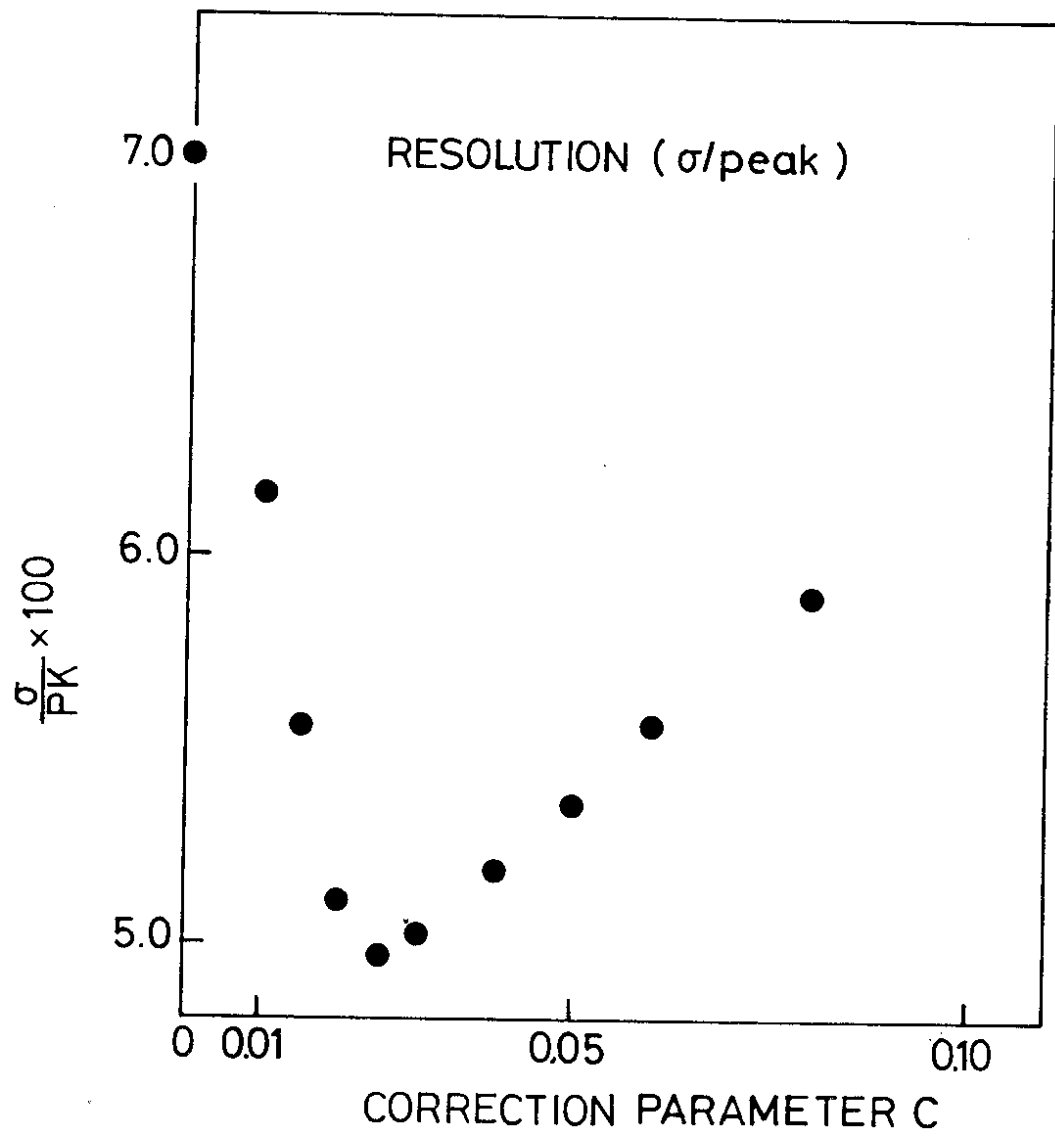


FIG. 8

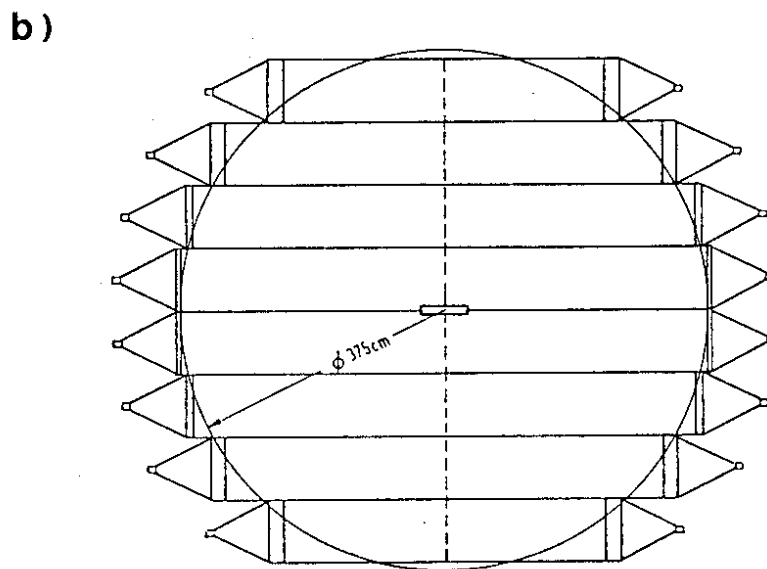
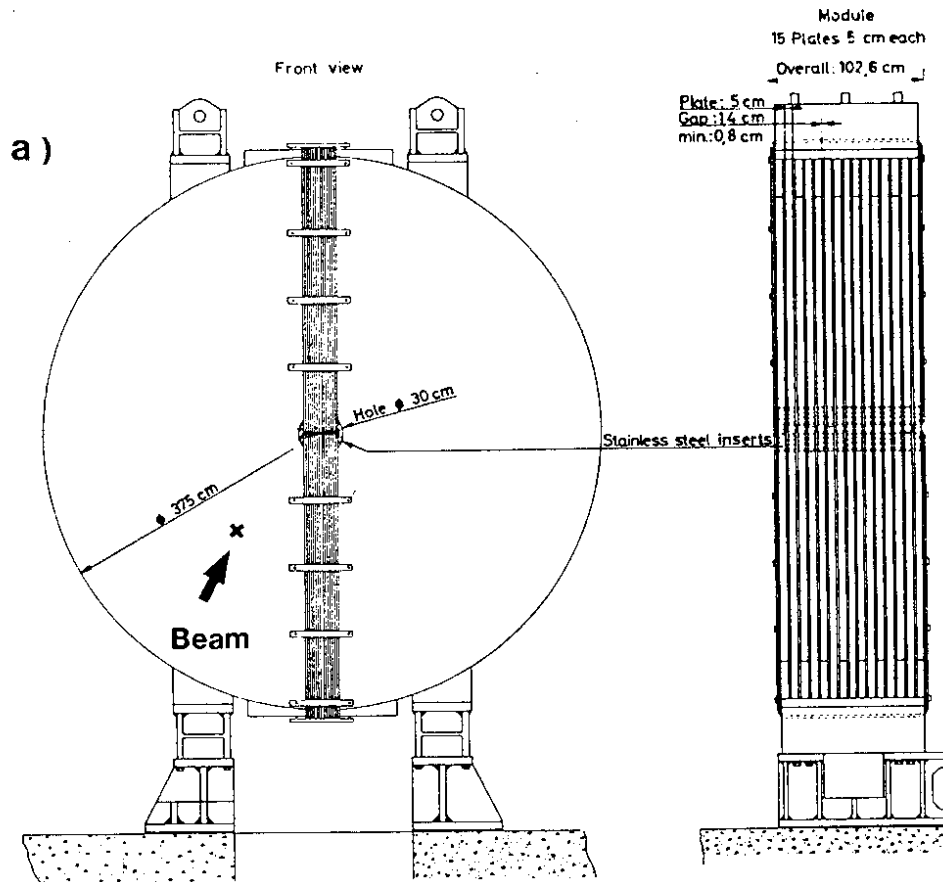


FIG. 9

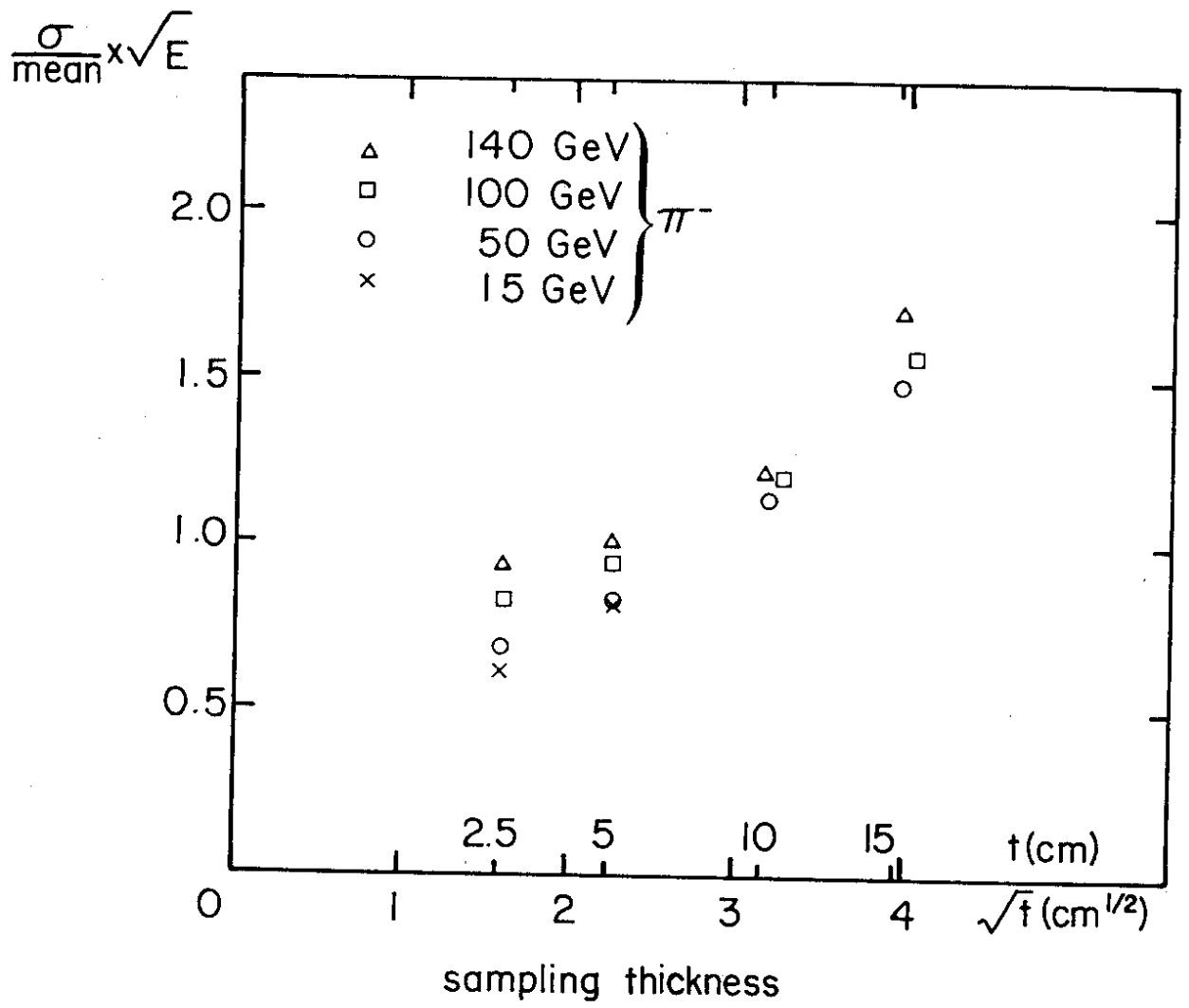


FIG. 10