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RESULTS FROM A TEST OF A Pb-Cu LIQUID ARGON CALORIMETER

by

H1 Collaboration

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ABSTRACT

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ABSTRACT

Results from a test with a lead-copper calorimeter in liquid Argon are presented. The electromagnetic energy resolution obtained is $10\%/\sqrt{E}$. For hadronic showers the software weighting technique is demonstrated to work. A hadronic energy resolution of $50\%/\sqrt{E}$ is found.

I. INTRODUCTION

In order to measure the energy of single particles and jets, the forthcoming H 1 experiment¹ at HERA relies heavily on liquid Argon (LAr) calorimetry. The energy and angles of electrons and photons will be measured in a first section with lead absorbers whereas the more penetrating hadrons are also recorded in a second section with stainless steel absorbers.

Here we report on a test experiment with the main goal to demonstrate that a non compensating lead/copper calorimeter performs as anticipated¹, in particular to verify that the energy resolution can be improved by corrections of π^0 fluctuations. This is expected by Monte Carlo studies² and has been shown in previous experiments for other types of calorimeters^{3,4}.

The experimental set-up is described in section II. Section III gives results on the performance of the calorimeter for incident electrons (III.2) and pions (III.3). We discuss only hadron showers which are fully contained in the LAr calorimeter. A more detailed report⁵ containing also results for showers penetrating in a gas tail catcher is in preparation.

II. EXPERIMENTAL SET-UP

II.1. INTRODUCTION

Using a CERN-SPS-beam, a series of run-periods between June and November 1986 was dedicated to test essentially two different versions of calorimeter configurations. A hadronic copper stack was common to both versions. In the first four run periods, a conventional electromagnetic (e.m.) stack and an additional stack using iron as tail catcher were installed inside the LAr (Version A). In the last run period, these stacks were replaced by an e.m. stack exploiting the technique of high resistive coating and a tail-catcher which operated with plastic streamer tubes outside of the LAr (Version B). An overview of the basic parameters is given in Tab. 1. All stacks operating in LAr were housed in a cryostat. The Fig. 1 sketches the layout of the experiment.

II.2. THE BEAM AND ITS DETECTORS

II.2.1. THE BEAM

The calorimeter was installed in the H6 beam⁶ of the North Hall 1 at the CERN SPS. The beam optics is summarized in Fig. 2. This beam provided electrons, muons, pions, protons, and kaons in the momentum range $5 \leq p \leq 250$ GeV. Most of the data were taken with electrons or pions. The beam was run in two modes:

a) Secondary mode ($p \geq 100$ GeV/c) In this mode, the beam was run with the primary target only. Electrons and pions were separated spatially by synchrotron radiation⁷. The typical loss of energy for electrons occurs mainly in BM3 and is for example about 2% at 120 GeV. When the beam after BM3 is tuned for electrons, the two profiles are easily separable at the collimator C3. The momentum spread was typically $\Delta p/p = 0.8\%$ for e and $\Delta p/p = 0.05\%$ for π .

b) Tertiary mode⁸ ($p \leq 100$ GeV/c) A secondary target (aluminum or polyethylene) was installed just after the collimator C3. The first part of the beam (between the two targets) was tuned for the highest possible energy (150–250 GeV), the second part for the requested low momentum. The tertiary particles (e or π) were tagged by two Cerenkov counters with ring selection (CEDAR's)⁹ in the momentum range $10 \leq p \leq 80$ GeV. The momentum spread was typically $\Delta p/p = 0.8\%$.

II.2.2. THE BEAM DETECTORS

Two multiwire proportional chambers (MWPC's) were installed in front of the calorimeter. Each has an active region of 25×25 cm² and consists of a horizontal and vertical anode plane. With the distance between the two chambers of 19 cm and the position resolution of 2 mm (FWHM). The chambers were used to monitor the beam geometry during tuning and to select events with only one hit per plane in the data analysis, removing therefore showers originating from the material located upstream in the beam (0.44 radiation lengths (X_0)).

II.2.3. THE TRIGGER DETECTORS

The beam particles were defined by the two CEDAR's, the two MWPC's, and two scintillation counters (B_1 and B_2) with lateral dimensions of 3×3 cm². Beam halo particles were detected by a set of three scintillator walls: one in front of the calorimeter (veto wall, VM), a second one behind the cryostat (M1), and a third wall (M2) behind the 1.6 m long beam-dump of iron (see Fig. 1). Each wall consisted of 10 scintillation counters, each 120 cm long and 20 cm wide, overlapping by about 5 mm and orientated vertically. The front part of the first wall was in addition covered with about $2 X_0$ of lead to improve the sensitivity for low energetic photons. Furthermore, the veto wall was shielded against back-scattering of particles from the calorimeter by an iron wall of 40 cm thickness. Holes in the lead (diameter 4.2 cm) as well as in the scintillator wall (diameter 2.0 cm) defined the aperture of the beam.

II.3. THE LIQUID ARGON SYSTEM

II.3.1. THE ELECTROMAGNETIC CALORIMETER (EC)

The relevant parameters of the two types of lead stacks of the calorimeter version A ($22.6 X_0$) and B ($26.2 X_0$) respectively are summarized in Tab. 2a. The total number of electronic channels in the EC is 240.

Version A:

One cell unit of the e.m. calorimeter version A is shown in Fig. 3a. The readout boards (ROB) were positioned in the center of the LAr gap by 20 teflon spacers of 1.5 mm thickness. The positioning of the absorber plates and readout boards was done by 4 rods with teflon washers (1.5 mm thickness). The ROB's were made out of 2 double sided FR4 boards glued together, with copper pads of 35 μ m thickness on both sides and read out lines in the middle. The pads are separated by 1 mm. The pad structure with the readout lines (0.3 mm) of one quadrant of the boards is shown in Fig. 4. A 5-fold longitudinal segmentation has been chosen with 8, 8, 8, and 32 ROB's connected longitudinally together. Each of these longitudinal sections has 48 towers connected to charge sensitive preamplifiers. The capacity of the individual towers (including cables) varied between 0.8 and 1.5 nF for the first

four sections and between 1.8 and 4.6 nF for the fifth one. The total gap capacities of the sections were measured to be 60 nF for each of the first four segments and 163 nF for the fifth.

The high voltage (HV) is applied via 5 separate lines to the lead plates of the longitudinal segments. The high voltage blocking capacitors (80, 195, 211, 178, and 221 nF) are connected to ground next to each section. Additional blocking capacitors (2000 nF per line) outside of the cryostat were added. With these blocking capacities the total negative crosstalk (Sec. III.1.2) was kept below 15 %.

Version B:

The main difference compared to configuration A is: The high voltage was applied via a high resistive foil glued either onto the ROB or onto the absorber plate. In order to minimize the variation of the high voltage over the area of the high-resistive-coated (HRC) plane, a line of conducting silver paint was applied along one side of the foil. All lead plates of the stack were connected in parallel to ground. Thus, a blocking capacity of typically 50 nF per plate was achieved and therefore, no blocking capacitors were needed.

The calorimeter consists of two parts differing in the cell structure. The structure of the first 15 cells of the calorimeter version B is shown in Fig. 3b. For HRC a Kapton-foil (75 μm) is glued to every other lead plate, and a mixture of epoxy glue and conducting soot (40 μm layer) has been sieve printed onto this foil. The resistance of the HRC varies from foil to foil between 10 and 70 $\text{M}\Omega$ / square. A lead plate with a ROB glued on each side is placed between the two lead plates with the HRC. The ROB is a two-layer board (0.8 mm thick) with the readout lines on the inner side. A Kapton-foil (75 μm) was glued between ROB and absorber. The LAr gap was defined by teflon spacers. The averaged gap thickness was 2.78 mm with a maximum variation of 0.35 mm. These first 15 cells were divided longitudinally into 4 sections consisting of 3, 4, 4, and 4 cells with 48 towers per section. The cell structure of the back part of the calorimeter is shown in Fig. 3c. In contrast to the front part, the HRC was glued to the ROB's. All 14 cells were longitudinally grouped in one section. The total gap capacities of the sections were measured to be 73, 91, 90, 89, and 343 nF. The HRC's of each longitudinal section were connected

in parallel to one high voltage channel. In this scheme, a large blocking capacity was achieved, and the preamplifiers were protected against possible HV breakdowns in the LAr gap. Thus, the number of dead channels was kept well below 1%.

II.3.2. THE HADRONIC CALORIMETER (HC)

The hadronic section of the calorimeter (see Tab. 2b) consisted of two sections, the first one with 6.12 interaction lengths (λ) of copper and the second one (version A only) with 2.88 λ of iron. This last section has been used for studying the leakage of the showers (tail catcher) and was removed when the gaseous tail-catcher was installed behind the cryostat. The basic cell structures are shown in Fig. 5a (copper section) and Fig. 5b (iron section).

Each cell consisted of an $820 \times 800 \text{ mm}^2$ absorber plate followed by a LAr gap, a G10 ROB, a second LAr gap and the next absorber plate. In the copper section, the plates were 5 mm thick with measured tolerances of the flatness of 0.4 mm and of the thickness of 0.05 mm. The argon gap was 1.5 mm wide and maintained by plastic spacers located 80 mm apart on either side of the ROB. In the iron section, the absorber plates were 25 mm thick with tolerances less than 0.1 mm on thickness and flatness. The argon gap was 4 mm thick, maintained in the same way as in the copper section. The ROB's were made of 1 mm thick G10 plates clad with 35 μm thick copper. They acted as charge collecting electrodes. These boards were etched on both sides to form a strip pattern as shown in Fig. 5c. In consecutive cells, the ROB's were mounted with the strip orientation alternating between vertical and horizontal. Each strip of a given orientation was ganged to the corresponding ones of the following ROB's with the same strip orientation, thus defining longitudinally segmented towers (Fig. 6). In this way, two interleaved cell structures were provided for each longitudinal segment. Such a configuration allows to study the effect of sampling fluctuations. In total, the copper section was subdivided into 6 longitudinal segments with 26 elementary cells each, except for the last one which had 24 cells. The iron section was subdivided into 2 longitudinal segments with 9 cells per segment (Fig. 6).

Each segment has 40 electronic channels (20 vertical and 20 horizontal). This

leads to a total of 320 channels for setup A and 240 channels for setup B.

The high voltage was applied to the absorber plates in an interleaved way to reduce the dead volume in case of a short circuit in one of the gaps. The 175 planes of setup A were connected to the high voltage via 28 separate lines. The blocking capacitors varied between 200 and 600 nF.

The EC calorimeter was mounted onto the same frame as the HC, just in front of the first copper plate of the HC. This whole assembly was mounted on rollers for moving into the cryostat.

II.3.3. CRYOSTAT AND CRYOGENICS

The cryostat is of the horizontal type and has a removable front end for loading the calorimeter. The carriage on which both the e.m. and the hadronic calorimeters are mounted can roll on rails fixed to the inner wall of the cryostat. The beam particles enter the cryostat through a 550 mm long vacuum tube of 100 mm diameter with thin windows at both ends. The useful diameter of the vessel is 1800 mm and the overall length 3000 mm. The capacity of this cryostat is about 6 m³ of liquid argon. Insulation against heat losses is provided with a layer of polyurethane foam 400 mm thick.

Refrigeration is provided by liquid nitrogen circulation in a heat exchanger located in the vapour phase of the argon. Total cool-down time to reach LAr temperature was about three days. In stable operation, the absolute pressure in the vapour phase of the argon was maintained at 1.2 bars, by regulating the liquid nitrogen flow in the heat exchanger. Warming up after emptying the cryostat took about five days. This was achieved by using a 1600 W heater located at the bottom of the vessel.

Nine ports on the top of the cryostat serve as feed-throughs of cryogenic and pumping lines, signal and HV cables, as well as cables connected to the sensors monitoring the pressure and temperature at various locations within the vessel.

The purity of the argon in the cryostat was monitored continuously throughout the experiment by sampling gas taken from the vapour phase of the argon. The O₂ contamination was of the order of 2ppm except during the September/October run

periods (data of set-up A) when it was of about 22 ppm.

II.3.4. ELECTRONICS

The electronics chain for the treatment of the LAr pulses is shown in Fig. 7. A total number of 560 channels was employed. Each channel consisted of 5 modules: charge sensitive preamplifier, line driver, differential amplifier, shaper, and ADC. The preamplifiers were located as close as possible to the feedthrough of the signal cables (97 Ω) out of the cryostat. The cable-length from the LAr cells to the preamplifiers was 9 m. The line driver differentiated the signal and transmitted it over a distance of 60 m to the differential amplifier and shaper. The shaping time was 2μs. The signal was digitized by a charge sensitive ADC of the type LCR 2280. The gate for the ADC was set to 500 nsec.

The intrinsic noise of the preamplifier depends on the capacitive load. The incoherent noise in an entire channel was found to be $Q_T[e_0] = 11000 + 4400 \cdot C_D [nF]$ where C_D is the detector-capacity, which was in the range of 0.3 – 9 nF. By summing over all electronic channels, we found a coherent contribution (pick up) to the total noise of 50 – 80% under beam-conditions.

The electronics chain was calibrated by feeding a voltage pulse via a 10 pF capacitor into each preamplifier. This capacitor was located on the preamplifier-card and had a precision of 1%. This charge input could be attenuated by a computer-controlled switch. Thereby, the whole dynamic range of the electronics was scanned in fine steps. The method guaranteed to find the exact pedestal values as well as the precise ADC channel to charge conversion for each channel, and to determine the crosstalk by pulsing simultaneously only non-adjacent channels. The calibration was repeated once per day. Over a period of 30 days the stability of the pedestals was around 1σ of the pedestal distribution, and the slopes did not change by more than 0.5%.

II.4. THE GAS TAIL CATCHER

The tail catcher calorimeter used iron as absorber and wire chambers as active detector elements. The chambers were operated in the limited streamer mode with the read out being performed by strips (digital) and pads (analogue).

The detector consisted of 20 iron plates with lateral dimensions $110 \times 125 \text{ cm}^2$, and with a thickness of 2.5 and 5.0 cm. The measurements described in this paper were performed with a sampling thickness of 7.5 cm ($4.26 X_0$, 0.44λ). The total thickness, including the active detector planes, amounted to 4.57λ . The inactive material between the HC and the front plate of the tail catcher corresponded to 1.4λ . A detailed description of this calorimeter and its performance will be given in forthcoming papers^{5,10}.

II.5. TRIGGER AND DATA ACQUISITION

The trigger scheme for the test set-up was laid out to provide basically two features:

- Identify the beam particle generating the trigger and in addition allow for some special purpose triggers.
- Ensure that for a triggered event only one particle enters the calorimeter.

Taking into account the settings of the two CEDAR's, separate triggers were available for electrons and/or pions. From the eight individual signals provided by each CEDAR, six were demanded to be in coincidence with B_1 and B_2 for triggering the event. The more restrictive options with higher coincidence level were latched for offline selection. For momenta $p \geq 100 \text{ GeV}/c$ electrons and pions were selected by synchrotron radiation as described above. Muons were identified by the scintillation wall behind the beam dump. For permanent pedestal monitoring events were randomly triggered during the burst time without any particle crossing the detector.

In order to avoid more than one particle entering the calorimeter within the sensitive time – given by the rather long charge collection time in the LAr gap – events were accepted only if there was no second beam particle within $10 \mu\text{sec}$ before and $3 \mu\text{sec}$ after the event.

Two computers have been used for the data acquisition, an IBM PC AT2 and a PDP 11-73, both boosted by a fast processor CAB¹¹, as shown in Fig. 8. The IBM-PC drove the CAB programs and monitored the whole set-up and the data acquisition. The CAB processor read the detector components in 2 ms and used another 2 ms for histograms and additional computations. Furthermore, it offered the possibility to filter the data online. Between bursts, the event buffer was dumped on a 3M cartridge (as an alternative for data recording) and to the PDP. The PDP 11-73 drove a 6250 BPI magnetic tape and had three functions: a) writing the events onto tape; b) histogramming for fast on line analysis; c) monitoring and recording the calibration and calorimeter data in a stand alone mode. With an event buffer size of 1.2 to 2 kbytes the typical data rate was 200 events per 2 s burst when writing on tape.

III. PERFORMANCE AND RESULTS

III.1. DATA CORRECTIONS

III.1.1. HIGH VOLTAGE PLATEAU CURVE

The Fig. 9 shows the dependence of the average deposited charge in EC or HC, on the electric field applied for electrons and pions, normalized to the response at the highest electric field. For the EC as well as for the HC of the set-up B, a plateau value of about 1 kV/mm was obtained. In contrast, the data of set-up A suffered from a serious oxygen contamination in the LAr and therefore, a plateau could not be reached. This, however, did not influence the energy resolution for set-up A.

III.1.2. CROSSTALK

The data had to be corrected for the following effects:

a) Negative cross-talk: The pads hit by a shower receive a positive signal, but the neighbouring pads a negative one. This is due to the fact that for transient state, the lead plates are effectively isolated from the high voltage. Thus, a positive charge in the center induces a negative one in the neighbouring region. These two charges are proportional to the ratio of pad capacity to blocking capacity and, therefore, can

be systematically corrected. The maximum correction applied for any longitudinal section of EC or HC was 15%.

b) Positive cross-talk: For the EC version B, we observe in contrary too much energy in the peripheral pads due to a insufficient grounding of the lead plates for higher frequencies. This has been corrected by studying the correlation between each channel and the total energy deposited by pions. This yields corrections per channel in the range 0.04 % to 0.6 % of the total energy in the EC. Varying these corrections within the uncertainties has no influence on the resolution of hadron showers.

III.2. RESULTS FOR INCIDENT ELECTRONS

Besides the beam trigger condition (see sect. II.5) the data selection criteria were:

- no hit in the veto-wall
- just one cluster in each of the 4 MWPC planes

As an example, Fig. 10 shows the distribution of the total deposited charge in the central pads (16 per longitudinal section) of the EC for electrons of 166 GeV for set-up B. The mean value and the width of these distributions were obtained from a gaussian fit to the data. The small low energy tail is mainly due to bremsstrahlung of electrons upstream in the beam line. The energy dependence of the total deposited charge per energy for the two configurations of the e.m. calorimeter is shown in Fig. 11. At 166 and 218 GeV, the energy deposited in the first longitudinal section of the HC has been included (about 1% of the total energy deposit). The energy response is linear over the full energy range from 10 to 218 GeV, the maximum deviation being 1.5%. For set-up A, the measured charge was lower due to some oxygen contamination of the LAr (see sect. II.3.3). From Monte Carlo (MC, EGS4)¹² the ratio of charge to energy deposit for incident electrons is expected to be 0.338 pC/GeV for set-up B. This agrees with the measured value of 0.357 pC/GeV within the uncertainty of the absolute charge prediction from MC. The longitudinal shower profile for 50 GeV incident energy is shown in Fig. 12 and compared with the Monte-Carlo (EGS4) prediction. Here the material in front of the e.m. calorimeter

(1.3 X₀ and 1.1 X₀ for set-up A and B respectively) has been included and good agreement is found. The Fig. 13a) and b) show the dependence of the energy resolution σ/E on the energy E as obtained from the energy deposited in the central pads (16 per longitudinal section) for the two versions of the e.m. calorimeter. This energy dependence can be parametrized

$$\sigma/E = \sqrt{a^2/E + b^2/E^2 + c^2}$$

where a represents the sampling fluctuations, b the contribution due to electronic noise as determined from randomly triggered events and c the momentum resolution of the beam and intercalibration errors. For set-up A (B) the parameters a and c (a) have been determined from a fit, and the parameter b has been determined from randomly triggered events. In addition, for set-up B, the parameter c has been fixed to $c = 0.007$. The open circles in Fig. 13 a) and b) are the values predicted from MC (GEANT¹³ respectively EGS4¹²) neglecting contributions due to noise and beam momentum resolution. The solid line represents the parametrization as described above. The Tab. 3 and Tab. 4 summarize the results, the errors are statistical only. The MC results are compatible with the parameter a obtained from the data. Instead of adding the energy deposited only in the central pads, also the total energy deposit was studied. Here, for noise suppression, a threshold cut of 3 sigmas of the pedestal distributions has been applied. The resolutions thus obtained are compatible with the results given above.

III.3. RESULTS FOR PIONS

The results presented are mainly from set-up B with pion energies of 30, 50, 170, and 230 GeV. Some results will also be given for set-up A.

III.3.1. EVENT SELECTION

For all energies besides the beam trigger condition (see II.5) at least 1 of the 2 Cerenkov counters was required. This was also true at 170 and 230 GeV where the electrons were identified by synchrotron radiation. Further selection criteria were:

- no hit in the veto wall

— in each of the 4 MWPC planes just 1 cluster

Events were accepted for further analysis only if none of the digital strips of the gas tail catcher (sect. II.4) fired. This corresponds to a rejection of events which deposit more than 2 GeV in the tail catcher. The veto implies that the showers are nearly fully contained within 8.6λ of which the first 7.2λ (sect. II.3) are used to measure the shower energy. The fraction of events removed by the veto is given in Tab. 5. At most 1.3% of the events are nevertheless not fully contained due to lateral leakage before the TC and were thus not vetoed. The energy measurement by the tail catcher will be discussed elsewhere¹⁰. For the data of set-up A, a similar cut of about 2 GeV in the liquid argon tail catcher was used.

III.3.2. CORRECTIONS AND NOISE REDUCTION

The data were corrected for cross talk effects as described in sect. III.1. The electronic noise when summing up all channels amounted to typically 1 GeV in the EC and 2 GeV in the HC. This influenced the energy resolution mainly at the lowest pion energy of 30 GeV. To reduce the noise contribution the following procedure was applied: Individual channel signals were only accepted if the measured charge was above a given threshold or if at least one of the directly neighbouring channels (in x or y or z direction) was above that threshold. These thresholds were taken to be 50 MeV for sections 1 to 4 of the EC, 100 MeV for section 5 of the EC, and 150 MeV for the HC. This corresponds roughly to 3 sigma of the pedestal distributions and also to about the energy deposit of one minimum ionizing particle.

With these cuts applied to the pions of 30 GeV, the noise contribution was reduced to 0.3 GeV in the EC and 0.8 GeV in the HC. Although at higher energies, the noise contribution was much less severe, the analysis procedure was kept the same.

III.3.3. ENERGY CALIBRATION WITHOUT π^0 -WEIGHTING

Each channel was calibrated for the charge deposited as outlined in sect. II.3.4. The relation to deposited energy was established by comparison with the various beam energies. The total deposited energy by an incident pion is calculated according to

$$E = c_E Q_E + c_H Q_H$$

where Q_E and Q_H are the total charges measured in EC and HC respectively. The two calibration constants c_E and c_H , which depend on the sampling ratio and absorber material, were determined for each beam energy by the two conditions:

- a) $\langle E \rangle = E_{beam}$
- b) the width of the energy distribution is minimal

The resulting calibration constants are given in Tab. 6. They decrease slowly with energy as expected if the signal for electrons is larger than for pions, since the electromagnetic fraction of the hadronic shower increases with energy. Using c_E and c_H as defined above for pions, a direct comparison of the mean measured energies for pions and electrons of the same energy leads to effective e/π ratios as given in Tab. 6. These e/π ratios are effective values for the present EC (1λ) and depend on the calibration procedure to determine c_E and c_H .

The energy distributions obtained are shown in Fig. 14 (dotted line). The resolution $\sigma/\langle E \rangle$, as obtained from a gaussian fit to the energy distribution, decreases with increasing energy, but slower than $1/\sqrt{E}$ (see Tab. 6 and Fig. 15).

III.3.4. π^0 -WEIGHTING

The fluctuations of the π^0 -content of hadronic showers deteriorate the energy resolution as the calorimeter response is different for electromagnetic and hadronic energy. Local high energy concentrations in the shower development are mainly due to π^0 's and increase the total measured energy of an event since $e/\pi > 1$. This is demonstrated in Fig. 16a showing the total measured energy (calibration as in sect. III.3.3) versus the maximal local single channel energy per event in the HC in the case of incident pions punching through the EC. Comparable plots have been shown before for different calorimeters (e.g. refs. 3, 4). Similarly, the measured total energy is large for showers, where most of the energy is absorbed in the EC (Fig. 17a). The measured energy of this kind of hadronic showers compares well to the energy of electron initiated showers. The method chosen to correct for the π^0 fluctuations is

motivated by the approach of ref. 3 (for a somewhat different algorithm see below). For each event "weighted energies" are defined for the EC and the HC by

$$E_E^w = \sum_{EC} [E_i(1 - \eta_E E_i)] \text{ with } (1 - \eta_E E_i) \geq C_E^{min}$$

$$E_H^w = \sum_{HC} [E_i(1 - \eta_H E_i)] \text{ with } (1 - \eta_H E_i) \geq C_H^{min}$$

where E_i are the energies of the individual channels calibrated as outlined in sect. III.3.3. and the corrections $(1 - \eta E_i)$ are limited to C_E^{min} and C_H^{min} respectively. At a given energy the parameter η_H is taken the same for all channels in the HC. Due to the varying tower size in the EC the parameter η_E is varying. The numeric values given below correspond to the small pads in the longitudinal section 5 of the EC and are scaled proportionally to $1/V$ for other towers, where V is the tower volume.

To compensate for the numeric reduction of the energies due to the weighting, the total energy of a shower is rescaled finally using

$$E^w = [\langle E_E \rangle / \langle E_E^w \rangle] \cdot E_E^w + [\langle E_H \rangle / \langle E_H^w \rangle] \cdot E_H^w$$

where $\langle E_E \rangle$ and $\langle E_H \rangle$ are the average measured energies for pions of a given beam energy for the EC and the HC respectively (calibrated according to sect. III.3.3), whereas $\langle E_E^w \rangle$ and $\langle E_H^w \rangle$ are the corresponding average weighted energies.

The parameters have been determined separately for each beam energy by the conditions

- i) $\langle E^w \rangle = E_{beam}$
- ii) the width of the energy distribution is minimal
- iii) electrons and pions of the same energy have the same response.

The parameters η_E and η_H turn out to be strongly correlated to C_E^{min} and C_H^{min} respectively. The latter can be fixed to $C_E^{min} = C_H^{min} = 0.68$ for all energies without significant loss of resolution.

To simulate realistic calorimeter measurements, it is important not to make any use of the knowledge of the beam energy in the analysis of individual events.

Therefore, the energy dependence of the quantities η_E, η_H and

$[\langle E_E \rangle / \langle E_E^w \rangle]$, $[\langle E_H \rangle / \langle E_H^w \rangle]$ and of the calibration constants c_E, c_H (see sect. III.3.3) has been parametrized in a simple first approach by a linear dependence as shown in Fig. 19. The energy of individual events has been obtained in the following way: First the true energy is estimated from the energy sum without weighting using $c_E = 3.11 \text{ GeV}/pC$ and $c_H = 4.30 \text{ GeV}/pC$ as determined at a beam energy of 50 GeV. (This estimated energy is already quite close to the corrected energy, for example, the average deviation is 4% for the pion data at 170 GeV). Then, the parameters at the estimated energy as obtained by the parametrization shown in Fig. 19 are used to compute the corrected energy as described above.

With this π^0 weighting technique the dependence of the energy E^w on the shower shape is considerably reduced as shown in Fig. 16 and Fig. 17. It is also evident from Fig. 18 that the ratio e/π is effectively 1. The resulting energy distributions are shown in Fig. 14, and the width of fitted gaussian distributions are given in Tab. 7 and Fig. 15. The energy resolution is substantially improved using the weighting method. The obtained mean energy deviates from the beam energy by less than 1% in all cases for both electron and hadron initiated showers. A fit to the resolutions of the form

$$\sigma/E = \sqrt{A^2/E + B^2}$$

yields $A = 50.4 \pm 0.4\%$, $B = 1.6 \pm 0.1\%$

A somewhat different weighting technique has been tried for the data of set-up A. For the dependence of the energy on the deposited charge in the electromagnetic and hadronic calorimeter sections a third order polynomial has been assumed:

$$E_{em} = \sum_{EC} \{C_1^{em} \cdot Q_i + C_2^{em} \cdot Q_i^2 + C_3^{em} \cdot Q_i^3\}$$

$$E_{had} = \sum_{HC} \{C_1^{had} \cdot Q_i + C_2^{had} \cdot Q_i^2 + C_3^{had} \cdot Q_i^3\}$$

Based on the same number of free parameters, this is an approximation of the method above, but using a smooth function rather than fixed cut off parameters C^{min} . The parameters C_1 to C_3 for the electromagnetic and hadronic sections have been uniquely defined from a fit to the energy distribution of pions of a given energy. In the fit the energy resolution is minimized, while the pion energy is constrained to the nominal beam energy. The parameters obtained for the electromagnetic section show a rather modest energy dependence. The energy dependence of the corresponding parameters for the hadronic section is somewhat more pronounced, reflecting the energy dependence of the electromagnetic fraction of the deposited pion energy. The Fig. 15 and the Tab. 8 show the energy resolution σ/E obtained for the data at 30 GeV, 80 GeV, 170 GeV and 230 GeV. A fit to a function

$$\sigma/E = \sqrt{A^2/E + B^2}$$

yields $A = 44.9\% \pm 1.6\%$ and $B = 2.6\% \pm 0.2\%$.

III.3.5. SAMPLING FLUCTUATIONS

The contribution of sampling fluctuations to the the resolutions can be evaluated due to the independent readout of x and y strips in the HC (see sect. II.3.2). Reading the x or y strips only corresponds to Cu absorber plates of 1 cm thickness. Assuming that the resolution for readout of x and y strips is given by

$$\sigma^2 = I^2 + S^2$$

and for readout of x or y strips only by

$$(\sigma')^2 = I^2 + 2 \cdot S^2$$

where S represents the sampling fluctuations and I the intrinsic resolution, the sampling fluctuations for 5 mm Cu can be determined and are given in Tab. 7. The sampling terms obtained without π^0 weighting are very similar.

III.3.6. JET ENERGY RESOLUTION

As a special case we studied a subsample of early interactions in the calorimeter which is a somewhat better approximation to HERA jets as just single pions which often punch through the EC. With the requirement of an energy deposit of more than 0.4 GeV in the second longitudinal EC segment, we obtain events with the fraction $\langle E_{EC} \rangle / E_{beam}$ in the range .54 (230 GeV) to .65 (30 GeV) which might be reasonable for jets. The maximum deviation of the mean measured energy for this sub-sample from that of the whole sample is 1 % (at 50 GeV). The resolutions are in the range $0.47/\sqrt{E}$ to $0.50/\sqrt{E}$. Further studies on jet reconstruction will be presented in a forthcoming paper⁵.

IV. CONCLUSIONS

A systematic study of a LAr calorimeter using lead (copper) in the e.m. (hadronic) section as absorber material has been performed for electrons and pions in the energy range from 10 to 230 GeV. For electrons an energy resolution of about $10\%/\sqrt{E}$ has been obtained, for pions the corresponding values range from $61\%/\sqrt{E}$ to $76\%/\sqrt{E}$. Even though the e/π ratio is not equal to one, it has been shown that by applying the π^0 -weighting technique the response to pions and electrons can be equalized. Exploiting this technique, an energy resolution of about $50\%/\sqrt{E}$ has been obtained for pions.

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We would like to thank all our technical collaborators for their help and their contributions to the successful test of this calorimeter. In particular, we wish to thank G. Falley, J. Koll, and K. Thiele from DESY, C. Billat from Ecole Polytechnique, John O'Connor, T. Paris, and T. Roberts from the University of Houston, H. Laskus, H. Brettel, W. Pimpl, and P. Weissbach from MPI, Munich, and G. Bertalmio, J. Bossard, and J. Tichit from Saclay. We also would like to thank the staff at CERN for the operation of the SPS accelerator and the H6 beam line.

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Table 1. Basic Parameters

		Version A	Version B
e.m. stack (EC)	material	Pb/LAr	Pb/LAr
	total length	22.8 X_0 1.1 λ	26.2 X_0 1.1 λ
hadronic stack (HC)	material	Cu/LAr	Cu/LAr
	total length	6.12 λ	6.12 λ
tail catcher (TC)	material	Fe/LAr	Fe/Plastic Streamer Tubes
	total length	2.88 λ	4.57 λ

Table 2a. Parameters of the two types of lead stacks

	version A	version B
lead plate	1.86x420x420 mm	2.4x420x420 mm
LAr gap	2 x 1.5 mm	2.8 mm
ROB thickness	1.12 mm	0.8 mm
ROB position	central in gap	on lead plate
number of ROB's	64	57
Moliere radius	3.7 cm	3.3 cm
length [mm/ X_0/λ]	376.0/22.8/1.06	377.5/26.2/1.13
long.segmentation	2.85/2.85/2.85/2.85/11.4 X_0	2.7/3.6/3.6/3.6/12.6 X_0
high voltage	on lead	on high resistive foil

Table 2b. Parameters of the copper stack

copper plate	5 x 820 x 800 mm
LAr gap	2 x 1.5 mm
number of ROB's	154
length [mm/ λ]	1391 / 6.12

Table 3. Comparison of the energy resolution for electrons with the MC prediction

	$a[\sqrt{GeV}]$	b [GeV]	c	$a[\sqrt{GeV}]$ (EGS4/GEANT)
version A	0.090 ± 0.004	0.286	0.010 ± 0.005	0.096 ± 0.003
version B	0.112 ± 0.003	0.250	0.007	0.104 ± 0.003

Table 4. Energy resolution for electrons

beam energy (GeV)	$\sigma/E[\%]$
version A	
10	3.56 ± 0.25
30	1.89 ± 0.06
50	1.63 ± 0.05
80	1.48 ± 0.04
166	1.22 ± 0.03
version B	
30	2.73 ± 0.12
50	1.86 ± 0.08
166	0.91 ± 0.07
218	1.01 ± 0.05

Table 5. Fraction of events vetoed by the tail catcher

$E[GeV]$	30	50	170	230
fraction	0.11	0.20	0.51	0.52

Table 6. Calibration constant, resolution and effective e/π ratio for pions (without π^0 weighting technique)

$E[\text{GeV}]$	30	50	170	230
$c_E[\text{GeV}/pC]$	3.26	3.11	3.00	2.96
$c_H[\text{GeV}/pC]$	4.38	4.30	4.10	4.18
σ/E	0.111	0.090	0.057	0.050
σ/\sqrt{E}	0.61	0.64	0.74	0.76
effective e/π	1.17	1.13	1.09	1.07

Table 7. Energy resolution with π^0 weighting and contribution due to sampling fluctuations

$E[\text{GeV}]$	30	50	170	230
σ/E	0.089	0.071	0.042	0.036
$\sigma/\sqrt{E}[\sqrt{\text{GeV}}]$	0.49	0.52	0.55	0.55
$S/\sqrt{E}[\sqrt{\text{GeV}}]$	0.27	0.24	0.24	0.22

Table 8. Energy resolution for pions using the π^0 -weighting method II (data of set-up A)

E_π (GeV)	30	80	170	230
σ/E	0.099	0.055	0.043	0.041
σ/\sqrt{E}	0.54	0.49	0.56	0.63

FIGURE CAPTIONS

1. Schematic view of the test set-up. The main elements are: electromagnetic calorimeter section (EC), hadronic calorimeter section (HC), tail catcher set-up A/B (TC).
2. Schematic of the optics of the H6 beam.
3. Cell structure of both EC versions:
 - a) version A,
 - b) version B (front part),
 - c) version B (back part).
4. Pad structure and readout lines of one quadrant of the EC-ROB.
5. Basic cell of the hadronic calorimeter
 - a) Copper section
 - b) Iron section
 - c) Strip pattern.
6. Longitudinal segmentation of the hadronic calorimeter.
7. Electronic chain.
8. Schematic diagram of the data acquisition system.
9. High voltage plateau curve for EC and HC (set-up A and B).
10. 166 GeV e^- : charge distribution for the sum over all central pads for the EC of set-up B.
11. Measured normalized charge for the EC of set-up A and B as function of the beam energy.
12. Longitudinal shower profile for electrons of 50 GeV (set-up B).
13. Energy resolution for a sum over all central pads (a: for set-up A; b: for set-up B). In the MC values effects due to noise and beam width are not

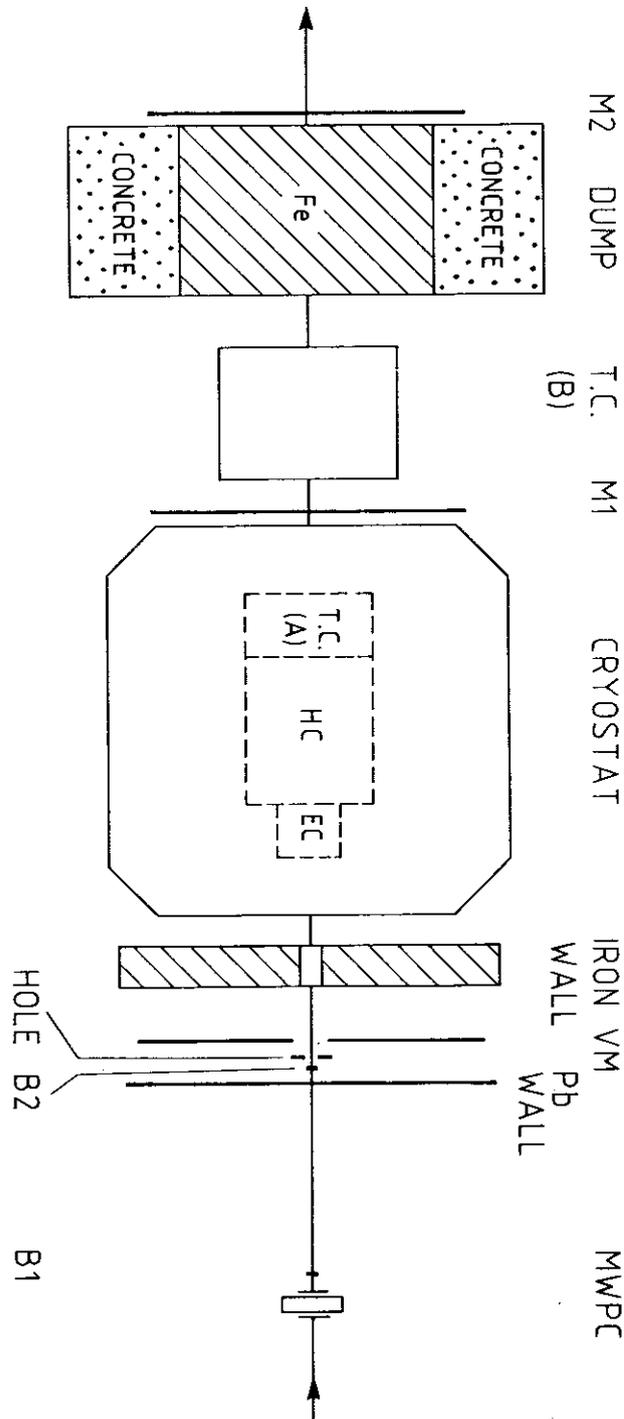


Fig. 1

taken into account.

14. Energy distributions for pions of 30 (a), 50 (b), 170 (c), and 230 (d) GeV. The dotted histogram shows the unweighted distribution, the solid histogram the corresponding distribution using the weighting technique. The solid line represents a gaussian fit to the weighted distribution.
15. $\sigma / \langle E \rangle$ vs. Pion energy. Shown are the results without and with weighting for the data of set-up B and with the weighting method 2 for the data of set-up A. The solid (dotted) line represents a fit using $\sigma / \langle E \rangle = \sqrt{A^2/E + B^2}$ to the data of set-up B (A). In addition, the pure sampling term contributions are shown as well.
16. Scatter plot E vs the maximum single channel energy E_{max} in HC, for pions of 30, 50, 170, and 230 GeV
 - a) no weighting , b) weighting.
17. Scatter plot E vs E_{EC}/E_{beam} for pions of 50 GeV.
 - a) no weighting , b) weighting.
18. Energy distribution for pions and electrons of 50 GeV.
 - a) no weighting , b) weighting.
19. Parametrization of C_E , C_H , and η_E , η_H and $\langle E_E \rangle / \langle E_E^w \rangle$, $\langle E_H \rangle / \langle E_H^w \rangle$ as function of energy. The points show the beam energies used.

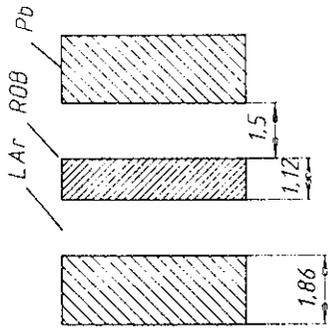


Fig. 3a

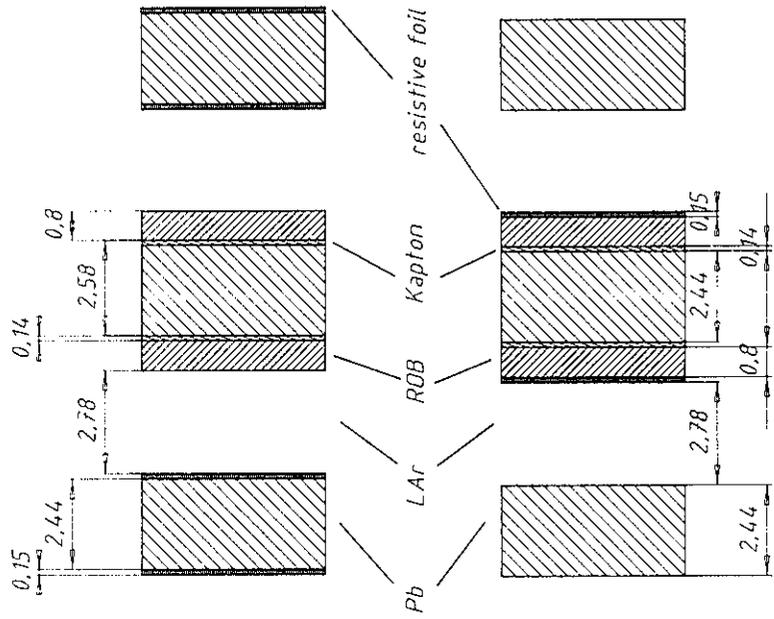


Fig. 3b

Fig. 3c

OPTICS OF BEAM H6 vertical plane

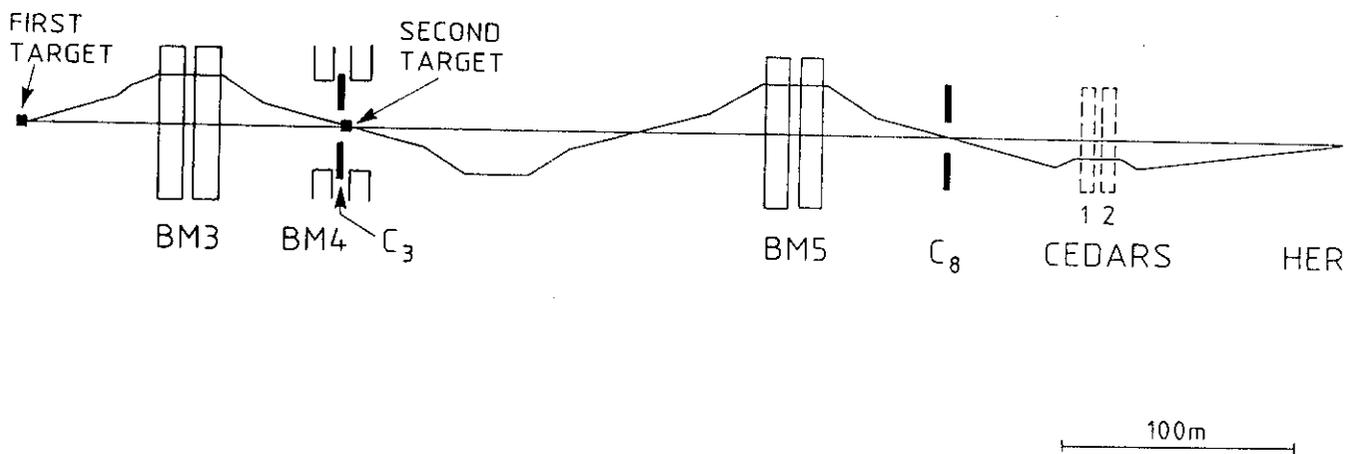


Fig. 2

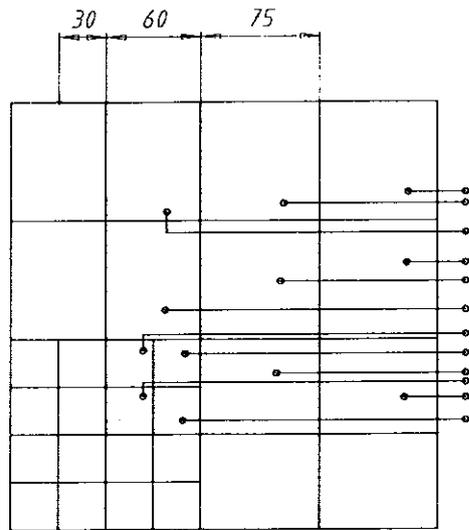


Fig. 4

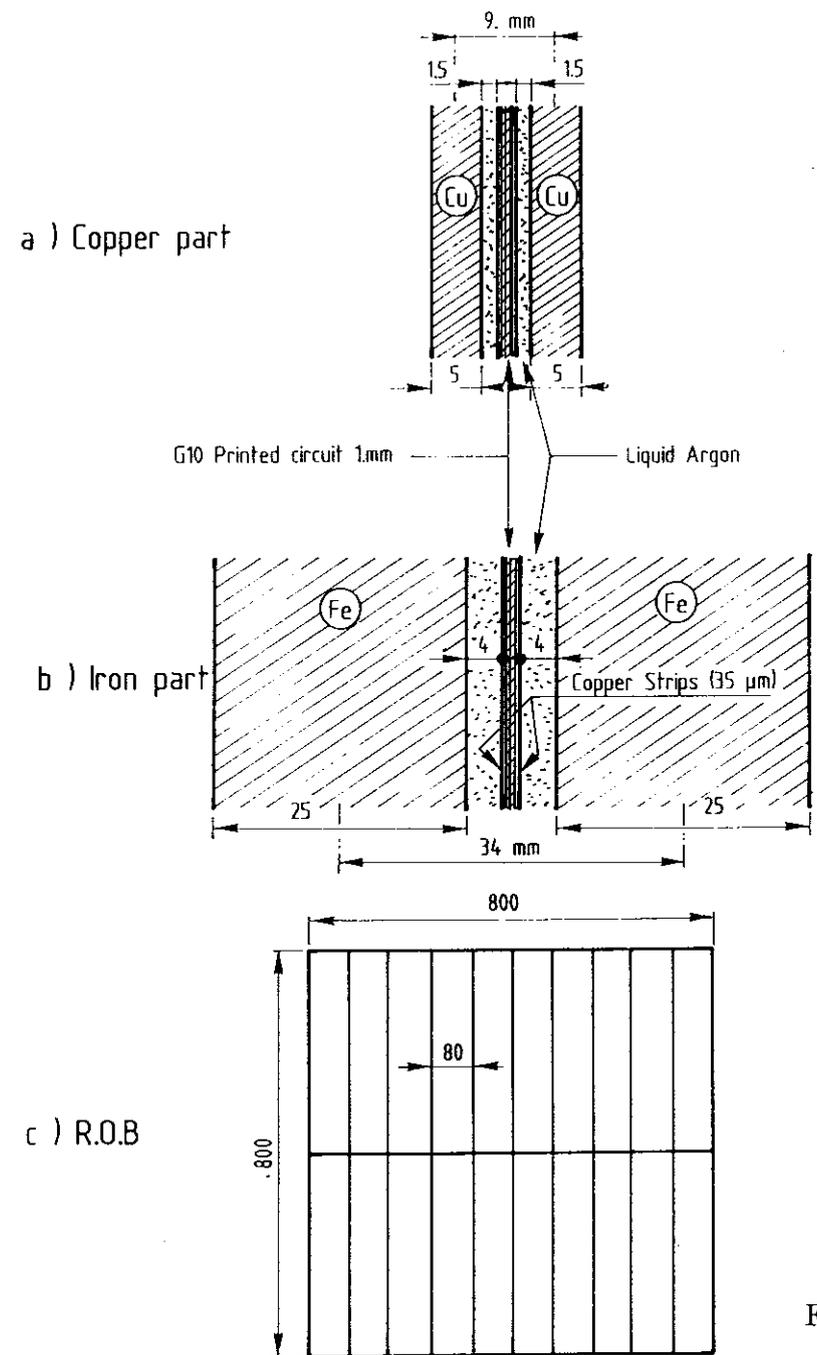


Fig. 5

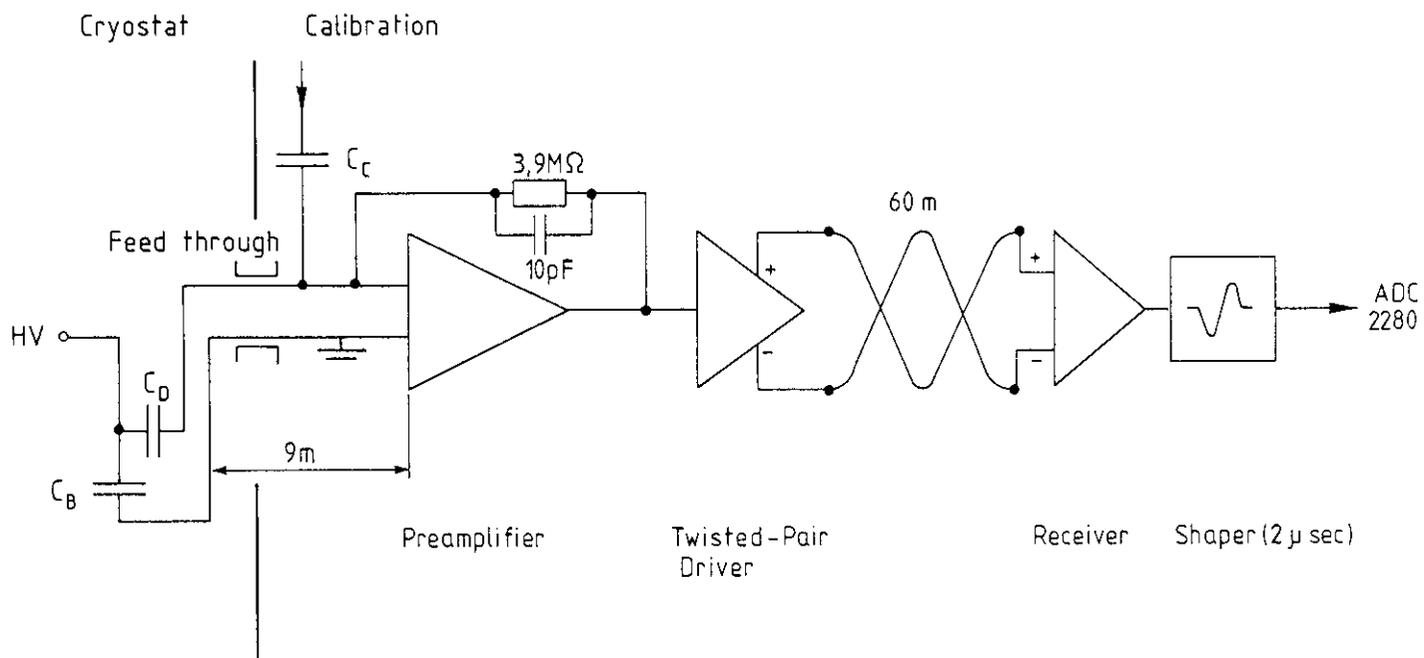


Fig. 7

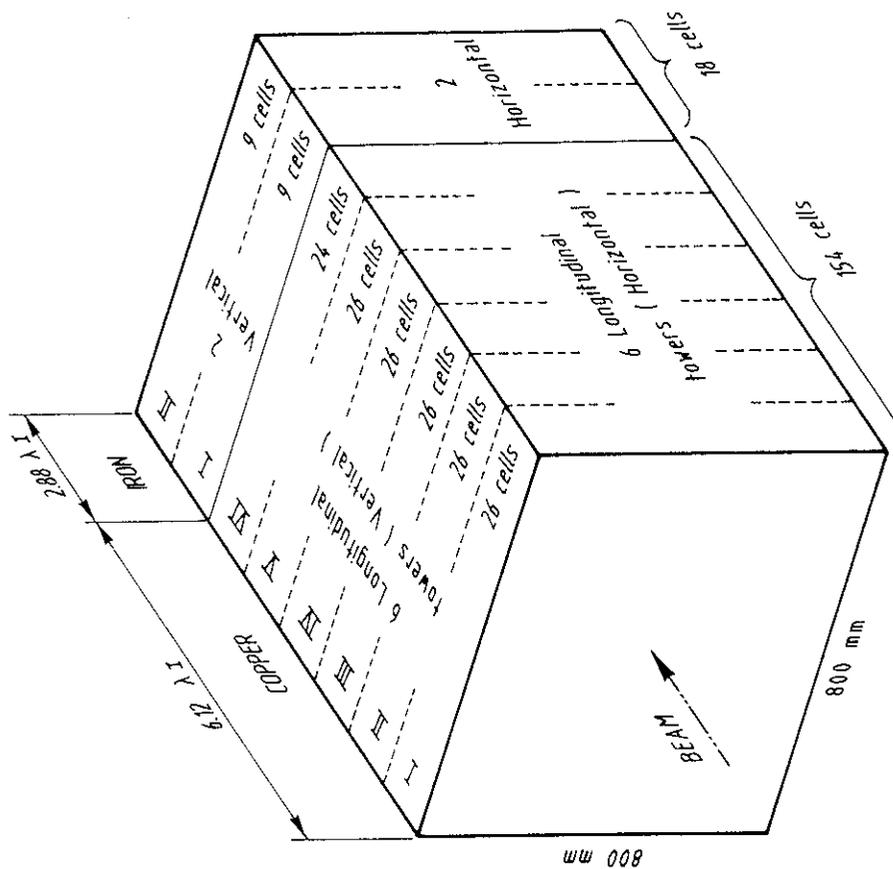


Fig. 6

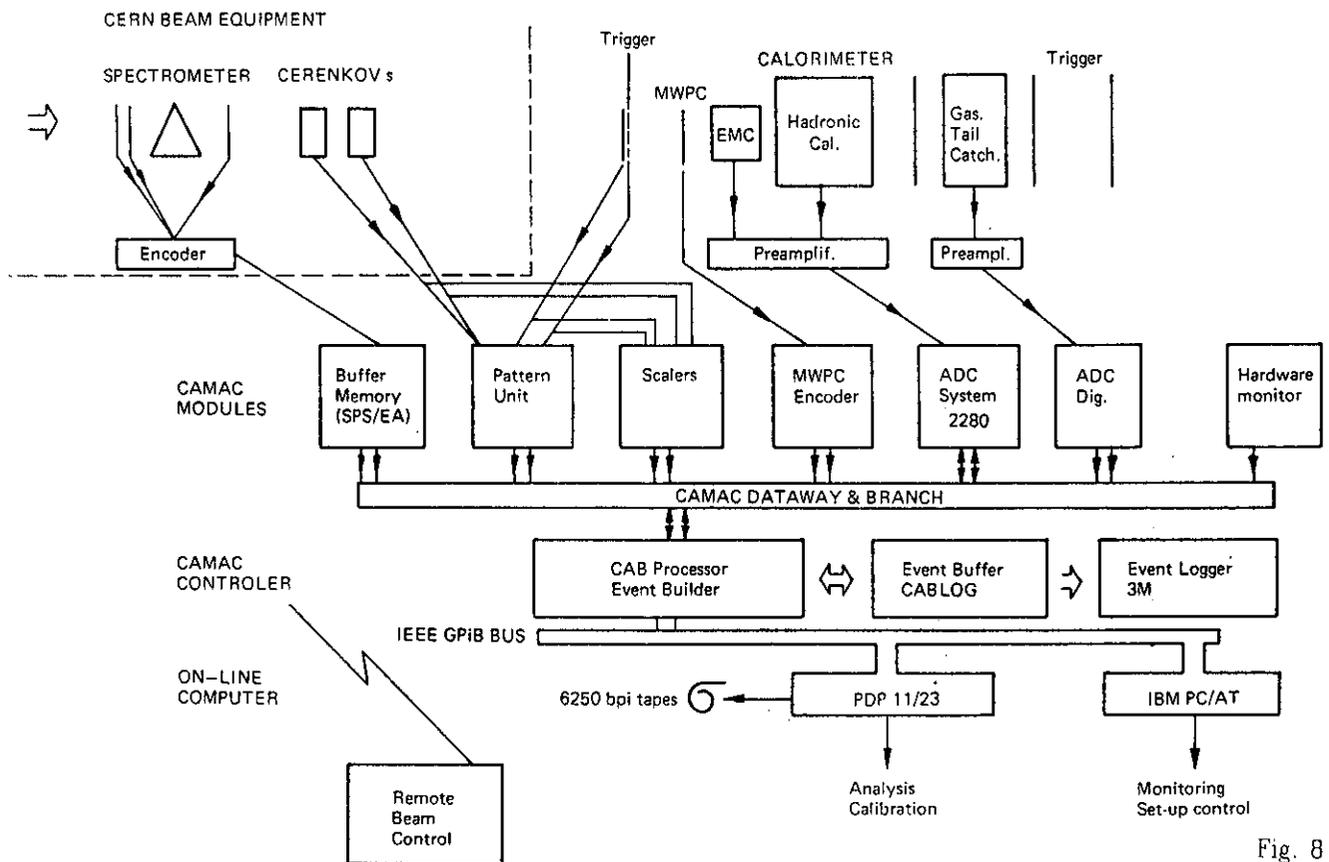
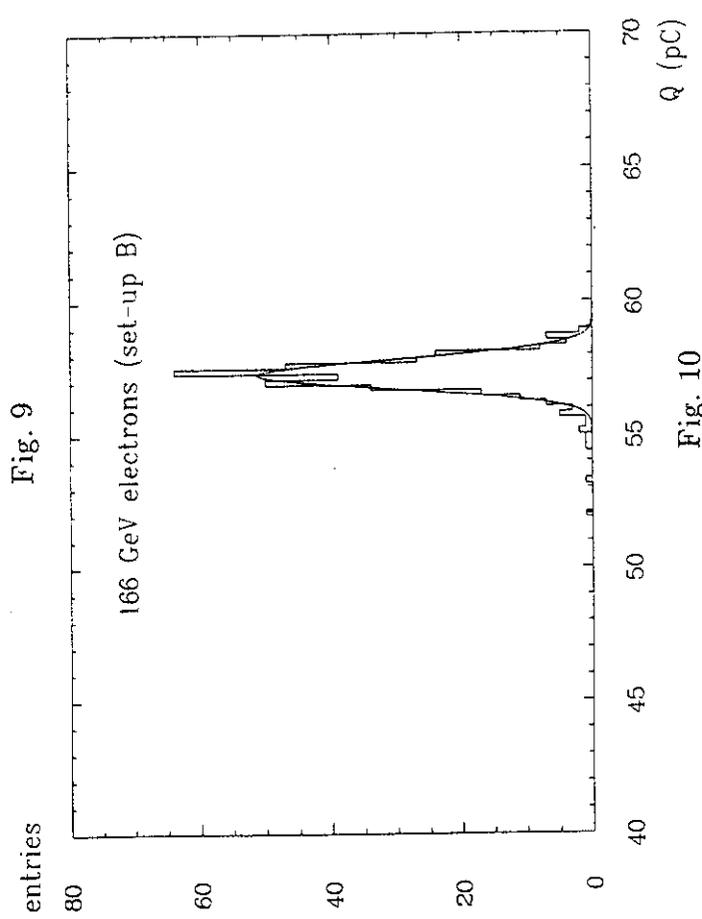
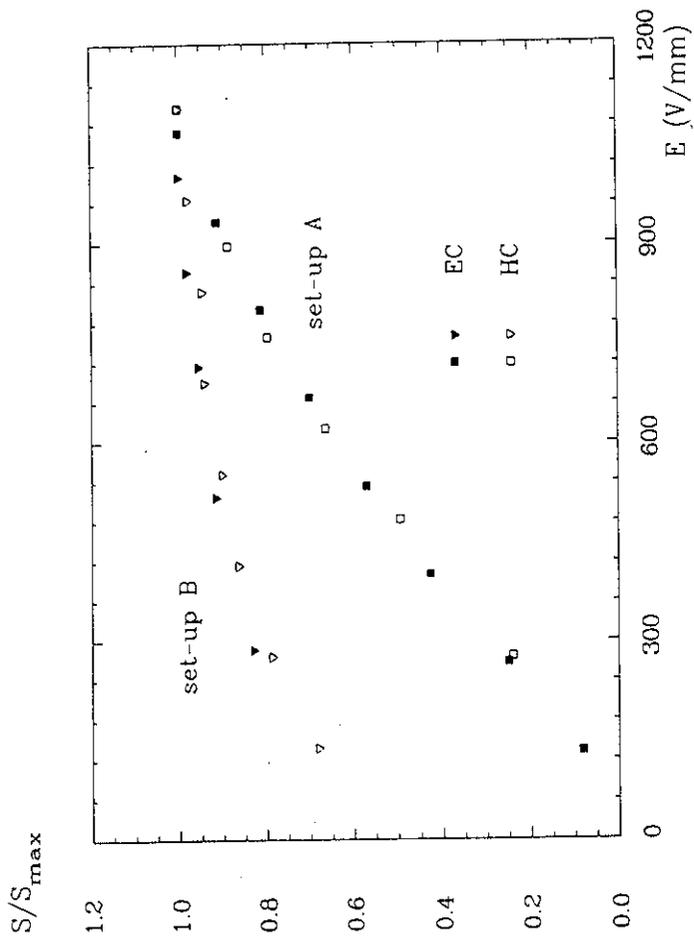


Fig. 8

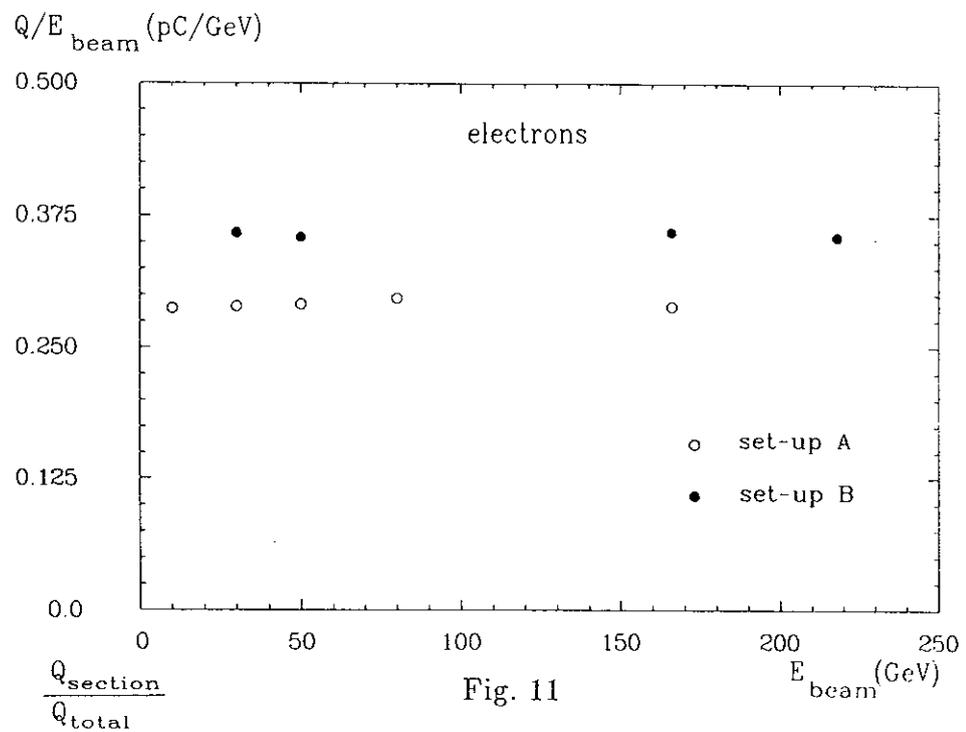


Fig. 11

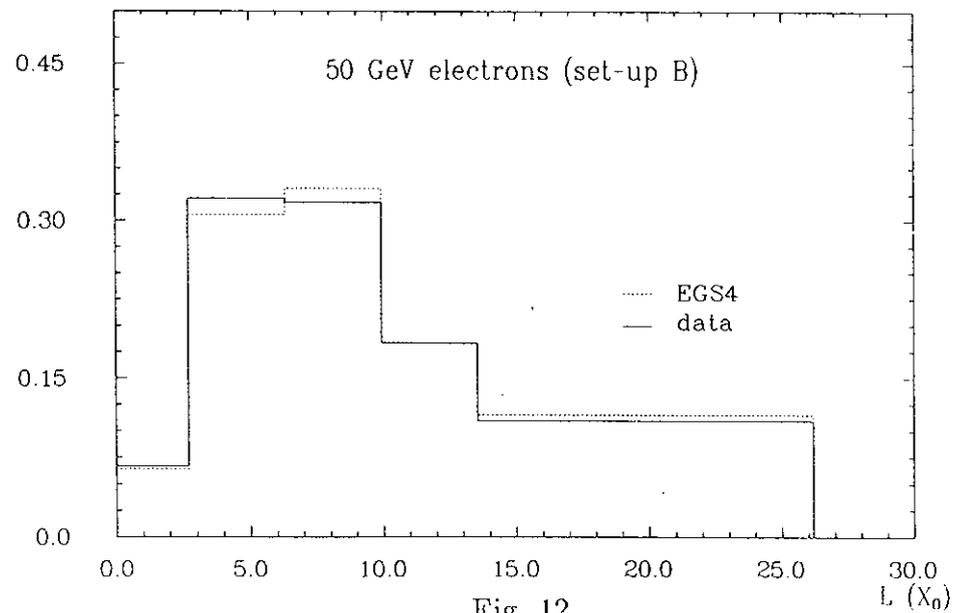


Fig. 12

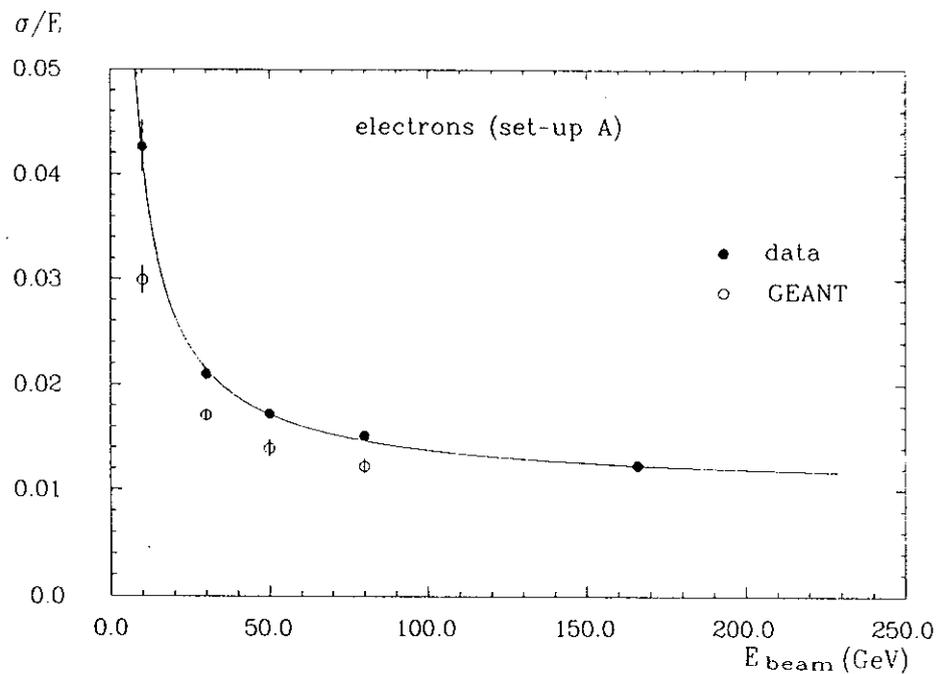


Fig. 13a

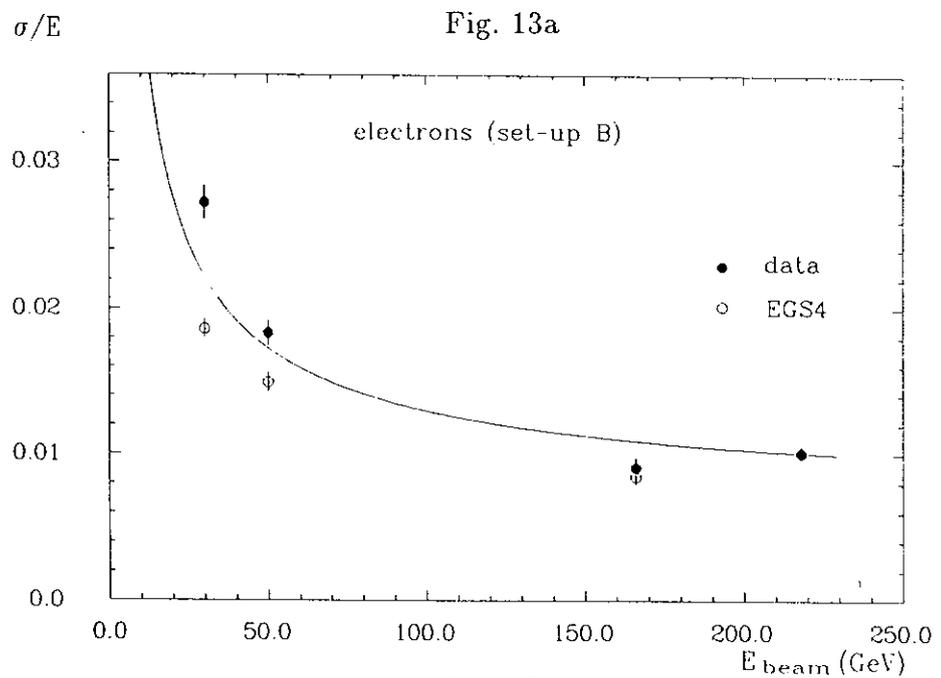


Fig. 13b

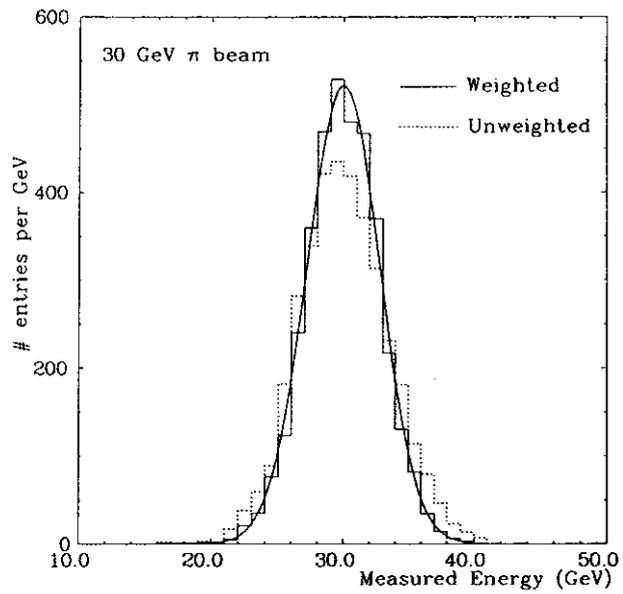


Fig. 14a

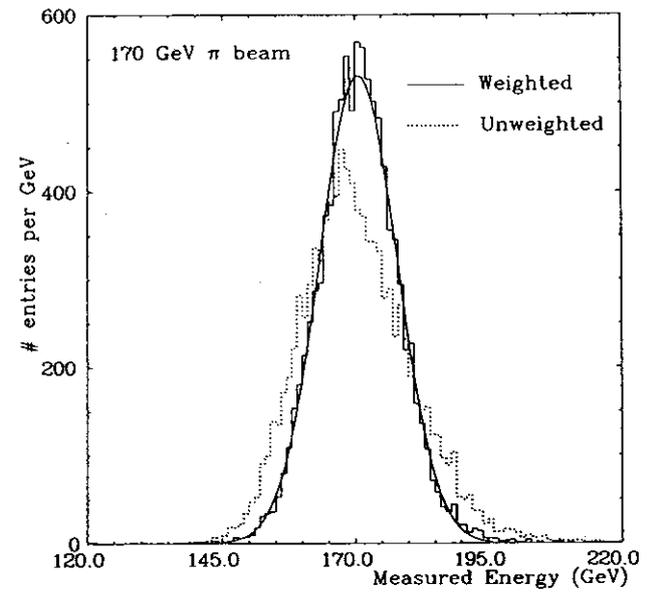


Fig. 14c

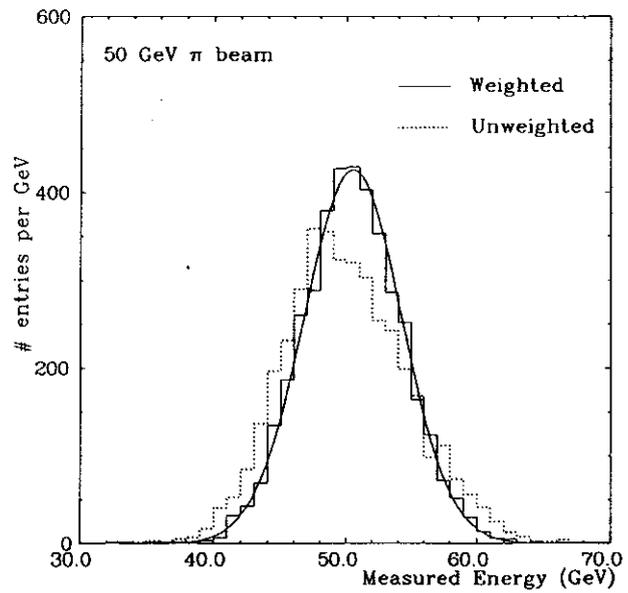


Fig. 14b

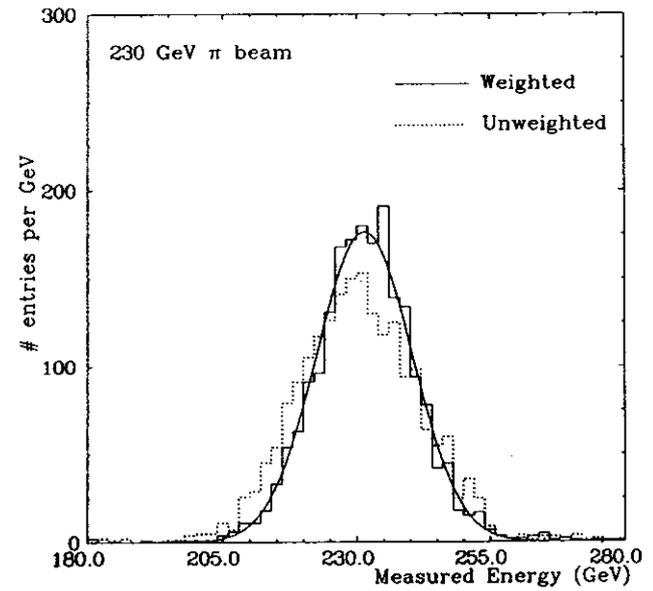


Fig. 14d

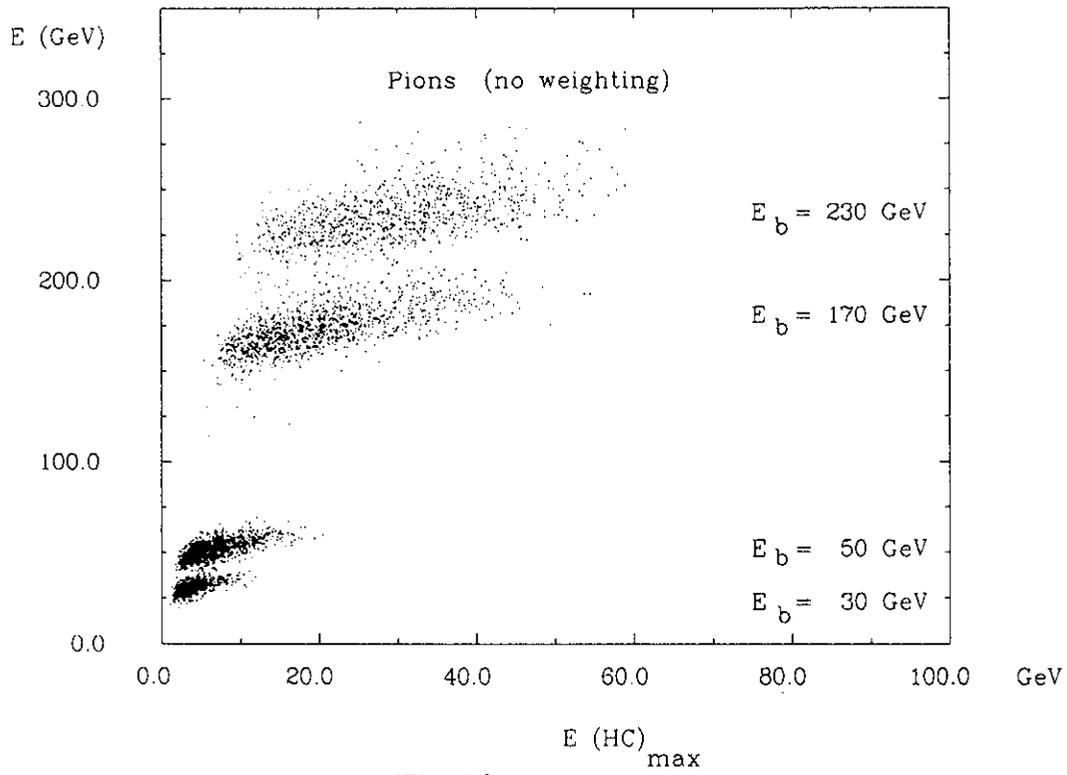


Fig. 16a

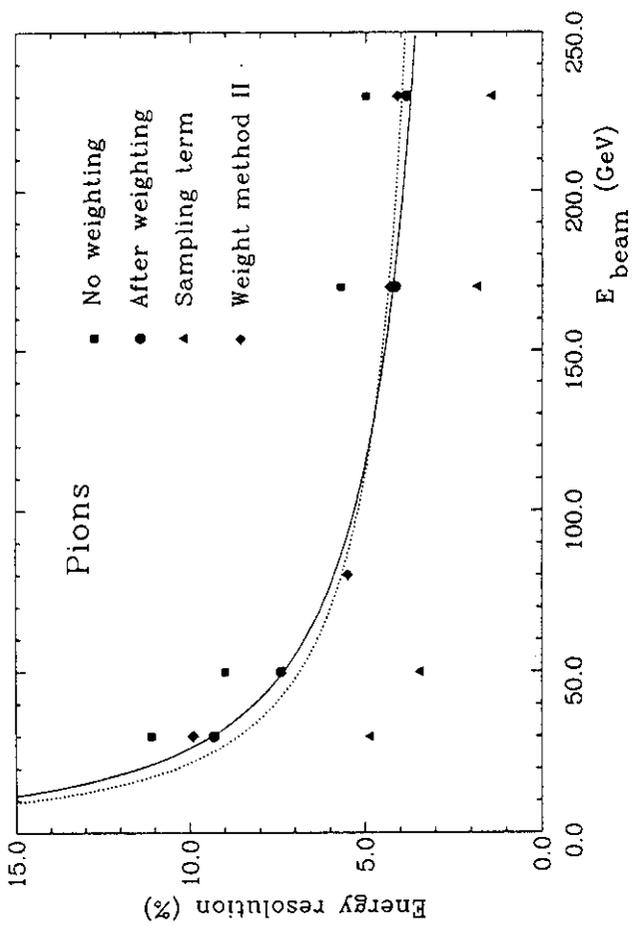


Fig. 15

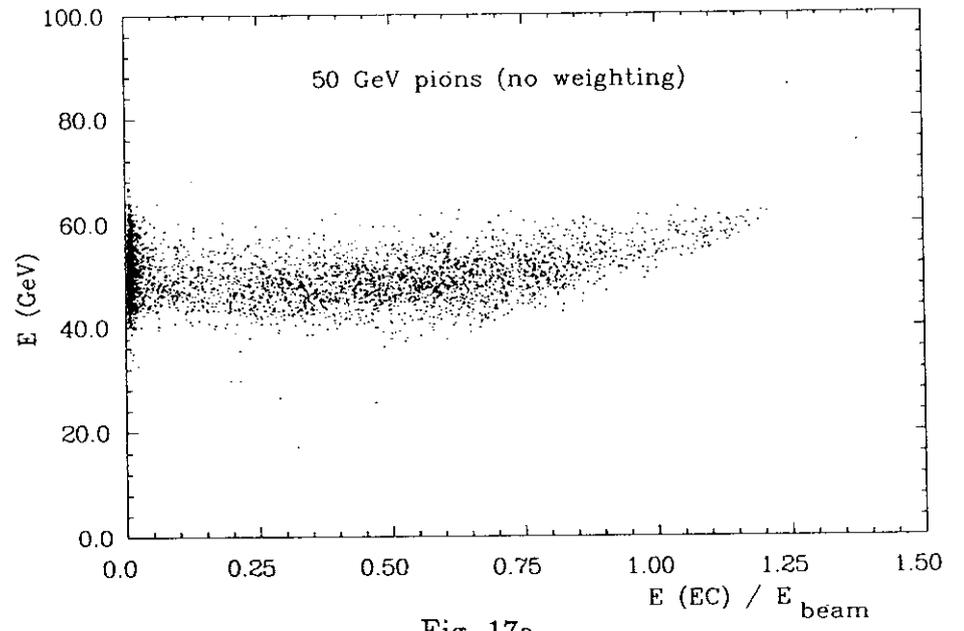


Fig. 17a

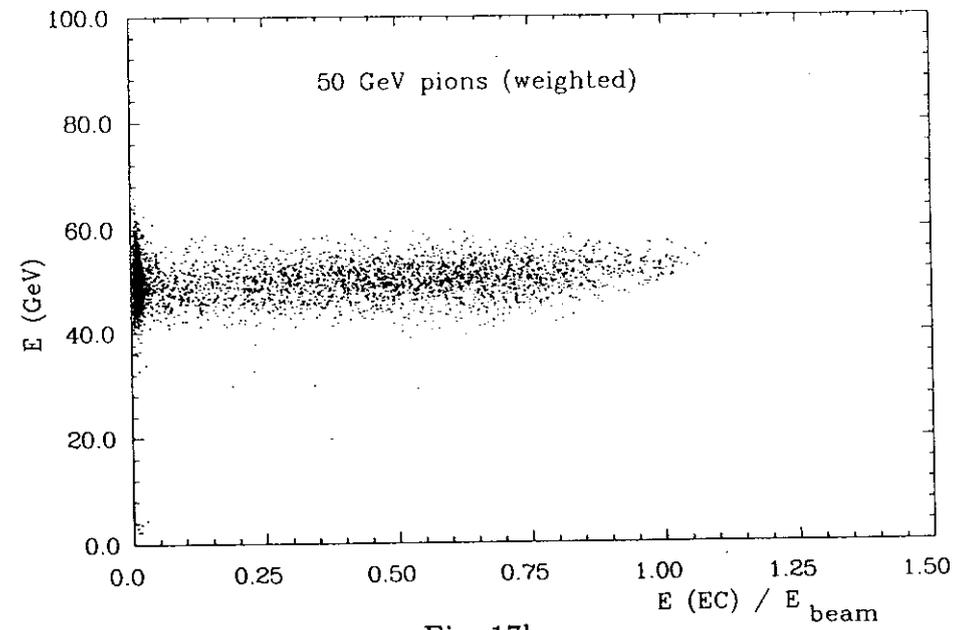


Fig. 17b

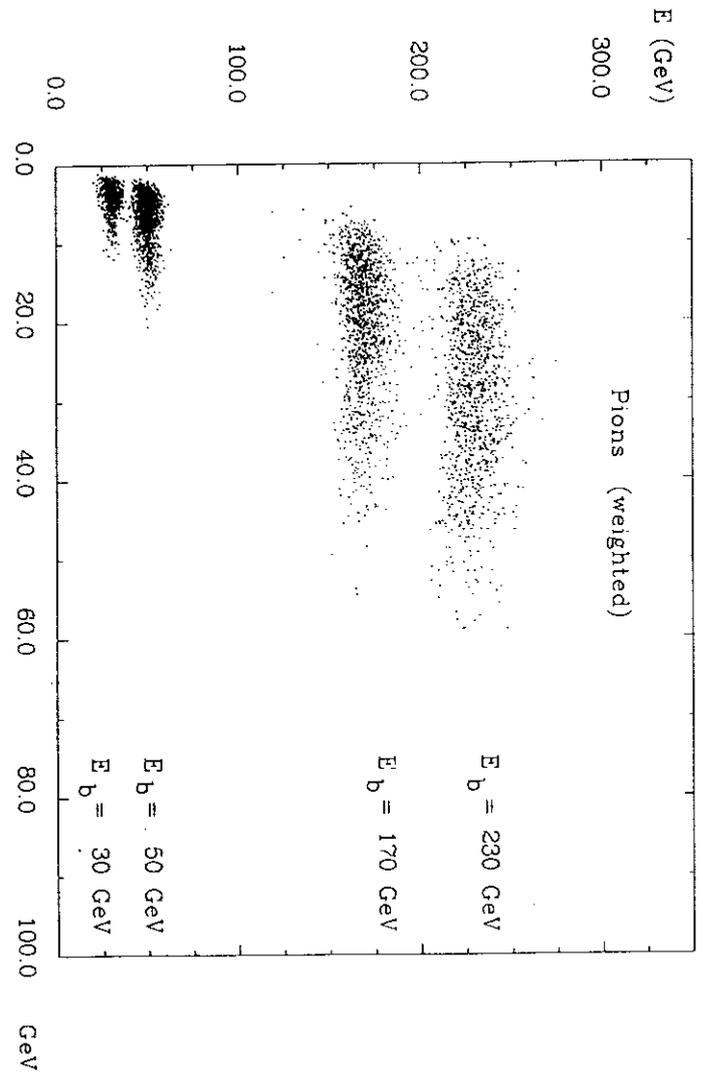


Fig. 16b

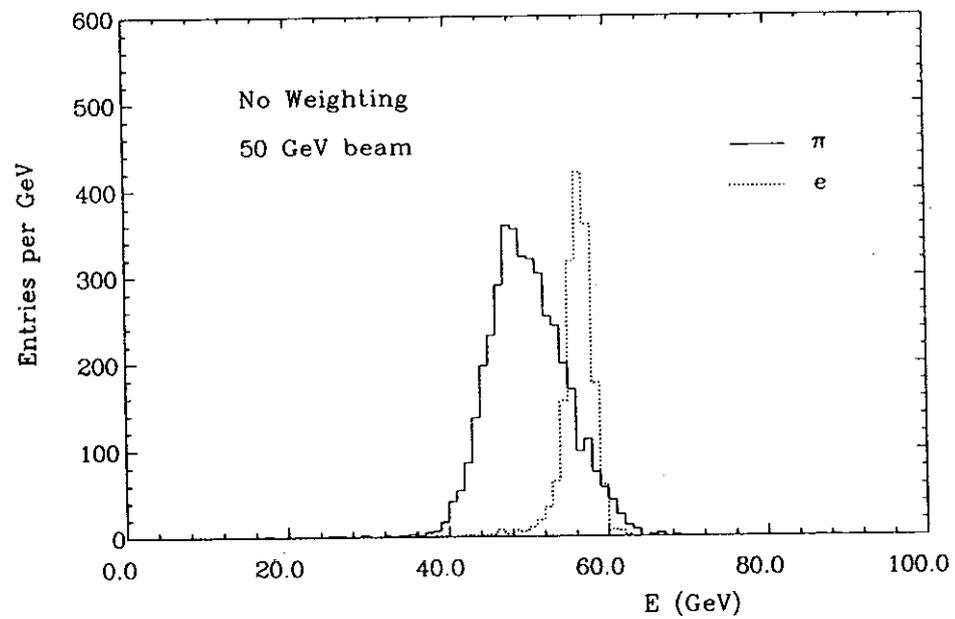


Fig. 18a

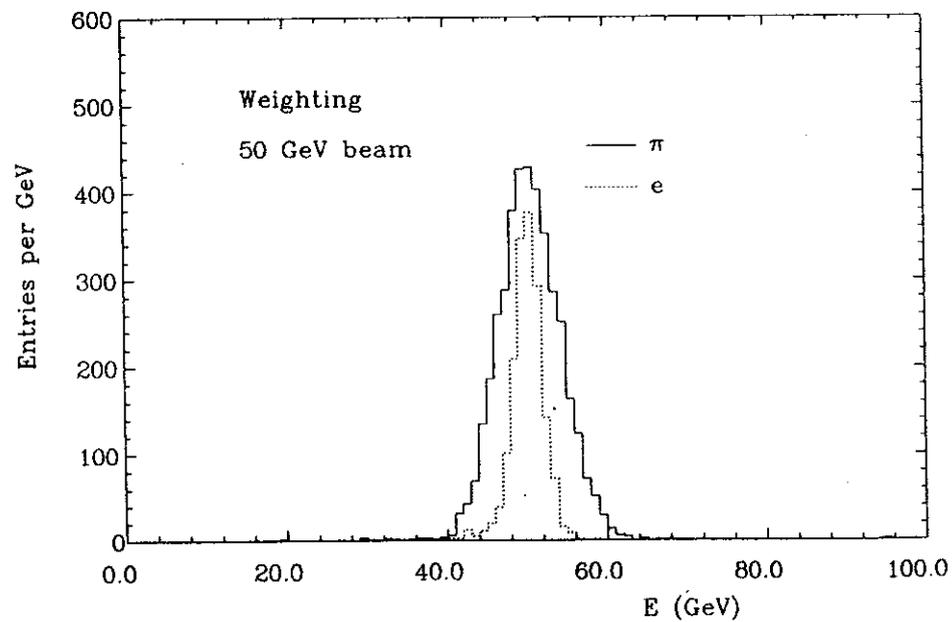


Fig. 18b

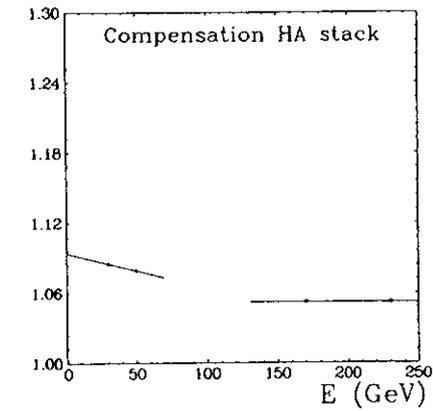
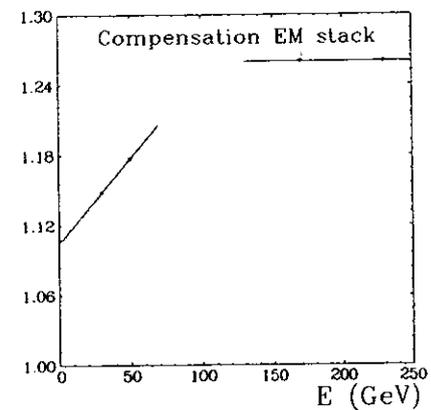
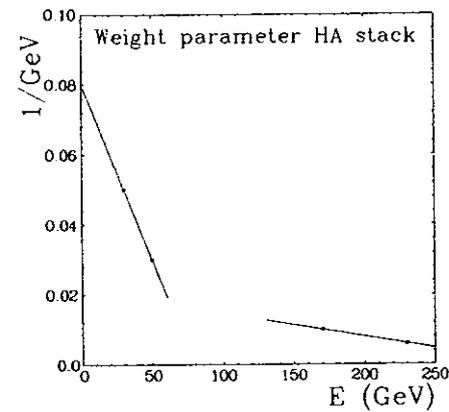
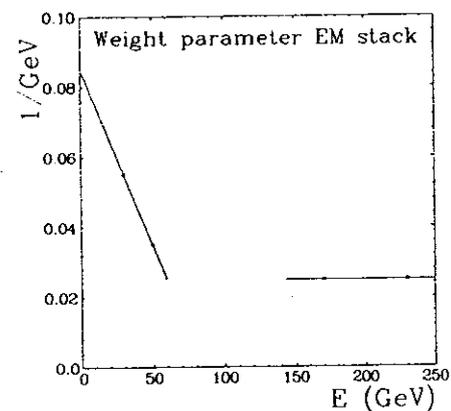
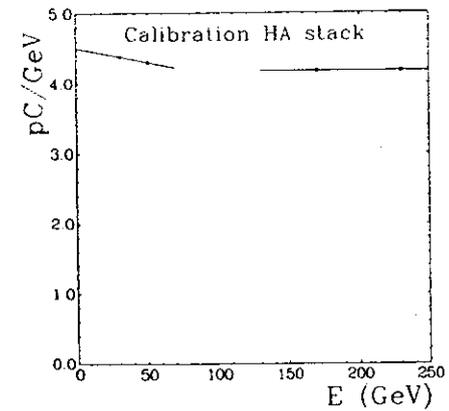
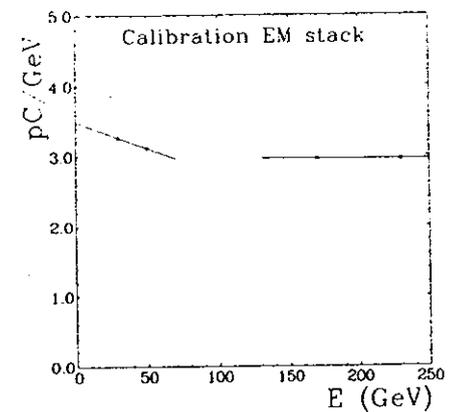


Fig. 19