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Performance of a parallel plate volume calorimeter prototype

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"Performance of a parallel plate volume calorimeter prototype"

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Abstract

An iron/gas parallel plate volume calorimeter prototype, working in the avalanche mode, has been tested using electrons of 20 to 150 GeV/c momentum with high voltages varying from 5400 to 5600 V (electric fields ranging from 36 to 37 KV/cm), and a gas mixture of CF_4/CO_2 (80/20%). The collected charge was measured as a function of the high voltage and of the electron energy. The energy resolution was also measured. Comparisons are made with Monte-Carlo predictions. Agreement between data and simulation allows the calculation of the expected performance of a full size calorimeter.

(To be submitted to Nucl. Instr. and Methods A)

"Comportamiento de un prototipo de carlorímetro volumétrico de placas paralelas"

Arefiev, A.; Bencze, Gy.L.; Bizzeti, A.; Choumilov, E.; Civinini, C.; D'Alessandro, R.; Ferrando, A.; Fouz, M.C.; Iglesias, A.; Ivochkin, V.; Josa, M.I.; Malinin, A.; Meschini, M.; Misyura, S.; Pojidaev, V.; Salicio, J.M.; Sikler, F.
-- pp. - figs. - refs.

Resumen

Se probó un prototipo de calorímetro volumétrico de placas paralelas de hierro/gas, trabajando en modo de avalancha, utilizando electrones de 20 a 150 GeV/c de momento con altas tensiones variables desde 5400 hasta 5600 V (campo eléctrico desde 36 hasta 37 kV/cm), y una mezcla de gas CF_4/CO_2 (80/20%). La carga recogida se midió en función de la alta tensión y de la energía del electrón. Se midió también la resolución en energía. Se hacen comparaciones con predicciones Monte-Carlo. El acuerdo entre los datos y la simulación permite el cálculo del comportamiento esperado de un calorímetro de tamaño real.

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30 November 1994

PERFORMANCE OF A PARALLEL PLATE VOLUME CALORIMETER PROTOTYPE

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Abstract

An iron/gas parallel plate volume calorimeter prototype, working in the avalanche mode, has been tested using electrons of 20 to 150 GeV/c momentum with high voltages varying from 5400 to 5600 V (electric fields ranging from 36 to 37 kV/cm), and a gas mixture of CF_4/CO_2 (80/20%). The collected charge was measured as a function of the high voltage and of the electron energy. The energy resolution was also measured. Comparisons are made with Monte-Carlo predictions. Agreement between data and simulation allows the calculation of the expected performance of a full size calorimeter.

(To be submitted to Nucl. Instr. and Methods A)

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1. Introduction

The requirements for calorimeters in the very forward region of the future Large Hadron Collider (LHC) experiments, extending the pseudorapidity coverage up to 5 units, are very demanding. The device should be fast, work in areas of very high occupancy [1], under serious radiation levels [2, 3] and be simple and unexpensive.

A very forward calorimeter (VFCAL), based on the parallel plate chambers (PPC) principle [4], has been proposed [5] for the CMS Experiment [6, 7].

A PPC detector consists of two metal or metallized flat electrodes (planarity better than 5 μm is needed). The small and precise gap (sizes ranging from 1 to 2 mm, with an accuracy of 5 μm) is filled with gas. It works in the avalanche mode with very uniform electric fields of 30 to 60 kV/cm, depending on the gas and gap used. The properties of the PPCs have been discussed elsewhere [8 - 13].

Among the possible technologies for building these detectors, we consider here the use of thick iron electrodes as a viable solution for a calorimeter. Two iron electrodes (15 to 40 mm thick), with a small gas gap in between, conforms an iron PPC cell [14]. When many of these cells are taken together, one obtain a volume of parallel iron plates (PPV). Volumes constructed in that way can be used as modules for an iron gas calorimeter, suitable in very demanding working conditions. Use of other technologies, as the ceramic PPCs [11], for the construction of calorimeter modules will be reported in a forthcoming publication.

The paper is organized as follows. Section 2 contains the mechanical aspects of the iron/gas VFCAL and its basic components. The description of the prototype, front-end electronics and experimental set-up is given in section 3. Results are presented in sections 4 to 6, while in section 7 the comparison between Monte-Carlo predictions and data is made. Conclusions are drawn in section 8.

2. The iron/gas PPV solution for CMS

One possible mechanical arrangement for the VFCAL is shown in fig. 1. It consists of 3 walls of dimensions X*Y*Z ≈ 440x440x80 cm^3, leaving a central hole X*Y*Z ≈ 40x40x80 cm^3, for the beam pipe. The first wall is located 11 m up and downstream the CMS interaction point, covering the pseudorapidity region $2.5 \leq |\eta| \leq 5.0$. Each wall is assembled from modules of PPV's, of dimensions X*Y*Z ≈ 20x40x80 cm^3. Each of these modules consists of a stainless steel box containing a series of 21 iron planes, of dimensions 20x40x3.5 cm^3, interleaved with 1.5 mm gas gaps provided by ceramic spacers. Fig. 2 shows the mechanical arrangement of one of these Volumes. Every second plane is made of 8 iron plates (dimensions 9.7x9.7x3.5 cm^3) acting as electrodes. The module has an equivalent length of ≈ 4 λ_I (around 40 X_0). The weight of such a unit is about 460 kg. The iron plates (in fact, low carbon steel plates) have to be machined up to a precision of few microns in flatness. Sharp borders must be avoided.

The PPV is filled with gas. The high voltage is applied to the small plates and the two adjacent plates are grounded. A single electrode reads the signal from two adjacent gas gaps. High voltage cables, of ≈ 80 cm, link the electrodes to the exit connectors. From there, twisted pair cables bring the signal along ≈ 2 m to the associated front-end electronics, located at the outer surface of the calorimeter. This arrangement is necessary in view of the high neutron flux (≈ 10^8 Hz cm^{-2}) expected when running at the highest luminosity [3].

In the configuration shown in fig. 1, one wall contains ≈ 200 modules and weights around 100 tons.

3. Experimental conditions

3.1 The prototype

The PPV prototype is equipped with only 5 iron planes. The used iron thickness (for both, grounded plates and electrodes) was 17 mm instead of 35. The gas gap between planes is always 1.5 mm. Electrodes are isolated by ceramic spacers. The iron plates are machined to an accuracy of ± 5 μm in flatness. Edges were rounded. The module contains a total of 16 electrodes. It is subdivided laterally into eight towers of two electrodes each (4 gas gaps). The length is equivalent to about 0.5 λ_I or 5 X_0. Results from a previous test with a single electrode cell prototype were already published [14].

The ionization charge produced by the particles going through the prototype led to avalanches in the four 1.5 mm gas gaps. The signal is read from the high voltage electrodes through a capacitor for high voltage decoupling. The intrinsic capacitance of the electrodes is of the order of 200 pF.

The amplifier (SPNPI-921-1-M), already used in [10] and [14], has 7 ns rise time, high gain (60 mV/μA) and relatively low noise (3000 electrons).

3.2 Experimental setup

The experimental setup is sketched in fig. 3. The module is located at the maximum of the electromagnetic cascades by installing passive iron plates in front of it. The total iron length in front of the first gas gap was equivalent to ≈ 8 X_0 and the one preceding the last gap was ≈ 11 X_0. The module was exposed to electron and muon beams from the CERN SPS (energy range from 20 to 150 GeV). The beams, 2 cm wide, were sent to the center of one of the electrodes. The data was taken at 5 different voltages (5400, 5450, 5500, 5550 and 5600 V).

A mixture CF4/CO2 (80/20%) at atmospheric pressure was used. The gas system consisted of a pressure reductor that sends the gas into the prototype through a flowmeter, a filter (removing dust particles down to 0.5 μm) and a trap for oxigen and water molecules. The final content in O_2 and H_2O in the gas gap was smaller than 10 ppm. Due to the sensitivity of the response to the atmospheric pressure and temperature conditions, the charge collection measurements are affected by a systematic error of about 10%.

The readout was done through a LeCroy 2249A ADC.

4 The spatial uniformity of the response

To study the position-dependent uniformity of the chamber response, i.e. the gap uniformity along the electrodes' plane, the influence of the side gaps between electrodes, etc., we made a position scan by sending 150 GeV/c muons impacting at 13 points along the dotted line in fig. 4 (upper left). About 30000 events were recorded for each point. The charge collected in the electrodes A6, A7 and A8 are also given in fig 4. A extends for the first plane of electrodes in the prototype. Full lines are interpolations between points. The charge collection is uniform, within 2 ADC counts (that is the typical width of the distributions of the pedestals), along the electrodes' surfaces. The effect when crossing the 3 mm gap between adjacent electrodes (following the dashed line in fig. 4) is seen as ≈ 30% loss in the charge collection.

5. Charge collection as function of the high voltage

Typical ADC charge spectra are shown in fig. 5. The cascade is laterally contained in the tower where the beam is centered. One ADC count corresponds to ≈ 5 fC of collected charge in the electrodes. The distributions correspond to 120 GeV electrons for various high voltages. The curves are the results of Gaussian fits to the data. The left side tails can be related to muon contamination. A very small amount of events showing saturation of the ADC channels is observed in the right hand side of the distribution at 5550 V. No saturation effects occurred at lower HV values.

The mean values of the ADC charge distributions are shown in fig. 6 as a function of the HV, for various electron energies. They all show the expected exponential behaviour.

6. Linearity of the response and energy resolution

The fitted collected charge is plotted, in fig. 7, as a function of the electron energy, for 4 HV values. The response is linear with the energy. The straight lines in the plots represent the corresponding fits to the data. The slope increases with the high voltage from 7.7 counts/GeV at 5450 V to 38.5 counts/GeV at 5600 V.

Finally, the resolution $\sigma(E_{rec})/<E_{rec}>$, E_{rec} being the reconstructed energy, versus $1/\sqrt{E}$, where E is the electron energy, is given in fig. 8 for various high voltages. We have fitted the data points to the form:

$$\sigma(E)/E = a/\sqrt{E} + c \qquad (1)$$

and obtained a = (1.68 ± 0.10), (1.64 ± 0.10), (1.56 ± 0.10) and (1.63 ± 0.10) $GeV^{1/2}$ for HV = 5450, 5500, 5550 and 5600 V, respectively. In all cases, in spite of the restricted active volume, c was very small ($\leq 10^{-3}$). Notice that the measured resolution corresponds to a calorimeter module consisting of about 220 mm of iron absorber and 6 mm of active gas.

7. Comparison with Monte-Carlo predictions

7.1 Monte-Carlo simulation

For cascade simulation, we have assumed a geometry similar to the experimental setup: 12 cm of iron followed by a volume made of 5 iron plates of dimensions 200x400x17 mm^3, interleaved with gas gaps of 1.5 mm. Every plate is subdivided into 8 cells, 100x100 mm^2 each, simulating the electrodes. GEANT 3.21 [15] was used to generate showers in the volume.

Since, in the avalanche mode, the number of collected electrons, depends on the distance between the primary ionization and the anode (for a given gas at constant temperature and pressure), we have divided each of the 1.5 mm gas gaps into 10 GEANT independent subvolumes of 0.15 mm. Information about dE/dx in the gas subvolumes was written on disk for a subsequent simulation of the avalanche operation. We assumed normal conditions of pressure and temperature.

Under these conditions we have simulated 500 electron showers for each energy setting.

7.2 Simulation of the avalanche mode of operation

Using the information provided by GEANT on the energy deposited by ionization, ΔE_i, in each of the 10 subvolumes of a given gas gap, we have approximated the expected number of electrons collected at the anode by:

$$N = \Sigma\, n_p{}^i\, e^{\alpha x_i} \qquad (2)$$

where $n_p{}^i$ is the expected primary electron-ion production, α is the first Townsend coefficient [16] and x_i is the distance from the i-th subgap gas to the anode.

The average number of primary pairs is:

$$n_o{}^i = \Delta E_i / W \qquad (3)$$

where W is the effective average energy to produce one electron - ion pair in the gas (W is 37.8 eV for the gas mixture used in the prototype).

This number of primary ionization events follows a Poisson-like distribution. We have then approximated $n_p{}^i$ in eq. (2), by randomly generating a number from a Poisson distribution having $n_o{}^i$ as mean value. This process is repeated for any ΔE_i in the gas.

The comparison was made for the data collected at 5550 V. The value α = 58 cm^{-1} was used for the first Townsend coefficient. This value corresponds to an average gain of about 700. We are assuming that the pressure was constant during the data taking, namely P = 719 Torr.

7.3 Comparison of experimental and Monte-Carlo data

Fig. 9 shows the collected charge distributions, in ADC counts, for the data (dashed line) and for the Monte-Carlo prediction for 8 electron energies. All distributions are normalized to one entry. Our Monte-Carlo reproduces quite well the data for all energies.

The comparison of measured and predicted energy resolutions is presented in fig. 10. The data points (full circles) and the Monte-Carlo (open circles) are in fair agreement. Nevertheless, and since we have not simulated the effects due to the side gaps between electrodes, the electronic noise, the beam contamination, etc., the Monte-Carlo points are systematically below the data.

Agreement between data and simulation allows to make predictions on the performance of a fullsize calorimeter module of 17 mm iron plates. Full and open squares in fig. 10 represent the expected energy resolution for electron and pion showers, respectively. We have fitted eq. (1) to the predicted points and found:

$$\sigma(E)_e/\langle E\rangle_e = (0.55 \pm 0.01)/\sqrt{E} \text{ and}$$
$$\sigma(E)_\pi/\langle E\rangle_\pi = (0.70 \pm 0.02)/\sqrt{E} + (0.02 \pm 0.01).$$

8. Conclusions

A prototype of an iron/gas parallel plate volume, based on the PPC technique, was tested at the CERN SPS secondary electron beams. The absorber (iron) acts at the same time as electrodes for electron/ion collection. Avalanches are produced in thin (1.5 mm) gaps of gas, provided by ceramic spacers between the iron plates.

We have observed that this type of calorimeter has a linear response. We have measured the resolution in the prototype and compared with our simulated prediction. The observed good agreement allows to predict a single pion energy resolution of about 70%$\sqrt{E}$ with a very small constant term, when plates 17 mm thick are used (90%$\sqrt{E}$, also with a small constant term, for 35 mm plates).

Having demonstrated the feasibility of the mechanical construction using only radiation resistant materials, the smooth operation of the device, the fast collection of the signal, the good performance of the prototype and being able to predict a good hadron resolution for a full size calorimeter, we conclude that the proposed solution fulfills the basic physics requirements of a very forward calorimeter for LHC experiments.

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Figure captions

Fig. 1: Layout of the iron/gas VFCAL.
Fig. 2: Sketch of an iron/gas module.
Fig. 3: Layout of the experimental arrangement.
Fig. 4: Charge collected (from muons) in electrodes A6, A7 and A8 versus the beam incident position in the x-y plane (see text).
Fig. 5: Collected charge distribution (ADC counts) from 120 GeV/c electrons, for various HV working values.
Fig. 6: Fitted collected charge as a function of the high voltage, for various electron energies.
Fig. 7: Fitted collected charge as a function of the electron energy, for various HV working values.
Fig. 8: Measured electron energy resolutions, for various HV working values.
Fig. 9: Normalized charge distributions for various electron energies. Dashed and continous lines correspond to the data and to the MonteCarlo predictions, respectively.
Fig. 10: Energy resolutions. Full circles: data from prototype (electrons); open circles: prototype simulation (electrons); full squares: expected electron energy resolution (see text); open squares: expected pion energy resolution (see text).

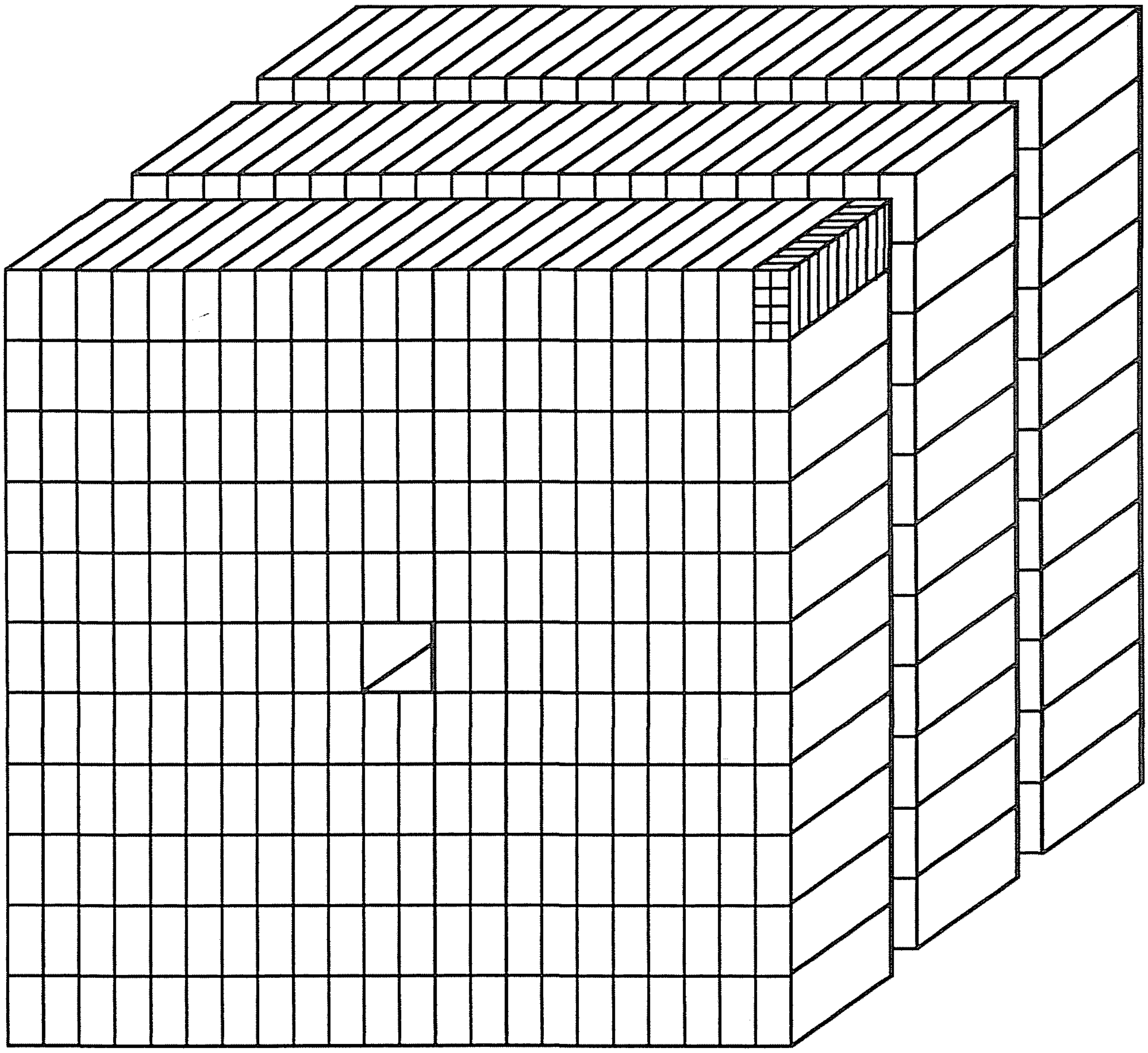
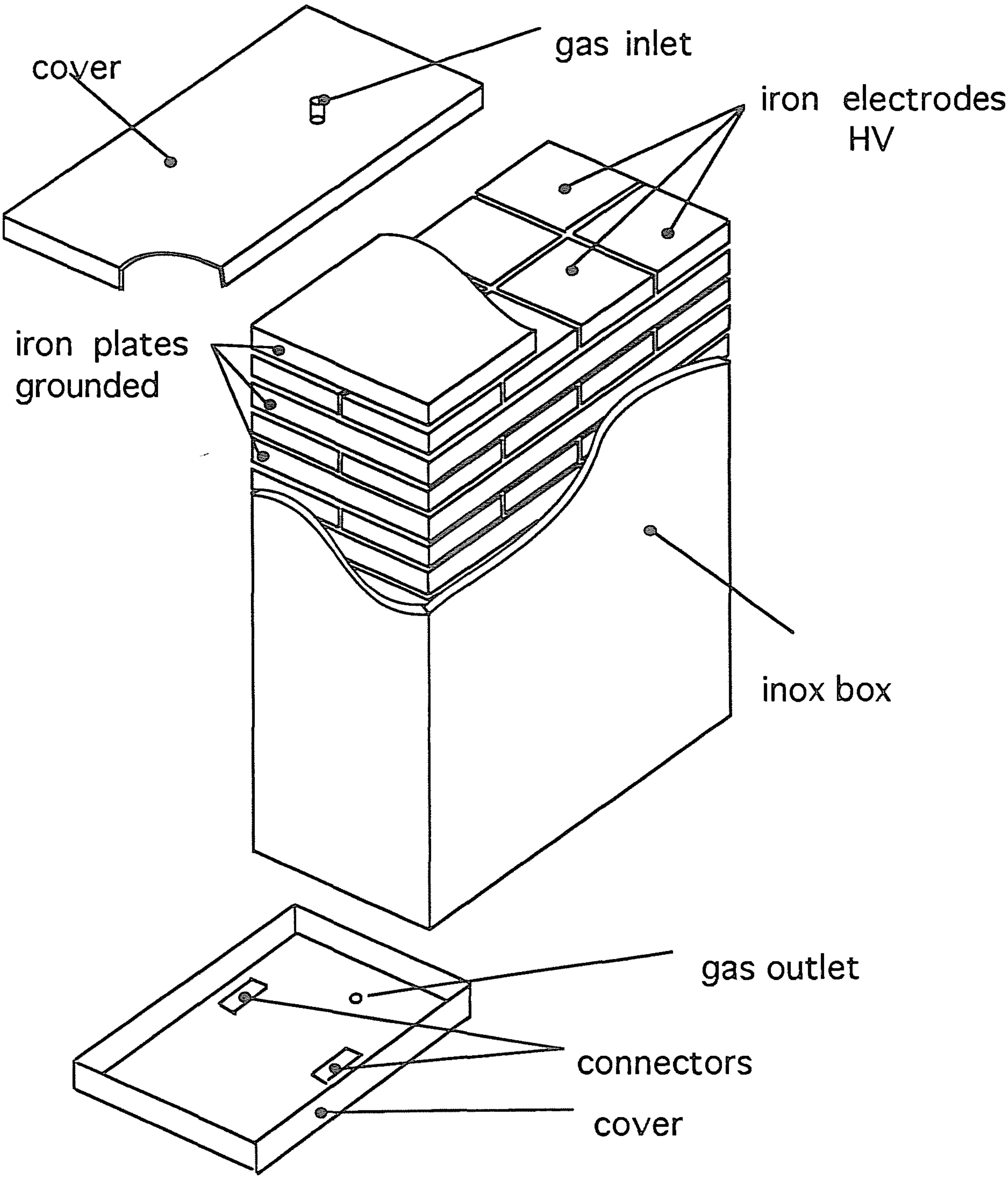
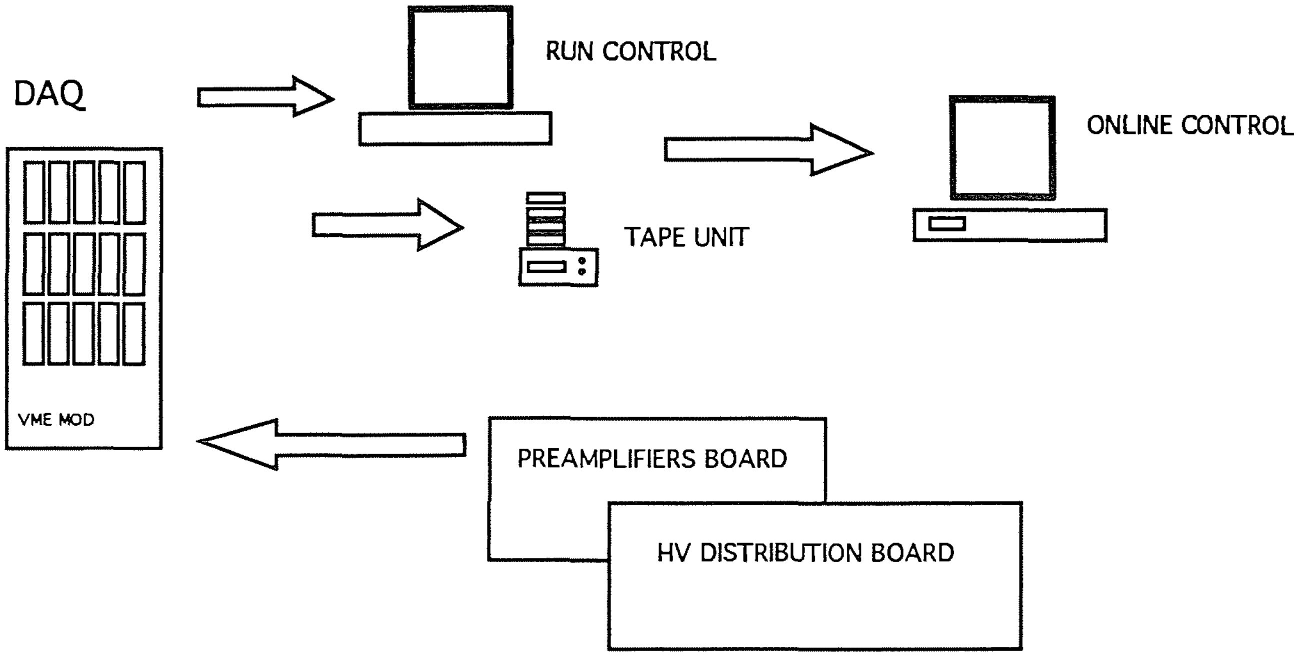


Fig. 1



gas inlet
cover
iron electrodes
HV
iron plates
grounded
inox box
gas outlet
connectors
cover

Fig. 2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ONLINE CONTROL
TAPE UNIT
VME MOD
PREAMPLIFIERS BOARD
HV DISTRIBUTION BOARD

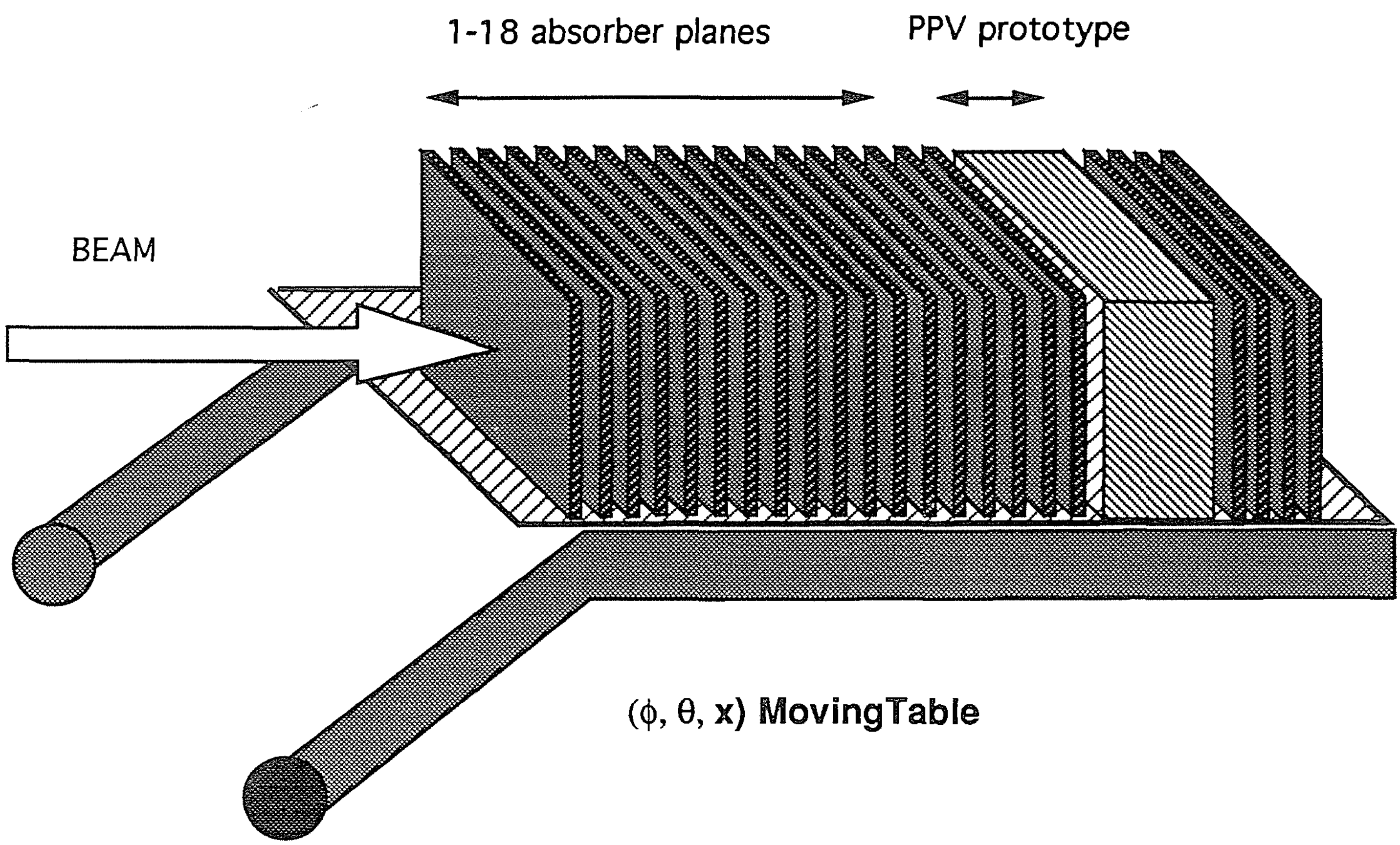
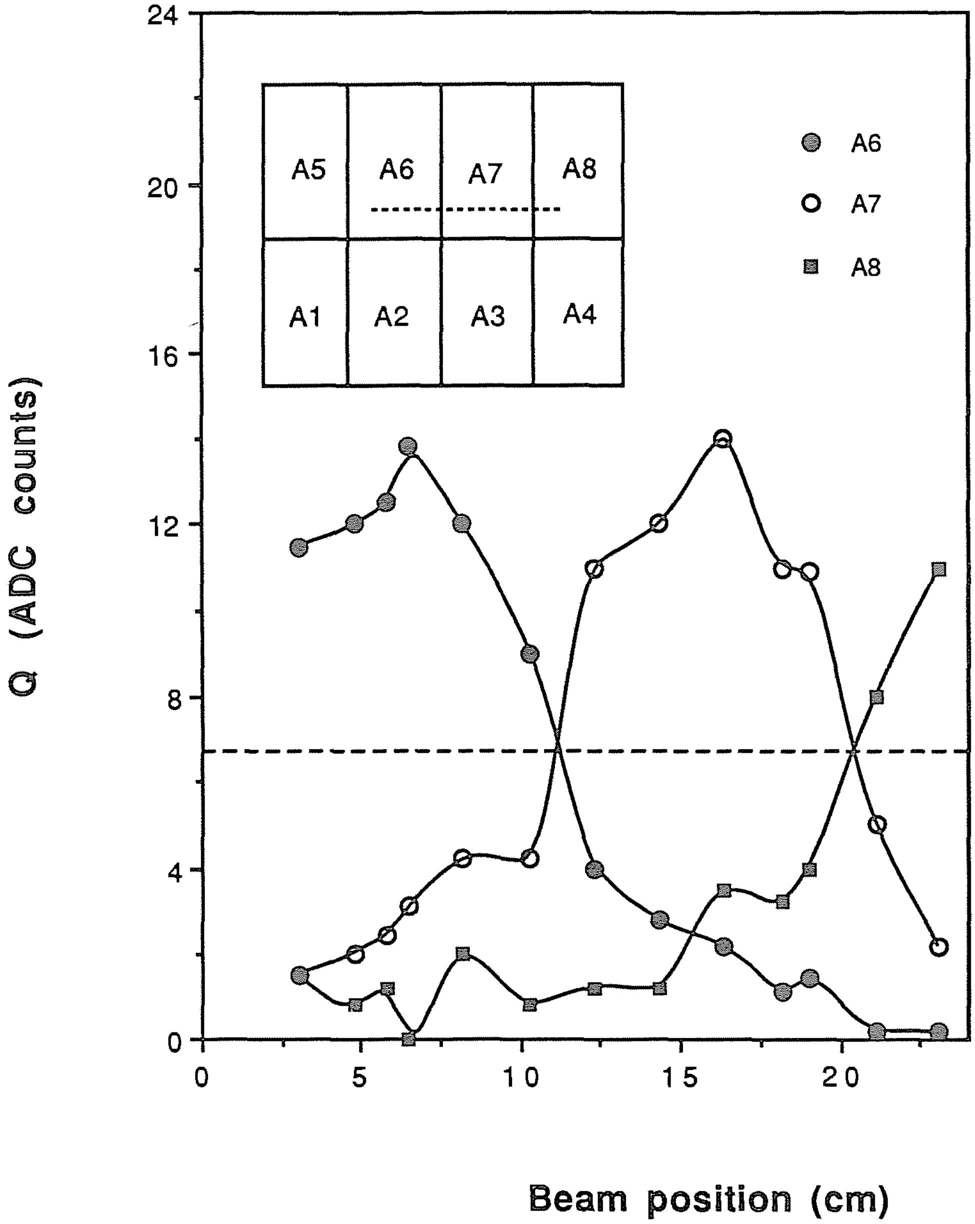

1-18 absorber planes
PPV prototype
BEAM
(φ, θ, x) MovingTable

Fig. 3


Q (ADC counts)
24
20
16
12
8
4
0
A5
A6
A7
A8
A1
A2
A3
A4
A6
A7
A8
0
5
10
15
20
Beam position (cm)
Fig. 4

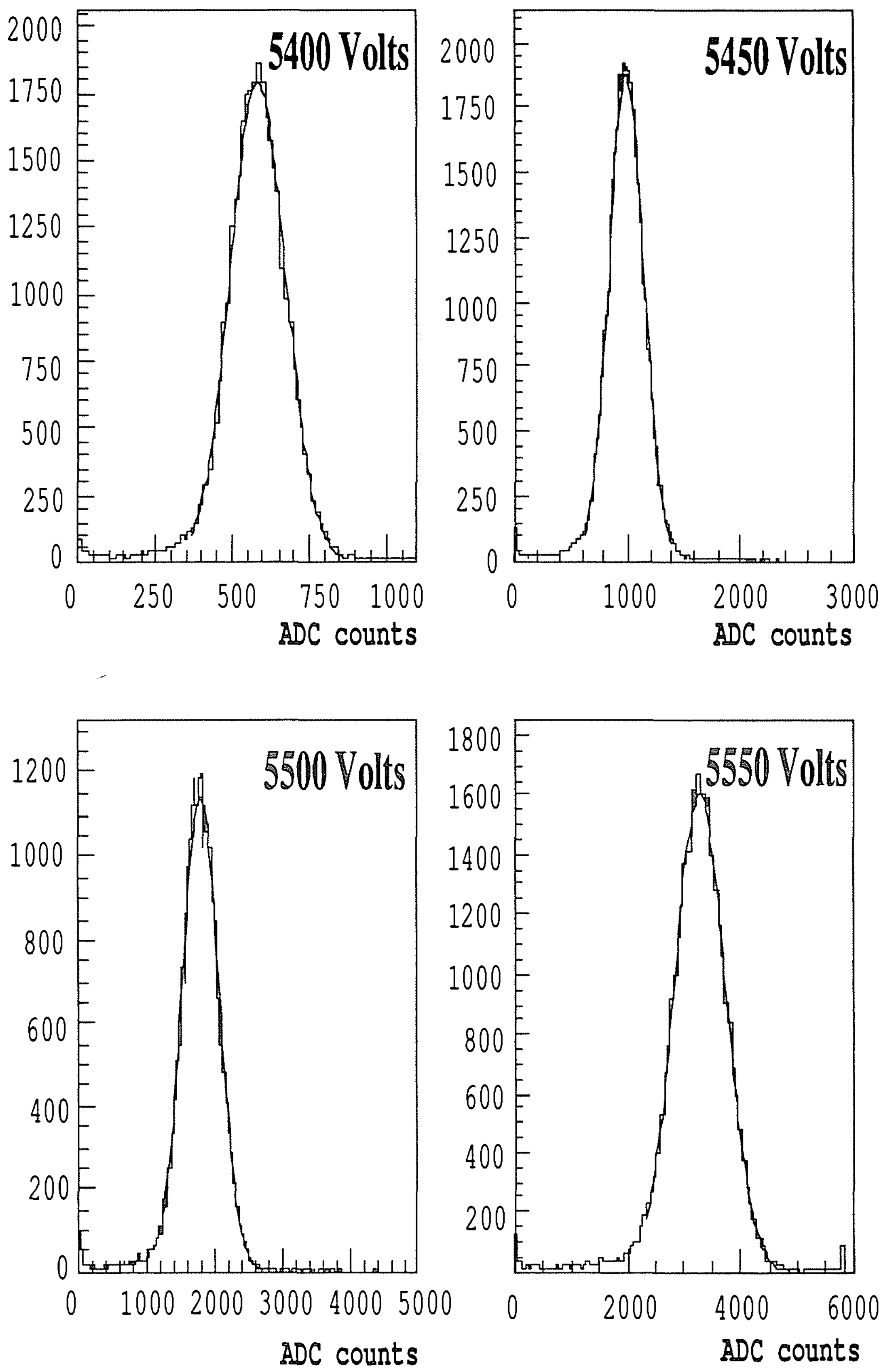
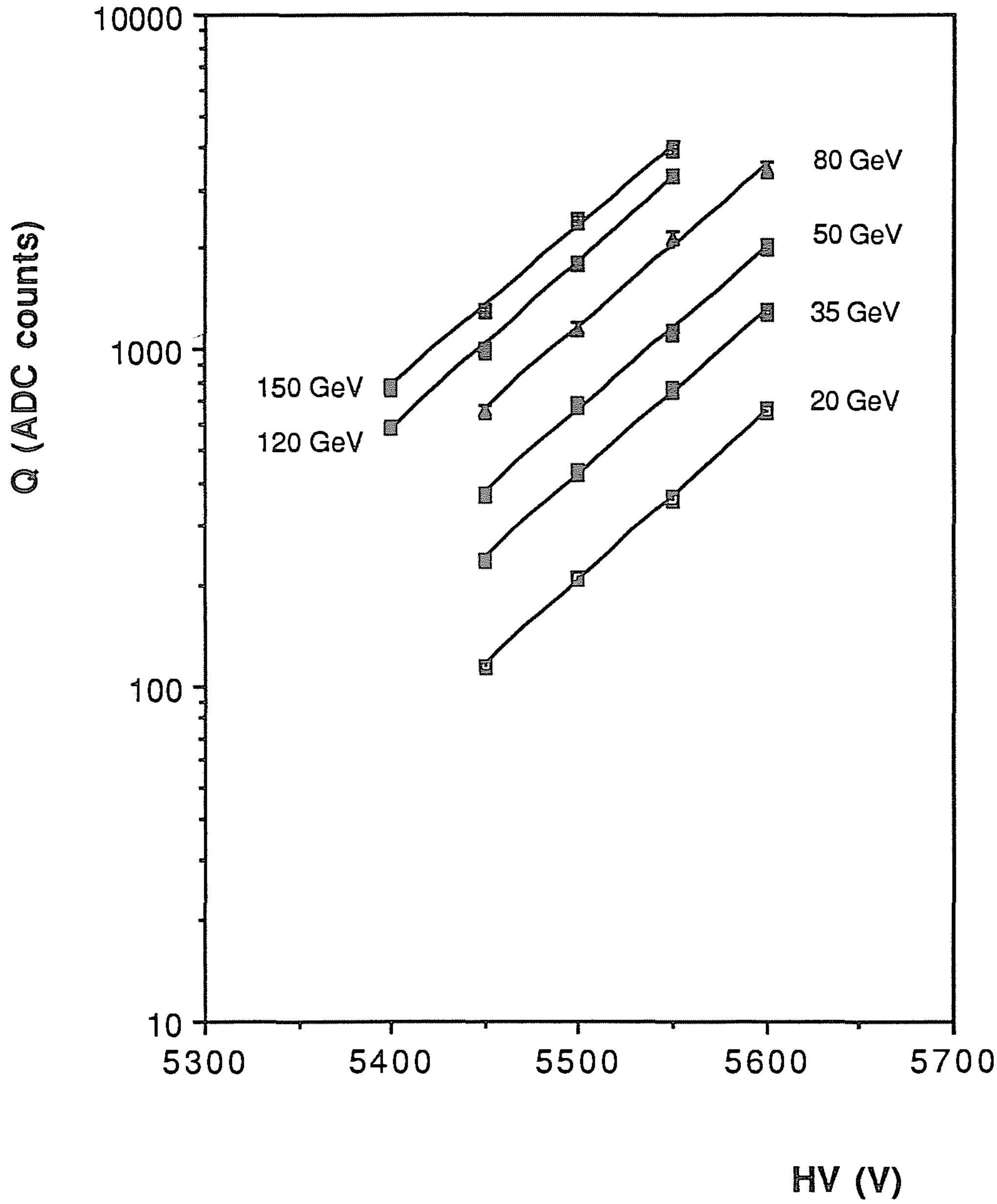

5400 Volts
2000
1750
1500
1250
1000
750
500
250
0
0 250 500 750 1000
ADC counts
5450 Volts
2000
1750
1500
1250
1000
750
500
250
0
0 1000 2000 3000
ADC counts
5500 Volts
1200
1000
800
600
400
200
0
0 1000 2000 3000 4000 5000
ADC counts
5550 Volts
1800
1600
1400
1200
1000
800
600
400
200
0 2000 4000 6000
ADC counts

Fig. 5



Q (ADC counts)
10000
1000
100
10
5300
5400
5500
5600
5700
HV (V)
150 GeV
120 GeV
80 GeV
50 GeV
35 GeV
20 GeV

Fig. 6

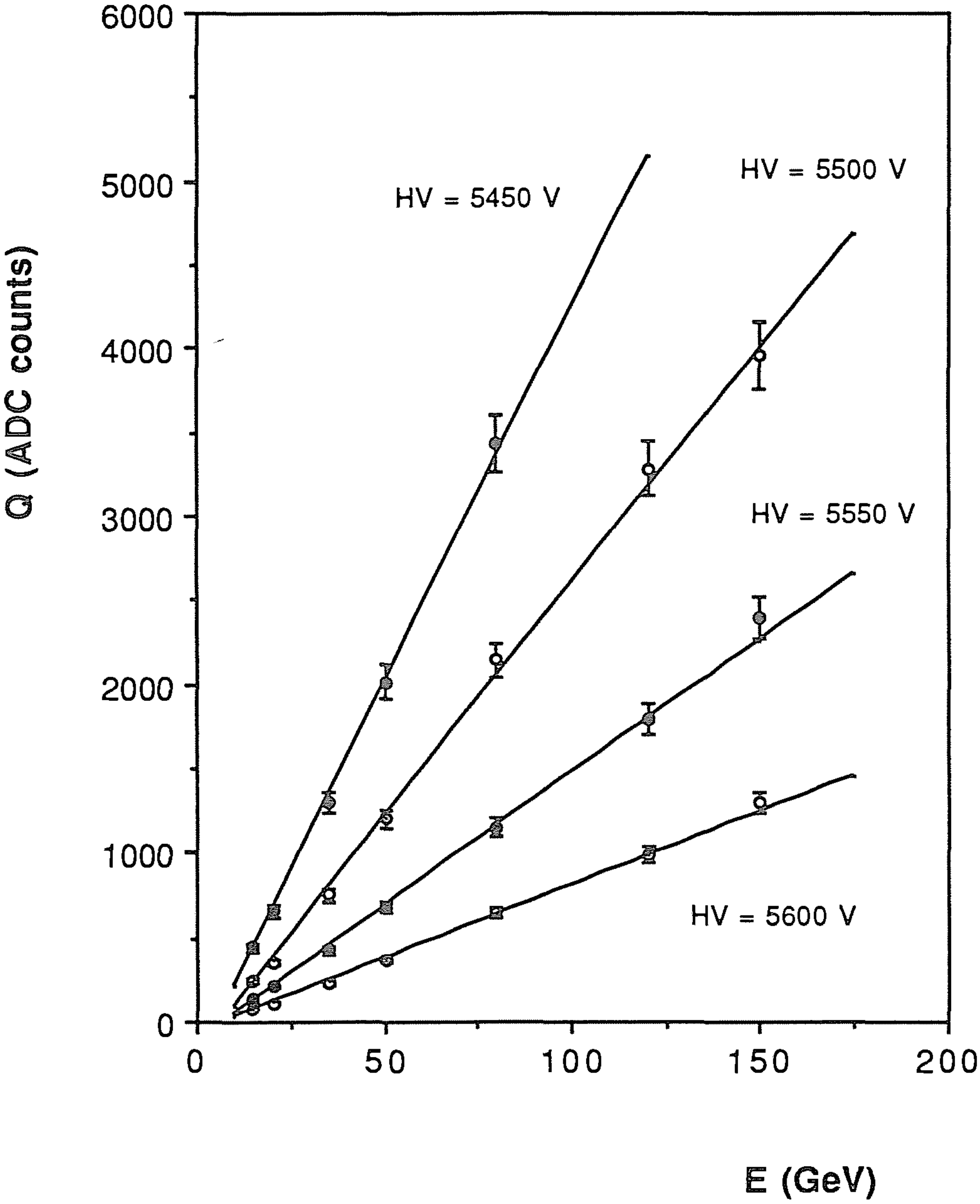

6000
5000
4000
3000
2000
1000
0
Q (ADC counts)
HV = 5450 V
HV = 5500 V
HV = 5550 V
HV = 5600 V
0
50
100
150
200
E (GeV)

Fig. 7

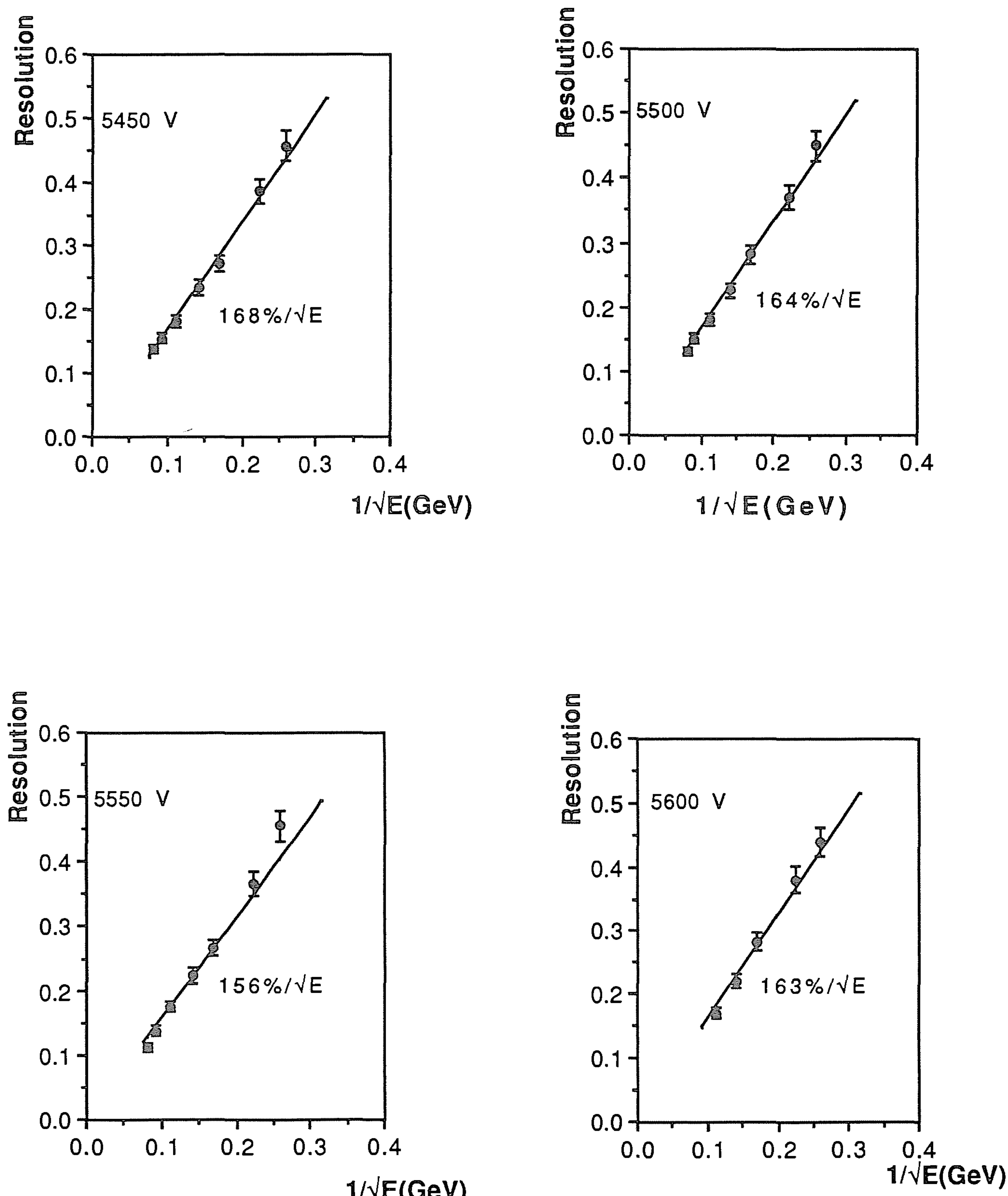

Resolution
5450 V
168%/√E
1/√E(GeV)
Resolution
5500 V
164%/√E
1/√E(GeV)
Resolution
5550 V
156%/√E
1/√E(GeV)
Resolution
5600 V
163%/√E
1/√E(GeV)

Fig. 8

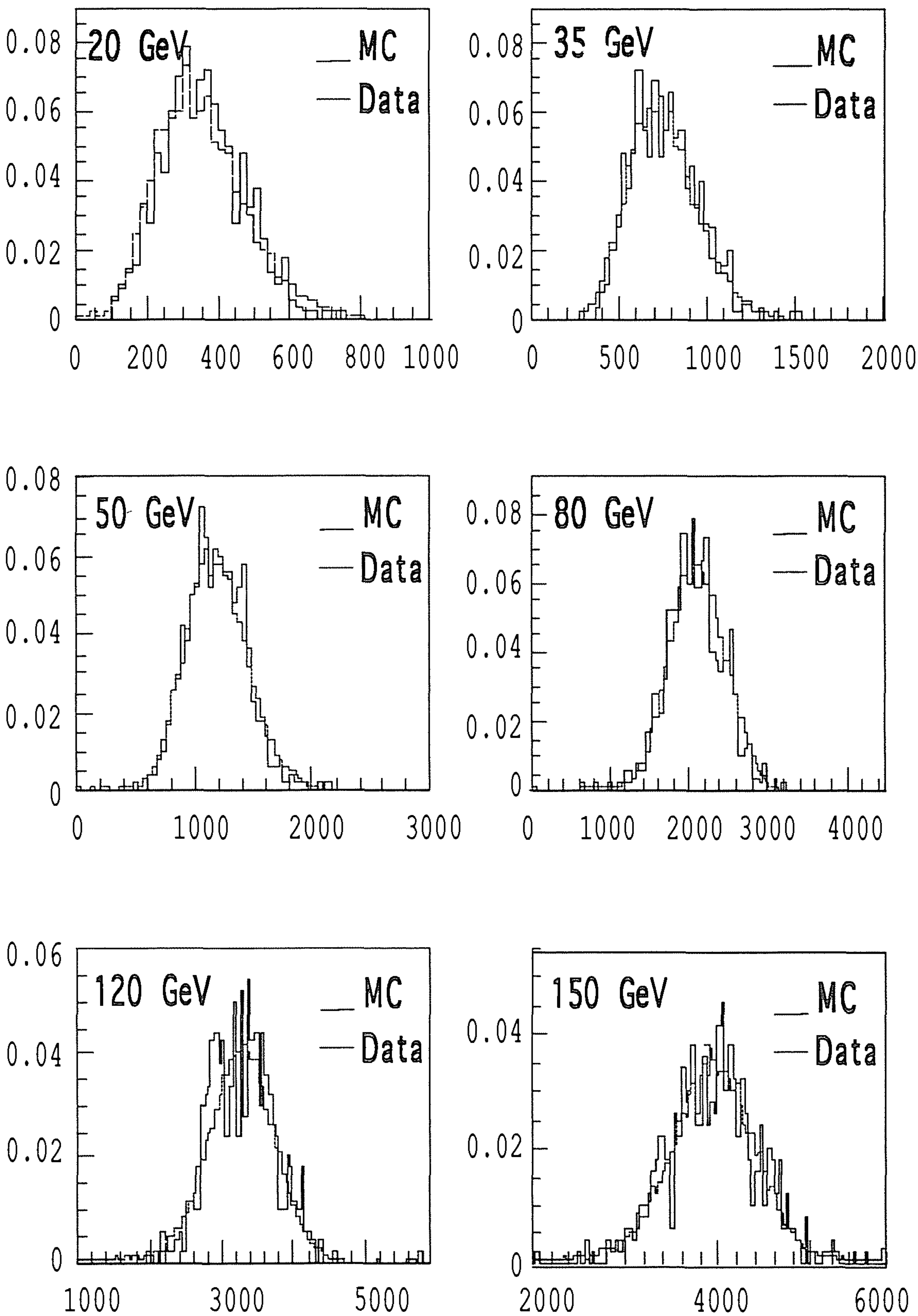


Fig. 9

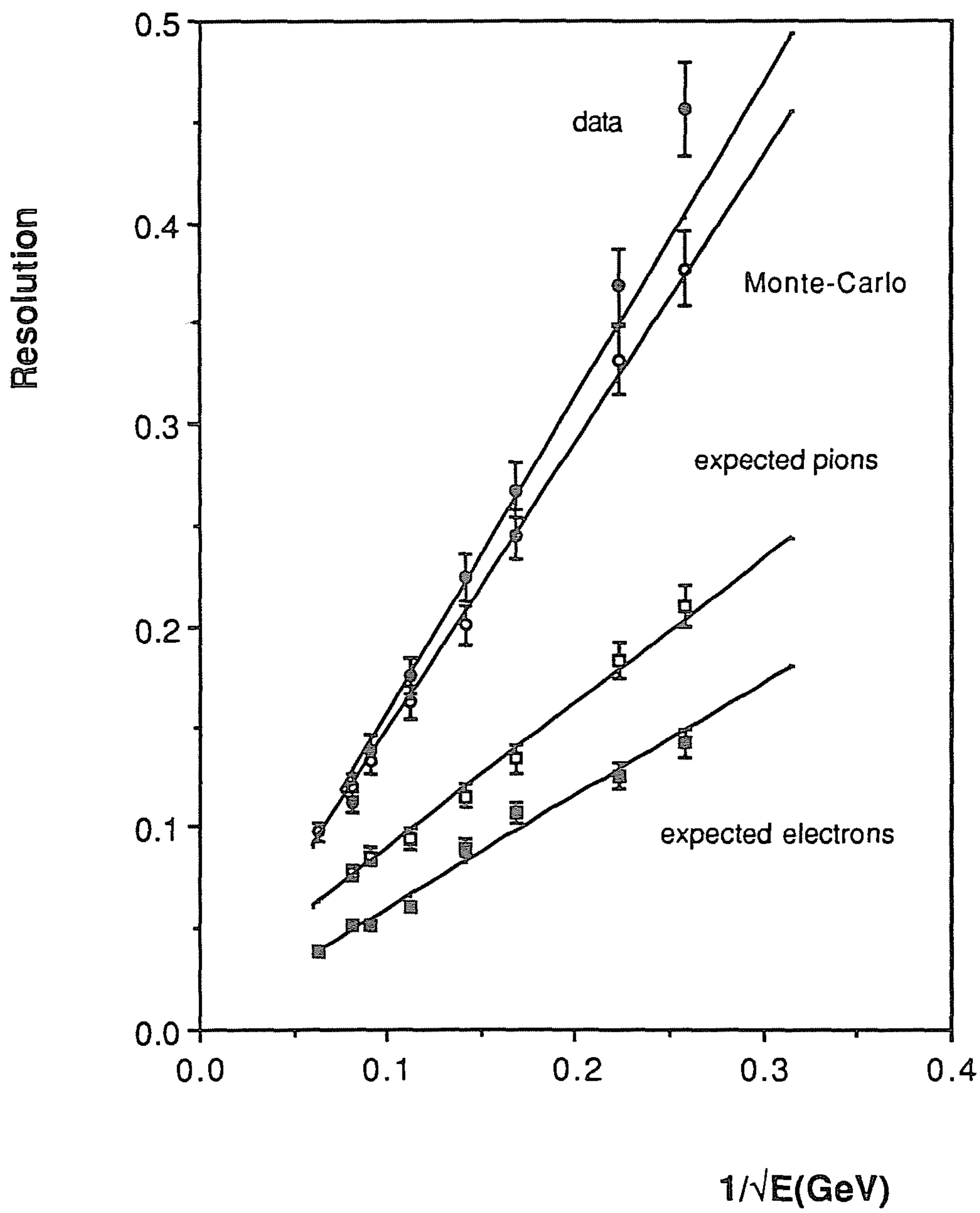

0.5
0.4
0.3
0.2
0.1
0.0
Resolution
data
Monte-Carlo
expected pions
expected electrons
0.0
0.1
0.2
0.3
0.4
1/√E(GeV)

Fig. 10