EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Report Number COO-2232-4Ex

Conf-730531--5

A LEAD-GLASS ČERENKOV DETECTOR FOR ELECTRONS AND PHOTONS

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ABSTRACT

An apparatus for the detection of high-energy electrons and photons is described. Lead-glass Čerenkov counters measure the energies, and charged particle tracks are reconstructed using an array of wire spark chambers. The mode of operation, calibration, and stability of the system are described, and details are given of the ability to discriminate electrons from hadrons.

Submitted to the International Conference on
Instrumentation for High-Energy Physics
Frascati, 8 - 12 May 1973

MASTER

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1. INTRODUCTION

The apparatus described here was constructed to detect electron pairs with large invariant mass at the CERN Intersecting Storage Rings (ISR). The requirements were

i) to identify electrons around 90° from a large background of hadrons;

ii) to measure, with good energy resolution, electrons in the range 1 to 10 GeV;

iii) a large solid angle;

iv) a good spatial resolution.

The last two requirements are necessary in order to minimize the error in determining the effective mass of the electron pair. The solid angle requirement prompted us to look for a solution which did not require a magnetic field, and a lead-glass Čerenkov counter array was decided on after some preliminary tests$^{1)}$. The apparatus was adapted for the simultaneous detection of photons and electrons.

Two identical spectrometers were built and placed on either side of an ISR intersection region. The construction, calibration, and performance of these will now be described.

2. DESCRIPTION OF A SPECTROMETER MODULE

The detector consists of four parts (Fig. 1):

i) A lead-glass array to measure the energy of electrons or photons.

ii) An array of thin lead-glass counters to enable the separation of electrons from hadrons on the basis of energy loss.

iii) Wire spark chambers to give the track of a charged particle.

iv) Scintillation counter hodoscopes used to trigger the apparatus.

Each spectrometer had 10 planes of wire spark chambers with magnetic core read-out on the ground planes only. The X-planes (vertical), Y-planes (horizontal), and η-planes (at 15° to the X-planes) were employed in a modular construction which grouped the planes in the form ηYX;YXηYX; XY. The wire spacing was 2 mm for the X- and Y-planes and 2.2 mm for the

η-planes. One thyratron, triggered by a Marx generator, was used for each gap, and a square pulse 200 nsec long was obtained using a 10 Ω cable as a shaper.

The chambers were filled with the standard He-Ne mixture with a small addition (1%) of isopropyl alcohol, and gave typical efficiencies of 99% per plane for single tracks. Good efficiencies were obtained for multitrack events, and event reconstruction produced an accuracy on the vertex of a two-particle event of typically ±1.5 mm.

The lead-glass$^{2)}$ array consisted of two parts: a wall of 16 blocks each $15 \times 35 \times 7.3$ cm^3 was placed in front of a 10×6 array of blocks each $15 \times 15 \times 35$ cm^3. Each lead-glass block was viewed by an RCA 8055 photomultiplier (5-inch), which was glued to the 15×15 cm^2 or 7.5×15 cm^2 face with Kodak HE-10 assembly cement. The glass was wrapped with aluminized mylar which had been bonded to black vinyl, and the PM tube was wrapped with Al foil. A μ-metal shield surrounded the PM, and each unit was then wrapped with soft iron foil. The arrays were mounted in closed boxes through which cool air was blown to maintain a constant temperature, this being necessary because the gain of a counter varied by 1% per °C. The anode signal from each PM was fed into an ADC $^{3)}$, the output of which went to a CAMAC microscaler. The output from the last dynode was used to provide a variable energy threshold for the event trigger in the experiment. Each module subtended a solid angle of approximately 1 sr.

The calibration of the Čerenkov counters is described in Section 3.

Four hodoscopes of NE102A plastic scintillator on 56 AVP photomultipliers were employed. The hodoscope A (Fig. 1) used 2 mm thick scintillator to reduce the probability of photon conversion. These five counters were 65 cm long horizontally, and were normally placed in coincidence with the hodoscope B, which consisted of six counters each 100 cm long. The hodoscopes were arranged so that particles from the interaction region, which passed through an A-counter, could then pass through only one of two possible B-counters of the six.

A third hodoscope Z was placed between the first two WSC modules. This consisted of 10 counters, $1 \times 15 \times 60$ cm^3, each viewed by two PM's, one at each end. These counters measured the ionization loss of detected particles. The gains of the two PM tubes were balanced, and their pulses were added passively before being recorded by an ADC and microscaler. The response of the counters was constant to 1% along their length.

A fourth set of counters, 1 × 15 × 65 cm^3 each, was placed behind the lead-glass blocks to enable the selection of particles passing through the array. The use of these ST (straight-through) counters is described below in the section on monitoring.

3. CALIBRATION OF THE ČERENKOV COUNTERS

It was decided that the simplest method of monitoring the gains of each unit of the arrays was to make use of a radioactive source and scintillator as a constant light source. Thus NaI(Tl) was chosen as the scintillator because of its large light output, and sources were obtained4) which consisted of encapsulated chips of NaI(Tl) with a small amount of ^{241}Am drifted into them. Each chip was about 0.2 × 0.2 × 0.1 cm^3, and emitted between 100 and 200 light pulses per second from the 5.5 MeV α-particles of ^{241}Am. Each lead-glass block had one of these sources glued on to it with Kodak HE-10 assembly cement. The large blocks had their sources glued onto the centre of the face furthest from the PM; the small blocks had theirs glued about 7 cm from the PM, as indicated in Fig. 2.

The initial calibration of the counters involved finding the electron energy which gave the same amount of Čerenkov light to the PM as did the NaI-Am light source. For the large blocks this could be done by stopping an electron beam of known energy in each block and comparing the spectrum obtained to that from the NaI. For the small blocks the situation was more complicated and the following procedure was adopted, which served to calibrate the light sources on both types of counter.

Electrons were selected from a high-momentum beam at the CERN Proton Synchrotron (PS) using He-filled gas Čerenkov counters. The arrangement was as shown in Fig. 2.

Plastic scintillators S1, S2, S3 were used to define a charged particle, S3 being 4 mm thick and 10 mm in diameter. The Čerenkov counters C1, C2 selected electrons which formed about 2% of a beam consisting mainly of pions. Two lead-glass counters were arranged as shown in Fig. 2, so that the beam entered at right angles to the PM of the small counter (A) and then passed along the length of the large glass block (B) behind.

The coincidence S1•S2•S3•C1•C2 defined an electron and opened the gate to enable the recording of the pulse heights in the two lead-glass counters A and B.

We now indicate the method by which we assign an equivalent energy to each of the light sources.

Let an electron of energy E be incident on two lead-glass counters, sharing its energy between them so as to leave energy corresponding to pulse height V_A from the photomultiplier of counter A and V_B from that of counter B. Let x be the ratio of the over-all gains of the two counter/ADC systems where

$$x = \text{Gain system B/Gain system A} ,$$

and let an electron of energy E totally absorbed in counter B correspond to pulse height V_E. Then

$$V_E = V_B + xV_A .$$

The values V_A and V_B for about 10 K incident electrons were recorded, and then the value of x was determined by minimizing the % resolution of the distribution of the summed pulse heights V_E. The value of V_E was then obtained from the peak of the distribution after x had been determined.

Spectra were taken for the light output of the NaI-Am light sources, and gave peak values of V_{NA} and V_{NB} counts for counters A and B, respectively.

An equivalent energy to the light emitted by the sources could now be assigned since

$$\text{Equivalent energy source A} = E \cdot x \cdot V_{NA}/V_E$$

$$\text{Equivalent energy source B} = E \cdot V_{NB}/V_E .$$

Calibrations were carried out at two electron energies for each counter, and the spectra from the light sources taken in each case. In the course of the analysis to assign the calibration energies, corrections were made for leakage of the electron shower. A linearity study was also carried out by observing the response of a two-counter system for electrons from 2 GeV up to 14 GeV. The linearity was good to 1%.

A further energy calibration point was obtained by observing the pulse-height distribution produced by μ's and π's which traversed the counters and did not interact. These straight-through particles gave a line of energy $\sim$ 460 MeV in the large blocks and $\sim$ 75 MeV in the small blocks.

4. MONITORING OF THE ENERGY CALIBRATION OF THE ARRAYS

In the course of the experiment the over-all gain of each counter had to be monitored, and three different methods were employed.

i) The spectrum of the NaI-Am light source was measured for each counter, typically once per day when the experiment was in progress.

ii) Spectra produced by straight-through particles could be obtained for counters in the centre of each array. The ISR produced a sufficient flux of energetic pions at 90° to enable us to trigger on particles which passed through the lead-glass and reached scintillation counters placed behind the arrays. Only the central blocks of the arrays could be monitored in this way, since the geometrical arrangement meant that particles from the interaction region would not pass along the axis of blocks which were far off centre.

In order to use straight-throughs as an absolute energy calibration, it is necessary to have a collimated high-energy beam normally incident on a block of glass. At the ISR the straight-through particles have a large spread of incident angles and are dominated by the lowest energy pions that are not absorbed in the glass. Therefore one does not observe the same straight-through peak energy at the ISR as one does in a high-momentum μ or π beam. However, one may assume that the straight-throughs represent a constant source of light and use them to study the time dependence of the energy calibration.

iii) The relative gains of the counters in an array could be monitored using a light flasher. This was a spark gap which could be fired 30 times/sec. The light from this gap was fed via a flexible fibre optics light pipe to a calibration box placed between the small and large glass blocks (Fig. 1). This Al box contained a 1 cm thick plate of plexiglas and had a hole 1 cm in diameter opposite each counter of the array. The light travelled inside the plexiglas plate by internal reflection, and was allowed to escape through the holes in the box by roughening the surface of the plexiglas in the region surrounding each hole. One spark gap fed light to the large and small blocks of both arrays simultaneously. Since the spark gap did not give out a constant amount of light, this system was used only to monitor the relative gains of the blocks. One central block in each spectrometer was chosen as a reference, and the gains of the other blocks relative to this one were monitored by dividing the pulse height produced in each counter by the corresponding pulse height produced in the reference counter. These ratios depended, of course, on the light-sharing between the blocks as well as on the gains of the counters, but when the sharing was kept fixed (it depended on geometry only) variation in the gains of the counters relative to the reference block could be observed. The average ratio was normally found for about 3000 light flashes and the measurements were reproducible to ±2%.

By following the variation of the absolute gain of the reference counters using straight-through particles, the over-all gain of each counter was monitored.

In addition, the gain of each ADC was checked using a precision pulse-generator.

5. RESPONSE OF THE DETECTOR

The response of the lead-glass detector to electrons and charged pions from 1 GeV to 10 GeV was studied in a test beam using an array of nine glass blocks (3 × 3) with three small blocks in front. Some additional tests were carried out to examine the response to antiprotons.

The response of the lead-glass to 5 GeV electrons incident normally in the centre of a small block is shown in Fig. 3. The energy deposited in the small block is presented as well as the total energy seen by the array as a whole. The energy resolution of the detector is given approximately by

$$\mathrm{FWHM} = (10/\sqrt{E} + 1)\% , \qquad E \text{ in GeV} .$$

The response to pions is indicated in Fig. 4 where the energy lost in the small block is given for two incident energies.

An extensive series of measurements were carried out to find the variation in the response of the detector with the energy of the incident particle, the angle at which it entered the glass, and the position of the entry point.

The first conclusion to be drawn from all these measurements was that, by demanding that a particle deposited 250 MeV in a small block, 87% of all pions incident could be rejected while 98% of electrons at 4 GeV or 90% at 2 GeV would still be accepted. This is illustrated in Fig. 5, which represents the response to a beam of 5 GeV pions which contained a small admixture of electrons.

More detailed examination of these test beam data indicated that the ratio of the energy-sharing between small and large blocks could be parametrized in terms of energy and angle of incidence to produce a universal curve for electrons which could be applied off-line to reject pions. The detector initially had a response which was not dependent on the entry point of a particle on the array.

Electron selection was also aided off-line by applying cuts on the radial distribution of the shower, the radius being smaller for an electron than for a pion. The method was to find the energy deposited by a charged particle in the blocks touched by a cylinder of radius r constructed around the continuation of the track of the particle within the array. This was determined for two values of r (2 cm and 5 cm) and the ratio of these energies calculated. For an electron, the ratio should be close to unity. This cut was additionally useful during the analysis of the experimental data to reject events in which a π^0 was in close proximity to a charged particle.

A major source of background for electrons detected at the ISR was from Dalitz pairs or photons converted in the wall of the ISR vacuum chamber. These events gave in general an electron pair in very close spatial proximity such that they appeared as one track in the spark chambers. However, most of these events could be identified by examining the ionization loss of the electron-like particle. The ionization loss was measured in the hodoscope Z, and particles with more than 1.7 times minimum ionization were rejected.

The studies with antiprotons were carried out at 1 GeV/c and 2 GeV/c incident momentum. At both momenta 20% of the incident $\bar{p}$'s deposited more than 300 MeV in the small block. However, at 2 GeV only 6% gave a total energy deposition greater than 1.5 GeV.

6. PHOTON DETECTION

It was necessary to measure the π^0 spectrum produced at the ISR, since a major source of background for electrons detected would be from π^0 decays. The lead-glass would, of course, detect all photons and hence π^0's incident on it, but to ensure that the observed energy deposited in the glass from neutral particles was due to π^0's, a lead sheet, 0.25 radiation length thick (1.5 mm), was placed between the first two WSC modules. Gamma-rays from π^0 decays could then convert to e^+e^- pairs in the lead sheet, and the conversion could be observed from the lack of sparks in the three gaps of the first WSC module with many sparks in the other two modules. The pulse height in the Z counter behind the conversion point would normally be due to more than one charged particle. The efficiency of photon detection when conversion was demanded varied with photon energy and depended on the thickness of the lead. Monte Carlo calculations were carried out to determine the efficiency for detection of different numbers of photons, with and without conversion in the lead being required.

7. LONG-TERM STABILITY OF THE DETECTOR

One arm of the detector was operated at the ISR for a period of about 13 months and the other for the last 8 months of that period. The values of the pulse heights of the NaI-Am sources were seen to drop throughout this time by approximately 2% per month. Drifts in the values of the straight-through peaks were also observed.

There were many possible explanations of these changes. For example:

i) the photomultiplier gain could drop with time, perhaps because of radiation damage to the photocathode;

ii) the NaI crystal could suffer from radiation damage, caused by either the ^{241}Am or the ISR, and emit less light;

iii) the lead-glass could darken because of radiation damage;

iv) the glue used to join the PM tube and the NaI-Am source to the glass could have deteriorated.

The monitoring of the gains with straight-through particles and the light flasher indicated that reasons (ii) and (iv) could not be responsible for most of the changes observed. The drift was understood only after the experiment had finished data-taking and another series of calibration runs had been taken on an electron and pion beam from the CERN PS.

Three things became obvious:

i) the equivalent energy assigned to a NaI-Am source had changed on the average by 20%;

ii) the resolution of the glass for monoenergetic electrons had deteriorated; typically for 4 GeV electrons it had gone from 6% to 8%;

iii) the apparent energy corresponding to a straight-through particle had increased from 460 MeV to 510 MeV in the large blocks.

All of these facts were consistent with the absorption coefficient of the glass having increased. (The straight-through energy increases relative to the energy of an electron because of the difference in the average path length of light reaching the PM.)

Further tests were then carried out on the small blocks by observing the value of the straight-through peak as a function of distance from the phototube. This measurement was repeated for some small blocks which had never been exposed to radiation at the ISR. The results are given qualitatively in Fig. 6, where it may be seen that the response of a block exposed to the ISR diminishes with distance from the photomultiplier, whereas an unexposed block gives a flat response. This supported the belief that the glass had darkened.

To eliminate any possible additional effects due to damage to the PM or glue deterioration, one block was unglued and recalibrated with a new PM optically coupled with silicon grease. No significant changes were observed in the calibration value of the NaI-Am source or straight-through peak relative to an electron beam.

It was thus apparent that most of the change in the equivalent energy of the NaI-Am source was caused by darkening of the lead-glass owing to radiation damage. In addition, a decrease in the light output of the NaI crystal could not be ruled out.

However, by making use of the data obtained with the different methods of monitoring the calibration of the counters, it is estimated that the absolute calibration of the system is known to ±2% for the final two months of the experiment and to ±5% for the whole duration of the experiment.

8. CONCLUSIONS

The main difficulty associated with this type of apparatus lies in following the gain of the Čerenkov counters. This is aggravated in high radiation areas because of possible changes induced in the transparency of the glass.

When using such counters in a beam line experiment, the calibration can always be checked by monitoring with straight-throughs. At the ISR this is not always possible since the interaction region is not a point source but is normally spread over 50 cm. In addition, the interaction rate is too low to enable calibration to be obtained quickly without interfering too much with normal data acquisition time. The NaI-Am sources are then invaluable for monitoring the calibration of the counters.

Acknowledgements

We should like to express our thanks to R. Bouhot and G. Sicher for their valuable contributions to the construction and handling of the apparatus. We appreciate the co-operation we received from the DNPL-Liverpool-QMC-RHEL and IPN-Orsay Collaborations who allowed us to make use of their beam lines as testing facilities for the lead-glass counters. We are grateful for the help given to us during the calibration runs by W. Duinker, M.N. Khatchaturian and W. Swiatek.

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3) ADC Type N 7216, CERN NP Documentation Service.

4) J. Menefree and Y. Cho, IEEE Trans. Nuclear Sci. NS-13, No. 3, 159 (1966).

Figure captions

Fig. 1 : One spectrometer arm as used at the ISR. The second arm was placed symmetrically on the opposite side of the interaction region.

Fig. 2 : Arrangement of the counters during calibration in a high-momentum beam.

Fig. 3 : Response of the lead-glass to a 5 GeV ±1% electron beam. The summed spectrum and the spectrum in the small front block are shown.

Fig. 4 : The energy deposited by π^-'s in the small glass block for 46,000 π^-'s incident at 2 GeV and 55,000 at 10 GeV.

Fig. 5 : Response of the lead-glass to a beam of 5 GeV π^-'s with a small admixture of e^-'s. Also indicated is the π rejection obtained by requiring that the incident particle leaves > 250 MeV in the small counter.

Fig. 6 : The response of small counters to straight-through π^-'s as a function of distance from the photomultiplier as measured for two counters, one of which had been used at the ISR for one year and the other never exposed to radiation at the ISR.

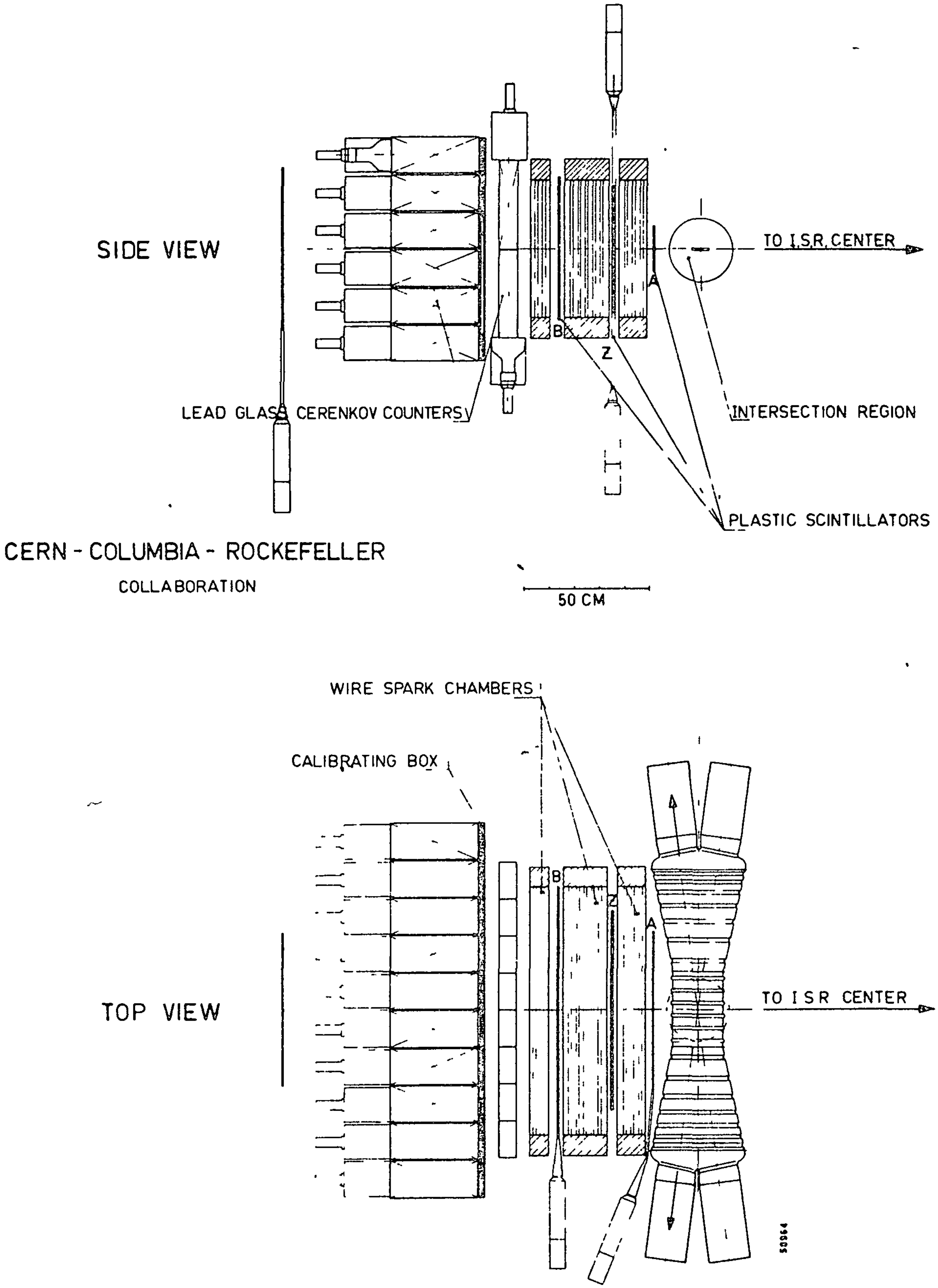

SIDE VIEW
TO I.S.R. CENTER
A
B
Z
LEAD GLASS CERENKOV COUNTERS
INTERSECTION REGION
PLASTIC SCINTILLATORS
CERN - COLUMBIA - ROCKEFELLER
COLLABORATION
50 CM
WIRE SPARK CHAMBERS
CALIBRATING BOX
B
Z
A
TOP VIEW
TO I S R CENTER
50064

Fig. 1

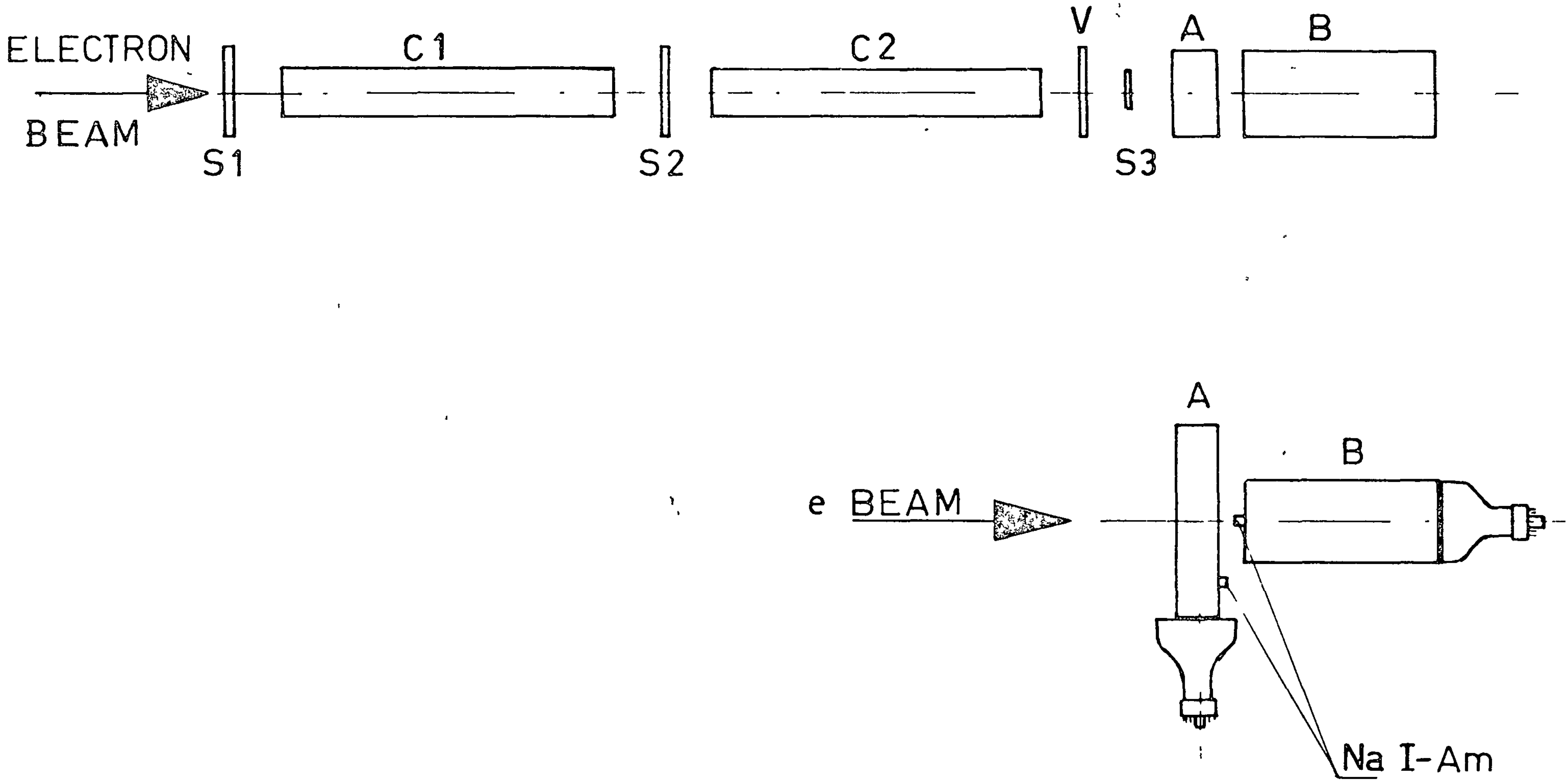


Fig. 2

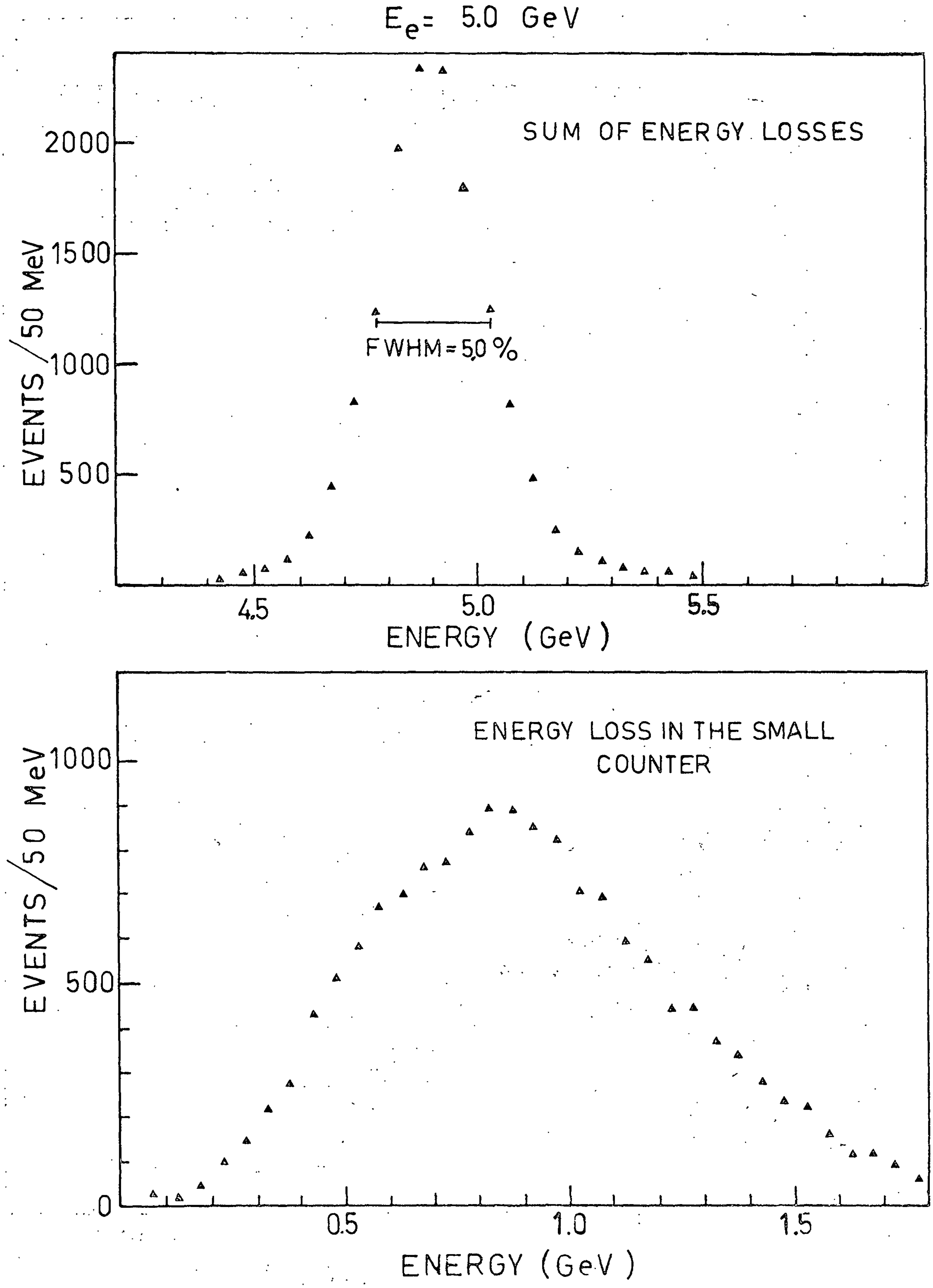
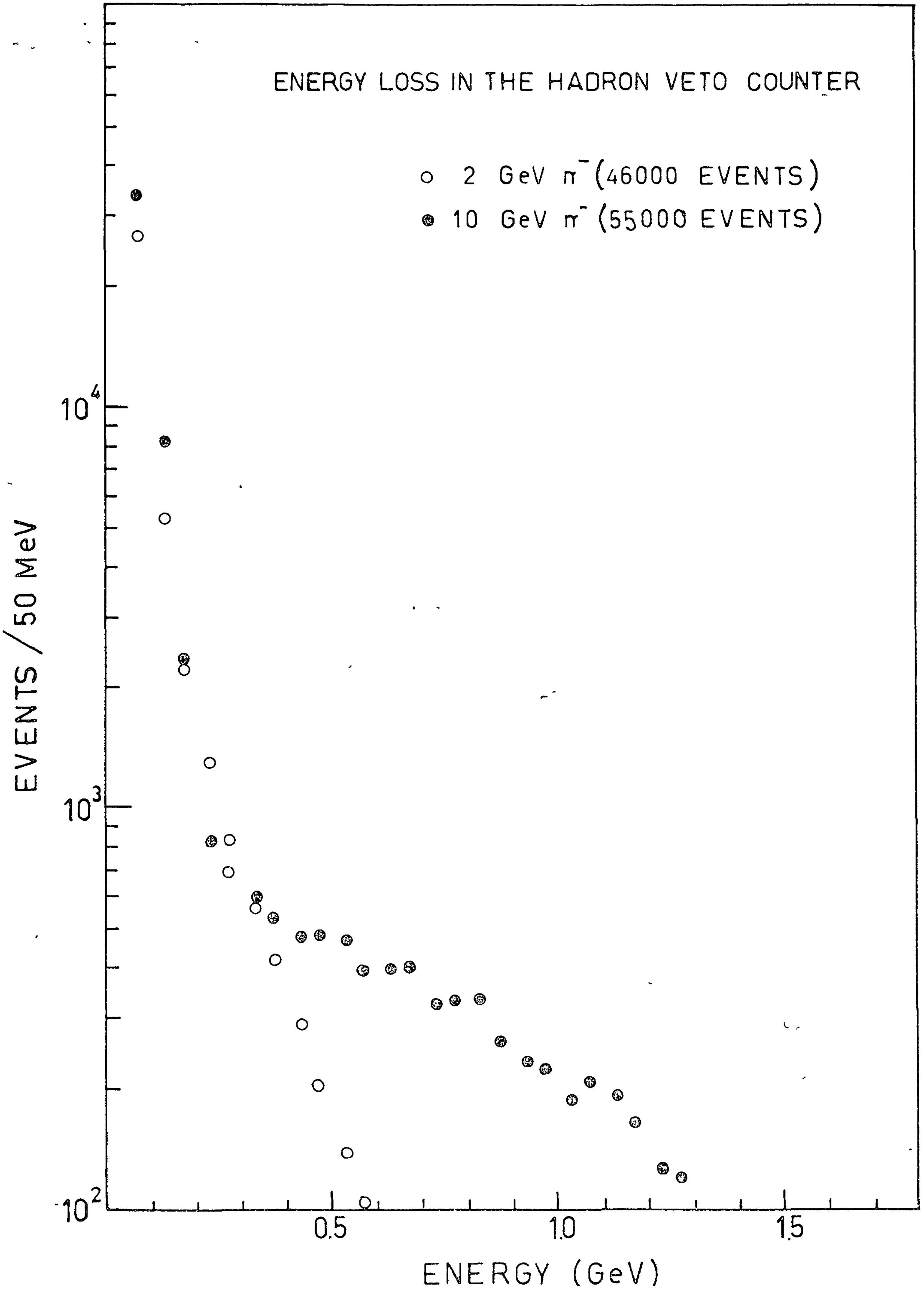

E_e= 5.0 GeV
SUM OF ENERGY LOSSES
FWHM = 5,0 %
EVENTS / 50 MeV
2000
1500
1000
500
4.5
5.0
5.5
ENERGY (GeV)
ENERGY LOSS IN THE SMALL COUNTER
EVENTS / 50 MeV
1000
500
0
0.5
1.0
1.5
ENERGY (GeV)

Fig. 3



ENERGY LOSS IN THE HADRON VETO COUNTER
○ 2 GeV π⁻ (46000 EVENTS)
● 10 GeV π⁻ (55000 EVENTS)
EVENTS / 50 MeV
10^4
10^3
10^2
0.5
1.0
1.5
ENERGY (GeV)

Fig. 4

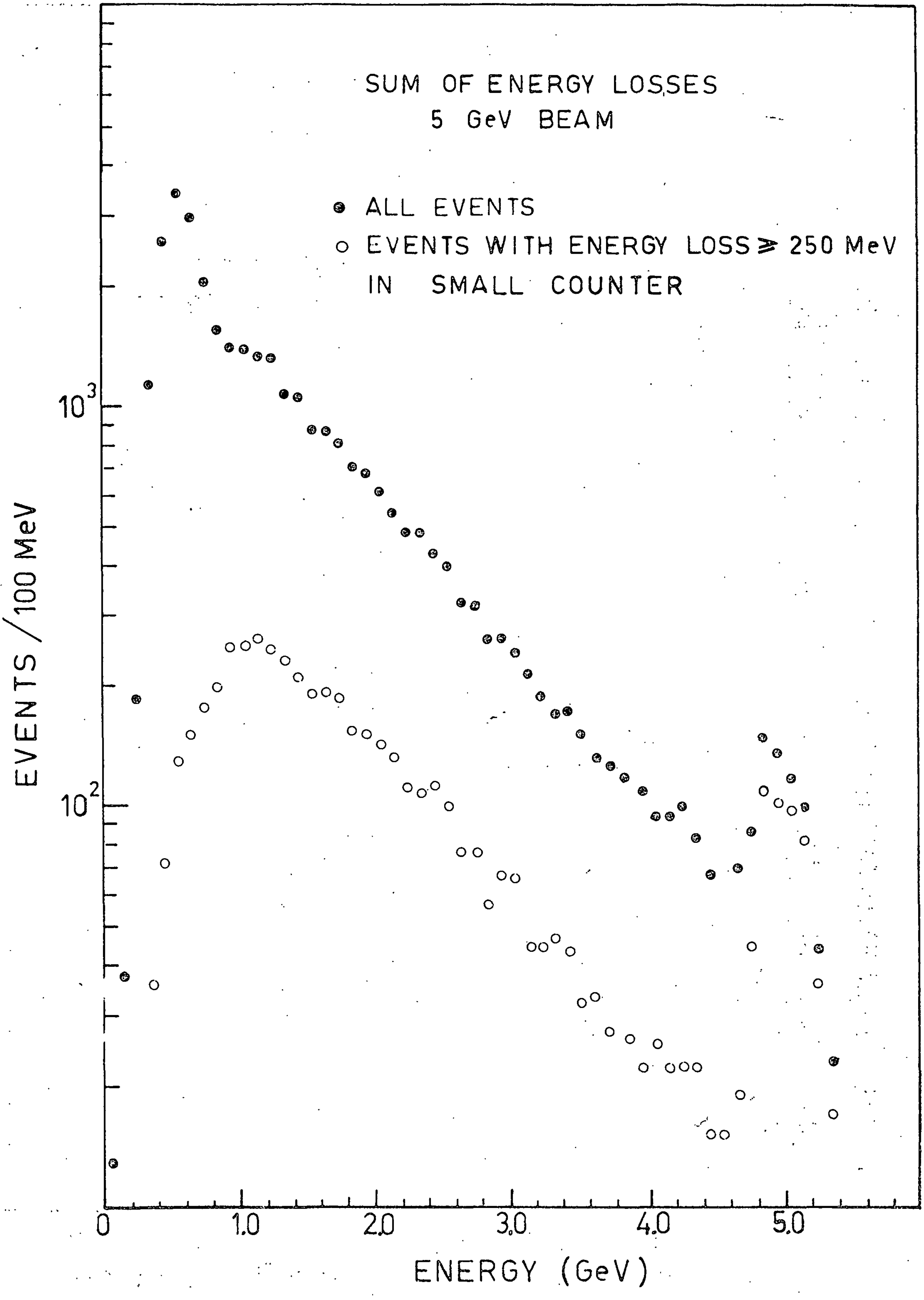
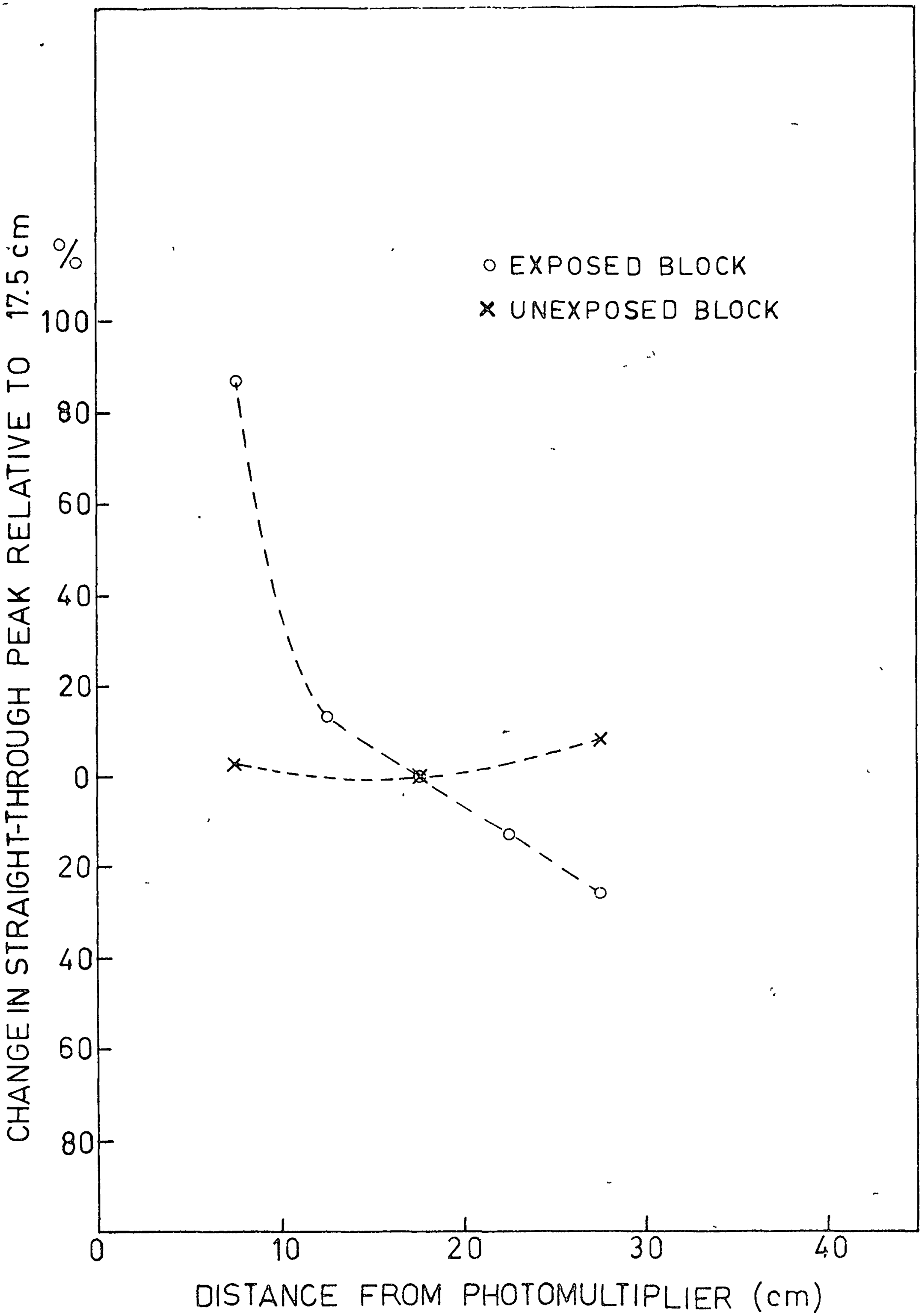

SUM OF ENERGY LOSSES
5 GeV BEAM
● ALL EVENTS
○ EVENTS WITH ENERGY LOSS ≥ 250 MeV IN SMALL COUNTER
EVENTS / 100 MeV
10^3
10^2
0
1.0
2.0
3.0
4.0
5.0
ENERGY (GeV)

Fig. 5



CHANGE IN STRAIGHT-THROUGH PEAK RELATIVE TO 17.5 cm %
100
80
60
40
20
0
20
40
60
80
○ EXPOSED BLOCK
× UNEXPOSED BLOCK
0
10
20
30
40
DISTANCE FROM PHOTOMULTIPLIER (cm)

Fig. 6