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Addendum to
Revised Proposal for A Search for Multigamma Events at the ISR

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1. INTRODUCTION

In the fall of 1970 we had proposed[1] a similar version of such an experiment to be carried out at the 28 GeV colliding beams (ISR) at CERN, Geneva, Switzerland. As stated then, our primary objective is to search for high energy events from which many gamma rays are emitted at the ISR and to study the characteristics and nature of these multigamma events in order to gain a better understanding of the origin of such processes. Interest in the investigation of multigamma events at the ISR was first generated by reports of such events in emulsions exposed to cosmic rays (see Appendix A). In addition, preliminary analysis of the exploratory experimental results obtained by us sharing the detection system of the CERN-Columbia-Rockefeller (CCR) group at the ISR at CERN show a large number of high multiplicity γ events. Furthermore, a large number of high transverse momentum gamma rays were also observed by the CCR group and by us as well The exact nature of the physical origin of these multigamma events is not yet understood. Our main purpose is to try to obtain sufficient information concerning these multigamma events to enable us to understand what they are. If these events are due to π^o production then a hitherto unexpected strong interaction mechanism is taking place at large transverse momentum. Of course, there are other theoretical speculations that some of these multigamma events could be due to the annihilation of magnetic monopole pairs,the annihilation of high Z lepton pairs, or the successive decay of high angular momentum particle states, etc. All these possibilities are highly speculative, but any one of them would be extremely exciting if proven true. In any case, the cause of these multigamma events can only be understood by careful study of characteristics such as multiplicity distribution, energy distribution, and angular distribution, etc. (see p. 2, Part I, of the original proposal, Ref. 1c). Only then can we compare such distributions with the corresponding charged pion distribution (see below) and appropriate models for the production of π^o and other known particles which transform to γ-rays. Such information is not now available, and would be a valuable addition to knowledge of inelastic hadron interactions. Of course, if some of these events could be demonstrated to be non-π^o in origin, this would be a very dramatic discovery.

Another significant objective is to study charged multiplicity in a corresponding way which not only is useful to the identification of non-π^o events from π^o background, but also of basic importance in understanding the pion production process at very high energies in general by obtaining the correlated charged pion multiplicity distribution, angular distribution, the π^o and π^c ratio, etc., especially their dependence on the center-of-mass energy.

Additionally, it is important to test out the designed high resolution (space as well as energy resolution) detector system which incorporates sandwich layers of multiwire proportional chambers (MWPC) and lead glass hodoscopes. Such a detector system is designed to determine the number of prompt gamma rays, the energy and space location of each gamma ray thus giving the energy and angular distribution of these multigamma rays covering a large solid angle. The basic components of the detector system have been well tested at the ISR, the 28-GeV Proton Synchrotron (also at CERN) and the Cornell 10-GeV Synchrotron and proven to work well as expected. These include the lead glass elements, the 1 m^2 MWPC and associated electronic and logic systems. Our present design of the detection system is quite novel and different in nature than the usual design. It possesses the capability to measure the shower development curve of each gamma ray thus enabling it to determine the direction of such gamma ray in question which is essential in such an experiment.

Some typical preliminary results from our exploratory experiment at the ISR using the shared equipment with the CCR group are presented in Section 3 of the present proposal with some tentative conclusions drawn from these preliminary results while Section 2 contains a summary of the physical considerations, which in the opinion of the proponents of this proposal, justify a considerable effort in this direction. These are discussed in more detail in Appendices A and C

Section 4 contains a slightly revised version of the original proposal (1c) incorporating some modifications as a result of the valuable experience we have gained both here at the ISR and from the tests carried out at the Cornell 10-GeV electron synchrotron. These modifications will provide a much more efficient detection system with a flexible utilization of the detector system. Most important of all, the tests made in the various aspects of the exploratory experiment have given extremely valuable information on the performance of both the lead glass detectors, the wire proportional chambers and the sophisticated electronic logic system that is necessary to select and analyze the desired results. The chief advantages of the proposed detection system, as compared with the system presently used are also listed.

Appendix D gives a summary of the extensive tests made on a prototype multiwire proportional chamber (MWPC) 1 m^2 in effective area. These tests include the wire grouping effects of a large size multiwire chamber, the selection of the most suitable of the various preamplifiers specially designed by the CERN Electronics Group of the NP Division and the effectiveness of the various gas mixtures suitable for this purpose.

Great interest has been shown by CERN in our proposed experiment, not only in the fact that they have provided as ISR beam time and various facilities and were instrumental in the successful equipment sharing arrangement, but they have also very generously provided 50.000 SF (~ $13,500 U.S.) in the calendar year of 1971 and 45.000 S.F. (~ $12,000 U.S.) in 1972 for helping our project in the design and construction of some of the wire proportional chambers,electronic and logic modules, etc.

In our proposal we intend to proceed with this experiment in two steps. During the first year of our experiment we plan to have only four out of the six detection units constructed (two type "A" units which have the full energy measuring capabilities to be placed in the forward directions in the upper hemisphere, and two type "B" units which do not include the large-sized lead glass blocks and are placed at the 90° region where lower energy gammas predominate). This has been spelled out in our budget estimate section, and we plan to add two more type "A" units during the second year of our experiment after we will have gained sufficient experience in the utilization of the first four units.

The Rome group which is responsible for the construction and financing of an entire type "A" unit has already received appropriate funding from their government.

2 SOME ASPECTS OF PHYSICAL INTEREST

Our interest in this type of research is motivated by a number of considerations The first one is the observation by various authors[2-4] of multigamma ray events in stacks of nuclear emulsions exposed to cosmic rays at high altitudes. These events could not be accounted for either by conventional electromagnetic showers originating from a single high-energy gamma (or electron), or by conventional nuclear interaction in the production of many π^o's. Rather, they appear to be a result of a large number of gammas produced simultaneously in a single process. Recently the exploratory experimental results obtained by us at the ISR at CERN show a large number of high multiplicity γ events. Furthermore, a large number of high transverse momentum gamma rays were also observed by the CCR group and by us as well. The exact nature of the physical origin of these multi-gamma events is not yet understood. If these events are entirely due to π^o this would yield a π^o spectrum quite different from what is anticipated from the customary $\exp(-ap_\perp)$ distribution, this would then necessitate a hitherto unexpected strong interaction mechanism for producing pions with large $p_\perp$. Since the center-of-mass energy of the ISR is sufficiently high to produce massive particles (~ 56 GeV), it is also possible that some of these multigamma events are due to non-π^o origin, in which case this could lead to an even more far-reaching discovery.

Rather recently, Ruderman and Zwanziger[5,1] put forward a plausible explanation for a possible non-π^o origin of this type of high multiplicity γ-ray event. They could be due to the creation and subsequent annihilation of Dirac magnetic monopole pairs. This assumption was discussed in detail in our previous Revised Proposal, CERN/ISRC/70-19/Revision No. 2.[1c] The main points discussed there are summarized in Appendix A.

Two other processes have been considered as possible explanations of the cosmic-ray events mentioned above.[1c] The first one, suggested by T.D. Lee, consists of the production and immediate annihilation of a pair of leptons of high Z This process is very similar to that proposed by Ruderman and Zwanziger with the possibility that it is characterized by different energy and angular distributions.

A third process suggested independently by Lee[1c] and Winter[6] involves in the production of a heavy boson of large angular momentum J. In sufficiently large values of J and mass M_J the dominating decay process of this particle would consist of the emission of a series of photons of energy $h\nu < m_\pi c^2$. A more detailed discussion of this process is given in the paper by Winter.[6]

In view of the extremely encouraging results in almost every respect obtained thus far both in regard to the fine performance of the lead glass detectors and large size wire proportional chambers as well as the preliminary physical results, we have designed a much improved version of our previous lead glass, wire proportional chamber multigamma detection system[1c] which is capable of measuring simultaneously the energy of each individual gamma ray, the angular distribution of the gamma rays in a multigamma event and covering a large solid angle (~ 70% of the total solid angle as compared with 60% of the previous design).

From the experimental point of view, the main problem involved in the establishment of the existence of multigamma events is in establishing that they are indeed gamma rays produced in high energy p-p collisions. As stated in our previous proposal[1c] the capability of measuring the actual shower developing process, can be used to great advantage to ensure the separation of gamma rays from charged particles.

The study of the neutral pion production process, is exceedingly interesting in itself, and would provide information of tremendous value on the multiproduction of hadrons. The data on charged particles will be important both as a check on the π^o distribution as well as allowing a study of π^o,π^c correlations to be performed which is becoming increasingly important. Further, such studies will also aid in searching for events of non-π^o origin. Appendix C discusses the data analysis procedure upon which our π^o studies as well as search for dramatic events of non-π^o origin are based.

These points will be discussed in more detail in Appendix C.

In any event, such a multigamma detection system, possessing the capabilities of measuring the energies of the gamma rays, their angular distribution, the shower developing process and the large geometrical factor would be extremely useful for high energy research applications in space laboratories as well as in high energy accelerators

3. PRELIMINARY RESULTS OF THE EXPLORATORY EXPERIMENT OBTAINED WITH THE SHARING OF THE DETECTION SYSTEM OF THE CCR GROUP AT CERN

In the summer of 1971, the ISR Committee of CERN recognized the interest of the physical problem proposed in our original proposal, but, in order to avoid the preparation of a new expensive detector system, suggested at that time that an exploratory search for multigamma events could be started immediately by making use of some equipment already installed at the ISR for some other experiment. One such detection equipment consisted of two hodoscope arrays of lead glass blocks of quite large dimensions in the hodoscope plane and there was no wire chamber in between these two arrays of lead glass blocks. The total solid angle covered by this detection system which includes also a number of spark chambers and scintillation counters placed in front of the lead glass arrays, amounts to 20% at $\sim 90^{\circ}$ to the direction of the colliding beams. Although such a detection system has a number of limitations for the purpose of our proposed objectives, a proper utilization of such equipment would serve well as an exploratory test to obtain some indication of the existence of multigamma events of some kind, and how well the lead glass detectors can be used in a layered hodoscope fashion as was designed in our original proposed experiment.

An arrangement was made in the fall of 1971 with the CERN-Columbia-Rockefeller (CCR) Group who designed and constructed the above-mentioned detector system to share the use of this equipment by providing duplicate signals from each detector element of some of these hodoscope arrays which are sent to each group and a separate electronic logic system was designed and constructed by our group to obtain the desired events. All our events and the associated information were recorded in a common magnetic tape used by the two groups (our group and the CCR group) and were analyzed separately using respective computer programs.

Data have been collected regularly with such an equipment sharing arrangement, whenever the ISR was operated for physics during the last few months of 1971 and the most part of 1972. Some preliminary results from this exploratory experiment are presented below

3 1 Experimental Setup

The experimental arrangement is shown in Fig. 1. Only one-half of the full two-sided detection system of the CCR experiment is shown which is the mode we operated in until April, 1972. Since then the complete detection system of the CCR group has been set up which covers 20% of the total solid angle at ~ 90^0 and is in operation; (only half of which is shown in Fig 1) our electronics and logic system was greatly improved and significantly expanded in the course of fully sharing the CCR complete detection system. We are deeply indebted to the various members of the CCR group who have helped us without reservation to accomplish the successful sharing of the use of their detectors, as well as with data recording. In the meantime, we have also augmented our electronics and logic system by purchasing an HP2100A computer and magnetic tape recorder, 48 channels of specially designed ADC units (analogue-to-digital converter), a Camac manual controller, and an all-Camac system for on-line operation for monitoring and recording certain specific data that are of particular interest.

The HV counters represent 16 lead glass Cerenkov counters on each side and each 14.6 x 35 cm^2 in area and 7.2 cm in thickness (i.e. ~ 3 radiation lengths). They provide an estimate of the number and energy of showers produced by incident gamma rays or electrons. In front of the HV's on each side there are 10 scintillation counters (Z) which allow a rough estimate of the number of associated charged particles. B_1 and B_2 are pairs of scintillation counters each connected in coincidence to detect beam particles scattered in the beam interaction region. Figure 2 is a block diagram showing the basic constitution of the electronics and logic system that we used indicating also the manner in which the detection equipment was shared with the CCR group. The dotted lines represent the walls of the electronics trailer of our group (B-R Hut) and that of the CCR group (CCR Hut). The electronic system located between the two huts are installed by us for the purpose of minimizing the lengths of those cables which must be short enough in order to obtain a short triggering time compatible with the CCR master trigger

Our trigger consisted of

$$\geq \text{nHV} \cdot (B_1B_2) \cdot \text{Inhibitor}$$

where one can set n = 2,3,4. ...B_1B_2 is the beam-beam coincidence signal and the inhibitor is the anticoincidence signal from spark chamber firing and other noise pickups

These large lead-glass LB counters have a thickness equivalent to 13 radiation lengths placed behind the HV counters which have only a thickness equivalent to 3 radiation lengths Therefore the corresponding total signal from the LB + HV gives the total energy of the γ-ray in question. These Z counters (50 x 6.5 cm in size and placed vertically 10 in a row on each side of the interaction region) also help us in obtaining some information on the extent of charged particles accompanying our multigamma events.

3.2 Analysis Procedures and Gamma Ray Identification

At the end of December of 1972 the total number of successful runs amounted to about 200

Extracting our triggered events from the magnetic tape used jointly with the CCR group, we have written a computer program (GLOBAL Program) for analyzing some of our desired results mainly from the data recorded by the 32 lead glass HV counters 120 large lead glass blocks, LB counters, (14.6 cm x 14.6 cm in area and 35 cm long) and 20 scintillation counters (Z counters) which were added since April by the CCR group in order to further reduce their background and to increase their trigger requirements.

Very recently the CCR group has also very kindly made available to us their computer program on the track fitting of the spark chamber data of the charged particles. Subsequently, we have succeeded in writing a similar track fitting program to extract the charged particle events that are correlated to our triggered multigamma events. Such information would further help us in isolating any possible non-π^o events, should they exist; and give some idea of the ratio of uncharged to charged particle production (of course within the 20% solid angle region around 90°), etc. We shall call the combined GLOBAL Program and the track fitting program the complete analysis program (CAP)

We have analyzed some of our runs obtained in our experiment using the GLOBAL Program, which does not include the spark chamber information. However, we have made a preliminary analysis of the individual events in some of the runs using the complete analysis program (CAP) and these results show that the majority of the HV's fired are not due to charged particles. In fact, more than 50% of the events which were analyzed by the CAP has no accompanying charged particle. Therefore, we shall designate as a first order approximation the firing of any single HV counter is usually set at 160 MeV, which is much higher than the energy loss of a high-energy charged particle coming from the general direction of the interaction region. Thus, each <u>triggered</u> HV is most likely a gamma ray event. The exact energy of this triggered HV count, as well as those of all the other HV counts which are fired simultaneously, are recorded on the magnetic tape. So the energy of each individual count can be checked. It should be noted that as the area presented by the HV blocks to the interactions is quite large (7.2 x 35 cm), a triggered HV count could be the result of one or more simultaneous counts. Hence,the multiplicities of the measured γ's could be the lower limit of the real multiplicities if these γ's are definitely established.

3.3 Preliminary Results

We shall present here the preliminary results from 10 available runs analyzed using only the GLOBAL Program. For the first part of the preliminary results presented here, we had to have at least four HV counters triggered simultaneously, i.e. corresponding to four or more multigamma events, and the beam energies for these data are 26.7 GeV in each beam.

The background in these results was measured by using a single beam only and it is subtracted out after normalization. By using a rather crude but straightforward normalization method, the background amounted to a few percent of the measured events.

The data presented below (Figs. 3-9) are taken under the condition that a lead-plate converter of 1 radiation length thick is placed immediately in front of the Z counters on the side facing the interaction region. This condition applies to both sides of the interaction region. Also, the triggers for these data are $\geq$ 4 HV's. Some representative data with no lead converter but with the triggers $\geq$ 3 HV's will also be shown (Figs. 10 and 11).

Figure 3 shows the number of HV and Z counters firing per triggered event (i.e. ≥ 4 HV's firing simultaneously). We see that the most preponderant number of HV counters firing is eight, among a total number of 32, although as many as 17 HV's are firing on five occasions in this run. Thus, the multiplicity within a comparatively small solid angle (20% of the total solid angle) is already much higher than one would expect in the usual production process, and the extension of these measurements to cover a much larger solid angle would be extremely important.

Figure 4 shows the energy distribution of a single HV counter (data for all the HV's, i.e. both the inside and outside HV's are combined). It should be noted here that the energy calibrations of the lead-glass counters were made sometime ago and these calibrations could be off by an appreciable amount. In any event it seems to indicate that most of the HV's firing <u>in excess</u> of the four triggered HV's (threshold energy = 160 MeV) are of the order of 40 MeV. These could be either low-energy gamma rays or charged particles. It is interesting to note that there is a knee in the energy distribution curve at around 200 MeV. The highest energy in a single HV counter in this case is ~ 640 MeV.

The energy distribution per triggered event in the HV's (inside and outside, respectively) is shown in Fig. 6, and a similar energy distribution for the LB + HV's) (inside and outside) is shown in Fig 7 The distribution of a single LB counter (inside or outside) is shown in Fig. 9. Owing to the center-of-mass angle of the two colliding beams, there is a preponderance of higher energy events in the outside region, as indicated by the above-mentioned curves.

With the lead converter removed from in front of the Z counters, we have recently analyzed the data from a run at the same beam energies (26 GeV/26 GeV) but with a less stringent trigger of ≥ 3 HV's. Figure 10 (solid curve) shows the total energy Σ(HV + LB) distribution per triggered event of ≥ 3 HV's, whereas the dotted curve shows the background in a scale which is larger by a factor of 10. Here the background is about 3%. For the more stringent triggers of ≥ 4 HV's the background would be even smaller. Figure 11 shows the energy distribution of a single HV counter also with a trigger of ≥ 3 HV's, and this curve also exhibits a knee similar to the one seen with the lead converter in place.

The current data are compared with theoretical predictions based on an uncorrelated model for pion production (see Fig. 12). As stated in Section 3.2, the HV's seem to be fired predominantly by γ-rays, therefore, Fig 12 very possibly represents a true γ-ray multiplicity distribution.

This model is described in detail in Appendix C. The experimental data show an apparent difference of several orders of magnitude in the high multiplicity.

3.4 Conclusions and Future Prospects

The following tentative conclusions may be drawn from our preliminary results under the conditions stipulated in sections 3.2 and 3.3. In addition, we are in the process of studying the possible effect of spill-over of a γ-ray shower from an HV to an adjacent one.

1. Gamma rays with large transverse momentum of the order of 7 GeV have been observed.

2. The multiplicity distribution of gamma rays in the 90° region differs significantly from the prediction of uncorrelated π^0 production in the high multiplicity region.

At the present we are beginning to analyze the rest of the data. We will study the very important problem of charged and neutral correlations within the 90° region as well as obtaining more definitive γ multiplicity distribution at various beam energies.

We plan to extend our solid angle coverage to 70% of the total in two steps as mentioned in the introduction with a high space and charge resolution detection system. We then not only will be able to study the γ-ray distribution in both wide angle and forward region, but also will be able to examine in detail the n_o,n_c correlation by an analysis procedure such as discussed in Appendix C. We will then be able to perform a very systematic study of the high multiplicity γ-ray and charged events and their interrelationship.

We are also in the process of developing a Monte Carlo program to aid in our data interpretation as well as detector design considerations for the detection system.

4. PROPOSAL FOR A HIGH RESOLUTION LARGE SOLID ANGLE MULTIGAMMA RAY DETECTOR SYSTEM

The design of the proposed detection system is based primarily on the exploratory tests on similar lead glass counters, prototype multiwire proportional chambers, and the associated electronic and logic system carried out at the ISR at CERN and at the 10 GeV-electron synchrotron at Cornell University.

The basic design consists of lead glass hodoscope counter arrays sandwiched with multiwire proportional chambers. There are six identical units of such sandwiched elements, the design of each unit is shown in Fig. 13. The wire chambers are of the size 1 m^2 in effective area similar to the prototype chamber constructed and tested at CERN and the lead glass hodoscope counter arrays L_1,L_2, L_3 and L_4 are identical arrays each containing 10 lead glass elements of 5 cm x 10 cm x 100 cm long. These four arrays are arranged in x-y coordinate fashion in alternate layers. The first MWPC would consist of more than 6 or 7 wire planes separated into two groups and spaced at a small distance apart between the two groups so as to determine the charged tracks. Tests were made at Cornell with 10 GeV electrons incident to a similar element 50 cm in length in a direction perpendicular to the longitudinal cross section of the element. With a single photomultiplier tube looking at one end of the element as shown in Fig. 14, the signal output due to 4.5 GeV electrons differ by about 10% only when the incident beam changed from position A (2.5 cm from the photomultiplier tube) to position B (47.5 cm from the photomultiplier tube). Behind the 1 m^2 sandwich hodoscope-wire chamber system, we have a hodoscope array of 20 cm x 20 cm (L_5) lead glass cubes 1.4 x 1.4 m in size (see Fig. 13). Two such units (1 and 2) will be placed on opposite sides of the interaction region as shown in Fig. 15. Four similar units are to be placed as shown in Figs. 15 and 16 where only the two bottom units 5 and 6 are shown. The solid angle covered by these six units amounts to $\sim$ 70% of the total solid angle.

In order to eliminate ambiguities in the space location of the multigammas some of the wire planes in the wire chambers will be placed at an angle different from the usual x-y planes.

The detailed description of the functions of the wire chambers and lead glass elements and of the scintillation and Cerenkov counters is given on pp 7-8 of the previous proposal (Ref. 1c) However, a slightly different logic circuitry will be employed since ADC will be used on all the lead glass elements and on some of the wire chambers.

In summary

i) The proposed system covers 70% of the total solid angle at the interaction region as compared to 20% of the present system The former also includes the very important forward angle regions as well as the 90^o region.

ii) The resolution in angular distribution of the new proposed detector system is 100 times higher than the present system. An additional increase in resolution by a factor of 4 can be realized if so desired.

iii) The maximum number of detection bins will be increased from 32 in the present detection system to 600 and possibly 1200 in the new proposed detection system. This would correspond to a similar increase in the maximum number of detectable γ-rays.

iv) The capability of the newly proposed detection system to measure the shower development curves of the multigammas will make it possible to distinguish γ-rays from charged particles even if a charged particle is closely associated with it. In addition, the direction of the γ-rays can be determined. This is extremely important to be able to ascertain whether the multigammas originate from the interaction region This is not possible in the present detection system.

v) The energy distribution of the multigammas can be determined much more accurately with the newly proposed detector system than with the present one because of the much higher resolution of the multiwire proportional chambers in the new detector system

vi) Finally, the proposed apparatus would allow us to look for a possible reconstruction of the π^o mass by combining all the detected γ-rays in all possible pairs. In this respect substantial increase in angular resolution and the almost complete coverage of the total solid angle is absolutely necessary to make a serious effort in this direction. A Monte Carlo method will be used to examine our capability of making these reconstructions.

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FIGURE CAPTIONS

Fig. 1 Plan of one side of the CCR detector system.

Fig. 2 Schematic diagram of the electronics and logic system.

Fig 3 Number of HV and number of Z counters firing per triggered event (≥ 4 HV's) E = 26.7 GeV. Pb converter in place.

Fig. 4 Distribution of energy deposited in a single HV counter. Trigger ≥ 4 HV's E = 26.7 GeV. Pb converter in place

Fig. 5 Distribution of energy deposited in all the lead glass counters (HV + LB). Trigger ≥ 4 HV's. E = 26.7 GeV. Pb converter in place.

Fig. 6 Distribution of energy deposited in the HV counters. Trigger ≥ 4 HV's E = 26.7 GeV. Pb converter in place

Fig. 7 Distribution of energy deposited in each side of the detector Trigger ≥ 4 HV's E = 26.7 GeV Pb converter in place.

Fig. 8 Comparison of the energy deposited in all HV counters with the energy deposited in all LB counters. Trigger ≥ 4 HV's. E = 26.7 GeV. Pb converter in place.

Fig. 9 Distribution of energy deposited in a single LB counter Trigger ≥ 4 HV's. E = 26.7 GeV. Pb converter in place.

Fig. 10 Distribution of the energy deposited in all the lead glass counters for a single beam and for two beams. Trigger ≥ 3 HV's. E = 26 6 GeV. No Pb converter.

Fig 11 Distribution of energy deposited in a single HV counter. Trigger ≥ 3 HV's. 26.6 GeV. No Pb converter.

Fig. 12 Comparison of the observed multiplicity distribution of gammas with the theoretical distribution calculated using an uncorrelated π^0 production model.

Fig 13 Design of lead glass MWPC sandwich detector unit.

Fig. 14 Test positions of 4.5 GeV electrons on a lead glass (SF5) block (5 cm x 10 cm x 50 cm).

Fig 15 Top view of 4 of the 6 detector units at the interaction region of the ISR.

Fig. 16 Side view of the 6 detector units at the interaction region of the ISR.

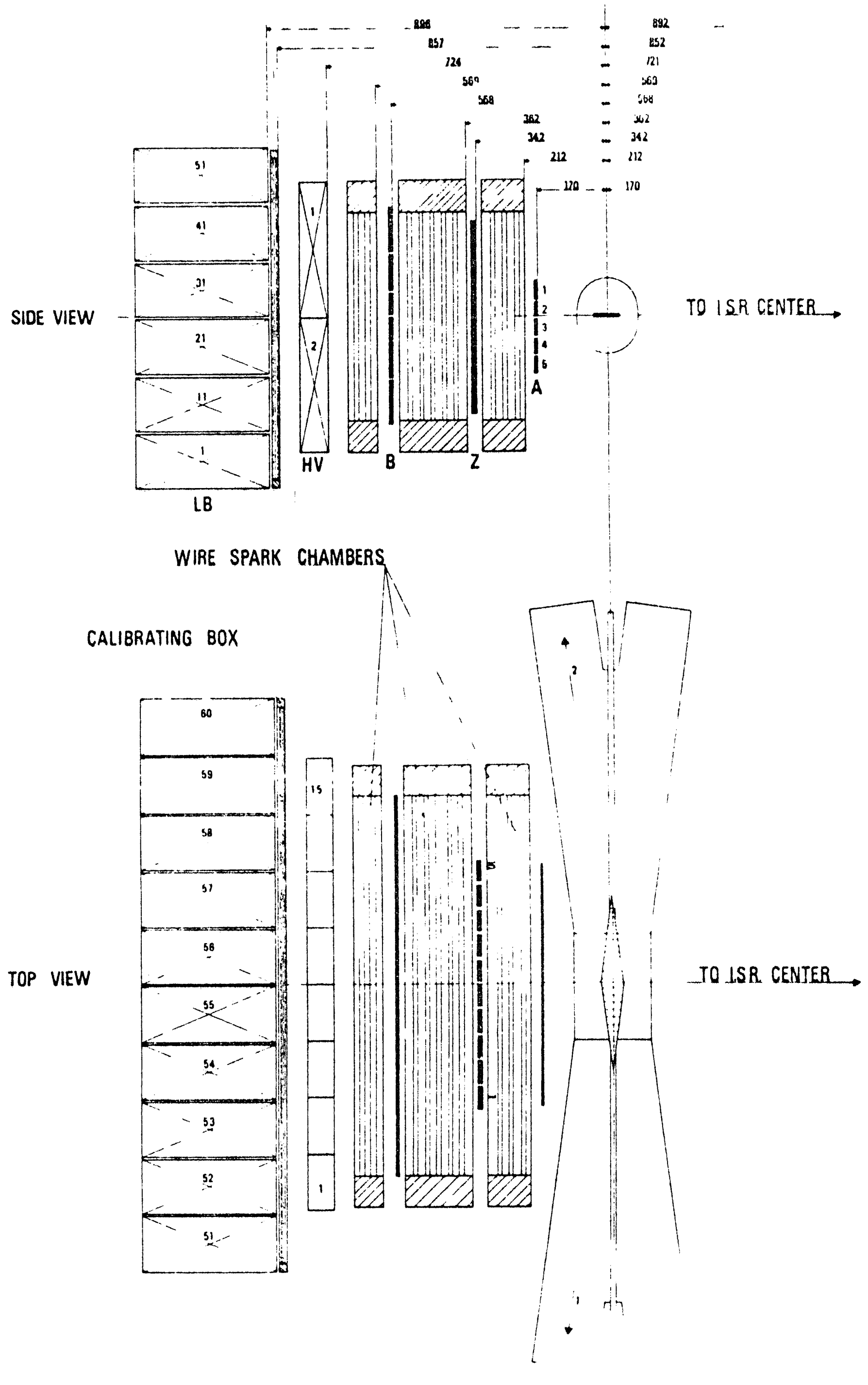

896
857
724
569
568
362
342
212
170
892
852
721
569
568
362
342
212
170
51
41
31
21
11
1
1
2
3
4
6
A
SIDE VIEW
TO ISR CENTER
HV
B
Z
LB
WIRE SPARK CHAMBERS
CALIBRATING BOX
60
59
58
57
56
55
54
53
52
51
15
1
2
1
TOP VIEW
TO ISR CENTER

Fig. 1

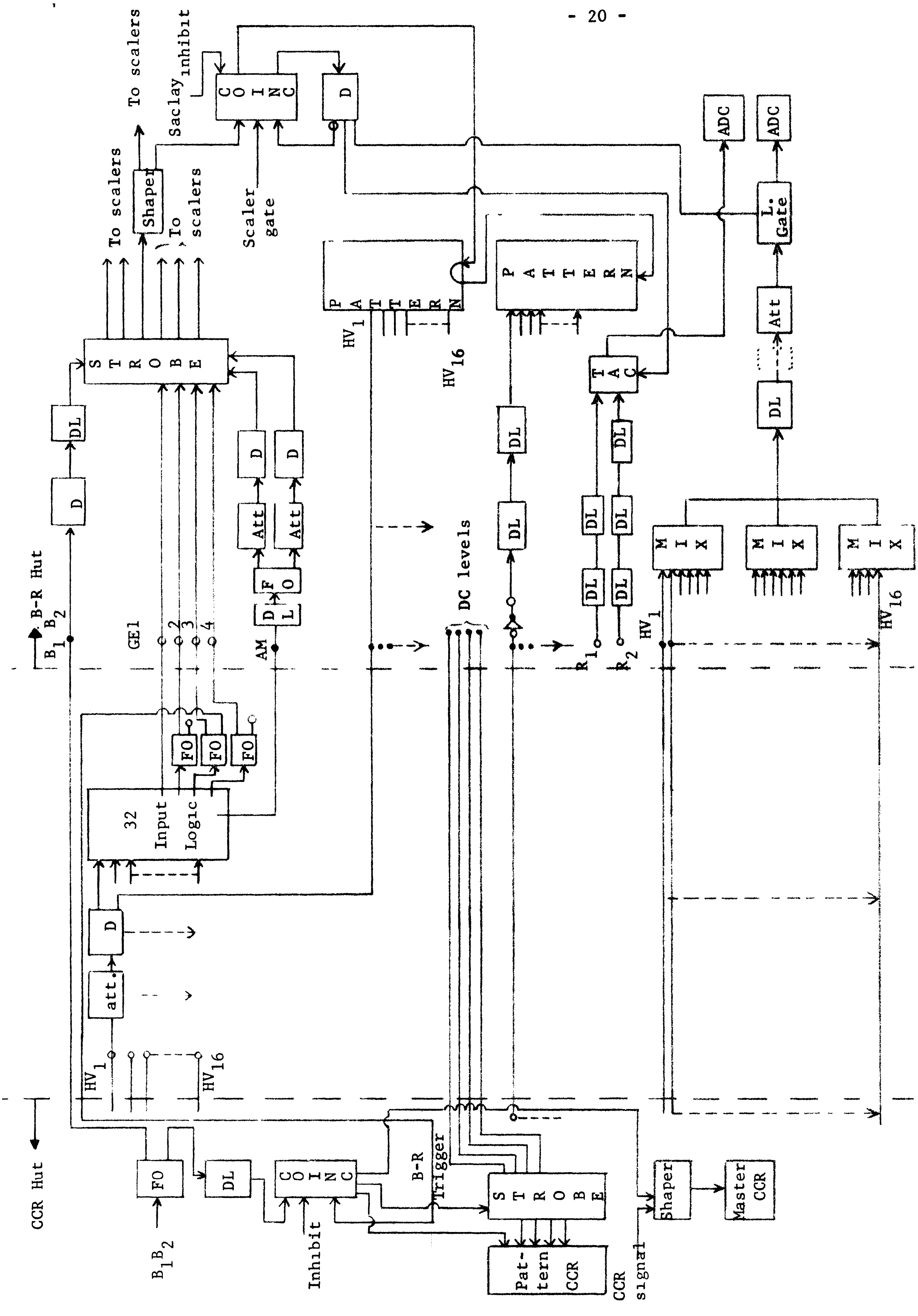

CCR Hut
B-R Hut
B_1B_2
$B_1 B_2$
FO
DL
COINC
Inhibit
B-R Trigger
STROBE
Pattern CCR
CCR signal
Shaper
Master CCR
HV_1
HV_{16}
att.
D
32 Input Logic
FO
FO
FO
GE1
2
3
4
AM
DL
FO
Att
Att
D
D
DL
D
STROBE
To scalers
Shaper
To scalers
To scalers
Saclay inhibit
Scaler gate
COINC
D
PATTERN
HV_1
HV_{16}
DC levels
DL
DL
PATTERN
R_1
R_2
DL
DL
DL
DL
DL
TAC
HV_1
HV_{16}
MIX
MIX
MIX
DL
Att
L. Gate
ADC
ADC

Figure 2

NUMBER OF HV AND Z COUNTERS FIRING PER TRIGGERED EVENT ≥ 4 HV's

Pb CONVERTER IN. E = 26.7 GeV, I_1 = 4.91 A, I_2 = 5.14 A.

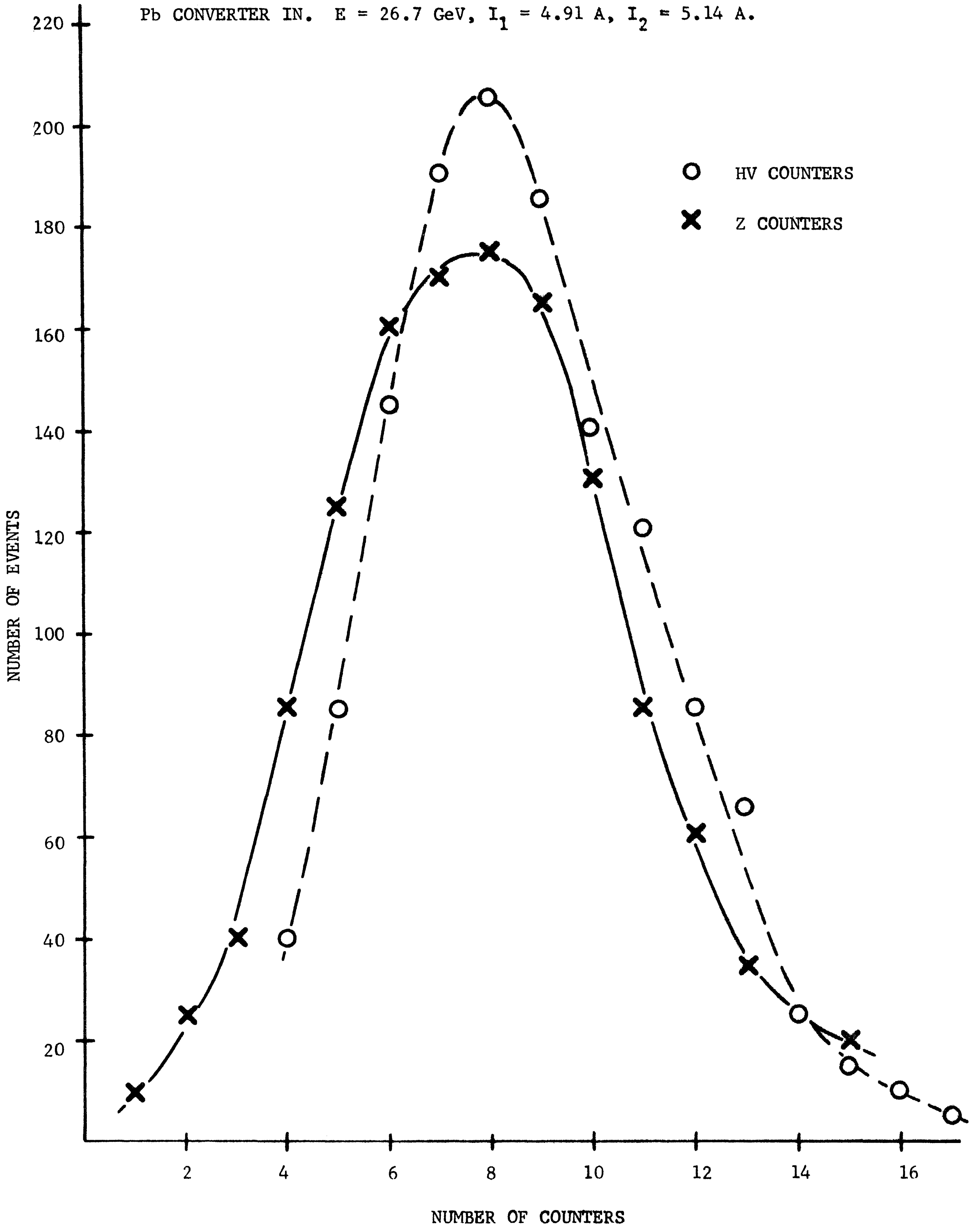


Fig.3

ENERGY DISTRIBUTION OF A SINGLE HV COUNTER.

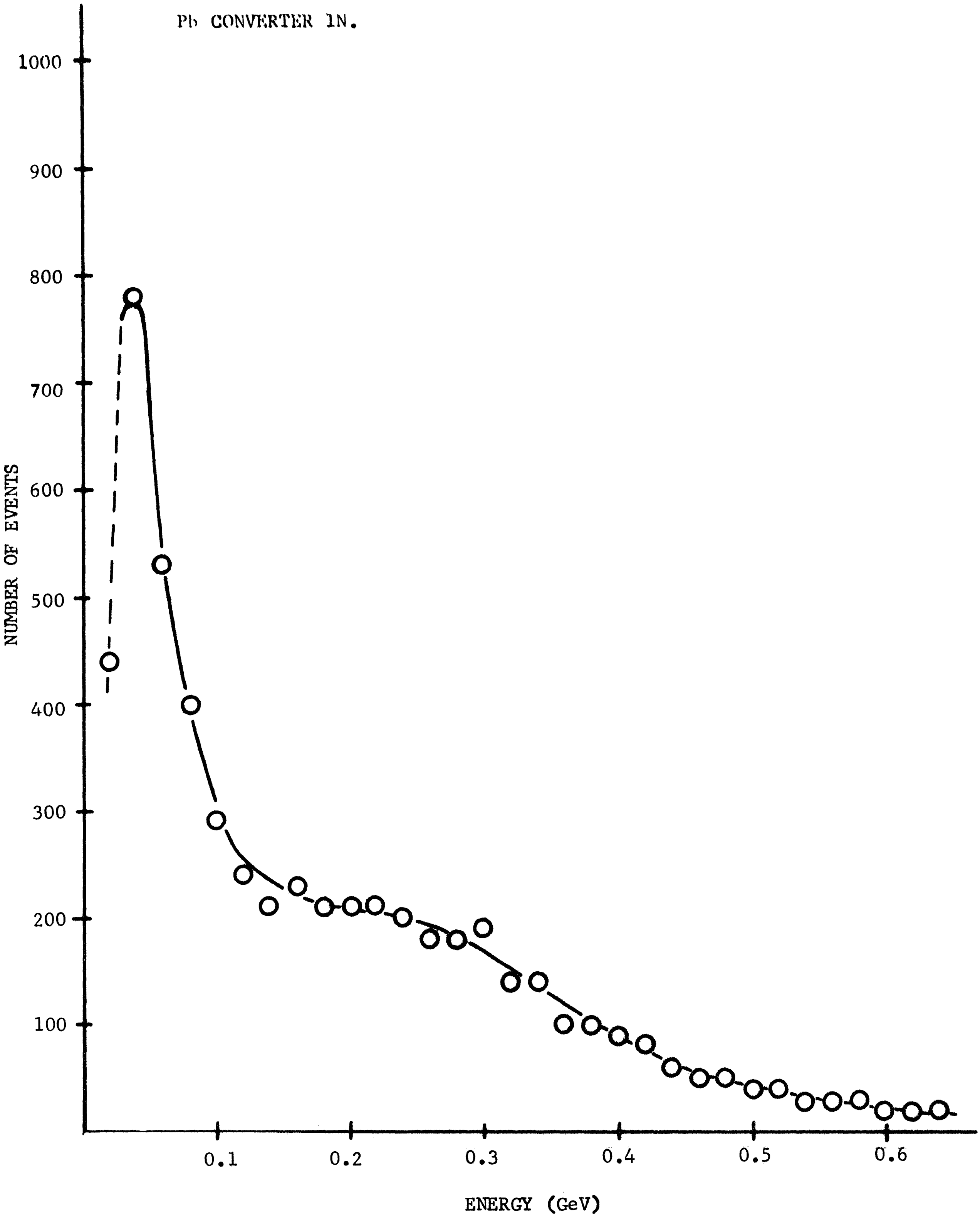
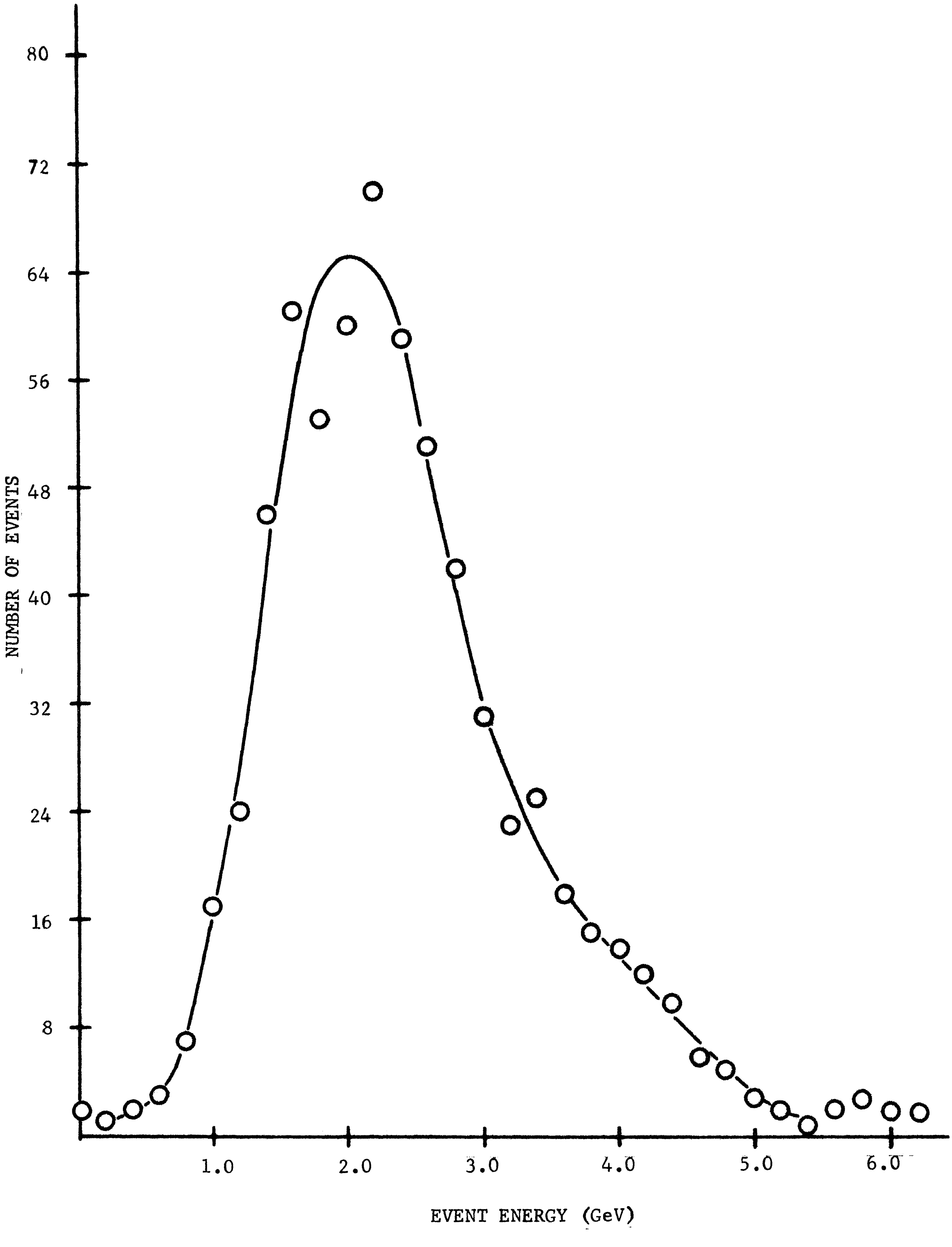


Fig. 4



TOTAL ENERGY (LB + HV) IN AND OUT

Pb CONVERTER IN E = 26.7 GeV, $I_1 = 4.91$, $I_2 = 5.14$

Fig. 5

ENERGY PER TRIGGERED EVENT ≥ 4 HV's

Pb CONVERTER IN $E = 26.7$ GeV, $I_1 = 4.91$ A, $I_2 = 5.14$ A

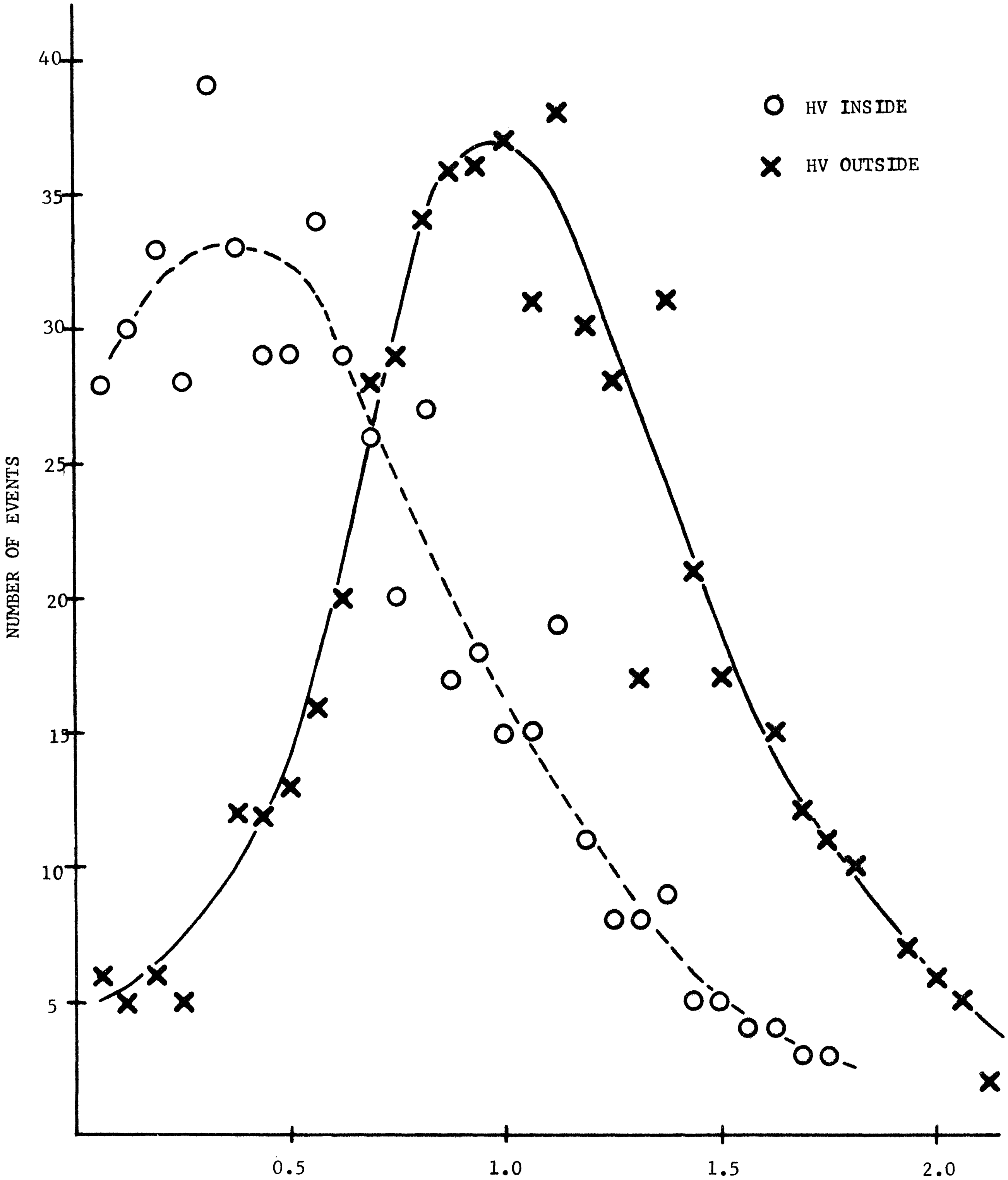


Fig. 6

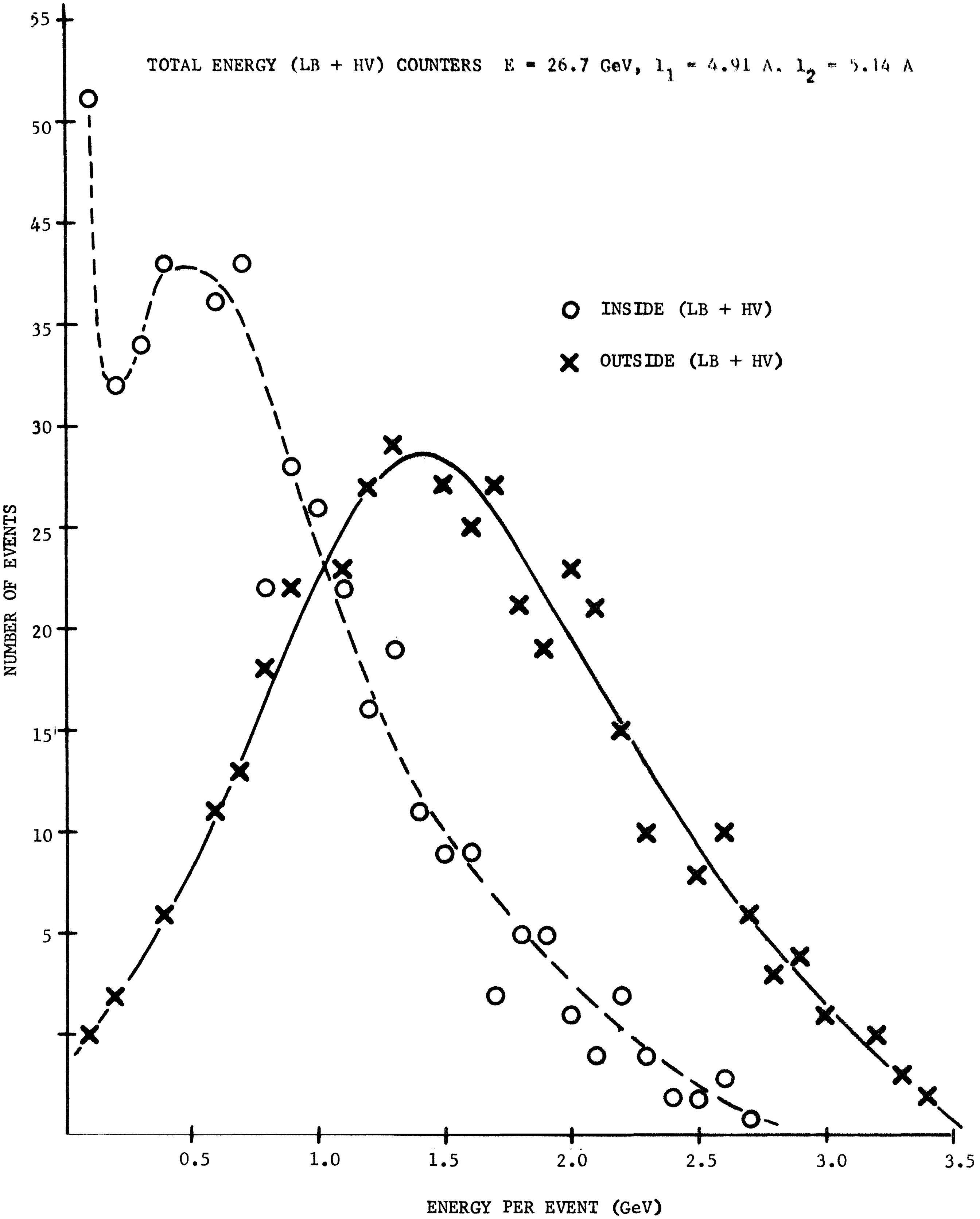

TOTAL ENERGY (LB + HV) COUNTERS E = 26.7 GeV, l1 = 4.91 A, l2 = 5.14 A
INSIDE (LB + HV)
OUTSIDE (LB + HV)
NUMBER OF EVENTS
55
50
45
35
30
25
20
15
10
5
0.5
1.0
1.5
2.0
2.5
3.0
3.5
ENERGY PER EVENT (GeV)

Fig. 7

DISTRIBUTION OF ENERGY DEPOSITED IN ALL HV's AND IN ALL LB's

Pb CONVERTER IN E = 26.7 GeV, I_1 = 4.91 A, I_2 = 5 14 A

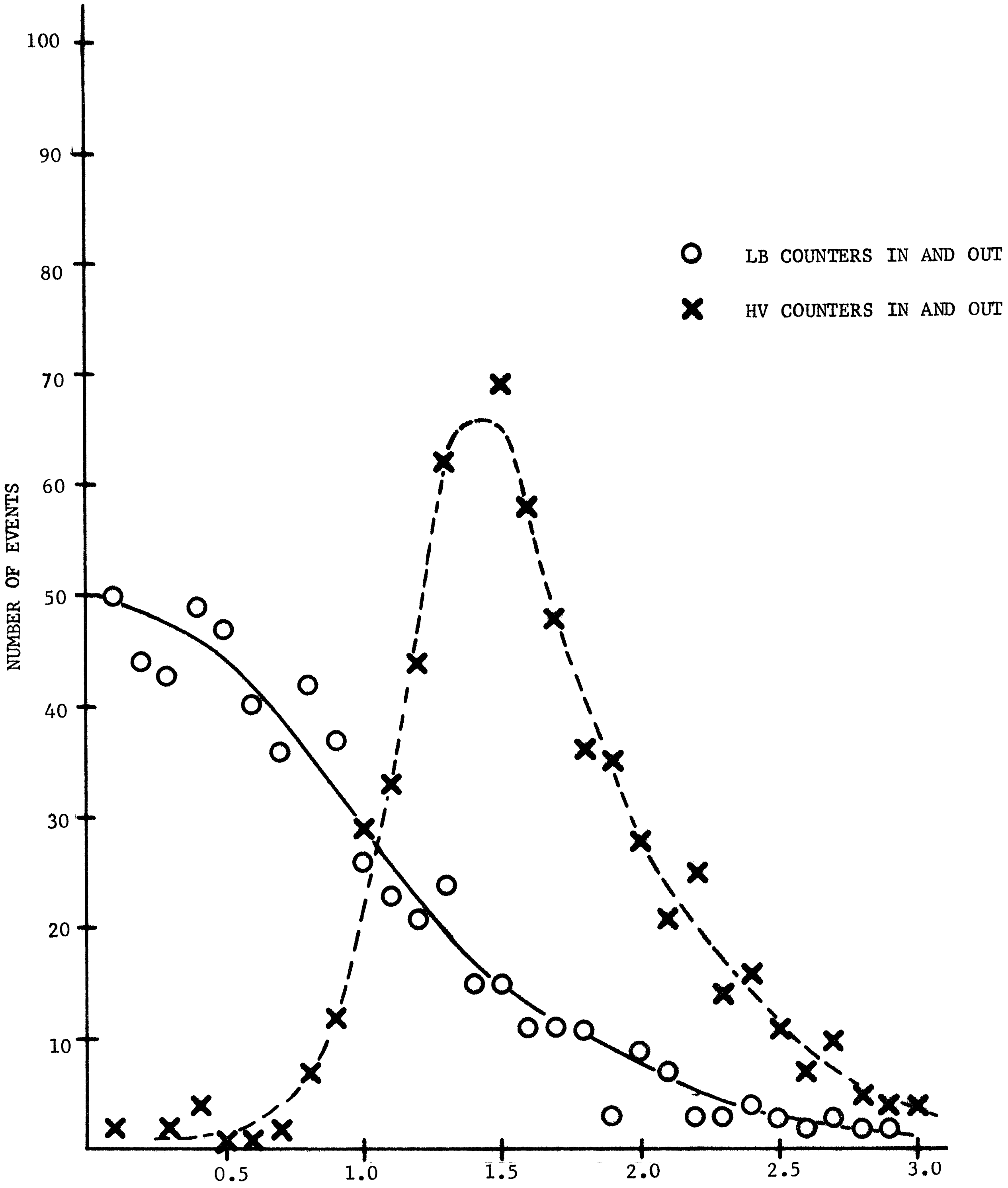


Fig. 8

ENERGY DISTRIBUTION OF A SINGLE LB COUNTER

Pb CONVERTER IN E = 26.7 GeV, I_1 = 4.91 A, I_2 = 5.14 A

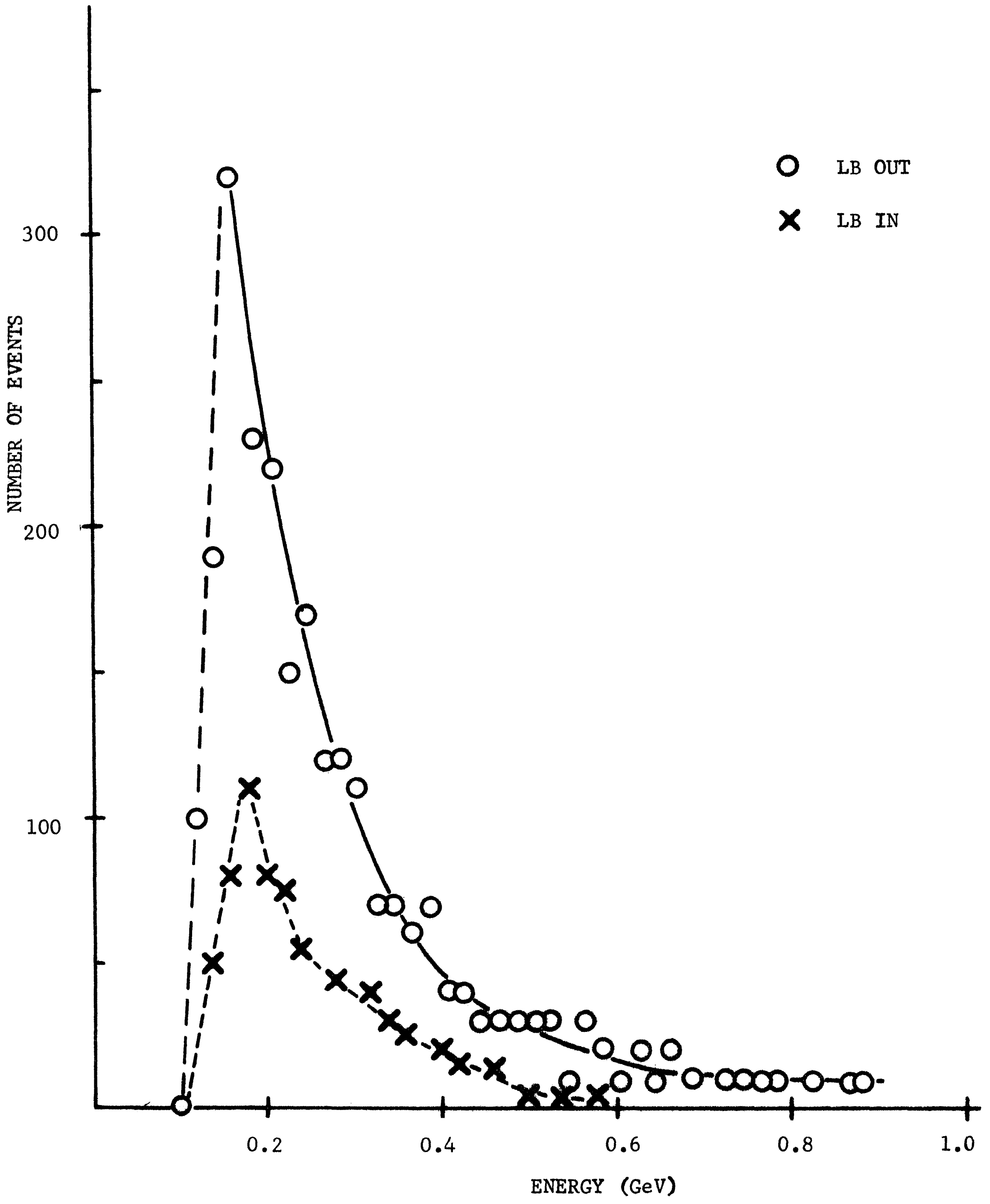


Fig. 9

TOTAL ENERGY [Σ(HV + LB)] PER TRIGGERED EVENT ≥ 3 HV's

E = 26.6 GeV

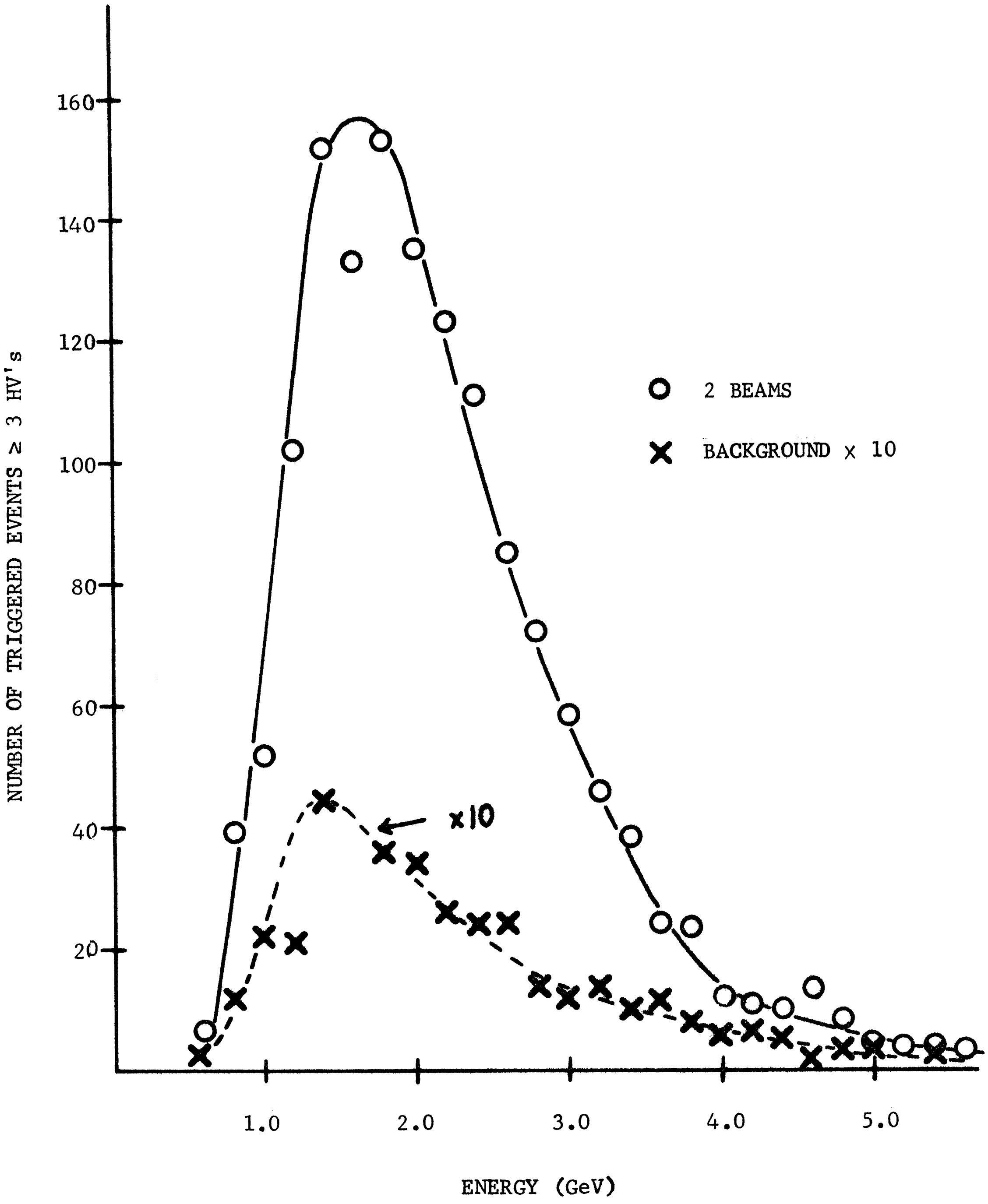


Fig. 10

ENERGY DISTRIBUTION OF A SINGLE HV COUNTER E = 26.6 GeV

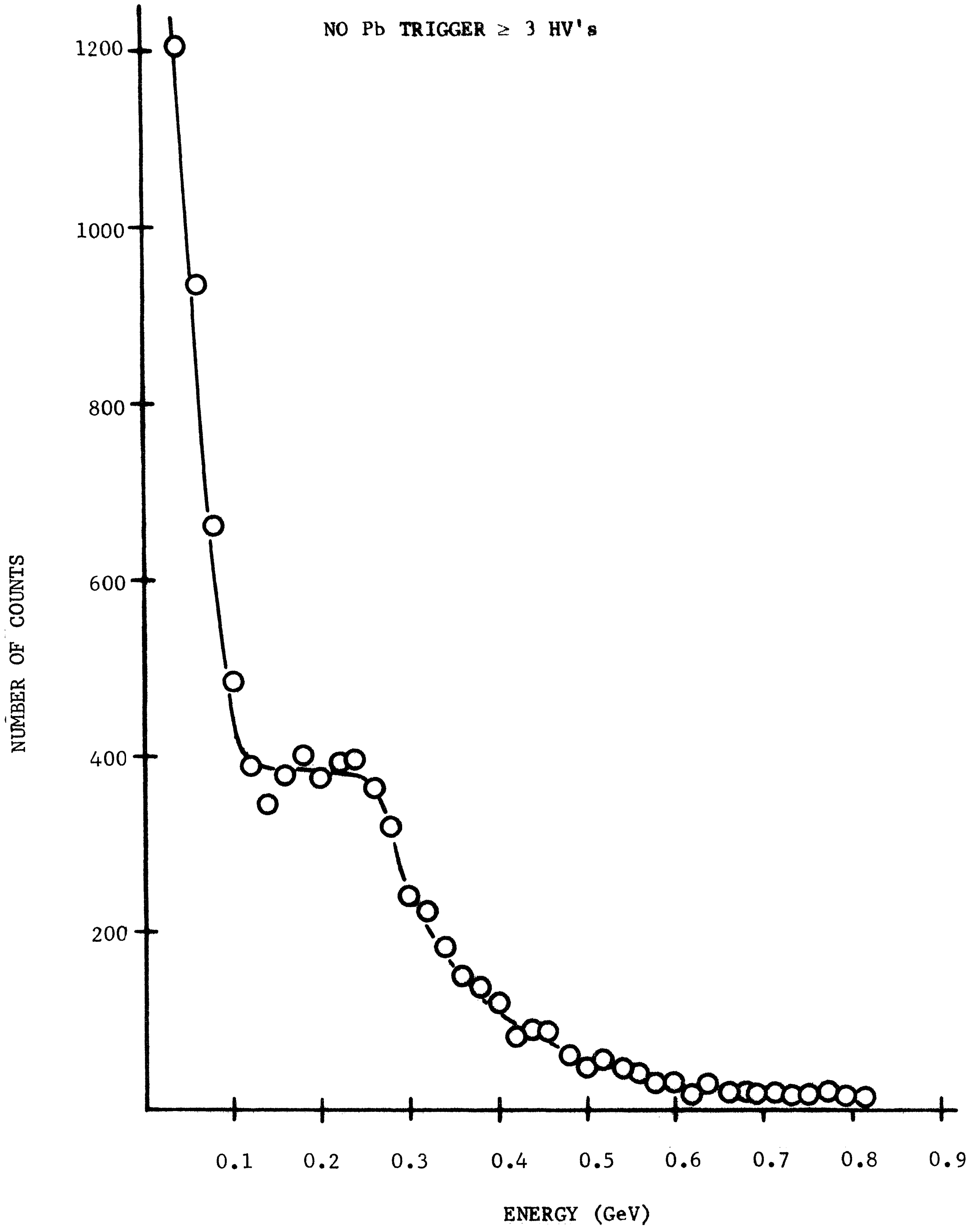
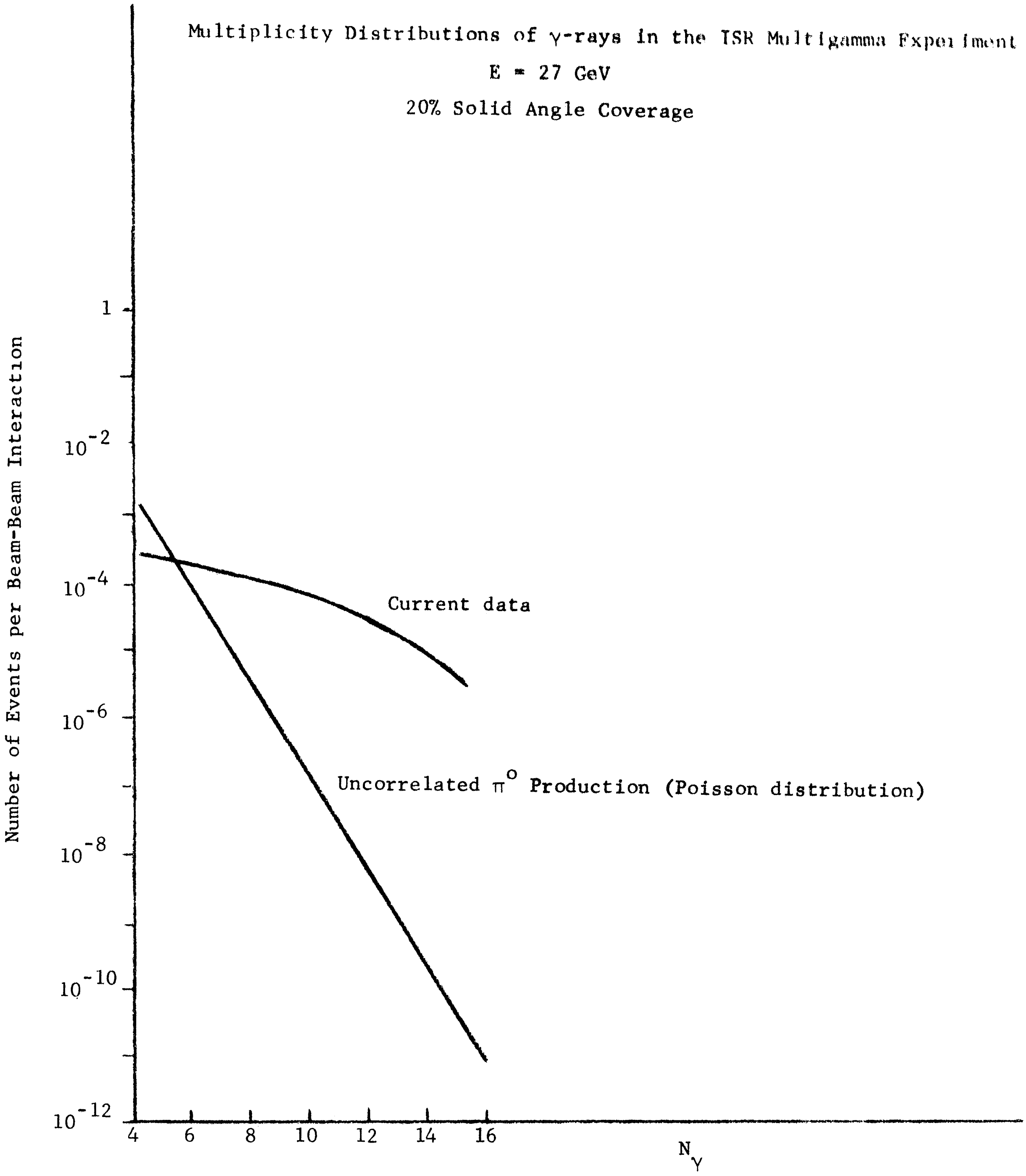


Fig 11



Multiplicity Distributions of γ-rays in the ISR Multigamma Experiment

E = 27 GeV

20% Solid Angle Coverage

Fig. 12

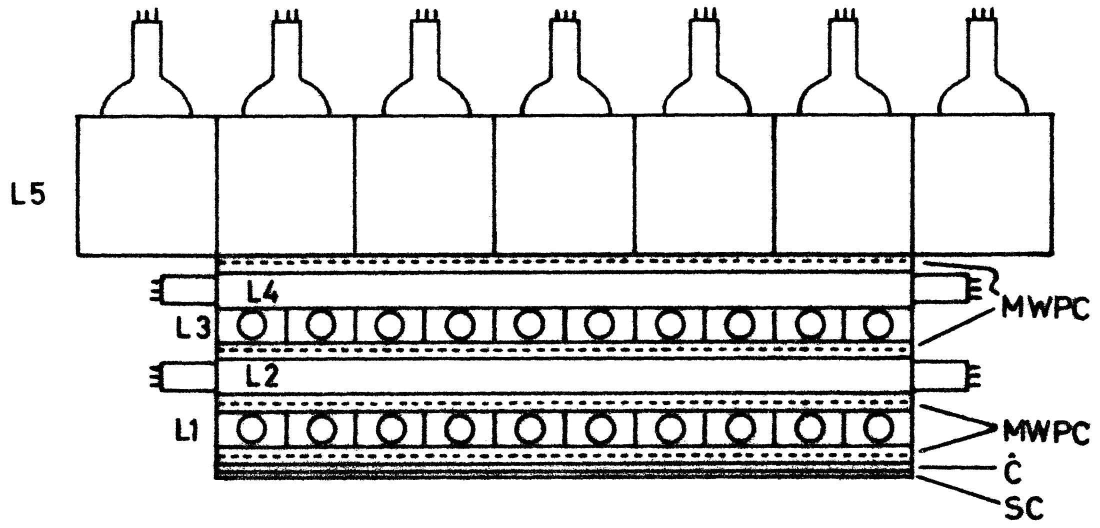


Fig 13

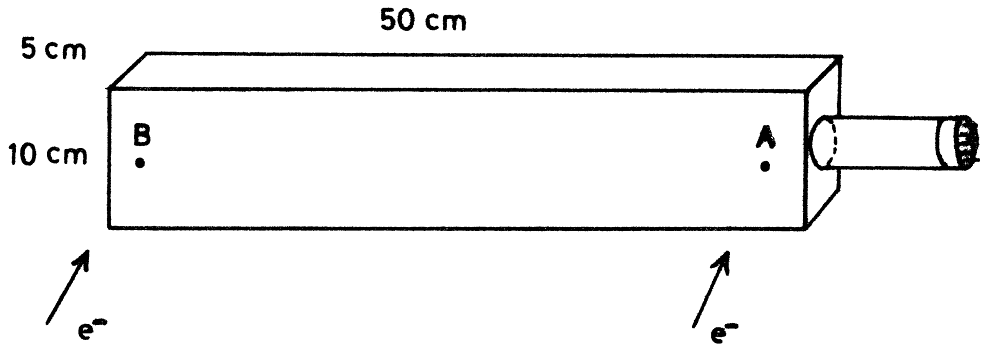


Fig 14

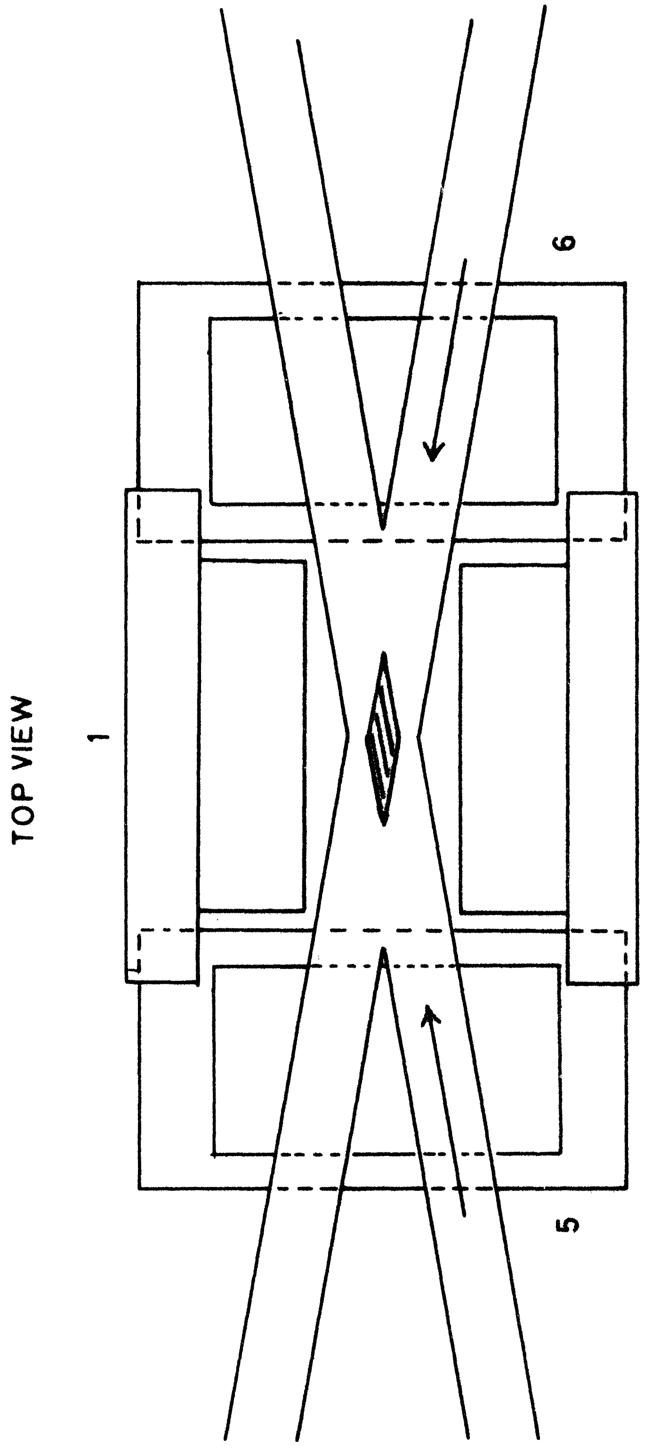


Fig 15

SIDE VIEW

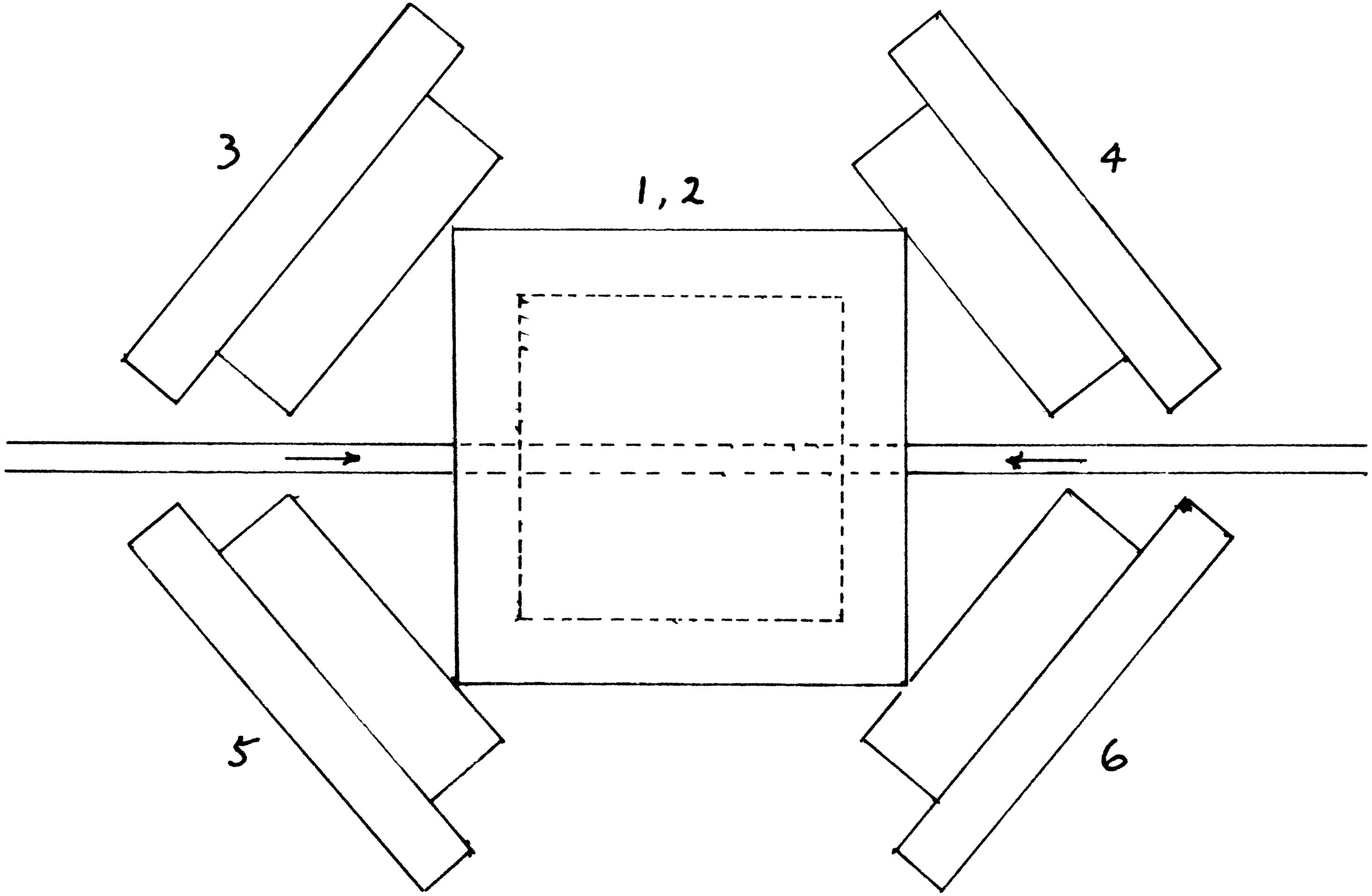


Fig. 16

APPENDIX A

FURTHER INFORMATION ON ASPECTS OF PHYSICAL INTEREST OF MULTIGAMMA EVENTS

1. THE MAIN FEATURES OF THE MULTIGAMMA EVENTS OBSERVED IN COSMIC RAYS

During the period 1953-56, a few events were observed in stacks of nuclear emulsions exposed to cosmic rays at high altitude.

Table A1 summarizes some of the main features of the three typical events, the first one of which was observed by the Chicago Group,[2] while the other two were seen by the Torino Group [3] Several events with the same general features were observed by other authors.[4] Figures A1, A2, and A3 show schematic drawings of these events.

The most interesting results concerning the events of Table A1 can be summarized as follows:

i) No incident charged particle can be observed within 200-300 μ of the axis of the events, with such a direction that it could be considered to be associated with them.

ii) The number of pairs materializing at a given distance increases approximately linearly, reaching a large value in one radiation length (L_{rad} = 2.5 cm).

iii) The energies of the pairs were estimated by one or the other of the following two methods.

a) when possible by measuring the energy of each electron from multiple scattering;

b) from the opening angle of the pair, under the assumption that this had its minimum value (so that the two electrons had the same energy). Table A2 shows the results of measurements of this type for the Chicago event. Similar results were obtained for the other events.

The following conclusions were reached by various authors:

a) Result (ii) excludes the interpretation of these events in terms of usual electromagnetic cascade showers.

b) Nuclear processes with the emission of a large number of π^o also seems to be excluded. Apart from the fact that the probability that a sufficient number of π^o are produced with no accompanying charged particles, the high collimation ($< 10^{-3}$ rad) of the bursts would be totally incompatible with energies of the order of 1 GeV as observed for several of the pairs (Table A2).

c) The interpretation of these events seems to require a process in which a large number N_γ of protons are emitted. For the Chicago event, Schein et al. estimate

$$N_\gamma = 21 \pm 3 \quad .$$

Similar or larger values are obtained from the other events.

d) From the opening angle of $< 10^{-3}$ rad one can estimate the energy of the primary to be $E_o \geq 10^{12}$ eV

It may be interesting to recall that Schein et al. remark in their first letter[2] that the Chicago event would easily be interpreted if it were produced by a high-energy particle annihilating in flight with the emission of only photons of rather low energy in the c.m.

2. A FEW REMARKS ABOUT THE CREATION AND SUBSEQUENT ANNIHILATION OF DIRAC POLE-ANTIPOLE PAIRS

In order to explain the cosmic-ray events discussed in Section 2, Ruderman and Zwanziger[5] have suggested that they could be due to the annihilation of a pair of Dirac magnetic poles produced in a bound state called, in the following, a dipolium. The conjectures of these authors stem from the well-known large value of the magnetic charge of Dirac poles

$$g = mg_o \qquad \pm\, m = 1,2,3, \quad . \tag{A.1a}$$

$$g_o = \frac{1}{2}\frac{\hbar c}{e^2} \; ; \qquad e = \frac{137}{2}\, e \quad , \tag{A.1b}$$

and from the remark that in order for the vacuum to be stable against spontaneous production of pole pairs at distances down to the Compton wavelength of the lightest hadron ($r_o \simeq \hbar/m_\pi c^2$), the mass m_g of the poles should satisfy the relationship

$$m_g \geq \frac{m^2}{4}\frac{g^2}{\hbar c} = \frac{m^2}{4}\, 9.6 \text{ GeV.} \qquad \text{(A.2)}$$

For distances shorter than r_o, one cannot even speak of pole-antipole separation

Ruderman and Zwanziger then stress the following points:

1) The coupling constant of Dirac poles to photons is so large,

$$\frac{g^2}{\hbar c} = \frac{m^2}{4}\, 137 \quad , \qquad \text{(A.3)}$$

that when, in a high-energy event, a pole and its antipole start to move away, a large number of photons are radiated. Consequently, even at energies much larger than the threshold energy, the pole-antipole pair reaches a maximum separation of the order of 2-3 × r_o and then falls back, irradiating other photons and finally annihilating; the time involved in the overall process is of the order of 10^{-22} sec.

2) The number of photons emitted in the production and subsequent annihilation of a dipolium is expected to be very roughly of the order of the coupling constant (A.3), i.e.

$$n_{ph}\, \frac{g^2}{\hbar c} = \frac{m^2}{2}\, 137 \quad . \qquad \text{(A 4)}$$

This general picture not only provides a very reasonable explanation of the anomalous gamma-ray showers discussed in Section 1 of this Appendix, it also explains why, until now, no experimental evidence has been found for the existence of isolated Dirac poles, even if they could actually exist

It should also be pointed out that the dipolium could be produced in virtual states and could give rise to multigamma events even below the corresponding threshold energy.

Conjecture (1) has been confirmed by Neumeyer and Trefil[10] who have applied the thermodynamical model in order to estimate the probability of producing a pair of poles in a high-energy collision. By taking into account the interaction in the final state, these authors find that the emission of radiation reduces the probability of production of the poles by two or more orders of magnitude, depending on the values of m and m_g Doubts can be raised about the use of the thermodynamical model in the case of the dipolium production,[1c] but the order of magnitude of the effect of the irradiation of photons should be correct and confirms conjecture (1).

Two more points were discussed in our previous proposal.[1c]

a) From the present experimental limits on QED breakdown, limits can be deduced for the production amplitude of the dipolium by a single photon. Are these limits so low that a search for dipolium production at the ISR is completely hopeless?

The problem was treated by Cabibbo and Testa who consider two sets of experimental data: i) the results of the (g_μ - 2) experiment, and ii) the results obtained at ADONE on the production of muon pairs. The second set of data gives a much lower upper limit,[1c] especially if one considers the more recent results.[11]

This upper limit is still pretty high,

$$\frac{\sigma_X^1}{\sigma_{\mu^+\mu^-}} < 137 \times 4 \quad , \tag{A.5}$$

where σ_X^1 is the cross section for production of the dipolium (X) by a single photon, and $\sigma_{\mu^+\mu^-}$ that for the production of pairs of muons.

b) The production cross section at the ISR was estimated by Cabibbo and Testa by using two different methods.

The first one is based on the comparison of the production (by a single photon) of a pair of Dirac poles

$$p + p \rightarrow X + \text{hadrons} \tag{A.6}$$

with that of a pair of muons

$$p + p \rightarrow \mu^+\mu^- + \text{hadrons} \quad . \tag{A.7}$$

One can write

$$\left(\frac{d\sigma_{pp \rightarrow X + hs}}{dM_X} \right)_{\substack{\text{real or} \\ \text{virtual}}} = K \frac{d\sigma_{pp \rightarrow \mu^+\mu^- + hs}}{dM_{\mu\mu}} \quad , \tag{A.8}$$

where K is a constant of the order of 137, and the cross section on the right-hand side is obtained by extrapolation of the value observed at the AGS[12] to the ISR energies by some convenient formula.

The results depend very much on the formula adopted for the extrapolation. Besides that used in our previous proposal,[13] there are two more recent estimates, both of which provide much lower values. The first one[14] is based on the use of the light-cone approach and represents an improvement with respect to the first paper quoted in Ref. 13. The other[15] is based on the notion of scaling and phenomenological considerations.

c) The second estimate -- based on the Weizsäcker-Williams formula -- gives, on the contrary, a very large cross section.

All these estimates should, however, be considered with great reservation since they are based on the assumption that the dipolium is produced by a single (virtual or real) photon emitted in the proton-proton collision, while the "effective coupling constant" between a charged particle and a monopole, i.e.

$$\frac{eg}{\hbar c} = \frac{e^2}{\hbar c}\frac{g}{e} = \frac{m}{2} \qquad (A.9)$$

is always of the order of one. Therefore one can expect that processes taking place via the exchange of 2,3,... photons should have an amplitude that is not much smaller than that pertaining to a single photon exchange.

3. A FEW POINTS OF INTEREST IN THE EMISSION OF GAMMA-RAYS THROUGH THE DECAY OF π^o (AND OTHER PARTICLES) PRODUCED IN p-p COLLISIONS

The interest of the problem is duly stressed in various excellent reports on the multiple production of secondary particles in high-energy collisions.[16-19] Here only a few remarks are collected in order to remind one of the kind of information that can be derived from experiments of the type proposed below, even in the case that no unusual multigamma events were observed. At the same time, these remarks provide the justification for our desire to increase, as much as possible, the solid angle covered by the gamma-ray detector.

In this discussion two simplifying assumptions will be made merely for the sake of clarity: the first one is that only pions are produced in p-p collisions, while we know that the frequencies of production of kaons and antiprotons at the ISR are of the order of 10% and 2.5%.[19]

The second simplification consists in discussing the problem as if the π^o were observed directly, while only the corresponding decay gamma-rays are actually recorded. The relationship between the angular distributions and spectra of the parent π^o and the daughter gamma-rays complicate the problem, which, however, can be treated by well-known standard methods.

In an ideal experiment the detector would cover the whole solid angle so that the following quantities could be measured for a few values of the c.m. energy:

i) the average multiplicity $\bar{n}_o$ of π^o produced;

ii) the frequency of production of n_o neutral pions and its correlation with the production of n_{ch} charged particles;

iii) the density and the correlation function for emission of two pions as they are defined, for example, by Wilson.[16]

It may be useful to add a few words about point (iii), i.e the distribution of the multiplicities $n_{o,ch}$, because such a problem is also directly connected to that of the background of multigamma events from which the possible unusual events should be disentangled.

The problem has been studied by various authors through the analysis of the existing data on the observed total number of charged particles emitted in high-energy collisions.[17,20,21]. The Polish authors[20] find that the n_{ch} distribution deviates appreciably from the Poisson law

$$P(n,\bar{n}) = \frac{\bar{n}^n}{2} e^{-\bar{n}} \quad . \qquad (A.10)$$

Apparently this behavior is mainly due to the presence of one or two protons in the final state. Wang[21] obtains the best fit of the charged pions' frequency distributions assuming that the production of pairs of $\pi^+\pi^-$ is Poissonian. This law could be a consequence of "local charge conservation" which, however, is incorporated in many theoretical models.

Among these one can recall a model based on the assumption that hadrons are composed of a number of sub-units,[22] the multiperipheral bootstrap model of Chew and Pignotti,[23] which gives a Poissonian law for the observed pion production.

Another model that can be mentioned here is that of Ballestrero et al.,[24] who obtain for the charged pions the Furry distribution[25]

$$F(n,\bar{n}) = \frac{1}{\bar{n}}\left(1 - \frac{1}{\bar{n}} \right) \quad n = 0,1,2,\ldots \qquad \text{(A.11)}$$

This is a multiperipheral model where the four-momentum of the produced pions is assumed to be negligibly small with respect to that of the incident particles.

Finally, Quigg, Wang and Yang[26] speculate on the fluctuations of the multiplicity in the fragmentation of hadrons in high-energy collisions, arriving at a few qualitative guesses. Among these, one may recall the fact that the multiplicity of the fragmentation of the two hadrons should not be much correlated. In particular,

$$\frac{\left(\overline{n^{R}_{ch}} \cdot \overline{n^{L}_{ch}} \right)}{\overline{n^{R}_{ch}} \cdot \overline{n^{L}_{ch}}} \xrightarrow[E_{cm} \to 1]{} 1 \quad ,$$

where R and L stand for "left" and "right" and refer to the two hemispheres within which the fragments of the incoming particles move. Similar considerations hold for neutral fragments.

TABLE A1

Main Features of Typical Multigamma Events

	Exit Angle (degrees)	Angle to Emulsion Surface* (degrees)	Total Length (cm)	No. of Pairs Observed	Half-cone Angle of Burst (rad)
Chicago 1	16	7.5	3.30	16	$\sim 2 \times 10^{-4}$
Torino 1	61	31	2.45	14	$\leqslant 10^{-3}$
Torino 2	32	16	4.68	24	$\leqslant 10^{-3}$

*The energy evaluation of the electron pairs (Table A2) is more reliable for small values of the angle of the shower axis to the emulsion surface.

TABLE A2

The first 16 pairs in narrow photon shower. The radial distance is the distance from the pair origin to the median of the electrons at the pair's point of origin. E_1, E_2 are the measured energies of individual electrons. E is the total energy of the photon. The estimate of E for pairs 6, 7, 8, 9 is made from the distance the pair goes before becoming resolvable into individual tracks.

Pair	Distance to Point of Conversion (μ)	Radial Distance (μ)	E_1 (MeV)	E_2 (MeV)	E (MeV)
1			400 ± 160	100 ± 40	500 ± 165
2	2,020	1	350 ± 140	300 ± 120	650 ± 330
3	4,440	12	350 ± 140	550 ± 220	900 ± 260
4	13,100	3	100 ± 40	800 ± 320	900 ± 325
5	13,350	23	500 ± 200	150 ± 60	650 ± 210
6	15,750	10			> 5,000
7	15,770	3			> 5,000
8	19,900	1			> 20,000
9	21,600	2			> 20,000
10	27,000	6			
11	27,200	8			
12	29,800	2			
13	30,800	4			
14	31,100	2			
15	31,400	26			
16	33,300	16			

FIGURE CAPTIONS

Fig. A1 Narrow shower of pure photons. Sections at arbitrary intervals to show development of shower. Note pair starting in last section.

Fig. A2 Projected points of origin and opening angles of the pairs of event To 1. The lateral slow pairs originate on tracks of the preceding pairs that have been deviated

Fig. A3 Projected points of origin and opening angles of 23 pairs of event To. 2 Pair No. 8 is probably a trident on a track of pair No. 2 and it is not drawn in this figure.

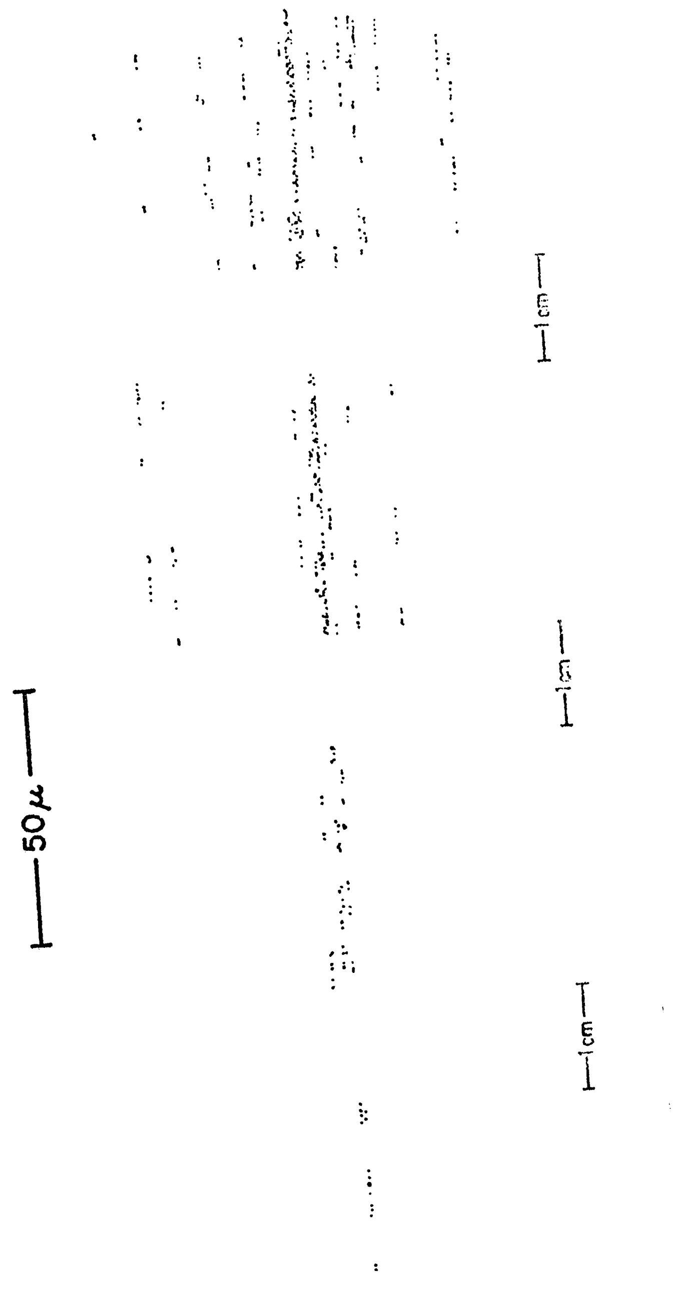


Fig A7

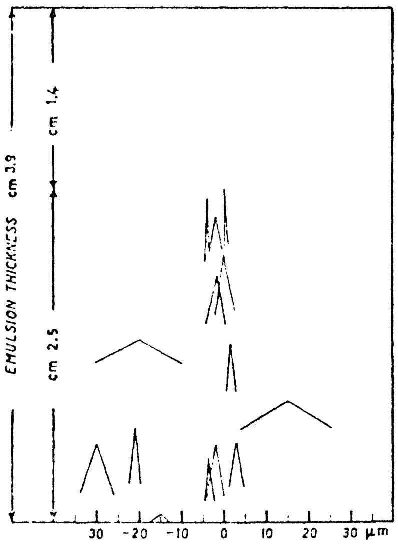

EMULSION THICKNESS cm 3.9
cm 1.4
cm 2.5
30
-20
-10
0
10
20
30 µm

Fig. A2

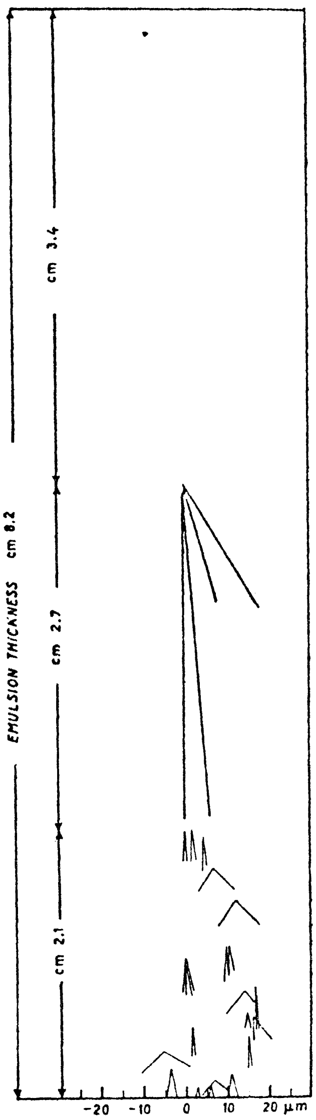

EMULSION THICKNESS cm 8.2
cm 3.4
cm 2.7
cm 2.1
-20
-10
0
10
20 µm

Fig A3

APPENDIX B

CONSIDERATIONS OF EXPERIMENTAL BACKGROUNDS

In this appendix the frequency of high multiplicity gamma events due to multiple π^o production is estimated from various considerations Experimental backgrounds are compared with this and with the possible frequency of multi-gamma events from non-π^o sources such as monopole annihilation. Ways of distinguishing between π^o and possible non-π^o events are also discussed

When the original proposal was written, we, of course, had no multiplicity data from NAL. A Poisson distribution was just as reasonable as anything else. However, we may now use data presented in the report of Jacob[27] and assume that it can be reasonably extrapolated to ISR energies. We will go to high multiplicities (the multiplicity from $m\,\bar{m}$ annihilation is expected to be about 100). We have

$$\frac{\sigma(24)}{\sigma(<n>)} = 7.4 \times 10^{-5} \ , \ \frac{\sigma(30)}{\sigma(<n>)} = 2 \times 10^{-6} \ ,$$

$$\frac{\sigma(36)}{\sigma(<n>)} = 5.5 \times 10^{-8} \ , \ \frac{\sigma(48)}{\sigma(<n>)} = 5.18 \times 10^{-11} \ .$$

We see that at NAL energies the high multiplicity π^o events have an exponential fall off with n. We shall be able to ascertain whether this result holds at ISR energies for neutral and charged pions. In addition, it would seem that a monopole annihilation into many tens of γ's as predicted by Ruderman with a cross section between 10^{-28} - 10^{-34} cm^2 as estimated by us should be detectable The π^o distribution will be computed by using charge independence and the experimental results on the spectrum angular distribution and multiplicity of $\pi^{\pm}$ observed at the same energy and angular region at the ISR. We do not expect phase-space restrictions to seriously complicate our analysis since we could produce 350 pions at ISR energies and if we allow the outgoing protons to carry away 50% of the total energy, we still can produce $\sim$ 200 pions. In fact, we could have 30 π^o mesons with an average energy of 1 GeV. The number of charged particles is not simply determined by phase-space considerations, but also by other factors (see Caneschi-Schwimmer articles and our discussions in Ref. 1) such as charge conservation and isospin considerations As we discussed in Ref. 1, this will cut down the $n_o >> n_c$ cross section There is evidence for these correlations, since the data reported by Jacob already indicates that $<n_o>$ is an increasing function of n_c. A table showing the effect of correlations is presented in Appendix C, which is based on the Caneschi-Schwimmer model

Also see Fig C-1 and C-2 and the discussion in Appendix C. It will be extremely interesting to see if these correlations, such as are pictured in Fig. C-2 are borne out by our experiments. Another point worth noting, is that pions will have restricted transverse momentum whereas non-π^o-γ events, such as would occur if a massive object like a monopole-antimonopole state decayed into many γ's, would presumably be isotropic. Therefore, as we discussed in our previous proposal, the acceptance of monopole γ's will be determined by total solid angle coverage whereas π^o - γ's will have a tendency to be in forward and backward cones. In performing such a complete survey of multigamma events as we propose to do we will not vetoe on $n_c > 0$ in our experiment.

We do not expect the high multiplicity π^o cross section to be much higher than 10^{-32} cm^2 for $n_o > 30$ as we have shown. This is based on an extrapolation of NAL data and, of course, we will have more definitive information at ISR energies as we have pointed out. One should note additionally that 10^{-34} cm^2 is not an upper limit, for $m,\bar{m}$ production, but a reasonable guess on the low side. This estimate based on comparison with μ pair production considers one out of a multitude of Feynman diagrams.[1] The Weiszacker-Williams estimate by Cabbibo and Testa[1] yields an estimate of 10^{-28} cm^2. In obtaining the μ pair estimate, we have simply replaced $\mu \longleftrightarrow m$ and $e \longleftrightarrow g$ so that assuming point-like electromagnetic interactions and spin ½ monopoles the processes are completely identical and the angle has already been integrated over in obtaining

$$\frac{d\sigma}{dm_x}(s,m_x) \text{ where } m_x = \sqrt{-(p_m + p_{\bar{m}})^2} \quad .$$

The various m_x values considered are listed in Ref. 1. However, all of such cross section estimates for $p + p \rightarrow n\gamma$ + anything with a superstrong monopole electromagnetic coupling are very uncertain. One certainly must do an experiment to investigate both the high multiplicity π^o events and the possible existence of a new multigamma producing phenomena of non-π^o origin, such as m, $\bar{m}$ annihilation, and not rely completely on uncertain theoretical estimates.

In our present plan, we will measure the multigamma events as well as the associated charged particles and will <u>not</u> veto events with charged particles during the detection. However, we will sort out the various multigamma events according to various associated charged particle multiplicities in the analysis.

In regard to the accidental background and assume a time resolution of 50 ns, the accidental background according to Jacob's report will be no larger than high multiplicity π^o rates, the accidentals will not affect appreciably our ability to examine high multiplicity π^o events and to observe anomolous multigamma events such as monopoles.

Let us assume that we look for an event the multiplicity of which is 80 Using Jacob's report and the time resolution of 50 ns, the accidental rate is 2×10^{-3}/sec. This rate corresponds to the cross section of 5×10^{-34} cm^2. The total energy of the accidentals will be larger than that of true events, if the accidentals come from two p-p interactions. The charge clustering effect significantly aids us to identify the accidentals (see Appendix C). The accidentals due to the beam-gas interactions will have different angular distributions and total energies. One way to check on the accidentals is to take data at different luminosities; because the real event rate is proportional to the luminosity and the accidental rate is proportional to the square of luminosity. In addition, other restraints in the analysis such as track reconstruction, the total energy requirements will further reduce the effect of accidentals.

As a matter of fact, in the present experiment, we easily recognize and separate the events in which charged tracks originate from two different points of the interaction region.

An effort will be made to minimize the conversion of gammas in the vacuum chamber by using the corrugated thin wall. If the gammas convert in the wall our lead glass counters and wire chambers will still detect them as the gammas and can distinguish them from hadrons. If we restrict the number of charged particles in our trigger requirement, then we loose some of the high multiplicity gamma events through this conversion process.

The possibility of a cosmic-ray muon triggering the beam-beam counters and then developing a multigamma shower in our detection system would be very slight indeed. If necessary, some anticounter arrangement can be easily incorporated to reduce such effects

In summary, we feel that the multigamma events will be distinguished from the backgrounds because of the reasons mentioned above and mainly because of the following reasons:

(a) Since the total cross section of a monopole pair production of 10^{-34} cm^2 which some people consider to be annoptimistic <u>upper</u> bound is in fact more reasonably considered to be a guess on the lower side as amply demonstrated by Cabibbo, Testa and ourselves (10^{-28} - 10^{-34} cm^2) and, therefore, we should be able to observe such a process, if it exists, in addition to high multiplicity π^o events.

Nobody knows if monopoles exist ($\sigma \neq 0$) or do not exist ($\sigma = 0$), and, if they exist, nobody really knows if they are bosons or fermions In this situation, all theoretical estimated cross sections have to be taken as crude guesses.

Anyway, the only meaningful indication from such calculations is the following. If the monopoles exist, they would affect the quantum electrodynamics predictions. In the known experimental verification of quantum electrodynamics, there is still room for monopole pairs (virtual or real) cross sections that could be some factor 10^2 greater than the $\mu^+\mu^-$ pairs cross section. Therefore, no general argument exists giving an upper limit to the monopole-pairs cross section such that it cannot be measured as a <u>byproduct</u> by the apparatus proposed for the investigation of multi-γ events at the ISR.

(b) No matter what distributions are used for the π^o multiplicities when high multiplicity events of many tens of gammas are examined which is what one would expect for monopole pair annihilation, we would expect the high multiplicity π^o cross section to decrease significantly for these multiplicities.

APPENDIX C

π^0 DISTRIBUTIONS IN THE ISR MULTIGAMMA EXPERIMENT

INTRODUCTION

In the multigamma experiment a sequence of detectors subtending a phase space volume Ω measures the energy and angular distribution of γ-rays produced in p-p collisions at $\sqrt{S} \simeq 60$ GeV. Data are recorded for $N_\gamma > 4$ where N_γ is the number of γ-rays in coincidence/event. The important point is that Ω includes the central region for π^0 production ($x = 2P_{11}/\sqrt{S} \leq 0.02$) which is the most important region for the study of multiparticle correlations. We now proceed to discuss the angular distribution and longitudinal rapidity distributions of the γ's.

SINGLE PARTICLE DISTRIBUTIONS FOR $2\pi^0$ COINCIDENCE

We shall define a single particle inclusive distribution function for $n_o \geq 2$. The standard single particle inclusive distribution for a π^0 is defined by

$$P_o^1\,(k) = \frac{1}{\sigma_o} \sum_{n_o=1}^{\infty} \sum_{n_c=0}^{\infty} \frac{1}{(n_o - 1)!}\,\frac{1}{n_c!} \int dk_2 \ldots dk_{n_o + n_c}\, |M|^2 \;, \qquad \text{(C.1)}$$

where

$$dk = \frac{d^3k}{2E}$$

and n_o, n_c represent the number of neutral and charged particles respectively. σ_o is the total inelastic cross section.

$$|M|^2 = \int dP_1 dP_2\, \delta^4\,(P_{tot} - P_1 - P_2)\, |T|^2 \quad . \qquad \text{(C.2)}$$

P_1 and P_2 are the outgoing proton momenta, T is the T matrix for the interaction which is a function of $k, k_2 \ldots, k_{n_o + n_c}$.

Equation (C.1) is the probability of measuring a π^0 with $[k, k + dk]/dk$.

Now in the multigamma experiment, we measure the distribution of π^0 mesons when there is at least one other particle in coincidence with it in Ω. The relevant quantity therefore is not Eq. (C.1) but rather $P^1_{02}(k)$ defined by

$$P^1_{02}(k) = \frac{1}{\sigma_o} \sum_{n_o=2}^{\infty} \sum_{n_c=0}^{\infty} \frac{1}{(n_o - 1)!} \frac{1}{n_c!} \int_\Omega dk_2 \int dk_3 \ldots dk_{n_o + n_c} |M|^2 \ . \tag{C.3}$$

The problem then is to calculate P^1_{02}. We write Eq. (C.3) in terms of exclusive distribution functions as follows

$$P^1_{02}(k) = \frac{1}{\sigma_o} \int_\Omega dk_2 \sum_{n_o=2}^{\infty} \frac{1}{(n_o - 1)!} \sum_{n_c=0}^{\infty} \frac{1}{n_c!} \int dk_3 \ldots dk_{n_o+n_c} \frac{d\sigma^{n_o+n_c}_{ex}}{dk\, dk_2 \ldots dk_{n_o + n_c}} \ . \tag{C.4}$$

Using the technique of Koba, Nielsen and Olesen[28] we can write the exclusive distribution functions

$$\frac{1}{\sigma_o} \frac{d^n\sigma_{ex}}{dk_1 \ldots dk_n}$$

in terms of the inclusive distribution functions

$$\frac{1}{\sigma_o} \frac{d\sigma^m_m}{dk_1 \ldots dk_m}$$

defined as follows

$$\frac{1}{\sigma_o} \frac{d\sigma^m_m}{dk_1 \ldots dk_m} = \frac{1}{\sigma_o} \sum_{\ell=0}^{\infty} \frac{1}{\ell!} \int \frac{d\sigma^{m+\ell}_{ex}}{dk_1 \ldots dk_{m+\ell}} dk_{m+1} \ldots dk_{m+\ell} \ .$$

The desired relation is

$$\frac{1}{\sigma_o} \frac{d\sigma^n_{ex}}{dk_1 \ldots dk_n} = \frac{1}{\sigma_o} \sum_{\ell_o, \ell_c} \frac{(-1)^{\ell_o+\ell_c}}{\ell_o!\ell_c!} \int \frac{d\sigma^{n+\ell_o+\ell_c}_{in}\, dk'_1 \ldots dk'_{\ell_o+\ell_c}}{dk_1 dk_n dk'_1\, dk'_{\ell_o+\ell_c}} \tag{C.5}$$

We now assume that the π^o mesons are uncorrelated. This assumption states:

$$\frac{1}{\sigma_o} \frac{d\sigma^{n+\ell_o+\ell_c}_{in}}{dk_1 \ldots dk'_{\ell_o+\ell_c}} = \frac{1}{\sigma_o} \frac{d\sigma_{in}}{dk_1} \cdots \frac{1}{\sigma_o} \frac{d\sigma_{in}}{dk'_{\ell_o+\ell_c}} \ . \tag{C.6}$$

We now insert this into Eq. (C.5). After some manipulations we obtain the simple result

$$P^1_{02} = P^1_0 \frac{\langle n_o\rangle_\Omega}{\langle n_o\rangle} \Psi^P(> 1) \quad , \qquad \text{(C.7)}$$

where we have used the definitions

$$P^1_0(k) = \frac{1}{\sigma_o} \frac{d\sigma_{in}}{dk} \quad , \qquad \text{(C 8)}$$

and

$$\int_\Omega P^1_0(k_2)\, dk_2 = \langle n_o\rangle_\Omega \quad , \qquad \text{(C.9)}$$

which is the average number of particles in Ω for all inelastic events. We note that the trigger requirements should be $N_\gamma \geq 1$ to obtain this quantity experimentally. Otherwise we must do the integral using an experimental π^o distribution, e.g. Winter et al.[6] and

$$\Psi^P(> N) = \sum_{n_o=N}^{\infty} \frac{\langle n_o\rangle^{n_o}}{n_o!} e^{-\langle n_o\rangle} \qquad \text{(C.10)}$$

Using our results and the distribution obtained by Winter et al. integrating over all momenta (an approximation since there is a lower threshold on the E detectors) we have

$$\frac{dN_\gamma}{d\Omega} = A \left(k_o^{-1} \cos^2\theta + \frac{2}{x_o\sqrt{s}} \sin\theta \cos\theta \right)^{-1} \frac{\langle n_o\rangle_\Omega}{\langle n_o\rangle} \Psi^P(> 1) \quad , \qquad \text{(C 11)}$$

with

$$A = 1.48\ \text{GeV}^{-1},\ k_o = 0.162\ \text{GeV},\ x_o = 0.083.$$

We have also written a Monte Carlo Program to obtain Eq. (C.7) using the fit of Bali et al.[29] for $P_o \simeq P_i$. We note that the π^o distribution which can be derived from Eq. (C.11) is given by[30]

$$\frac{dN\pi^o}{d\Omega} = \frac{a_1}{(a_2 + \cos^2\theta)} \frac{\langle n_o\rangle_\Omega}{\langle n_o\rangle} \Psi^P(> 1) \quad ,$$

with $a_1 = 0.106(\text{sr}^{-1})$, $a_2 = 6.31 \times 10^{-3}$ all angles are measured with respect to the $\perp$ to the beam direction.

CORRELATIONS

If there are correlations, as we should expect, between pions in multipion events then our equations must be modified In general this can be done using Eqs (C 5) and (C. 4) However, if $2\pi^o$ coincidences dominate then we may use

$$P^1_{02}(k) = \int P^2_0(k,k_2)\, dk_2 \qquad \text{(C 12)}$$

where P_0^2 is the two particle distribution function defined by

$$P_0^2\ (k,k_2) = \sum_{n_o=2}^{\infty} \frac{1}{(n_o-2)!} \sum_{n_c=0}^{\infty} \frac{1}{n_c!} \int dk_1 \ldots dk_{n_o+n_c}\ |M|^2 \qquad (C.13)$$

Writing

$$P_0^2(k,k_2) = P_0'(k)\ P_0'(k_2) - C_0'^2(k,k_2) \qquad (C.14)$$

we may interpret deviations from Eq. (C. 7) as due correlations. We can then obtain some idea about the correlation function $C_0'^2(k,k_2)$.

Of course the most dramatic type of correlation would be if the γ's came from monopole annihilation.

RAPIDITY DISTRIBUTIONS

The longitudinal rapidity of a particle is defined by

$$Y = \sin h^{-1} \left(\frac{q_{11}}{\sqrt{\mu^2 + q_\perp^2}} \right) \qquad (C.15)$$

where 11, $\perp$ refer to the beam direction. Now if $C_0'^2 = 0$ then it is straightforward to show that over a reasonable portion of Ω the distribution of π^o mesons should be uniform. In general for the weak correlation model $C_0'^2$ is a function only of $|Y_1 - Y_2|$. Therefore there should be a dip in the rapidity plot for $Y_1 \simeq Y_2$.

The distribution of γ-ray rapidities should follow that of the pions. Specifically if the π^o mesons are distributed uniformly then so will the γ's. Deviations from uniformity therefore can be related to the $2\pi^o$ correlation function using the $\pi^o \to 2\gamma$ kinematics. In making a rapidity plot to determine the two particle distribution function all 4-fold multigamma coincidences must be plotted. For example, if there are nγ rays then there are $n!/4!(n-4)!$ coincidences to plot.

MULTIPLICITY DISTRIBUTIONS

Applications of Eqs. (C.5) and a suitable generalization of (C.4) yield in the uncorrelated model the total event rate for N-fold π^o coincidences

$$r_\Omega(N) - \left(\frac{\langle n \rangle_\Omega}{\langle n_o \rangle} \right)^N \Psi^P(> N) \qquad (C\ 16)$$

Therefore a demonstration of Eq. (C.16) would indicate the Poisson distribution is obeyed by the π^o mesons. Any deviation from this indicates the influence of correlations. Eq. (C.16) is compared with our current data in Fig 12.

DISCUSSION

Our formalism, especially Eq. (C.4) and (C.5) allow for a relatively simple inclusion of various strong interaction models into calculation of the relevant quantities of the multigamma experiment. In particular, the result of the coincidence event rate has a very simple interpretation. The probability of a particle entering Ω is given by

$$P(1) \simeq \frac{\langle n\rangle_\Omega}{\langle n_o\rangle} \quad . \qquad (C.17)$$

Therefore if π^o production is uncorrelated then

$$P(N) = \left(\frac{\langle n_o\rangle_\Omega}{\langle n_o\rangle} \right)^N \Psi^P(> N) . \qquad (C.18)$$

If there are strong multihadron correlations then this equation [Eq. (C.18)] must be modified. For example, if the π^o's come from ρ or σ mesons ($\sigma \rightarrow 2\pi^o$) we would expect something like

$$P(> N) = (P_1)^{N/2}\, \Psi^P(> N/2) \quad , \qquad (C.19)$$

where P_1 is now multiplied times itself N/2 times because a ρ or σ yields 2 pions. In general, we could expect something like $P(> N) = (P_1)^{N'}\Psi(> N)$ where $1 \le N' \le N$ for correlations. The maximal correlation therefore would be something like $(N' = 1)$ $P(N) \simeq P_1 \times 1/N^2$ using $\Psi \sim 1/N^2$ following Yang et al. This corresponds to all the pions coming from some object which decays into a cluster of pions $(N' = 1)$.

π^o, π^c Correlations

Since our present proposal plans to cover a large solid angle, we will neglect solid angle restrictions in the following discussion.

Because of the fact that the multi-γ production rate in p-p collisions could be quite small ($\sigma \sim 10^{-34}\text{cm}^2$), it is necessary to estimate the production rate of high multiplicity π^o events because of their prompt decay into 2 γ-rays they could be confused with monopole induced multi-γ events. We first must choose a reasonable model for pion production in p-p collisions since there is at present very little reliable data on high multiplicity π^o events. In general, if there is some simple dynamical mechanism operating in the production of pions (as we would certainly expect), then there would be strong correlations between the number of π^o and π^+, π^- mesons in a p-p collision. For example, if pions were produced via emission and decay of ρ mesons, there would be no way of producing a large number of π^o's with no accompanying charged pions. Therefore, to cut down the number of high multiplicity π^o events, the total charge of the collision process should be restricted to as low a value as possible (e.g. 2e). We next discuss the reduction in π^o background which ensues.

A logical extension of the multiperipheral model, constructed by Caneschi and Schwimmer,[12] is to correlate π^o, and π^+, π^- multiplicities by assuming the pions are produced by the decay of ρ and σ mesons emanating from the multiperipheral chain. The production of ρ's and σ's follows the Poisson distribution law. Under these assumptions, the cross section for producing N π^o mesons with no accompanying charged mesons is given by

$$\sigma = \frac{\sigma_o \left(\frac{1}{3}\right)^{N/2} \left(\frac{\bar{N}}{2}\right)^{N/2} e^{-3\bar{N}/2}}{\left(\frac{N}{2}\right)!} \qquad \text{(C 20)}$$

In Eq. (C.20), σ_o is the total inelastic cross section (~ 30 mb), $\bar{N}$ is the average π^o multiplicity (which is ~ 6 at ISR energies) and N is the number of π^o mesons produced in a specific event. Equation (C.20) is essentially the production cross section for N/2 σ mesons via the multiperipheral model multiplied by the probability for each of these σ's to decay into $2\pi^o$'s [~ $(1/3)^{N/2}$]. In Table C-1, the ratio σ_N/σ_o is calculated for several π^o multiplicities.

We now discuss an appropriate method of analyzing π^o, π^c correlations.

Charge Cluster Analysis (CCA)

This analysis is to be performed in the following way. We make a two-dimensional plot of n_c and n_γ. On this plot are put population densities of events. Now draw the line $2n_o = n_\gamma = n_c$ as reference line. If π^o, π^c production is uncorrelated then the population densities will fill the circular regions about $<n_\gamma> = 2<n_o> = <n_c>$ (see Fig. C-1). If there are strong n_o, n_c correlations as indicated by recent ISR and NAL data, then the population densities will fill elongated regions such as are shown in Fig. C-2. Now m, $\bar{m}$ annihilation will produce an excess of γ's. Therefore we would expect a cluster such as M shown on Figs. C-1 and C-2. We now note that in Fig. C-2, M lies in a region of lower population density than in Fig. C-1, and therefore will be more easily seen above the π^o background. The number on the figures represent possible population densities and are to be understood as guides which qualitatively represent π^o background. They are only qualitative and not the result of detailed calculations, however, they should show the trend. We see that charge clustering significantly aids the data analysis. We have also drawn the cluster for accidentals A, which even if large is far removed from M. We conclude that CCA is an important data analysis procedure.

Table C-1

$\frac{\sigma_N}{\sigma_0}$	N (No. of π^0's)
1.7×10^{-7}	12
3.0×10^{-10}	16
3.3×10^{-12}	20
2.5×10^{-14}	24
1.37×10^{-16}	28
5.7×10^{-19}	32
1.9×10^{-21}	36
5.0×10^{-24}	40
1.1×10^{-26}	44
2.0×10^{-29}	48
3.1×10^{-32}	52

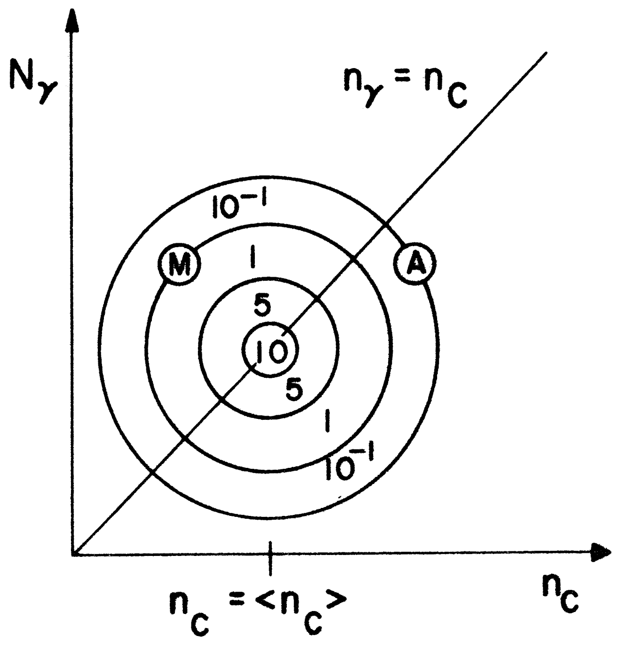


FIG. C1

CCA PLOT
-NO CORRELATIONS

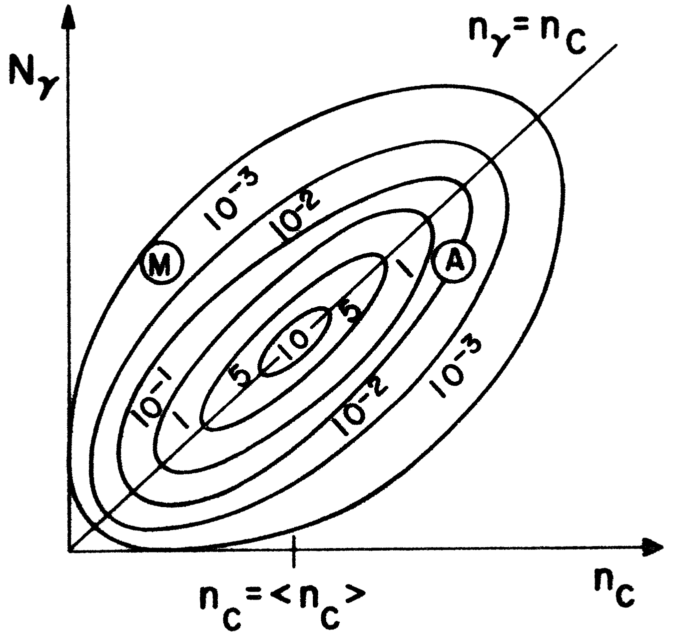


FIG. C2

CCA PLOT
-STRONG
CORRELATIONS

APPENDIX D

TESTS ON WIRE GROUPING IN A MULTIWIRE PROPORTIONAL CHAMBER

In order to obtain high detection efficiency and ease of operation, a wire chamber with an effective area of 1 m^2 and a wire spacing of 3 mm was constructed. Since the resolution in the space location of the multigamma events does not need to be high in an inherent center-of-mass system which is characteristic of a colliding beam machine, much economy can be realized if a number of signal wires can be grouped together, which reduces the number of amplifier + logic channels by a factor equivalent to the number of wires grouped together. Otherwise one such channel would be required by each individual wire. It was decided that an eight-wire grouping would be a good compromise in space resolution and an economy in the electronics systems' cost. Although a seven-wire grouping in a smaller size (50 cm x 50 cm) wire proportional chamber has been successfully used (with 5 mm spacing and a standard argon-methane gas mixture) at Brookhaven on another experiment,[7] and similar wire groupings have also been tried[8] in comparatively small chambers, no data seem to be available on multiwire grouping in large chambers such as those having a 1 m^2 effective area. A grouping together of such long wires would certainly present a considerably higher effective input capacity, thus reducing appreciably the chamber signal pulse-height. The main purpose of the present investigation on the wire grouping effect is to ascertain to what extent an eight-wire grouping in such a large-size chamber will affect the signal output; and what kind of simple and economic preamplifier with a sufficient gain to give an adequately safe signal-to-noise ratio, and to yield a 100% detection efficiency in the chambers, will be required.

A prototype multiwire proportional chamber was designed, constructed, and kindly provided by the CERN NP Division so that we could make a thorough investigation of this matter.

This chamber consists of one signal wire plane, with a wire spacing of 3 mm, and two high-voltage wire planes of 1 mm wire spacing on either side of the signal wire plane. Tests were performed on this chamber using radioactive sources and in a 6.4 GeV/c π^- beam. Different gas mixtures and two different types of preamplifiers were also tried.

Using a high-gain current amplifier specially designed[9] by the NP Electronics Group, and using the "magic gas" mixture in the chamber, a good high-voltage plateau curve was obtained (as shown in Fig. D1) with a 100% detection efficiency at 4 kV operating voltage. The chamber noise and noise pick-up problems at the PS have also been carefully investigated.

The main conclusions of these tests are that

a) The detection efficiency of the wire chamber filled with the "magic gas" and using a high-gain current amplifier is 100% at 4 kV;

b) the effects of the chamber noise and all other noise pick-ups can easily be eliminated;

c) the present design of the wire chamber as demonstrated by the tests performed with the prototype chamber has shown that it operates extremely well and remains stable over long periods of time.

We are deeply indebted to Prof. G. Charpak for many helpful suggestions and valuable discussions, and we are grateful to Dr G Muratori, Messrs F Doughty and J Guezennec for the design and construction of the prototype wire chamber, and to Messrs H Verweij and J Tarlé for the design and construction of the preamplifiers and helpful discussions We also wish to express our grateful thanks to the Rome-Rutherford Group in their pion beam, and for their generous help in many ways.

Voltage plateau of the 1 m^2 test chamber filled with magic gas

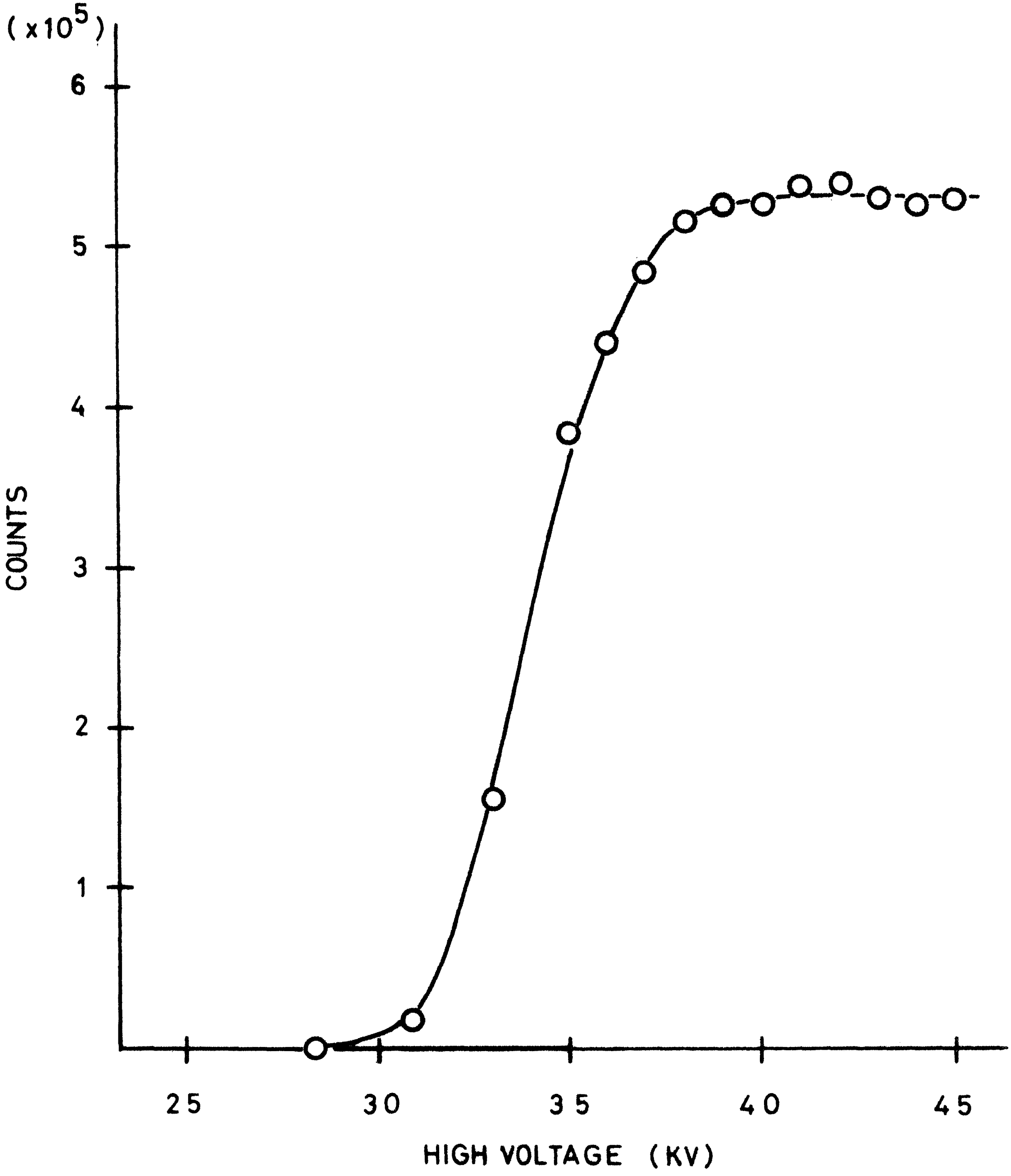


Fig D1