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Scientific Spokesman
Wit Busza
Massachusetts Institute of Technology-24-510
Cambridge, Massachusetts 02139
617-864-6900 ext. 7586

A STUDY OF THE AVERAGE MULTIPLICITY AND MULTIPLICITY DISTRIBUTIONS IN HADRON-NUCLEUS COLLISIONS AT HIGH ENERGIES

W. Busza, J.I. Friedman, H. W. Kendall and L. Rosenson

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ABSTRACT

In a simple counter experiment requiring about 40 hours of data taking time we propose to study the detailed shape of the multiplicity distribution for larger values of n and the average charged particle multiplicity in hadron-nucleus collisions at 100 and 200 Gev.

The results of the experiment should be a valuable input for comparison with theoretical models, in particular they should provide a sensitive test of whether multiparticle production in hadron-nucleon collisions proceeds through a one or two step process.

I. INTRODUCTION:

We propose to study the detailed shape of the multiplicity distribution for large values of n, and also its A-dependence in hadron-nucleus collisions at 100 and 200 GeV. Hadron-nucleon distributions will be extrapolated from the data. We further propose to compare distributions from pions, kaons and protons. Later if possible we would like to extend the measurements to higher energy.

a) Theoretical motivation:

The average number of particles produced in hadron-nucleon collisions increases logarithmically with energy. At NAL energies it is already ~7. It is thus not surprising that as higher and higher energies become accessible to experimental investigation, there is more and more theoretical interest in reactions with multiparticle final states. We shall not attempt to review theoretical models of multiparticle production since there are several excellent recent review articles in the literature[1]. Instead we briefly discuss characteristics of the models which motivate this proposal.

There are two categories of theoretical models of multiparticle production:

i) models such as the particle fragmentation model, multiperipheral model, bremsstrahlung analogy model or field theoretical model which assume that the final particles are produced in a one step process,

ii) models such as the diffraction excitation model and the one or two fireball models which assume that the multiparticle production mechanism is a two step process; first one or two compound systems are produced which then, in life-times long compared to the collision time, decay into the final multiparticle states.

All the present theoretical models have sufficient flexibility that, to the best of our knowledge, there is no one experimental measurement which can differentiate between them. In order to rule out many of the models it is necessary to study in detail various properties of multiparticle production. To illustrate this point we reproduce in table I a comparison of experimental predictions compiled by Frazer et al [1].

From this compilation it is apparent that the average multiplicity, $\langle n \rangle$, the multiplicity distribution P(n), in particular at large values of n, and partial cross-sections $\sigma(n)$ are a very useful filter. Here n is the number of particles produced in an inelastic collision and P(n) is the probability of producing n particles in any one inelastic collision.

Further, Dar and Vary [2] have pointed out to us that a study of the A-dependence of mean multiplicities in hadron-nucleus collisions is probably the only sensitive test which differentiates between the two general categories of theoretical models mentioned above. They point out that for category ii) the A-dependence should be energy independent whilst for category i) there should be a strong energy dependence, as illustrated in fig. 1.

b) Present knowledge of mean multiplicities and multiplicity distributions at high energy:

Figures 2 and 3 illustrate the present experimental knowledge of the mean charged multiplicities, $\langle n_{ch} \rangle$, and $P(n_{ch})$ at energies above 70 GeV. The Echo lake experiment [3] and cosmic ray emulsion exposures [4] have given some preliminary information on the A-dependence of $\langle n \rangle$. There is indication that $\langle n_{ch} \rangle \sim A^{0\cdot1}$ or $A^{0\cdot15}$. In summary, cosmic ray experiments have not yielded sufficiently accurate measurements of $\langle n_{ch} \rangle$, $P(n_{ch})$ or on the A-dependence of $\langle n_{ch} \rangle$ to differentiate between the various theoretical models.

c) The proposed experiment:

The partial cross-sections for various target materials, ranging from beryllium to uranium, will be measured at 100 GeV and 200 GeV. An extrapolation of the data to A=1 will yield distributions for hadron-nucleon collisions. The principle of the experimental technique proposed for the measurements is as follows:

Partially surround the target with Čerenkov counters and measure the spectrum of pulse heights in the counter. Adequate coverage is assured with a counter array of less than 4π owing to the pronounced forward peaking in the secondaries angular distribution. For relativistic particles the number of photons per unit path length in a Čerenkov radiator is independent of the momentum and mass of the particle, and thus the total number of photons radiated is proportional to the number of relativistic particles passing through the radiator, that is to the charged multiplicity of the interaction.

The simplicity of measurement allows data to be collected at rates greater than 10^4 interactions/sec, so that statistics are no problem in a run of even modest length, and all errors reside in systematic effects. On the other hand because of the rate at which data can be collected we feel that sufficient number of tests (e.g. runs with many target and counter thicknesses) can be performed to eliminate most of the systematic errors and obtain a reliable result. A 5% measurement of $\langle n_{ch} \rangle$ should be possible. In addition, should particle identifying Čerenkov counters in the beam line be available at the time of measurement, we would be able to investigate whether P(n) is a function of the incident particle. It will be very interesting to see if for all values of n, P(n) is identical for pions, kaons and protons, as commonly believed.

Comparing this technique with bubble chamber measurements we find that because of high statistics we can study $P(n_{ch})$ for much larger value of n (up to ~ 30)

and also determine the A-dependence of $\langle n_{ch} \rangle$ for a very small fraction of the machine time and without the engineering effort a bubble chamber measurement of this kind could involve. The present experiment can contribute results of importance substantially earlier than any by a high priority specially dedicated bubble chamber program.

II. Description of Experimental Method:

a) Geometry of detector:

Fig. 4 illustrates the detector arrangement. The beam is defined by two trigger counters T_1 and T_2 and by a veto counter V. The target is placed at the center of a box made of Čerenkov counters $\check{C}_1$, $\check{C}_3$-$\check{C}_6$. Targets will range from 3 cms of Be to 0.4 mms of U.

Particles produced up to angles of 30° pass through a high quality Čerenkov counter Č1. It consists of a polystyrene radiator (which has an optimum ratio of light output to radiation length) whose thickness is adjusted such that the path of the particle in the radiator is independent of angle and $\approx$ 1 cm. The intensity of Čerenkov light produced in the radiator is measured, with high efficiency, using a RCA 8854 photomultiplier as shown. Particles produced at angles of more than 30° are detected by four separate threshold Čerenkov counters $\check{C}_3$ - $\check{C}_6$.

$\check{C}_2$ is used to measure background due to high energy γ-emission from excited nuclei in the target. It also samples any particles emitted backwards in the laboratory.

b) Electronics and trigger logic:

An incident particle is defined by

- i) T_1 and T_2 both have a coincident signal of amplitude $\leqslant 1.5$ times minimum ionizing.
- ii) No other particle in T_1 or T_2 during 10ns preceeding or 10ns following the T_1T_2 signal.
- iii) No signal in V during the above 20ns interval.

These three conditions insure that only one incident particle enters the equipment during its sensitive time.

Whenever an incident particle trigger is received the pulse height of č1 is stored in one of the quadrants of a 1024 channel pulse height analyser. The quadrants are designated by the following conditions:

1: No signals in $\check{C}_3 - \check{C}_6$
2: signal in one of $\check{C}_3 - \check{C}_6$
3: signals in two of $\check{C}_3 - \check{C}_6$
4: signals in at least three of $\check{C}_3 - \check{C}_6$

Following a trigger the electronics is gated off for a period 10 μsec, corresponding to the maximum dead time of the analyser.

Special runs to study very high multiplicity interactions would also be carried out; only events with large pulse heights in č1 would be stored.

Throughout the experiment the coincidence rate of $\check{C}_2$ with the beam trigger will be monitored.

The system should be capable of handling beam rates of up to 5×10^7 particles/sec and collecting data at up to 5×10^4 interactions/sec.

c) Properties of the Čerenkov counters:

A crucial part of the detector system is the Čerenkov counter č1, and it is important to consider what limitations it imposes on the measurements.

i) Minimum momentum of detected particles:

Fig. 5 shows the number of photons radiated in č1 by particles of different momenta. It can be seen that č1 is sensitive only for particles of $\beta > 0.7$ (e.g. $P_{\pi} \geqslant 140$ MeV/c). The cut-off in momentum is higher for kaons and protons however; since the major contribution to multiplicity is expected to be from pions, this should not introduce major systematic errors.

ii) Resolution:

In the range $3500\ \text{Å} < \lambda < 5000\ \text{Å}$ approximately 200 photons will be radiated in č1 by each relativistic particle. We estimate that because of the efficient light collecting system these will give rise to $\geqslant 30$ photoelectrons. Based on this number we estimate the resolution of č1 to be as shown in fig. 6. We have included in the resolution curve the tail due to δ- rays and due to hadron interactions in the radiator. The experiment would still be feasible with a resolution worse by a factor two, as observed [5] in Čerenkov counters with light collected in a less optimum configuration.

III. Discussion of Experimental Problems, Choice of Target Thickness, etc.

In designing the experiment we have considered the following effects which could distort the results:

a) loss of prongs with production angle $> 30^{\circ}$

b) loss of non-relativistic prongs

c) contamination of data by high energy gamma rays from the decay of excited target nuclei.

d) hadron showers in the target and Čerenkov counters

e) electro-magnetic showers from $\pi^{0} \to 2\gamma$.

f) distortion of pulse height spectra due to resolution of č1.

A discussion of these six effects follows:

a) & b) Using Cocconi's [6] semi-empirical formula

$$\frac{d^2N}{dp_\perp \, dp_\parallel} = \frac{B p_\perp}{b^2} e^{-p_\parallel/G} e^{-p_\perp/b}$$

with

$$BG = \langle n \rangle$$

$$BG^2 = \frac{1}{2} E_{\mathrm{INCIDENT}}$$

$$b = 0.22 \ \mathrm{GeV}/c$$

and assuming all prongs are pions, we estimate that for $E_{\mathrm{incident}} \gtrsim 100$ GeV

i) probability of losing a prong because of β cut-off is $\lesssim 1.5\%$

ii) probability of production angle $> 30°$ is $\lesssim 10\%$; thus with 4 counters covering angles $\gtrsim 30°$ the probability of two prongs hitting the same counter and thus being lost is $\lesssim 0.1\%$. In any case should this estimate be optimistic it will reflect in the $C_3 - C_6$ rates.

c) An excited nucleus can emit a γ of energy up to ~8 MeV in times short compared to the resolving time of the detector. These γ's can in principle, produce relativistic e^+e^- pairs in $\check{c}1$. All estimates indicate the effect to be negligible. As a precaution it will be measured using $\check{C}_2$, as described earlier.

d) & e) Approximately one third of the particles produced will be π^0's. These decay into 2 γ's which can shower both in the target and in $\check{c}1$. In addition to the electro-magnetic showers, the produced particles can further multiply in subsequent collisions.

For these reasons it is necessary to minimize the number of collision and radiation lengths in the target and in č1.

Photon statistics put a practical limit on the thickness of č1 at about 1 cm. Polystyrene is chosen to minimize the number of radiation lengths in the radiator. The material in č1 dictates the minimum thickness of targets for a meaningful target-in/target-out rate. Table II lists optimum target thickness, together with estimates of contamination due to electromagnetic and hadronic showers. Most of these systematic effects can be corrected for by extrapolating to zero thickness data obtained with several targets and radiators of different thickness.

The effect of the finite resolution of č1 is to smear out the final spectrum. In general clear peaks at different values of n will not be visible. Fig. 7 illustrates the results that will be obtained from a 2 cms Be target if in inelastic collisions the multiplicity has a poisson distribution with $\langle n \rangle = 6$.

In every run the peaks due to uninteracted particles and pseudoelastic scatters will automatically calibrate the resolution and pulse height scale of the complete system.

Taking all the above effects into consideration we estimate that the experiment is capable of measuring the charged prong cross-section, $\sigma(n)$, to $\sim\pm$ 10% and $\langle n_{ch} \rangle$ to $\sim\pm$ 5%. It should be noted that even prior to extrapolating the data to zero counter and target thickness, the measured $\langle n_{ch} \rangle$ will exceed the correct value by only $\sim$ 15%.

IV. Plan of Measurements and Running Time Estimates:

For the A-dependence study we plan to take data for three thicknesses each of 8 target materials (Be, C, Al, Cu, Sn, Pb, U and No-target) and each for two thicknesses of Čerenkov counter č1. That is a total of 48 runs at each of two energies, 100 and 200 GeV.

In order not to be limited by statistics each run should contain $\gtrsim 10^6$ interactions, which corresponds to 10^8 incident particles for a 1% collision length target.

Beam intensities in the range $5 \times 10^4 - 5 \times 10^7$ particles/sec would be suitable for this part of the experiment. At 10^5 particles/sec a typical run would take less than 15 mins.

In addition we would like to take a few one hour runs with $\sim 10^7$ particles/sec on Be to look at distributions at very large values of n ($\lesssim$30).

In total we request 40 hours of data taking time, 20 hours at 100 GeV and 20 hours at 200 GeV. In addition we would require about 20 hours of setting up time. Since the beam requirements are so loose, all of the setting up and probably most of the data could be taken whilst the beam itself was being set up and tested for other experiments. Before going to NAL we plan to test the technique at one of the BNL beams.

The 2.5 mr beam, where the group is participating in an already approved experiment and which offers the opportunity of using incident particle identifying Čerenkov counters, would probably be the most suitable location for the experiment.

If approved, we could be ready in 2 months.

References

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4. Reference to cosmic ray studies of multiplicities in hadron-nucleus scattering can be found in M. Mięsowicz, Progress in Elementary particles and cosmic ray physics, Vol X. 1971 p.101; also in IZ. Artykov et al NP B6, 11, 1968.
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7. W. Galbraith et al, BNL 11598; G. Bellettini et al. NP 79, 609, 1966.
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9. T. Gemesi et al., paper 380 Amsterdam Conference, July 1971.
10. S. N. Gamgul et al., Phys. Lett. 39B, 632, 1972. In this paper they calculate $\langle n_{\pi\pm} \rangle$ from the ISR data on γ-production. When plotting thier results we assume $\langle n_{ch} \rangle = \langle n_{\pi\pm} \rangle + 1.4$
11. N. A Dobrotin et al, Canadian J. of Phys. 46, S675, 1968.

FIGURE AND TABLE CAPTIONS

Table I: Comparison of experimental predictions of various theoretical models, compiled by Frazer et al (1).

Table II: Optimum thickness of targets and physical properties of target materials. Collision length calculated from inelastic proton-nucleus cross-sections (7). In calculating the additional tracks in Č1 due to electro-magnetic and hadronic showers the following assumptions were made:

i) thickness of Č1 = 1 cm

ii) $\langle n_{\pi^0} \rangle = \frac{1}{2} \langle n_{ch} \rangle_{\text{primary interation}} = 3$

iii) $\langle n_{ch} \rangle_{\text{secondary interactions}} = 4$

Fig. 1: Dar and Vary's (2) predictions of the energy and A-dependence of t mean multiplicity in hadron-nucleus collisions, assuming the part production nechanism is a one step process (see text). For a two step process they predict an A-dependence which is indepen of energy.

Fig. 2: Compilation of data on the mean number of charged particles produced at various energies.

Fig. 3: Charged prong multiplicity distributions measured at Echo lake (3) with cosmic rays of 203 Gev mean energy.

Fig. 4: Geometrical arrangement of detector system.

Fig. 5: β dependence of the photon yield in a 1cm polystyrene čerenkov detector. The curve gives the number of photons which are not absorbed in the radiator or photomultiplier windows, ie those with 3500 Å $< \lambda <$ 5000 Å.

Fig. 6: Calculated resolution curve of Č1 assuming the mean number of photo electrons is 30. Tails due to δ -rays of energy $\geqslant$ 0.75 Mev and due to hadron interactions in Č1 have been included.

Fig. 7: An example of data that will be obtained from a few minute run on 2c Be target. In simulating this data it was assumed that i) the sing particle resolution is as in Fig. 6, ii) that in every inelastic collision there are produced two protons plus a poisson distribution of pions with $\langle n_{\pi^\pm} \rangle = 6$.

Summary of models, types of experiments, and the predictions made by various models.

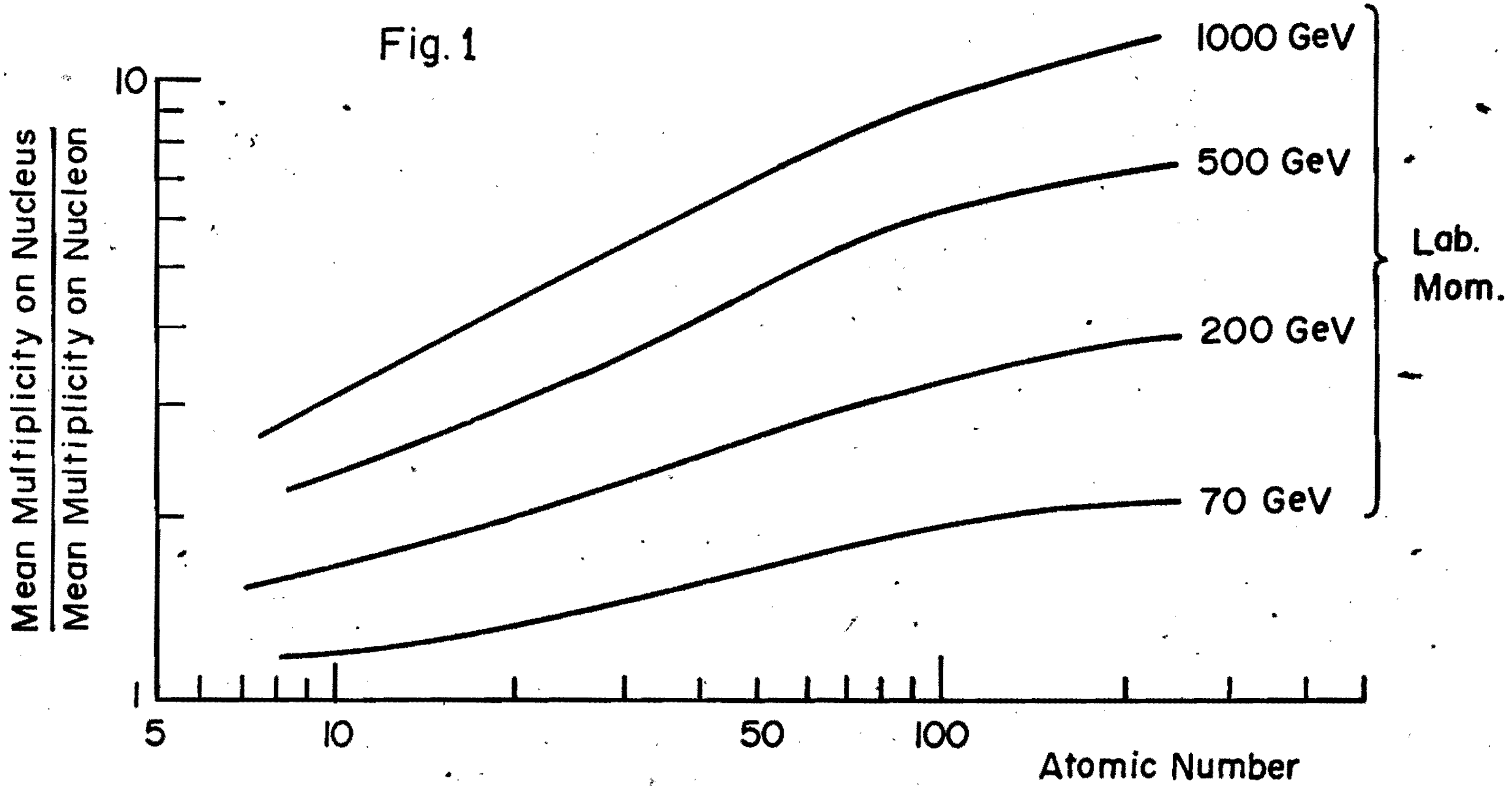
	Model					
Experiment	(a) Mueller analysis	(b) Multiperipheral	(c) Diffractive fragmentation	(d) Statistical thermodynamical	(e) Cheng-Wu	Beam energy region
(1) Average multiplicity $(n(E))$	$(n(E))=a \ln E+b$		No prediction; can accommodate any reasonable behavior	(n) grows faster than $\ln E$	$(n)\propto s^a$, $a>0$	$E>E_p$
(2) Multiplicity distribution $P(n)$	No prediction	Roughly Poisson	$P(n)\propto n^{-2}$ if $(n)\propto \ln E$	No prediction	?	$E>E_p$
Partial cross sections $\sigma_n(E)$	No prediction	$(K \ln s)^{n-2} s^{-K}/(n-2)!$, $K=2-2\alpha_M(0)\approx 1$	Constant	No prediction	?	$E>E_p$
(3) One-particle spectra: limiting fragmentation?	Yes	Yes	Yes	Yes	No; $\rho(q)\propto s^a$	$E>E_f$
(4) One-particle spectra: central plateau?	Yes	Yes	No prediction; can be accommodated	Not in present version; can be accommodated	Yes	$E>E_p$
(5) One-particle spectra: factorization in fragmentation regions	Yes	Yes	?	No prediction	?	$E>E_f$
(6) One-particle spectra: factorization in plateau region	Yes	Yes	No	No prediction	?	$E>E_p$
(7) Two-particle spectra: correlations?	Only short-range correlations, if Regge poles$\gg$Regge cuts.		No prediction	No prediction	?	$E>E_f$
(8) Diffraction dissoc. into high missing mass	$\propto g_{PPP}^2$, triple Pomeron coupling	g_{PPP} small or zero	"Favored"	No prediction	?	
(9) $\sigma_{tot}(E)$	$\sigma\propto$ const. or $s^{-\epsilon}$, $\epsilon\ll 1$.		Constant	No prediction	$\sigma\propto \ln^2 s$	

TABLE I

Table II

Target Material	A	Z	Coll. length gms/cm²	Rad. Length gms/cm²	Approx. Optimum Thickness		Inelastic Collisions in Target Per 10^6 inc. Particles	Additional Tracks in Č1 Due to Showers in Target and Č1	
					CMS	gms./cm²		E. M.	Hadronic
Be	9.01	4	66	65.7	1.3	2.39	3.6×10^4	5%	10%
C	12.01	6	94	42.4	1.3	2.0	2.1×10^4	6%	8%
Al	26.98	13	119	24.0	.70	1.89	1.6×10^4	9%	7%
Cu	63.54	29	152	12.0	.12	1.07	7.0×10^3	10%	5%
Sn	118.7	50	182	8.89	.11	.81	4.5×10^3	10%	5%
Pb	207.2	82	209	6.52	.06	.68	3.3×10^3	11%	5%
U	238.1	92	219	6.13	.04	.75	3.4×10^3	13%	5%
NO TGT. ONLY Č1	≈ 12	≈6	≈ 55	≃ 43.4	1	1.05	1.9×10^4		

Fig. 1



10
1
Mean Multiplicity on Nucleus / Mean Multiplicity on Nucleon
5
10
50
100
Atomic Number
1000 GeV
500 GeV
200 GeV
70 GeV
Lab. Mom.

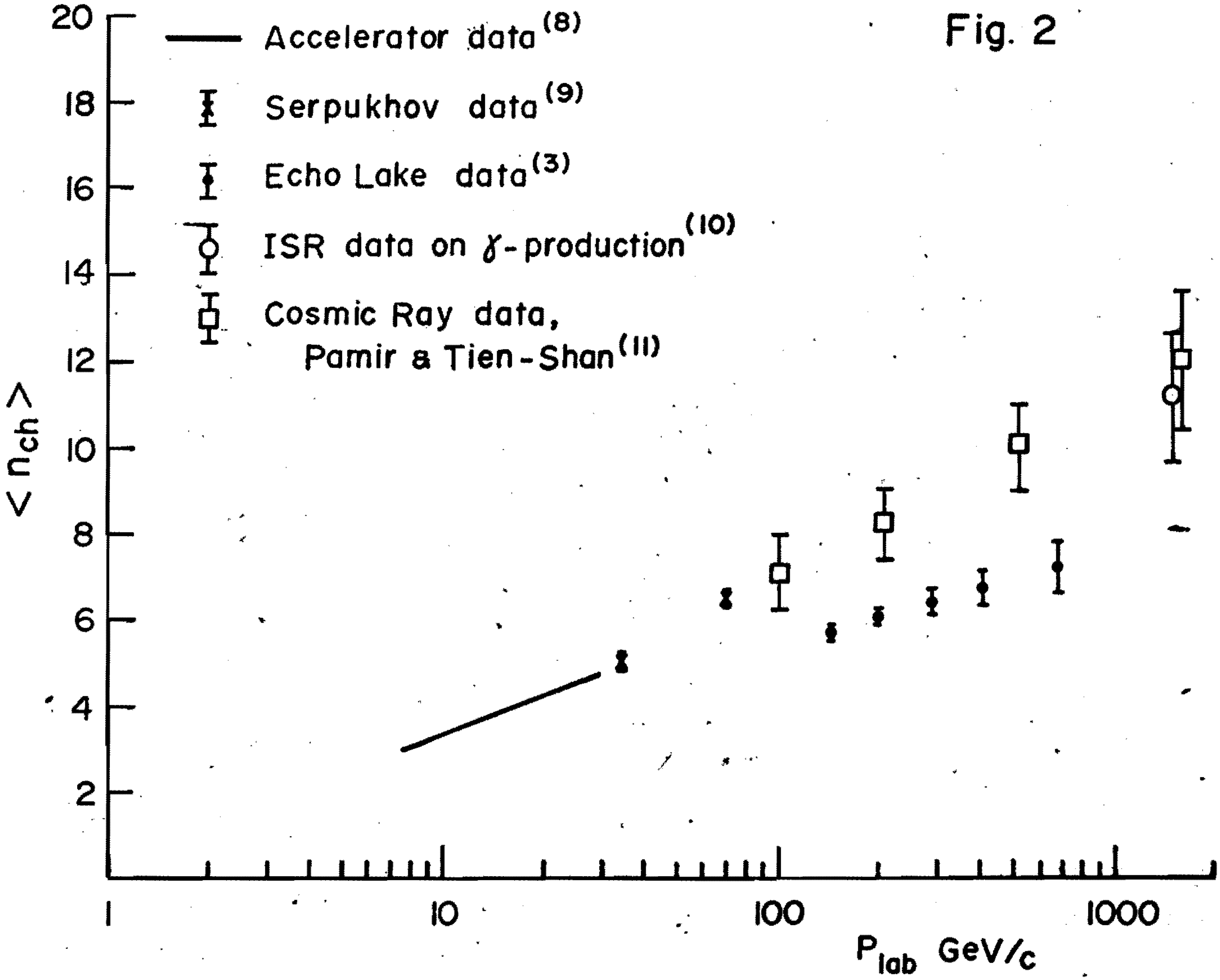


Fig. 2
Accelerator data(8)
Serpukhov data(9)
Echo Lake data(3)
ISR data on γ-production(10)
Cosmic Ray data, Pamir & Tien-Shan(11)
$\langle n_{ch} \rangle$
20
18
16
14
12
10
8
6
4
2
1
10
100
1000
P_{lab} GeV/c

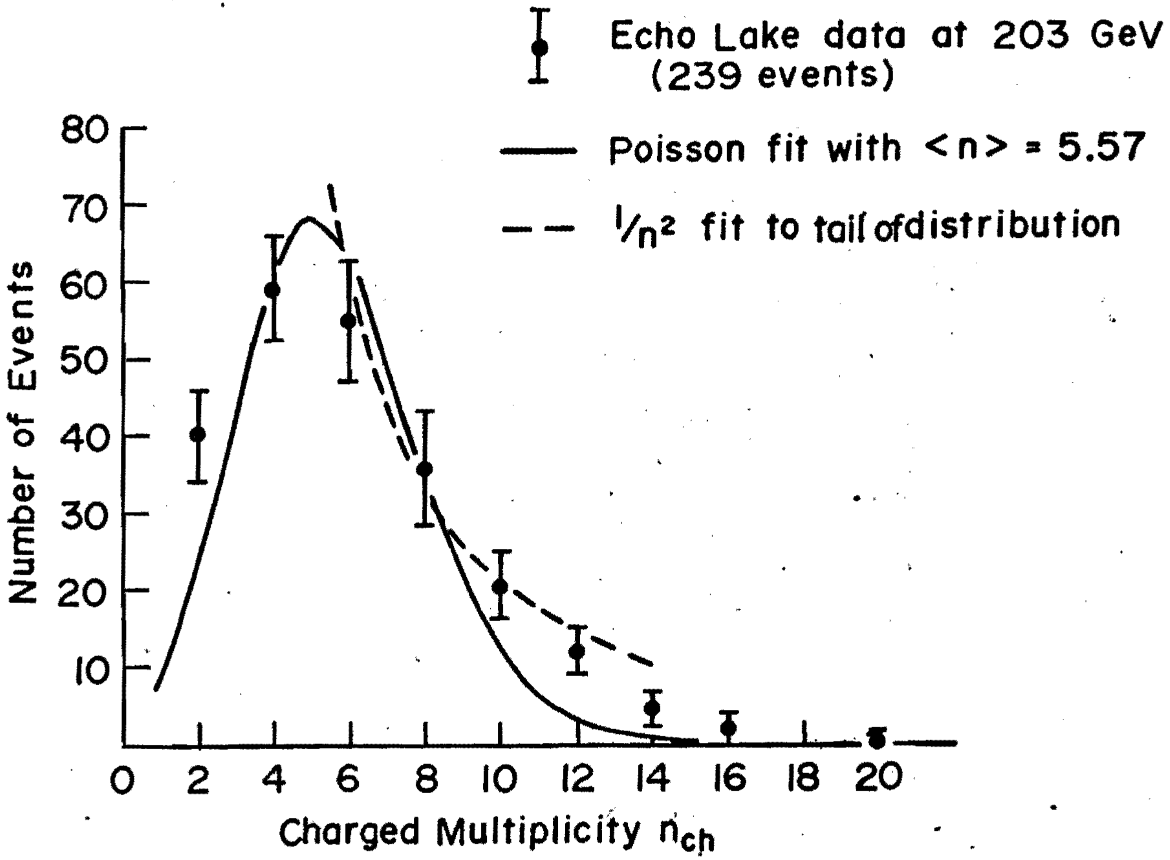
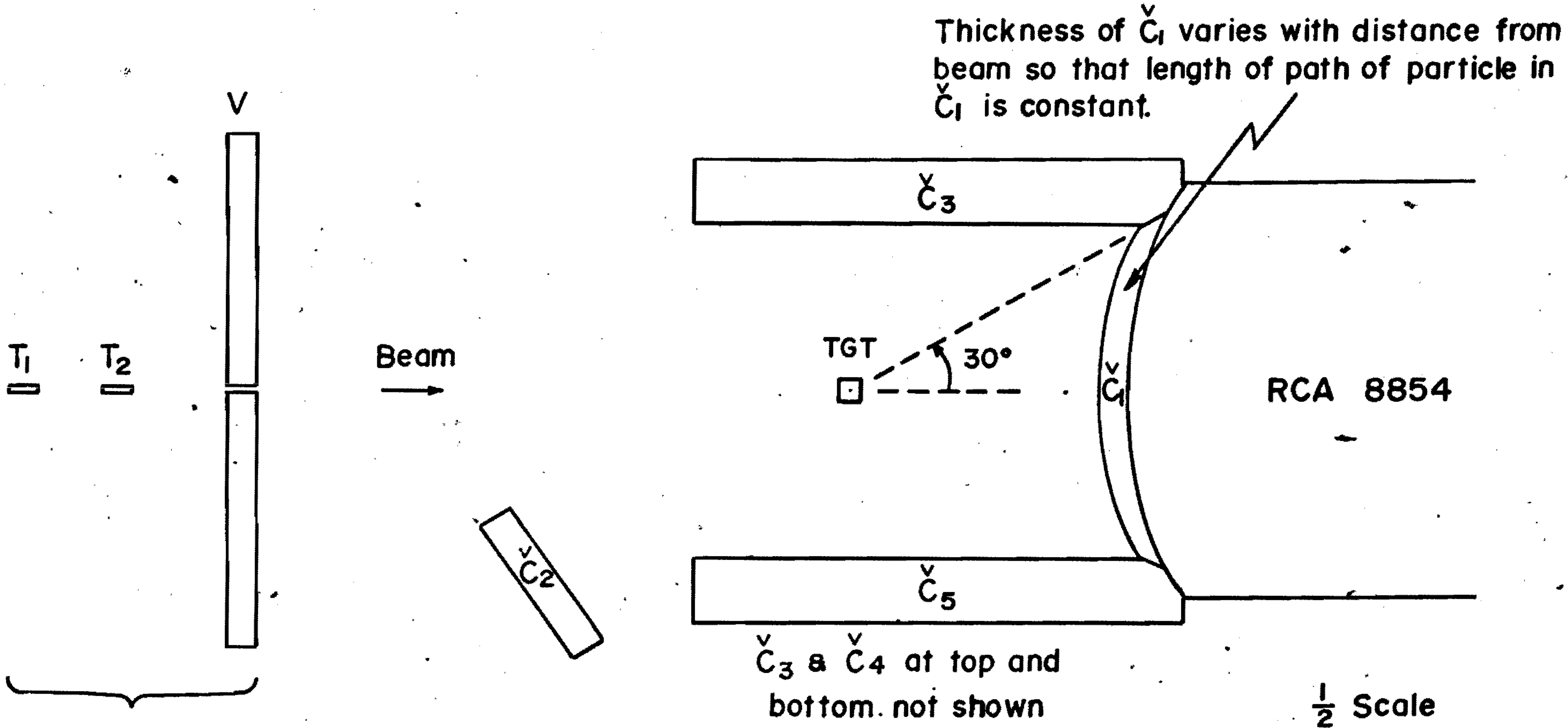

Echo Lake data at 203 GeV (239 events)
Poisson fit with <n> = 5.57
1/n² fit to tail of distribution
Number of Events
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
20
Charged Multiplicity n_ch

Fig.3

T_1, T_2 & V : Scintillation Counters
$\check{C}_1$ & $\check{C}_2$: Čerenkov Counters with Polystyrene Radiators
$\check{C}_3 - \check{C}_6$: Čerenkov Counters with Pilot 425 Radiators



Thickness of $\check{C}_1$ varies with distance from beam so that length of path of particle in $\check{C}_1$ is constant.

$\check{C}_3$ & $\check{C}_4$ at top and bottom. not shown

$\frac{1}{2}$ Scale

Rel. Position not to scale.
Counters placed few meters up stream

Fig. 4

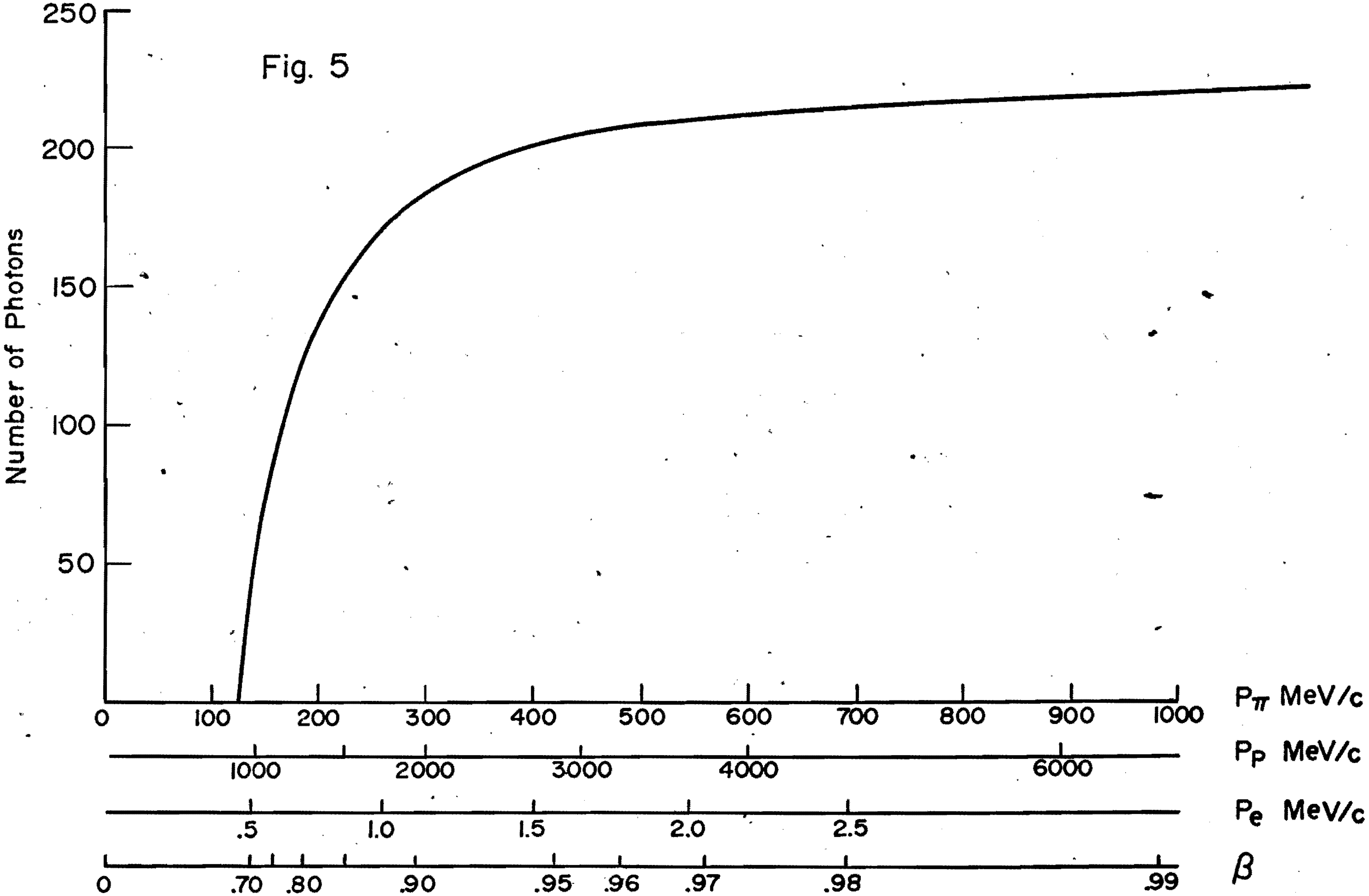
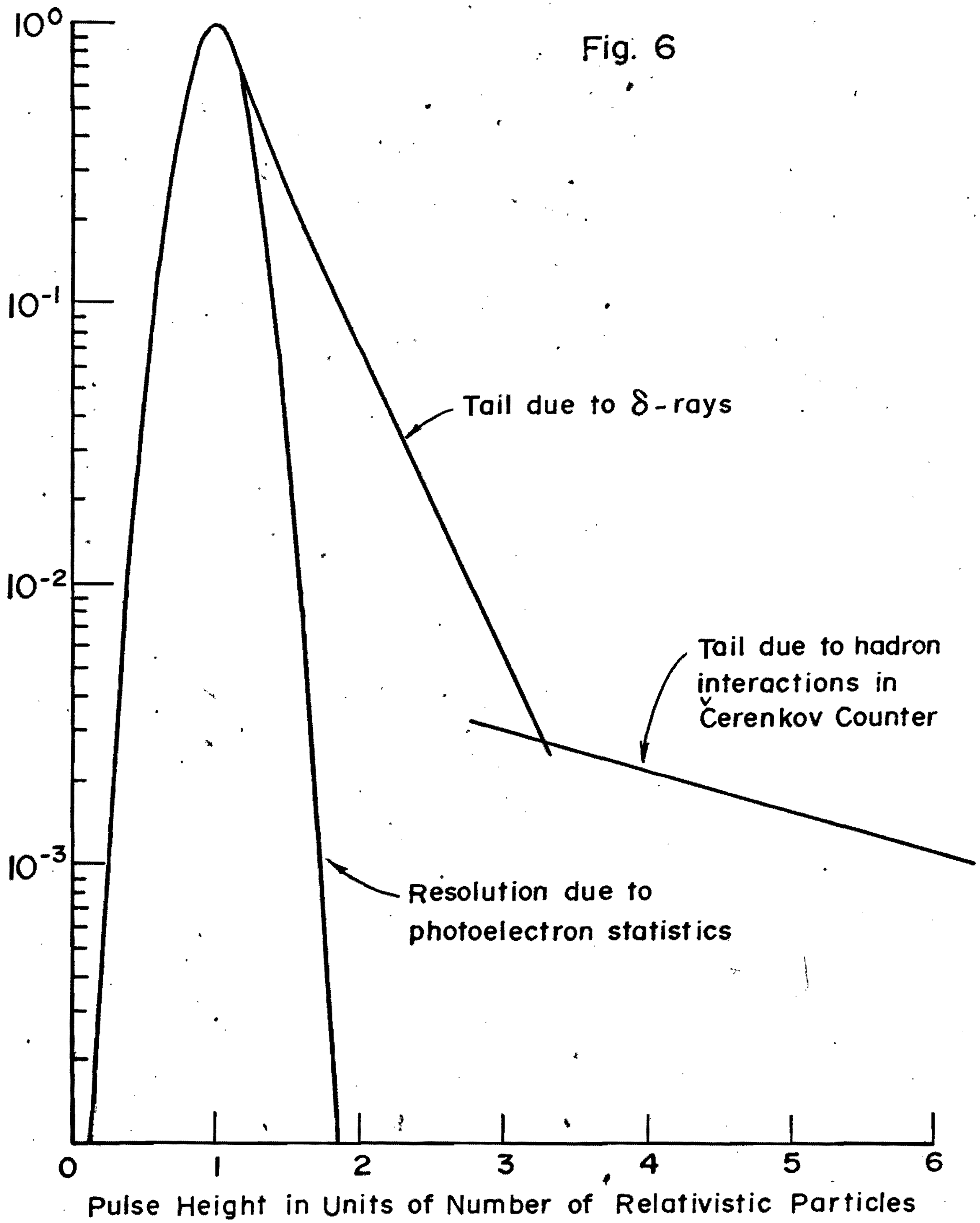


Fig. 5

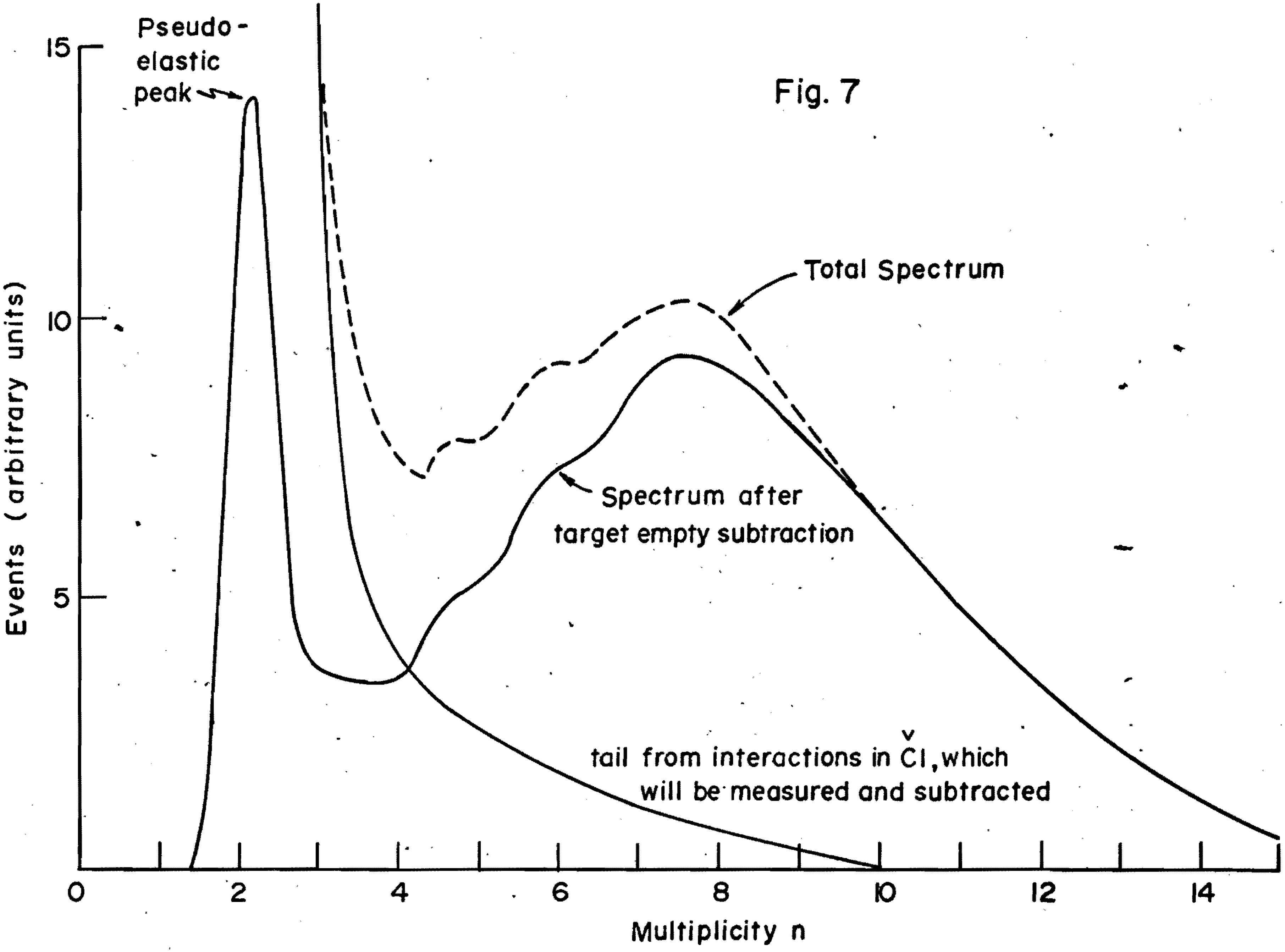
Number of Photons
250
200
150
100
50
0
100
200
300
400
500
600
700
800
900
1000
P_π MeV/c
1000
2000
3000
4000
6000
P_p MeV/c
.5
1.0
1.5
2.0
2.5
P_e MeV/c
0
.70
.80
.90
.95
.96
.97
.98
.99
β

Fig. 6



10⁰
10⁻¹
10⁻²
10⁻³
Tail due to δ-rays
Tail due to hadron interactions in Čerenkov Counter
Resolution due to photoelectron statistics
0
1
2
3
4
5
6
Pulse Height in Units of Number of Relativistic Particles

Fig. 7



Pseudo-elastic peak
Total Spectrum
Spectrum after target empty subtraction
tail from interactions in ČI, which will be measured and subtracted
Events (arbitrary units)
15
10
5
0
2
4
6
8
10
12
14
Multiplicity n