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ABSTRACT

An analysis is presented on the nuclear interactions (incident energy $\geqslant$ 100 TeV) observed by the emulsion chamber exposed at Mt. Chacaltaya and Norikura. Measurements are made on transverse momentum, and energy spectrum of γ-rays (π^{0}-mesons) and secondary interactions (surviral nucleons, charged π-mesons, ...).

The inelasticity of nucleons and mesons and the transverse momentum of a fire ball are derived from the above results. Consistencies are examined among the results of the present work and of others in ref. 1.

* * *

INTRODUCTION

The emulsion chambers exposed at high mountain altitudes (Norikura 2800 m and Chacaltaya 5200 m) provide means to observe atmospheric nuclear interactions produced by cosmic ray nucleons of energy $10^{14} \sim 10^{15}$ eV. The design of the emulsion chamber here analyzed is shown in Fig. 1, some details will be found in reference 1.

As was already reported,[2] π^{0}-mesons produced by the interaction are detected as a group of γ-rays with parallel direction (called as a γ-ray family). Since the thickness of the emulsion chambers in the present analysis is large about 2 nuclear mean free path, one is able to observe produced particles of the other kinds through their nuclear interaction occuring in the chamber (called as a Pb jet). The detection probability of the nuclear particles is 70%. In this way the chamber provides information on individual values of partial location and energy of almost all of produced particles.

SELECTION OF THE EVENTS

For the present analysis on nuclear interactions, we selected those events with production hight less than 1 km in order to avoid complication in the interpretation of the events. Further we imposed a restiction on total liberated energy to minimize an effect of the detection thresholds.

Generally the criterion adopted is

$$\sum E_{\gamma} + 3\left(\sum (E_{Pb}) - E_{Pb_1}\right| = 20 \text{ TeV} \;, \qquad [3]$$

E_{γ}, E_{Pb} and E_{Pb_1} being energy of γ-rays, Pb jets and the highest energy of Pb jet, and summation is made over all concerned particles in a family with energy greater than 2 TeV. The total number of thus selected events is 13. Other criterion is adopted for a certain analysis, if it is necessary.

IDENTIFICATION OF PARTICLES

π° mesons are identified through coupling of a γ-ray pair. It is suggested from studies on mechanisms of the multiple production that the surviving nucleon should be distinguished from other produced particles, a large part of which are believed to be originated from a fire ball.

As a working hypothesis for the present analysis, we assume that the surviving nucleons are responsible to the highest energy Pb jet. Further, all of produced particles are assumed as π-mesons and contribution of K-mesons are neglected for the moment. Examination on consistencies among the results thus obtained and other information will be carried out later to see validity of the above assumptions.

TRANSVERSE MOMENTUM MEASUREMENT

(i) $P_{T\gamma}$ and $P_{T\pi^\circ}$. The histogram of γ-ray transverse momentum, $P_{T\gamma}$, is given in Fig. 2a. The average value is 250 ± 30 MeV/c in agreement with previous measurements.[2] The average transverse momentum of π°-mesons is $\langle P_{T\pi o} \rangle = 530 \pm 50$ MeV/c. Both $P_{T\gamma}$ and $P_{T\pi o}$ are measured in reference to the energy-weighted center of γ-rays.

(ii) P_{TPb}. The distribution of the transverse momentum of Pb jets, P_{TPb}, constructed taking their energy as its radiated energy itself, E_{Pb}, and assuming the same center axis of the events as the above. Fig. 2b shows the two P_{TPb} distribution, one for the highest energy Pb jets in families, P_{TPb1}, and the other for the rest of Pb jets, P_{TPb2}. The two distribution show appreciable difference. The lower energy Pb jets are, by the assumption, considered due to charged π-mesons, so that their P_T value can be compared with that of π°-meson.[4]

Expressing a fraction of energy transferred to γ-rays in the π-meson interactions as k_γ, one has now,

$$\langle k_\gamma \rangle = \langle P_{Tb2} \rangle / \langle P_{T\pi o} \rangle = 0.4 \pm 0.1 \ .$$

(iii) P_{TF}. As a measure of the transverse momentum of emitted fire balls, the following quantities are constructed. It is transverse momentum of the center of mass of all emitted π°-

mesons with respect to direction of the survival nucleon, which is by assumption identified as the highest energy Pb jet. Expressing the quantity as P_{TF}, one has

$$\langle P_{TF} \rangle = 3.9 \pm 0.6 \text{ Bev/c}$$

and its distribution is shown in Fig. 3. [5] Some detailed discussions on P_{TF} will be made in Appendix 1.

OBSERVATION OF RESIDUAL NUCLEONS

All of the observed Pb jets are plotted in the diagram shown in Fig. 4, with its energy E_{Pb} and the total γ-ray energy of the family

$$\sum E_{\gamma}.$$

Since the highest energy Pb jets are assumed to be survival nucleons, one has now examples of successive nucleon interaction. Expressing the radiated energy of the first and the second interaction by E_1 and E_2, one has in our case, $E_1 = \sum E_{\gamma}$ and $E_2 = E_{Pb1}$. The frequency distribution of the events having a certain value of E_1/E_2 reflect the character of the inelasticity of nucleon at the time of collisions.

Information on inelasticity K of the nucleon interaction are now derived from the E_1/E_2 distribution, eliminating detection bias and taking the fluctuation effect into account. Details of the method in relating the analysis of the events of sucessive interactions is given in App. 1 of ref. 1. The average value is given by

$$\langle K \rangle = \sim 0.5 \text{ .}$$

CHARGE TO NEUTRAL RATIO OF SECONDARY PARTICLES

Now let us compare the production rate of charged and neutral π-mesons in nuclear event. Their total liberated energies are derived, by using

$$\sum E_{\pi o}$$

and

$$\sum E_{\pi^{+}} = \frac{C}{k_{\gamma}} \left[\sum (E_{Pb}) - E_{Pb_1} \right] = \frac{C}{k_{\gamma}} \sum{}' E_{Pb} ,$$

where E_{Pb_1} is the highest energy among the Pb jets in a family. C is a correction factor of over-all detection efficiency. Fig. 5 shows the diagram of $\sum E_{\pi o}$ and $\sum E_{\pi \pm}$ for the detected events. One sees that our detection is in favor of cases with large $\sum E_{\gamma}$ as is expected.

To see consistencies with the assumption of secondary particles being mainly π-meson, we assumed $\sum E_{\pi o} = (1/2) \sum E_{\pi \pm}$ and imposed the criterion on $\sum E_{\pi o}$ as well as $\sum E_{\pi}$ to eliminate the detection bias. Number of produced π°-mesons and $\pi^{\pm}$-mesons are constructed for the 5 events satisfying the criterion and are presented in Fig. 6 in normalized energy scale $E/(\sum E_{\gamma} + 3\sum{}' E_{Pb})$. As is seen, the result is consistent with the view that the produced number of $\pi^{\pm}$-mesons is about twice of π°-mesons if one takes the value of $k_{\gamma} = 0.4 \pm 0.1$.

CONSISTENCY AMONG RESULTS FROM VARIOUS METHODS

The logical relations are shown in Fig. 7 between various method of analysis in the project. It is now important to examine validity of the two assumptions made throughout the present analysis.

i) survival nucleons to be the highest energy jets. If the assumption is not correct, the nucleon inelasticity will become larger than the derived value. Large observed value of P_{TF} suggests that particles producing the highest energy Pb jets do not belong to a fire ball. This as well as the values of inelasticity derived from argument of the observed absorption mean free path and interaction mean free pathgives a support for the assumption.[6]

ii) π-mesons being a major part of secondary particles. Let $\mathcal{E}$ be the ratio of Pb jets from K-meson to those from π-mesons. Then the result of P_{TPb} analysis is expressed as,

$$k_\gamma = \frac{k_\gamma(\pi)}{1+\mathcal{E}} \left(1 + \mathcal{E}\,\frac{k_\gamma(K)}{k_\gamma(\pi)}\;\frac{P_T(K)}{P_T(\pi)}\right)$$

and the result on the charge-neutral ratio is,

$$(1+\mathcal{E})\;\frac{k_\gamma(\pi)}{k_\gamma} = \alpha$$

where α and k_γ are experimentally observed quantities, $k_\gamma =$ $= 0.4 \pm 0.1$ and $\alpha = 1 \pm 0.3$. The inelasticities, $k_\gamma(\pi)$ and $k_\gamma(K)$, and the transverse momenta, $P_T(\pi)$ and $P_T(K)$, can be determined as a function of assumed value of $\mathcal{E}$. It is reminded here that there are informations showing small value of $\mathcal{E}$ from other method of analysis.[7]

Then the second equation shows that the value of $k_\gamma(\pi)$ will not be affected, and the first equation shows

$$\frac{k_{\gamma'}(K)\ P_T(K)}{k_{\gamma'}(\pi)\ P_T(\pi)} \sim 1$$

under the same condition.

CONCLUSION

The following are summaries of the new results obtained by the present analysis on atmospheric nucleon interaction of incident energy 100 ~ 1000 TeV.

(i) Nucleon inelasticity K = ~ 0.5, which gives $k_{\gamma'} \sim 1/6$. For the π-mesons, one has $k_{\gamma'} = 0.4 \pm 0.1$, different from $K_{\gamma'}$.[8]

(ii) Transverse momentum of a fire-ball, $P_{TF} = 3.9 \pm 0.6$ GeV/c, shows the residual nucleon are aparted from the fire ball.

(iii) Velocity of survival nucleons can not be far larger than that of the highest energy π-mesons.

(iv) A consistency can be seen between the observed data and the assumption of π-meson being a main part of secondary particles.

At the end, a short description will be made on the two events of some interest. The first event (Fig. 8a) shows existence of three π°-mesons with small relative motion with each other. Transforming back to their center of mass system, one finds that the Q-value is as small as about 130 MeV. One can interpret this as decay of a η° meson into 3 π°-mesons. The second event (Fig. 8b) is a similar example. Here one sees close association of three Pb jets, which may be interpreted as due to an excited baryon or meson.

* * *

APPENDIX I

P_{TF} distribution

There are two corrections to be made on P_{TF} obtained by the described method. One is contribution of charged π-mesons, which will make the P_{TF} value larger. The other is an effect introduced by assuming the incident direction of motion as that of the highest Pb jet, and it will make P_{TF} value smaller. These two effects, both being an order of unity and having opposite signs, will not affect the result in serious way.

Let us now see whether the observed values of P_{TF} is significantly larger than values expected from simple statistical summation of P_T of individual produced π°-mesons. For this purpose we constructed the distribution of P_T of the highest energy π°-mesons with respect to direction of the highest energy Pb jets (the residual nucleons). It is compared in Fig. A1 with the P_T distribution of all π°-mesons measured

in reference to the energy-weighted center of π°-meson (the fire balls).[5] If P_{TF} is of purely statistical origin, one should expect an agreement between the two distribution. But this is not the case, and moreover one sees that the constructed $P_{T\pi o_1}$ distribution is more close to the P_{TF} distribution. This seems to indicate that the fire ball is emitted with P_T of several GeV.

APPENDIX II

Survival nucleons

Let us now discuss some experimental results on properties of the highest energy Pb jets. Fig. A2 shows energies of the highest π°-mesons, $E_{\pi o_1}$, and of the highest Pb jets, E_{Pb_1}, in families in the form of diagram. The Pb jet from the highest energy charged π-mesons will have energy, k_{γ} $E_{\pi o_1}$. One see that energy of the highest Pb jets is slightly more than expected from the charge π-meson interaction.

The above situation can be made clearer when one makes comparison between E_{Pb1}, E_{Pb2}, $E_{\pi o1}$ and $E_{\pi o2}$. Fig. A3 shows integral distribution of the ratio $E_{\pi o1}/E_{\pi o2}$ and E_{Pb1}/E_{Pb2}. One finds that average value of the ratio is about twice for Pb jets compared to the case of π°-meson. If those Pb jets are π-mesons, one expectes that the ratio for Pb jets will be smaller. This result gives a support for the assumption of the highest energy Pb jets being survival nucleon.

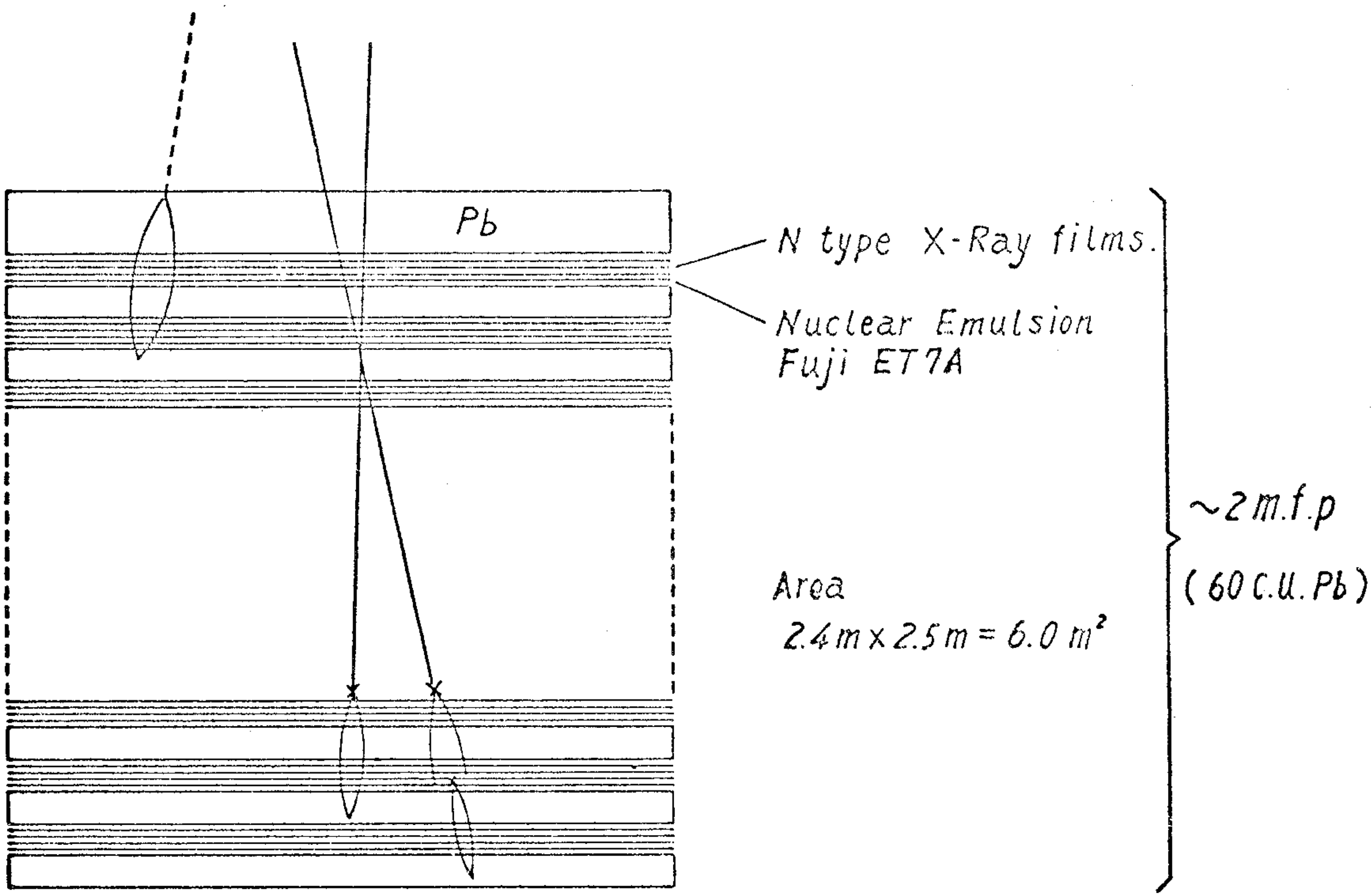

Fig. 1 - Design of the Chamber

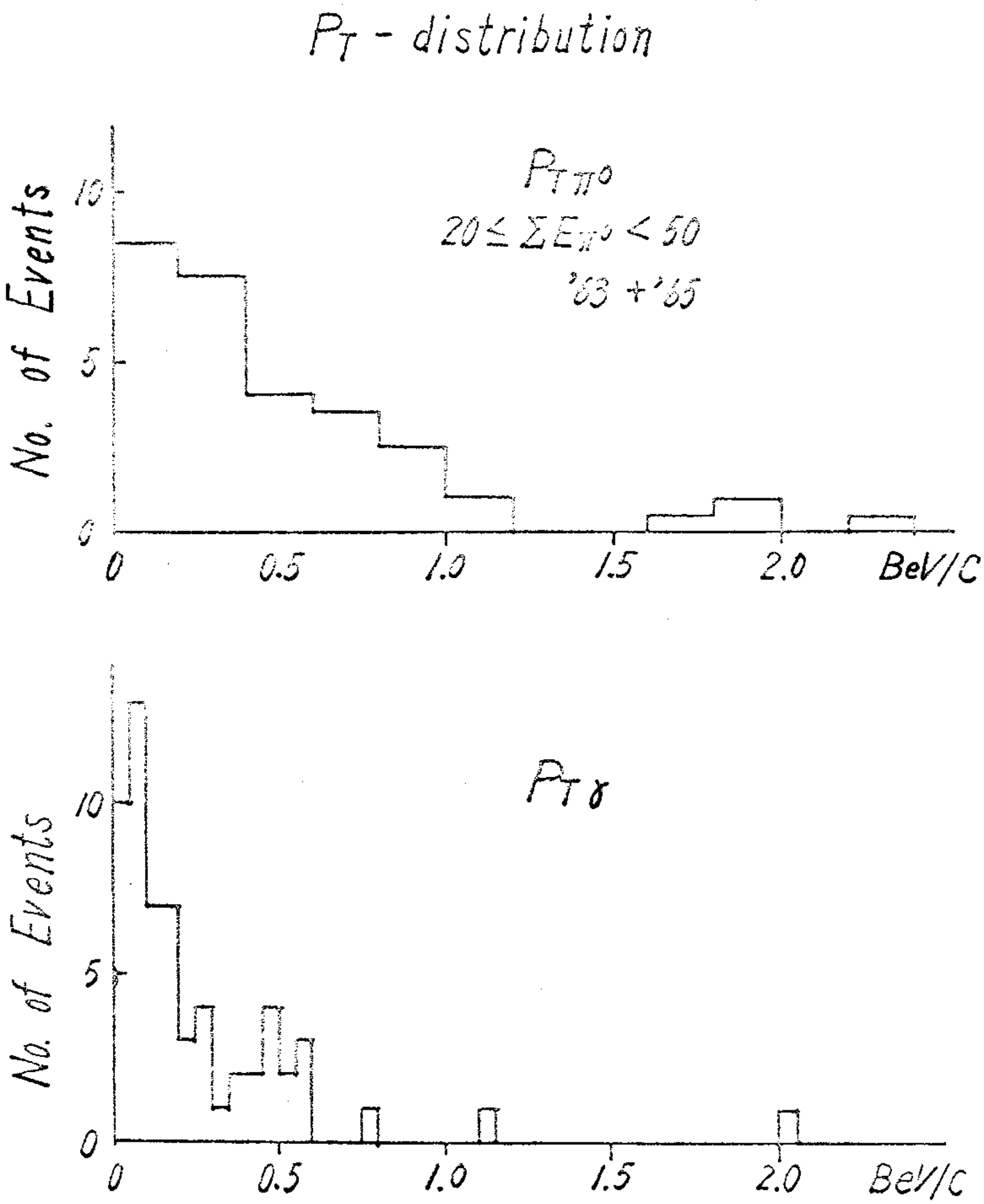

Fig. 2a – Distribution of $P_{T\gamma}$ and $P_{T\pi o}$

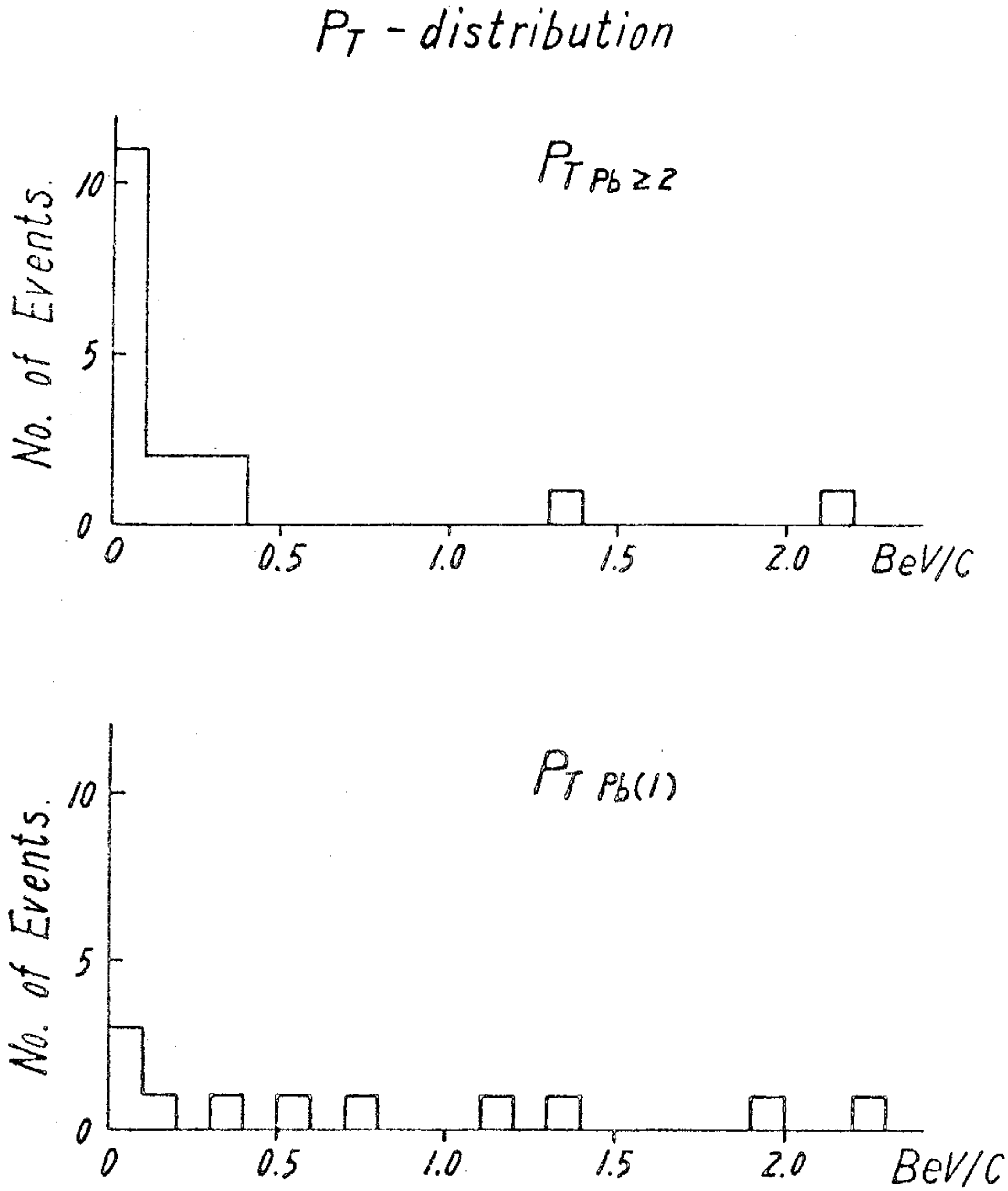

Fig. 2b - Distribution of P_{TPb1} and P_{TPb2}

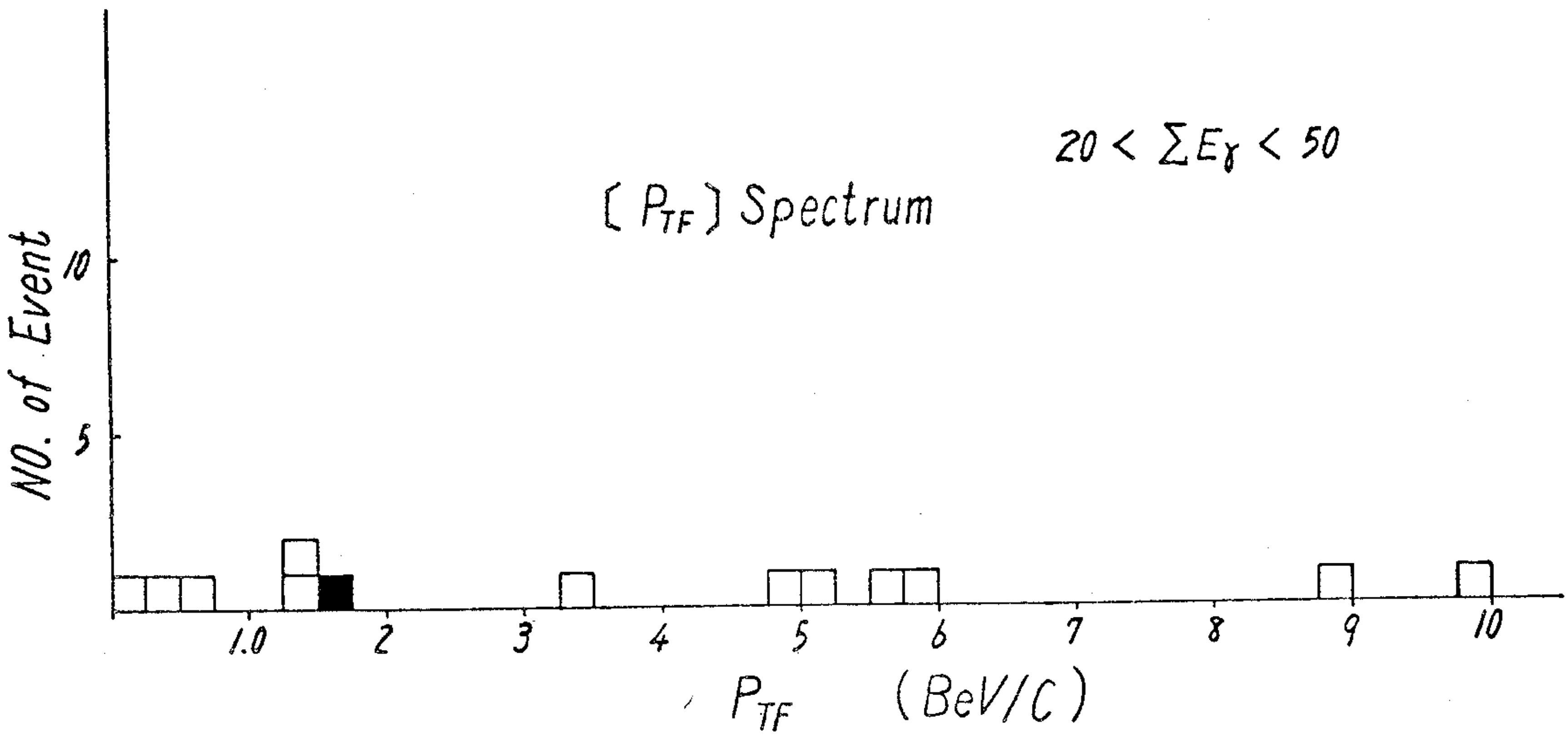

Fig. 3 - Distribution of P_{TF}

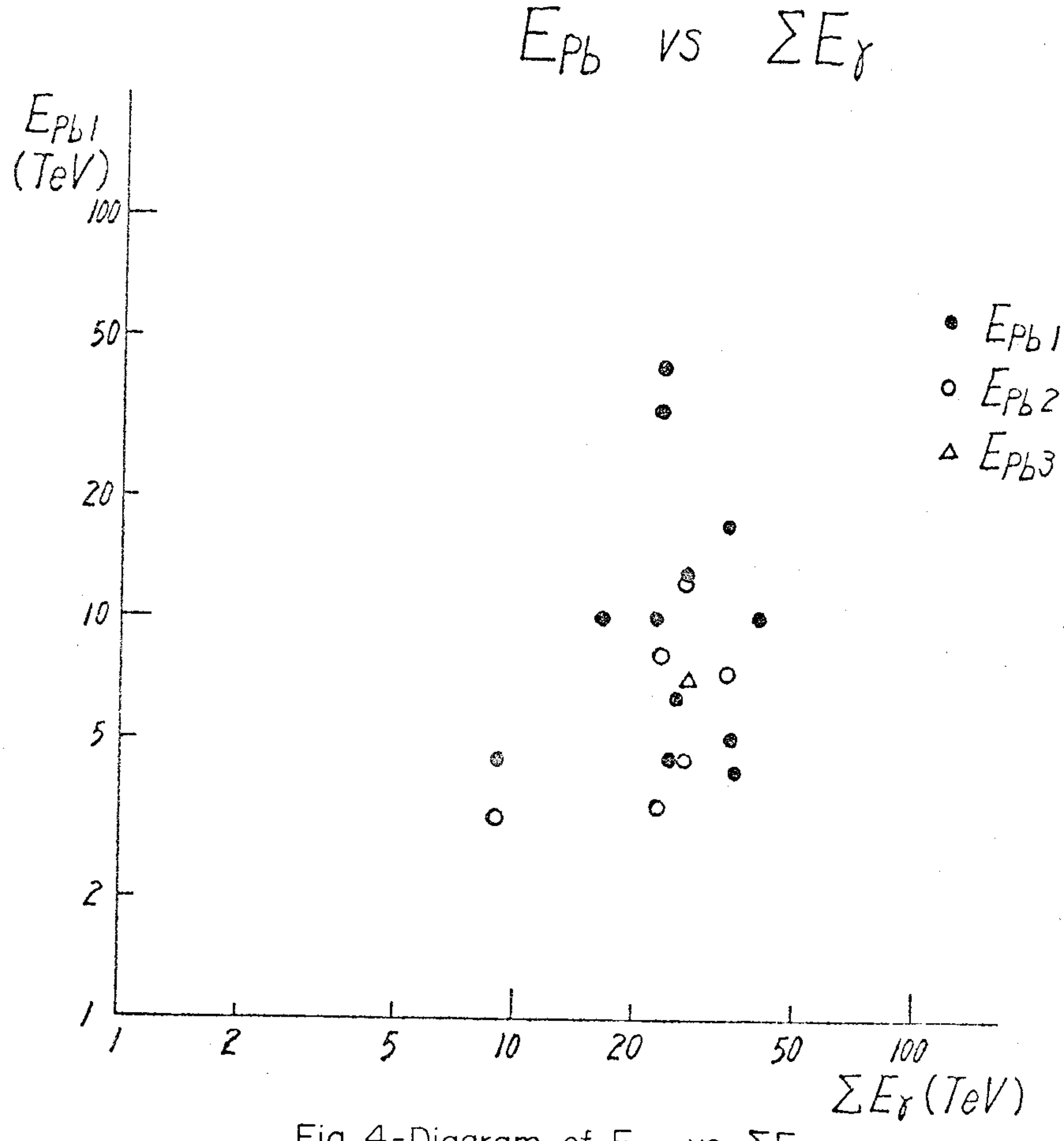

Fig 4-Diagram of E_{Pb} vs. ΣE_γ

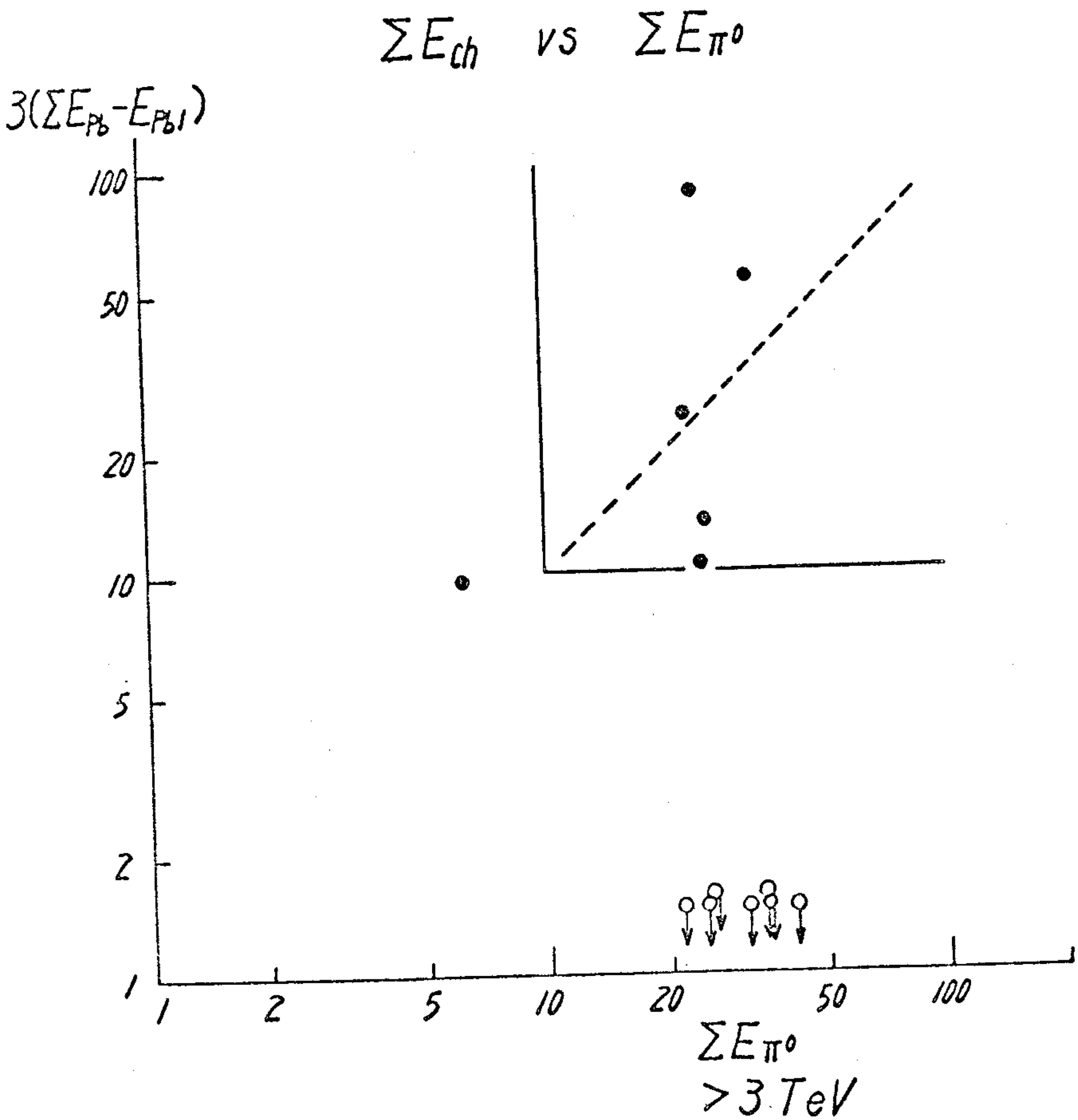

Fig. 5 - Diagram of $E_{\pi o}$ vs. $E_{\pi^{\pm}}$

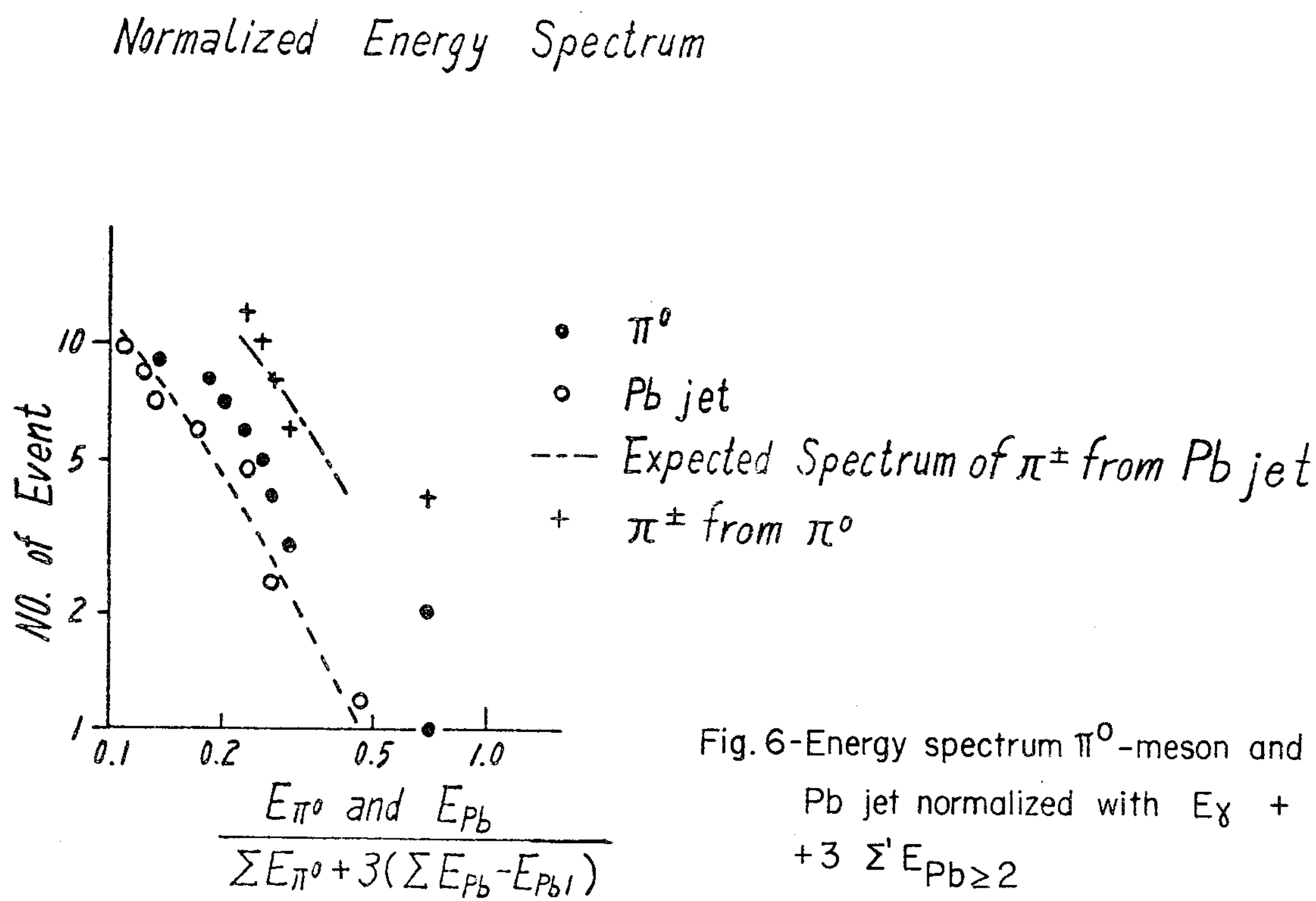

Fig. 6-Energy spectrum π^0-meson and Pb jet normalized with E_γ + +3 $\Sigma' E_{Pb \geq 2}$

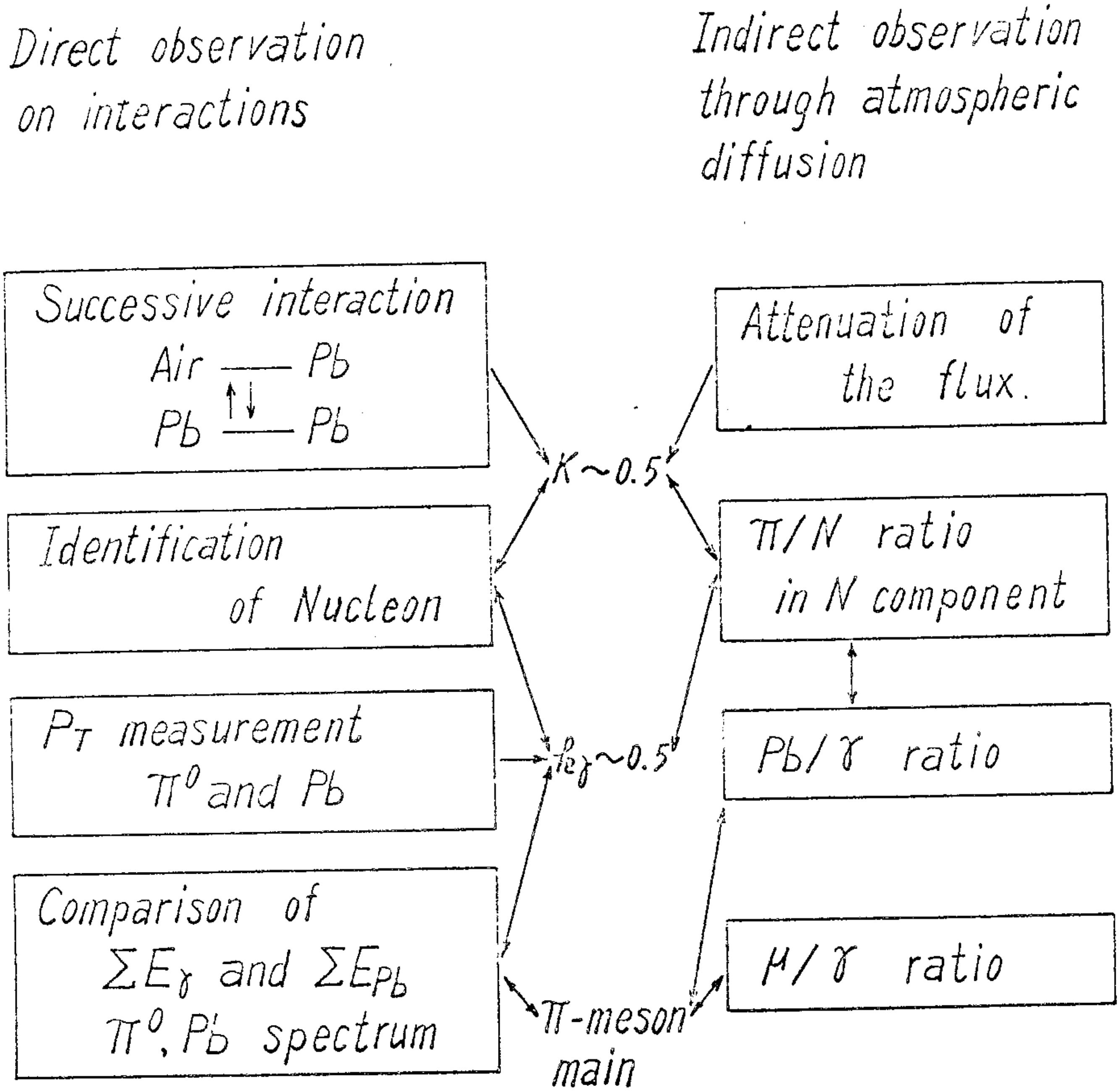

Fig. 7 - Logical relation of our data by various methods of analysis

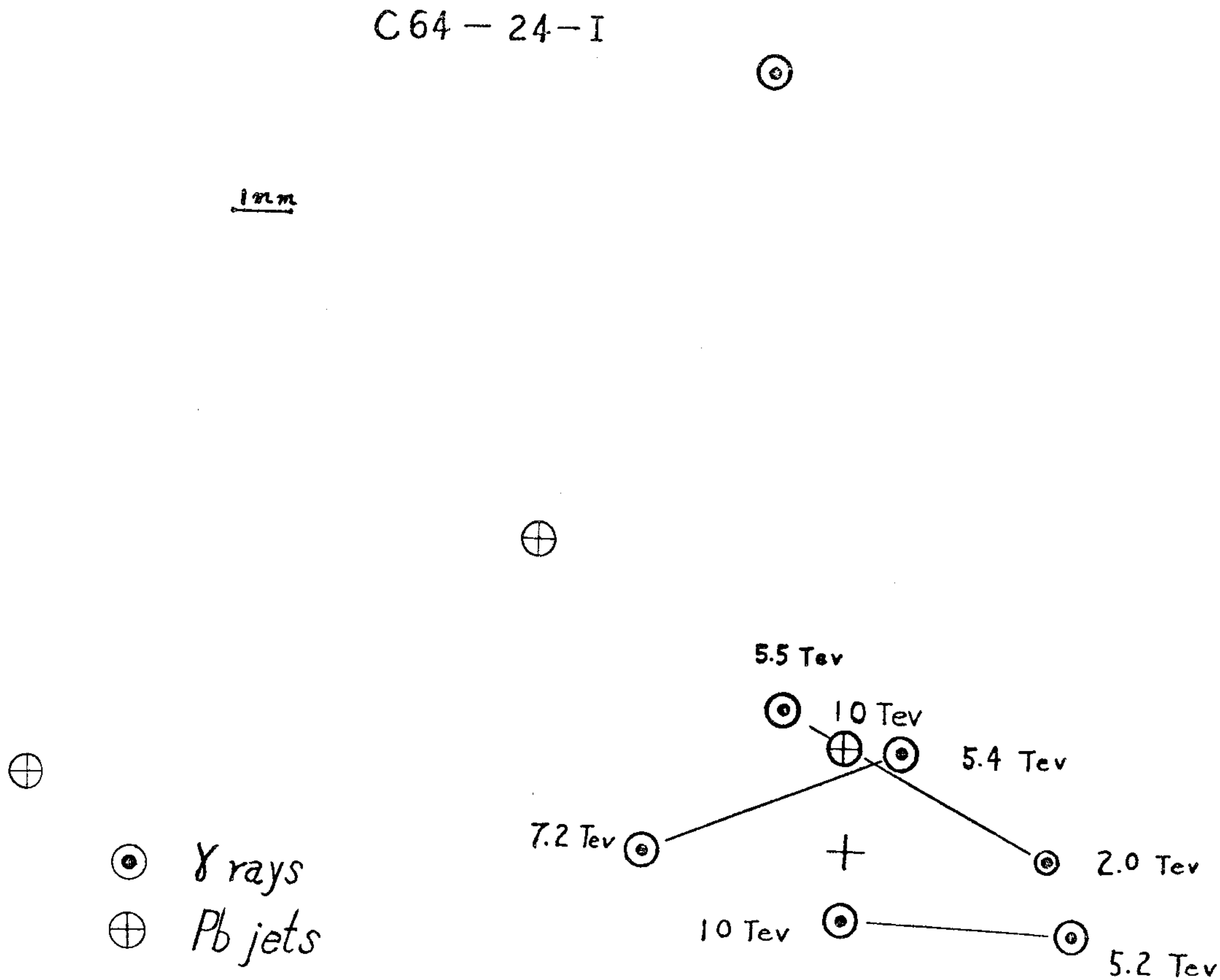

Fig. 8a-Example of interesting event showing small relative motion of 3 π^0 -mesons

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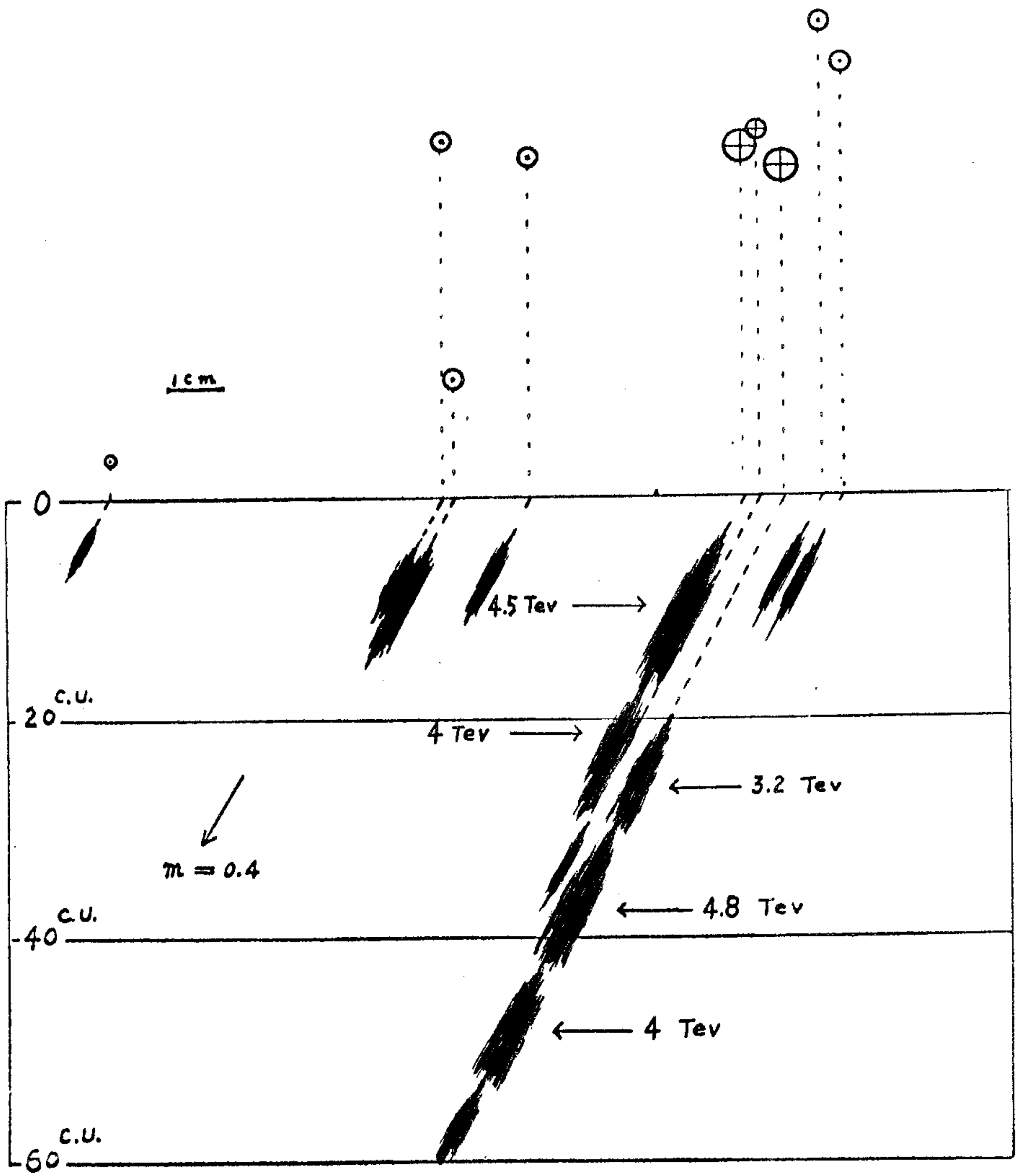

Fig. 8b-A similar event of 3 Pb jets

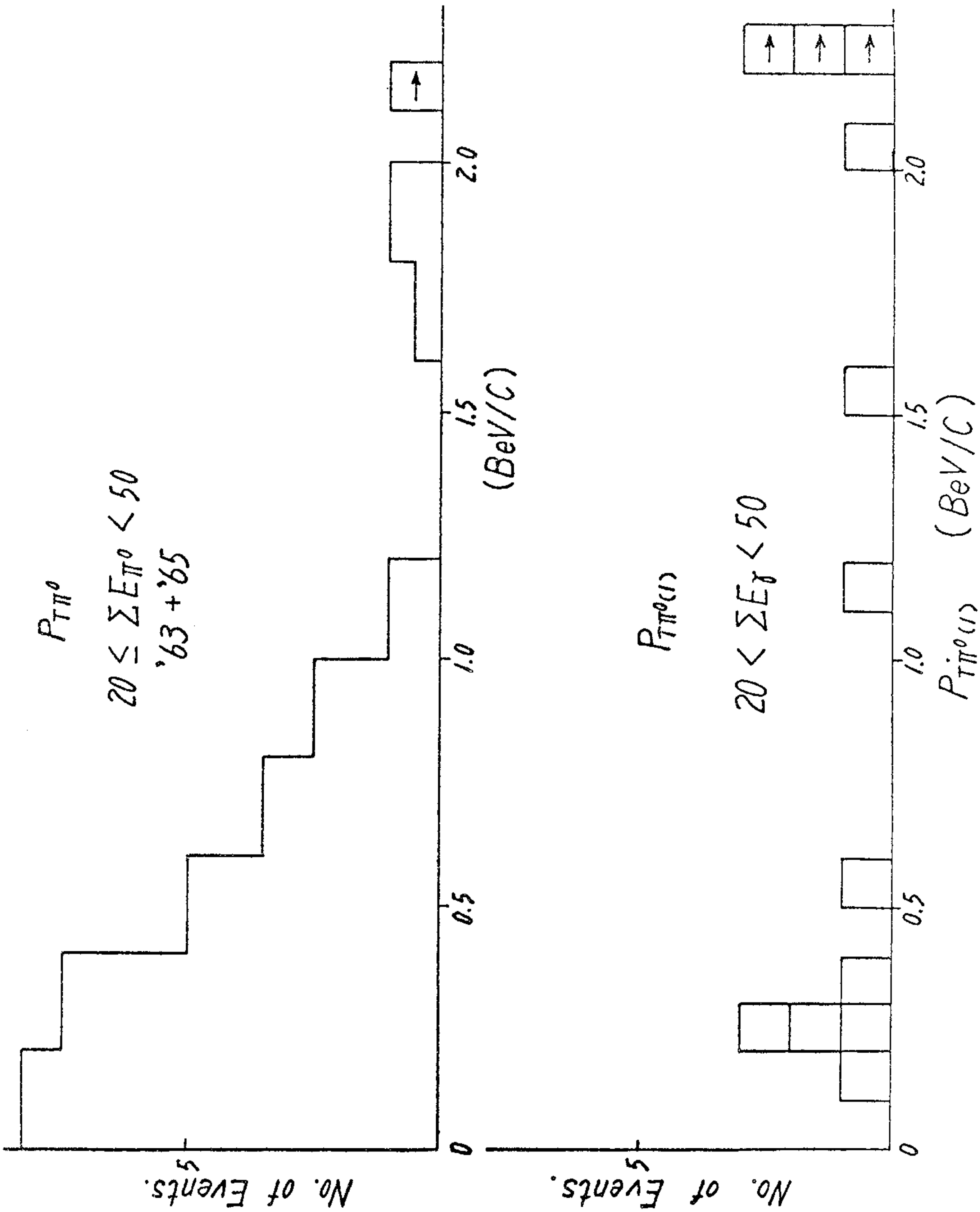

Fig. A1-Comparison of $P_{T\pi^0 1}$ with $P_{T\pi^0 \geq 2}$

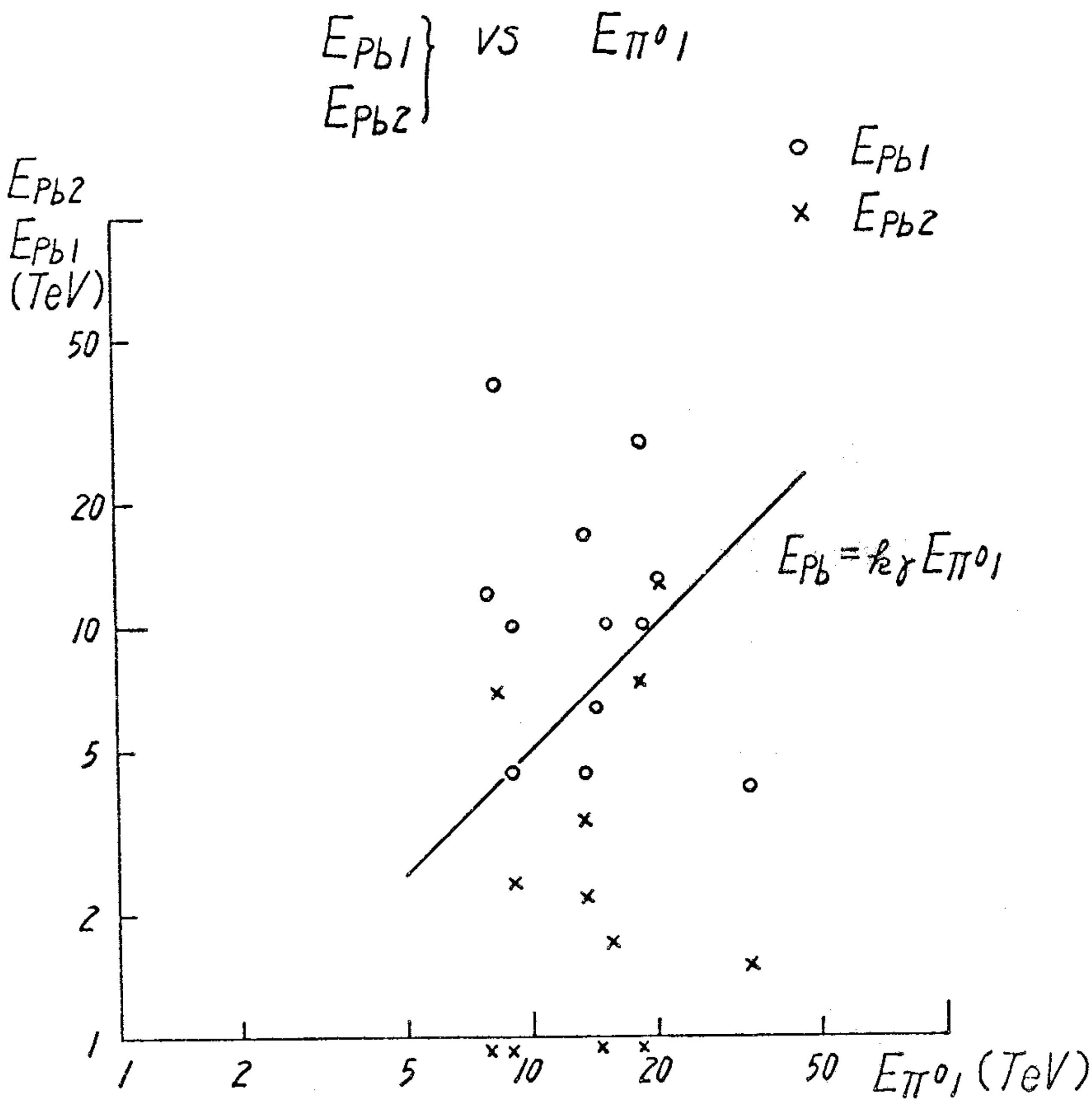

Fig. A2–Diagram of $E_{\pi^0 1}$ vs. E_{Pb1}

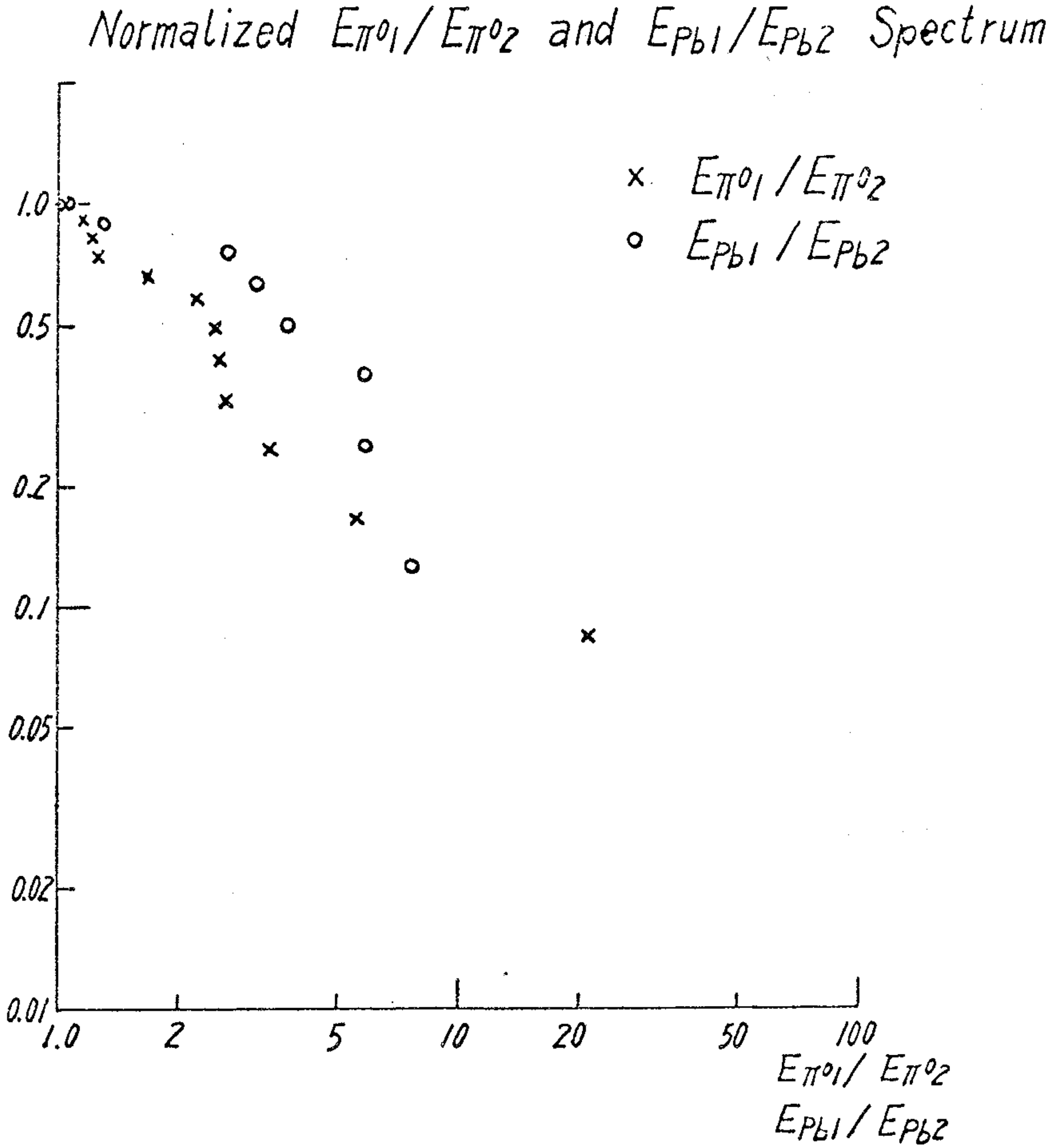

Fig. A3-Normalized integral spectrum of $E_{\pi^0 1}/E_{\pi^0 2}$ and E_{Pb1}/E_{Pb2}

CAPTIONS OF FIGURES

Fig. 1 – Design of the chamber.

Fig. 2a – Distribution of $P_{T\gamma}$ and $P_{T\pi o}$.

Fig. 2b – Distribution of P_{TPb1} and P_{TPb2}.

Fig. 3 – Distribution of P_{TF}.

Fig. 4 – Diagram of E_{Pb} vs. ΣE_γ.

Fig 5 – Diagram of $E_{\pi o}$ vs. $E_{\pi\pm}$.

Fig. 6 – Energy spectrum of π^o-meson and Pb jet normalized with $E_\gamma + 3 \sum' E_{Pb} \geqslant 2$.

Fig. 7 – Logical relation of our data by various methods of analysis.

Fig. 8a – Example of interesting event showing small relative motion of 3 π^o-mesons.

Fig. 8b – A similar event of 3 Pb jets.

Fig. A1 – Conparison of $P_{T\pi^o 1}$ with $P_{T\pi^o \geqslant 2}$.

Fig. A2 – Diagram of $E_{\pi^o 1}$ vs. E_{Pb1}.

Fig. A3 – Normalized integral spectrum of $E_{\pi^o 1}/E_{\pi^o 2}$ and E_{Pb1}/E_{Pb2}.

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REFERENCES

1. M. AKASHI et al., in this proceeding.

2. Y. FUJIMOTO et al., Proc. Moscow Conf. 1, 41 (1961).
   M. AKASHI et al., Proc. Kyto Conf., 3, 427 (1962).
   M. AKASHI et al., Proc. Jaipur Conf. 5, 326 (1964).

3. The meaning of this formula will be found in later sections.

4. For lower energy Pb jets, measurement of their P_T value will not be affected by ambiguities in locating the center axis of the event. It is not so for the highest energy Pb jets.

5. One may not eliminate completely a possibility of the highest energy Pb jets with large P_{TF} being not survival nucleons. They could be high energy π-mesons which belong to earlier generations of the nucleon cascades in the atmosphere, though it is unlikely from the probability argument. The question will be made clear by the emulsion chambers with producer layers, which are now under exposure at Mt. Chacaltaya and Norikura.

6. See appendix II.

7. S. HAYAKAWA, J. NISHIMURA and Y. YAMAMOTO, Prog. Theor. Phys. Suppl., Nº 32 (to be published).

8. The observed value of $\langle k_\gamma \rangle$ should not be taken as a averaged value over the event produced by beam of homogeneous energy. The figures here observed are the weighted average with the energy spectrum of the incident particles.

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