UCRL-9581

UNIVERSITY OF CALIFORNIA

Ernest O. Lawrence Radiation Laboratory

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545

BERKELEY, CALIFORNIA

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Review of Modern Physics

UCRL-9581

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

FINAL STATES OF THE ANTIPROTON-PROTON SYSTEM

Gerald R. Lynch

February 22, 1961

FINAL STATES OF THE ANTIPROTON-PROTON SYSTEM*

Gerald R. Lynch

Lawrence Radiation Laboratory
University of California
Berkeley, California

February 22, 1961

This paper reports some of the results from two antiproton experiments which were the first major experiments performed with the Alvarez 72-inch hydrogen bubble chamber. The beam momentum at the center of the chamber was 1.61 Bev/c for the first experiment and 1.99 Bev/c for the second. Details of these beams have been published elsewhere.[1]

Rare Two-Body Final States

A primary motivation for the choice of these momenta was that 1.61 Bev/c is above the threshold for the reaction $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda$, and 1.99 Bev/c is above the thresholds for producing antisigma particles. In a total of about 21,000 antiproton interactions at 1.61 Bev/c there were found 11 events of the $\bar{\Lambda}\ \Lambda$ reaction. Figure 1 shows the first one of these events found. This one was unusually easy to identify because both the $\bar{\Lambda}$ and the Λ decayed via the charged mode and the antiproton from the $\bar{\Lambda}$ decay annihilated within the chamber. At 1.61 Bev/c the cross section for this reaction is 57 ± 18 μb. At the higher momentum, in addition to two events of the $\bar{\Lambda}\ \Lambda$ reaction, there were (among about 5000 antiproton interactions) two events which were either $\bar{p} + p \rightarrow \bar{\Sigma}^0 + \Lambda$ or $\Sigma^0 + \bar{\Lambda}$.

There are two other rare two-body final states in $\bar{p}$-p interactions, namely the annihilation into two pions or two kaons: $\bar{p} + p \rightarrow \pi^+ + \pi^-$ or $\bar{p} + p \rightarrow K^+ + K^-$. Neither of these reactions had been observed among the many thousands of antiproton interactions studied before this experiment.

This fact has been considered mysterious,[2] and has led to some speculation about possible selection rules against these reactions. Actually there have been

reported only about 600 events[3,4] that could be attributed to antiproton interactions with free protons and among which these two-body reactions have been sought. In view of the fact that the average pion multiplicity in antiproton annihilations is about five, it is not surprising that this rate is so small. Figure 2 shows the prediction of the Fermi statistical model (using a Lorentz-invariant phase space) for the ratio of the number of annihilations resulting in two charged pions and no neutral ones, to the number of all annihilations in which kaons are not produced. Although this ratio is plotted only for the energy of this experiment, it has wider applicability because for a given multiplicity this ratio, as well as most other statistical-model predictions, is quite insensitive to the center-of-mass energy.

A search was made for these events among the approximately 13,000 two-prong events in the film. All but 125 of these were easily eliminated by crude measurements on the scanning table. These 125 events were measured with the Franckenstein measuring projector and kinematically analyzed. Figure 3 shows the χ^2 distribution for the events for the tests of the $\pi^+\pi$ and the K^+K^- hypotheses. Events not shown on the plots had χ^2 greater than 100.

The mean of these distributions is about twice the mean expected value (four), for these four-constraint fits. This is an indication that the assigned errors were underestimated by a factor of about 1.5, on the average. We find that our χ^2 distributions are too large in other cases, such as Λ or K_1^0 decays where the identity of the events is not in doubt. In other words there are systematic errors in the analysis of 72-inch hydrogen bubble chamber film which are not yet understood, and these χ^2 distributions seem reasonable on the basis of other experience with the 72-inch chamber.

There are 20 events which fit $\bar{p} + p \rightarrow \pi^+ + \pi^-$ and 11 events which fit $\bar{p} + p \rightarrow K^+ + K^-$. The discrimination between the $\pi^+\pi^-$ and the K^+K^- hypotheses is

very good. Most of the events that fit one of these interpretations have a χ^2 of more than 100 for the other interpretation. Only for one event is the discrimination between the two interpretations poor. In this case the χ^2 for K^+K^- is 4 and χ^2 for $\pi^+\pi^-$ is 24. However, on this event the negative outgoing track scatters elastically. This scattering fits well the hypothesis that it is a scattering of a kaon from the K^+K^- reaction, and fits only poorly the hypothesis that it is a scattering of a pion from the $\pi^+\pi^-$ reaction. Together these two pieces of information give strong evidence in favor of the K^+K^- interpretation in preference to the $\pi^+\pi^-$ interpretation.

The question that arises is: How many of these events that fit the two-body annihilations are really three-body events which happen to fit the two-body ones? If our resolution were good enough, we could always distinguish these reactions. However, since measurement errors are such that calculations of the missing energy have an uncertainty of about one pion mass, on the average, it is possible for a three-body process to simulate the two-body ones. Six of the twenty events which fit $\pi^+\pi^-$ do not fit any three-body process (i.e., the χ^2 for all these fits having one degree of freedom is greater than 15). But the rest of the $\pi^+\pi^-$ candidates and all the K^+K^- cnadidates do fit $\pi^+\pi^-\pi^0$. In all these cases $\pi^+\pi^-\pi^0$ fits better than any other three-body final state. In fact most of all 11 K^+K^- candidates give a better fit for the $\pi^+\pi^-\pi^0$ hypothesis than the K^+K^- hypothesis.

The first evidence that few of these events are $\pi^+\pi^-\pi^0$ events is the χ^2 distribution itself. One would expect that, if these events were "fake" events, the χ^2 distribution would form a flat continuum rather than peaking near zero, which is observed and which one would expect from true two-body events.

One might object by pointing out that a selection has already been made at the scanning table and, therefore, those three-body events which would contribute large χ^2 had been eliminated. That most of the events had χ^2 greater than 100 shows that the scanning table selection was not as restrictive as this.

Further evidence that there are few background events is obtained by looking at the coplanarity distribution of the measured events. The measurement of coplanarity, C, used here is the triple scalar product of the unit vectors in the directions of the three measured momenta. Figure 4 shows this coplanarity plot for those of the measured events which had C less than 0.12. All of these look coplanar on the scanning table. The plot demonstrates that those events which fit two-body processes form a large cluster about C = 0. Those which fit no two-body process form a relatively sparsely populated and evenly distributed band. This is consistent with the interpretation that most of the coplanar events are two-body events and are not merely $\pi^+\pi^-\pi^0$ events which happen to be coplanar.

In order to obtain a better understanding of how often an event can fake the two-body annihilations, we generated 1000 $\pi^+\pi^-\pi^0$ events were generated by a Monte Carlo program which chose events distributed uniformly in phase space. Since any one of the three pions can be chosen as the π^0 this corresponds effectively to 3000 events. In these 3000 events there were only 57 with C less than 0.2 and also a π^0 total energy of less than 400 Mev. Each of these two cutoff values corresponds to four times the average measurement error. Of these 57 events, 12 had opening angles within 2 deg of the appropriate values for K^+K^-. At least half these events clearly could not fit the two-body reactions because the center-of-mass momentum of one of the pions deviated too much from the required value. Thus if the $\pi^+\pi^-\pi^0$ events are uniformly distributed in phase space only about one $\pi^+\pi^-\pi^0$ event in 600 has a chance of fitting $\pi^+\pi^-$ or of fitting K^+K^-. Corresponding to the average pion multiplicity which we find for annihilation at this energy, the statistical model predicts that there should be about 400± 100 $\pi^+\pi^-\pi^0$ events in our sample. Thus we should expect that no more than one of the 20 $\pi^+\pi^-$ events and no more than one of the 11 K^+K^- events to be fake. After correcting for efficiencies and making use of the previously measured[5] total antiproton cross section, we find, at 1.61 Bev/c,

σ for $\bar{p} + p \rightarrow \pi^+ + \pi^- = 100 \pm 25\ \mu b$,

σ for $\bar{p} + p \rightarrow K^+ + K^- = 55 \pm 18\ \mu b$,

and the ratio

$$\frac{\bar{p} + p \rightarrow \pi^+ + \pi^-}{\bar{p} + p \rightarrow n\pi(\bar{\pi})} = 2.0 \pm 0.5 \times 10^{-3}.$$

In the search for $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda$ events, all the zero-prong events with associated decays have been examined. None of the cases in which there were two associated neutral decays fits the reaction $\bar{p} + p \rightarrow K^0 + \bar{K}^0$. One event with a single neutral associated decay did fit this reaction well, and another one fitted it poorly ($\chi^2 = 9$ for a one-degree-of-freedom fit). These events could be background events. Since the probability of observing at least on K^0 from this reaction is about 5/9, we can say with at least 90% confidence that the cross section for $\bar{p} + p \rightarrow K^0 + \bar{K}^0$ is less than 50 μb.

The center-of-mass angular distributions of the π^- and the K^- from the two-body annihilations as well as the c.m. angular distributions of the $\bar{\Lambda}$ from the reaction $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda$ are shown in Fig. 5. The pion distribution seems to be anisotropic, with eight going forward and three going backward. The striking feature is that the K^- distribution is strongly peaked forward. Seven of the eleven events are in the forward one-tenth of the total solid angle. That this effect is not produced by a scanning bias is clearly shown by the fact that the $\pi^+\pi^-$ events, which were chosen by the same scanning techniques, do not exhibit this effect. This angular distribution demonstrates that the reaction $\bar{p} + p \rightarrow K^+ + K^-$ is not dominated by a statistical process.

The Inelastic Events

The $\bar{p}$-p total, inelastic, elastic, and charge-exchange cross sections have been measured for energies up to 2 Bev by two counter groups[5] at Berkeley. They find that out of a total cross section of 98 mb at 1.61 Bev/c, there is 56 mb

of inelastic cross section. These inelastic events are of two types, the annihilation events--those which have no nucleons in the final state--and the inelastic events analogous to the nucleon-nucleon inelastic processes, namely

$$\bar{p} + p \rightarrow \bar{p} + p + \pi^0, \tag{1}$$

$$\bar{p} + p \rightarrow \bar{p} + n + \pi^+, \tag{2}$$

$$\bar{p} + p \rightarrow p + \bar{n} + \pi^-, \tag{3}$$

$$\bar{p} + p \rightarrow n + \bar{n} + \pi^0, \tag{4}$$

as well as the interactions with additional pions produced. We have measured the cross sections for Reactions (1), (2), and (3) for antiprotons of 1.61 Bev/c.

Because many antiprotons annihilate into two charged pions plus several neutral pions ($\bar{p} + p \rightarrow \pi^+ + \pi^- + n\pi^0$), it is extremely difficult to identify unambiguously Reactions (1), (2), and (3) out of a random sample of two-prong events. Therefore in order to study Reactions (1) and (2) we have analyzed only those events in which the negative secondary produces a four- or a six-prong event. A six-prong event is nearly certain to be an annihilation of an antiproton. Since almost all secondary four-prong events produced by pions have no more than one associated neutral pion, they can be identified by kinematic analysis.

Among the 21,000 antiproton interactions there were 495 connected events of this type. A careful scanning table measurement of these enabled us to identify almost all the elastic scatterings among these events. The Franckenstein measuring projector was used to measure the remaining 55 candidates for the inelastic reactions. Kinematic analysis of these (supplemented by an ionization measurement of the positive track for a few events) yielded

25 events of $\bar{p} + p \rightarrow \bar{p} + p + \pi^0$,

17 events of $\bar{p} + p \rightarrow \bar{p} + n + \pi^+$,

and 1 which fitted either reaction.

The remaining 12 events were either elastic scatterings of antiprotons or pion interactions. In all subsequent statements I shall treat the one ambiguous event as if it were one-half Reaction (1) and one-half Reaction (2).

In order to study Reaction (3), we analyzed the 75 two-prong events which were possibly associated with three-, five-, or seven-prong stars. Most of these stars were found to be associated with a zero-prong event in the same frame and were produced by antineutrons from the reaction $\bar{p} + p \rightarrow \bar{n} + n$. Careful kinematic analysis yielded that only 19 of these events were the reaction $\bar{p} + p \rightarrow p + \bar{n} + \pi^-$.

To calculate the cross section for these inelastic processes with secondary annihilation events it was necessary to assign a weight to each event. This weight was equal to the reciprocal of the average probability that the antinucleon from such an event would produce an annihilation with more than two charged prongs in the 72-inch chamber. After weighting the events, correcting for scanning efficiencies, and making use of the known $\bar{p}$-p total cross sections,[5] we obtained

$$\sigma \text{ for } \quad \bar{p} + p + \pi^0 = 1.6 \pm 0.3 \text{ mb},$$

$$\sigma \text{ for } \quad \bar{p} + n + \pi^+ = 1.16 \pm 0.3 \text{ mb},$$

$$\sigma \text{ for } \quad p + \bar{n} + \pi^- = 0.96 \pm 0.22 \text{ mb}.$$

No event of the type $\bar{p} + p \rightarrow \bar{p} + p + \pi^+ + \pi^-$ with a subsequent annihilation of the antiproton into a four-or six-prong event was observed. This sets an upper limit of about 0.1 mb for the cross section for this reaction.

A statistical-model calculation[6] predicts the ratio 4:5:5:4 for Reactions (1): (2): (3): (4). The isobaric model[7] predicts the ratio 2:1:1:2. Our results are intermediate between the rpedictions of these two models. If either the isobaric model or the statistical model is assumed, the cross section for Reactions (1) and (4) are equal. On the basis of the assumption that they are indeed equal, the total inelastic cross section is $\sigma_{inelastic} = 5.3 \pm 1$ mb. It is interesting to note

that this value is small compared with the nucleon-nucleon inelastic cross sections. These cross sections are 21± 1 mb for the sum of the proton-proton inelastic reactions and 21±4 mb for the sum of the neutron-proton inelastic reactions at this energy.[8]

The sum of the inelastic plus the annihilation cross sections at this energy has been measured and found to be 56± 2 mb.[5] Therefore the annihilation cross section is 51± 3 mb.

Charge-Conjugation Invariance

There are many experiments that test parity conservation in strong interactions. But, as far as we know, there is still no direct experimental test of charge-conjugation invariance in strong interactions; that is to say, there is no experimental result that is predicted by charge-conjugation invariance and is not also predicted by some other generally accepted symmetry principle.

Although the statistics of this experiment are too limited to make a very definitive test of charge conjugation, I shall nevertheless use this as a framework within which to discuss the data.

For an unpolarized beam and target, the $\bar{p}$ + p system is invariant under the operators CP or CR, where R is a rotation of 180 deg around any axis perpendicular to the direction of motiomof both the p and the $\bar{p}$. We assume R invariance to be true and therefore treat a test of CR as a test of C alone. For Reaction (1), C and CP both make the following predictions in the center-of-mass system: (a) the angular distribution of the π^0 is symmetric about 90 deg; (b) the angular distribution of the proton is equal to the reflection of the angular distribution of the antiproton.

Figures 6 and 7 show that the angular distributions agree very well with these predictions. The π^0 distribution seems to be isotropic. The other distributions are very anisotropic. The antiproton tends to go forward and the proton tends to go backward relative to the incident antiprotons.

The final states in Reactions (2) and (3) are charge conjugates of each other. Both C and CP predict that the cross section of these two reactions should be equal as well as predicting that the angular distribution of one final-state particle in one reaction must be the reflection of the angular distribution of the charge conjugate of this particle in the other reaction. We have already seen that the cross sections are in agreement, as predicted. Figures 8, 9, and 10 show that the angular distributions are in agreement with the prediction. Just as was the case with $\bar{p} + p + \pi^0$, antinucleons prefer to go forward and the nucleons to go backward relative to the incident antiproton.

All the previously mentioned tests have been tests in which the predictions of C and CP are identical. However, if one looks at the distribution in the angle ϕ_{12}--the azimuthal angle between Particle 1 and Particle 2 in the plane normal to the incident antiproton direction--the predictions of C and CP are different.[10] Figure 11 shows the $\phi\bar{p}n$ and the $\phi p\bar{n}$ distributions.

The prediction of C is that the two distributions should be reflections of each other. The prediction of CP is that they should be identical. Within the statistics the data are in agreement with both these predictions.

Pion Multiplicities in Antiproton Annihilation

Measurements of pion multiplicities in antiproton annihilations are usually compared with the predictions of the Fermi statistical model,[10] or some modification of it. This is done even though this model has been unsuccessful in two respects in describing the annihilation process. The one arbitrary parameter that enters the model is the interaction volume Ω, which is expressed in units of $(4\pi/3\pi)(\frac{\hbar}{m_\pi c})^3$. Since one would expect the range of the nucleon-antinucleon force to be close to a pion Compton wave length, one would expect that Ω should be close to unity. However, one needs an Ω which is much larger than unity in order to explain the observed multiplicities. Furthermore, the statistical-model prediction of the number of kaons in $\bar{p}$ annihilations is much larger than what is actually observed.

Nevertheless it is instructive to compare the data with the statistical-model predictions for the same reason that one compares energy and angular distributions with the predictions of phase space, not because one necessarily expects agreement, but because one may learn something about the interesting features of the reaction by investigating the points of disagreement.

The original formulation of the Fermi model used phase-space factors which were non-Lorentz-invariant. Most recent calculations have used a Lorentz-invariant phase space.[11] In addition to its virtue of being Lorentz-invariant, it has the advantage that one can make calculations much more easily with it than with the non-Lorentz-invariant phase space. However, in the statistical model using the Lorentz-invariant phase space the arbitrary parameter that is introduced has the dimension of energy, and this parameter is only somewhat artificially converted to the volume Ω in order to obtain correspondence with the non-Lorentz-invariant theory. These two formulations of the statistical model give similar, but not identical, results. For annihilation at rest the prediction of the non-Lorentz-invariant model with an Ω of 10 is very nearly the same as the prediction of the Lorentz-invariant model with an Ω of 8.

In comparing the model with the data, the approach used here is to use the model to predict charged-prong multiplicities,[12] rather than to attempt to measure or estimate the π^0 multiplicity and then combine the data before making the comparison. Figure 12 shows the prediction of the charged-pion multiplicity as a function of the center-of-mass energy of the $\bar{p}$-p system for various values of Ω, using the Lorentz-invariant phase space (and without introducing any additional Lorentz contraction factor). The experimental points come from two experiments on annihilations at rest,[4, 13] from the Goldhaber et al experiment[3] at 1.05 Bev/c, and from our two experiments. The points are in good agreement with the prediction of the statistical model with an Ω between 4 and 6. Since the data can

give a not unreasonable fit even to a horizontal straight line, this cannot be said to be much of a victory for the statistical model. It does indicate that if the statistical model is a good description, a value of Ω close to 5 is necessary.

Table I shows the fraction of the pion annihilations at 1.61 Bev/c which results in 0-, 2-, 4-, 6-, and 8-prong annihilations, as well as the fraction resulting in the $\pi^+\pi^-$ final state. The data have been corrected for the approximately 9 % of the annihilations that have pairs of kaons. Also on Table I are the values of Ω needed to fit each of these measured quantities. A value of Ω equal to 4.8 ± 0.3 is implied by and is consistent with all these data at 1.61 Bev/c. This is considerably smaller than the values of Ω quoted by other experimenters. From the data presented here we can say that the statistical model seems to give self-consistent predictions for annihilations into pions.

Acknowledgments

The results of this antiproton experiment are the product of the efforts of many physicists. Most of the credit for the antihyperon work should go to Dr. Janice Button and Professor M. Lynn Stevenson. Much of the analysis of the inelastic events was originated and carried out by N. G. Xuong. George R. Kalbfleisch contributed significantly to many phases of the experiment. Dr. Philippe Eberhard, Dr. Silvia Limentani, Dr. Joseph Lannutti, and Dr. Bogdan Maglić also contributed to the antiproton analysis. The antineutron work was performed by Dr. John Poirier and Keith Heinrichs. I am greatly indebted to Professor Luis W. Alvarez for his encouragement and support.

Footnotes

* This work was done under the auspices of the U.S. Atomic Energy Commission.

1. J. Button, P. Eberhard, G.R. Kalbfleisch, J.F. Lannutti, G.R. Lynch, B.C. Maglić, M.L. Stevenson, N.H. Xuong, The Reaction $\bar{p}+p \rightarrow \bar{\Lambda}+\Lambda$ Phys. Rev. (to be published).
2. J. Sakurai, An. Phys. 11, 1 (1960).
3. S. Goldhaber, G. Goldhaber, W.M. Powell, and R. Silberberg, Antiproton Annihilation in Propane UCRL-9319, Aug. 1960 (Submitted to Phys. Rev.) Among the 500 events of this experiment there was one event which could not be eliminated as a two-meson annihilation. The measurement errors on this event were quite large.
4. N. Horwitz, D. Miller, J. Murray, and R. Tripp, Phys. Rev. 115, 472 (1959).
5. T. Elioff, L. Agnew, O. Chamberlain, H. Steiner, C. Weigand, and T. Ypsilantis, Phys. Rev. Letters 3, 285 (1959); R. Armenteros, C.A. Comber B. Cork, G.R. Lambertson, and W. Wentzel, Phys. Rev. 119, 2068 (1960).
6. J. McConnel (Fordham University), private communication, 1960
7. S.J. Lindenbaum and R.M. Sternheimer, Phys. Rev. 105, 1874 (1957).
8. A.P. Batson, B.B. Cerlevick, J.G. Hill, and L. Riddiford, Proc. Roy. Soc. (London) 251, 218 (1959); A.P. Batson, B.B. Cerlevick, H.B. Kelpp, and L. Riddiford, Proc. Roy. Soc. (London) 251 233 (1959).
9. These relations were pointed out by A. Pais, Phys. Rev. Letters 3, 242 (1959).
10. For a discussion of application of the Fermi statistical model to antiproton annihilations see E. Segré, Ann. Rev. Nuclear Sci. 8, 127 (1958).
11. P.P. Srivastava and G. Sudarshan Phys. Rev. 110, 765 (1958).
12. In order to do this one needs the branching ratio predicted by the statistical model. These are tabulated by A. Pais, Ann. Phys. 9, 548 (1960).
13. L. Agnew, T. Elioff, W.B. Fowler, R. Lander, W.M. Powell, E. Segré, H. Steiner, H. White, C. Wiegand, and T. Ypsilantis, Phys. Rev. 118, 1371 (1960).

Table I. Pion multiplicities in antiproton annihilations at 1.61 Bev/c.

Type of event	Measured fraction of pion annihilations in percent	Values of Ω needed to fit the measurement
0-prong	$1.0^{+3}_{-0.6}$	----
2-prong	36.0 ± 5.2	4.6 ± 1.3
4-prong	54.6 ± 1.3	5.1 ± 0.9
6-prong	8.4 ± 0.3	4.6 ± 0.3
8-prong	0.15 ± 0.4	5.8 ± 0.7
$\pi^+\pi^-$	0.20 ± 0.05	4.8 ± 0.4

LEGENDS

Fig. 1. First example of antilambda production in the 72-inch hydrogen bubble chamber. The antiproton from the decay of the antilambda annihilated with a proton in the chamber to produce four charged pions.

Fig. 2. The prediction of the Fermi statistical model for the fraction of pion annihilations that result in $\bar{p} + p \rightarrow \pi^+ + \pi^-$ as a function of the average pion multiplicity for an antiproton momentum of 1.61 Bev/c.

Fig. 3. A histogram of the χ^2 distribution for the measured two-prong events for the hypothesis of $\bar{p} + p \rightarrow \pi^+ + \pi^-$ and $\bar{p} + p \rightarrow K^+ + K^-$. Some events occur on both plots. The hatched squares represent events which have a smaller χ^2 for the other two-meson interpretation.

Fig. 4. The distribution of the coplanarity of the measured events.

Fig. 5. A histogram of the center-of-mass angular distributions for the $\pi^+\pi^-$, K^+K^- and $\bar{\Lambda}\Lambda$ reactions.

Fig. 6. Angular distributions of the proton and the antiproton from the reaction $\bar{p} + p \rightarrow \bar{p} + p + \pi^0$.

Fig. 7. Angular distribution of the pion from the reaction $\bar{p} + p \rightarrow \bar{p} + p + \pi^0$.

Fig. 8. Angular distributions of the proton and the antiproton from the reactions $\bar{p} + p \rightarrow \bar{p} + n + \pi^+$ and $p + \bar{n} + \pi^-$.

Fig. 9. Angular distributions of the neutron and the antineutron from the reactions $\bar{p} + p \rightarrow \bar{p} + n + \pi^+$ and $p + \bar{n} + \pi^-$.

Fig. 10. Angular distributions of the positive and negative pions from the reactions $\bar{p} + p \rightarrow \bar{p} + n + \pi^+$ and $p + \bar{n} + \pi^-$.

Fig. 11. Distributions in the angle ϕ for the reactions $\bar{p} + p \rightarrow \bar{p} + n + \pi^+$ and $p + \bar{n} + \pi^-$.

Fig. 12. Measurements of the charged-pion multiplicity at various center-of-mass energies compared with the statistical-model predictions.

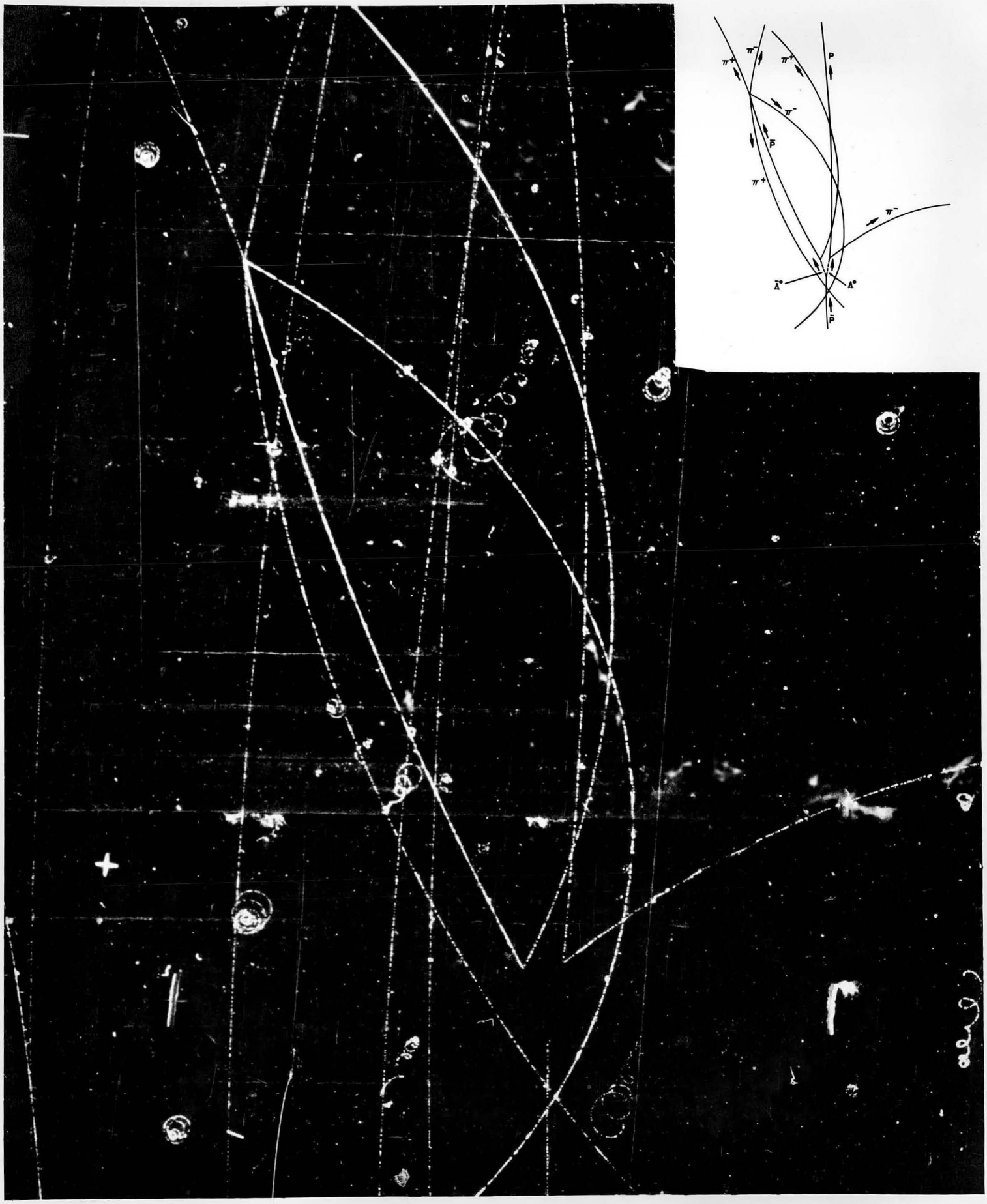
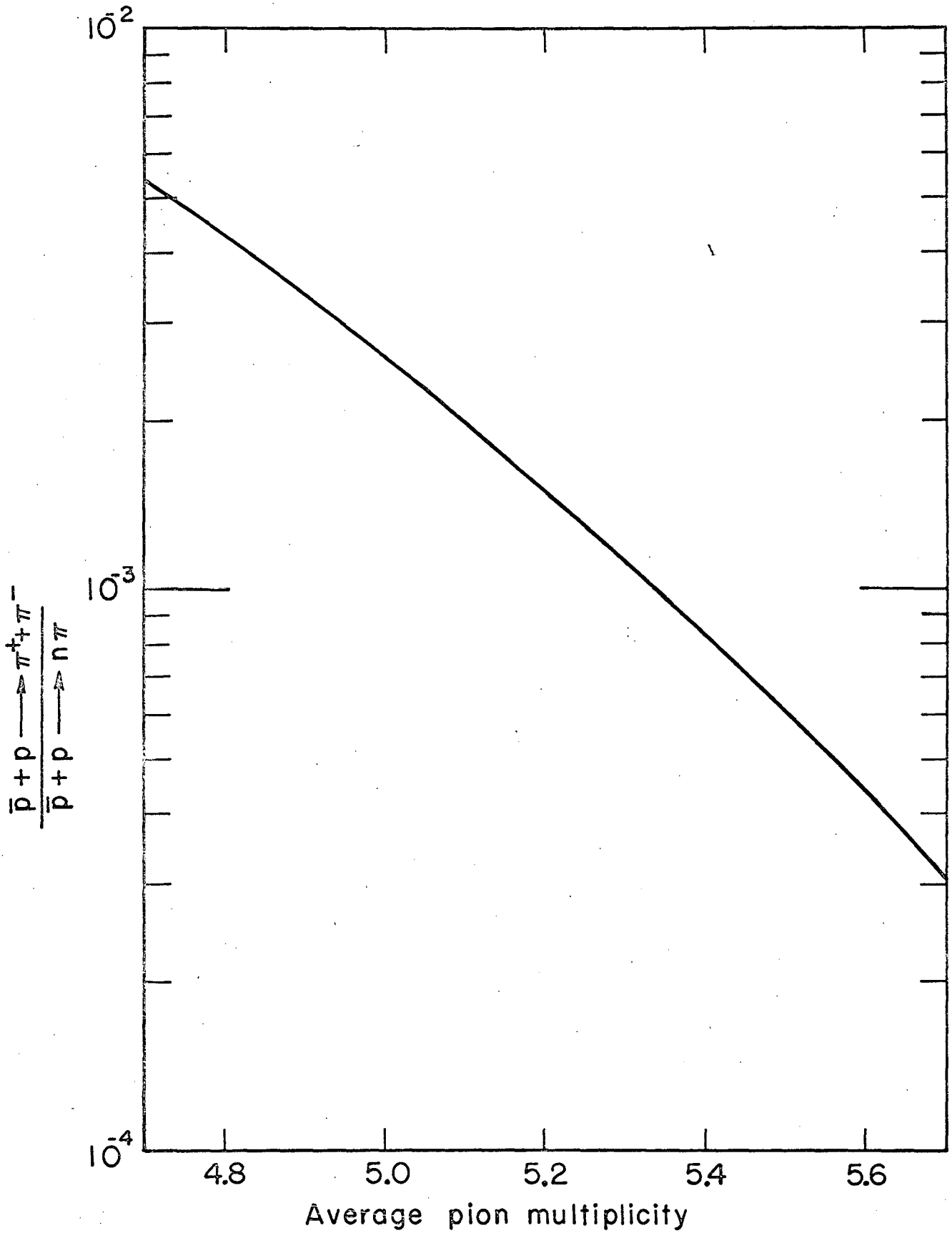
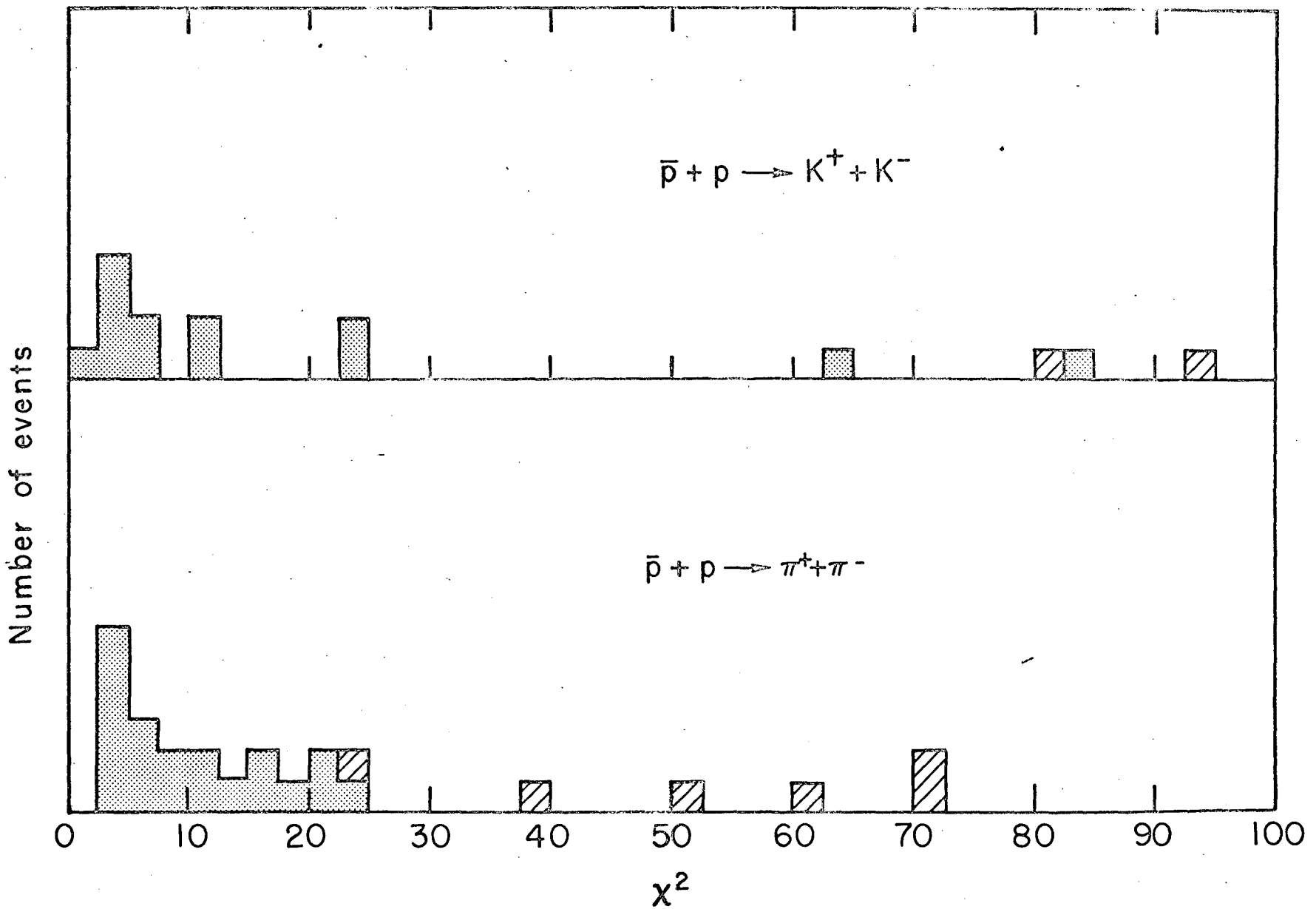


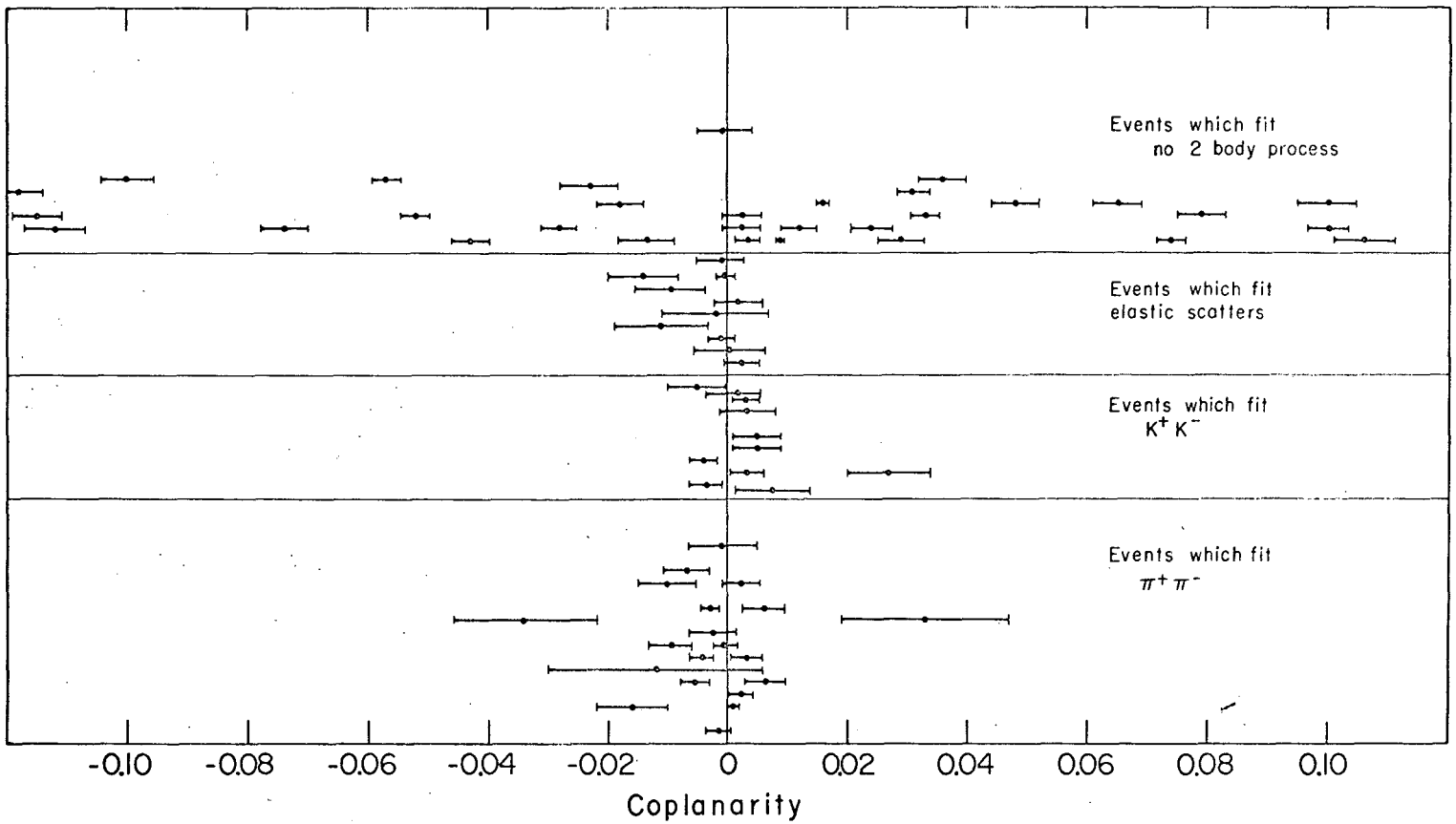
Fig. 1



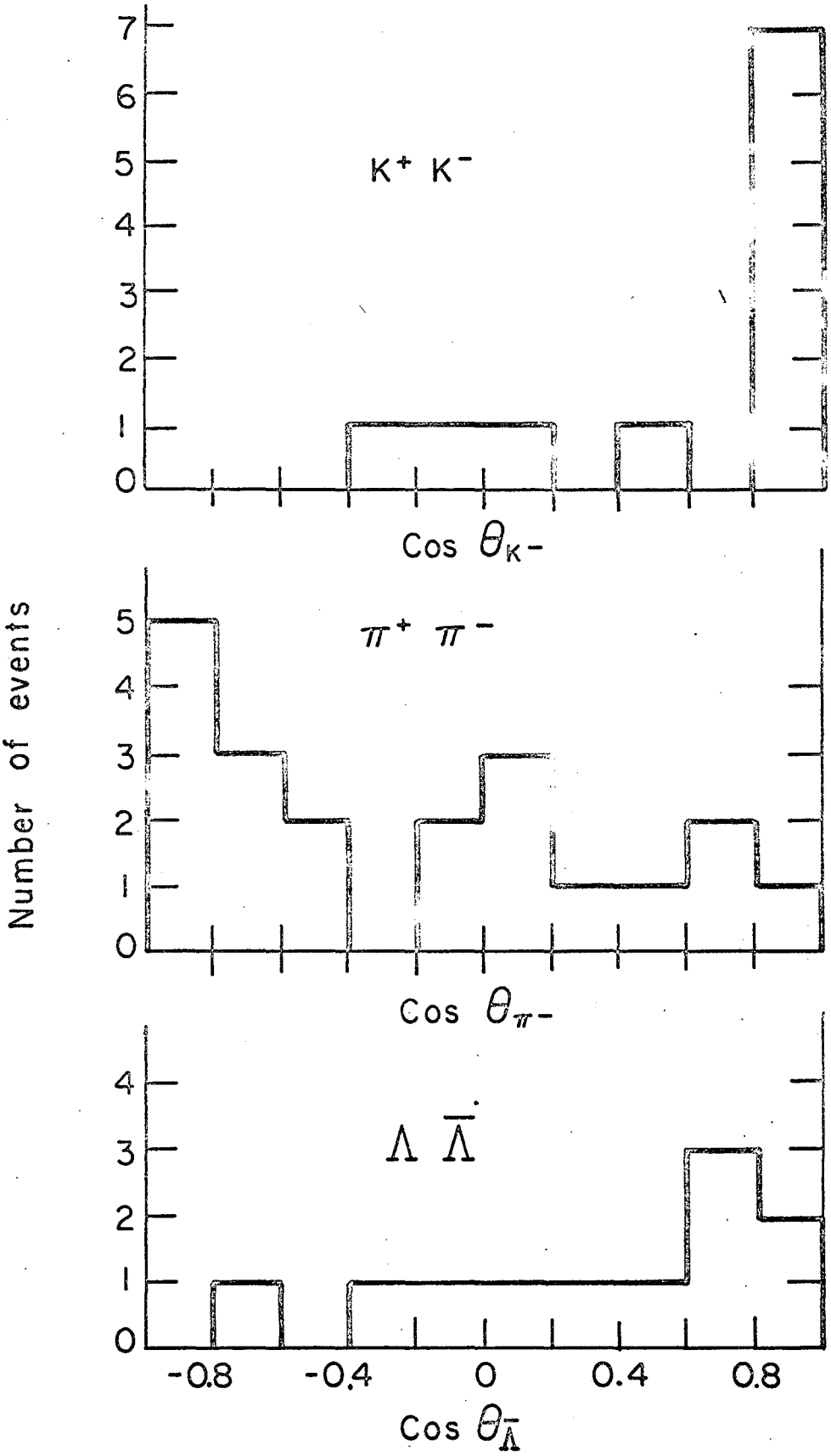
Mu-21983 Fig. 2



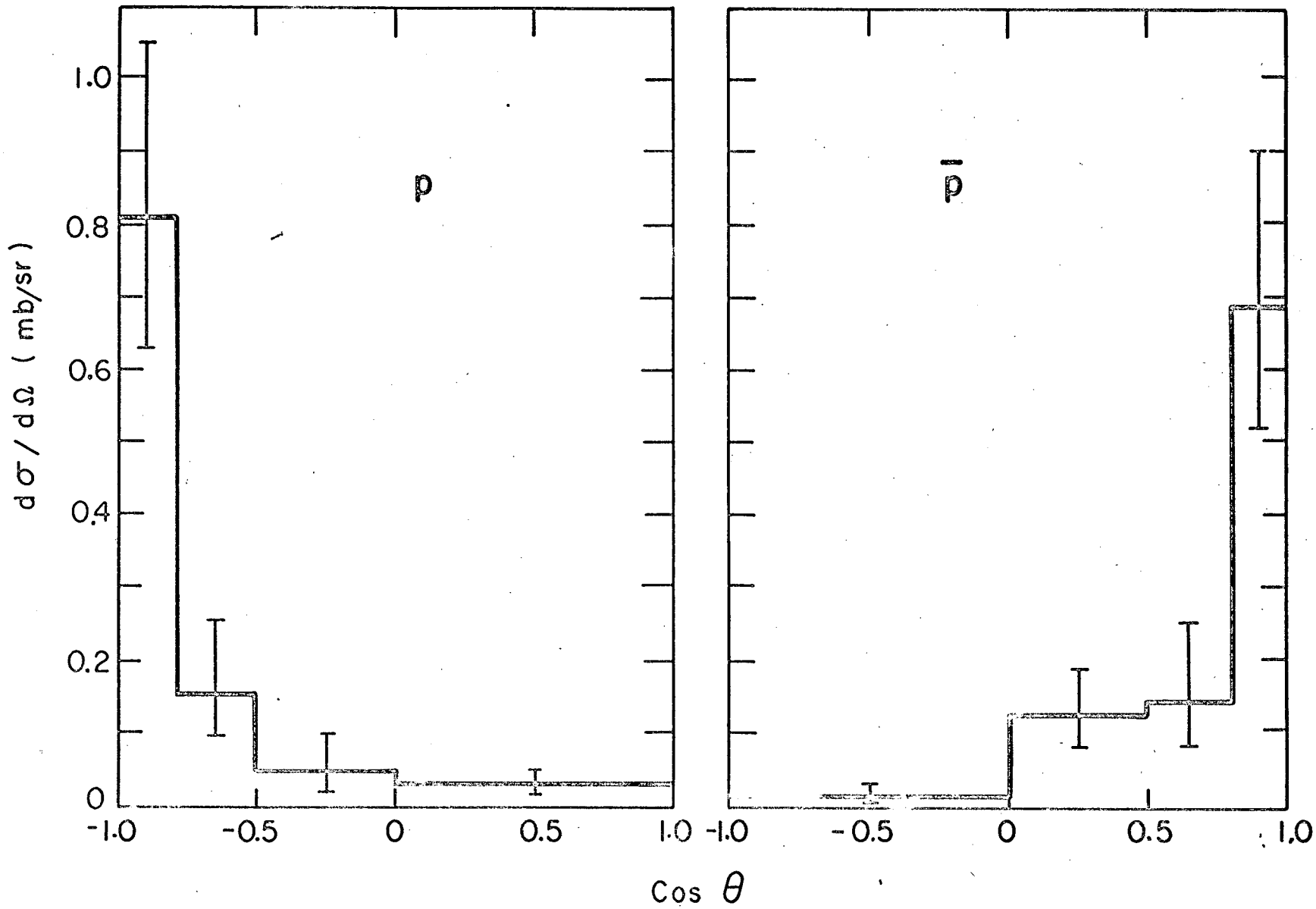
Mu-21984 Fig. 3


Events which fit
no 2 body process
Events which fit
elastic scatters
Events which fit
$K^+ K^-$
Events which fit
$\pi^+ \pi^-$
-0.10
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.10
Coplanarity

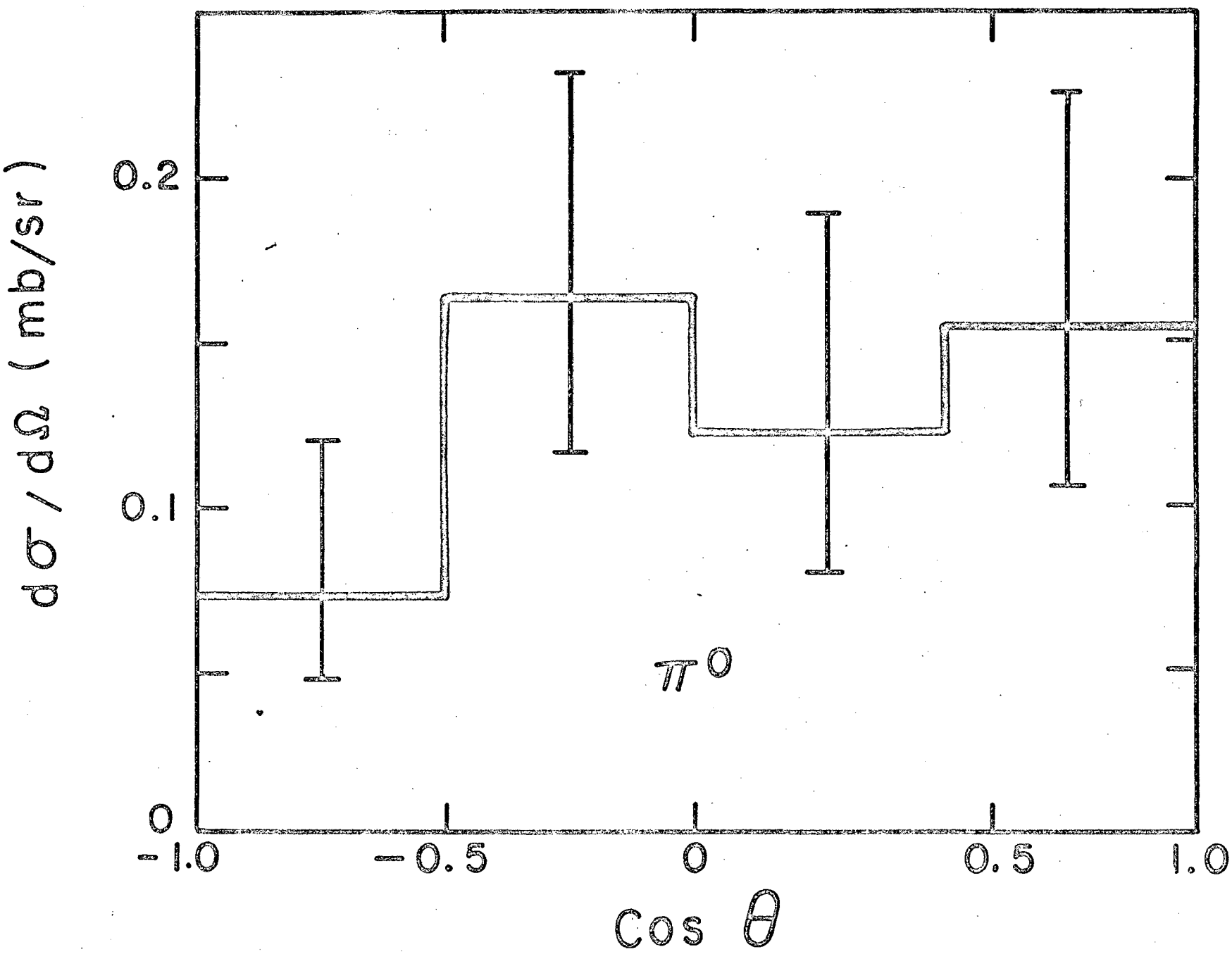
MuB-501 Fig. 4



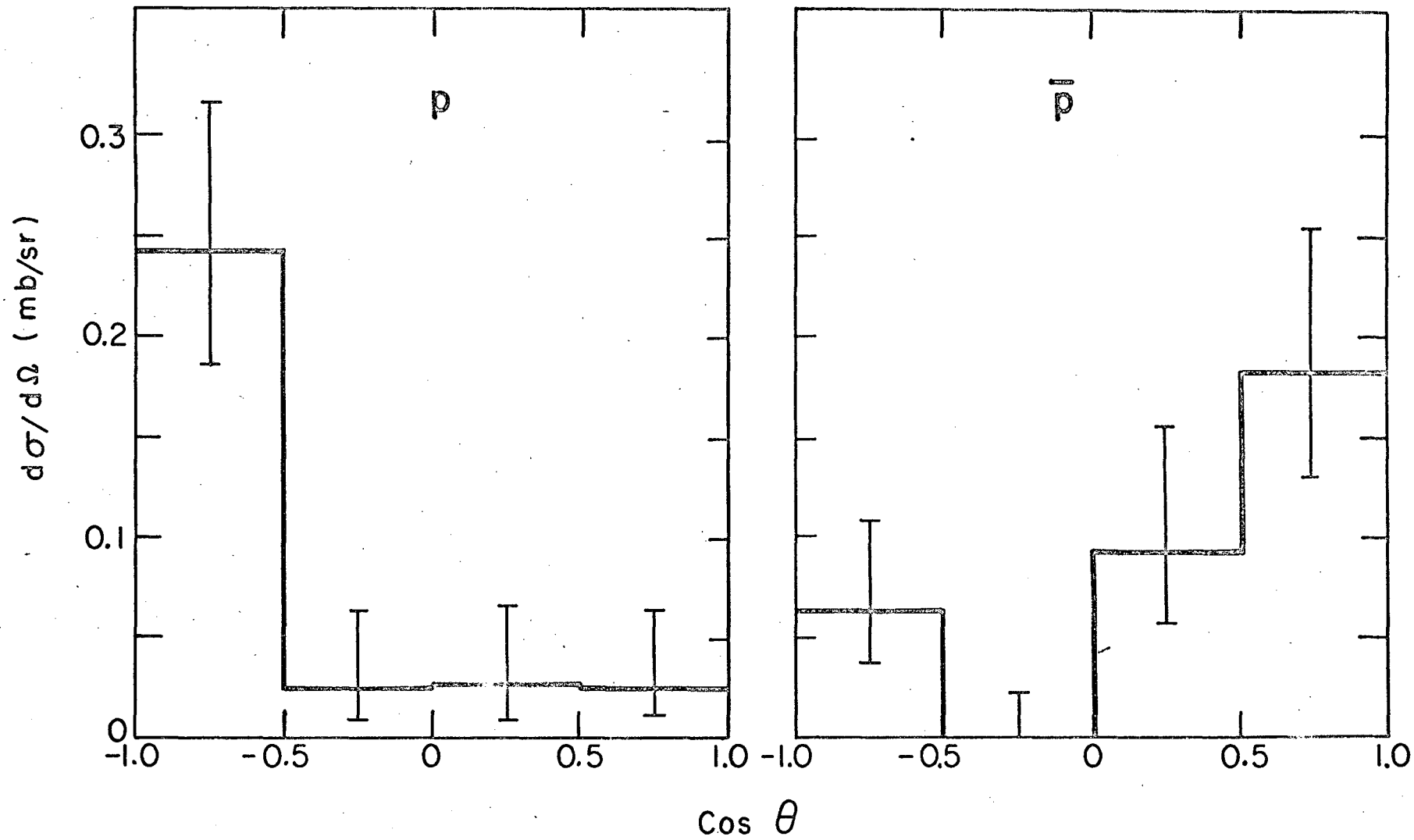
Mu-22674 Fig. 5



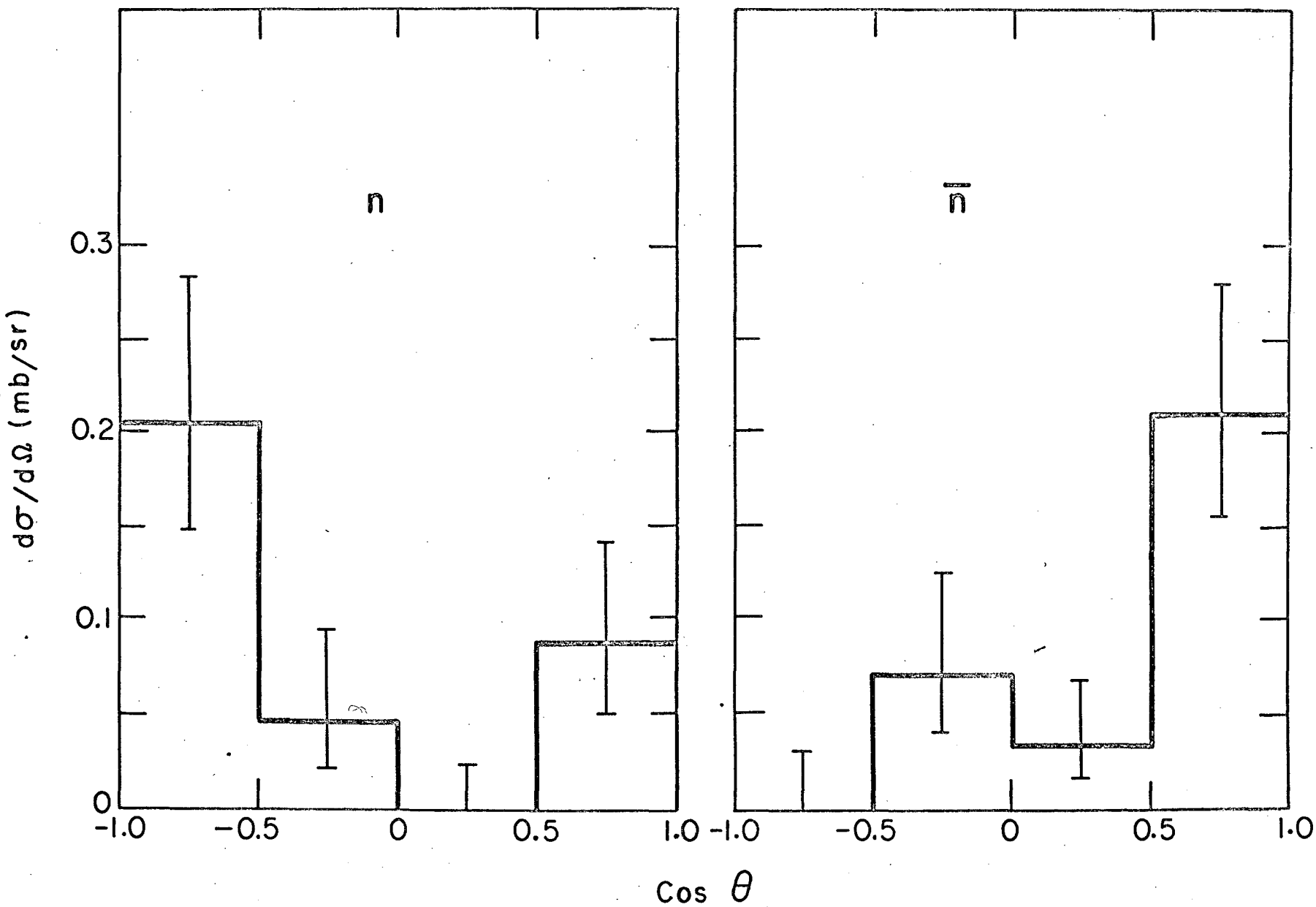
Mu-22673 Fig. 6



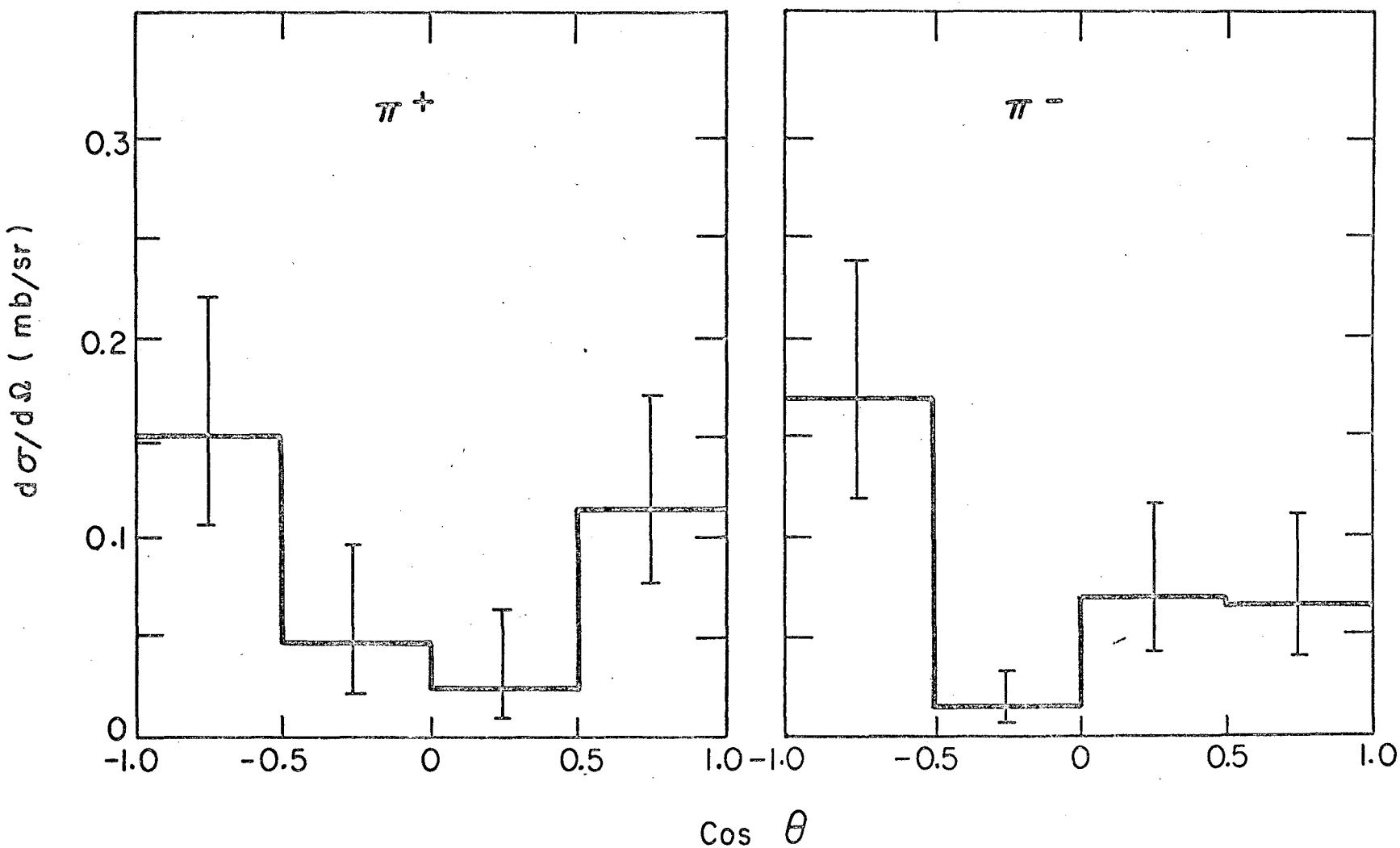
Mu-22671 Fig. 7



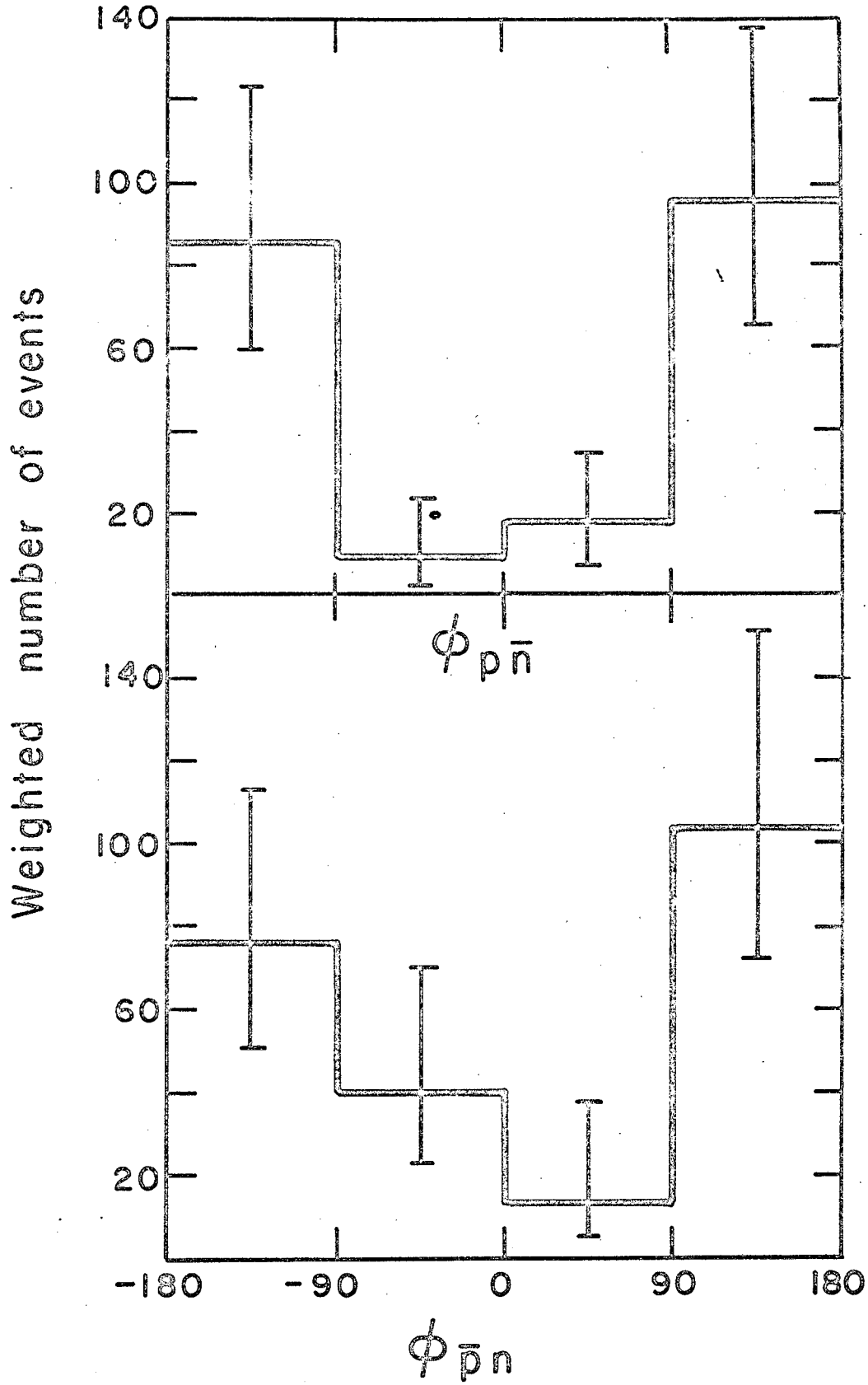
Mu-22672 Fig. 8



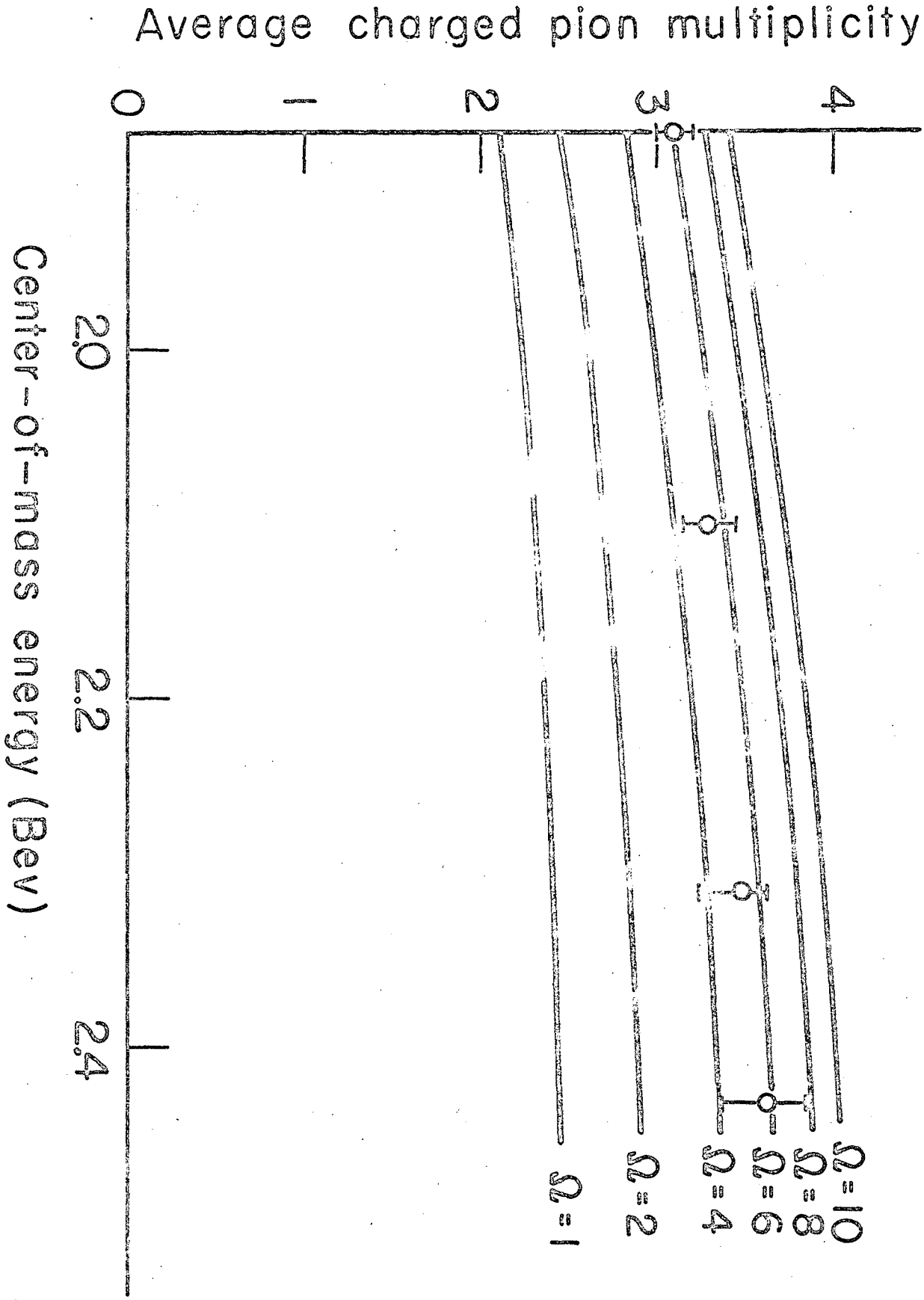
Mu-22668 Fig. 9



Mu-22669 Fig. 10



Mu-22670 Fig. 11



Mu-22229 Fig. 12