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ABSTRACT

Proton-antiproton annihilations at 1.61 BeV/c with only two mesons in the final state have been examined in the 72-inch bubble chamber. The partial cross sections measured are

$$\bar{p} + p \rightarrow \pi^- + \pi^+ \quad 119 \pm 30\ \mu b$$

$$\bar{p} + p \rightarrow K^- + K^+ \quad 55 \pm 18\ \mu b.$$

The K^- distribution in $\bar{p} + p \rightarrow K^- + K^+$ is peaked strongly forward, with 7 of the 11 K^- mesons produced in the forwardmost tenth of the total solid angle. The π^- events show no such effect, with only 2 of the 22 π^- mesons being produced in the same forward interval. Careful study of possible contamination of these events indicates that almost all of them are genuine two-meson annihilations.

TWO-MESON ANNIHILATIONS OF 1.61-BeV/c ANTIPROTONS IN HYDROGEN*

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Nucleon-antinucleon annihilations into two mesons are likely to assume increasing importance in high-energy physics. From the S-matrix point of view, these reactions may become important because they are described by analytic continuation of the same functions that describe the much studied meson-nucleon scattering. In addition, Unitary Symmetry models give predictions[1] about some of the relative two-meson-annihilation cross sections at large energy and large momentum transfer. In particular, the Sakata model predicts

$$\sigma_{\bar{p}+p\to\pi^+ + \pi^-} \overset{t,\, s\to\infty}{=} \sigma_{\bar{p}+p\to K^+ + K^-} ,$$

and the Gell-Mann - Ne'eman model predicts

$$\sigma_{\bar{p}+p\to\pi^+ + \pi^-} \overset{t,\, s\to\infty}{=} \sigma_{\bar{p}+p\to K^0 + \bar{K}^0} .$$

Two experimental measurements of two-meson annihilations have been reported, the first for 1.61-BeV/c antiprotons[2] and the second for antiprotons at rest.[3] This paper is a more complete report of the 1.61-BeV/c antiproton annihilations and contains a more careful analysis of the possible biases than did the preliminary report. This paper also complements the preceding paper,[4] and between the two papers a fairly complete analysis of all two-prong antiproton annihilations at 1.61 BeV/c is presented.

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This experiment was done in the 72-inch hydrogen bubble chamber. A beam of 1.64-BeV/c antiprotons was sent into the chamber. The details of the beam are published elsewhere.[5] In the portion of the film used for the search for two-meson annihilations, there are about 20,200 antiproton interactions and about 2800 pion interactions. Of these 23,000 interactions, 13,560 have two charged particles in the final state.

All these two-prong events found in the first scan of the film were examined on the scanning table and, if necessary, roughly measured to see if they were coplanar, and if they otherwise satisfied two-body annihilation kinematics. These scanning-table measurements had a precision of one to two degrees for angle measurements and typically 10% for momentum measurements. Only events that undoubtedly were not two-meson annihilations were eliminated at this stage.

This procedure eliminated all but 125 of the two-prong events as candidates. These 125 events were measured with the Franckenstein measuring projector and analyzed with the track-reconstruction program PANG and the kinematics program KICK.

There were 32 events in which the incident particle had a momentum more than three standard deviations below the average momentum of the antiproton beam, and they were eliminated from the sample. Most of them were interactions of incident pions. Of the remaining 93 events, one fitted elastic antiproton scattering, and 9 fitted elastic pion scattering; these elastic events did not fit either of the two-body annihilation processes. Most of the rest of the events gave a reasonable fit to $\pi^+\pi^-\pi^0$, and a few events fitted the other three-body annihilation processes. Figure 1 shows the χ^2 distributions for the tests of the $\pi^+\pi^-$ and K^+K^- hypotheses. All 60 of the 93 events not shown on these plots had $\chi^2 > 100$.

These distributions have a mean two or three times the expected value of the mean for these four-constraint fits, which is 4. This is an indication that the errors assigned were underestimated by an average factor of about 1.6. We find that our χ^2 distributions are too large in other cases, such as Λ or K_1^0 decays in which the identity of the events is not in doubt. In other words, there are systematic errors in the analysis of the 72-inch hydrogen bubble chamber film not accounted for, and these χ^2 distributions seem reasonable on the basis of other experience with the 72-inch chamber.[6]

There are 20 events that fit $\bar{p} + p \rightarrow \pi^+ + \pi^-$ and 11 events that fit $\bar{p} + p \rightarrow K^+ + K^-$ with $\chi^2 < 30$. The discrimination between the $\pi^+\pi^-$ and K^+K^- hypotheses is 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 the χ^2 for $\pi^+\pi^-$ is 24. However, on this event the negative outgoing track scatters elastically. This scatter fits kaon elastic scattering well and fits pion elastic scattering only poorly. Together these two pieces of information give good evidence that the event is a K^+K^- event.

The question that arises is how many of these events fitting the two-body annihilations are really three-body events just happening 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 a two-body one. Six of the twenty events fitting $\pi^+\pi^-$ do not fit any three-body process (i.e., the χ^2 for all these fits having one degree of freedom is greater than 150). But the rest of the $\pi^+\pi^-$ candidates and all the K^+K^- candidates 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, for only 2 of the 11 events that fit K^+K^- is the probability associated with the χ^2 better for the K^+K^- than for the $\pi^+\pi^-\pi^0$ interpretation.

Nevertheless, we believe that nearly all these events are true two-body events. The first pieces of evidence to this effect are the χ^2 distributions themselves. It would be expected that if these events were misinterpreted events, the χ^2 distribution would form a flat continuum rather than form the observed peaking near zero. This peaking, on the other hand, is expected from true two-body events. One might object by pointing out that a selection has already been made at the scanning table and, therefore, that those three-body events which would contribute large χ^2 had been eliminated. That most of the events had $\chi^2 > 100$ shows that the scanning-table selection was not as restrictive as would be required for the objection to hold.

A more direct check of possible scanning-table bias against high χ^2 was made when a large random sample of two-prong events were measured. The events measured included all inelastic two-prong events from a sample of about 8800 antiproton interactions--a sample nearly one-half as large as the entire sample. In this sample were found 9 $\pi^+\pi^-$ events and 5 K^+K^- events with $\chi^2 < 30$. Of these, seven of the $\pi^+\pi^-$ events and all the K^+K^- events had been found before. One of the new events had been missed in the first scan of the film, and the other had been missed in the search for two-meson annihilations. The χ^2 distributions for these events is shown in Fig. 2. These distributions indicate that the χ^2 distribution of the background events is flat. On the basis of this, we estimate that in the entire sample there is one background event in the K^+K^- distribution and one-half a background event in the $\pi^+\pi^-$ distribution with $\chi^2 < 30$.

As a further check on this background calculation, a random sample of antiproton annihilations was simulated by program FAKE and processed by the same data-analysis system that analyzed the real data. That this sample is a fairly good representation of the two-prong annihilations is demonstrated in the analysis of the many-pion annihilations. The distributions obtained by using this simulated sample is shown on Fig. 3. The number of background events indicated by these data is consistent with the number seen in the real data. Furthermore, the FAKE distributions support the contention that the background distribution is fairly flat and that there are few background events with $\chi^2 < 30$.

It still remains to be explained why most of the K^+K^- events fit the $\pi^+\pi^-\pi^0$ interpretation better than they do the K^+K^- interpretation. The kinematics are such that a K^+K^- event can be expected to fit $\pi^+\pi^-\pi^0$ well most of the time. In a sample of 50 K^+K^- events generated by FAKE, 40% fit $\pi^+\pi^-\pi^0$ better than they fitted K^+K^-. This FAKE run was made under the assumption that the real errors and the quoted errors were identical. However, in our case we know that the quoted errors are underestimated. Therefore, another FAKE run was made in which the errors on the angles were increased without increasing the quoted errors. This resulted in doubling the average χ^2 for the K^+K^- hypothesis (more nearly in agreement with the actual data) while making only a slight change in the $\pi^+\pi^-\pi^0$ χ^2 values. In this case, 60% of the events fit $\pi^+\pi^-\pi^0$ better than K^+K^-. Thus when errors are poorly estimated, it is indeed possible for events of one type to have a wrong hypothesis as the best fit a majority of the time.

After correcting for efficiencies and making use of the total antiproton-proton cross section, we find the following cross sections at 1.61 BeV/c:

$$\sigma_{\bar{p}+p \to \pi^+ + \pi^-} = 119 \pm 30\,\mu b$$

and

$$\sigma_{\bar{p}+p \to K^+ + K^-} = 55 \pm 18\,\mu b\,.$$

The fraction of annihilations proceeding by the $\pi^+\pi^-$ and K^+K^- modes is $(2.3 \pm 0.6) \times 10^{-3}$ and $(1.1 \pm 0.4) \times 10^{-3}$, respectively. This two-pion-annihilation frequency is 0.58 ± 0.15 times as great as the frequency observed for annihilation at rest, and the two-kaon-annihilation frequency is, correspondingly, 0.8 ± 0.3 times as great.

In the previous search for $\bar{p} + p \to \bar{\Lambda} + \Lambda$ events,[5] all of the zero-prong events with associated decays were examined. None of the cases in which there were two associated neutral decays fitted the reaction $\bar{p} + p \to \bar{K}^0 + K^0$. One event with a single associated decay did fit this reaction well, and another one fitted it poorly. These events could be background events. Since the probability of observing at least one K^0 from this reaction is about 5/9, we can say with at least 90% confidence that the cross section for $\bar{p} + p \to \bar{K}^0 + K^0$ is less than 55 μb.

The center-of-mass angular distributions of the π^- and the K^- from the two-body annihilations are shown on Fig. 4. The distributions are plotted in such a way that one can compare the differential cross sections of these two reactions at the same momentum transfer. At this energy and these momentum transfers the prediction of the Sakata model that the $\pi^+\pi^-$ and the K^+K^- cross sections are equal is not well satisfied.

The striking feature of these distributions 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 bias is clearly shown by the fact that the $\pi^+\pi^-$ events, which were chosen and analyzed by the same techniques, do not exhibit this effect. A further indication of this is that the events that have $30 < \chi^2_{K^+K^-} < 500$ do not exhibit this forward peaking. This strong forward peaking of the K^- suggests an exchange phenomenon. The simplest exchange model is the one in which the antiproton and proton exchange a Λ or a Σ^0. First Born-approximation calculations of the contribution of these lowest-order diagrams result in a predicted cross section about two orders of magnitude too large, and predict angular distributions that do not agree with the data for either parity of the Σ. Sopkovich[7] has done a modified Born-approximation calculation that fits the K^+K^- angular-distribution data fairly well for even $\Sigma\Lambda$ parity but not for odd $\Sigma\Lambda$ parity.

ACKNOWLEDGMENTS

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FOOTNOTES AND REFERENCES

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LEGENDS

Fig. 1. Histograms of the χ^2 distribution for the selected sample of two-prong events for the hypotheses of $\bar{p} + p \rightarrow \pi^+ + \pi^-$ and $\bar{p} + p \rightarrow K^+ + K^-$. Some events occur on both plots. The cross-hatched squares represent events that have a smaller χ^2 for the other two-meson interpretation.

Fig. 2. Histograms of the χ^2 distribution for the $\pi^+\pi^-$ and K^+K^- hypotheses for events from the random sample of two prongs. Each event is plotted only once.

Fig. 3. Histograms of the χ^2 distribution for the $\pi^+\pi^-$ and K^+K^- hypotheses for the simulated events. Each event is plotted only once.

Fig. 4. Histograms of the distribution of the c.m. angle for the events that fit the $\pi^+\pi^-$ and K^+K^- hypotheses. The distributions are plotted in such a way that one can directly compare the differential cross sections $\frac{d\sigma}{d\Delta}$ as a function of momentum transfer.

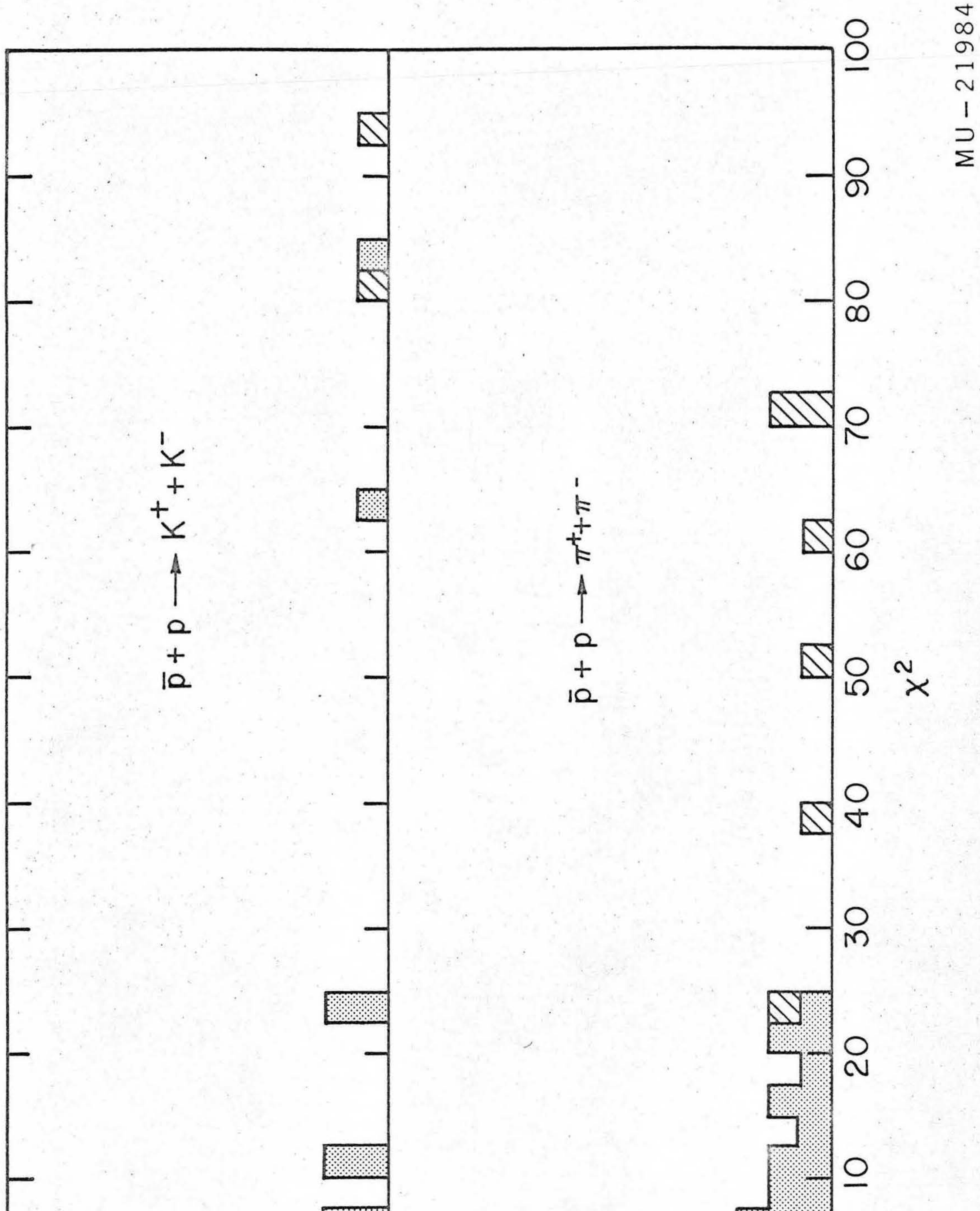

$\bar{p} + p \longrightarrow K^+ + K^-$
$\bar{p} + p \longrightarrow \pi^+ + \pi^-$
Number of events
0
10
20
30
40
50
60
70
80
90
100
χ^2
MU - 21984

Fig. 1

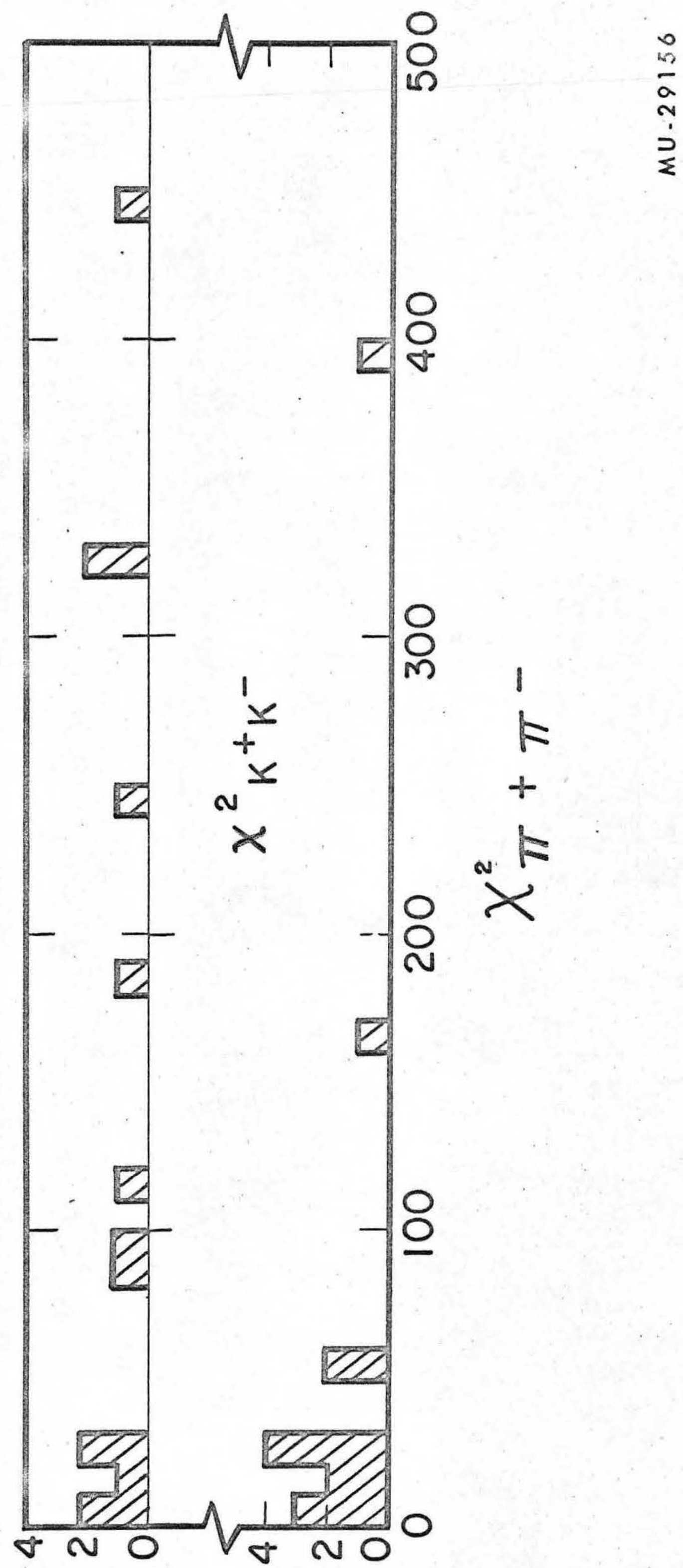

Number of events
0 2 4
0 2 4
0 100 200 300 400 500
χ² K⁺K⁻
χ² π⁺ + π⁻
MU-29156

Fig. 2

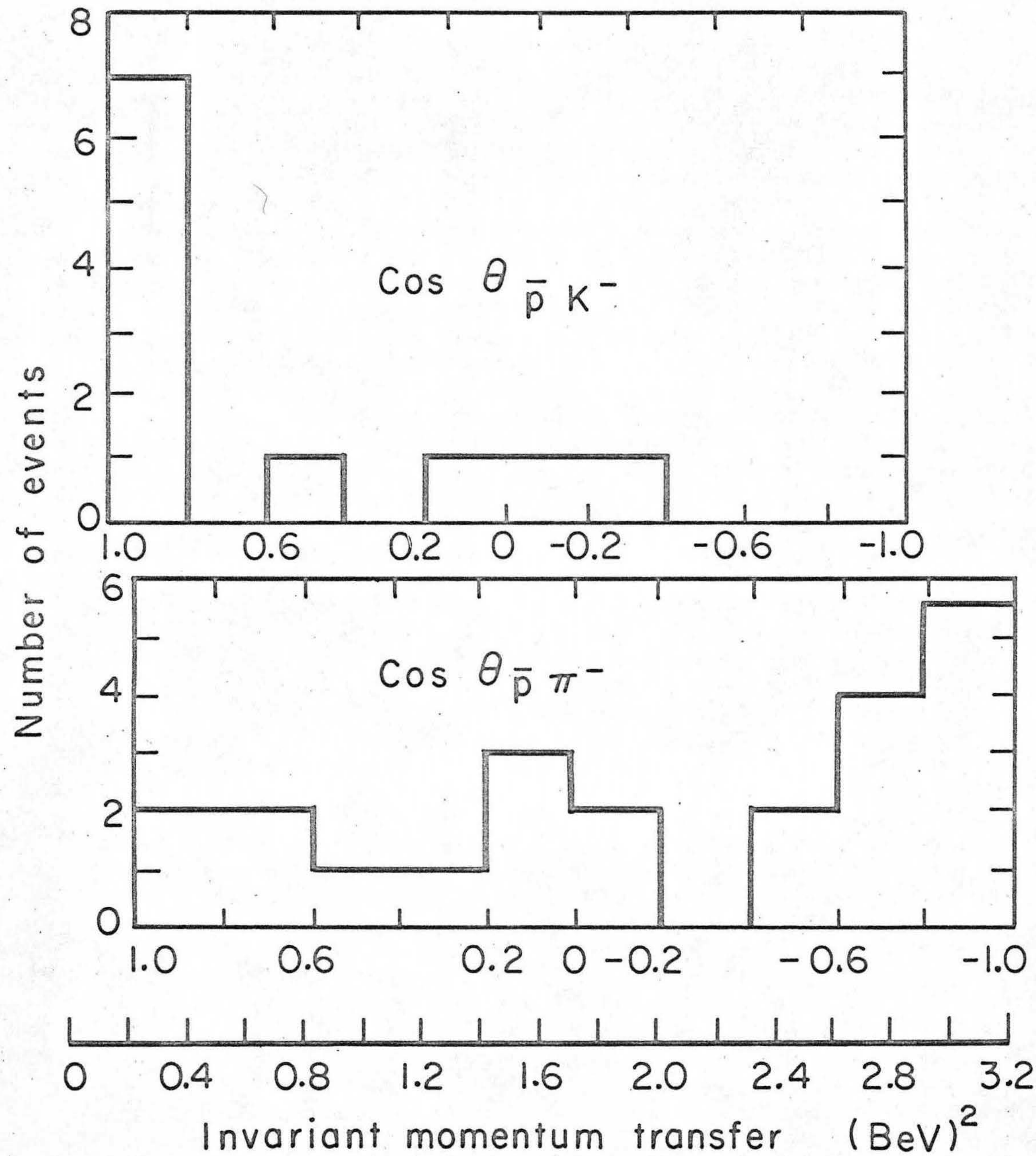
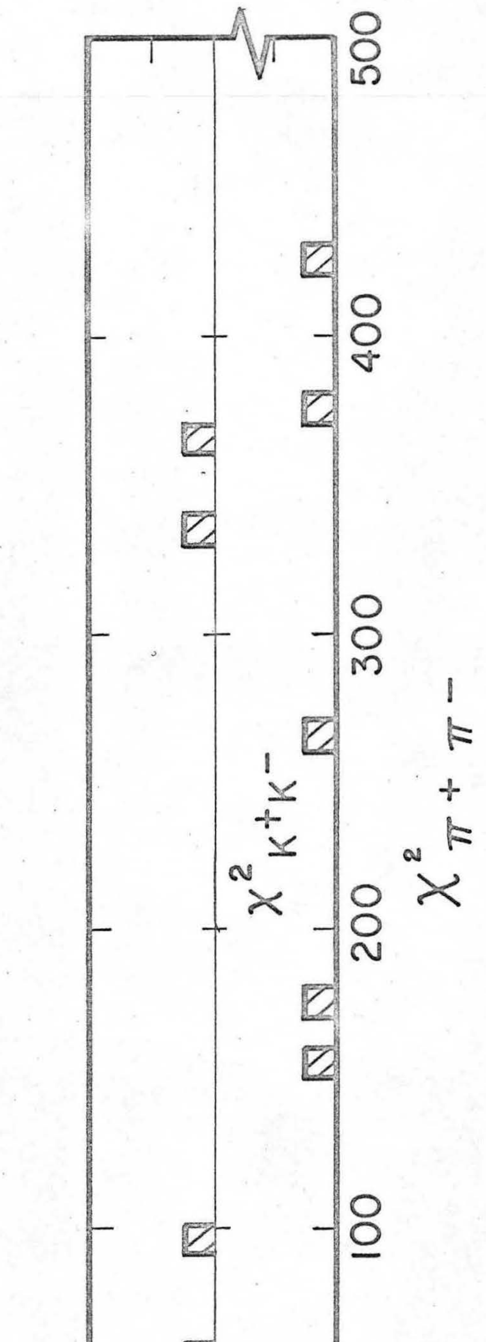


Fig. 4

MU-29144



MU-29155

Fig. 3