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D. Duane Carmony, Fernand Grard, Remy T. Van de Walle, and Nguyen-huu Xuong

May 18, 1962

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An analysis of four-prong events produced by 2.03-GeV/c π^- mesons (E^* = 2.16 GeV) in the 72-inch hydrogen bubble chamber yielded

633 events of the type $\pi^- + p \rightarrow \pi^- + p + \pi^- + \pi^+$, (1)

283 events of the type $\pi^- + p \rightarrow \pi^- + p + \pi^- + \pi^+ + \pi^0$, (2)

134 events of the type $\pi^- + p \rightarrow \pi^- + \pi^+ + \pi^- + \pi^+ + n$. (3)

We used the PACKAGE computer program (combination of PANG and KICK programs) for the track-reconstruction and fitting process. An event is found to fit Reaction (1) when it has $\chi^2 \leq 25.0$ for this reaction. It is found to fit Reaction (2) or (3) when it has $\chi^2 \leq 10.0$ for this reaction. A track-ionization examination on the scanning table helped to resolve all ambiguous events.

Using a known total cross section, we get for the cross section of Reactions (1), (2), and (3) the values 1.64±.15 mb, 0.74±.08 mb, and 0.35±.04 mb respectively.

Reaction (1)

Figure 1 shows the distribution of the effective mass of proton-pion pairs ($M_{p\pi}$) of all events of Reaction (1), (a) for $p\pi^-$ and (b) for $p\pi^+$. The $M_{p\pi^+}$ distribution shows a peak corresponding to $N^*_{3/2,3/2}$. We estimate that about 27±3% of Reaction (1) goes through the reaction $\pi^- + p \rightarrow N^{*+3/2}_{3/2,3/2} + \pi^- + \pi^-$ with $N^{*+3/2}_{3/2,3/2} \rightarrow p + \pi^+$. We assume that these events with $N^*_{3/2,3/2}$ are produced according to Fig. 2 (a) (as suggested by Freda and George Salzman[1]).

We base our assumption on two observations:

(a) We have plotted in Fig. 3 the distribution of the invariant-four-momentum transfer, Δ^2, between the initial proton and final $p\pi^+$ pair for events of Reaction (1) with the effective mass $M_{p\pi^+}$ in the region of the $N^*_{3/2,3/2}$ energy (1.12 GeV $\leq M_{p\pi^+} \leq$ 1.32 FeV) (round points). This distribution seems to agree with the curve predicted by Salzman[1] (proportional to $((W-M)^2 + \Delta^2) / (\Delta^2 + \mu^2_{\pi^-})^2$, where μ_{π^-} = mass of the pion, $W = M_{p\pi^+} \approx 1238$ Mev, and M = mass of the proton, solid curve), whereas the distribution of other events of Reaction (1) (with $M_{p\pi^+} \leq$ 1.12 GeV or $M_{p\pi^+} >$ 1.32 GeV) does not agree at all with this curve (triangular points).

(b) In diagram (a) of Fig. 2, in which the pion vertex is of the type $\pi^- + \pi^- \rightarrow \pi^- + \pi^-$, it is impossible to produce ρ mesons. This seems to be verified by our results. In Fig. 4 we have plotted the distribution of the effective mass $M_{\pi\pi}$ of the events of Reaction (1), (a) for $\pi^-\pi^-$, and (b) for $\pi^+\pi^-$. The $M_{\pi^+\pi^-}$ distribution does not show a significant peak in the region of the mass of the ρ meson. On the other hand, in the π^+-p interaction, the corresponding diagram would be 1(b). In this diagram the pion vertex is of the form $\pi^+ + \pi^- \rightarrow \pi^+ + \pi^-$, and it is possible to produce ρ mesons. This seems to be verified by the Steinberger group,[2] which finds many ρ mesons in the reaction $\pi^+ + p \rightarrow \pi^+ + p + \pi^+ + \pi^-$ (about 30% of these events are $\pi^+ + p \rightarrow \pi^+ + p + \rho^0$).

Reaction (2)

Figure 5 shows the $M_{3\pi}$ distribution of all events of Reaction (2), (a) for $\pi^+\pi^-\pi^-$, and (b) for $\pi^+\pi^-\pi^0$. The $M_{\pi^+\pi^-\pi^0}$ distribution shows a peak in the region of 550 Mev corresponding to the η meson, and another peak at about 785 Mev corresponding to the ω meson. We estimate that 12±4 events (31± 10 μb) of Reaction (2) proceed through $\pi^- + p \rightarrow \pi^- + p + \eta$ and 55 ± 12 events (142.± 31. μb) through $\pi^- + p \rightarrow \pi^- + p + \omega$ with η (or ω) $\rightarrow \pi^+ + \pi^- + \pi^0$.

To verify if the ω mesons are produced by the process illustrated by the diagram 2(c) (as suggested by Sakurai[3]), we have plotted in Fig. 6 the distribution of the invariant-four-momentum transfer, Δ^2, between the initial and final proton for events of Reaction (2) with $M_{\pi^+\pi^-\pi^0}$ in the mass region of the ω (760 to 820 Mev) (triangular points). This distribution does not agree with the curve predicted by the one-pion-exchange model (proportional to $\Delta^2/(\Delta^2 + \mu^2_{\pi^0})$ --solid curve), whereas the Δ^2 distribution of all events of Reaction (2) (round points) agrees with this curve. The ω mesons do not, then, seem to be produced by the process illustrated by Fig. 2(c). We offer the hypothesis that the ω mesons are produced by the process illustrated by Fig. 2(d). Our hypothesis is supported by two observations:

(a) The distribution of the effective mass of the p-π^- pairs, which are produced with a $\pi^+\pi^-\pi^0$ triplet having an effective mass in the ω mass region (Fig. 7), seems to show a peak corresponding to the $N^{*-1/2}_{3/2,3/2}$ over the phase-space estimate (solid curve normalized over the background). This could mean that the mesons are produced via the reaction $\pi^- + p \rightarrow \omega + N^{*-1/2}_{3/2,3/2}$, with $N^{*-1/2}_{3/2,3/2} \rightarrow \pi^- + p$. (This evidence is rather weak, because it is difficult to know how to normalize the phase-space curve).

(b) The reaction $\pi + p \rightarrow \omega + N^{*}_{3/2,3/2}$, proceeding through a pure $I = 3/2$ channel, must be much stronger for $\pi^+ + p$ (Fig. 2e) than for $\pi^- + p$. This assumption seems to be verified by the Steinberger group,[2] which finds that the events of the type $\pi^+ + p \rightarrow \pi^+ + p + \pi^+ + \pi^- + \pi^0$ are dominated by ω production (about 80% of these events are $\pi^+ + p \rightarrow \pi^+ + p + \omega$).

Figure 8 shows the Dalitz plot of 17 events with $540\ \text{MeV} \leq M_{\pi^+\pi^-\pi^0} \leq 550\ \text{MeV}$, of which only 12 ± 4 can be attributed to the η mesons. The points tend to be in the region of small T_{π^0} as observed by Bastien et al.[4]

Figure 9 shows the $M_{p\pi}$ distribution of events of Reaction (2), (a) for $p\pi^-$ pairs, (b) for $p\pi^+$ pairs, and (c) for $p\pi^0$ pairs. The $M_{p\pi^+}$ distribution shows the peak at $N^*_{3/2,3/2}$ energy. Figure 10 shows the $M_{4\pi}$ distribution of all events of Reaction (2) ($\pi^+\pi^-\pi^-\pi^0$). This distribution agrees with the phase-space calculation (solid curve).

Reaction 3

Figure 11 shows the distribution of the effective mass of neutron-pion pairs of Reaction (3) events, (a) for $n\pi^+$, (b) for $n\pi^-$. The $N^*_{3/2,3/2}$ seem to be there, but it is difficult to determine them quantitatively.

Figure 12 shows the $M_{3\pi}(\pi^\pm\pi^\pm\pi^\mp)$ and the $M_{4\pi}(\pi^+\pi^-\pi^+\pi^-)$ distributions of Reaction (3) events. Both distributions agree with the phase-space calculation (solid curves).

We want to thank Professor Luis W. Alvarez, Professor Donald H. Miller, and Dr. George Kalbfleisch for their encouragement and help. We are indebted to Professor Jack Steinberger for letting us know the results of his group's work before publication.

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* Work done under the auspices of the U.S. Atomic Energy Commission.

† On leave from the Institut Interuniversitaire des Sciences Nucléaires, Belgium.

1. Freda Salzman and George Salzman, Phys. Rev. 120, 599 (1960).
2. Jack Steinberger (Nevis Laboratory, Columbia University) private communication. The Steinberger group analyzed $\pi^+ p$ interactions at 2.3 GeV/c ($E^* = 2.27$ GeV). We do not believe that the difference of this energy alone (0.11 GeV) could produce such a large difference in the rates of production of the ρ and ω mesons between their experiment and ours.
3. J. Sakurai, Phys. Rev. Letters 8, 300 (1962).
4. P. Bastien, J. P. Berge, O. I. Dahl, M. Ferro-Luzzi, D. H. Miller, J. J. Murray, A. H. Rosenfeld, and M. B. Watson, Phys. Rev. Letters 8, 114 (1962).

FIGURE LEGENDS

Fig. 1. Distributions of the effective mass of proton-pion pairs, $M_{p\pi}$, of events of Reaction (1): (a) for $p\pi^-$ pairs and (b) for $p\pi^+$ pairs. The solid curves are estimations, 73% from pure phase-space prediction and 27% with $p\pi^+$ in the $N^{*+3/2}_{3/2,3/2}$ resonance.

Fig. 2. Diagrams illustrating some processes of multipion production by pion-nucleon interaction (see text).

Fig. 3. Distribution of the invariant-four-momentum transfer, Δ^2, between the initial proton and final $p\pi^+$ pair for events of Reaction (1); $\vdash\!\!-\!\!\circ\!\!-\!\!\dashv$ for events with 1.12 GeV $\leq M_{p\pi^+} \leq$ 1.32 GeV, $\vdash\!\!-\!\!\Delta\!\!-\!\!\dashv$ for other events (μ_{π^-} = mass of the charged pions). The solid curve represents the prediction of the Salzman model.

Fig. 4. Distributions of the effective mass of two pions M_2 of Reaction (1) events, (a) for $\pi^-\pi^-$, (b) for $\pi^+\pi^-$. The solid curves are phase-space estimations.

Fig. 5. Distributions of the effective mass of three pions, M_3, of Reaction (2) events, (a) for $\pi^+\pi^-\pi^-$, (b) for $\pi^+\pi^-\pi^0$. The solid curves are phase-space estimates.

Fig. 6. Distribution of the invariant-four-momentum transfer, Δ^2, between the initial and final protons of Reaction (2) events, $\vdash\!\!-\!\!\Delta\!\!-\!\!\dashv$ for events with 760 MeV $\leq M_{\pi^+\pi^-\pi^0} \leq$ 820 MeV, $\vdash\!\!-\!\!\circ\!\!-\!\!\dashv$ for all events of reaction (2). The solid curve represents the one pion-exchange-model prediction.

Fig. 7. Distribution of the effective mass of the p-π^- pairs, $M_{p\pi^-}$, of events of Reaction (2) produced with a $\pi^+\pi^-\pi^0$ triplet having 760 MeV $\leq M_{\pi^+\pi^-\pi^0} \leq$ 820 MeV.

Fig. 8. Dalitz plot of 17 events with 540 MeV $\leq M_{\pi^+\pi^-\pi^0} \leq$ 550 MeV ($Q = M_{\pi^+\pi^-\pi^0}$ $(2 M_{\pi^\pm} + M_0)$) (only 12 ± 4 are η mesons).

Fig. 9. Distribution of the effective mass of the p-π pairs, $M_{p\pi}$, of all events of Reaction (2), (a) for $p\pi^-$, (b) for $p\pi^+$, and (c) for $p\pi^0$. The solid curves are phase-space estimates.

Fig. 10. Distribution of the effective mass of pion quadruplets ($\pi^+\pi^-\pi^-\pi^0$), M_4, of Reaction (2) events. The solid curve is a phase-space estimate.

Fig. 11. Distributions of the effective mass of neutron-pion pairs, $M_{n\pi}$, of events of Reaction (3) (a) for $n\pi^+$, (b) for $n\pi^-$. The solid curves are phase-space estimates.

Fig. 12. Distribution of the effective masses of(a)pion triplets ($\pi^\pm\pi^\pm\pi^\mp$), M_3, of Reaction (3) events, (b) of pion quadruplets ($\pi^+\pi^-\pi^+\pi^-$), M_4, of Reaction (3) events. The solid curves are phase-space estimates.

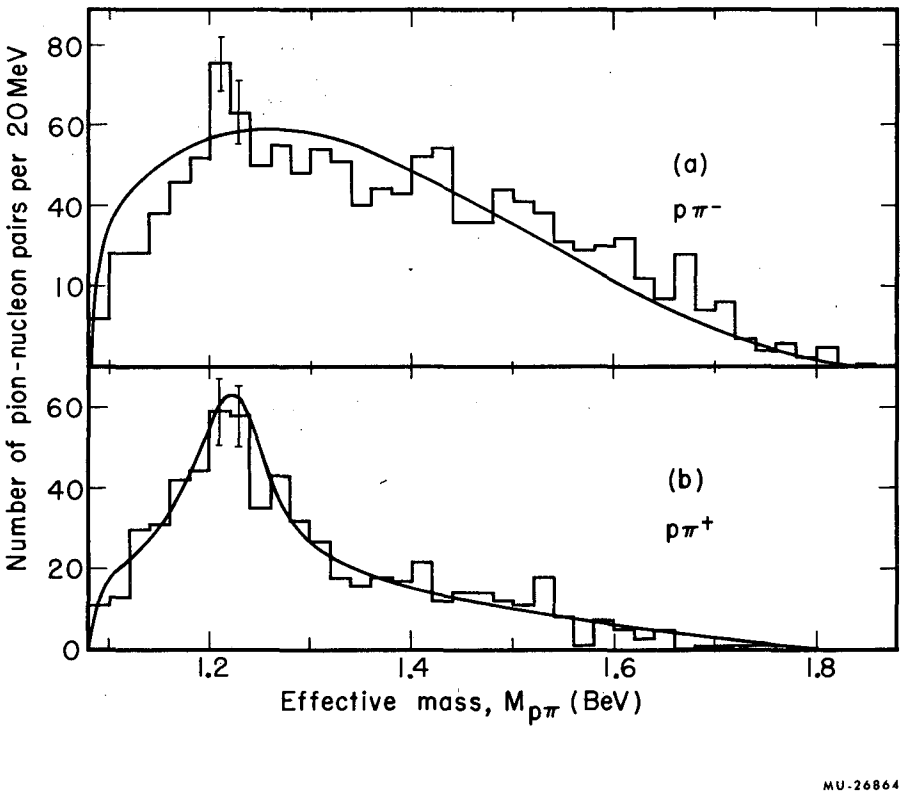
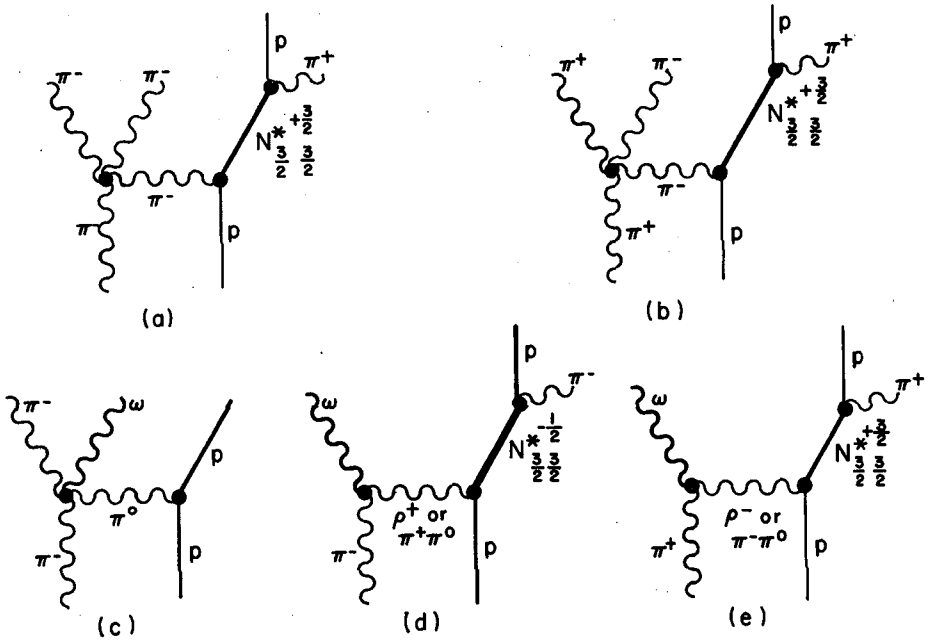

Number of pion-nucleon pairs per 20 MeV
80
60
40
10
(a)
pπ⁻
60
40
20
0
(b)
pπ⁺
1.2
1.4
1.6
1.8
Effective mass, Mpπ (BeV)
MU-26864

Fig. 1



MU-26863

Fig. 2

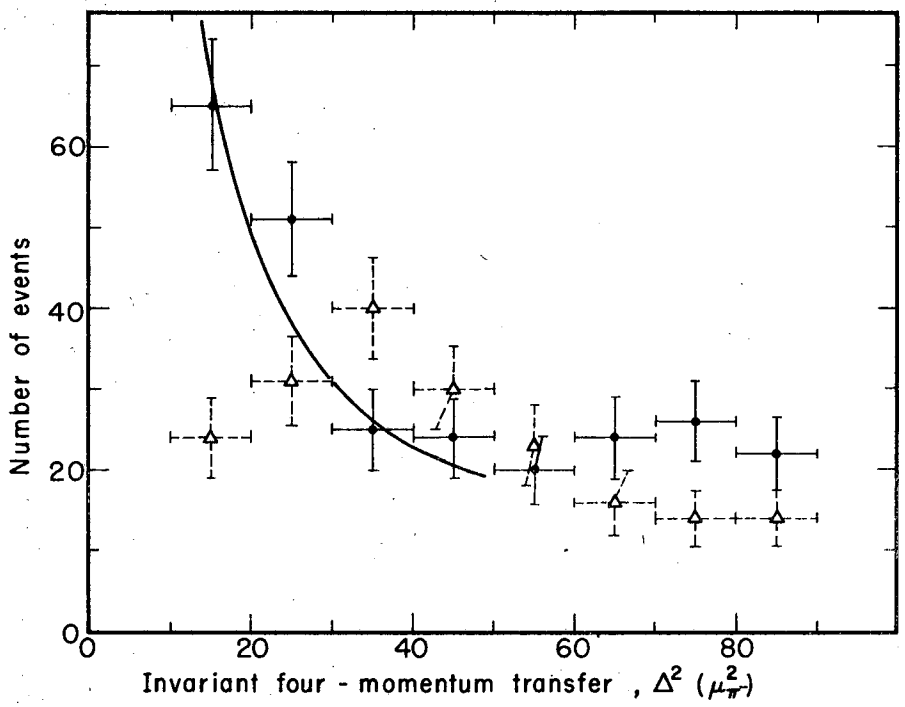

Number of events
0
20
40
60
0
20
40
60
80
Invariant four - momentum transfer , Δ^2 ($\mu_{\pi^-}^2$)
MU-26865

Fig. 3

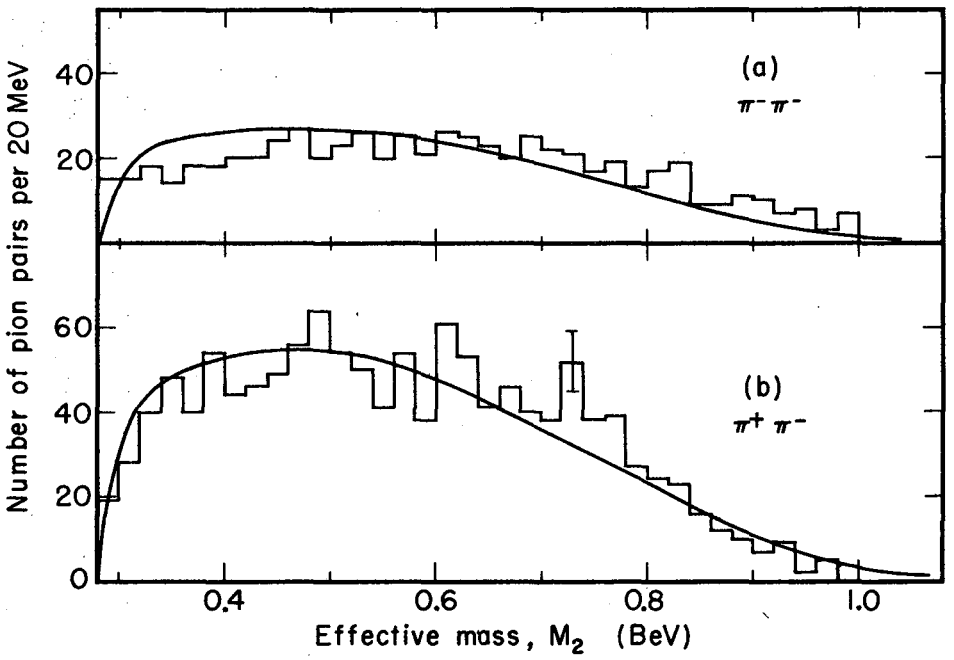
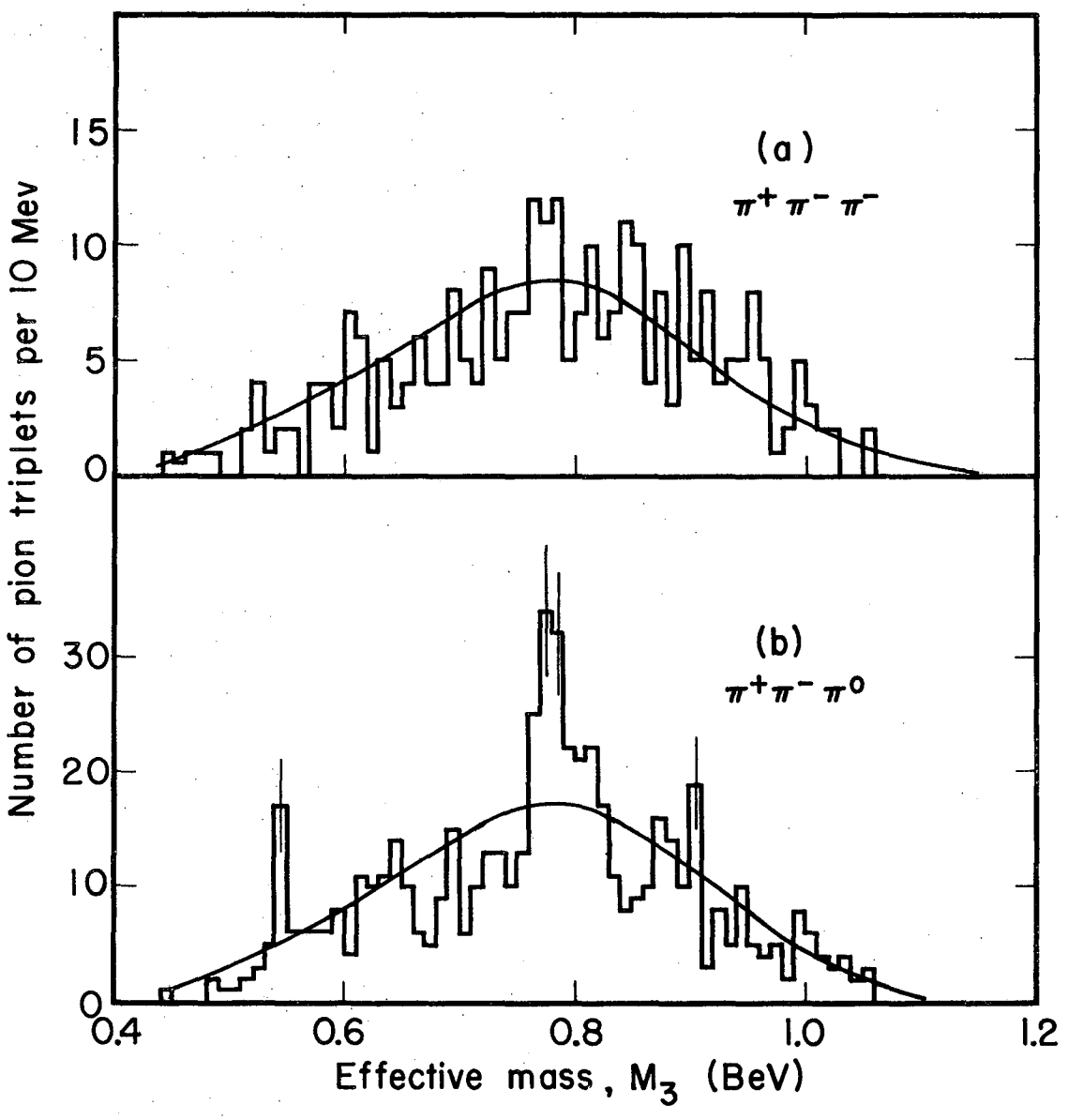

Number of pion pairs per 20 MeV
40
20
(a)
$\pi^-\pi^-$
60
40
20
0
(b)
$\pi^+\pi^-$
0.4
0.6
0.8
1.0
Effective mass, M_2 (BeV)
MU-26866

Fig. 4



MUB-1092

Fig. 5

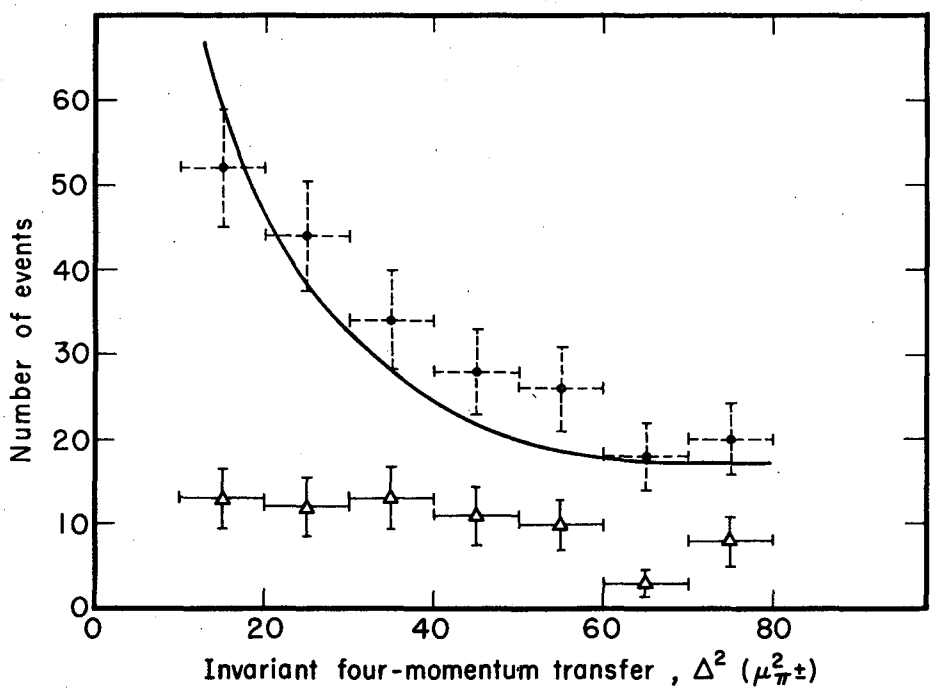
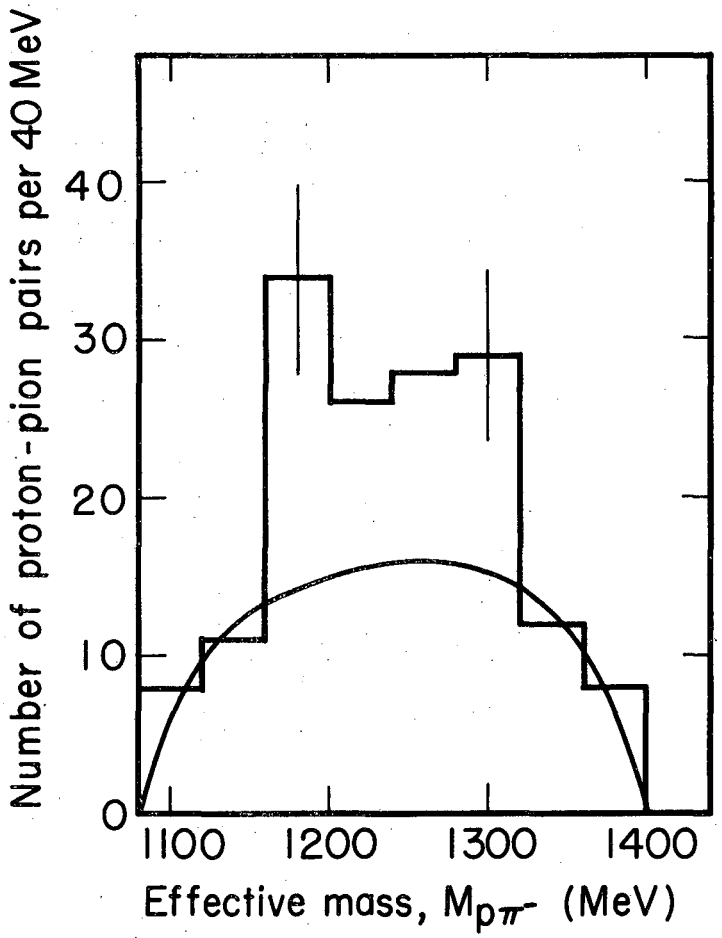
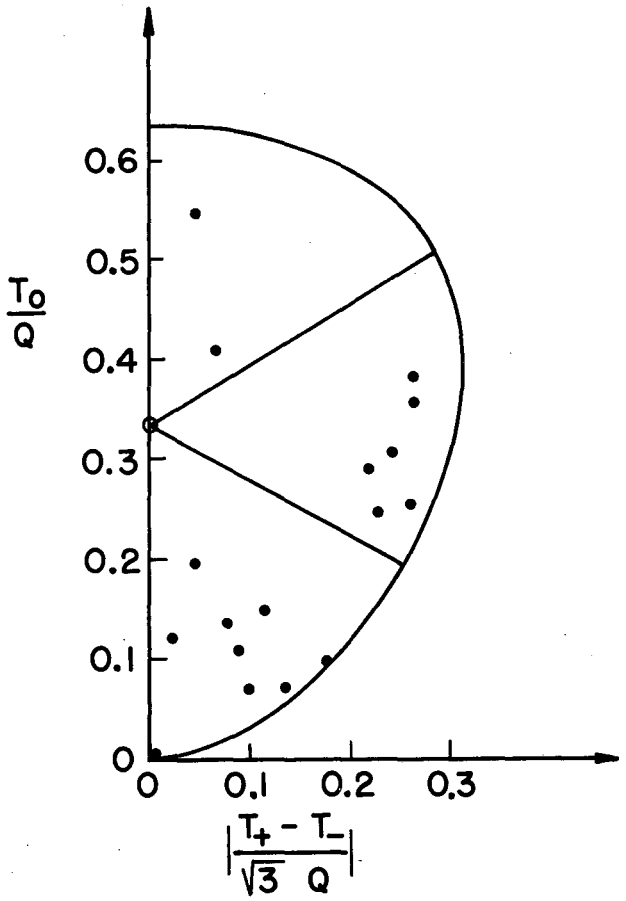

Number of events
0
10
20
30
40
50
60
0
20
40
60
80
Invariant four-momentum transfer , Δ^2 ($\mu^2_{\pi^\pm}$)
MU-26867

Fig. 6



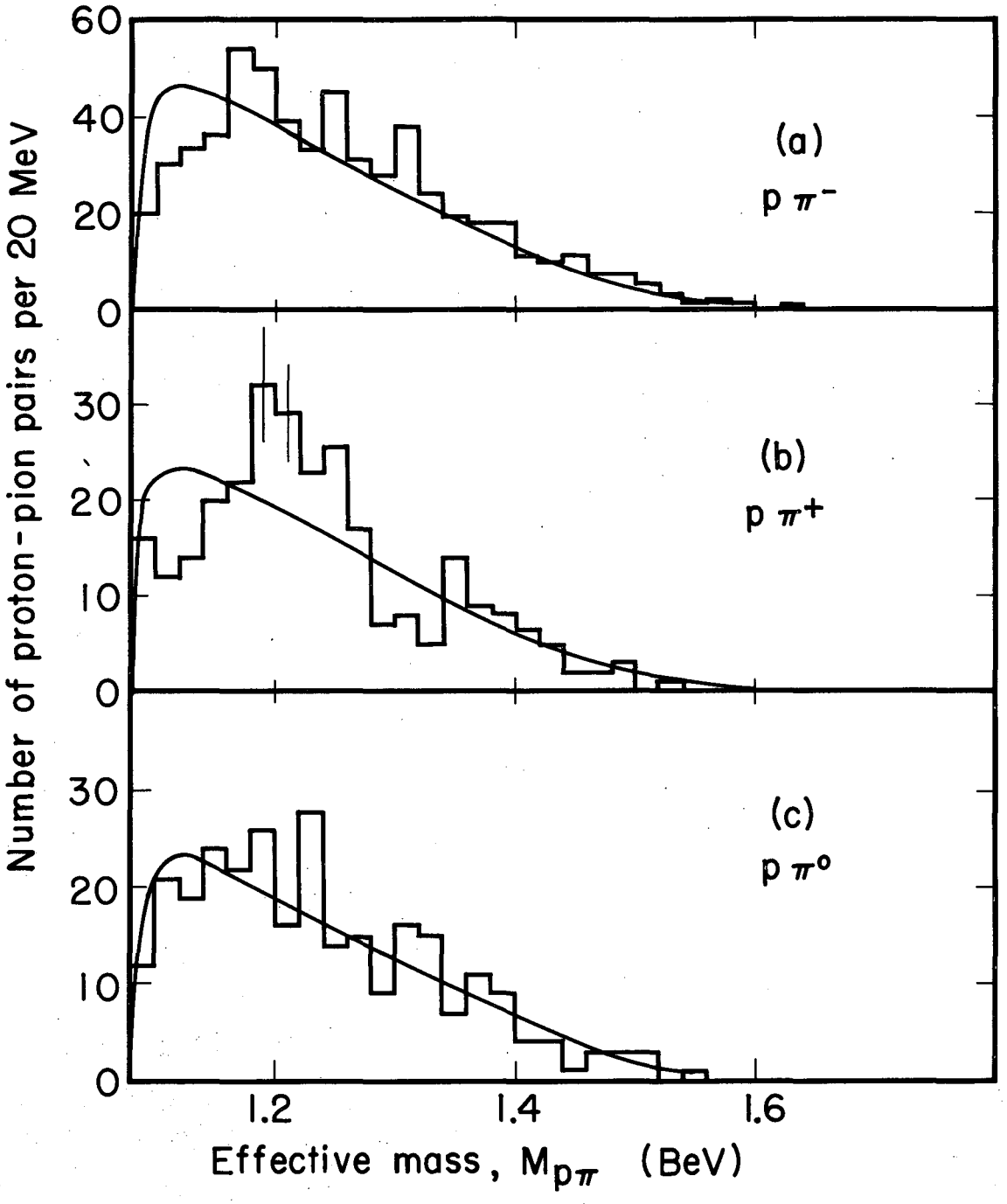
MU-26868

Fig. 7



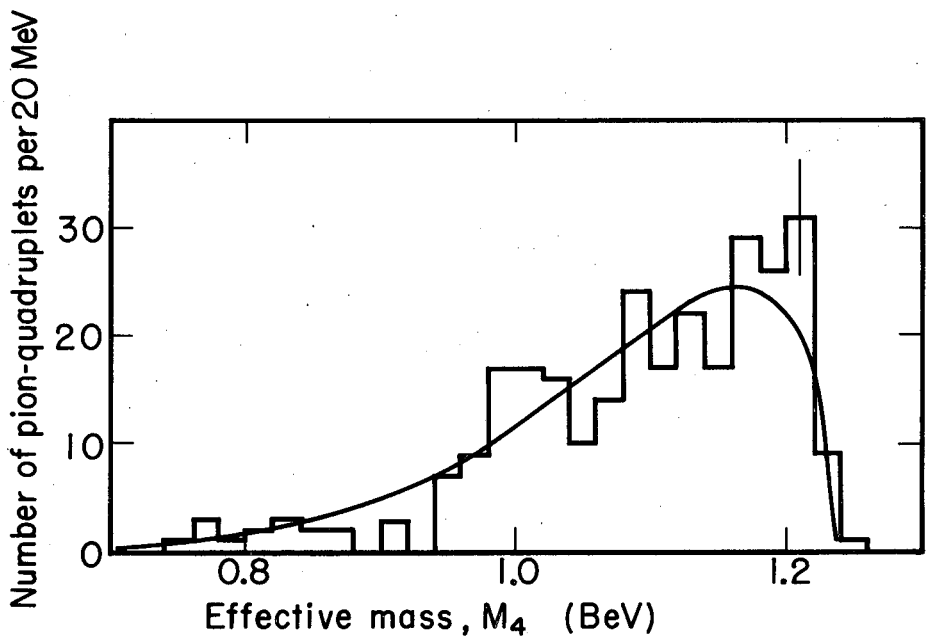
MU-26869

Fig. 8



MUB-1093

Fig. 9



MU-26870

Fig. 10

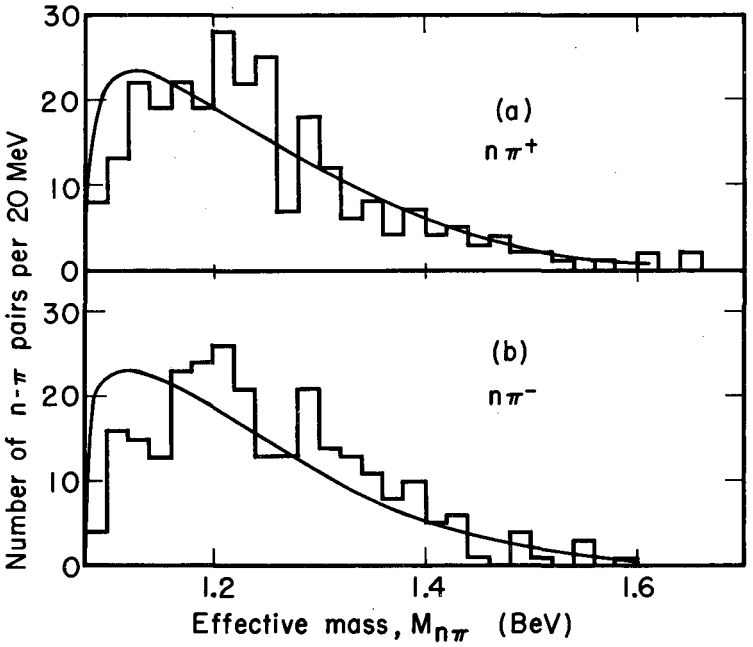

30
20
10
0
(a)
$n\pi^+$
30
20
10
0
(b)
$n\pi^-$
Number of n-π pairs per 20 MeV
1.2
1.4
1.6
Effective mass, $M_{n\pi}$ (BeV)
MU-26871

Fig. 11

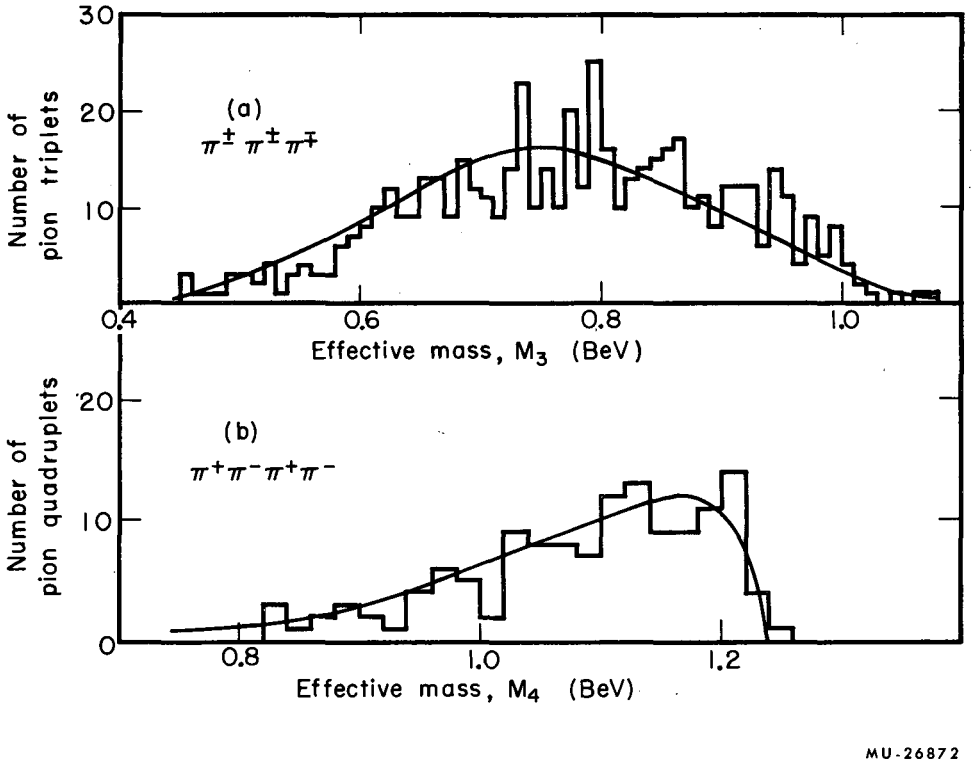

30
20
10
Number of pion triplets
(a)
$\pi^{\pm}\pi^{\pm}\pi^{\mp}$
0.4
0.6
0.8
1.0
Effective mass, M_3 (BeV)
20
10
0
Number of pion quadruplets
(b)
$\pi^{+}\pi^{-}\pi^{+}\pi^{-}$
0.8
1.0
1.2
Effective mass, M_4 (BeV)
MU-26872

Fig. 12