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In this paper we discuss the resonance structures present in the four particle final state in the π^+p interaction, i.e.,

$$\pi^+ + p \rightarrow \pi^+ + \pi^- + \pi^+ + p \qquad (1)$$

We wish to discuss here four possible channels which lead to these particles in the final state. These channels are illustrated by the Feynman diagrams in Fig. 1. The first channel corresponds to a double resonance formation in which a ρ^0 is formed at the top vertex and an $N^{*++}(1238)$ is formed at the lower vertex (see Fig. 1a). The second channel corresponds to three pions being formed at the top vertex. This is the case where the A mesons (A_1 and A_2) are being produced which then decay into $\rho^0 + \pi^+$. In the third channel we want to present evidence for possible higher nucleon isobar formation. In this case a "three particle state" is being formed at the lower vertex which then decays into an N^{*++} and a π^-. We will show evidence for such a state formed at $E(p\pi^+\pi^-) = 1480$ MeV and $\Gamma = 120$ MeV, which may be associated with the inelastic decay of the $N^*_{1/2}(1510)$. There is also a slight indication that the $N^*_{1/2}(1688)$ may be formed in a similar manner. The fourth channel corresponds to the case where the π^- is produced in the forward direction together

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with a possible triply-charged nucleon isobar at the lower vertex. Here we observe $E(p\pi^+\pi^+) = 1560$ MeV and $\Gamma = 220$ MeV. This state subsequently decays to an $N^{*++}_{3/2}(1238)$ and a π^+ meson. Here it must be noted that the above channels do not appear as clear and distinct channels but rather that considerable overlap occurs between them. In order to separate the various effects we have relied heavily on the Chew-Low plots for the various particle combinations. In the last two channels the mass peaking we observe shows up clearly for low four momentum transfer squared, Δ^2.

The Mass Enhancement in the πρ System

Here we show the three pion mass distribution from reaction (1) as well as from the corresponding π^-p reaction at 3.7 BeV/c. In both cases the N^{*++} band has been removed. In Fig. 2 we present the $\pi^{\pm}\rho^{o}$ mass distribution. The A_2 resonance[1] shows up clearly $E(A_2) = 1335 \pm 10$ MeV and $\Gamma(A_2) = 90 \pm 10$ MeV. We must point out, however, that while there is a definite enhancement above phase space in the A_1 region which is distinct from the A_2 resonance we do not observe a clearly resolved peak there. As we have pointed out earlier the A_1 enhancement may be due to the Peierls mechanism[2] and would thus not correspond to a unique angular momentum state.

The Mass Enhancement in the $N^{*++}\pi^-$ System

As each event gives two $p\pi^+\pi^-$ mass triplets we have separated these by ordering them according to the production angle of the π^+ in the overall c.m. system. This is essentially the same as ordering them according to the $\Delta^2(p\pi^+\pi^-)$ value. The pion produced with the smaller angle we call π^+_a, the other π^+_b. The distribution of the π^+_a production angle shows a very pronounced peaking at small angles indicative of small four momentum transfer squared, Δ^2, to the $p\pi_b^+\pi^-$ system. The mass squared distribution of the $p\pi_b^+\pi^-$ system and the corresponding Chew-Low plot show a clustering of events primarily associated with the N^{*++} formation. This occurs for the $N^{*++}\pi^-$ system, (see Fig. 3), at low Δ^2 values ($\Delta^2(p\pi_b^+\pi^-) \leq 15\ m_\pi^2$) and at a mass of $E(N^{*++}\pi^-) = 1480 \pm 10$ MeV and $\Gamma = 120$ MeV. This peak may be associated with the three-particle decay of the $N_{1/2}^{*+}(1510)$ resonance. When we now examine the three particles participating in this peak defined here by $1.4 \leq M(N^{*++}\pi^-) \leq 1.6$ BeV, they appear to interact in pairs with each other. As selected, the proton and π^+ give $N_{3/2}^{*++}(1238)$ formation exclusively, the proton and the π^- mass combination lie principally in the $N_{3/2}^{*o}(1238)$ band, (see Fig. 4e). In this kinematically highly constrained system, the $\pi^+\pi^-$ mass distribution peaks strongly at ~390 MeV. We find $E(\pi^+\pi^-) = 390 \pm 10$ MeV and a width of $\Gamma \cong 110$ MeV. This peak may be the same effect as the one observed by Samios et al.[3] Here we must note that the masses of the four composites involved ($p\pi_b^+\pi^-$, $p\pi_b^+$, $p\pi^-$, $\pi_b^+\pi^-$) are no longer independent. For a three-particle composite of mass M_{123} the following kinematical relation results from energy conservation:

$$M_{13}^2 = M_{123}^2 - M_{12}^2 - M_{23}^2 + m_1^2 + m_2^2 + m_3^2 \qquad (2)$$

where M_{jk} and m_i are the masses of the two-particle composites and of the individual particles respectively. These relations determine the physically allowed kinematical boundary, i.e., the Dalitz plot. Thus by using the Breit Wigner distribution in M_{123}, the observed peak at 1480 MeV and in M_{12} and M_{23} the $N_{3/2}^{*++}(1238)$ and $N_{3/2}^{*o}(1238)$ resonances respectively as weight functions, we can compute the distribution in M_{13}^2, the $\pi_b^+\pi^-$ peak. The curve in Fig. 4f gives the result of such a calculation. The agreement of the kinematic calculation with the experimental distribution is very good.

We will refer to the above phenomenon as "compound resonance" formation. There is no doubt in our experiment that N^{*++} (1238) formation occurs strongly. If we accept the current ideas, in which the N^*(1510) is considered as a bonafide resonance,[4] then we must conclude that the $\pi\pi$(390) peak occurs as a kinematical consequence. The inverse point of view, i.e., that the observed 1480 MeV peak is a consequence of a $\pi\pi$ (390) state appears less likely to us as we do not observe $\pi\pi$ (390) formation outside the 1480 MeV peak.

If we now examine the $\pi_a^+\pi^-$ mass distribution (see Fig. 4), we note that about half of the negative pions which we have attributed to the decay of the 1480 MeV peak appear to participate in ρ^o formation as well. In fact, the ρ^o mesons so produced contribute about 20% to the events classified in the sample: $\rho^o + N^*$(1238). Furthermore, if we examine the distribution in $\cos\alpha_\rho$ (the $\pi\pi$ scattering angle in the ρ center of mass) for this sample of ρ^o mesons, we find that all the $\cos\alpha_\rho$ values are very strongly forward peaked. There is thus an intimate connection between the 1480 mass peak and an asymmetry in the distribution of $\cos\alpha_\rho$. In Fig. 5 we illustrate this asymmetry.

Observation on the $p\pi^+\pi^+$ Mass Distribution

Due to isotopic spin conservation an $I = 5/2$ isobar cannot be produced elastically in a πp collision. No such restriction exists, however, for inelastic production processes. We have thus looked for such an isobar in reaction (1). We have noted a marked <u>forward</u> peaking of the π^- meson in the overall c.m. system which of course corresponds to an enhancement in the small four momentum transfer $\Delta^2(p\pi^+\pi^+)$ to the $p\pi^+\pi^+$ system.

Furthermore, we note from Chew-Low plot that the enhancement at small $\Delta^2(p\pi^+\pi^+)$ values is associated with an enhancement in $p\pi^+\pi^+$ mass distribution where this particle combination corresponds uniquely to the I = 5/2 state. If we consider this enhancement as an I = 5/2 isobar $E(N^*_{5/2})$ = 1560 ± 20 MeV and $\Gamma_{5/2}$ = 220 ± 20 MeV, we also note a clustering at higher Δ^2 values which corresponds to the $M(p\pi^+\pi^+)$ mass peaking near 2.65 BeV. We ascribe this to a reflection of mass peaking effects in the $M(p\pi^+\pi^-)$ system.

If we plot the mass squared of $p\pi_1^+$ against that of $p\pi_2^+$ and vice-versa, we obtain a scatter plot which corresponds to the superposition of Dalitz plots for various $p\pi^+\pi^+$ masses. In this plot every point occurs twice symmetrically with respect to the 45° axis, (see Fig. 7). We note the N^{*++} bands and particularly the enhancement at the overlap of the bands. The overlap region is particularly enhanced when we consider events with $\Delta^2(p\pi^+\pi^+) \leq 15m_\pi^2$, (see Fig. 7). In Fig. 7 we also present the density distribution along one of the N^* bands. By our plotting procedure we would expect the density of events to increase by a factor of 2 at the overlap region barring interference effects. Experimentally we observe the density to increase by about a factor of four compared with the adjacent region. This is further accentuated if we limit ourselves to events with $\Delta^2(p\pi^+\pi^+) \leq 15m_\pi^2$. Thus, whether we are dealing with a true isobar or not, the observed phenomenon appears to <u>correspond to complete constructive interference between the two N^{*++} bands</u>. For contrast, we also show the corresponding plot for the $p\pi^-\pi^-$ system in the $p\pi^-$ reaction, (see Fig. 8). In this case no marked enhancement is observed in the overlap region of the two N^{*o}(1238) bands. For a $N^*_{5/2}$ resonance the expected intensity for the mass projection $p\pi^-\pi^-$ is 1/50 of that for the $p\pi^+\pi^+$ intensity. We therefore consider that this comparison may lend support to the dynamic origin of the $p\pi^+\pi^+$ mass peak. On the other hand some of the features related to the

$p\pi^+\pi^+$ mass peak can be reproduced qualitatively by a simplified version of the matrix element (neglecting the spin factors) corresponding to the Feynman diagram in Fig. 1a. Here we consider ρ^0 and N^{*++} production taking into account the interference term which comes from the symmetrization of the two π^+ mesons.[5]

It is interesting to note here that for the $p\pi^+\pi^+$ "state" we deal again with a "compound resonance" in which the proton forms mass values with both π^+ mesons which lie in the $N^*(1238)$ bands. This in turn determines the $\pi^+\pi^+$ mass distribution from energy and momentum conservation as given in equation (2). The computed $\pi^+\pi^+$ mass distribution is shown in Fig. 8 together with the experimental distribution for $1420 \leq M(p\pi^+\pi^+) \leq 1760$ MeV. The $\pi^+\pi^+$ mass distribution does not give as pronounced a peak as the $\pi^+\pi^-$ distribution near 390 MeV, however, a general enhancement near 500 MeV is observed.

Finally, we have attempted to obtain information on the spin of the $p\pi^+\pi^+$ system, should it correspond to a unique spin state. We have computed the cosine of the angle between the line of flight of the N^{*++} in the $p\pi^+\pi^+$ c.m. system and the proton in the N^{*++} c.m. system.[6] This distribution, which measures the correlation of the momentum of the N^{*++} to its polarization vector in the c.m. of the $p\pi^+\pi^+$ system, turns out to be consistent with isotropy.

The work described here was carried out with the Brookhaven National Laboratory's 20-inch hydrogen bubble chamber exposed in the Brookhaven-Yale separated beam.

FIGURE CAPTIONS

Fig. 1. Feynman diagrams for various channels occuring in the reaction $\pi^+ + p \rightarrow \pi^+\pi^-\pi^+ p$

Fig. 2. The $\pi^\pm\pi^-\pi^+$ mass distribution.

Fig. 3. Chew-Low plot for the system $p\pi^+\pi^-$.

Fig. 4. Events selected by $\Delta^2(p\pi^+\pi^-) = 15\ m_\pi^2$ showing the mass peaking at 1480 MeV and two particle masses associated with this peak.

Fig. 5. Angular distribution in the $N^* + \pi^+ + \pi^-$ reaction.

Fig. 6. Scatter plots in $p\pi^+$, $p\pi^+$, and $p\pi^-$, $p\pi^-$ mass squared planes for the $p\pi^+$ and $p\pi^-$ reactions respectively.

Fig. 7. Chew-Low plot for the $p\pi^+\pi^+$ system.

Fig. 8. $p\pi^+\pi^+$ mass distribution for $\Delta^2(p\pi^+\pi^+) \leq 15\ m_\pi^2$.

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4. The dynamical approach suggested by Peierls and extended by R. C. Hwa (Phys. Rev. 130, 2580 (1963)), indicates that while the $N^*(1510)$ isobar is related to the $N^*(1238)$ isobar its occurrence can still be ascribed to a pole. Considerations were further extended by I. P. Gyuk and S. F. Tuan, Nuovo Cimento 32, 227 (1964).

5. We have greatly benefited from discussions with Professor F. Low on this subject.

6. C. Zemach, communication to this conference.

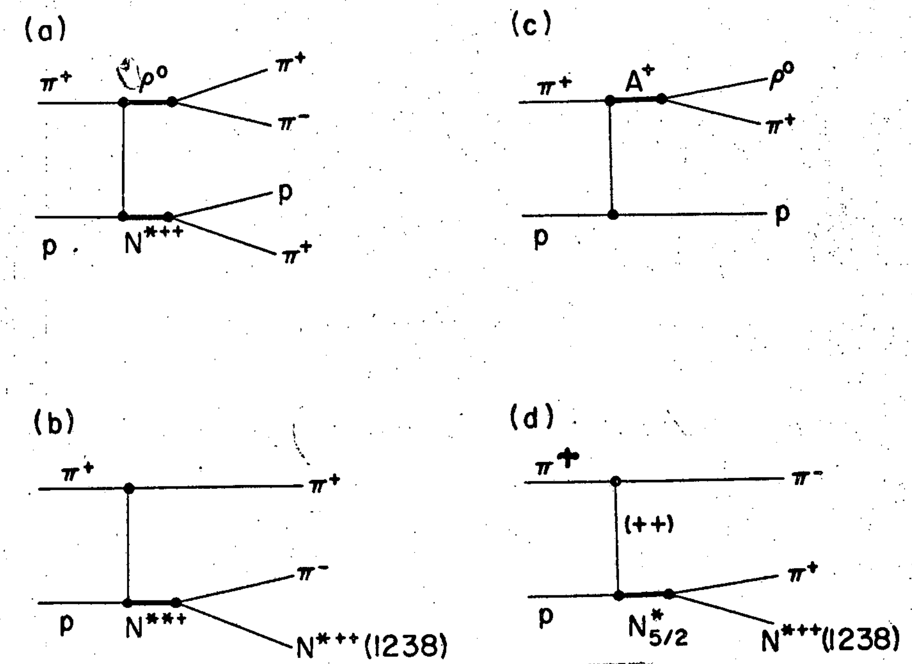
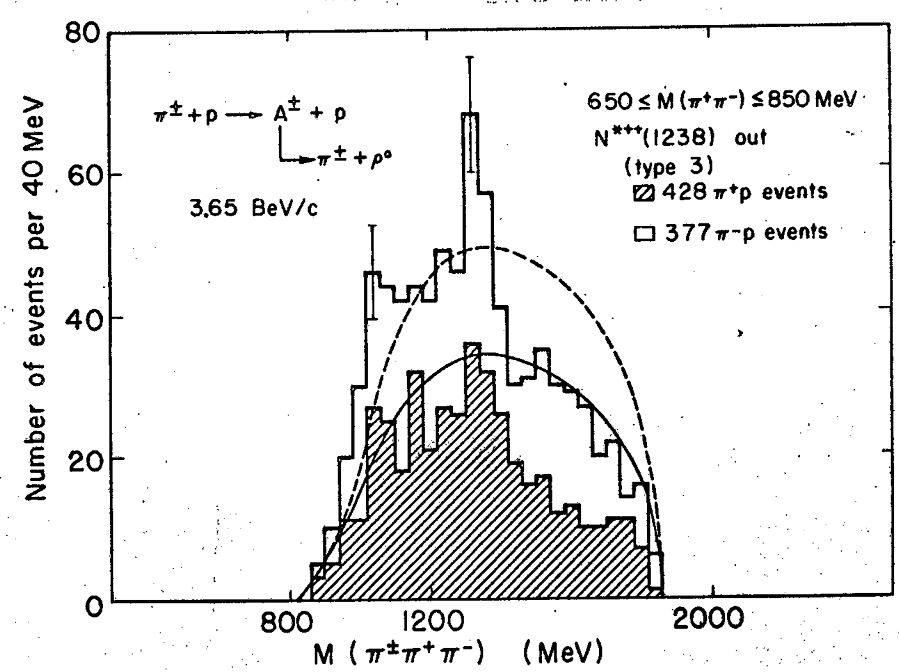


Figure 1



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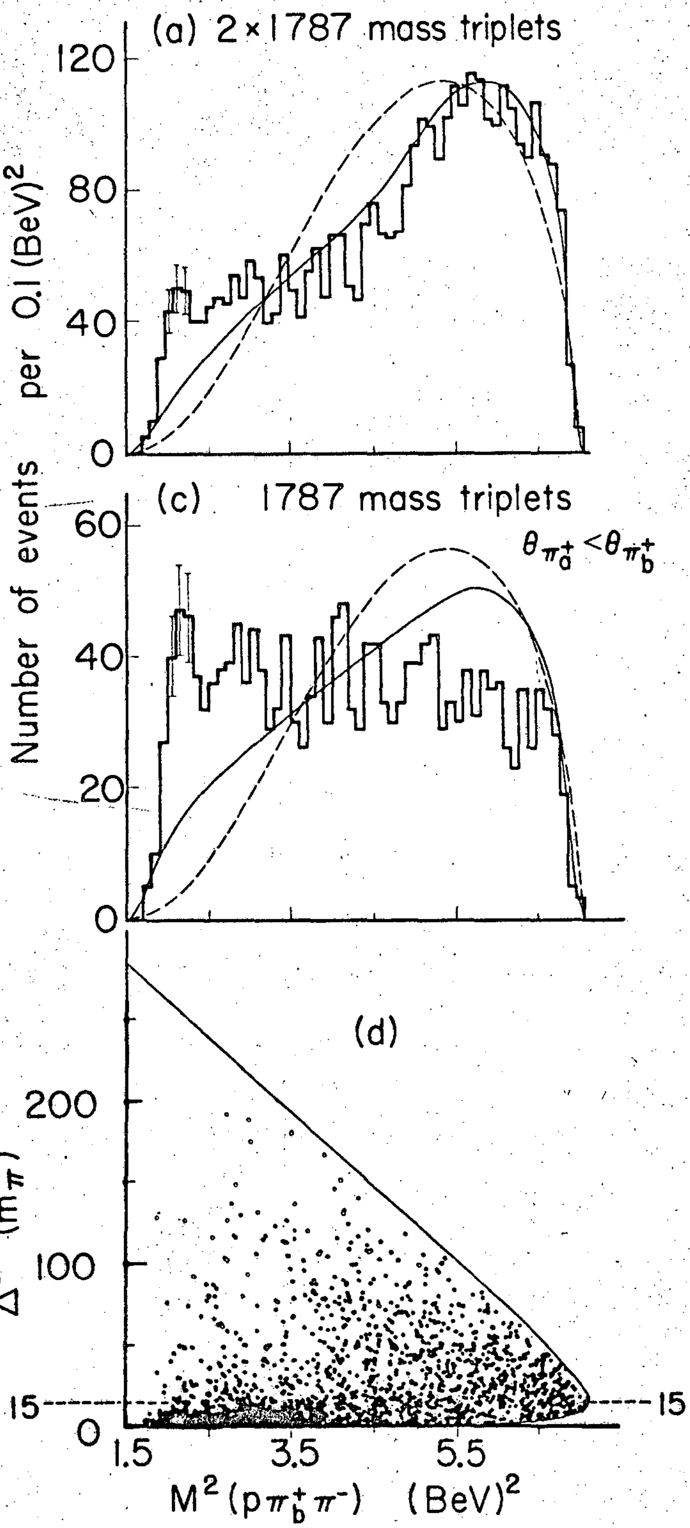

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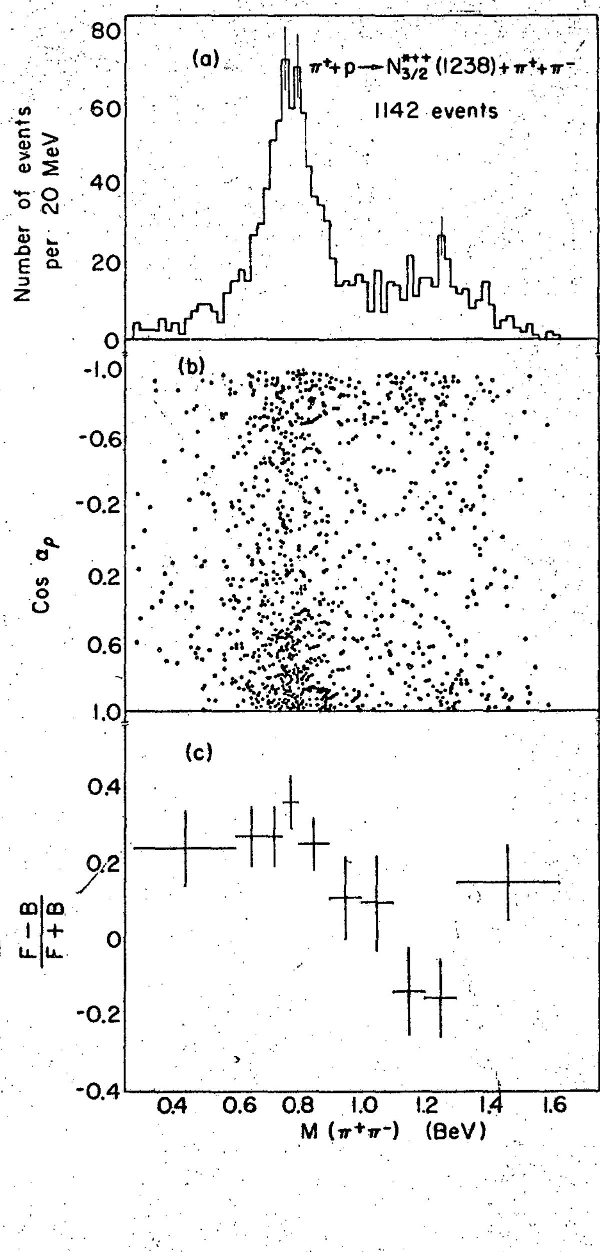

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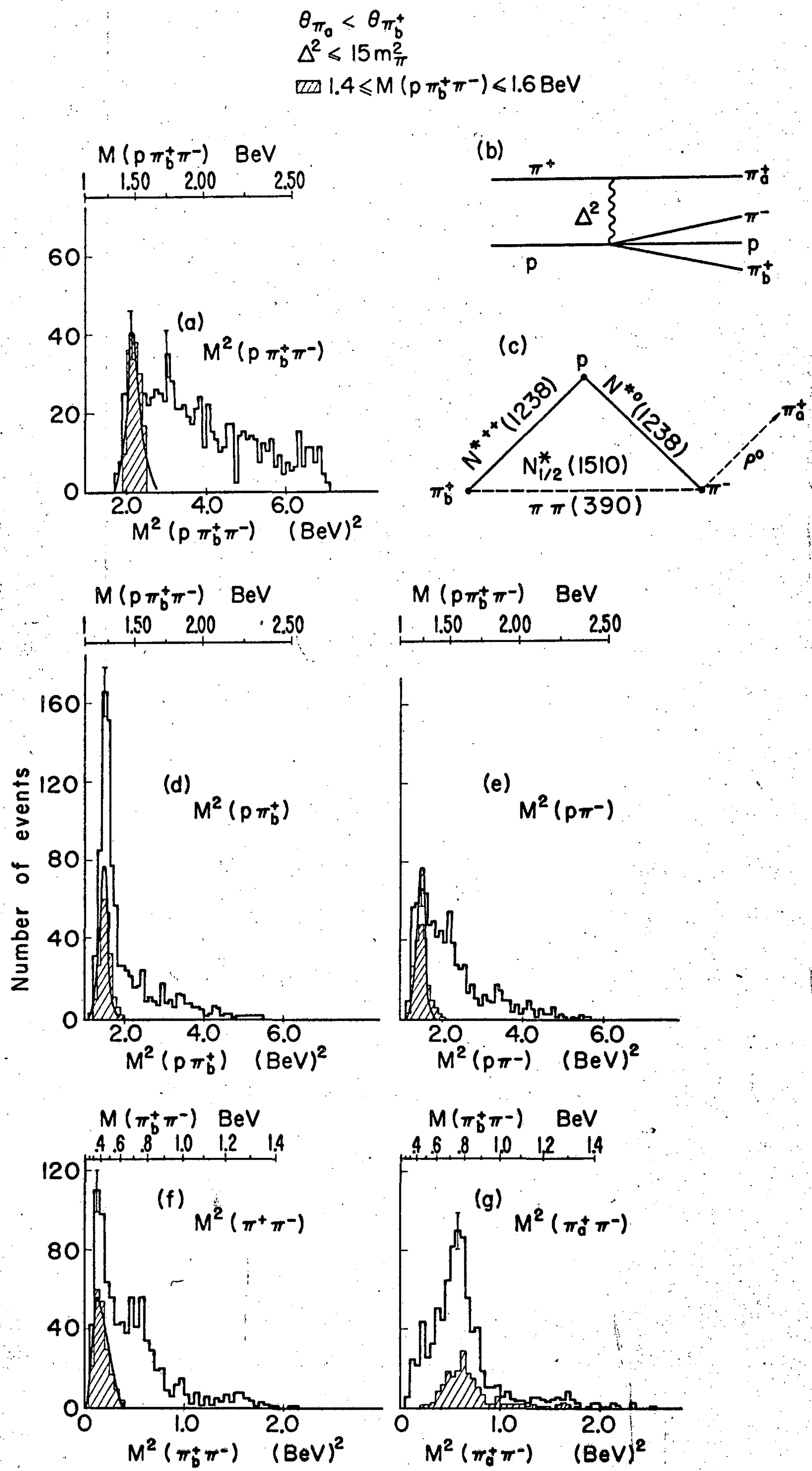

Figure 4

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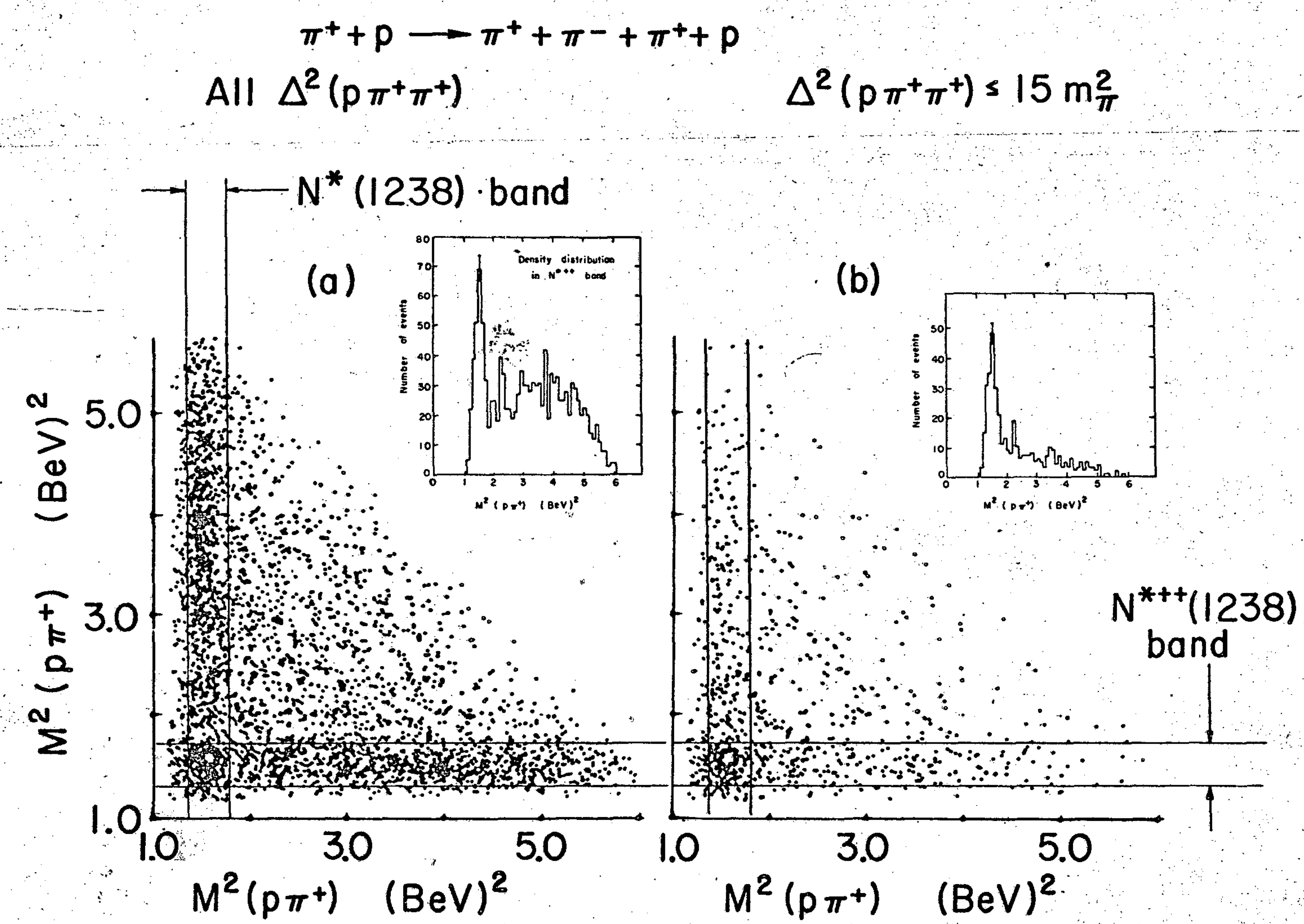

Figure 6

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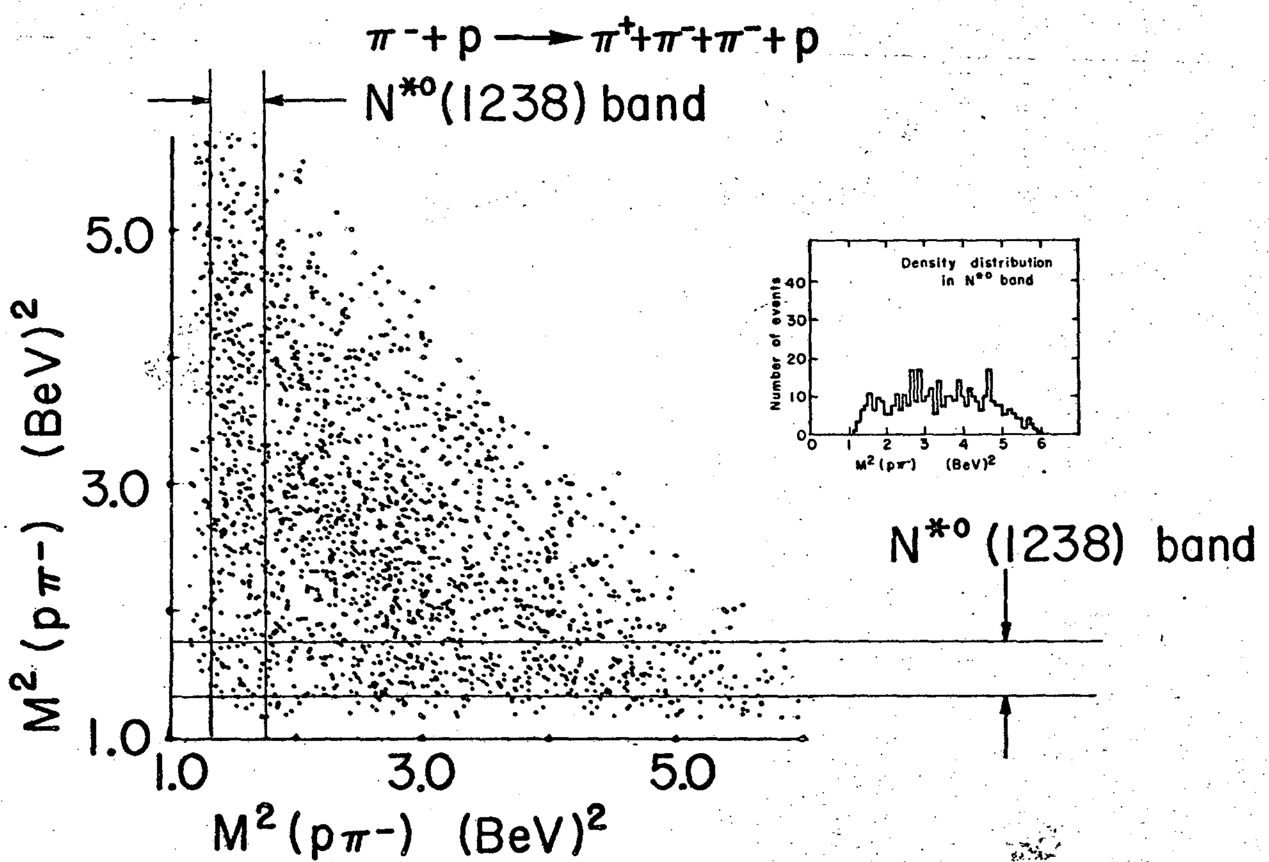

Figure 6c

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$\pi^+ + p \longrightarrow N^{*++}(1238) + \pi^+ + \pi^-$

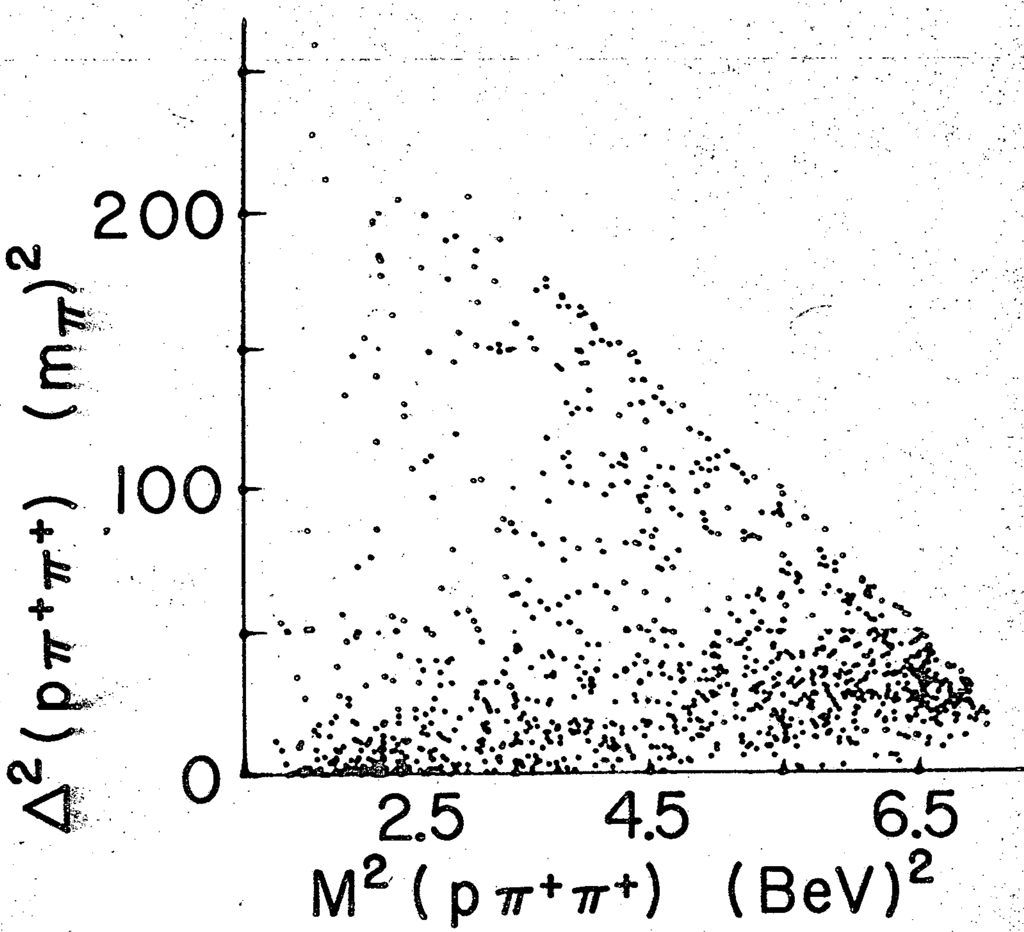

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Figure 7

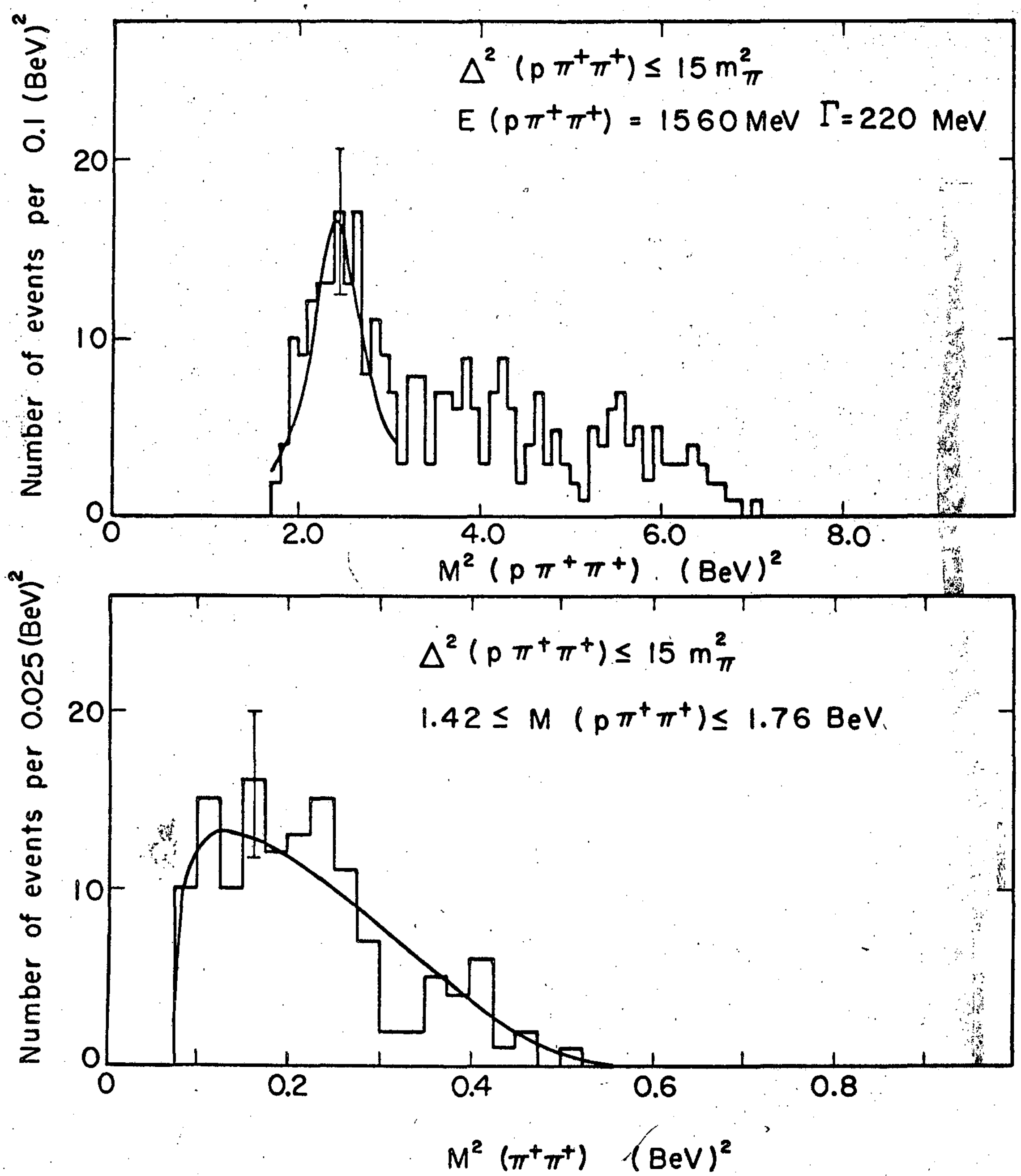

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Figure 8