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Analysis of the 1.0- to 1.4-BeV π-ρ Enhancement*

Suh Urk Chung, Orin I. Dahl, Lyndon M. Hardy, Richard I. Hess, George R. Kalbfleisch, Janos Kirz, Donald H. Miller, and Gerald A. Smith

Department of Physics and Lawrence Radiation Laboratory
University of California, Berkeley, California

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Peripheral interactions of 8- to 16-BeV/c π mesons in heavy-liquid bubble chambers have been studied by Bellini et al.[1] and Husom and Fretter.[2] Both groups observed significant enhancements in the $\pi^-\pi^+\pi^-$ effective-mass distributions in the 1.0- to 1.4-BeV region; however, it was not possible to determine whether the effect resulted from the production of a new resonant state or from kinematics of diffraction dissociation. Recently, in a thorough analysis of the $\pi^+p \to \pi^+\pi^+\pi^-p$ reaction at 3.65 BeV/c, Goldhaber et al. showed that most events could be classified into two distinct groups, $\rho^0N^{*++}(1238)$ and $\rho^0\pi^+p$.[3] They observed the 1.0- to 1.4-BeV enhancement only in the $\rho^0\pi^+p$ events. We have studied this strong π-p interaction in $\pi^-p \to \pi^+\pi^-\pi^-p$ and find that the enhancement consists of two clearly resolved peaks. In addition, decay of the higher-mass system into $K\bar{K}$ is observed in the $K\bar{K}N$ final states. Possible spin and parity assignments for the two states are discussed.

The film was obtained in the course of a systematic study of 1.5- to 4.2-BeV/c π^-p interactions in the Lawrence Radiation Laboratory's 72-in. hydrogen bubble chamber. Approximately 30 000 pictures at 3.22 BeV/c with an average of 10 pions each were scanned for interactions leading to four charged secondaries; 7500 events were measured and processed. Where possible, ambiguities were removed by comparison of track ionization on the film with that calculated from the kinematic fits. For the remainder of the events, the fit with the highest confidence level was used. In the present

Letter, we discuss only the 1967 events fitting $\pi^- p \rightarrow \pi^+\pi^-\pi^- p$. Since this final state represents the only four-constraint fit, these events constitute a particularly pure sample.

The $\pi^+ p$ effective masses, $M(\pi^+ p)$, are plotted in Figs 1, a and b. At low momentum transfer to the $\pi^+ p$ system, $\Delta^2(\pi^+ p) \leq 0.8\ (\mathrm{BeV/c})^2$, the events consist almost entirely of $N^{*++}(1238)$. Figure 1, c and d shows the distributions in $M(\pi^+\pi^-)$. In this case, a strong ρ^0 peak is observed only in those events not containing an $M(\pi^+ p)$ in the N^{*++} interval. Consequently, all events with $M^2(\pi^+ p)$ in the interval 1.30 to 1.79 $(\mathrm{BeV})^2$ have been suppressed so that background in the $\rho^0\pi^- p$ final state is greatly reduced for the subsequent analysis. The shaded part of Fig. 1d indicates that most events with low momentum transfer to the proton, $\Delta^2(p) \leq 0.65$ $(\mathrm{BeV/c})^2$, contain at least one $M(\pi^+\pi^-)$ which may be ascribed to ρ^0 decay.

The $\pi^-\pi^+\pi^-$ effective-mass distribution is given in Fig. 2b. Two clearly resolved peaks are observed above the 3π phase-space background: the first at 1090 MeV with full-width $\Gamma \simeq 150$ MeV, the second at 1310 MeV with $\Gamma \simeq 80$ MeV. It is important to note that as long as the trend of the background is as indicated, the exact normalization does not affect the existence of the two peaks; however, the widths will be underestimated if the normalization is too large. To demonstrate that the peaks are associated primarily with $\rho^0\pi^-$, events with $\Delta^2(p) \leq 0.65\ (\mathrm{BeV/c})^2$ are shown separately. Although the background has been markedly decreased by this selection, little reduction occurs in the peaks.

In order to search for $K\bar{K}$ decays that might be related to either 3π peak, all candidates for $K^- K_1^0 p$ and $K_1^0 K_1^0 n$ final states were measured in 120 000 pictures at 3.2 BeV/c and 60 000 pictures at 4.2 BeV/c. The effective-mass distributions for the fitted events are shown in Fig. 2a. The combined $K^- K_1^0$ and $K_1^0 K_1^0$ distributions show an enhancement of approximately five

standard deviations in the 1260-through 1380-MeV interval. This peak corresponds closely in position and width with the higher peak in the $\pi^-\pi^+\pi^-$ events, providing additional evidence for the presence of two distinct effects. Consequently, we conclude that a previously unresolved meson exists with $M = 1310$ MeV, $\Gamma \simeq 80$ MeV, and $I = 1$, which decays into $\pi\rho$ and $K\bar{K}$. No significant enhancement is apparent in the region of the 1090-MeV $\pi^-\pi^+\pi^-$ peak.

Decay of the 1310-MeV peak into $K^-K_1^0$ is allowed for spin-parity assignments $J^P = 0^+, 1^-, 2^+, 3^-$, etc; $K_1^0K_1^0$ decay can occur only for $J^P = 0^+, 2^+$, etc.[4] It has been noted that both $\pi^-\pi^+\pi^-$ peaks persist at low $\Delta^2(p)$, so production probably results from peripheral collisions involving ρ exchange. In this case we may expect $\pi^-\rho^0 p$; $\pi^\pm\rho^\mp n \simeq 1:2$ and correspondingly $K^-K_1^0 \simeq K_1^0K_1^0$, in good agreement with the observed relative enhancements after correction for K_1^0 detection efficiency. Since the $K^-K_1^0$ and $K_1^0K_1^0$ distributions peak in the same mass interval, the data strongly suggest that decay into $K_1^0K_1^0$ is allowed. However, $K_1^0K_1^0$ events may also result from decay of the $I = 0$, $J^{PG} = 2^{++}$, f_0 meson with $M = 1250$ MeV and $\Gamma \simeq 140$ MeV.[5] A fit of the observed $K_1^0K_1^0$ distribution to a phase-space background plus a Breit-Wigner resonance centered at 1250 MeV yields a confidence level less than 5%. Consequently, it is unlikely that the $K_1^0K_1^0$ enhancement arises entirely from f_0 decay. In this case, the lowest possible assignment is $J^{PG} = 2^{+-}$, since 3π decay of a $J^{PG} = 0^{+-}$ state is forbidden.

If the assignment $J^{PG} = 2^{+-}$ for the 1310-MeV state is correct, the dominant features of the Dalitz plot are determined. To minimize background, we show only events with $\Delta^2(p) \leq 0.65\ (\mathrm{BeV}/c)^2$ in Fig. 3c; for convenience in comparison with theory, each event is plotted twice. The general properties of 3π decays of unstable particles have been discussed by Zemach for arbitrary

spin-parity assignments.[6] He shows that the matrix element for decay of an I = 1 or 2 state through an intermediate $\pi\rho$ may be written

$$M(\pi_1^-\pi_2^+\pi_3^-) = M_{1,23} - M_{3,12}, \tag{1}$$

where $M_{k,lm}$ is an antisymmetric function in lm. If momenta in the 3π center of mass are $\underset{\sim}{p}_1, \underset{\sim}{p}_2$, and $\underset{\sim}{p}_3$, and for $\underset{\sim}{q} = \underset{\sim}{p}_1 \times \underset{\sim}{p}_3$, the simplest matrix elements for the $J^P = 1^-$ and 2^+ states may be calculated by using

$$1^- \quad M_{k,lm} = a_k \underset{\sim}{q} \tag{2a}$$

$$2^+ \quad M_{k,lm} = a_k(\underset{\sim}{p}_k \underset{\sim}{q} + \underset{\sim}{q}\,\underset{\sim}{p}_k), \tag{2b}$$

where $a_k \simeq (\Gamma_\rho/2\pi)^{1/2}\,[M_{lm}^2 - M_\rho^2 + i\,M_\rho\,\Gamma_\rho + (\Gamma_\rho/2)^2]^{-1}$.

The presence of the axial vector $\underset{\sim}{q}$ requires that the density vanish at the edge of the plot in either case. However, for 1^-, the density must also vanish along the entire line $M^2(\pi_1^-\pi_2^+) = M^2(\pi_2^+\pi_3^-)$.[7] Explicit calculation indicates that the width of the destructive interference in the overlapping ρ bands is $\approx \Gamma_\rho$. In contrast, for 2^+, the density is a maximum where the ρ bands overlap. The substantial background in Fig. 3c tends to mask the vanishing of the ρ bands towards the edge of the plot; however, within statistics, the highest density occurs where expected for the 2^{+-} assignment.

The Dalitz plot for the 1090-MeV peak is given in Fig. 3a. In the projected distribution, Fig. 2b, a marked enhancement is apparent at low $M^2(\pi^+\pi^-)$. Since this peak is concentrated in the ρ^0 bands, it is probably not associated with the small background of non-ρ^0 events. Consequently, both the 1^- and 2^+ assignments must be rejected. With no observed decay into $K\bar{K}$, other possible assignments are $J^P = 0^-, 1^+, 2^-$, etc. The pertinent matrix elements are obtained by using

$$0^{-} \quad M_{k,lm} = a_k \underline{p}_k \cdot (\underline{p}_l - \underline{p}_m) \tag{3a}$$

$$1^{+} \quad M_{k,lm} = a_k (\underline{p}_l - \underline{p}_m) \tag{3b}$$

$$2^{-} \quad M_{k,lm} = a_k [\underline{p}_k \cdot (\underline{p}_l - \underline{p}_m) + (\underline{p}_l - \underline{p}_m) \cdot \underline{p}_k - (2/3)\, \mathbb{I}\, \underline{p}_k \cdot (\underline{p}_l - \underline{p}_m)] \,, \tag{3c}$$

where $\mathbb{I}$ is a unit dyadic. The expected densities in the ρ bands are readily estimated. In the absence of Bose statistics (approximately valid outside the overlapping ρ bands) the decay angular correlations are: for 0^-, $\cos^2\theta$; for 1^+, isotropic; for 2^-, $1+(1/3)\cos^2\theta$; where $\cos\theta = \underline{p}_k \cdot (\underline{p}_l - \underline{p}_m)/|\underline{p}_k||\underline{p}_l - \underline{p}_m|$ as measured in the $\pi_l\pi_m$ rest frame. Since the Dalitz plot is linear in $\cos\theta$ for a given $\pi_1^-\pi_2^+\pi_3^-$ energy and fixed p_1, the density distributions for low $M^2(\pi_2^+\pi_3^-)$ are apparent. The strong depopulation observed in the ρ bands at $M^2(\pi^+\pi^-) \sim 0.32\ (\mathrm{BeV})^2$ is expected only for $J^{PG} = 0^{--}$. Both the $J^{PG} = 1^{+-}$ and 2^{--} appear incompatible with the data.[8]

The possibility for peaks in meson systems due to the Peierls mechanism has been discussed by Nauenberg and Pais[9] and Oakes.[10] They predict an enhancement in the $\pi\rho$ system in the region 1090 through 1125 MeV. However, the peak will not represent a state of pure J^P or I. The present data are not sufficient to determine whether the lower $\pi\rho$ enhancement arises from this mechanism. For convenience, we shall retain the term <u>A meson</u> used by Goldhaber et al. for this peak.[3] If the A meson represents a pure state with $M_A = 1090$ MeV and $\Gamma_A \simeq 150$ MeV, the assignment $J^{PG} = 0^{--}$ is preferred.

Since the Peierls mechanism cannot generate two peaks, it is likely that the enhancement at 1310 MeV with $\Gamma \simeq 80$ MeV represents a pure state, with the data strongly favoring the assignment I = 1, and $J^{PG} = 2^{+-}$. It has

recently been pointed out by Pignotti that if bootstrap dynamics can account for an octet of 1^- mesons, the existence of a 2^+ octet is implied.[11] Consequently, we shall use the name R meson for the 1310-MeV state, as suggested by Pignotti for the S = 0, I = 1 member of the octet.

It is a pleasure to acknowledge the importance of the paper by Goldhaber et al. in stimulating our interest in this problem. In addition, we thank Professor Charles Zemach for helpful discussion on his paper.

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FOOTNOTES AND REFERENCES

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8. It must be emphasized that these statements are valid only for pure states. Additional information is available from correlations in production and decay. Because of the $\pi^-\pi^+\pi^-$ background (and possibly nonresonant $\pi\rho$ events), these correlations require a more extensive study.
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FIGURE LEGENDS

Fig. 1. Effective-mass distributions for (a, b) π^+p combinations at high and low momentum transfer; (c, d) $\pi^+\pi^-$ combinations with and without N^{*++}.

Fig. 2. Effective-mass distributions for (a) $K^-K_1^0$ and $K_1^0K_1^0$ pairs; (b) $\pi^-\pi^+\pi^-$ combinations for events with $M(\pi^+p)$ outside the N^{*++} interval. The smooth curves represent 3π phase space normalized to events outside the peaks. Bars indicate mass intervals used in the Dalitz plots.

Fig. 3. (a, b) Dalitz plot for events with $M(\pi^-\pi^+\pi^-)$ between 1.00 and 1.18 BeV, and projection onto the $M^2(\pi_2^+\pi_3^-)$ axis; (c, d) Dalitz plot for events with $M(\pi^-\pi^+\pi^-)$ between 1.22 and 1.40 BeV, with projection onto $M^2(\pi_2^+\pi_3^-)$ axis. The shaded areas are projections for ρ^0 bands only, $M(\pi_1^-\pi_2^+)$ between 0.64 and 0.86 BeV. Events with $\Delta^2(p) > 0.65\ (\mathrm{BeV}/c)^2$ and $M(\pi^+p)$ in the N^{*++} interval are not shown. The solid curves represent the phase space limits for 1.18 BeV in (a) and 1.40 BeV in (c).

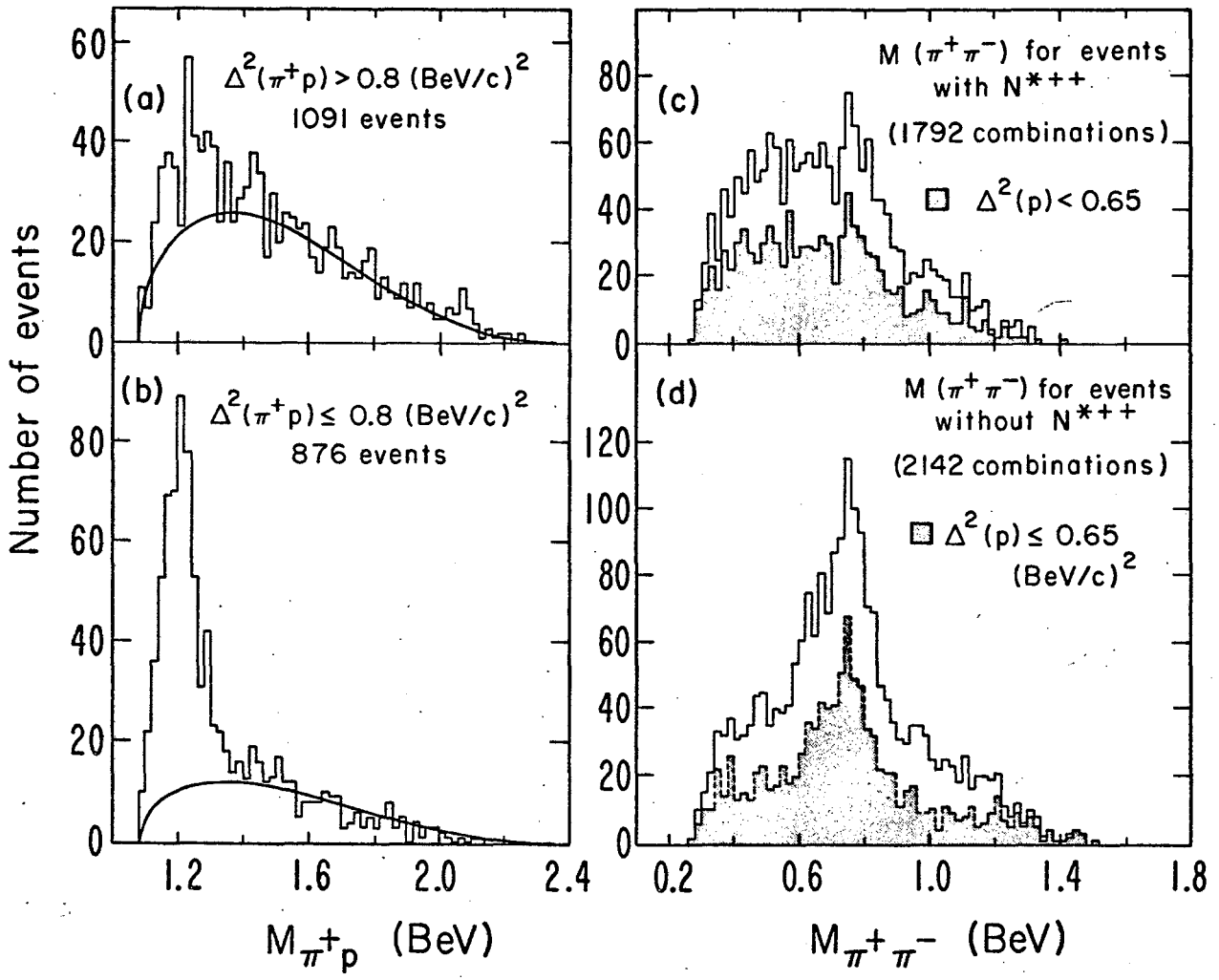

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Fig. 1

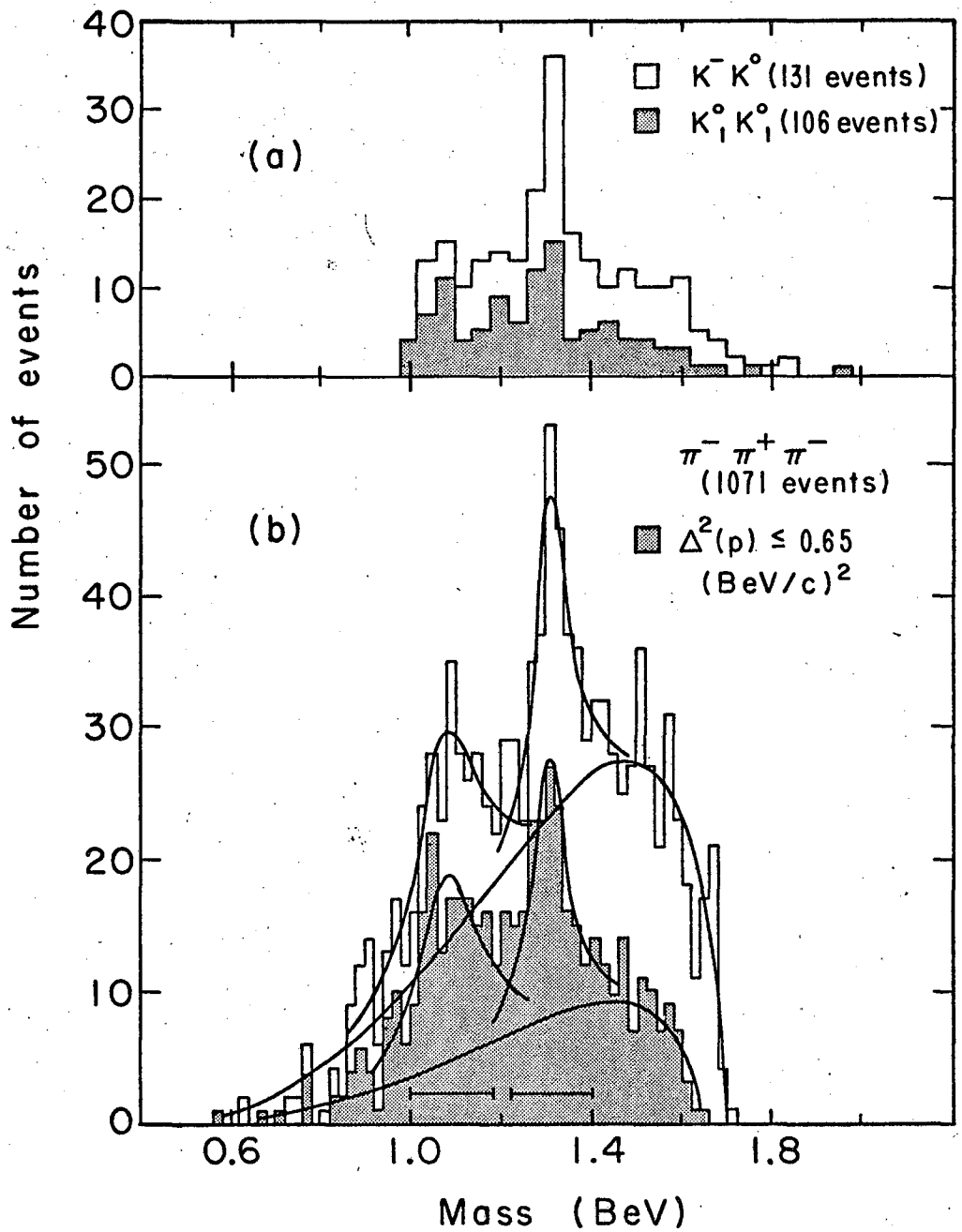

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Fig. 2

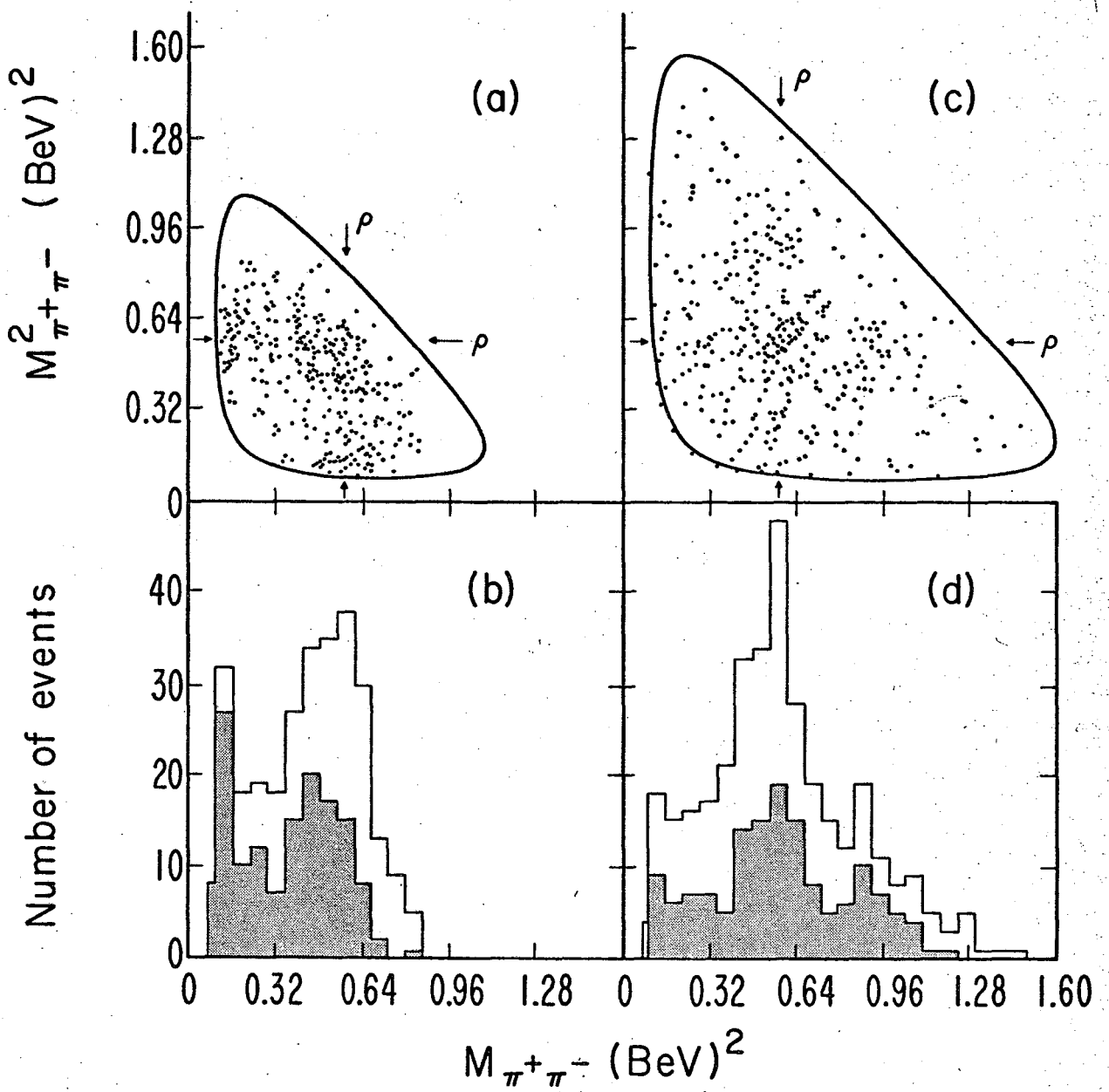

Fig. 3

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