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Test of Helicity Conservation and Spin-Parity Analysis of the $N^*(1700)$ †

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ABSTRACT

The diffractively produced low-mass $\pi^+\pi^-p$ system is studied in the reaction $\pi^\pm p \rightarrow \pi^\pm\pi^+\pi^-p$. We observe strong $N^*(1700)$ production and determine the branching fraction to $\pi^-\Delta^{++}$ to be 65 ± 15%. A spin-parity analysis (assuming $J < 7/2$) yields $J^P = 5/2^+$ for the $N^*(1700)$. The study of the decay angular distribution of the $N^*(1700)$ indicates that helicity is conserved in the t-channel rather than in the s-channel.

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DISCLAIMER

The question of helicity conservation in the production of resonances is of current interest. In this paper we study the diffractively produced low-mass $\pi^+\pi^-p$ system. In particular we examine the $N^*(1700)$[1] produced in the reaction:

$$\pi p \rightarrow \pi N^*(1700) \qquad (1)$$

where $N^*(1700) \rightarrow \pi^+\pi^-p$. Helicity conservation in the s-channel has been demonstrated for ρ^o photoproduction and for elastic scattering.[2] It has been argued that s-channel helicity conservation (SCHC) might hold for diffractive processes in general.[3] Although there is strong evidence for t-channel helicity conservation in the diffractive production of the A_1 enhancement,[4] this reaction does not provide a good test of SCHC. Most, if not all, of the data in the A_1 enhancement can be explained in terms of a double-Regge model[5] which by virtue of its kinematical nature cannot conserve s-channel helicity.[6] Reaction (1), on the other hand, is a diffractive process involving a definite resonance that cannot be explained as a kinematic enhancement from a double-peripheral model. To determine the properties of the $N^*(1700)$ we have performed a spin-parity decomposition for the $\pi^+\pi^-p$ system as a function of the effe[illegible]ive mass.

The data from this Purdue-Notre Dame collaboration come from the reactions:

$$\pi^+p \rightarrow \pi^+\pi^+\pi^-p \qquad (2)$$

and

$$\pi^-p \rightarrow \pi^-\pi^-\pi^+p. \qquad (3)$$

The Purdue data consist of 10,[illegible] 13.1 GeV/c in the 82 inch hydrogen bubble chamber at SLAC. The Notre Dame data consist of 4,494 events of reaction (2) at 18.5 GeV/c, 4,800 events of reaction (3) at 18.5 GeV/c and 2,515 events of reaction (3) at 8.05 GeV/c in the BNL 80 inch hydrogen bubble chamber. In Fig. 1 (a) is shown the $\pi^+\pi^-p$ effective mass spectrum below 2.4 GeV for the combined data. The $N^*(1700)$ peak observed in this figure is also very [illegible]inent in the individual samples.

A fit using an s-wave Breit-Wigner shape plus a smooth hand-drawn background yields M = 1715 ± 5 MeV. Since the width is sensitive to the shape of the background we only quote an approximate value $\Gamma \sim 80$ MeV.

In our spin-parity analysis of the $N^*(1700)$ we assume that the low mass $\pi^+\pi^-p$ system is diffractively produced. Cross sections for the broad low mass ($\leqslant$ 2 GeV) $\pi\pi N$ region and for the I = 1/2 N^* peaks, including the $N^*(1700)$ peak, have been found in many experiments to be approximately independent of incident momentum.[7] Our results are consistent with these experiments.

We observe a very strong $\Delta^{++}(1236)$ signal in the events with $\pi^+\pi^-p$ mass below $\approx$ 2 GeV. To determine the fraction of $N^*(1700)$'s which decay to $\pi^-\Delta^{++}$, the following method was used. For a given $\pi^+\pi^-p$ mass region, a phase-space distribution was fitted to the π^+p mass distribution in the regions above and below the Δ^{++} mass region. The number of events above the background curve in the region between 1.160 and 1.280 GeV was determined. This Δ^{++} signal, corrected for the Breit-Wigner tails, is plotted in Fig. 1(b). We observe strong $\pi^-\Delta^{++}$ enhancements in the intervals centered at 1.480 and 1.720 GeV. The number of $N^*(1700) \rightarrow \pi^-\Delta^{++}$ events was determined by counting events above the hand-drawn dotted curve shown in Fig. 1(b) and the total number of $N^*(1700)$ events was obtained from the signal in Fig. 1(a). The branching fraction $(N^*(1700) \rightarrow \pi^-\Delta^{++})/N^*(1700) \rightarrow \text{all } \pi^+\pi^-p) = 65 \pm 15\%$.†

† The branching fraction was also determined by counting the $N^*(1700)$ events with and without a narrow Δ^{++} cut and assuming a linear combination of phase space and $\pi\Delta$ decays. (This method is fully described in R. B. Willmann et al., Phys. Rev. Letters 24 (1970) 1260.) The branching fraction thus obtained was also 65%.

To study the angular momentum structure of the $\pi^+\pi^-p$ system we have used angular functions[8] for a $\pi^-\Delta^{++}$ intermediate state. The functions are expressed in terms of two angles: θ, the angle of the π^- with respect to the target proton direction in the $\pi^-\Delta^{++}$ rest system (Gottfried-Jackson Frame) and β, the angle of the π^- in the Δ^{++} rest system with respect to the line of flight of the Δ^{++} defined in the $\pi^-\Delta^{++}$ rest system. We have considered the following spin-parity (J^P) states:† $1/2^{\pm}$, $3/2^-$, $5/2^+$ and $5/2^-$. In each case the lower ℓ-wave has been assumed. Because of the evidence[7] for diffraction production we have assumed Pomeron exchange (i.e. $J^P = 0^+$ exchange) and have therefore set the spin-density matrix element $\rho_{\frac{1}{2}\frac{1}{2}} = 1/2$. The likelihood function (LF) used to fit the data consisted of a sum of squared amplitudes, $|A(J^P)|^2$. For the results which we present here we have used $LF = a|A(1/2^{\pm})|^2 + b|A(3/2^-)|^2 + c|A(5/2^+)|^2$, where $a + b + c = 1$.‡ We also considered $J^P = 5/2^-$ but it gave negligible contributions to all mass regions. A maximum-likelihood fit was made for 40 MeV intervals of $\pi^+\pi^-p$ effective mass. In an earlier study[9] it was shown that background from final states such as $\pi^{\pm}\rho^o p$ and $\pi^{\pm}f^o p$ is eliminated if the analysis is restricted to events with $\cos\theta > 0.0$ and $M(\pi^+p) < 1.5$ GeV. We have therefore incorporated these cuts in our analysis.

Results of the fit are shown in Fig. 2. In Fig. 2(a) is shown the effective mass spectrum for all events used in the fit; in Fig. 2(b)-(d) are

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†These J^P states are sufficient to describe all of the known $I = 1/2$ N^* states below ~ 1.9 GeV.

‡ $$|A(1/2^{\pm})|^2 = 1/8[1 + 3\cos^2\beta],$$
$$|A(3/2^-)|^2 = 1/4\left[1 + 1/4(3\cos^2\theta - 1)(3\cos^2\beta - 1)\right],$$
$$|A(5/2^+)|^2 = 3/40\left[2 + 4\cos^2\theta + 1/2(1 - 10\cos^2\theta + 15\cos^4\theta)(3\cos^2\beta - 1)\right].$$

shown the contributions from $J^P = 1/2^{\pm}$, $3/2^-$ and $5/2^+$ respectively. We note that the $N^*(1700)$ region is consistent with being almost entirely $J^P = 5/2^+$. The same conclusion was also reached using an analysis which did not assume a $\pi\Delta$ intermediate state.†

The results of tests for helicity conservation in production of the $N^*(1700)$ in the s-channel or in the t-channel are shown in Figs. 3 and 4. In Fig. 3 we compare the cos θ distribution in the t-channel (Gottfried-Jackson Frame) with the distribution of cos θ_H in the s-channel (helicity frame) for the $N^*(1700)$ mass region and for adjacent control regions above and below the $N^*(1700)$. Here θ_H is the angle of the π^- in the $\pi^-\Delta^{++}$ rest system with respect to the line of flight of the $\pi^-\Delta^{++}$ in the overall center of mass. (For distributions in the s-channel we have used only events for which cos $\theta_H > 0.0$.) We note that the angular distribution for the $N^*(1700)$ region is more peaked at cos $\theta = +1.0$ in the t-channel (Fig. 3(b)) than at cos $\theta_H = +1.0$ in the s-channel (Fig. 3(e)). This might be expected if the $N^*(1700)$ were produced aligned along the t-channel quantization axis. The control regions show neither the peaking characteristic of high spin nor any dramatic differences between the reference frames.

In Figs. 4(a) and 4(b) are shown the value of the spin-density matrix element $\rho_{\frac{1}{2}\frac{1}{2}}$ for the t-channel and s-channel as a function of $|t|$, the four-momentum transfer from the target proton to the $N^*(1700)$. Here we have assumed that the $N^*(1700)$ region is entirely $J^P = 5/2^+$ (see Fig. 2(d)) and

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†A maximum-likelihood fit was made to the distribution of the angle between the normal to the $\pi^+\pi^-p$ decay plane and the target proton direction in the $\pi^+\pi^-p$ rest system. The same angular momentum states (J = 1/2, 3/2 and 5/2) were used in the fit. The contributions obtained by this method were very similar to those shown in Fig. 2. The $N^*(1700)$ region is predominantly J = 5/2.

have determined $\rho_{\frac{1}{2}\frac{1}{2}}$ in the t- and s- channels from maximum likelihood fits. We find that $\rho_{\frac{1}{2}\frac{1}{2}}$ for the t- channel is consistent with a value of 1/2 over a wide range of $|t|$ while for the s-channel the value decreases with increasing $|t|$. This result again suggests that helicity is conserved in the t-channel rather than in the s-channel.

Finally, in Figs. 4 (c)-(f) we show results of fits of the function $[1 + A \cos(\varphi) + B \cos(2\varphi)]^{\dagger}$ to distributions of the azimuthal angle of the π^- in the t-channel and s-channel reference frames as a function of $M(\pi^+\pi^-p)$. The distribution of the azimuthal angle is expected to be isotropic in the frame in which helicity is conserved independent of the spin of the resonance or the existence of intermediate decay states such as $\pi\Delta$.[10] We find the distribution in the t-channel (Figs.4(c) and (e)) to be consistent with isotropy for the $N^*(1700)$ mass region; the distribution in the s-channel (Figs. 4(d) and (f)) is not. We conclude that there is no evidence for s-channel helicity conservation in reaction (1). Instead our observations are consistent with t-channel helicity conservation in this reaction.

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†Higher order terms in $\cos(n\varphi)$ were found to be unnecessary.

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Figure Captions

Figure 1. a) Distribution of the $\pi^+\pi^-p$ effective mass for the combined data;

b) Distribution of the $\pi^-\Delta^{++}(1236)$ effective mass for the combined data using the fitted number of Δ^{++} events as a function of $\pi^+\pi^-p$ mass.

Figure 2. a) Distribution of the $\pi^+\pi^-p$ effective mass for events with $\cos\theta > 0$ and π^+p effective mass less than 1.5 GeV;

b)-(d) Fitted numbers of events for the various spin-parity states $1/2^{\pm}$, $3/2^-$, $5/2^+$ as a function of the $\pi^+\pi^-p$ effective mass. The fit is described in the text.

Figure 3. a)-(c) Distribution of $\cos\theta$ in the Gottfried-Jackson frame (or t-channel);

d)-(f) Distribution of $\cos\theta_H$ in the helicity frame (or s-channel).

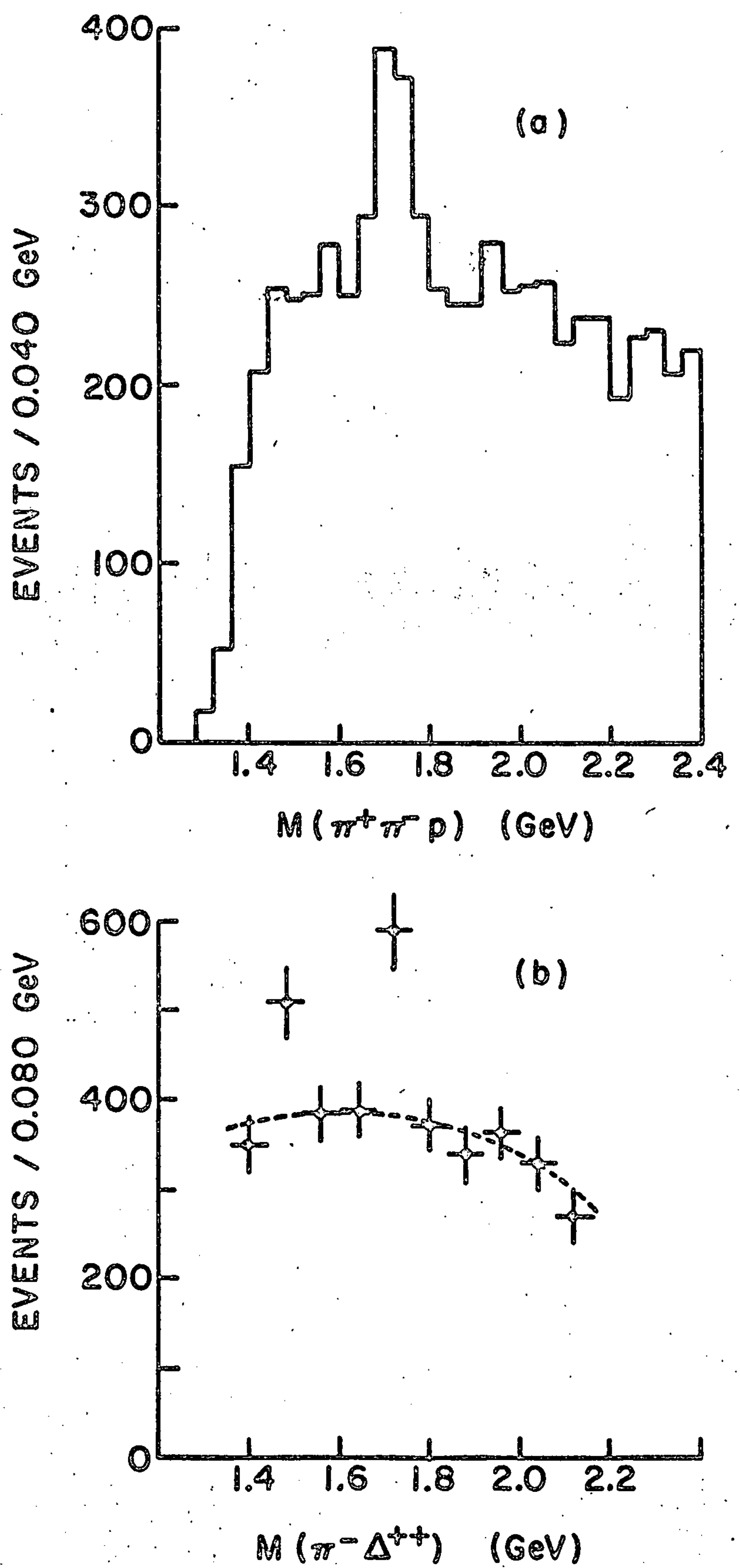
Figs. (b) and (e) correspond to the $N^*(1700)$ region (1.660 to 1.780 GeV) while the other figures correspond to control regions (Figs. (a) and (d) 1.540 to 1.660 GeV, and Figs. (c) and (f) 1.780 to 1.900 GeV). The curve in Fig. 3(b) represents the angular distribution expected for $J^P = 5/2^+$ with $\rho_{\frac{1}{2}\frac{1}{2}} = 1/2$.

Figure 4. a)-(b) Fitted values for $\rho_{\frac{1}{2}\frac{1}{2}}$ in the t-channel (a) and s-channel (b) for the $N^*(1700)$ region (1.620 to 1.820 GeV);

c)-(f) Fitted parameters of the function $1 + A\cos\varphi + B\cos 2\varphi$ to the azimuthal angle for the $N^*(1700)$ decay.

(c) and (e) show A and B in the t-channel

(d) and (f) show A and B in the s-channel.



400
300
200
100
0
EVENTS / 0.040 GeV
(a)
1.4
1.6
1.8
2.0
2.2
2.4
M ($\pi^+\pi^-$p) (GeV)
600
400
200
0
EVENTS / 0.080 GeV
(b)
1.4
1.6
1.8
2.0
2.2
M ($\pi^-\Delta^{++}$) (GeV)

FIG. 1

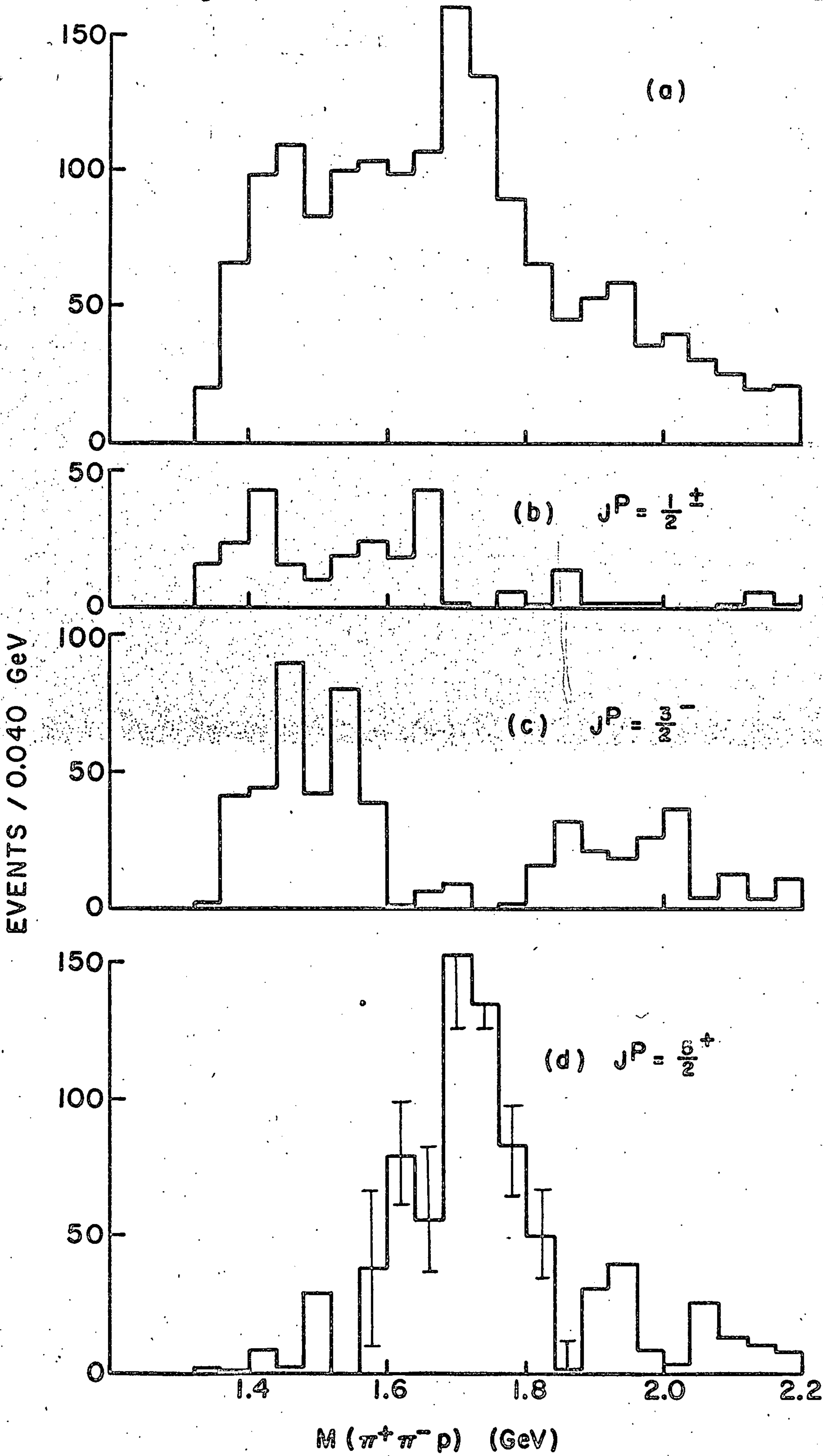

150
100
50
0
(a)
50
0
(b) JP = 1/2 ±
100
50
0
(c) JP = 3/2 −
150
100
50
0
(d) JP = 5/2 +
EVENTS / 0.040 GeV
1.4
1.6
1.8
2.0
2.2
M (π+ π− p) (GeV)

FIG. 2

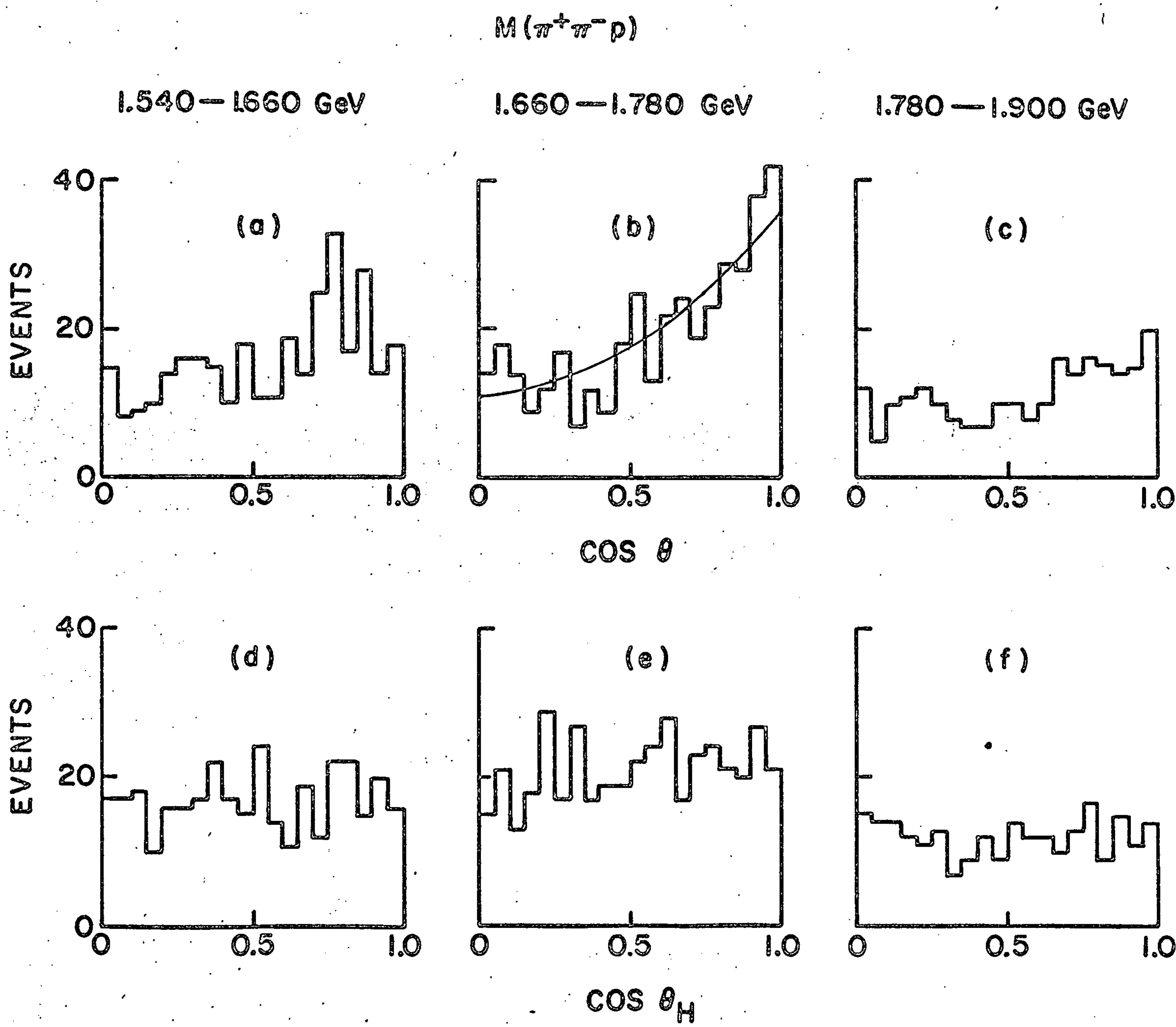
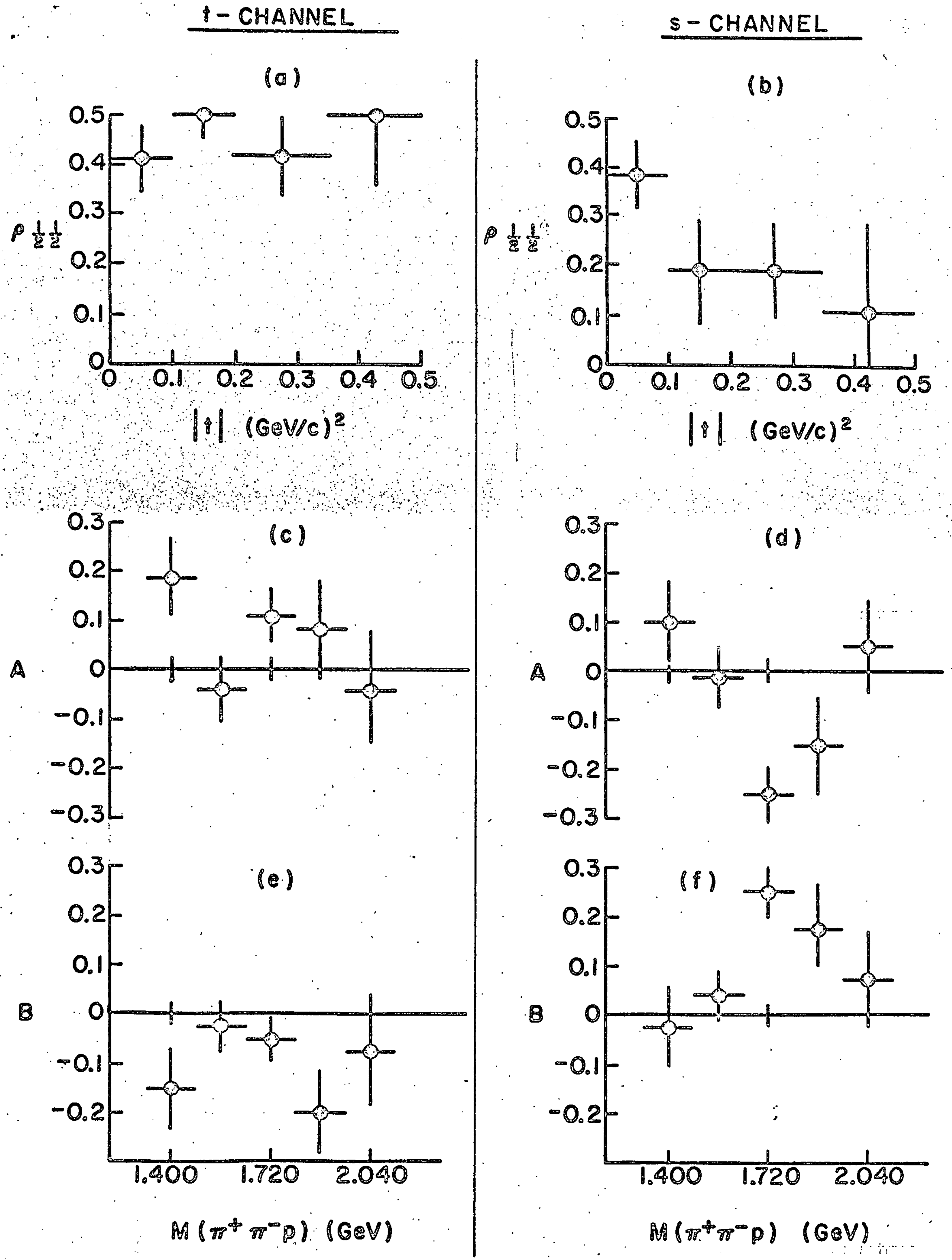

M($\pi^+\pi^-p$)
1.540—1.660 GeV
1.660—1.780 GeV
1.780—1.900 GeV
(a)
(b)
(c)
(d)
(e)
(f)
EVENTS
40
20
0
0
0.5
1.0
COS θ
COS θ_H

FIG. 3



t - CHANNEL
s - CHANNEL
(a)
(b)
(c)
(d)
(e)
(f)
ρ ½ ½
A
B
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0.1
0.2
0.3
0.4
0.5
|t| (GeV/c)²
1.400
1.720
2.040
M (π⁺ π⁻ p) (GeV)

FIG. 4