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OBSERVATION OF A FOUR-PION VECTOR-MESON STATE OF MASS $\cong$ 1.5 GeV PRODUCED BY LINEARLY POLARIZED 9.3 GeV PHOTONS*

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ABSTRACT

From a study of $\gamma p \rightarrow 2\pi^+ 2\pi^- p$ using 9.3 GeV linearly polarized photons, evidence is found for a $J^P = 1^-$, $I^G = 1^+$ four pion enhancement of mass ~ 1.5 GeV with a production cross section of $1.6 \pm 0.4\,\mu b$.

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Previous indications of possible vector meson states, other than ρ, ω, and Φ, have been wide enhancements near 1.6 GeV in $\gamma p \rightarrow 2\pi^+2\pi^- p$ and in $e^+e^- \rightarrow 4\pi$ (+ neutrals).[1,2] We confirm the existence of a 4π enhancement at ~ 1.5 GeV in the reaction $\gamma p \rightarrow 2\pi^+2\pi^- p$ and demonstrate, using the linear polarization of the beam, that it is in a $J^P = 1^-$, $I^G = 1^+$ state. Preliminary results have been reported elsewhere.[3]

The data presented here originate from a systematic study[4] of γp reactions at 2.8, 4.7, and 9.3 GeV, using the LBL-SLAC 82" HBC exposed to the SLAC monochromatic backscattered laser beam.[5,6] The 4π enhancement is observed most clearly at 9.3 GeV, and therefore we present results based on this exposure. At 9.3 GeV the beam momentum spread is $\Delta p/p \approx \pm 3\%$, and the degree of linear polarization, P_γ, is 77%. The event analysis is described in Ref. 6. From a total of 1.2 million pictures we obtained 1041 events of the reaction

$$\gamma p \rightarrow 2\pi^+2\pi^- p \qquad (1)$$

with $8.0 < E_\gamma < 10.3$ GeV and a kinematic confidence level greater than 1%. The channel cross section is 4.1 ± 0.2 μb.[6]

Mass Distributions

The 4π mass distribution for reaction (1) is shown in Fig. 1a. From the t-distribution (not shown) we find that 4π production is peripheral with a t-dependence $\sim e^{6t}$ for $M_{4\pi} < 2.4$ GeV (t is the momentum transfer squared to the proton). Phase space weighted by this t-distribution peaks at a 4π mass ~ 2.5 GeV. The reflection from Δ^{++} production, which is strong in reaction (1) (see Fig. 1b), also peaks at high 4π mass. In contrast, the 4π mass spectrum shown in Fig. 1a is enhanced at ~ 1.5 GeV.

Figure 1b shows the π^+p mass distribution; events having $M_{4\pi} < 1.7$ GeV are shaded. There is no Δ^{++} peak present for low 4π masses. By removing

Δ^{++} events from reaction (1) we find an upper limit of $2.1 \pm 0.2\ \mu$b for the cross section of the 4π enhancement (shaded events of Fig. 1a).

A strong ρ^o signal is present in the $\pi^+\pi^-$ mass distribution (Fig. 1d). The shaded portion of Fig. 1d demonstrates that ρ^o production also occurs in the low mass 4π enhancement. Figure 1c shows the $\pi^+\pi^-$ mass distribution, for $M_{4\pi} < 1.7$ GeV, when the opposite $\pi^+\pi^-$ mass combination is in the rho region. There is no evidence for a substantial contribution of $\rho^o\rho^o$. This is confirmed by a maximum-likelihood fit, with incoherent $\rho^o\rho^o$ (dashed curve on Fig. 1c), $\rho^o\pi^+\pi^-$, and phase space, to the mass distribution of events with $M_{4\pi} < 1.7$ GeV; the fit required no $\rho^o\rho^o$, ~80% $\rho^o\pi^+\pi^-$, and ~ 20% phase space. The solid curve on Fig. 1c shows the result of this fit.

Angular Distribution

We have shown[3] that in the 4π rest frame, the vector $\vec{Q} = \vec{P}_{\pi_1^+} + \vec{P}_{\pi_2^+}$ may be a good analyzer for a $J^P = 1^-$, $I^G = 1^+$, 4π state. Following our procedures introduced for vector-meson analysis,[4] we give in Fig. 2a, for $M_{4\pi} < 1.7$ GeV, the distribution of the angles θ, ψ calculated[7] in the helicity frame using the analyzer $\vec{Q}$. Strong $\sin^2\theta$ and $\cos^2\psi$ components, characteristic of the decay of an s-channel helicity-conserving vector meson produced via natural-parity exchange, are evident in the angular distribution. A similar plot in the Gottfried-Jackson frame (not shown) shows weaker $\sin^2\theta$ and $\cos^2\psi$ terms indicating that, like the ρ^o in $\gamma p \rightarrow p\rho^o$, the 4π system is more strongly aligned in the helicity frame.

The amount of $\sin^2\theta \cos^2\psi$ component in the 4π angular distribution, and consequently the number of s-channel helicity-conserving $J^P = 1^-$ 4π events, can be determined[4] from

$$\Pi = \frac{1}{P_\gamma} \sqrt{\frac{40\pi}{3}}\ \Sigma\ \mathrm{Re}\ Y_2^2(\theta,\psi) \ , \qquad (2)$$

if $\vec{Q}$ is a perfect analyzer. The quantity Π is shown as a function of 4π mass in Fig. 2b; Π peaks near 1.5 GeV and has a FWHM of ~ 0.5 GeV. We note that only the Y_2^0, and Y_2^2 moments are significant for $M_{4\pi} < 1.8$ GeV. Thus our data are consistent with a $J^P = 1^-$ 4π enhancement which we refer to as the ρ'. The cross section corresponding to Π, which is a lower limit for the ρ' cross section, is 0.8 ± 0.2 μb.

Isospin

We have shown that the ρ' decays predominantly into $\rho^o\pi^+\pi^-$. The $\pi^+\pi^-$ pair could have isospin 0, 1, or 2. We can rule out the dominance of I=2 for the dipion state since it requires $R = (\rho' \to \rho\pi\pi \to \pi^+\pi^-\pi^o\pi^o)/(\rho' \to \rho^o\pi^+\pi^-) \geq 4$, which is incompatible with the observed number of events in the ρ' region in the channel $\gamma p \to p\pi^+\pi^-$MM (not shown). Isospin 1 for the dipion pair implies a $\rho^o\rho^o$ decay, which is inconsistent with the dipion mass distribution (Fig. 1c). Thus the $\pi^+\pi^-$ pair is likely to be in a predominantly isospin zero state, giving a branching ratio $R \simeq 0.5$, which is consistent with our data. We conclude that the ρ' isospin is 1 (C = -1); this allows us to associate the ρ' with the state observed in e^+e^- experiments.

Spin-Parity Analysis

We have made a spin-parity analysis for events with $M_{4\pi} < 1.7$ GeV, assuming that the 4π system is produced conserving s-channel helicity and that it decays into $\rho^o + \sigma$, where σ is an s-wave isoscalar $\pi\pi$ state. Further, we must have natural (unnatural) parity t-channel exchanges in the production of natural (unnatural) parity 4π states in order to reproduce the experimental $\cos^2\psi$ distribution.

The angular distribution of $\vec{Q}$ has been calculated[8] for the states $1^\pm$, $2^\pm$, and 3^- assuming the lowest allowed angular momentum between the ρ^o and σ.

The states 1^+, 2^+ and 3^- yield $\cos^2\theta$ and $\cos^2\psi$ components in contrast to the experimentally observed $\sin^2\theta$ and $\cos^2\psi$ distributions. States with helicity other than ±1 could introduce $\sin^2\theta$ terms but only with a reduction in the amount of the $\cos^2\psi$ component. Thus we rule out the dominance of the 1^+, 2^+ and 3^- states in the low $M_{4\pi}$ region. Both 1^- and 2^- give angular distributions having large $\sin^2\theta$ and $\cos^2\psi$ components; to determine which of these states fits the data best, a maximum-likelihood fit was made with a matrix element consisting of an incoherent sum of 1^-, 2^- and phase space. Specifically, assuming the simplest form for the decay of a 1^- state into $\rho^o\pi^+\pi^-$, we write the matrix element for production of an s-channel helicity-conserving ρ', followed by its s-wave decay into a ρ^o and an s-wave isospin-zero dipion system, as

$$T_{\rho'} = \vec{\mathscr{E}} \cdot \sum_{i=1}^{4} \vec{q}_i \; \frac{\sin\delta_i^p \, e^{i\delta_i^p}}{q_i^3} \cdot \frac{\sin\delta^s \, e^{i\delta^s}}{q} \tag{3}$$

where $\vec{\mathscr{E}}$ is the polarization of the photon rotated by the ρ' c.m.s. production angle about the production normal; the other quantities are defined in Footnote 8.

We find that $J^P = 1^-$ and phase space is required to fit the data; 2^- is rejected by the fit.[9] The curves on Fig. 1d and Fig. 2a show that the matrix element (3) describes the data well.

Cross Section for s-Channel Helicity Conserving 4π 1^- States

For the decay matrix element (3) we have calculated, using Monte Carlo events, the efficiency of the analyzer $\vec{Q}$; the efficiency is 70% at $M_{4\pi} \sim 1.5$ GeV, and falls to 40% at 2.6 GeV. We use this efficiency to correct the values of Π (Fig. 2b) obtained experimentally and display the result in Fig. 1a. The corrected Π peaks at ~ 1.5 GeV and has a FWHM of ~ 0.60 GeV; it accounts for practically all events with $M_{4\pi}$ less than 1.5 GeV. The production cross section calculated from the corrected Π is 1.3 ± 0.4 μb. We note that the corresponding cross section at 4.7 GeV is 0.8 ± 0.4 μb.

Next we estimate the upper limit for decay of the ρ' into $\pi^+\pi^-$ and K^+K^- from Σ Re $Y_2^2(\theta, \psi)$ for $\gamma p \rightarrow \pi^+\pi^- p$, and $K^+K^- p$. We use the mass interval 1.15 - 1.75 GeV and the t-interval 0.02 - 1.0 GeV^2. The resulting upper limits (2 standard deviations) are $\rho' \rightarrow \pi^+\pi^- / \rho' \rightarrow \rho^o\pi^+\pi^- = 0.2$, and $\rho' \rightarrow K^+K^- / \rho' \rightarrow \rho^o\pi^+\pi^- = 0.04$.

Maximum Likelihood Fits

We have attempted to obtain a better estimate of the ρ' cross section by making an overall maximum-likelihood fit to reaction (1) including, besides the ρ', the channels $\Delta^{++}3\pi$, $\Delta^{++}\rho^o\pi^-$, $\Delta^{++}A_2^-$, $\rho^o\pi^+\pi^- p$, and phase space. The ρ' is parameterized by a Breit-Wigner of the form $\exp(At/2)/\left(M_{\rho'} - M_{4\pi} - \frac{i}{2}\gamma_{\rho'} \cdot \frac{K(M_{4\pi})}{K(M_{\rho'})}\right)$ which multiplies the RHS of Eq. (3). K describes the energy dependence of the width,[10] and A is the slope of the t-distribution. The amplitudes of the other channels are described in Ref. 3.

We obtain a good description of the channel,[11] as shown by the curves on the mass and decay distributions in Figs. 1 and 2. For the ρ' mass and width ($\gamma_{\rho'}$) we obtain 1.43 ± 0.05 GeV and 0.65 ± 0.1 GeV, respectively. We note however that these quantities are sensitive to the choice of the function K.[3] We find a cross section for $\rho' \rightarrow \rho^o\pi^+\pi^-$ of 1.6 ± 0.4 μb, which is insensitive to K. The slope of the ρ' t-distribution is 5.6 ± 0.3 GeV^{-2}.

Conclusion

We have confirmed the existence of a 4π enhancement at a mass ~ 1.5 GeV and have shown that it is an $I^G = 1^+$, $J^P = 1^-$ state which decays primarily into $\rho^o\pi^+\pi^-$. It is photoproduced via natural parity exchange with a cross section of

$\sigma(\gamma p \rightarrow p\rho' \rightarrow p\rho^{o}\pi^{+}\pi^{-}) = 1.6 \pm 0.4\ \mu b$. The production mechanism is predominantly s-channel helicity-conserving.

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7. We analyze the vector meson (VM) decay in the helicity frame, where the z axis is the direction of the VM in the overall (γp) CMS. The y axis is the normal to the production plane, defined by the cross product $\hat{k} \times \hat{v}$ of the directions of the photon and the vector meson. The x axis is given by $\hat{x} = \hat{y} \times \hat{z}$. The angle Φ between the polarization of the photon, $\hat{\epsilon}$, and the production plane in the total c.m. system is defined by $\cos \Phi = \hat{\epsilon} \cdot (\hat{y} \times \hat{k})$, $\sin \Phi = \hat{y} \cdot \hat{\epsilon}$. The decay angles θ, ϕ are the polar and azimuthal angles of the appropriate analyzer $\hat{n}$: for two body decays we use the direction of one of the decay mesons in the vector meson CMS; for 3π decay the decay plane normal is used. For 4π decay we use the vector sum of the two π^+

momenta in the 4π CMS (see text for discussion): $\cos\theta = \hat{n}\cdot\hat{z}$, $\cos\phi = \hat{y}\cdot(\hat{z}\times\hat{n})/|\hat{z}\times\hat{n}|$, $\sin\phi = -\hat{x}\cdot(\hat{z}\times\hat{n})/|\hat{z}\times\hat{n}|$, and $\psi = \phi - \Phi$. In the forward direction ψ is the angle between the photon polarization and the meson decay plane.

8. For a state of spin-parity J^P decaying into $\rho\sigma$ with relative angular momentum ℓ, we use amplitudes of the form $T = \sum_{i=1}^{4} (e^{-i\Phi}A_i(J,1) - P(-1)^J e^{i\Phi}A_i(J,-1))$ with

$$A_i(J,M) = p^\ell q_i \sum_{mm'} c(JM;\ell m\ 1m')\, Y_\ell^m(\theta,\phi) Y_1^{m'}(\theta',\phi') \frac{\sin\delta_i^p e^{i\delta_i^p}}{q_i^3} \frac{\sin\delta^s e^{i\delta^s}}{q}$$

The summation over i symmetrizes the amplitude over all $\pi^+\pi^-$ combinations. Φ is defined in Footnote 7. p, θ, ϕ are respectively the momentum, polar angle, and azimuth of the ρ in the ρ' CMS; q_i, θ', ϕ' are respectively the momentum, polar angle, and azimuth of the π^+ resulting from the decay of the ith ρ in the ρ rest frame; q is the momentum of the π^+ in the rest frame of the σ opposite to the ith ρ. $Y_1^{m'}(\theta',\phi')$, $Y_\ell^m(\theta,\phi)$ are spherical harmonics describing the decay $\rho\to\pi^+\pi^-$ and $\rho'\to\rho\sigma$ respectively. The I=1 p-wave and I=0 s-wave dipion phase shifts are given by δ^p and δ^s respectively. We use the phase shifts of S. D. Protopopescu et al., LBL 787 (1972) and Proceedings of Philadelphia Conference on Meson Spectroscopy (1972), to be published.

9. Fitting $J^P=1^-$ and phase space alone gives a $P(\chi^2)$ of 80% in the ψ distribution, whereas a fit of 2^- and phase space alone gives a $P(\chi^2) < 1\%$.

10. We use $K = G(M_{4\pi})/(1+G(M_{4\pi})/G(M_{\rho'}))$ where

$$G(M_{4\pi}) = \frac{1}{M_{4\pi}} \int |\text{Breit-Wigner}_\rho|^2 \prod_{i=1}^{4} \frac{d^3p_i}{2E_i}\, \delta_4\left(p - \sum_{i=1}^{4} p_i\right)$$

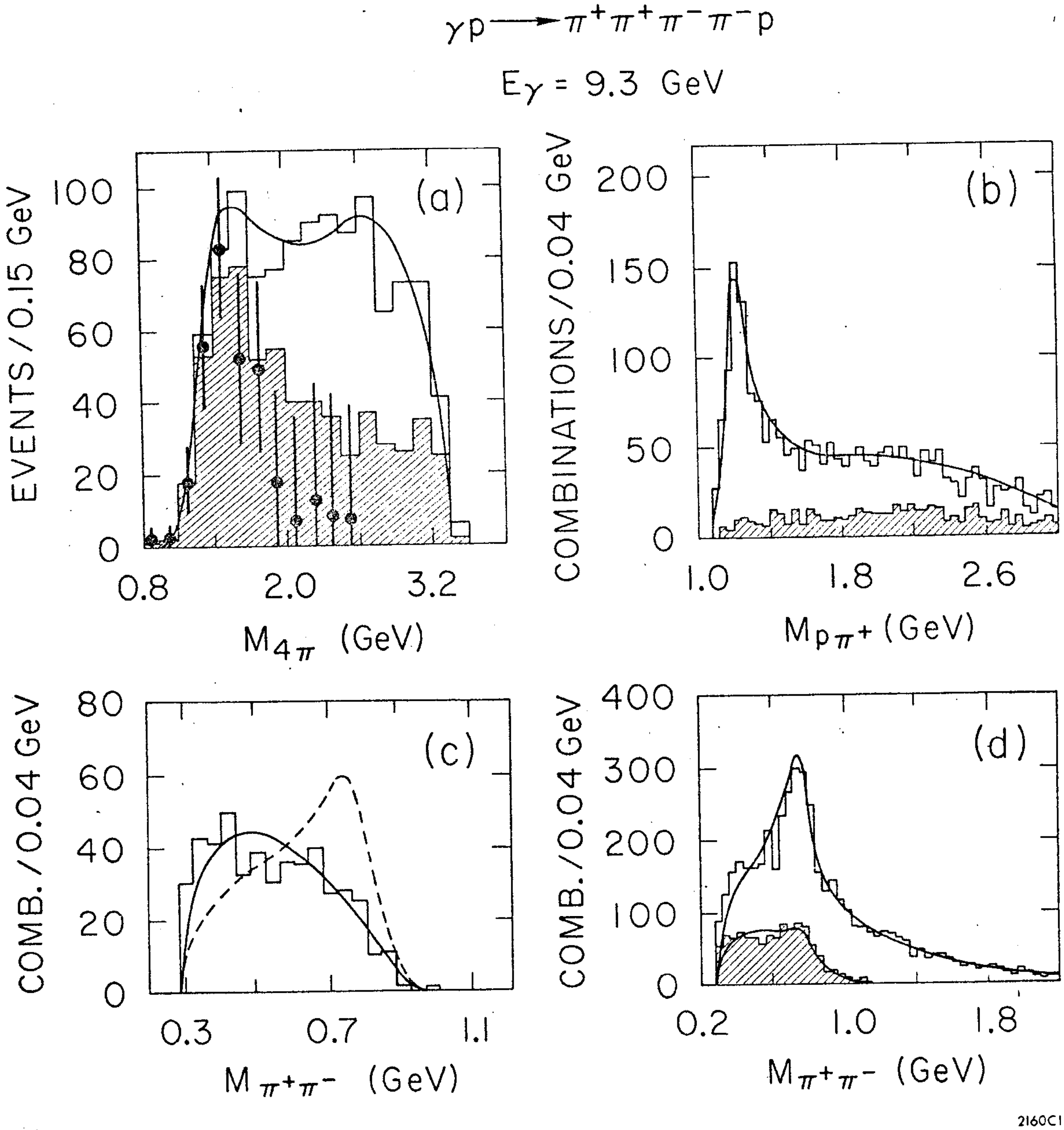
This approaches a constant at large 4π masses in contrast to the parameterization used in Ref. 3.

11. The fitted percentages of the channels $p\rho'$, $\Delta^{++}3\pi$, $\Delta^{++}\rho^{o}\pi^{-}$, $\Delta^{++}A_2^{-}$, $\rho^{o}\pi^{+}\pi^{-}p$, and phase space are 40 ± 8, 16 ± 4, 25 ± 6, 7 ± 2, 3 ± 3, 10 ± 4, respectively.

FIGURE CAPTIONS

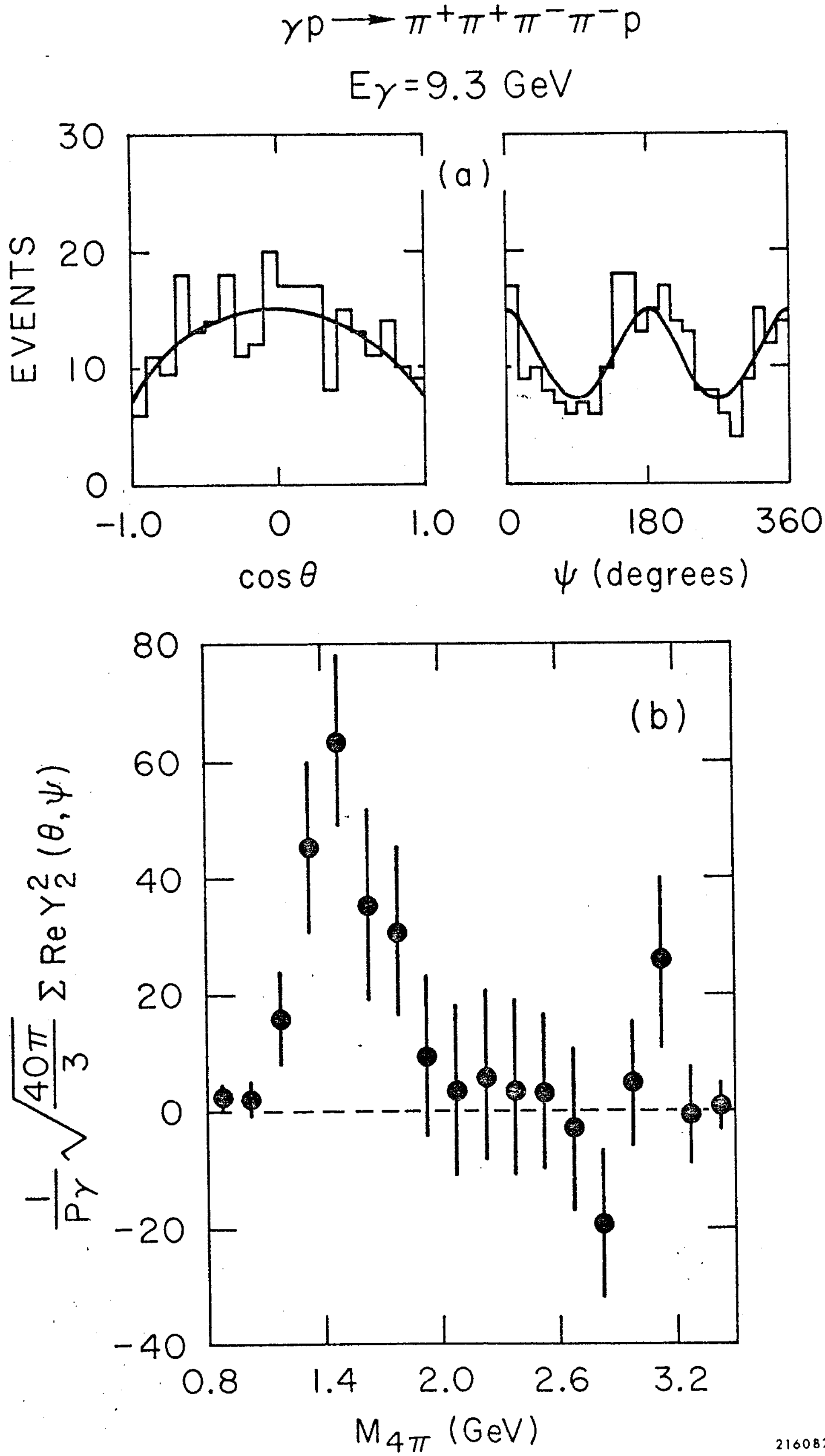
1. Reaction $\gamma p \rightarrow 2\pi^{+}2\pi^{-}p$ (a) Four pion mass spectrum. The shaded histogram has events with Δ^{++} removed ($M_{p\pi^{+}} > 1.32$ GeV). The points are Π (see Eq. (2)) corrected for efficiency. The curve is from a maximum-likelihood fit to the channel. (b) $\pi^{+}p$ mass distribution. The shaded events are for $M_{4\pi} < 1.7$ GeV. The curve is from the maximum-likelihood fit. (c) $\pi^{+}\pi^{-}$ mass distribution ($M_{4\pi} < 1.7$ GeV) for $\pi^{+}\pi^{-}$ pairs opposite a ρ^{o}. The dotted (solid) curve shows the distribution expected for $\rho^{o}\rho^{o}$ ($\rho^{o}\pi^{+}\pi^{-}$ + phase space). (d) $\pi^{+}\pi^{-}$ mass distribution. The shaded events are for $M_{4\pi} < 1.7$ GeV. The curve is from the maximum-likelihood fit.

2. (a) Distribution of the angles θ and ψ for $M_{4\pi} < 1.7$ GeV. The curve is from the maximum-likelihood fit. (b) Π uncorrected for analyzer efficiency.



γp ⟶ π⁺π⁺π⁻π⁻p
Eγ = 9.3 GeV
(a)
EVENTS / 0.15 GeV
M4π (GeV)
0.8
2.0
3.2
(b)
COMBINATIONS / 0.04 GeV
Mpπ+ (GeV)
1.0
1.8
2.6
(c)
COMB. / 0.04 GeV
Mπ+π- (GeV)
0.3
0.7
1.1
(d)
COMB. / 0.04 GeV
Mπ+π- (GeV)
0.2
1.0
1.8
2160C1

Fig. 1



$\gamma p \to \pi^+\pi^+\pi^-\pi^- p$
$E_\gamma = 9.3$ GeV
(a)
EVENTS
30
20
10
0
-1.0
0
1.0
$\cos\theta$
0
180
360
ψ (degrees)
(b)
$\frac{1}{P_\gamma}\sqrt{\frac{40\pi}{3}}\ \Sigma\ \mathrm{Re}\, Y_2^2(\theta,\psi)$
80
60
40
20
0
-20
-40
0.8
1.4
2.0
2.6
3.2
$M_{4\pi}$ (GeV)

216082

Fig. 2