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OBSERVATION OF $S^* \to \pi^+\pi^-$ IN ψ DECAY*

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Abstract

Copious production of S^* decaying into $\pi^+\pi^-$ is observed in ψ decay. The S^* pole parameters are measured to be (974±4 −i 14±5) MeV, consistent with the parameters extracted from coupled channel fits to peripheral $\pi^+\pi^-$ and K^+K^- production experiments. The inclusive branching ratio for $\psi \to S^* + X$ is found to be (0.42±0.08)%.

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Until recent years the S^* was thought to belong to the $0^{++}q\bar{q}$ nonet, although the distinction between a Breit Wigner resonance and a $K\bar{K}$ virtual bound state has never been clearly established[1]. Recent experiments[2] have, however, shifted the center of gravity of this nonet to around 1400 MeV. The possible existence of $q\bar{q}q\bar{q}$ bound states[3] and glue-balls[4] in the 1 GeV mass region has also revived interest in the properties and nature of the S^*. Most of our knowledge concerning the S-wave S^* comes from analysis of its interference with the usually dominant p-wave amplitude in peripheral dipion production experiments[5]. It has been directly observed in $\pi^- p \to \pi\pi n$ near threshold[6,7] and with limited statistics in the reaction $K^- p \to \pi^+\pi^-(\Lambda,\Sigma^0)$.[8] The Zweig suppressed hadronic decays of the $\psi(3095)$ provide a new production mechanism for the isoscalar mesons.

In this letter we report the observation of $S^* \to \pi^+\pi^-$ in inclusive and exclusive ψ decays and compare its properties with current models. We use a sample of 1.3×10^6 ψ decays collected with the SLAC-LBL Mark II magnetic detector at the e^+e^- storage ring facility SPEAR. The detector has been extensively described elsewhere.[9] Only charged tracks are used in this study. They are reconstructed from hits in the sixteen cylindrical drift chamber layers which provide solid angle coverage over 85% of 4π sr. The trigger requires two or more charged tracks, at least one of which must be within the central 67% of the 4π sr.

Inclusive Production

For the inclusive studies all events with two or more charged tracks are included if at least two tracks were assigned as pions. Particles with momenta below 1.6 GeV/c could be identified as proton and K from time of flight. Muons with momenta above 1.4 GeV/c were also identified. Electrons were identified from time of flight up to 250 MeV/c and with the lead-liquid Argon calorimeters for higher momenta. Furthermore, tracks were eliminated when $|\cos\theta_{12}| > 0.9985$. This cut reduces the number of converted γ's ($\cos\theta_{12}$ near 1) and multiprong Bhabhas ($\cos\theta_{12}$ near -1) that might otherwise be confused with pions. All tracks not assigned or eliminated as above are considered pions. Finally pions originating at an identified second vertex (K^0, Λ^0) were eliminated.

In Figure 1a we show the measured inclusive $\pi^+\pi^-$ and $\pi^\pm\pi^\pm$ spectra. The contributions of the ρ^0 and K^0 decays close to the primary vertex are clearly seen. In order to study the ρ, S^*, and f^0, the $\pi^+\pi^-$ mass spectrum (m) between .65 GeV and 1.46 GeV was fit with the function

$$F(m) = R(m)\cdot b(m) + b(m) \text{, where} \tag{1}$$

$$R(m) = C_\rho \cdot F_{BW}(\rho) + C_\omega \cdot F_{BW}(\omega) + C_{S^*} \cdot F_{BW}(S^*) + C_f \cdot F_{BW}(f^0) \text{ ,}$$

$$F_{BW}(x) = \frac{2}{\pi} \cdot \frac{m m_x \Gamma(m)}{(m^2 - m_x^2)^2 + m_x^2 \Gamma^2(m)} \text{ , and}$$

$$\Gamma(m) = \Gamma_x \frac{m_x}{m} \left(\frac{q}{q_x}\right)^{2\ell+1} .$$

The pion momentum in the dipion center of mass was denoted by q; q_x refers to the same momentum at the resonance of mass m_x, width Γ_x, and angular momentum ℓ.

The background was parameterized as $b(m) = A + Bme^{-(Cm+Dm^2)}$ and was also taken to represent the dipion phase space. This background contribution is shown suitably renormalized as the solid curve in Figure 1a and is very similar to the measured like pion spectrum in the mass region studied. The systematic disagreement at higher masses could be the effect of long range charge correlations and/or reflections of resonances.

The resonance contribution to the fit, $R(m)\cdot b(m)$, is shown as the solid curve in Figure 1b. The data points in Figure 1b are the measured $\pi^+\pi^-$ data from Figure 1a with the smooth fitted background, b(m), subtracted. The resonance contribution to the fit (with $\chi^2/NDF = 55/66$) is shown as the solid curve in Figure 1b. The inclusion of an incoherent direct $\omega^0 \rightarrow \pi^+\pi^-$ decay term was required by the shape near 780 MeV. The dashed curve shows the ρ contribution in this region. A momentum dependent Gaussian resolution function (with mean $\sigma = \pm 12$ MeV), determined by Monte Carlo simulation, was convoluted with the Breit-Wigner to include the effects of measurement and reconstruction on the narrow ω^0 and S^* resonances. Leaving the ω^0 mass variable gives $m_\omega = 780\pm2$ MeV. Fixing the ω^0 mass at 782.4 MeV while leaving the width variable gives $\Gamma_\omega = 8\pm4$ MeV, consistent with the accepted value. The results of a fit which includes the possibility of ρ,ω interference are consistent with no coherence.(10) Since the G-parity of the ψ is odd, the allowed direct decays are (ω^0 plus even numbers of pions) or (ρ^0 plus odd numbers of pions). When $\omega^0 \rightarrow \pi^+\pi^-$, these will be different final states and hence incoherent. The only possibility of coherence would be with the smaller $\psi \rightarrow \gamma^* \rightarrow$ even G-parity final state.

The resonance parameters determined from the fit are shown in Table I. The ρ mass is somewhat low but is consistent with the mass measured in higher energy inclusive e^+e^- annihilations[11] and in $\bar{p}p$ annihilations.[12] The f^0 mass and width are consistent with established values.

The observation of both the $\omega^0 \to \pi^+\pi^-$ and the $S^* \to \pi^+\pi^-$ decays are striking because of the relatively copious production implied. To calculate the absolute branching ratios (BR) we use an average Monte Carlo inclusive $\pi^+\pi^-$ detection efficiency of 0.50±.05. Measurements of the trigger efficiency using a sample of $\psi' \to \psi\pi^+\pi^-$ events, in which the ψ was inferred from the observed recoil $\pi^+\pi^-$ pair, tell us that our data sample corresponds to $(1.33\pm0.04)\times10^6$ produced ψ's. We use the average BR($\omega^0 \to \pi^+\pi^-$) of (1.4±0.4)%,[13] although individual measurements and limits range from 0.2% to 4%. The branching ratio for ψ to decay inclusively into each of the observed resonances is then given in Table II. The observed ratios of ω^0/ρ^0 and f^0/ρ^0 are consistent with the values measured in πp, pp, and $\bar{p}p$ interactions.[14] Requiring a $K^\pm$ in the event reduces the inclusive $\pi^+\pi^-$ sample by about an order of magnitude but does not enhance the S^* peak with respect to the ρ peak.

Figure 1c shows a closeup of the S^* region of Figure 1b to compare the data with parameterizations other than a Breit Wigner. We have repeated our fit using a coupled channel Breit-Wigner to represent the S^*.

$$F(S^*) = \left| \frac{m_0 \Gamma_\pi}{m_0^2 - m^2 - i\, m_0(\Gamma_\pi + \Gamma_K)} \right|^2 \qquad (2)$$

where $\Gamma_\pi = g_\pi q_\pi$ and $\Gamma_K = g_K q_K$, the positive imaginary value of q_K being used below $K\bar{K}$ threshold.(15) The pole position derived from the $\pi^+\pi^-$ spectrum is rather insensitive to g_K, which is taken as 0.2. The best fit values are m_0 = (956±6) MeV, g_π = 0.088±.029, corresponding to a pole position of (974±4 −i 14±5) MeV. This fit falls within the range of previous determinations and is shown as the solid curve in Figure 1c.

We also show in Figure 1c the $K\bar{K} \to \pi\pi$ fits of A. Martin and collaborators(16) with the resolution inferred from the Monte Carlo folded in. These fits describe the S^* with a coupled channel K-matrix formalism, treating the S^* as a $K\bar{K}$ bound state, similar to the description of the $\Lambda(1405)$ below the $\bar{K}N$ threshold. For the dotted curve, the pole parameters are fixed primarily from the measured peripheral $\pi\pi$ scattering moments near $K\bar{K}$ threshold. For the dashed curve, the pole parameters are fixed from the data of reference (8). The dot-dashed curve represents the contribution of the ρ, ω, and f. The agreement is reasonable, although small mass shifts seem to be called for. Note that we observe the S^* as a mass peak, as does the experiment of Binnie, et al., near threshold. In peripheral dipion production experiments ($\pi\pi \to \pi\pi$) the background S-wave phase shift has already reached almost 90° so that the S^* appears as a sharp drop in the mass spectrum.

In order to investigate the S^* production mechanism, we then look at the recoil spectra for both like and unlike pairs in the S^* mass region (.955 GeV $\leq m_{\pi\pi} \leq$ .985 GeV). In Figure 2 we show the unlike pion recoil spectrum with 1.68 (as determined from the fit above) times the like pion recoil spectrum subtracted. The spectrum is peaked towards higher masses indicating that many of the S^*'s result from multibody final states or higher mass cascade decays. The number of events in the ϕ region (allowing for the poor resolution in the recoil spectrm) agrees with the estimate below. There are about 75 events in the ω peak.(17) The higher mass region is more difficult to interpret. A search for states decaying into $S^{*}\pi^{\pm}$, using a similar background subtraction technique, failed to show any structure.

Exclusive States

Turning now to the exclusive measurements, 63,900 events with 3 tracks and 41,800 events with 4 tracks were constrained with the kinematic fitting program SQUAW to the hypotheses

$$\psi \to K^{+}K^{-}\pi^{+}\pi^{-} \tag{3}$$

$$\psi \to K^{+}K^{-}K^{+}K^{-} \tag{4}$$

To minimize losses from K decays, we accepted all tracks with at least 7 drift chamber hits used in their reconstruction. Only loose time-of-flight consistency requirements were placed on each mass hypothesis. A confidence level of at least .05 was required for each fit. The $K^{+}K^{-}$ mass distributions for reaction (3) is shown in Figure 3a. Monte Carlo studies show that there is considerable feed down contamination to the resultant 3 track fits to reaction (3), but requiring the $K^{+}K^{-}$ pair to be in the ϕ mass band reduces this background to a negligible level. There is no evidence for feed down to reaction (4).

The selection of a ϕ meson in the final state preferentially selects recoiling states that couple to $s\bar{s}$ quarks, as the S^{*} is thought to do. In Figure 3b we show the background subtracted $\pi^{+}\pi^{-}$

mass distribution for reaction (3) when the mass of the K^+K^- pairs is required to be in the ϕ region (1.010-1.030 GeV) and the background is derived from the regions 1.000-1.010 GeV and 1.030-1.040 GeV. Indeed we see a peak which we identify with the S^*.

We can use the 50±10 events between $0.85 \leq m_{\pi\pi} \leq 1.05$ GeV and Monte Carlo efficiencies (including the fact that one third of the time the isoscalar S^* decays into $\pi^0\pi^0$) to estimate that 400±80 ϕS^* events were produced, or

$$BR(\psi \to \phi S^*) \cdot BR(S^* \to \pi\pi) = (2.0 \pm 0.5)\times 10^{-4} .$$

This would predict that 163±40 events in Figure 2 should come from $\psi \to \phi S^*$, consistent with the number of events observed near 1 GeV. Although the statistics are limited, a fit to a coupled channel Breit-Wigner[18], including resolution, over a constant background, gives a pole position of (964 - i 14) with $\chi^2 = 7.5/9$. Imposing the pole parameters determined from the inclusive fits above gives $\chi^2 = 9.0/10$, and we show this prediction as a solid histogram spanning the fitted bins.

Although the S^* is below $K\bar{K}$ threshold, it couples predominantly to $K\bar{K}$, so that one might expect a small threshold enhancement in the K^+K^- system recoiling from the ϕ in reaction (4). The actual number of events expected depends on the pole position and g_K. This K^+K^- spectrum is shown in Figure 3c and is dominated by a strong f'(1510) signal. Although there are some events near threshold, about half can be associated with the background under the ϕ. We estimate that 9±10 events are due to ϕS^*.

The 46±10 f' events above background correspond to 450±110 events produced or

$$BR(\psi \to \phi f')\cdot BR(f' \to K\bar{K}) = (3.4 \pm 1.3)\times 10^{-4}$$

In conclusion, we have observed substantial inclusive S^* production in ψ decay. Exclusive two body final states observed so far account for only a small fraction of these events. The observed S^* pole parameters approximately agree with those deduced from analyses of pion production experiments.

Acknowledgments

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15. $q_M(m) = (m^2/4 - m_M^2)^{1/2}$ is the final-state c.m. momentum of the meson M. g_M is the coupling for $S \to MM$. The numerator in (2) assumes that inclusive S^* production is primarily $\pi\pi \to \pi\pi$. However, using $(\Gamma_\pi \Gamma_K)^{1/2}$ in the numerator doesn't affect the χ^2 and gives a similar pole position (981 - i 10).

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18. Here we assume that the ϕ recoil selects S^*'s produced in $KK \to \pi\pi$, requiring a $(\Gamma_K \Gamma_\pi)^{1/2}$ in the numerator of (2).

Table Captions

Table I. Results of overall fit to inclusive $\pi^+\pi^-$ spectrum as described in text. N is the number of events attributed to each resonance.

Table II. Measured branching fractions for inclusive ψ decay into each of the resonances R. These branching fractions are given relative to ρ production and as an absolute value.

Table I

	m (MeV)	Γ (MeV)	$N \cdot 10^{-3}$
ρ	760 ±2	150 ±10	110 ±10
ω	782.4 (fixed)	10.1 (fixed)	2.5± 0.5
S^*	972 ±3	24 ± 8	3.7± 0.7
f	1281 ±7	186 ±27	11.6± 1.0

Table II

R	R/ρ	BR(ψ→R+X) %
ρ	1	8.3 ±0.8
ω	1.6 ±0.6	13.4 ±4.7
S^*	.05± .01	0.42±0.08
f	.19± .03	1.6 ±0.2

Figure Captions

Figure 1a. Measured inclusive $\pi^+\pi^-$ and $(\pi^+\pi^+ + \pi^-\pi^-)$ spectra. Solid line is the renormalized fitted background, b(m) from overall fit to $\pi^+\pi^-$ spectrum.

Figure 1b. Resonance contribution to inclusive $\pi^+\pi^-$ spectrum from overall fit described in text.

Figure 1c. Closeup of resonance contribution to overall fit (solid curve) of $\pi^+\pi^-$ inclusive spectrum, to show S^* region. Solid curve is result of the coupled channel fit; the other curves are the parameterizations of Martin et al. discussed in the text.

Figure 2. Recoil spectrum from inclusive $\pi^+\pi^-$ pairs with invariant mass in the S^* region; the recoil spectrum from like sign pion pairs, normalized according to the overall fit, has been subtracted.

Figure 3a. Invariant mass of K^+K^- pairs for events which fit $\psi \to K^+K^-\pi^+\pi^-$.

Figure 3b. Background subtracted invariant mass of $\pi^+\pi^-$ pairs for events which fit $\psi \to K^+K^-\pi^+\pi^-$ and have a K^+K^- invariant mass in the ϕ region. The solid histogram shows the normalized prediction from the S^* parameters obtained in the fit to Figure 1b.

Figure 3c. Invariant mass of K^+K^- pairs for events which fit $\psi \to K^+K^-K^+K^-$ and for which the other K^+K^- pair has an invariant mass in the ϕ region.

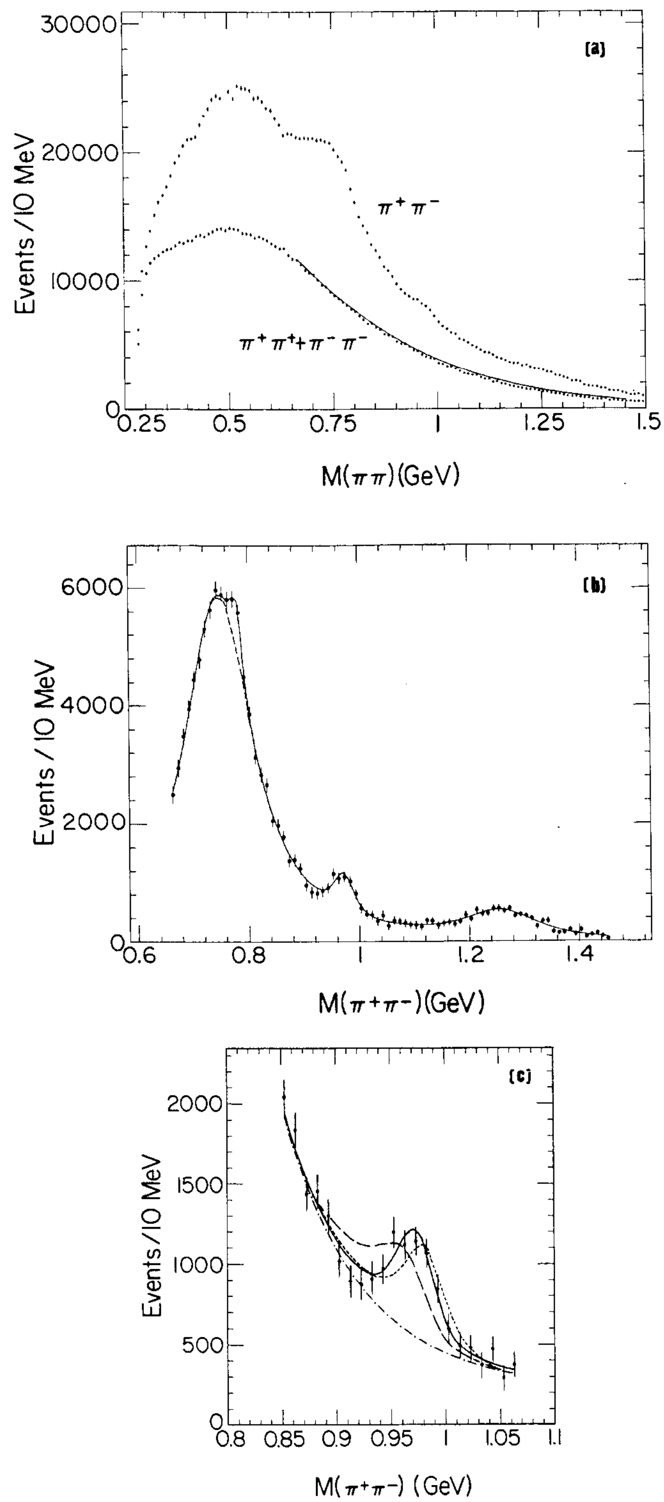

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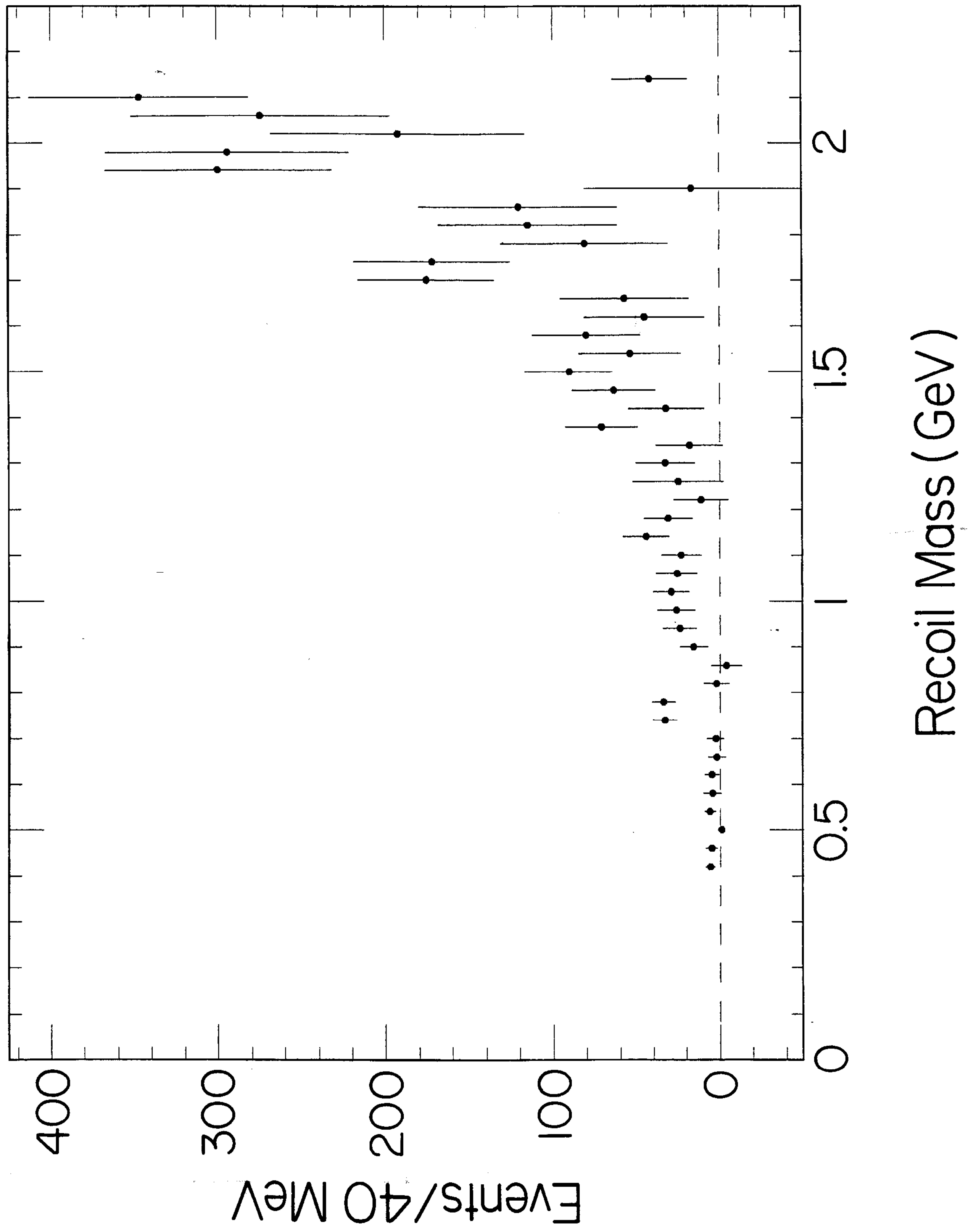
Fig 1



XBL 818-1238

Fig. 2

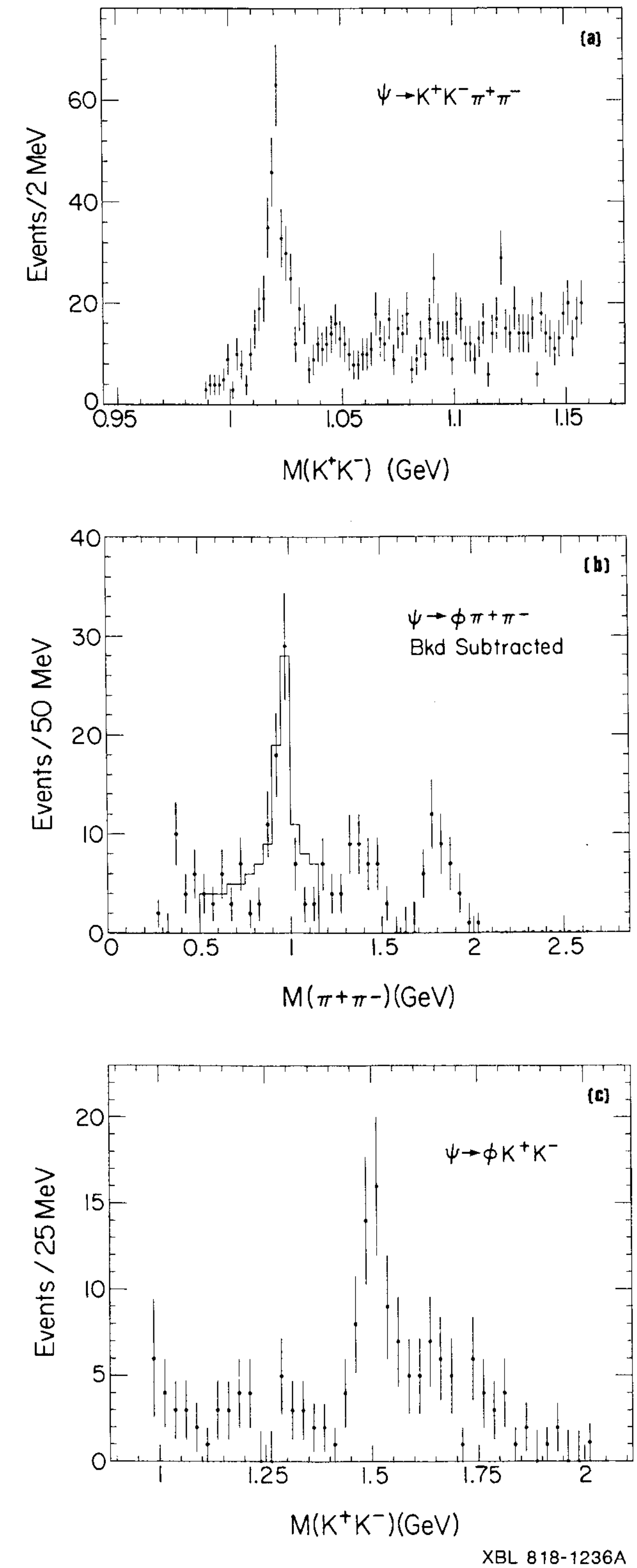

(a)
ψ→K⁺K⁻π⁺π⁻
Events/2 MeV
M(K⁺K⁻) (GeV)
(b)
ψ→φπ+π-
Bkd Subtracted
Events/50 MeV
M(π+π-)(GeV)
(c)
ψ→φK⁺K⁻
Events / 25 MeV
M(K⁺K⁻)(GeV)
XBL 818-1236A

Fig. 3