# Study of $J/\psi \to \phi\pi^+\pi^-$ and $\phi K^+K^-$

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**Abstract**

A partial wave analysis is presented of $J/\psi \to \phi\pi^+\pi^-$ and $\phi K^+K^-$ from a sample of 23M $J/\psi$ events in the BES II detector. The $\phi\pi\pi$ data exhibit strong signals due to $f_0(980) \to \pi^+\pi^-$ and $f_0(1370) \to \pi^+\pi^-$. For the latter, the pole position is at $M = (1335 \pm 30) - i(102 \pm 13)$ MeV. There is a small but definite signal due to $f_0(1770) \to \pi^+\pi^-$ with $M = 1770 \pm 20$ MeV, $\Gamma = 130 \pm 40$ MeV. The $\phi K\bar{K}$ data contain a strong signal due to $f_2'(1525)$. This peak is asymmetric, and requires some contribution from $f_J(1710)$. This contribution is definitely lower in mass than $f_0(1770)$; two separate $f_J(1710)$ and $f_0(1770)$ resonances are required.

The processes $J/\psi \to \phi\pi^+\pi^-$ and $\phi K^+K^-$ have been previously studied in the Mark III [1] and DM2 [2] experiments. Here we report BES II data on these channels with significantly larger statistics. They come from a new sample of $2.3 \times 10^7$ $e^+e^- \to J/\psi$ interactions. They are used to study the properties of $f_0(980)$, $f_0(1370)$, $f_J(1710)$ and $f_0(1770)$.

The intensity of the BEPC accelerator has been increased to an average luminosity of $\sim 4.0 \times 10^{30} cm^{-2}s^{-1}$. The BES detector [3] has been upgraded with a new main drift chamber (MDC) and improved time-of-flight (TOF) scintillators. For present purposes, the essential element is a cylindrical drift chamber detecting charged particles and measuring $dE/dx$. It is supplemented by lead-scintillator sandwiches for photon detection, but photons are not crucial to the present study.

We begin by outlining the separation of events. They are selected initially by demanding four charged tracks which satisfy a 4C kinematic fit with balancing charges and $\chi^2 < 10$. These tracks are required to lie well within the MDC acceptance with a polar angle $\theta$ satisfying $|\cos\theta| < 0.84$, and with transverse momenta $> 60$ MeV/c. The vertex is required to lie within 2 cm of the beam axis and within $\pm 20$ cm of the centre of the interaction region. Events containing more than one photon are rejected.

Kaons, pions and protons are identified by time-of-flight and $dE/dx$. For the new detector, the $\sigma$ of the TOF measurement is 180 ps. Kaons may be identified by TOF up to a momentum of 700 MeV/c by requiring the probability of $\chi^2$ for the kaon identification $> 0.1\%$ and a $\chi^2$ better than for $\pi$ or $p$ identifications. They may also be identified by $dE/dx$ up to 700 MeV/c by requiring a probability of $\chi^2$ for the kaon identification $> 0.1\%$

and $\chi^2$ better than for $\pi$ or $p$. For the $\phi K^+K^-$ channel, the kaons must not be identified as pions.

The $K^+K^-$ invariant mass distributions for $J/\psi \to K^+K^-\pi^+\pi^-$ and $J/\psi \to K^+K^-K^+K^-$ are shown in Figs. 1(a) and (b) rspectively. The peaks of the $\phi$ lie at 1019.6 and 1020.0 MeV in (a) and (b), in excellent agreement with values of the Particle Data Group (PDG) [4]. In both cases, there is a clear $\phi$ signal over a modest background. Events containing a $\phi$ are selected by demanding $|M_{K^+K^-} - M_\phi| < 15$ MeV and at least one identified kaon. The $\pi^+\pi^-$ and $K^+K^-$ invariant mass distributions for $J/\psi \to \phi\pi^+\pi^-$ and $\phi K^+K^-$ are shown in Fig. 1(c) and (d) respectively. The dark shaded histograms show the background distribution estimated from the sideband of $\phi$. The resulting background is 18.2% in (c) and 4.5% in (d).

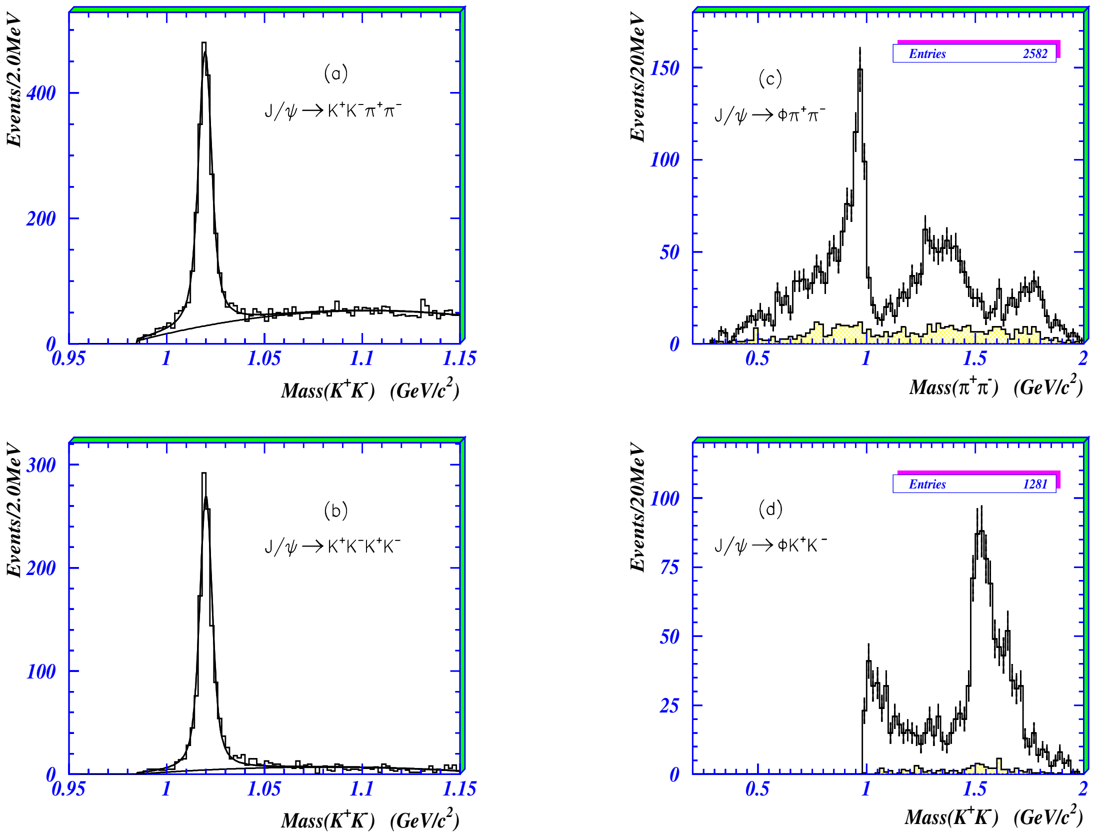


Figure 1: The $K^+K^-$ invariant mass distributions for (a) $J/\psi \to K^+K^-\pi^+\pi^-$, (b) $J/\psi \to K^+K^-K^+K^-$(Curves show the fitted backgrounds) and the $\pi^+\pi^-$ and $K^+K^-$ invariant mass distributions for (c) $J/\psi \to \phi\pi^+\pi^-$ and (d) $J/\psi \to \phi K^+K^-$ (Dashed histograms show the estimated background distribution from $\phi$ sideband).

Fig. 2 shows resulting Dalitz plots for (a) $J/\psi \to \phi\pi^+\pi^-$ (2582 events) and (b) $J/\psi \to \phi K^+K^-$ (1281 events). The branching ratios for production of $\phi\pi\pi$ and $\phi K\bar{K}$ (for all charges) are deduced by (i) correcting for backgrounds, (ii) allowing for the efficiencies for detecting the two channels, and (iii) correcting for unobserved charge states. Results are:

$$BR(J/\psi \to \phi\pi\pi) = (1.1 \pm 0.1) \times 10^{-3} \quad (1)$$
$$BR(J/\psi \to \phi K\bar{K}) = (1.2 \pm 0.1) \times 10^{-3}. \quad (2)$$

These agree within the errors with the earlier determinations by DM2 [2], $(1.17 \pm 0.045 \pm 0.18) \times 10^{-3}$ for $\phi\pi\pi$ and $(1.48 \pm 0.08 \pm 0.21) \times 10^{-3}$ for $\phi K\bar{K}$, but are somewhat more accurate.

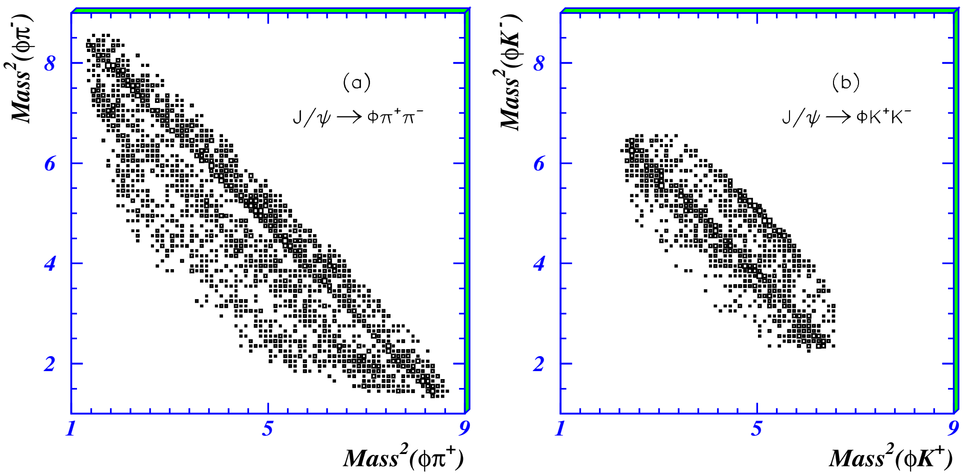


Figure 2: Dalitz plots for (a) $J/\psi \to \phi\pi^+\pi^-$, (b) $J/\psi \to \phi K^+K^-$.

Fig. 3 shows mass projections for $J/\psi \to \phi\pi^+\pi^-$ on to (a) $M(\pi^+\pi^-)$, (b) $M(\phi\pi^\pm)$. Fig. 4 shows corresponding mass projections for $J/\psi \to \phi K^+K^-$ on to (a) $M(K^+K^-)$ and (b) $M(\phi K^\pm)$. Histograms show results from the fit described below. The dotted curves in (a) and (b) show the projections of backgrounds discussed below. Figures labelled (c) and (d) show $f_0$ and $f_2$ contributions from the fits.

There is a strong $f_0(980) \to \pi^+\pi^-$ signal in Fig. 3(a) and a low mass enhancement in Fig. 4(a) due to $f_0(980) \to K^+K^-$. The $\phi\pi^+\pi^-$ data exhibit the clearest signal yet observed for $f_0(1370) \to \pi^+\pi^-$. Both Mark III and DM2 groups observed a similar peak with lower statistics. There have been earlier reports of similar but less conspicuous peaks in $\pi\pi \to K\bar{K}$ from experiments at ANL [5,6] and BNL [7]. The amplitude analysis locates a small signal in $\phi K^+K^-$, Fig. 4(a), due to $f_0(1370) \to K^+K^-$; it is obscured by the tails of $f_0(980)$ and $f_2'(1525)$. It will be used to estimate the branching ratio of $f_0(1370)$ between $K\bar{K}$ and $\pi\pi$. At the highest $\pi\pi$ masses, the $\phi\pi^+\pi^-$ data of Fig. 3(a) exhibit a clear peak at 1770 MeV which will be fitted as $f_0(1770)$ [8].

The $\phi K^+K^-$ data of Fig. 4(a) contain a strong $f_2'(1525)$ peak. However, it is asymmetric and may only be fitted by including on its upper side $f_J(1710) \to K^+K^-$. The mass of the $f_J(1710)$ signal is clearly lower than that of $f_0(1770)$, hence requiring two separate resonances.

To investigate the form of the backgrounds, we select sidebins to the $\phi$ in Fig. 1 in the mass range $M(K^+K^-) = 1.035$ to 1.095 GeV. The Dalitz plots from these sidebins are shown in Figs. 5(a) and (c). For $\phi\pi^+\pi^-$ of Fig. 5(a), the background is distinctly non-uniform. The form of this background has been fitted empirically and is used in the maximum likelihood fit described below. The peaks in $M(\phi\pi^\pm)$ of Fig. 5(b), may be fitted with two bands at 1490 and 2110 MeV. The two bands at 2110 MeV in $\phi\pi^+$ and $\phi\pi^-$ nearly meet at the right-hand edge of the Dalitz plot; they interfere constructively there and generate a peak

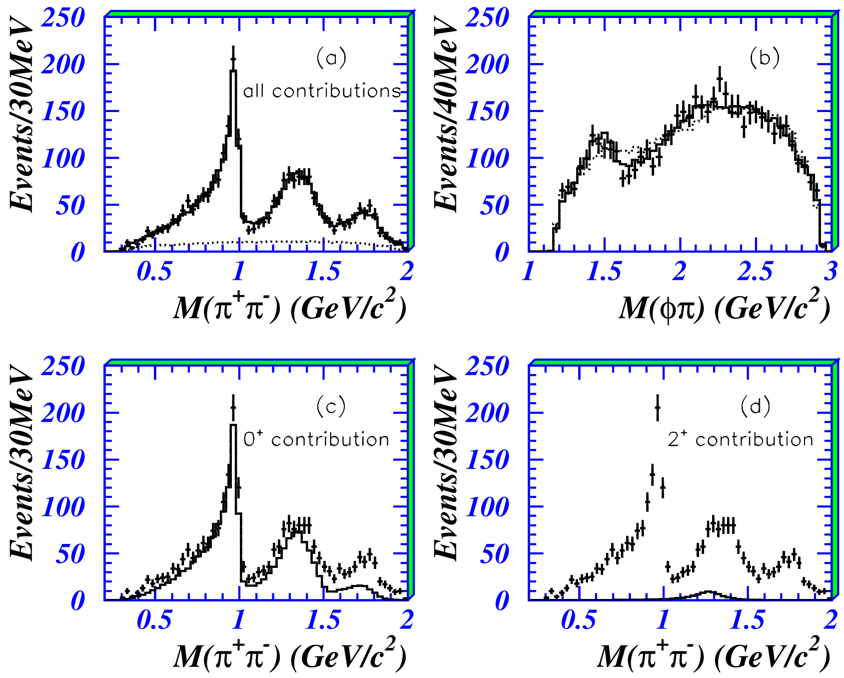


Figure 3: Mass projections for $J/\psi \to \phi\pi^+\pi^-$ on to (a) $M(\pi^+\pi^-)$, (b) $M(\phi\pi^\pm)$. Crosses are data and histograms the fit. In (a), the dotted curve shows the projection of the background. In (b), the dotted curve shows the fit with the background subtracted incoherently; (c) shows the $f_0$ contribution from the fit and ($d$) the $f_2$ contribution.

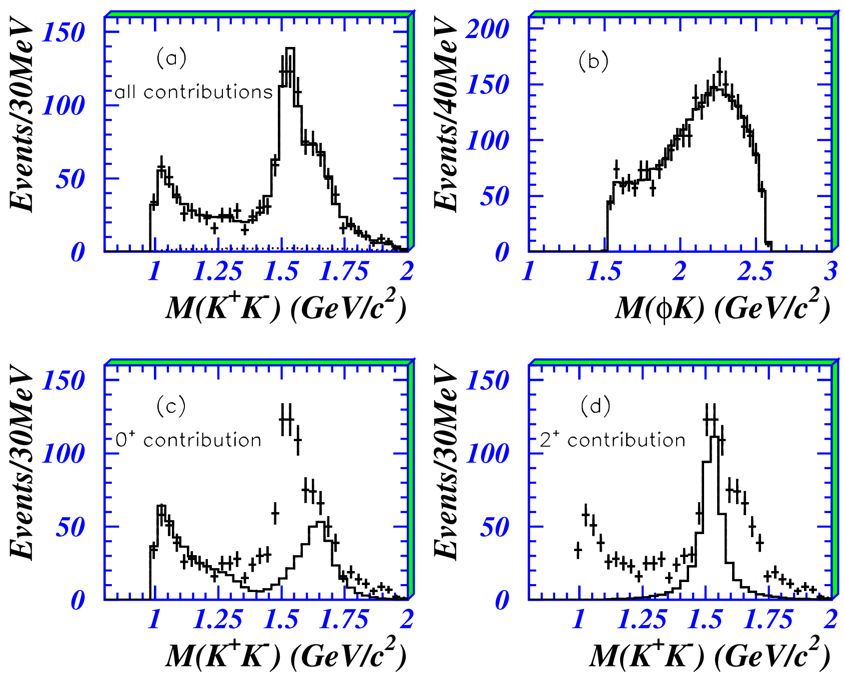


Figure 4: As Fig. 3 for $J/\psi \to \phi K^+K^-$.

along the edge of the Dalitz plot centred at a $\phi\pi$ mass of 2400 MeV and visible in Fig. 5(b). For $\phi K^+K^-$, the background in Fig. 5(c) is almost uniform, with slight enhancements in diagonal bands due to $f_0(980)$ and $f_2'(1525)$; these are sufficiently weak to have very little effect. The extrapolation from the sidebands to the $\phi$ peak is made by scaling 4-vectors of $K^+$ and $K^-$ by $M_\phi/M(K^+K^-)$.

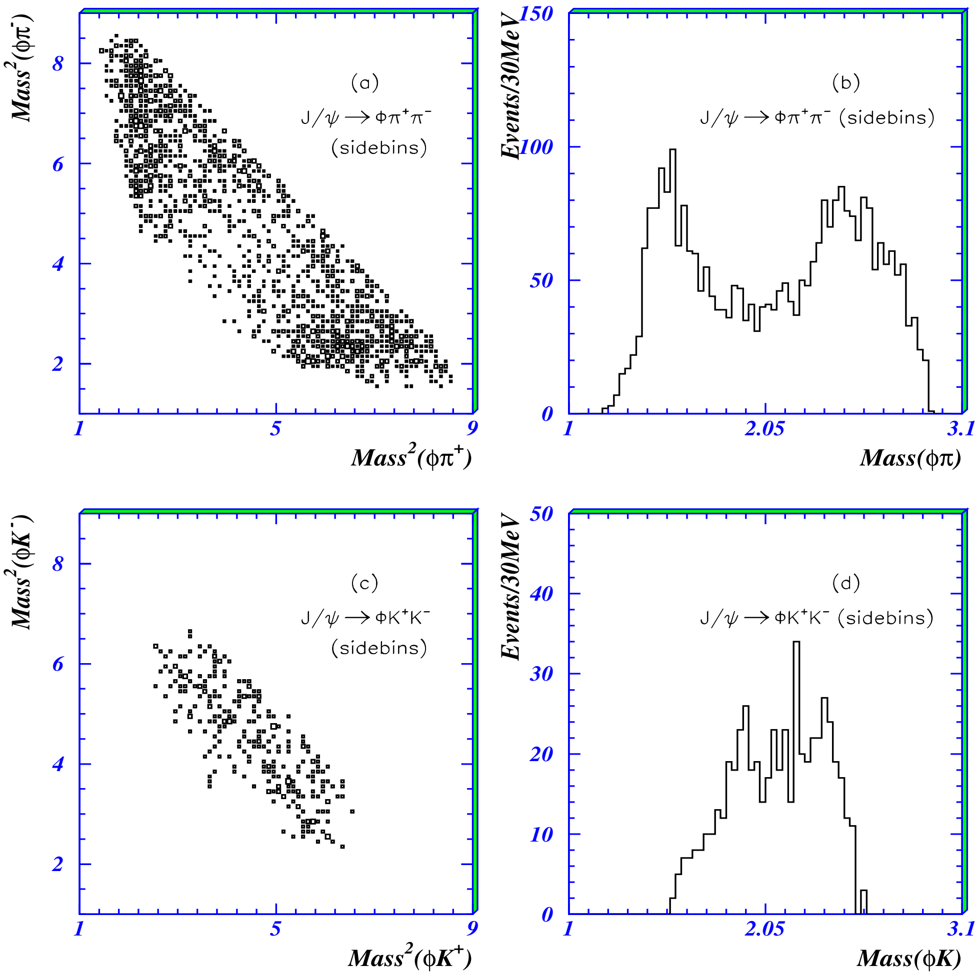


Figure 5: Dalitz plots for a sidebin to the $\phi$ with $M(K^+K^-) = 1.035$ to 1.095 GeV, (a) for $K^+K^-\pi^+\pi^-$ data, (c) for $K^+K^-K^+K^-$ data; (b) and (d) show projections against $\phi\pi^\pm$ mass.

We now describe the maximum likelihood fits to the data, first $J/\psi \to \phi\pi^+\pi^-$. As well as the obvious components $f_0(980)$, $f_0(1370)$ and $f_0(1770)$, we find that the fit is improved substantially by including a broad component due to $f_0(400-1200)$ decaying to $\pi^+\pi^-$; as a shorthand, we denote this by $\sigma$. This component is required to obtain a good fit to the lower side of the $f_0(980)$. It is fitted with the prescription of Bugg et al. [9]. A very small contribution is found from $f_0(1500)$. Table 1 shows branching fractions of each component and also the changes in log likelihood when each component is dropped from the fit and remaining components are re-optimised.

We include production of $J^P = 0^+$ resonances with orbital angular momentum $L = 0$ and

| Data | Channel | Mass (MeV) | Width (MeV) | Branching fraction (%) | $\Delta S$ |
|---|---|---|---|---|---|
| $\phi\pi^+\pi^-$ | $f_0(980)$ | $980 \pm 10$ | see text | 26.0 | 257.7 |
| | $f_0(1370)$ | $1335 \pm 30$ | $102 \pm 13$ | 15.4 | 57.3 |
| | $f_0(1500)$ | PDG | PDG | 1.9 | 5.2 |
| | $f_0(1770)$ | $1770 \pm 20$ | $130 \pm 40$ | 5.6 | 19.2 |
| | $f_2(1270)$ | PDG | PDG | 3.9 | 5.6 |
| | $\sigma$ | | | 37.1 | 45.3 |
| | $B_1$ | | | 5.9 | 17.0 |
| | $B_2$ | | | 8.8 | 16.4 |
| $\phi K^+K^-$ | $f_0(980)$ | $980 \pm 10$ | see text | 42.9 | 123.4 |
| | $f_0(1370)$ | $1335 \pm 30$ | $102 \pm 13$ | 11.1 | 5.9 |
| | $f_2'(1525)$ | PDG | PDG | 35.8 | 101.2 |
| | $f_0(1710)$ | $1660 \pm 40$ | $160 \pm 40$ | 46.5 | 59.5 |

Table 1: Parameters of fitted resonances. Branching factions for each channel after correction for background; these add up to slightly more than 100% because of interferences. Improvements in $S = \log$ likelihood for channels fitted to $\phi\pi^+\pi^-$ and $\phi K^+K^-$; $B_1$ and $B_2$ are backgrounds fitted to the $\phi\pi$ peaks at 1490 and 2110 MeV respectively.

2 in the process $J/\psi \to \phi f_0$. The phases of these two amplitudes are constrained to be the same, since they are due to the same resonance; this requires 3 fitted parameters. Likewise, for production of $J^P = 2^+$ resonances, we include $L = 0$ and 2 and again constrain the phases to be the same. This requires 5 fitted parameters, since there are now three helicity amplitudes for the $2^+$ state.

A major issue is the treatment of the background. If one subtracts the background incoherently, the $\phi\pi^\pm$ projection of Fig. 3(b) is poorly fitted, as shown by the dotted curve. From Fig. 3(b), one sees that the $\phi\pi^+\pi^-$ data themselves require peaks in $\phi\pi^\pm$ like those in the background. It appears that there is constructive interference between the background coming from $J/\psi \to K^+K^-\pi^+\pi^-$ and the $\phi\pi^+\pi^-$ channel itself.

The explanation we suggest for this surprising but unavoidable result is that pairs of kaons in the process $J/\psi \to K^+K^-\pi^+\pi^-$ may rescatter through a final state interaction to the $\phi$. This type of phenomenon is well known in nucleon-nucleon physics, where low energy $NN$ pairs may rescatter through the strong $NN$ ${}^1S_0$ and ${}^3S_1$ interactions near the $NN$ threshold. A calculation of the effect would require projecting the $K^+K^-$ pair into the $J^P = 1^-$ eigenstate, then multiplying the $K^+K^-\pi^+\pi^-$ amplitude by the Jost function for the $\phi$ [10]. For the channel $J/\psi \to K^+K^-\pi^+\pi^-$, there are ambiguities from a multitiude of possible final states, notably large contributions from $K^*(890)K_0$, where $K_0$ is the $K\pi$ S-wave amplitude, $K^*(890)K_2(1430)$ and a smaller contribution from $K^*(890)K^*(890)$; there may be further contributions from weaker $K_1$ signals. In summary, the projection to the $K^+K^-$ eigenstate with $J^P = 1^-$ is not presently possible with sufficient accuracy to fit $\phi\pi^+\pi^-$ data.

Our remedy for this situation is to include in the fit two amplitudes with the form of the peaks at 1490 and 2100-2400 MeV (denoted $B_1$ and $B_2$ as a shorthand) with arbitrary magnitudes and phases. It turns out that this gives an excellent fit to the $\phi\pi^+\pi^-$ data. The peaks themselves may be fitted either by Breit-Wigner amplitudes or as real amplitudes having the same intensity variation as the Breit-Wigner amplitude with $\pi\pi$ mass, but without its phase variation. Either prescription fits the data with similar log likelihood (differing by only 5.9). We do not interpret the $\phi\pi$ peaks as exotic resonances because of $(a)$ the absence of evidence for phase variation over the peaks, (b) the fact that the peaks are very close in form to those observed in the background. It remains a possibility that the peaks originate from exotic resonances, both in the $\phi\pi\pi$ data and in $K^+K^-\pi^+\pi^-$. We note that there was an earlier claim to observe an exotic resonance in $\phi\pi$ at 1480 MeV [11], but this was later attributed to experimental problems. DM2 [2] also observed a $\phi\pi$ peak around 1490 MeV in their $J/\psi \to \phi\pi^+\pi^-$ data, similar to ours but with lower statistics.

Let us now consider the $f_0(980)$ peak in $\phi\pi^+\pi^-$ and $\phi K^+K^-$. Because it is well known to have spin 0, it should produce a flat decay angular distribution, hence a uniform band in the Dalitz plots of Fig. 2. We find that this is accurately true when the $\phi\pi^\pm$ background is fitted as described above. However, without the peaks $B_1$ and $B_2$ in $\phi\pi^\pm$, a quite significant spin 2 component would be required in the 980 MeV peak. This is an important reason for including the peaks $B_1$ and $B_2$. Angular distributions are well fitted with these peaks included, as illustrated in Fig. 6; without them, the fit is poor (dotted curves).

Next we consider the $f_0(1370)$ peak. Again, with the inclusion of the $B_1$ and $B_2$ peaks, this fits as spin 0. Omitting the phase variation makes the fit much worse, so there is definitely a resonant signal, even though its shape may be somewhat distorted by the opening of the $4\pi$ channel; this latter effect is illustrated in Fig. 2 of Ref. [9]. The data suggest a small contribution due to $f_2(1270) \to \pi^+\pi^-$, as shown in Fig. 3(d). It improves log likelihood by only 5.6 for 5 fitted parameters, and is therefore of marginal significance (a $2\sigma$ effect); our definition of log likelihood is such that it changes by 0.5 for a one standard deviation change in one fitted parameter. From the OZI rule, one does not expect the $f_2(1270)$ to be produced strongly with a $\phi$.

Including the $f_0(1370)$ improves log likelihood by 57.3, even when $f_2(1270)$ and $f_0(1500)$ are included freely in the fit. This is highly significant ($> 9\sigma$). The $f_0(1370)$ has a strong constructive interference with the broad $\sigma$ amplitude. This helps to make it much more conspicuous than in other data. In our final fit, $f_0(1370)$ alone contributes 324 events out of a total of 2582 in $\phi\pi^+\pi^-$; interference with the $\sigma$ contributes a further 363.

This constructive interference helps explain what would otherwise be an anomaly concerning $4\pi$ decays of $f_0(1370)$. It is known that the branching fraction of $f_0(1370)$ to $\pi\pi$ is $\leq 20\%$ of that to $4\pi$ [12,13]. As explained in Ref. [13], the effect of the rapidly increasing phase space for the $4\pi$ channel is to make the $f_0(1370) \to 4\pi$ peak appear $\sim 75$ MeV higher in mass than that for $2\pi$. From present data, we find the pole in the $2\pi$ channel is at $M = 1335 \pm 30$ MeV with a width of $204 \pm 26$ MeV. The large uncertainty in the mass arises because interference with the broad $\sigma$ allows the peak to be fitted over a significant range of masses. The peak in $4\pi$ data is then expected at $\sim 1410$ MeV, in reasonable agreement with several determinations of the mass of $f_0(1370)$ from $4\pi$ data [4]. Close to this mass, there is an enhancement in data on $J/\psi \to \phi(4\pi)$ [14]; it can be reconciled with a branching fraction 5 times larger than for $2\pi$. However, without the constructive interference in the $2\pi$ channel with the $\sigma$, the predicted peak in data of Ref. [15] would be too large by a factor 2.

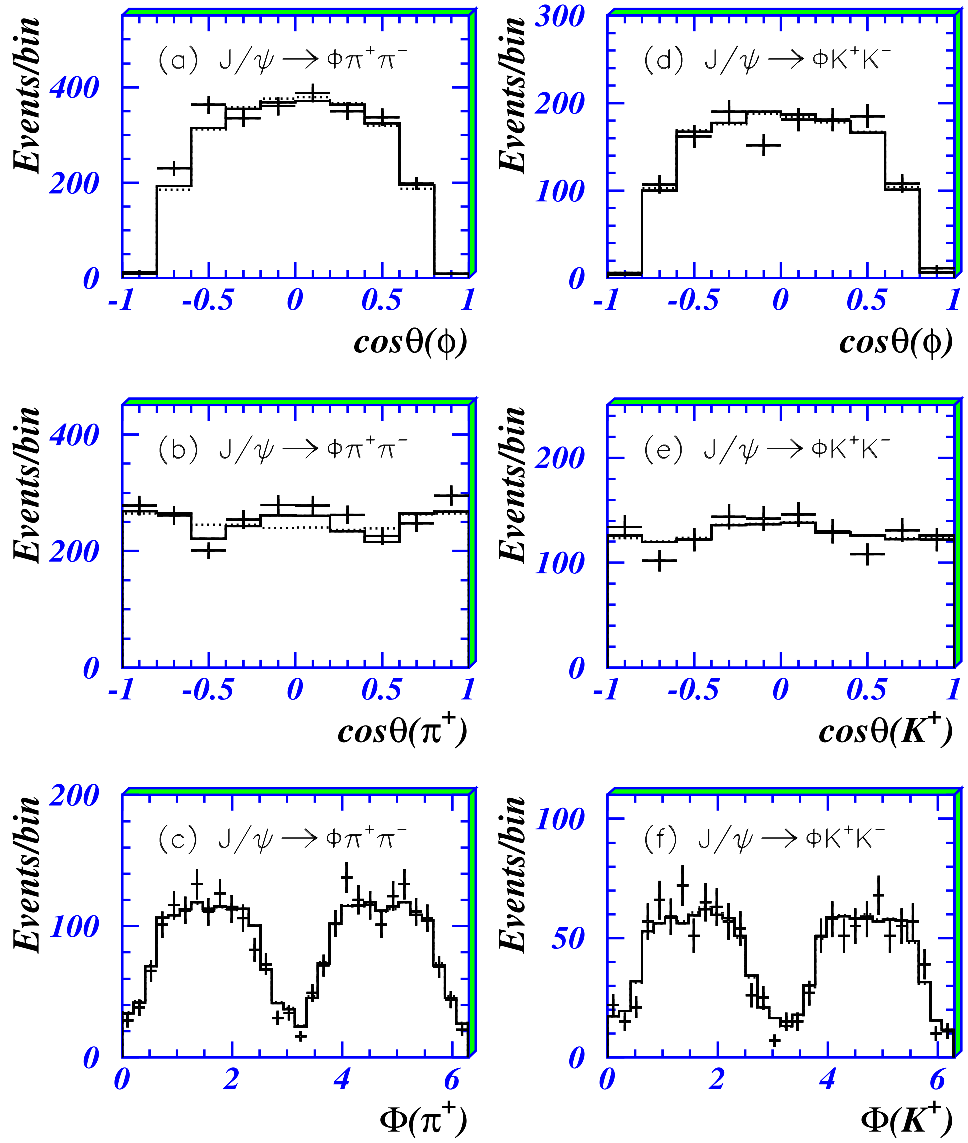


Figure 6: (a) The angular distribution in $\phi\pi^+\pi^-$ data for the polar angle $\theta$ of (a) the $\phi$ and (b) the $\pi^+$ with respect to the $\phi$ direction in the rest frame of $\pi^+\pi^-$; (b) the azimuthal angle $\Phi$ of the $\pi^+$ with respect to the plane defined by the beam and the $\phi$; (d), (e) and (f) show corresponding distributions for the $\phi$ and $K^+$ in $\phi K^+K^-$ data. Dotted curves show fits without the backgrounds $B_1$ and $B_2$.

The peak in $\pi^+\pi^-$ at 1770 MeV in Fig. 3(a) may be fitted with either $J^P = 0^+$ or $2^+$ with $M = 1770 \pm 20$ MeV, $\Gamma = 130 \pm 40$ MeV. For spin 2, log likelihood is better than for spin 0 by a very small amount (2.7), but with 5 fitted parameters for $2^+$ instead of 3 for $J^P = 0^+$. There is therefore little to choose between these two possibilities. The fitted mass agrees well with the $f_0(1770)$ reported in $\bar{p}p \to (\eta\eta)\pi^0$ [8]. The width we find is somewhat lower than the $220 \pm 40$ MeV reported in Ref. [8], but the values are compatible when one allows for the errors.

The $f_0(1500)$ makes a small, almost negligible contribution to $\phi\pi\pi$ data. From its small branching ratio to $K\bar{K}$ compared with $\pi\pi$ [4], its contribution to $\phi K^+K^-$ is then negligible.

We turn now to the fit to $\phi K^+K^-$. There is a conspicuous peak due to $f_2'(1525)$. However, if fitted only by this resonance, it requires unreasonably large mass and width, namely $M = 1565$ MeV, $\Gamma = 190$ MeV; the latter is in serious disagreement with the PDG value of $76 \pm 10$ MeV. This problem is readily solved by including a significant contribution on its upper side from $f_J(1710) \to K^+K^-$. Using PDG mass and width for $f_2'(1525)$, this requires for $f_J(1710)$ a mass $M = 1660 \pm 40$ MeV and width $\Gamma = 160 \pm 40$ MeV. The fit is slightly better to spin 0 than 2, by 6.5 in log likelihood; the fit with spin 2 also includes two more fitted parameters. This preference is not decisive, but is in agreement with recent $J^P$ determinations by Dunwoodie [15] and in WA102 $K^+K^-$ Central Production data [16].

There is no significant indication in the $\phi K^+K^-$ data for any signal due to $f_0(1770) \to K^+K^-$. Nor is there any significant evidence for $\sigma \to K^+K^-$; including it, log likelihood improves only by 0.7.

The production of $f_0(1370)$ in the $\phi\pi\pi$ channel in association with the $\phi$ suggests it contains a significant $s\bar{s}$ component. It is therefore of interest to determine its branching ratio between $K\bar{K}$ and $\pi\pi$. There is a small signal at 1370 MeV in the mass projection to $K^+K^-$, Fig. 4(a). It is somewhat hidden by the tails of $f_0(980)$ and $f_2'(1525)$. Including $f_0(1370) \to K^+K^-$ in the fit, log likelihood improves by 5.9. Allowing for all charges, we find a branching ratio

$$\frac{BR[f_0(1370) \to K\bar{K}]}{BR[f_0(1370) \to \pi\pi]} = 0.71 \pm 0.28(stat) \pm 0.29(syst). \tag{3}$$

The systematic error covers variations in the magnitude of the broad $\sigma$ contribution in $\phi\pi^+\pi^-$ and its possible contribution to $\phi K^+K^-$ data. Our value compares with $0.46 \pm 0.15 \pm 0.11$ found from WA102 Central Production data [17].

We have likewise attempted to determine the branching ratio of $f_0(980)$ between $K\bar{K}$ and $\pi\pi$. However, this attempt is frustrated by uncertainties in the magnitude of the interference with the broad $\sigma \to \pi\pi$ and $K^+K^-$. We use for $f_0(980)$ the Flatté form:

$$f = \frac{1}{M^2 - s - i(g_1\rho_{\pi\pi} + g_2\rho_{K\bar{K}})}; \tag{4}$$

here $\rho$ is Lorentz invariant phase space above the threshold for each channel and is analytically continued below threshold [9]. We find $g_2/g_1$ from the observed numbers of events fitted to $K\bar{K}$ and $\pi\pi$ in the mass range 0.9 to 1.1 GeV, chosen so as to minimise errors due to possible form factors. The result is

$$g_2/g_1 = 4.8 \pm 1.3, \tag{5}$$

with $M = 980$ MeV, $g_1 = 0.111$ GeV. The error is due to uncertainties in the $\sigma$ backgrounds and also uncertainty in the coherent backgrounds $B_1$ and $B_2$. The larger the $\sigma$ contribution in $\phi\pi^+\pi^-$ data, the larger is the value $g_2/g_1$. However, by omitting the backgrounds $B_1$ and $B_2$, a value $g_2/g_2 = 4.0$ may be obtained, even with the $\sigma$ included; this is at the price of a poorer log likelihood, because the $\phi\pi$ mass projection is not fitted perfectly. Earlier work [9] fitting CERN-Munich data for $\pi\pi \to \pi\pi$ and data of Refs. [3-6] for $\pi\pi \to K\bar{K}$ arrived at $g_2/g_1 = 2.6$. However, there is a discrepancy of a factor 1.5 between normalisations of Refs. [4] and [5,6]. If the normalisation of Etkin et al. [3] is used in fitting $\pi\pi \to K\bar{K}$ data instead of that of the ANL groups [5,6], $g_2/g_1$ rises to 3.9, within the errors of the present determination. The present result is compatible with the value 3.8 of Ref. [18], fitted to CERN-Munich data for $\pi\pi \to \pi\pi$ and data of central production processes.

In summary, the $\phi\pi^+\pi^-$ data have two important features. There is the clearest signal to date of $f_0(1370) \to \pi^+\pi^-$, with a pole in the $2\pi$ amplitude at $M = 1335 - i102$ MeV. There is also a clear peak at 1770 MeV, consistent with $f_0(1770)$. The $\phi K^+K^-$ data contain a strong but asymmetric signal with a large $f_2'(1525)$ component. However, this peak can only by fitted by including a significant $f_J(1710)$ signal, with a mass which is quite distinct from $f_0(1770)$.

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