Evidence of σ particle in $J/\psi \to \omega\pi\pi$ *

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Abstract

Based on a sample of 7.8×10^6 BESI J/ψ events, the decay of $J/\psi \to \omega\pi^+\pi^-$ is studied. A low mass enhancement in the $\pi^+\pi^-$ invariant mass spectrum recoiling against ω particle is clearly seen which does not come from the phase space effect and the background. According to PWA analysis, this low mass enhancement is a broad 0^{++} resonance, the σ particle. If a Breit-Winger function of constant width is used to fit the σ signal, its mass and width are 384 ± 66 MeV and 458 ± 100 MeV respectively, which correspond to the pole position at (434 ± 78) - i (202 ± 43) MeV.

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Key words: σ particle, chiral particles, new resonance, J/ψ decay.

The evidence of σ-particle is found in $\pi\pi$ s-wave. The analysis of $\pi\pi$ phase shift obtained from CERN-Munich experiment in 1974 found that the $I = 0$ $\pi\pi$ S-wave phase shift δ_0^0 up to $m_{\pi\pi} =$ 1300 MeV turned out to be only 270° [1]. After subtracting a rapid contribution of the resonance $f_0(980)$ (180°), the remained phase shift is 90°. Thus, most analyses made on the σ particle have yielded conclusions against the existence of σ. As a result, the light σ-particle had been disappeared from the list of PDG since the 1976 edition[2]. However, more and more evidences from both experimental and theoretical analysis have been accumulated since then in supporting the existence of the σ particle. As a result the σ particle has reappeared in the recent editions of the PDG. In the pp-central collision experiment, a huge event concentration in $I = 0$ S-wave $\pi\pi$-channel was seen in the region of $m_{\pi\pi}$ around 500 $\sim$ 600 MeV[3]. This huge event concentration is too large to be explained as a simple "background" and it strongly suggests the existence of σ[4].

Various recent analysis on $\pi\pi$ phase shift data showed strong evidence for the existence of the σ particle, using Breit–Wigner parametrization form[5], or other parametrizations[6, 7, 8]. Applying analyticity and single-channel unitarity, H. Q. Zheng proves that the σ resonance is necessary for chiral symmetry to explain the $\pi\pi$ scattering process[9]. A recent analysis based on Chiral Perturbation Theory and the Roy equation has been made by Colangelo, Gasser and Leutwyler, with the result of $M_\sigma = (490 \pm 30) - i(295 \pm 20)$ MeV[10].

A broad low mass enhancement in $\pi^+\pi^-$ invariant mass spectrum in $J/\psi \to \omega\pi^+\pi^-$ is observed by DM2[11], MARKIII[12] and BES[13]. It is also observed in D decay [14] and Υ decay. In this work, we study the structure of the broad low mass enhancement in the $\pi^+\pi^-$ invariant mass spectrum in $J/\psi \to \omega\pi^+\pi^-$.

A sample of 7.8×10^6 BESI J/ψ events, which were accumulated by Beijing Spectrometer[15], is used in the analysis. Candidate tracks are required to have a good track fit with vertex position within the interaction region of 2 cm in $\sqrt{x^2 + y^2}$ and 20 cm in Z (beam direction), and in the polar angle region of $|cos\theta| < 0.8$. For neutral tracks, it is required that the deposit energy of each neutral track in Barrel Shower Counter(BSC) is greater than 50 MeV, the hitted showers start in the first six radiation length, and the angle between the direction from the event vertex to the position at the first layer of BSC and the developing direction of the cluster is less than 30°. Every candidate event is then required to have at least two neutral tracks, four charged tracks with zero net charge. Time of Flight counter(TOF) information is used for particle identification. All surviving events are submitted to the $\gamma\gamma\pi^+\pi^-\pi^+\pi^-$ $4C$ kinematic fit and $\pi^0\pi^+\pi^-\pi^+\pi^-$ $5C$ kinematic fit. In the final data selection, $\chi^2_{4C}(J/\psi \to 2\gamma\pi^+\pi^-\pi^+\pi^-) < 30$ and $\chi^2_{5C}(J/\psi \to \pi^0\pi^+\pi^-\pi^+\pi^-) < 50$ are imposed. The difference between the invariant mass of two γ and rest mass of π^0 is less than 100 MeV. There are four combinations of $\pi^0\pi^+\pi^-$. The one with the invariant mass closest to the rest mass of ω meson is regarded as the right combination.

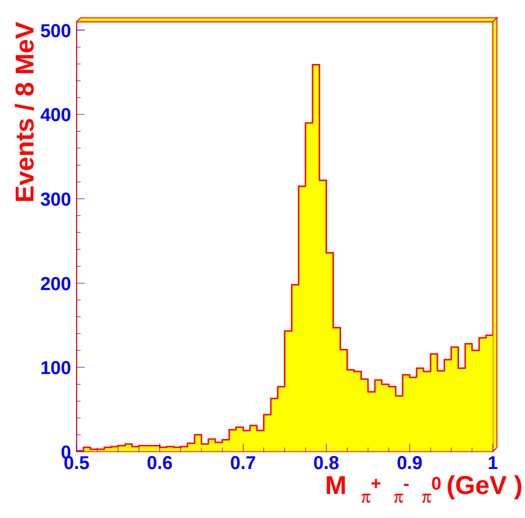

Figure 1: Invariant mass spectrum of $\pi^+\pi^-\pi^0$.

Fig.1 shows the $\pi^0\pi^+\pi^-$ invariant mass spectrum after the above cuts, where ω signal can be clearly seen with a low background level. The $\pi^+\pi^-$ invariant mass spectrum, recoiling against ω with $|M_{\pi^+\pi^-\pi^0} - M_\omega| < 0.05$, is shown in Fig.3 and the corresponding Dalitz plot is shown in Fig.2. A

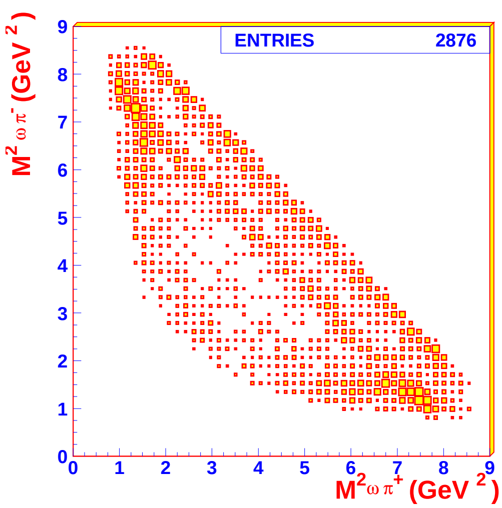

Figure 2: Dalitz plot of $M^2_{\omega\pi^-}$ vs $M^2_{\omega\pi^+}$. The top slope band corresponds to the σ particle, the second top slope band corresponds to the $f_2(1270)$, the vertical band corresponds $b_1(1235)^+$ and the horizontal band corresponds to $b_1(1235)^-$.

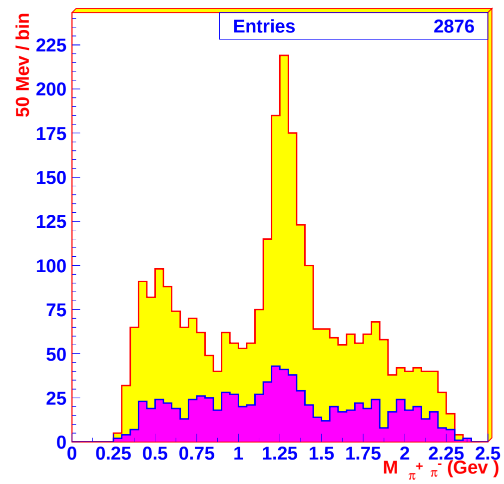

Figure 3: The invariant mass spectrum of $\pi^+\pi^-$. The heavy shaded region shows the ω side-band structure.

in $\pi^+\pi^-$ invariant mass spectrum, the corresponding band can also be seen in the Dalitz plot, and the shape of the low mass enhancement is quite different from that of the phase space(Fig.4). If the broad low mass enhancement came from the phase space effect, the corresponding events would be uniformly scattered in the whole Dalitz plot region, so there would be no band corresponding to it. Therefore, this low mass enhancement does not originate from phase space effect. We can also see that the band is evenly distributed which is the signature of a 0^{++} resonance. In figure 3, the heavy shaded histogram shows the $\pi^+\pi^-$ invariant mass which recoils against ω side-band where no clear low mass structures was found. Fig.4 shows the $\pi^+\pi^-$ invariant mass spectrum after ω side-band subtraction. The low mass enhancement can still be clearly seen, which means that it does not come from those background channels which contain no ω particle in its decay sequence.

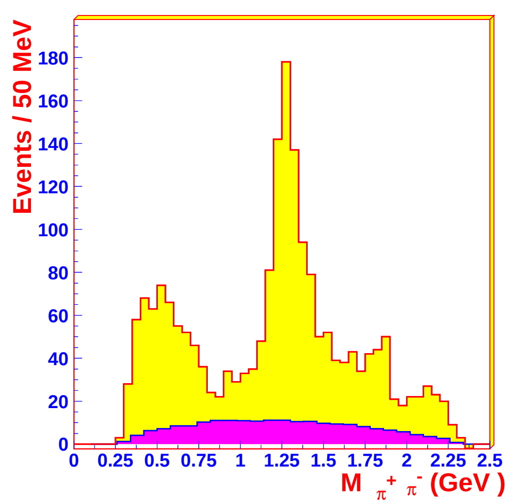

Figure 4: The invariant mass spectrum of $\pi^+\pi^-$ after ω side-band subtraction. The heavy shaded region shows the shape of phase space. The broad low mass enhancement at about 500 MeV is the σ particle, and the high peak at 1270 MeV is $f_2(1270)$.

We perform detailed Monte Carlo study and find that the background events from other known J/ψ decay channels are very small. The backnels can not produce an enhancement here.

According to the above study, we know that the low mass enhancement in the $\pi\pi$ invariant mass spectrum does not come from the phase space effect and the background. We perform Partial Wave Analysis(PWA) on the $\pi^+\pi^-$ invariant mass spectrum to study the structure of the low mass enhancement. Covariant helicity coupling amplitude method is used[19, 20]. The analysis method and the theoretical formula used in our analysis can be found in literature [20]. σ, $f_2(1270)$, $f_0(980)$, $f_0(1710)$ and $f_2(2300)$ are considered as contributions in the $\pi^+\pi^-$ invariant mass spectrum, $b_1(1235)$ is considered in the $\omega\pi$ invariant mass spectrum. We add an non-interference amplitude to fit backgrounds from $J/\psi \rightarrow \rho 3\pi$ directly. All other backgrounds are approximated by a non-interference phase space background.

Mass and width of σ particle are somewhat model dependent. In this paper, several Breit–Wigner functions are tried to fit σ particle[16, 21, 8]

$$\begin{cases} BW_\sigma = \frac{1}{m_\sigma^2 - s - i m_\sigma \Gamma_\sigma} \\ \Gamma_\sigma \text{ is a constant} \end{cases}, \tag{1}$$

$$\begin{cases} BW_\sigma = \frac{1}{m_\sigma^2 - s - i\sqrt{s}\Gamma_\sigma(s)} \\ \Gamma_\sigma(s) = \frac{g_\sigma^2\sqrt{\frac{s}{4} - m_\pi^2}}{8\pi s} \end{cases}, \tag{2}$$

$$\begin{cases} BW_\sigma = \frac{1}{m_\sigma^2 - s - i\sqrt{s}\Gamma_\sigma(s)} \\ \Gamma_\sigma(s) = \alpha\sqrt{\frac{s}{4} - m_\pi^2} \end{cases}, \tag{3}$$

$$\begin{cases} BW_\sigma = \frac{1}{m_\sigma^2 - s - i m_\sigma(\Gamma_1(s) + \Gamma_2(s))}, \\ \Gamma_1(s) = G_1 \frac{\sqrt{1-4m_\pi^2/s}}{\sqrt{1-4m_\pi^2/m_\sigma^2}} \cdot \\ \quad \cdot \frac{s - m_\pi^2/2}{m_\sigma^2 - m_\pi^2/2} e^{-(s-m_\sigma^2)/4\beta^2}, \\ \Gamma_2(s) = G_2 \frac{\sqrt{1-16m_\pi^2/s}}{\sqrt{1-16m_\pi^2/m_\sigma^2}} \frac{1+e^{\Lambda(s_0 - m_\sigma^2)}}{1+e^{\Lambda(s_0 - s)}}. \end{cases} \tag{4}$$

where parameter $G_1 = 1.378$ GeV, $\beta = 0.7$ GeV $G_2 = 0.036$ GeV and $\Lambda = 3.5$ GeV^{-1} [8]. The width of σ particle given in this paper is the width at its mass, i.e., $\Gamma_\sigma(m_\sigma)$. We first use a 0^{++} to fit the first peak, then we test its statistical significance

has about 18 σ statistical significance in this channel. If we change its spin-parity from 0^{++} to 2^{++} (or 4^{++}), the log likelihood will become worse by about 29 (or 37), which is a 6.6 (or 7.7) σ effects. So, its spin-parity should be 0^{++}. Mass and width of σ particle are determined through mass and width scan. Our final results on mass, width and pole of σ particle are listed in Table 1. If we use eq. (1) to fit sigma, its branching ratio is $BR(J/\psi \rightarrow \omega\sigma \rightarrow \omega\pi^+\pi^-) = (11.7 \pm 1.7 \pm 5.6) \times 10^{-4}$, where the first error is statistical and the second is systematic. The systematic error comes from the different parametrization of the Breit-Wigner formula(39%), the uncertainty of the detection efficiency(20%) and the uncertainty of the J/ψ total number(20%).

BW Function	Mass (MeV)	width (MeV)	Pole (MeV)
Eq.(1)	384 ± 66	458 ± 100	(434 ± 78) - i (202 ± 43)
Eq.(2)	442 ± 28	346 ± 86	(470 ± 39) - i (164 ± 38)
Eq.(3) [21]	559 ± 52	566 ± 136	(432 ± 54) - i (179 ± 28)
Eq.(4) [8]	—-	—-	(384 ± 15) - i (285 ± 30)

Table 1: Masses, widths and poles of σ particle

The final fit on the angular θ distributions for events in σ mass region ($M_{\pi^+\pi^-} < 0.8$ GeV) is shown in Fig.5, where θ is the polar angle of π^+ in the $\pi^+\pi^-$ rest frame. In this channel, besides σ particle, $f_2(1270)$, $f_0(980)$, $b_1(1235)^+\pi^-$ and $b_1(1235)^-\pi^+$ are added into the final fit. For the whole mass region, Fig.6 shows the fit of the θ angular distributions, while Fig.7 shows the fit of the $\pi^+\pi^-$ invariant mass spectrum, where σ contribution is indicated by the heavy shaded region.

In summary, a broad low mass enhancement is found in the recoil $\pi^+\pi^-$ invariant mass spectrum against ω particle in $J/\psi \rightarrow \omega\pi^+\pi^-$, and the correponding band can be clearly seen in the Dalitz

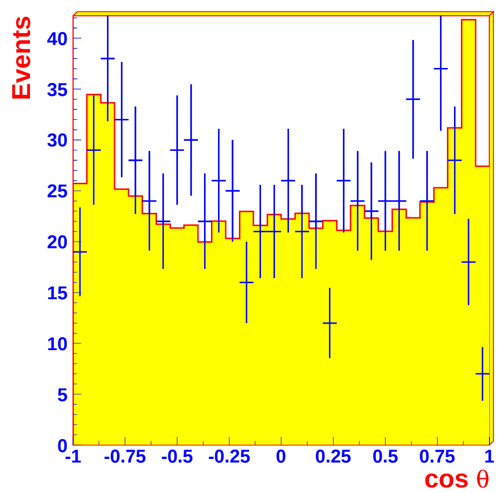

Figure 5: Final fit to the angular distributions for events in σ mass region ($M_{\pi^+\pi^-} < 0.8$ GeV). Error bar is the data and histogram is our final fit using eq. (1). θ is the polar angle of π^+ in $\pi^+\pi^-$ rest frame.

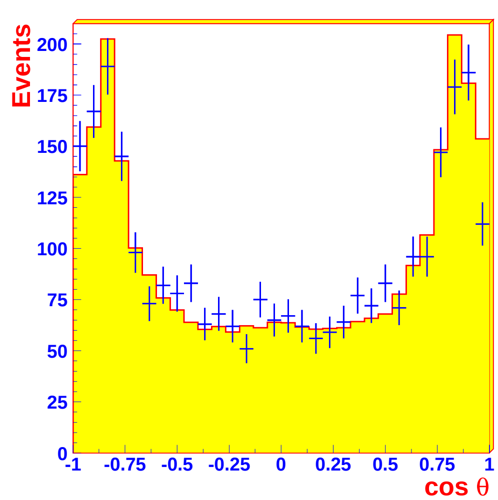

Figure 6: Final fit to the angular distributions for events in the whole mass region. Error bar is the data and histogram is our final fit using eq. (1). θ is the polar angle of π^+ in $\pi^+\pi^-$ rest frame.

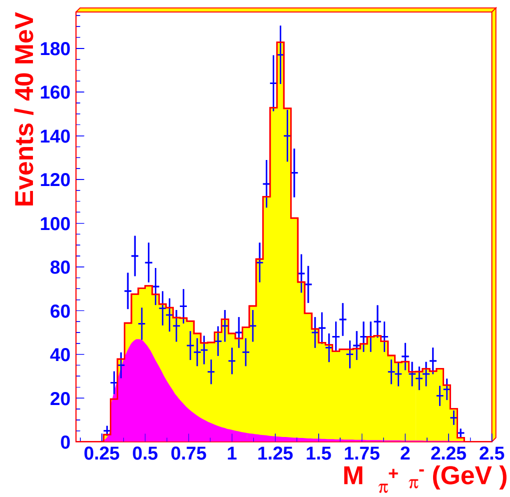

Figure 7: Final fit on the $\pi^+\pi^-$ invariant mass spectrum recoil against ω particle. The error bar is the real data, the shaded histogram is the global fit and the heavy shaded curve region is the contribution from σ-particle.

ground study, the low mass enhancement does not come from the backgrounds of other J/ψ decay channels. It also does not come from the phase space effects, and is considered to be the σ particle. the existence of the σ particle can be clearly seen in both the $\pi^+\pi^-$ invariant mass spectrum and the Dalitz plot. According to PWA analysis, σ particle is highly needed in the final fit and its spin-parity is 0^{++}. The mass and width are somewhat model-dependent, but its pole position is much less dependent on theory model. If a Breit-Winger function with constant width is used to fit σ particle, its mass and width are 384 ± 66 MeV and 458 ± 100 MeV respectively, which correspond to the pole position of (434 ± 78) - i (202 ± 43) MeV. Its branching ratio is $BR(J/\psi \to \omega\sigma \to \omega\pi^+\pi^-) = (11.7 \pm 1.7 \pm 5.6) \times 10^{-4}$.

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