PROCEEDINGS OF SCIENCE

Results on conventional and exotic charmonium at *BABAR*

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The B factories provide a unique playground for studying the properties of conventional and exotic charmonium states. We present recent results in initial state radiation and two-photon fusion, obtained using the full data set collected by the *BABAR* experiment.
Amongst *BABAR* 's harvest presented in this talk, the determination of the quantum numbers of the X(3915) resonance, a body of concording evidence pointing to $J^{PC} = 1^{++}$ for the X(3872), and updates on the family of the Y resonance to the full integrated luminosity.

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In this talk I have presented recent results obtained by the BaBar experiment on charmonium and charmonium-like resonances, using production mechanisms that select the quantum numbers. Angular momentum conservation, and for strong decays parity conservation and charge conjugation invariance then imply that these quantum numbers also apply to the final state. In the case of two-photon fusion, charge conjugation is positive, and for non-tagged events, for which the initial electron and positron are unobserved, the event selection performed during the analysis is such that the two intermediate photons are quasi-real : allowed J^{PC} are $0^{\pm+}, 2^{\pm+}, 4^{\pm+} \cdots$ and $3^{++}, 5^{++} \cdots$. In the case of initial state radiation (ISR), for which a photon is emitted by either of the incoming leptons, $J^{PC} = 1^{--}$.

Results presented here are related to understanding the nature and the properties of "new" resonances X(3872), X(3915), and the Y family.

1. Study of X(3915) and search for X(3872), decaying to $J/\psi\,\omega$ in two-photon collisions

Several charmonium-like states have been observed by the B factories in the mass region above the $D\overline{D}$ threshold, with properties that disfavor their interpretation as conventional charmonium mesons [1, 2, 3, 4, 5, 6, 7, 8, 9].

The X(3915) resonance, decaying to the $J/\psi\,\omega$ final state, was first observed by the Belle Collaboration in two-photon collisions [10]. The $Z(3930)$ resonance was discovered in the $\gamma\gamma \to D\overline{D}$ process [6, 7]. Its interpretation as the $\chi_{c2}(2P)$, the first radial excitation of the ${}^3P_2$ charmonium ground state, is commonly accepted [11]. Interpretation of the X(3915) as the $\chi_{c0}(2P)$ [12] or $\chi_{c2}(2P)$ state [13] has been suggested. The latter would imply that the X(3915) and $Z(3930)$ are the same particle, observed in different decay modes.

Despite the many measurements available [11], the nature of the $X(3872)$ state, which was first observed by Belle [14], is still unclear [15]. The observation of its decay into $\gamma J/\psi$ [16] ensures that this particle has positive C-parity. The spin analysis performed by CDF on the decay $X(3872) \to J/\psi\,\pi^+\pi^-$ concludes that only $J^P = 1^+$ and $J^P = 2^-$ are consistent with data [17]. If $J^P = 2^-$, the production of the $X(3872)$ in two-photon collisions would be allowed, while for $J = 1$ if would be forbiden.

BABAR searched for the X(3872) and the X(3915) resonances in the decay mode $J/\psi\,\omega$ and studied the quantum numbers of the X(3915) with angular analyses [18], in a sample of events corresponding to 519.2 fb^{-1}. Intermediate mesons are reconstructed in the modes $J/\psi \to \ell^+\ell^-$, ($\ell = e$ or μ) and $\omega \to \pi^+\pi^-\pi^0$. Besides the usual event reconstruction and signal selection, several cuts are applied to reject specific backgrounds. Events with extra tracks with momentum greater than 0.1 GeV/c, or with a large energy non-associated with the event ($E_{extra} > 0.3\,$GeV), events from ISR $J/\psi\,\pi^+\pi^-\pi^0$ production, and residual ISR $\psi(2S) \to J/\psi\,\pi^+\pi^-$ production are vetoed. The π^0 mass is constrained to its nominal value [11]. To improve the mass resolution, we define the $J/\psi\,\omega$ mass as $m(J/\psi\,\omega) = m(\ell^+\ell^-\pi^+\pi^-\pi^0) - m(\ell^+\ell^-) + m(J/\psi)^{\mathrm{PDG}}$.

We observe a prominent peak near 3915 MeV/c^2 over a small background (Fig. 1), with 59 ± 10 signal events, a mass of $(3919.4 \pm 2.2 \pm 1.6)$ MeV/c^2 and a width of $(13 \pm 6 \pm 3)$ MeV with a significance of 7.6σ, results which are compatible with those of Belle [10]. No structure is seen around 3872 MeV/c^2, with an upper limit of $\Gamma_{\gamma\gamma}[X(3872)] \times \mathscr{B}(X(3872) \to J/\psi\,\omega) < 1.7$ eV at 90% CL, assuming $J = 2$. We first discriminate between $J^P = 0^\pm$ and $J^P = 2^+$ by using the

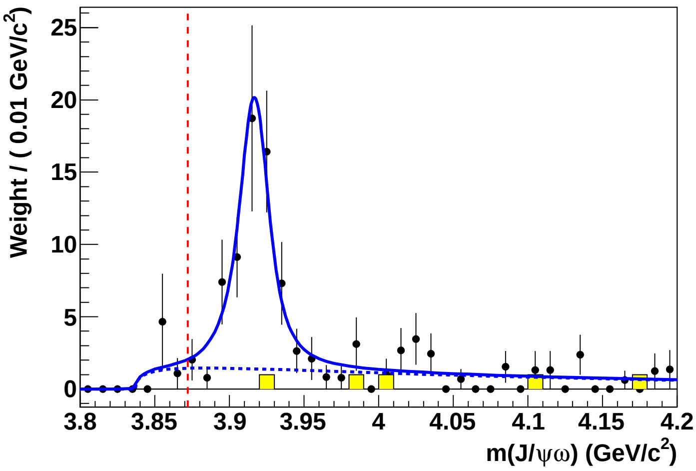

Figure 1: The efficiency-corrected $m(J/\psi\,\omega)$ distribution (solid points) [18]. The shaded histogram is the non-$J/\psi\,\omega$ background estimated from sidebands. The vertical dashed (red) line is at $m(J/\psi\,\omega) = 3.872$ GeV/c^2.

Rosner [19] predictions. The distribution of several angles that determine the final state are examined. In all cases the $J^P = 0^\pm$ hypothesis describes the data better than the $J^P = 2^+$ [18]. For the distribution of the angle θ_n^* between the normal to the decay plane of the ω and the two-photon axis (Fig. 2 right) χ^2 probabilities for $J^P = 0^\pm$ and $J^P = 2^+$ are respectively 64.7% and 9.6×10^{-9}% respectively. We then discriminate between $J^P = 0^-$ and $J^P = 0^+$. In all cases the $J^P = 0^+$ hypothesis gives a smaller χ^2 than the $J^P = 0^-$ hypothesis. For the distribution of the angle θ_n between the normal to the ω decay plane and the ω direction in the $J/\psi\,\omega$ rest frame (Fig. 2 left) χ^2 probabilities for $J^P = 0^+$ and $J^P = 0^-$ are 6.1% and 4.8×10^{-11}% respectively. We find that $J^P = 0^\pm$ is

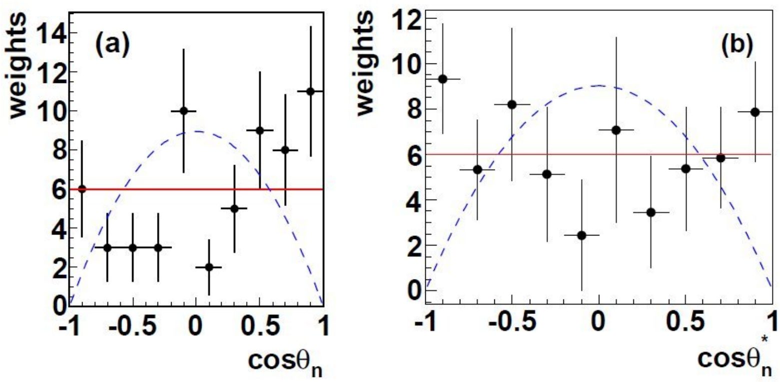

Figure 2: The efficiency-corrected distributions of $\cos\theta_n$ and $\cos\theta_n^*$ for events in the X(3915) mass signal region [18].

largely preferred over $J^P = 2^+$ and that $J^P = 0^+$ is largely preferred $J^P = 0^-$, which points to an interpretation of the X(3915) resonance being the $\chi_{c0}(2P)$ charmonium meson.

2. Search for resonances decaying to $\eta_c\pi^+\pi^-$ in two-photon interactions

An other final state that may be considered to test X(3872) production in two-photon, still with the hope to discriminate $J^{PC} = 1^{++}$ from $J^{PC} = 2^{-+}$, is $\eta_c\pi^+\pi^-$. Voloshin [20] compared the $\eta_c' \to \eta_c$ and $\psi(2S) \to J/\psi$ dipion transitions in terms of QCD multipole expansion, and predicted $\mathscr{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-)/\mathscr{B}(\psi(2S) \to J/\psi\pi^+\pi^-) = 2.9$, that is $\mathscr{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) = (2.2^{+1.6}_{-0.6})\%$.

In the same spirit, with the possible assignment of the X(3872) to the charmonium meson η_{c2} (1^1D_2, with $J^{PC} = 2^{-+}$), the branching fraction of the isospin-conserving decay $X(3872) \to \eta_c\pi^+\pi^-$ would be larger than that of the isospin-violating decay discovery channel $X(3872) \to J/\psi\pi^+\pi^-$ [21], which is larger than 2.6 %[11]. Two photon production would be allowed, and the event rate could be sizable.

The BABAR experiment studied resonances decaying to $\eta_c\pi^+\pi^-$ in two-photon interactions, using a data sample that corresponds to 473.9 fb^{-1} [22]. η_c candidates were reconstructed in the $K^0_S K^+\pi^-$ decay mode. Background rejection is performed in a very sophisticated way. After an usual event reconstruction and a two-photon-like preselection of the candidates, cuts are applied in the η_c decay Dalitz plane to take advantage of the fact that $\eta_c \to K^0_S K^+\pi^-$ decays often proceed via intermediate $K_0^*(1430)$ states, while background events often contain a $K^*(892)$ meson. Finally a cut is applied on the output of a neural network whose inputs include general properties of the $\eta_c\pi^+\pi^-$ candidate such as p_T and E_{extra}, and particle identification information for the charged tracks.

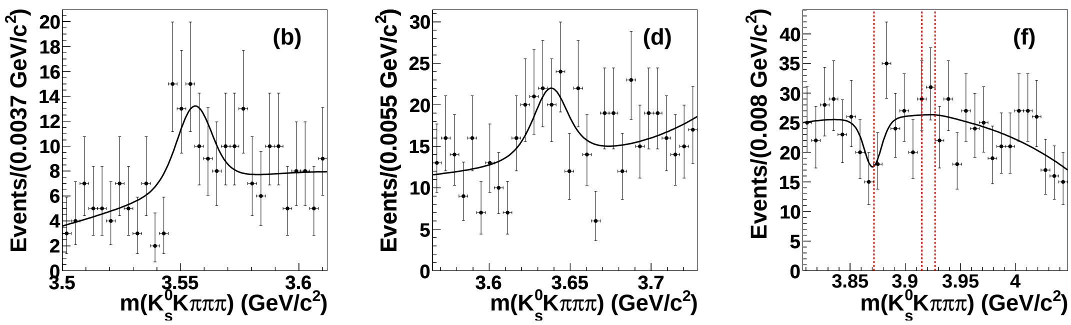

Figure 3: Distributions of $m_{K^0_S K^+\pi^-\pi^+\pi^-}$ in three mass ranges of interest, corresponding to the $\chi_{c2}(1P)$, to the $\eta_c(2S)$, and to the $X(3872)$, $X(3915)$ and $\chi_{c2}(2P)$ (the masses of which are indicated by the vertical lines) [22].

Two strutures are found, for masses that are compatible with that of the $\chi_{c2}(1P)$ and of the $\eta_c(2S)$ meson, but no sign of any signal is detected for the $X(3872)$, $X(3915)$ and $\chi_{c2}(2P)$ (Fig. 3) which indicates again that the 2^{-+} assignment is disfavored for the $X(3872)$. We obtain an upper limit $\mathscr{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) < 7.4\,\%$ that is compatible with the prediction of 2.2%.

3. Study of ISR-produced resonances decaying to $\psi\pi^+\pi^-$

The Y(4260) resonance discovered by *BaBar* [1] in ISR production to $J/\psi\pi^+\pi^-$ final state, has escaped firm intepretation to date. Most likely is it not a regular charmonium meson since all attempts to detect its decays to either $D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$, $D_s^+D_s^-$, $D_s^{*+}D_s^-$, $D_s^{*+}D_s^{*-}$ have failed. Most likely it is not a four-quark system since the most natural assignment would have it decay dominantly to $D_s^+D_s^-$ [23], which are not seen. Searching for Y(4260) decays to $\psi(2S)\pi^+\pi^-$, *BaBar* didn't find any, but found instead a new similar resonance at an invariant mass of 4.32 GeV/c^2 [4], now named the the Y(4330). Belle confirmed the existence of the Y(4260) resonance, claimed a hint of an other object at a lower mass, close to 4 GeV/c^2, confirmed the existence of the Y(4330) resonance, and discovered a new resonance, the Y(4660), in the same channel $\psi(2S)\pi^+\pi^-$ [5].

We report here a recent update by *BaBar* of the $J/\psi\pi^+\pi^-$ analysis to 454 fb^{-1} [24], and the first *BaBar* study of the $\psi(2S)\pi^+\pi^-$ final state, using 520 fb^{-1} [25]. *BaBar* confirms ([24],

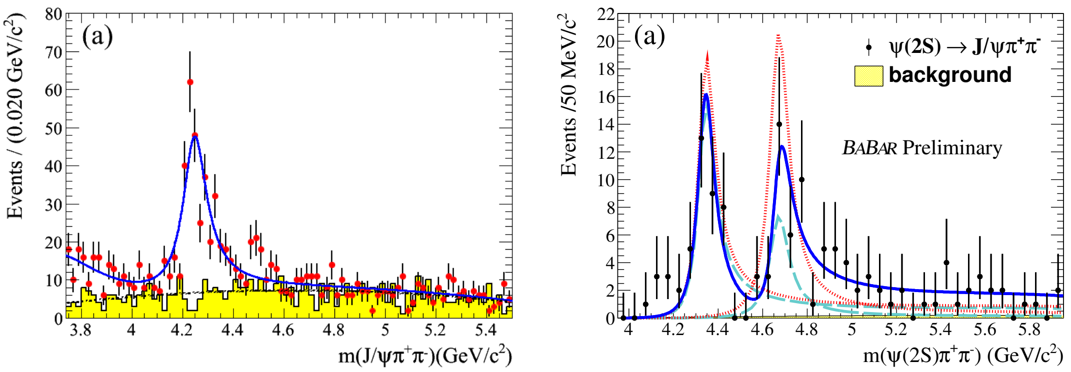

Figure 4: Mass distributions of the $J/\psi\pi^+\pi^-$ (left, [24]) and $\psi(2S)\pi^+\pi^-$ (right, [25]) final states.

Fig. 4 left) its discovery of the ISR-produced $Y(4260) \to J/\psi\pi^+\pi^-$ [1] and Belle's observation of $Y(4360)$ and $Y(4660)$ to $\psi(2S)\pi^+\pi^-$, but does not see any sign of an $Y(4008) \to J/\psi\pi^+\pi^-$ ([25], Fig. 4 right). I agree with the Belle speaker [26] that this thing, which was presented without a significance, should be handled with quotes.

4. Conclusion

We have presented studies of untagged production in two-photon fusion with the $J/\psi\omega$ and $\eta_c\pi^+\pi^-$ final states. Together with its two-photon production, angular analyses of $X(3915) \to J/\psi\omega$ determine the quantum numbers of the $X(3915)$ to be $J^{PC} = 0^{++}$, indicating the possible assignment to a $\chi_{c0}(2P)$ charmonium meson. The searches of $X(3872)$ in these two final states don't show any significant signal, despite at least the branching fraction of $X(3872)$ to $\eta_c\pi^+\pi^-$ is expected to be sizable in the case of the $J^{PC} = 2^{-+}$. These two results, together with LHCb's preliminary angular analysis of $X(3872) \to J/\psi\pi^+\pi^-$ [27] point to a $J^{PC} = 1^{++}$ assignment for the $X(3872)$. The proximity of its mass to the $D^{*0}\bar{D}^0$ threshold suggested it to be a $J^{PC} = 1^{++}$

hadronic molecule [28] or a a tetraquark [29]. The family of the $J^{PC} = 1^{--}$ Y states produced in ISR with $\psi\pi^+\pi^-$ is now well established, with 3 confirmed states. We may be seeing the dawn of a hybrid charmonium spectroscopy [30].

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PoS(DIS 2013)179