PROCEEDINGS OF SCIENCE

Measurements of cross-sections of e^+e^- annihilation into hidden charm states

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Based on e^+e^- annihilation data collected with the BESIII detector at the BEPCII produced, several measurements of cross section of e^+e^- annihilation into final states including hidden charm resonances are presented in this talk. The first analysis is the measurement of the Born cross section for $e^+e^- \to \eta h_c$. A resonant structure in the cross-section line shape near 4.2 GeV is observed with a statistical significance of 7σ. The second analysis is the search for $e^+e^- \to K^+K^-\psi(3770)$. No significant signal of $e^+e^- \to K^+K^-\psi(3770)$ is found. The third measurement is the energy-dependent cross section for $e^+e^- \to \eta\psi(2S)$ and the upper limits on its cross sections are provided at 90% confidence level. The first search for the reaction $e^+e^- \to \eta\tilde{X}(3872)$ is also performed, but no evidence is found for the $\tilde{X}(3872)$ in the $\pi^+\pi^- J/\psi$ mass distribution. The fourth analysis is the study of $e^+e^- \to \omega\chi_{c1}$ and $\omega\chi_{c2}$. For each process, a nontrivial feature is observed in the cross section line shape. In addition, a new production process for $X(3872)$ reported by BESIII is being discussed.

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*Speaker

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1. Introduction

The charmonium model has emerged as the most successful theory thus far. It interpreted J/ψ and ψ' as charmed quark-antiquark ($c\bar{c}$) bound states, and predicted most of the phenomena that were subsequently observed. In recent years, more vector states have been observed in the charmonium energy region, which challenges the conventional charmonium states predicted by the quark potential model [1–3]. The vector charmonium(-like) states ($J^{pc} = 1^{--}$) have been observed by analyzing the line shape of the cross sections of electron-positron annihilating into inclusive hadron states [4] that are dominated by hidden-charm processes. The overpopulation of observed vector states compared to the expected charmonium states in this energy region implies the presence of new formation mechanisms. Some theoretical models interpret these as charmonium hybrids or tetraquark states [5–7]. More experimental measurements are needed to understand the nature of these states.

2. Measurement of the Born cross section for $e^+e^- \to \eta h_c$

Studying transitions from vector states to the h_c meson is intriguing because a strong coupling to h_c suggests a hybrid state with a $c\bar{c}$ pair in a spin-singlet configuration [8]. The process $e^+e^- \to \eta h_c$ was first observed at BESIII [9], hinting at a structure around 4.200 GeV. Although similar resonant structures around 4.2 GeV were observed across $e^+e^- \to \pi^+\pi^- J/\psi$ or $e^+e^- \to K^+K^- J/\psi$, the measured resonant parameters varied depending on the process.

In this analysis, we reconstruct all the particles in the final state, including the bachelor η in $e^+e^- \to \eta h_c$, the photon in the electric dipole (E1) transition $h_c \to \gamma\eta_c$, and η_c, which is reconstructed with sixteen hadronic final states with a total branching fraction of about 40%: $p\bar{p}$, $2(\pi^+\pi^-)$, $2(K^+K^-)$, $K^+K^-\pi^+\pi^-$, $p\bar{p}\pi^+\pi^-$, $3(\pi^+\pi^-)$, $K^+K^-2(\pi^+\pi^-)$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $K^0_S K^\pm\pi^\mp$, $K^0_S K^\pm\pi^\mp\pi^\pm\pi^\mp$, $\pi^+\pi^-\eta$, $K^+K^-\eta$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-\pi^0\pi^0$, and $2(\pi^+\pi^-)\pi^0\pi^0$. The η/π^0 candidates are reconstructed using two photons and the K^0_S candidates are reconstructed via the $\pi^+\pi^-$ decay channel. For the selected candidates, we apply a fit to the distribution of the η recoil mass to obtain the ηh_c signal yield.

The cross section of $e^+e^- \to \eta h_c$ is parameterized as $\sigma^{dressed}(s) = |BW_1(s) + BW_2(s)e^{i\phi}|^2 + |BW_3(s)|^2$. The relativistic BW amplitude for a resonance $Y \to \eta h_c$ in the fit is written as

$$BW(s) = \frac{\sqrt{12\pi\Gamma_{ee}\Gamma_{tot}\mathcal{B}(Y \to \eta h_c)}}{s - M^2 + iM\Gamma_{tot}}\sqrt{\frac{PS(\sqrt{s})}{PS(M)}} \tag{1}$$

where M, Γ_{tot}, Γ_{ee}, and $\mathcal{B}(Y \to \eta h_c)$ are the mass, full width, electronic partial width, and branching fraction of the corresponding resonance, respectively, and $\sqrt{PS(\sqrt{s})/PS(M)}$ is the two-body phase space factor. The fit results are shown in Figure 1. In the cross section lineshape, a resonant structure near 4.200 GeV is observed with a statistical significance of 7σ. The parameters of this resonance are measured to be $M = 4188.8 \pm 4.7 \pm 8.0$ MeV/c^2 and $\Gamma = 49 \pm 16 \pm 19$ MeV.

3. Search for $e^+e^- \to K^+K^-\psi(3770)$

Searching for new high-mass vector states involving both $\psi(3770)$ and kaons would provide valuable information to determine the nature of these new structures. a naive presumption suggests

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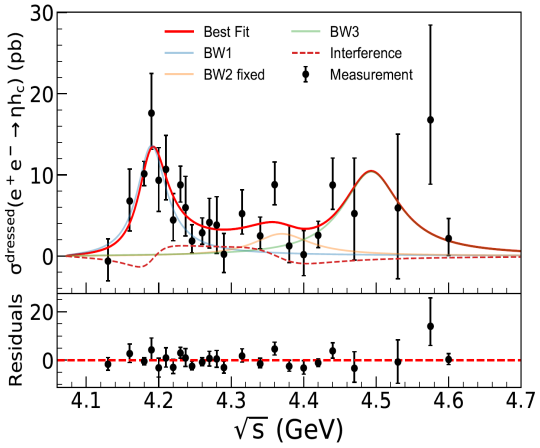

Figure 1: Result of the nominal fit to the $\sqrt{s}$-dependent cross section σ dressed$(e^+e^- \to \eta h_c)$ with two coherent BW functions and one independent BW function. Dots with error bars are data, and the red solid curve shows the fit with three resonances. The dashed curves show the interference between BW_1 and BW_2.

that $e^+e^- \to K^+K^-\psi(3770)$ would be suppressed in conventional charmonium [10] or $[cs\bar{c}\bar{s}]$ tetraquark assumptions [11], while an enhancement is expected in the $f_0(980)\psi(2S/1D)$ molecule model [12].

The dominant decay channel of $\psi(3770)$ is $\psi(3770) \to D\bar{D}$. For the signal process $e^+e^- \to K^+K^-\psi(3770)$, we only reconstruct two charged kaons and one $\bar{D}$ meson, the presence of D mesons is inferred by the recoiling mass of $K^+K^-\bar{D}$. To reconstruct the $\bar{D}$ mesons, we select nine decay modes with large branching fraction and clean backgrounds, including three modes $\bar{D}^0 \to K^+\pi^-$, $\bar{D}^0 \to K^+\pi^-\pi^0$ and $\bar{D}^0 \to K^+\pi^+\pi^-\pi^-$; six modes $D^- \to K^+\pi^-\pi^-$, $D^- \to K^+\pi^-\pi^-\pi^0$, $D^- \to K^0_S\pi^-$, $D^- \to K^0_S\pi^-\pi^0$, $D^- \to K^0_S\pi^-\pi^+\pi^-$, and $D^- \to K^+K^-\pi^-$ [13]. Throughout the whole text, charge conjugated decays are always implied.

To extract the signal yields, a two-dimensional (2D) unbinned maximum likelihood fit is performed to the recoiling mass distributions $RM(K^+K^-D^-)$ versus $RM(K^+K^-)$. No obvious signal is found for the process $e^+e^- \to K^+K^-\psi(3770)$, we determine the upper limits of the Born cross sections at 90% confidence level (CL) to be 1-3 pb.

4. Cross-section for $e^+e^- \to \eta\psi(2S)$ and search for the reaction $e^+e^- \to \eta\tilde{X}(3872)$

Since the BESIII experiment observed the $Y(4230)$ in the $e^+e^- \to \eta J/\psi$ and $\eta' J/\psi$ processes, it follows that the process $e^+e^- \to \eta\psi(2S)$ can be an important way to search for Y states. In addition, we search for the $\tilde{X}(3872)$ state reported by the COMPASS experiment [14]. This state has quantum numbers $J^{pc} = 1^{-+}$ and a mass of 3860 MeV/c^2, therefore, it is regarded as the partner state of the $X(3872)$, since their masses and widths are close to each other but with different C parities. Inspired by Ref [14], we search for the $\tilde{X}(3872)$ in the process $e^+e^- \to \eta\tilde{X}(3872)$, with $\tilde{X}(3872) \to \pi^+\pi^- J/\psi$.

Signal MC samples for the processes $e^+e^- \to \eta\psi(2S)$ and $\eta\tilde{X}(3872)$ are generated using helicity-amplitude [40,41] and phase-space [40,41] models. We study two different scenarios for the $\tilde{X}(3872)$ width. In setting I, the mass and width of $\tilde{X}(3872)$ are set to 3860 MeV/c^2 and 51 MeV

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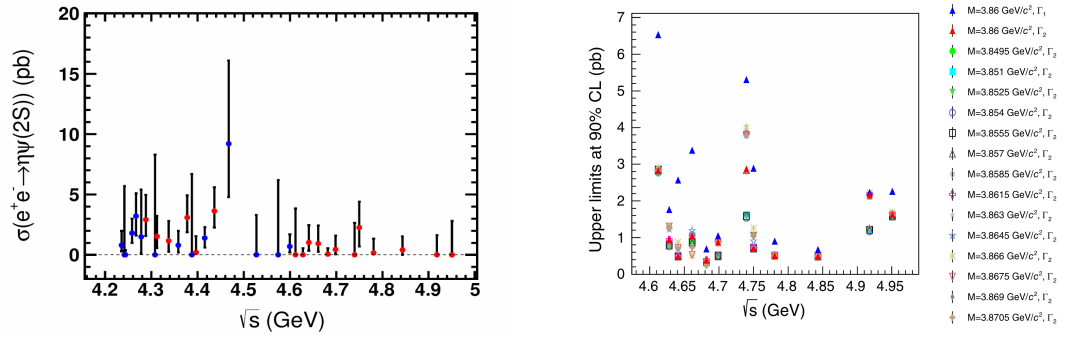
based on the COMPASS result [14], respectively; in setting II, the width is set to 1.19 MeV based on the $\tilde{X}(3872)$ width quoted from the Particle Data Group (PDG) [13], and the mass is scanned with a step of 1.5 MeV/c^2 in the mass interval from 3849.5 to 3870.5 MeV/c^2. Under these two different assumptions, the $e^+e^- \to \eta\tilde{X}(3872)$ cross sections are measured with the same methods.

Due to the limited statistics, upper limits on the cross sections of $e^+e^- \to \eta\psi(2S)$ are provided at 90% CL. In addition, we do not find any evident signal for the $\tilde{X}(3872)$, and the upper limits on the cross sections of $e^+e^- \to \eta\tilde{X}(3872)[\tilde{X}(3872) \to \pi^+\pi^- J/\psi]$ at 90% CL assuming two different width hypotheses is set, which are consistent with each other. Figure 2 shows the measured Born cross sections for $e^+e^- \to \eta\psi(2S)$ and $e^+e^- \to \eta\tilde{X}(3872)$.



(a) (b)

Figure 2: (a) The measured Born cross sections for $e^+e^- \to \eta\psi(2S)$. The blue dots and red triangles are from Ref. [24] and this measurement, respectively. The error bars represent the statistical errors only. (b) Upper limits of $e^+e^- \to \eta\tilde{X}(3872)[\tilde{X}(3872) \to \pi^+\pi^- J/\psi]$ at 90% CL for different assumptions of the $\tilde{X}(3872)$ widths (Γ) and masses (M). The widths of 51 and 1.19 MeV are represented by Γ_1 and Γ_2, respectively. The blue and red triangles are the results from settings I and II with the COMPASS $\tilde{X}(3872)$ mass 3.86 GeV/c^2, respectively. Other markers represent the results from the assumptions of the $\tilde{X}(3872)$ width with 1.19 MeV and the masses scanned with a step of 1.5 MeV/c^2 in the mass interval from 3849.5 to 3870.5 MeV/c^2.

5. Study of $e^+e^- \to \omega\chi_{c1,2}$

The conventional vector charmonium states above the open-charm threshold have not been well understood yet. Besides the inclusive hadronic final states, are rarely observed in exclusive final states. Especially the $\psi(4415)$ has never been observed in any hidden-charm decay [13]. Therefore, a search for new decays is essential to enhance our understanding of vector charmonium states.

In this work, we report studies of the processes $e^+e^- \to \omega\chi_{c1,2}$, where $\chi_{c1,2}$ are reconstructed via the decay modes $\chi_{c1,2} \to \gamma J/\psi$, where the J/ψ candidate is reconstructed with lepton pairs (i.e.e^+e^- or $\mu^+\mu^-$) and ω is reconstructed via its decay $\omega \to \pi^+\pi^-\pi^0, \pi^0 \to \gamma\gamma$.

Assuming that each of the $\omega\chi_{c1}$ and $\omega\chi_{c2}$ signals each come from one single resonance, we fit these cross sections with a maximum likelihood method. In the fit, the structure is described by a BW function,

$$BW(s) = \frac{12\pi\Gamma_{ee}\Gamma\mathcal{B}(\omega\chi_{cJ})}{(s-M^2)^2 + M^2\Gamma^2} \times \frac{\Phi(\sqrt{s})}{\Phi(M)} \tag{2}$$

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where M is the mass, Γ is the total width, Γ_{ee} is the electronic partial width, and $\Phi(\sqrt{s})$ is the two-body phase space factor. Figure 3 shows the $e^+e^- \to \omega\chi_{c1,2}$ dressed cross sections. Under the assumption that one single resonance describes the corresponding shape, the mass and width for $e^+e^- \to \omega\chi_{c1}$ are determined to be $M = (4544.2 \pm 18.7 \pm 1.7)$ MeV/c^2 and $\Gamma = (116.1 \pm 33.5 \pm 1.7)$ MeV. This structure is observed for the first time with a significance of 5.8σ. The mass is significantly higher compared to the structures recently observed around 4.480 GeV/c^2 in $e^+e^- \to K^+K^-J/\psi$ and $e^+e^- \to D^{*0}D^{*+}\pi^-$ [10, 31]. For the $e^+e^- \to \omega\chi_{c2}$ process, the extracted parameters are $M = (4413.6 \pm 9.0 \pm 0.8)$ MeV/c^2 and $\Gamma = (110.5 \pm 15.0 \pm 2.9)$, suggesting that this is likely the well known $\psi(4415)$ and implying the existence of the hidden charm decay $\psi(4415) \to \omega\chi_{c2}$.

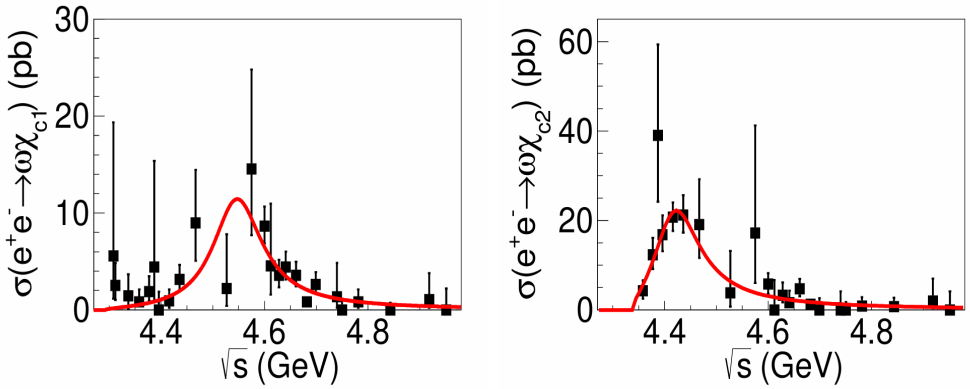

Figure 3: Fits to the cross sections of $e^+e^- \to \omega\chi_{c1}$ (left) and $e^+e^- \to \omega\chi_{c2}$ (right) with one single resonance.

6. Study of $X(3872)$ production above 4 GeV

The well-known $X(3872)$ state was first observed by the Belle experiment in the $B^\pm \to K^\pm\pi^+\pi^-J/\psi$ decay [15]. Investigating its production provides valuable insight into its properties.

In this part, we present a study of the processes $e^+e^- \to \gamma X(3872)$, $e^+e^- \to \omega X(3872)$ and $e^+e^- \to \phi X(3872)$. We measure the branching fraction ratio $R = \frac{X(3872)\to\gamma J/\psi}{X(3872)\to\pi^+\pi^-J/\psi}$ as $0.38 \pm 0.20_{stat.} \pm 0.01_{syst.}$ ($R < 0.83$ at 90% CL) through the $e^+e^- \to \omega X(3872)$ production channel. In addition, using two decay modes of the $X(3872)$, $X(3872) \to \pi^+\pi^-J/\psi$ and $\gamma J/\psi$, we have measured the ratios of average cross sections, $\sigma_{\omega X(3872)}/\sigma_{\omega\chi_{c1}} = 5.2 \pm 1.0_{stat.} \pm 1.9_{syst.}$ and $\sigma_{\omega X(3872)}/\sigma_{\omega\chi_{c2}} = 5.5 \pm 1.1_{stat.} \pm 2.4_{syst.}$. The relatively large cross section for the $e^+e^- \to \omega X(3872)$ process is mainly attributed to the cross section enhancement around 4.75 GeV as shown in Figure 4, which may indicate a potential structure in the cross section of $e^+e^- \to \omega X(3872)$. We have also searched for the process of $e^+e^- \to \gamma X(3872)$ within the same energy range, but have not observed any obvious signal. We set the upper limit on the cross section ratio as $\sigma_{\gamma X(3872)}/\sigma_{\omega X(3872)} < 0.23$ at 90% CL. Finally, considering the cross section $\sigma(e^+e^- \to \phi\chi_{c1}) \sim 2.6$ pb near the production threshold [16], we obtain a rough estimation for the production ratio $\sigma_{\phi X(3872)}/\sigma_{\phi\chi_{c1}} < 9$. It is in the same order as the relative production ratio $\sigma_{\omega X(3872)}/\sigma_{\omega\chi_{c1}}$ [17, 18].

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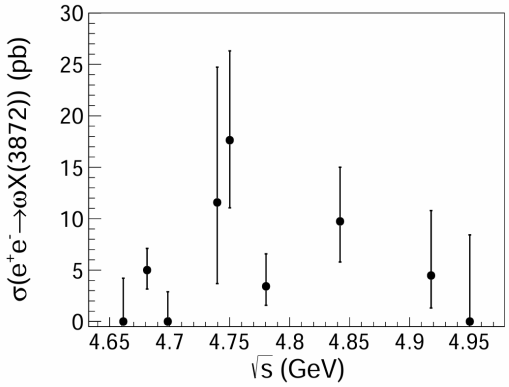

Figure 4: The Born cross sections for the process of $e^+e^- \to \omega X(3872)$. The errors are statistical only.

7. Summary

In summary, we reported several measurements of cross sections including hidden charm final states at BESIII. Recent research has verify that the understanding of charmonium(-like) states is not enough. BESIII shows excellent performance in the charmonium(-like) states studies. The upcoming upgrades to BEPCII and BESIII will provide higher luminosity and energy, allowing for more precise measurements.

References

[1] E. Eichten et al. Charmonium: The Model. *Phys. Rev. D*, 17:3090, 1978.

[2] E. Eichten et al. Charmonium: Comparison with Experiment. *Phys. Rev. D*, 21:203, 1980.

[3] S. Godfrey and N. Isgur. Mesons in a Relativized Quark Model with Chromodynamics. *Phys. Rev. D*, 32:189–231, 1985.

[4] M. Ablikim et al. Determination of the psi(3770), psi(4040), psi(4160) and psi(4415) resonance parameters. *eConf*, C070805:02, 2007.

[5] Hua-Xing Chen, Wei Chen, Xiang Liu, and Shi-Lin Zhu. The hidden-charm pentaquark and tetraquark states. *Phys. Rept.*, 639:1–121, 2016.

[6] Yan-Rui Liu, Hua-Xing Chen, Wei Chen, Xiang Liu, and Shi-Lin Zhu. Pentaquark and Tetraquark states. *Prog. Part. Nucl. Phys.*, 107:237–320, 2019.

[7] Nora Brambilla, Simon Eidelman, Christoph Hanhart, Alexey Nefediev, Cheng-Ping Shen, Christopher E. Thomas, Antonio Vairo, and Chang-Zheng Yuan. The XYZ states: experimental and theoretical status and perspectives. *Phys. Rept.*, 873:1–154, 2020.

[8] Rubén Oncala and Joan Soto. Heavy Quarkonium Hybrids: Spectrum, Decay and Mixing. *Phys. Rev. D*, 96(1):014004, 2017.

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[9] Medina Ablikim et al. Observation of $e^+e^- \to \eta h_c$ at center-of-mass energies from 4.085 to 4.600 GeV. *Phys. Rev. D*, 96(1):012001, 2017.

[10] Ri-Qing Qian and Xiang Liu. Production of charmonium $\chi_{cJ}(2P)$ plus one ω meson by e^+e^- annihilation. *Phys. Rev. D*, 108(9):094046, 2023.

[11] Qi-Fang Lü and Yu-Bing Dong. X(4140) , X(4274) , X(4500) , and X(4700) in the relativized quark model. *Phys. Rev. D*, 94(7):074007, 2016.

[12] Feng-Kun Guo, Christoph Hanhart, and Ulf-G. Meissner. Evidence that the Y(4660) is a f(0)(980)psi-prime bound state. *Phys. Lett. B*, 665:26–29, 2008.

[13] R. L. Workman et al. Review of Particle Physics. *PTEP*, 2022:083C01, 2022.

[14] M. Aghasyan et al. Search for muoproduction of $X(3872)$ at COMPASS and indication of a new state $\widetilde{X}(3872)$. *Phys. Lett. B*, 783:334–340, 2018.

[15] S. K. Choi et al. Observation of a narrow charmonium-like state in exclusive $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ decays. *Phys. Rev. Lett.*, 91:262001, 2003.

[16] M. Ablikim et al. Study of $e^+e^- \to \gamma\phi J/\psi$ from $\sqrt{s}$ = 4.600 to 4.951 GeV. *JHEP*, 01:132, 2023.

[17] M. Ablikim et al. Observation of a New X(3872) Production Process $e^+e^- \to \omega X(3872)$. *Phys. Rev. Lett.*, 130(15):151904, 2023.

[18] Medina Ablikim et al. Study of $e^+e^- \to \omega X(3872)$ and $\gamma X(3872)$ from 4.66 to 4.95 GeV. *Phys. Rev. D*, 110(1):012006, 2024.

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