Studies of charmonium-like states at BESIII (Presented at the 32nd International Symposium on Lepton Photon Interactions at High Energies, Madison WI, August 25-29 2025)

Benjamin Moses (on behalf of the BESIII Collaboration) [a]

[a] *Indiana University, Bloomington IN, 47405*

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Abstract

The BESIII collaboration has made and continues to make major progress towards observing, studying, and describing new and previously discovered exotic hadronic states. The BESIII experiment is well suited to search for exotic states in the τ-charm energy region, and has made significant progress in describing charmoinum-like states. In this paper, we share recent results from the BESIII collaboration on this subject.

1 Introduction

The BESIII collaboration studies symmetric e^+e^- collisions provided by the BEPCII storage ring at center-of-mass energies in the range of $1.85 - 4.95$ GeV [1, 2]. We achieve a peak luminosity of $1.0 \times 10^{33} cm^{-2} s^{-1}$ at 3.773 GeV, the mass of the $\psi(3770)$ resonance, and have collected large samples of J/ψ, $\psi(2S)$, and $\psi(3770)$ events. BESIII currently has collected 20 fb^{-1} of data above 4.0 GeV [3] to study the XYZ exotic states, and in this paper we discuss some recent results from within the collaboration.

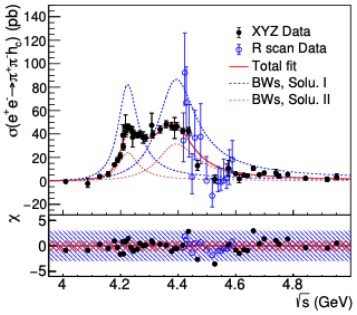
Quantum Chromodynamics (QCD) allows for the possibility of exotic hadronic states beyond the quark model. These include tetraquark states, pentaquark states, loosely bound meson molecules, glueballs, and more. One example, typically called the Y states, are a group of $J^{PC} = 1^{--}$ states with charm content, that do not match predictions of the charmonium spectrum from potential models. At this point, these states are numerous and not well understood, but there has been a lot of recent progress at BESIII.

In addition, there are other exotic states, such as the $Z_c(3900)^{\pm}$, which has been observed by BESIII and Belle in the $\pi^{\pm} J/\psi$ mass spectrum [7, 8]. This

state has $c\bar{c}$ quark content, but must have some other quark content as well due to its electric charge, making it manifestly exotic. There are ongoing efforts to further studying its properties and composition at BESIII and elsewhere.

2 Updates on $e^+e^- \to \pi^+\pi^- h_c$

BESIII observed two states, $Y(4220)$ and $Y(4390)$ in $e^+e^- \to \pi^+\pi^- h_c$ previously in 2017 [9]. Given these Y states have 1^{--} quantum numbers, strong coupling to h_c, which has 1^{+-} quantum numbers, is an indication of exotic internal structure. As such, this channel was investigated again with new data points and higher statistics by BESIII [4]. When fitting the cross section $\sigma(e^+e^- \to \pi^+\pi^- h_c)$ with this new data, a three resonance structure was observed. In addition to the $Y(4220)$ and $Y(4390)$, a better fit was achieved when including a third resonance with a mass around 4470 MeV. The cross section fit results and resulting resonance parameters are shown in Figure 1.



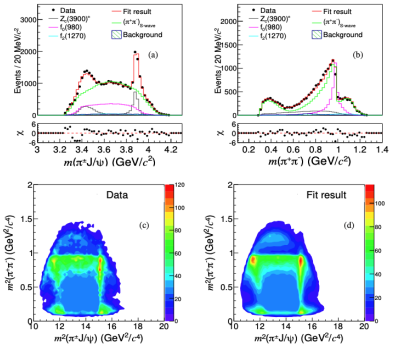
Resonance	Parameter	this measurement (3BW)	this measurement (2BW)	previous measurement
R_1	M (MeV/c^2)	$4223.6^{+2.8+2.6}_{-2.5-2.9}$	4219.7 ± 3.4	$4218.4 \pm 4.0 \pm 0.9$
	$\Gamma_{\rm tot}$ (MeV)	$58.5^{+10.4+8.3}_{-11.4-8.6}$	83.8 ± 5.5	$66.0 \pm 9.0 \pm 0.4$
R_2	M (MeV/c^2)	$4327.4^{+20.1+10.7}_{-15.9-3.3}$	4382.6 ± 6.0	$4391.6 \pm 6.3 \pm 1.0$
	$\Gamma_{\rm tot}$ (MeV)	$244.1^{+34.0+23.3}_{-27.1-13.2}$	163.1 ± 10.4	$139.5 \pm 16.1 \pm 0.6$
R_3	M (MeV/c^2)	$4467.4^{+5.4+2.7}_{-5.4-2.7}$	–	4421 ± 4
	$\Gamma_{\rm tot}$ (MeV)	$62.8^{+19.2+9.8}_{-14.4-6.6}$	–	62 ± 20 (from PDG)
	χ^2/ndf	41.9/70	78.5/66	–

Figure 1: Fit to $\sigma(e^+e^- \to \pi^+\pi^- h_c)$ using 3 Breit-Wigner resonances, and the resulting parameters for the Y states.

3 PWA of $e^+e^- \to J/\psi$

In 2013, the aforementioned exotic $Z_c(3900)^\pm$ state was observed simultaneously in $\pi^\pm J/\psi$ by BESIII and Belle [7, 8]. If this state is a molecular or tetraquark state, we expect a strong correlation between the $\pi Z_c(3900)$ system and the $Y(4220)$. As such, it is promising to study the relationship between the $Z_c(3900)^\pm$ and Y states, as well as $\pi^+\pi^-$ resonances and Y states, to understand the internal structure of the $Z_c(3900)^\pm$.

Recently, BESIII performed a partial wave analysis (PWA) of $e^+e^- \to \pi^+\pi^- J/\psi$ to address this [5]. In doing so, fits were performed to the $\pi^\pm J/\psi$ mass spectrum and the mass and width of the $Z_c(3900)$ were extracted from this Breit-Wigner fit. These results improved upon the uncertainties of the initial BESIII measurements, and were consistent with the current PDG averages.



Sample	M (MeV/c^2)	Γ (MeV)
$4.1567 - 4.1989$	3883.5 ± 1.6	38.6 ± 3.6
$4.2091 - 4.2357$	3884.0 ± 1.0	37.8 ± 1.6
$4.2438 - 4.2776$	3884.9 ± 1.8	34.2 ± 3.3
$4.2866 - 4.3583$	3890.0 ± 2.3	36.1 ± 4.2
Average	$3884.6 \pm 0.7 \pm 3.3$	$37.2 \pm 1.3 \pm 6.6$

Figure 2: Fits to the $\pi^{\pm}J/\psi$ and $\pi^+\pi^-$ invariant masses, and the resulting parameters for the $Z_c(3900)^{\pm}$.

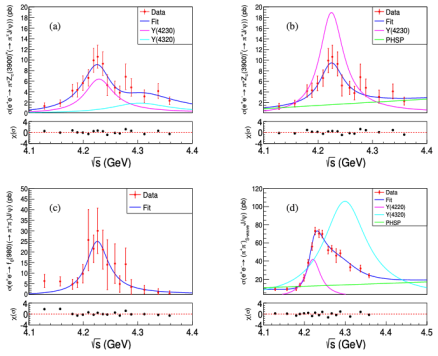


Figure 3: Fits to the cross sections of the sub processes in $e^+e^- \to \pi^+\pi^- J/\psi$.

Additionally, this paper measured for the first time the cross sections of the subprocesses $e^+e^- \to \pi^{\pm}Z_c(3900)^{\mp}(\to \pi^{\mp}J/\psi)$, $e^+e^- \to f_0(980)(\to \pi^+\pi^-)J/\psi$, and $e^+e^- \to (\pi^+\pi^-)_{S-wave}J/\psi$. In the last case, there was an observation of the $Y(4220)$ exceeding 10σ. The fits to the invariant masses and the results of the fits are shown in Figure 2, and the cross section fits are shown in Figure 3.

4 Prompt Inclusive J/ψ and $\psi(2S)$ Production

One last set of recent results comes from studying the prompt production cross sections of J/ψ and $\psi(2S)$ [6]. Recent results on the double charmonium production cross sections from B factories were larger than expected, prompting questions of whether there are hidden states or processes not yet being accounted for [10, 11, 12, 13, 14]. At BESIII, we can investigate this by studying prompt inclusive production of $J/\psi X$ and $\psi(2S)X$ below the double charmonium threshold.

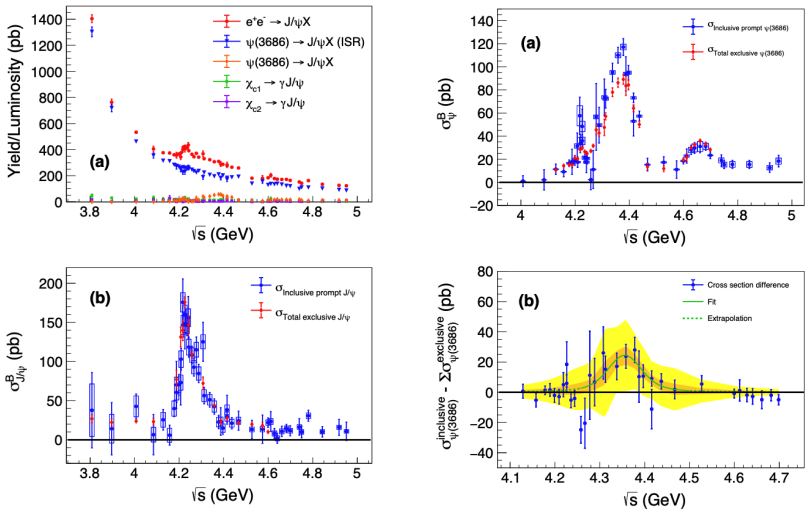


Figure 4: Comparison of prompt inclusive cross sections of J/ψ (left) and $\psi(2S)$ (right) production compared to the sum of all known exclusive production cross sections.

Recently, BESIII did just this using data samples from $3.8 - 4.95$ GeV. For the J/ψ production, the process $J/\psi \to \mu^+\mu^-$ was reconstructed, and events coming from initial state radiation (ISR) production or conventional charmonium decays (e.g., $\psi(2S) \to \pi^+\pi^- J/\psi$) were subtracted. Similarly, the $\psi(2S)$ production was studied by reconstructing $\psi(2S) \to \pi^+\pi^- J/\psi$ with $J/\psi \to \mu^+\mu^-, e^+e^-$, again subtracting off ISR production events. The inclusive cross sections were then measured for each of these cases and compared to the sum of all known exclusive cross sections, shown in Figure 4. For the J/ψ there was good agreement, however, there was a discrepancy between $4.2-4.4$ GeV in the $\psi(2S)$ case. It is believed that $\sim 20\%$ of this discrepancy is due to unknown decays of $\psi(4360) \to \psi(2S)X$.

5 Summary

In summary, we have shown some recent results from BESIII regarding charmonium-like states. In particular, we have recently observed an additional Y state in $\sigma(e^+e^- \to \pi^+\pi^- h_c)$, remeasured the parameters of the $Z_c(3900)^\pm$ in a PWA, and investigated potential hidden processes/states in charmonium production. As we continue taking new data and using the large amount already collected, we expect many new results on this subject in the near future.

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