PROCEEDINGS OF SCIENCE

Recent charmonium decay measurements at BESIII

Xueqiang Yan[a,b,*] **and Zhiyong Wang (for the BESIII Collaboration)**[a,b]

[a] *Institute of High Energy Physics, Chinese Academy of Sciences, Yuquan Road 19B, Beijing, P. R. China*

[b] *University of Chinese Academy of Sciences, Yuquan Road 19A, Beijing, P. R. China*

E-mail: yanxueqiang@ihep.ac.cn, wangzy@ihep.ac.cn

The BESIII experiment at the BEPCIII storage has accumulated the world's largest data samples in the τ-charm energy region, including 10 billion J/ψ events for the study of light hadrons and hyperons, 2.7 billion $\psi(3686)$ events for charmonium study, 20 fb^{-1} $\psi(3770)$ events for D mesons study, and high luminosity scan for research on XYZ, D_s, and Λ_c states. This presentation delves into recent experimental measurements of charmonium decays, including four independent measurements performed at BESIII experiment. The evidence of the $\chi_{c0} \to \Lambda\bar{\Lambda}\phi$ decay, along with the observation of the $\chi_{c1,2} \to \Lambda\bar{\Lambda}\phi$ and $\chi_{c0,1,2} \to \Lambda\bar{\Lambda}\omega$ decays, are firstly reported. The decay $h_c \to \gamma\eta$ is observed for the first time, but no significant signal is found for the decay $h_c \to \gamma\pi^0$. Additionally, the first search for the radiative transition $\chi_{c1}(3872) \to \gamma\psi_2(3823)$ is performed with no significant signal.

The 43rd International Symposium on Physics in Collision (PIC2024)
22–25 October 2024
Athens, Greece

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0) All rights for text and data mining, AI training, and similar technologies for commercial purposes, are reserved. ISSN 1824-8039 . Published by SISSA Medialab.

PoS(PIC2024)041

1. Introduction

Quantum Chromodynamics (QCD) serves as the cornerstone of our understanding of strong interactions, having undergone rigorously testing throughout its development. Due to the non-Abelian nature of QCD, a non-perturbative approach is essential, heavily relying on techniques such as lattice QCD (LQCD) or QCD-inspired models. Therefore, experimental measurements in the low-energy regime are crucial to verify the pertinent models, calibrate their parameters, and stimulate the development of new theoretical computations [1]. The charmonium states are multi-scale systems that allow for the exploration of a wide range of energy regimes in QCD, from the hard region where expansions in the coupling constant are legitimate, to the low-energy region dominated by non-perturbative effects [2]. Within the BESIII energy range, accessible charmonium states exist both below and above the open-charm threshold. The relative simplicity of the lowest-lying charmonium states allows for precise tests of QCD and QCD-inspired models, particularly in regions where both non-perturbative and perturbative aspects are relevant. Conversely, higher-mass states introduce serious challenges to our qualitative understanding of mesons, while some of these states provide potential evidence of a wealth of exotic configurations of quarks and gluons [3–5].

Unlike J/ψ and $\psi(3686)$, people have relatively few understanding to other charmonium states, such as χ_{cJ} ($J = 0, 1, 2$) and h_c. As for the P-wave spin-triplet states $\chi_{c1,2}$, the dominant decay modes are the transitions $\chi_{c1,2} \to \gamma J/\psi$. However, the sum of all measured $\chi_{c0,1,2}$ branching fractions is significantly less than 1, making the search for χ_{cJ} hadronic decays highly desirable for understanding their decay dynamics. The sum of the branching fractions of known h_c decay modes is only about 3% [6], except for the E1 decay of $h_c \to \gamma\eta_c$, which has a branching fraction of $(60\pm4)\%$. Studies of the radiative decays of h_c are particularly desirable since they will provide more direct information on non-perturbative effects in heavy quarkonia [7]. Additionally, the charmoniumlike state $\chi_{c1}(3872)$ was discovered by the Belle experiment [8] above open charm threshold, which can not be explained as the traditional charmonium states. The experimental measurement of its radiative transition will help to determine whether the $\chi_{c1}(3872)$ is the conventional charmonium state, $\chi_{c1}(2P)$ [9].

2. $\chi_{cJ} \to \Lambda\bar{\Lambda}\phi$

The decays of χ_{cJ} have not been studied as extensively as the vector charmonium states J/ψ and $\psi(3686)$ in both experiment and theory. The χ_{cJ} mesons can be produced via radiative decays of $\psi(3686)$, with a sizable branching fraction of about 9% [6] for each χ_{cJ} state. This provides an ideal site for investigating their properties. Studies of the processes involving the $B\bar{B}V$ final states, where B and V denote baryons and vector mesons, respectively, are valuable for searching potential $B\bar{B}$ threshold enhancements and excited baryon states [10, 11].

By analyzing $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events, the decays $\chi_{c1,2} \to \Lambda\bar{\Lambda}\phi$ are observed for the first time, with statistical significance to be 11.3σ and 13.0σ, respectively. Evidence is also found for the decay $\chi_{c0} \to \Lambda\bar{\Lambda}\phi$ with a statistical significance of 4.1σ [12]. The fit result is shown in Fig. 1. The branching fractions are determined to be $\mathcal{B}(\chi_{c0} \to \Lambda\bar{\Lambda}\phi) = (2.99\pm1.24\pm0.19)\times10^{-5}$, $\mathcal{B}(\chi_{c1} \to \Lambda\bar{\Lambda}\phi) = (6.01\pm0.90\pm0.40)\times10^{-5}$, and $\mathcal{B}(\chi_{c2} \to \Lambda\bar{\Lambda}\phi) = (7.13\pm0.81\pm0.36)\times10^{-5}$, where the first uncertainties are statistical and the second systematic. No obvious enhancement is

PoS(PIC2024)041

observed near the $\Lambda\bar{\Lambda}$ production threshold. No obvious excited Λ state is found in the $M_{\Lambda\phi(\bar{\Lambda}\phi)}$ spectra, either.

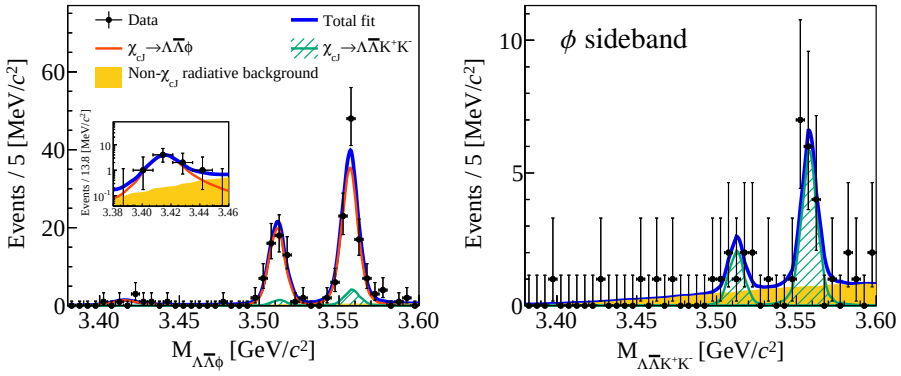

Figure 1: Simultaneous fit to the $M_{\Lambda\bar{\Lambda}K^+K^-}$ distributions in the ϕ (left) signal and (right) sideband regions.

3. $\chi_{cJ} \to \Lambda\bar{\Lambda}\omega$

By analyzing the same $\psi(3686)$ samples, the decays $\chi_{c0,1,2} \to \Lambda\bar{\Lambda}\omega$ are also observed for the first time, with statistical significance to be 11.7σ, 11.2σ, and 11.8σ, respectively [13]. The fit results are shown in Fig. 2. The branching fractions are determined to be $\mathcal{B}(\chi_{c0} \to \Lambda\bar{\Lambda}\omega) = (2.37 \pm 0.22 \pm 0.25) \times 10^{-4}$, $\mathcal{B}(\chi_{c1} \to \Lambda\bar{\Lambda}\omega) = (1.01 \pm 0.10 \pm 0.11) \times 10^{-4}$, and $\mathcal{B}(\chi_{c2} \to \Lambda\bar{\Lambda}\omega) = (1.40 \pm 0.13 \pm 0.17) \times 10^{-4}$, where the first uncertainties are statistical and the second systematic. With the current statistics, no deviations are observed between the data and phase space Monte Carlo samples for the $M(\Lambda\bar{\Lambda})$ and $M(\Lambda\omega/\bar{\Lambda}\omega)$ distributions, indicating that no threshold enhancement or intermediate states are observed.

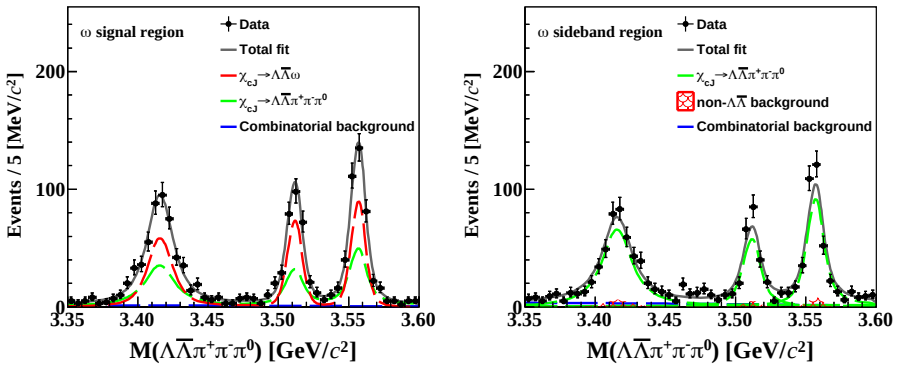

Figure 2: Simultaneous fit to the $M_{\Lambda\bar{\Lambda}\pi^+\pi^-\pi^0}$ distributions in the ω signal (left) and sideband (right) regions.

PoS(PIC2024)041

4. $h_c \to \gamma\,\eta'/\eta/\pi^0$

Previous measurements of the branching fractions of $h_c \to \gamma\,\eta'(\eta)$ have large uncertainties [14], and the decay $h_c \to \gamma\,\pi^0$ hasn't yet been observed. Additionally, the study of $\eta-\eta'$ mixing is a powerful laboratory for testing the $U(1)_A$ anomaly [15, 16] and SU(3) breaking in QCD [17, 18]. The mixing angle between $\eta-\eta'$, associated with the ratio $R_{h_c} = \mathcal{B}(h_c \to \gamma\eta)/\mathcal{B}(h_c \to \gamma\eta')$, is determined to be $\phi = 33.8^\circ \pm 2.5^\circ$ through a perturbative QCD calculation [19]. This value is compatible with recent LQCD calculations [20, 21], but deviates from other calculations [22, 23]. Since the uncertainty of the ϕ is dominated by R_{h_c}, a more precise measurement is essential.

We study the decays $h_c \to \gamma\,\eta'/\eta/\pi^0$ via $\psi(3686) \to \pi^0 h_c$. The decay $h_c \to \gamma\eta$ is observed for the first time with a statistical significance of 9σ, and the corresponding branching fraction is measured to be $(3.77 \pm 0.55 \pm 0.13 \pm 0.26) \times 10^{-4}$, where the first uncertainty is statistical, the second systematic, and the third arises from the $\mathcal{B}(\psi(3686) \to \pi^0 h_c)$. Additionally, an improved measurement of $\mathcal{B}(h_c \to \gamma\eta') = (1.40 \pm 0.11 \pm 0.04 \pm 0.10) \times 10^{-3}$ is done. We also conducted for the first time a search for $h_c \to \gamma\pi^0$, no significant signal is found, and an upper limit of $\mathcal{B}(h_c \to \gamma\pi^0) < 5.0\times10^{-5}$ is set at the 90% confidence level (C.L.) [24]. The fit result is shown in Fig. 3. The ratio R_{h_c} is calculated to be $(27.0\pm4.4\pm1.0)\%$, which favors the prediction in ref. [19], suggesting comparable contributions from both the quark-antiquark content and the gluonic content in $\eta^{(\prime)}$.

5. $\chi_{c1}(3872) \to \gamma\psi_2(3823)$

Measurements of new decay modes for $\chi_{c1}(3872)$ can improve our understanding of its internal structure. If the $\chi_{c1}(3872)$ contains a component of the excited spin-triplet state $\chi_{c1}(2P)$, then the radiative decay $\chi_{c1}(3872) \to \gamma\psi_2(3823)$ could naturally happen via an E1 transition [9], where the $\psi_2(3823)$ is considered as the 1^3D_2 charmonium state.

By analyzing the e^+e^- collision data accumulated at $\sqrt{s} = 4.178 - 4.278$ GeV, we search for the radiative decay $\chi_{c1}(3872) \to \gamma\psi_2(3823)$ for the first time. Fig. 4 shows the distribution of the $M(\gamma\psi_2(3823))$ for the selected candidates, summed over all the energy points. No signal is observed in the $\chi_{c1}(3872)$ signal region in data, and the upper limit on the branching fraction ratio $\mathcal{R}_{\chi_{c1}(3872)} \equiv \mathcal{B}(\chi_{c1}(3872) \to \gamma\psi_2(3823), \psi_2(3823) \to \gamma\chi_{c1})/\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi)$ is determined to be 0.075 at the 90% C.L. [25]. This upper limit is more than 1σ below the theoretical calculations under the assumption that the $\chi_{c1}(3872)$ is the pure charmonium state $\chi_{c1}(2P)$. Thus, our result indicates that the $\chi_{c1}(3872)$ is not a pure $\chi_{c1}(2P)$ charmonium state.

6. Summary

BESIII has achieved significant progress in the study of charmonium decays using the data samples collected in the τ−charm energy region. The largest datasets of $c\bar{c}$ vector states provide a powerful framework to investigate the χ_{cJ} and h_c decays with unprecedented precision. Datasets above the $D\bar{D}$ threshold shed new insights into the decays of charmonium-like states and hint at possible connections between XYZ states and the conventional charmonium. We made the first observation of the decays $\chi_{c1,2} \to \Lambda\bar{\Lambda}\phi$ and $\chi_{c0,1,2} \to \Lambda\bar{\Lambda}\omega$, and reported the first evidence for

PoS(PIC2024)041

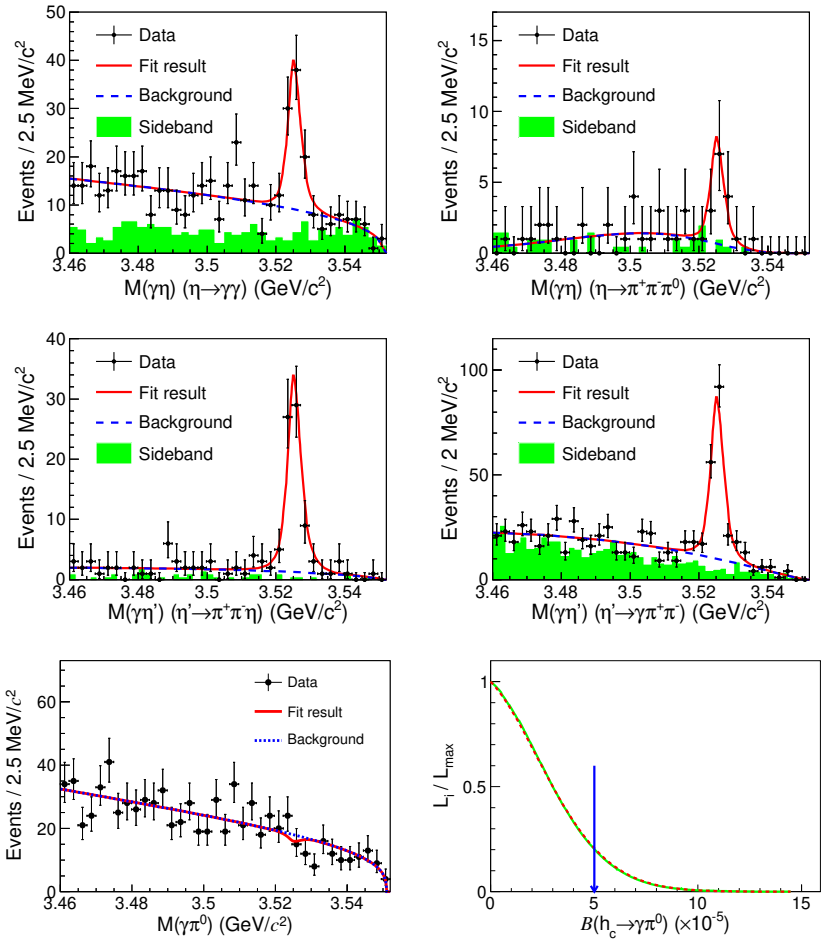

Figure 3: (First row) The simultaneous fit to the $M(\gamma\gamma\gamma)$ and $M(\gamma\pi^+\pi^-\pi^0)$ distributions; (Second row) The simultaneous fit to the $M(\gamma\pi^+\pi^-\eta)$ and $M(\gamma\gamma\pi^+\pi^-)$ distributions; (Third row) The fit to the $M(\gamma\pi^0)$ distribution and the normalized likelihood scan.

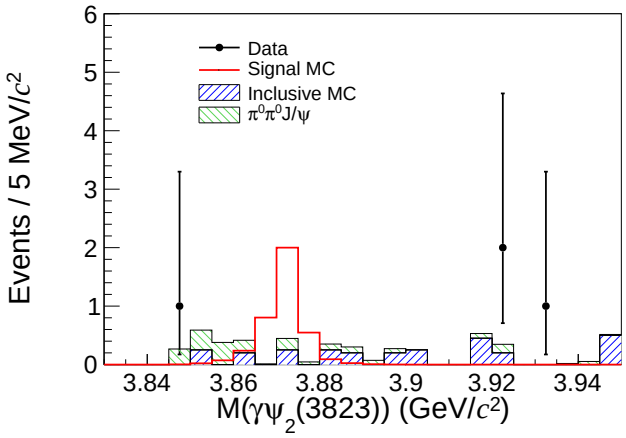

Figure 4: The distribution of $M(\gamma\psi_2(3823))$.

PoS(PIC2024)041

the decay $\chi_{c0} \to \Lambda\bar{\Lambda}\phi$. Additionally, the decay $h_c \to \gamma\eta$ is observed for the first time, while no significant signal is found for the decay $h_c \to \gamma\pi^0$. We also conducted the first search for $\chi_{c1}(3872) \to \gamma\psi_2(3823)$ with no significant signal. New datasets are currently under analysis, much more results will be presented in the future.

References

[1] N. Brambilla *et al*. (Quarkonium Working Group), arXiv:hep-ph/0412158.

[2] D. M. Asner *et al*., Physics at BES-III, Int. J. Mod. Phys. A**24** (2009) S1 arXiv:0809. 1869.

[3] N. Brambilla *et al*., Phys. Rept. **873**, 1-154 (2020).

[4] F. K. Guo *et al*., Rev. Mod. Phys. **90**, 015004 (2022).

[5] N. Brambilla *et al*., Eur. Phys. J. C **71**, 1534 (2011).

[6] R. L. Workman *et al*. (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).

[7] R. Zhu and J. P. Dai, Phys. Rev. D **94**, 094034 (2016).

[8] S. K. Choi *et al*. (Belle Group), Phys. Rev. Lett. **91**, 262001 (2003).

[9] N. Li *et al*., Phys. Rev. D **109**, 014513 (2024).

[10] M. Ablikim *et al*. (BESIII collaboration), Phys. Rev. D **104**, 052006 (2021).

[11] M. Ablikim *et al*. (BESIII collaboration), Phys. Rev. D **106**, 072004 (2022).

[12] M. Ablikim *et al*. (BESIII collaboration), Phys. Rev. D **110**, 032016 (2024).

[13] M. Ablikim *et al*. (BESIII collaboration), Phys. Rev. D **110**, 032022 (2024).

[14] M. Ablikim *et al*. (BESIII collaboration), Phys. Rev. Lett. **116**, 251802 (2016).

[15] E. Witten, Nucl. Phys. B **156**, 269 (1979).

[16] G. Veneziano, Nucl. Phys. B **159**, 213 (1979).

[17] F. J. Gilman and R. kauffman, Phys. Rev. D **36**, 2761 (1987).

[18] R. Escribano and E. Royo, Phys. Lett. B **807**, 135534 (2020).

[19] J. K. He and C. J. Fan, Phys. Rev. D **103**, 114006 (2021).

[20] E. B. Gregory *et al*., Phys. Rev. D **86**, 014504 (2012).

[21] K. Ottnad *et al*., Phys. Rev. D **97**, 054508 (2018).

[22] T. Feldmann, P. Kroll and B. Stech, Phys. Rev. D **58**, 114006 (1998).

[23] C. Michael *et al*., Phys. Rev. Lett. **111**, 181602 (1998).

[24] M. Ablikim *et al*. (BESIII collaboration), JHEP **08**, 180 (2024).

[25] M. Ablikim *et al*. (BESIII collaboration), Phys. Rev. D **110**, 012012 (2024).

PoS(PIC2024)041