PROCEEDINGS OF SCIENCE

Charmonium Decays at BESIII

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Although the charmonium spectrum seems to be well investigated, charmonia can still be used as benchmarks to test our QCD predictions, as these states lay in the transition region between perturbative and non-perturbative QCD. Despite the need for experimental confirmations, setbacks arise from limited statistics because of the production processes of all non-vector states. The properties and many decay channels of some charmonium states (such as h_c, χ_{cJ}, or $\eta_c(2S)$) are still far from being known. Since 2009, BESIII has been scanning and investigating the charmonium region to shed light on open questions. Thanks to its unique J/ψ and $\psi(2S)$ datasets, BESIII could overcome statistical limitations. Recent results on charmonium decays from the BESIII Collaboration are presented.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

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1. Introduction

The BESIII (BEijing Spectrometer III) detector records symmetric e^+e^- collisions provided by the BEPCII (Beijing Electron Positron Collider II) storage ring, which operates in the center-of-mass energy ($\sqrt{s}$) range from 2.0 to 4.9 GeV. The machine is hosted by the Institute of High Energy Physics (IHEP) in Beijing, People's Republic of China. Details on the detector and its resolution can be found in Ref. [1]. As a τ-charm factory, BESIII physics programme [2] covers charmonium(-like) and light hadrons spectroscopy, charmed mesons and baryons decays, τ studies, QCD measurements, and new physics searches.

BESIII can profit from direct production of vector states ($J^{PC} = 1^{--}$), which allowed the collaboration to obtain the biggest datasets in the world of the J/ψ, $\psi(2S)$, and $\psi(3770)$ states. Thanks to the statistics of the $\psi(nS)$ decays, also the non-vector states can be studied with high precision. The datasets at $\sqrt{s} > 3.8$ GeV give BESIII the possibility to probe the charmonium spectrum above the $D\bar{D}$ threshold and to investigate the XYZ exotic states [3]. Four analyses are presented to give a glimpse of what the BESIII Collaboration can provide with charmonium decays.

2. Measurement of Branching Fractions of J/ψ and $\psi(3686)$ decays to Σ^+ and $\bar{\Sigma}^-$

Aim of the analysis [4] is to measure the branching fractions of J/ψ and $\psi(3686)$ decaying to Σ^+ and $\bar{\Sigma}^-$ providing a test on the "12% rule"[1]. Candidates of $\psi \to \Sigma^+ \bar{\Sigma}^-$ decays are reconstructed from Σ^+ and ($\bar{\Sigma}^-$) going into $p\pi^0$ ($\bar{p}\pi^0$). The number of signal events are counted by fitting the invariant $p\pi^0$ mass distribution, while requiring the invariant $\bar{p}\pi^0$ mass ($M_{\bar{p}\pi^0}$) to be within $1.17 < M_{\bar{p}\pi^0} < 1.20\,\text{GeV}/c^2$. Signal numbers and branching fractions are shown in Table 1, where for the latter the systematic uncertainties are reported too. Finally, from the branching fractions of the two channels, their ratio is obtained and found to be $\frac{\mathcal{B}_{\psi(3686)\to h}}{\mathcal{B}_{J/\psi\to h}} = (23.8 \pm 1.3)\%$, where the statistical and systematic uncertainties are combined. The ratio is consistent with a previous measurement in the $\Sigma^0\bar{\Sigma}^0$ final states by the BESIII Collaboration [6], and both violate the "12% rule".

Table 1: The number of signal events and branching fractions are presented for both the channels. Both the branching fraction measurements are in agreement with the PDG values within 2σ [5], and the precision on the $\mathcal{B}(J/\psi \to \Sigma^+\bar{\Sigma}^-)$ is improved by a factor of 7.

Channel	N_{Sig}	$\mathcal{B} \times 10^{-4}$
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	86976 ± 314	$10.61 \pm 0.04 \pm 0.38$
$\psi(3686) \to \Sigma^+\bar{\Sigma}^-$	5447 ± 76	$2.52 \pm 0.04 \pm 0.10$

[1] Empirical rule that states that the ratio between the branching fractions of J/ψ and $\psi(3686)$ decays to the same final states approximate to 12%. A large number of decay channels follows the rule, but a significant violation was observed with the $\rho\pi$ decay [5].

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3. Measurements of the branching fractions of $\psi(3686) \to \bar{\Sigma}^0\Lambda + c.c.$ and $\chi_{cJ\,(J=0,1,2)} \to \Lambda\bar{\Lambda}$

In the first part, this study [7] aims to measure the branching fraction of the isospin violating decay $\psi(3686) \to \bar{\Sigma}^0\Lambda + c.c.$. The decay is reconstructed through the $\bar{\Sigma}^0 \to \gamma\bar{\Lambda}$, $\bar{\Lambda}(\Lambda) \to \bar{p}\pi^+(p\pi^-)$ chain. The signal yields are obtained with a two-dimensional fit to the invariant $\gamma\bar{\Lambda}$ and $\gamma\Lambda$ mass distributions ($M_{\gamma\bar{\Lambda}}$ and $M_{\gamma\Lambda}$, respectively), where the background is described taking into account the $\psi(3686) \to \gamma\chi_{cJ} \to \gamma\Lambda\bar{\Lambda}$ and $\psi(3686) \to \Sigma\bar{\Sigma}^0$ decays (modelled via a MC simulation) and other sources (described by a first-order polynomial function). The projections from the two-dimensional fit to $M_{\gamma\bar{\Lambda}}$ and $M_{\gamma\Lambda}$ are shown in Fig. 1. The numbers of signal events are determined to be $N^{\gamma\bar{\Lambda}}_{\mathrm{Sig}} = 26.1 \pm 6.6$ and $N^{\gamma\Lambda}_{\mathrm{Sig}} = 37.2 \pm 7.7$. Finally, the branching fraction of $\psi(3686) \to \bar{\Sigma}^0\Lambda + c.c.$ is found to be $(1.60 \pm 0.31 \pm 0.13 \pm 0.58) \times 10^{-6}$, where the first uncertainty is statistical, the second is systematic, and the third one comes from the $\psi(3686)$-continuum interference. Despite the result being consistent within $1 \sim 2\sigma$ with theoretical predictions [8], it is in tension with CLEO-c measurement of $(12.30 \pm 2.4) \times 10^{-6}$ [9].

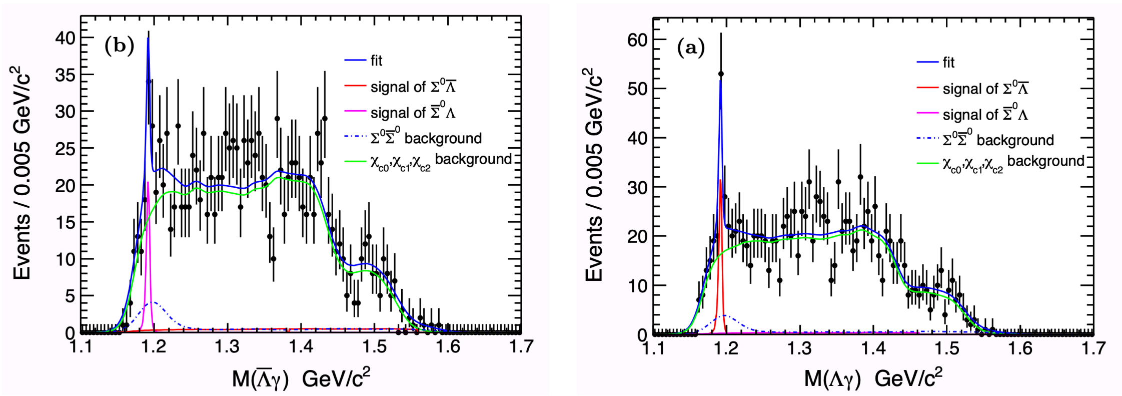

Figure 1: Projections from the two-dimensional fit to $M_{\gamma\bar{\Lambda}}$ (left) and $M_{\gamma\Lambda}$ (right). Dots with error bars are data, blue solid curves are the total fitting functions, red and pink lines are the signal components, blue dotted curves are from $\psi(3686) \to \Sigma\bar{\Sigma}^0$ background contribution, green lines show the $\psi(3686) \to \gamma\chi_{cJ}$ background contribution, while the contributions from other background sources are too small to be appreciated.

In the second portion of the article, with the same final state, it is determined the branching fractions for the $\chi_{cJ\,(J=0,1,2)} \to \Lambda\bar{\Lambda}$. The signal yields are obtained from a fit to the invariant $\Lambda\bar{\Lambda}$ mass distribution. A summary of the $\chi_{cJ} \to \Lambda\bar{\Lambda}$ signal yields ($N_{\chi_{cJ}}$) and of the branching fractions ($\mathcal{B}(\chi_{cJ})$) is shown in Table 2. Despite an improvement on the branching fractions knowledge can be appreciated for the J = 0,1 states, the results are not consistent with theoretical predictions of Ref. [10] (e.g., $\mathcal{B}(\chi_{c0})$ is (1.19 - 1.51) $\times 10^{-4}$).

4. Measurement of $e^+e^- \to \gamma\chi_{cJ}$ cross sections at center-of-mass energies between 3.77 and 4.60 GeV

With 34 energy points and a total integrated luminosity ($\mathcal{L}_{\mathrm{int}}$) of 19.3 fb^{-1}, in this analysis [11] the $e^+e^- \to \gamma\chi_{cJ}$ cross sections are studied to investigate the intermediate resonant states.

Table 2: The number of signal events and branching fractions are presented for the three channels. For the $\mathcal{B}(\chi_{cJ})$, the uncertainties are statistical, systematic, and coming from the uncertainty on the $\mathcal{B}(\psi(3686) \rightarrow \gamma\chi_{cJ})$.

Mode	$N_{\chi_{cJ}}$	$\mathcal{B}(\chi_{cJ}) \times 10^{-4}$
χ_{c0}	1486 ± 42	3.64 ± 0.10 ± 0.10 ± 0.07
χ_{c1}	528 ± 24	1.31 ± 0.06 ± 0.06 ± 0.03
χ_{c2}	670 ± 27	1.91 ± 0.08 ± 0.17 ± 0.04

The $\chi_{c1,2}$ states selection is similar, as their radiative branching fractions are the largest [5]. These resonances are reconstructed via the $\gamma J/\psi$ decay, with $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = e$ or μ). For the datasets with $\mathcal{L}_{\text{int}} > 400$ pb^{-1}, the number of signal events is determined from fitting the invariant $\gamma_{\text{H}} J/\psi$ (at $\sqrt{s} < 4.009$ GeV) or $\gamma_{\text{L}} J/\psi$ (at $\sqrt{s} > 4.009$ GeV) [2]. This allows the first observation of the $e^+e^- \rightarrow \gamma\chi_{c1,2}$ process at $4 < \sqrt{s} < 5$ GeV, with a significance of 7.6σ and 6.0σ for the χ_{c1} and χ_{c2}, respectively. Finally, a fit is performed to the production cross section of $e^+e^- \rightarrow \gamma\chi_{c1,2}$ for each energy point, as shown in Fig. 2. A combination of a coherent sum of two Breit-Wigner resonances (modelling the $\psi(4040)$ and the $\psi(4160)$ states), a continuum term, and incoherent sum (for high energy tail contributions) of the $\psi(3686)$ and the $\psi(3770)$ resonances is implemented to describe the χ_{c1} data. A similar description is used for the χ_{c2} process, without the contribution from the continuum and with an additional resonance to the coherent sum. With a significance of 5.8σ, this supplementary resonance has a mass M = 4371.7 ± 7.5 ± 1.8 MeV/c^2 and a width Γ = 51.1 ± 17.6 ± 1.9 MeV and it is consistent with either the Y(4360) or the Y(4390) resonance [5].

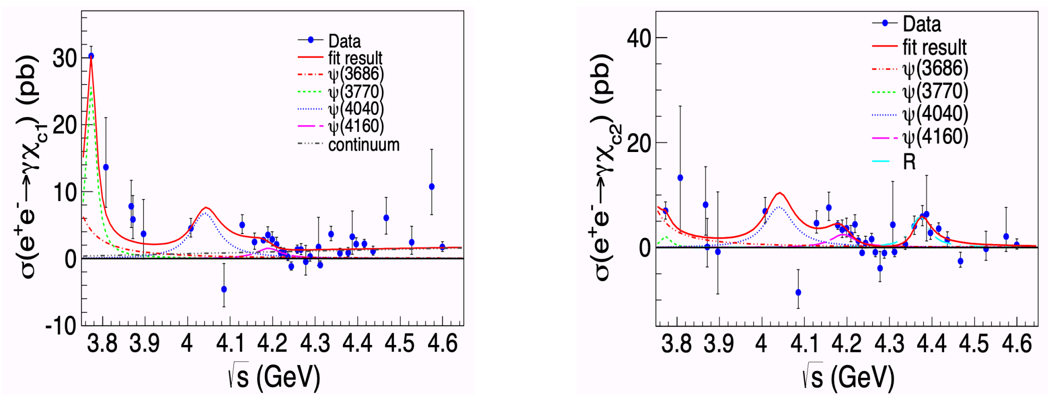

Figure 2: Cross section of $e^+e^- \rightarrow \gamma\chi_{c1}$ (left) and $e^+e^- \rightarrow \gamma\chi_{c2}$ (right) processes with a fit to the line shape superimposed. Dots with error bars are data, the red solid curve shows the fit results, and the dashed curves describe the contribution of each component.

The last χ_{cJ} process, namely the χ_{c0}, is studied via hadronic decays, with the final states being $K^+K^-\pi^+\pi^-$, K^+K^-, or $2(\pi^+\pi^-)$. Despite only the energy points with $\mathcal{L}_{\text{int}} > 400$ pb^{-1} are used, the significance for this process is estimated to be less than 2σ for each energy point.

[2]The subscripts H or L are due to the fact that at $\sqrt{s} < 4.009$ GeV, the energy of the coming from the $\chi_{c1,2}$ decay is higher than the one of the photon coming from the e^+e^- interaction.

5. Search for new decay modes of the $\psi_2(3823)$ and the process $e^+e^- \to \pi^0\pi^0\psi_2(3823)$

Using the reaction $e^+e^- \to \pi^+\pi^-\psi_2(3823)$ and $\mathcal{L}_{\rm int}$ of 19 fb^{-1}, seven decay modes of the $\psi_2(3823)$ resonance are searched for. Aim of the study [12] is to define the nature of the $\psi_2(3823)$ state, either $\psi(1^3D_2)$ or $\psi(1^3D_3)$.

A summary of the decay modes, with the relative numbers of $\psi_2(3823)$ events ($\mathrm{N}_{\psi_2(3823)}$) and branching fractions normalised to the $\psi_2(3823) \to \gamma\chi_{c1}$ one, is persented in Table 3. These decay modes are reconstructed through the final states already discussed in the previous sections. The signal yields are extracted from a simultaneous fit to the seven $\psi_2(3823)$ decay modes $\pi^+\pi^-$ recoil mass distributions. The $\psi_2(3823) \to \gamma\chi_{c1}$ process is confirmed with a significance of 11.8σ and the $\psi_2(3823) \to \gamma\chi_{c2}$ decay is observed for the first time with a significance of 3.2σ. The $\frac{\mathcal{B}(\psi_2(3823)\to\gamma\chi_{c2})}{\mathcal{B}(\psi_2(3823)\to\gamma\chi_{c1})}$ measured value, reported in Table 3, is consistent within 1σ with theoretical predictions (i.e., 0.317 - 0.324) of the $\psi_2(3823)$ being the $\psi_2(1^3D_2)$ state [13].

Table 3: Number of $\psi_2(3823)$ events and normalised branching fractions for each decay mode. For $\mathrm{N}_{\psi_2(3823)}$ only the statistical uncertainty is reported, while for the branching fractions the first uncertainty is statistical and the second one is systematic.

Mode	$\mathrm{N}_{\psi_2(3823)}$	$\frac{\mathcal{B}(\psi_2(3823)\to\ldots)}{\mathcal{B}(\psi_2(3823)\to\gamma\chi_{c1})}$
$\gamma\chi_{c1}$	63.1 ± 8.5	—
$\gamma\chi_{c2}$	$8.8^{+4.3}_{-3.4}$	$0.28^{+0.14}_{-0.11} \pm 0.02$
$\gamma\chi_{c0}$	< 6.3	< 0.24
$\pi^+\pi^-J/\psi$	< 21.0	< 0.06
$\pi^0\pi^0J/\psi$	< 10.0	< 0.11
$\eta J/\psi$	< 9.8	< 0.14
$\pi^0 J/\psi$	< 5.6	< 0.03

Through the $\psi_2(3823) \to \gamma\chi_{c1}$ decay, the $e^+e^- \to \pi^0\pi^0\psi_2(3823)$ reaction is studied as well. The signal yield is obtained from a fit to the $\pi^0\pi^0$ recoil mass and is estimated to be $\mathrm{N}^{\rm Sig} = 15.9^{+5.1}_{-4.4}$, finding evidence for this process with a significance of 4.3σ. Lastly, the average cross-section ratio is measured as $\frac{\sigma(e^+e^-\to\pi^0\pi^0\psi_2(3823))}{\sigma(e^+e^-\to\pi^+\pi^-\psi_2(3823))} = 0.64^{+0.22}_{-0.20} \pm 0.05$, which confirms the isospin conservation within the uncertainty.

6. Summary

As shown in Sections 2 and 3, the large datasets of $c\bar{c}$ vector states collected by the BESIII Collaboration provide the power to investigate not only rare vector decays, but also the non vector ones (such as the χ_{cJ}), the decays of which are mostly unknown. These analyses provide a violation of the "12% rule" in the Σ-sector [4] and a measurement of the $\psi(3686) \to \bar{\Sigma}^0\Lambda + c.c.$ branching fraction in tension with CLEO-c result [9], updating the $\chi_{cJ\,(J=0,1,2)} \to \Lambda\bar{\Lambda}$ branching fractions measurements as well [7].

On the other hand, in the Sections 4 and 5 it was shown that datasets above the $D\bar{D}$ threshold can shed new light on the charmonium spectrum and hint at connections between XYZ states and conventional charmonia. The two studies report the evidence of a resonance in the $e^+e^- \to \gamma\chi_{c2}$ cross section line-shape [11] and the fact that the $\psi_2(3823)$ resonance is consistent with being the $\psi_2(1^3D_2)$ charmonium state [12].

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