# Measurement of Charmonium decays at BESIII 

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> Summary


## Beijing Electron Positron Collider II (BEPCII)



2020: energy upgrade to 2.45 GeV \& top-up mode
2004: started BEPCII upgrade, BESIII construction
2008: test run
2009 - now: BESIII physics run

- 1989-2004 (BEPC):
$\mathrm{L}_{\text {peak }}=1.0 \times 10^{31} / \mathrm{cm}^{2} \mathrm{~s}$
- 2009-now (BEPCII):
$\checkmark$ about 10 billion $J / \psi$
$\checkmark$ about 2.7 billion $\psi(3686)$
$\checkmark$ data sets for the study of $R$ value, exotic states, charmed hadrons...


## Helicity amplitude analysis of $\chi_{c J} \rightarrow \phi \phi$

- Study of the $\chi_{c J}(J=0,1,2)$ decays helps to test QCD
- Predictions are smaller than measured branching fraction [Phys. Lett. B 93 (1980) 119, Phys. Lett. B 93 (1980) 119, Phys. Lett. B 93 (1980) 119]
- BESIII measured $\chi_{c J} \rightarrow \phi \phi$ before without amplitude analysis [Phys.Rev.Lett. 107 (2011) 092001]
- The analysis of the $\phi$ meson polarization: probe hadronic-loop effects in the $\chi_{c J} \rightarrow \phi \phi$ decay [Phys. Lett. B 93 (1980) 119]
- The ratios of the helicity amplitudes are effective in the discrimination between the proposed models [Phys. Lett. B 611 (2005) 123, Phys. Lett. B 611 (2005) 123, Phys. Lett. B 93 (1980) 119]

Table 1. Numerical results of predictions from pQCD [6], ${ }^{3} P_{0}$ [9] and $D \bar{D}$ loop models [10].

| Decay channel | $\chi_{c 0} \rightarrow \phi \phi$ | $\chi_{c 2} \rightarrow \phi \phi$ |  |  |
| :--- | :---: | :---: | :---: | :---: |
| Parameter | $x$ | $\omega_{1}$ | $\omega_{2}$ | $\omega_{4}$ |
| pQCD | $0.293 \pm 0.030$ | $0.812 \pm 0.018$ | $1.647 \pm 0.067$ | $0.344 \pm 0.020$ |
| ${ }^{3} P_{0}$ | $0.515 \pm 0.029$ | $1.399 \pm 0.580$ | $0.971 \pm 0.275$ | $0.406 \pm 0.017$ |
| $D \bar{D}$ loop | $0.359 \pm 0.019$ | $1.285 \pm 0.017$ | $5.110 \pm 0.057$ | $0.465 \pm 0.002$ |

- $x=\left|F_{1,1}^{0} / F_{0,0}^{0}\right|$ for $\chi_{c 0}$
- $\omega_{1}=\left|F_{0,1}^{2} / F_{0,0}^{2}\right|, \omega_{2}=\left|F_{1,-1}^{2} / F_{0,0}^{2}\right|, \omega_{4}=\left|F_{1,1}^{2} / F_{0,0}^{2}\right|$ for $\chi_{c 2}\left(F_{\lambda_{1}, \lambda_{2}}^{J=0,2}\right.$ are the helicity amplitudes)


## Helicity amplitude analysis of $\chi_{c J} \rightarrow \phi \phi$

- Based on 448.1 million $\psi(3686)$ data
- The joint distribution for the sequential decays $e^{+} e^{-} \rightarrow \psi(3686) \rightarrow \gamma \chi_{c J}, \chi_{c J} \rightarrow \phi \phi$ and $\phi \rightarrow K^{+} K^{-}$ is constructed in the helicity system
- An unbinned likelihood fit is performed
- Interference is only considered for $\chi_{c 0}$ due to the much wider width compared with $\chi_{c 1}$ and $\chi_{c 2}$


Figure 2. Definitions of helicity angles.

$$
\begin{aligned}
& \mathcal{M}\left(R_{i}\right)= \frac{1}{2} \sum_{M, \lambda_{R}, \lambda_{1}, \lambda_{2}} A_{\lambda_{R}, \lambda_{\gamma}}^{1} D_{M, \lambda_{R}-\lambda_{\gamma}}^{1 *}\left(0, \theta_{0}, 0\right) F_{\lambda_{1}, \lambda_{2}}^{J} D_{\lambda_{R}, \lambda_{1}-\lambda_{2}}^{J *}\left(\phi_{1}, \theta_{0}, 0\right) \\
& \times B_{0,0}^{1} D_{\lambda_{1}, 0}^{1 *}\left(\phi_{2}, \theta_{2}, 0\right) B_{0,0}^{1} D_{\lambda_{2}, 0}^{1 *}\left(\phi_{3}, \theta_{3}, 0\right) B W\left(m_{\phi \phi}, m_{i}, \Gamma_{i}\right), \\
& \mathrm{d} \sigma \propto \frac{1}{2} \sum_{M, \lambda_{\gamma}}\left|\sum_{R_{i}} \mathcal{M}\left(R_{i}\right)\right|^{2} \mathrm{~d} \Phi
\end{aligned}
$$

## Helicity amplitude analysis of $\chi_{c J} \rightarrow \phi \phi$

$>$ Properties of $\chi_{c 0}$ :

- $m_{\chi_{c 0}}=3415.42 \mathrm{MeV} / c^{2}$
- $\Gamma_{\chi_{c 0}}=11.4 \mathrm{MeV} / \mathrm{c}^{2}$
$>$ For $\chi_{c 0}$ :
- $x=\left|F_{1,1}^{0} / F_{0,0}^{0}\right|=0.299 \pm 0.003 \pm 0.019$
$>$ For $\chi_{c 1}$ (statistical uncertainty only):
- $u_{1}=\left|F_{1,0}^{1} / F_{0,1}^{1}\right|=1.05 \pm 0.05$
- $u_{2}=\left|F_{1,1}^{1} / F_{1,0}^{1}\right|=0.07 \pm 0.04$
$>$ For $\chi_{c 2}$ :
- $\omega_{1}=\left|F_{0,1}^{2} / F_{0,0}^{2}\right|=1.265 \pm 0.054 \pm 0.079$
- $\omega_{2}=\left|F_{1,-1}^{2} / F_{0,0}^{2}\right|=1.450 \pm 0.097 \pm 0.104$
- $\omega_{4}=\left|F_{1,1}^{2} / F_{0,0}^{2}\right|=0.808 \pm 0.051 \pm 0.009$
$>$ Branching fractions
$\Rightarrow B\left(\chi_{c 0} \rightarrow \phi \phi\right)=(8.59 \pm 0.27 \pm 0.20) \times 10^{-4}$
$>B\left(\chi_{c 1} \rightarrow \phi \phi\right)=(4.26 \pm 0.13 \pm 0.15) \times 10^{-4}$
$>B\left(\chi_{c 2} \rightarrow \phi \phi\right)=(12.67 \pm 0.28 \pm 0.33) \times 10^{-4}$





## Helicity amplitude analysis of $\chi_{c J} \rightarrow \phi \phi$

> Discussions:

- For the decay of $\chi_{c 1}$, no evidence of identical particle symmetry breaking
- For the deday of $\chi_{c 0}$, consistent with the pQCD prediction
- For the decay of $\chi_{c 2}$, the $D \bar{D}$ loop model ruled out due to the large deviation, while the other models cannot describe the measurements, either.
- Using about 2.7 billion $\psi(3686)$ accumulated at BESIII now, more attractive results will be reported in future



## Evidence for the $\eta_{c}(2 S) \rightarrow \pi^{+} \pi^{-} \eta$ decay

- Charmonium states play an important role in understanding the strong interaction
- The knowledge about $\eta_{c}(2 S)$ is still limited [Eur. Phys. J. C 71, 1534 (2011)], suffering from the very soft photon from $\psi(3686)$ transition
- The total measured branching fraction of $\eta_{c}(2 S)$ is less than $5 \%$
- $\frac{\operatorname{Br}\left(\eta_{c}(2 S) \rightarrow h\right)}{\operatorname{Br}\left(\eta_{c} \rightarrow h\right)} \approx \frac{\operatorname{Br}(\psi(3686) \rightarrow h)}{\operatorname{Br}(/ / \psi \rightarrow h)}=0.128$, so-called '12\% rule' [Phys. Rev. D 44, 1597 (1991)], which is violated especially in the $\psi \rightarrow \rho \pi$ [Phys. Rev. Lett. 51, 963 (1983)]

| Decay Mode | Branching fraction |
| :---: | :---: |
| $\eta_{c}(2 S) \rightarrow K K \pi$ | $(1.9 \pm 1.2) \%$ |
| $\eta_{c}(2 S) \rightarrow K K \eta$ | $(5 \pm 4) \times 10^{-3}$ |
| $\eta_{c}(2 S) \rightarrow K^{+} K^{-} \pi^{+} \pi^{-} \pi^{0}$ | $(1.4 \pm 1.0) \%$ |
| $\eta_{c}(2 S) \rightarrow \gamma \gamma$ | $(1.9 \pm 1.3) \times 10^{-4}$ |

## Evidence for the $\eta_{c}(2 S) \rightarrow \pi^{+} \pi^{-} \eta$ decay

- Based on 448.1 million $\psi(3686)$ data
- $\operatorname{Br}\left(\psi(3686) \rightarrow \gamma \eta_{c}(2 S)\right) \times \operatorname{Br}\left(\eta_{c}(2 S) \rightarrow \pi^{+} \pi^{-} \eta\right)=(2.97 \pm$ $0.81 \pm 0.26) \times 10^{-6}$
- $\operatorname{Br}\left(\eta_{c}(2 S) \rightarrow \pi^{+} \pi^{-} \eta\right)=(42.4 \pm 11.6 \pm 3.8 \pm 30.3) \times$ $10^{-4}$
- The evidence for the decay $\eta_{c}(2 S) \rightarrow \pi^{+} \pi^{-} \eta$ is found for

 $\psi(3686)$


## Observation of $\psi(3770) \rightarrow \eta J / \psi$

- The conventional model for $\psi(3770)$, the lowest-mass $D$-wave charmonium state above the $D \bar{D}$ threshold [Phys. Rev. D 17, 3090 (1978)], cannot explain the measured large non-D $\bar{D}$ decay width of the state [Phys. Rev. Lett. 101, 112001 (2008)]
- Various theoretical models are developed for this puzzle
$\checkmark$ tetra-quark component [Phys. Rev. Lett. 101, 112001 (2008)]
$\checkmark 2 S-1 D$ mixing between $\psi(3686)$ [Phys. Rev. D 81, 034011 (2010)]
$\checkmark \psi(3770)$ or rescattering mechanism with $D$ mesons [Phys. Rev. D 85, 114007 (2012)]
- The only well established non- $D \bar{D}$ channel is $\psi(3770) \rightarrow \pi^{+} \pi^{-} J / \psi$ [Rev. Mod. Phys. 80, 1161-1193 (2008)]
- CLEO reports the branching fraction $\operatorname{Br}(\psi(3770) \rightarrow \eta J / \psi)=(8.7 \pm 3.3 \pm 2.2) \times 10^{-4}$ at a statistical significance of $3.5 \sigma$ without considering the interference [Phys. Rev. Lett. 96, 082004 (2006)]
- $\operatorname{Br}(\psi(3770) \rightarrow \eta J / \psi)$ is usually used as an input for the calculation of charmonium(-like) states [Phys. Rev. D 88, 014010 (2013), Phys. Rev. D 95, 114031 (2017)]

| Decay Mode | Branching fraction |
| :---: | :---: |
| $\psi(3770) \rightarrow \pi^{+} \pi^{-} J / \psi$ | $(1.93 \pm 0.28) \times 10^{-3}$ |
| $\psi(3770) \rightarrow \pi^{0} \pi^{0} J / \psi$ | $(8.0 \pm 3.0) \times 10^{-3}$ |
| $\psi(3770) \rightarrow \eta J / \psi$ | $(9 \pm 4) \times 10^{-4}$ |
| $\psi(3770) \rightarrow \phi \eta$ | $(3.1 \pm 0.7) \times 10^{-4}$ |

## Observation of $\psi(3770) \rightarrow \eta J / \psi$

- Based on $2.93 \mathrm{fb}^{-1}$ data @ 3.773 GeV
- The observed signal yield $N^{\text {obs }}=232 \pm 23$
- The Born cross section

$$
\sigma^{B}\left(e^{+} e^{-} \rightarrow \eta J / \psi\right)=\frac{N^{\mathrm{obs}}}{L \cdot\left(1+\delta^{\mathrm{ISR}}\right) \cdot\left(1+\delta^{\mathrm{VP}}\right) \cdot \varepsilon \cdot \operatorname{Br}(\eta \rightarrow \gamma \gamma) \cdot \operatorname{Br}\left(J / \psi \rightarrow \mu^{+} \mu^{-}\right)}
$$

- $\sigma^{B}\left(e^{+} e^{-} \rightarrow \eta J / \psi\right)=\left(8.88 \pm 0.87_{\text {stat }} \pm 0.42_{\text {sys }}\right) \mathrm{pb} @ 3.773 \mathrm{GeV}$




| $\mathcal{L}\left(\mathrm{pb}^{-1}\right)$ | $\varepsilon(\%)$ | $\left(1+\delta^{\mathrm{ISR}}\right) \cdot\left(1+\delta^{V P}\right)$ | $\mathcal{B}\left(J / \psi \rightarrow \mu^{+} \mu^{-}\right)(\%)$ | $\mathcal{B}(\eta \rightarrow \gamma \gamma)(\%)$ | $N^{\text {obs }}$ | $\sigma^{B}(\mathrm{pb})$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $2931 \pm 15$ | $47.8 \pm 0.1$ | 0.79 | $5.96 \pm 0.03$ | $39.4 \pm 0.2$ | $232 \pm 23$ | $8.88 \pm 0.87$ |

## Observation of $\psi(3770) \rightarrow \eta J / \psi$

- $\operatorname{Br}(\psi(3770) \rightarrow \eta J / \psi)$ is obtained by fittting to the dressed cross section of $e^{+} e^{-} \rightarrow \eta J / \psi$ from $\sqrt{s}=$ 3.773 to 4.60 GeV
- Two treatments of the $\psi(3770)$ resonant decay amplitude:
$\checkmark \psi(3770)$ is coherent with the other amplitudes:

$$
\sigma_{\mathrm{co} .}=\left|C \cdot \sqrt{\Phi(s)}+e^{i \phi_{1}} \mathrm{BW}_{\psi(3770)}+e^{i \phi_{2}} \mathrm{BW}_{\psi(4040)}+e^{i \phi_{3}} \mathrm{BW}_{Y(4230)}+e^{i \phi_{4}} \mathrm{BW}_{Y(4390)}\right|^{2}
$$

$\checkmark \psi(3770)$ is incoherent with the other amplitudes:

$$
\sigma_{\mathrm{co} .}=\left|\mathrm{BW}_{\psi(3770)}\right|^{2}+\left|C \cdot \sqrt{\Phi(s)}+e^{i \phi_{2}} \mathrm{BW}_{\psi(4040)}+e^{i \phi_{3}} \mathrm{BW}_{Y(4230)}+e^{i \phi_{4}} \mathrm{BW}_{Y(4390)}\right|^{2}
$$




## Observation of $\psi(3770) \rightarrow \eta J / \psi$

- Incoherent:
$\checkmark \operatorname{Br}(\psi(3770) \rightarrow \eta J / \psi)=\left(8.7 \pm 1.0_{\text {stat }} \pm 0.8_{\text {sys }}\right) \times 10^{-4}$, close to the result of CLEO
- Coherent:
$\checkmark$ Four solutions between $\operatorname{Br}(\psi(3770) \rightarrow \eta J / \psi)=\left(11.2 \pm 5.8_{\text {stat }} \pm 1.1_{\text {sys }}\right) \times 10^{-4}$ and $(11.6 \pm$ $\left.6.0_{\text {stat }} \pm 1.1_{\text {sys }}\right) \times 10^{-4}$
- There exists substantial interference effect, especially between $\psi(3770)$ and highly excited vector charmonium(-like) states


## Observation of the decay $\chi_{c J} \rightarrow \Omega^{-} \bar{\Omega}^{+}$

- The decays of the $P$-wave charmonium states, $\chi_{c J}(J=0,1,2)$, to baryon anti-baryon $(B \bar{B})$ have a nontrivial color-octet contribution [Phys. Lett. B 57, 407 (1975), Phys. Lett. B 57, 407 (1975)]
- Multiple models have been developed for $\chi_{c J}$ to $B \bar{B}$, including $p \bar{p}, \Lambda \bar{\Lambda}, \Sigma^{+} \bar{\Sigma}^{-}, \Sigma^{0} \bar{\Sigma}^{0}$, while none of them can describe all the final states [Phys. Lett. B 57, 407 (1975), Phys. Rev. D 81, 014017 (2010)]
- For spin $3 / 2$ baryons, only $\chi_{c J} \rightarrow \Sigma(1385)^{ \pm} \bar{\Sigma}(1385)^{\mp}$ has been studied by BESIII Collaboration [Phys. Rev. D 86, 052004 (2012)]
- The decay $\chi_{c J} \rightarrow \Omega^{-} \bar{\Omega}^{+}$is unique due to the presence of three pairs of strange quarks in the final states

| Decay Mode | Branching fraction |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | $\chi_{c 0}$ | $\chi_{c 1}$ | $\chi_{c 2}$ |  |
| $\chi_{c J} \rightarrow p \bar{p}$ | $(2.21 \pm 0.08) \times 10^{-4}$ | $(7.60 \pm 0.34) \times 10^{-5}$ | $(7.33 \pm 0.33) \times 10^{-5}$ |  |
| $\chi_{c J} \rightarrow \Lambda \bar{\Lambda}$ | $(3.59 \pm 0.15) \times 10^{-4}$ | $(1.27 \pm 0.08) \times 10^{-4}$ | $(1.83 \pm 0.16) \times 10^{-4}$ |  |
| $\chi_{c J} \rightarrow \Sigma^{0} \bar{\Sigma}^{0}$ | $(4.68 \pm 0.32) \times 10^{-4}$ | $(4.2 \pm 0.6) \times 10^{-5}$ | $(3.7 \pm 0.6) \times 10^{-5}$ |  |
| $\chi_{c J} \rightarrow \Sigma^{+} \bar{\Sigma}^{-}$ | $(4.6 \pm 0.8) \times 10^{-4}$ | $(3.6 \pm 0.7) \times 10^{-5}$ | $(3.4 \pm 0.7) \times 10^{-5}$ |  |
| $\chi_{c J} \rightarrow \Sigma^{-} \bar{\Sigma}^{+}$ | $(5.1 \pm 0.5) \times 10^{-4}$ | $(5.7 \pm 1.5) \times 10^{-5}$ | $(4.4 \pm 1.8) \times 10^{-5}$ |  |
| $\chi_{c J} \rightarrow \Xi^{0} \bar{\Xi}^{0}$ | $(3.1 \pm 0.8) \times 10^{-4}$ | $<6 \times 10^{-5}$ | $<1.0 \times 10^{-4}$ |  |
| $\chi_{c J} \rightarrow \Xi^{-} \bar{\Xi}^{+}$ | $(4.8 \pm 0.7) \times 10^{-4}$ | $(8.0 \pm 2.1) \times 10^{-5}$ | $(1.42 \pm 0.32) \times 10^{-4}$ |  |

## Observation of the decay $\chi_{c J} \rightarrow \Omega^{-} \bar{\Omega}^{+}$

- Based on 2.708 billion $\psi(3686)$ data
- Signal yield is obtained by fitting to the recoil mass spectrum of the radiative photon ( $R M_{\gamma}$ )

$$
\operatorname{Br}\left(\chi_{c J} \rightarrow \Omega^{-} \bar{\Omega}^{+}\right)=\frac{N_{\chi_{c J}}^{\text {obs }}}{N_{\psi(3686)} \cdot \operatorname{Br}\left(\psi(3686) \rightarrow \gamma \chi_{c J}\right) \cdot \varepsilon}
$$

- Measured $\operatorname{Br}\left(\chi_{c J} \rightarrow \Omega^{-} \bar{\Omega}^{+}\right)$is one order of magnitude smaller than other $B \bar{B}$ channels. Useful to investigate the helicity selection rule evading mechanism in $\chi_{c 0}$ decays
- Used to probe the spin polarization of $\Omega^{-}$baryon in the charmonium production at the future tau-charm factories [arxiv: 2303.15790]

| Mode | $N_{\chi_{c J}}^{\text {obs }}$ | $\epsilon_{\chi_{c J}}(\%)$ | Sig. $(\sigma)$ | $\mathcal{B}\left(\times 10^{-5}\right)$ |
| :--- | :---: | :---: | :---: | :---: |
| $\chi_{c 0}$ | $284 \pm 44$ | 3.05 | 5.6 | $3.51 \pm 0.54$ |
| $\chi_{c 1}$ | $277 \pm 42$ | 7.02 | 6.4 | $1.49 \pm 0.23$ |
| $\chi_{c 2}$ | $1038 \pm 56$ | 8.91 | 18 | $4.52 \pm 0.24$ |



## Summary

$>$ Helicity amplitude analysis of $\chi_{c J} \rightarrow \phi \phi$ [JHEP 05, 069 (2023)]

- Present models is tested by the ratio of helicity amplitudes
- The branching fractions of $\chi_{c J} \rightarrow \phi \phi$ is measured
$>$ Evidence for the $\eta_{c}(2 S) \rightarrow \pi^{+} \pi^{+} \eta$ decay [Phys.Rev.D 107 (2023) 5, 052007]
- The evidence of the decay $\eta_{c}(2 S) \rightarrow \pi^{+} \pi^{+} \eta$ is found for the first time with a statistical significance of $3.5 \sigma$
$>$ Observation of $\psi(3770) \rightarrow \eta J / \psi$ [Phys.Rev.D 107 (2023) 9, L091101]
- The Born cross section of $e^{+} e^{-} \rightarrow \eta J / \psi$ is measured at $\sqrt{s}=3.773 \mathrm{GeV}$
- The branching fraction of $\psi(3770) \rightarrow \eta J / \psi$ is measured in two cases associated with interference
$>$ Observation of the decay $\chi_{c J} \rightarrow \Omega^{-} \bar{\Omega}^{+}$[Phys.Rev.D 107 (2023) 9, 092004]
- The decay $\chi_{c J} \rightarrow \Omega^{-} \bar{\Omega}^{+}$is observed and measured for the first time


## Outlook

$>$ BESIII has accumulated about 2.7 billion $\psi(3686)$ data in 2009, 2012 and 2021, the largest dataset around the world now
$>$ The following topics will be further studied at BESIII
$\checkmark$ The transtion between low-lying charmonium states $\left(\psi(3686) \rightarrow \eta_{c} / \eta_{c}(2 S), \psi(3686) \rightarrow \chi_{c J} \ldots\right)$
$\checkmark$ The decays of charonia into light hadrons
$\checkmark$ The precise validation of the calculation of non-perturbative QCD, such QCD sum rules and lattice QCD
$\checkmark$ Study on the light hadron spectroscopy
$\checkmark$ Search for the rare decays of charmonia, leptonic, semi-leptonic, invisible...
$\checkmark$ Constrain the new physics models related with axion, dark matter...

# Thank you ! 

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