***11th International Workshop on Charm Physics (CHARM 2023)***

# Study $\chi_{cJ}$ and ψ decays @ BESIII


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BESIII

# Outline

- **Introduction**
  - ✓ Physics motivation
  - ✓ BESIII experiment
- **Recent Physics Highlights on $\chi_{cJ}$ and $\psi$ decays**
  - Measurement of $B(\psi(3686) \to \phi K_S^0 K_S^0)$
  - Helicity amplitude analysis of $\chi_{cJ} \to \phi\phi$
  - Observation of $\chi_{cJ} \to \Omega^- \bar{\Omega}^+$
  - Observation of $\psi(3770) \to \eta J/\psi$
- **Summary**

# Physics Motivation


❖ The decays of J/ψ and ψ(3686) to hadronic final states are used to test the "12% rule".

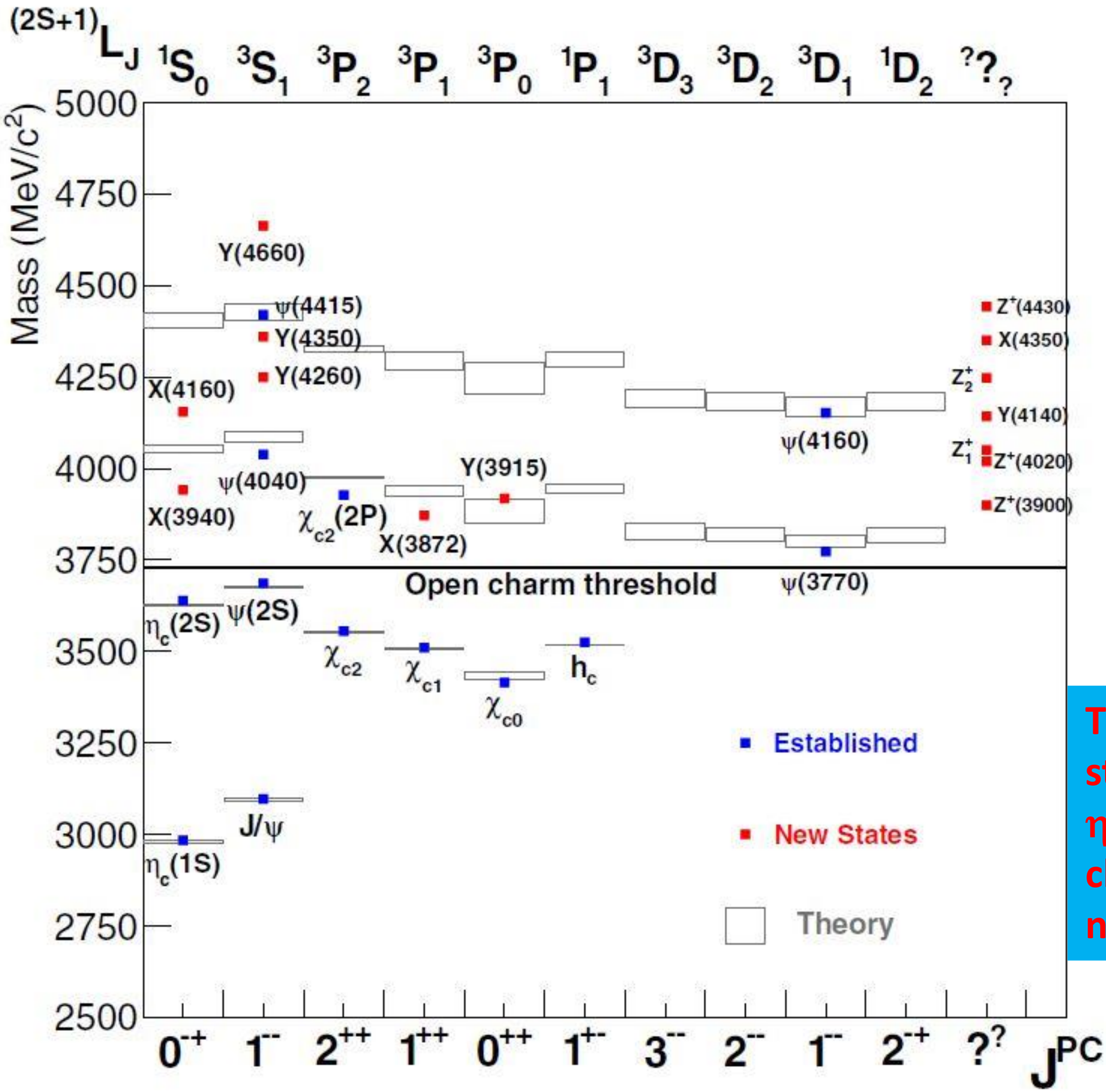
$$Q_h = \frac{\mathcal{B}_{\psi(3686)\to h}}{\mathcal{B}_{J/\psi\to h}} \approx \frac{\mathcal{B}_{\psi(3686)\to e^+e^-}}{\mathcal{B}_{J/\psi\to e^+e^-}} \approx 13.3\%$$

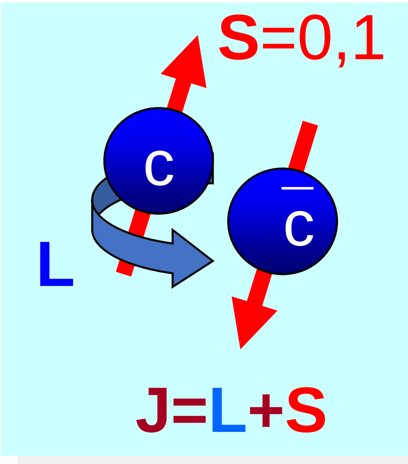
❖ The baryon/meson pair decays of $\chi_{c0,1,2}$ are essential to test pQCD, e.g. helicity selection rule (HSR) . In addition, it is used to test color-octet mechanism (COM).

❖ The search of ψ(3770) non-DD decay modes is helpful to understand not only the properties of ψ(3770) and ψ(3686), e.g., 2S-1D mixing, but also for exotic charmoniumlike (XYZ) states.

Kind reminder: $\psi(3686) \equiv \psi(2S) \equiv \psi'$

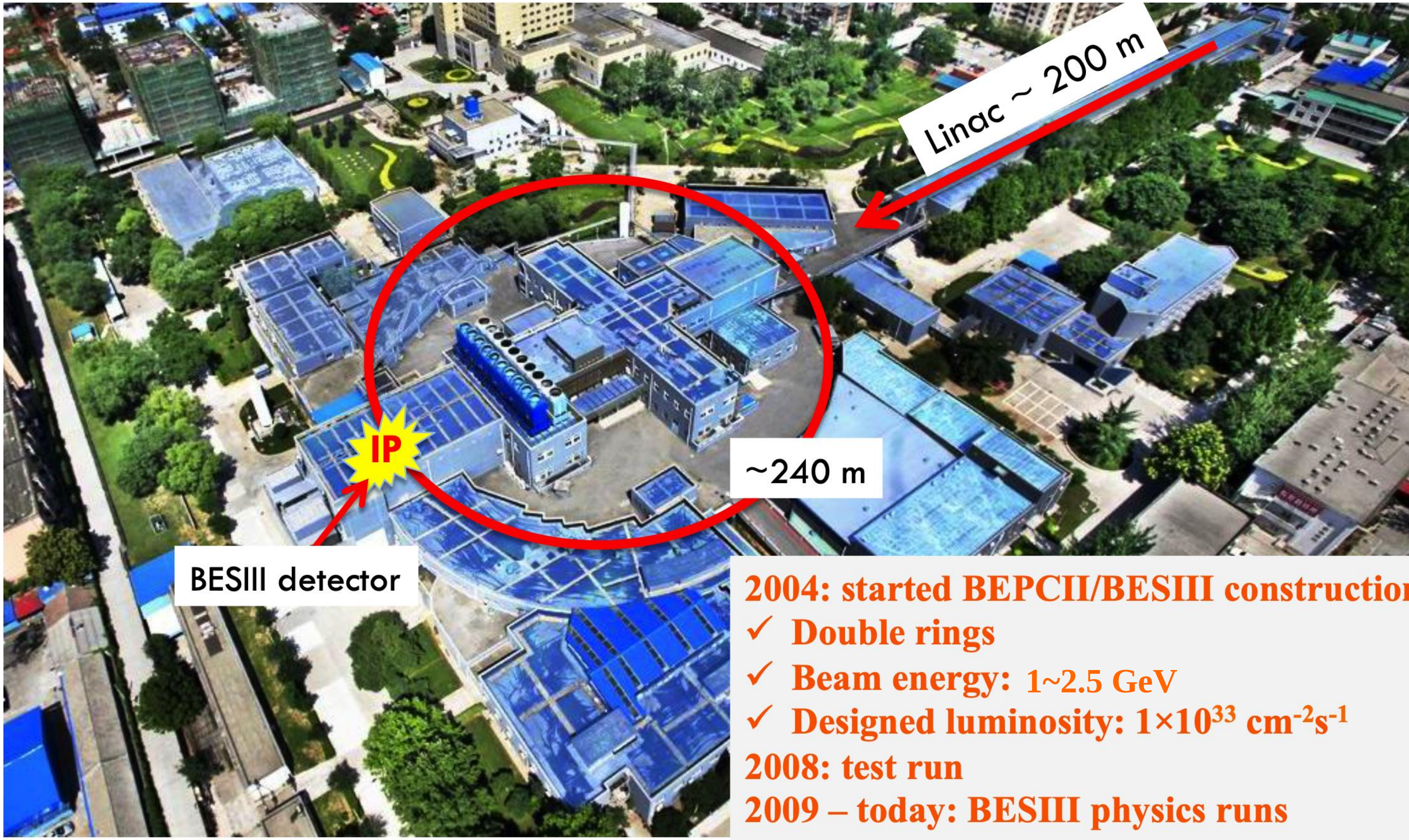
# Charmonium Spectrum




**Traditional charmonium states are named as $\eta_c$,ψ,$h_c$,$\chi_c$…… charmoniumlike states are named with “XYZ” states,**

# BEPCII

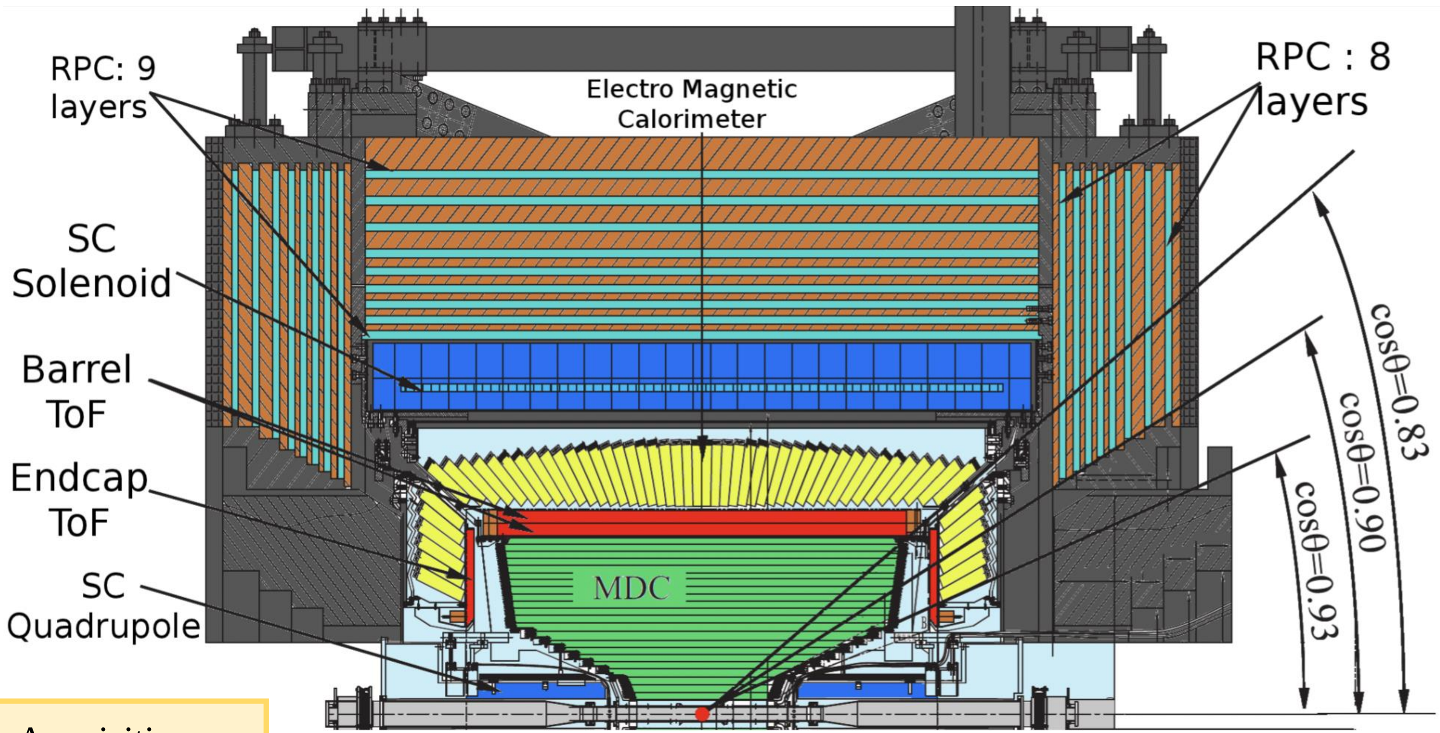



**2004: started BEPCII/BESIII construction**
- ✓ **Double rings**
- ✓ **Beam energy: 1~2.5 GeV**
- ✓ **Designed luminosity: $1\times10^{33}$ $cm^{-2}s^{-1}$**

**2008: test run**
**2009 – today: BESIII physics runs**

# BESIII Detector

Nucl. Instr. Meth. A614, 345 (2010)




Data Acquisition:
Event rate = 3 kHz
Throughput ~ 50 MB/s

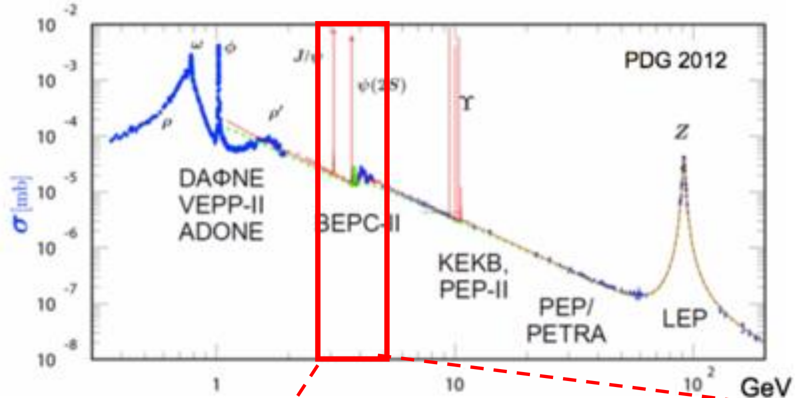
Drift Chamber
$\sigma_{r\varphi}$ ~ 130 μm (single wire)
$\sigma_{p_t}/p_t$ ~ 0.5 % @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E$ < 2.5% @ 1 GeV (barrel)
$\sigma_E/E$ < 5% @ 1 GeV (end caps)
$\sigma_{xy}$ ~ (6 mm)/$E^{1/2}$ @ 1 GeV

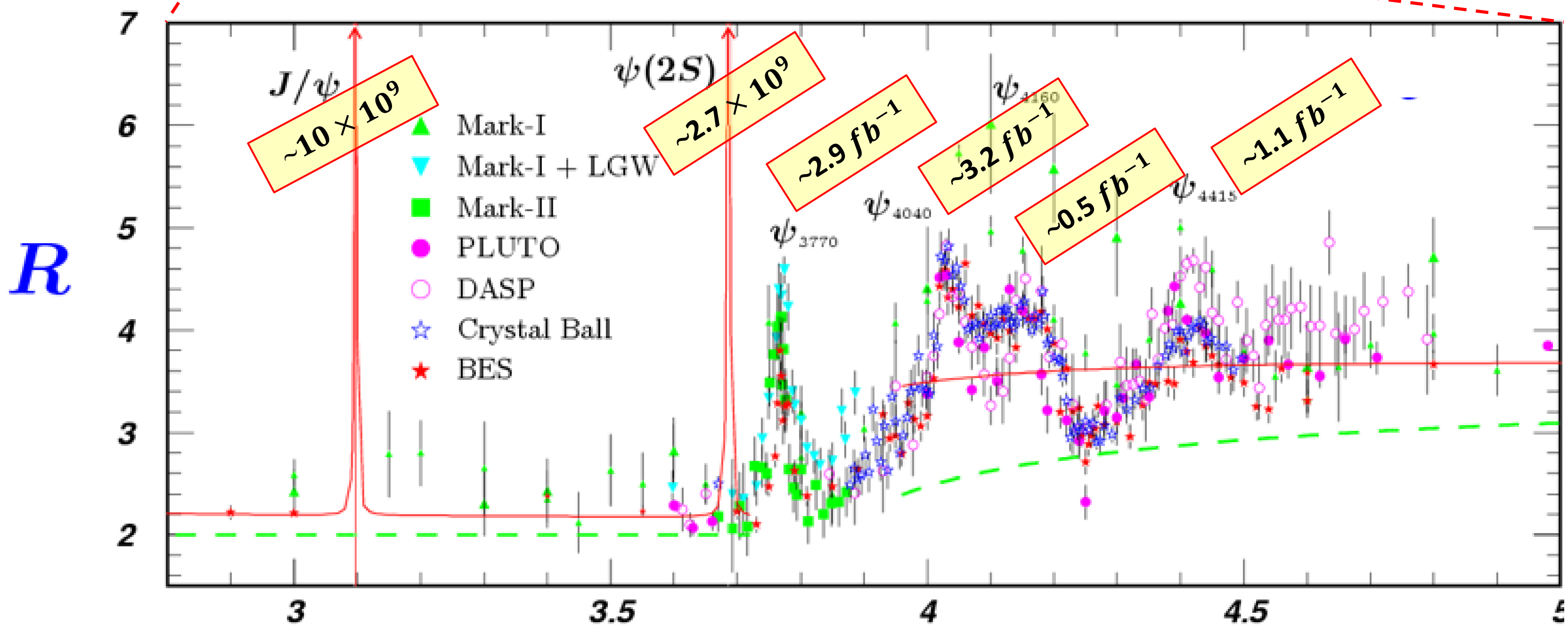
ToF
$\sigma_t$ ~ 68 ps (barrel)
$\sigma_t$ ~ 60ps (end caps)

RPC Muon Counter
$\Delta\Omega/4\pi$=93%

# BESIII Data Collections




- ✓ BESIII detector has collected the largest data samples in the $\psi$ energy region in the world.
- ✓ ~30% of $\psi(3686)$ produces $\chi_{cJ}$ in its EM radiative transition decay.



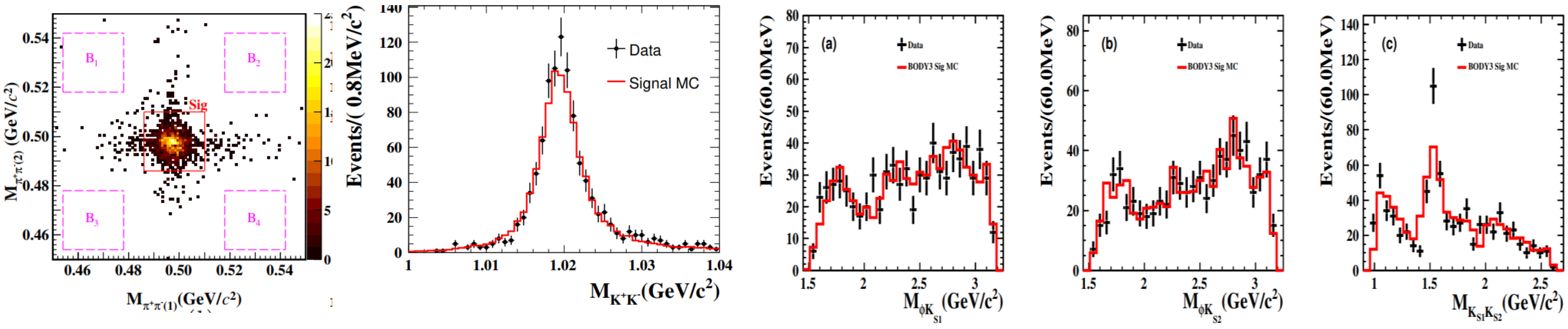
# Recent Physics Highlights on $\chi_{cJ}$ and $\psi$ decays

- Measurement of B[$\psi(3686) \to \phi K_S^0 K_S^0$]
- Helicity amplitude analysis of $\chi_{cJ} \to \phi\phi$
- Observation of $\chi_{cJ} \to \Omega^-\overline{\Omega}^+$
- Observation of $\psi(3770) \to \eta J/\psi$

# Measurement of $B[\psi(3686) \to \phi K_S^0 K_S^0]$

➤ Test the known "12% rule"

**submit to PRD, arXiv: 2303.08317**




- The QED background is investigated using the continuum data @3.65 GeV by luminosity normalization. It is determined to be $\overline{N}_{QED} = 108 \pm 5$
- The interference between ψ(3686) and continuum production is considered by fitting to the cross section around ψ(3686). The number of events due to interference is determined to be $N_{inter} = 228 \pm 24$

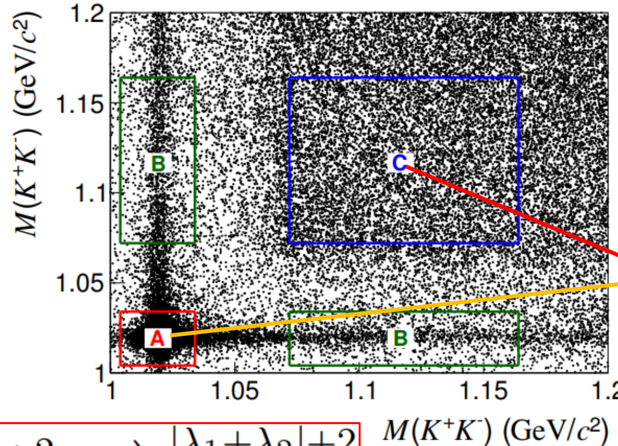
$$\mathcal{B}_{\psi(3686)\to\phi K_S^0 K_S^0} = \frac{N_{\rm net}^{\psi(3686)} - \overline{N}_{\rm QED} - N_{\rm inter}}{N_{\psi(3686)} \cdot \varepsilon \cdot \mathcal{B}_{\phi\to K^+K^-} \cdot \mathcal{B}^2_{K_S^0\to\pi^+\pi^-}} = (3.53 \pm 0.20 \pm 0.21) \times 10^{-5}$$

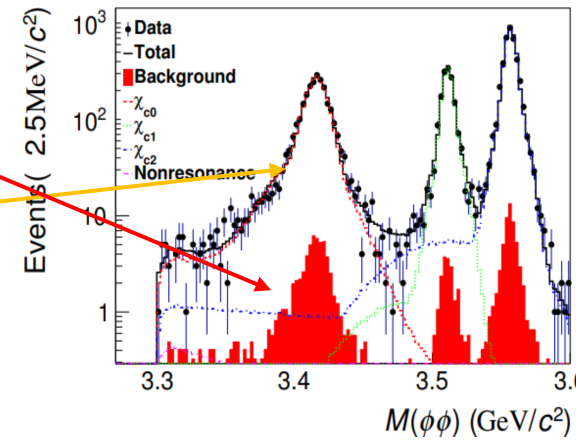
$Q_{\psi(3686)\to\phi K_S^0 K_S^0} = (6.0 \pm 1.6)\%$, which is suppressed relative to "12% rule"

# Helicity amplitude analysis of $\chi_{cJ} \to \phi\phi$ (1)

**JHEP05, (2023) 069**

- The asymptotic behavior of the BF of charmonium state $\psi(\lambda)$ decaying into light hadron $h_1(\lambda_1)$ and $h_2(\lambda_2)$ is evaluated in pQCD calculation

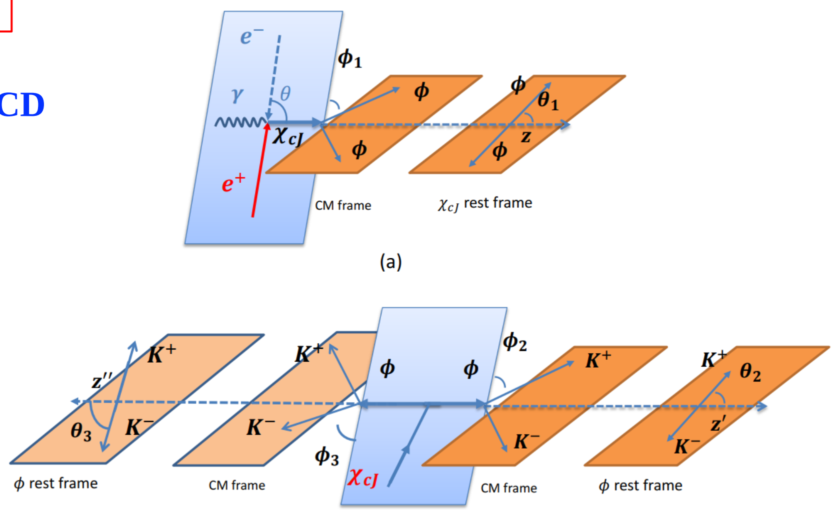



$$\mathcal{B}[\psi(\lambda) \to h_1(\lambda_1)h_2(\lambda_2)] \sim \left(\frac{\Lambda^2_{\text{QCD}}}{m_c^2}\right)^{|\lambda_1+\lambda_2|+2}$$

where, $\lambda$ denotes the helicity of hadrons, $\Lambda_{\text{QCD}}$ denotes the QCD scale parameter

- The $\chi_{c1}$ decay rate is suppressed relative to $\chi_{c0,2}$ due to helicity selection rule (HSR) according to pQCD prediction, which is not consistent with the experimental measurement.

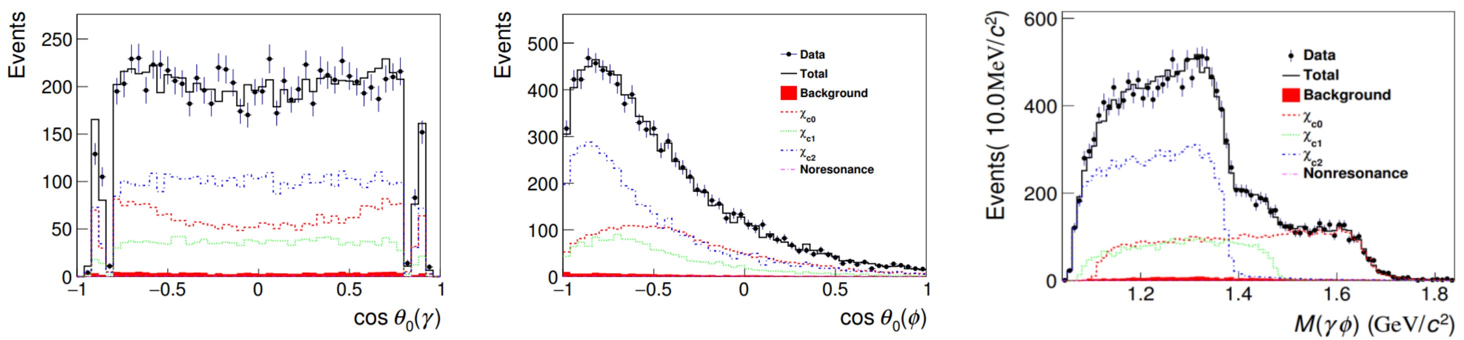



Definitions of helicity angle

# Helicity amplitude analysis of $\chi_{cJ} \to \phi\phi$ (2)

| Decay Mode | Helicity Angle | Amplitude |
|---|---|---|
| $\psi(3686)(M) \to R_i(\lambda_R)\ \gamma(\lambda_\gamma)$ | $\theta_0$ | $A^1_{\lambda_\gamma,\lambda_R}\ D^{1*}_{M,\lambda_R-\lambda_\gamma}(0,\theta_0,0)$ |
| $R_i(\lambda_R) \to \phi(\lambda_1)\phi(\lambda_2)$ | $\theta_1,\phi_1$ | $F^J_{\lambda_1,\lambda_2}\ D^{J*}_{\lambda_R,\lambda_1-\lambda_2}(\phi_1,\theta_0,0)$ |
| $\phi(\lambda_1) \to K^+(0^-)\ K^-(0^-)$ | $\theta_2,\phi_2$ | $B^1_{0,0}\ D^{1*}_{\lambda_1,0}(\phi_2,\theta_2,0)$ |
| $\phi(\lambda_2) \to K^+(0^-)\ K^-(0^-)$ | $\theta_3,\phi_3$ | $B^1_{0,0}\ D^{1*}_{\lambda_2,0}(\phi_3,\theta_3,0)$ |

**Table 2.** Definitions of helicity angles and amplitudes of sequential decays.




For $\chi_{c1} \to \phi\phi$, the ratios of amplitude moduli (T/L) are determined to be

$$u_1 = |F^1_{1,0}/F^1_{0,1}| = 1.05 \pm 0.05 \text{ and } u_2 = |F^1_{1,1}/F^1_{1,0}| = 0.07 \pm 0.04.$$

The results are consistent with the expectation of identical particle symmetry and parity conservation.

# Helicity amplitude analysis of $\chi_{cJ} \to \phi\phi$ (3)

**For $\chi_{c0}$** → $|F^0_{1,1}| / |F^0_{0,0}| = 0.299 \pm 0.003 \pm 0.019$

**For $\chi_{c2}$** →

$$|F^2_{0,1}| / |F^2_{0,0}| = 1.265 \pm 0.054 \pm 0.079,$$
$$|F^2_{1,-1}| / |F^2_{0,0}| = 1.450 \pm 0.097 \pm 0.104,$$
$$|F^2_{1,1}| / |F^2_{0,0}| = 0.808 \pm 0.051 \pm 0.009,$$

| Decay Mode | 2011 BESIII [8] | this work | PDG value [22] |
|---|---|---|---|
| $\mathcal{B}[\chi_{c0} \to \phi\phi](\times 10^{-4})$ | 7.8±0.4±0.8 | $8.59 \pm 0.27 \pm 0.20$ | 8.0±0.7 |
| $\mathcal{B}[\chi_{c1} \to \phi\phi](\times 10^{-4})$ | 4.1±0.3±0.5 | $4.26 \pm 0.13 \pm 0.15$ | 4.2±0.5 |
| $\mathcal{B}[\chi_{c1} \to \phi\phi](\times 10^{-4})$ | 10.7±0.4±1.2 | $12.67 \pm 0.28 \pm 0.33$ | 10.6±0.9 |

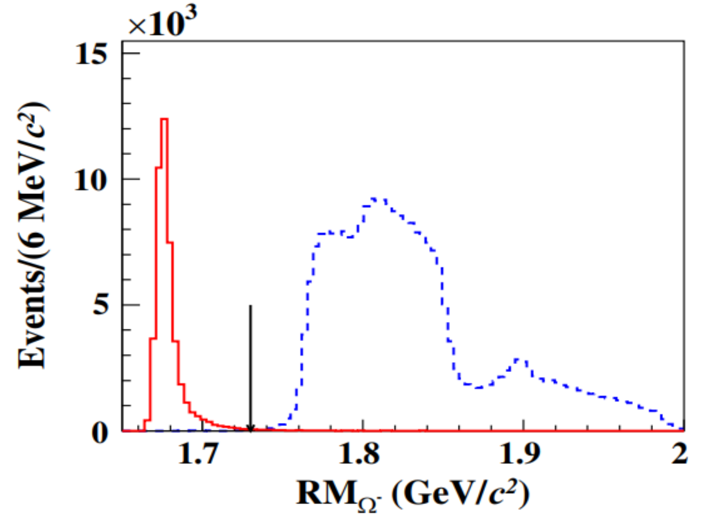
**Table 6.** Comparsion of measured branching fractions ($\mathcal{B}$).

**This measurements are the most precise!**

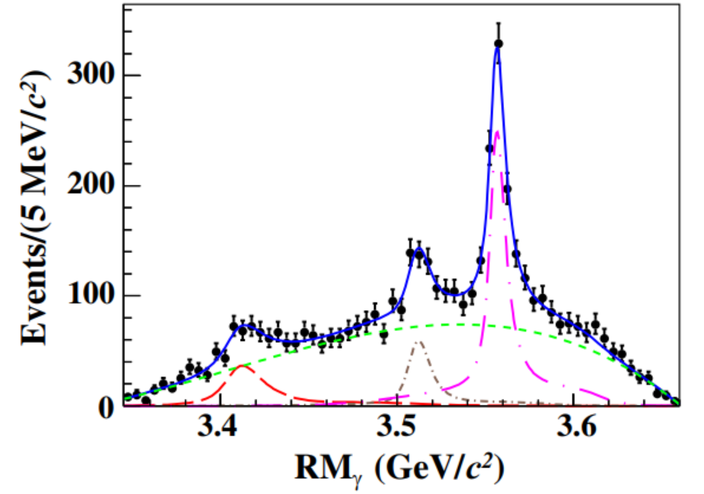
# Observation of $\chi_{cJ} \to \Omega^- \bar{\Omega}^+$

PRD 107, 092004 (2023)

- This decay is unique due to the presence of three pairs of strange quarks in the final state.
- $\Omega$ is the only baryon of the ground-state decuplet decaying through weak interaction. Therefore, it has a long lifetime.
- Single baryon reconstruction technique is applied to enhance the detection efficiency. i.e., we reconstruct $\Omega^-$, and $\bar{\Omega}^+$ is tagged by the recoil mass.

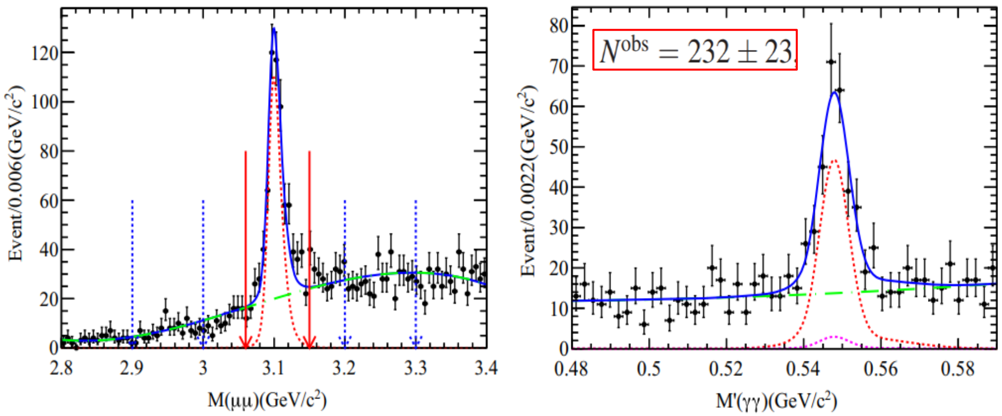


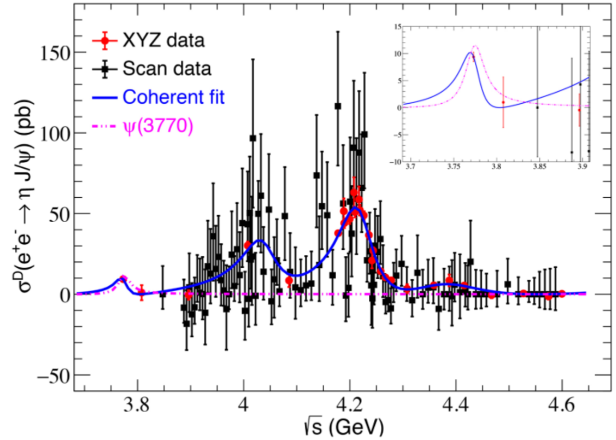

| Mode | $N^{obs}_{\chi_{cJ}}$ | $\epsilon_{\chi_{cJ}}$ (%) | Sig.($\sigma$) | $\mathcal{B}(\times 10^{-5})$ |
|---|---|---|---|---|
| $\chi_{c0}$ | $284 \pm 44$ | 3.05 | 5.6 | $3.51 \pm 0.54$ |
| $\chi_{c1}$ | $277 \pm 42$ | 7.02 | 6.4 | $1.49 \pm 0.23$ |
| $\chi_{c2}$ | $1038 \pm 56$ | 8.91 | 18 | $4.52 \pm 0.24$ |




- The measured $\chi_{c0}$ decay branching fraction is obviously small than those decaying into with spin ½ and 3/2.

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

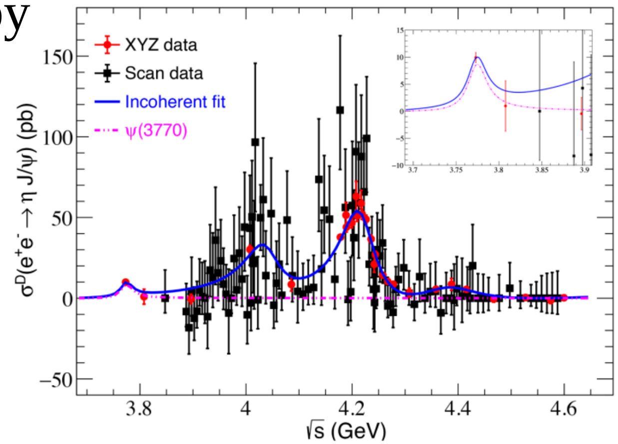



- The Born cross section at 3.773 GeV is determined by

$$\sigma^B(e^+e^- \to \eta J/\psi) = \frac{N^{\text{obs}}}{\mathcal{L}\cdot(1+\delta^{\text{ISR}})\cdot(1+\delta^{\text{VP}})\cdot\varepsilon\cdot\mathcal{B}r},$$

$$= (8.88 \pm 0.87_{stat} \pm 0.42_{sys.})\ \text{pb}$$




$\mathcal{B}(\psi(3770) \to \eta J/\psi) = (8.7 \pm 1.0_{stat} \pm 0.8_{sys.}) \times 10^{-4}$

is determined by the global fit to line-shape without considering the interference with the other processes, which is close to CLEO's result.

- **If consider the interference,** the BF varies between $\mathbf{11.2 \pm 5.8_{stat} \pm 1.1_{sys.}) \times 10^{-4}}$ to $\mathbf{11.6 \pm 6.0_{stat} \pm 1.1_{sys.}) \times 10^{-4}}$

**PRD 107, L091101 (2023)**

- The statistical significance is above **7σ** whether the interference is considered or not

# Summary

- The branching fraction of $\psi(3686) \to \phi K_S^0 K_S^0$ is observed for the first time, and the ratio $\mathcal{B}(\psi(3686) \to \phi K_S^0 K_S^0)/\mathcal{B}(J/\psi \to \phi K_S^0 K_S^0)$ is found to be suppressed relative to "12% rule".
- The branching fractions for $\chi_{cJ} \to \phi\phi$ are significantly improved, and the corresponding polarization parameters are measured for the first time.
- $\chi_{cJ} \to \Omega^- \bar{\Omega}^+$ are firstly observed and the corresponding branching fractions are measured.
- A new non-DD decay mode, $\psi(3770) \to \eta J/\psi$, is confirmed, and the corresponding branching fraction is measured with and without considering the interference.
- Much more results will be presented in the future.

**Thank you!**

# Backup

# $\psi(3686) \to \phi K_S^0 K_S^0$

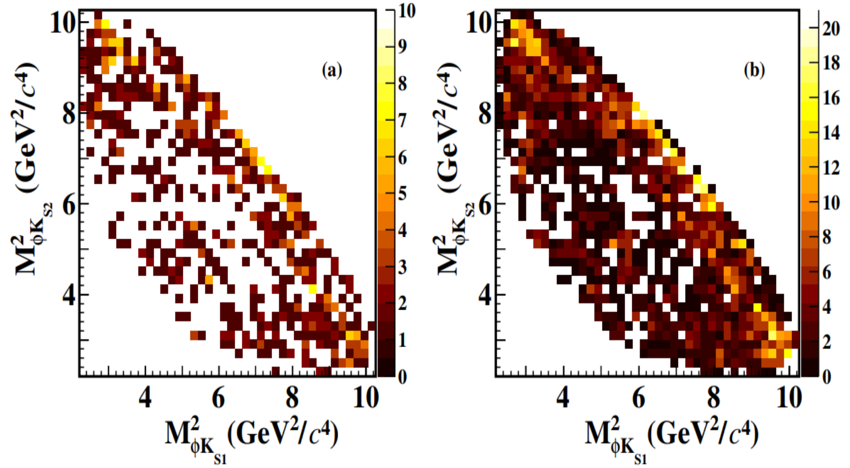
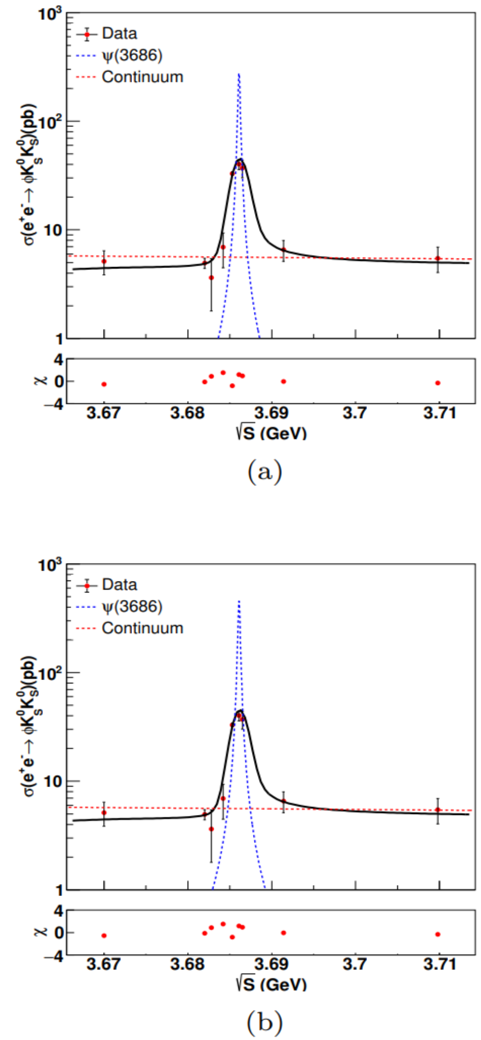



FIG. 3. Dalitz plots of $M^2_{\phi K^0_{S1}}$ vs. $M^2_{\phi K^0_{S2}}$ for the accepted candidates in (a) data and (b) BODY3 signal MC events.




$$\sigma^{\text{dressed}}(s) = |A_{\text{cont}}(s) + A_{\text{res}}(s) \times e^{i\varphi}|^2$$

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

Then the joint amplitude for the sequential process is obtained by

$$\mathcal{M}(R_i) = \frac{1}{2} \sum_{M,\lambda_R,\lambda_1,\lambda_2} A^1_{\lambda_R,\lambda_\gamma} D^{1*}_{M,\lambda_R-\lambda_\gamma}(0,\theta_0,0) F^J_{\lambda_1,\lambda_2} D^{J*}_{\lambda_R,\lambda_1-\lambda_2}(\phi_1,\theta_0,0)$$
$$\times B^1_{0,0} D^{1*}_{\lambda_1,0}(\phi_2,\theta_2,0) B^1_{0,0} D^{1*}_{\lambda_2,0}(\phi_3,\theta_3,0) BW(m_{\phi\phi}, m_i, \Gamma_i),$$

# $\psi(3770) \to \eta J/\psi$

$$\sigma_{\rm co} = |C \cdot \sqrt{\Phi(s)} + e^{i\phi_1}{\rm BW}_{\psi(3770)} + e^{i\phi_2}{\rm BW}_{\psi(4040)} + e^{i\phi_3}{\rm BW}_{Y(4230)} + e^{i\phi_4}{\rm BW}_{Y(4390)}|^2,$$

$$\sigma_{\rm inco} = |{\rm BW}_{\psi(3770)}|^2 + |C \cdot \sqrt{\Phi(s)} + e^{i\phi_2}{\rm BW}_{\psi(4040)} + e^{i\phi_3}{\rm BW}_{Y(4230)} + e^{i\phi_4}{\rm BW}_{Y(4390)}|^2.$$

TABLE III. Fitting results of the $e^+e^- \to \eta J/\psi$ decay. The uncertainties on the branching fractions and $\phi$ are statistical and systematic. The $C_0$ of the four solutions in the coherent fit are the same.

| | Coherent fit | | | | |
|---|---|---|---|---|---|
| Parameters | Solution1 | Solution2 | Solution3 | Solution4 | Incoherent fit |
| $M_1$(MeV/$c^2$) | 3773.7 (fixed) | | | | 3773.7 (fixed) |
| $\Gamma_1$(MeV) | 27.2 (fixed) | | | | 27.2 (fixed) |
| $C_0$ | $13.3 \pm 1.9$ | | | | $11.0 \pm 1.6$ |
| $\mathcal{B}r_1(\times 10^{-4})$ | $11.3 \pm 5.9 \pm 1.1$ | $11.6 \pm 6.0 \pm 1.1$ | $11.2 \pm 5.8 \pm 1.1$ | $11.5 \pm 6.0 \pm 1.1$ | $8.7 \pm 1.0 \pm 0.8$ |
| $\phi_1$(rad) | $3.9 \pm 0.6 \pm 0.07$ | $4.2 \pm 0.6 \pm 0.09$ | $3.7 \pm 0.6 \pm 0.05$ | $4.1 \pm 0.6 \pm 0.08$ | |

# $\psi(3770) \to \eta J/\psi$

TABLE IV. Relative systematic uncertainties in percent on the branching fraction of $\psi(3770) \to \eta J/\psi$.

| | Coherent fit | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Solution1 | | Solution2 | | Solution3 | | Solution4 | | Incoherent fit |
| Source | $Br$ | $\phi$ | $Br$ | $\phi$ | $Br$ | $\phi$ | $Br$ | $\phi$ | $Br$ |
| Center-of-mass energy | 3.3 | 0.2 | 3.5 | 0.1 | 3.4 | 0.1 | 3.2 | 0.2 | 2.1 |
| Energy spread | 0.8 | 0.1 | 0.9 | 0.1 | 0.9 | 0.1 | 0.8 | 0.1 | 1.0 |
| $\psi(3770)$ mass | 1.5 | 0.1 | 1.4 | 0.1 | 1.5 | 0.1 | 1.4 | 0.1 | 0.9 |
| $\psi(3770)$ width | 4.2 | 0.1 | 4.2 | 0.1 | 4.1 | 0.1 | 4.1 | 0.1 | 3.6 |
| $\psi(3770)\Gamma_{e^+e^-}$ | 6.9 | | 6.9 | | 6.9 | | 6.9 | | 6.9 |
| $\psi(4040)$ mass | 0.5 | 0.4 | 0.2 | 0.1 | 0.4 | 0.3 | 0.3 | 0.1 | 0.4 |
| $\psi(4040)$ width | 0.7 | 0.3 | 1.0 | 0.8 | 1.1 | 0.5 | 0.8 | 0.8 | 0.7 |
| Continuum term | 0.9 | 1.8 | 0.9 | 2.0 | 0.9 | 1.3 | 1.0 | 1.6 | 1.3 |
| Correlated systematic uncertainties | 3.0 | | 3.0 | | 3.0 | | 3.0 | | 3.0 |
| Uncorrelated systematic uncertainties | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 2.0 | 0.5 | 0.1 |
| Total | 9.5 | 1.9 | 9.5 | 2.2 | 9.5 | 1.4 | 9.6 | 1.9 | 8.8 |