# Studies of Charmonium at BESIII

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**Charm2015, May 18-22, Wayne State University, Detroit**

# Introduction

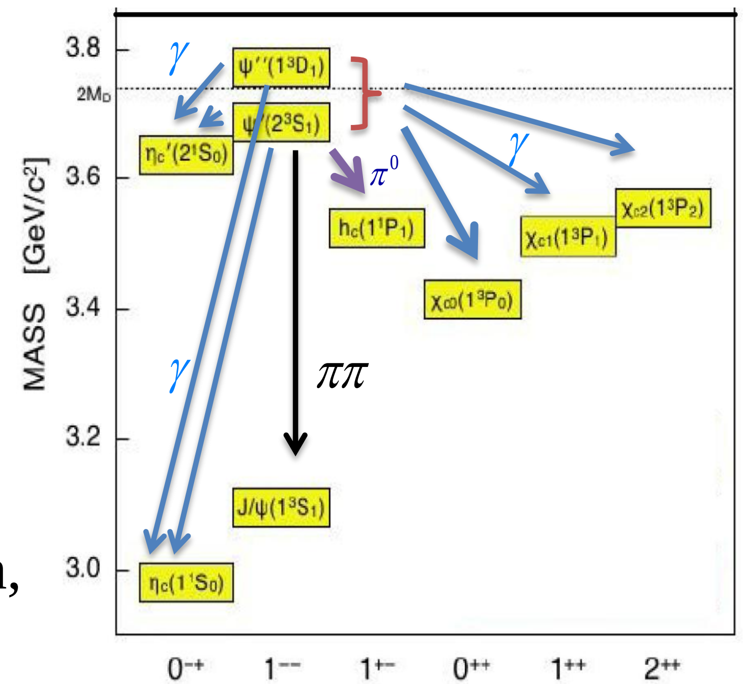
- Vector charmonium data sets

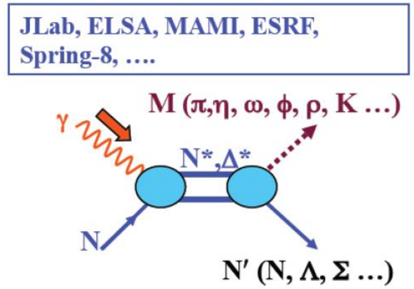
| Vector charmonium | Previous data | BESIII now | Goal |
|---|---|---|---|
| $J/\psi$ | BESII: 58 M | 1.2B(20×BESII) | 10 B |
| $\psi(3686)$ | CLEO: 28 M | 0.5B(20×CLEO) | 3 B |
| $\psi(3770)$ | CLEO: 0.8 fb$^{-1}$ | 2.9fb$^{-1}$(3.5×CLEO) | 20 fb$^{-1}$ |

- $\eta_c, \eta_c(2S), \chi_{cJ}$ are available via $\gamma$ transition, and $h_c$ available via pion transiton.

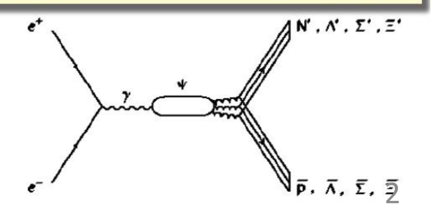
- charmonium physics
  - $\rho\pi$ puzzle, and violation of the 12% rule
  - non-$D\bar{D}$ decays of $\psi(3770)$
  - light hadron structure and properties

- rare decays: $J/\psi \to \gamma\gamma,\ \gamma\phi,\ \phi\pi^0$




$J/\psi(\psi') \to \bar{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*$



# Search for $\psi(3770)$ decays to light hadrons

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- $\psi(3770)$ decays are dominated by DD mode

$$\text{PDG 2014: } Br[\psi(3770) \to D\bar{D}] = 93^{+8}_{-9}\%$$

- Non DD decay measurements

$$Br[\psi(3770) \to \text{light hadrons}] =$$

$(14.7 \pm 3.2)\%$ : BESII: Phys. Lett. B641, 145 (2006)

$(-3.3 \pm 1.4^{+6.6}_{-1.8})$ : CLEO: Phys. Rev. Lett., 96, 092002 (2006)

- NRQCD calculation yields upper limits of 5% for light hadron decays (PRL101, 112001), while other phenomenological model, e.g., hadron loops give large fractions(PRL102, 172001).

- Searchers for the exclusive non-DD decays are desirable, such as the radiative and light hadron decays.

- Using 2.9 $fb^{-1}$ taken at 3.773 GeV.
- Continuum backgrounds are subtracted using 44 $pb^{-1}$ data taken at 3.65 GeV.
- No significant events are observed .

| Mode $f$ | $N^f_{obs}$ (3.773) | $N^f_{B}$ (3.773) | $N^f_{obs}$ (3.650) | $N^f_{B}$ (3.650) | $f^{3.773}_{co}$ | $\mathcal{B}_{\psi(3770)\to f}$ [$\times 10^{-4}$] | $\mathcal{B}^{up}$ [$\times 10^{-4}$] |
|---|---|---|---|---|---|---|---|
| $\Lambda\bar{\Lambda}\pi^+\pi^-$ | $844.0 \pm 33.6$ | 5.2 | $14.2^{+5.6}_{-4.2}$ | 0.1 | 45.27 | $1.80^{+1.74}_{-2.30} \pm 0.40$ | $<4.7$ |
| $\Lambda\bar{\Lambda}\pi^0$ | $124.9 \pm 14.4$ | 3.4 | $7.1^{+5.0}_{-2.2}$ | 0.0 | 42.50 | $-1.28^{+0.67}_{-1.51} \pm 0.15$ | $<0.7$ |
| $\Lambda\bar{\Lambda}\eta$ | $74.0 \pm 9.5$ | 0.9 | $3.0^{+3.6}_{-1.6}$ | 0.0 | 44.76 | $-1.22^{+1.44}_{-3.21} \pm 0.19$ | $<1.9$ |
| $\Sigma^+\bar{\Sigma}^-$ | $100.5 \pm 11.9$ | 0.7 | $3.3^{+4.3}_{-1.7}$ | 0.1 | 38.27 | $-0.21^{+0.63}_{-1.56} \pm 0.05$ | $<1.0$ |
| $\Sigma^0\bar{\Sigma}^0$ | $43.5 \pm 6.7$ | 0.0 | $0.0^{+2.2}_{-0.0}$ | 0.0 | 38.69 | $0.30^{+0.05}_{-0.58} \pm 0.05$ | $<0.4$ |
| $\Xi^-\bar{\Xi}^+$ | $48.5 \pm 7.0$ | 0.0 | $0.5^{+2.8}_{-1.4}$ | 0.0 | 41.74 | $0.31^{+0.66}_{-1.32} \pm 0.05$ | $<1.5$ |
| $\Xi^0\bar{\Xi}^0$ | $43.5 \pm 6.6$ | 1.3 | $2.0^{+3.2}_{-1.2}$ | 0.0 | 40.13 | $-0.80^{+1.03}_{-2.72} \pm 0.14$ | $<1.4$ |

**PRD 87, 112011 (2013)**

# $\psi(3770)\to\gamma\eta_c,\ \gamma\eta_c(2S)\to\gamma K_S^0 K\pi$

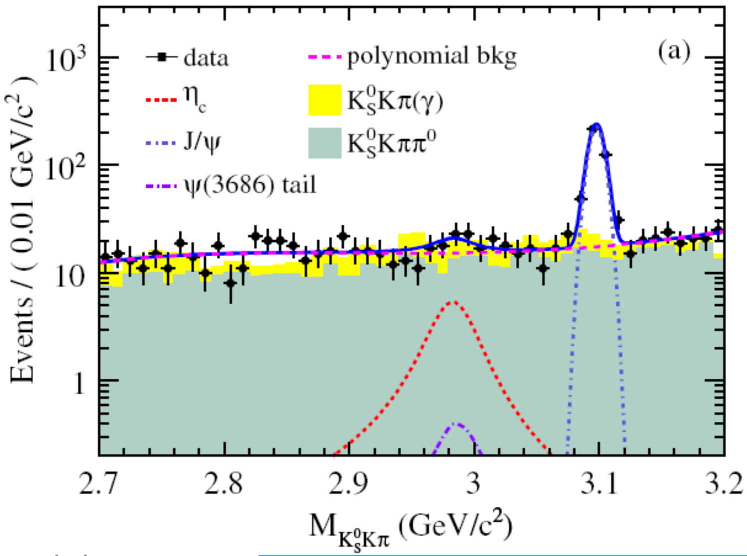
- If $\psi(3770)$ is assigned as $1^3D_1$ state, the radiative transitions $\psi(3770)\to\gamma\eta_c,\gamma\eta_c(2S)$ are supposed to be highly suppressed.
- High multipoles beyond the leading one could be contributed.

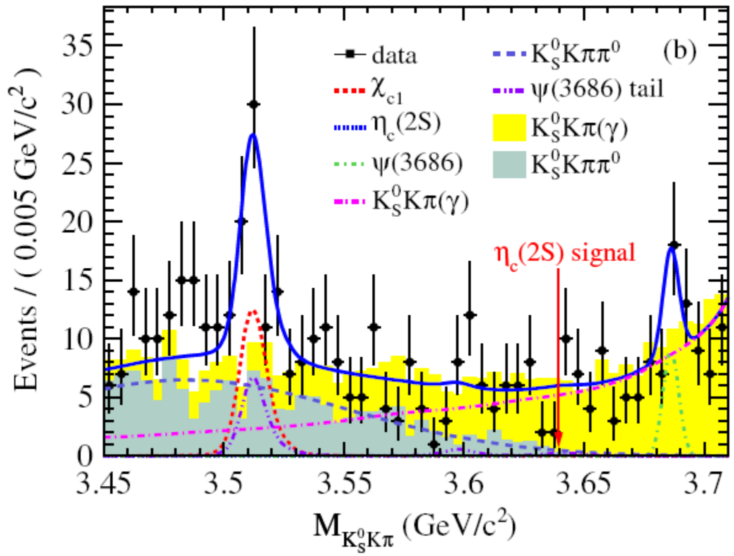
$$B(\psi(3770)\to\gamma\eta_c)=6.3^{+8.4}_{-4.4}\times10^{-4}$$

**PRD 84, 074005 (2011)**

$$B(\psi(3770)\to\gamma\eta_c(2S))=6.7^{+7.2}_{-4.4}\times10^{-5}$$

BESIII: the 2.92 fb$^{-1}$ $\psi''$ data set




Phys. Rev. D 89, 112005

Phys. Rev. D 89, 112005

$\psi(3770) \to \gamma\eta_c,\ \gamma\eta_c(2S) \to \gamma K_S^0 K\pi$

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| Quantity | $\eta_c$ | $\eta_c(2S)$ | $\chi_{c1}$ |
|---|---|---|---|
| $N_{\rm obs}$ | $29.3 \pm 18.2$ | $0.4 \pm 8.5$ | $34.9 \pm 9.8$ |
| $N_{\rm up}$ | 56.8 | 16.1 | ... |
| $\epsilon$ (%) | 27.87 | 25.24 | 28.46 |
| $\mathcal{B}(\psi(3770) \to \gamma X \to \gamma K_S^0 K^\pm \pi^\mp)$ $(\times 10^{-6})$ | $< 16$ | $< 5.6$ | $8.51 \pm 2.39 \pm 1.42$ |
| $\mathcal{B}(\psi(3770) \to \gamma X)$ $(\times 10^{-3})$ | $< 0.68$ | $< 2.0$ | $2.33 \pm 0.65 \pm 0.43$ |
| $\mathcal{B}_{\rm CLEO}(\psi(3770) \to \gamma X)$ $(\times 10^{-3})$ | ... | ... | $2.9 \pm 0.5 \pm 0.4$ |
| $\Gamma(\psi(3770) \to \gamma X)$ (keV) | $< 19$ | $< 55$ | ... |
| $\Gamma_{\rm IML}$ (keV) | $174.1^{+22.93}_{-12.03}$ | $1.82^{+1.95}_{-1.19}$ | ... |
| $\Gamma_{\rm LQCD}$ (keV) | $10 \pm 11$ | ... | ... |

- Upper limites are set for the radiative transitions $\psi(3770) \to \gamma\eta_c, \gamma\eta_c(2S)$
- The upper limits for the $\Gamma(\psi(3770) \to \gamma\eta_c/\eta_c(2S))$ cover the theoretical predictions, but the upper limits for $\Gamma(\psi(3770) \to \gamma\eta_c(2S))$ is too high due to the large systematic uncertainties.

# $\psi(3770) \to \gamma\chi_{cJ}$ with $\chi_{cJ} \to \gamma J/\psi \to \gamma l^+l^-$

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- No significant non $D\bar{D}$ exclusive decays are established. How to understand the $\psi(3770)$ decay mechanisms and properties?
- If it contains additional light quarks or gluons, it may have large branching fractios decays into ligh hadrons.
- Light hadron transition or radiative transitions, e.g. $\pi\pi J/\psi, \pi J/\psi, \eta J/\psi$, and $\gamma\chi_{cJ}$, can probe the $\psi(3770)$

**PDG2014**

| Radiative decays | | | |
|---|---|---|---|
| $\gamma\chi_{c2}$ | $< 9 \times 10^{-4}$ | CL=90% | 211 |
| $\gamma\chi_{c1}$ | $(2.9 \pm 0.6) \times 10^{-3}$ | | 253 |
| $\gamma\chi_{c0}$ | $(7.3 \pm 0.9) \times 10^{-3}$ | | 341 |

- $S$-$D$ mixing model: (PRD44,3562; PRD64,094002, PRD69,094019)

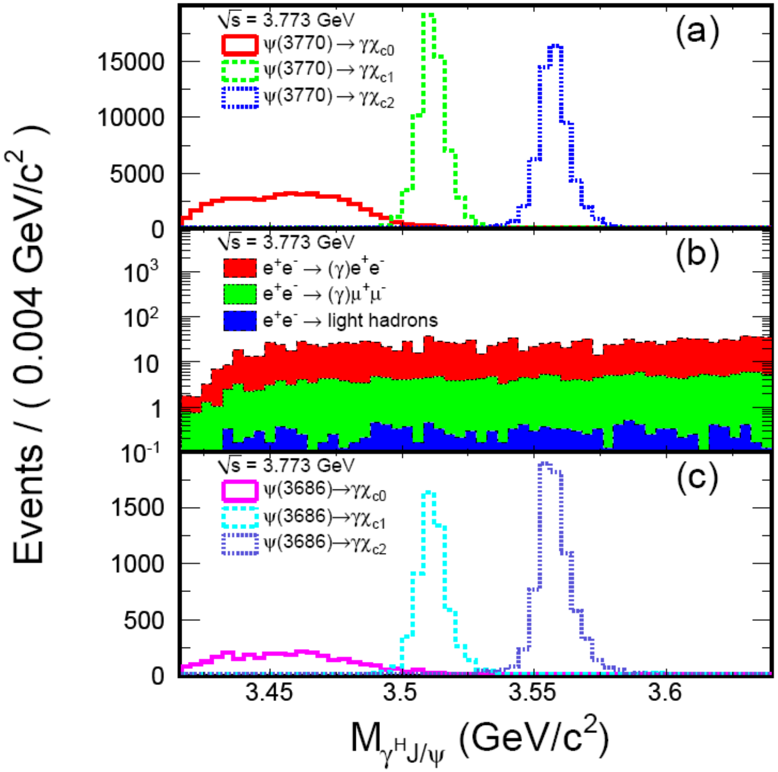
$$\Gamma(\psi(3770) \to \gamma\chi_{c1}): \text{ 59~183 KeV}$$

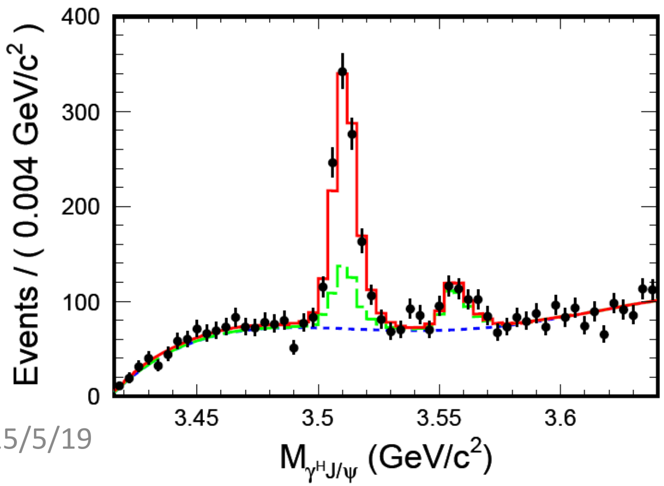
$$\Gamma(\psi(3770) \to \gamma\chi_{c2}): \text{ 3~24 KeV}$$

**Large uncertainties!**

# $\psi(3770) \to \gamma\chi_{cJ}$

**arXiv:1504.07450v01**




- The analysis is based on the 2.92 $fb^{-1}$ $\psi''$ data.
- The $\chi_{cJ}$ are reconstructed with the decay

$$\chi_{cJ} \to \gamma J/\psi \to \gamma l^+ l^-$$

| Experiment/Theory | $\Gamma(\psi(3770) \to \gamma\chi_{cJ})$ (keV) $J = 1$ | $J = 2$ |
|---|---|---|
| This work | $67.5 \pm 4.1 \pm 6.7$ | $< 17.4$ |
| Ding-Qin-Chao [12] | | |
| non-relativistic | 95 | 3.6 |
| relativistic | 72 | 3.0 |
| Rosner $S$-$D$ mixing [13] | | |
| $\phi = 12^\circ$ [13] | $73 \pm 9$ | $24 \pm 4$ |
| $\phi = (10.6 \pm 1.3)^\circ$ [32] | $79 \pm 6$ | $21 \pm 3$ |
| $\phi = 0^\circ$ (pure $1^3D_1$ state) [32] | 133 | 4.8 |
| Eichten-Lane-Quigg [14] | | |
| non-relativistic | 183 | 3.2 |
| with coupled-channel corr. | 59 | 3.9 |
| Barnes-Godfrey-Swanson [15] | | |
| non-relativistic | 125 | 4.9 |
| relativistic | 77 | 3.3 |

$$\mathcal{B}(\psi(3770) \to \gamma\chi_{c1}) = (2.48 \pm 0.15 \pm 0.23) \times 10^{-3},$$

$$\mathcal{B}(\psi(3770) \to \gamma\chi_{c2}) < 0.64 \times 10^{-3}$$

# Searches for isospin-violating transition $\chi_{c0,2} \to \pi^0\eta_c$

BESIII

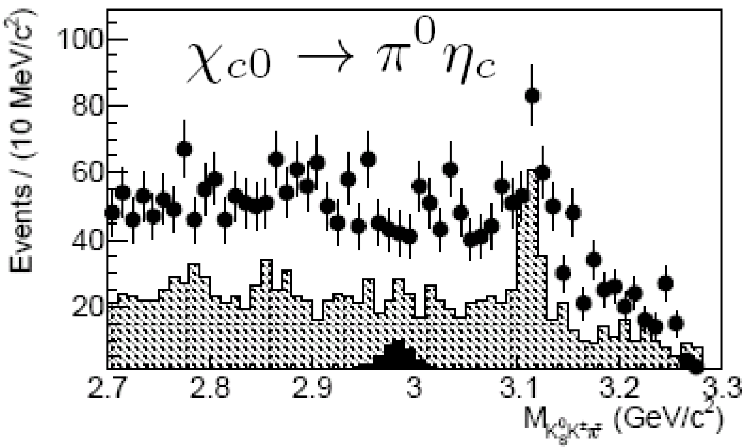
- In quark model, the isospin-violating is broken due to the electromagnetic interaction or the up-down quark mass difference. The expected decay rates are very small.
- However, a larger isospin decay ratio is observed in charmonium transitions, e.g. R=Br($\psi$(2S) $\to \pi^0$J/$\psi$)/Br ($\psi$(2S) $\to \eta$J/$\psi$)=0.374$\pm$0.072, indicates the important role played by the nonperturbative effects. (PRL103,082003)
- Searches for the isospin-violating decay $\chi_{cJ} \to \pi^0\eta_c$ gives insights in the isospin-violating mechanisms.
- QCD multipole expansion gives the relation: $Br(\chi_{c0} \to \pi^0\eta_c) \approx Br(\chi_{c1} \to \pi^+\pi^-\eta_c)$ (PRD86, 074033), and $Br(\chi_{c1} \to \pi^+\pi^-\eta_c) \approx (2.22\pm1.24)\%$. (PRD 75, 054019)
- The analysis is based on the 106 million $\psi$(2S) data set at the BESIII, and the $\eta_c$ is constructed with the decay $\eta_c \to K_S^0 K^\pm \pi^\mp$.

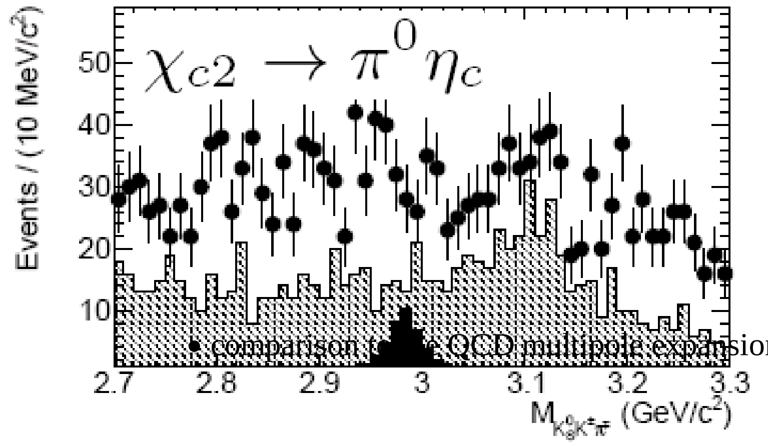
# Searches for isospin-violating transition $\chi_{c0,2} \to \pi^0 \eta_c$

BESIII

- The peack near 3.12 GeV is due to the background $\psi(2S) \to \pi^0 \pi^0 J/\psi$.
- No significant $\eta_c$ signals are observed, and upper limits are set.

**arXiv: 1502.02641**




| | $\chi_{c0} \to \pi^0 \eta_c$ | $\chi_{c2} \to \pi^0 \eta_c$ |
|---|---|---|
| $N_J^{UL}$ | 14.1 | 35.9 |
| $\varepsilon_J$ | 5.8% | 8.6% |
| $\delta_J$ | 13.8% | 20.2% |
| $B(\chi_{cJ} \to \pi^0 \eta_c)(10^{-3})$ | $< 1.6$ | $< 3.2$ |

- **Comparison to the QCD multipole expansion**

  **if B($\chi_{c0} \to \pi^0 \eta_c$)=0.022, then one expect the observed events in the $106 \times 10^6$ data sets $N^{obs}$=302.**

- **The comparison indicates that the QCD multipole expansion predicts that the branching fraction is 20 times of magnitude larger than our measurement**

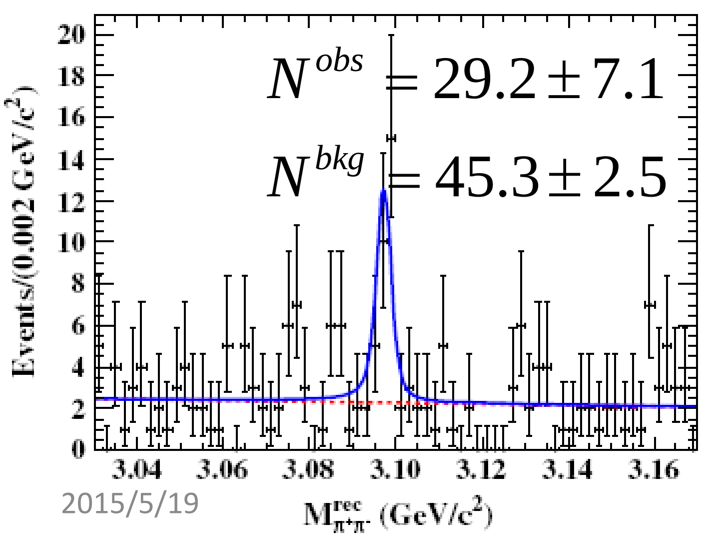
# Search for $C$ – violation decay $J/\psi \to \gamma\gamma, \gamma\phi$ BESIII

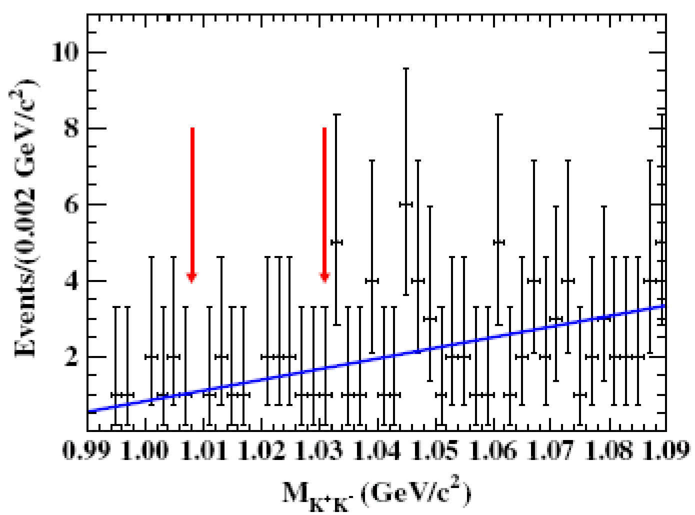
- The $C$-parity violation is forbidden in the electromagnetic interatction, any observation of the $J/\psi \to \gamma\gamma$ decay indicates a new physics.
- Based on the 106 million $\psi(3686)$ data set, we use the decay $\psi(2S) \to \pi^+\pi^- J/\psi$ to search for $J/\psi \to \gamma\gamma$
- Dominant backgrounds, $J/\psi \to \gamma\pi^0, \gamma\eta, \gamma\eta_c \to 3\gamma$, and $J/\psi \to 3\gamma$, are carefully studied with MC simulation.

**PRD 90, 092002**

**No *C*-violation decays were observed!**

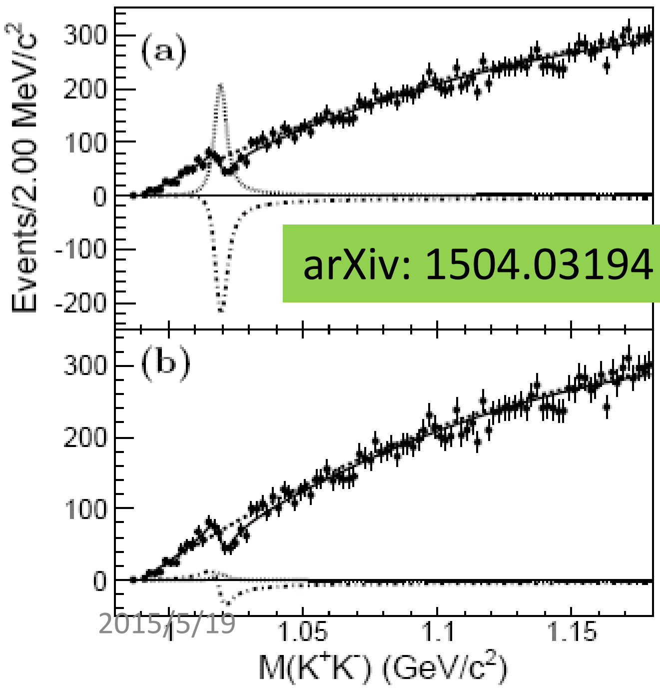
| | $\gamma\gamma$ | $\gamma\phi$ |
|---|---|---|
| $\mathcal{B}(J/\psi \to)$ (this work) | $< 2.7 \times 10^{-7}$ | $< 1.4 \times 10^{-6}$ |
| $\mathcal{B}(J/\psi \to)$ (PDG [1]) | $< 50 \times 10^{-7}$ | – |



# Search for OZI-suppressed decay $J/\psi \to \pi^0\phi$

- The decay $J/\psi \to \phi\pi^0$ is highly suppressed dut to double OZI rule.
- The observation is helpful to understand the $\omega-\phi$ mixing and SU(3) flavor symmetry breaking.
- The analysis is based on the 1.31 billion $J/\psi$ data sample, and the $\pi^0$ candidates are reconstructed with two photons
- The structure at the $\phi$ mass region is assumed due to the interference between the $J/\psi \to \phi\pi^0$ and $K^+K^-\pi^0$ decays.




arXiv: 1504.03194

- **Two solutions are obtained.**

| Solution | $N^{sig}$ | $\delta$ | $2\Delta\log\mathcal{L}/N_f$ | $Z$ |
|---|---|---|---|---|
| I | $838.5 \pm 45.8$ | $-95.9° \pm 1.5°$ | 45.8/2 | $6.4\sigma$ |
| II | $35.3 \pm 9.3$ | $-152.1° \pm 7.7°$ | 45.8/2 | $6.4\sigma$ |

Branching fraction:

I: $[2.94 \pm 0.16(stat.) \pm 0.16(syst.)] \times 10^{-6}$

II: $[1.24 \pm 0.33(stat.) \pm 0.30(syst.)] \times 10^{-7}$

# Search for OZI-suppressed decay $J/\psi \to \pi^0\phi$

BESIII

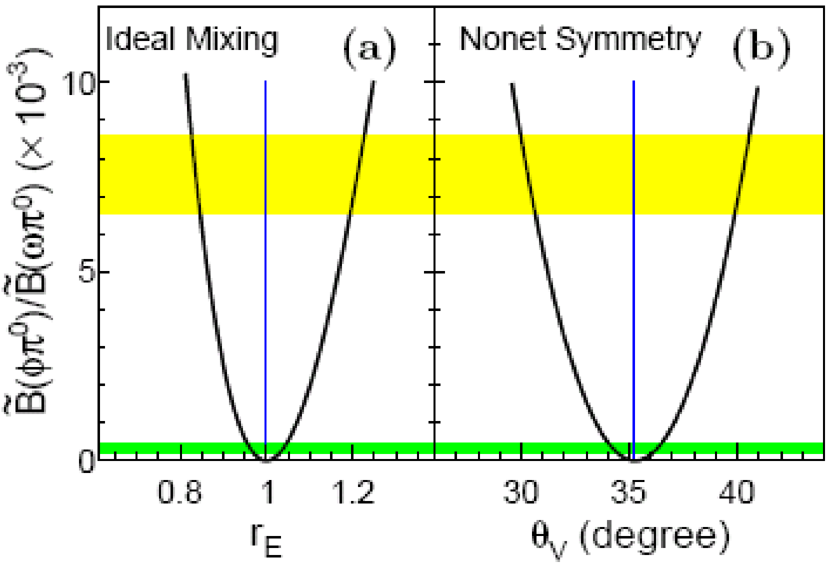
- Nonet symmetry broken

PRD32,2961

$$\frac{B(\phi\pi^0)}{B(\omega\pi^0)} = \left(\frac{p_\phi}{p_\omega}\right)^3 \frac{(r_E \tan\theta_V - 1/\sqrt{2})^2}{(r_E + \tan\theta_V/\sqrt{2})^2}$$

$$r_E = 1 \text{ (nonet symmetry)}$$

$$\theta_V = arc\tan(1/\sqrt{2}) \text{ (ideal } \omega-\phi \text{ mixing)}$$




$$\text{ideal mixing: } r_E - 1 = (21.0 \pm 1.6)\% \text{ or } (-16.4 \pm 1.0)\% \quad \text{(solution I)}$$

$$(3.9 \pm 0.8)\% \text{ or } (-3.7 \pm 0.7)\% \quad \text{(solution II)}$$

$$\text{Nonet symmetry: } \phi_V = |\theta_V - \theta_V^{ideal}| = 4.97^\circ \pm 0.33^\circ \quad \text{(solution I)}$$

$$= 1.03^\circ \pm 0.19^\circ \quad \text{(solution II)}$$

$$\text{quardratic mass formula: } \phi_V = 3.84^\circ \quad \text{(PDG)}$$

$$\text{fit to radiative transition: } 3.34^\circ \pm 0.09^\circ \quad \text{(J. High Energy Phys. 0907,105)}$$

**Nonet asymmetry indication!**

# Summary

By using BESIII data sets taken at $J/\psi$, $\psi(3686)$ and $\psi(3770)$ peak, we search for the radiative and rare decays:

- No significant decays of $\psi(3773) \to \gamma\eta_c, \gamma\eta_c(2S)$ are observed.
- The measurement of $Br(\psi(3770) \to \gamma\chi_{c1})$ is improved.
- No significant decays for the isospin-violating transition $\chi_{c0/2} \to \pi^0\eta_c$ are observed.
- The double -OZI decay $J/\psi \to \pi^0\phi$ is observed .

**A more interesting light hadron decays of charmonium will come soon!**