



# Recent Charmonium Results at BESIII

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(for the collaboration of BESIII)

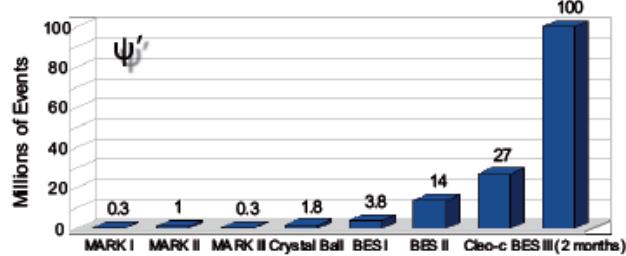
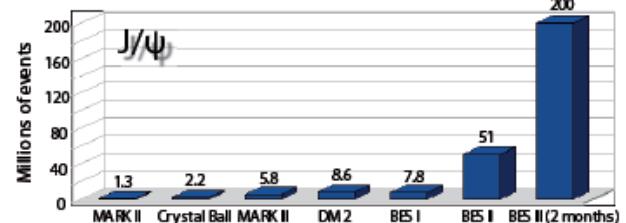
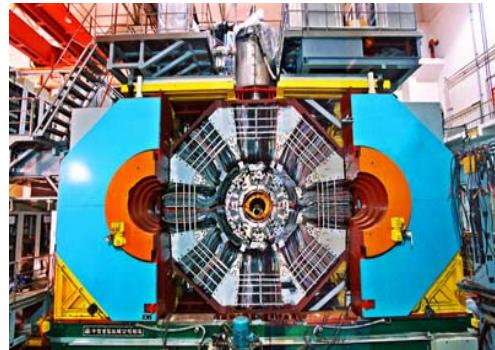
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**OCPA7, August 1-5, 2011, Kaohsiung, Taiwan**

# Outline

- Brief introduction of BEPCII & BESIII
- Recent charmonium results:
  - Spectrum:  $\eta_c$ ,  $h_c$ ,  $\eta'_c$
  - Decay:  $\psi' \rightarrow \gamma P$ ,  $\chi_{cJ} \rightarrow \gamma V$ ,  $\chi_{cJ} \rightarrow VV$
- Summary

# Why BEPCII & BESIII?



Large luminosity

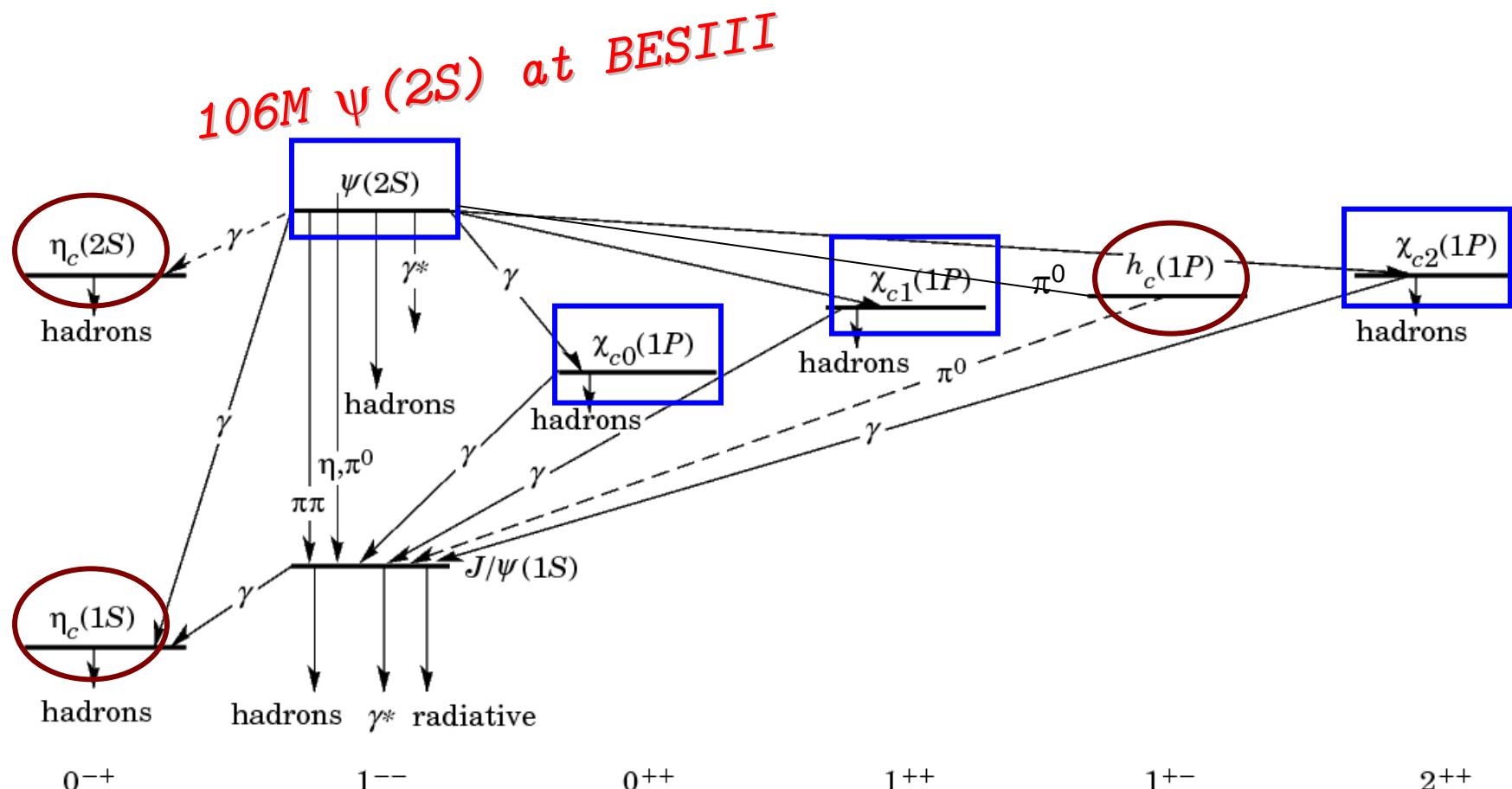
Updated detectors

Charm energy region

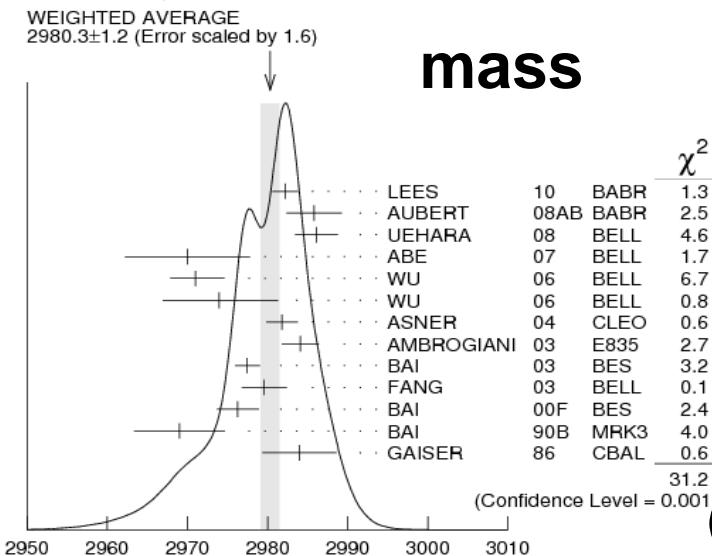
**BESIII is special!**

**Abundant potential physics with BESIII.**

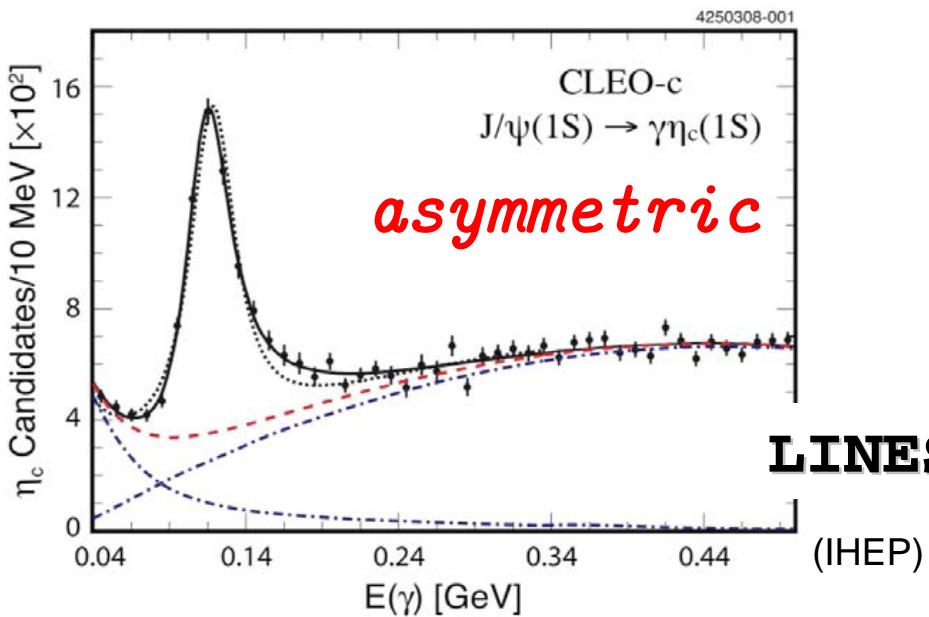
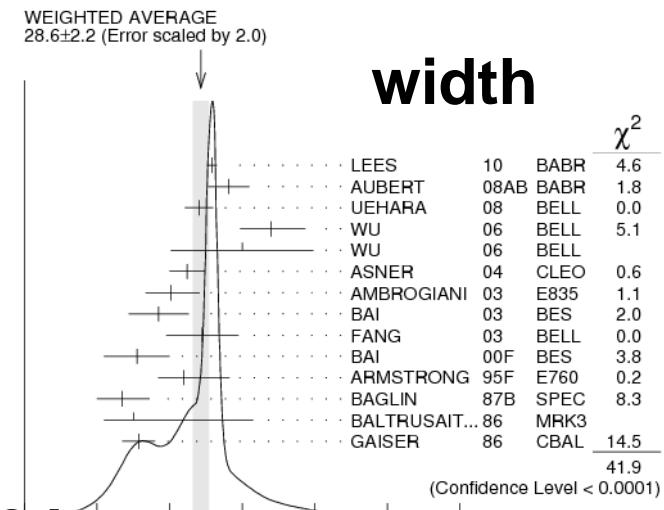
# Charmonium spectrum below open charm threshold



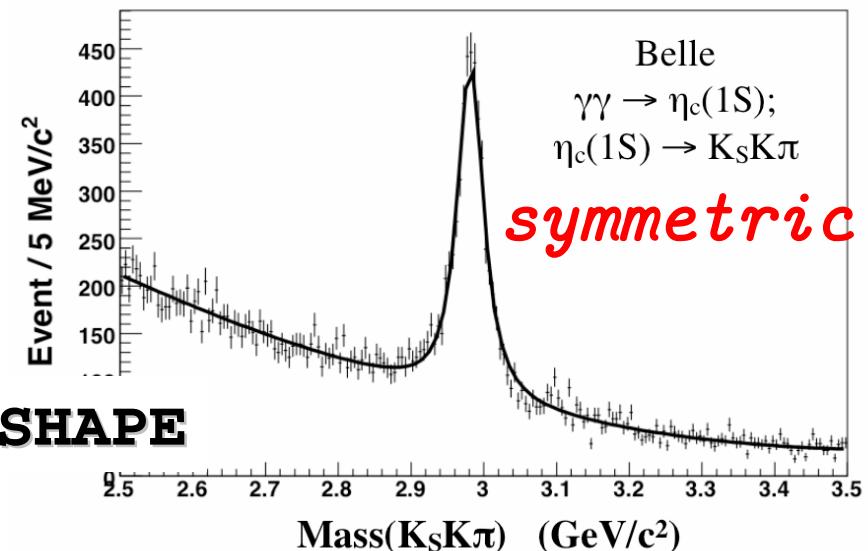
# $\eta_c$ , the lightest charmonium state



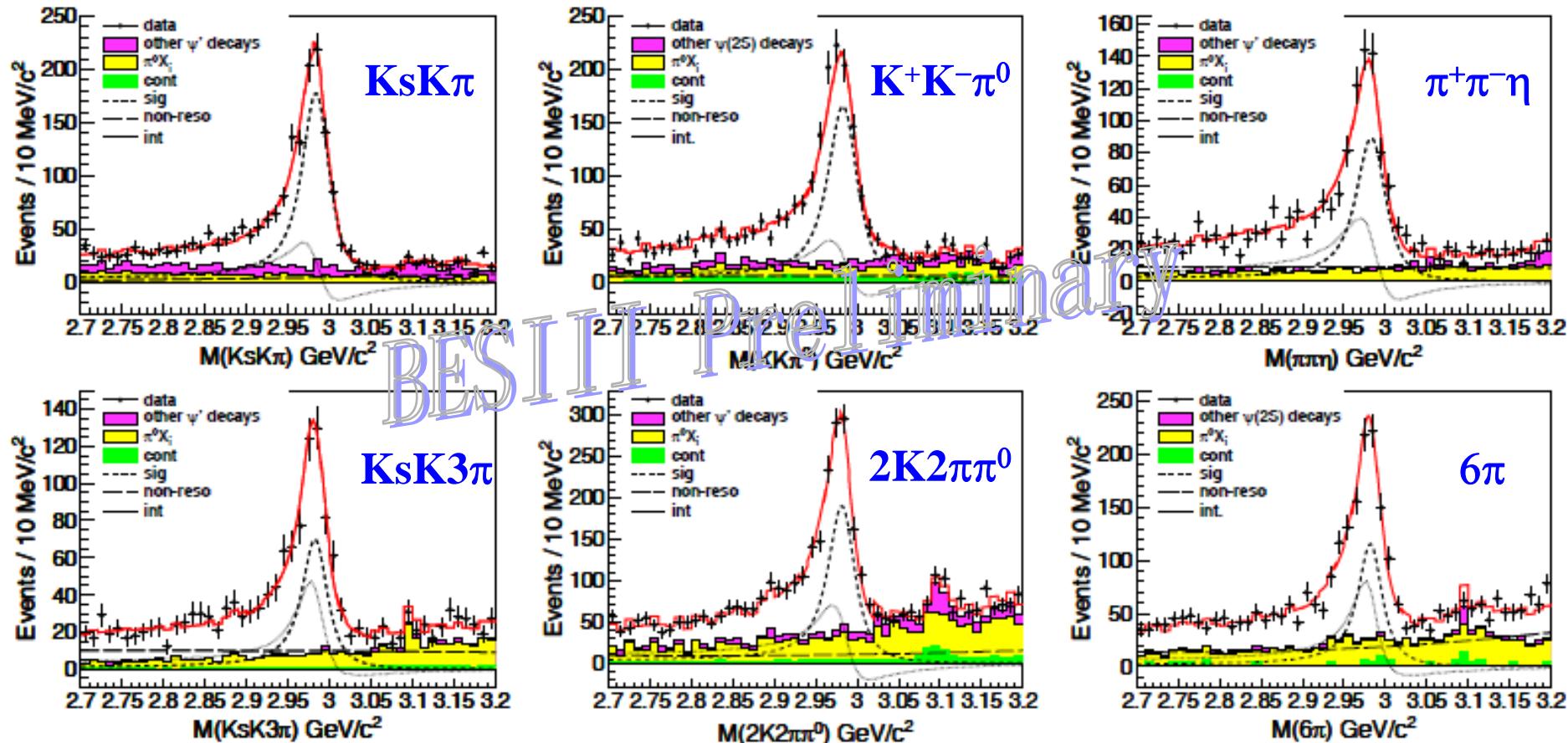
**PDG**  
**(2010)**



**LINESHAPE**



# $\eta_c$ resonance parameters from $\psi' \rightarrow \gamma \eta_c$



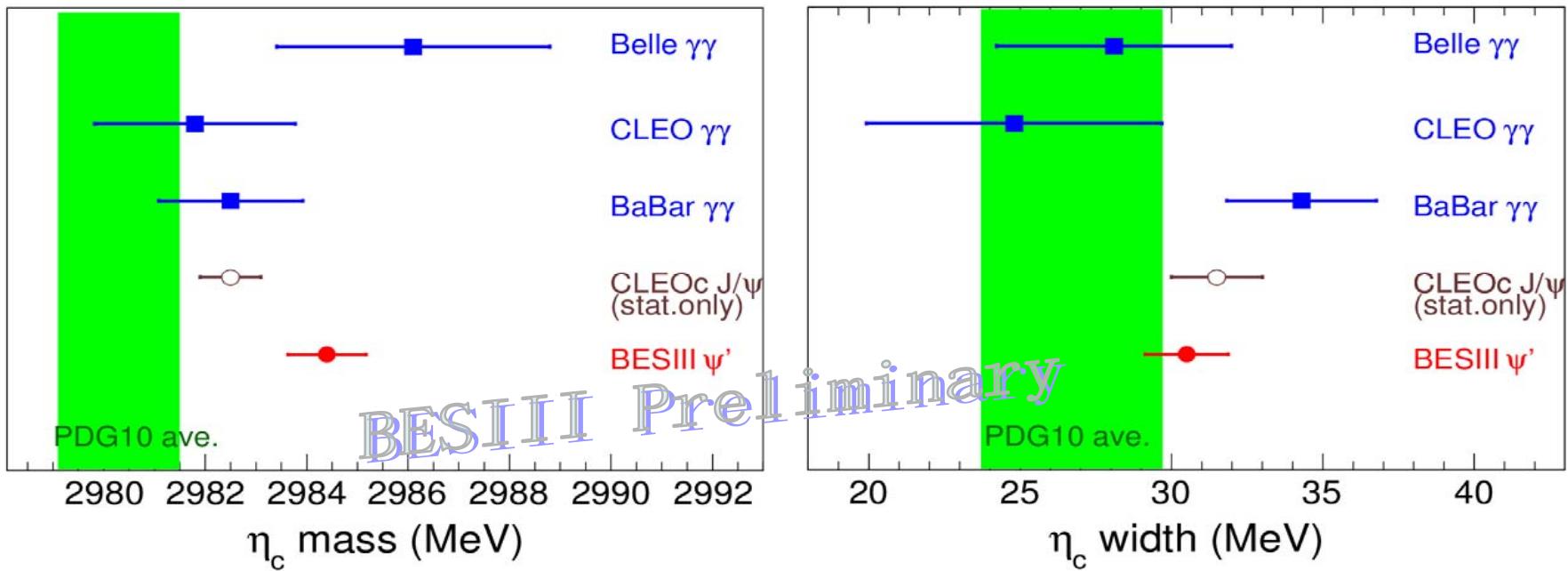
Simultaneous fit with modified Breit-Wigner (hindered M1) with considering **interference** between  $\eta_c$  and non- $\eta_c$  decays

# Mass and Width of $\eta_c$

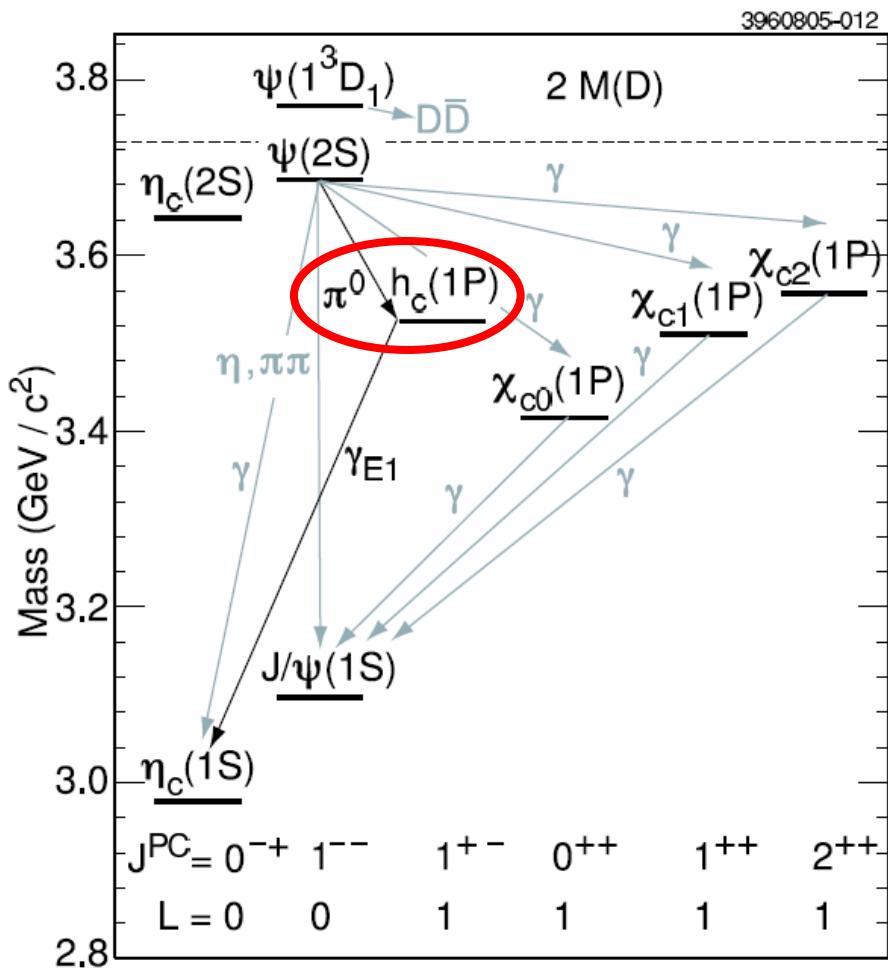
*BESIII preliminary*

- ◆ mass =  $2984.4 \pm 0.5_{\text{stat}} \pm 0.6_{\text{syst}}$  MeV/c<sup>2</sup>
- ◆ width =  $30.5 \pm 1.0_{\text{stat}} \pm 0.9_{\text{syst}}$  MeV
- ◆  $\phi = 2.35 \pm 0.05_{\text{stat}} \pm 0.04_{\text{syst}}$  rad

The world average in PDG2010 was using earlier results.



# $h_c(^1P_1)$ , singlet 1P wave state



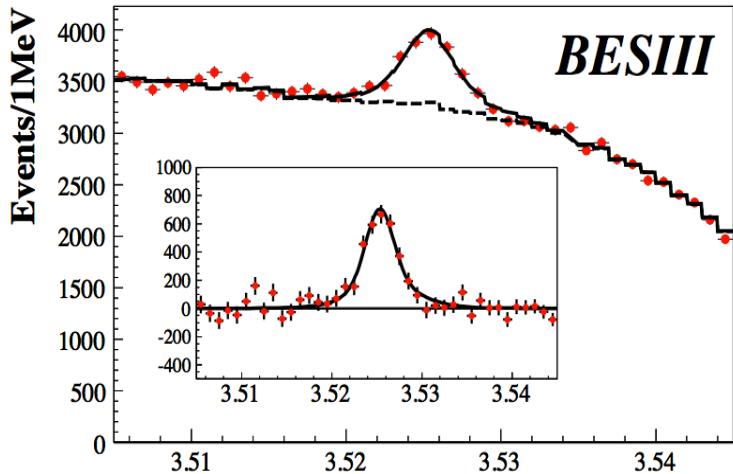
- Predicted for a long time
- Hyperfine splitting of 1P states (spin-spin)
- iso-spin forbidden transition  $\psi' \rightarrow \pi^0 h_c$
- Mass and product Brs from CLEO-c  
**[PRL101.182003(2008)]**

|  | Inclusive                   | Exclusive                   |
|--|-----------------------------|-----------------------------|
| Counts   | $1146 \pm 118$              | $136 \pm 14$                |
| Significance                                     | $10.0\sigma$                | $13.2\sigma$                |
| $M(h_c)$ (MeV)                                   | $3525.35 \pm 0.23 \pm 0.15$ | $3525.21 \pm 0.27 \pm 0.14$ |
| $\mathcal{B}_1 \times \mathcal{B}_2 \times 10^4$ | $4.22 \pm 0.44 \pm 0.52$    | $4.15 \pm 0.48 \pm 0.77$    |

# Observe $h_c$ in inclusive reaction

E1-tagged  $\psi' \rightarrow \pi^0 h_c$ ,  $h_c \rightarrow \gamma \eta_c$

PRL 104, 132002 (2010)



Inclusive  $\psi' \rightarrow \pi^0 h_c$

$$M(h_c) = 3525.40 \pm 0.13 \text{ MeV}$$

$$N(h_c) = 3679 \pm 319$$

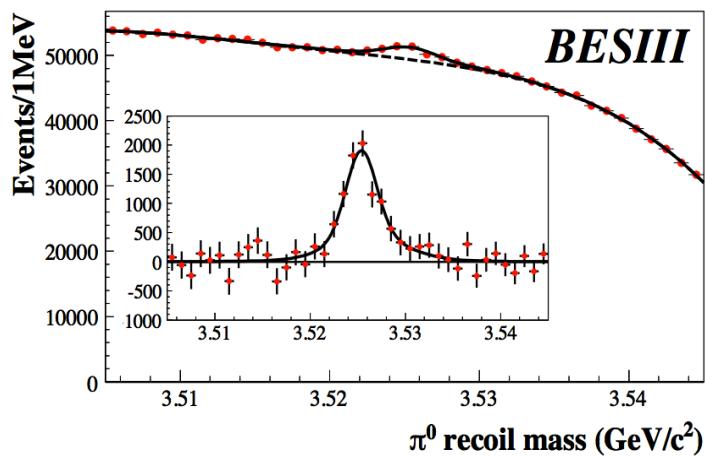
$$\Gamma(h_c) = 0.73 \pm 0.45 \text{ MeV}$$

Consistent with CLEO-c

result:  $3525.35 \pm 0.23$

and theoretical prediction.

*First  
observation*



$$N(h_c) = 10353 \pm 1097$$

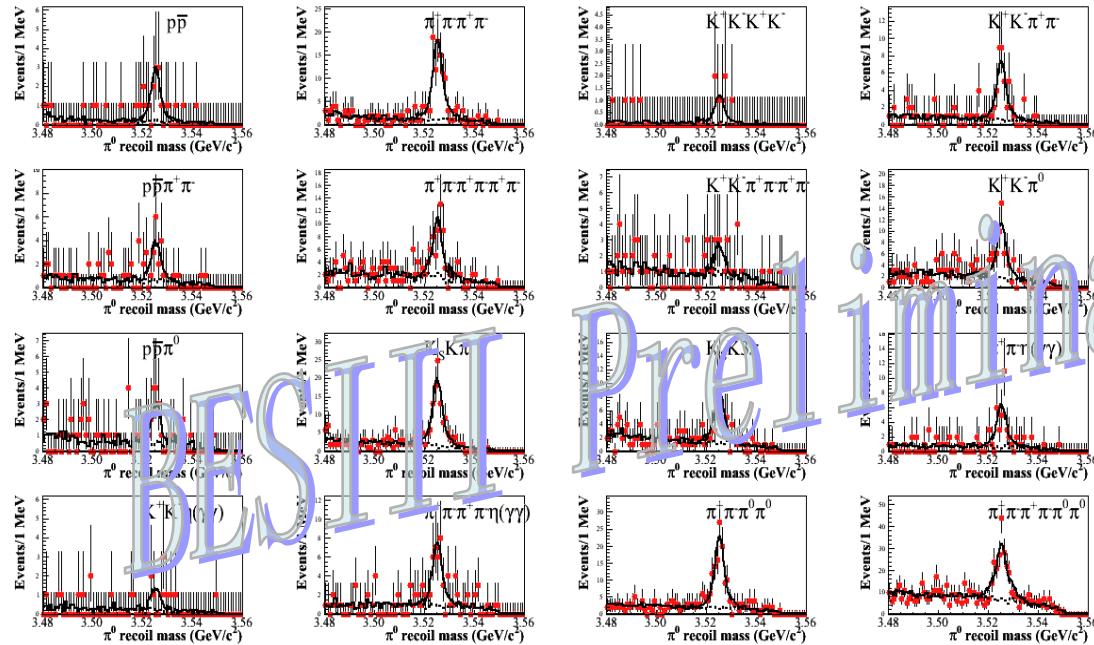
$$B(\psi' \rightarrow \pi^0 h_c) = (8.4 \pm 1.3) \times 10^{-4}$$

$$B(h_c \rightarrow \gamma \eta_c) = (54.3 \pm 6.7)\%$$

Consistent with CLEO-c result:

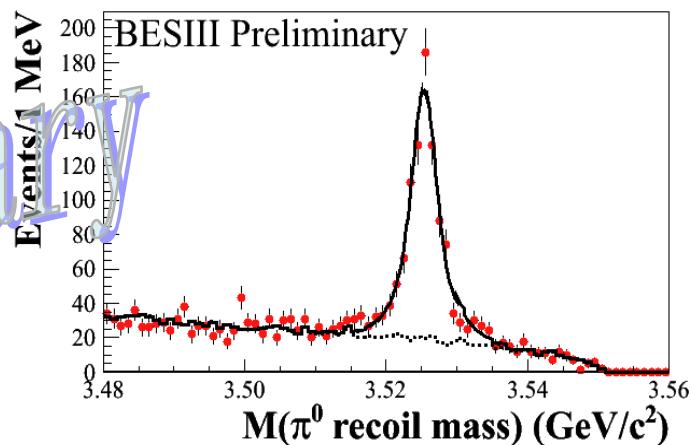
$$Br(\psi' \rightarrow \pi^0 h_c) \times Br(h_c \rightarrow \gamma \eta_c) = (4.22 \pm 0.44 \pm 0.52) \times 10^{-4}$$

# Observe $h_c$ in exclusive reaction



**BESIII Preliminary**  
 Simultaneous fit to  $\pi^0$  recoiling mass  
 $M(h_c) = 3525.31 \pm 0.11 \pm 0.15 \text{ MeV}/c^2$   
 $\Gamma(h_c) = 0.70 \pm 0.28 \pm 0.25 \text{ MeV}$   
 $N = 832 \pm 35$   
 $\chi^2/\text{d.o.f.} = 32/46$

Summed  $\pi^0$  recoil mass



**Consistent with**  
**BESIII inclusive results**  
 PRL104,132002(2010)  
**and**  
**CLEO-c exclusive results**  
 $M(h_c) = 3525.21 \pm 0.27 \pm 0.14 \text{ MeV}/c^2$   
 $N = 136 \pm 14$   
 PRL101, 182003(2008)

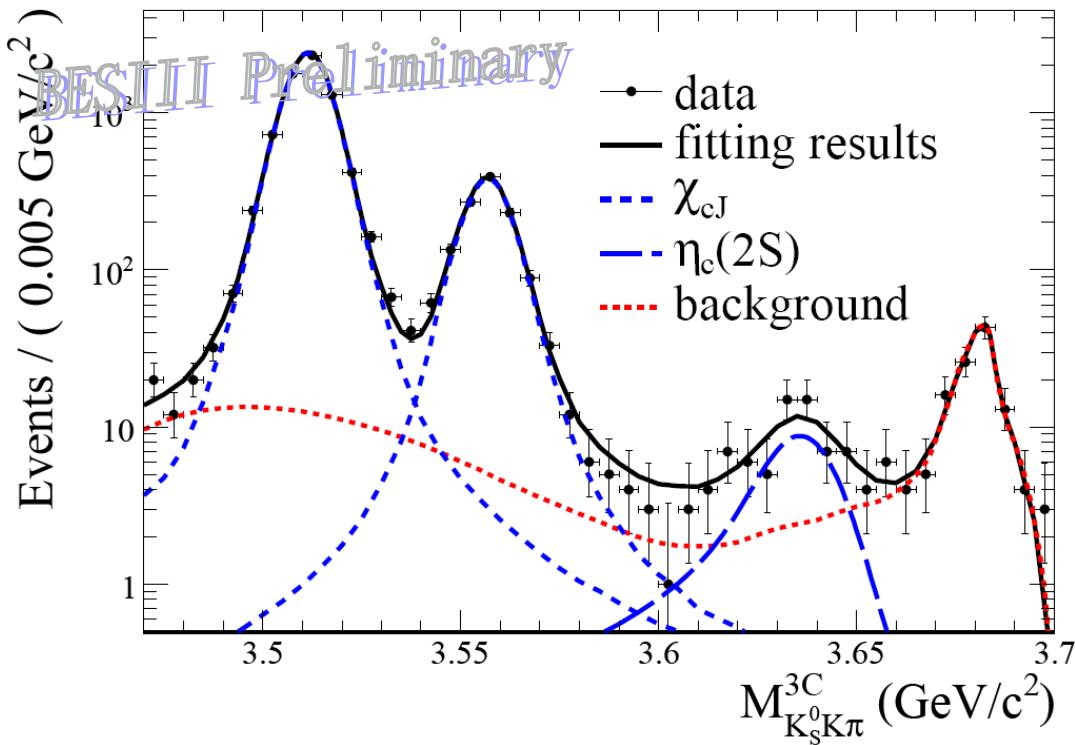
# $\eta_c(2S)$ , never confirmed in M1 transition

- First “observation” by Crystal Ball in 1982 ( $M=3.592\text{GeV}$ ,  $\text{Br}=0.2\%-1.3\%$  from  $\psi' \rightarrow \gamma X$ , never confirmed. Experimental challenge for **50MeV photon.**)
- Published results about  $\eta_c(2S)$  observation:

| Experiment | $M$ [MeV]                    | $\Gamma$ [MeV]         | Process  |
|------------|------------------------------|------------------------|--|
| Belle [1]  | $3654 \pm 6 \pm 8$           | —                      | $B^\pm \rightarrow K^\pm \eta_c(2S), \eta_c(2S) \rightarrow K_S K^\pm \pi^\mp$ |
| CLEO [2]   | $3642.9 \pm 3.1 \pm 1.5$     | $6.3 \pm 12.4 \pm 4.0$ | $\gamma\gamma \rightarrow \eta_c(2S) \rightarrow K_S K^\pm \pi^\mp$            |
| BaBar [3]  | $3630.8 \pm 3.4 \pm 1.0$     | $17.0 \pm 8.3 \pm 2.5$ | $\gamma\gamma \rightarrow \eta_c(2S) \rightarrow K_S K^\pm \pi^\mp$            |
| BaBar [4]  | $3645.0 + 5.5_{-7.8}^{+4.9}$ | —                      | $e^+e^- \rightarrow J/\psi c\bar{c}$   |
| PDG [5]    | $3638 \pm 4$                 | $14 \pm 7$             | —  |

- Combined with the results based on two-photon processes from BaBar and Belle reported at ICHEP 2010, the world average  $\Gamma(\eta_c(2S)) = 12 \pm 3 \text{ MeV}$
- Decay mode studied:  $\psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma K_s K \pi$  ( $K^+K^- \pi^0$  etc. in progress), better chance with  $106M \psi'$  data at BESIII.

# Simultaneous fit of $\eta_c(2S)$ and $\chi_{cJ}$



- ◆  $N(\eta_c(2S)) = 50.6 \pm 9.7$
- ◆ Pure statistical significance more than  $6\sigma$
- ◆ Significance with systematic variations not less than  $5\sigma$
- ◆  $\chi^2/\text{ndf}=0.9$

- $\eta_c(2S)$  signal: modified BW (M1) with fixed width. (The resolution is extrapolated from  $\chi_{cJ}$ )
- $\chi_{cJ}$  signal: MC shape smeared with Gaussian.
- BG from  $e^+ e^- \rightarrow K_s K \pi$ (ISR),  $\psi' \rightarrow K_s K \pi$  (FSR),  $\psi' \rightarrow \pi^0 K_s K \pi$ , : are measured from data.

# Preliminary measurements from

$$\psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma K_s K \pi$$

➤  $M(\eta_c(2S)) = 3638.5 \pm 2.3_{\text{stat}} \pm 1.0_{\text{sys}} \text{ (MeV/c}^2)$

➤  $\text{Br}(\psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma K_s K \pi) = (2.98 \pm 0.57_{\text{stat}} \pm 0.48_{\text{sys}}) \times 10^{-6}$

$\text{Br}(\eta_c(2S) \rightarrow K K \pi) = (1.9 \pm 0.4 \pm 1.1)\%$  from BaBar



➤  $\text{Br}(\psi' \rightarrow \gamma \eta_c(2S)) = (4.7 \pm 0.9_{\text{stat}} \pm 3.0_{\text{sys}}) \times 10^{-4}$

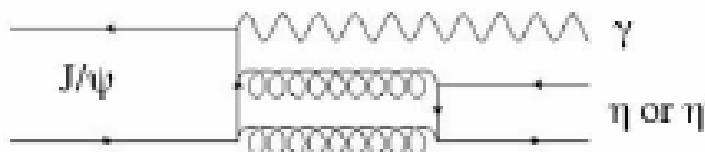
CLEO-c:  $< 7.6 \times 10^{-4}$  (PRD81,052002(2010))

Potential model:  $(0.1 - 6.2) \times 10^{-4}$  (PRL89,162002(2002))

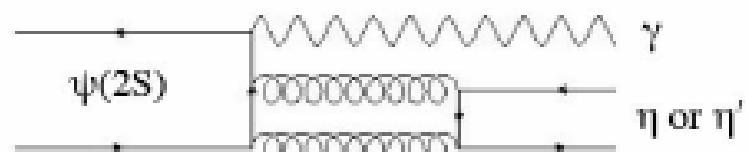
# $\psi' \rightarrow \gamma P(\pi^0, \eta, \eta')$ , arise surprises

$V \rightarrow \gamma P$  are important tests for various mechanisms:

**Vector meson Dominance Model (VDM); Couplings & form factor; Mixing of  $\eta$ - $\eta'$ (- $\eta_c$ ); FSR by light quarks; 12% rule and “ $\rho$   $\pi$  puzzle”.**



VS



theory

experiment

$$R_{(c\bar{c})} = \frac{Br((c\bar{c}) \rightarrow \gamma\eta)}{Br((c\bar{c}) \rightarrow \gamma\eta')}$$

LO-pQCD



$$R_{\psi'} \simeq R_{J/\psi}$$

PRP 112,173 (1984)

CLEO-c:  $J/\psi, \psi', \psi'' \rightarrow \gamma P$

$$R_{J/\psi} = (21.1 \pm 0.9)\%$$

No Evidence for  $\psi' \rightarrow \gamma \pi^0$  or  $\gamma \eta$

$$Br(\psi' \rightarrow \gamma\eta') = (1.19 \pm 0.09)\%$$

$$R_{\psi'} < 1.8\% \text{ at } 90\% \text{ CL}$$

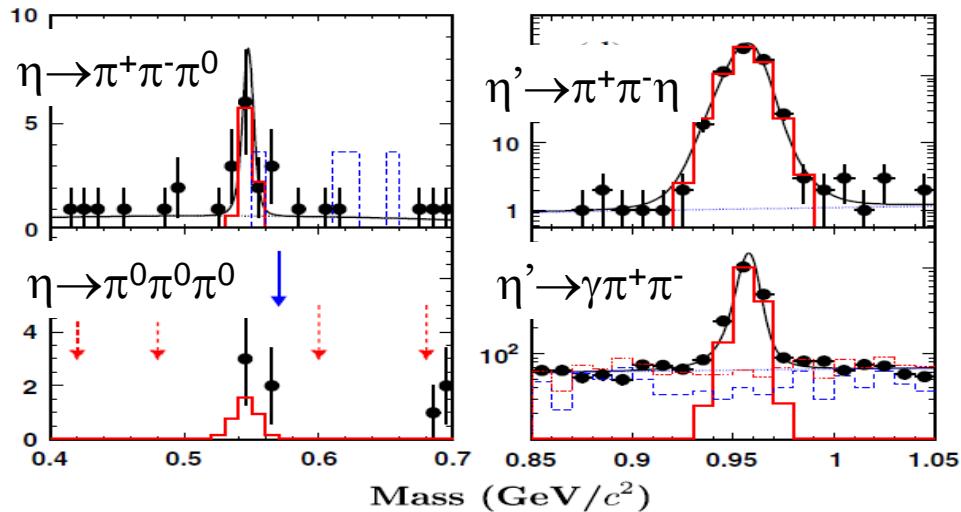
$$R_{\psi'} \ll R_{J/\psi}$$

PRD 79, 111101 (2009)

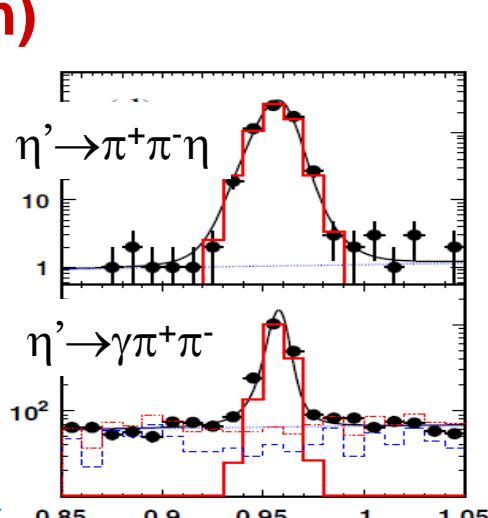
# $\psi' \rightarrow \gamma P$ at BESIII

PRL 105, 261801 (2010)

$\psi' \rightarrow \gamma \eta$   
**(First observation)**

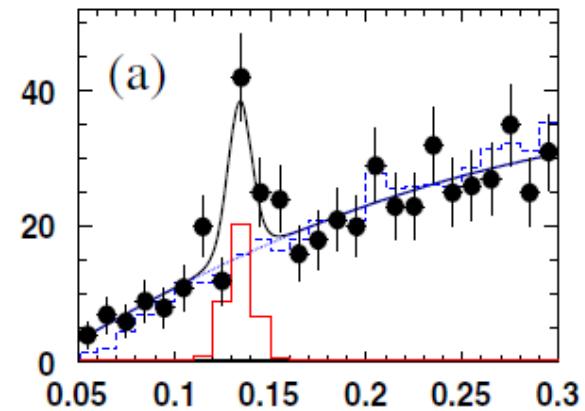


$\psi' \rightarrow \gamma \eta'$



$\psi' \rightarrow \gamma \pi^0$

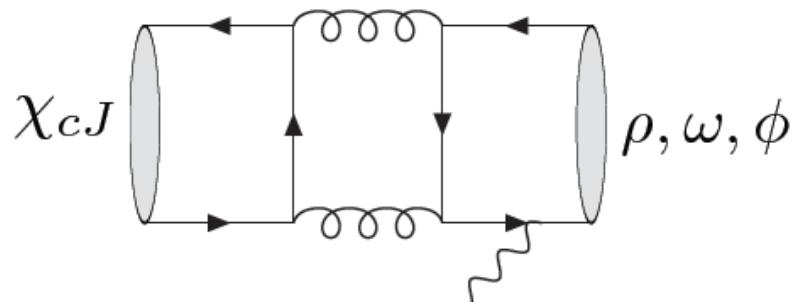
**(First observation)**



$$R_{\psi'} = 1.10 \pm 0.38 \pm 0.07\% \ll R_{J/\psi}$$

| Mode          | $B(\psi') [x10^{-6}]$ | $B(J/\psi) [x10^{-4}]$ | Q (%)           |
|---------------|-----------------------|------------------------|-----------------|
| $\gamma\pi^0$ | $1.58 \pm 0.42$       | $0.35 \pm 0.03$        | $4.5 \pm 1.3$   |
| $\gamma\eta$  | $1.38 \pm 0.49$       | $11.04 \pm 0.34$       | $0.13 \pm 0.04$ |
| $\gamma\eta'$ | $126 \pm 9$           | $52.8 \pm 1.5$         | $2.4 \pm 0.2$   |

# $\chi_{cJ} \rightarrow \gamma V(\rho, \omega, \phi)$ , prediction by pQCD much lower than experiment



- Information of C-even state
- Two gluon coupling
- Possible glue-ball or hybrid states
- Hadronization

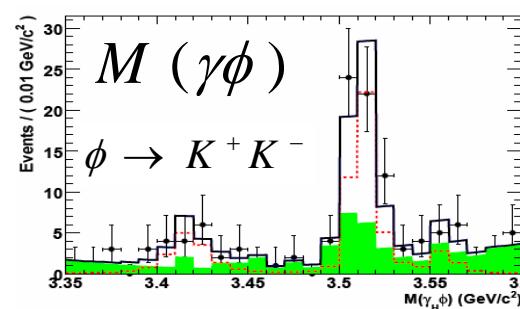
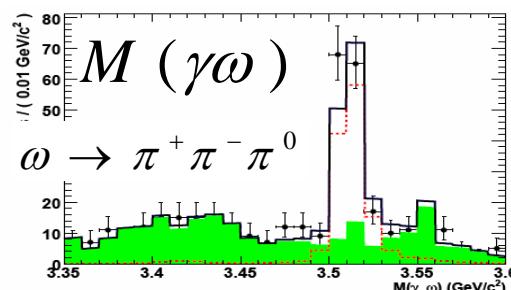
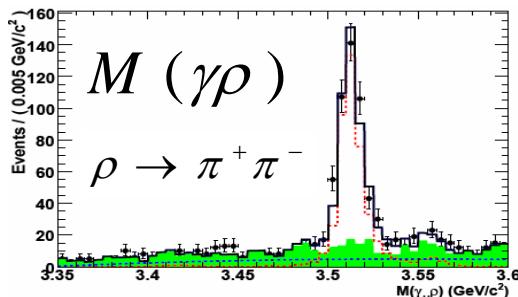
Br. are in unit of  $10^{-6}$ .

| Mode                                  | CLEO <sup>1</sup>   | pQCD <sup>2</sup> | QCD <sup>3</sup> | QCD+QED <sup>3</sup> |
|---------------------------------------|---------------------|-------------------|------------------|----------------------|
| $\chi_{c0} \rightarrow \gamma \rho^0$ | $< 9.6$             | 1.2               | 3.2              | 2.0                  |
| $\chi_{c1} \rightarrow \gamma \rho^0$ | $243 \pm 19 \pm 22$ | 14                | 41               | 42                   |
| $\chi_{c2} \rightarrow \gamma \rho^0$ | $< 50$              | 4.4               | 13               | 38                   |
| $\chi_{c0} \rightarrow \gamma \omega$ | $< 8.8$             | 0.13              | 0.35             | 0.22                 |
| $\chi_{c1} \rightarrow \gamma \omega$ | $83 \pm 15 \pm 12$  | 1.6               | 4.6              | 4.7                  |
| $\chi_{c2} \rightarrow \gamma \omega$ | $< 7.0$             | 0.5               | 1.5              | 4.2                  |
| $\chi_{c0} \rightarrow \gamma \phi$   | $< 6.4$             | 0.46              | 1.3              | 0.03                 |
| $\chi_{c1} \rightarrow \gamma \phi$   | $< 26$              | 3.6               | 11               | 11                   |
| $\chi_{c2} \rightarrow \gamma \phi$   | $< 13$              | 1.1               | 3.3              | 6.5                  |

1. PRL 101, 151801 (2008). 2. Chin. Phys. Lett. 23, 2376 (2006). 3. hep-ph/0701009

# $\chi_{cJ} \rightarrow \gamma V(\rho, \omega, \phi)$ results at BESIII

Phys. Rev. D 83, 112005 (2011)



| Mode                                 | CLEO <sup>1</sup>   | pQCD <sup>2</sup> | QCD <sup>3</sup> | QCD+QED <sup>3</sup> | BESIII                 |
|--------------------------------------|---------------------|-------------------|------------------|----------------------|------------------------|
| $\chi_{c0} \rightarrow \gamma\rho^0$ | $< 9.6$             | 1.2               | 3.2              | 2.0                  | $< 10.5$               |
| $\chi_{c1} \rightarrow \gamma\rho^0$ | $243 \pm 19 \pm 22$ | 14                | 41               | 42                   | $228 \pm 13 \pm 16$    |
| $\chi_{c2} \rightarrow \gamma\rho^0$ | $< 50$              | 4.4               | 13               | 38                   | $< 20.8$               |
| $\chi_{c0} \rightarrow \gamma\omega$ | $< 8.8$             | 0.13              | 0.35             | 0.22                 | $< 12.9$               |
| $\chi_{c1} \rightarrow \gamma\omega$ | $83 \pm 15 \pm 12$  | 1.6               | 4.6              | 4.7                  | $69.7 \pm 7.2 \pm 5.6$ |
| $\chi_{c2} \rightarrow \gamma\omega$ | $< 7.0$             | 0.5               | 1.5              | 4.2                  | $< 6.1$                |
| $\chi_{c0} \rightarrow \gamma\phi$   | $< 6.4$             | 0.46              | 1.3              | 0.03                 | $< 16.2$               |
| $\chi_{c1} \rightarrow \gamma\phi$   | $< 26$              | 3.6               | 11               | 11                   | $25.8 \pm 5.2 \pm 2.0$ |
| $\chi_{c2} \rightarrow \gamma\phi$   | $< 13$              | 1.1               | 3.3              | 6.5                  | $< 8.1$                |

*First observation*

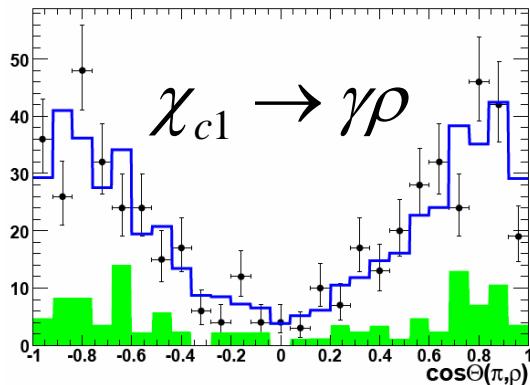
An non-pQCD explanation “hadronic loop correction”,

D.Y Chen et al., EPJC70, 177-182 (2010), arXiv:1005.0066v2[hep-ph]

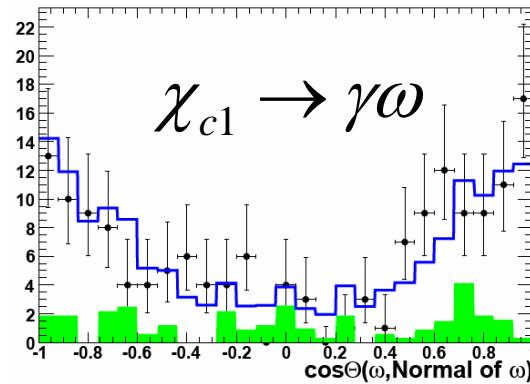
# Polarization of $\chi_{c1} \rightarrow \gamma V(\rho, \omega, \phi)$

L: Longitudinal polarization, T: Transverse polarization,  
 $\theta$  : Helicity angle

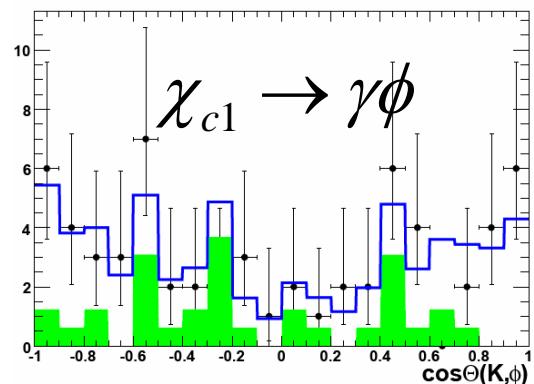
$$\frac{d\Gamma}{\Gamma d \cos \theta} \propto (1 - f_T) \cos^2 \theta + \frac{1}{2} f_T \sin^2 \theta \quad f_T = \frac{|A_T|^2}{|A_T|^2 + |A_L|^2}$$



$$f_T = 0.158 \pm 0.034^{+0.015}_{-0.014}$$



$$f_T = 0.247^{+0.090}_{-0.087}{}^{+0.044}_{-0.026}$$



$$f_T = 0.29^{+0.13}_{-0.12}{}^{+0.10}_{-0.09}$$

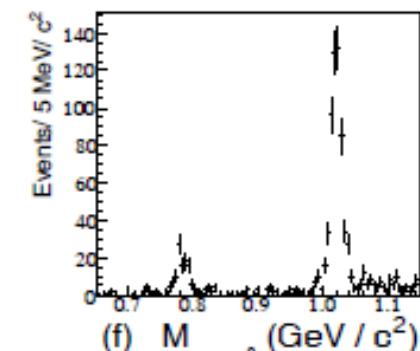
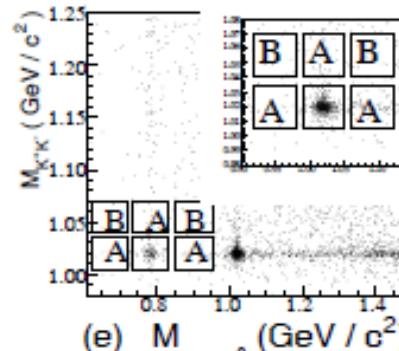
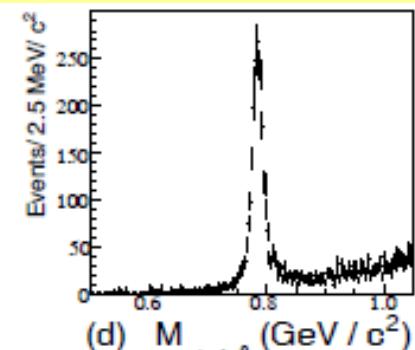
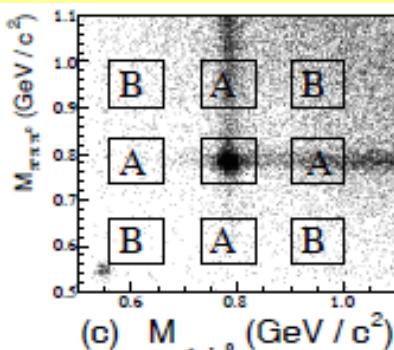
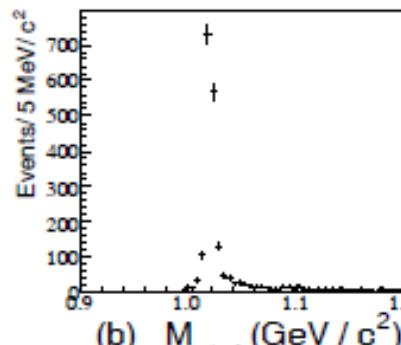
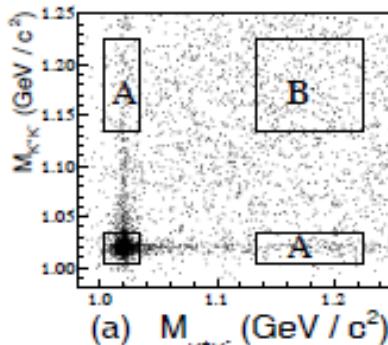
**Longitudinal polarization dominates**

# $\chi_c \rightarrow VV$ ( $V = \omega, \phi$ ), suppressed decays

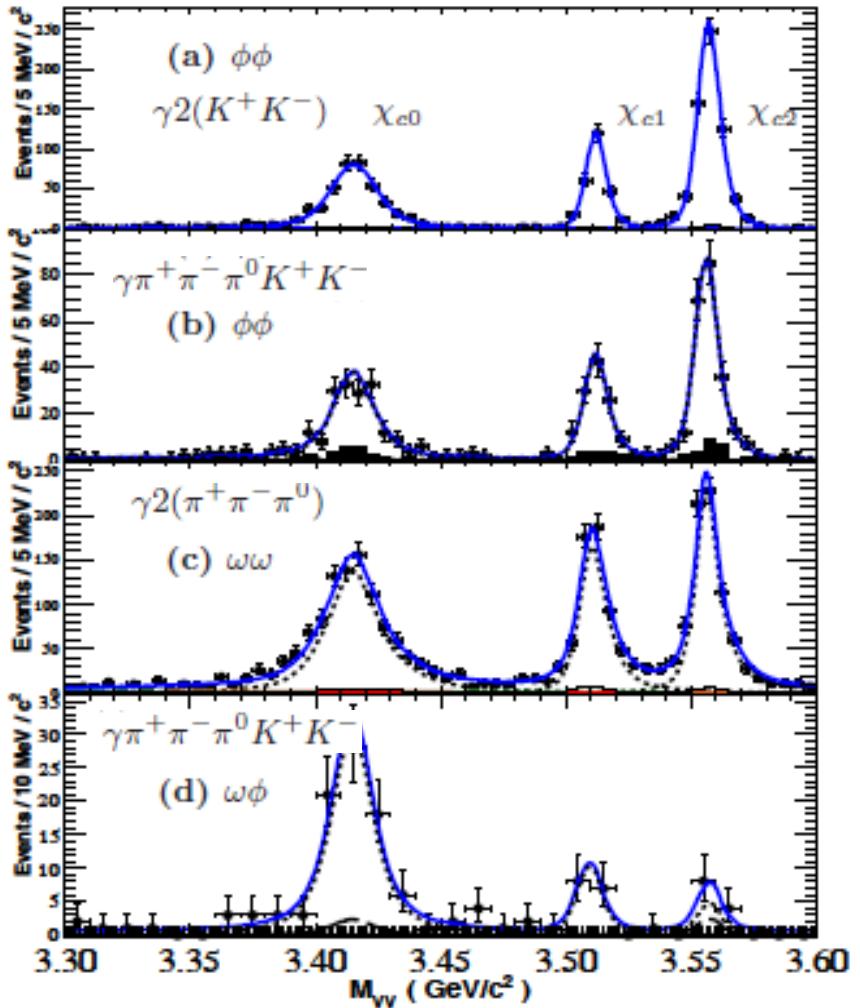
- $\chi_{cJ} \rightarrow \phi \phi$  and  $\chi_{cJ} \rightarrow \omega \omega$  are **Singly OZI suppressed**
- $\chi_{c1} \rightarrow \phi \phi$  and  $\chi_{c1} \rightarrow \omega \omega$  is suppressed by helicity selection rule.
- $\chi_{cJ} \rightarrow \phi \omega$  is **doubly OZI suppressed**, not measured yet

BESII on  $\chi_{c0,2} \rightarrow \phi \phi / \omega \omega$   
PLB 642,197(2006), PLB 630,7 (2005)

Reconstruct  $\phi$  and  $\omega$   
via  $K^+K^-$  or  $\pi^+\pi^-\pi^0$



# $\chi_c \rightarrow VV$ at BESIII



First observation

Accepted by PRL

| Mode                                 | $N_{\text{net}}$ | $\epsilon$ (%) | $\mathcal{B} (\times 10^{-4})$ |
|--------------------------------------|------------------|----------------|--------------------------------|
| $\chi_{c0} \rightarrow \phi\phi$     | $433 \pm 23$     | 22.4           | $7.8 \pm 0.4 \pm 0.8$          |
| $\chi_{c1} \rightarrow \phi\phi$     | $254 \pm 17$     | 26.4           | $4.1 \pm 0.3 \pm 0.4$          |
| $\chi_{c2} \rightarrow \phi\phi$     | $630 \pm 26$     | 26.1           | $10.7 \pm 0.4 \pm 1.1$         |
| $\rightarrow 2(K^+K^-)$              |                  |                |                                |
| $\chi_{c0} \rightarrow \phi\phi$     | $179 \pm 16$     | 1.9            | $9.2 \pm 0.7 \pm 1.0$          |
| $\chi_{c1} \rightarrow \phi\phi$     | $112 \pm 12$     | 2.3            | $5.0 \pm 0.5 \pm 0.6$          |
| $\chi_{c2} \rightarrow \phi\phi$     | $219 \pm 16$     | 2.2            | $10.7 \pm 0.7 \pm 1.2$         |
| $\rightarrow K^+K^-\pi^+\pi^-\pi^0$  |                  |                |                                |
| Combined:                            |                  |                |                                |
| $\chi_{c0} \rightarrow \phi\phi$     | —                | —              | $8.0 \pm 0.3 \pm 0.8$          |
| $\chi_{c1} \rightarrow \phi\phi$     | —                | —              | $4.4 \pm 0.3 \pm 0.5$          |
| $\chi_{c2} \rightarrow \phi\phi$     | —                | —              | $10.7 \pm 0.3 \pm 1.2$         |
| $\chi_{c0} \rightarrow \omega\omega$ | $991 \pm 38$     | 13.1           | $9.5 \pm 0.3 \pm 1.1$          |
| $\chi_{c1} \rightarrow \omega\omega$ | $597 \pm 29$     | 13.2           | $6.0 \pm 0.3 \pm 0.7$          |
| $\chi_{c2} \rightarrow \omega\omega$ | $762 \pm 31$     | 11.9           | $8.9 \pm 0.3 \pm 1.1$          |
| $\rightarrow 2(\pi^+\pi^-\pi^0)$     |                  |                |                                |
| $\chi_{c0} \rightarrow \omega\phi$   | $76 \pm 11$      | 14.7           | $1.2 \pm 0.1 \pm 0.2$          |
| $\chi_{c1} \rightarrow \omega\phi$   | $15 \pm 4$       | 16.2           | $0.22 \pm 0.06 \pm 0.02$       |
| $\chi_{c2} \rightarrow \omega\phi$   | < 13             | 15.7           | < 0.2                          |
| $\rightarrow K^+K^-\pi^+\pi^-\pi^0$  |                  |                |                                |

Evidence

# summary

- With very high luminosity, BEPCII/BESIII provide a good chance to study the physics at  $\tau$ -charm region.
- This report reviewed recent charmonium results at BESIII of resonant states  $\eta_c$ ,  $h_c$  and  $\eta_c(2S)$  as well as decays of  $\psi' \rightarrow \gamma P$ ,  $\chi_{cJ} \rightarrow \gamma V$  and  $\chi_{cJ} \rightarrow VV$ .
- Most of them are precision measurement or first observation with the accumulated 106M  $\psi'$  sample.
- More exciting/interesting results are upcoming.

**Thanks!**