

# Search for the missing charmonium and charmoniumlike states

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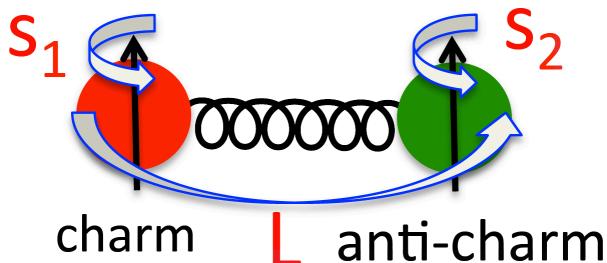


On behalf of BESIII Collaboration

# Outline

1. Status of charmonium(like) spectroscopy
2. BESIII experiment and data sets
3. Search for the  $h_c(2P)$ ,  $X(3915)$ ,  $X(4013)$  at BESIII
4. Summary

# Charmonium



- Coulomb + linear confinement

$$V(r) = -\frac{4 \alpha_s}{3 r} + kr + g_{ss} \vec{S}_c \vec{S}_c + g_{ls} \vec{L} \vec{S}$$

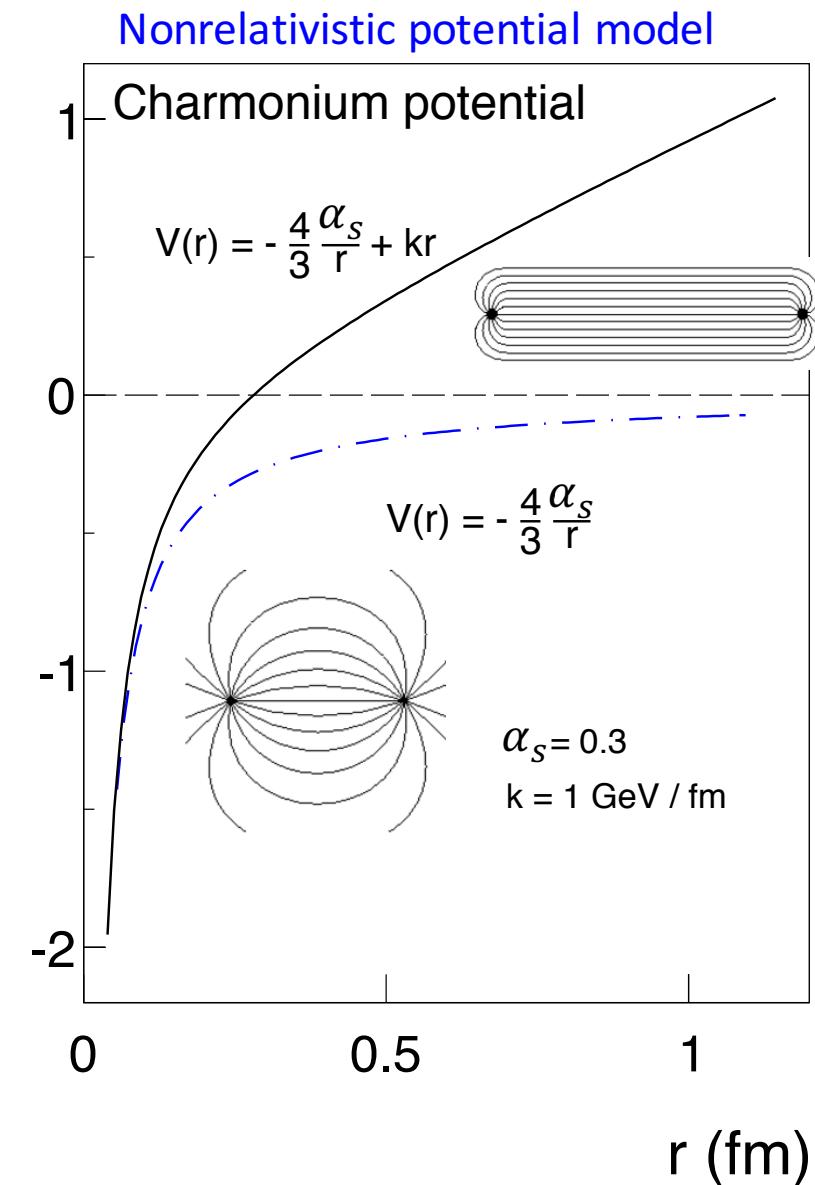
(Spin-spin)      (Spin-orbit)

+ ...

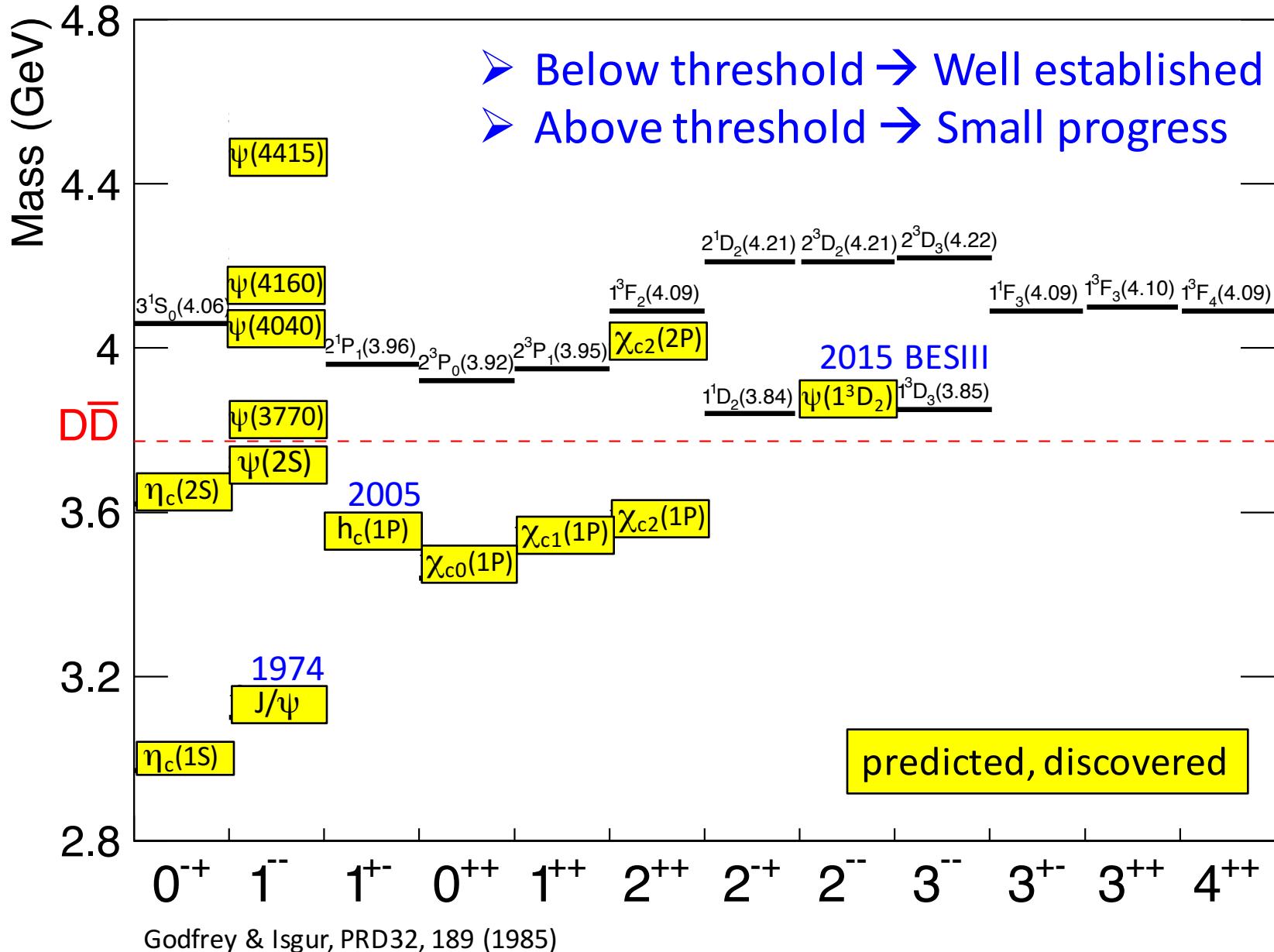
- Solve Schrödinger equation

$$[\frac{-\hbar^2}{2m} \nabla^2 + V(r)] \psi(r, \theta, \phi) = E_{nl} \psi(r, \theta, \phi)$$

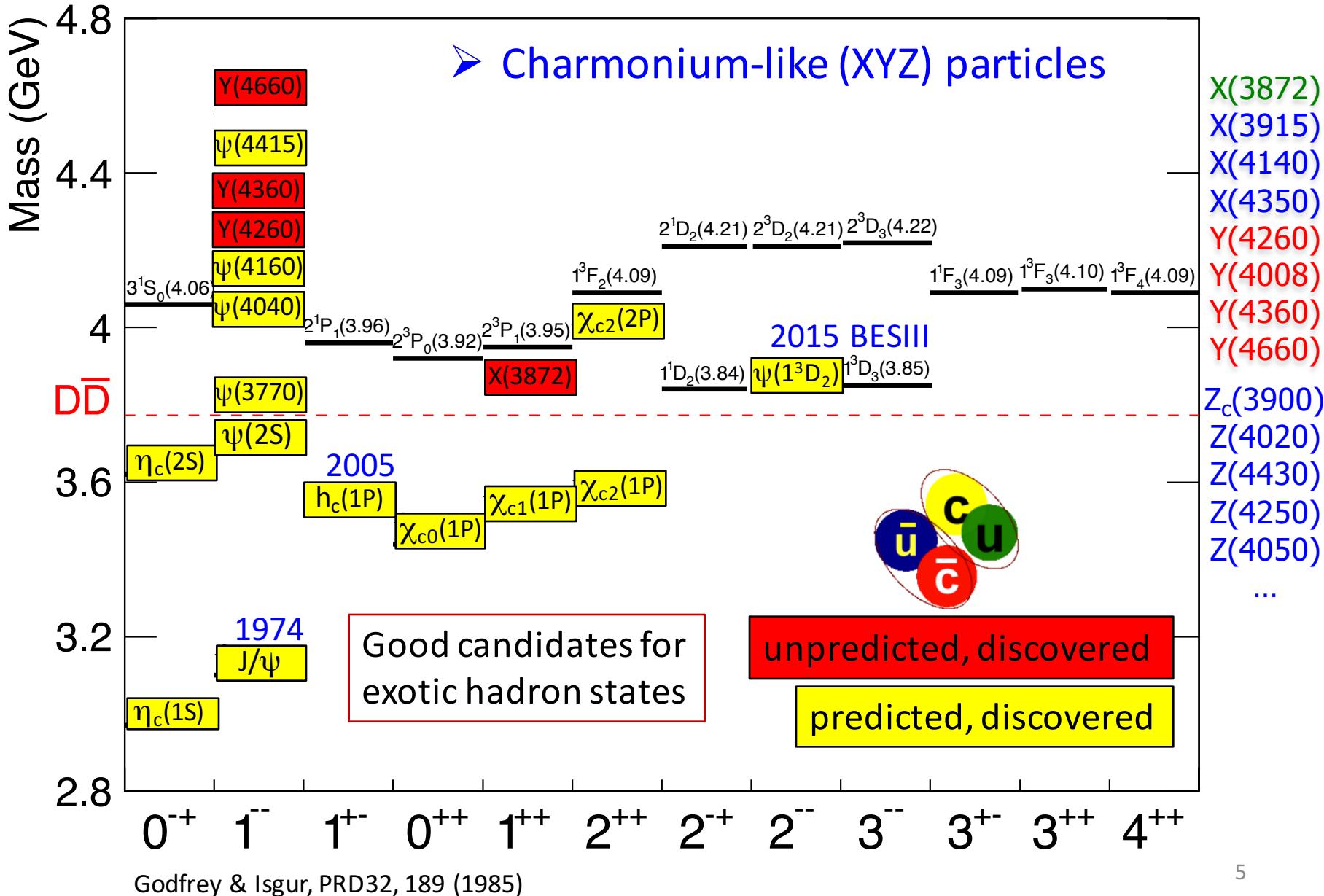
$$\psi(r, \theta, \phi) = R_{nl}(r) Y_{lm}(\theta, \phi)$$



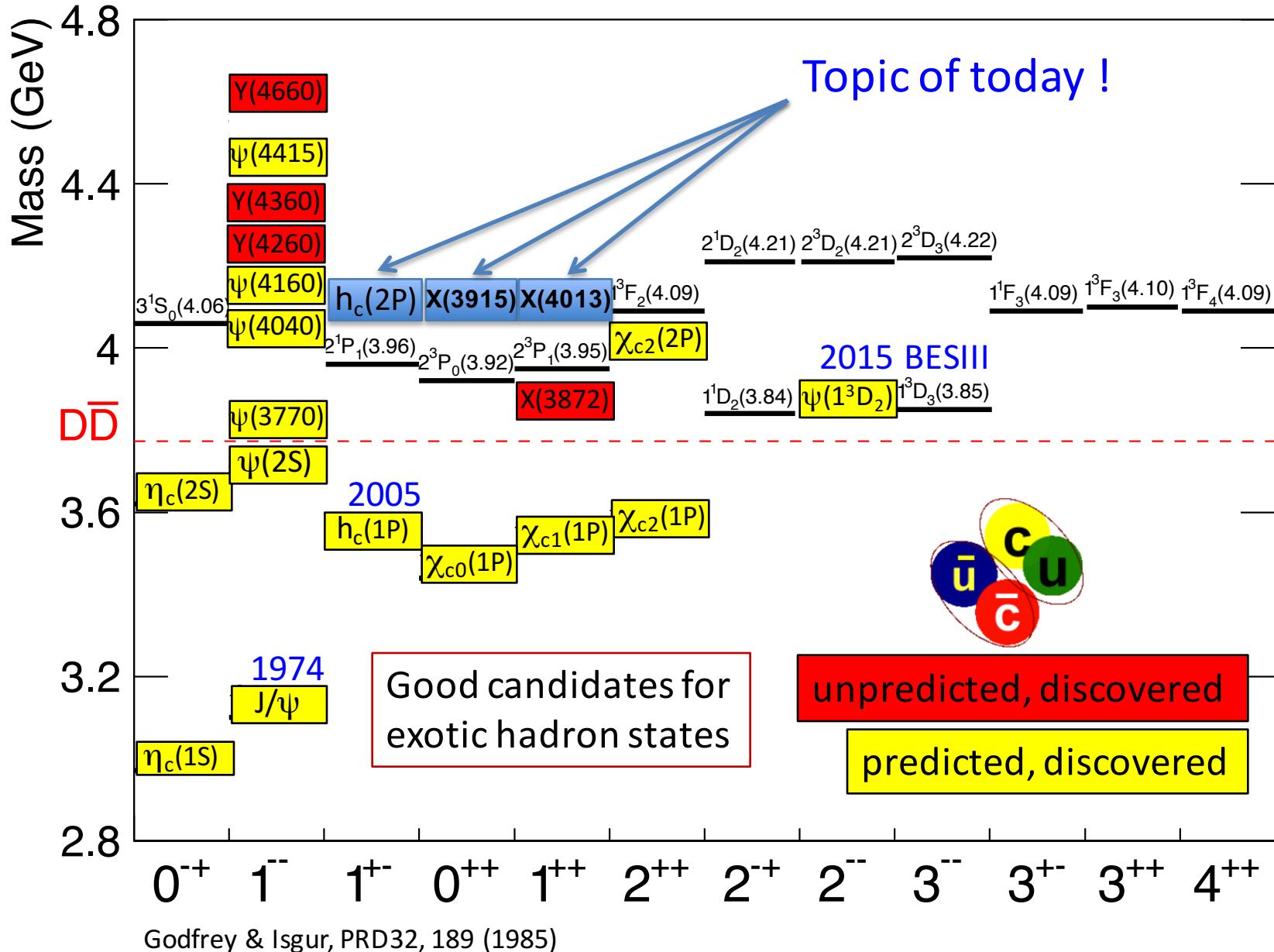
# Charmonium spectroscopy

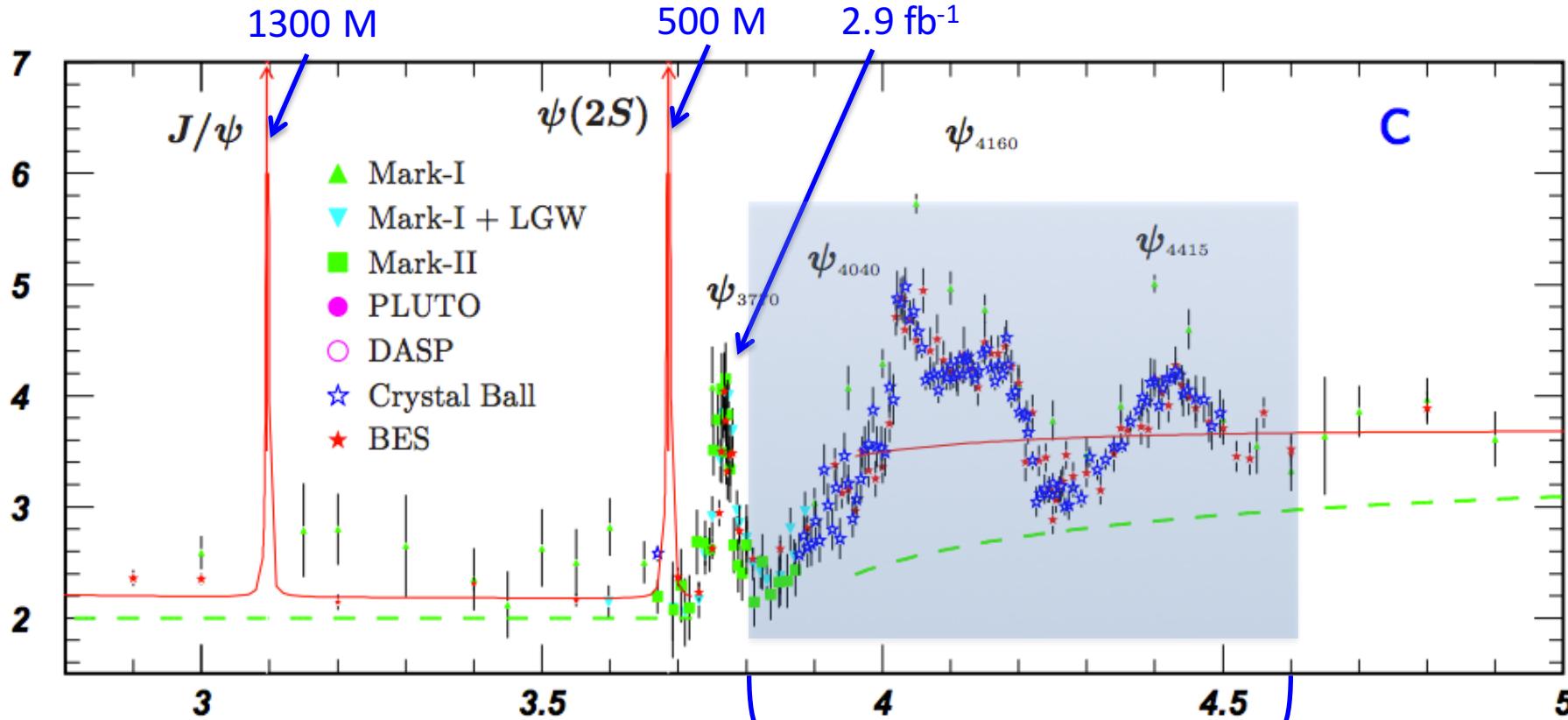


# Charmonium spectroscopy

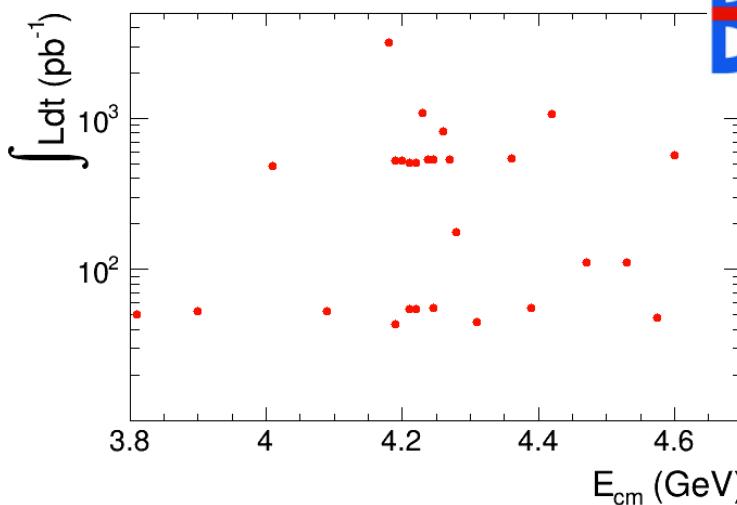


# Charmonium spectroscopy



**R**

Integrate luminosity between  
3.8 and 4.6 GeV  $\rightarrow \sim 12 \text{ fb}^{-1}$



**BES III**

# Search for the $h_c(2P)$

PHYSICAL REVIEW D **72**, 054026 (2005)

**$h_c(2P)$**

**$J^{PC}=1^{+-}$**

Multiplet	State	Expt.	Input (NR)	Theor. NR	Theor. GI
2P	$\chi_2(2^3P_2)$			3972	3979
	$\chi_1(2^3P_1)$			3925	3953
	$\chi_0(2^3P_0)$			3852	3916
	$h_c(2^1P_1)$			3934	3956

$$M(D) + M(D^*) \sim 3879.9 \pm 0.2 \text{ MeV}$$

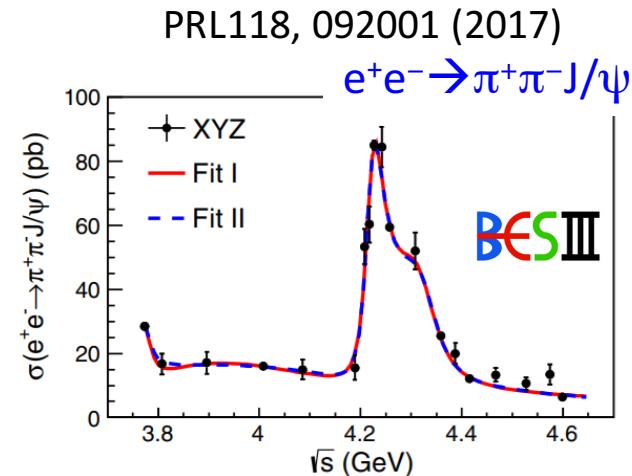
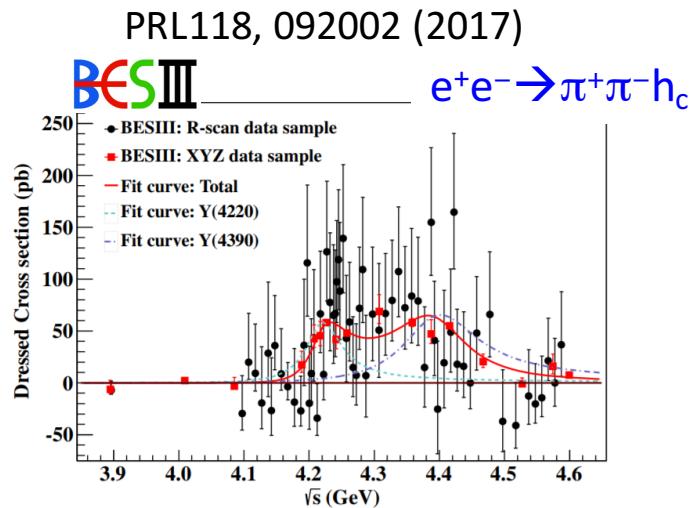
Meson	State	Mode	$\Gamma_{\text{thy}}$ (MeV)	Amps. ( $\text{GeV}^{-1/2}$ )
$h_c(3934)$	$2^1P_1$	$DD^*$	87	${}^3S_1 = -0.1847$ ${}^3D_1 = -0.0851$

Dominant decay channel is  $DD^*$  final state

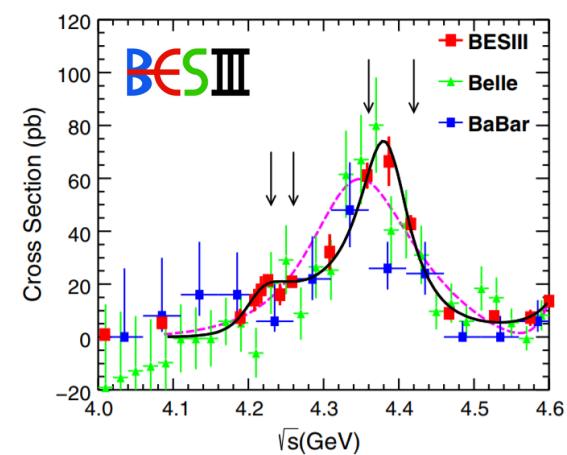
# Search for the $h_c(2P)$

$h_c(2P)$

$J^{PC}=1^{+-}$

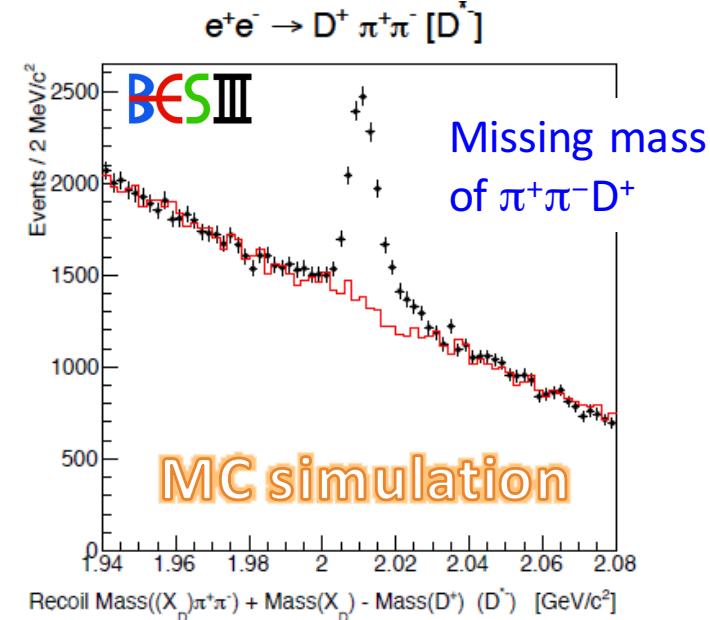
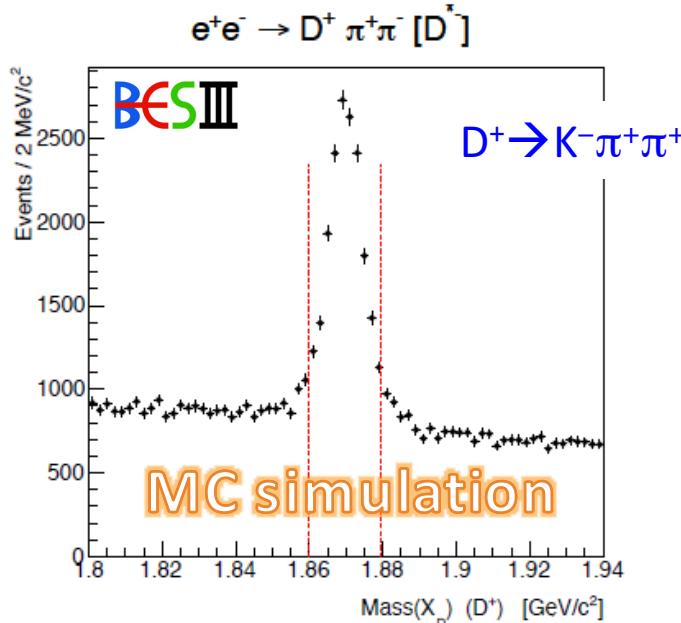


- How to produce  $h_c(2P)$  at BESIII?  $e^+e^- \rightarrow \pi^+\pi^- h_c(2P)$
- How large is the cross section?  $\sim 50 - 80$  pb
- Chance to hunt it via  $e^+e^- \rightarrow \pi^+\pi^- (DD^*)$  at BESIII



# Search for the $h_c(2P)$

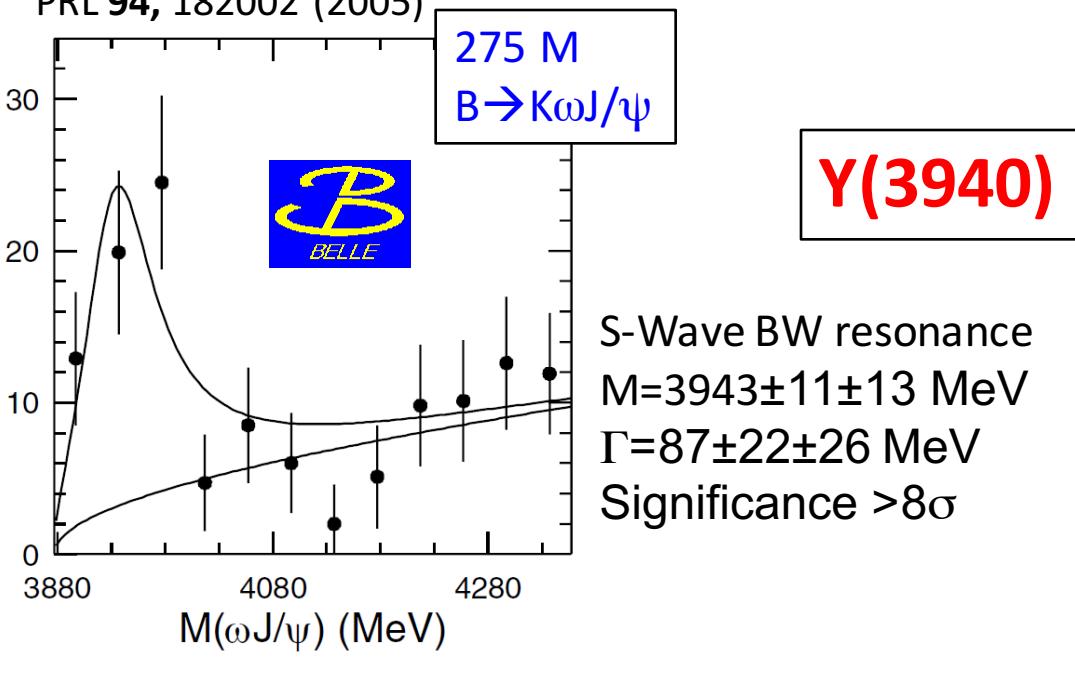
**$h_c(2P)$**



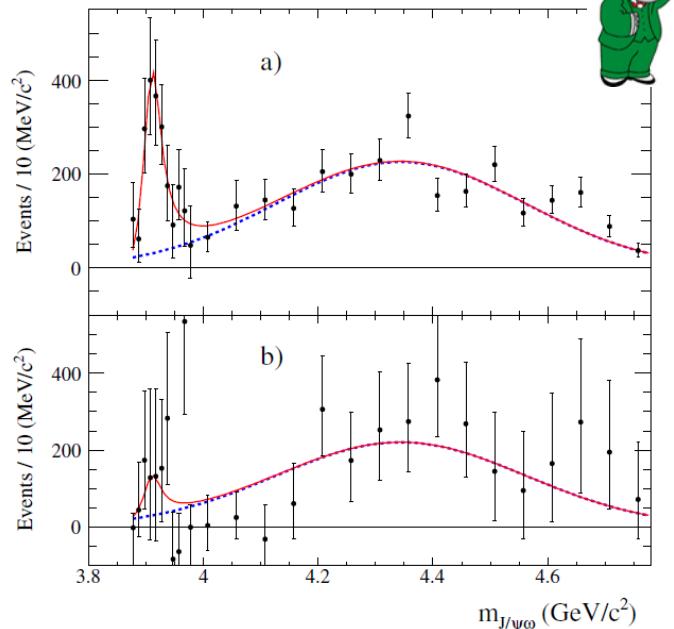
- Study  $e^+e^- \rightarrow \pi^+\pi^-D$  [ $D^*$ ] process, with the strategy of missing one  $D^*$
- The  $M(DD^*)$  mass distribution are then obtained by counting the  $D^*$  events in each  $M(DD^*)$  bin
- Data analysis is under progress.

# Study X(3915) at BESIII

PRL 94, 182002 (2005)



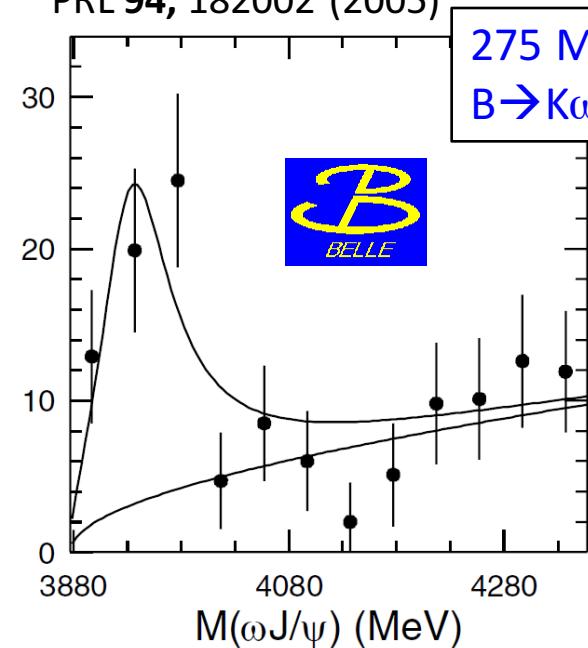
Confirmed in  
PRL 101, 082001 (2008)



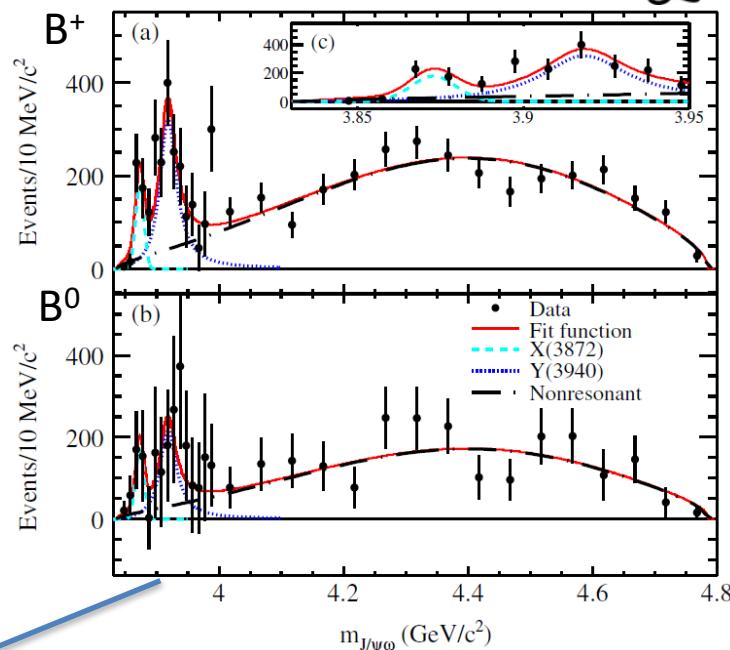
# Study X(3915) at BESIII

PRL 94, 182002 (2005)

275 M  
 $B \rightarrow K\omega J/\psi$



467 M Further precise measurement  
 PRD 82, 011101(R) (2010)



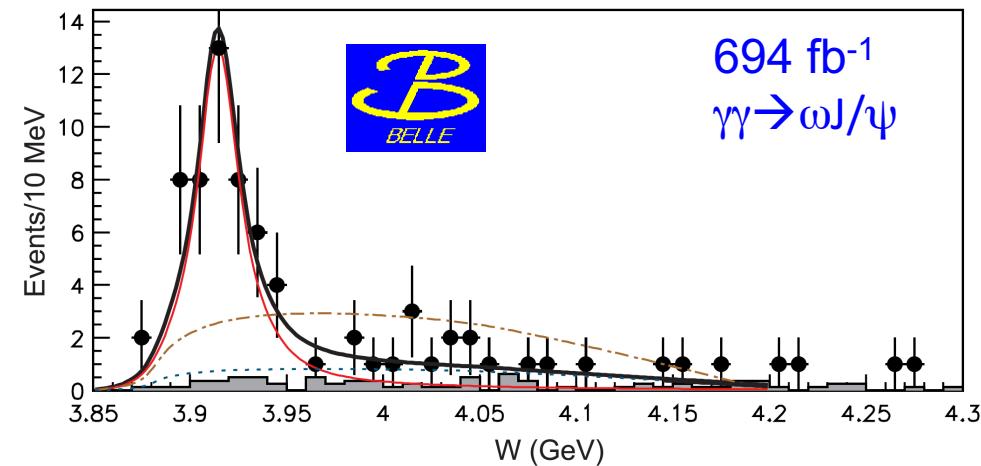
- The overlap of two resonances:  $Y(3940)$  and  $X(3872)$
- $M[Y(3940)] = 3919.1^{+3.8}_{-3.4} \pm 2.0$  MeV,  $\Gamma[Y(3940)] = 31^{+10}_{-8} \pm 5$  MeV
- $M[X(3872)] = 3873.0^{+1.8}_{-1.6} \pm 1.3$  MeV; significance  $4.0\sigma$

arXiv:0505037

$$\frac{\mathcal{B}(X \rightarrow \pi^+ \pi^- \pi^0 J/\psi)}{\mathcal{B}(X \rightarrow \pi^+ \pi^- J/\psi)} = 0.8 \pm 0.3 \text{ (BABAR)} \& 1.0 \pm 0.4 \pm 0.3 \text{ (Belle)}$$

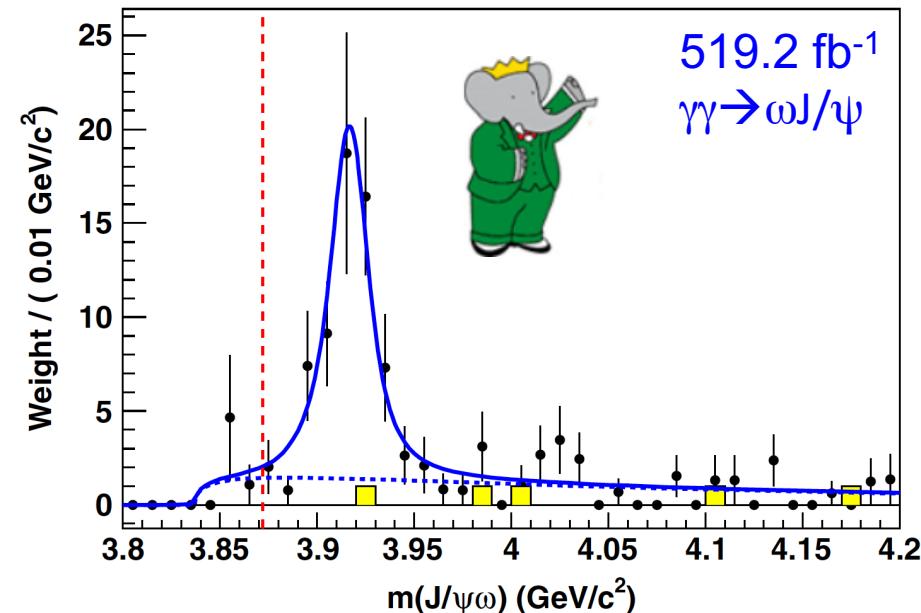
# Study X(3915) at BESIII

PRL 104, 092001 (2010)



$M = 3915 \pm 3 \pm 2 \text{ MeV}$   
 $\Gamma = 17 \pm 10 \pm 3 \text{ MeV}$   
 Significance  $7.7\sigma$

PRD 86, 072002 (2012)



$M = 3919.4 \pm 2.2 \pm 1.6 \text{ MeV}$   
 $\Gamma = 13 \pm 6 \pm 3 \text{ MeV}$   
 Significance  $7.6\sigma$

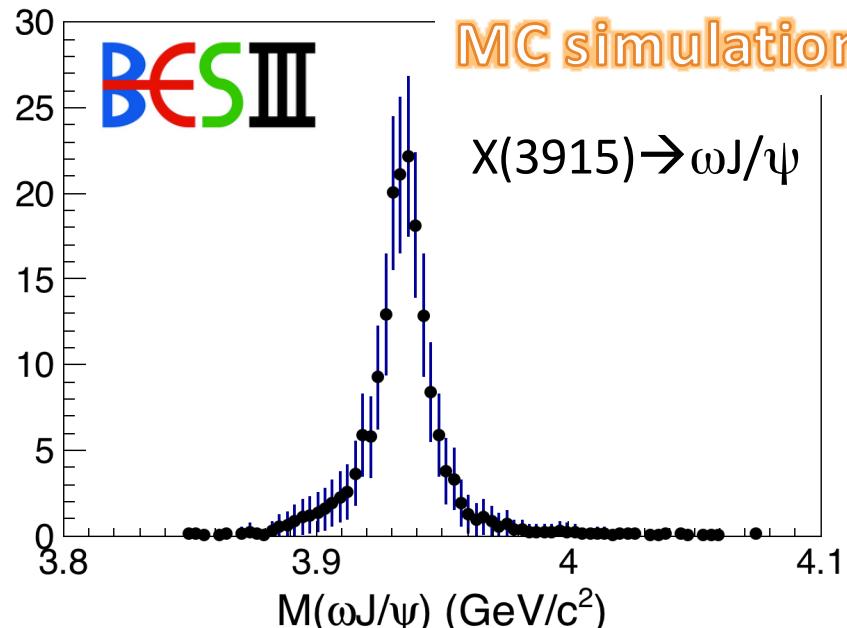
**PDG:** X(3915)=Y(3940)

$J^P = 0^+$ ,  $\chi_{c0}(2P)?$

[Belle, V. Zhukova]

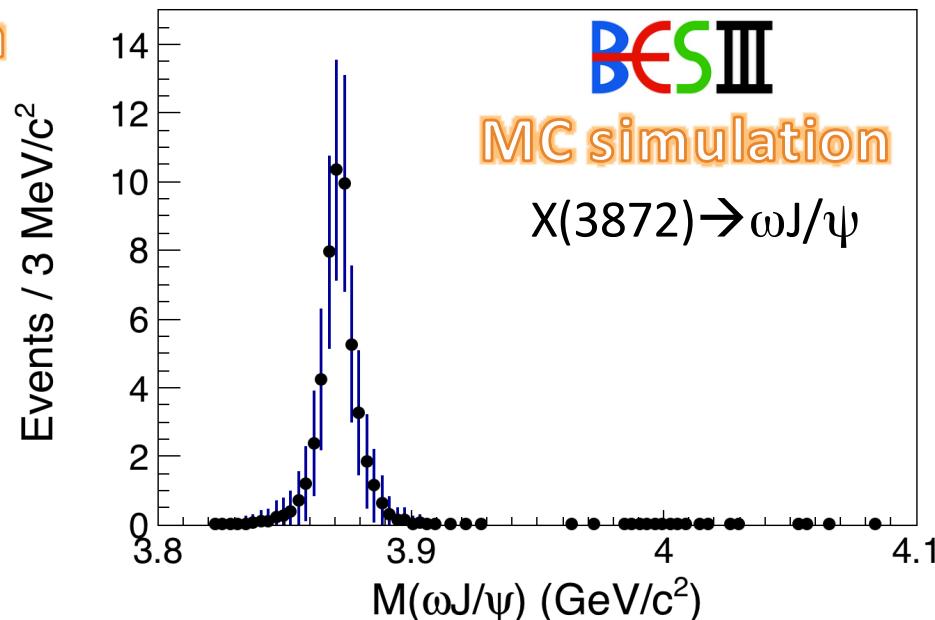
# Study X(3915) at BESIII

E1 radiative transition



[ PRD 72, 054026 (2005) ]

- Decay width 200 – 500 keV ( $\sim 250$  keV)
- Assume decay branching ratio  $\sim 10\%$



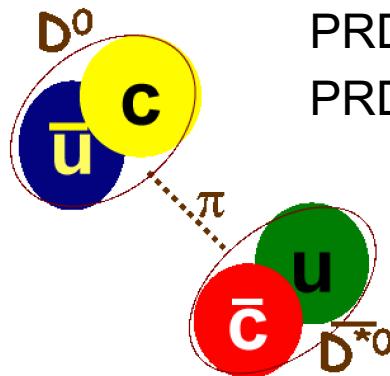
$$\frac{\mathcal{B}(X \rightarrow \pi^+ \pi^- \pi^0 J/\psi)}{\mathcal{B}(X \rightarrow \pi^+ \pi^- J/\psi)} = 1.0$$

BESIII has high potential to hunt X(3915) and measure X(3872) decay

# Search for the $X(4013)$ at BESIII

$X(3872)$

$J^{PC}=1^{++}$



$D^0 - \bar{D}^{*0}$  "molecule"

PRD 86, 056004 (2012)

PRD 87, 076006 (2013)

$X_2(4013)$

$J^{PC}=2^{++}$

[ $D^*D^*$ ] Partner

**Heavy Quark Spin Symmetry (HQSS)**

PRD 81, 014029 (2010)

$$M_{X_2} - M_{X(3872)} \approx M_{D^*} - M_D \approx 140 \text{ MeV}$$

**M[ $X_2(4013)$ ]~4013 MeV**

# Search for the X(4013) at BESIII

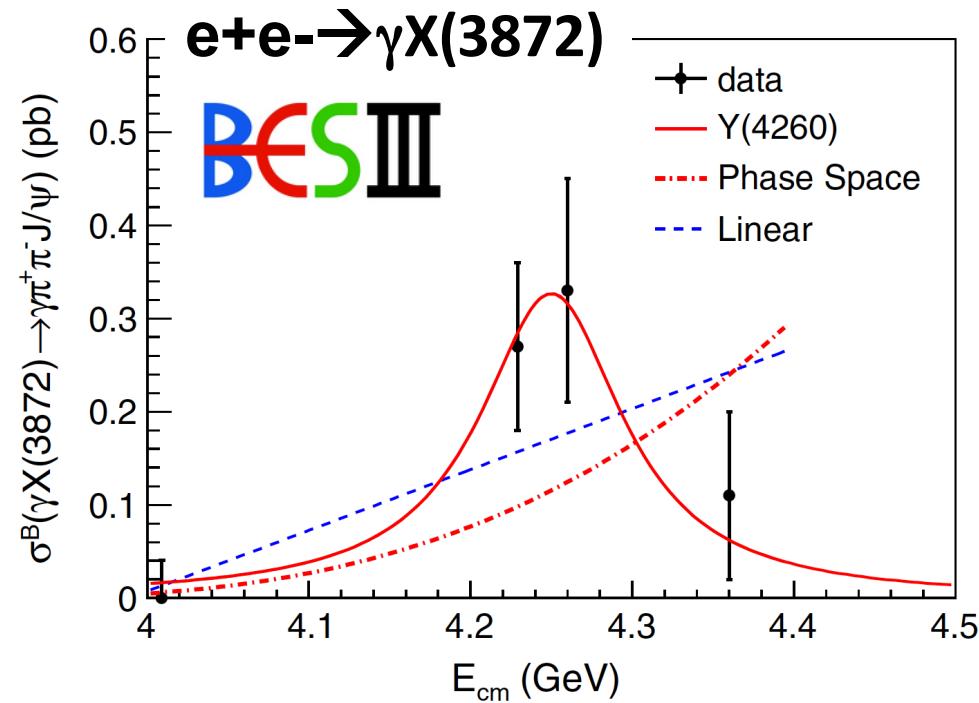
**X<sub>2</sub>(4013)**

Feng-Kun Guo et al., arXiv:1504.00861.

J<sup>PC</sup>=2<sup>++</sup>

$$\Gamma(X_2 \rightarrow D\bar{D}) = (1.2 \pm \underbrace{0.3}_{sys(\Lambda)} {}^{+1.3}_{-0.4}) \text{ MeV}.$$

$$\Gamma(X_2 \rightarrow D\bar{D}^*) + \Gamma(X_2 \rightarrow D^*\bar{D}) = (2.9 \pm \underbrace{0.5}_{sys(\Lambda)} {}^{+2.0}_{-1.0}) \text{ MeV}.$$

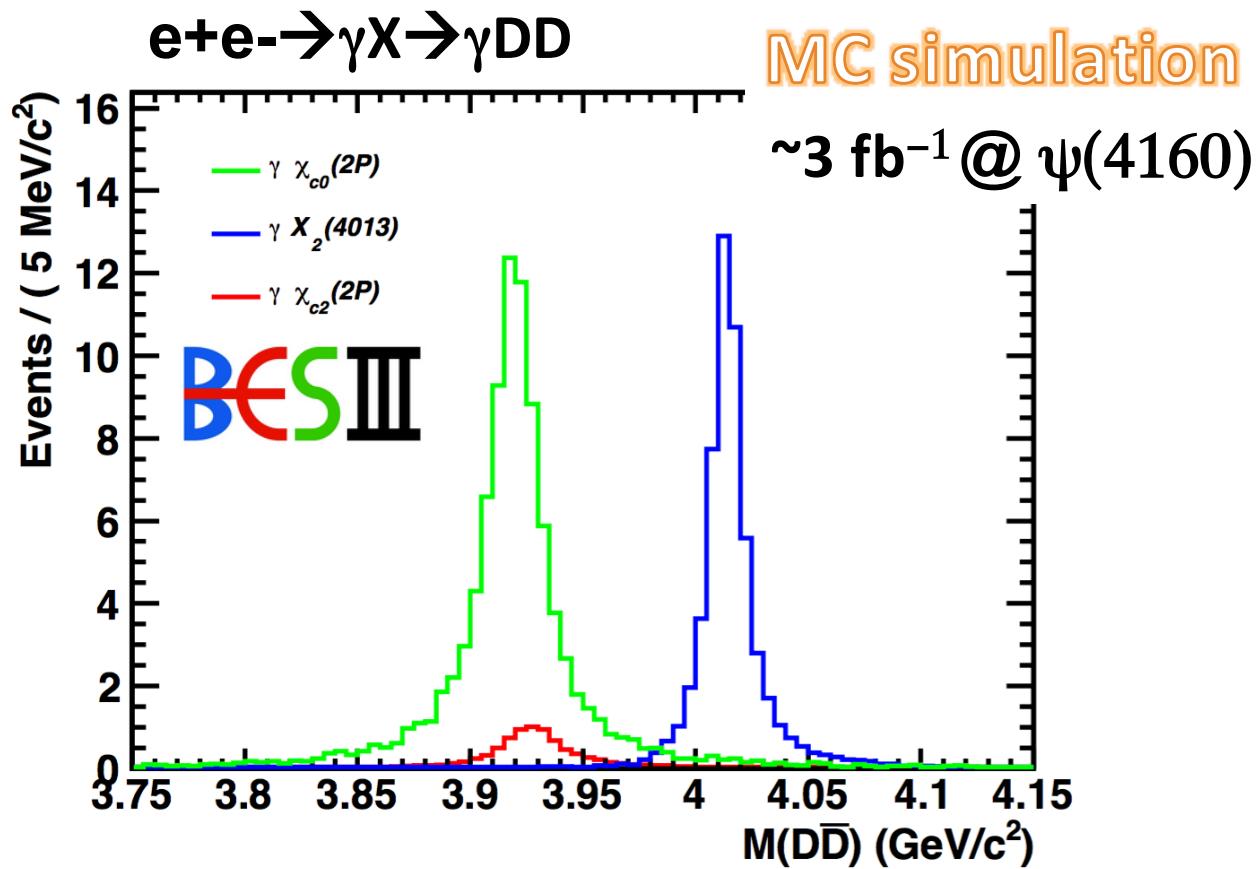


- Produce the X(3872) with E1 radiative transition
- $e+e-\rightarrow\gamma X(4013)$  similar?

# Search for the X(4013) at BESIII

X(4013)

$J^{PC}=2^{++}$



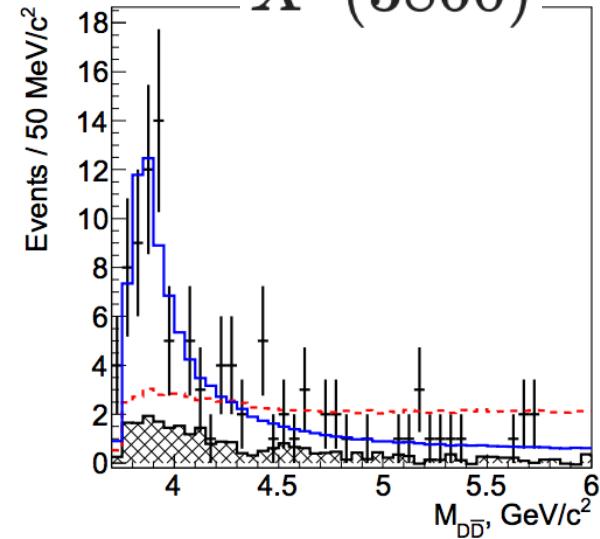
- Assume similar production cross section with X(3872)
- Possible  $\chi_{c0}(2P)$  &  $\chi_{c2}(2P)$  candidate [arXiv:1201.4155]

# Summary

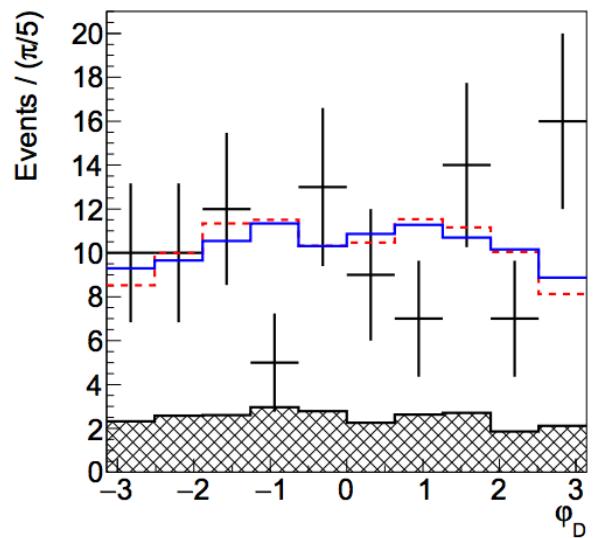
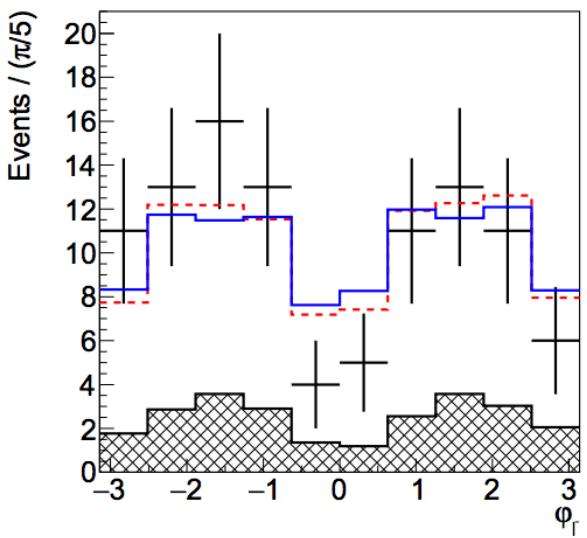
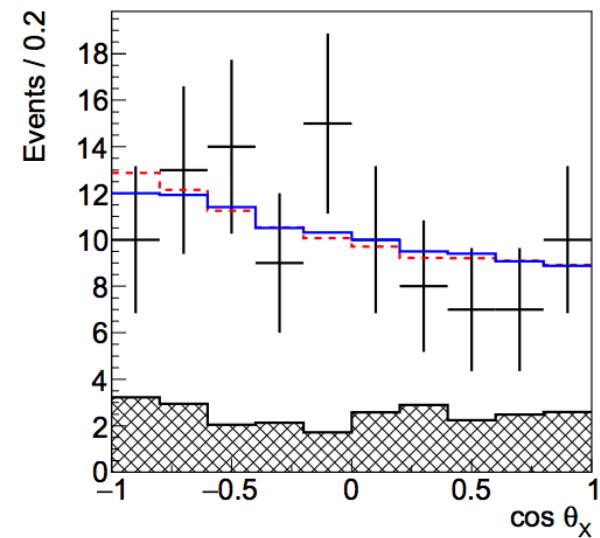
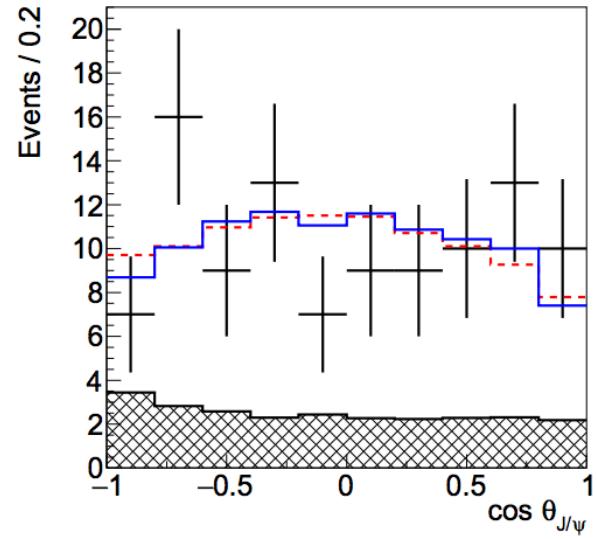
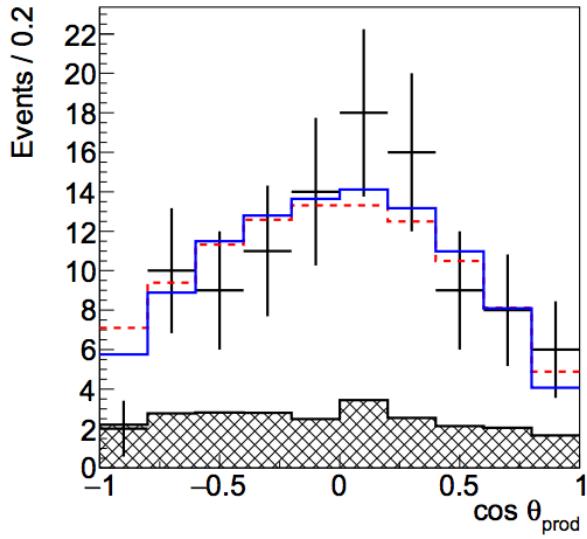
- BESIII has accumulated  $\sim 12 \text{ fb}^{-1}$  data for the study of XYZ particles
- Good chance to search for the missing charmonium state, such as  $h_c(2P)$ ,  $\chi_{c0,c2}(2P)$
- High potential to study the charmoniumlike state, such as X(3915) and X(4013)

Thank you (谢谢) !

$X^*(3860)$



Belle, Phys. Rev. D 95, 112003 (2017)



Mass:  $(3862^{+26+40}_{-32-13}) \text{ MeV}/c^2$

Width:  $(201^{+154+88}_{-67-82}) \text{ MeV}$