

# “Relativistic Nuclear Physics and Quantum Chromodynamics”

XXII International Baldin Seminar on High Energy Physics Problems

15<sup>th</sup> - 20<sup>th</sup> September 2014

JINR - Dubna (RUSSIA)



## Highlights on BESIII results

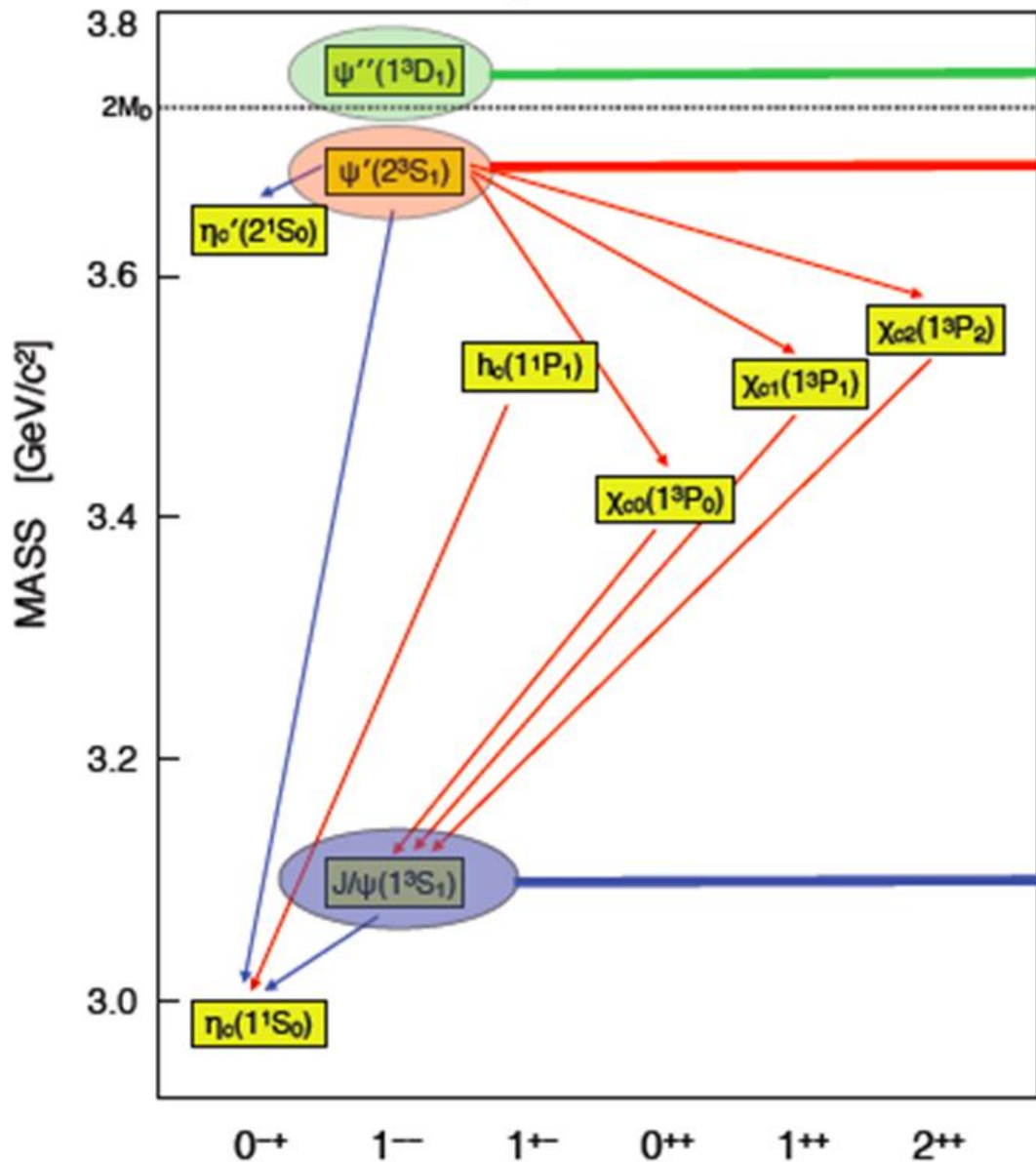
Marco Maggiora on behalf of the BESIII Collaboration

Department of Physics and INFN – Turin, Italy



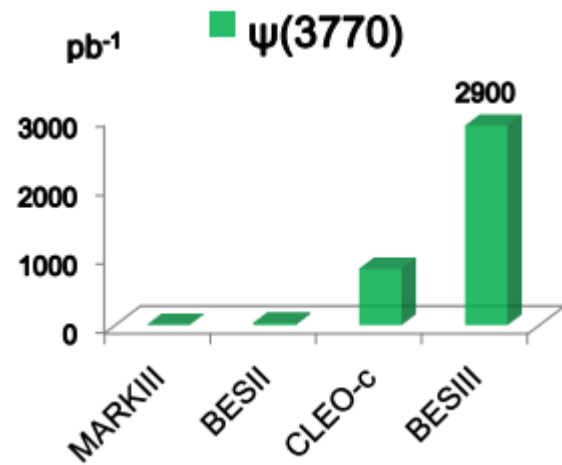


# BESIII data set

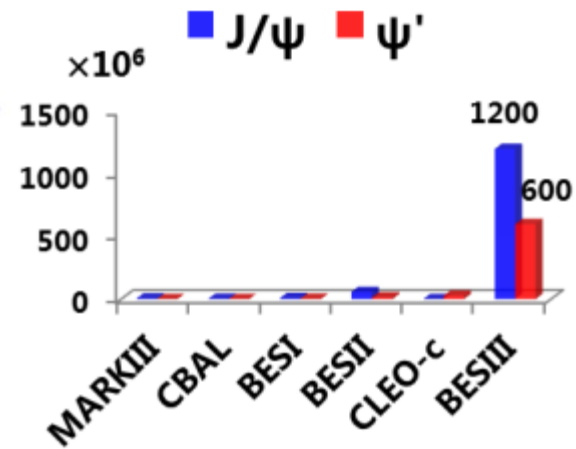


2.9 fb<sup>-1</sup> / 20 fb<sup>-1</sup>

0.6 B / 3 B (106 M)

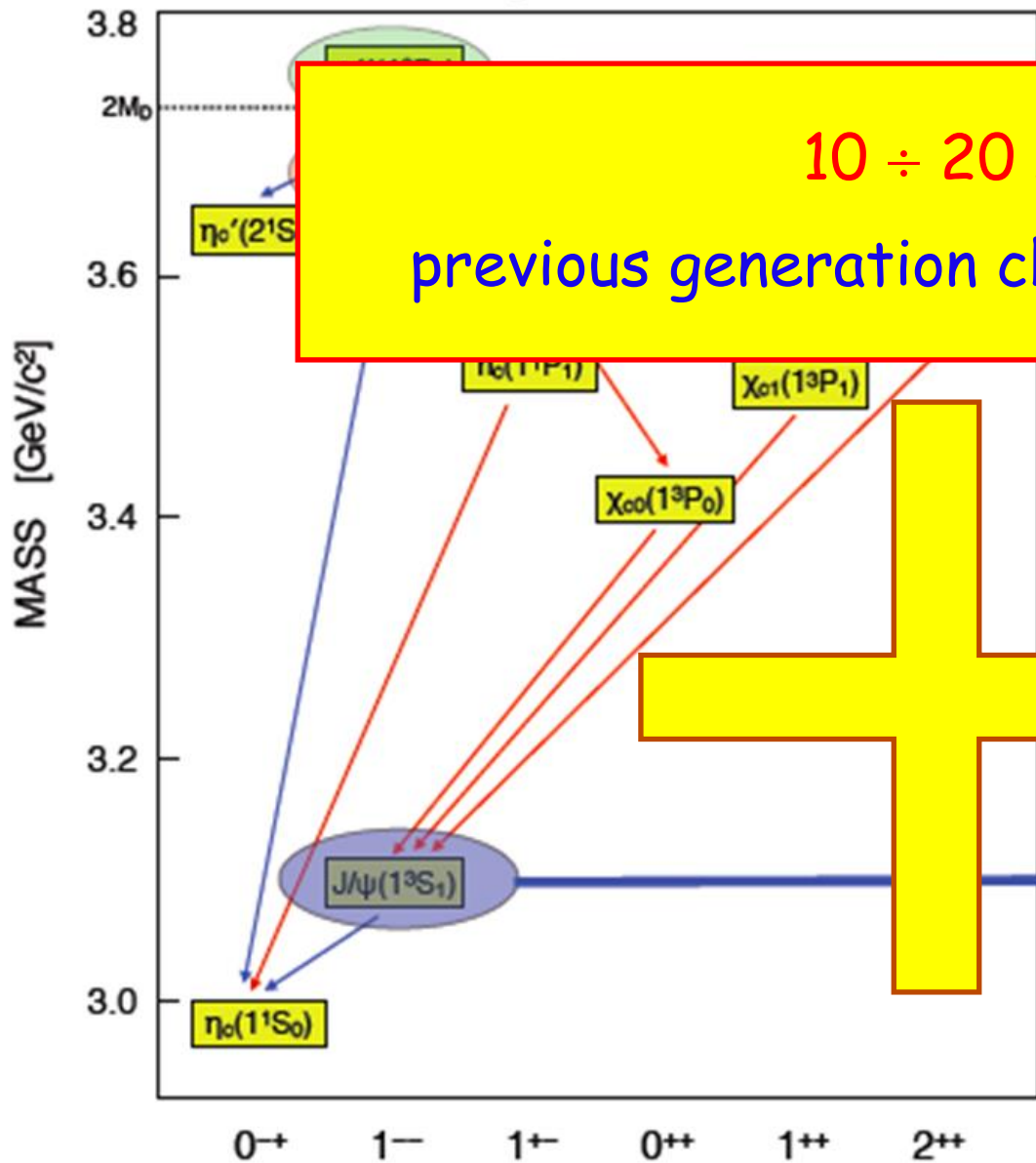


1.3 B / 10 B (225 M)

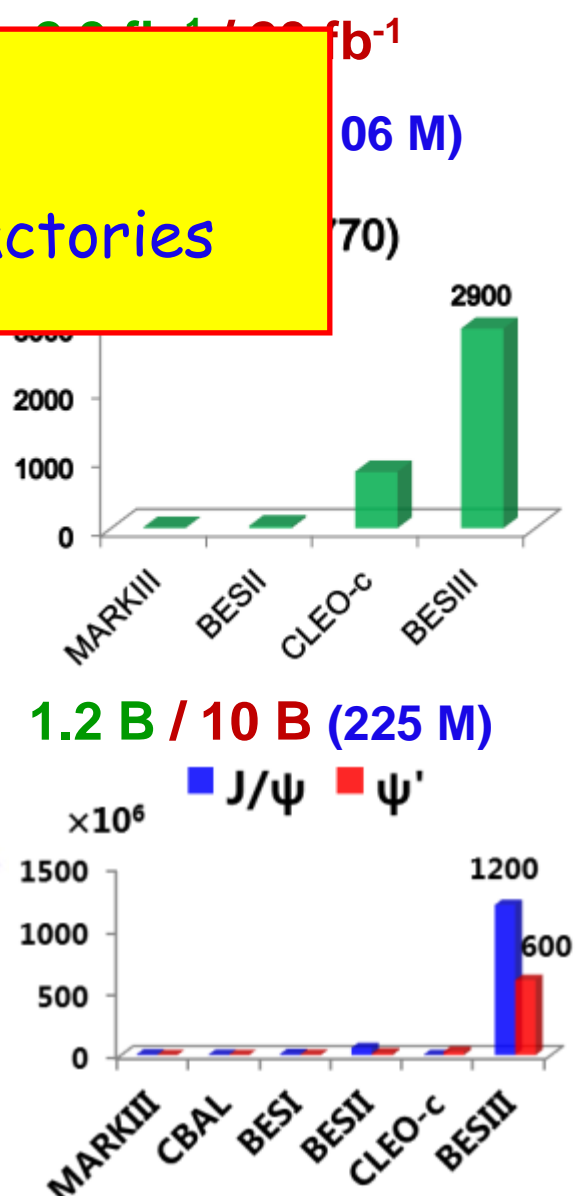




# BESIII data set



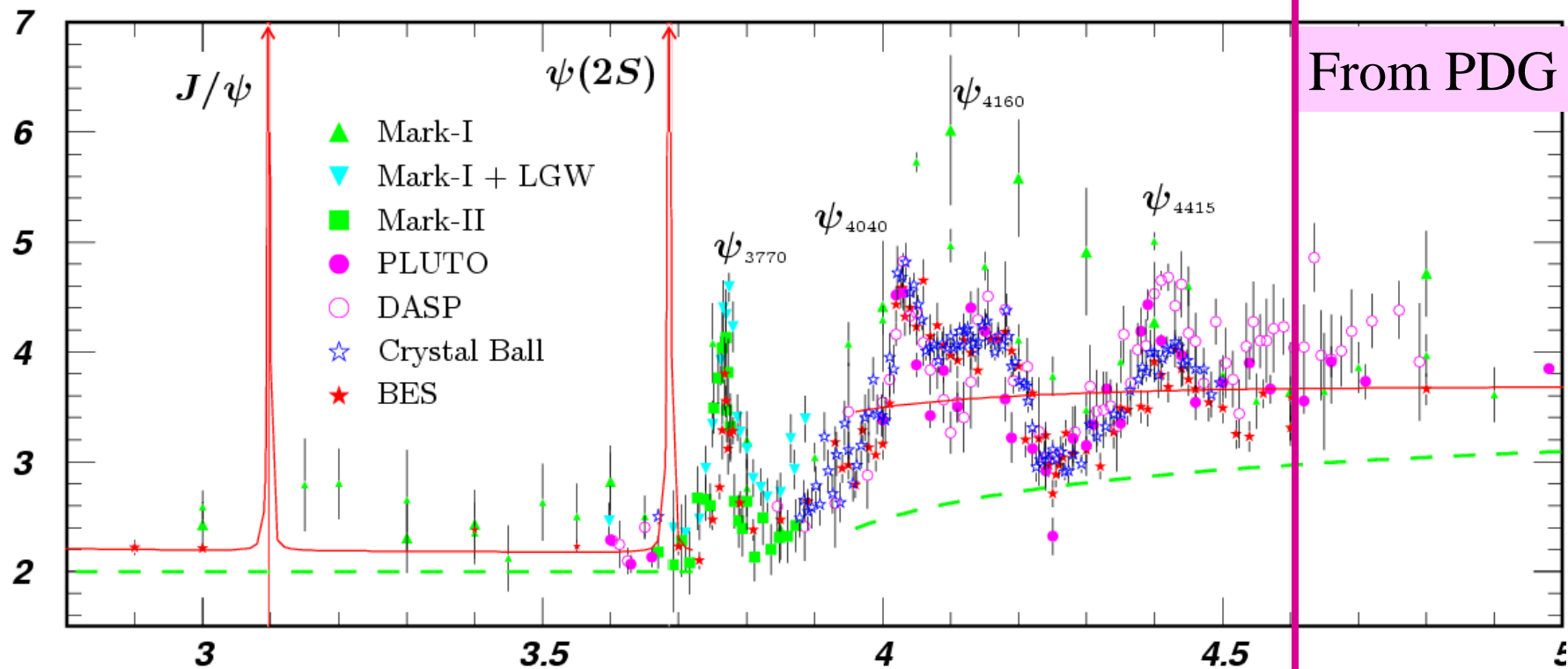
10 ÷ 20 ×  
previous generation charm factories





# BESIII production of Charmonium(like) states

$R$

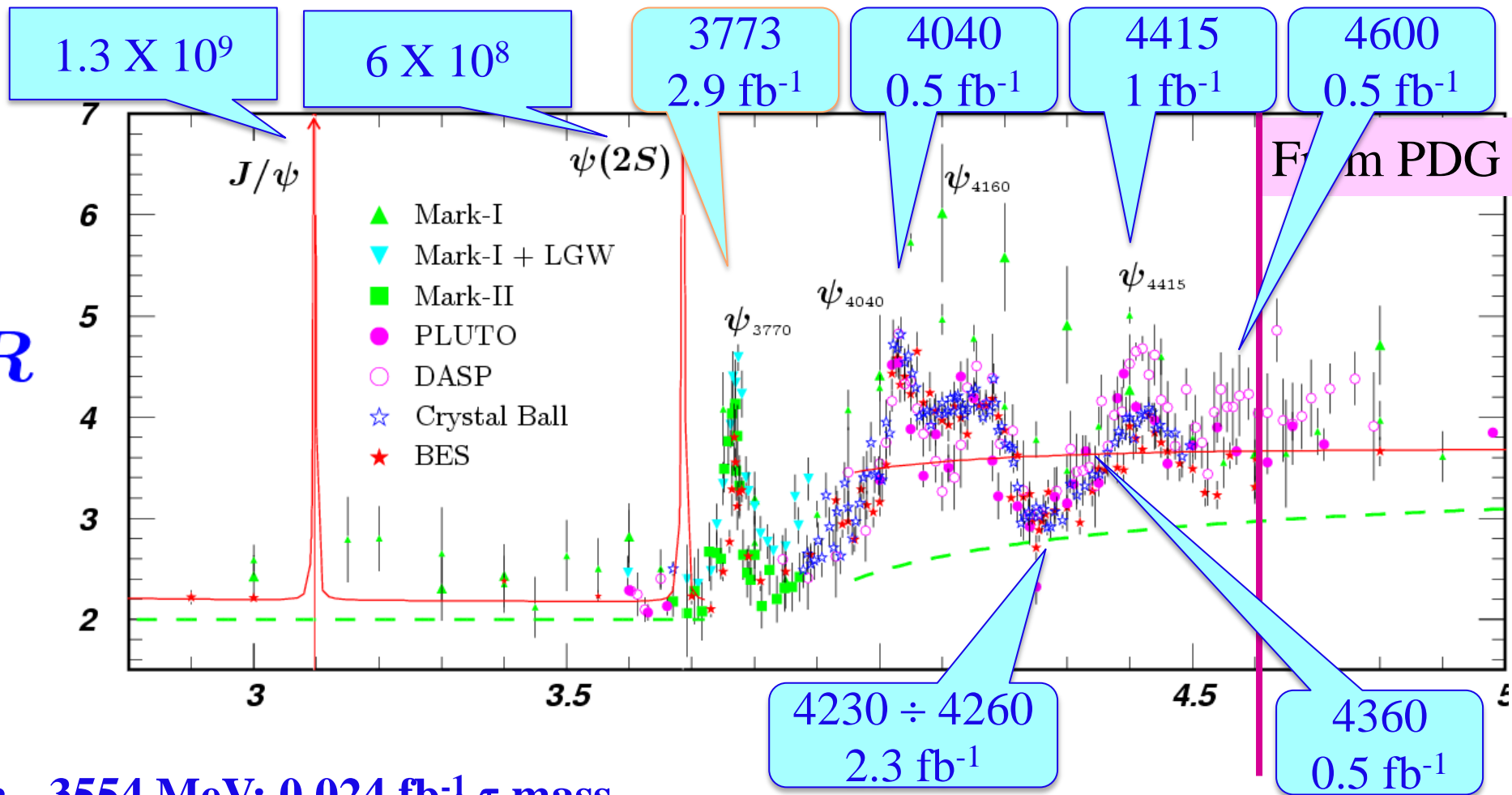


BEPCII can reach here!



# BESIII production of Charmonium(like) states

$R$



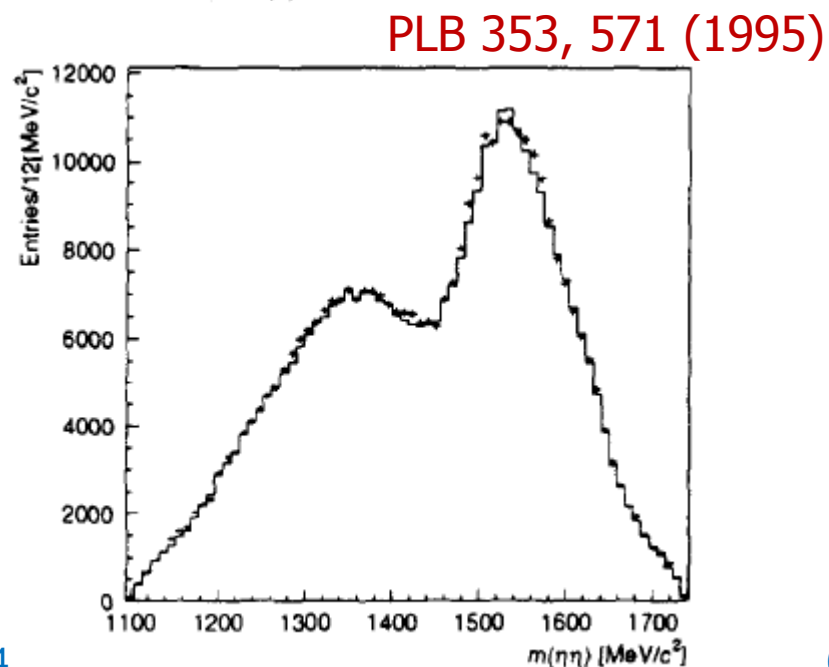
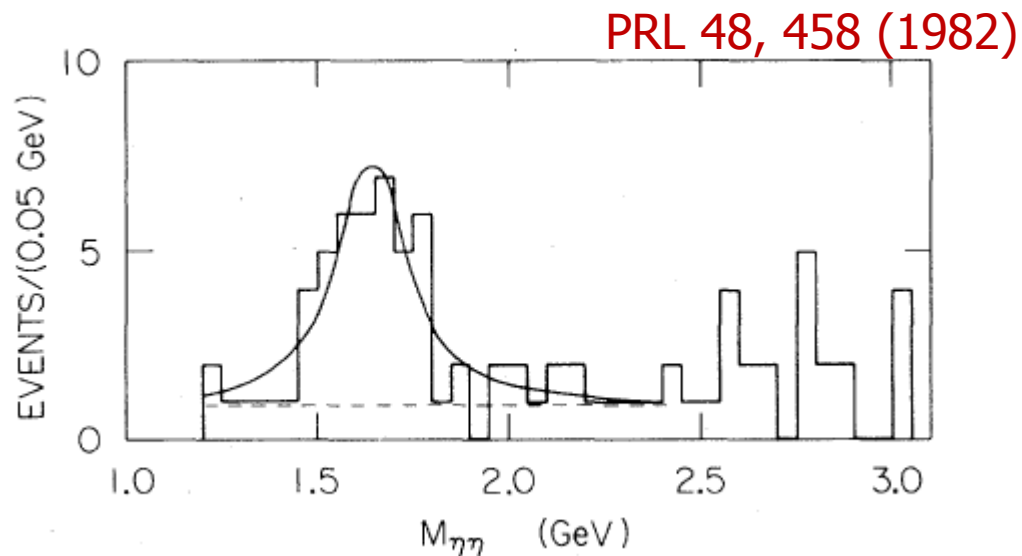
- 3554 MeV: 0.024 fb<sup>-1</sup>  $\tau$  mass
- 4100 ÷ 4400 MeV: 0.5 fb<sup>-1</sup> coarse scan
- 3850 ÷ 4590 MeV: 0.5 fb<sup>-1</sup> fine scan

BEPCII can reach here!



# $J/\psi \rightarrow \gamma\eta\eta$

- first studied by Crystal Ball (1982):  
 $f_0(1710)$
- Crystal Barrel (1995):  
 $f_0(1500)$  [ $p\bar{p} \rightarrow \pi^0\eta\eta$ ]
- E835 (2006):  
 $f_0(1500)$  [ $p\bar{p} \rightarrow \pi^0\eta\eta$ ]  
 $f_0(1710)$  [ $p\bar{p} \rightarrow \pi^0\eta\eta$ ]
- WA102, GAMS:  
 $f_0(1500)$  [ $\eta\eta$  mode]





## best solution:

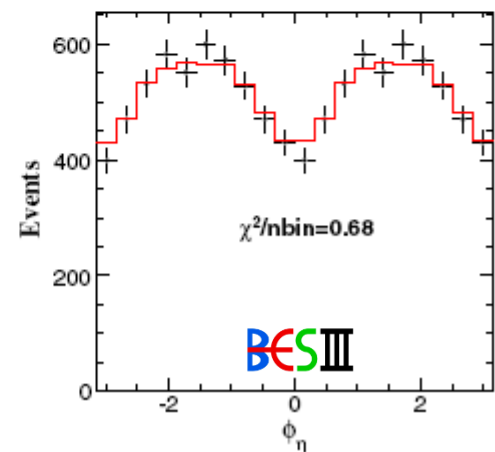
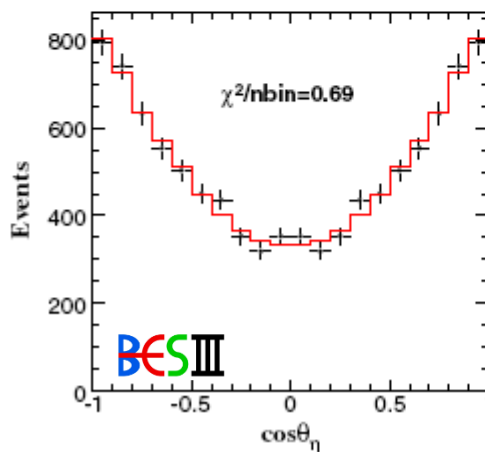
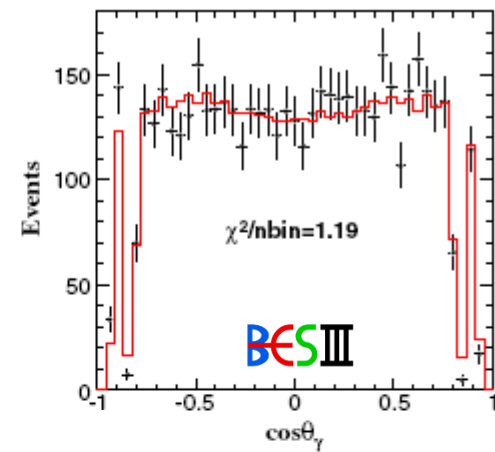
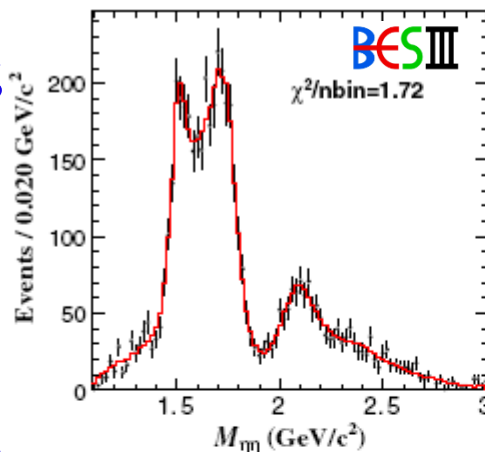
- $f_0(1500), f_0(1710), f_0(2100);$   
 $f_2'(1525), f_2(1810), f_2(2340);$   
 $0^{++}$  phase space,  $\phi\eta$

## no significant evidence of:

- scalar:  
 $f_0(1370), f_0(1790), f_0(2020)$   
 $f_0(2200), f_0(2330)$
- tensor:  
 $f_2(2010), f_2(2150), f_J(2220)$   
 source of sys. unc.

## $\phi\eta$ background:

- interference of  $\phi$  tail accounted for
- source of systematic uncertainties





Resonance	Mass(MeV/c <sup>2</sup> )	Width(MeV/c <sup>2</sup> )	$\mathcal{B}(J/\psi \rightarrow \gamma X \rightarrow \gamma\eta\eta)$	Significance
$f_0(1500)$	$1468^{+14+23}_{-15-74}$	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	$8.2 \sigma$
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	$25.0 \sigma$
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	$273^{+27+70}_{-24-23}$	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	$13.9 \sigma$
$f'_2(1525)$	$1513 \pm 5^{+4}_{-10}$	$75^{+12+16}_{-10-8}$	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	$11.0 \sigma$
$f_2(1810)$	$1822^{+29+66}_{-24-57}$	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	$6.4 \sigma$
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	$7.6 \sigma$

**no significant evidence of:**

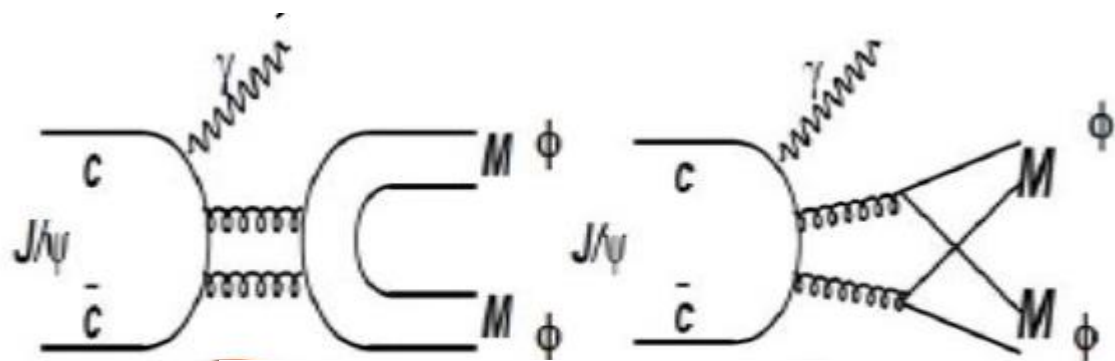
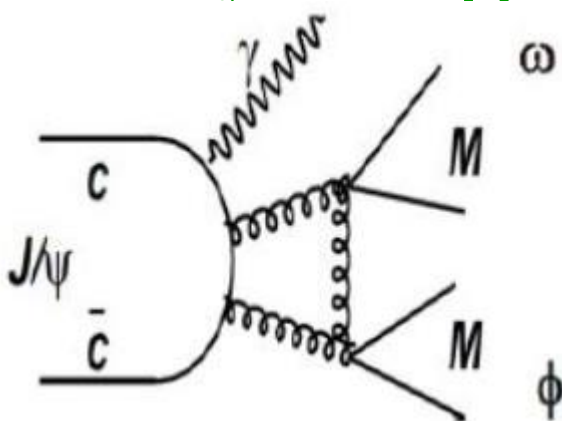
- scalar:  $f_0(1370)$ ,  $f_0(1790)$ ,  $f_0(2020)$ ,  $f_0(2200)$ ,  $f_0(2330)$
- tensor:  $f_2(2010)$ ,  $f_2(2150)$ ,  $f_J(2220)$





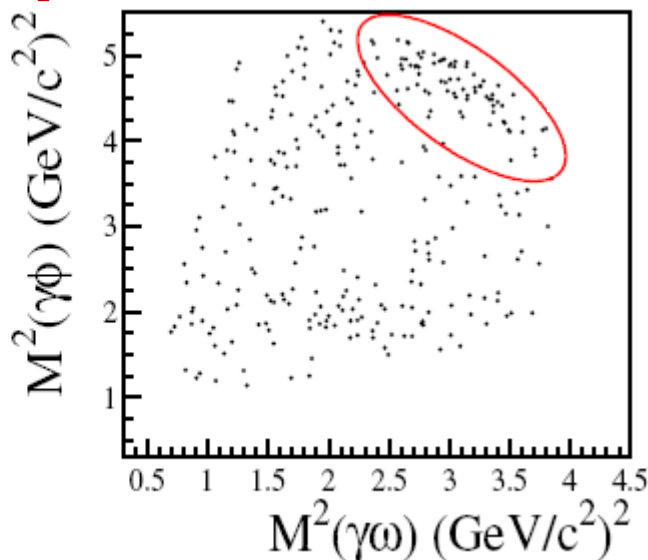
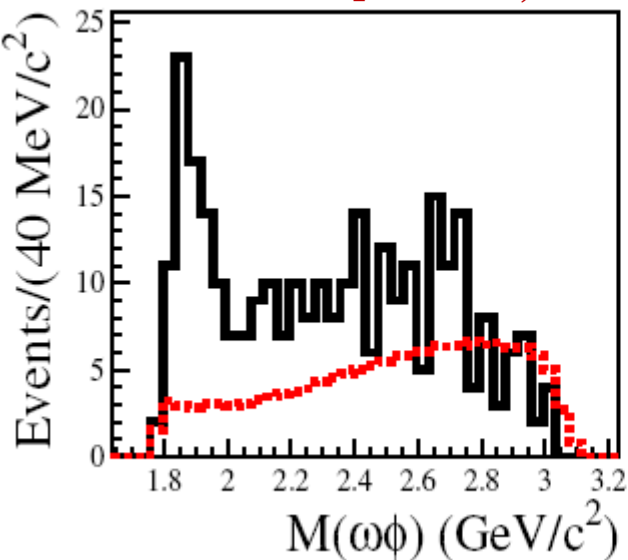
# $J/\psi \rightarrow \gamma \omega \phi$

- doubly OZI suppressed



$\psi \rightarrow \gamma \omega \phi$  (DOZI) predicted  $\propto 1/10$      $\psi \rightarrow \gamma \phi \phi$  (OZI)

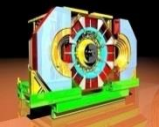
- BESII: [PRL 96, 162002]



$$M = (1812^{+19}_{-26} \pm 18) \text{ MeV}/c^2$$

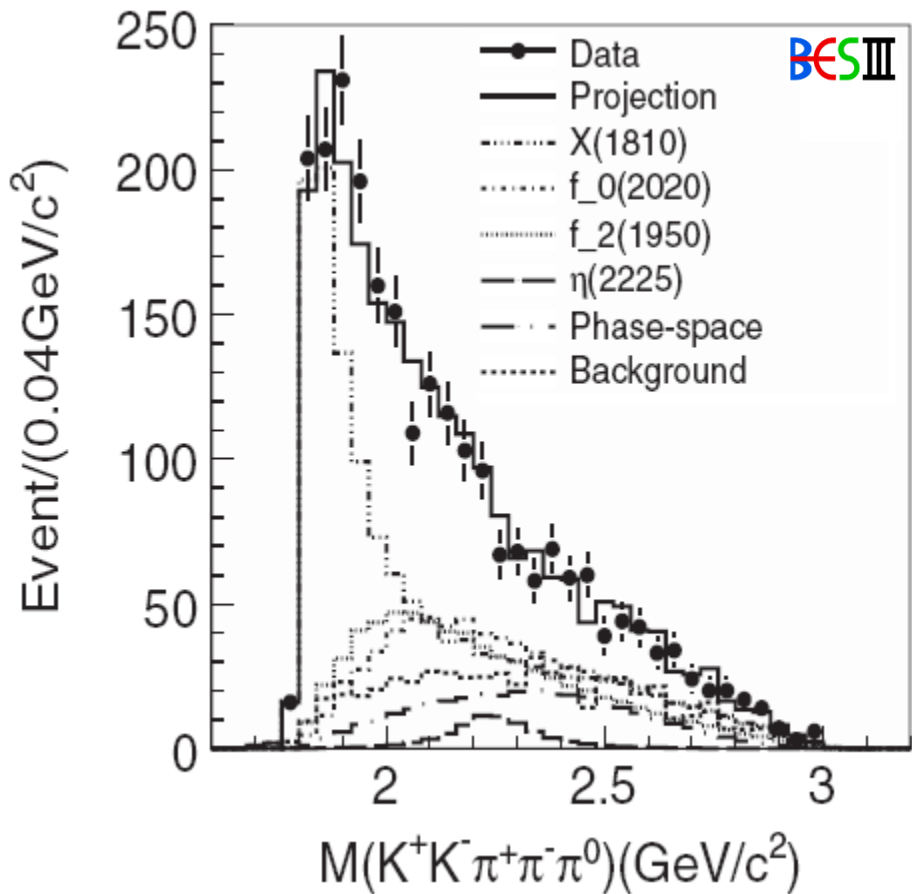
$$\Gamma = (105 \pm 20 \pm 28) \text{ MeV}/c^2$$

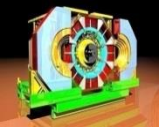
$0^{++}$  favoured over  
 $0^+$  and  $2^{++}$



- **looking for best solution:**
  - $M, \Gamma$  and  $J^{PC}$  of  $X(1810)$
  - other know mesons [PDG]
  - different  $J^{PC}$  of phase space
  - different combinations of additional mesons [PDG]
- **best solution:**

$X(1810), f_0(2020), f_2(1950), \eta(2225), f_0(2020),$  phase space and background
- **systematic uncertainties:**
  - $f_2(1920), f_0(2020), \eta(2225)$ : standard deviation from PDG, replacing by other of similar mass but same  $J^{PC}$
  - model dependence





- **X(1810) resonance parameters:**

$$M = 1795 \pm 7(\text{stat})_{-5}^{+13}(\text{sys}) \pm 19(\text{mod}) \text{ MeV}/c^2$$

$$\Gamma = 95 \pm 10(\text{stat})_{-34}^{+21}(\text{sys}) \pm 75(\text{mod}) \text{ MeV}/c^2$$

$$\mathcal{B}(J/\psi \rightarrow \gamma X(1810)) \times \mathcal{B}(X(1810) \rightarrow \omega\phi) =$$

$$(2.00 \pm 0.08(\text{stat})_{-1.00}^{+0.45}(\text{sys}) \pm 1.30(\text{mod})) \times 10^{-4}$$

- **confirmed @ BESIII: best solution:**

$$J^{PC} = 0^{++}$$

- **X(1810) vs  $f_0(1710)$ :**

unconclusive, further investigation is needed

- **search for X(1810):**

- in other decay modes:  $K^*K^*$ ,  $\omega\omega$ , ...

[ $J/\psi \rightarrow \gamma\eta(1760)$ ,  $\eta(1760) \rightarrow \omega\omega$  observed by BESII: PRD 73, 112007]

- in other production processes:  $J/\psi \rightarrow \phi\omega\phi$ ,  $J/\psi \rightarrow \omega\phi\omega$

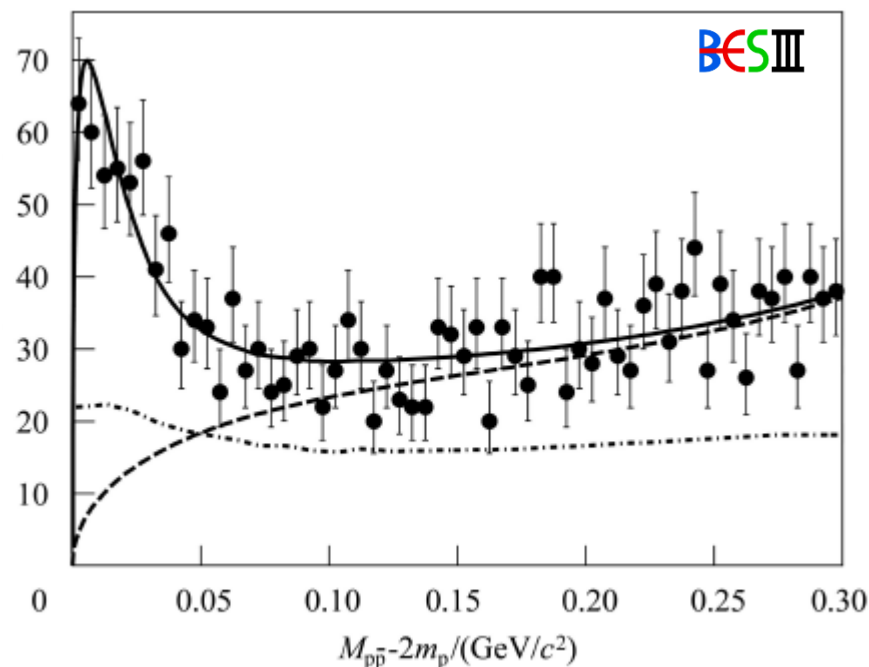
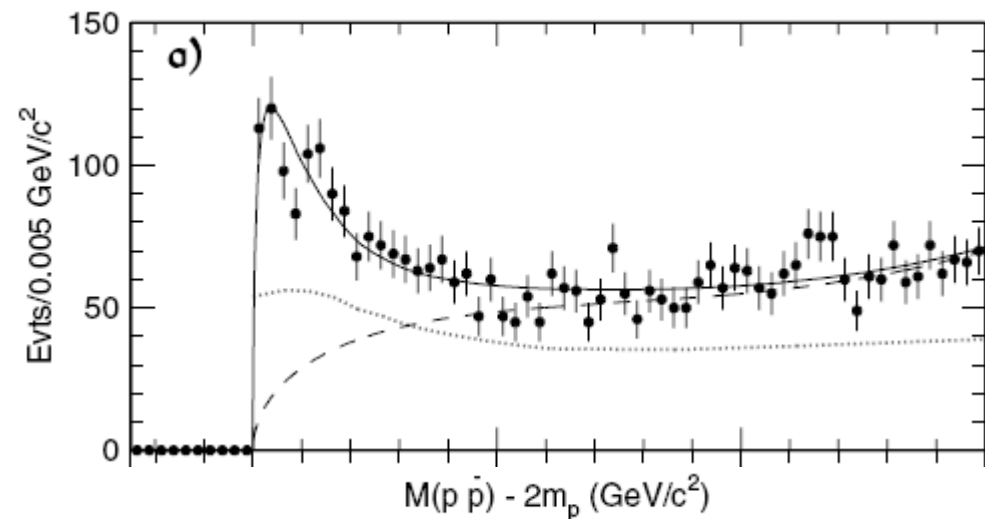


# $J/\psi \rightarrow \gamma p\bar{p}$ : enhancement at threshold

normal meson? pp bound state? multiquark? glueball? FSI effect?

BESII: PRL 91, 022001 (2003)

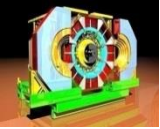
BESIII: CPC 34, 421 (2010)



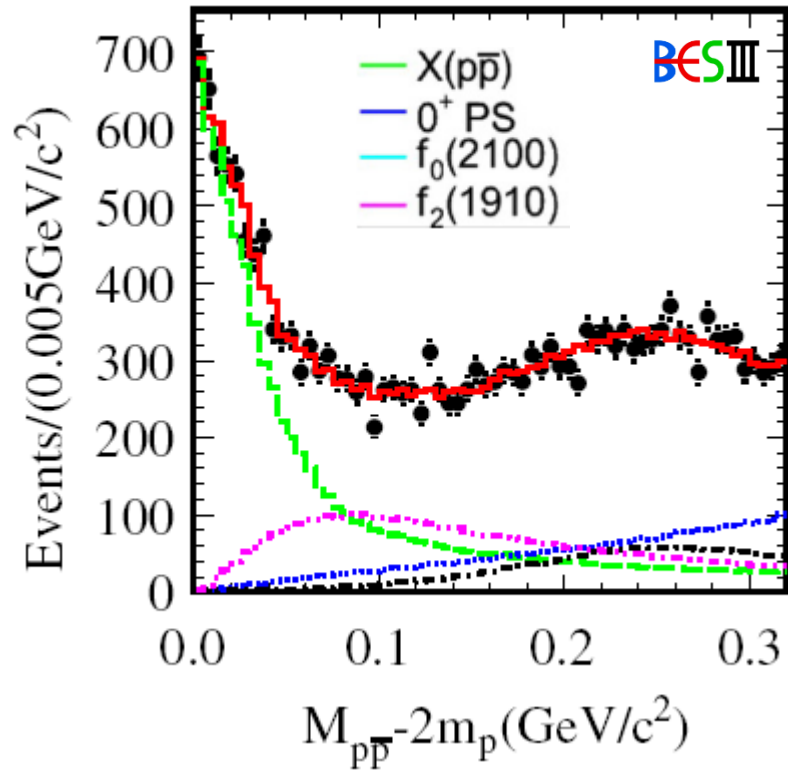
$M = (1860_{-10}^{+3} \quad -25^{+5}) \text{ MeV}/c^2$   
 $\Gamma < 38 \text{ MeV}/c^2$  (90% C.L.)  
 compatible with S-wave BW

$M = (1861_{-13}^{+6} \quad -26^{+7}) \text{ MeV}/c^2$   
 $\Gamma < 30 \text{ MeV}/c^2$  (90% C.L.)  
 compatible with S-wave BW

Spin-parity analysis essential to determine nature and role in spectrum



- **PWA of  $J/\psi \rightarrow \gamma p\bar{p}$  :**
  - never performed before
- **best solution:**  
 $X(p\bar{p}) [ \gg 30\sigma ]$ ,  $f_2(1910)$   
 and  $f_0(2100)$  fixed @PDG,  
 $0^{++}$  phase space and  
 S-wave ( $I=0$ ) FSI
- **systematic uncertainties:**
  - $f_2(2150)$ ,  $f_2(1950)$ , and other resonances from PDF,  $0^{++}$  PS
  - FSI model dependence

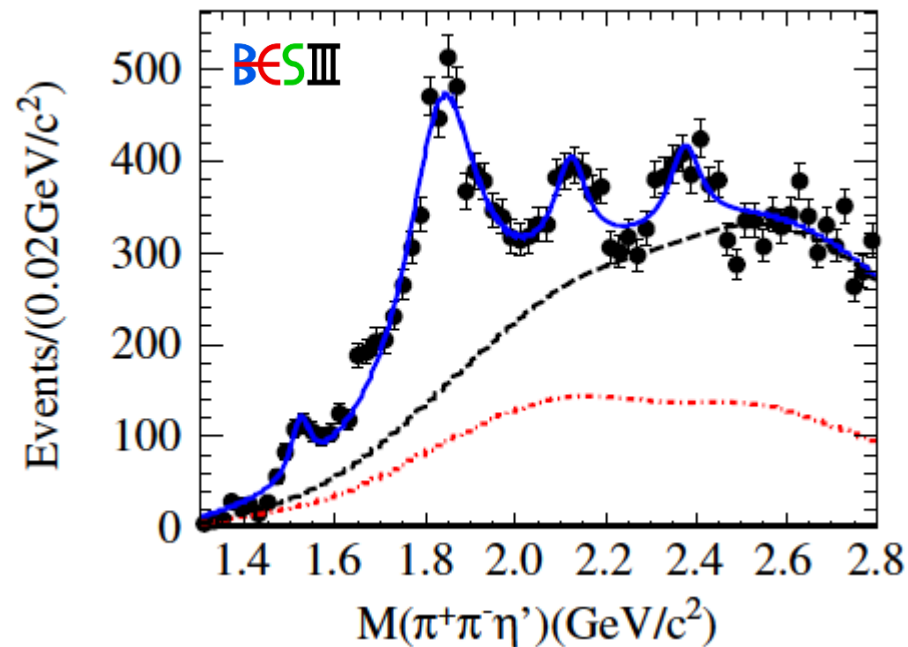
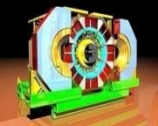


$J^{PC} = 0^{++}$ ,  $> 6.8\sigma$  better than other  $J^{PC}$  assignments

$$M = 1832_{-5}^{+19}(\text{stat})_{-17}^{+18}(\text{sys}) \pm 19(\text{mod}) \text{ MeV}/c^2$$

$$\Gamma = 13 \pm 39(\text{stat})_{-13}^{+10}(\text{sys}) \pm 4(\text{mod}) \text{ MeV}/c^2 \text{ or } \Gamma < 76 \text{ MeV}/c^2 \text{ (90\% C.L.)}$$

$$\mathcal{B}(J/\psi \rightarrow \gamma X(p\bar{p})) \times \mathcal{B}(X(p\bar{p}) \rightarrow p\bar{p}) = 9.0_{-1.1}^{+0.4}(\text{stat})_{-5.0}^{+1.5}(\text{sys}) \pm 2.3(\text{mod}) \times 10^{-5}$$



**X(1835):**

$$M = (1836.5 \pm 3.0^{+5.6}_{-2.1}) \text{ MeV}/c^2$$

$$\Gamma = (190 \pm 9^{+38}_{-36}) \text{ MeV}/c^2$$

$>20\sigma$

**X(2120):**

$$M = (2122.4 \pm 6.7^{+4.7}_{-2.7}) \text{ MeV}/c^2$$

$$\Gamma = (83 \pm 16^{+31}_{-11}) \text{ MeV}/c^2$$

$>7.2\sigma$

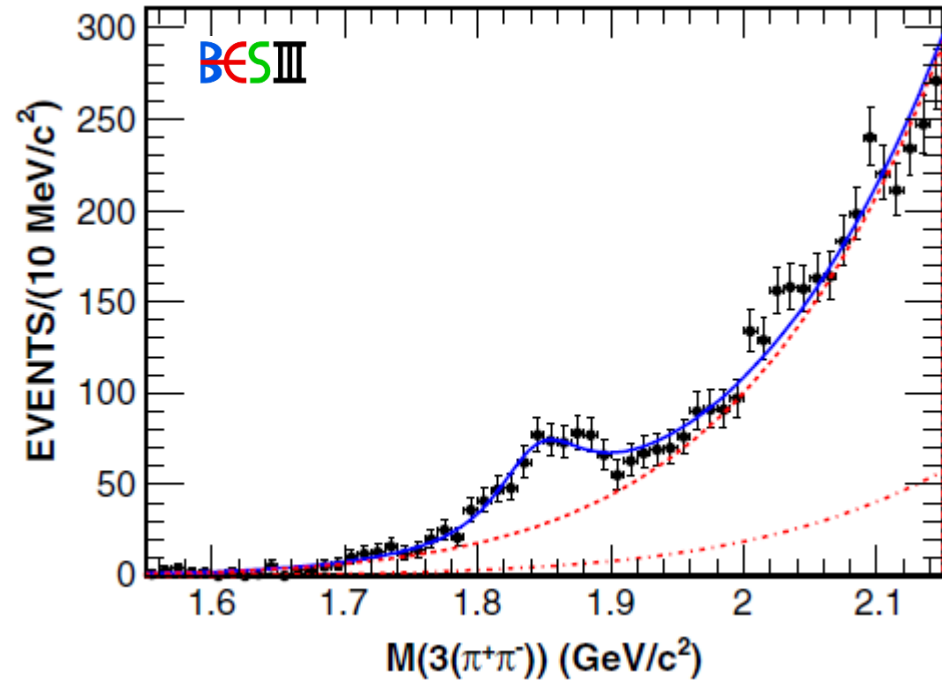
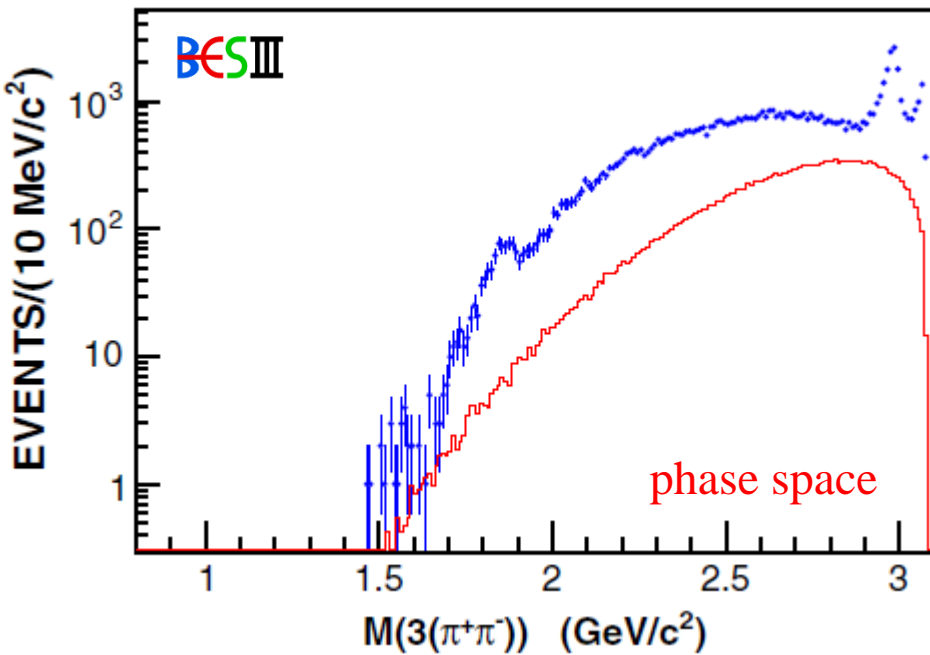
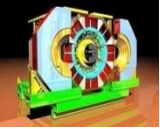
**X(2370):**

$$M = (2376.3 \pm 8.7^{+3.2}_{-4.3}) \text{ MeV}/c^2$$

$$\Gamma = (83 \pm 17^{+44}_{-6}) \text{ MeV}/c^2$$

$>6.4\sigma$

- PWA is needed to determine spin and parity
- consistent with  $J^P = 0^-$

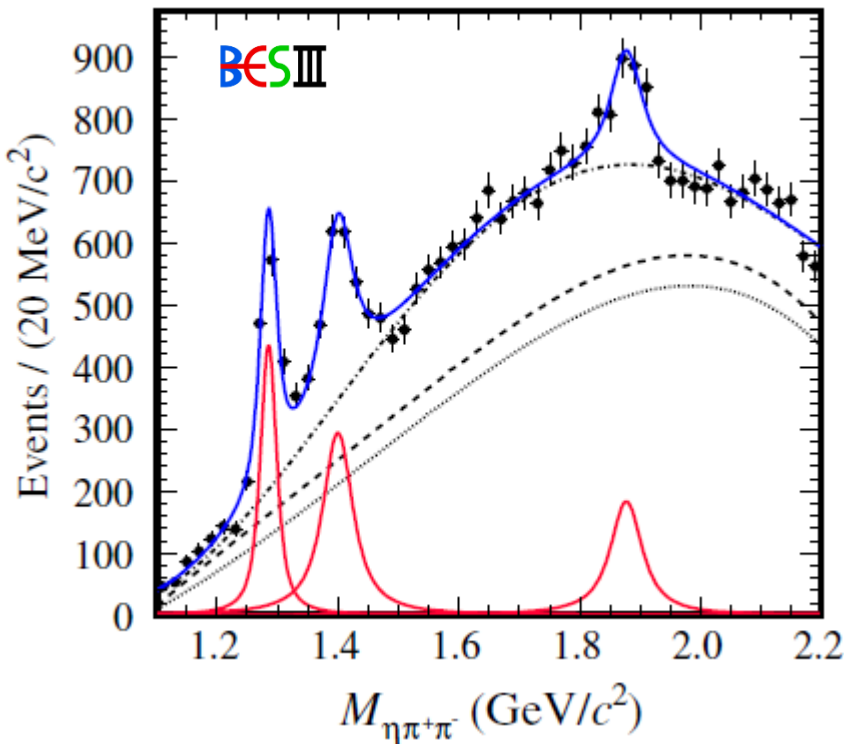


$$M = (1842.2 \pm 4.2^{+7.1}_{-2.6}) \text{ MeV}/c^2$$
$$\Gamma = (83 \pm 14 \pm 11) \text{ MeV}/c^2$$
$$>7.6\sigma$$

- PWA is needed to determine spin and parity
- **no  $\eta'$  detected**



## $J/\psi \rightarrow \omega\eta\pi^+\pi^-$



- PWA is needed to determine spin and parity

### $X(1870)$ :

$$M = (1877.3 \pm 6.3^{+3.4}_{-7.4}) \text{ MeV}/c^2$$

$$\Gamma = (57 \pm 12^{+19}_{-4}) \text{ MeV}/c^2$$

$$B = (1.50 \pm 0.26^{+0.72}_{-0.36}) \cdot 10^{-4}$$

### $\eta(1405)$ :

$$M = (1399.8 \pm 2.2^{+2.8}_{-0.1}) \text{ MeV}/c^2$$

$$\Gamma = (52.8 \pm 7.6^{+0.1}_{-7.6}) \text{ MeV}/c^2$$

$$B = (1.89 \pm 0.21^{+0.21}_{-0.23}) \cdot 10^{-4}$$

### $f_1(1285)$ :

$$M = (1285.1 \pm 1.0^{+1.6}_{-0.3}) \text{ MeV}/c^2$$

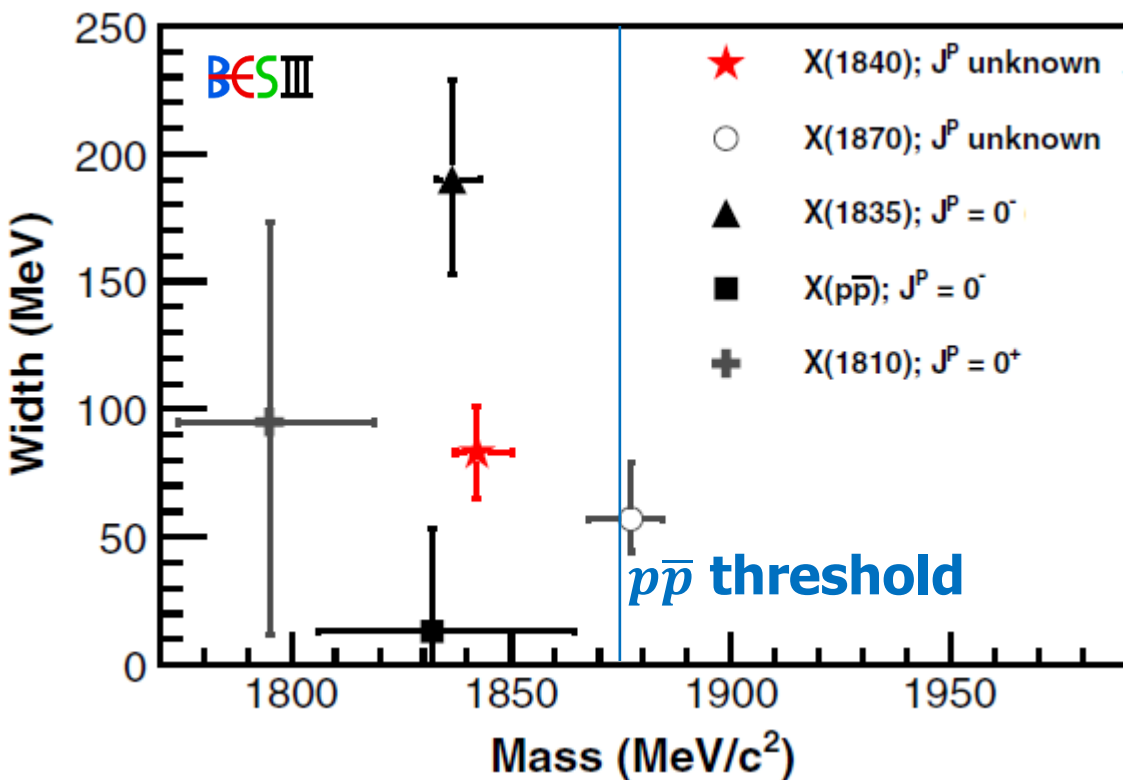
$$\Gamma = (22.0 \pm 3.1^{+2.0}_{-1.5}) \text{ MeV}/c^2$$

$$B = (1.25 \pm 0.10^{+0.19}_{-0.20}) \cdot 10^{-4}$$

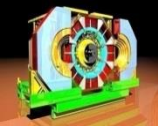




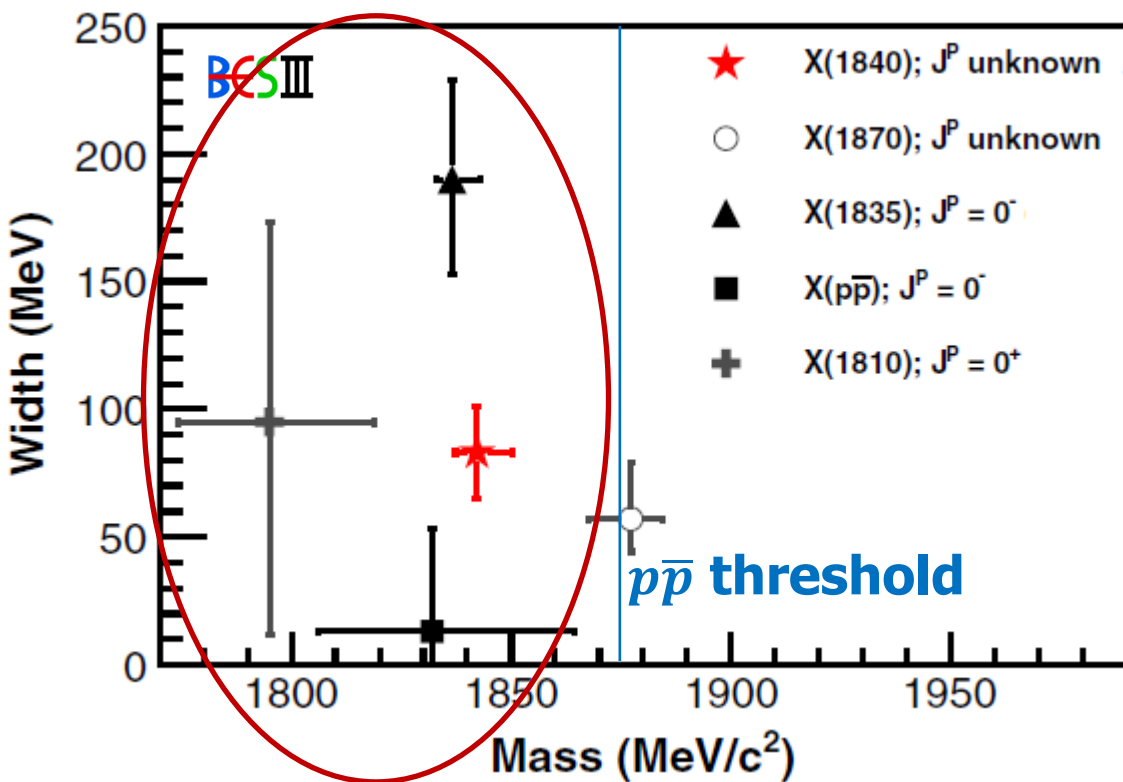
# BESIII: a partial summary



- ★ X(1840):  $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$  [PRD88, 091502]
- X(1870):  $J/\psi \rightarrow \omega\eta\pi^+\pi^-$  [PRL107, 182001]
- ▲ X(1835):  $J/\psi \rightarrow \gamma(\eta\pi^+\pi^-)$  [PRL106, 072002]
- X(1840):  $J/\psi \rightarrow \gamma(p\bar{p})$  [PRL108, 112003]
- + X(1840):  $J/\psi \rightarrow \gamma(\omega\phi)$  [PRD87, 032008]



# BESIII: a partial summary



- $J/\psi$  radiative decays
- not found in  $\psi'$  radiative decays
- non a pure FSI
- PWA is needed

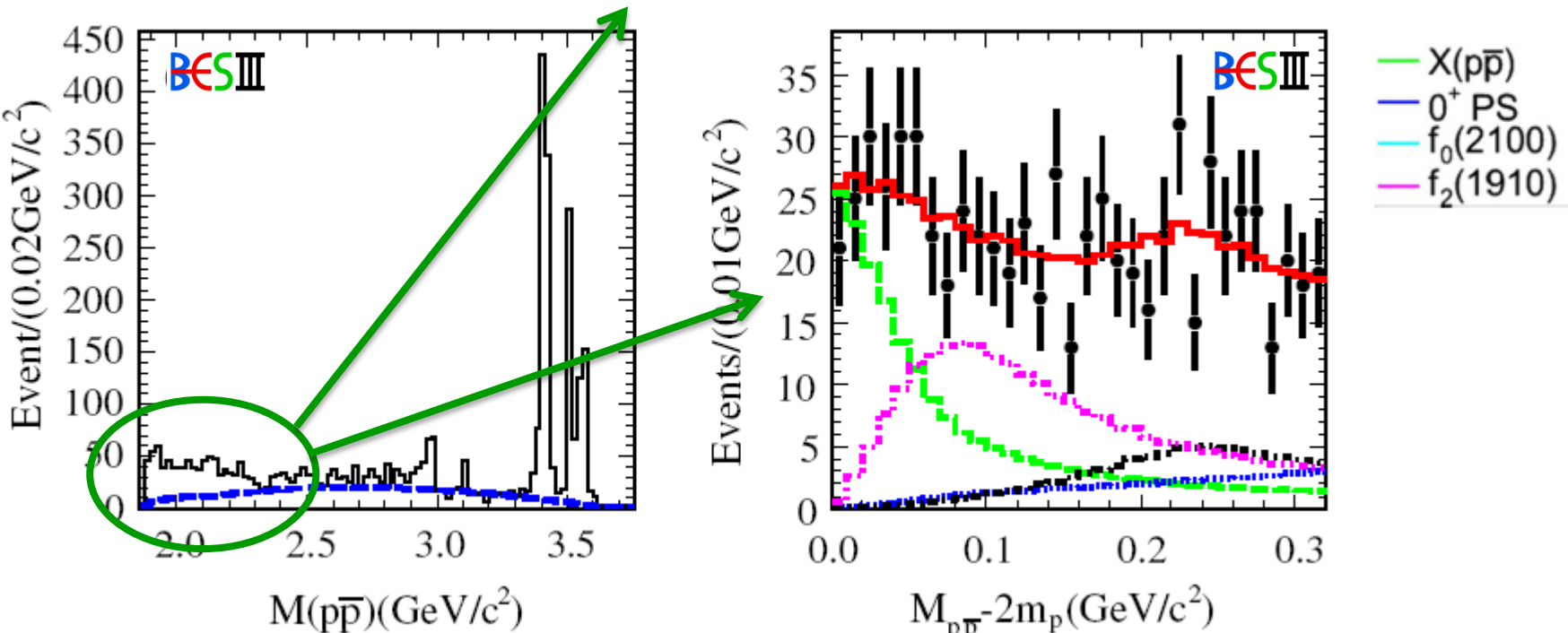
- ★  $X(1840): J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$  [PRD88, 091502]
- $X(1870): J/\psi \rightarrow \omega\eta\pi^+\pi^-$  [PRL107, 182001]
- ▲  $X(1835): J/\psi \rightarrow \gamma(\eta\pi^+\pi^-)$  [PRL106, 072002]
- $X(1840): J/\psi \rightarrow \gamma(p\bar{p})$  [PRL108, 112003]
- ⊕  $X(1840): J/\psi \rightarrow \gamma(\omega\phi)$  [PRD87, 032008]

## $X(18??)$ :

- near  $(p\bar{p})$  threshold
- is a single particle?!?



$p\bar{p}$  mass-spectrum at threshold clearly differs from that in  $J/\psi$  decays



$M, \Gamma,$  and  $J^{PC}$  fixed to those obtained for  $J/\psi$  decays

$$\mathcal{B}(\psi(2S) \rightarrow \gamma X(p\bar{p})) \times \mathcal{B}(X(p\bar{p}) \rightarrow p\bar{p}) =$$

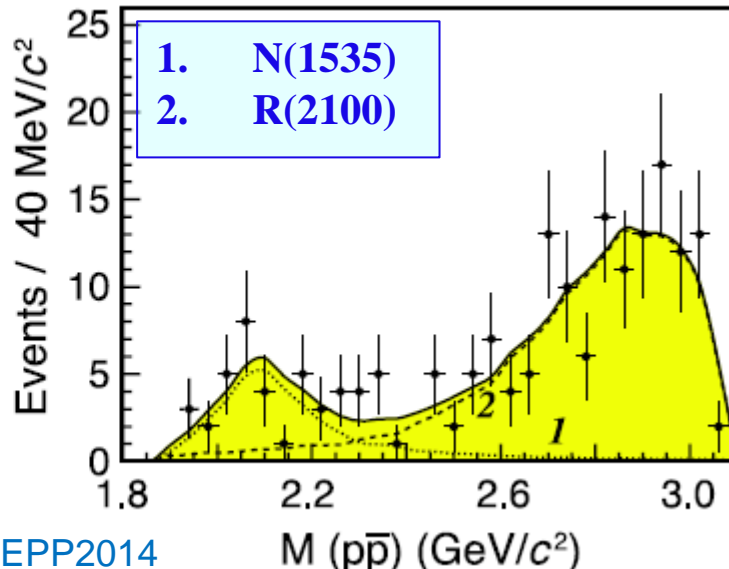
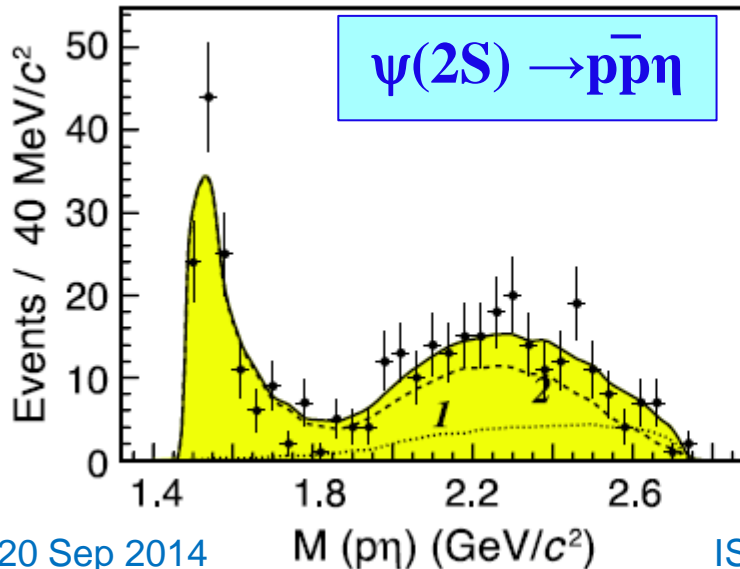
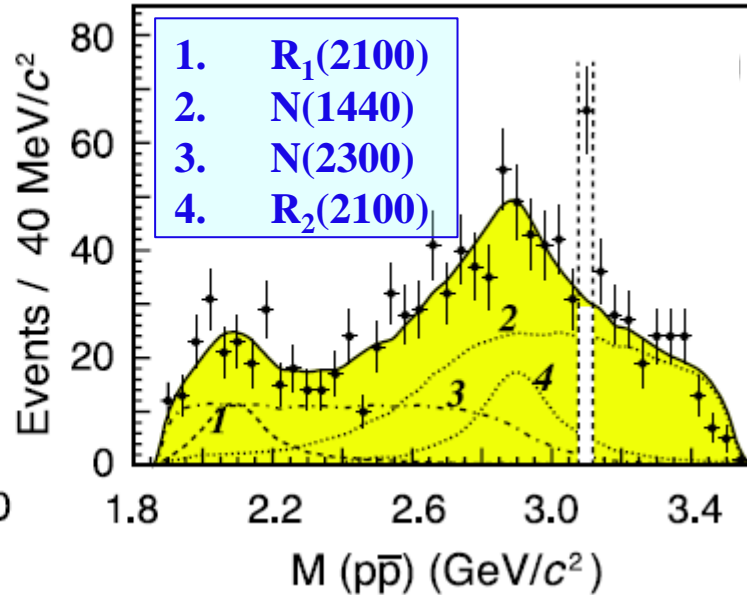
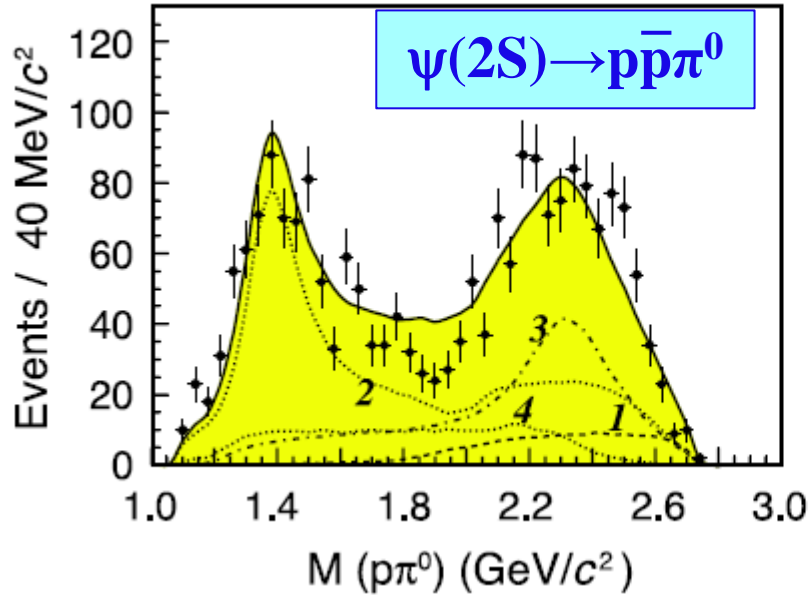
$$4.57 \pm 0.36(\text{stat})^{+1.23}_{-4.07}(\text{sys}) \pm 1.28(\text{mod}) \times 10^{-6}$$

$$R = \frac{\mathcal{B}(\psi(2S) \rightarrow \gamma X(p\bar{p}))}{\mathcal{B}(J/\psi \rightarrow \gamma X(p\bar{p}))} = 5.08^{+0.71}_{-0.45}(\text{stat})^{+0.67}_{-3.58}(\text{sys}) \pm 0.12(\text{mod}) \% < 12\%$$



# PWA of $\psi(2S) \rightarrow p\bar{p}\pi^0$ and $\psi(2S) \rightarrow p\bar{p}\eta$

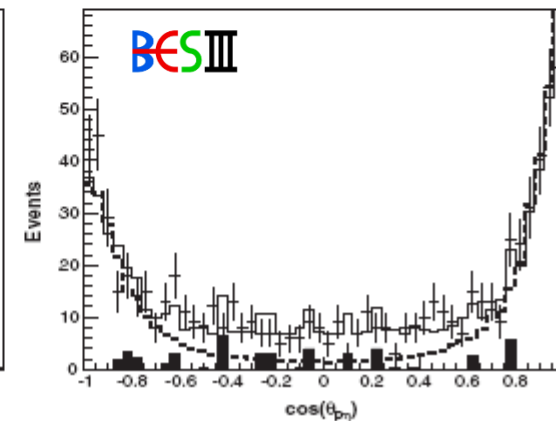
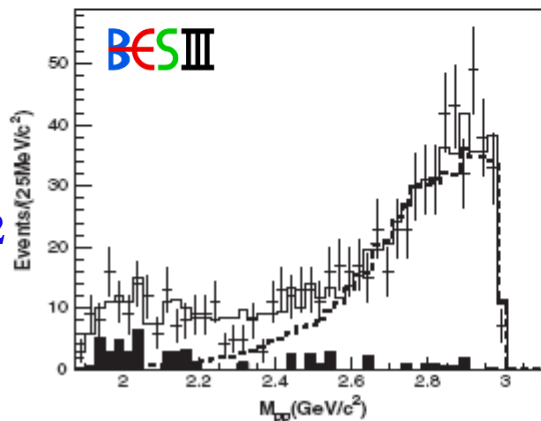
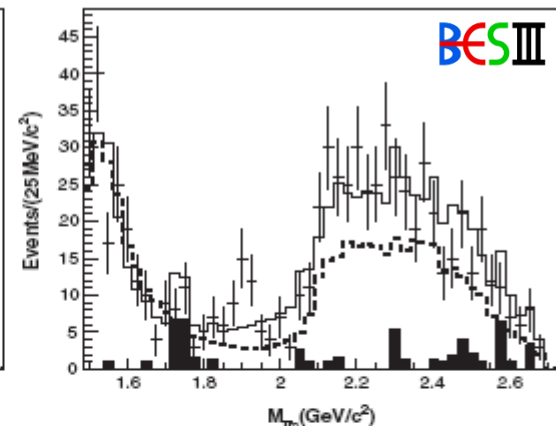
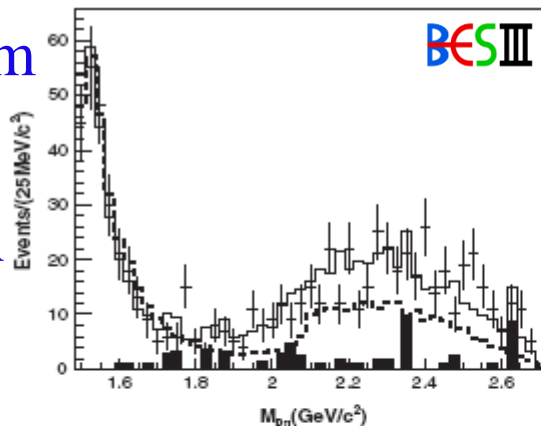
CLEOc: 24.5 M  $\psi(2S)$  [PRD 82, 092002]



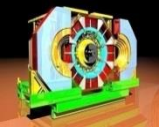
Without interference effects



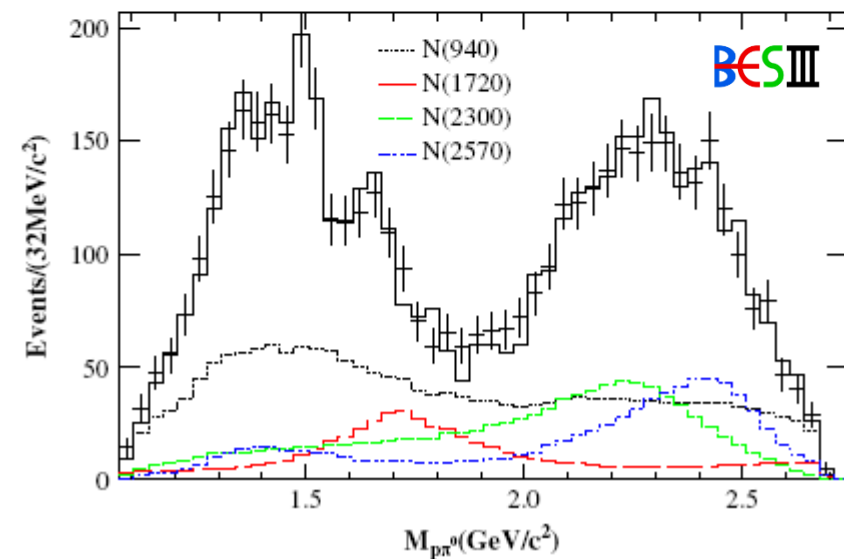
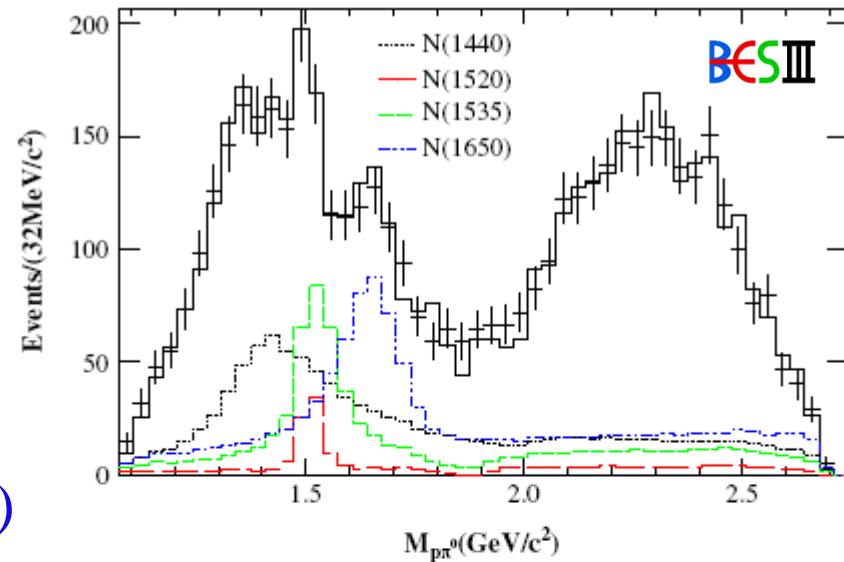
- **low background:**
  - sidebands and continuum
- **best solution:**  
N(1535) combined with an interfering phase space
- **$p\bar{p}$  enhancement:**  
 $<3\sigma$
- **N(1535):**
  - $M=(1524\pm 5^{+10}_{-4}) \text{ MeV}/c^2$
  - $\Gamma=(130^{+27+10}_{-24-10}) \text{ MeV}/c^2$
- **suppressed ( $<12\%$ ):**

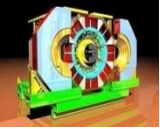


$$Q_{p\bar{p}\eta} = \frac{\mathcal{B}(\psi(2S) \rightarrow p\bar{p}\eta)}{\mathcal{B}(J/\psi \rightarrow p\bar{p}\eta)} = (3.2 \pm 0.46)\%$$

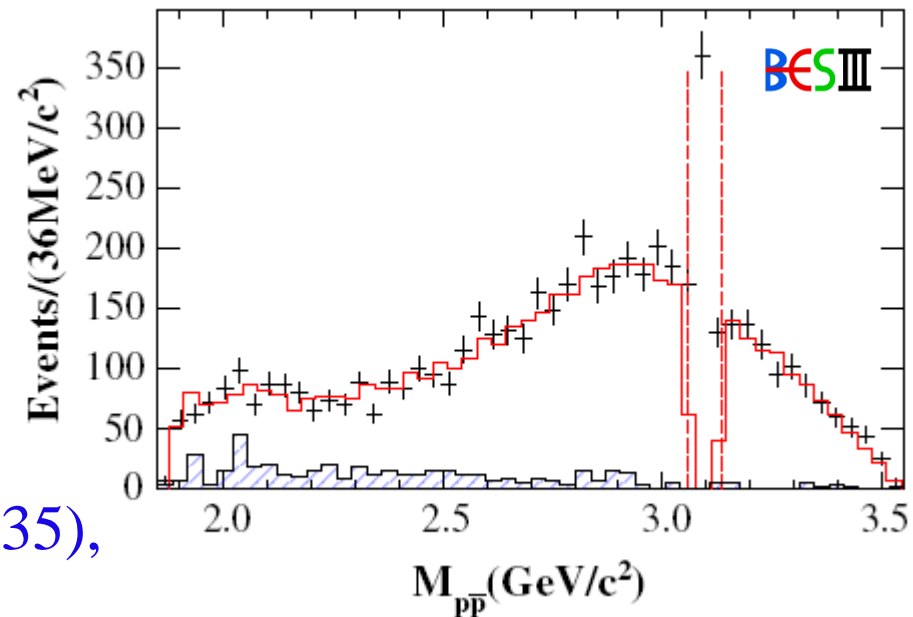


- **2-body decay:**
  - $\psi(2S) \rightarrow X\pi^0, X \rightarrow p\bar{p}$
  - $\psi(2S) \rightarrow p\bar{N}^*, \bar{N}^* \rightarrow \bar{p}\pi^0 + c.c.$
- **isospin conservation:**
  - $\Delta$  suppressed
- **best solution:**
  - N(1440), N(1520), N(2090), N(1535)
  - N(1650), N(1720),
  - N(2300) [1/2<sup>+</sup>], N(2570) [5/2<sup>-</sup>]**
- **no significant evidence:**
  - N(1885), N(2065)
  - $p\bar{p}$  enhancement
- **systematic uncertainties:**
  - additional possible resonances





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  - N(1885), N(2065)
  - $p\bar{p}$  enhancement
- **systematic uncertainties:**
  - additional possible resonances





▪ **branching fraction:**

$$\mathcal{B}(\psi(2S) \rightarrow p\bar{p}\pi^0) = (1.65 \pm 0.03 \pm 0.15) \times 10^{-4}$$

▪ **PWA:**

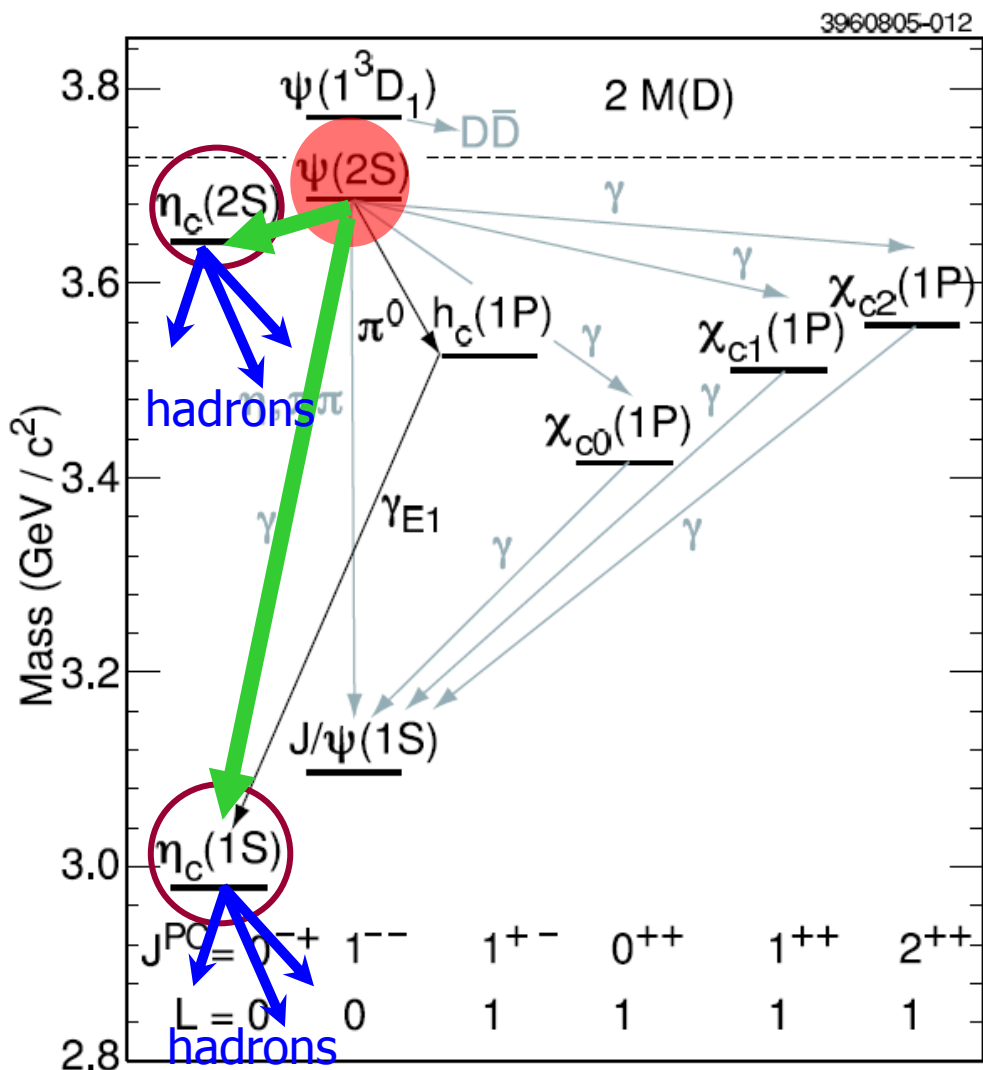
- **two new resonances**
- N(1885) and N(2065),  $< 5\sigma$
- $p\bar{p}$  resonance  $< 4\sigma$

Resonance	$M(\text{MeV}/c^2)$	$\Gamma(\text{MeV}/c^2)$	$\Delta S$	$\Delta N_{\text{dof}}$	Sig.
N(1440)	$1390^{+11+21}_{-21-30}$	$340^{+46+70}_{-40-156}$	72.5	4	$11.5\sigma$
N(1520)	$1510^{+3+11}_{-7-9}$	$115^{+20+0}_{-15-40}$	19.8	6	$5.0\sigma$
N(1535)	$1535^{+9+15}_{-8-22}$	$120^{+20+0}_{-20-42}$	49.4	4	$9.3\sigma$
N(1650)	$1650^{+5+11}_{-5-30}$	$150^{+21+14}_{-22-50}$	82.1	4	$12.2\sigma$
N(1720)	$1700^{+30+32}_{-28-35}$	$450^{+109+149}_{-94-44}$	55.6	6	$9.6\sigma$
<b>N(2300)<math>_{1/2^+}</math></b>	<b><math>2300^{+40+109}_{-30-0}</math></b>	<b><math>340^{+30+110}_{-30-58}</math></b>	<b>120.7</b>	<b>4</b>	<b><math>15.0\sigma</math></b>
<b>N(2570)<math>_{5/2^-}</math></b>	<b><math>2570^{+19+34}_{-10-10}</math></b>	<b><math>250^{+14+69}_{-24-21}</math></b>	<b>78.9</b>	<b>6</b>	<b><math>11.7\sigma</math></b>





# $\psi(2S) \rightarrow \gamma\eta_c(1S), \gamma\eta_c(2S)$



**$\eta_c$  mass:**  
**charmonium**  
**ground state**

**M1 transition:**  
**first observation of**  
 $\psi' \rightarrow \gamma\eta'_c$



# $\eta_c(1S)$

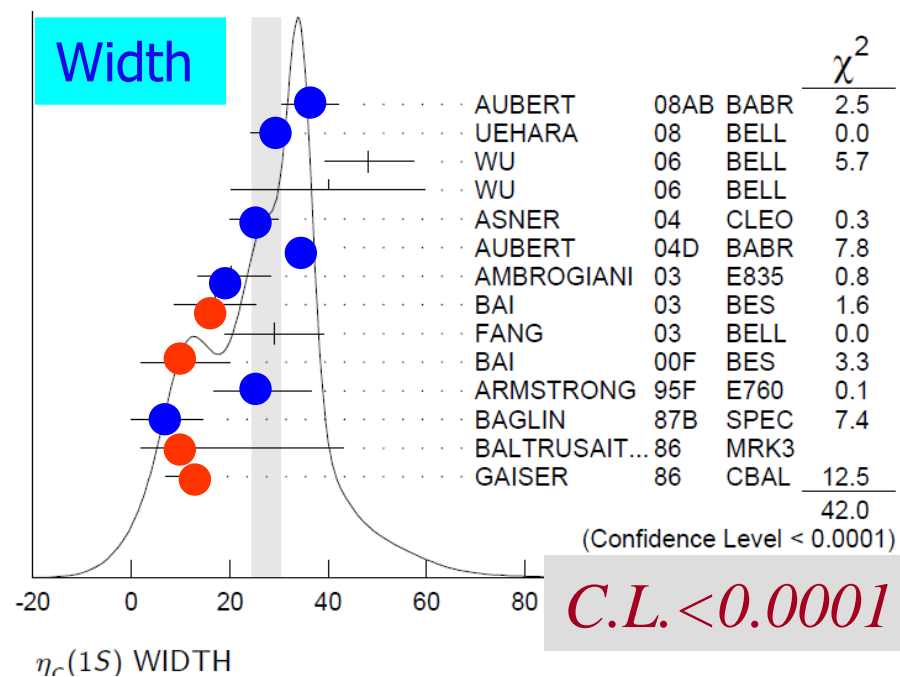
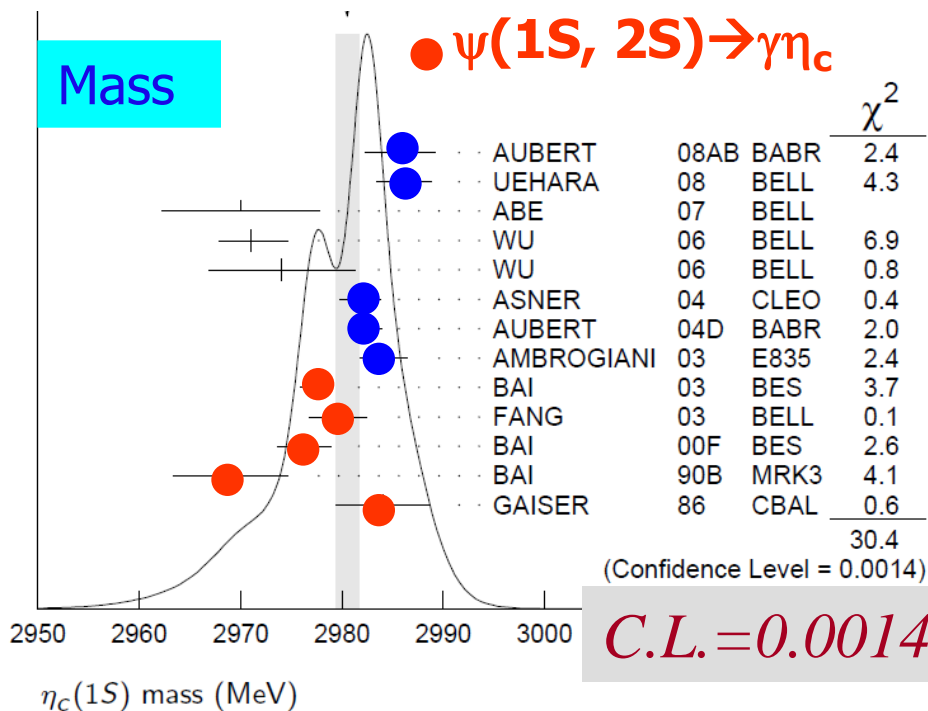
The S-wave spin-singlet charmonium ground state, found in 1980

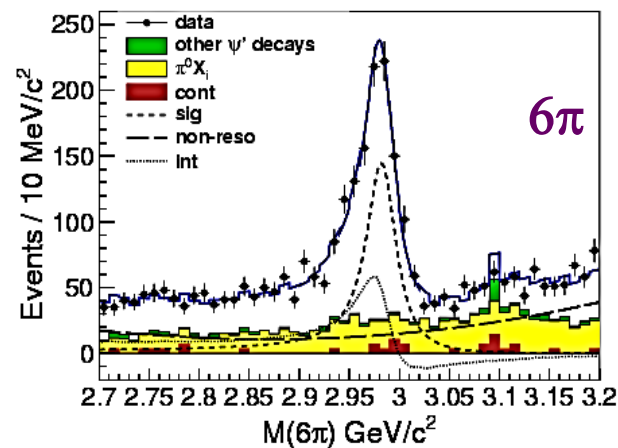
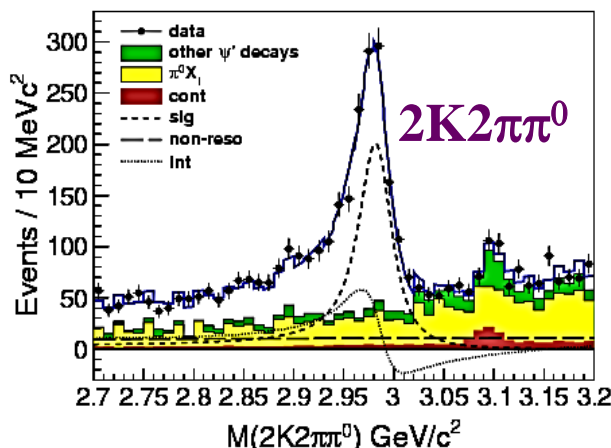
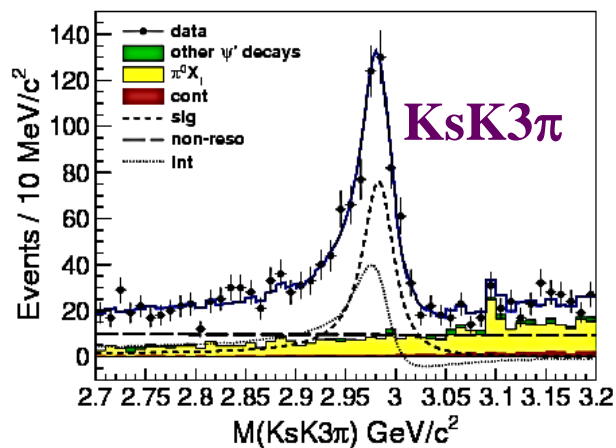
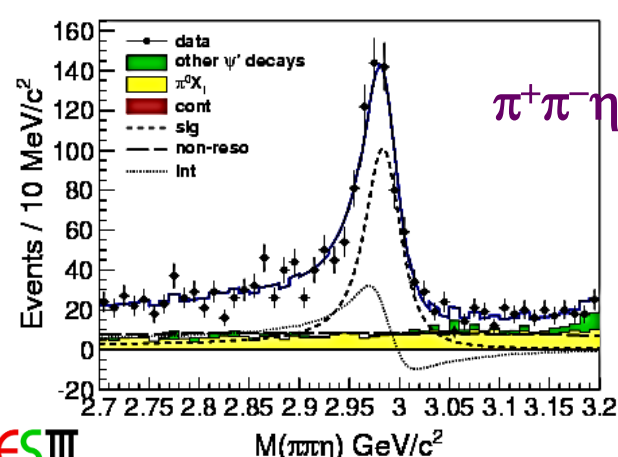
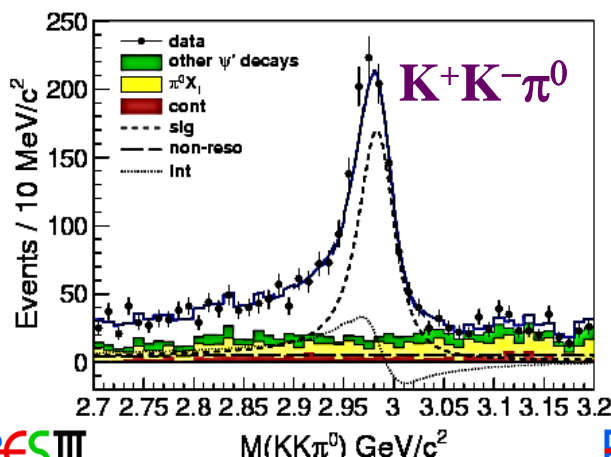
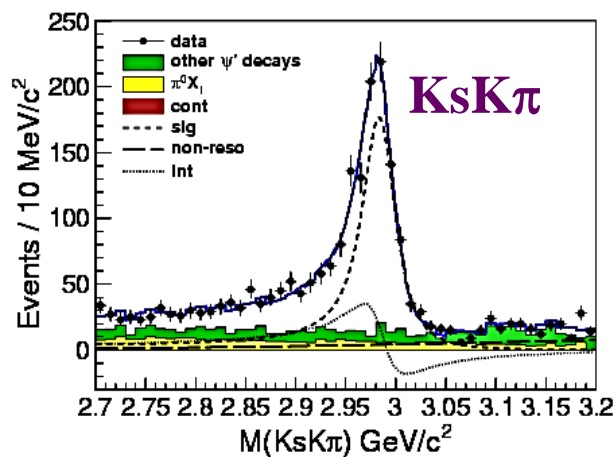
M &  $\Gamma$  measurements:

- $J/\psi$  radiative transitions:  $M \sim 2978.0 \text{ MeV}/c^2$ ,  $\Gamma \sim 10 \text{ MeV}/c^2$
- $\gamma\gamma$  processes /  $B \rightarrow K\eta_c$ :  $M = (2983.1 \pm 1.0) \text{ MeV}/c^2$ ,  $\Gamma = (31.3 \pm 1.9) \text{ MeV}/c^2$

●  $\gamma\gamma$ ,  $p\bar{p}$ , B decay

●  $\psi(1S, 2S) \rightarrow \gamma\eta_c$

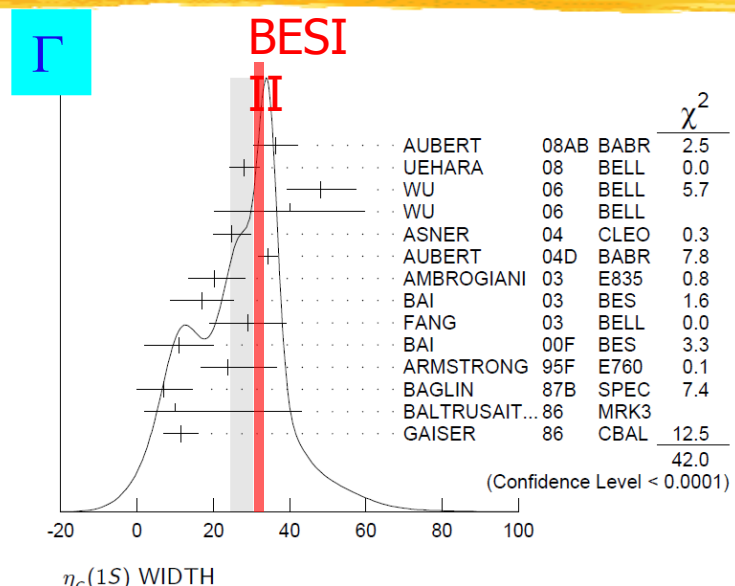
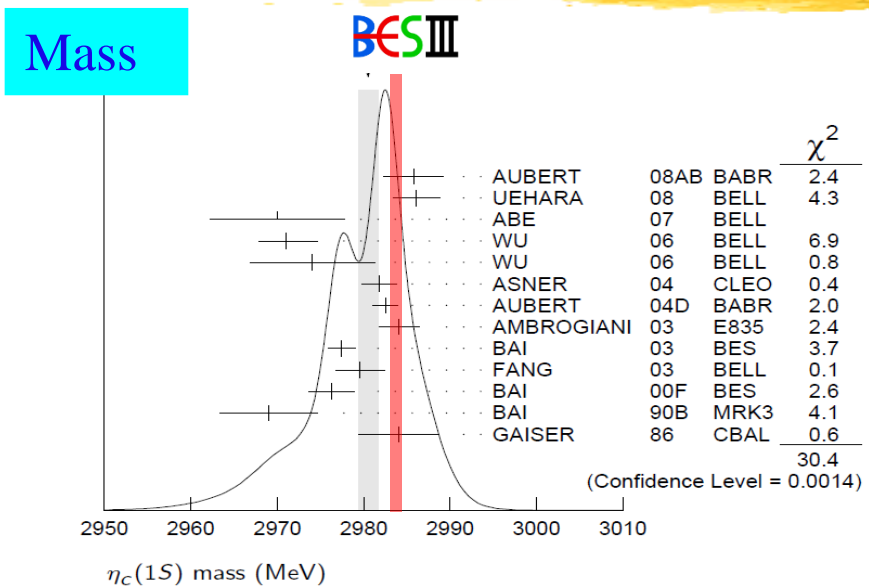




**Significant interference between  $\eta_c$  and non-resonant**

**→ simultaneous fit to 6 modes, Mass =  $2984.3 \pm 0.6 \pm 0.6$  MeV/c $^2$**

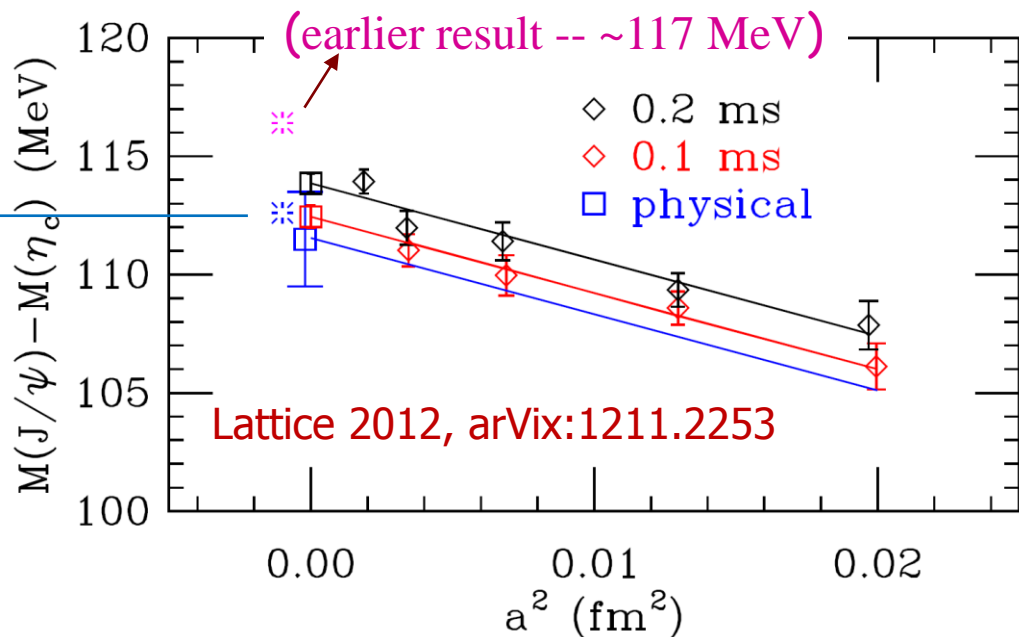
**$\Gamma = 32.0 \pm 1.2 \pm 1.0$  MeV/c $^2$**



Hyperfine splitting (BESIII alone)

$$\Delta M(1S) = 112.5 \pm 0.8 \text{ MeV}/c^2$$

Closer to prediction  
then earlier result





## Observed in different production mechanisms

1.  $B \rightarrow K\eta_c'$  Belle: PRL 89 102001 (2002)  
CLEOc: PRL 92 142001 (2004)
2.  $\gamma\gamma \rightarrow \eta_c' \rightarrow KK\pi$  Belle: NPPS.184 220 (2008); PRL 98 082001(2007)  
BaBar: PRL 92 142002 (2004); PR D72 031101(2005)
3. double charmonium production BaBar: PR D84 012004 (2011)

## M1 transition $\psi' \rightarrow \gamma\eta_c'$

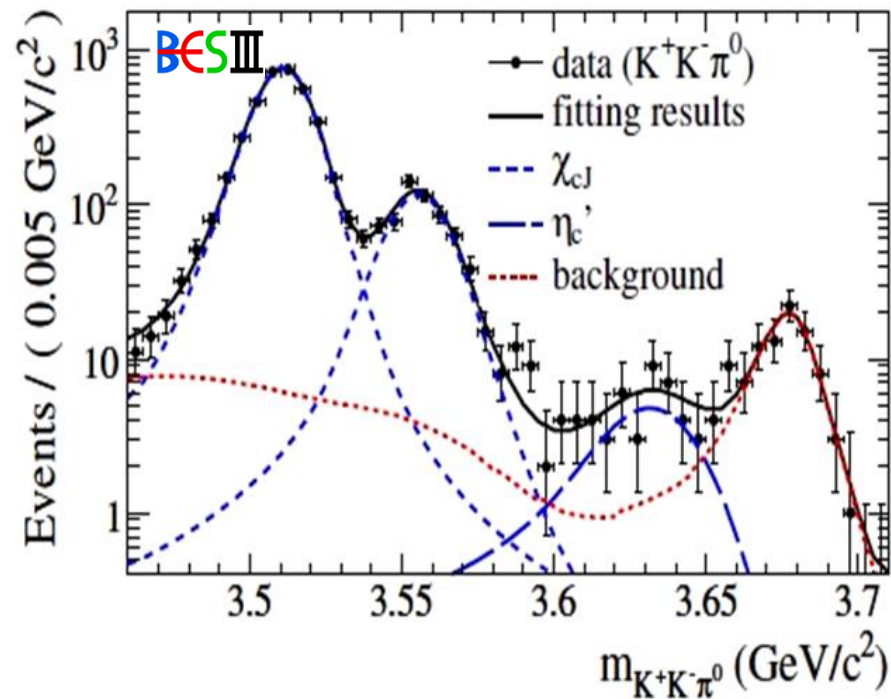
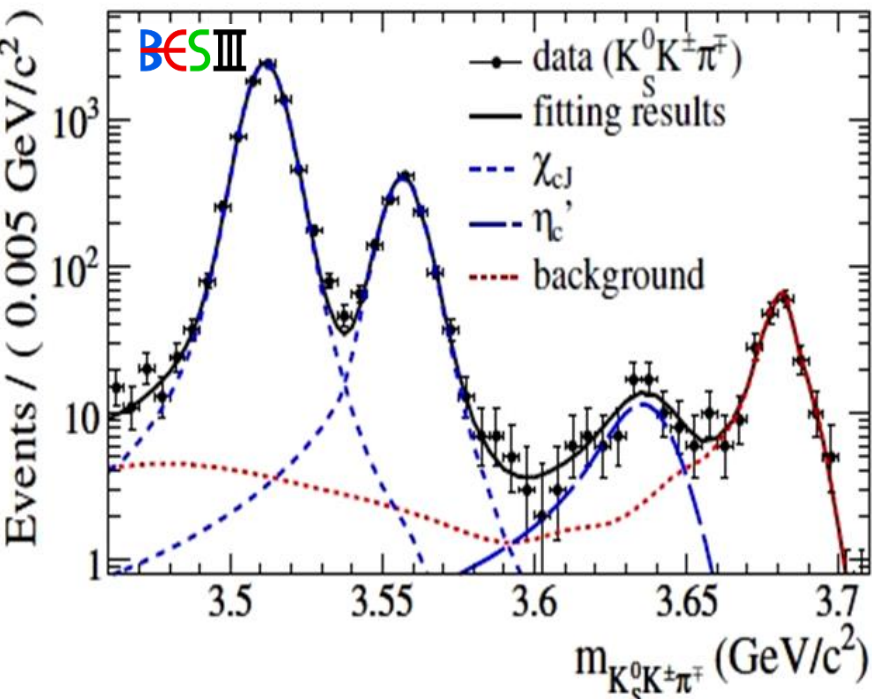
1. CLEO found no signal in 25M  $\psi'$ .

$$\mathcal{B}(\psi' \rightarrow \gamma\eta_c') < 7.6 \times 10^{-4}$$

PRD 81 052002 (2010)

2. BESIII: first observation of  $\eta_c' \rightarrow KK\pi$  ;  
find evidence in  $\eta_c' \rightarrow K_s K3\pi$

**Experimental challenge : search for photons of 50 MeV**



$M = 3637.6 \pm 2.9 \pm 1.6 \text{ MeV}/c^2$

$\Gamma = 16.9 \pm 6.4 \pm 4.8 \text{ MeV}/c^2$

$\mathcal{B}(\psi' \rightarrow \gamma\eta_c' \rightarrow \gamma KK\pi) = (1.30 \pm 0.20 \pm 0.30) \times 10^{-5}$       Significance  $> 10 \sigma$

$\mathcal{B}(\eta_c' \rightarrow \gamma KK\pi) = (1.9 \pm 0.4 \pm 1.1)\%$

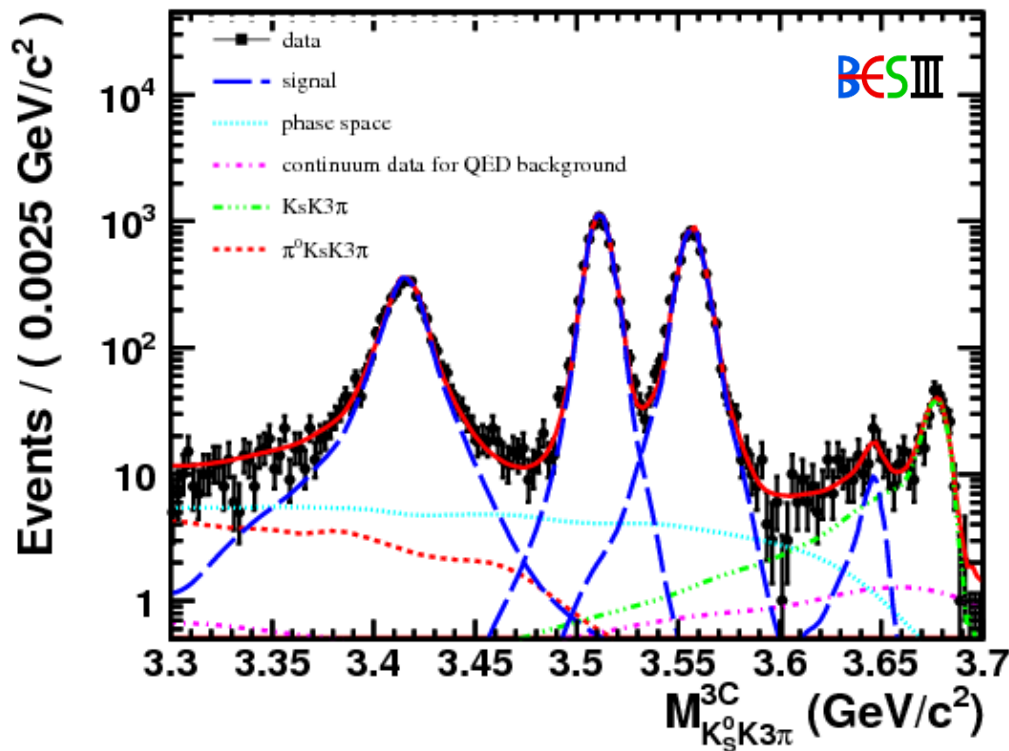
BABAR: PRD78, 012006 (2008)

$\mathcal{B}(\psi' \rightarrow \gamma\eta_c') = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$

FIRST OBSERVATION!

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

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



Significance

4.2  $\sigma$

$$M = 3646.9 \pm 1.6 \pm 3.6 \text{ MeV}/c^2$$

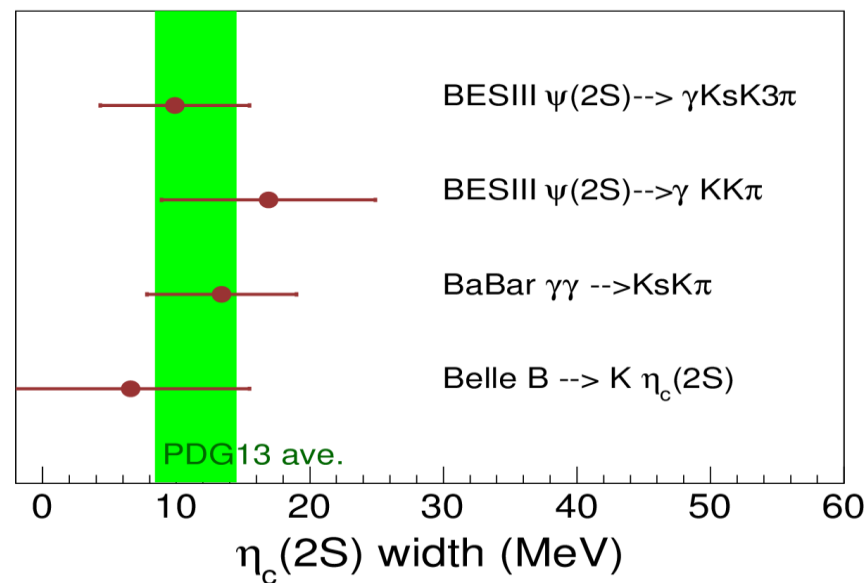
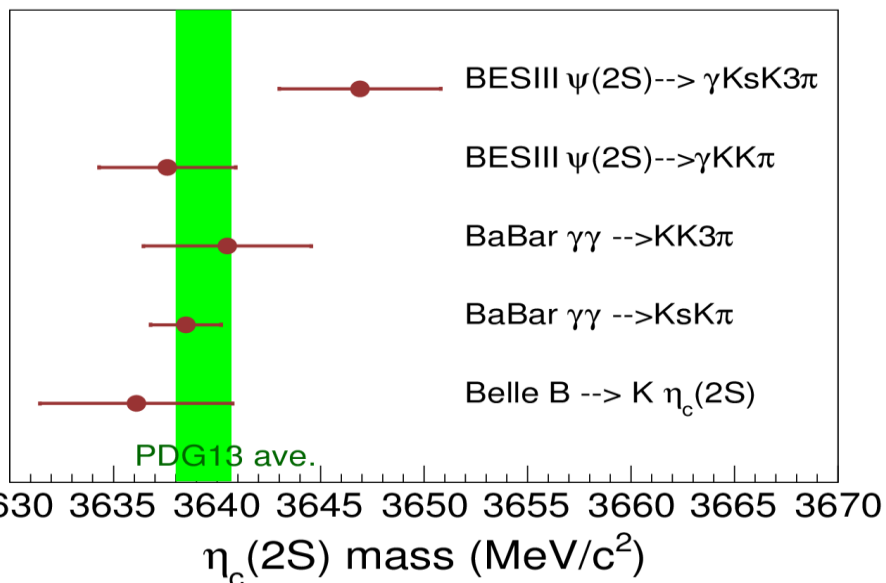
$$\Gamma = 9.2 \pm 4.8 \pm 2.9 \text{ MeV}/c^2$$

$$\mathcal{B}(\psi' \rightarrow \gamma\eta_c' \rightarrow \gamma K_s K3\pi) = (7.03 \pm 2.10 \pm 0.70) \times 10^{-6}$$

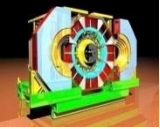


# $\eta_c(2S)$ : BESIII vs literature

PRL 109, 042003  
PRD 87, 052005



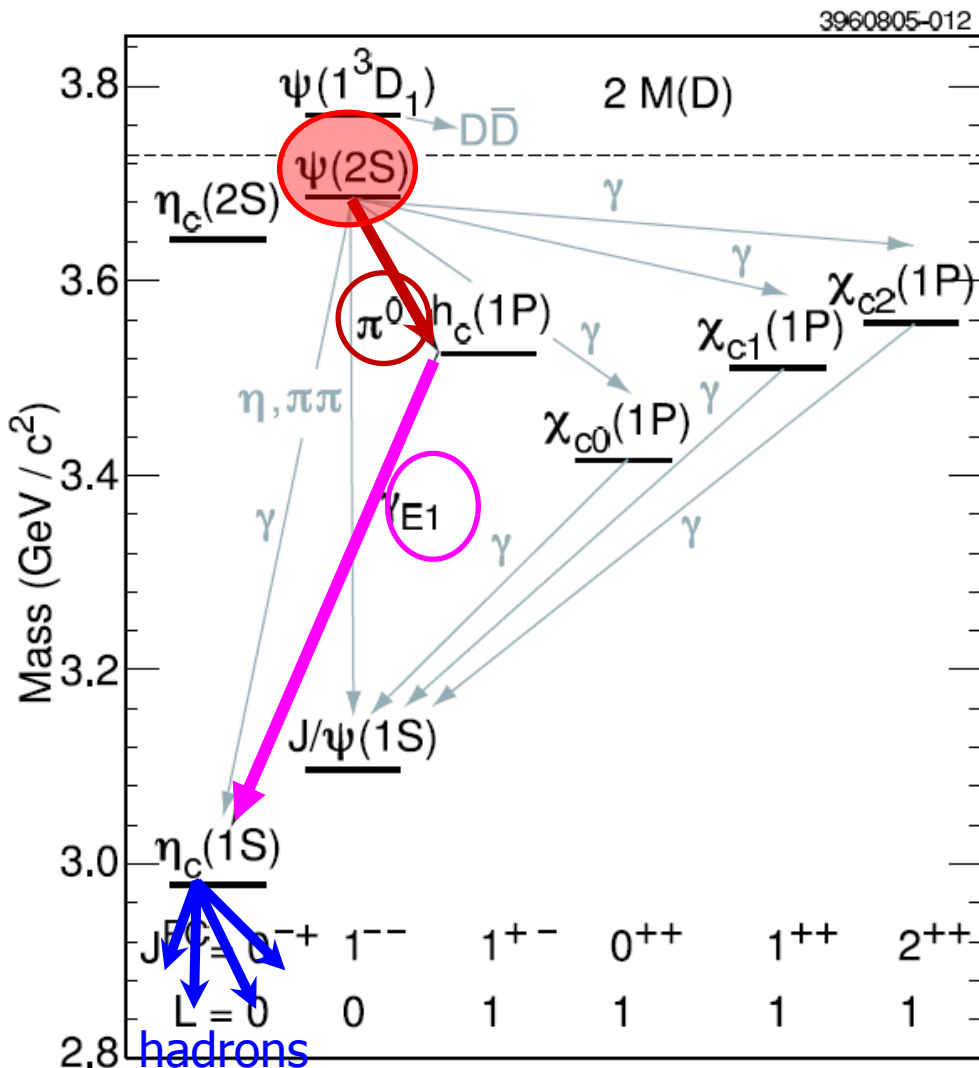




# $h_c(1P)$

- **Spin singlet P wave (S=0, L=1)**
- Potential model: if non-vanishing P-wave spin-spin interaction,  
 $\Delta M_{hf}(1P) = M(h_c) - \langle M(1^3P_J) \rangle \neq 0$ ,  
 $\langle M(1^3P_J) \rangle = [M(\chi_{c0}) + 3M(\chi_{c1}) + 5M(\chi_{c2})] / 9$
- **Theoretical predictions:**
  - $\mathcal{B}(\psi' \rightarrow \pi^0 h_c) = (0.4-1.3) \times 10^{-3}$ ,  $\mathcal{B}(h_c \rightarrow \gamma \eta_c) = 41\%$  (NRQCD)  
 $\mathcal{B}(h_c \rightarrow \gamma \eta_c) = 88\%$  (PQCD)  

Y. P. Kuang, PR D65, 094024 (2002)  
Godfrey and Rosner, PR D66, 014012 (2002)
  - $\mathcal{B}(h_c \rightarrow \gamma \eta_c) = 38\%$
- First reported by E760 in decay  $pp \rightarrow h_c \rightarrow J/\psi \pi^0$ , not confirmed  
Evidence found by E835 in  $pp \rightarrow h_c \rightarrow \gamma \eta_c$  PR D72 032001 (2005)
- Observed by CLEO in  $\psi' \rightarrow \pi^0 h_c$ ,  $h_c \rightarrow \gamma \eta_c$  PRL 95 102003 (2005)
- **Recent results from BESIII**



“inclusive”

only detect the  $\pi^0$

(compute  $M(h_c)$  from kinematic)

Rate  $\propto \mathcal{B}(\psi' \rightarrow \pi^0 h_c)$

“E1 tagged”

detect the  $\pi^0$  &  $\gamma$

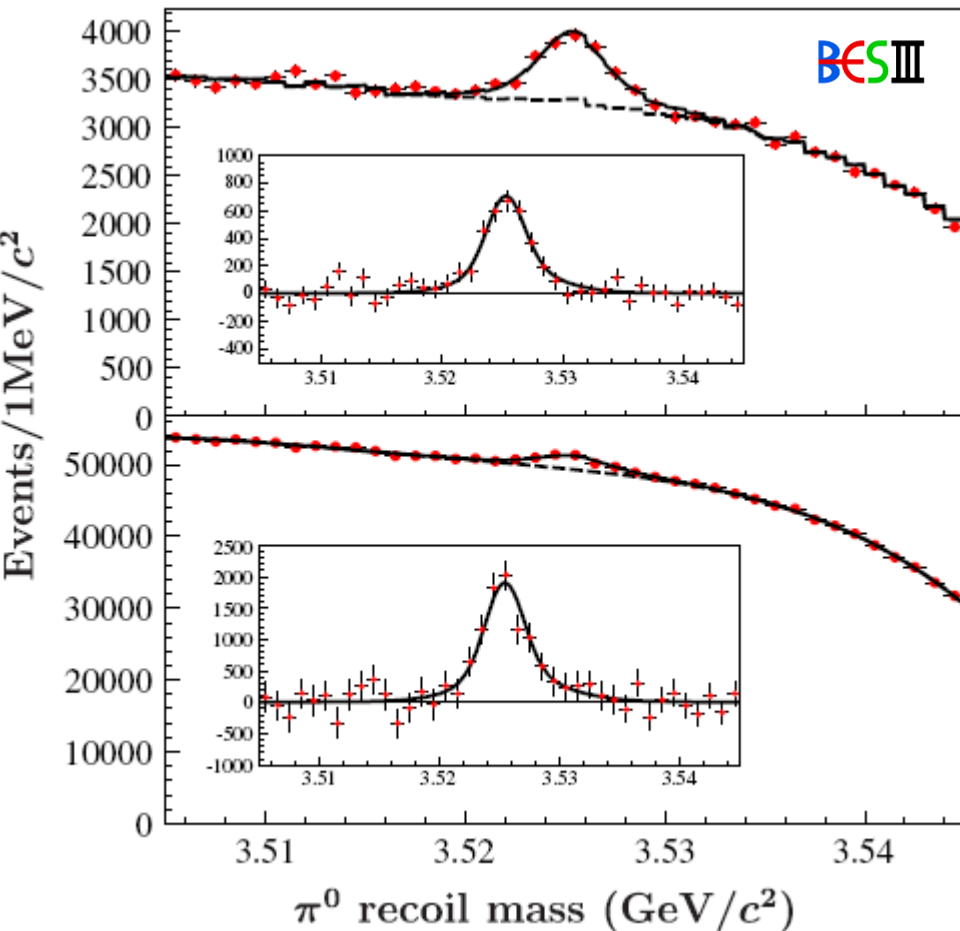
Rate  $\propto \mathcal{B}(\psi' \rightarrow \pi^0 h_c) \times \mathcal{B}(h_c \rightarrow \gamma \eta_c)$

“exclusive”

detect the  $\pi^0$ ,  $\gamma$  &  $\eta_c \rightarrow X_i$  decay prod.

Rate  $\propto$

$\mathcal{B}(\psi' \rightarrow \pi^0 h_c) \times \mathcal{B}(h_c \rightarrow \gamma \eta_c) \times \mathcal{B}(\eta_c \rightarrow X_i)$



$M = 3525.40 \pm 0.13 \pm 0.18 \text{ MeV}/c^2$   
 $\Gamma = 0.73 \pm 0.45 \pm 0.28 \text{ MeV}/c^2$   
 $< 1.44 \text{ MeV} @ 90\%$

CLEOc: PRL 101 182003 (2008)

$M = 3525.28 \pm 0.19 \pm 0.12 \text{ MeV}/c^2$   
 $\Gamma$  : fixed at 0.9 MeV

Hyperfine mass splitting  
 $\Delta M_{hf}(1^1P) = M(h_c) - \langle m(1^3P_J) \rangle$

BESIII:  $0.10 \pm 0.13 \pm 0.18 \text{ MeV}/c^2$   
 CLEOc:  $0.02 \pm 0.19 \pm 0.13 \text{ MeV}/c^2$

**By combining inclusive results with E1-photon tagged results**

$\mathcal{B}(\psi' \rightarrow \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$

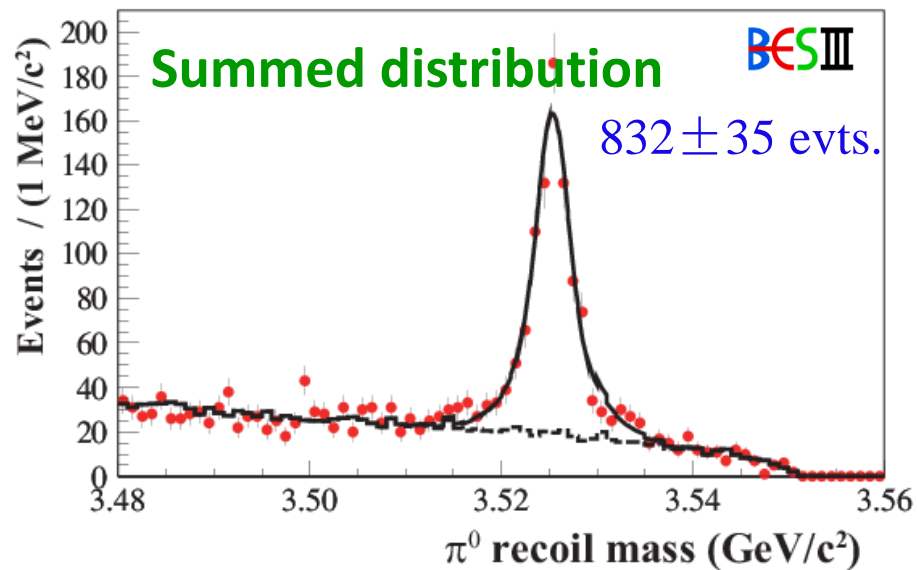
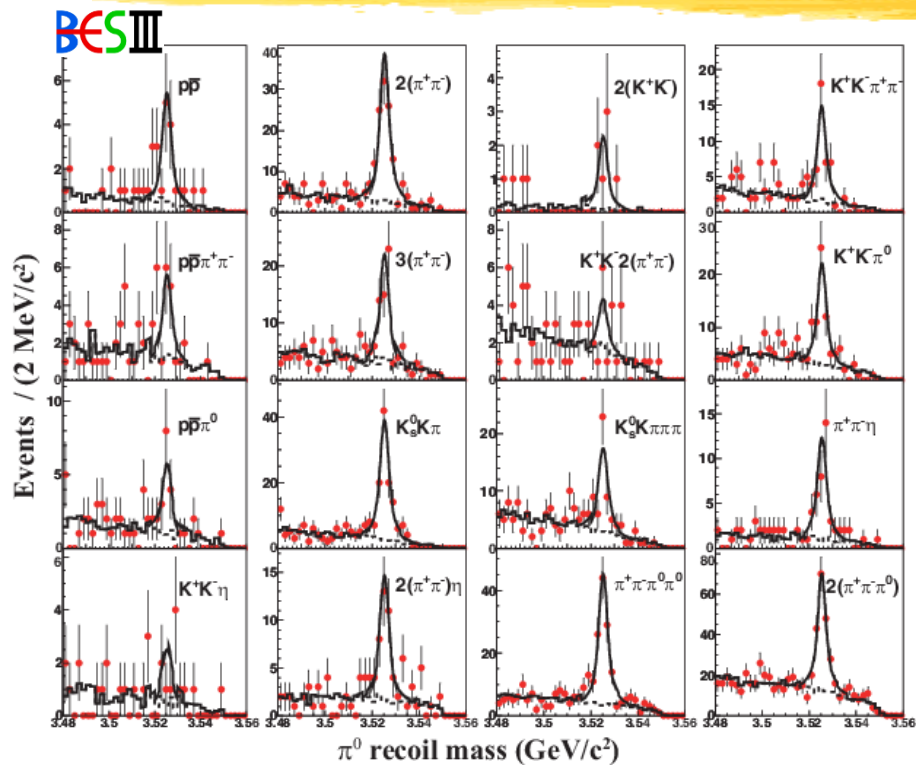
$\mathcal{B}(h_c \rightarrow \gamma \eta_c) = (54.3 \pm 6.7 \pm 5.2)\%$

Agrees with prediction from  
 Kuang, Godfrey, Dude et al.



# BESIII: 16 $h_c(1P)$ decay modes ( $\sim 40\%$ $\eta_c(1S)$ decays)

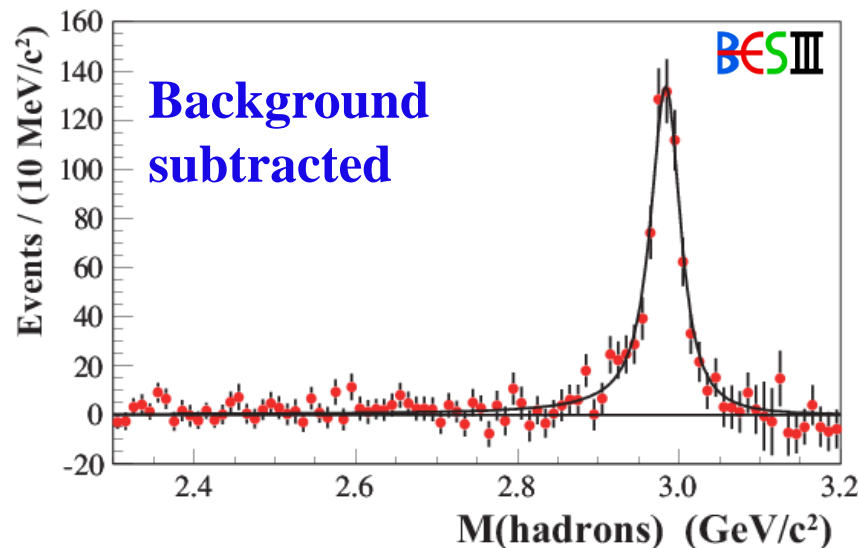
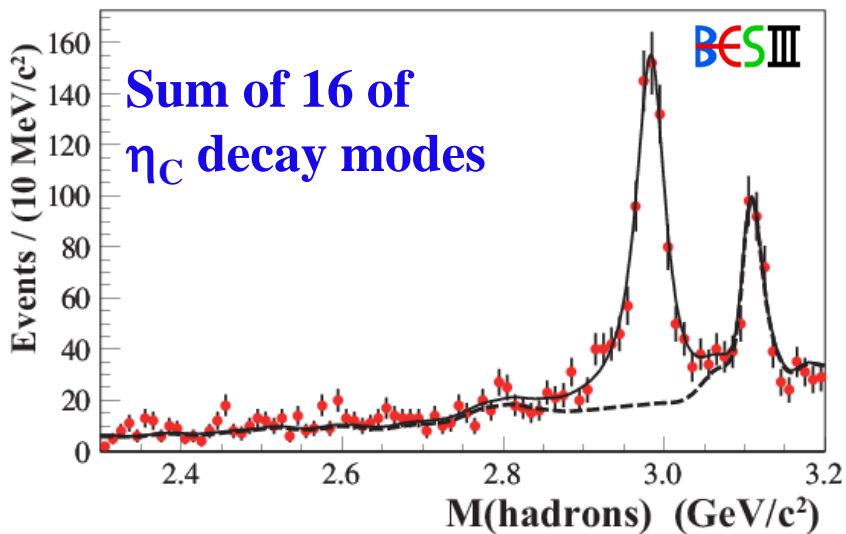
PRD 86, 092009



( $\text{MeV}/c^2$ )	BESIII Exclusive	BESIII Inclusive	CLEO
<b>M</b>	$3525.31 \pm 0.11 \pm 0.14$	$3525.40 \pm 0.13 \pm 0.18$	$3525.21 \pm 0.27 \pm 0.14$
<b><math>\Gamma</math></b>	$0.70 \pm 0.28 \pm 0.22$	$0.73 \pm 0.45 \pm 0.28$	--
<b><math>\Delta M_{hf}(1P)</math></b>	$-0.01 \pm 0.11 \pm 0.15$	$0.10 \pm 0.13 \pm 0.18$	$0.08 \pm 0.18 \pm 0.12$

BESIII: PRL 104 132002 (2010)

CLEOc: PRL 101 182003 (2008)



$\eta_c$  lineshape in  $h_c \rightarrow \gamma \eta_c$  is **not as distorted** as in  $\psi' \rightarrow \gamma \eta_c$  decays:  
 $\Rightarrow$  non-resonant interfering background is smaller than  $\psi' \rightarrow \gamma h_c$   
 $\Rightarrow$  this channel best suited to determine  $\eta_c$  resonance parameters

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

$M = 2984.49 \pm 1.16 \pm 0.52 \text{ MeV}/c^2$   
 $\Gamma = 36.4 \pm 3.2 \pm 1.7 \text{ MeV}$

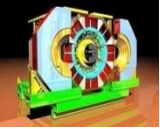
$\psi' \rightarrow \gamma \eta_c$

PRL 108, 222002

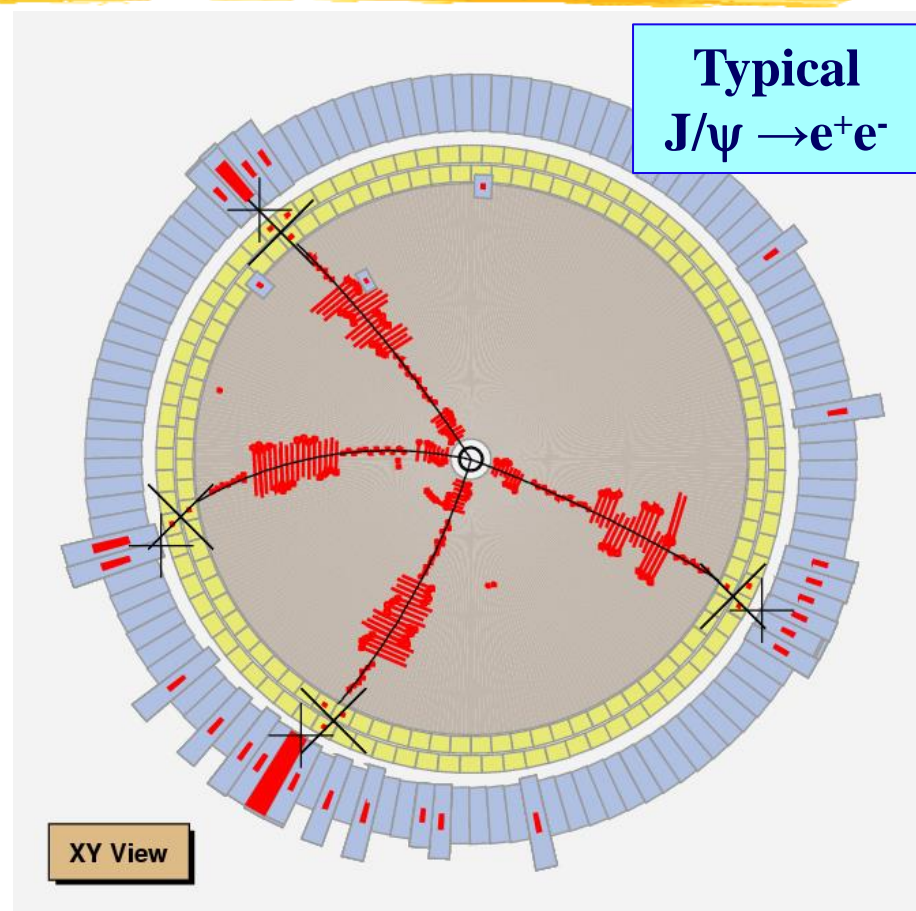
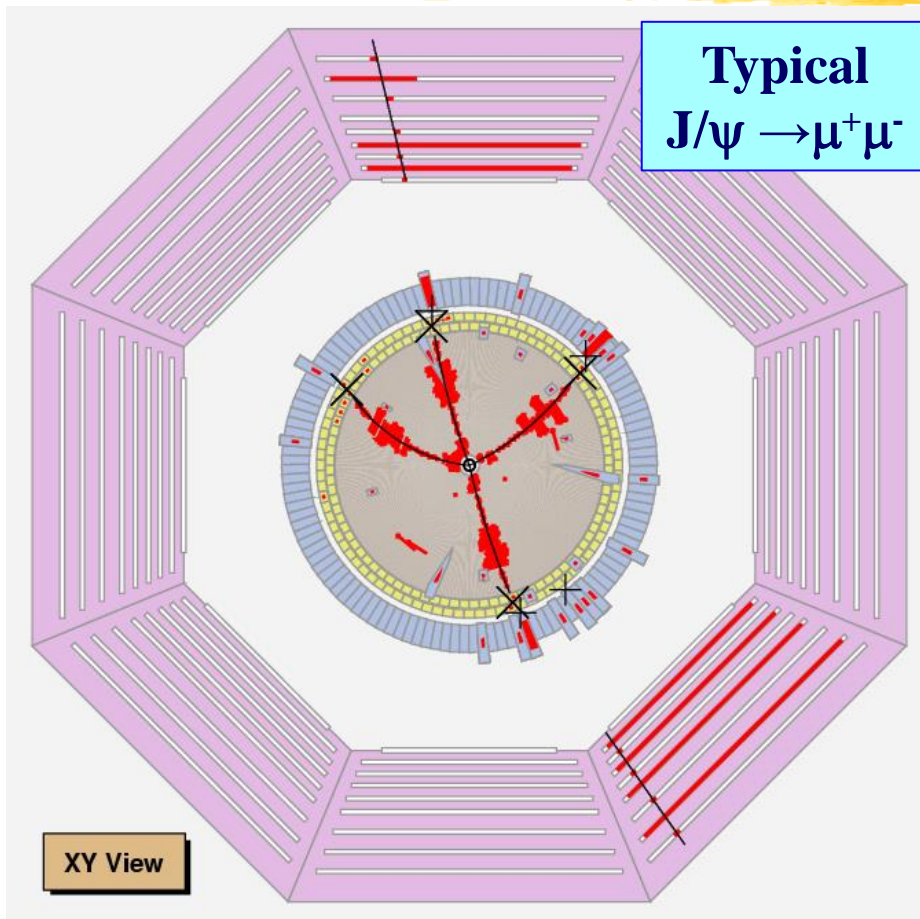
$M = 2984.3 \pm 0.6 \pm 0.6 \text{ MeV}/c^2$   
 $\Gamma = 32.0 \pm 1.2 \pm 1.0 \text{ MeV}$

Consistent results, but still dominant statistical errors: more statistics is needed!

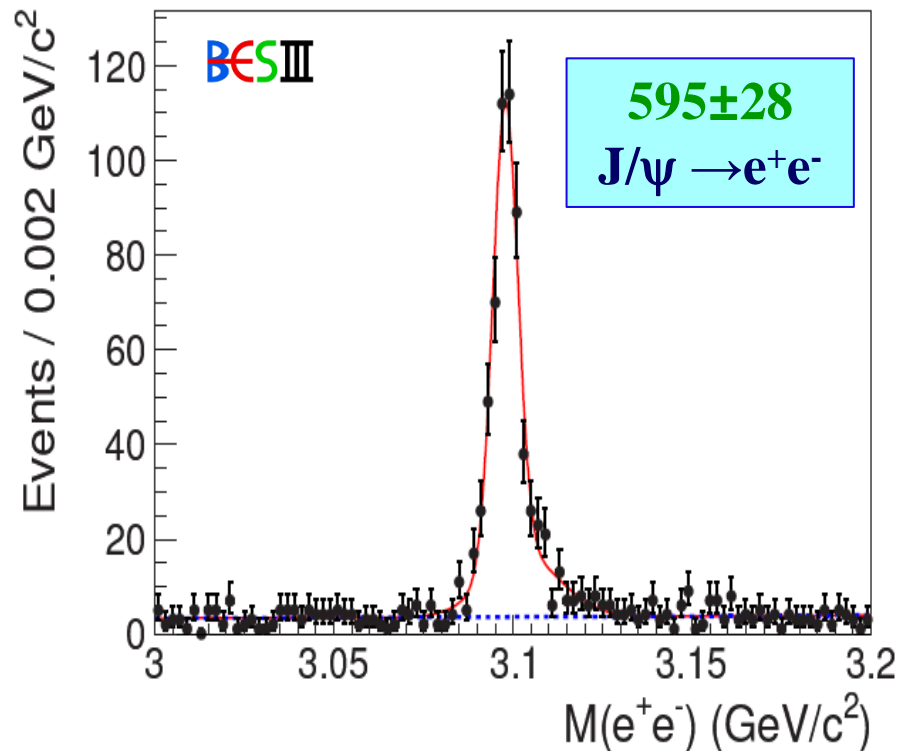
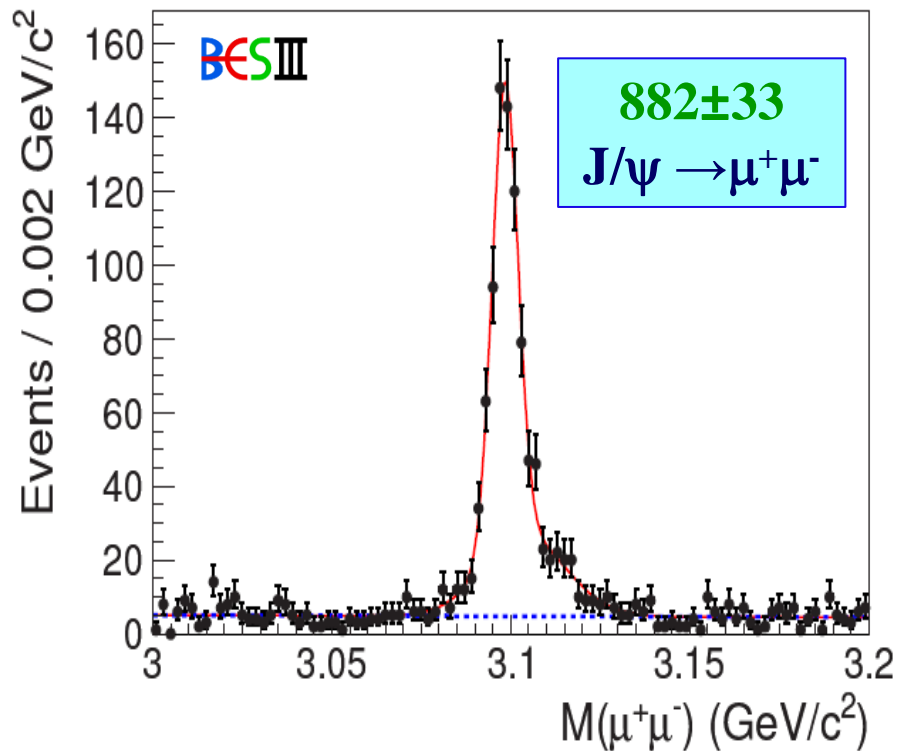




# BESIII: $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ events



- 4 charged tracks,  $J/\psi$  reconstruct via lepton pairs
- very clean sample, very high efficiency, kinematic fit used
- only use MDC & EMC information, MC simulation reliable



- Dominant background  $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$
- $J/\psi$  signal: [3.08,3.12] GeV
- $J/\psi$  sideband: [3.0,3.06] GeV or [3.14,3.20] GeV

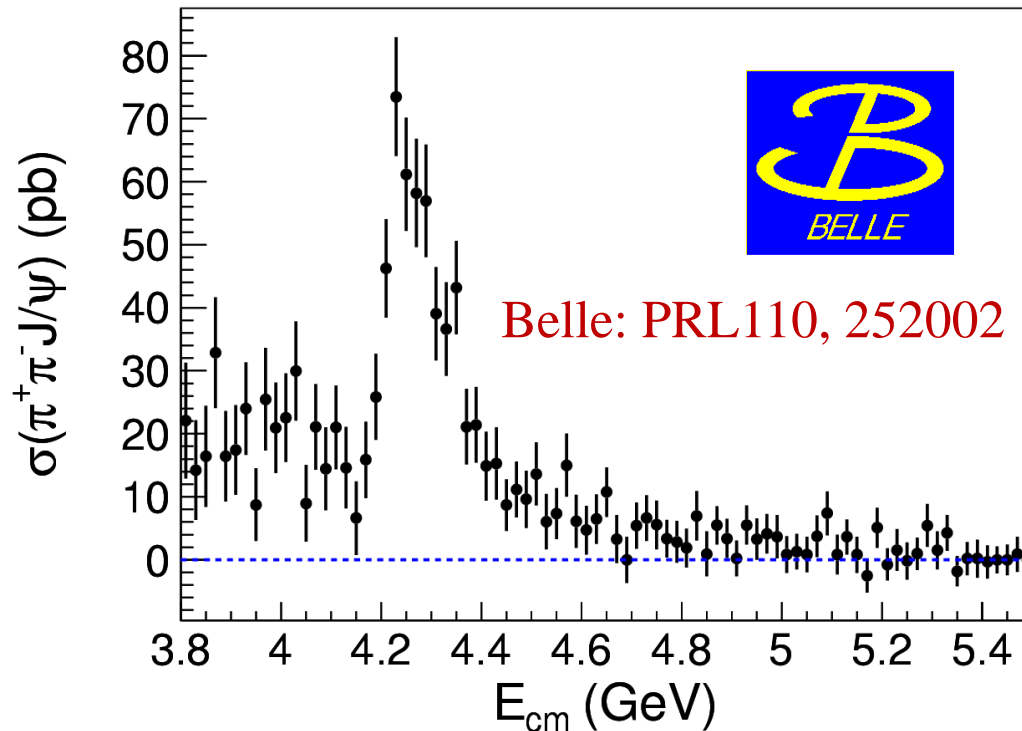
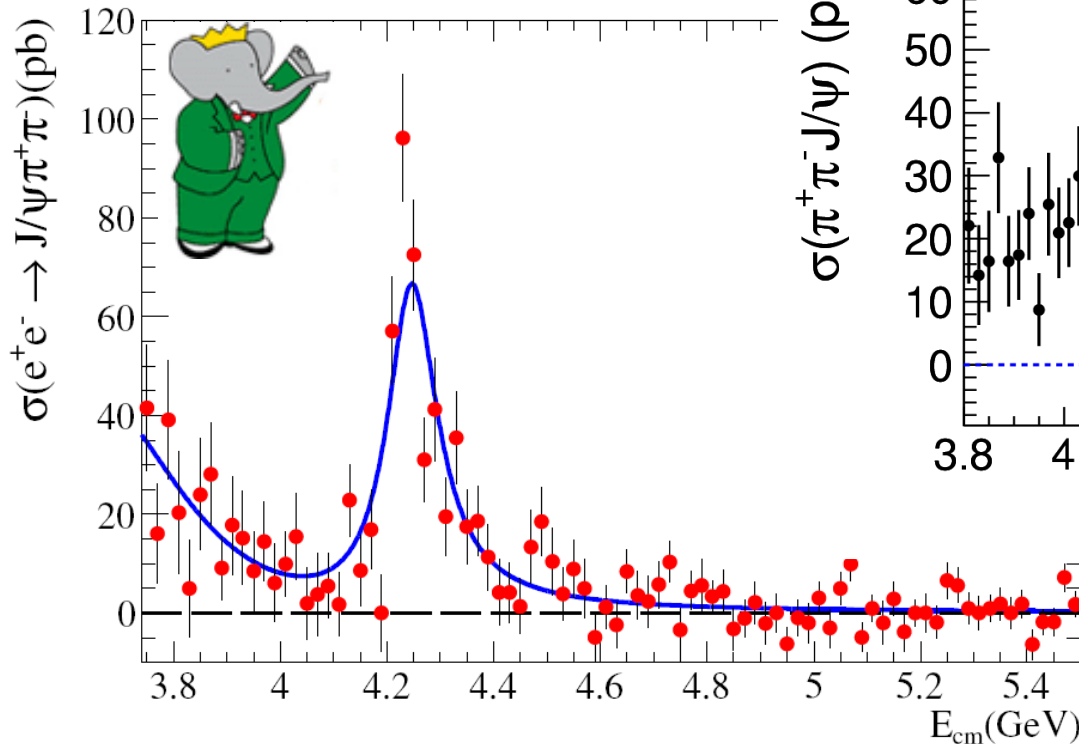




# $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ – cross sections @ 4.260 GeV

PRL 110, 252001

BaBar: PRD86, 051102 (2012)



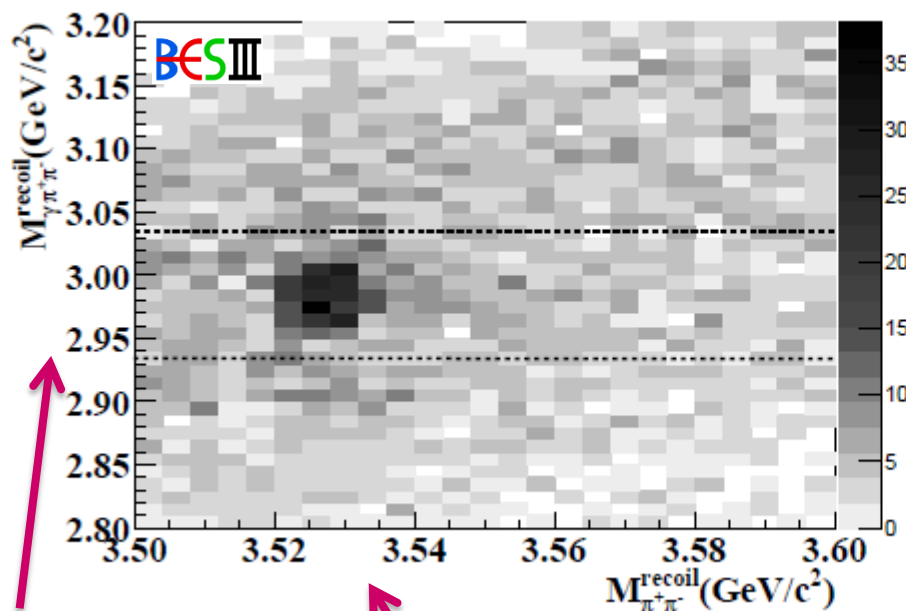
- BESIII cross sections:
- more energy points
  - more data!

BESIII:  $\sigma_B(e^+e^- \rightarrow \pi^+\pi^-J/\psi) = (62.9 \pm 1.9 \pm 3.7) \text{ pb}$

- agreement with BaBar & Belle
- best precision!

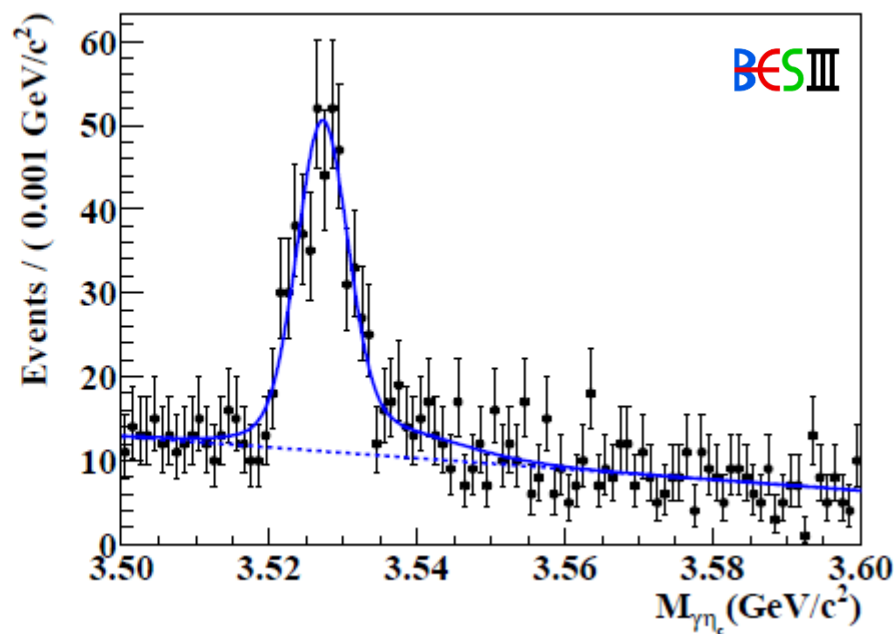


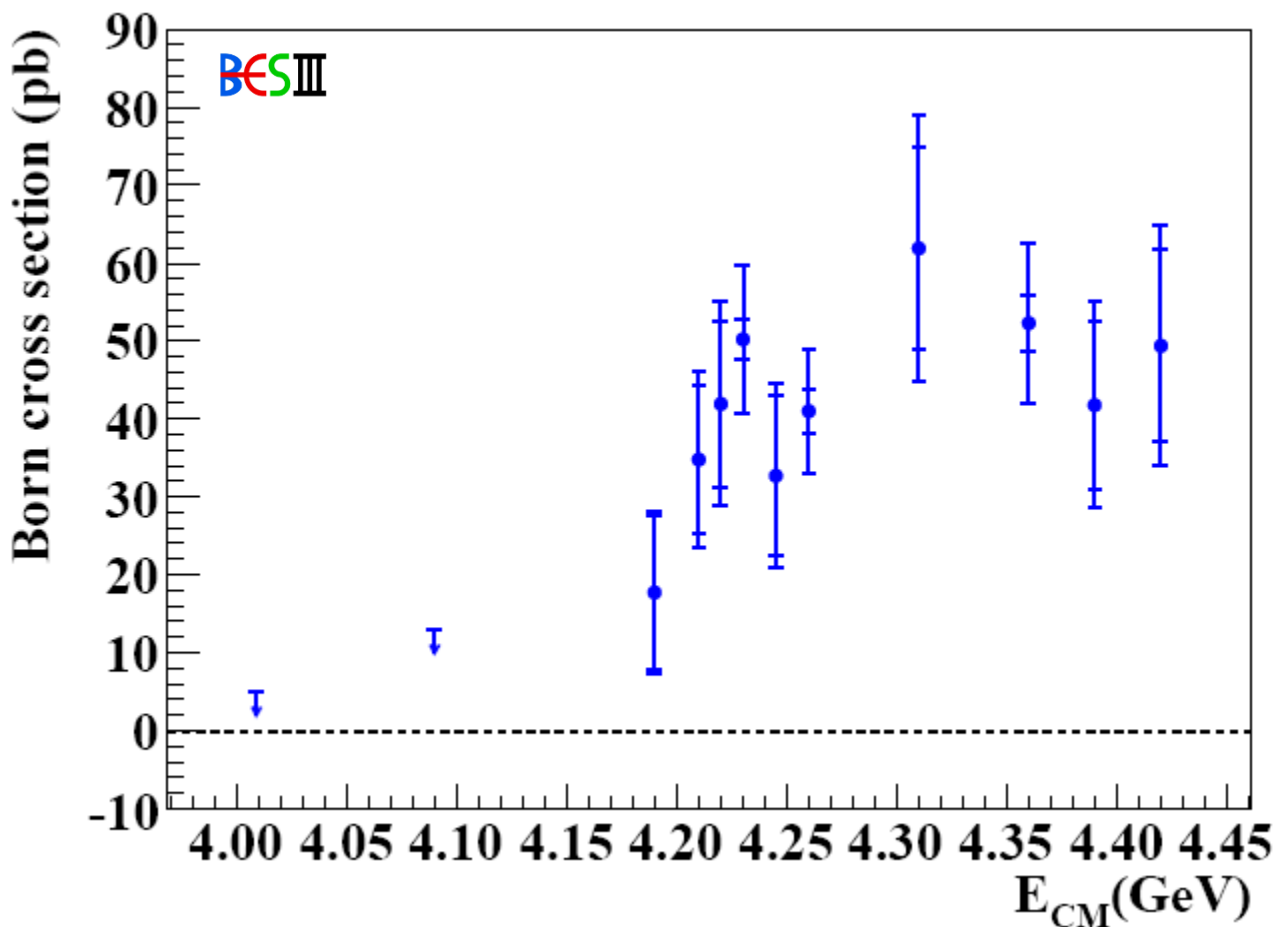
- $h_c \rightarrow \underline{\gamma}\eta_c, \eta_c \rightarrow \text{hadrons}$  [16 exclusive decay modes]
  - $p \bar{p}, \pi^+\pi^-K^+K^-, \pi^+\pi^-p \bar{p}, 2(K^+K^-), 2(\pi^+\pi^-), 3(\pi^+\pi^-)$
  - $2(\pi^+\pi^-)K^+K^-, K_S^0K^+\pi^-+c.c., K_S^0K^+\pi^-\pi^+\pi^-+c.c., K^+K^-\pi^0$
  - $p \bar{p}\pi^0, K^+K^-\eta, \pi^+\pi^-\eta, \pi^+\pi^-\pi^0\pi^0, 2(\pi^+\pi^-)\eta, 2(\pi^+\pi^-\pi^0)$



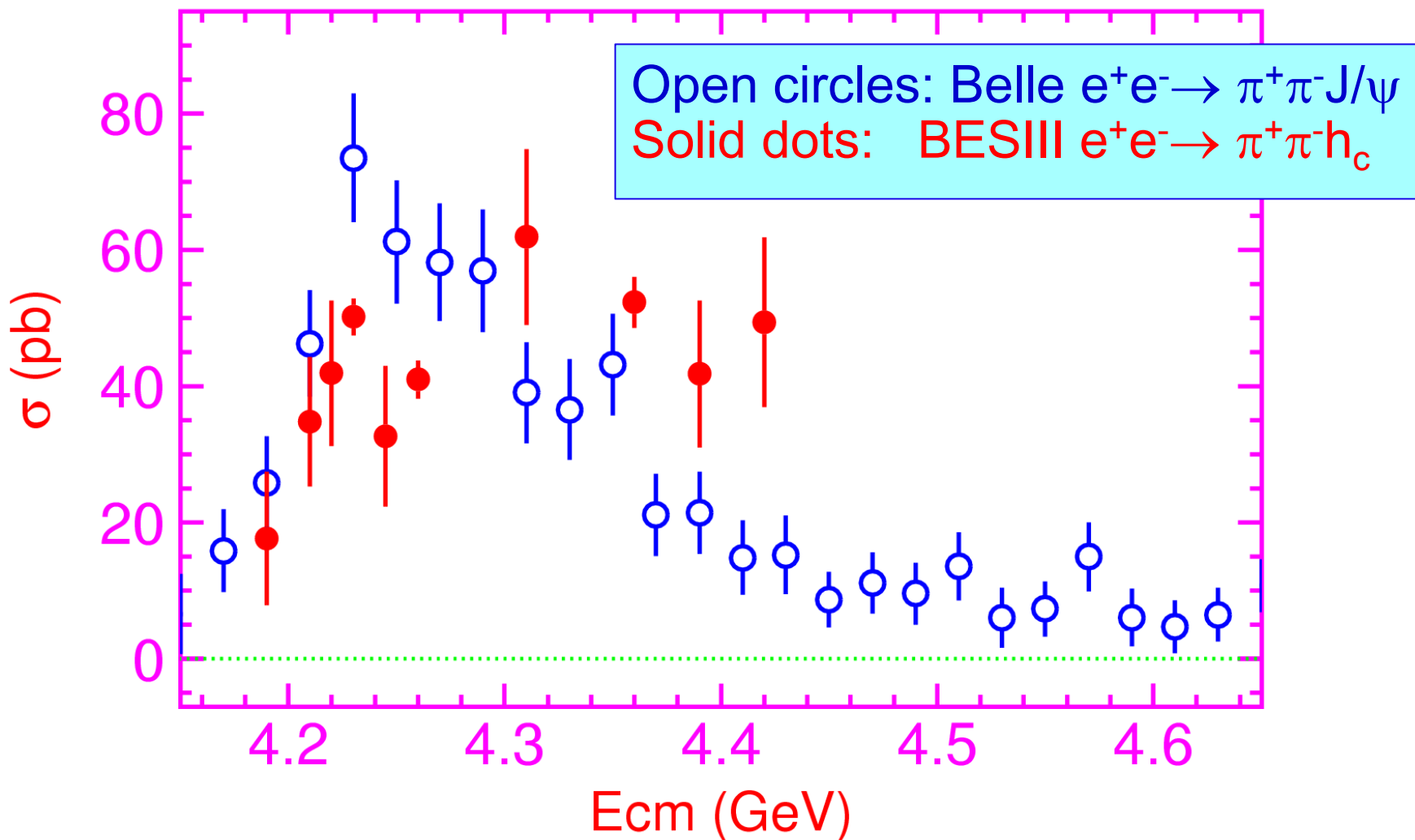
$\eta_c$  candidate

$h_c$  candidate

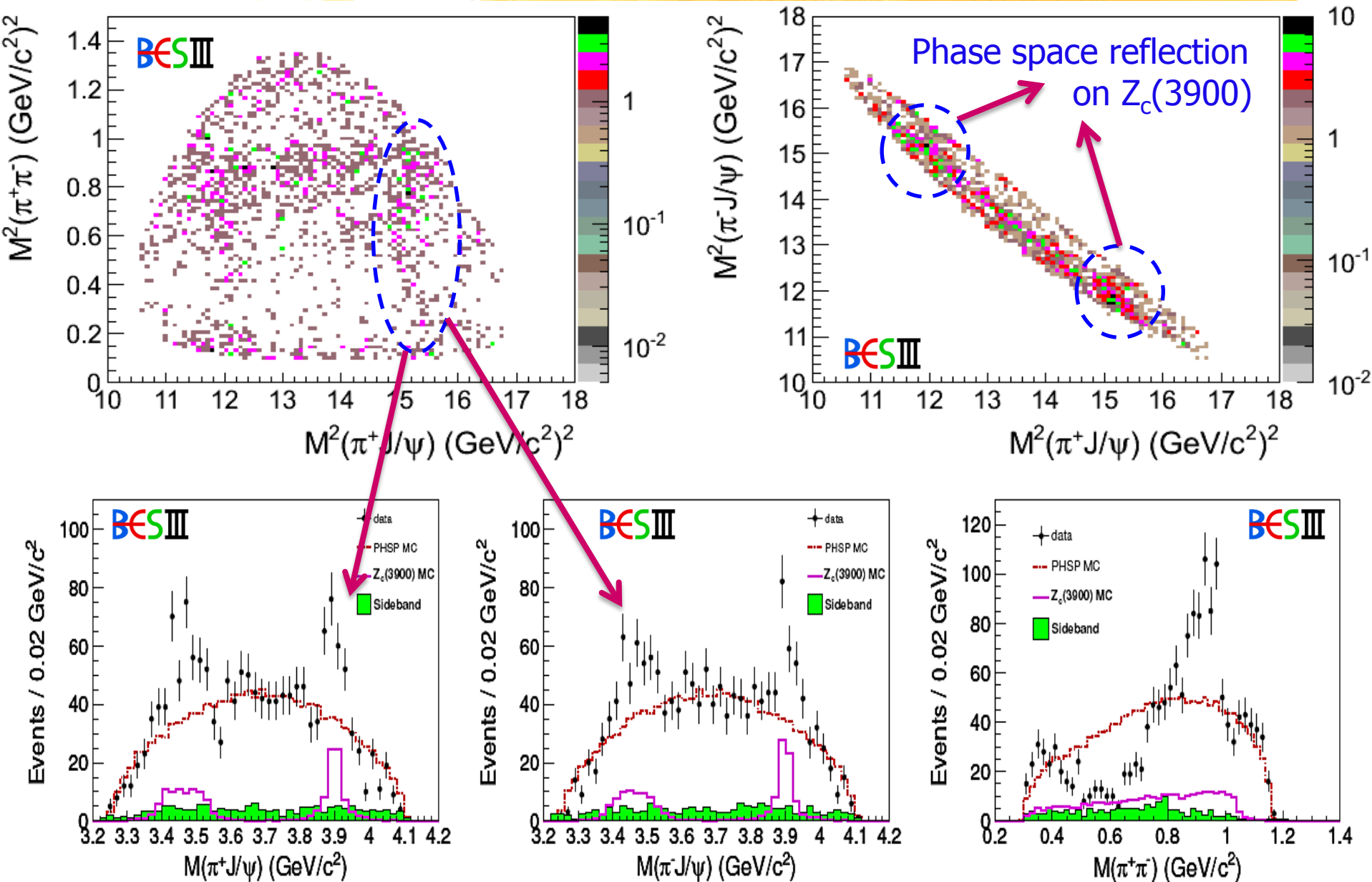


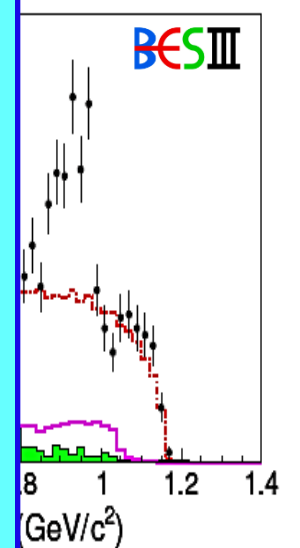
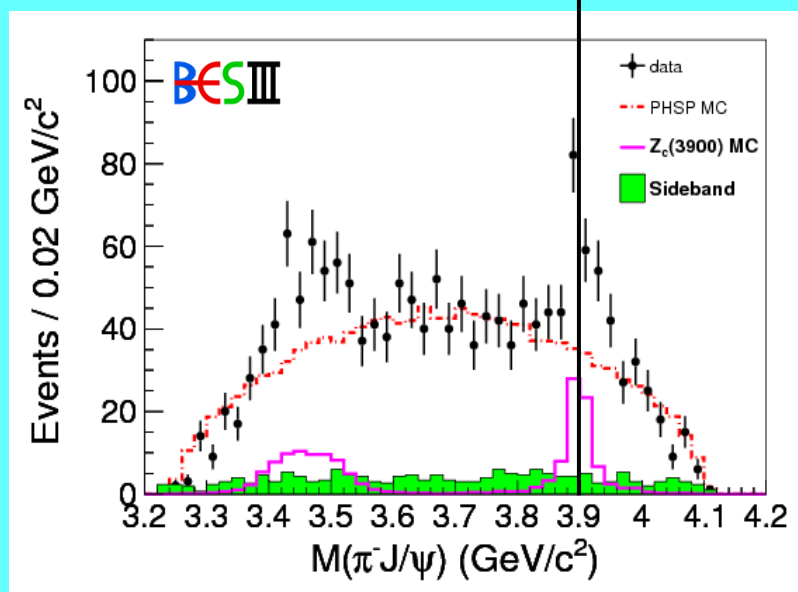
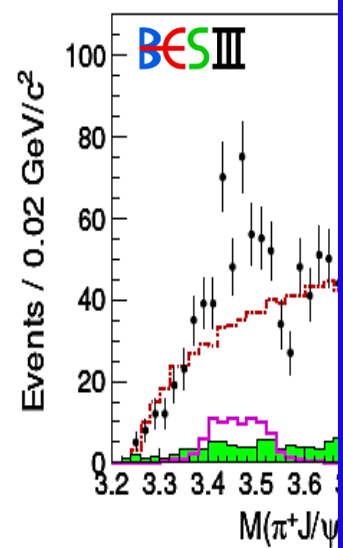
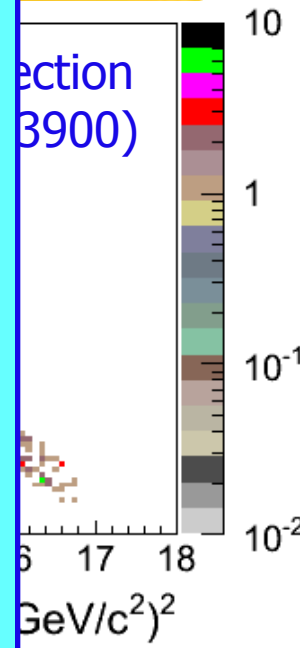
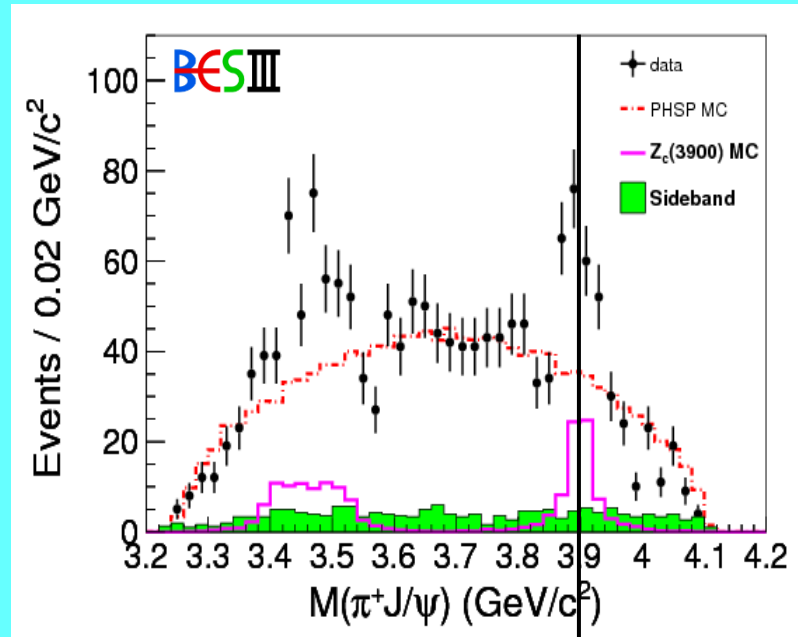
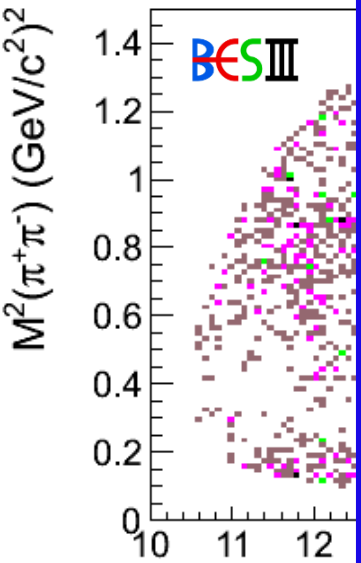


- $\sigma(e^+e^- \rightarrow \pi^+\pi^-h_c) \sim \sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi)$  but line shape different
- Local maximum  $\sim 4.23$  GeV



More data at higher energies needed to complete line shape measurement

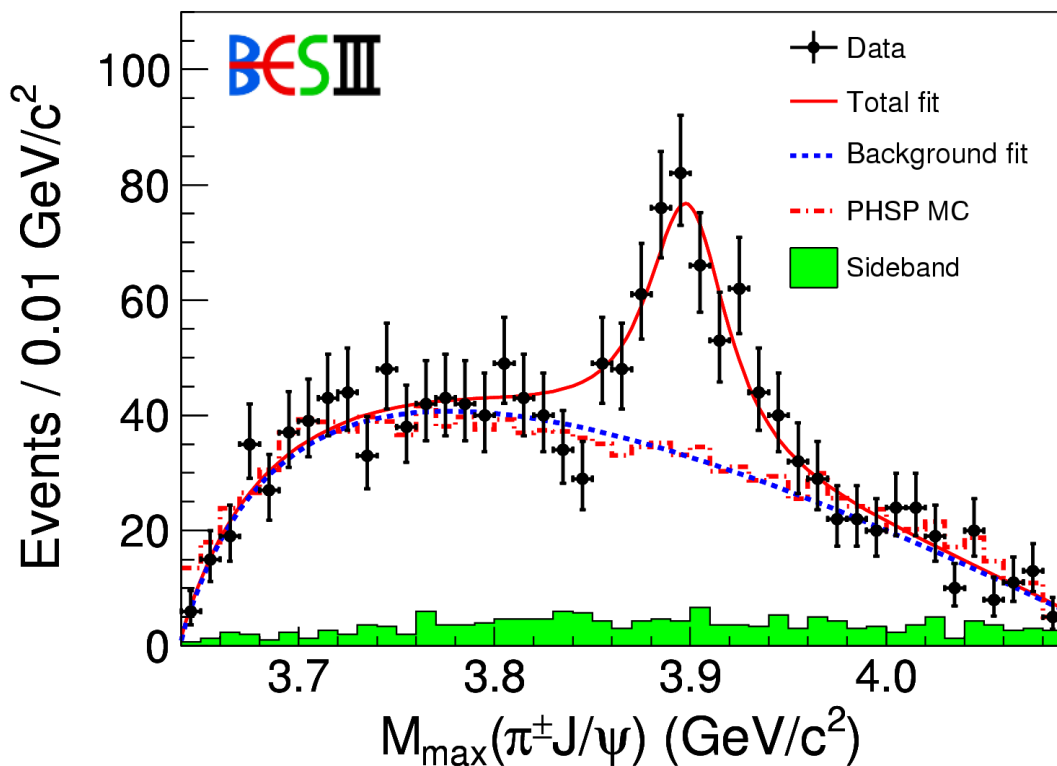




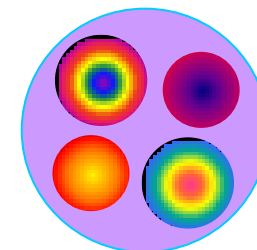


# BESIII: $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi^+\pi^-J/\psi$ @ 4.260 GeV

PRL 110, 252001



- couples to  $c\bar{c}$
- has electric charge
- at least 4-quarks
- what is its nature?



**S-wave Breit-Wigner with efficiency correction**

$M = (3899.0 \pm 3.6 \pm 4.9) \text{ MeV}/c^2$

$\Gamma = (46 \pm 10 \pm 20) \text{ MeV}/c^2$

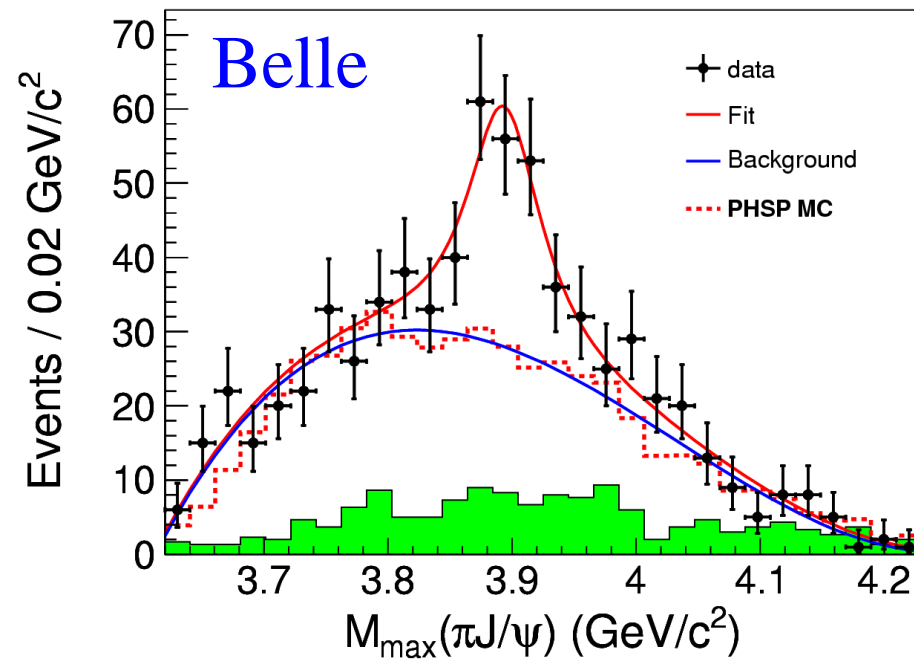
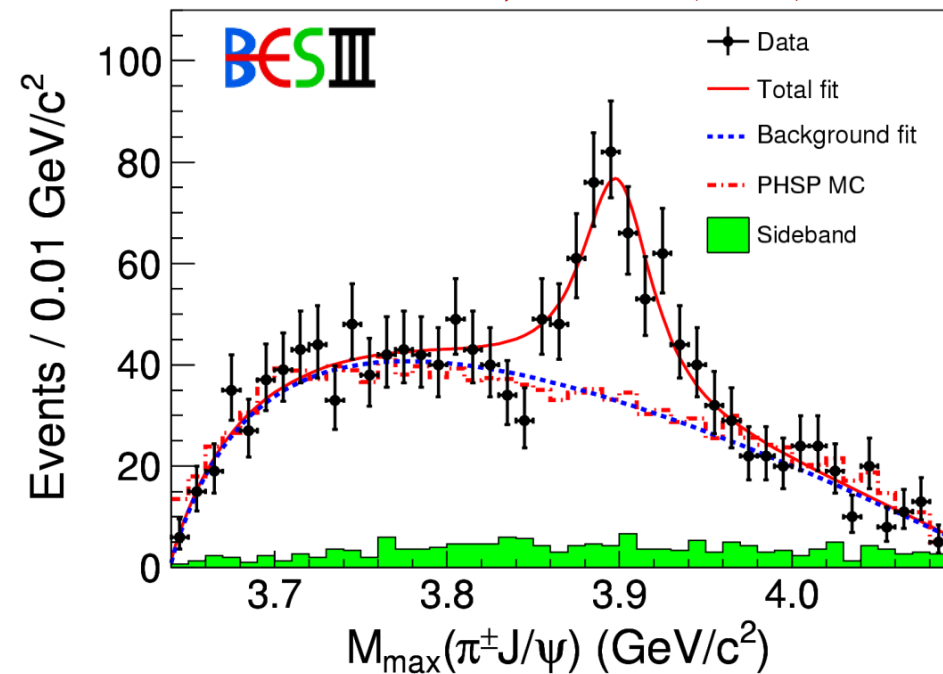
$R = (21.5 \pm 3.3 \pm 7.5)\%$

**Significance**  
**>8σ**



PRL 110, 252001 (2013)

PRL 110, 252002 (2013)



$$M = (3899.0 \pm 3.6 \pm 4.9) \text{ MeV/c}^2$$

$$\Gamma = (46 \pm 10 \pm 20) \text{ MeV/c}^2$$

$307 \pm 48$  events

$> 8\sigma$

$$M = (3894.5 \pm 6.6 \pm 4.5) \text{ MeV/c}^2$$

$$\Gamma = (63 \pm 24 \pm 26) \text{ MeV/c}^2$$

$159 \pm 49$  events

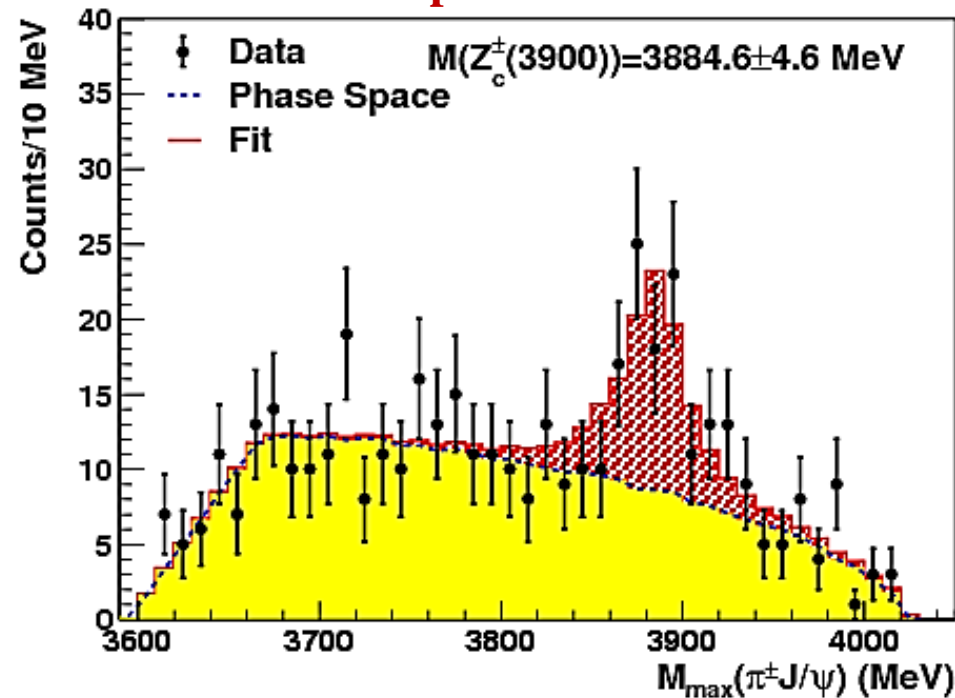
$> 5.2\sigma$





K. Seth & co. @ 4.170 GeV

hep-ex:1304.3036

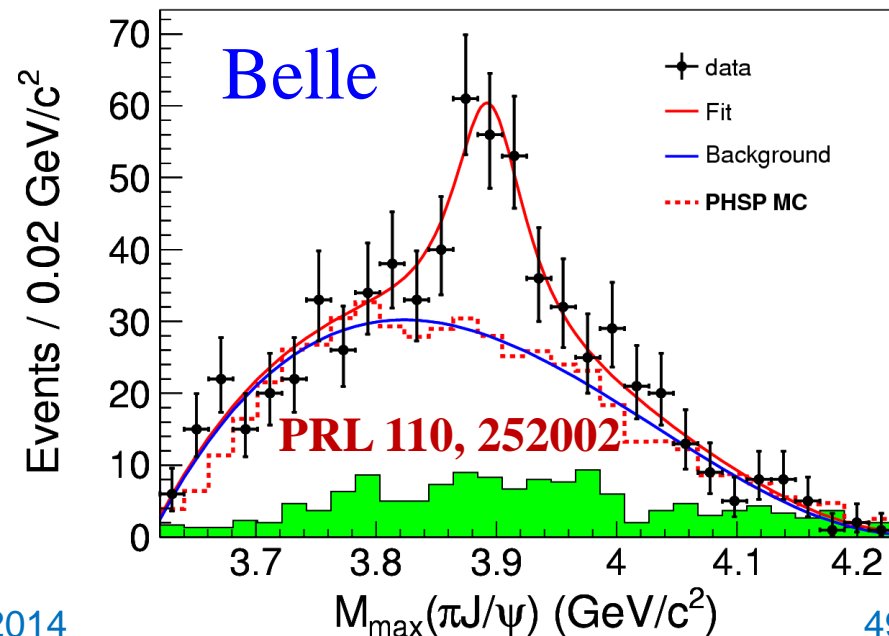
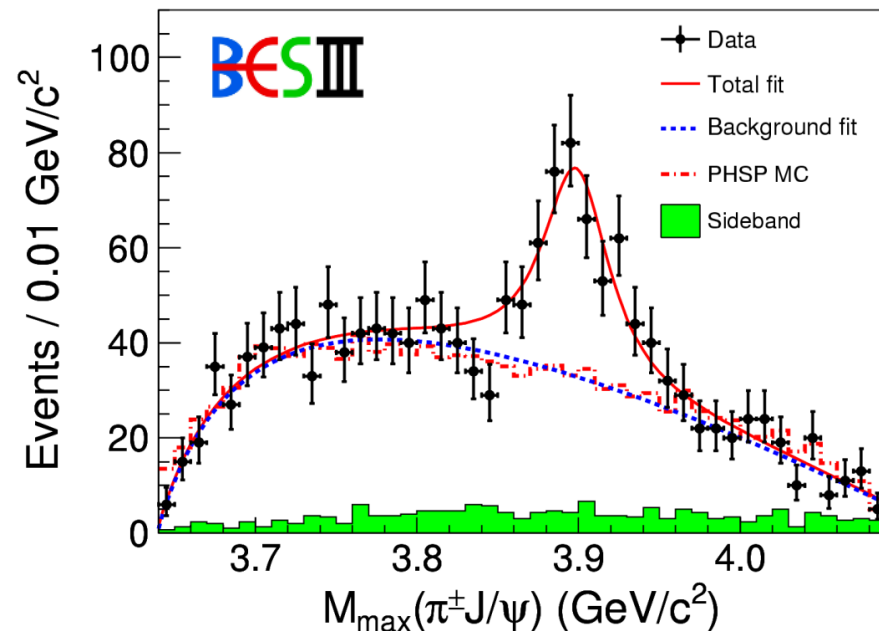


$M = (3885 \pm 5 \pm 1) \text{ MeV}/c^2$

$\Gamma = (34 \pm 12 \pm 4) \text{ MeV}/c^2$

81 ± 20 events

6.1σ





# $e^+e^- \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0\pi^0 J/\psi$ @ 4.230-4.260 GeV

Preliminary

CLEOc: PLB 727, 366

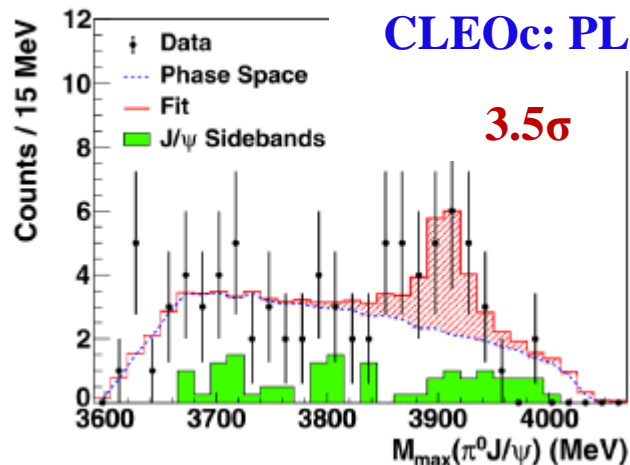
**BESIII PRELIMINARY!**

- 2.8fb<sup>-1</sup> data at 10 energy points from 4230~4420 MeV
- $Z_c(3900)^0$  is observed clearly at:  
 $E_{cm} = 4230, 4260, 4360 \text{ MeV}$

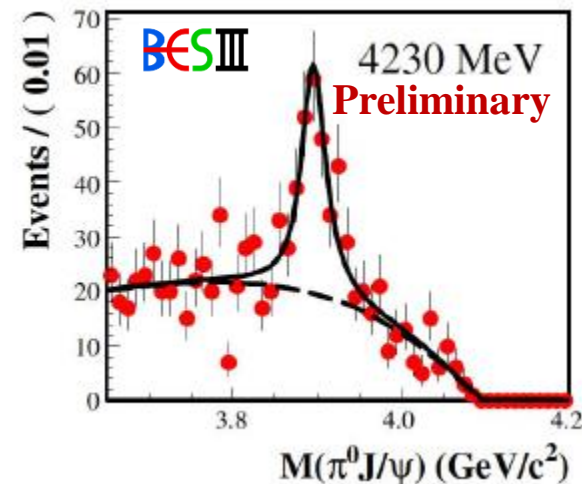
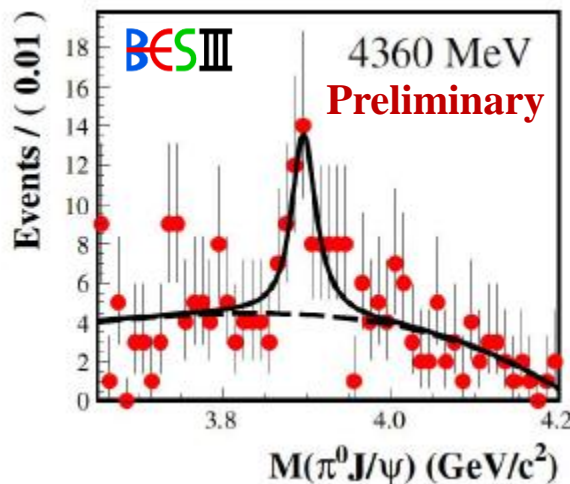
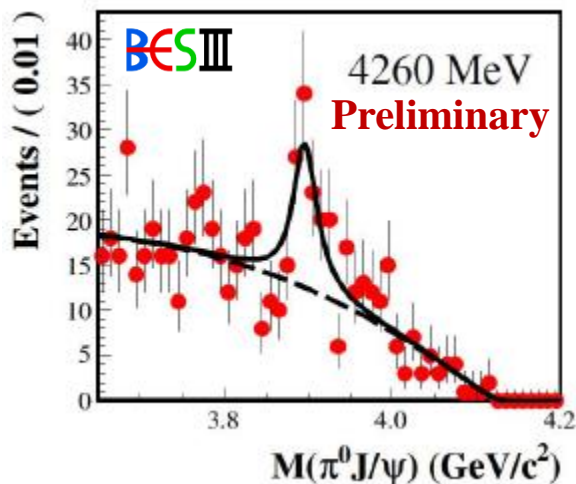
$$M = (3894.8 \pm 2.3) \text{ MeV}/c^2$$

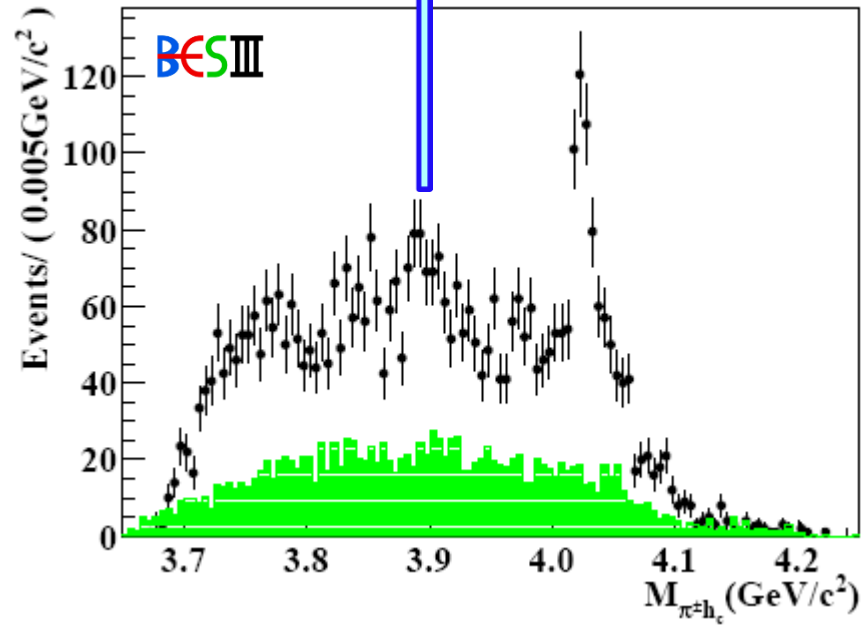
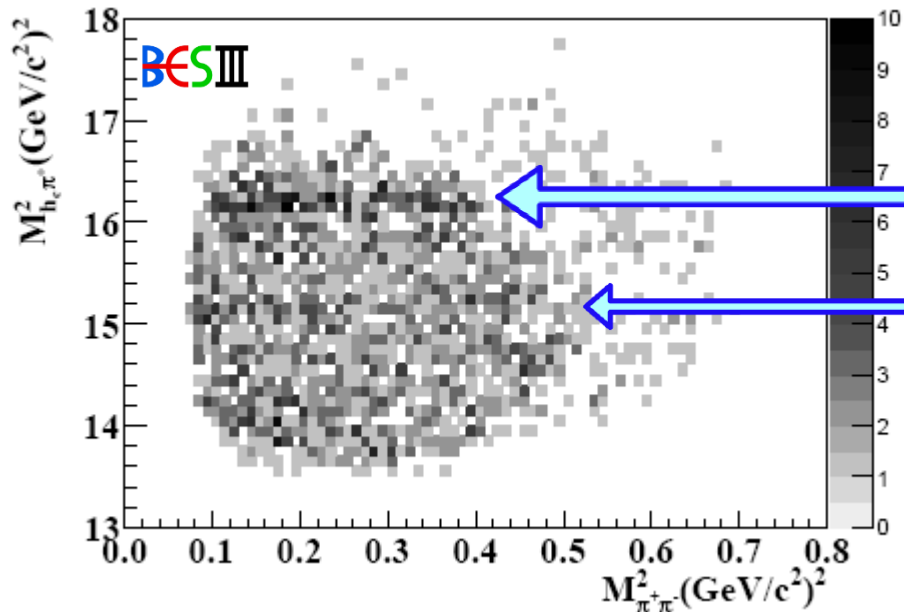
$$\Gamma = (29.6 \pm 8.2) \text{ MeV}/c^2$$

**10.4 $\sigma$**



**An isospin triplet for  $Z_c(3900)$  has been established**



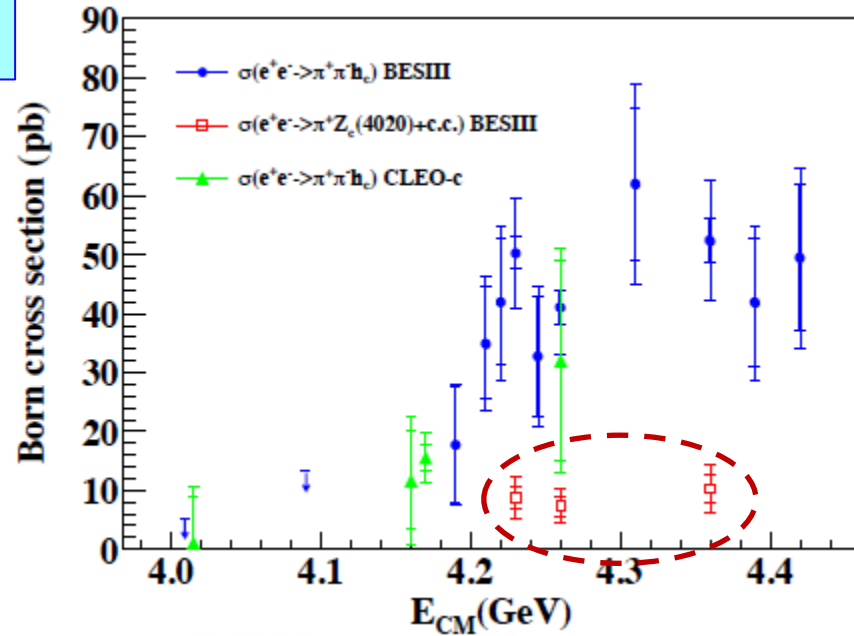
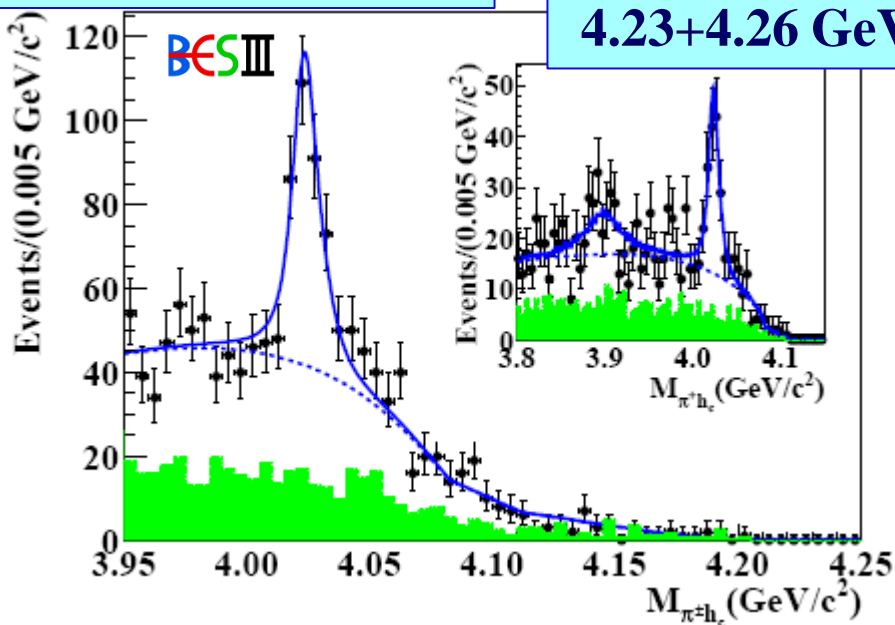


- all collected energies  
[3.900 ÷ 4.420 GeV]
- $h_c \rightarrow \gamma\eta_c, \eta_c \rightarrow$  hadrons  
[16 exclusive decay modes]



Simultaneous fit to 4.26/4.36 GeV data and 16  $\eta_c$  decay modes.

4.23+4.26+4.36 GeV



$M = (4022.9 \pm 0.8 \pm 2.7) \text{ MeV}/c^2$   
 $\Gamma = (7.9 \pm 2.7 \pm 2.6) \text{ MeV}/c^2$   
 $> 8.9\sigma$

$\sigma(e^+e^- \rightarrow \pi Z_c(4020) \rightarrow \pi^+\pi^-h_c)$   
 $\sigma(4.23 \text{ GeV}) = (8.7 \pm 1.9 \pm 2.8 \pm 1.4) \text{ pb}$   
 $\sigma(4.26 \text{ GeV}) = (7.4 \pm 1.7 \pm 2.1 \pm 1.2) \text{ pb}$   
 $\sigma(4.36 \text{ GeV}) = (10.3 \pm 2.3 \pm 3.1 \pm 1.6) \text{ pb}$

4.26 GeV:

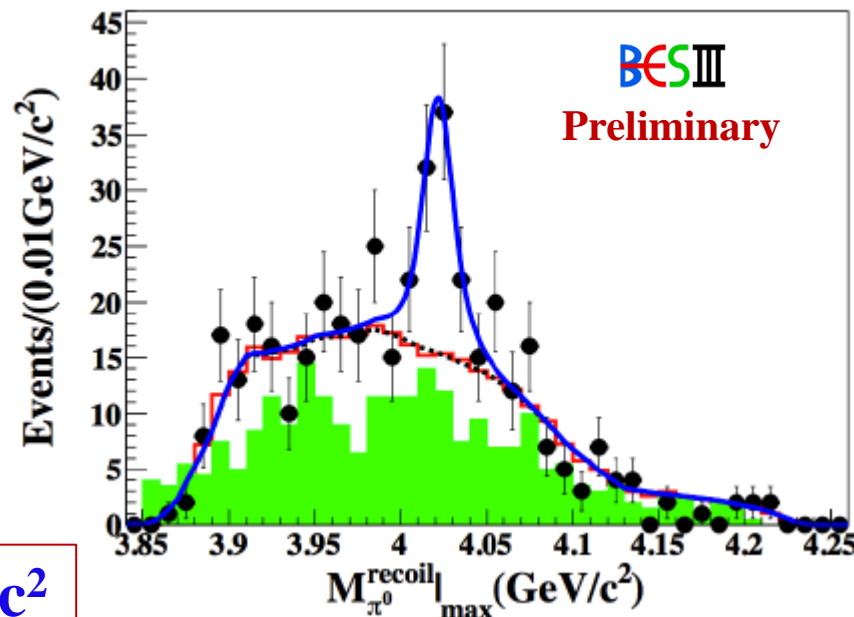
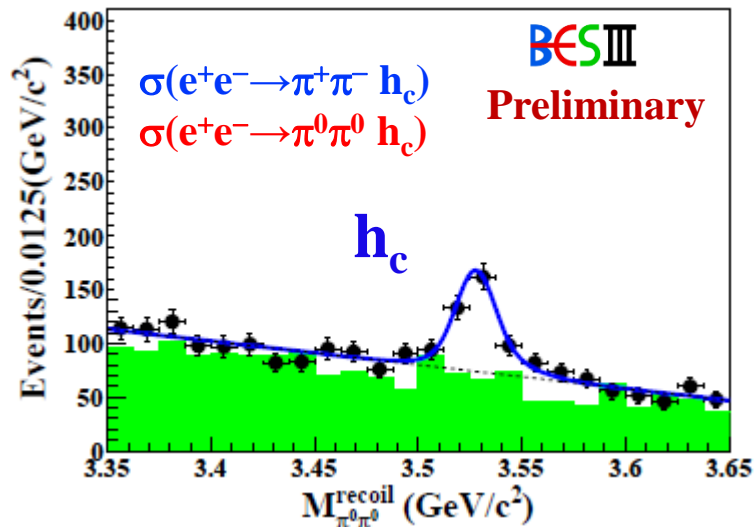
$\sigma(e^+e^- \rightarrow \pi Z_c(3900) + \pi^- \rightarrow \pi^+\pi^-h_c) = < 11 \text{ pb (90\% C.L.)}$

$\mathcal{B}(h_c \rightarrow \gamma \eta_c)$



**BESIII PRELIMINARY!**

- $2.8\text{fb}^{-1}$  data at 10 energy points from 4230~4420 MeV
- $Z_c(4020)^0$  is observed clearly at:  $E_{\text{cm}}=4230, 4260, 4360\text{MeV}$



$$M_{Z_c(4020)^0} = (4023.6 \pm 2.2 \pm 3.9) \text{ MeV/c}^2$$

$$M_{Z_c(4020)^\pm} = (4022.9 \pm 0.8 \pm 2.7) \text{ MeV/c}^2$$

$$\Gamma_{Z_c(4020)^0} \text{ fixed @ } \Gamma_{Z_c(4020)^\pm}$$

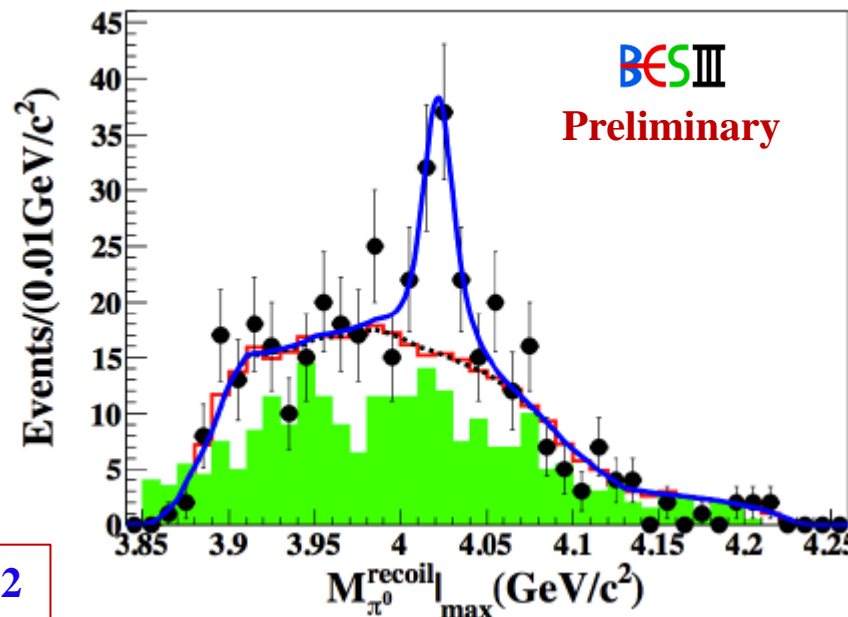
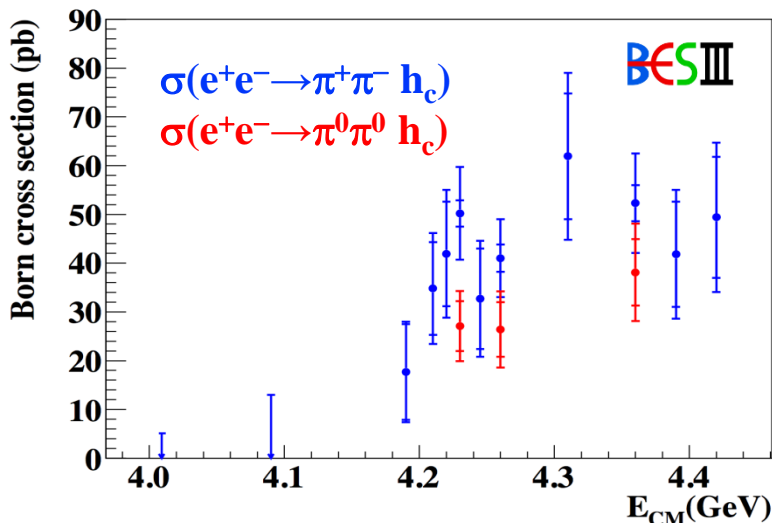
$>5\sigma$

An isospin triplet for  $Z_c(3900)$  has also been observed



**BESIII PRELIMINARY!**

- $2.8\text{fb}^{-1}$  data at 10 energy points from 4230~4420 MeV
- $Z_c(4020)^0$  is observed clearly at:  $E_{\text{cm}}=4230, 4260, 4360\text{MeV}$



$M_{Z_c(4020)^0} = (4023.6 \pm 2.2 \pm 3.9) \text{ MeV}/c^2$

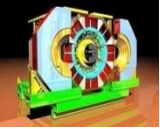
$M_{Z_c(4020)^\pm} = (4022.9 \pm 0.8 \pm 2.7) \text{ MeV}/c^2$

$\Gamma_{Z_c(4020)^0}$  fixed @  $\Gamma_{Z_c(4020)^\pm}$

$>5\sigma$

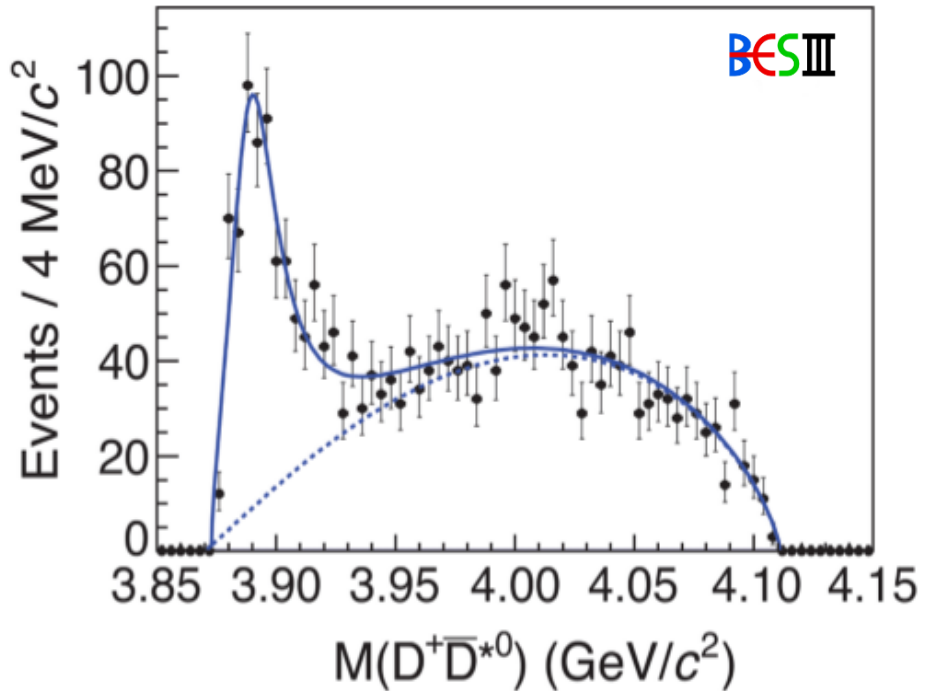
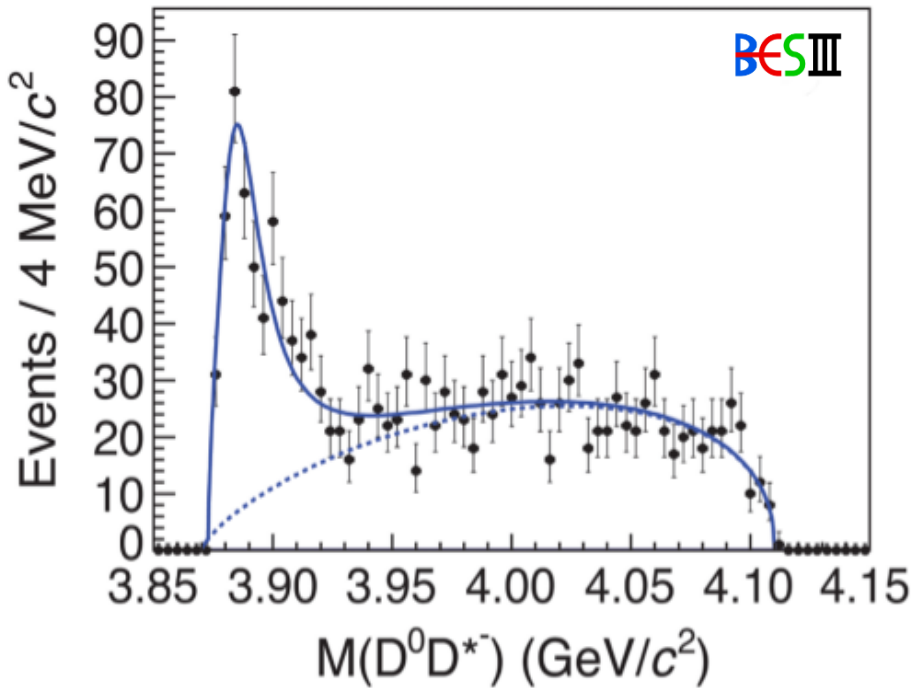
An isospin triplet for  $Z_c(4020)$  has also been observed

$\sigma(e^+e^- \rightarrow \pi^+\pi^- h_c) \sim 2 \sigma(e^+e^- \rightarrow \pi^0\pi^0 h_c)$   
isospin conservation



# BESIII: $e^+e^- \rightarrow \pi Z_c(3885) \rightarrow \pi^- (DD^*)^+ + c.c. @ 4.260 \text{ GeV}$ PRL 112, 022001

525 pb<sup>-1</sup> data @ 4260 MeV



$M = (3883.9 \pm 1.5 \pm 4.2) \text{ MeV}/c^2$   
 $\Gamma = (24.8 \pm 3.3 \pm 11.0) \text{ MeV}/c^2$   
 $> 18\sigma$

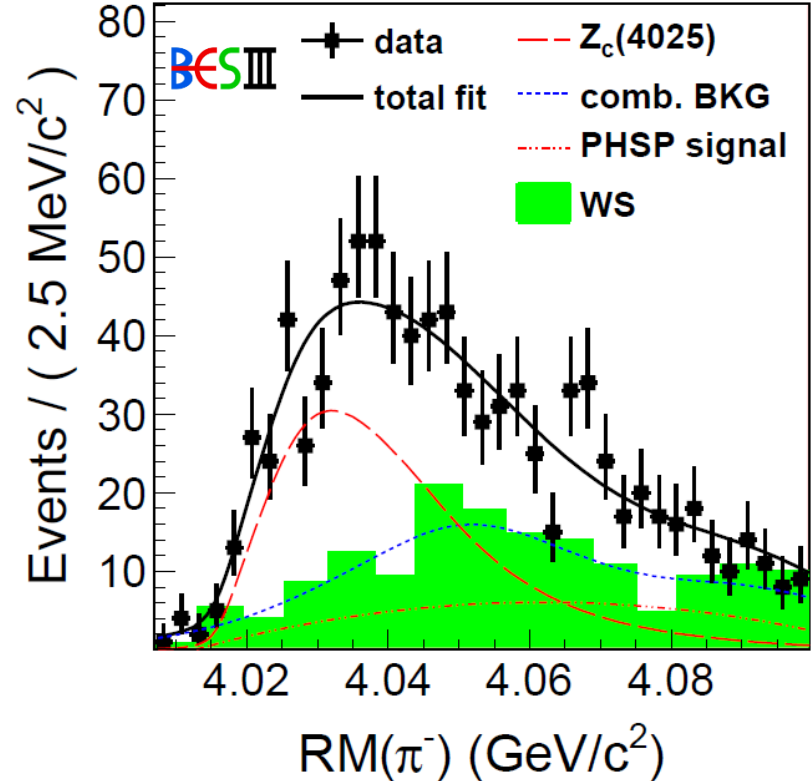
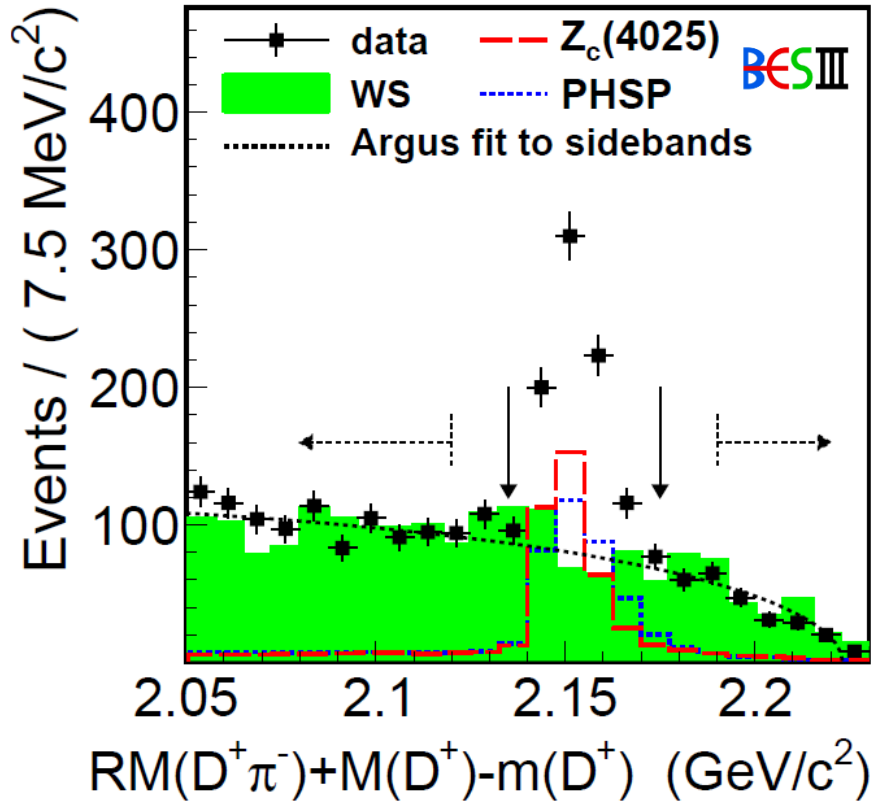
$\pi Z_c(3885)$  ang. dist. favours  $J^P = 1^+$   
 disfavours  $1^- e 0^-$

$$\sigma(e^+e^- \rightarrow \pi^- Z_c(3885)^+ \times Z_c(3885)^+ \rightarrow (DD^*)^+ + c.c.) = (83.5 \pm 6.6 \pm 22.0) \text{ pb}$$

$$R = \frac{\Gamma(Z_c(3885) \rightarrow D^* \bar{D}^*)}{\Gamma(Z_c(3900) \rightarrow \pi J/\psi)} = (6.2 \pm 1.1 \pm 2.7)$$



# BESIII: $e^+e^- \rightarrow \pi Z_c(4025) \rightarrow \pi^- (D^* \bar{D}^*)^+ + c.c. @ 4.260 \text{ GeV}$ PRL 112, 132001



$$M = (4026.3 \pm 2.6 \pm 3.7) \text{ MeV}/c^2$$

$$\Gamma = (24.8 \pm 5.7 \pm 7.7) \text{ MeV}/c^2$$

$$> 10\sigma$$

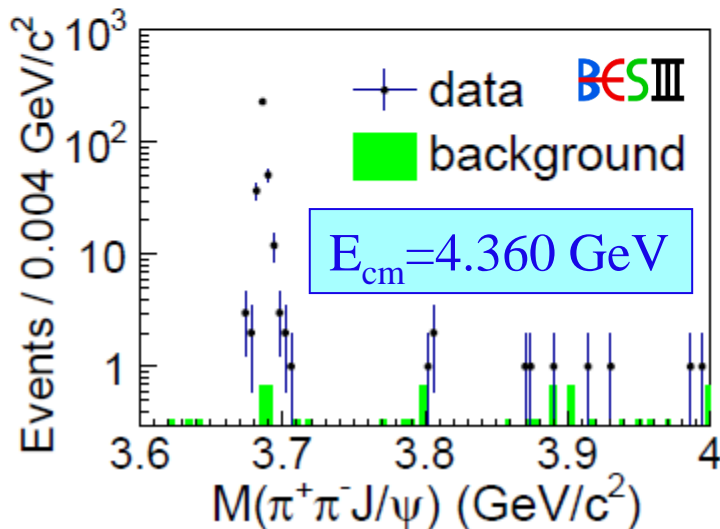
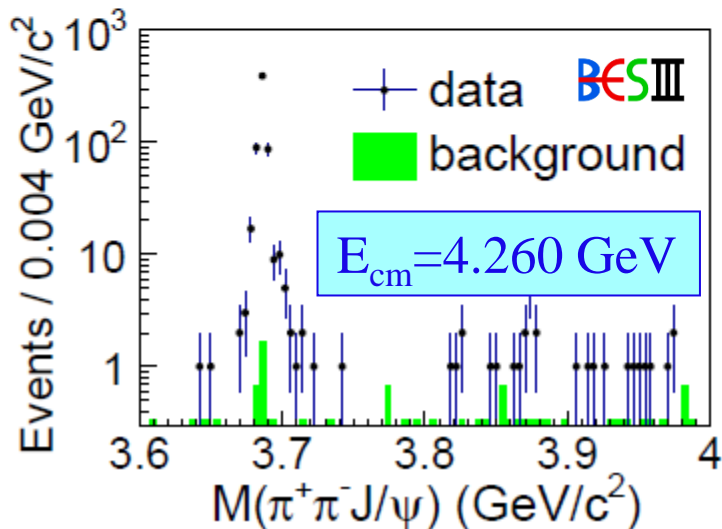
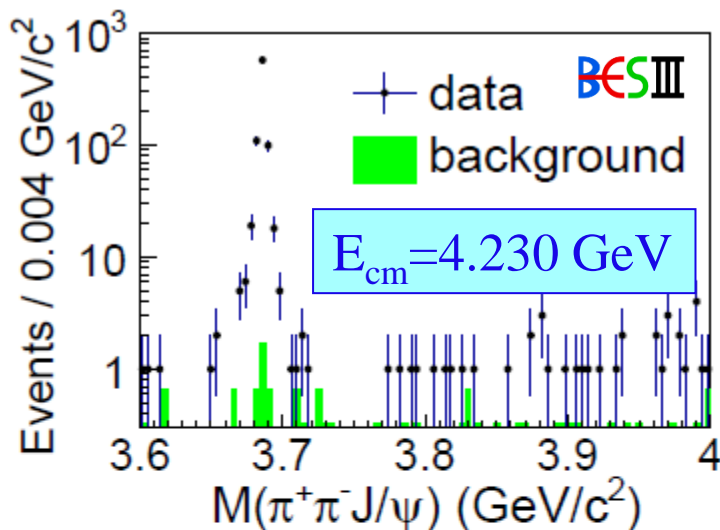
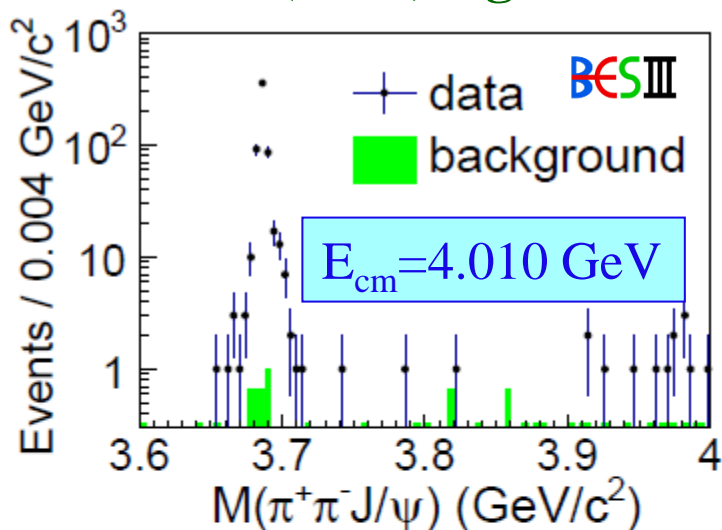
$$\sigma(e^+e^- \rightarrow \pi^- (D^* \bar{D}^*)^+ + c.c.) = (137 \pm 9 \pm 15) \text{ pb}$$

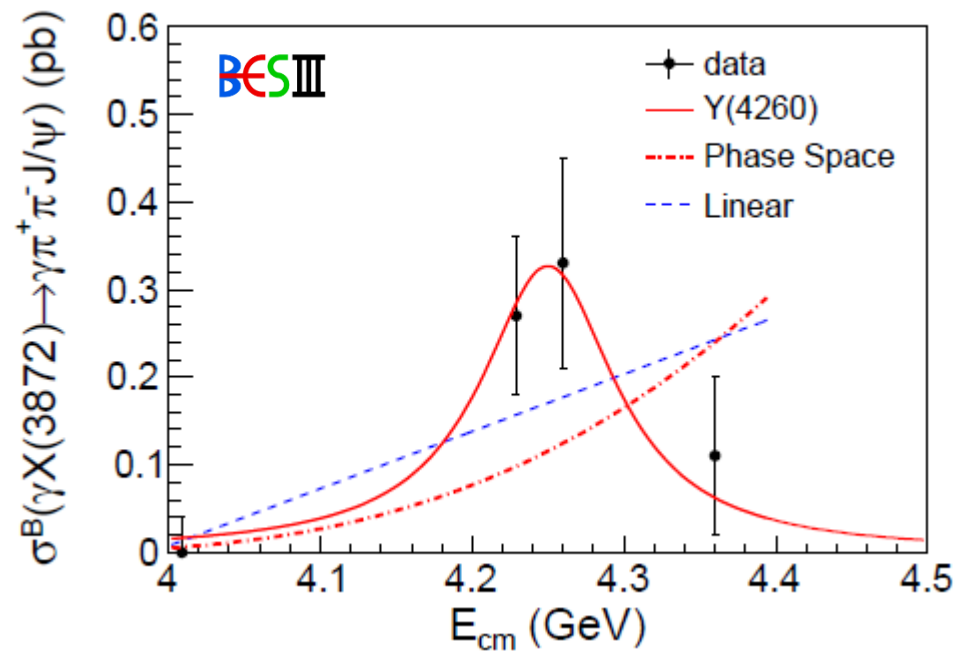
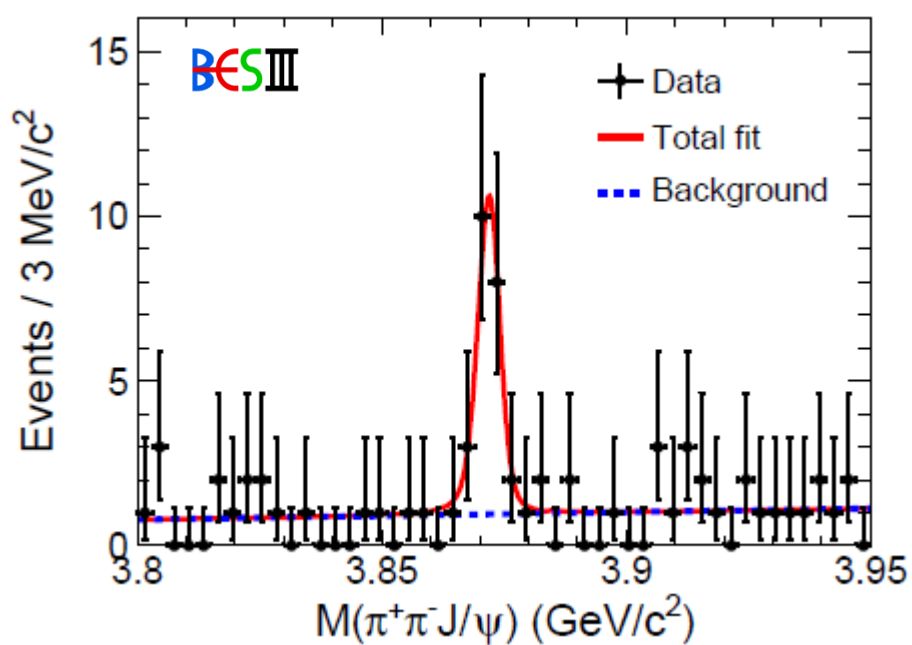
$$R = \frac{\sigma(e^+e^- \rightarrow \pi^- Z_c^+ \rightarrow \pi^- (D^* \bar{D}^*)^+ + c.c.)}{\sigma(e^+e^- \rightarrow \pi^- (D^* \bar{D}^*)^+ + c.c.)} = (65 \pm 9 \pm 6)\%$$





## Clear ISR $\psi'$ signal for data validation X(3872) signal at around 4.230-4.260 GeV





ISR  $\psi'$  signal is used for rate, mass, and mass resolution calibration.

$$\mu_{\psi(3686)} = - (0.34 \pm 0.04) \text{ MeV}/c^2; \quad \sigma_M = (1.14 \pm 0.07) \text{ MeV}$$

$$N(X(3872)) = 20.1 \pm 4.5$$

$$M = (3871.9 \pm 0.7 \pm 0.2) \text{ MeV}/c^2$$

$$\Gamma = < 2.4 \text{ MeV}/c^2 \text{ with } 90\% \text{ CL}$$

$$[\text{PDG: } 3871.68 \pm 0.17 \text{ MeV}]$$

Could be a  $Y(4260) \rightarrow \gamma X(3872)$ !

$$R = \frac{\sigma(Y(4260) \rightarrow \gamma X(3872))}{\sigma(Y(4260) \rightarrow \pi^+ \pi^- J/\psi)} \sim 11\%$$



# BESIII: $Z_c$ states

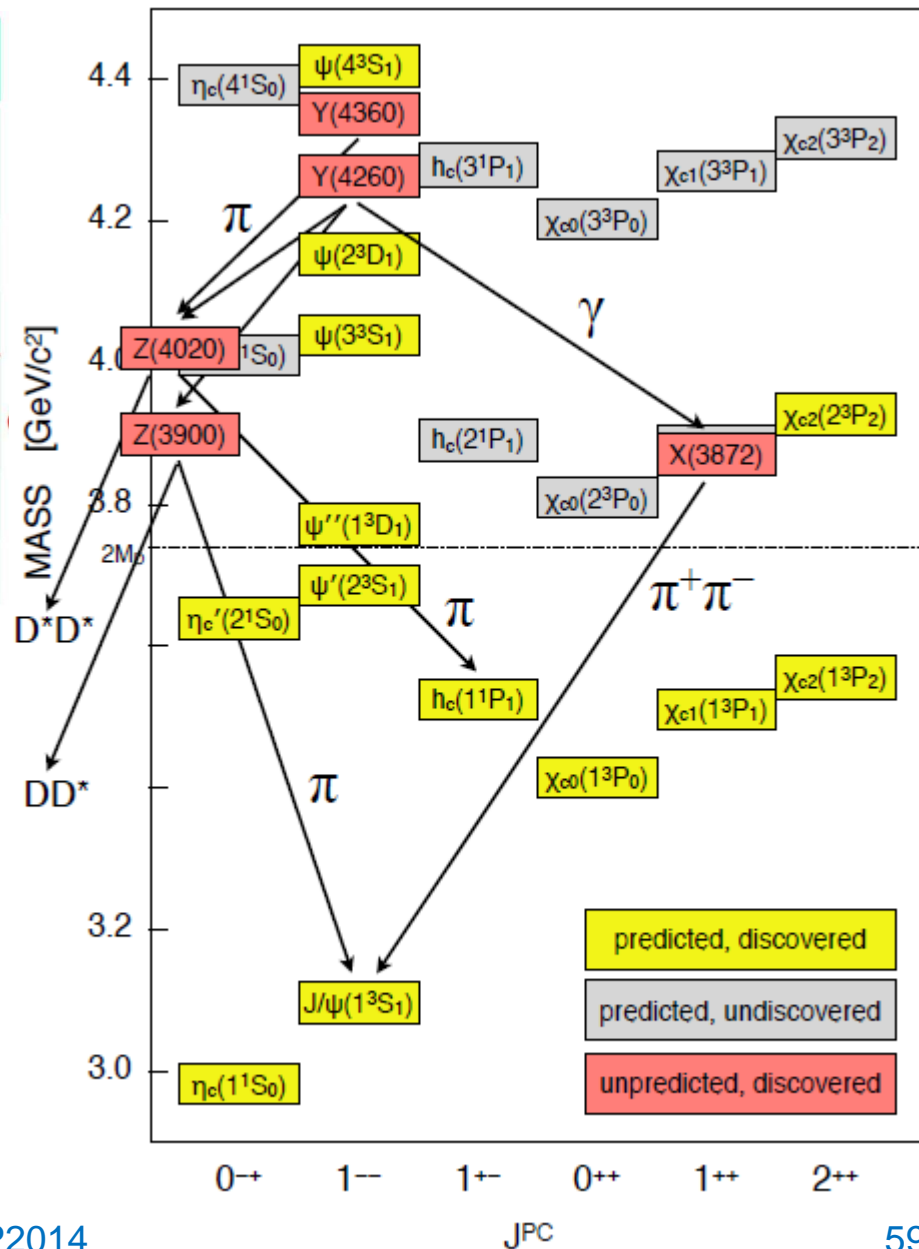
Channel	Mass (MeV/c <sup>2</sup> )	Width (MeV)
$\pi J/\psi$	$3899.0 \pm 3.6 \pm 4.9$ $3894.8 \pm 2.3$ (Prel.)	$46 \pm 10 \pm 20$ $29.6 \pm 8.2$ (Prel.)
$(D \bar{D}^*)^\pm$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
	2 $\sigma$ difference	1 $\sigma$ difference
$\pi h_c$	$4022.9 \pm 0.8 \pm 2.7$ $4023.6 \pm 2.2 \pm 3.9$ (Prel.)	$7.9 \pm 2.7 \pm 2.6$
$(D^* \bar{D}^*)^\pm$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$
	1 $\sigma$ difference	2 $\sigma$ difference

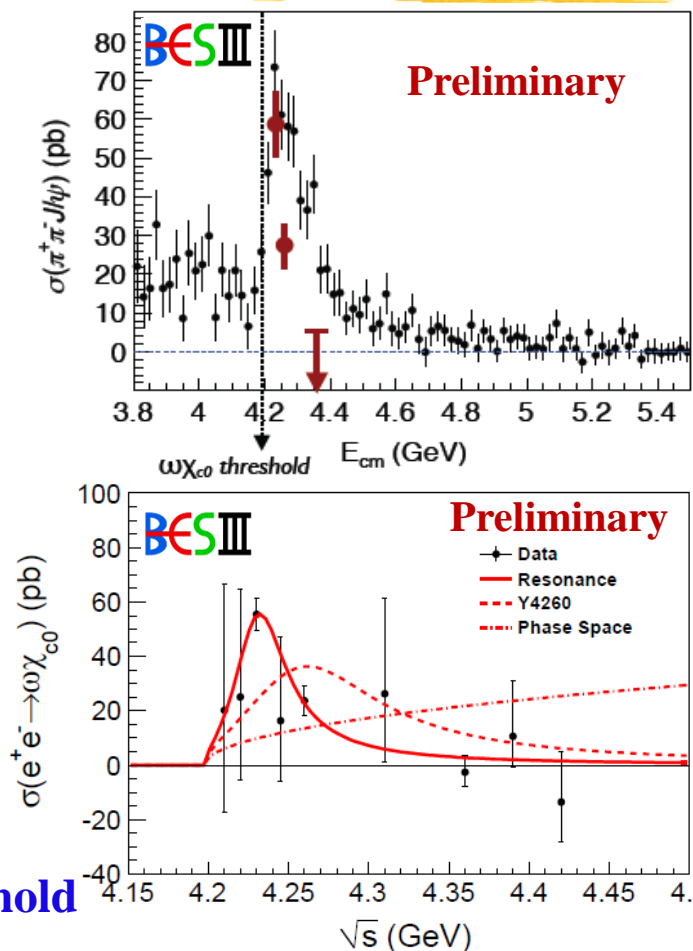
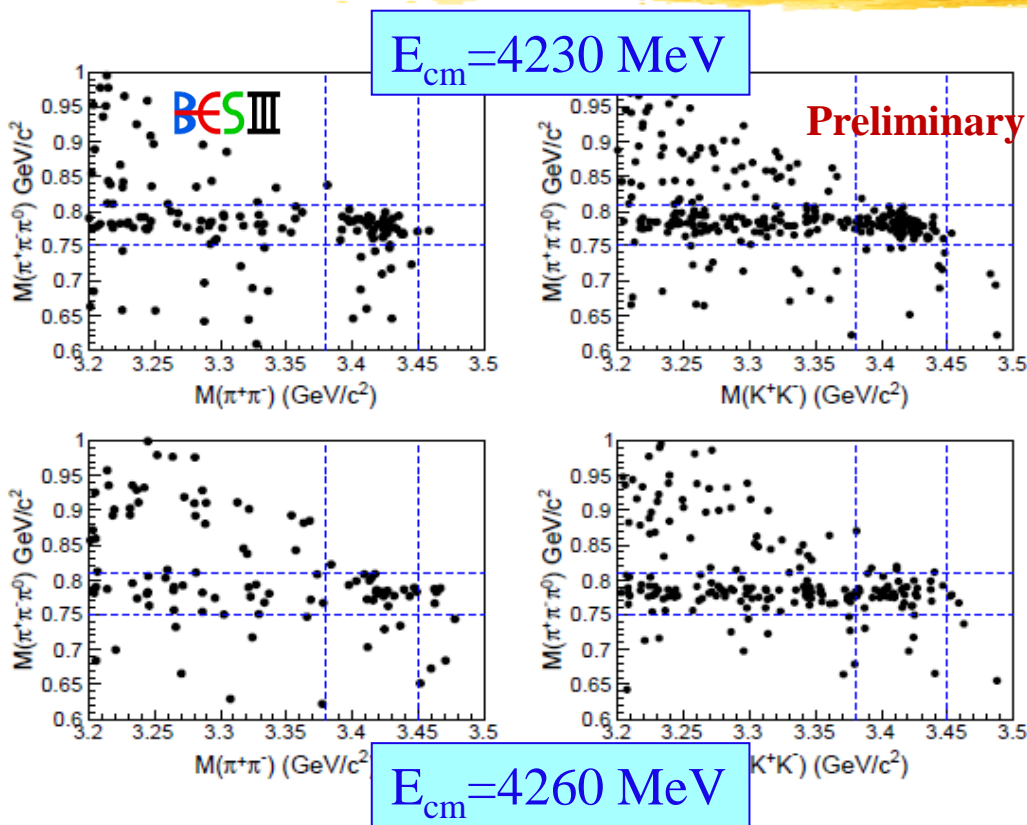
## Thresholds:

- $DD^*$ : 3875 MeV
- $D^*D^*$ : 4014 MeV

## $Z_c$ states @ BESIII:

- at least 4 quarks: charged
- near threshold
- isospin I=1
- are they one or two states





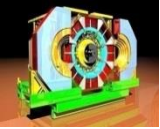
- The mass of Y(4260) is very close to  $\omega\chi_{c0}$  mass threshold
- Observation of  $\omega\chi_{c0}$  at 4230, 4260 MeV data
- No evidence at 4360MeV
- Line shape seems inconsistent with Y(4260)
- BW fitting: a narrow structure around 4230MeV.

A fine structure at 4230MeV?

**Preliminary**

$M = (4229 \pm 11 \pm 6) \text{ MeV}/c^2$

$\Gamma = (40 \pm 14 \pm 2) \text{ MeV}/c^2$



# Summary

- **huge statistics:**
  - $J/\psi$ ,  $\psi(2S)$ ,  $\psi(1D)$
  - XYZ studies
  - R scans
  
- **near future:**
  - collect data at higher energies to complete scans
  - higher luminosity expected from BEPCII
  - analyse the full data samples
  - many PWA to be completed
  
- **stay tuned:**
  - many new exciting results on their way



# Question time

Thanks!



# BESIII Collaboration

<http://bes3.ihep.ac.cn>

Political Map of the World, June 1999

■ METROLINE Independent state  
 ■ National Country in part of special arrangement  
 ■ UN - ADMIRAL Island / Grand group  
 ■ Capital  
 ■ UN - ADMIRAL Island / Grand group  
 ■ UN - ADMIRAL Island / Grand group

## US (6)

Univ. of Hawaii  
 Univ. of Washington  
 Carnegie Mellon Univ.  
 Univ. of Minnesota  
 Univ. of Rochester  
 Univ. of Indiana

## Europe (13)

**Germany:** Univ. of Bochum,  
 Univ. of Giessen, GSI  
 Univ. of Johannes Gutenberg  
 Helmholtz Ins. In Mainz  
**Russia:** JINR Dubna; BINP Novosibirsk  
**Italy:** Univ. of Torino,  
 Frascati Lab, Univ. of Ferrara  
**Netherland :** KVI/Univ. of Groningen  
**Sweden:** Uppsala Univ.  
**Turkey:** Turkey Accelerator Center

## Pakistan (2)

Univ. of Punjab  
 COMSAT CIIT

## Korea (1)

Seoul Nat. Univ.

## Japan (1)

Tokyo Univ.

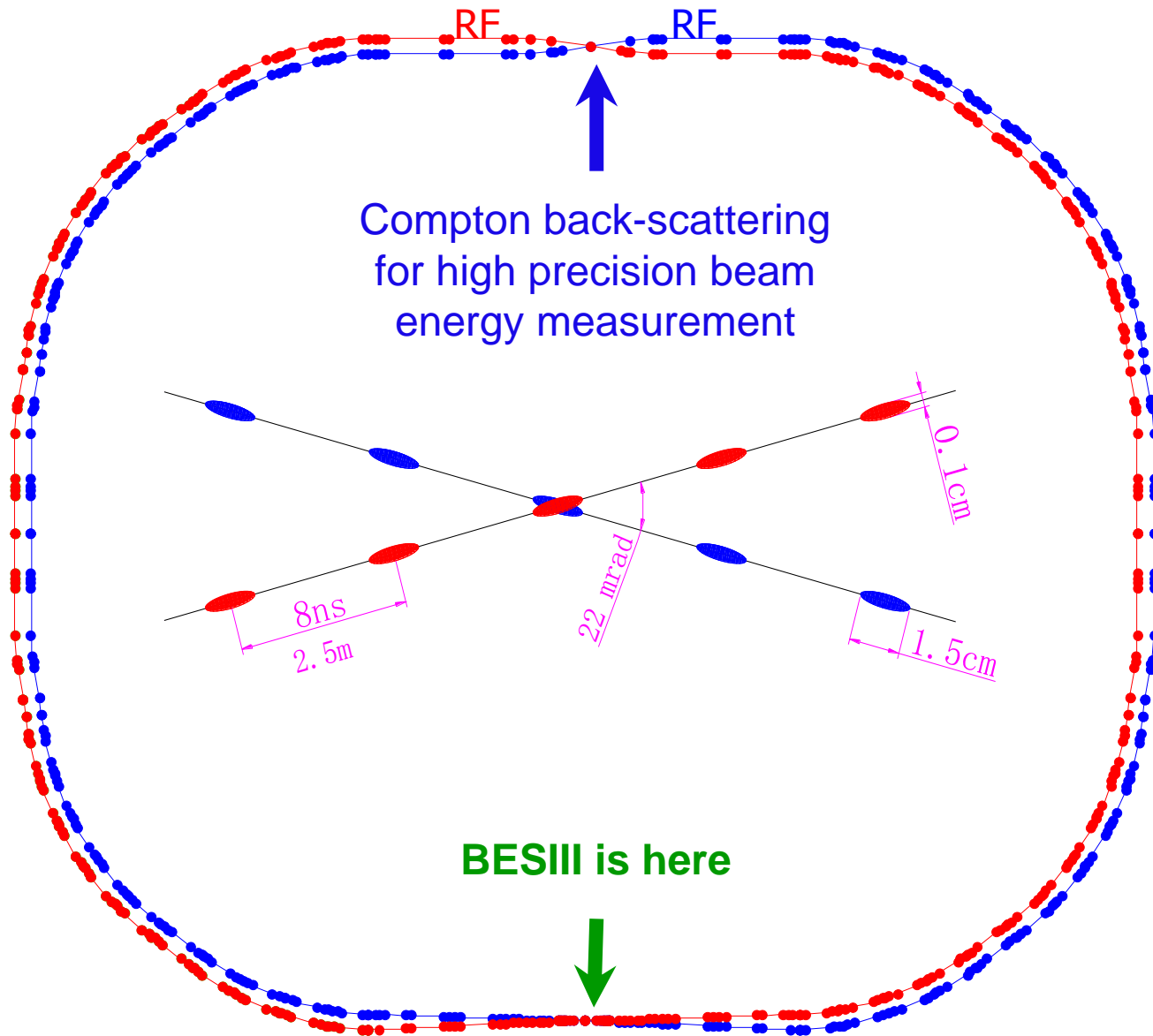
## China(30)

IHEP, CCAST, GUCAS, Shandong Univ.,  
 Univ. of Sci. and Tech. of China  
 Zhejiang Univ., Huangshan Coll.  
 Huazhong Normal Univ., Wuhan Univ.  
 Zhengzhou Univ., Henan Normal Univ.  
 Peking Univ., Tsinghua Univ. ,  
 Zhongshan Univ., Nankai Univ.  
 Shanxi Univ., Sichuan Univ., Univ. of South China  
 Hunan Univ., Liaoning Univ.  
 Nanjing Univ., Nanjing Normal Univ.  
 Guangxi Normal Univ., Guangxi Univ.  
 Suzhou Univ., Hangzhou Normal Univ.  
 Lanzhou Univ., Henan Sci. and Tech. Univ.  
 Hong Kong Univ., Hong Kong Chinese Univ.

~350 members  
 53 institutions  
 11 countries



# BEPCII



Beam energy:

1-2.3 GeV

Crossing angle:

22 mrad

**Luminosity:**

**$1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$**

**Optimum energy:**

**1.89 GeV**

Energy spread:

$5.16 \times 10^{-4}$

No. of bunches:

93

Bunch length:

1.5 cm

Total current:

0.91 A

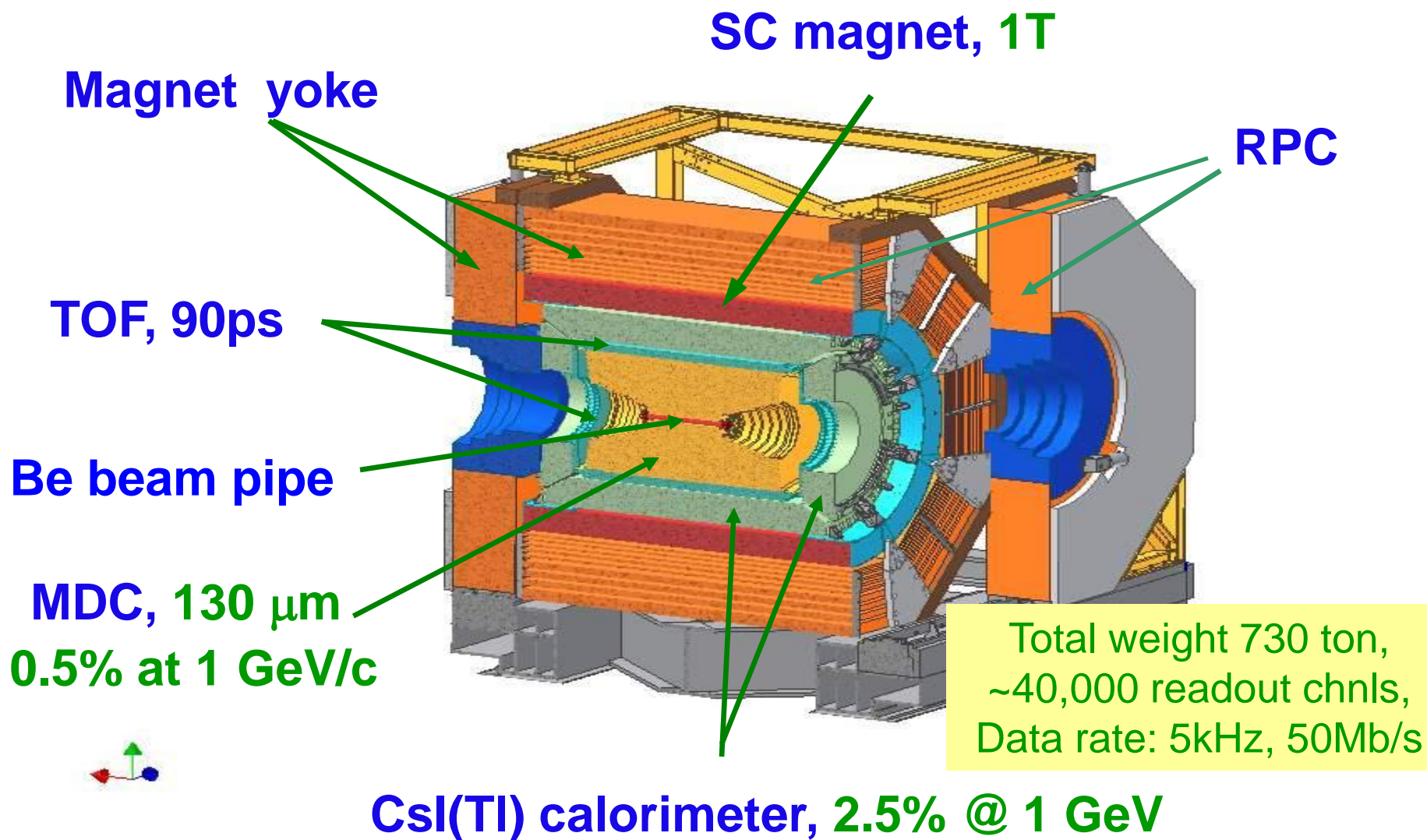
SR mode:

0.25A @ 2.5 GeV





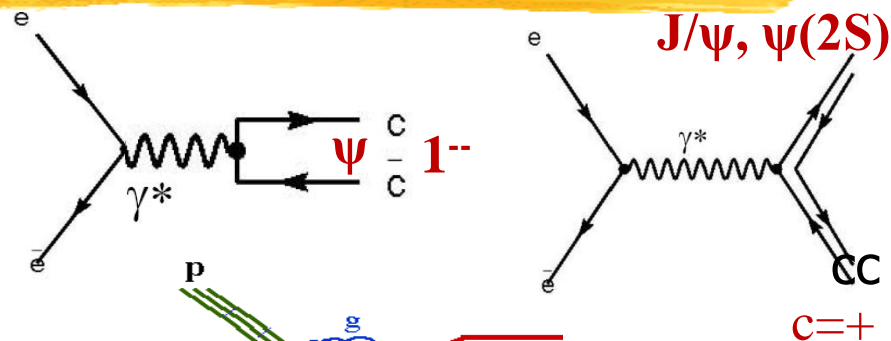
# BESIII Spectrometer



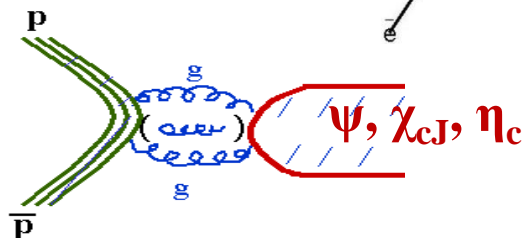


# How to produce Charmonium states

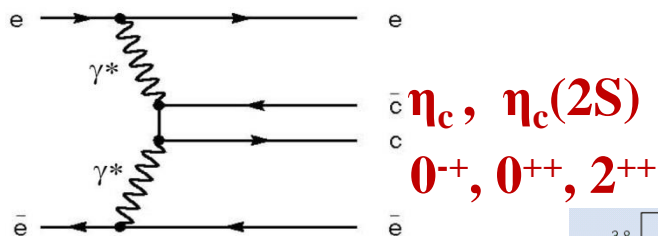
1.  $e^+e^-$  annihilation (including ISR/double charmonium)



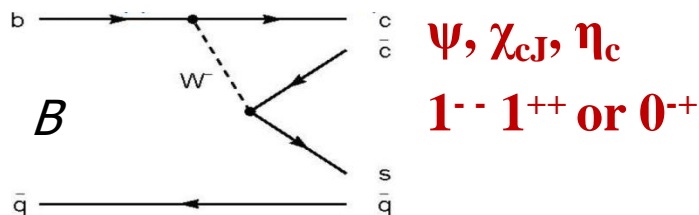
2.  $p\bar{p}$  annihilation



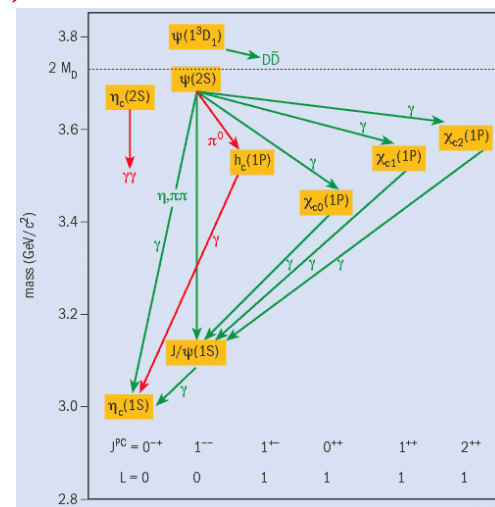
3. Two-photon process



4. B decays



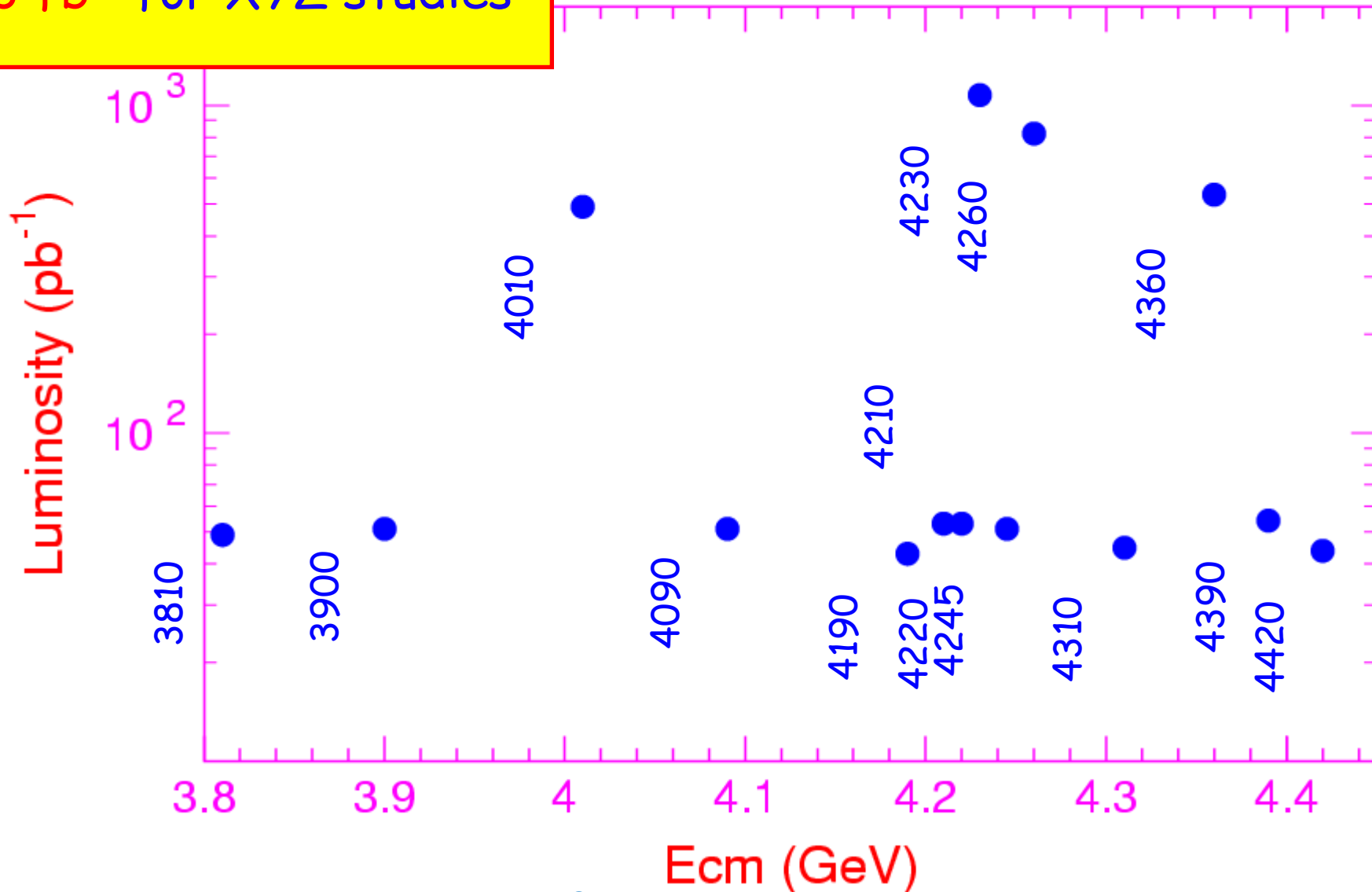
5. Charmonium transition

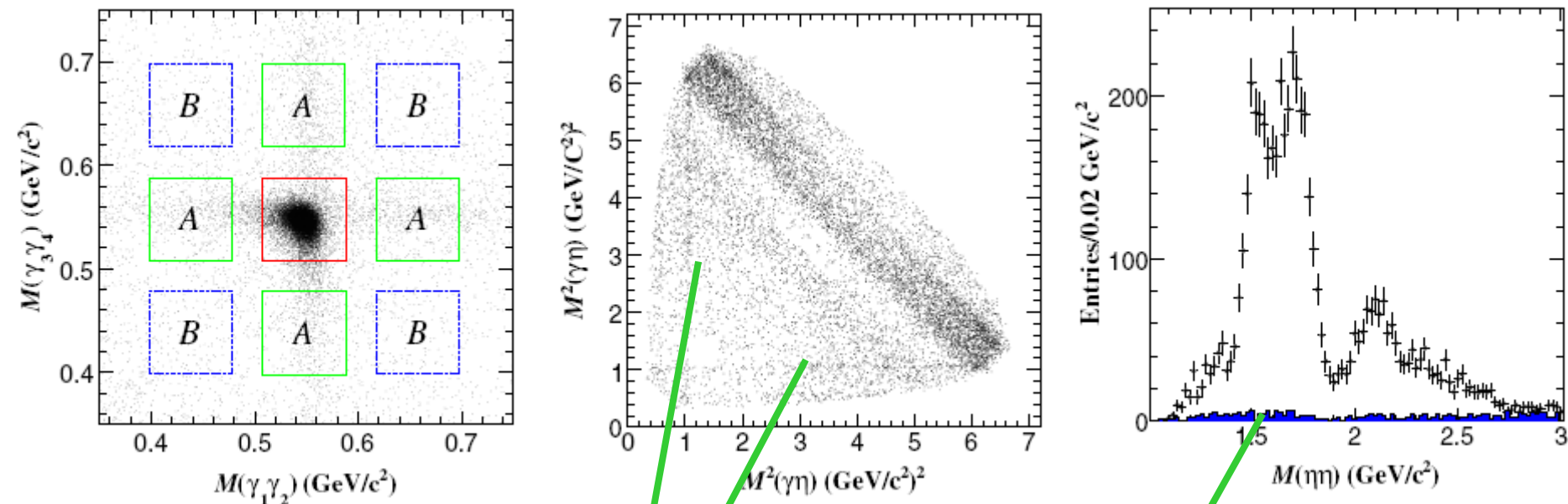




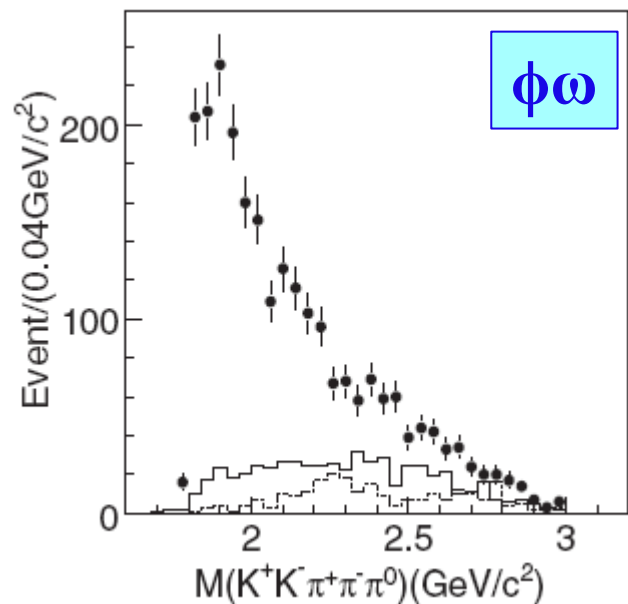
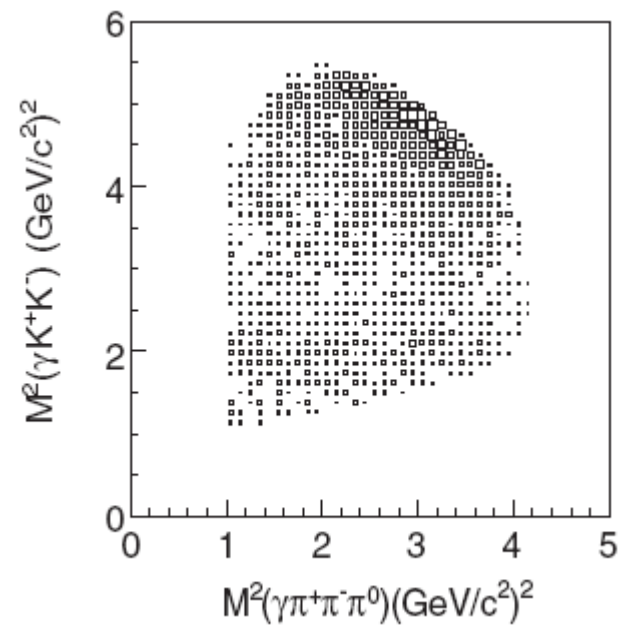
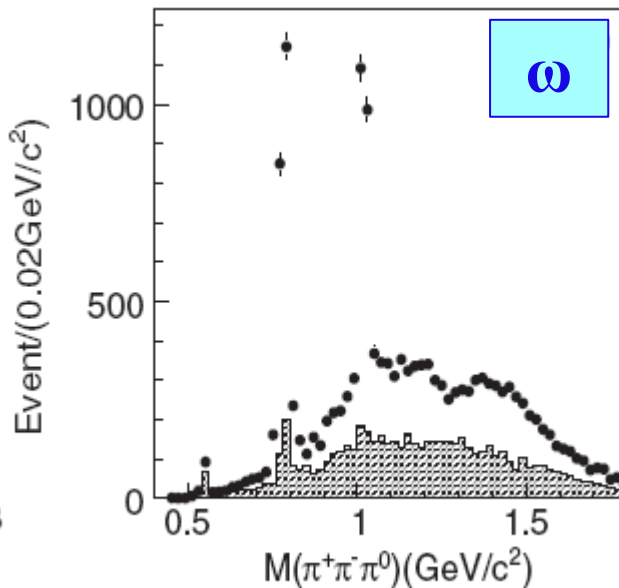
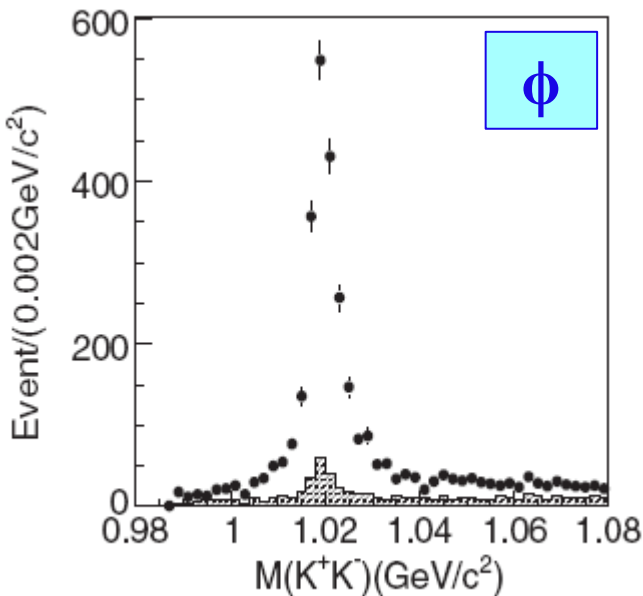
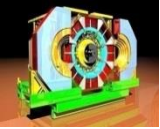
# BESIII data set

3.3 fb<sup>-1</sup> for XYZ studies





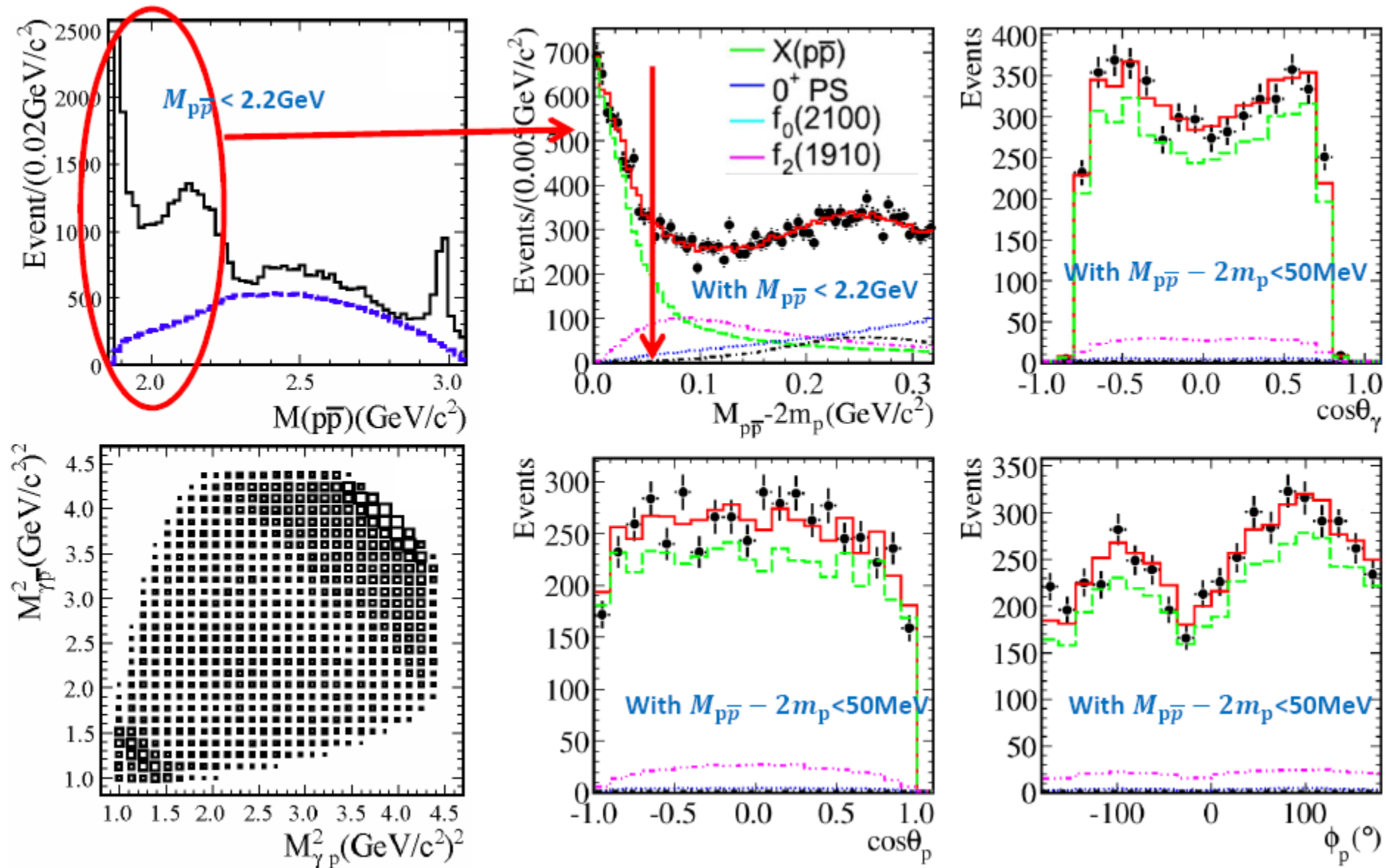
- **$J/\psi \rightarrow \phi\eta$ ,  $\phi \rightarrow \gamma\eta$ :**
  - select events outside  $\phi$  window
- **background:**
  - low and mostly non- $\eta$  background,
  - estimated by  $\eta$  sidebands (blue shadow)
- **background subtraction:**
  - $\ln \mathcal{L}^{\text{signal}} = \ln \mathcal{L}^{\text{data}} - \ln \mathcal{L}^{\text{sideband}}$

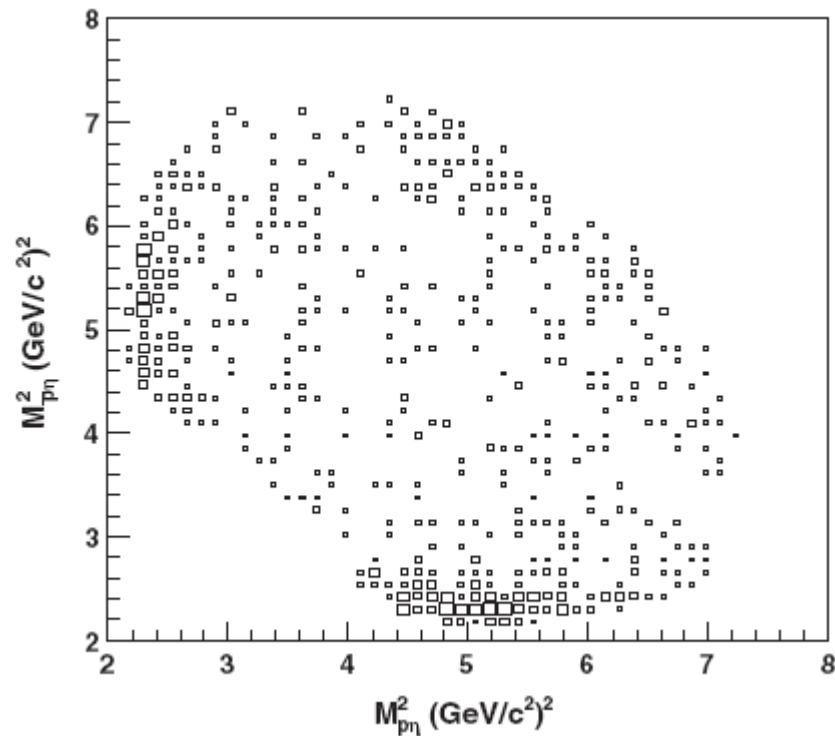
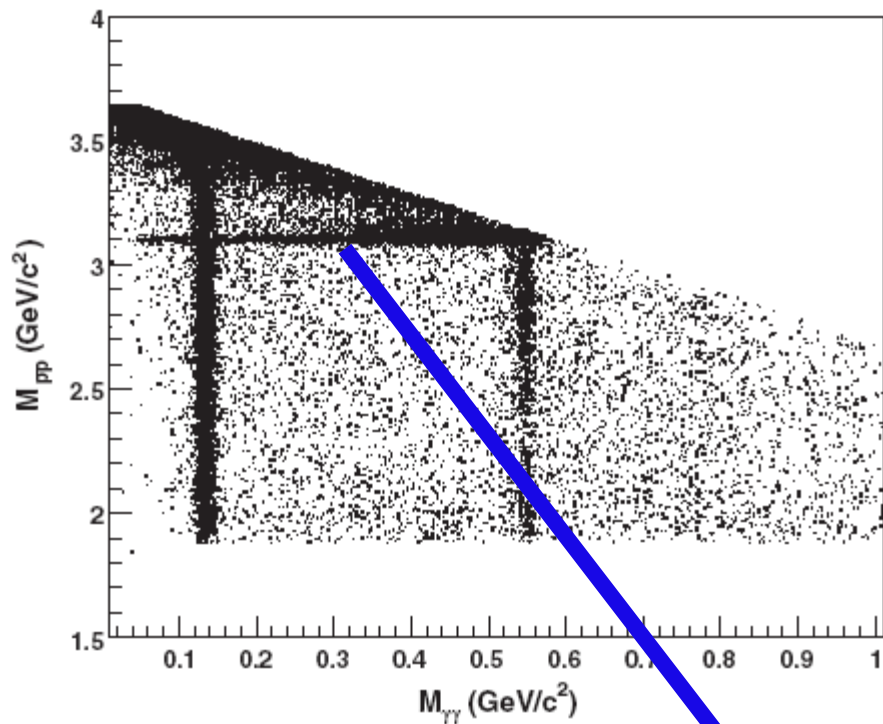


- **solid:**
  - background estimated from sidebands
- **dashed:**
  - inclusive  $J/\psi$  MC samples
- **background subtraction:**
  - $\ln \mathcal{L}^{\text{signal}} = \ln \mathcal{L}^{\text{data}} - \ln \mathcal{L}^{\text{sideband}}$

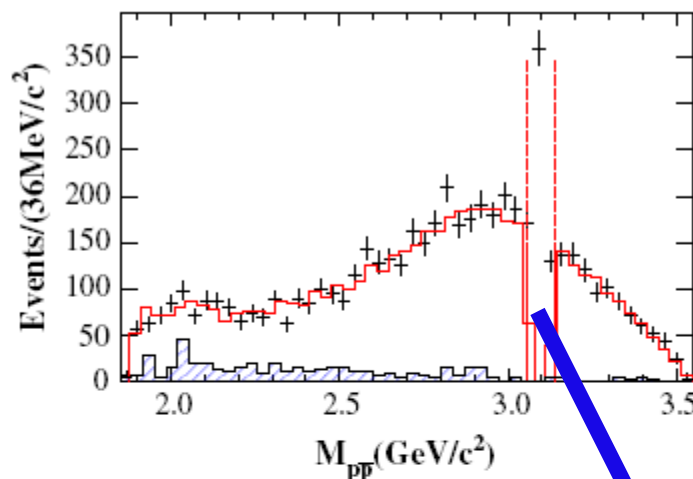
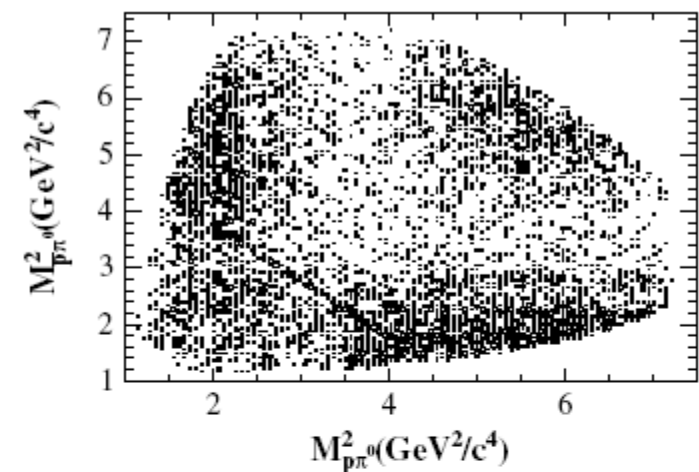


# BESIII: PWA of $J/\psi \rightarrow \gamma p\bar{p}$ , $M_{p\bar{p}} < 2.2 \text{ GeV}$ PRL 108, 112003

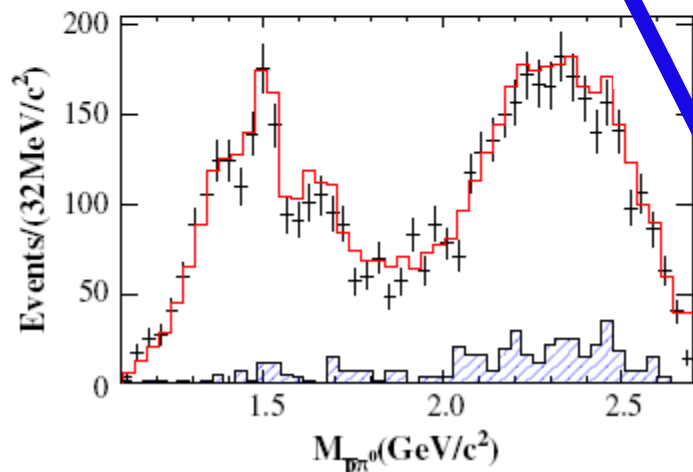
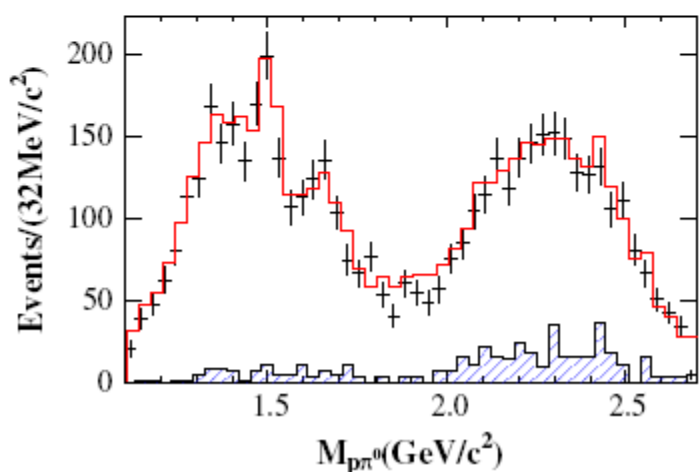




$\psi(2S) \rightarrow J/\psi X$  ,  $J/\psi \rightarrow p\bar{p}$  subtracted



shaded:



- background:
  - continuum
  - non- $\pi^0$
- background

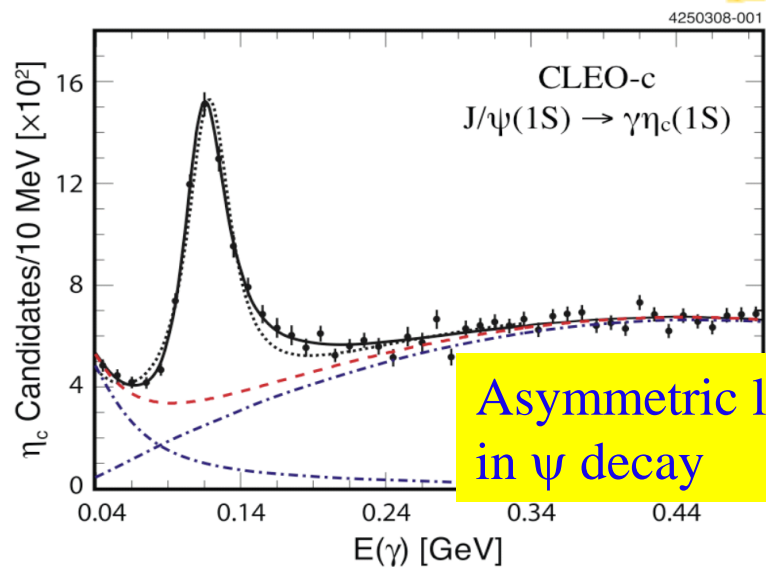
$\psi(2S) \rightarrow J/\psi X$  ,  $J/\psi \rightarrow p\bar{p}$  subtracted





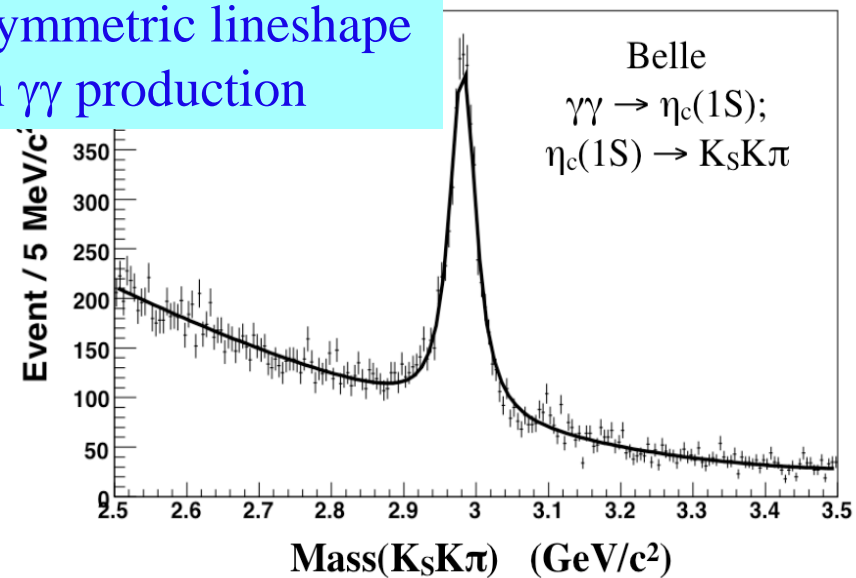
# BESIII: $\eta_c$ parameters from $\psi(2S) \rightarrow \pi^0 h_c(1P)$ , $h_c(1P) \rightarrow \gamma \eta_c(1S)$

PRD 86, 092009

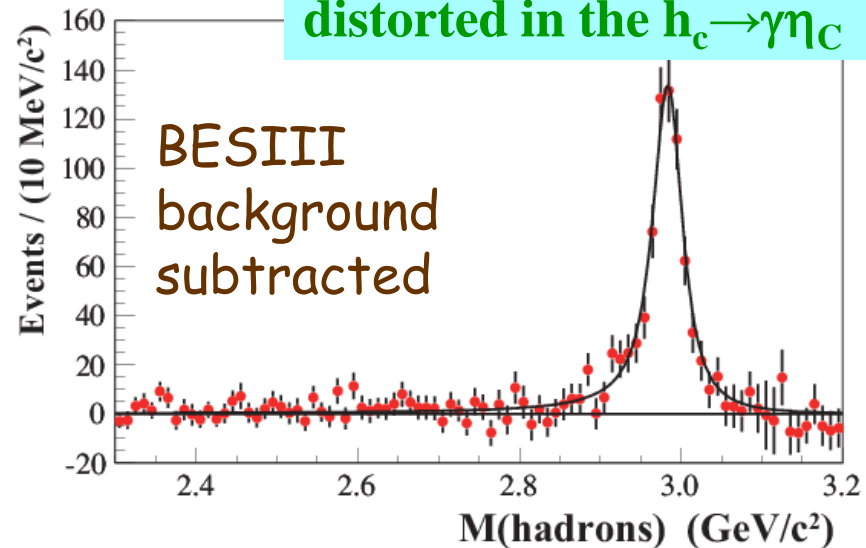


Asymmetric lineshape  
in  $\psi$  decay

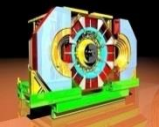
Symmetric lineshape  
in  $\gamma\gamma$  production



The  $\eta_c$  lineshape is not  
distorted in the  $h_c \rightarrow \gamma \eta_c$



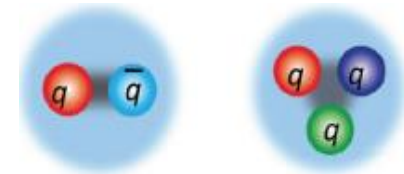
- CLEO-c observe a distortion of  $\eta_c$  lineshape in charmonium radiative decay  
PRL102, 011801 (2009)
- The lineshape of  $\eta_c$  from BELLE is symmetric
- The abnormal line shape is also observed in BESIII exclusive channels in  $\psi' \rightarrow \gamma \eta_c$  but not in  $\psi' \rightarrow \pi^0 h_c$ ,  $h_c \rightarrow \gamma \eta_c$



# Hadronic exotic states

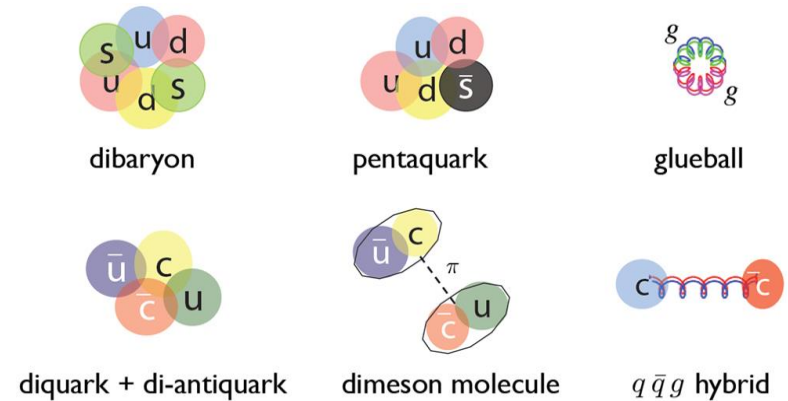
- Experiments :

- Hadrons are composed of 2 (meson) or 3 (baryon) quarks
- Described very well in quark model (QM)



- QCD suggests:

- Confinement : stable hadrons need to be colorless
- Gluon-gluon interactions : hadron with gluons (hybrids and glueballs) could exist
- Allow hadrons with  $N_{\text{quarks}} \neq 2, 3$  (multi-quarks)

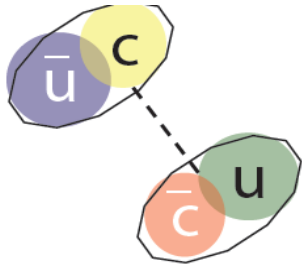


Can we find evidence for these interesting exotic hadrons?

A long history of searching for the exotic hadron,  
no solid conclusion was reached in past a few decades,  
some hints on charmonium-like and bottomonium-like particles, recently.

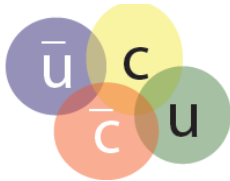


# Exotic Meson (Charmonium-Like)



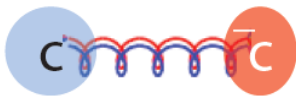
## Molecular states:

- Loosely bound states of a pair of mesons,
- bound by the long-range color-singlet pion exchange,
- weakly bound, mesons tend to decay as if they were free.



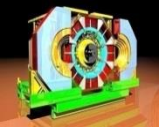
## Tetraquarks:

- bound states of four quarks,
- bound by colored-force between quarks,
- decay through rearrangement,
- many states with the same multiplet, some are with non-zero charge, or strangeness



## Hybrids:

- bound states with a pair of quarks and one excited gluon
- Lattice and model predictions for lowest lying charmonium hybrid  $m \sim 4200$  MeV



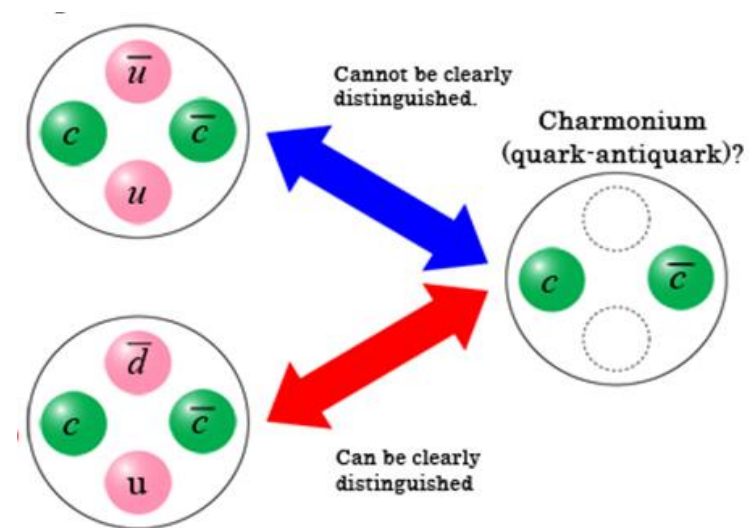
# $Z_c$ states

## The most promising way to searching for the exotic hadrons

- Decay into a charmonium or  $D^{(*)}D^{(*)}$  pair
  - thus contains hidden-cc pair
- Have electric charge,
  - thus has two more light quarks

At least 4 quarks, not a conventional meson

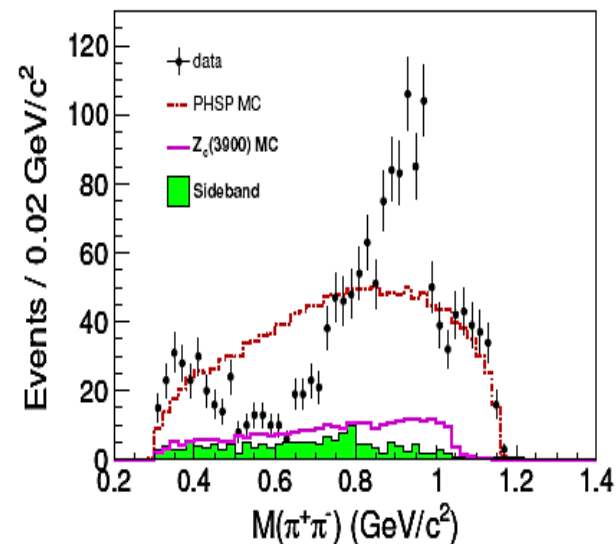
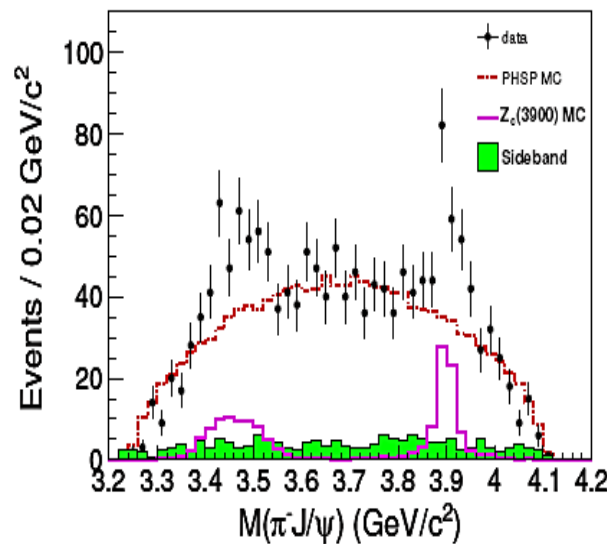
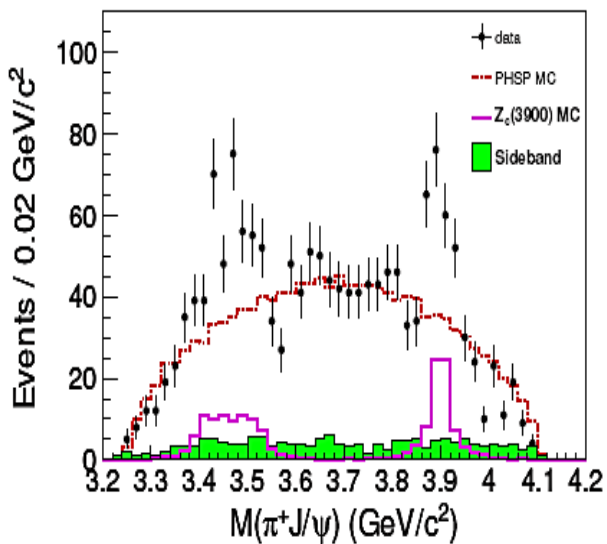
- Observed in final states :
  - $\pi^\pm J/\psi$ ,  $\pi^\pm \psi(2S)$ ,  $\pi^\pm h_c$ ,  $\pi^\pm \chi_{cJ}$ ,  $(D^{(*)}D^{(*)})^\pm, \dots$
- Experimental search:
  - BESIII/CLEO-c :  $e^+e^- \rightarrow \pi^\pm + \text{Exotics}$ , ....
  - Belle/BaBar :  $e^+e^- \rightarrow (\gamma_{\text{ISR}})\pi^\pm + \text{Exotics}$ , ....
  - Belle/BaBar/LHCb:  $B \rightarrow K^\pm + \text{Exotics}$ , ...

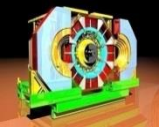




## Is it a real signal?

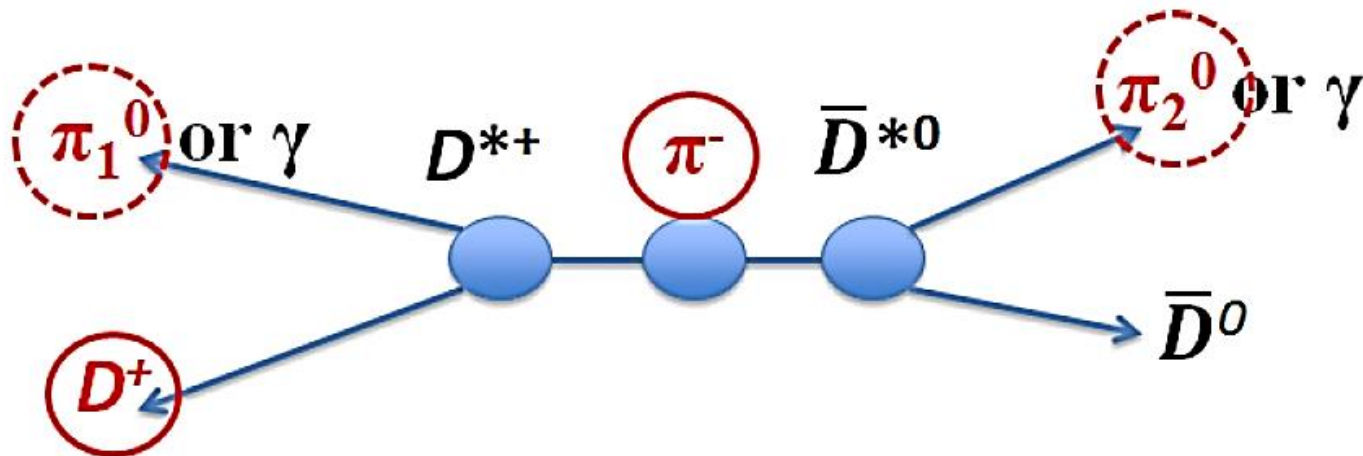
- Is it due to  $\pi^+\pi^-$  S-wave states, like  $\sigma$ ,  $f_0(980)$ , ...? N
- Is it due to  $\pi^+\pi^-$  D-wave states, like  $f_2(1270)$ , ...? N
- Are there two states, one at 3.4, the other 3.9 GeV? N
- Exist in both  $e^+e^-$  &  $\mu^+\mu^-$  samples? Y
- Exist in both  $\pi^+\pi^-$  low mass and high mass samples? Y
- Background fluctuation? N





# BESIII: $e^+e^- \rightarrow \pi Z_c(4025) \rightarrow \pi^- (D^* D^*)^+ + \text{c.c.}$ @ 4.260 GeV hep-ex:1308.2760

- **827 pb<sup>-1</sup>** data at  $E_{\text{CM}}=4.260$  GeV
- Tag a  $D^+$  and a bachelor  $\pi^-$ , reconstruct one  $\pi^0$  to suppress the background.



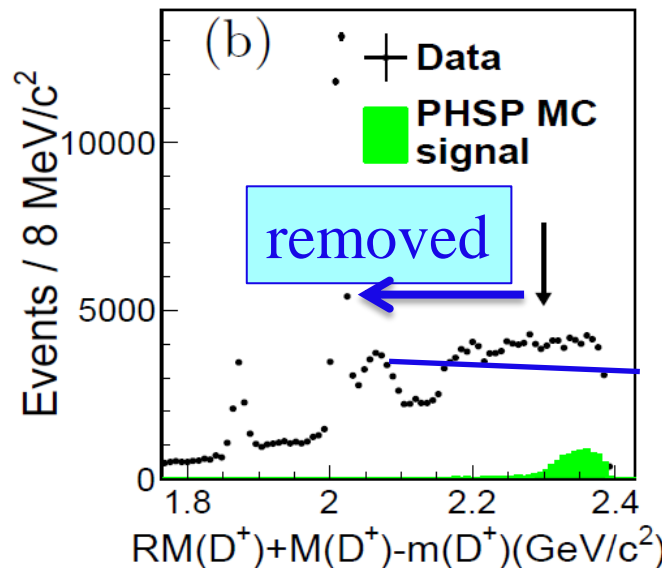
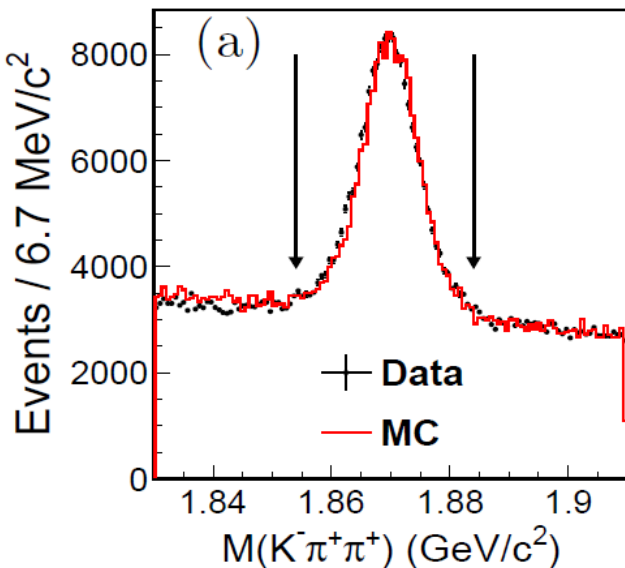
## Topology of the decays of the signal process:

- thick line circled:  $D^+$  and  $\pi^-$  detected in the final states
- dashed line circled: at least of  $\pi_1^0$  or  $\pi_2^0$  tagged

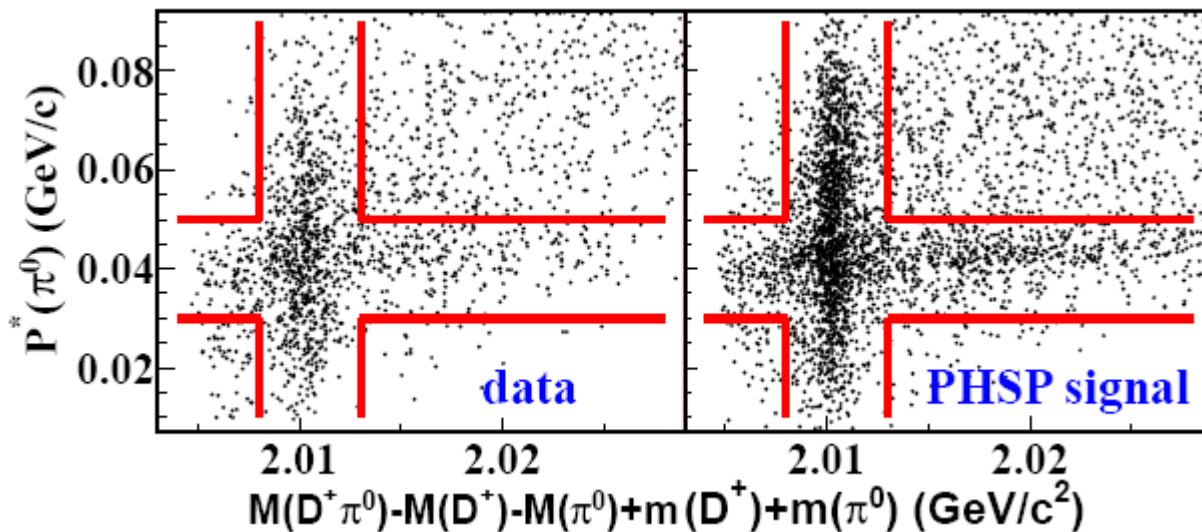


# BESIII: $e^+e^- \rightarrow \pi Z_c(4025) \rightarrow \pi^- (D^* D^*)^+ + c.c.$ @ 4.260 GeV

hep-ex:1308.2760

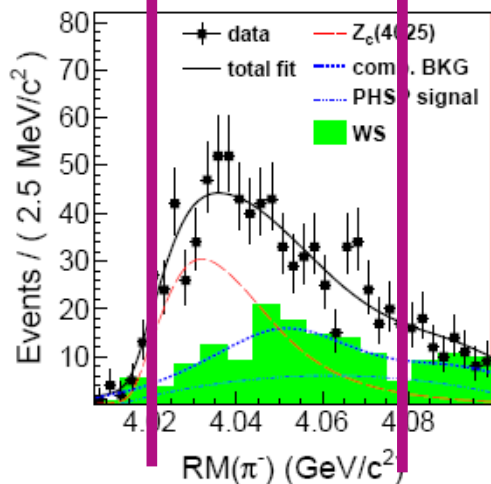
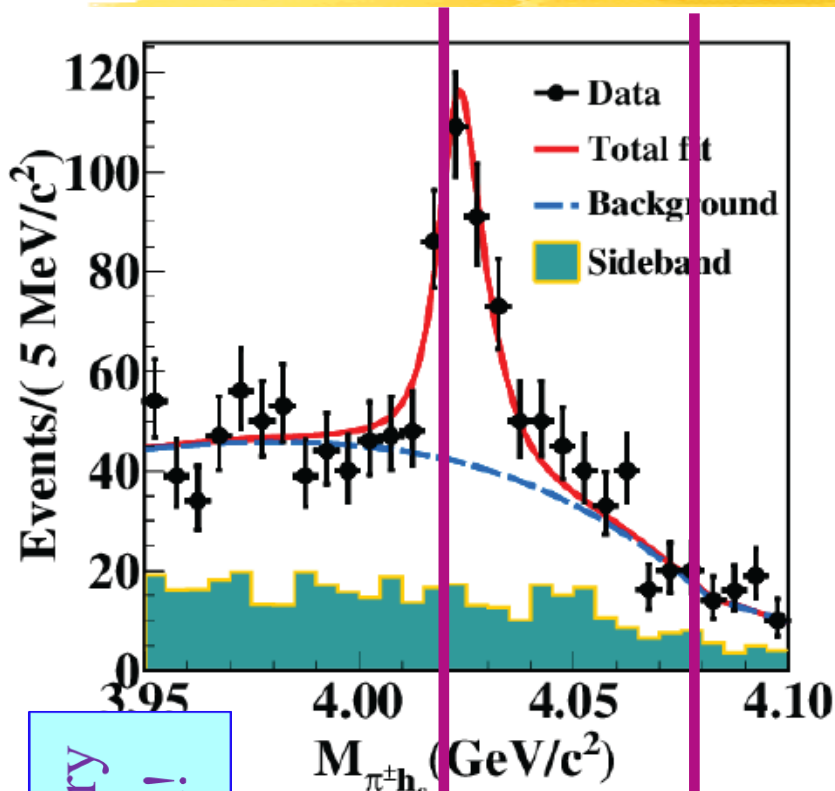


Remove  
DD, DD\*,  
D\*D\*,  
DsDs, ...





# BESIII: $Z_c(4020)=Z_c(4025)$ ?



BESIII preliminary  
The  $Z_c'$  is found!

$$M(4020) = (4021.8 \pm 1.0 \pm 2.5) \text{ MeV}$$

$$M(4025) = (4026.3 \pm 2.6 \pm 3.7) \text{ MeV}$$

$$\Gamma(4020) = (5.7 \pm 3.4 \pm 1.1) \text{ MeV}$$

$$\Gamma(4025) = (24.8 \pm 5.7 \pm 7.7) \text{ MeV}$$

Close to  $D^*\bar{D}^*$  threshold (4017 MeV)

Mass consistent with each other  
but.. width  $\sim 2\sigma$  difference

Interference with other amplitudes  
may change the results

Coupling to  $\bar{D}^*D^*$  is much larger  
than to  $\pi h_c$  if they are the same state

Will fit with Flatte formula





# What is the X(3872)?

- Mass: Very close to  $\bar{D}^0 D^{*0}$  threshold
- Width: Very narrow,  $< 1.2$  MeV
- $J^{PC}=1^{++}$  [LHCb]
- Production
  - in  $\bar{p}p/pp$  collision – rate similar to charmonia
  - In B decays –  $KX$  similar to  $\bar{c}c$ ,  $K^*X$  smaller than  $\bar{c}c$
  - $Y(4260) \rightarrow \gamma + X(3872)$  [BESIII, preliminary]
- Decay BR: open charm  $\sim 50\%$ , charmonium  $\sim O(\%)$
- Nature (very likely exotic)
  - Loosely  $\bar{D}^0 D^{*0}$  bound state (like deuteron?)?
  - Mixture of excited  $\chi_{c1}$  and  $\bar{D}^0 D^{*0}$  bound state?
  - Many other possibilities (if it is not  $\chi'_{c1}$ , where is  $\chi'_{c1}$ ?)

