

# Hadron spectroscopy at BESIII

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- Introduction to BESIII
- Hadron spectroscopy
  - I. Light meson
  - II. Baryon
  - III. XYZ states
- Summary





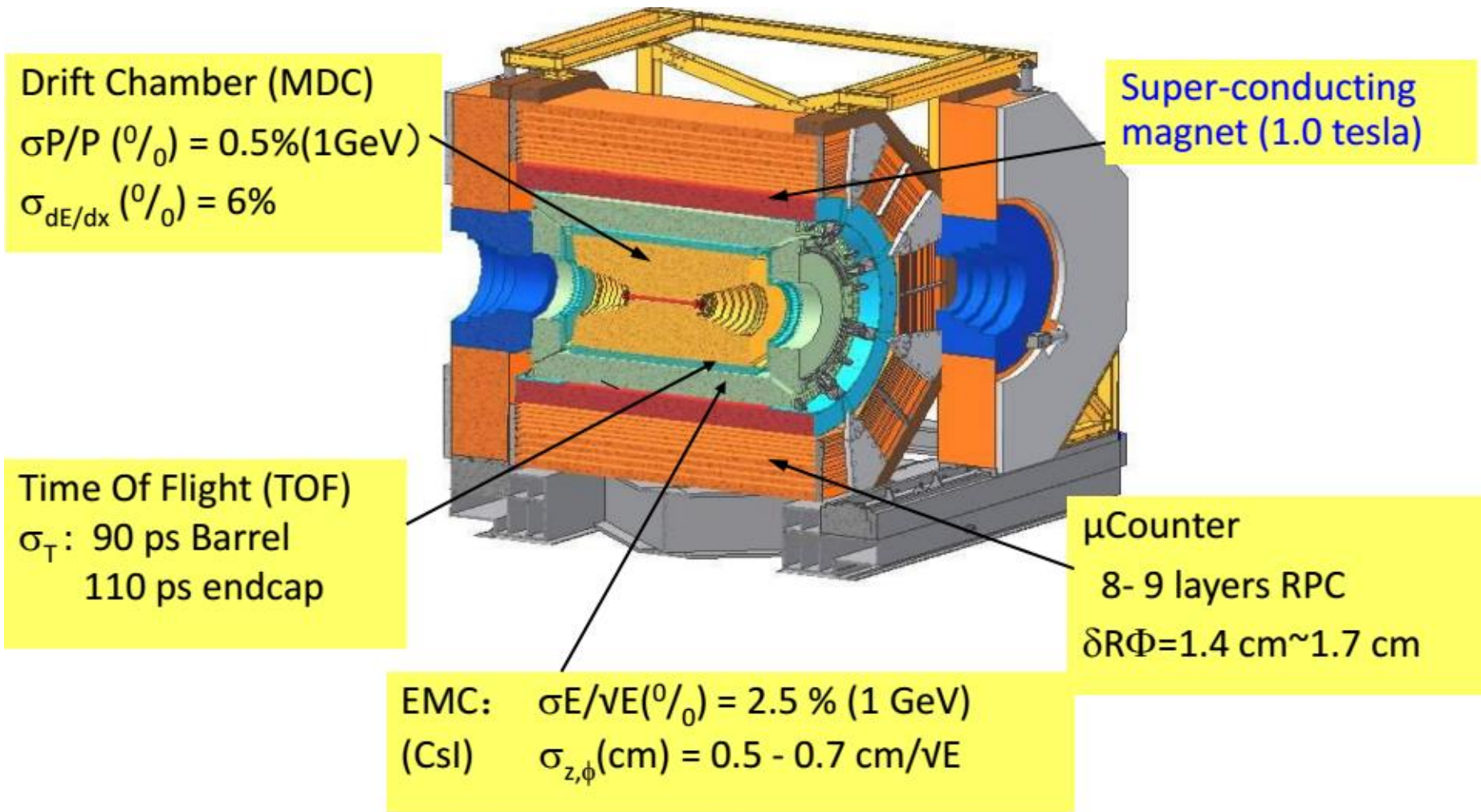
**LINAC**

**BESIII  
detector**

**Storage ring**

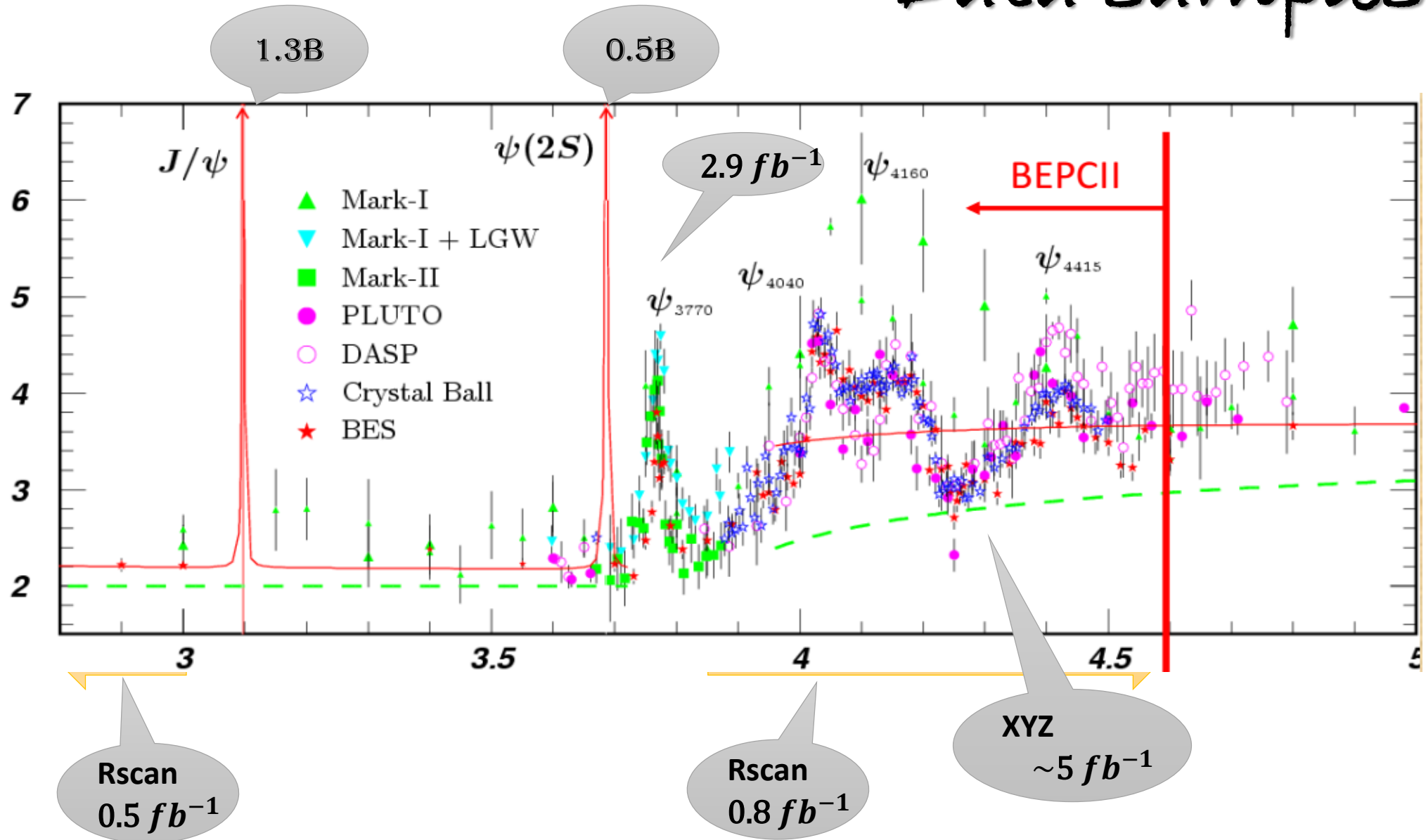
2004: Start BEPCII construction  
2008: Test run of BEPCII  
2009-now: data taking





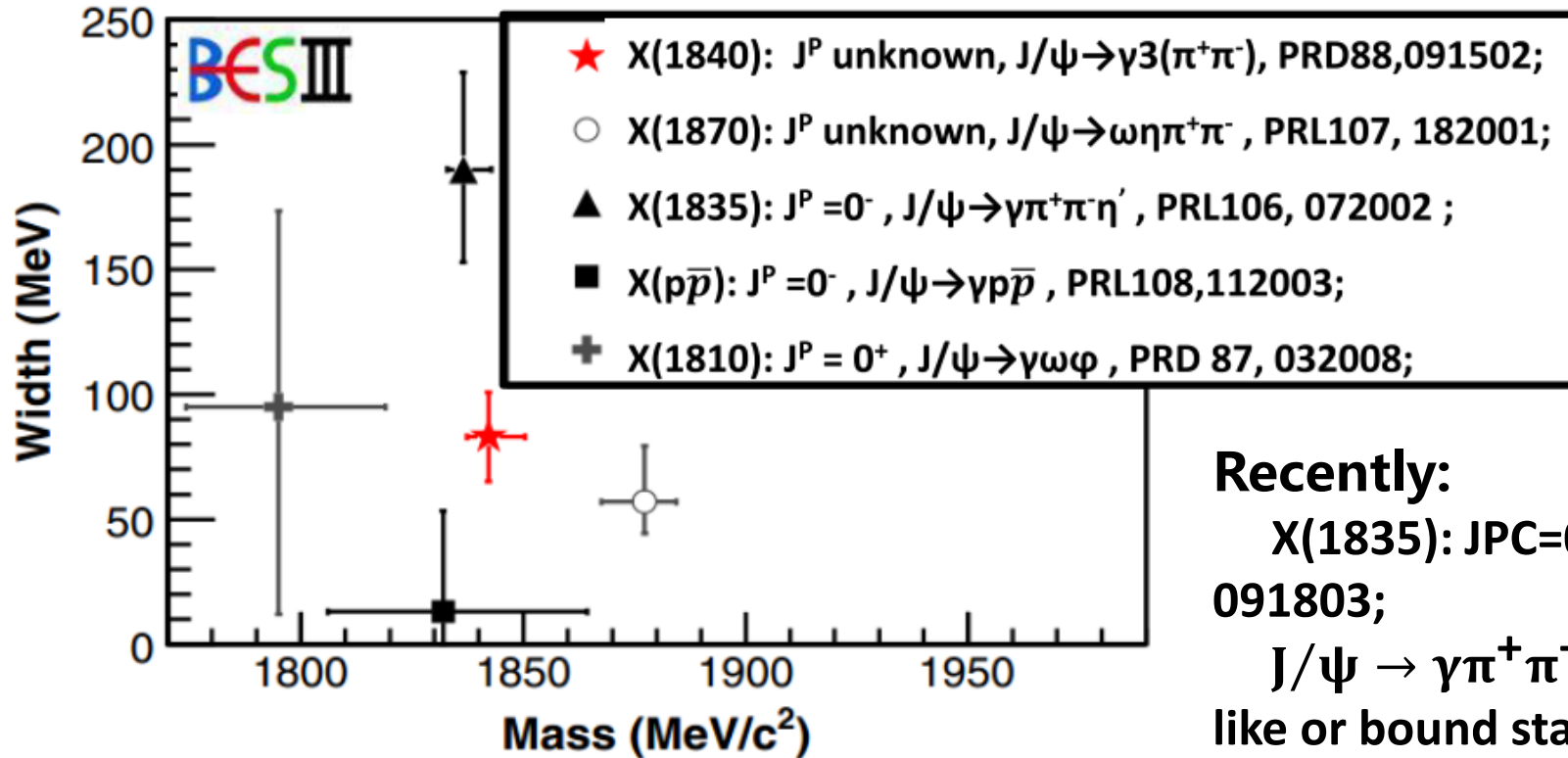
# Data samples

$R$



# Light meson spectroscopy at BESIII

# Observation of X(18??) on BESIII



Recently:

X(1835):  $J^{PC}=0^{-+}$ ,  $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$ , PRL115, 091803;

$J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$ , existence of a  $p\bar{p}$  molecule-like or bound state, arxiv 1603.09653.

☘ Are X(18??) the same resonant state?

☘ Nature?  $p\bar{p}$  bound state, second radial excitation of  $\eta$ , pseudoscalar glueball?

More PWA work are needed to confirm

# Glueball candidates

## Glueballs are expected:

- ✓ Copiously produced in radiative  $J/\psi$  decay
- Mix with nearby  $q\bar{q}$  nonet

## Systematic PWA study on:

$J/\psi \rightarrow \gamma\eta\eta$  PRD 87, 092009 (2013)

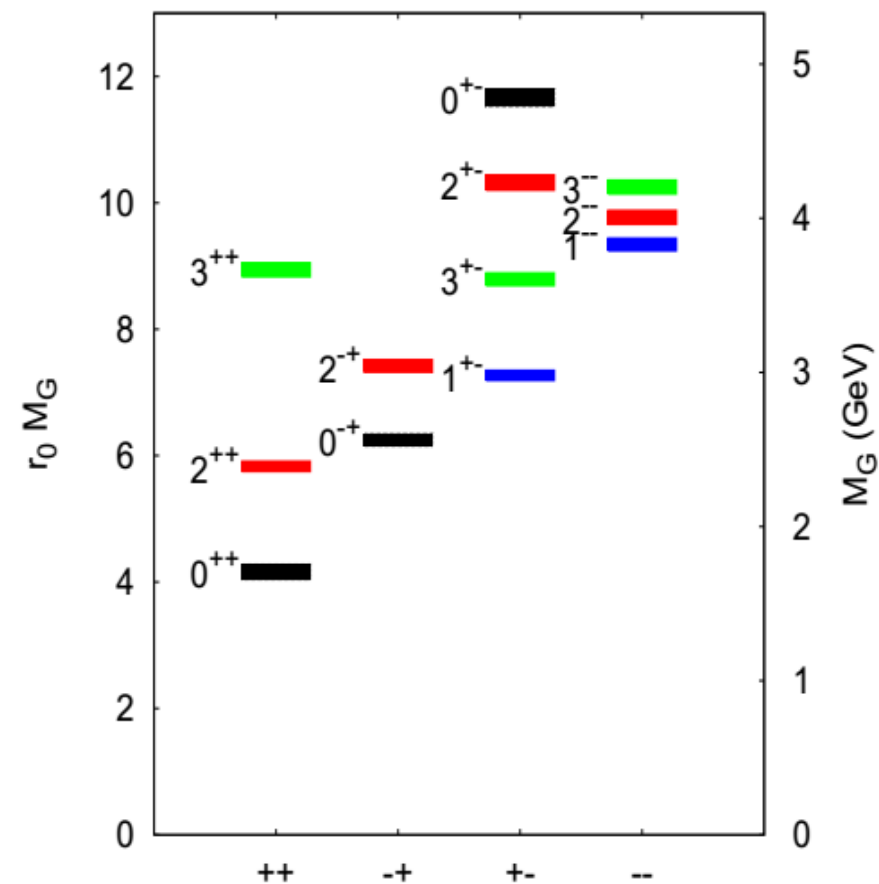
$J/\psi \rightarrow \gamma\pi^0\pi^0$  PRD 92, 052003 (2015)

$J/\psi \rightarrow \gamma\phi\phi$  arxiv 1602.01523

$J/\psi \rightarrow \gamma\eta\eta'$     $J/\psi \rightarrow \gamma\eta'\eta'$     $J/\psi \rightarrow \gamma K_S K_S$

$J/\psi \rightarrow \phi X, \omega X$

## Lattice QCD





# $\eta$ and $\eta'$ physics at BESIII

With 1.3B  $J/\psi$   $B(J/\psi \rightarrow \gamma\eta) \sim 1.10 \times 10^{-3} \sim 1.44 \times 10^6 \eta$  events  
 $B(J/\psi \rightarrow \gamma\eta') \sim 5.15 \times 10^{-3} \sim 6.74 \times 10^6 \eta'$  events

## Test/Constrain of Models, Decay dynamics

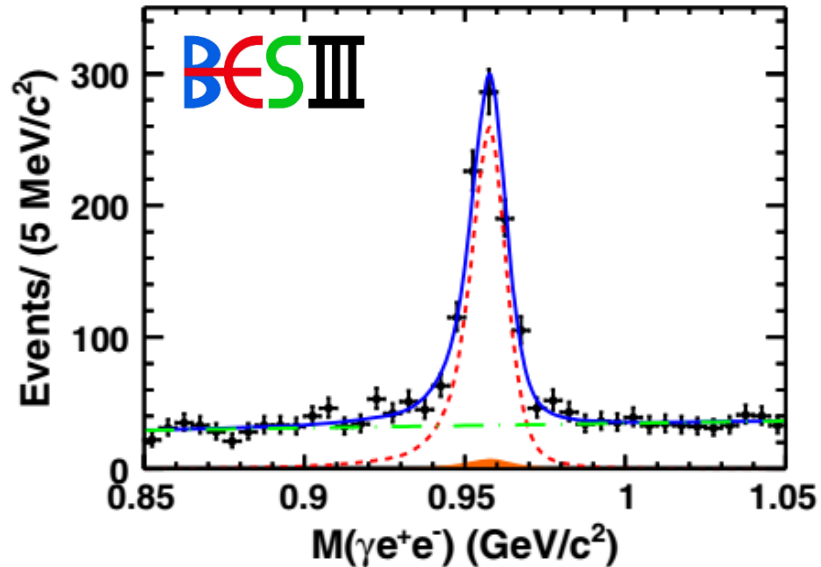
|   |                             |                      |
|---|-----------------------------|----------------------|
| $\clubsuit \eta' \rightarrow \pi^+ \pi^- \eta$    | ChPT                        | PRD 83,012003(2011)  |
| $\clubsuit \eta' \rightarrow 2(\pi \pi)$          | ChPT&VMD                    | PRL 112,251801(2014) |
| $\clubsuit \eta/\eta' \rightarrow 3\pi$           | Isospin breaking            | PRL 108,182001(2012) |
| $\clubsuit \eta' \rightarrow \pi^+ \pi^- l^+ l^-$ | VMD/ChPT                    | PRD 89,092011(2013)  |
| $\clubsuit \eta' \rightarrow \gamma e^+ e^-$      | VMD, Transition form factor | PRD 92,012001(2015)  |
| $\clubsuit \eta' \rightarrow \gamma \pi^+ \pi^-$  | VMD&Box anomaly             | preliminary          |
| $\clubsuit \eta' \rightarrow \gamma \gamma \pi^0$ | LσM and VMD                 | preliminary          |

## Search for New Physics

|  |                                 |                     |
|--|---------------------------------|---------------------|
| $\clubsuit \eta/\eta' \rightarrow \pi\pi$                | CP violation                    | PRD 84,032006(2011) |
| $\clubsuit \eta/\eta' \rightarrow \pi^+ e^- \bar{\nu}_e$ | New charged current interaction | PRD 87,032006(2013) |
| $\clubsuit \eta/\eta' \rightarrow$ invisible             | Light invisible particle        | PRD 87,012009(2013) |

# Observation of the Dalitz decay $\eta' \rightarrow \gamma e^+ e^-$

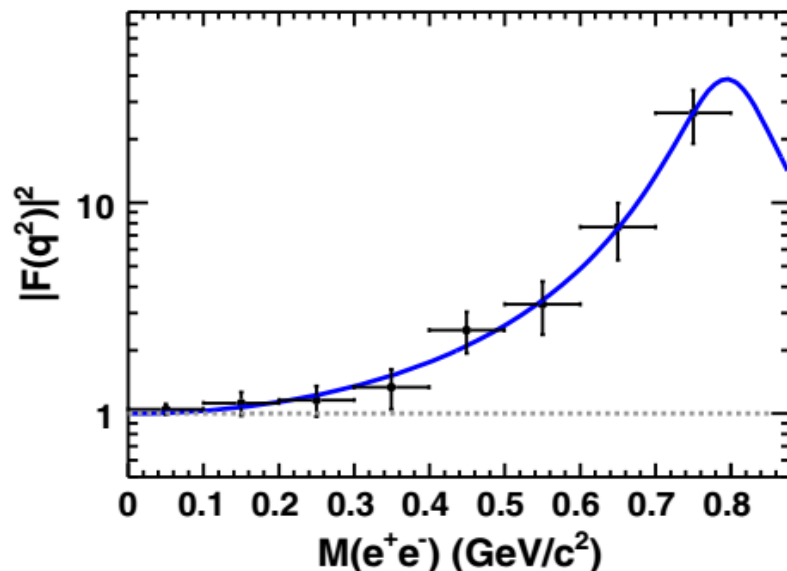
PRD 92,012001(2015)



$$|F(q^2)|^2 = \frac{\Lambda^2(\Lambda^2 + \gamma^2)}{(\Lambda^2 - q^2)^2 + \Lambda^2\gamma^2}$$

$$\Lambda_{\eta'} = (0.79 \pm 0.04(\text{stat}) \pm 0.02(\text{sys})) \text{ GeV}$$

$$\gamma_{\eta'} = (0.13 \pm 0.06(\text{stat}) \pm 0.03(\text{sys})) \text{ GeV}$$

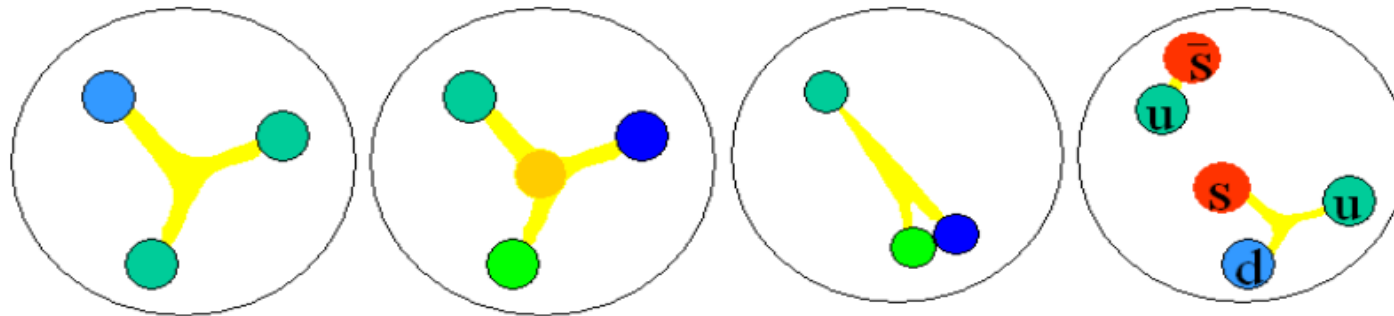


- ☘ Agrees within errors with the VMD model predictions.
- ☘ The uncertainty matches the best result in space-like region
- ☘ TFF useful input for studies of the HLbL contribution to the  $a_\mu = (g_\mu - 2)/2$

# Baryon spectroscopy at BESIII



# Baryon spectroscopy



(a)

**qqq**

(b)

**qqqq**

(c)

**diquark**

(d)

**meson-baryon state**

## 3-quark(a) configurations

- ✓ **Explicit classification for light baryons in terms of group symmetry.**
- ✓ **Successful in describing ground state baryons**

## □ **Predicts more excited states**

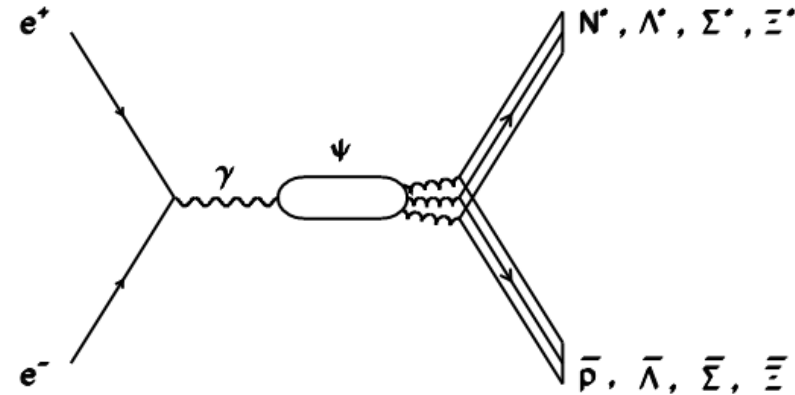
'missing  $N^*$  states' around 2 GeV:

fewer effective degrees of freedom? -> diquark(c) configuration



# Baryon spectroscopy at BESIII

- ◆ **Access to  $N^*$   $\Lambda^*$   $\Sigma^*$   $\Xi^*$  baryons**
- ◆ **Favorable environment for producing:**
  - hybrid (qqq-g) baryons;
  - missing  $N^*$  strong coupling to  $g3N$
- ◆ **Complementary to  $\pi N$  experiments**



## Selected results at BESIII

- ❄ PWA of  $\psi' \rightarrow \bar{p}p\pi^0$   
PWA of  $\psi' \rightarrow \bar{p}p\eta$
- ❄ Measurement of  $\psi' \rightarrow (\gamma)K^- \Lambda \bar{\Xi}^+ + cc.$   
Observation of  $\psi' \rightarrow \Lambda \bar{\Sigma}^\pm \pi^\mp + cc.$
- ❄ Hadronic Branching Fractions of  $\Lambda_c^+$  decays  
Branching Fractions of  $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$

PRL 110, 022001(2013)

PRD 88,032010 (2013)

PRD 91, 092006 (2015)

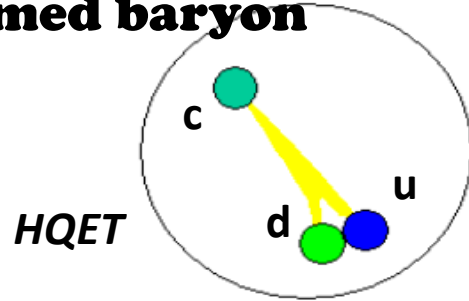
PRD 88, 112007 (2013)

PRL 116, 052001 (2016)

PRL 115, 221805 (2015)

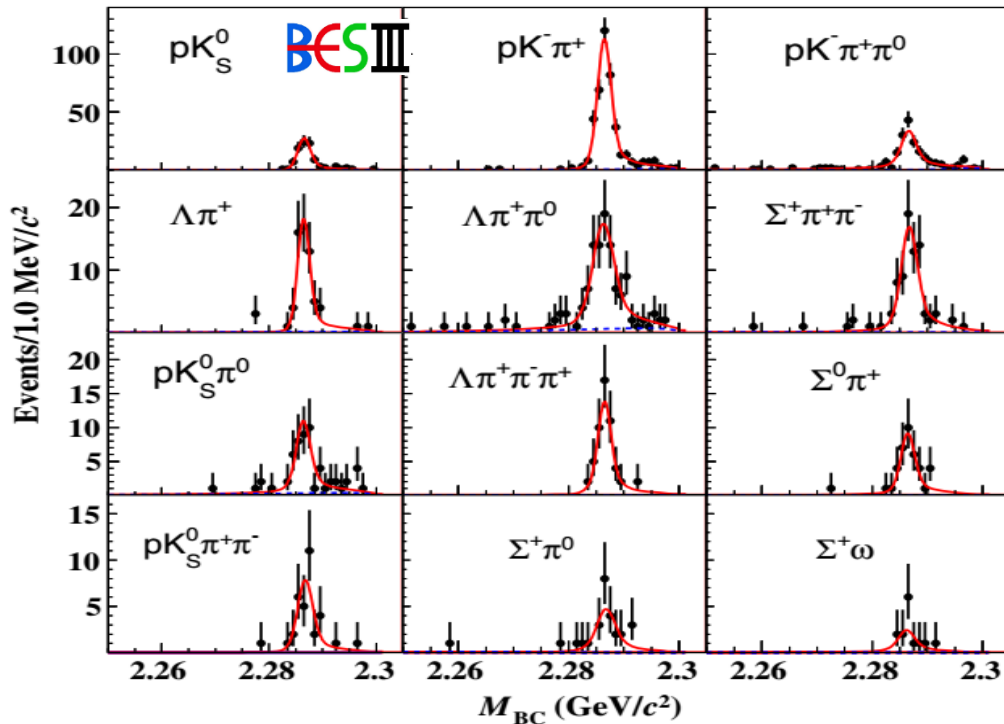


$\Lambda_c^+$  lightest charmed baryon



**First measurement of absolute hadronic BR**

**12 Cabibbo-favored  $\Lambda_c^+$  decay rates measured by double-tag technique**

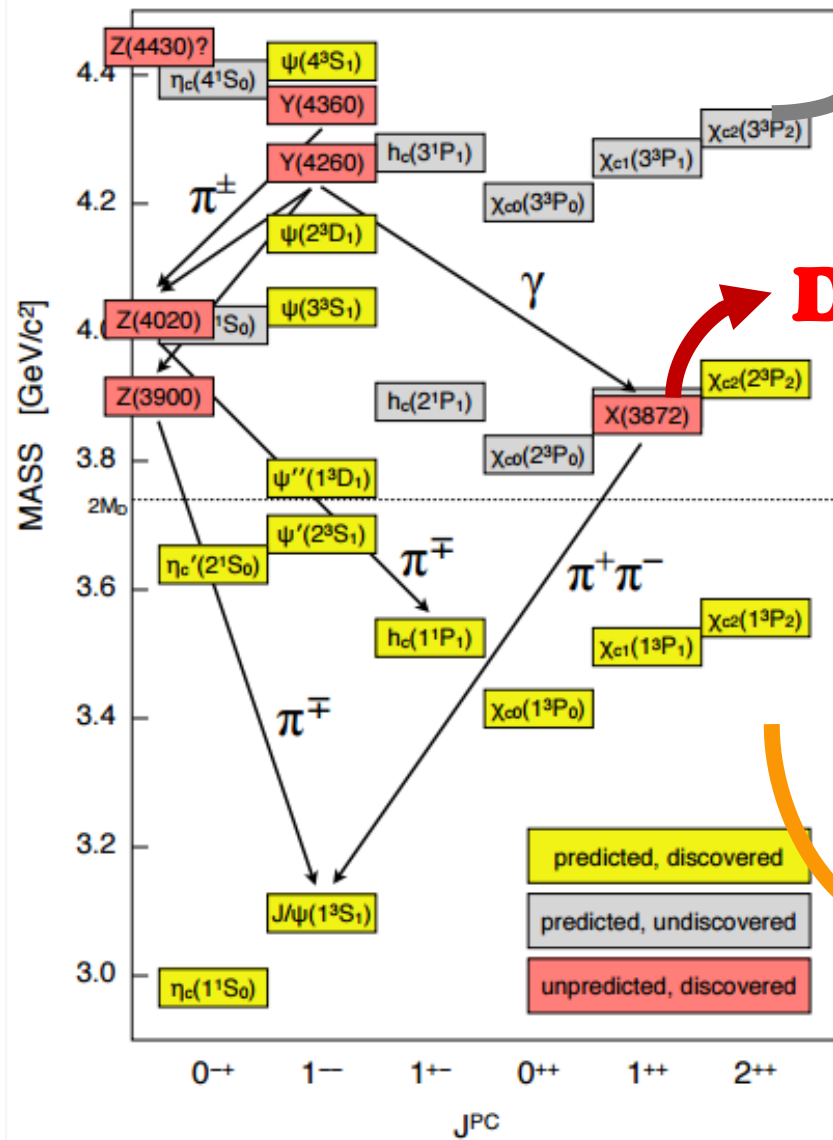


| Mode                        | This work (%)            | PDG (%)         |
|-----------------------------|--------------------------|-----------------|
| $\rho K_S^0$                | $1.52 \pm 0.08 \pm 0.03$ | $1.15 \pm 0.30$ |
| $\rho K^- \pi^+$            | $5.84 \pm 0.27 \pm 0.23$ | $5.0 \pm 1.3$   |
| $\rho K_S^0 \pi^0$          | $1.87 \pm 0.13 \pm 0.05$ | $1.65 \pm 0.50$ |
| $\rho K_S^0 \pi^+ \pi^-$    | $1.53 \pm 0.11 \pm 0.09$ | $1.30 \pm 0.35$ |
| $\rho K^- \pi^+ \pi^0$      | $4.53 \pm 0.23 \pm 0.30$ | $3.4 \pm 1.0$   |
| $\Lambda \pi^+$             | $1.24 \pm 0.07 \pm 0.03$ | $1.07 \pm 0.28$ |
| $\Lambda \pi^+ \pi^0$       | $7.01 \pm 0.37 \pm 0.19$ | $3.6 \pm 1.3$   |
| $\Lambda \pi^+ \pi^- \pi^+$ | $3.81 \pm 0.24 \pm 0.18$ | $2.6 \pm 0.7$   |
| $\Sigma^0 \pi^+$            | $1.27 \pm 0.08 \pm 0.03$ | $1.05 \pm 0.28$ |
| $\Sigma^+ \pi^0$            | $1.18 \pm 0.10 \pm 0.03$ | $1.00 \pm 0.34$ |
| $\Sigma^+ \pi^+ \pi^-$      | $4.25 \pm 0.24 \pm 0.20$ | $3.6 \pm 1.0$   |
| $\Sigma^+ \omega$           | $1.56 \pm 0.20 \pm 0.07$ | $2.7 \pm 1.0$   |



XYZ spectroscopy at BESIII

# XYZ spectroscopy



*Predicted not discovered*

**Discovered not predicted**

X X(3823) X(3872) ...

Y vector e<sup>+</sup>e<sup>-</sup> → hidden charm final states

Z Z<sub>c</sub> charged charmonium-like states

**Don't fit in the quark model**

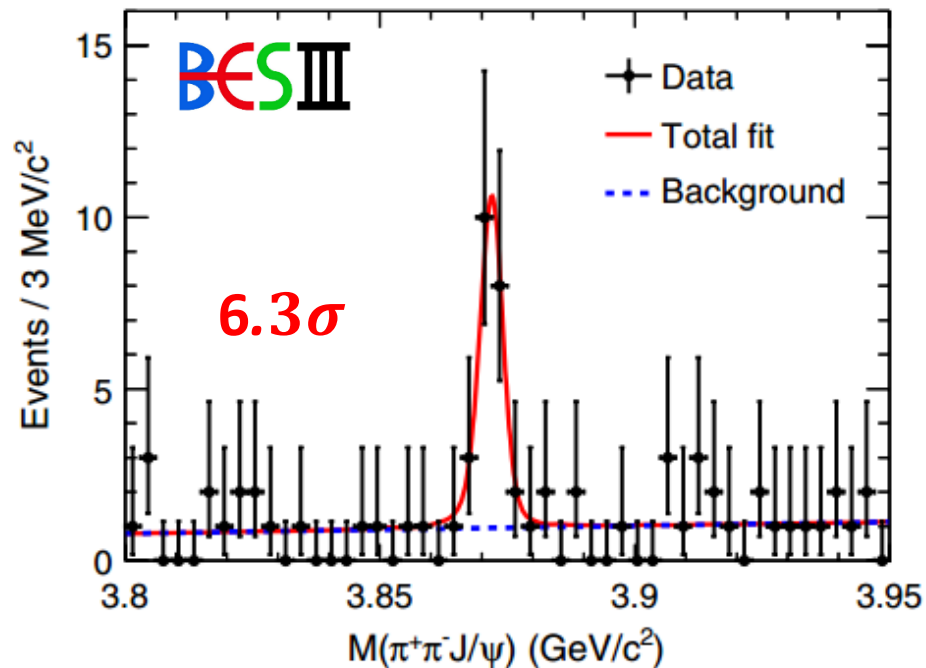
*Good agreement between prediction and discovery*

# $X(3872)$ in $Y(4260) \rightarrow \gamma\pi^+\pi^- J/\psi$

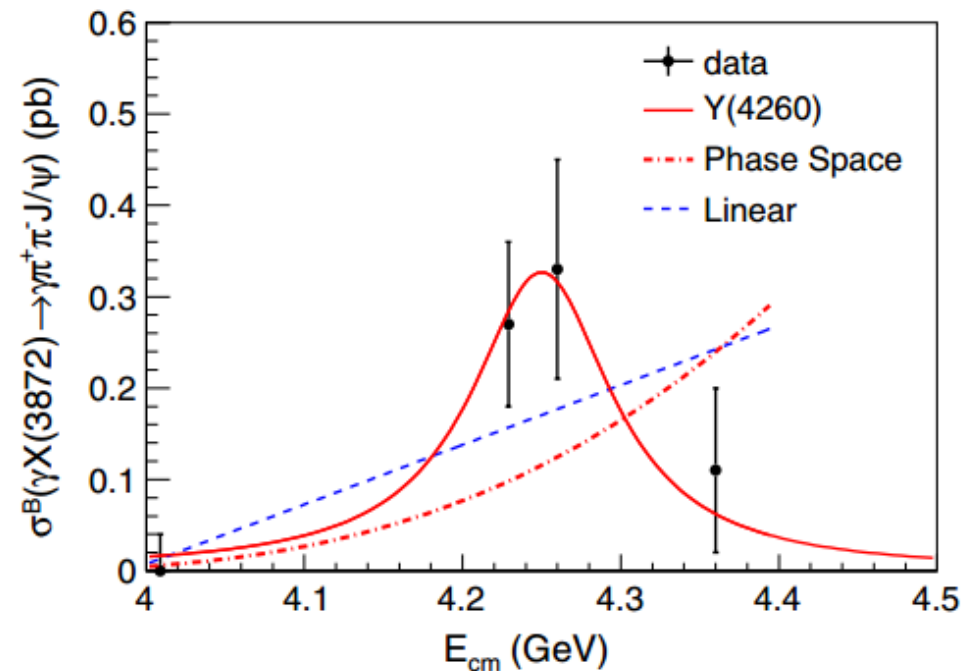
narrow  $1^{++}$  state close to  $\bar{D}^0 D^{*0}$  threshold

PRL 112, 092001 (2014)

- 🍏  $\bar{D}^0 D^{*0}$  molecular state?
- 🍏 mixture of  $\chi'_{c1}$  and  $\bar{D}^0 D^{*0}$  bound state?



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

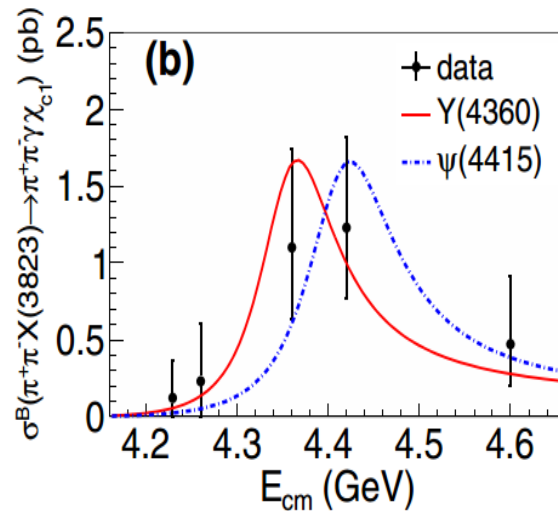
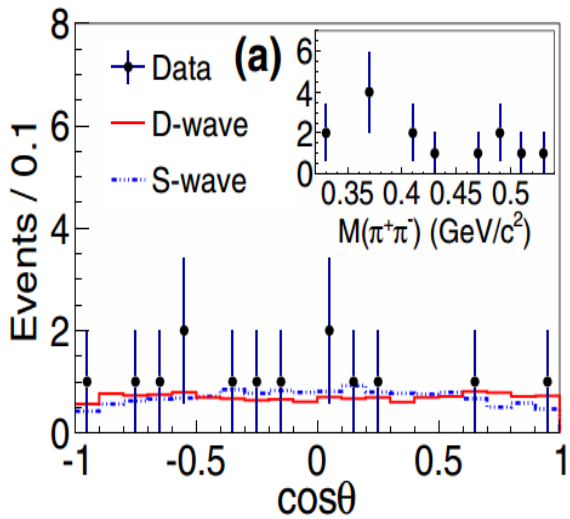
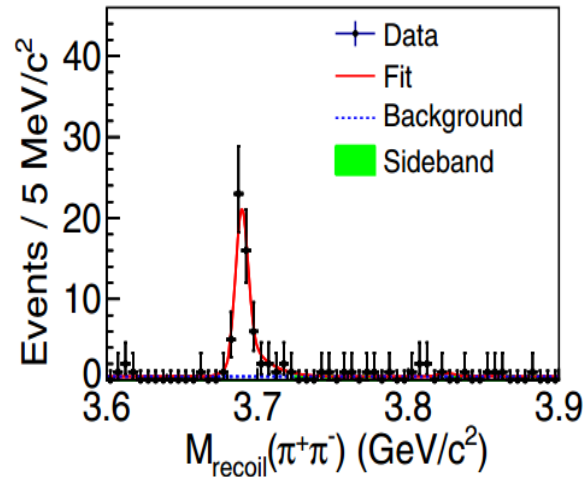
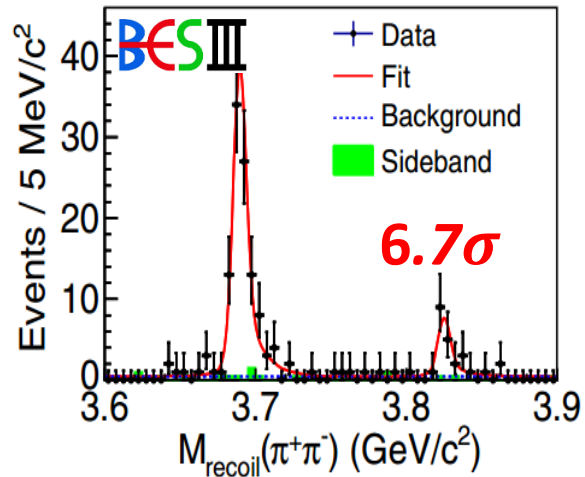


**Suggestive of  $Y(4260) \rightarrow \gamma X(3872)$**



# $X(3823)$ in $e^+e^- \rightarrow \pi^+\pi^-\gamma\chi_{c1}$

PRL 115, 011803 (2015)



First observed by Belle in  $B \rightarrow \chi_{c1}\gamma K$

PRL111, 032001 (2013)

Good candidate of  $\psi(1^3D_2)$

🍏  $M = (3821.7 \pm 1.3(stat.) \pm 0.7(syst.)) MeV/c^2$

🍏  $\Gamma < 16 MeV$  at 90%C.L. consistent with Belle

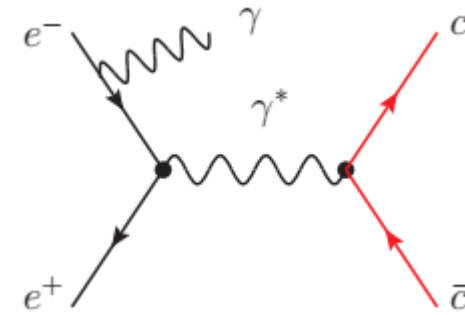
🍏  $R = \frac{B(X(3823) \rightarrow \gamma\chi_{c2})}{B(X(3823) \rightarrow \gamma\chi_{c1})} < 0.43$        $R \sim 0.2$  predict.

(a) D wave expected, with limited statistics

(b) Both  $Y(4360)$   $\psi(4415)$  line shape give reasonable description

# Y states

Abundant structures observed above 4GeV  
 $1^-$  can be produced in  $e^+e^-$  annihilation



## BESIII Exclusive cross section line shape measurement

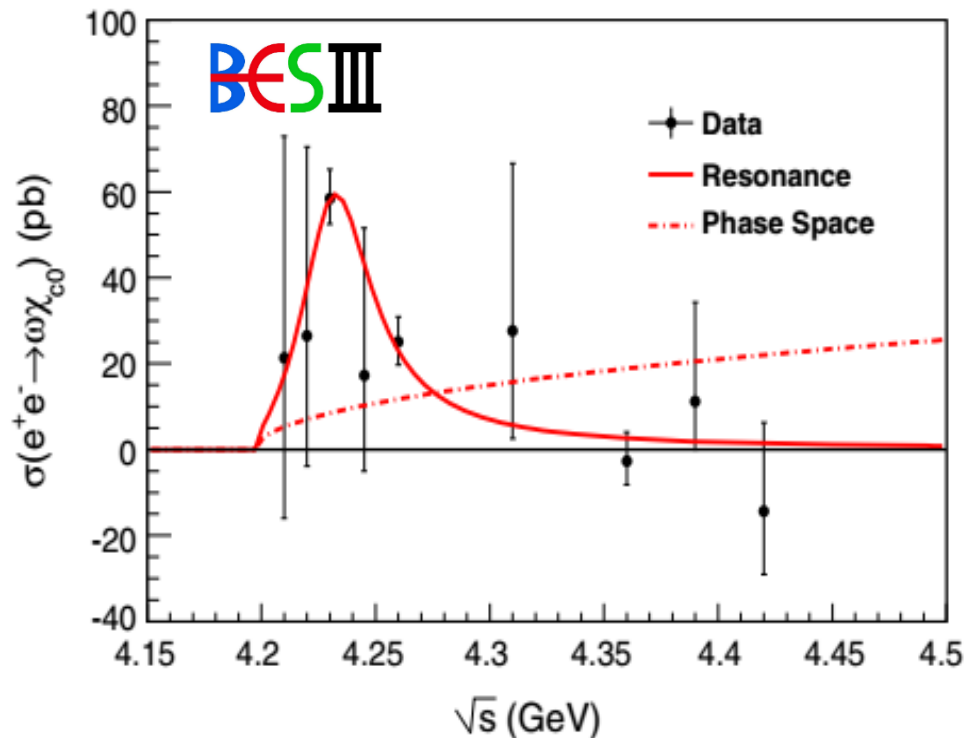
- 🍏  $e^+e^- \rightarrow \pi^+\pi^-h_c$  PRL 111,242001(2013)
- $e^+e^- \rightarrow \omega\chi_{c0}$  PRL 114,092003(2015)
- $e^+e^- \rightarrow \eta J/\psi$  PRD 91,112005(2015)
- $e^+e^- \rightarrow \eta' J/\psi$  Preliminary
  
- 🍏 Search for  $Y(4140) \rightarrow \phi J/\psi$  PRD 91,032002(2015)
- Search for  $Y(4260) \rightarrow J/\psi \eta\pi^0$  PRD 92, 012008(2015)
- Search for  $e^+e^- \rightarrow \gamma\chi_{cJ}$  CPC39 (2015) no.4, 041001

# Study of $e^+e^- \rightarrow \omega\chi_{c0}$ from 4.21 to 4.42 GeV

PRL 114, 092003 (2015)

Y(4260)

- 🍏 strong coupling to the  $J/\psi\pi\pi$  final state
  - 🍏 relatively small coupling to open charm
- coupling between Y(4260) and  $\omega\chi_{c0}$  by threshold effect?



Fit with a single BW

Mass =  $4230 \pm 8 \pm 6$  MeV

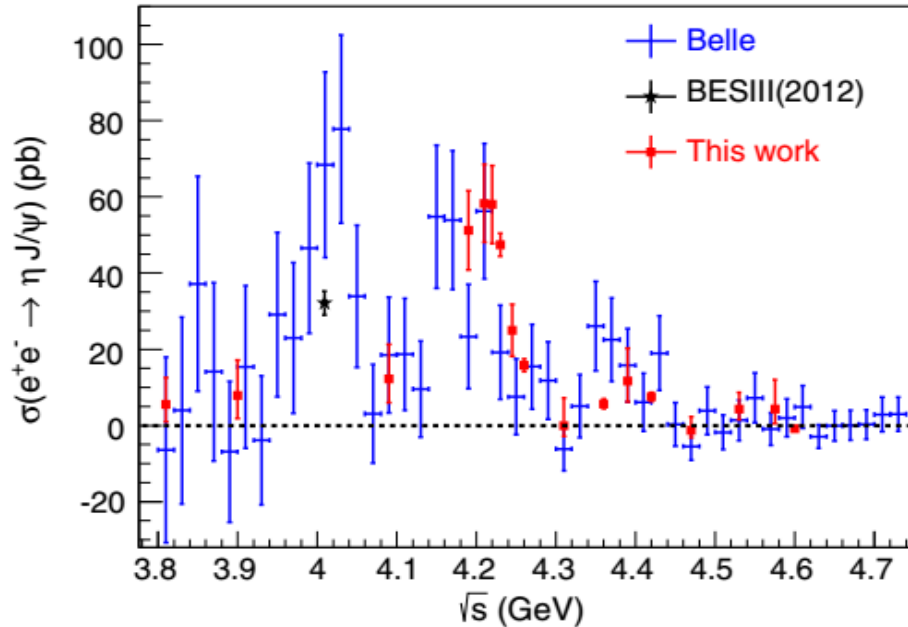
Width =  $38 \pm 12 \pm 2$  MeV

Significance  $> 9\sigma$

Inconsistent with the line shape of the Y(4260)

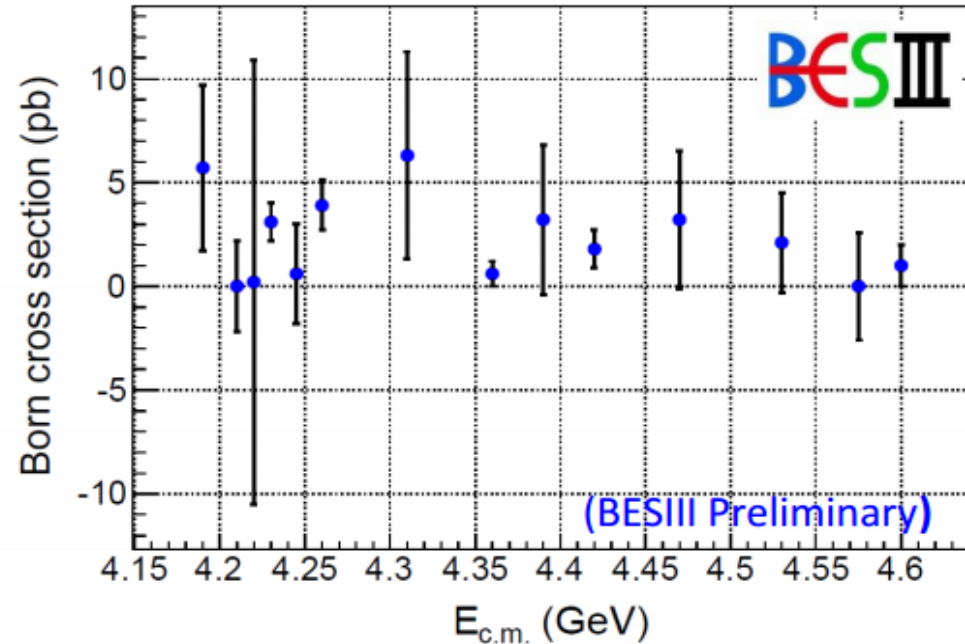
- 🍏  $\psi(4S)$ ? EPJC 74:3208 (2014)
- 🍏 Tetraquark? PRD 91, 117501 (2015)
- 🍏 Threshold effect?

# $e^+ e^- \rightarrow \eta J/\psi$



- 🍏 Agree with previous results with improved precision
- 🍏 Structure around 4.2 GeV  
 $\psi(4160) \rightarrow \eta J/\psi$ ?

# $e^+ e^- \rightarrow \eta' J/\psi$



- 🍏 Cannot tell the line shape due to statistics
- 🍏  $\sigma(\eta' J/\psi)$  much lower than  $\sigma(\eta J/\psi)$   
lower than NRQCD calculation

# Zc(3900) in $e^+e^- \rightarrow \pi(\pi J/\psi)$

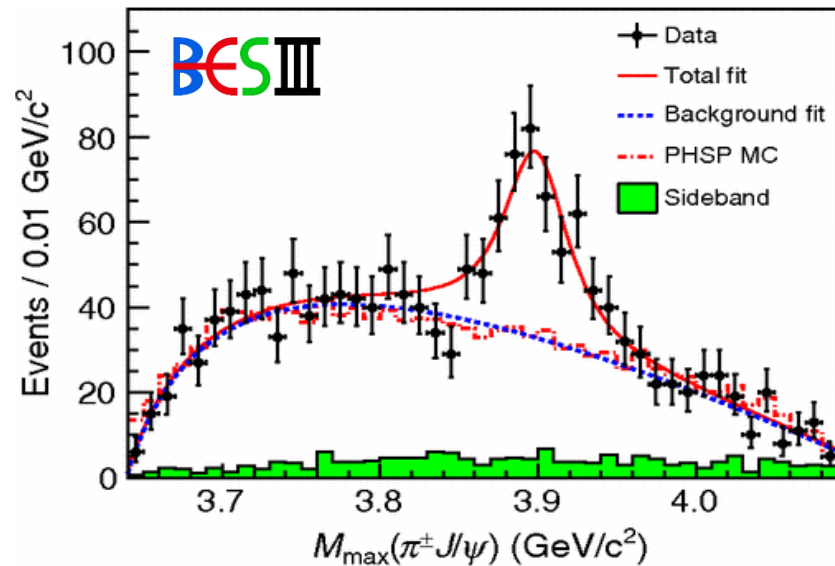
| State                 | Mass (MeV/c <sup>2</sup> ) | Width (MeV)      |
|-----------------------|----------------------------|------------------|
| Zc(3900) <sup>±</sup> | 3899.0 ± 3.6 ± 4.9         | 46 ± 10 ± 20     |
| Zc(3900) <sup>0</sup> | 3894.8 ± 2.3 ± 2.7         | 29.6 ± 8.2 ± 8.2 |

Zc(3900)<sup>±</sup>

PRL 110, 252001 (2013)

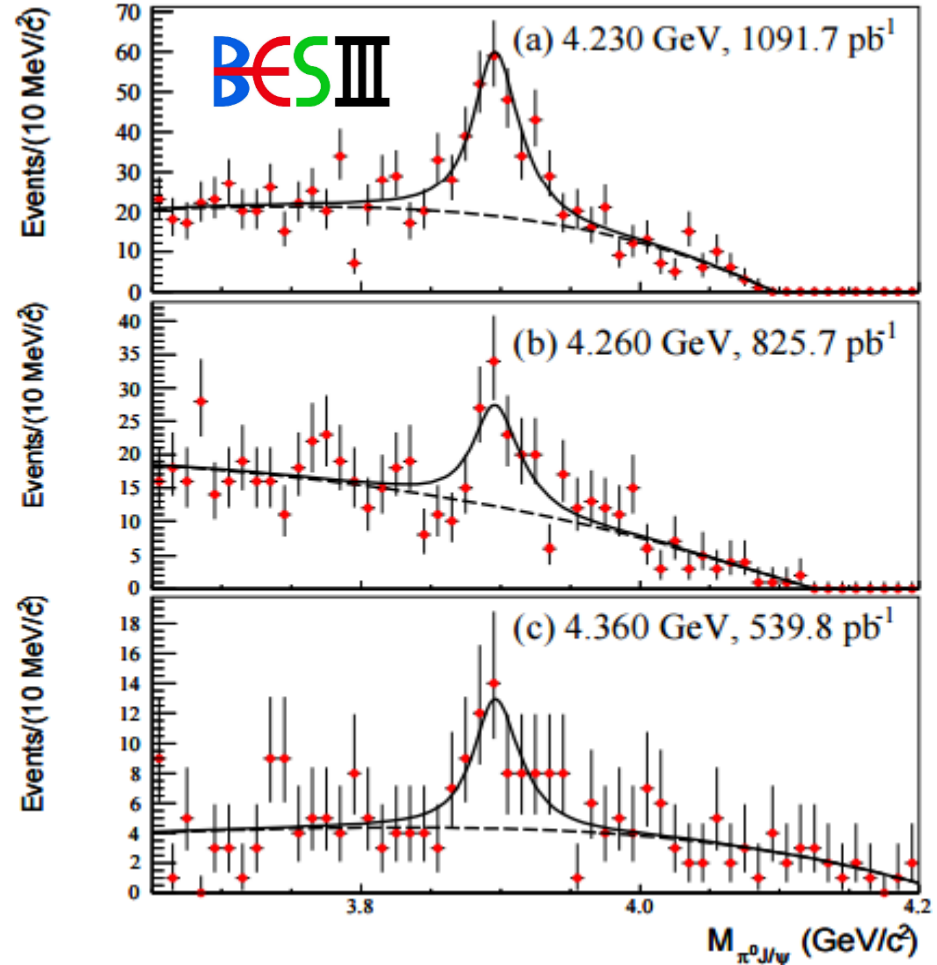
- 🍏 couples to  $J/\psi$
- 🍏 electric charge

$c\bar{c}$   
 $u\bar{d}/\bar{u}d$



Zc(3900)<sup>0</sup>

PRL 115, 112003 (2015)



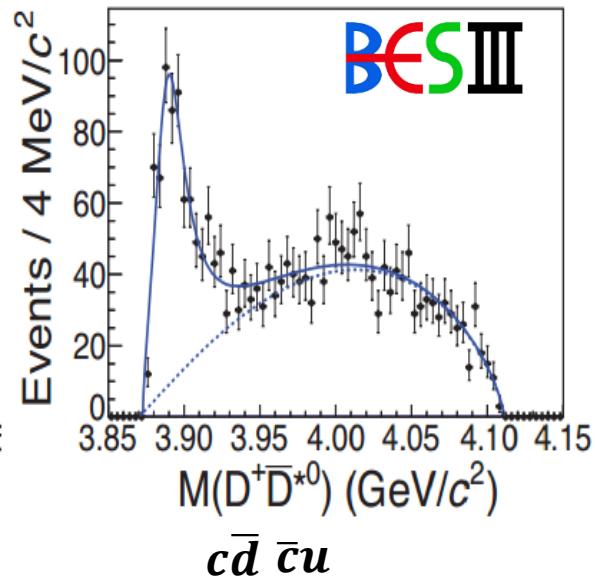
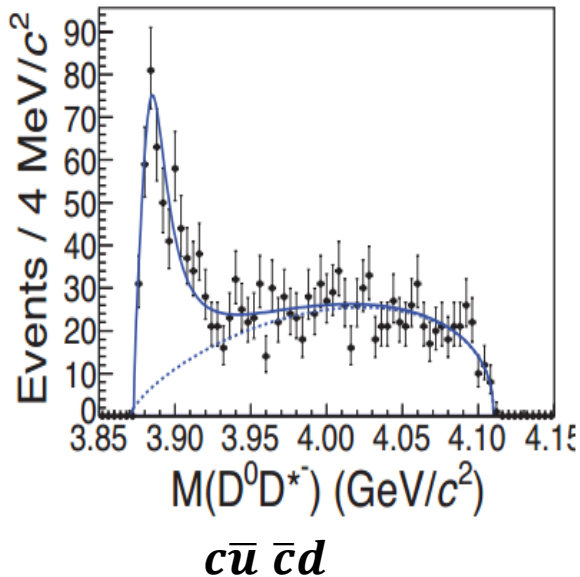


# Z<sub>c</sub>(3885) in $e^+e^- \rightarrow \pi(D\bar{D}^*)$

| State                              | Mass (MeV/c <sup>2</sup> )                   | Width (MeV)                           |
|------------------------------------|--|---------------------------------------|
| Z <sub>c</sub> (3885) <sup>±</sup> | 3881.7 ± 1.6 ± 2.1                           | 26.6 ± 2.0 ± 2.3                      |
| Z <sub>c</sub> (3885) <sup>0</sup> | 3885.7 <sup>+4.3</sup> <sub>-5.7</sub> ± 8.4 | 35 <sup>+11</sup> <sub>-12</sub> ± 15 |

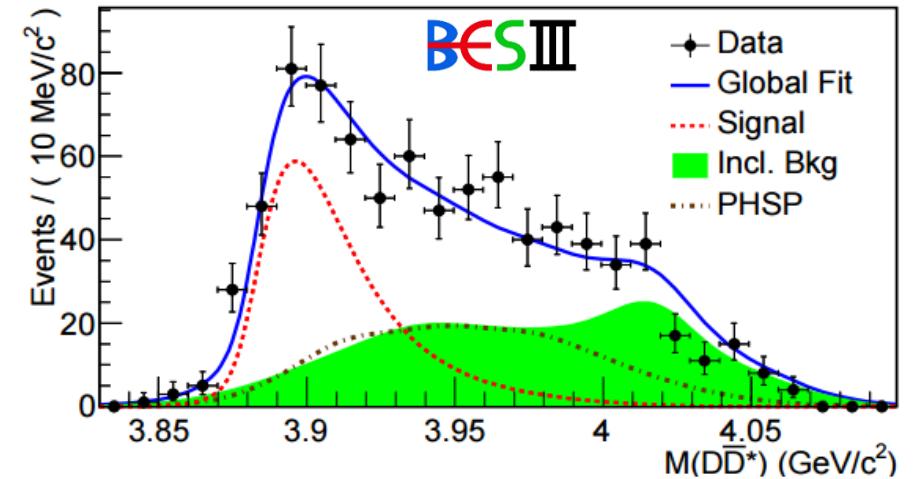
Z<sub>c</sub>(3885)<sup>±</sup>

PRL 112, 022001 (2014)



Z<sub>c</sub>(3885)<sup>0</sup>

PRL 115, 222002 (2015)



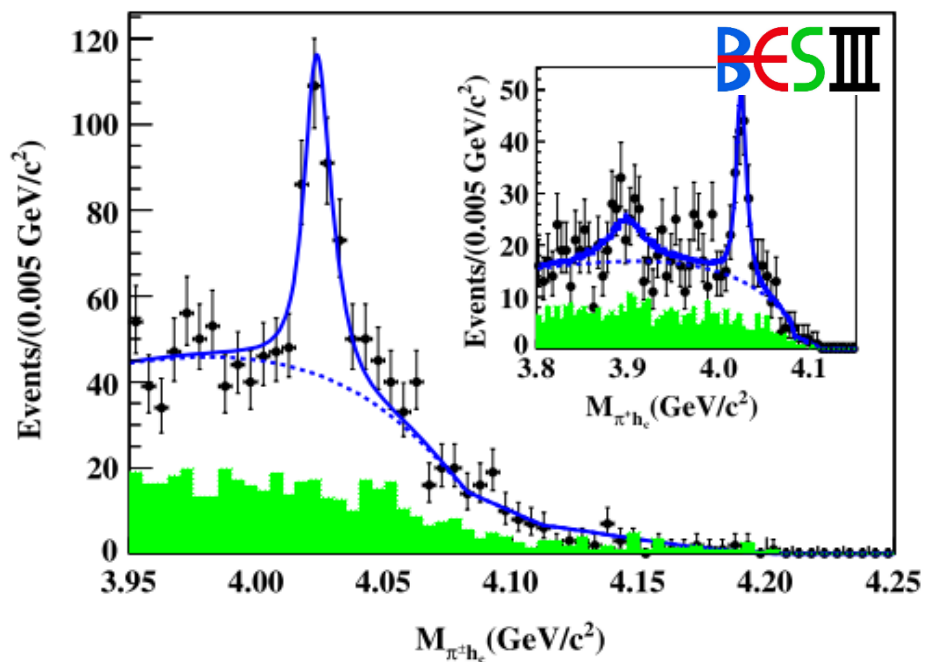
Z<sub>c</sub>(3900) & Z<sub>c</sub>(3885)

- 🍏 mass and width are consistent within 2σ
- 🍏 Z<sub>c</sub>(3885) favor 1<sup>+</sup>    Z<sub>c</sub>(3900) ?
- 🍏  $\frac{\mathcal{B}(Z_c \rightarrow D^* \bar{D})}{\mathcal{B}(Z_c \rightarrow J/\psi \pi)} = 6.2 \pm 1.1 \pm 2.7$

# $Z_c(4020)$ in $e^+e^- \rightarrow \pi(\pi h_c)$

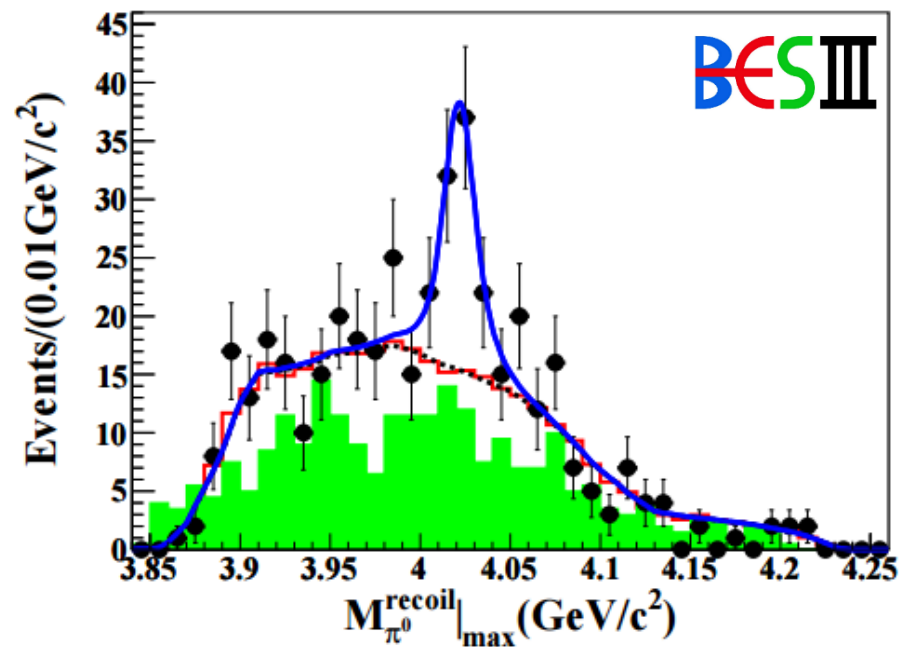
$Z_c(4020)^\pm$

PRL 111, 242001 (2013)



$Z_c(4020)^0$

PRL 113, 212002 (2014)

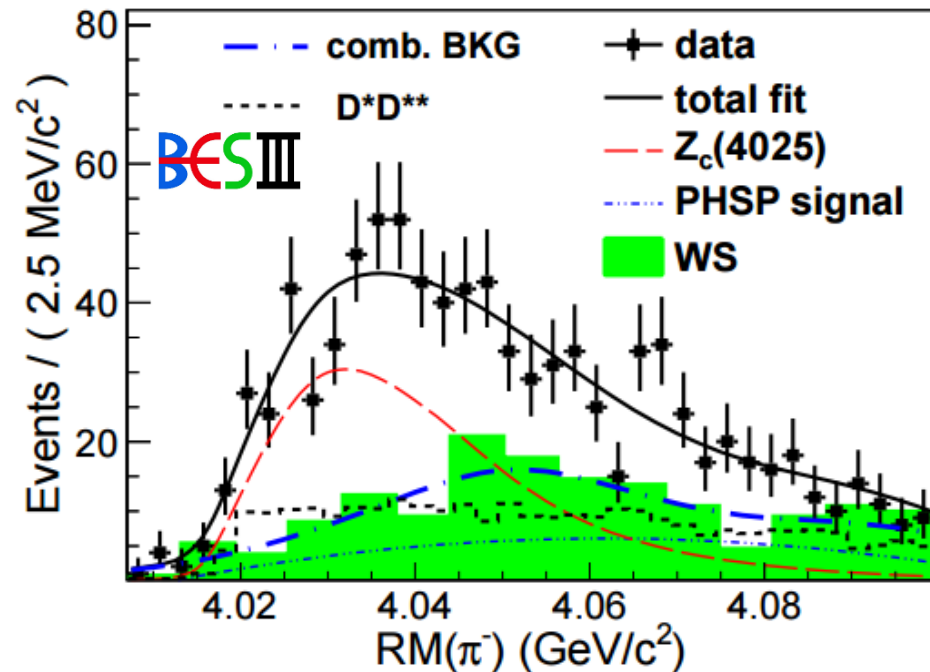


| State           | Mass (MeV/c <sup>2</sup> ) | Width (MeV)           |
|-----------------|----------------------------|-----------------------|
| $Z_c(4020)^\pm$ | $4022.9 \pm 0.8 \pm 2.7$   | $7.9 \pm 2.7 \pm 2.6$ |
| $Z_c(4020)^0$   | $4023.9 \pm 2.2 \pm 3.8$   | fixed(7.9)            |

# Zc(4025) in $e^+e^- \rightarrow \pi D^* \bar{D}^*$

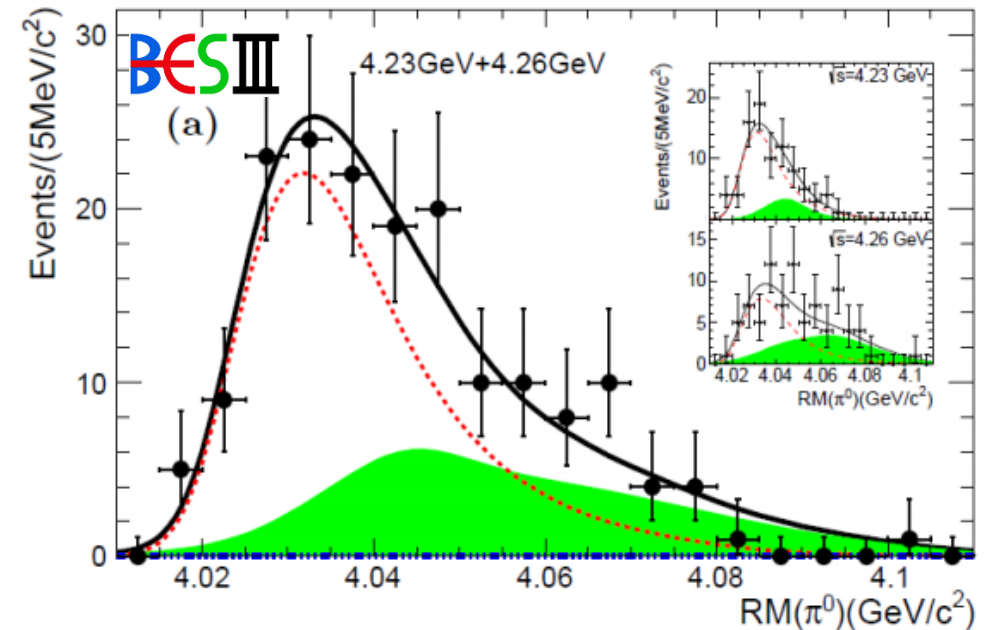
Zc(4025)<sup>±</sup>

PRL 112, 132001 (2014)



Zc(4025)<sup>0</sup>

PRL 115, 182002 (2015)



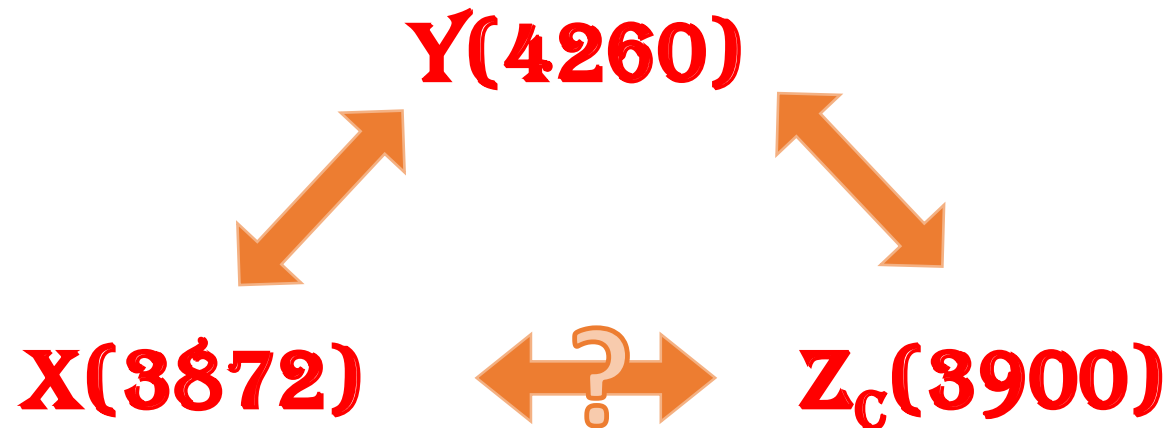
| State                 | Mass (MeV/c <sup>2</sup> )                   | Width (MeV)      |
|-----------------------|--|------------------|
| Zc(4025) <sup>±</sup> | 4026.3 ± 2.6 ± 3.7                           | 24.8 ± 5.6 ± 7.7 |
| Zc(4025) <sup>0</sup> | 4025.5 <sup>+2.0</sup> <sub>-4.7</sub> ± 3.1 | 23.0 ± 6.0 ± 1.0 |

Zc(4020) & Zc(4025)

🍏 resonance parameter consistent within 1.5σ

# Nature of XYZ states

- 🍏 Tetraquark state?
- 🍏  $D(^*)\bar{D}(^*)$  molecule state?
- 🍏 Meson-Loop?
- 🍏 FSI?
- 🍏 Cusp?



# Summary

BESIII collects large data sample at 2-4.6 GeV in  $e^+e^-$  collision

BESIII is an ideal laboratory for studying hadron spectrum

- 🍀 Light hadron --  $X(18??)$ , glueball, rare decay ...
- ❄️ Baryon -- excited nucleons, baryon decay ...
- 🍏 XYZ -- XYZ and transition ...

**More data are taking & More exciting results are expected!**



Thank you!