Recent results on charmonium from BESIII

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(for BESIII collaboration)

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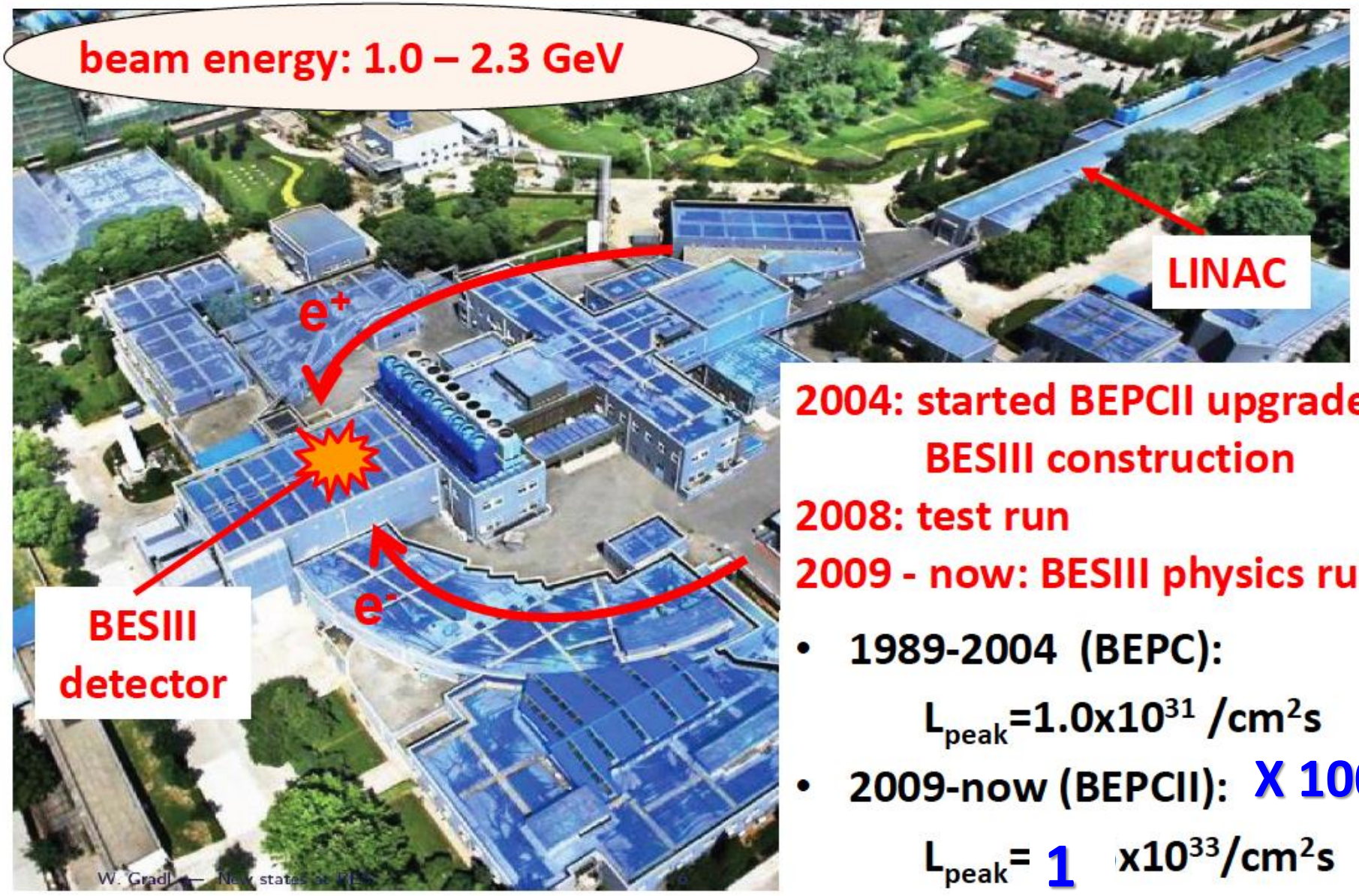
Beijing Electron Positron Collider (BEPC)



2004: started BEPCII upgrade,
BESIII construction

2008: test run

2009 - now: BESIII physics run

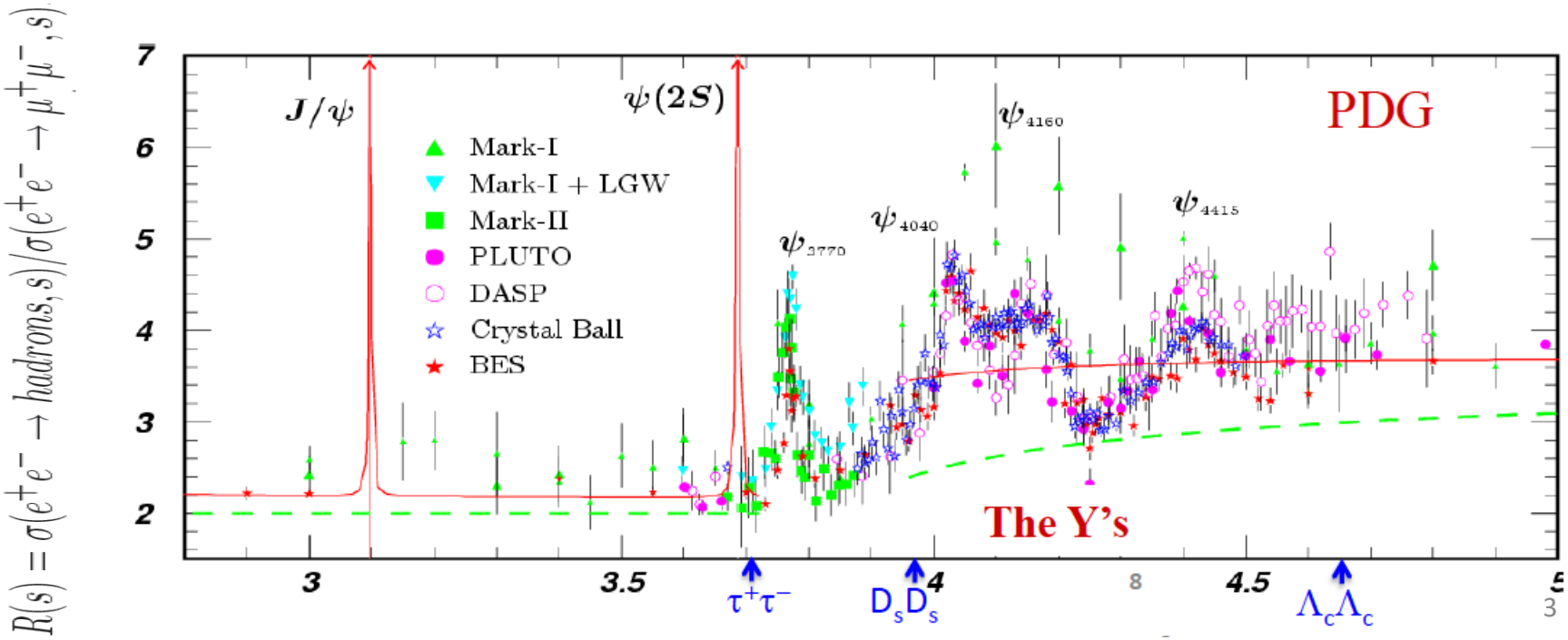
- 1989-2004 (BEPC):

  L_{peak}=1.0x10^{31} /cm^{2}s
- 2009-now (BEPCII): X 100

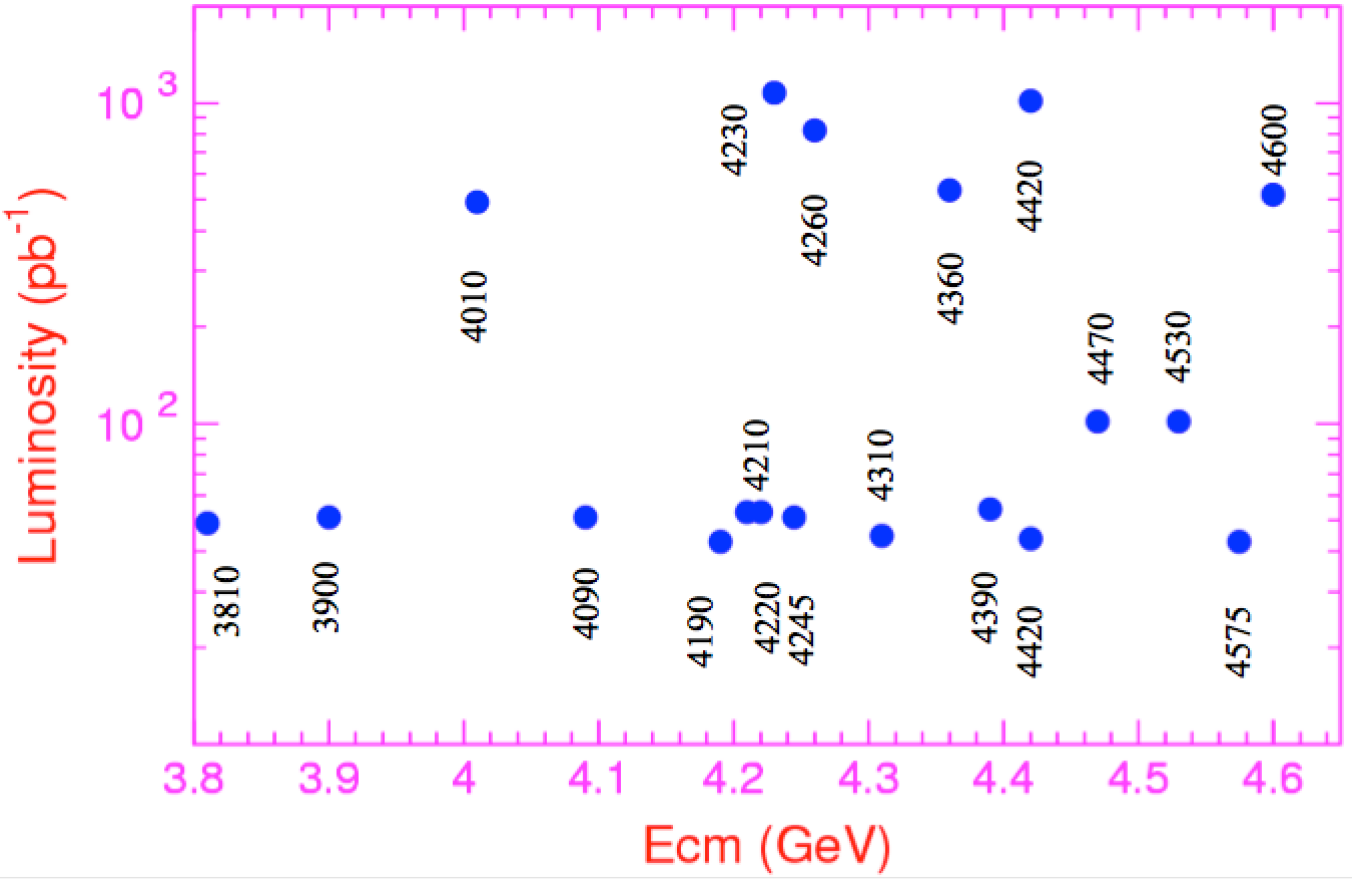
  L_{peak}= 1 x10^{33}/cm^{2}s

Features of the BEPC Energy Region

- Rich of **resonances:** charmonia and charmed mesons
- **Threshold** characteristics (pairs of τ, D, D_s, …)
- **Transition between** continuum and resonances, perturbative and non-perturbative QCD
- Energy location of the **gluonic excitations and multi-quark states**

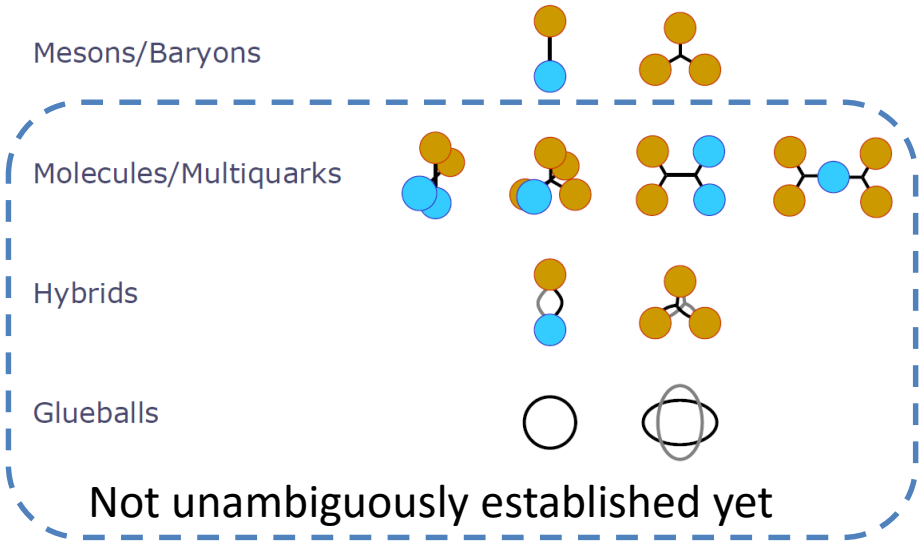


BESIII data samples for XYZ study (5 fb^{-1})



For the XYZ states study, BESIII has accumulated about 5 fb-1 data. Around ψ (4040), Y(4260), and Y(4360) peaks, we collected the largest data sample in the world so far for the study of their decays. Data samples with small statistics at other energy points are collected for the line-shape study.

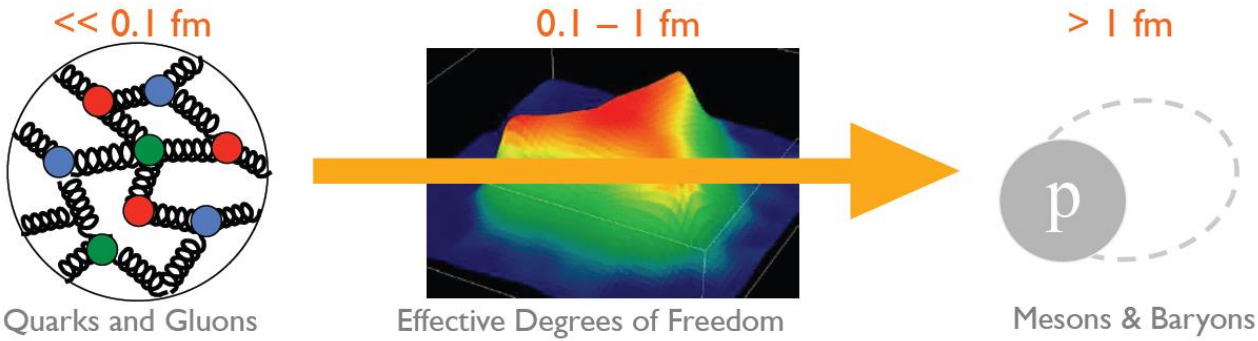
Hadron spectrum



Continuous efforts in experiment and theory

- Hadron spectroscopy is a key tool to investigate QCD

- testing QCD in the confinement regime
- providing insights into the fundamental degrees of freedom



From V. Crede

XYZ states:

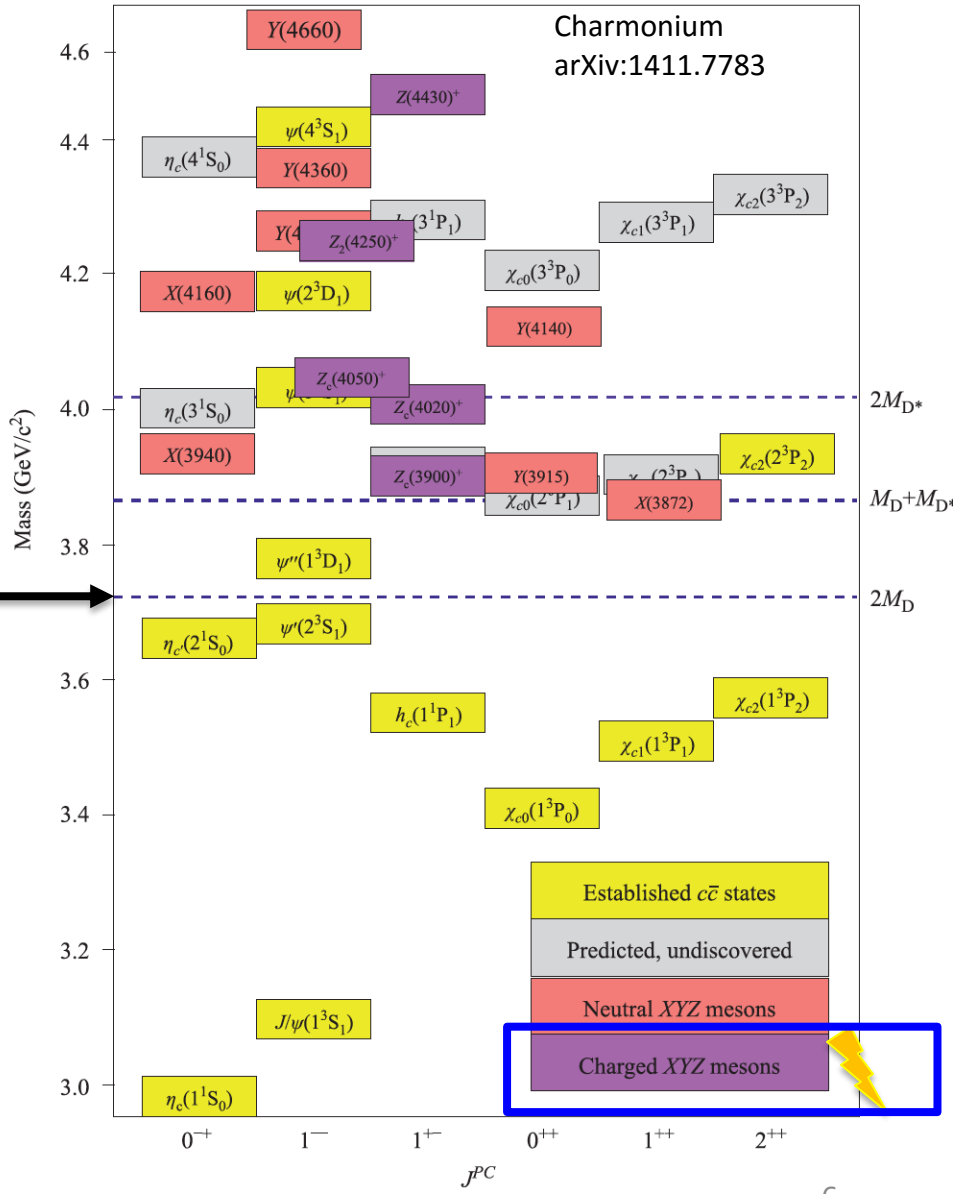
Cannot fit in the spectrum of conventional heavy quarkonia

Additional degree of freedom from light quarks and gluons?

Open charm threshold

c- and b-quark are heavy
Non-relativistic QM applies

NRQCD approach is a spectacular success, validated by the consistency between ($c\bar{c}$) and ($b\bar{b}$)



X States at BESIII

7

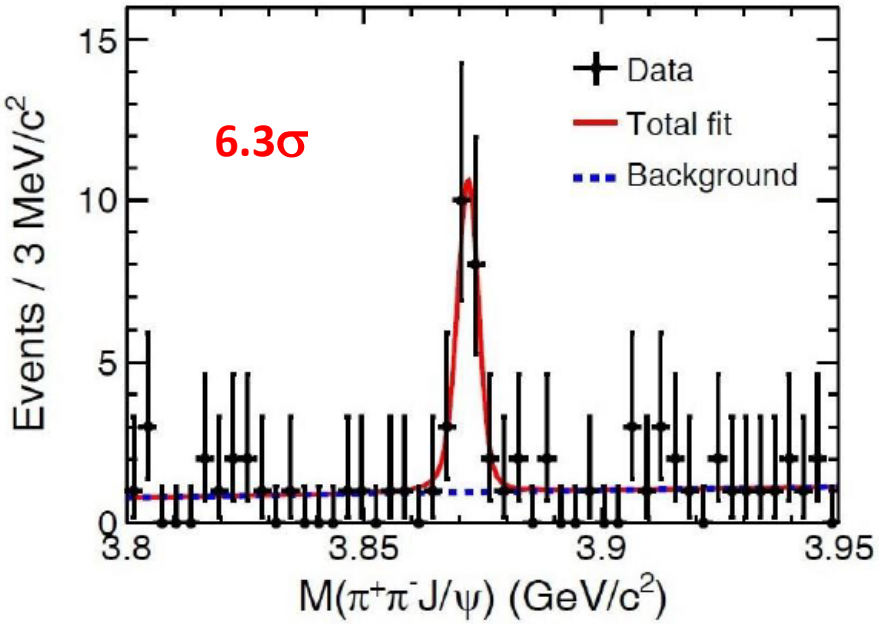
Observation of $e^+e^- \to \gamma X(3872)$

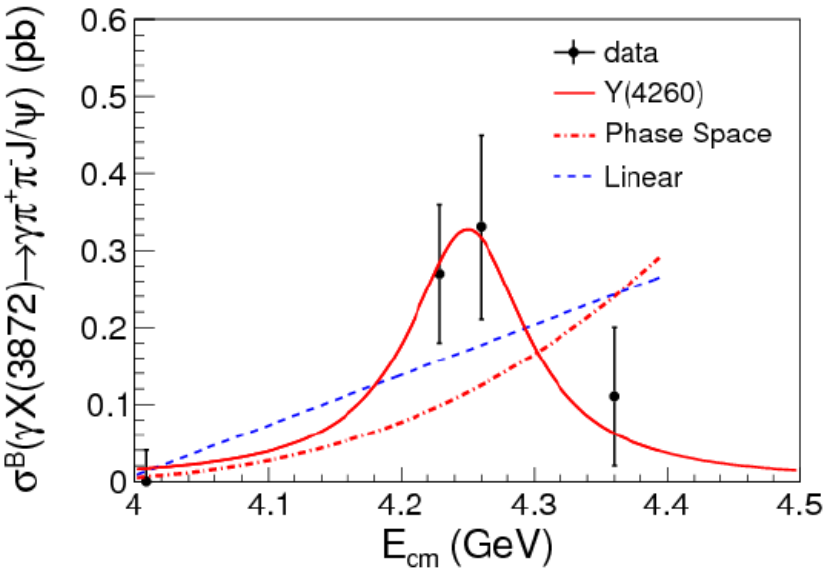
Strong evidence for
$X(3872) \to \pi\pi\, J/\psi$

PRL 112, 092001 (2014)

$M = 3871.9 \pm 0.7 \pm 0.2$ MeV/c^2

Suggestive of
$Y(4260) \to \gamma\, X(3872)$



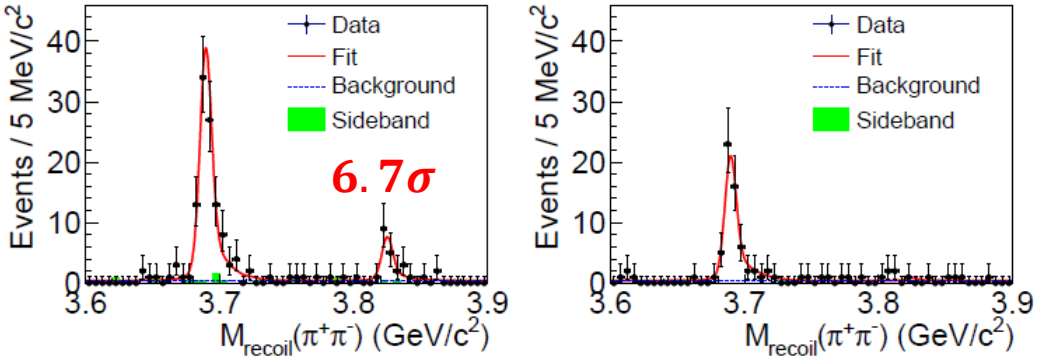


❖ **New mode of production of X(3872) and Y(4260) decay?**

If we take $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) \sim 5\%$, (>2.6% in PDG)

$\frac{\sigma(e^+e^- \to \gamma X(3872))}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} \sim$: 10% Large transition ratio !

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



Phys. Rev. Lett. 115, 011803 (2015)

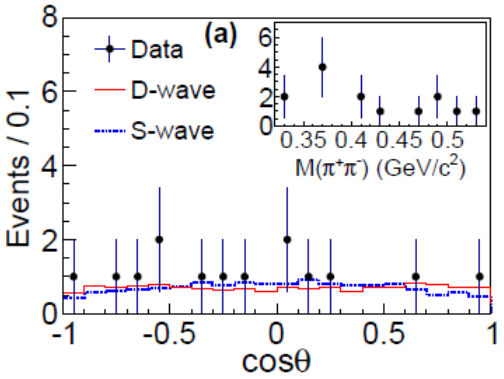
Reconstruct $\chi_c \rightarrow \gamma J/\psi \rightarrow \gamma l^+ l^-$
look for $\pi^+\pi^-$ recoil

Simultaneous fit of $\gamma\chi_{c1}$ (left) and $\gamma\chi_{c2}$ (right) events

$$M(X(3823)) = (3821.7 \pm 1.3(stat) \pm 0.7(syst))\ \text{MeV}/c^2$$

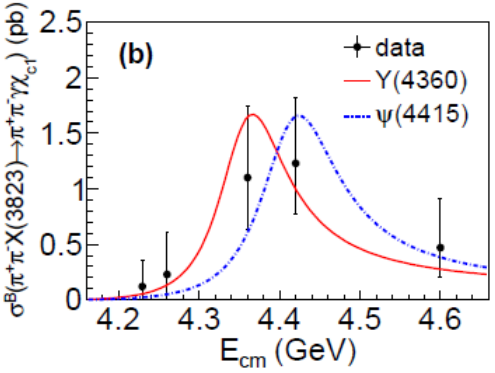
$$\Gamma(X(3823)) < 16\ \text{MeV at 90\% C.L. consist with Belle}$$

$$\frac{\mathcal{B}(X(3823) \rightarrow \gamma\chi_{c2})}{\mathcal{B}(X(3823) \rightarrow \gamma\chi_{c1})} < 0.42 \quad \text{at 90\% C.L.}$$



X(3823) scattering angle distribution

D-wave is expected.
Limited statistics



Cross section VS energy

Both Y(4360) and Ψ(4415) line shape give reasonable description

Good candidate of $\Psi(1^3D_2)$.

Search for $\phi\ J/\psi$ structure in $e^+e^-\rightarrow\gamma\phi\ J/\psi$

PHYSICAL REVIEW D **91,** 032002 (2015)

Search for the $Y(4140)$ via $e^+e^- \rightarrow \gamma\phi J/\psi$ at $\sqrt{s} = 4.23$, 4.26 and 4.36 GeV

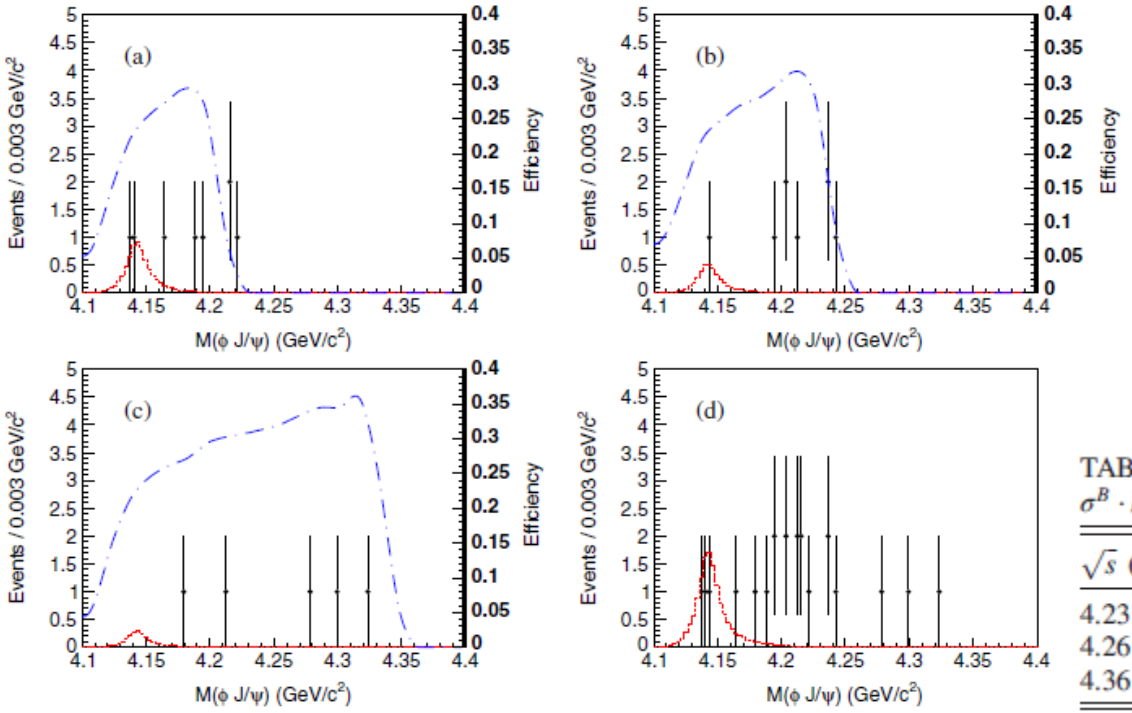


TABLE II. Upper limits at the 90% C.L. for measurements of $\sigma^B \cdot \mathcal{B} = \sigma(e^+e^- \rightarrow \gamma Y(4140)) \cdot \mathcal{B}(Y(4140) \rightarrow \phi J/\psi)$.

$\sqrt{s}$ (GeV)	Luminosity (pb^{-1})	$(1+\delta)$	n^{prod}	$\sigma^B \cdot \mathcal{B}$ (pb)
4.23	1094	0.840	< 339	< 0.35
4.26	827	0.847	< 207	< 0.28
4.36	545	0.944	< 179	< 0.33

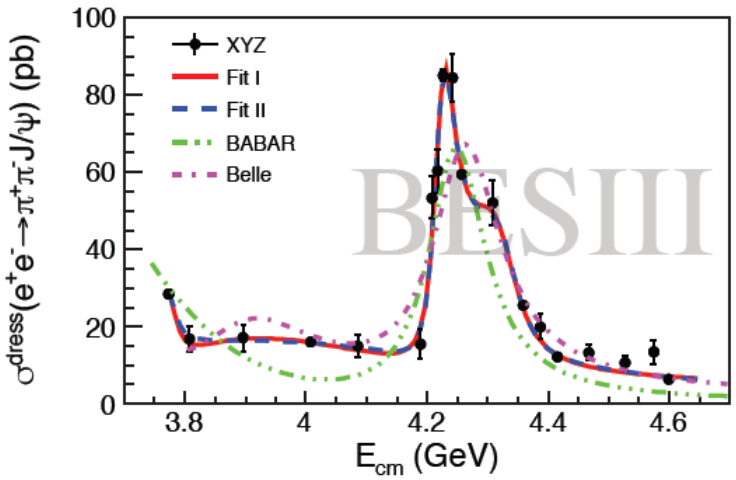
No evidence for X(4140) $\rightarrow\phi\ J/\psi$ using BESIII data

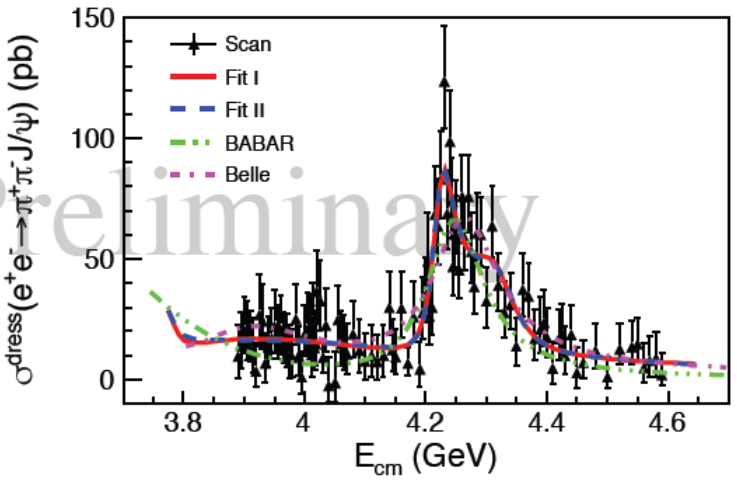
Y States at BESIII

Cross sections of $e^+e^- \to \pi^+\pi^- J/\psi$

$e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII (direct)

Inconsistent with a single BW of Y(4260)



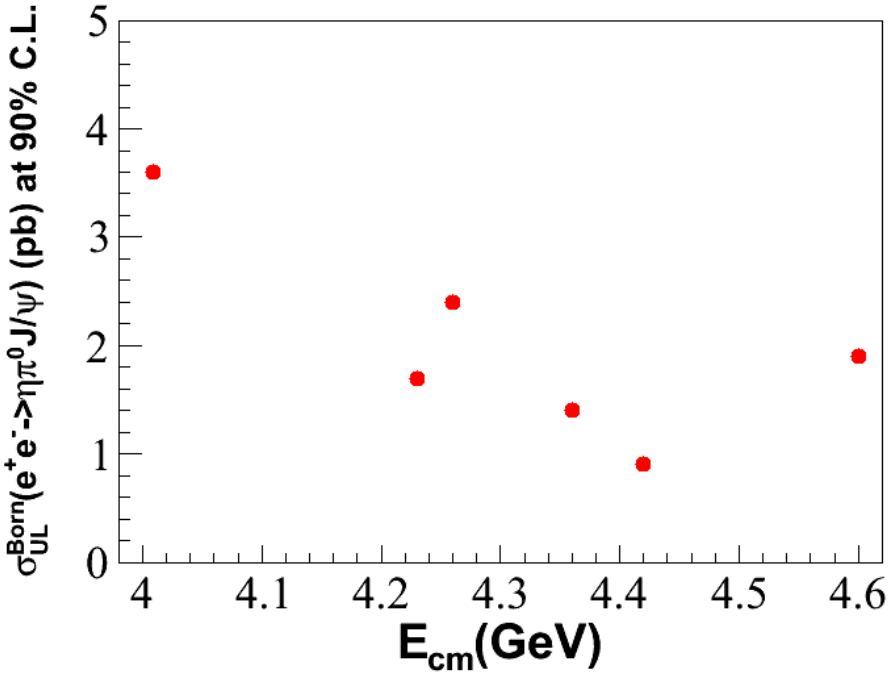


significance of an additional narrow structure > 7 σ

TABLE I: The measured masses and widths of the resonances from the fit to the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section with three coherent Breit-Wigner functions. The numbers in the brackets correspond to a fit by replacing R_1 with an exponential continuum. The errors are statistical only.

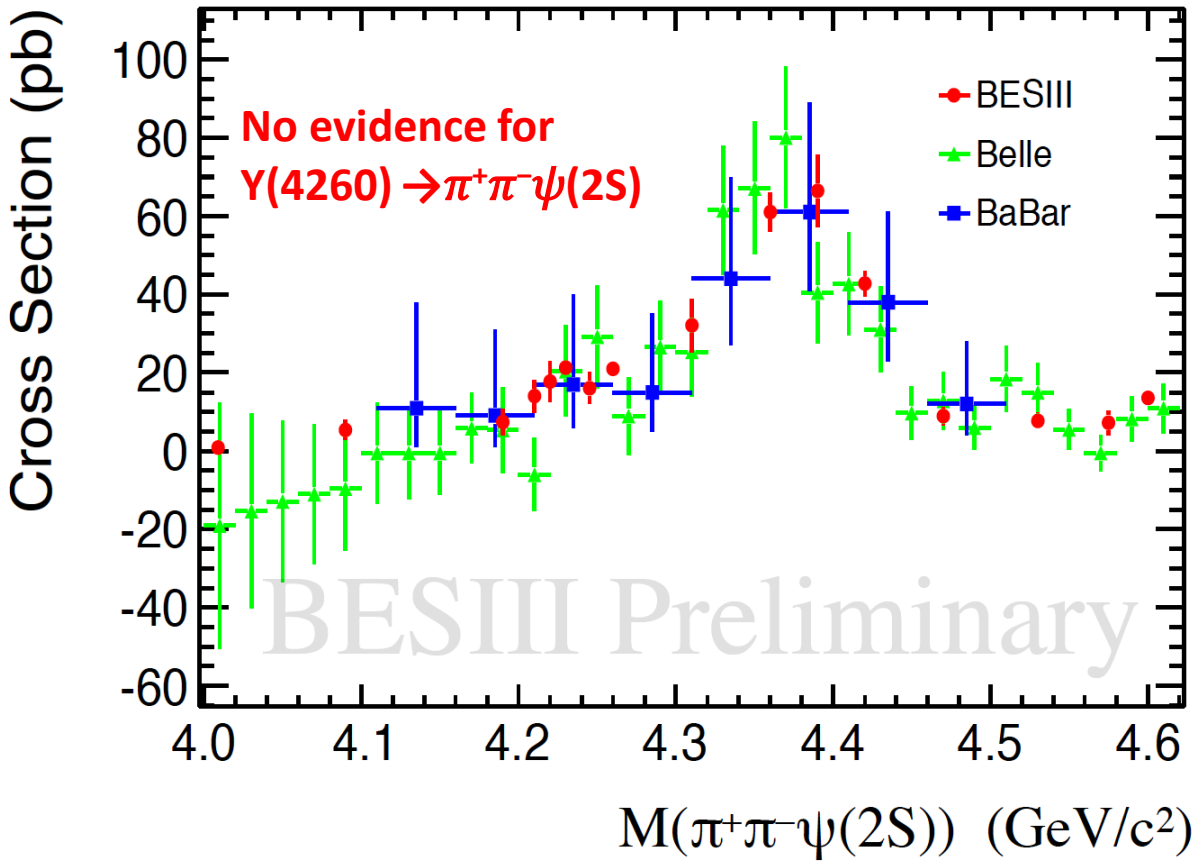
Parameters	Fit result
$M(R_1)$	$3815.9^{+59.6}_{-89.1}$ $(\cdots)$
$\Gamma_{\rm tot}(R_1)$	$467.9^{+74.4}_{-62.7}$ $(\cdots)$
$M(R_2)$	4223.7 ± 3.2 (4222.4 ± 3.0)
$\Gamma_{\rm tot}(R_2)$	43.1 ± 4.1 (43.1 ± 3.7)
$M(R_3)$	$4318.6^{+9.4}_{-10.2}$ (4325.5 ± 9.4)
$\Gamma_{\rm tot}(R_3)$	$95.7^{+22.7}_{-18.0}$ $(92.5^{+23.2}_{-18.1})$

Search for the isospin violating decay $Y(4260)\to J/\psi\eta\pi^0$



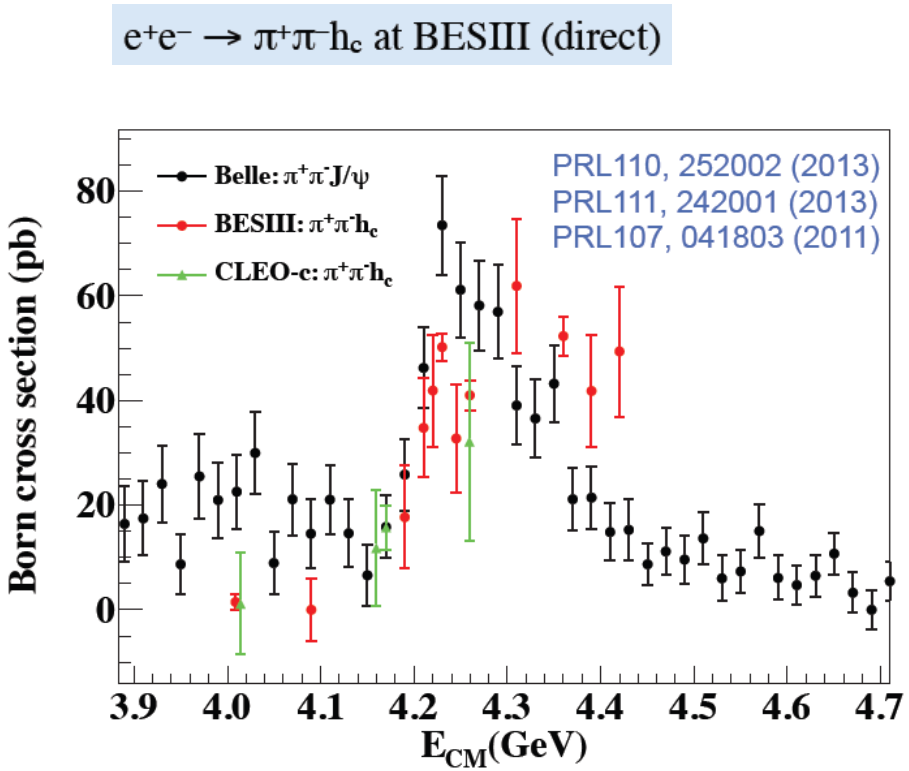
- Considerable decay width expected in hadrocharmonium model and tetra quark model of Y(4260) [PRD 86 034013, PRD 87 111102]
- Measured upper limit is well above the prediction of D_1D molecule model (0.05 pb at 4.260 GeV) [PRD 89, 054038]

Cross sections of $e^+e^- \to \pi^+\pi^-\psi(2S)$

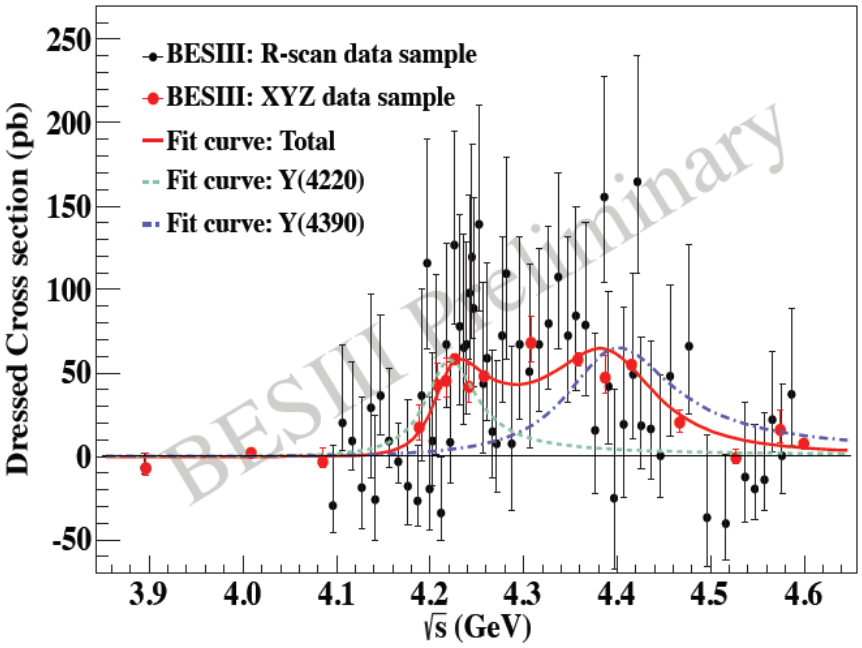


- BESIII confirms the lineshape for the Y(4360).
- More data will be taken soon to thoroughly study the region between 4.2 and 4.3 GeV.
- An analysis of the $\pi^{\pm}\psi(2S)$ substructure will be released soon.

Cross sections of $e^+e^-\to\pi^+\pi^- h_c$



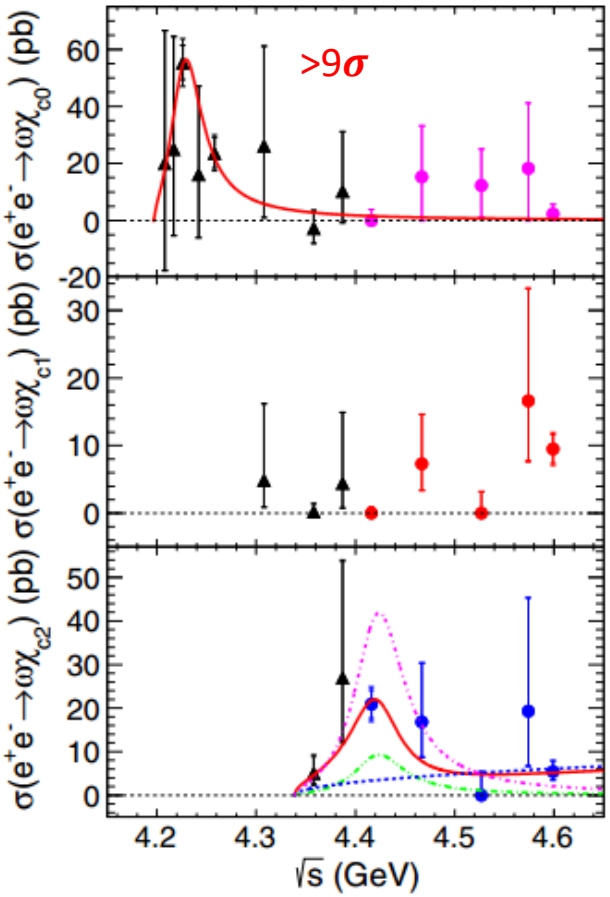
Clearly different from $\pi\pi J/\psi$



significance of two structures assumption over one structure > 10 σ

M (MeV)	Γ_{tot} (MeV)
4218.4±4.0±0.9	66.0±9.0±0.4
4391.6±6.3±1.0	139.5±16.1±0.6

Cross sections of $e^+e^- \to \omega\chi_{cJ}$ (J=0,1,2)



The triangle black data points are from

Phys. Rev. Lett. 114,092003(2015)

Other data points are from

Phys. Rev. D93, 011102 (2016)

$e^+e^- \to \omega\chi_{c0}$:

Fit with a single BW

Mass = $4226 \pm 8 \pm 6$ MeV

Width = $39 \pm 12 \pm 2$ MeV

Significance > 9s

$e^+e^- \to \omega\chi_{c2}$:

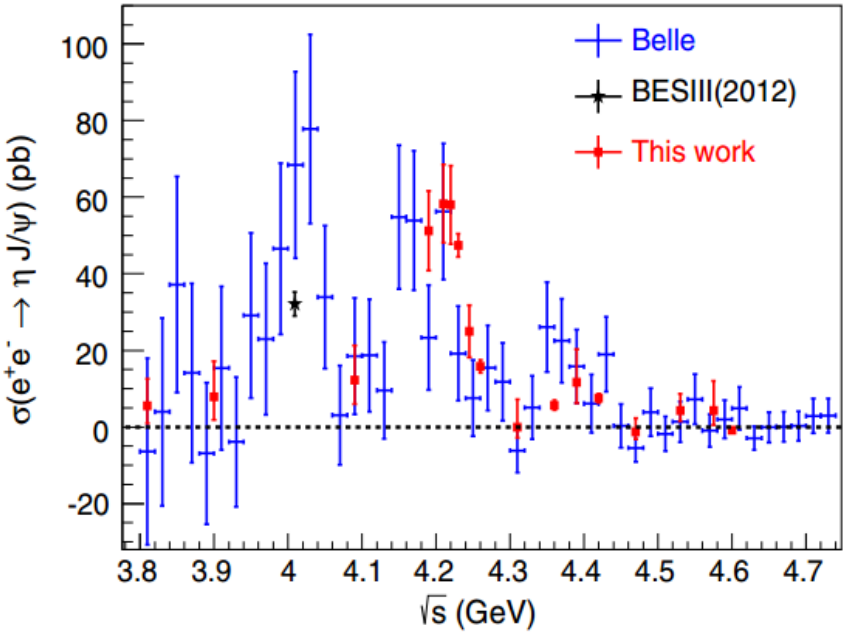
Agree with from ψ(4415) with

BR=$(1.4 \pm 0.5) \times 10^{-3}$ (sol. I), or

BR=$(6 \pm 1) \times 10^{-3}$ (sol. II)

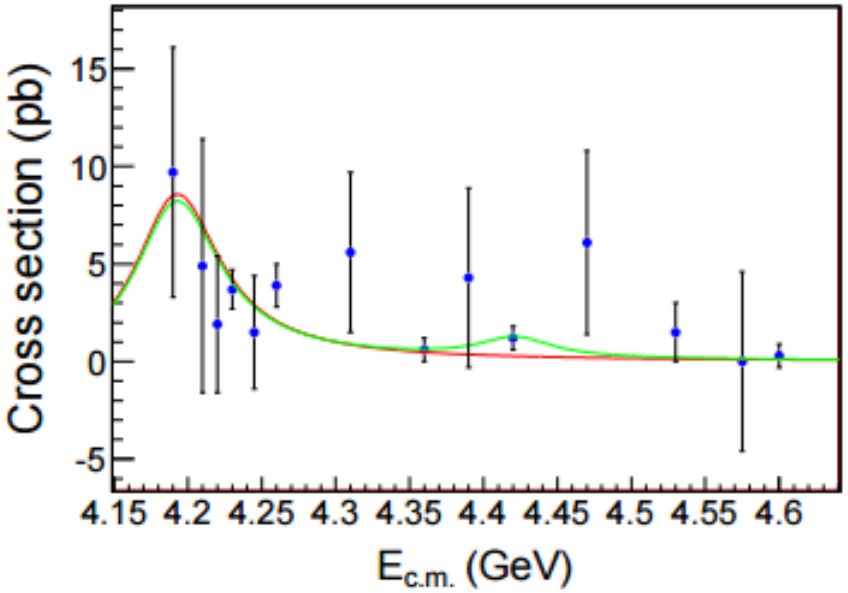
Need data beyond 4.6 GeV to check structure in $\omega\chi_{c1}$.

Cross sections of e^+e^-→ η/η'J/ψ



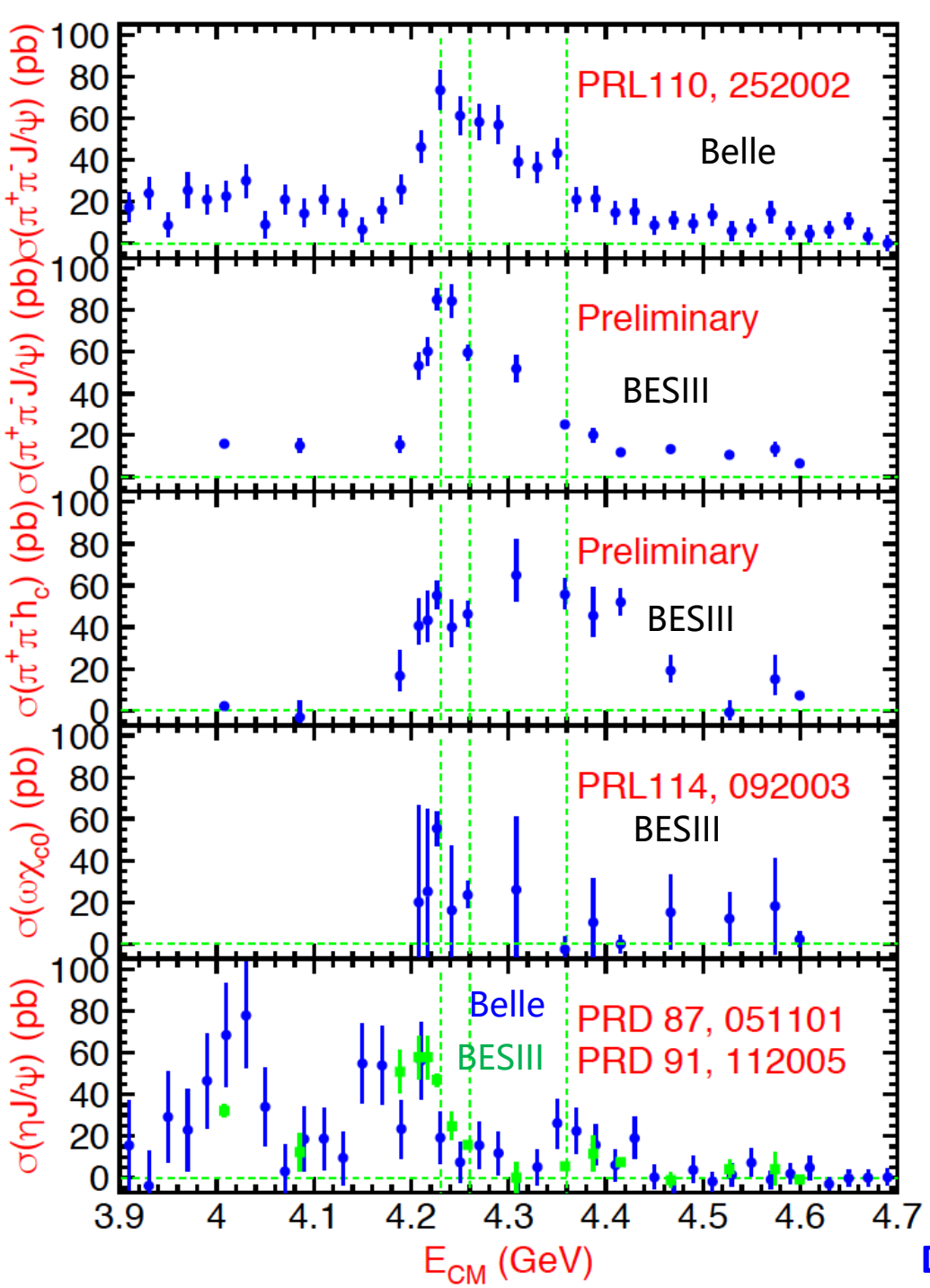
Phys. Rev. D 91, 112005 (2015)

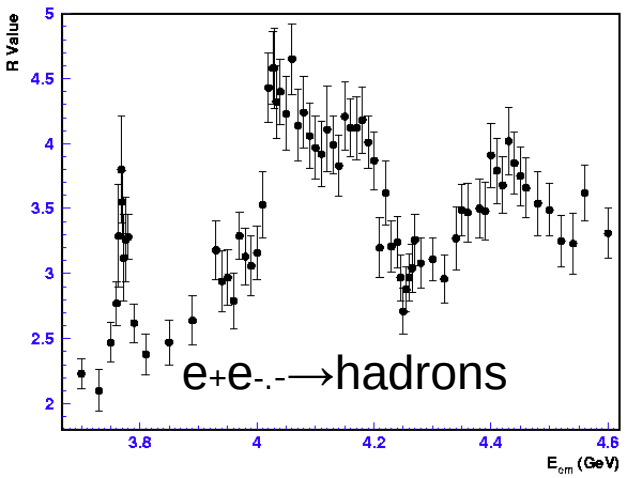
- Agree with previous results with improved precision
- Narrow structure around 4.2GeV possible from $\psi(4160)\rightarrow\eta\, J/\psi$?



arXiv:1605.03256

- Fit with ψ(4160) and ψ(4415) resonances
  ψ(4415) is not significant
- $\sigma(\eta' J/\psi)$ much lower than $\sigma(\eta\, J/\psi)$, lower than NRQCD calculation





Revisit the Y(4260)

-- with improved cross section measurements

Not a single/simple BW?

Is there any connection to

$\bar{D}_s^* D_s^*$ threshold (4224 MeV) .

$\bar{D}_1 D$ threshold (4293 MeV)?

Different in $\bar{b}b$, see S.Elderman's talk

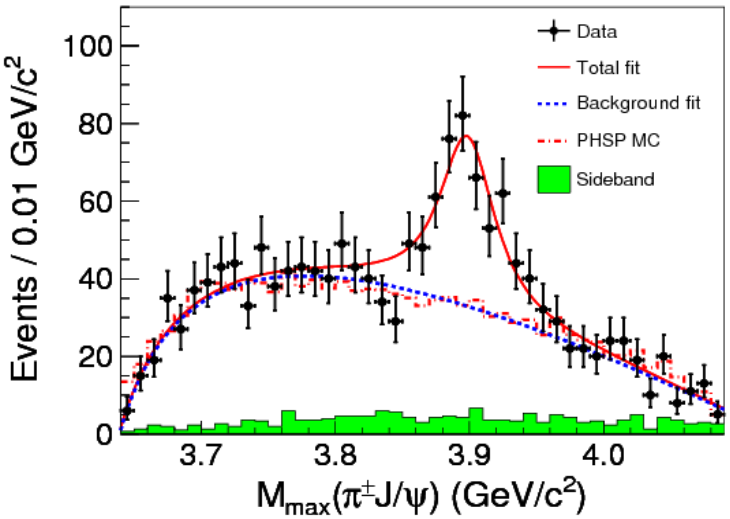
Z_c 's at BESIII

• $Z_c(3900)^{\pm}$ in $e^+e^- \to \pi^+ \pi^- J/\psi$	PRL 110,252001 (2013)
• $Z_c(3900)^0$ in $e^+e^- \to \pi^0 \pi^0 J/\psi$	PRL 115, 112003 (2015)
• $Z_c(3885)^{\pm}$ in $e^+e^- \to \pi^+ (D\bar{D}^*)^-$	PRL 112, 022001 (2014)
• $Z_c(3885)^0$ in $e^+e^- \to \pi^0 (D\bar{D}^*)^0$	PRL 115, 222002 (2015)
• $Z_c(4020)^{\pm}$ in $e^+e^- \to \pi^+ \pi^- h_c$	PRL 111.242001 (2013)
• $Z_c(4020)^0$ in $e^+e^- \to \pi^0 \pi^0 h_c$	PRL 113,212002 (2014)
• $Z_c(4025)^{\pm}$ in $e^+e^- \to \pi^+ (D^*\bar{D}^*)^-$	PRL 112,132001 (2013)
• $Z_c(4025)^0$ in $e^+e^- \to \pi^0 (D^*\bar{D}^*)^0$	PRL 115, 182002 (2015)

$ee \to \pi Z_c(3900)^{\pm/0} \to \pi(\pi J/\psi)$

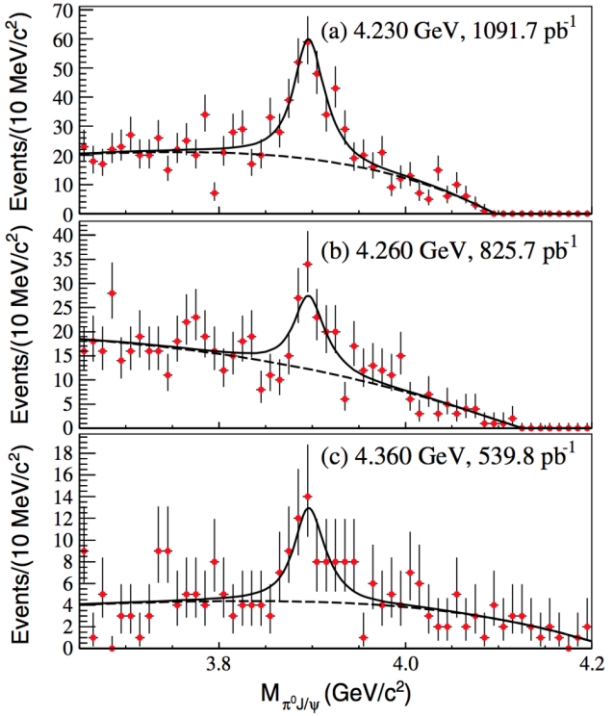
PRL 110, 252001 (2013)

$ee \to \pi^+ Z_c(3900)^- (\pi^- J/\psi)$ @4.26GeV

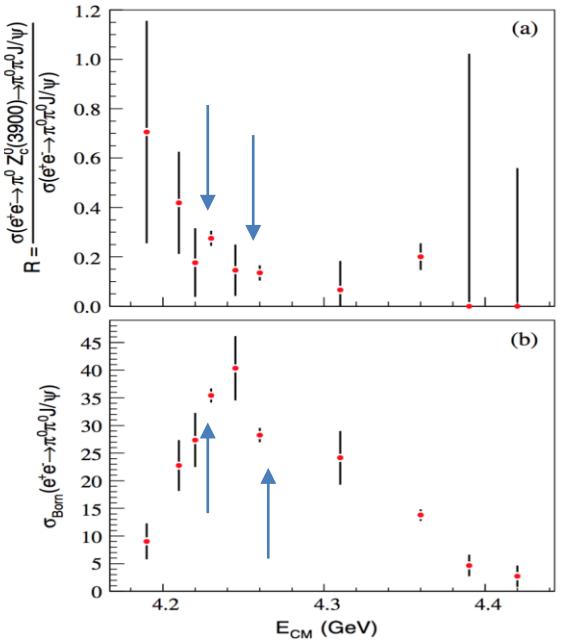


PRL 115, 112003(2015)

$ee \to \pi^0 Z_c(3900)^0 (\pi^0 J/\psi)$



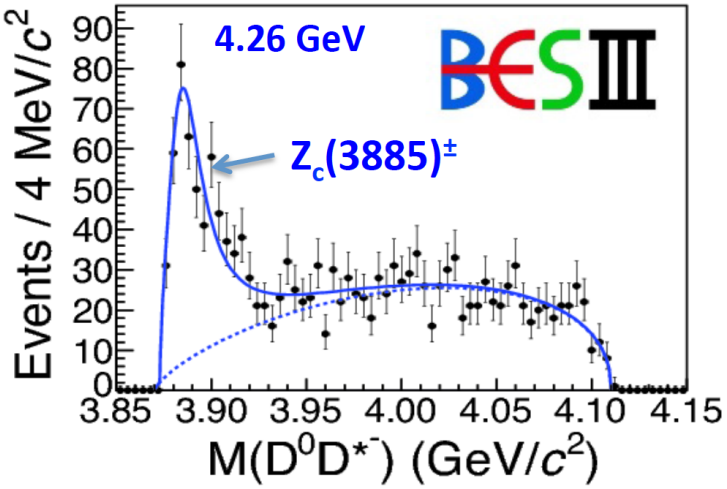
$$\frac{\sigma(ee \to \pi^0 Z_c(3900)^0)}{\sigma(ee \to \pi^0\pi^0 J/\psi)}$$

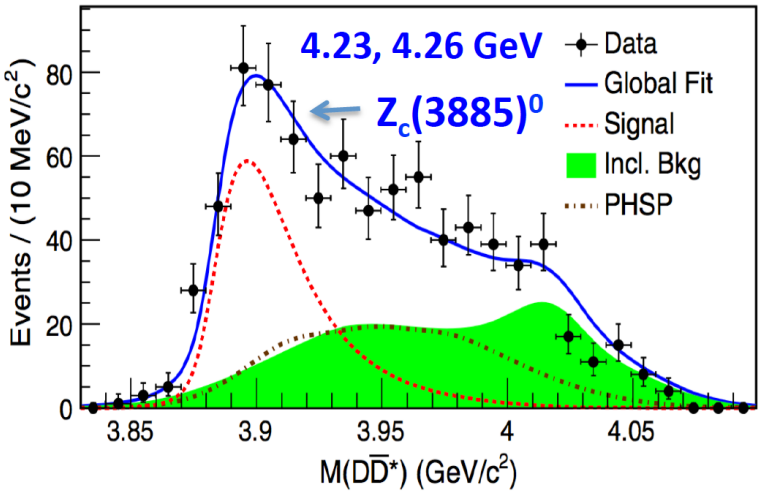


$\sigma(ee \to \pi^0\pi^0 J/\psi)$

More data is needed for the line shape of **$\sigma(ee \to \pi^0 Z_c(3900)^0)$**

$e^+e^- \to \pi Z_c(3885) \to \pi(\bar{D}\, D^*)$

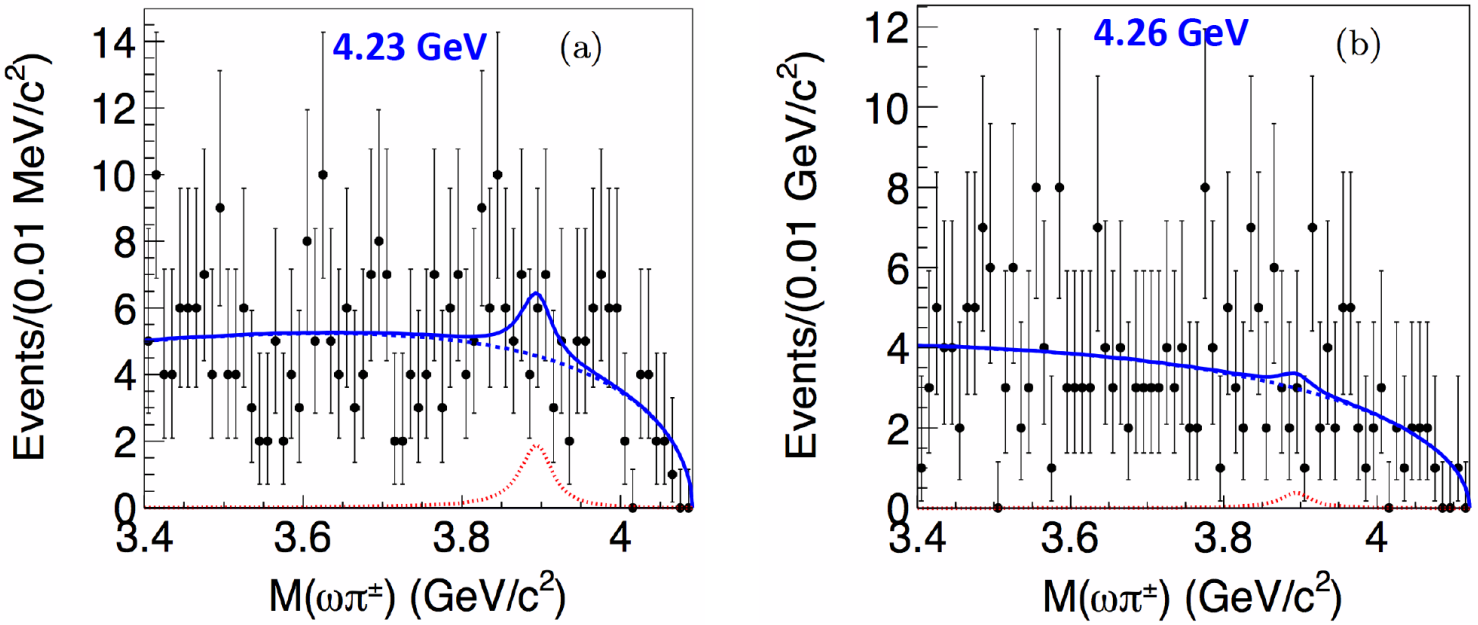




$Z_c(3885)$	Mass(MeV)	Width(MeV)	reference
$Z_c(3885)^{\pm}$ (single D-tag)	3883.9±1.5±4.2	24.8±3.3±11.0	PRL 112, 022001(2014)
$Z_c(3885)^{\pm}$ (double D-tag)	3881.7±1.6±2.6	26.6±2.0 ±2.3	PRD 92, 092006 (2015)
$Z_c(3885)^0$ (single D-tag)	$3885.7^{+4.3}_{-5.7}$±8.4	35^{+11}_{-12}±15	PRL 115, 222002 (2015)

Search for light hadron decays of Zc in $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi(\omega\pi)$

PRD 92, 032009(2015)



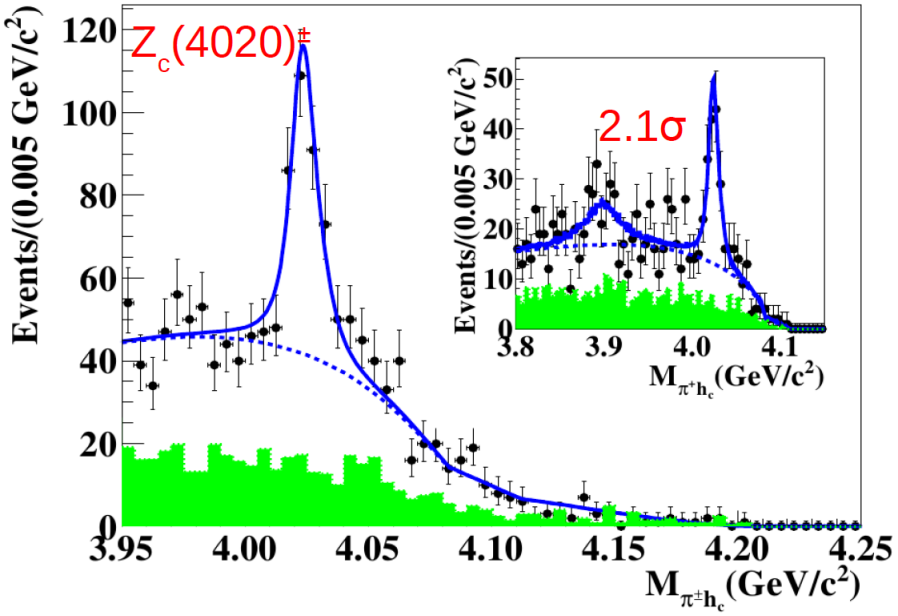
- Searching for new decays of Zc(3900) to light hadrons: distinguish a resonance from threshold effects
- No significant $Zc \rightarrow \omega\pi$ is observed:
  $\sigma(e^+e^- \rightarrow Zc\pi, Zc \rightarrow \omega\pi) < 0.26$ pb @ 4.23 GeV
  $\sigma(e^+e^- \rightarrow Zc\pi, Zc \rightarrow \omega\pi) < 0.18$ pb @ 4.26 GeV

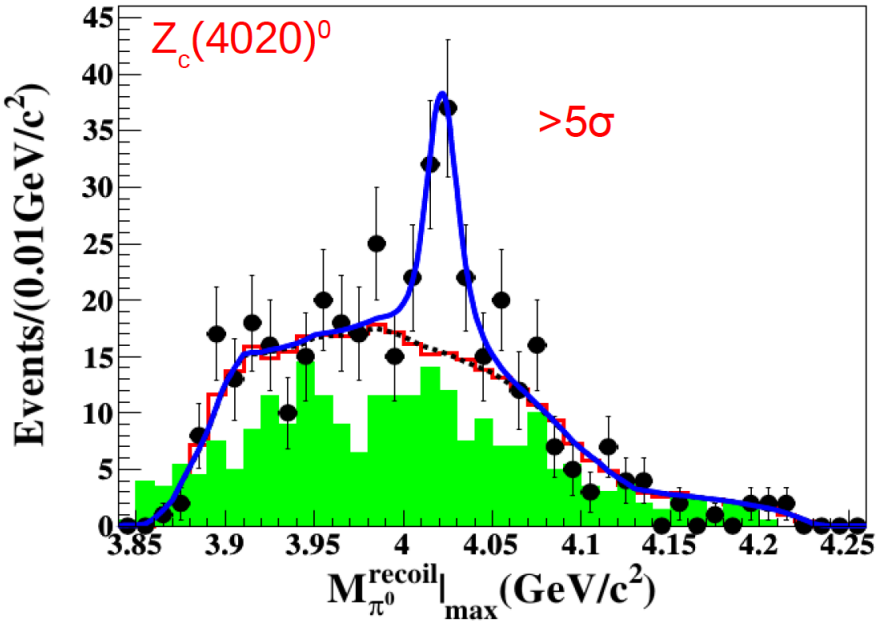
$e^+e^- \to \pi Z_c(4020) \to \pi\pi h_c$

$e^+e^- \to \pi^+\pi^- h_c$ and $\pi^0\pi^0 h_c$

h_c reconstructed through E1 transition $h_c \to \gamma\eta_c$, reconstructed from 16 exclusive hadronic modes.

$$\sqrt{s} = 4.23,\ 4.26,\ \text{and}\ 4.36\ \text{GeV}$$





Phys.Rev.Lett.111, 242001 (2013)

M=4022.9 ± 0.8 ± 2.7 MeV/c²

Γ = 7.9 ± 2.7 ± 2.6 MeV

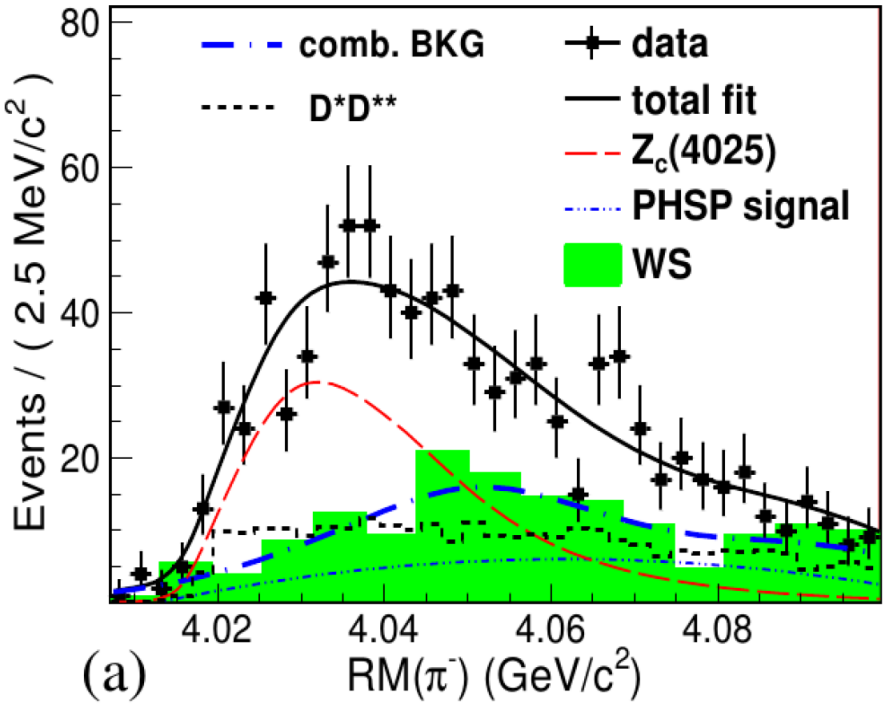
Phys.Rev.Lett.113.212002(2014)

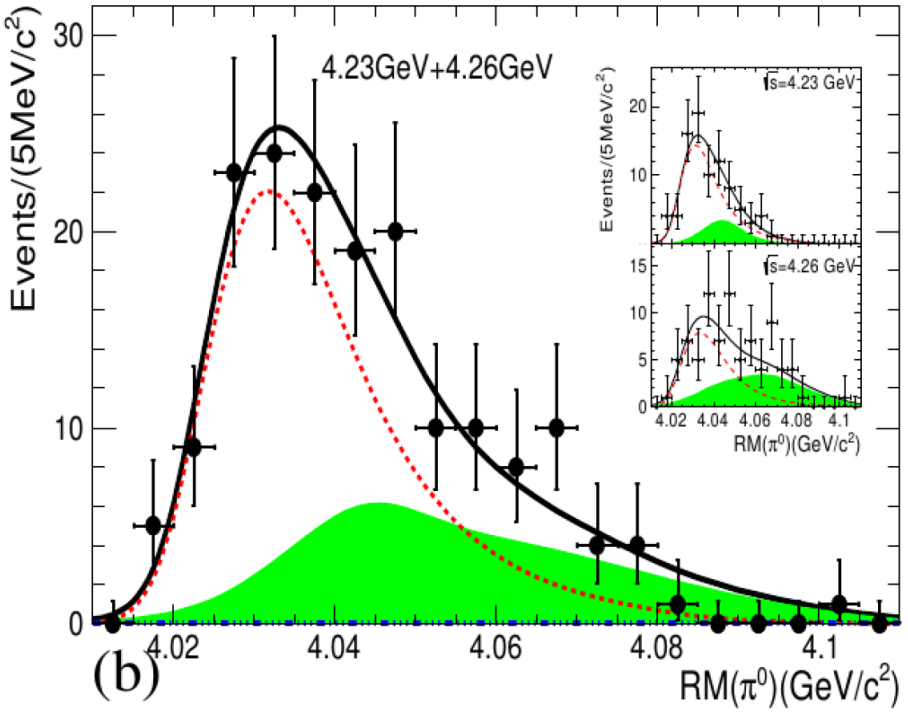
M=4023.9 ± 2.2 ± 3.8 MeV/c²

Fixed Γ

Close to $D^*\bar{D}^*$ threshold

$e^+e^- \to \pi Z_c(4025) \to \pi (D^*\bar{D}^*)$





Phys. Rev. Lett. 112, 132001 (2014)

$e^+e^- \to (D^*\bar{D}^*)^+\pi^-$ + c.c.

0.8 fb^{-1} @ 4.26 GeV

Partial reconstruction technique

M = 4026.3 ± 2.6 ± 3.7 MeV/c^2

Γ = 24.8 ± 5.6 ± 7.7 MeV

Phys. Rev. Lett. 115, 182002 (2015)

$e^+e^- \to (D^*\bar{D}^*)^0\pi^0$

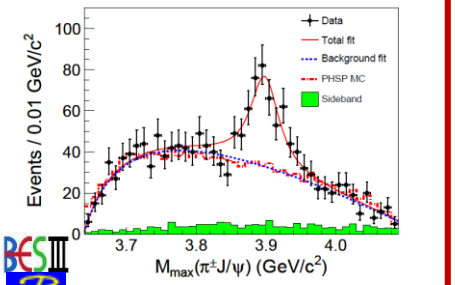
1.1 fb^{-1} @ 4.23 and 0.8 fb^{-1} @ 4.26 GeV

Partial reconstruction technique

M = $(4025.5^{+2.0}_{-4.7} \pm 3.1)\ \mathrm{MeV}/c^2$

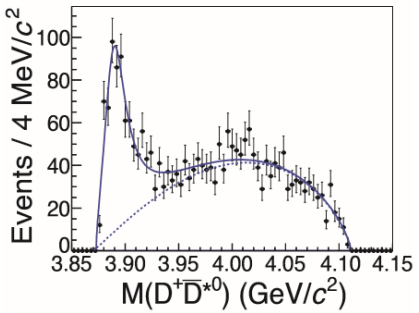
Γ = $(23.0 \pm 6.0 \pm 1.0)\ \mathrm{MeV}$

Observations of Z_c



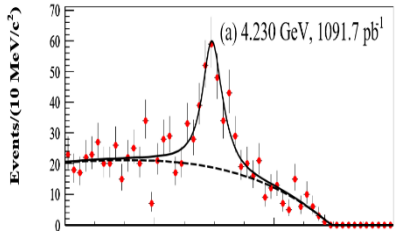
BESIII

$e^+e^- \to \pi^+ \pi^- J/\psi$



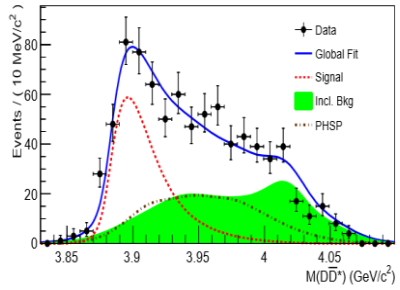
BESIII $e^+e^- \to \pi^+ (D\bar{D}^*)^-$

$Z_c(3900)^{\pm}$?



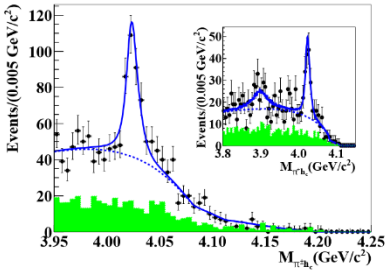
BESIII

$e^+e^- \to \pi^0 \pi^0 J/\psi$

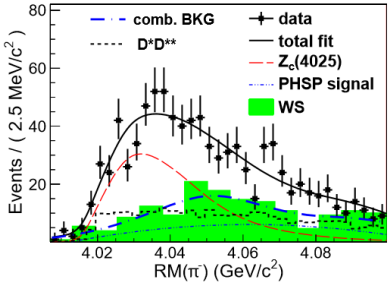


BESIII $e^+e^- \to \pi^0 (D\bar{D}^*)^0$

$Z_c(3900)^0$?

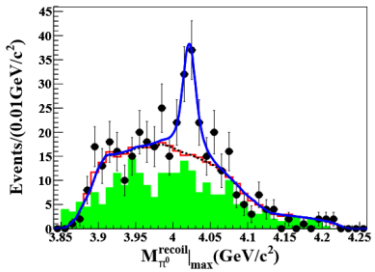


BESIII $e^+e^- \to \pi^+ \pi^- h_c$

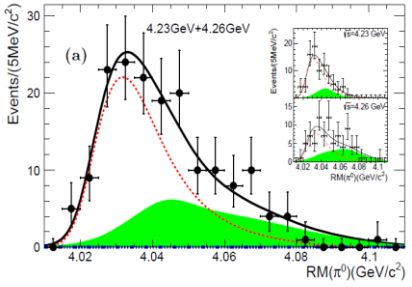


BESIII $e^+e^- \to \pi^+ (D^*\bar{D}^*)^-$

$Z_c(4020)^{\pm}$?



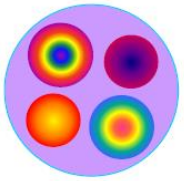
BESIII $e^+e^- \to \pi^0 \pi^0 h_c$



BESIII $e^+e^- \to \pi^0 (D^*\bar{D}^*)^0$

$Z_c(4020)^0$?

Tetraquark? Hadroquarkonium? Molecule?
Threshold effect?



Summary of the Z_c at BESIII

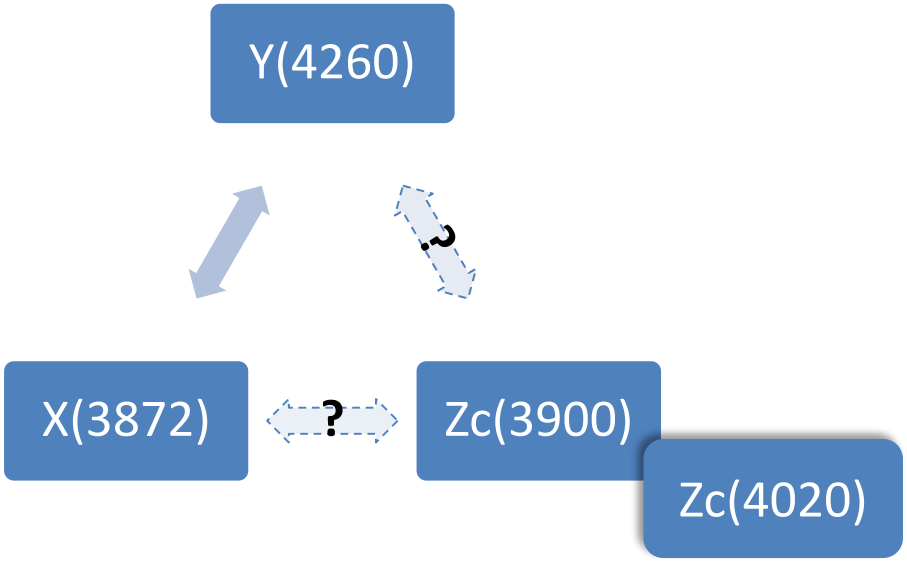
$Z_c^{\pm}(3900)$	$Z_c^{\pm}(4020)$
$e^+e^- \to \pi^+\pi^- J/\psi$ M=3899.0±3.6±4.9MeV Γ = 46±10±20 MeV	$e^+e^- \to \pi^+\pi^- h_c$ M= 4022.9±0.8±2.7MeV Γ = 7.9±2.7±2.6 MeV
Z_c^0 (3900)	**Z_c^0(4020)**
$e^+e^- \to \pi^0\pi^0 J/\psi$ M=3894.8±2.3 MeV Γ =29.6±8.2 MeV	$e^+e^- \to \pi^0\pi^0 h_c$ M=4023.9±2.2±3.8 MeV Γ Fixed at $Z_c^{\pm}(4020)$
$Z_c^{\pm}(3885)$	**$Z_c^{\pm}(4025)$**
$e^+e^- \to \pi(D\bar{D}^*)^{\pm}$ M=3882.2±1.1±1.5 MeV Γ =26.5±1.7±2.1 MeV	$e^+e^- \to \pi(D^*\bar{D}^*)^{\pm}$ M= 4026.3±2.6±3.7 MeV Γ = 24.8±5.6±7.7 MeV
Z_c^0(3885)	**Z_c^0(4025)**
$e^+e^- \to \pi^0(D\bar{D}^*)^0$ M=3885.7±5.7±8.4 MeV Γ = 35±12±15 MeV	$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$ M= 4025.5±4.7±3.1 MeV Γ = 23.0±6.0 ±1.0MeV

Two isospin triplets established

Above DD* threshold (3875 MeV), **D*D* threshold** (4017 MeV)

Mass/width difference in two modes to be understood

- **J^P of $Z_c(3900)=1^+$ determined from PWA**
- **DD* dominates $Z_c(3900)$ decays, D*D* dominates $Z_c(4025)$ decays**
- **No significant $Z_c(3900) \to h_c\pi$, $Zc(4020) \to J/\psi\pi$**



Multiquark Hybrid
Hadrocharmonium
Molecule Threshold effects
Cusps…

States or/and interactions

What is the role of threshold

--Many new observations near thresholds: D*D,D*D*, D_1D, …

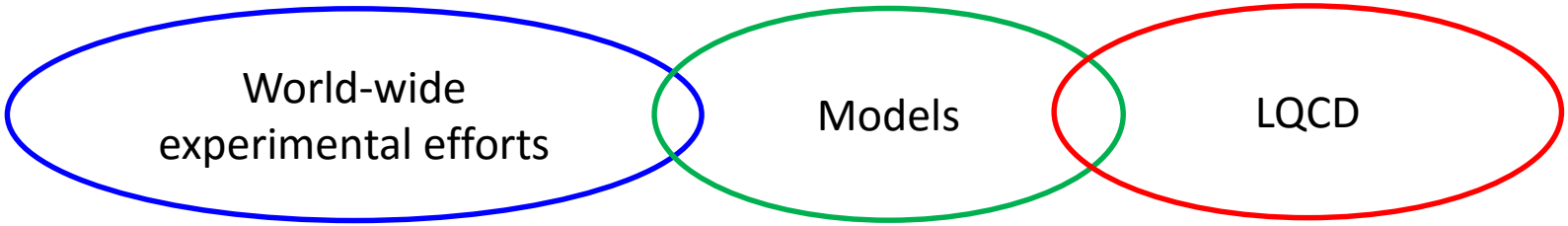
See reviews by Swanson (Hadron2015) , Eichten (QWG2016), Zhao(MENU2016) and ref. within

* Phase variations appear in many process: not unique for resonance

To have a complete picture, more clues are needed

- **Energy-dependence**
- **Patterns in productions and decays**

Pole properties **For XYZ, the picture is still unclear**



Prospects of hadron spectroscopy at BESIII

- **BESIII collected world's largest samples of J/ψ, ψ(2S), ψ(3770), Y(4260), … from e^+e^- production.**
- **It will continue to run a few years.**

	BESIII	Goal
J/ψ	$1.3*10^9$ 21x BESII	$10*10^9$
ψ'	$0.6*10^9$ 24x CLEO-c	$3*10^9$
$\psi(3770)$	2.9 fb^{-1} 21x CLEO-c	20 fb^{-1}
Above open charm threshold	0.5 fb^{-1}@ψ(4040), 1.9 fb^{-1} @~4260, 0.5 fb^{-1}@4360, 1.0 fb^{-1} @4420, 0.5 fb^{-1} @4600	5-10 fb^{-1}
R scan and tau	3.8-4.6 GeV at 105 energy points 2.0-3.1 GeV at 20 energy points	
Y(2175)	100 pb^{-1} (2015)	
ψ(4170)	3 fb^{-1} (2016)	

Opportunities for both heavy and light hadron spectroscopy

Thank you