Exotics and Charmonium (-like) states at BESIII

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Outline

- Introduction

  Exotic states, XYZ, BESIII

- Selected results:

  X states: X(3823), X(3872), X(4140)

  Y states: Cross section of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$,

  $\pi^+\pi^- h_c$, $\omega\chi_{cJ}$, $\eta/\eta' J/\psi$.

  Z states: $Z_c(3900)/Z_c(3885)$, $Z_c(4020)/Z_c(4025)$

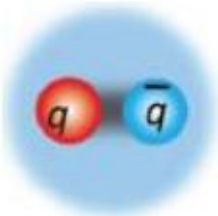
- Summary

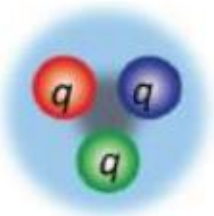
What are exotic states?

- Conventional hadrons consist of 2 or 3 quarks:

Naive Quark Model:

meson



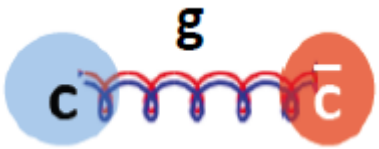


baryon

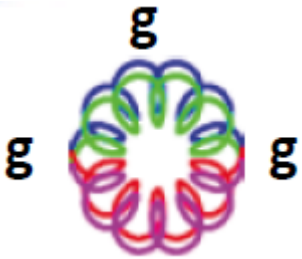
- QCD allows for the existence of exotic states:

Multi-quark states: (N >= 4)

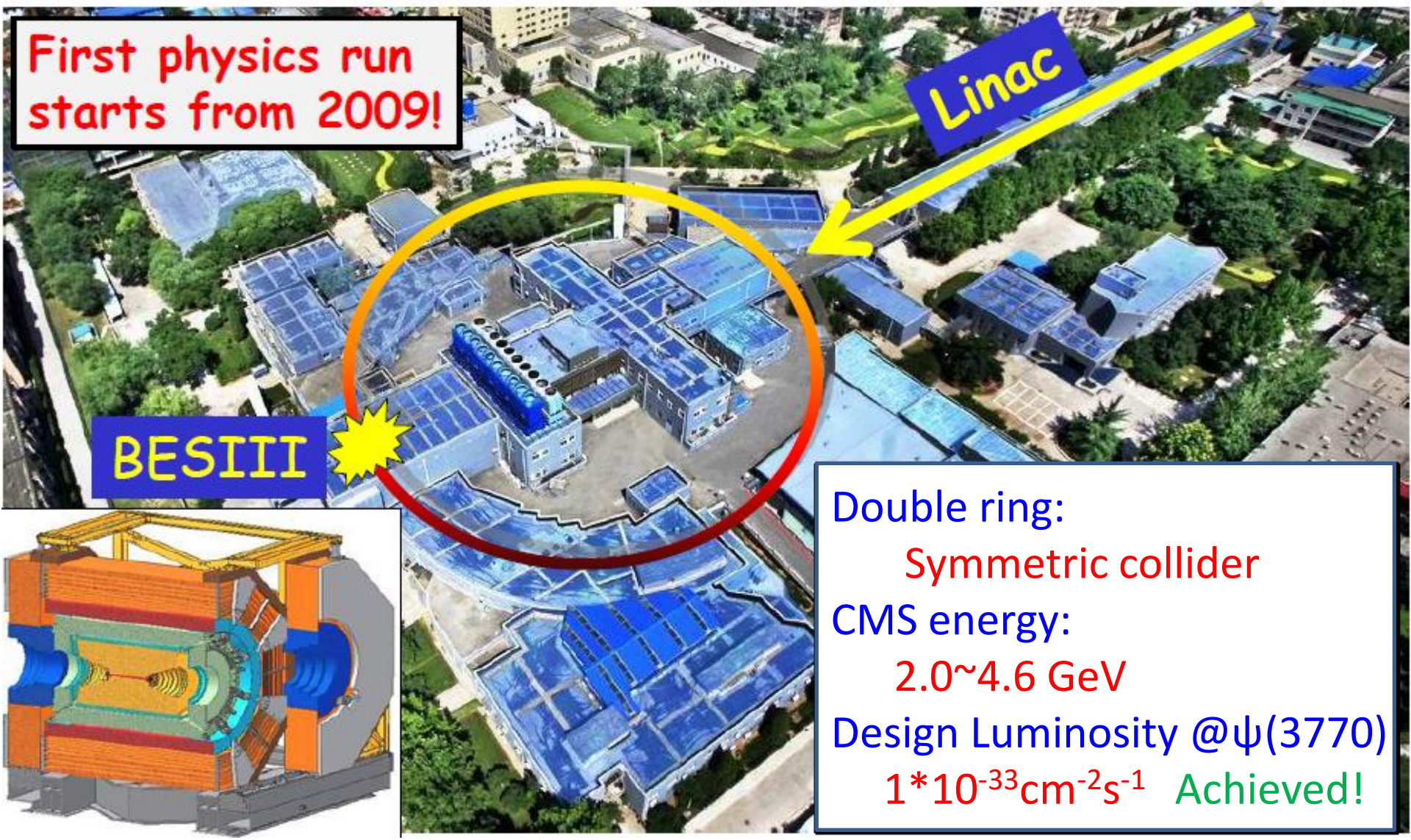
Hybrids: $q\bar{q}g$, qqqg…



Glueballs: gg, ggg



The BESIII Experiment



Double ring:

Symmetric collider

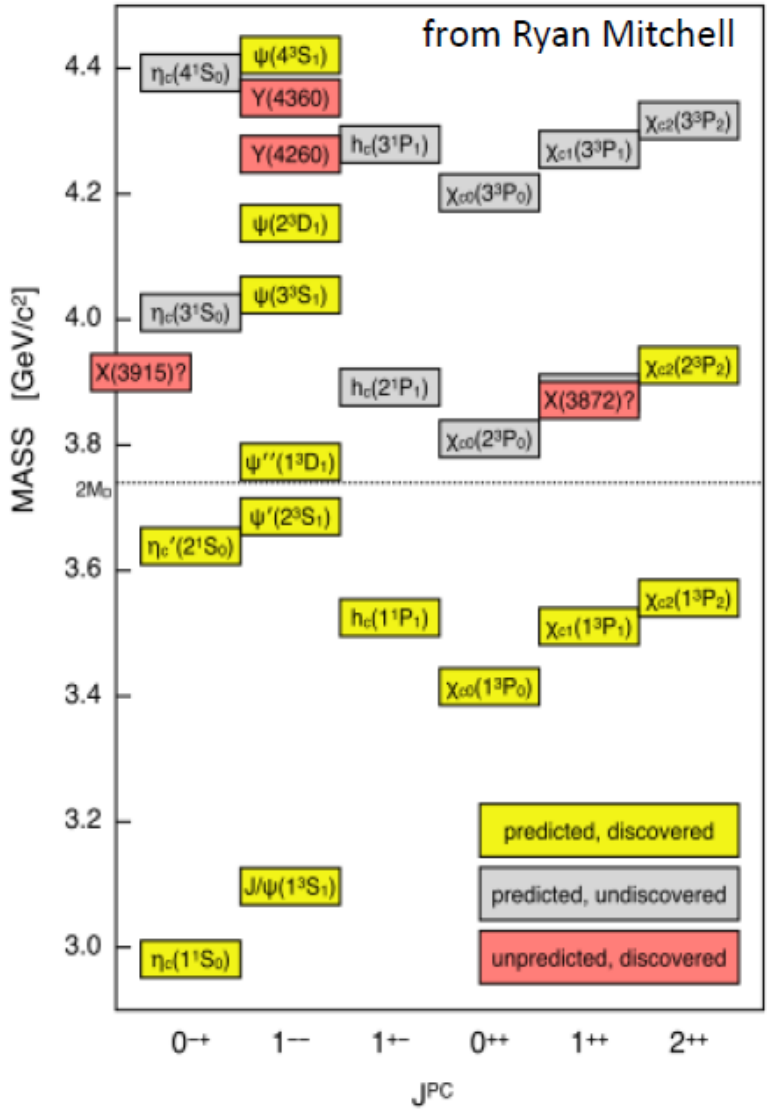
CMS energy:

2.0~4.6 GeV

Design Luminosity @ψ(3770)

$1*10^{-33}cm^{-2}s^{-1}$ Achieved!

Charmonium Spectroscopy

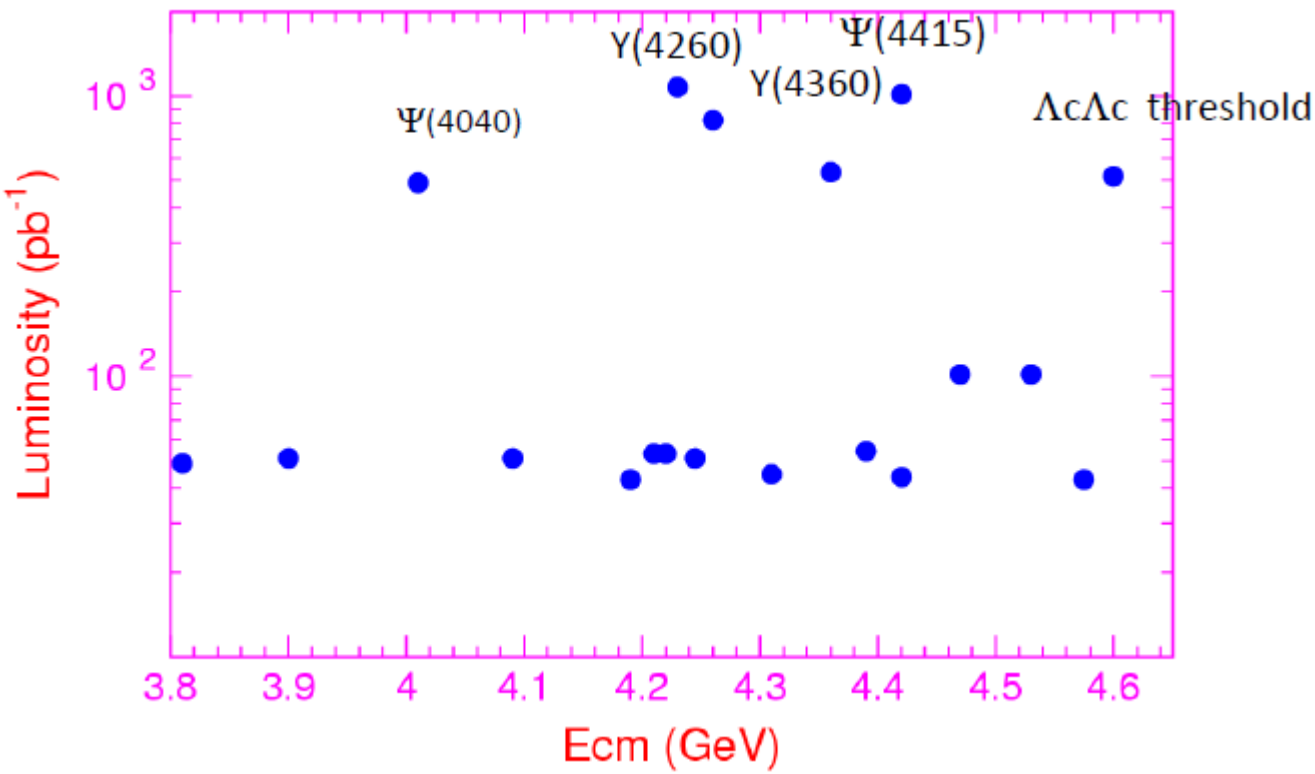


- **Above open charm threshold:**
  - many expected states not observed
  - many unexpected observed

- **Below open charm threshold:**

  Good agreement between discovery and theoretical prediction.

Data samples for XYZ physics at BESIII



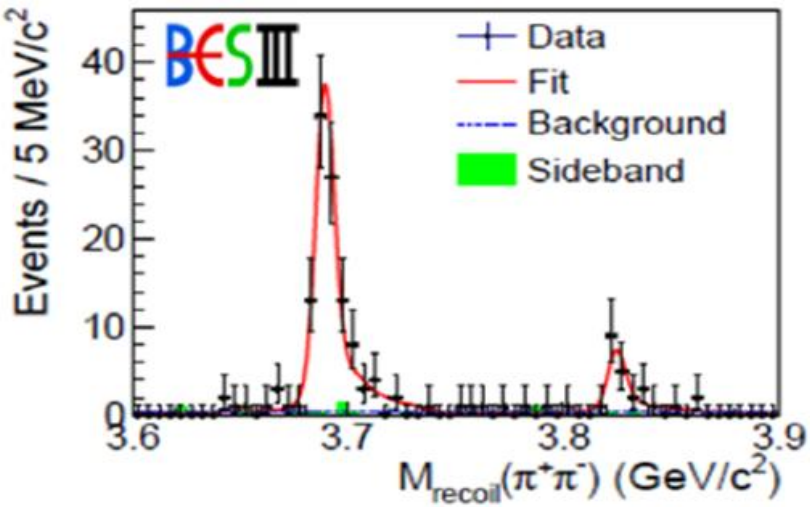
CM energy (GeV)	L (pb^{-1})
3.81	50.54±0.03
3.90	52.61±0.03
4.009	481.96±0.01
4.09	52.63±0.03
4.19	43.09±0.03
4.21	54.55±0.03
4.22	54.13±0.03
4.23^1	44.40±0.03
4.23^2	1047.34±0.14
4.245	55.59±0.04
4.26^1	523.74±0.10
4.26^2	301.93±0.08
4.31	44.90±0.03
4.36	539.84±0.10
4.39	55.18±0.04
4.42^1	44.67±0.03
4.42^2	1028.89±0.13
4.47	109.94±0.04
4.53	109.98±0.04
4.575	47.67±0.03
4.60	566.93±0.11

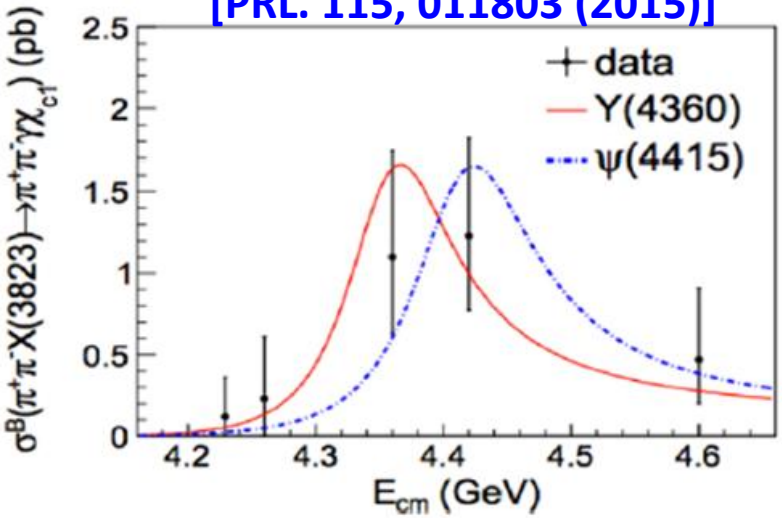
- Luminosity ~ 5/fb.
- Large data samples around ψ(4040), Y(4260), Y(4360), ψ(4415), Y(4660).

X States at BESIII

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

[PRL. 115, 011803 (2015)]





- M = 3821±1.3±0.7 MeV, Γ < 16 MeV, Significance: 6.2σ!
- R = B[X(3823)→$\gamma\chi_{c2}$]/B[X(3823)→$\gamma\chi_{c1}$]<0.43 @ 90% C.L.
- Both Y(4360) and Ψ(4415) line shape give reasonable description.

Agree with BELLE's 3.7σ evidence (PRL111, 032001)

- Potential Model: D wave. M~(3.810-3.840) GeV, narrow.
- R ~ 0.2

X(3823) : good candidate for $\Psi(1^3D_2)$

$e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma\pi^+\pi^- J/\psi$

[BESIII PRL112, 092001(2014)]

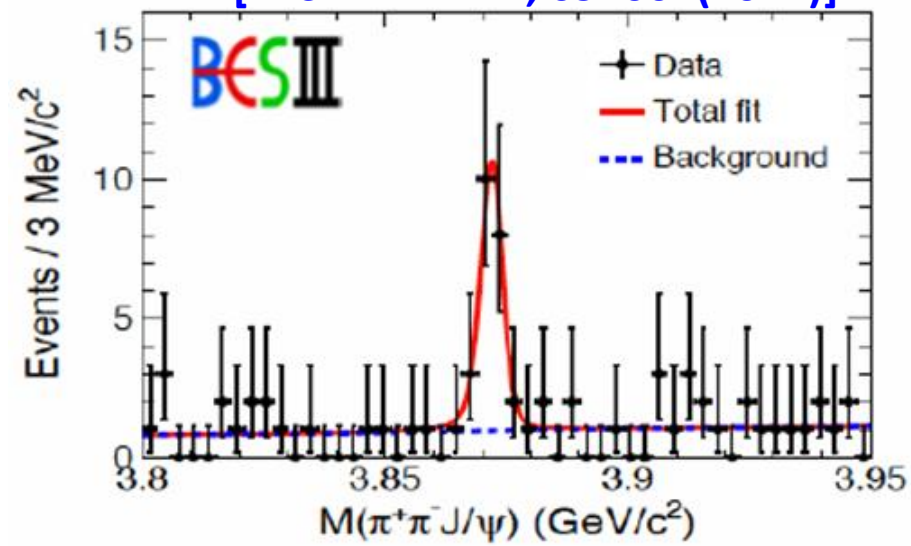
- Search for $\gamma X(3872)$ with $X(3872) \rightarrow \pi^+\pi^- J/\psi$ at Ecm = 4.23, 4.26, 4.36 GeV.

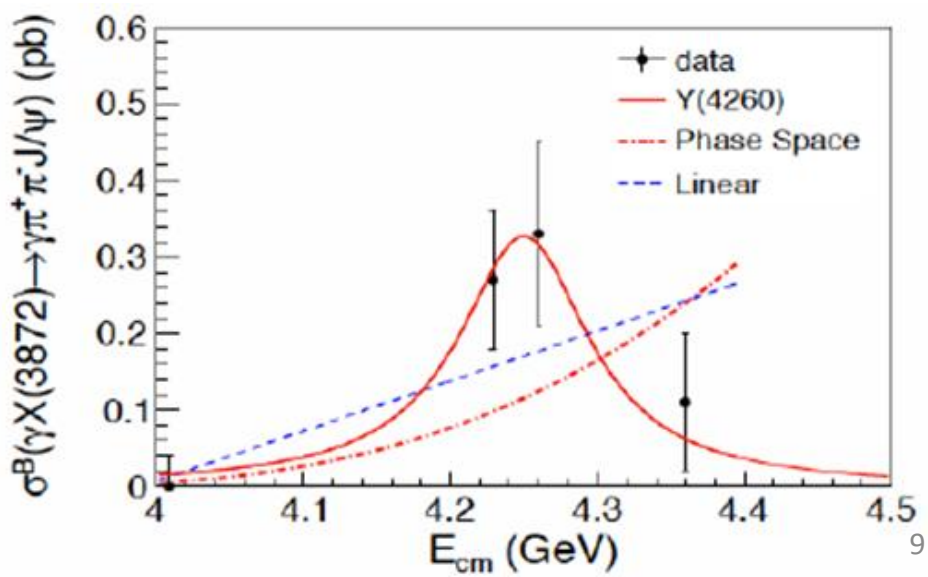
- X(3872) significance = 6.3σ, summed over all data.

- Production in Y(4260) decay suggestive, but not conclusive.

If from Y(4260):

$$\frac{B(Y(4260) \rightarrow \gamma X(3872))}{B(Y(4260) \rightarrow \pi^+\pi^- J/\psi)} \sim 0.1$$

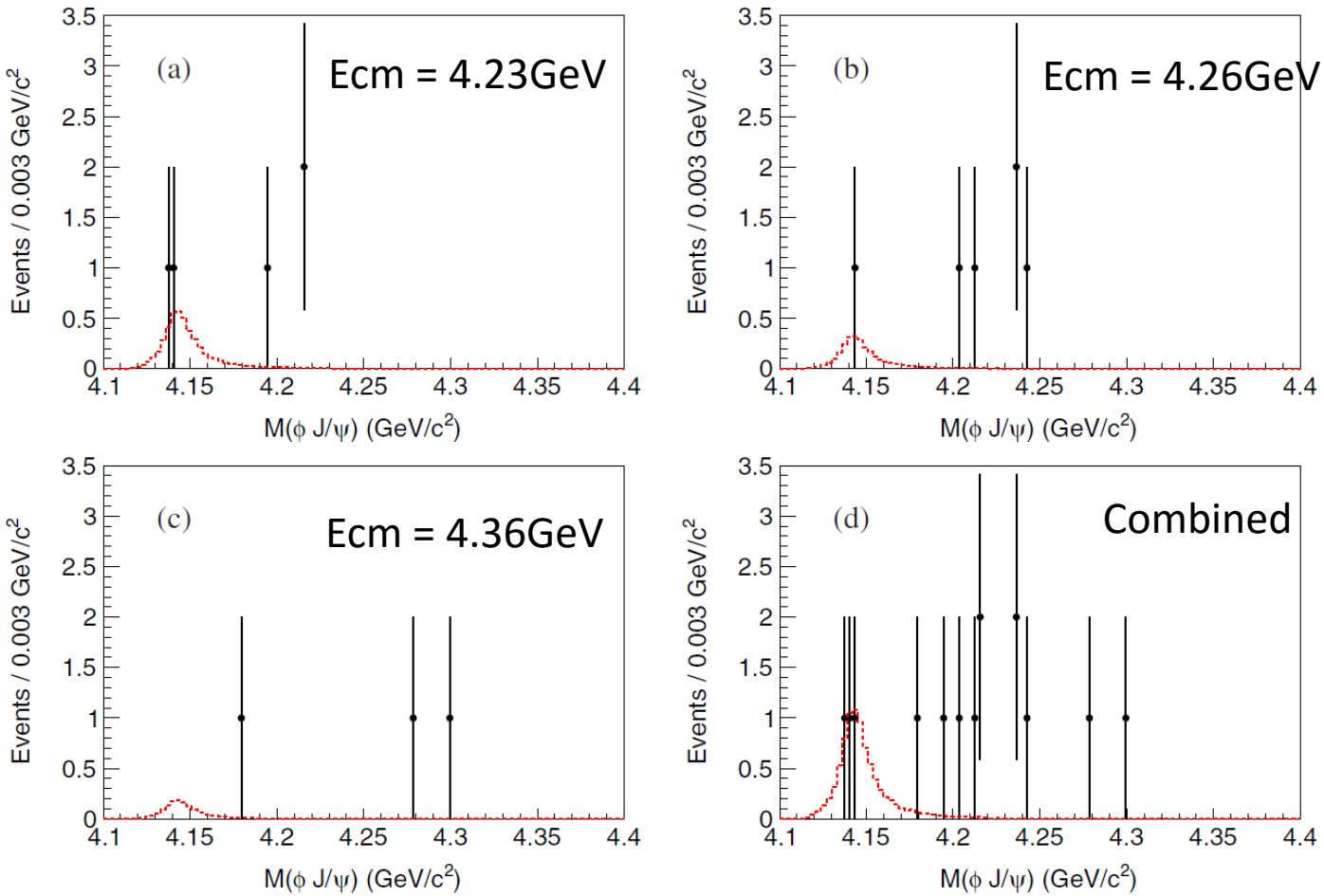




$e^+e^- \rightarrow \gamma X(4140) \rightarrow \gamma\ \phi J/\psi$

The X(4140) (or "Y(4140)") seen by CDF, [PRL 102, 242002 (2009)]

[BESIII PRD 91, 032002 (2015)]



BESIII sets upper limit for $e^+e^- \rightarrow \gamma X(4140)$ with $X(4140) \rightarrow \phi J/\psi$

Y States at BESIII

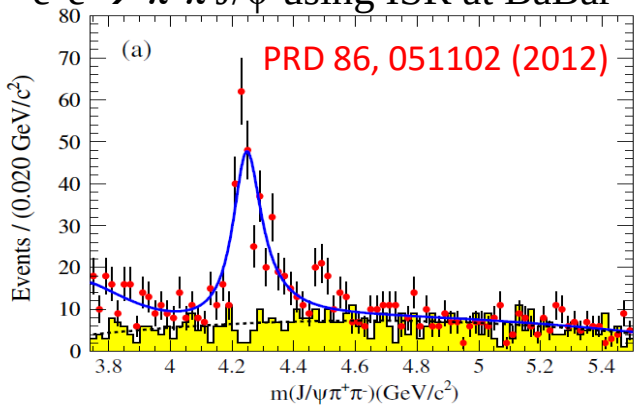
Y states

Exclusive measurements of the line shapes of the cross sections to search for Y states:

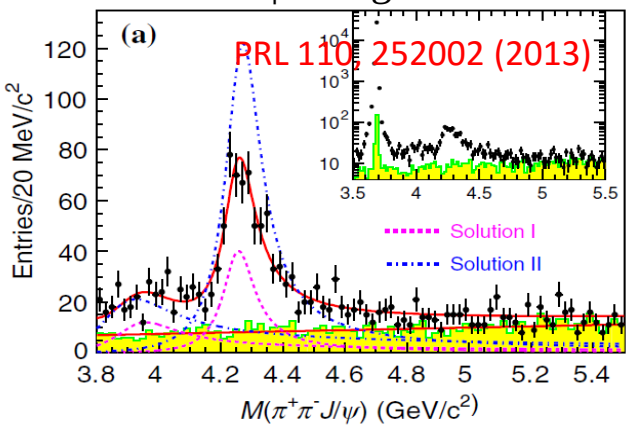
1. Cross section of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
2. Cross section of $e^+e^- \rightarrow \pi^+\pi^- \psi(2S)$
3. Cross section of $e^+e^- \rightarrow \pi^+\pi^- h_c$
4. Cross section of $e^+e^- \rightarrow \omega\chi_{cJ}$
5. Cross section of $e^+e^- \rightarrow \eta/\eta' J/\psi$

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

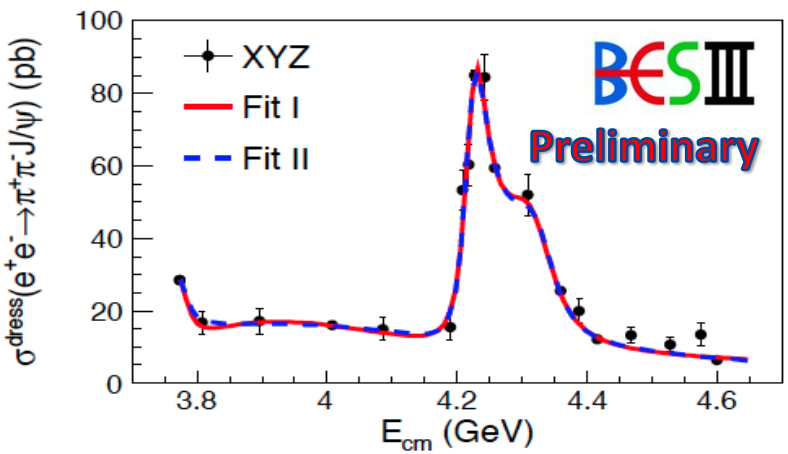
$e^+e^- \to \pi^+\pi^- J/\psi$ using ISR at BaBar

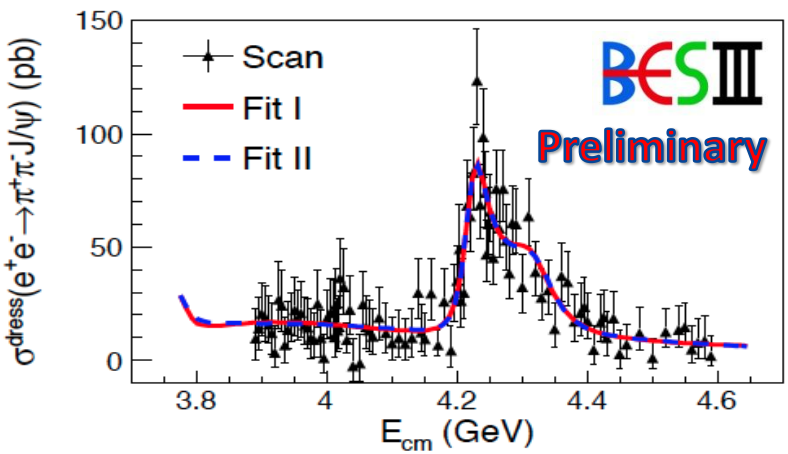


$e^+e^- \to \pi^+\pi^- J/\psi$ using ISR at Belle



Asymmetric shape?
Low-mass Y(4008)?





The cross section is inconsistent with a single peak for the Y(4260)!

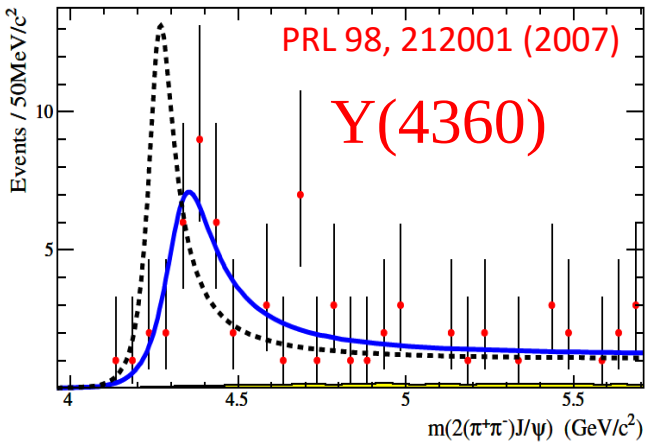
Two peaks are favored over one peak by > 7 σ

Peak 1: $4223.7 \pm 3.2\ (4222.4 \pm 3.0)$
$43.1 \pm 4.1\ (43.1 \pm 3.7)$

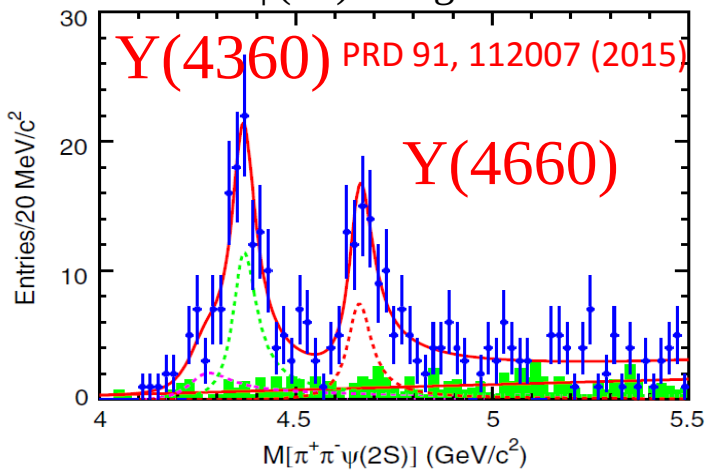
Peak 2: $4318.6^{+9.4}_{-10.2}\ (4325.5 \pm 9.4)$
$95.7^{+22.7}_{-18.0}\ (92.5^{+23.2}_{-18.1})$

Cross section of $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$

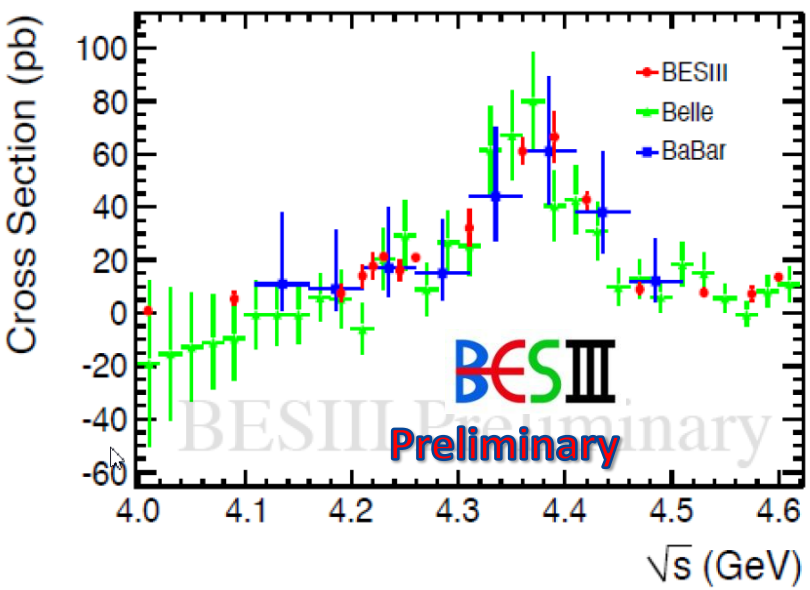
$e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ using ISR at BaBar



$e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ using ISR at Belle



No evidence for Y(4260)



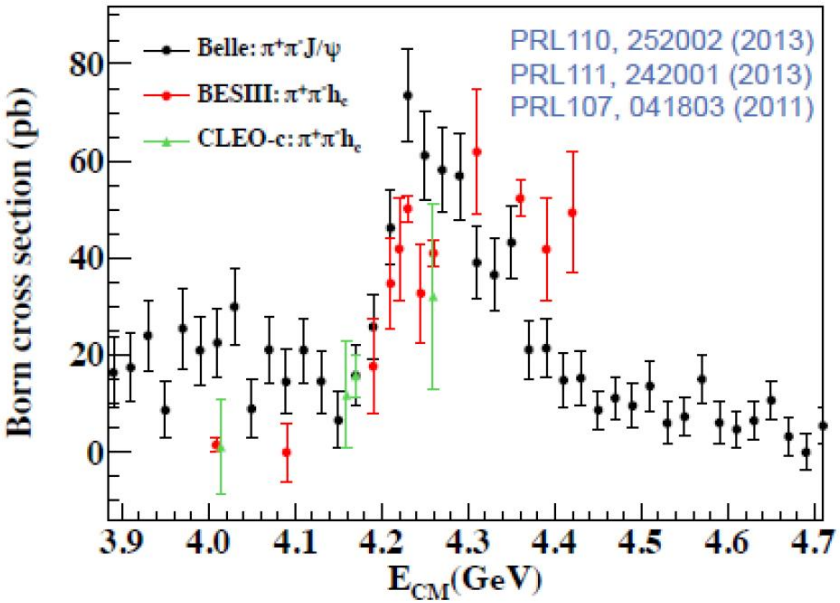
✓BESIII confirms the line shape for Y(4360)

☐More data will be taken soon to thoroughly study the region 4.2 ~ 4.3 GeV.

☐An analysis of the $\pi^{\pm}\psi(2S)$ substructure will be released soon.

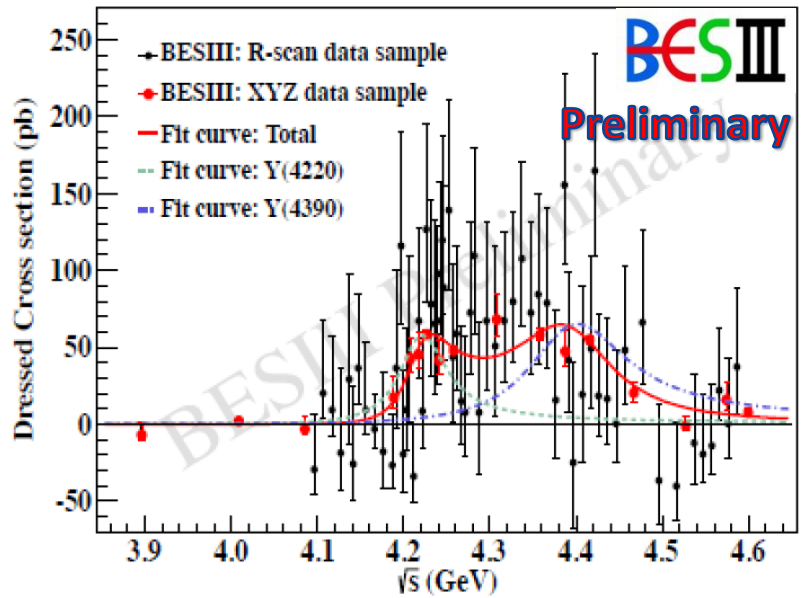
Cross section of $e^+e^- \rightarrow \pi^+\pi^- h_c$

Previous measurements on line shape of $\pi^+\pi^- h_c$ and comparison with $\pi^+\pi^- J/\psi$.



The $\pi^+\pi^- h_c$ shape is different from the $\pi^+\pi^- J/\psi$.

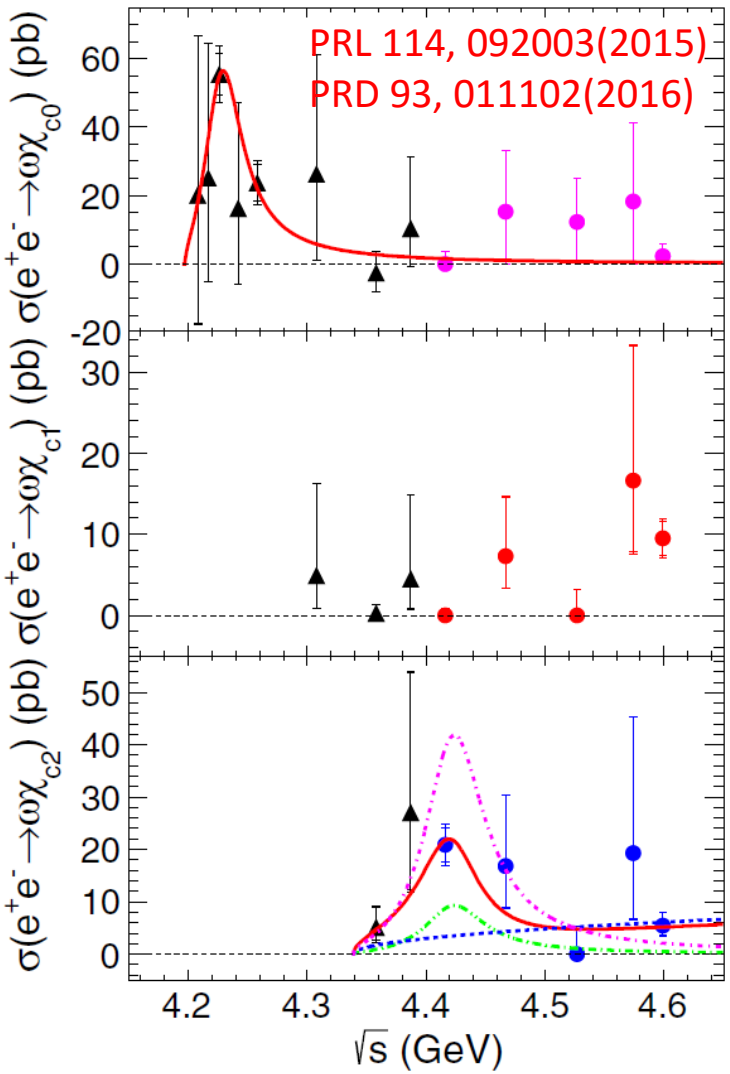
BESIII new preliminary result on the line shape of $\pi^+\pi^- h_c$.



With more data, the $\pi^+\pi^- h_c$ shape appears to be consistent with two peaks:

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 section of $e^+e^- \rightarrow \omega\chi_{cJ}$



- $e^+e^- \rightarrow \omega\chi_{c0}$ significant at 4.23 and 4.26 GeV
- Cross section peak near 4.23 GeV

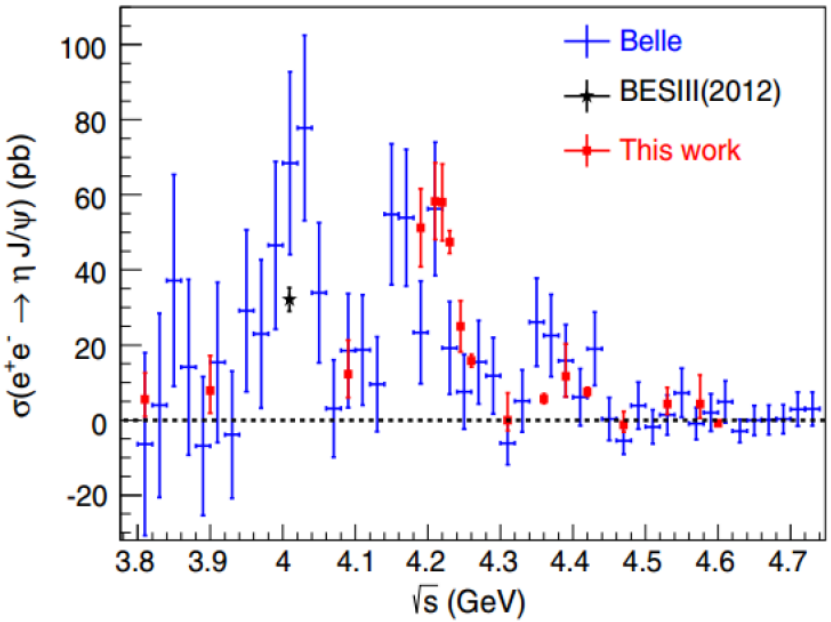
M=(4230±8±6) MeV, Γ=(38±12±2) MeV

- A new structure?
- Ψ(4S) EPJC 74:3208(2014)
- Tetraquark? PRD 91, 117501 (2015)
- Threshold effect?

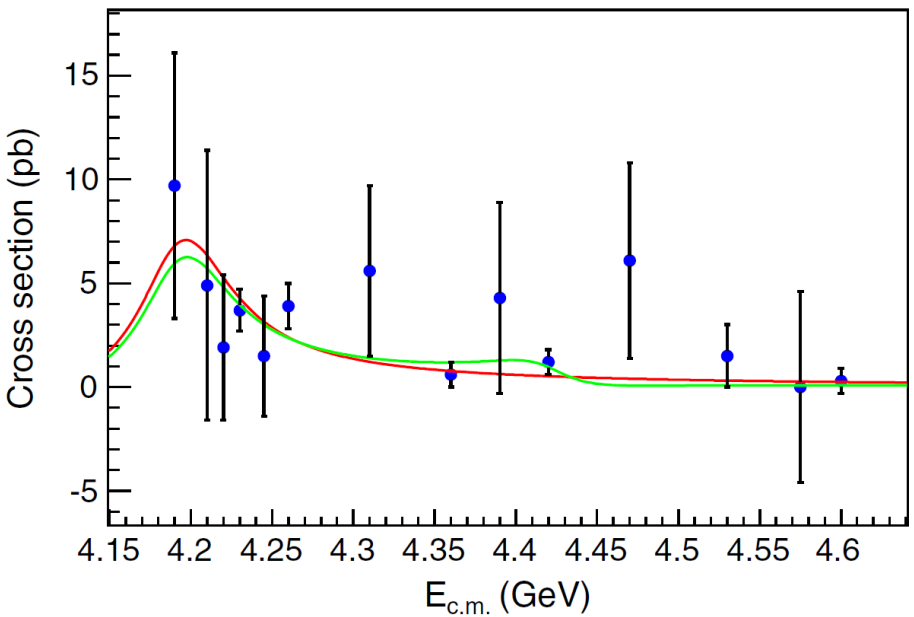
- $e^+e^- \rightarrow \omega\chi_{c2}$ is fitted with the coherent sum of the ψ(4415) BW function and a phase-space term.

Cross section of $e^+e^- \rightarrow \eta/\eta' J/\psi$

PRD 91, 112005 (2015)



PRD 94, 032009 (2016)



- Agrees with previous results with improved precision
- Structure around 4.2 GeV possibly from $\Psi(4160) \rightarrow \eta J/\psi$

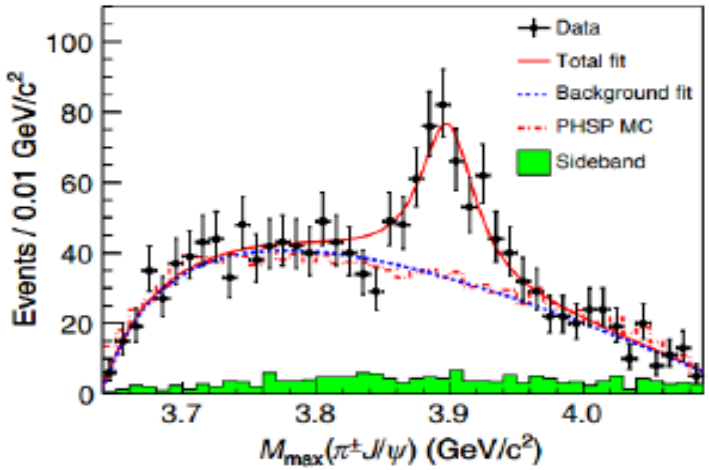
- Fit with $\Psi(4160)$ and $\Psi(4415)$ $\Psi(4415)$ not significant.
- $\sigma(\eta' J/\psi)$ much lower than $\sigma(\eta J/\psi)$, lower than NRQCD calculation [1].

[1]C. F. Qiao, R. L. Zhu, PRD, 074006 (2014)

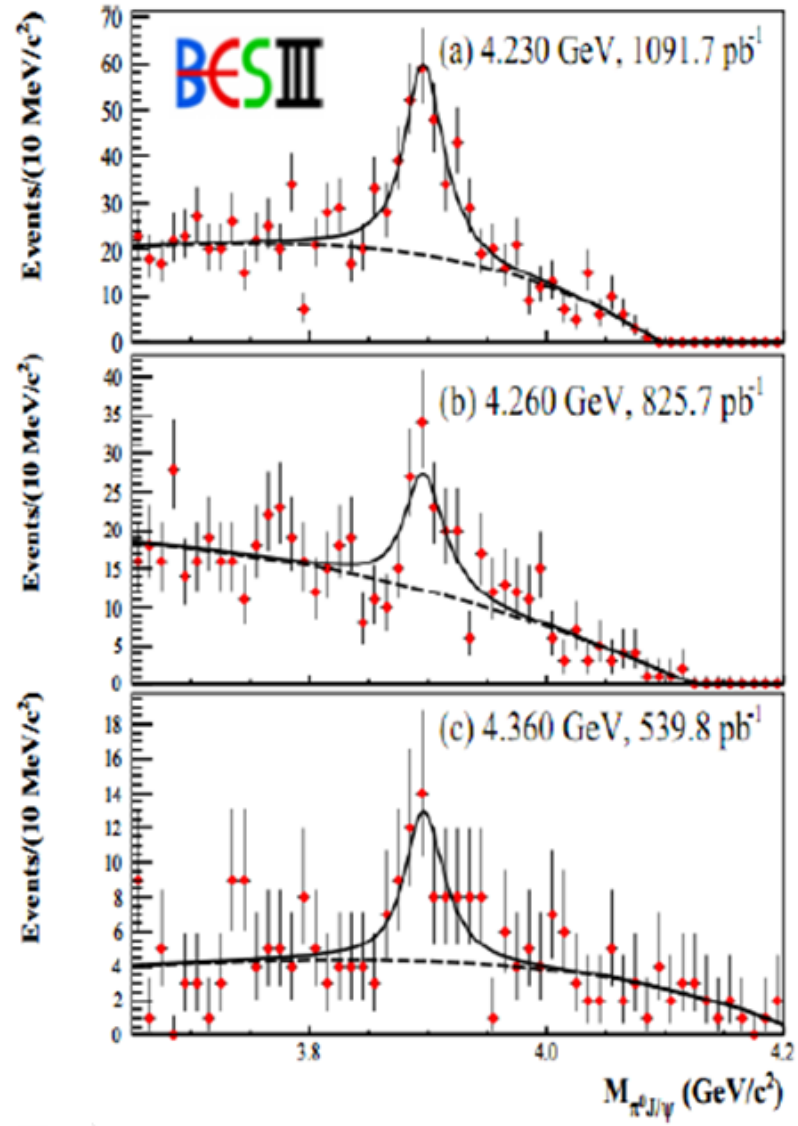
Z States at BESIII

$Z_c(3900)^{\pm/0}$ in $e^+e^- \rightarrow \pi\pi J/\psi$

[BESIII PRL 110, 252001(2013)]



[PRL 115, 112003(2015)]



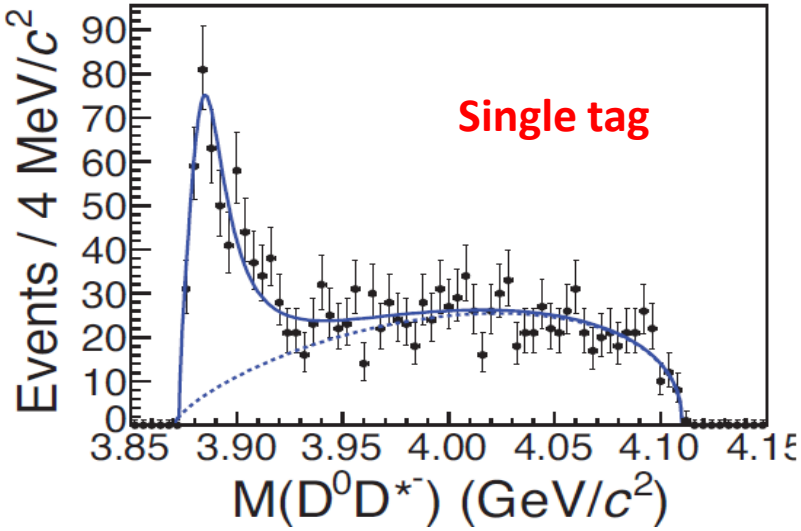
- $Z_c(3900)^{\pm}$, BESIII, Belle, CLEOc data, in 2013
- $Z_c(3900)^0$, evidence with 3.7σ by CLEOc, observed with >10σ by BESIII

Zc(3900)	Mass(MeV)	Width(MeV)
$Z_c(3900)^{\pm}$	3899.0±3.6±4.9	46±10±20
$Z_c(3900)^0$	3894.8±2.3±2.7	29.6±8.2±8.2

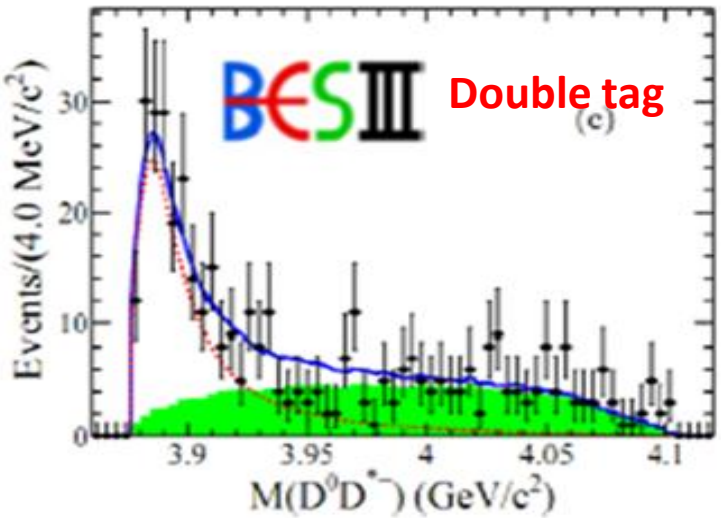
An iso-spin triplet established!

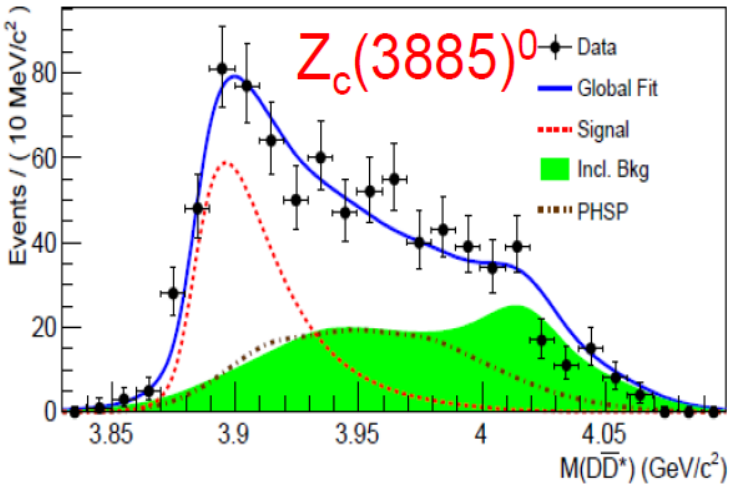
$Z_c(3885)^{\pm/0}$ in $e^+e^- \rightarrow \pi(D\bar{D}^*)$

[BESIII PRL 112, 022001(2014)]



[BESIII PRD 92, 092006(2015)]



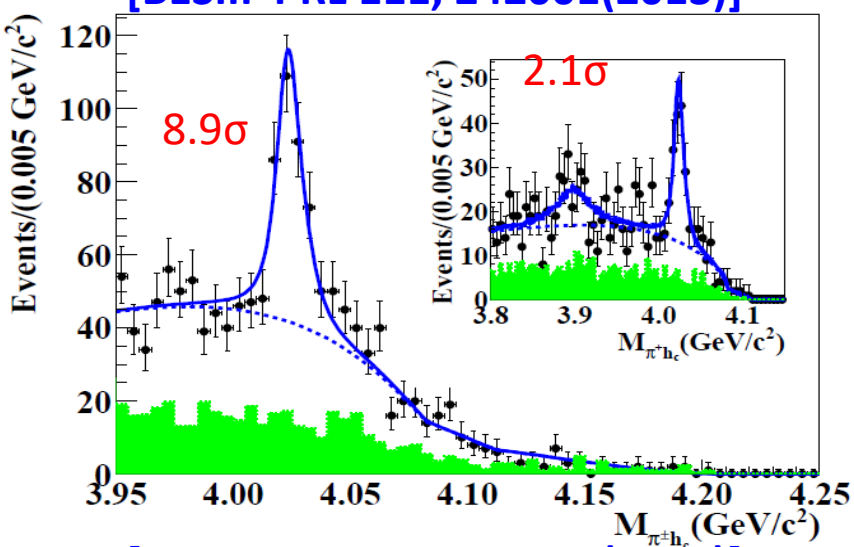


[BESIII PRL 115, 222002(2015)]

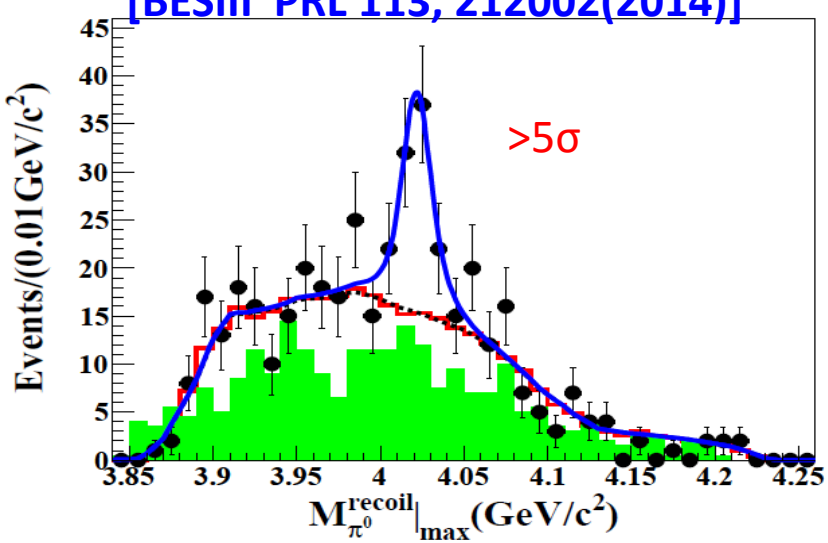
State	Mass (MeV/c^2)	Width (MeV)
$Z_c(3885)^{\pm}$	$3883.9 \pm 1.5 \pm 4.2$ Single D tag	$24.8 \pm 3.3 \pm 11.0$ Single D tag
	$3881.7 \pm 1.6 \pm 1.6$ Double D tag	$26.6 \pm 2.0 \pm 2.1$ Double D tag
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$

$Z_c(4020)^{\pm/0}$ in $e^+e^- \rightarrow \pi\pi h_c$

[BESIII PRL 111, 242001(2013)]



[BESIII PRL 113, 212002(2014)]

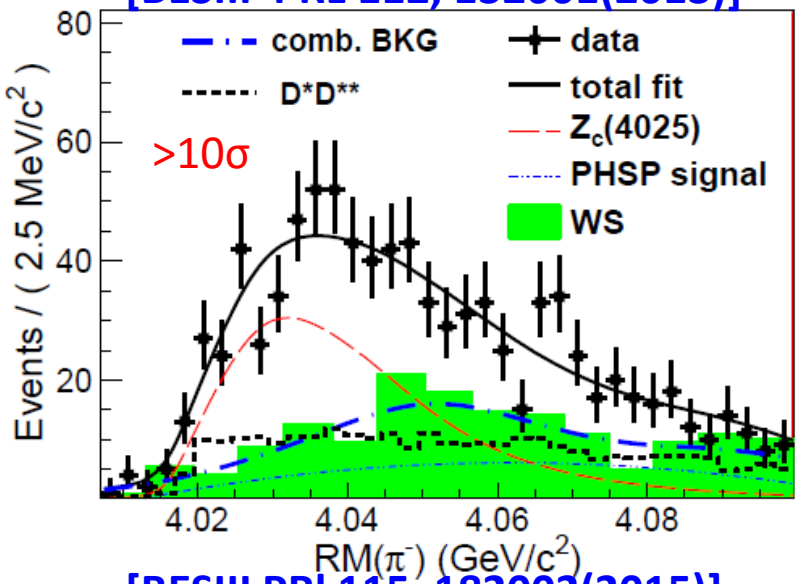


Zc(4020)	Mass(MeV)	Width(MeV)
$Z_c(4020)^\pm$	4022.9±0.8±2.7	7.9±2.7±2.6
$Z_c(4020)^0$	4023.8±2.2±3.8	Fixed(=7.9)

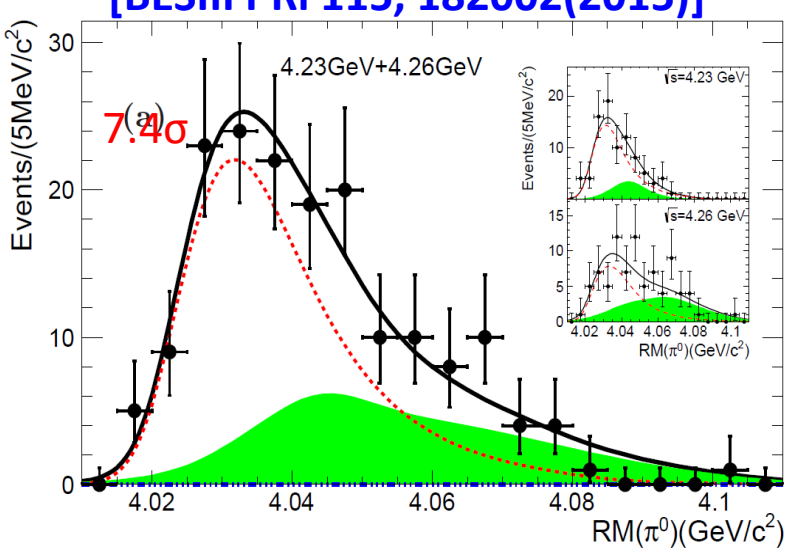
- $h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$ 16 hadronic channels
- $Z_c(4020)^\pm$, observed
- A weak evidence for $Z_c(3900) \rightarrow \pi^\pm h_c$
- $Z_c(4020)^0$, observed
- Another iso-spin triplet established!
- $Z_c(4020)$, near the threshold of D*D*-bar.

$Z_c(4025)^{\pm/0}$ in $e^+e^- \rightarrow \pi^{\pm/0}(D^*\bar{D}^*)^{-/+/0}$

[BESIII PRL 112, 132001(2013)]



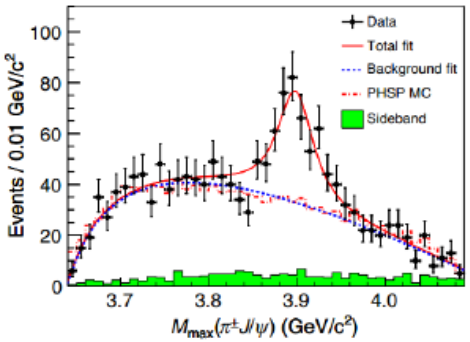
[BESIII PRl 115, 182002(2015)]



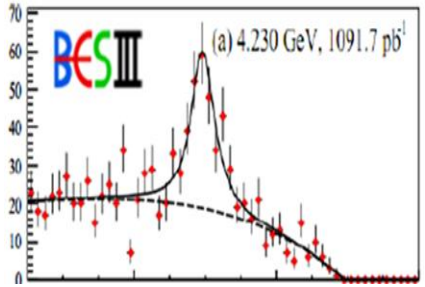
Zc(4025)	Mass(MeV)	Width(MeV)
$Z_c(4025)^{\pm}$	4026.3±2.6±3.7	24.8±5.6±7.7
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7}\pm3.1$	23.0±6.0±1.0

- Tag a D^+ and a bachelor π^-, reconstruct one π^0 to suppress the background
- $Z_c(4025)^{\pm}$, observed
- Coupling to D*D*-bar is much larger than to πh_c if $Z_c(4025)$ and $Z_c(4020)$ are the same state.
- $Z_c(4025)^0$, observed

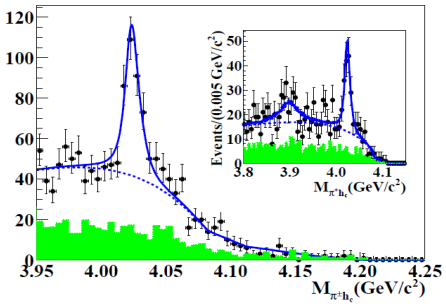
Overview of Z_c states



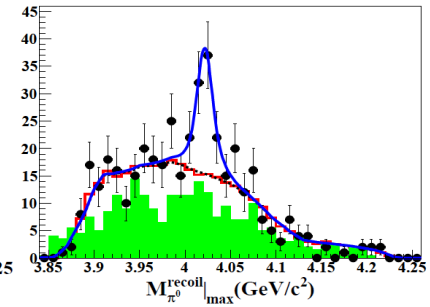
$e^+e^- \rightarrow \pi^-\pi^+ J/\psi$



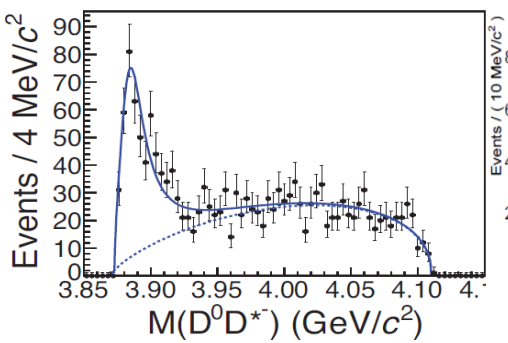
$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$



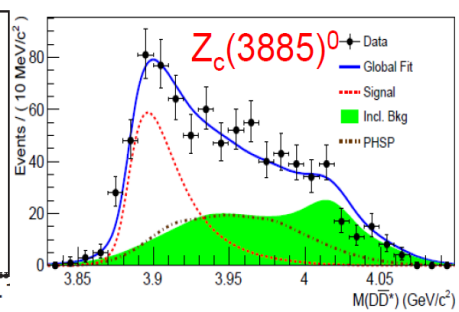
$e^+e^- \rightarrow \pi^-\pi^+ h_c$



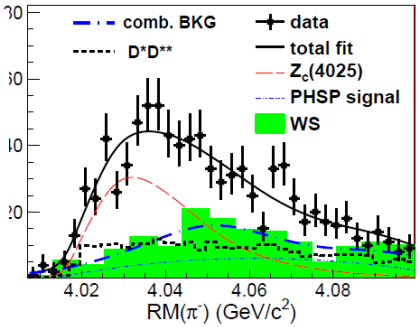
$e^+e^- \rightarrow \pi^0\pi^0 h_c$



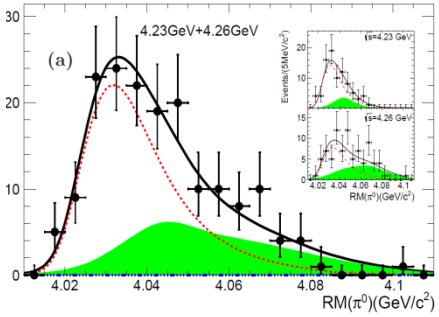
$e^+e^- \rightarrow \pi^{\pm}(D\bar{D}^*)^{-/+}$



$e^+e^- \rightarrow \pi^0(DD^*)^0$



$e^+e^- \rightarrow \pi^{\pm}(D^*\bar{D}^*)^{-/+}$

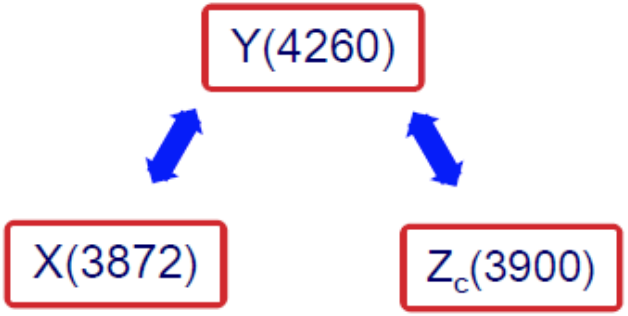


$e^+e^- \rightarrow \pi^0(D^*\bar{D}^*)^0$

$Z_c(3900)^{\pm}$? **$Z_c(3900)^0$?** **$Z_c(4020)^{\pm}$?** **$Z_c(4020)^0$?**

Summary

- Lots of progress in charmonium-like studies recently.
- X(3823), X(3872) observed, X(4140) not found.
- Y states are studied with line shapes of exclusive channels.
- Z states, charged and neutral, have been observed.
- X, Y, Z particles are connected via transitions.



- More experimental effort is needed.

Thank You

Backup

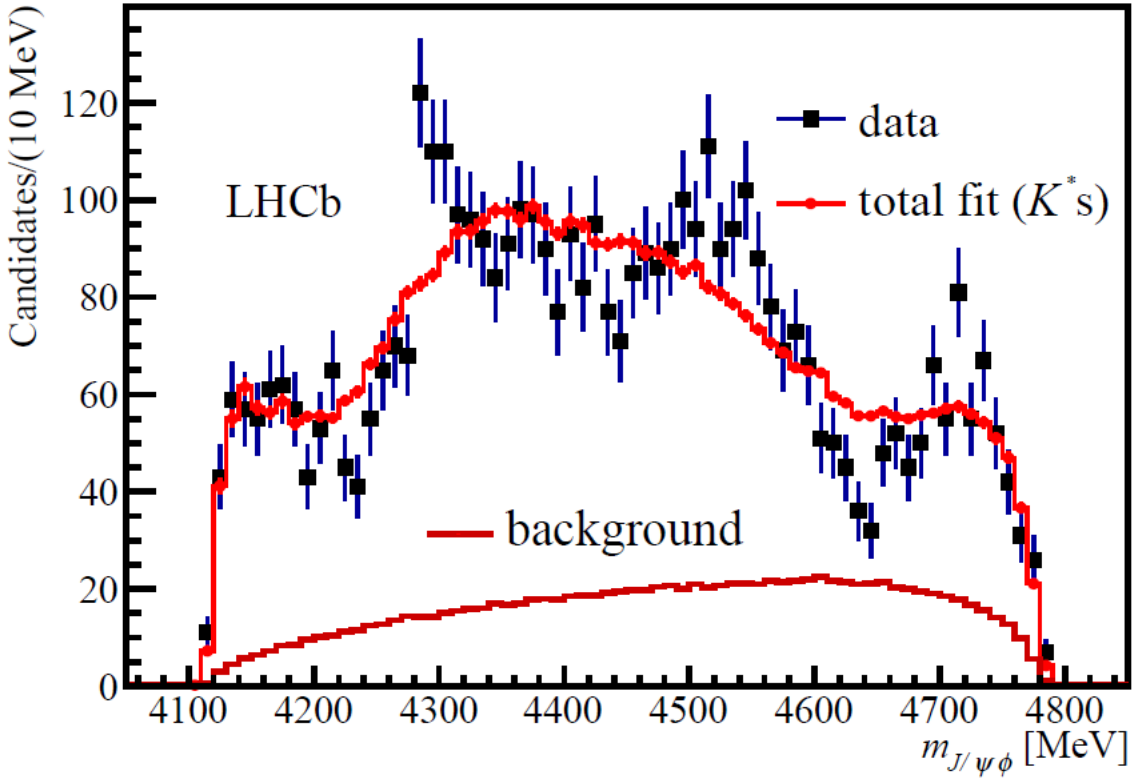
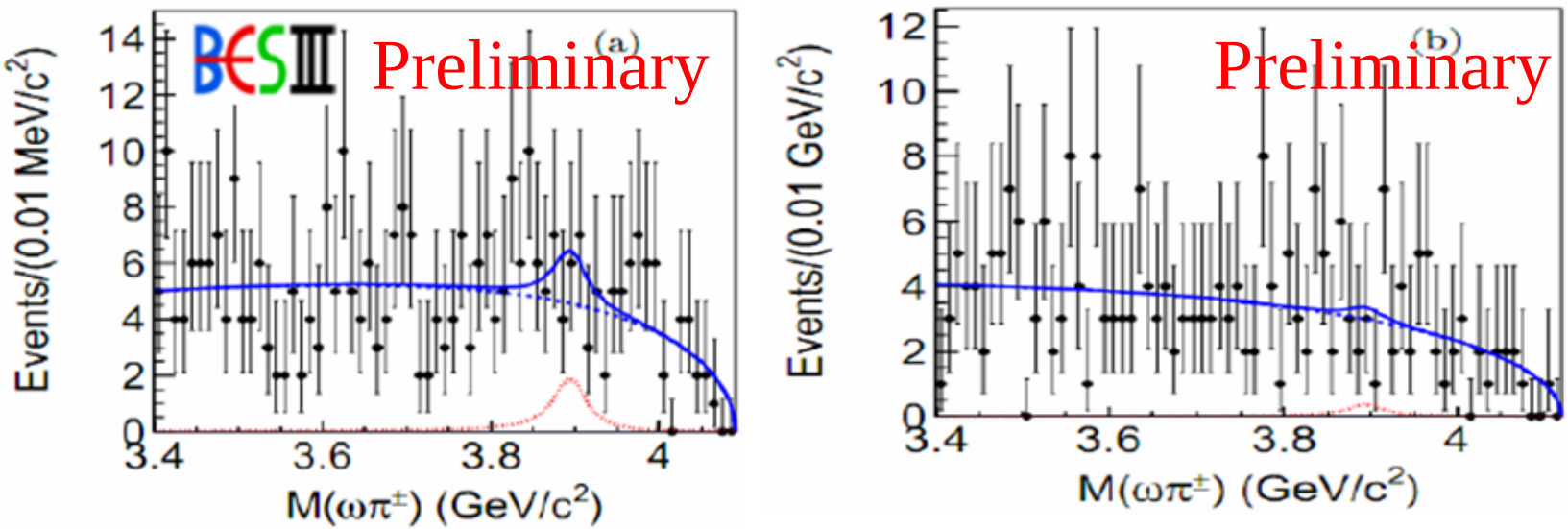


Figure 15: Distribution of $m_{J/\psi\phi}$ for the data and the fit results with a model containing only $K^{*+} \to \phi K^+$ contributions.

A near-threshold $J/\psi\phi$ structure in our data is the most significant (8.4σ) exotic contribution to our model. We determine its quantum numbers to be $J^{PC} = 1^{++}$ at 5.7σ significance (Appendix C). When fitted as a resonance, its mass ($4146.5 \pm 4.5\,^{+4.6}_{-2.8}$ MeV) is in excellent agreement with previous measurements for the $X(4140)$ state, although the width ($83 \pm 21\,^{+21}_{-14}$ MeV) is substantially larger. The upper limit which we previously set for production of a narrow ($\Gamma = 15.3$ MeV) $X(4140)$ state based on a small subset of our present data [21] does not apply to such a broad resonance, *i.e.* the present results are consistent with our previous analysis.

Search for $Z_c(3900)^{\pm}$ in $\omega\pi^{\pm}$

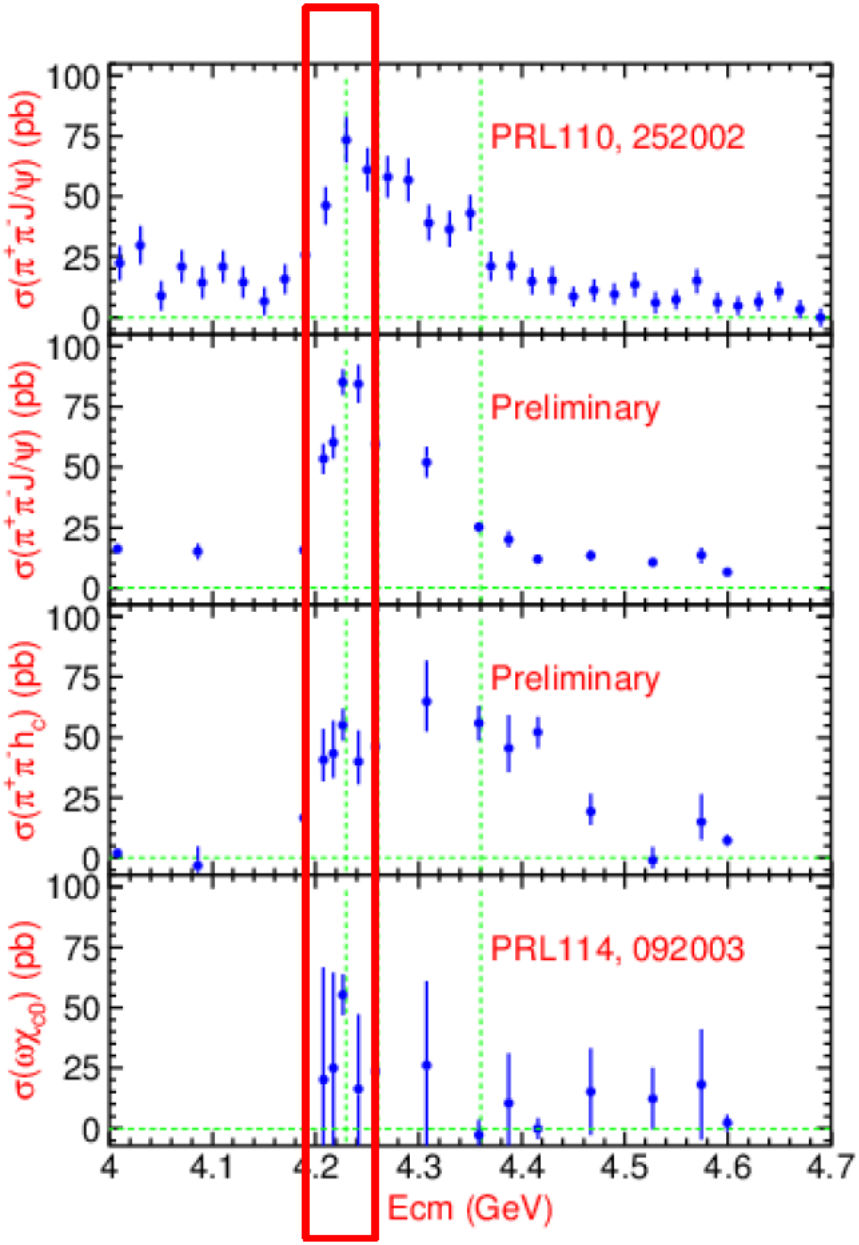
e^+e^- @4.23GeV **e^+e^- @4.26GeV**



- Searching for new decay of $Z_c(3900)$ can provide useful information on its internal structure.
- No significant signals observed.

$\sigma(e^+e^- \to Z_c\pi,\ Z_c \to \omega\pi) < 0.27$ pb @ 4.23 GeV

$\sigma(e^+e^- \to Z_c\pi,\ Z_c \to \omega\pi) < 0.18$ pb @ 4.26 GeV

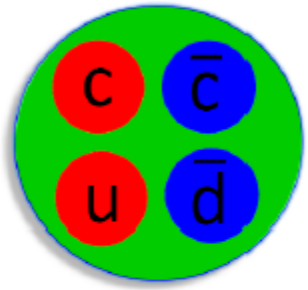


From the line shapes of $\pi^+\pi^- J/\psi$, $\pi^+\pi^- h_c$, $\omega\chi_{cJ}$ in the left plot, we may conclude the Y(4260) has a lower mass and narrower width than previous measurements.

NATURE of Z_c STATES

- At least 4 quarks, not a conventional meson

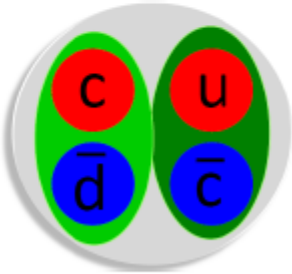
- Tetraquark state?



Phys. Rev. D87,125018(2013); Phys. Rev. D88, 074506(2013);

Phys. Rev. D89,054019(2014); Phys. Rev. D90,054009(2014); etc

- $D^{(*)}\ \bar{D}^{(*)}$ molecule state?



Phys. Rev. Lett. 111, 132003 (2013); Phys. Rev. D 89, 094026 (2014)

Phys. Rev. D 89, 074029 (2014); Phys. Rev. D 88, 074506 (2013); etc

- Final States Interactions?
- …

The nature of $Z_c(3900)$?

From SPIRE HEP Database (17th, May)

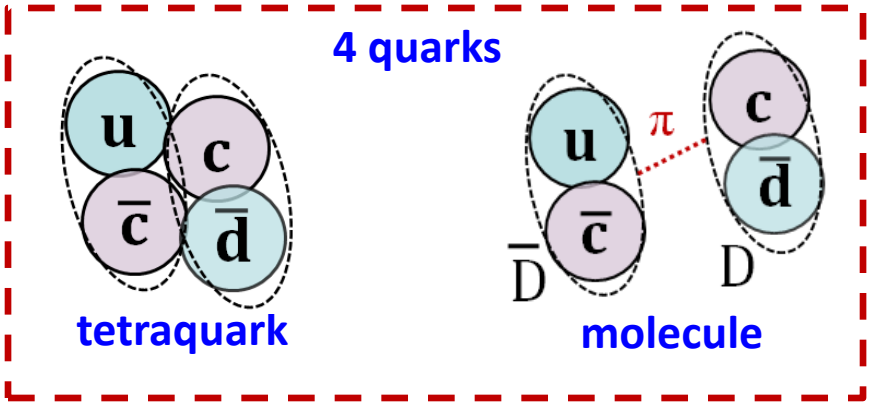
1. Tetraquarks
   arXiv: 1110.1333, 1303.6857
   arXiv: 1304. (0345, 1301, 6433, 7080, 7816)

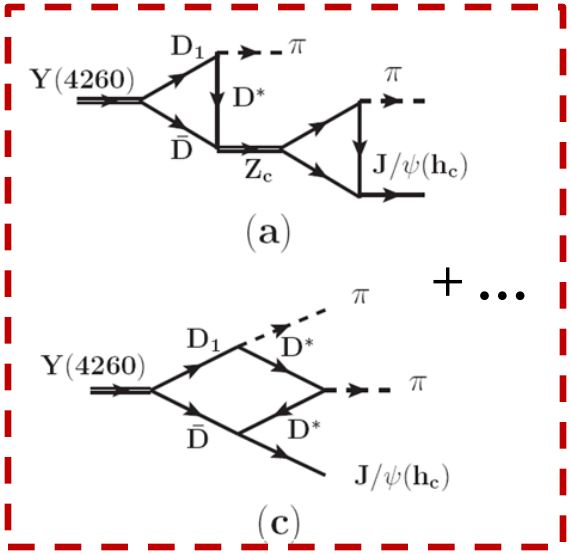
2. Hadronic molecules
   arXiv: 1303.6608,
   arXiv: 1304.(2882, 1850, 5748, 7467)

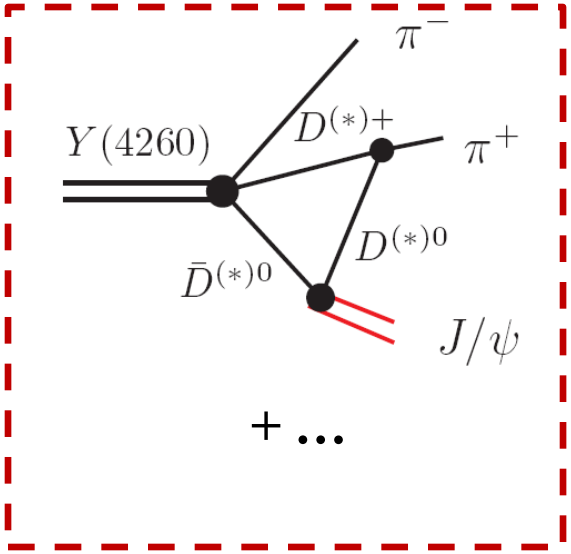
3. Four quark state (1 or 2)
   arXiv: 1304.0380

4. Meson loop
   arXiv: 1303.6355, 1304.4458

5. Initial State Pion Emission (ISPE) model
   arXiv: 1303.6842, 1304.5845







meson loop

ISPE model

Compared with the Born cross section of $e^+e^- \to \eta J/\psi$ [11], the measured Born cross section of $e^+e^- \to \eta' J/\psi$ is much smaller, which is in contradiction to the calculation in Ref. [13]. There are two possible reasons contributing to this discrepancy. The cross section of $e^+e^- \to \eta' J/\psi$ is investigated at an order of $O(\alpha_s^4)$; therefore, higher order corrections might need to be considered; additionally, the proportion of gluonic admixture in η' needs to be further studied to make certain the contribution of a gluonium component on the results.