

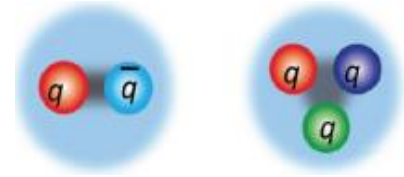
Recent results in (exotic) charmonium spectroscopy

Wenbiao Yan

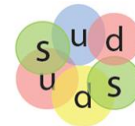
University of Science and Technology of China

Hadrons

- Hadrons:
 - ✓ 2 quarks (meson) or 3 quarks (baryon)
 - ✓ described with quark model (QM)



- QCD suggests :
 - ✓ Molecule: bound state of two hadrons
 - ✓ Multiquark state: (qqqq, qqqqq, ...)
 - ✓ Glueball: (gg, ggg, ...)
 - ✓ Hybrid: (qqg, ...)



dibaryon



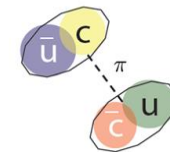
pentaquark



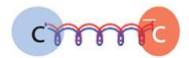
glueball



diquark + di-antiquark



dimeson molecule

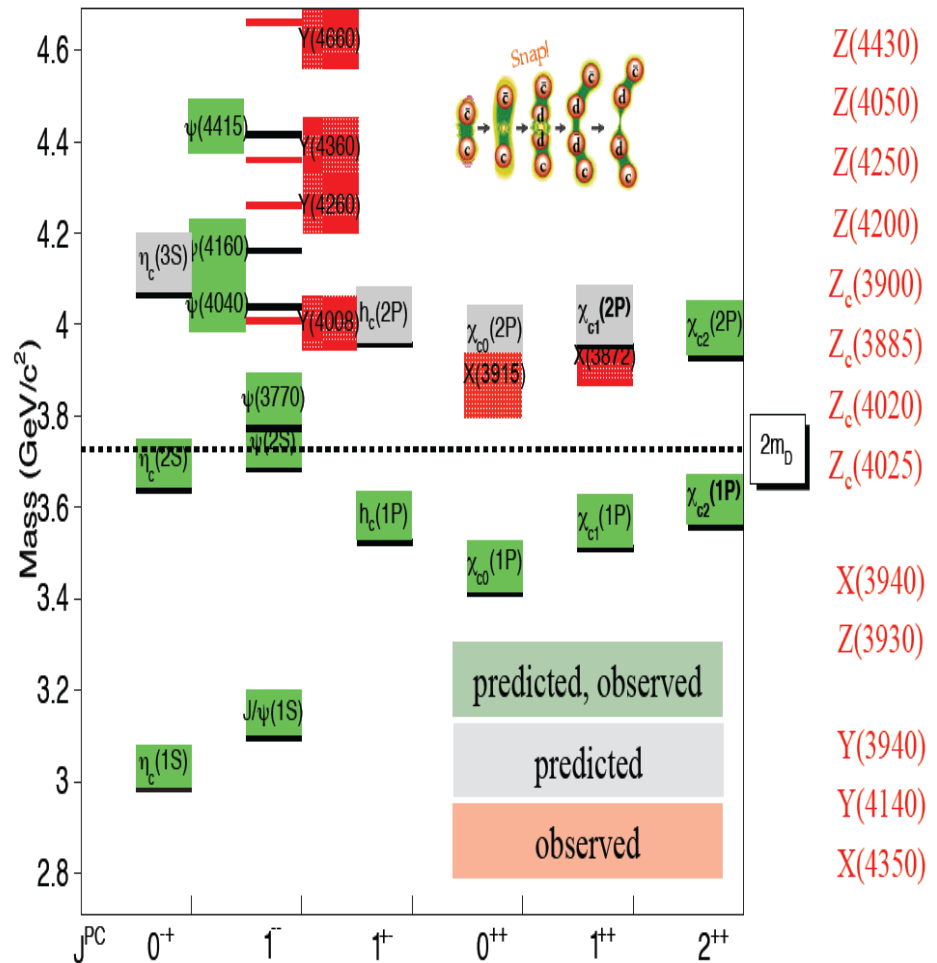


$q \bar{q} g$ hybrid

Search for these exotic hadrons

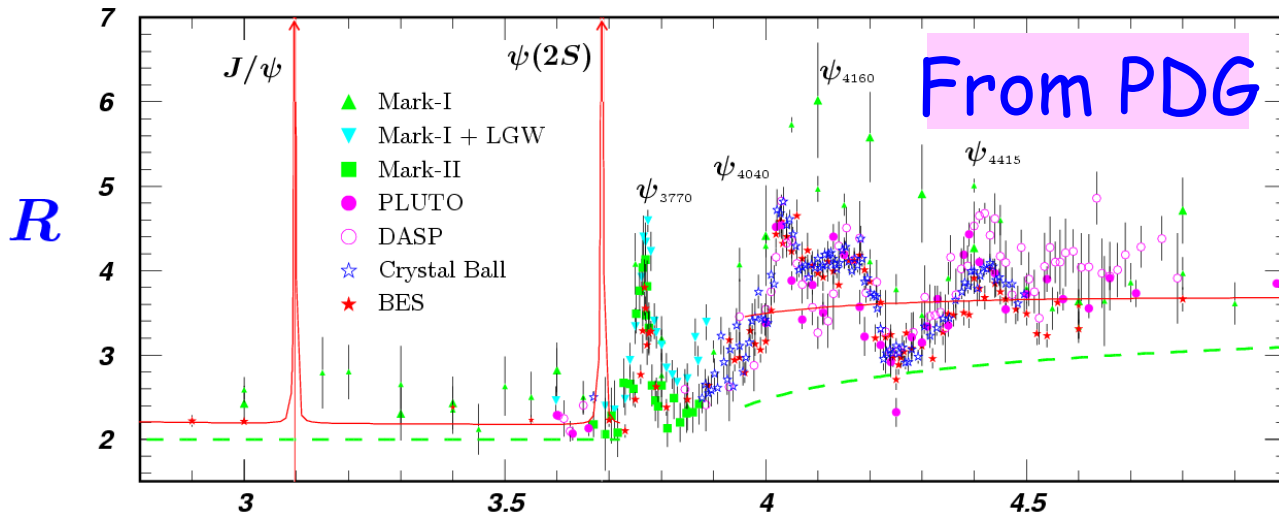
Charmonium spectroscopy

- Below charm threshold, all states have been observed
- Charm anti-charm potential model described spectrum very well
- Many missing states above charm threshold.
- A number of new states above charm threshold that do not fit into $c\bar{c}$ slots
 - ✓ Not all of them are charmonium
 - ✓ What are they ?



XYZ production

BESIII



$\psi(4040)$ @4.008GeV
 @4.23GeV
 $Y(4260)$ @4.26GeV
 $Y(4360)$ @ 4.36GeV
 $\psi(4415)$ @ 4.42GeV
 $Y(4660)$ @ 4.6GeV

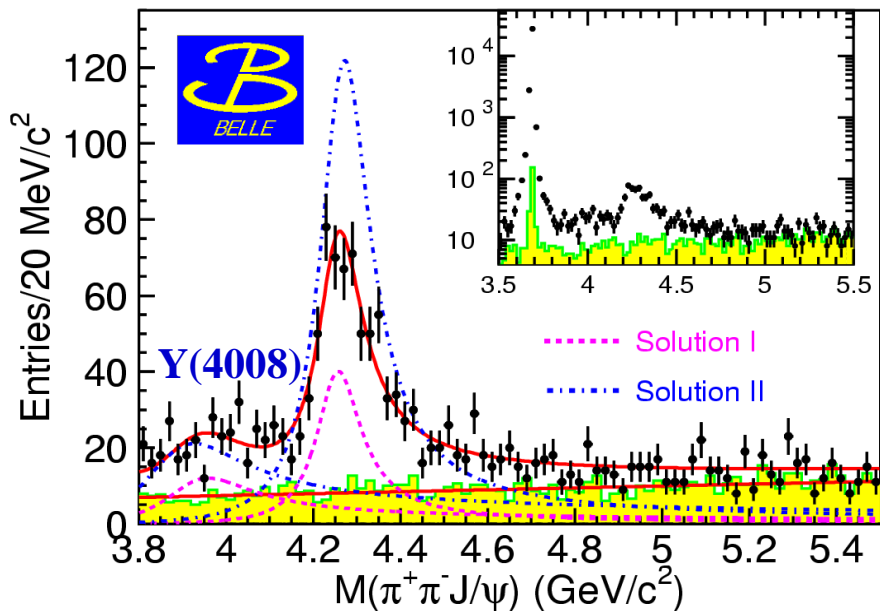
- Vector ψ/Y states can be produced directly

- ISR production
- B decay

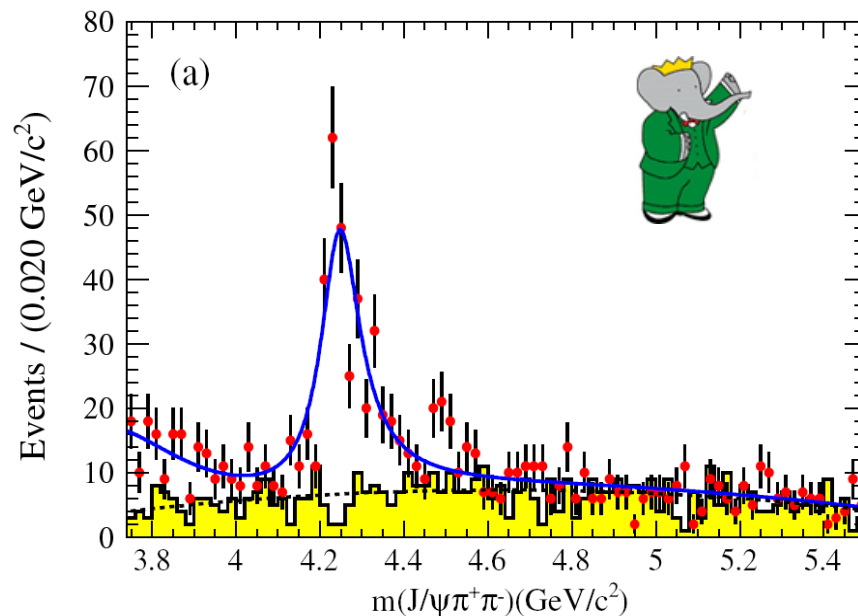


Y(4260) and Y(4008)

PRL110,252002 (2013), 967 fb⁻¹



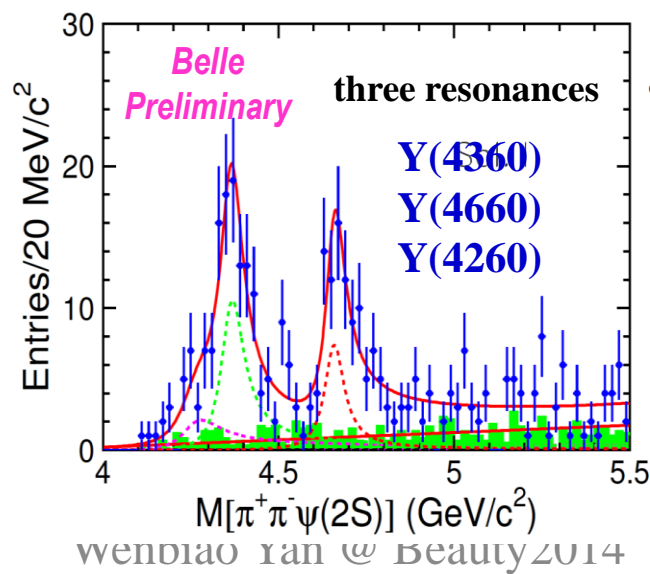
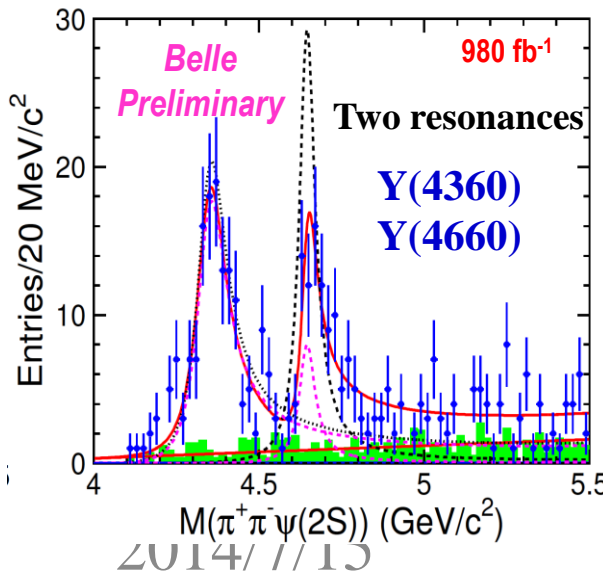
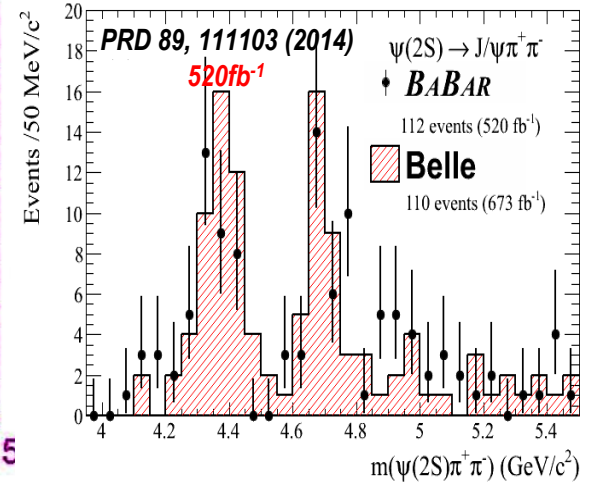
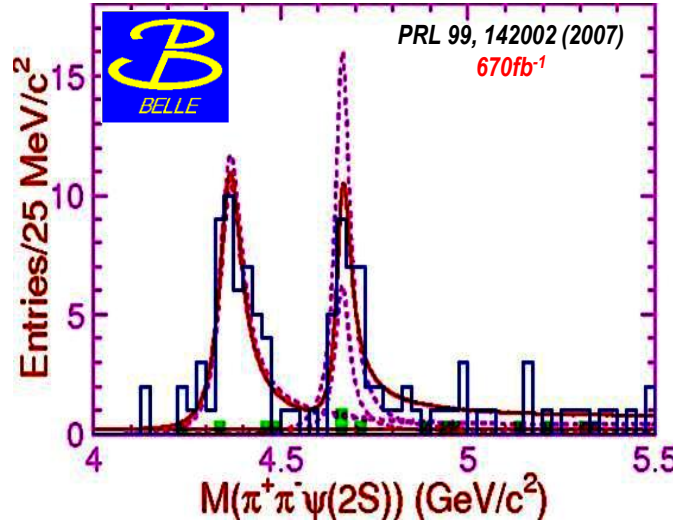
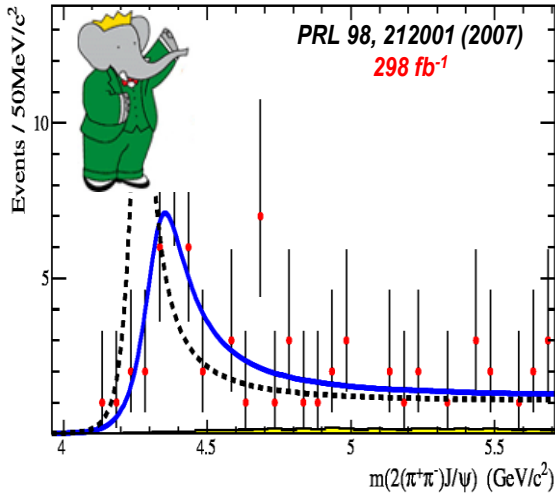
PRD86,051102 (2012), 454 fb⁻¹



- Both Belle and Babar updated results, consistent with previous measurements
- Discrepancy between two experiments still exist: Belle observed additional Y(4008), BaBar updated with more data, no Y(4008) observed.

BESIII data could clarify

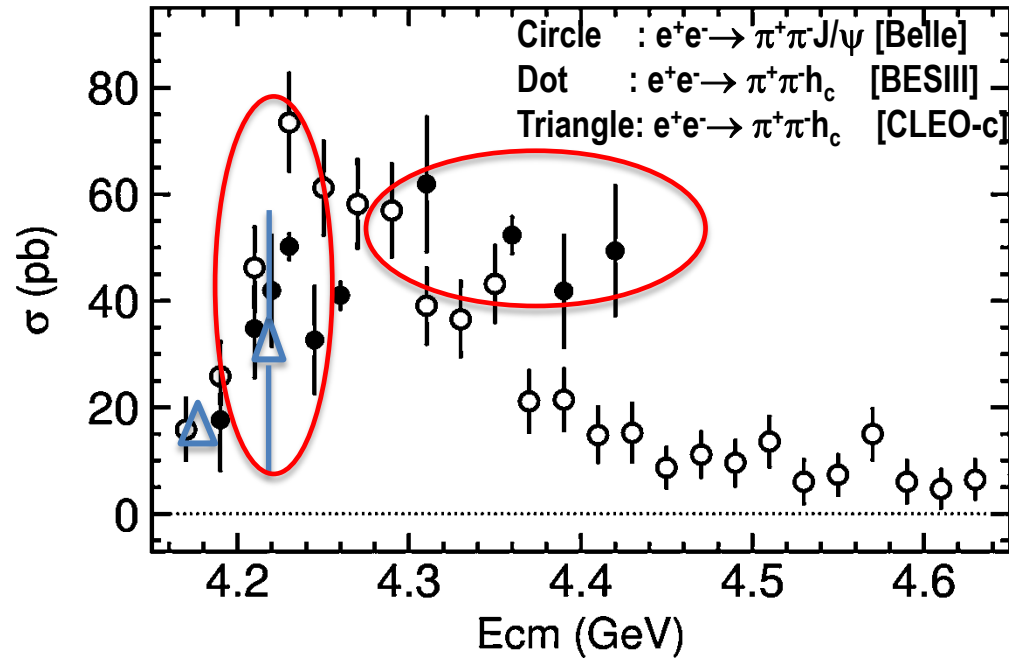
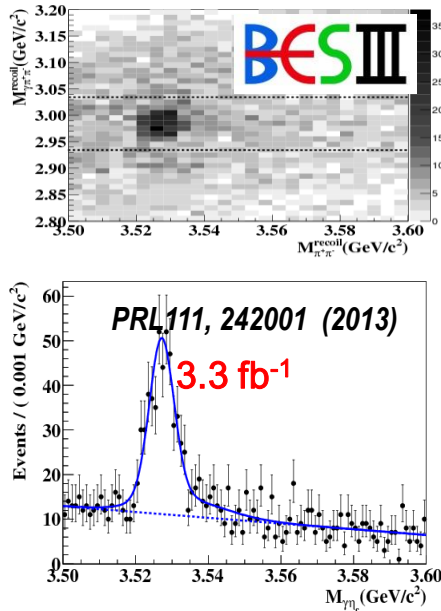
Y(4360)/Y(4660): $e^+e^- \rightarrow \gamma_{ISR} \psi' \pi^+ \pi^-$



- BaBar and Belle observed Y(4360)
- Belle with additional Y(4660)
- BaBar updated results in good agreement with Belle
- Belle preliminary results in good agreement with previous results, Y(4260) significance 2.1σ only.

Y(4660) confirmed

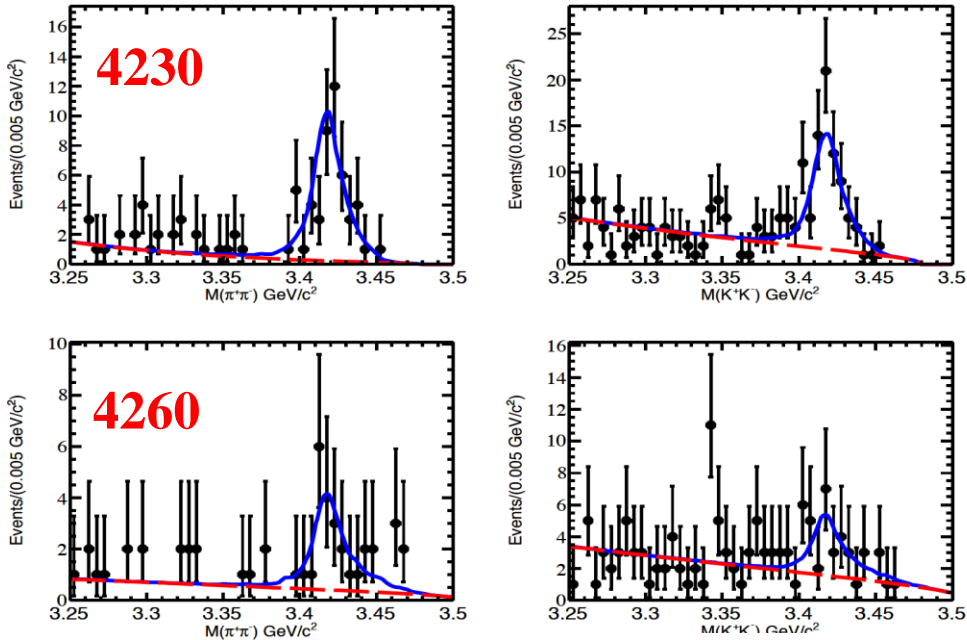
$e^+e^- \rightarrow \pi^+\pi^-h_c$



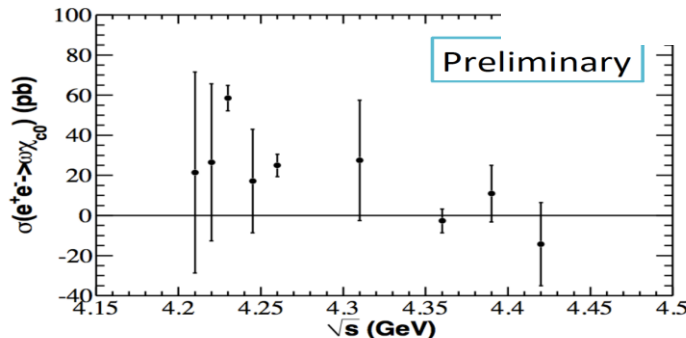
- $\sigma(e^+e^- \rightarrow \pi^+\pi^-h_c) \sim \sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi)$, but different line shape.
- Local maximum ~ 4.23 GeV, broad structure at ~ 4.4 GeV?
- More data around 4.23 GeV and above 4.4 GeV is very help.

Cross section of $e^+e^- \rightarrow \omega\chi_{c0}$

BES III



- Data samples at 9 energy points from 4.21 GeV to 4.42 GeV
- $\omega \rightarrow \pi^+\pi^-\pi^0$; $\chi_{\chi 0} \rightarrow \pi^+\pi^-/K^+K^-$
- Signal observed at 4.23 MeV and 4.26 MeV
- Simultaneous fit performed



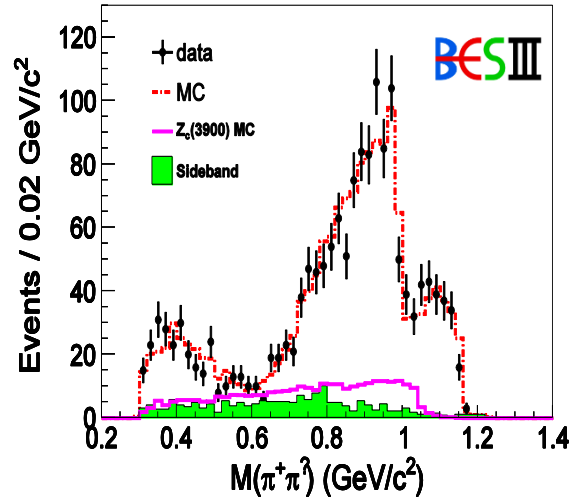
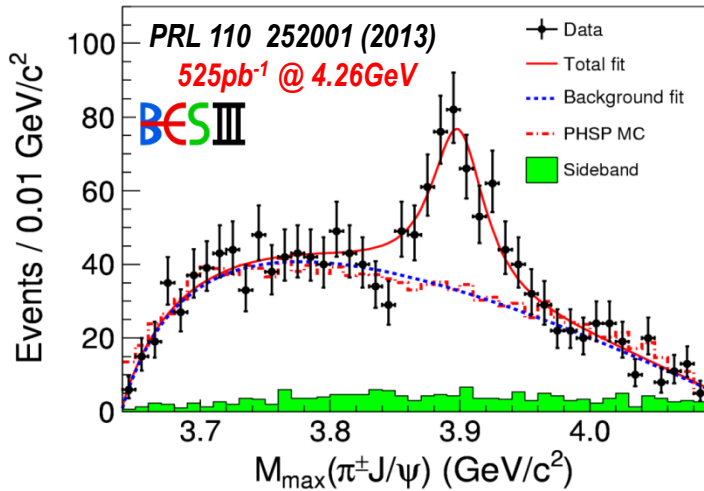
Cross section peaks around 4.23 GeV

Charged charmonium-like states

- Have electric charge, thus has two more light quarks
 - ✓ At least 4 quarks, not a conventional meson
- Could exist in $\pi^\pm J/\psi$, $\pi^\pm \psi(2S)$, $\pi^\pm h_c$, $\pi^\pm \chi_{cJ}, \dots$
 - ✓ Search for Neutral isospin partner
- Experimental search:
 - ✓ BESIII/CLEO-c: $e^+e^- \rightarrow \pi^\pm$ exotics,...
 - ✓ Belle/BaBar: $e^+e^- \rightarrow (\gamma_{ISR})\pi^\pm$ exotics,...
 - ✓ Belle/BaBar/LHCb: $B \rightarrow K$ exotics,...

Observation of $Z_c(3900)^\pm$

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



BESIII

$$M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}$$

$$\Gamma = 46 \pm 10 \pm 20 \text{ MeV}$$

$$307 \pm 48 \text{ events, } >8\sigma$$

BELLE

$$M = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV}$$

$$\Gamma = 63 \pm 24 \pm 26 \text{ MeV}$$

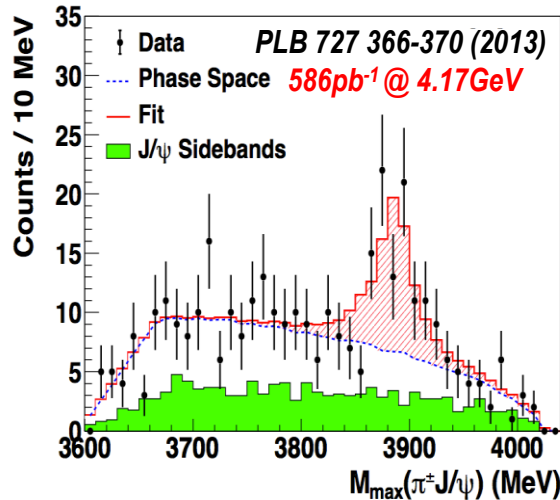
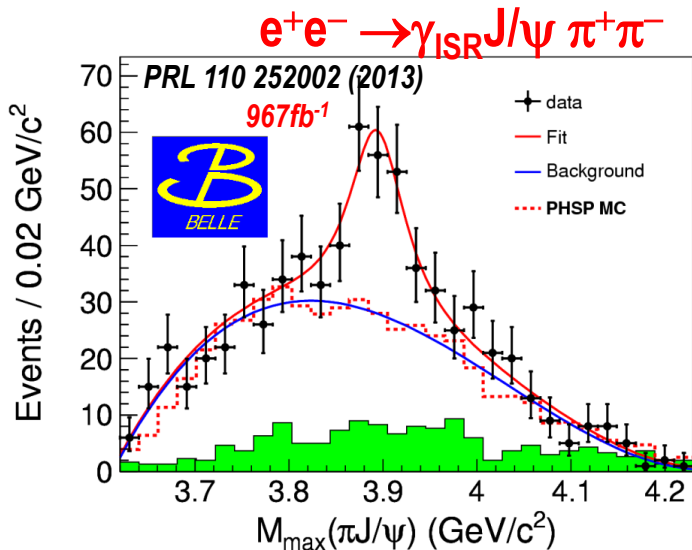
$$159 \pm 49 \text{ events, } >5.2\sigma$$

CLEO-c Data

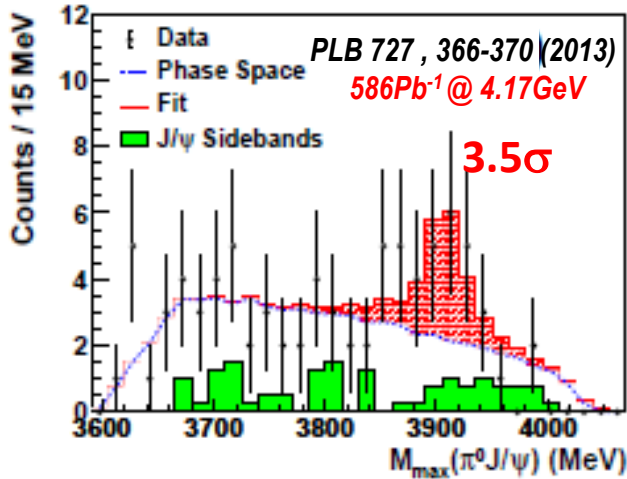
$$M = 3886 \pm 4 \pm 2 \text{ MeV}$$

$$\Gamma = 37 \pm 4 \pm 8 \text{ MeV}$$

$$81 \pm 16 \text{ events, } >5\sigma$$



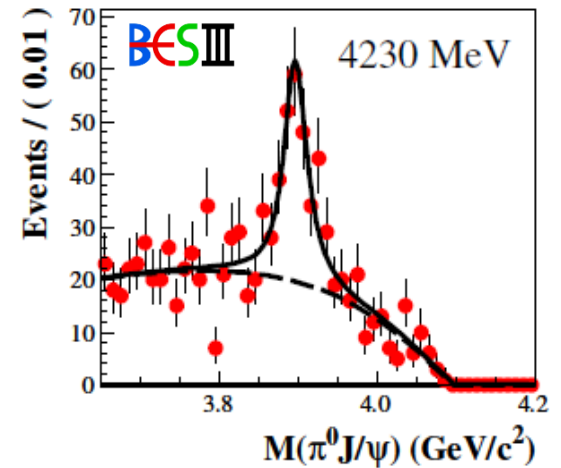
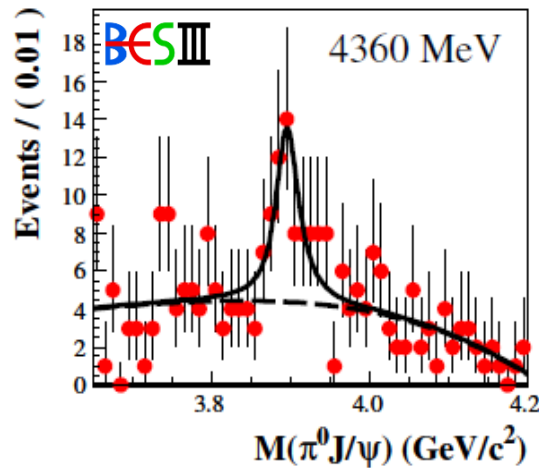
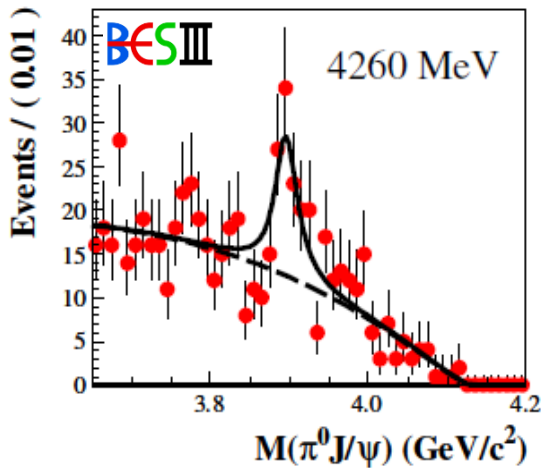
$Z_c(3900)^0 @ e^+e^- \rightarrow \pi^0\pi^0 J/\psi$



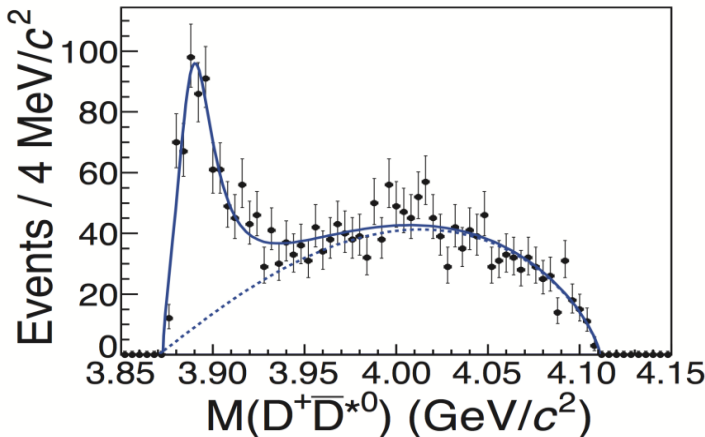
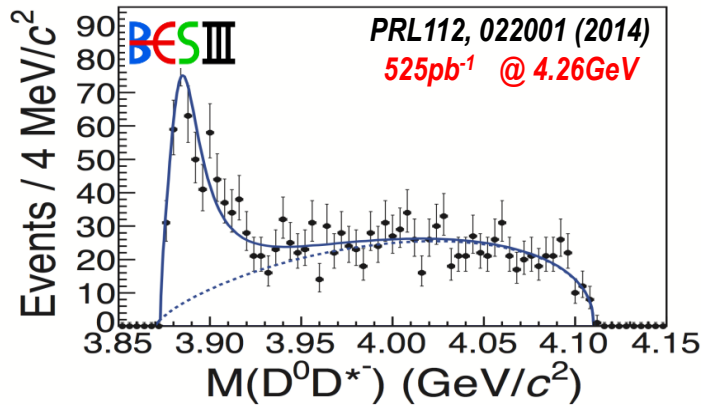
BESIII Preliminary

- $Z_c(3900)^0$ is observed clearly at $\sqrt{s} = 4.23, 4.26, 4.36$ GeV
- BESIII preliminary results :
 - $M = 3894.8 \pm 2.3$ MeV, $\Gamma = 29.6 \pm 8.2$ MeV
 - Significance = 10.4 σ

Neutral isospin partner, $Z_c(3900)^0$ observed



$e^+e^- \rightarrow \pi^\pm (DD^*) \bar{\Upsilon} @ 4.26\text{GeV}$

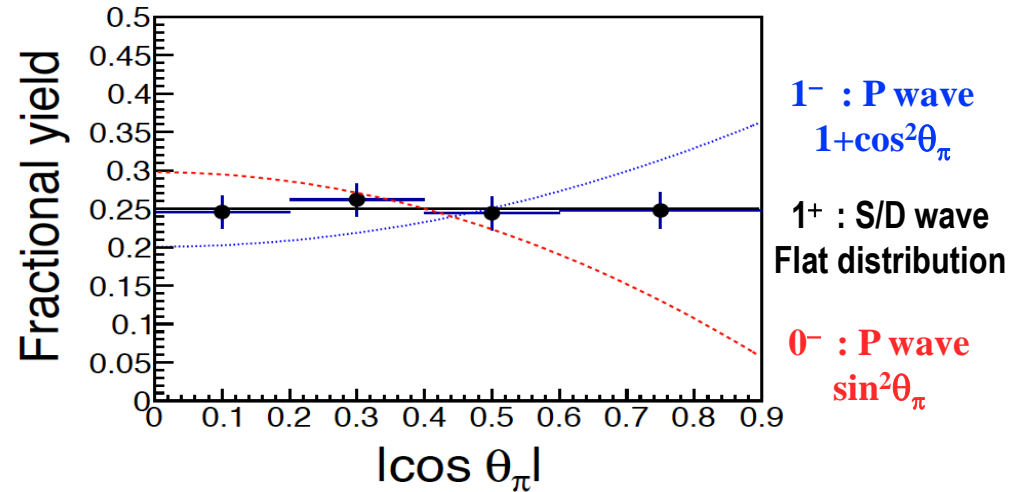


$$M[Z_c(3885)] = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV}$$

$$\Gamma[Z_c(3885)] = 24.8 \pm 3.3 \pm 11.0 \text{ MeV}$$

2 σ /1 σ below those of Z_c(3900)

- Bachelor π angular distribution
favors a $J^P=1^+$ assignment



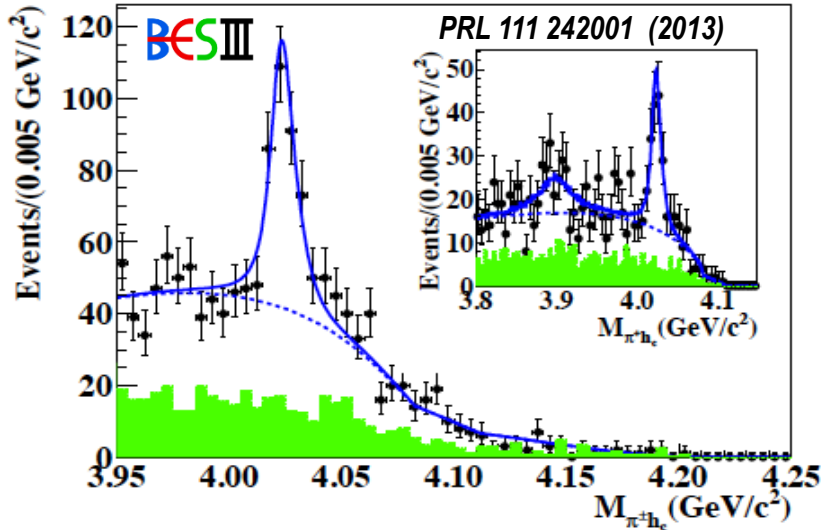
- If Assuming Z_c(3885) is Z_c(3900)

$$\frac{\Gamma(Z_c(3900) \rightarrow DD^*)}{\Gamma(Z_c(3900) \rightarrow \pi J/\psi)} = 6.2 \pm 2.9$$

Large non-DDbar coupling

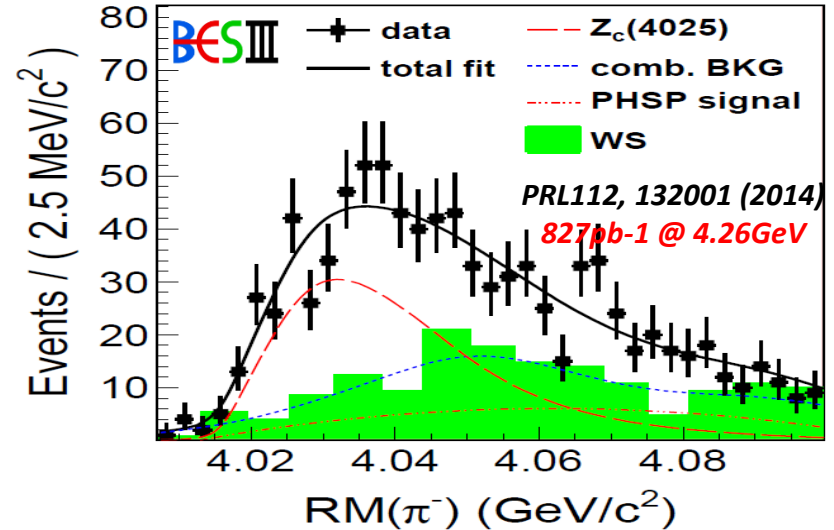
Observation of $Z_c(4020)$

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



- Narrow $\pi^\pm h_c$ structure observed
 - $M = 4022.9 \pm 0.8 \pm 2.7$ MeV;
 - $\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV
 - Significance : 8.9σ
 - No significant evidence for $Z_c(3900) \rightarrow \pi^\pm h_c$
 - Significance 2.1σ
- $$\sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^-h_c) < 11 \text{ pb}$$
- $$\sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^-J/\psi) = 13 \pm 5 \text{ pb}$$

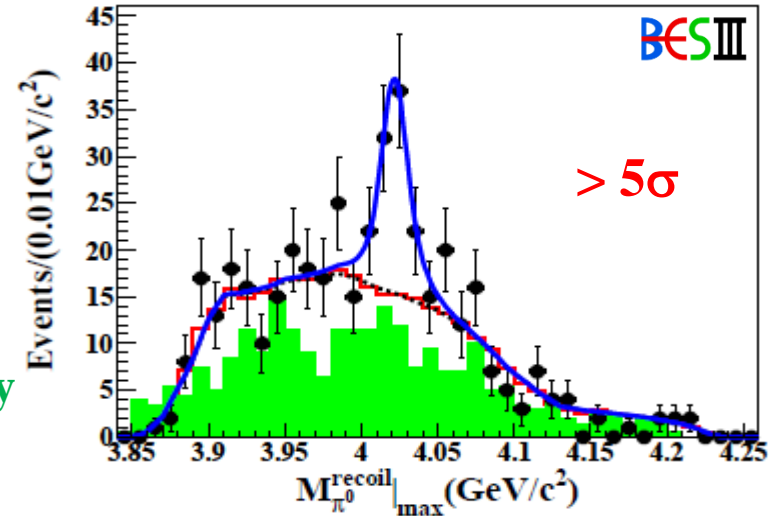
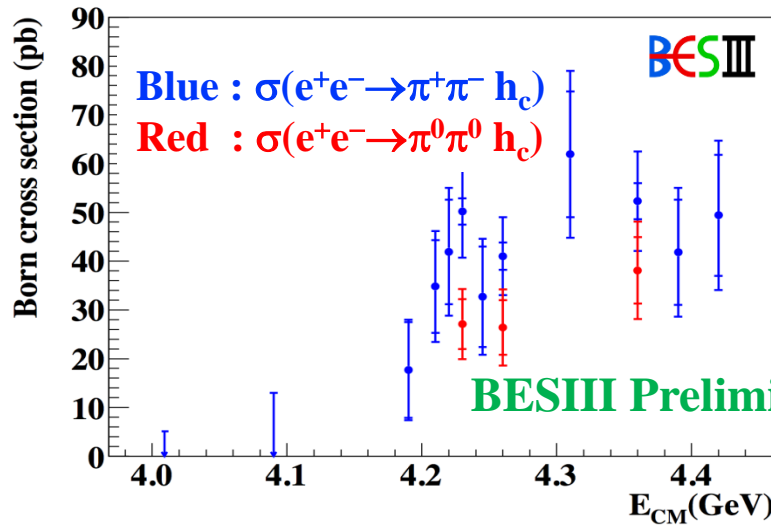
$$e^+e^- \rightarrow \pi^\pm(D^*D^*)^\mp$$



- Deviation from phase space decay
 - $M = 4026.3 \pm 2.6 \pm 3.7$ MeV
 - $\Gamma = 24.8 \pm 5.6 \pm 7.7$ MeV
 - Significance : 10σ
- If assume $Z_c(4025)$ is $Z_c(4020)$

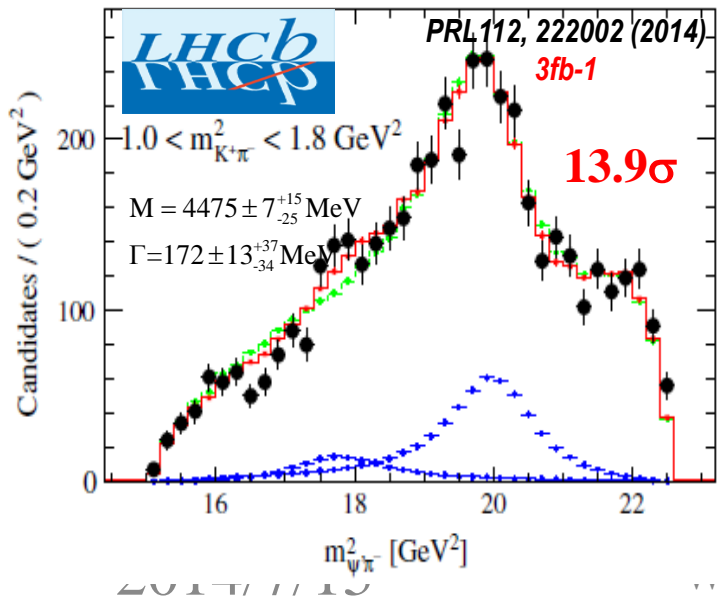
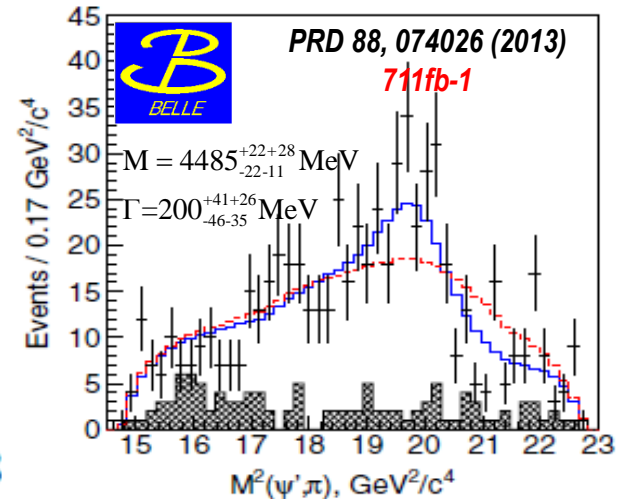
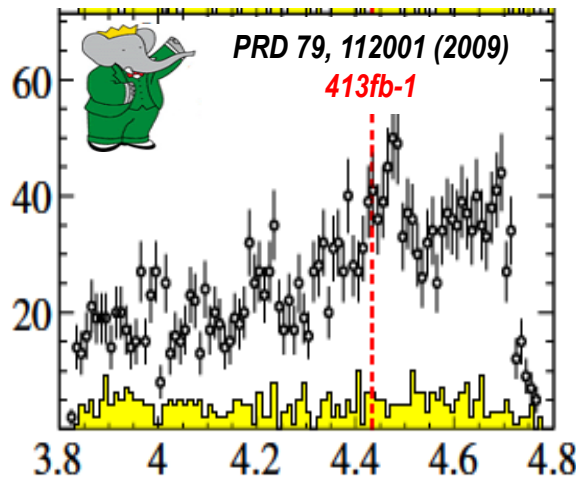
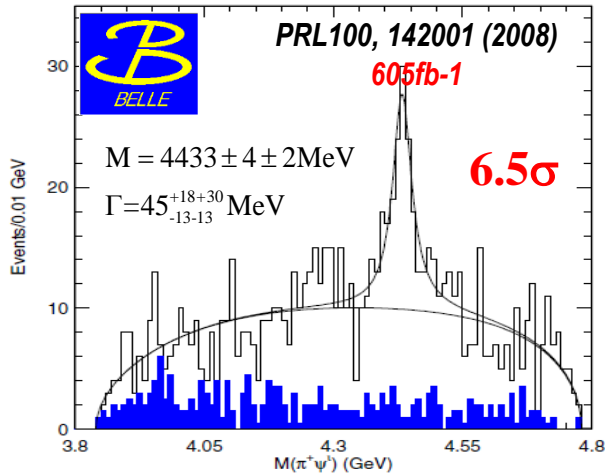
$$\frac{\Gamma(Z_c(4020) \rightarrow D^*\bar{D}^*)}{\Gamma(Z_c(4020) \rightarrow \pi h_c)} = 12 \pm 5$$

Neutral partner of $Z_c(4020)$



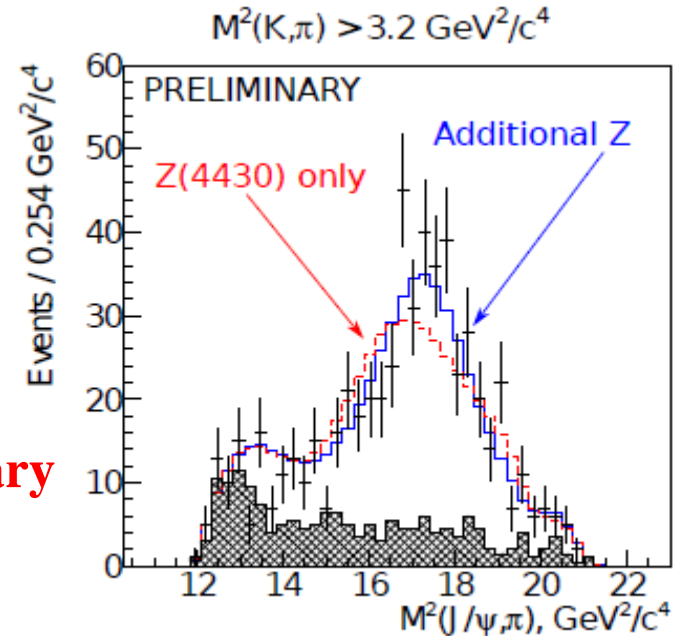
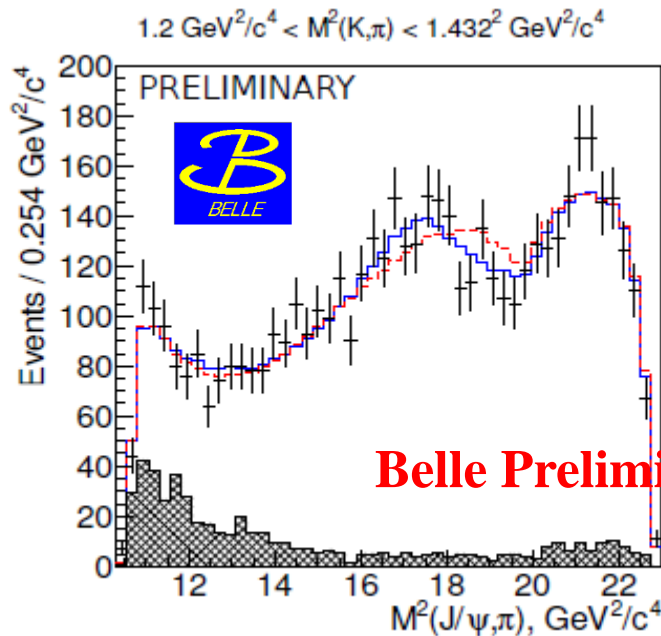
- X-sec. is about half of charged process, agree with expectation of isospin symmetry
- Observe $Z_c(4020)^0$ structure in $\pi_0 h_c$ mass distribution
- Simultaneous fit to 4.23 / 4.26 / 4.36 GeV data, BESIII preliminary Result :
 - $M[Z_c(4020)^0] = 4023.6 \pm 2.2 \pm 3.9$ MeV [$M[Z_c(4020)^\pm] = 4022.9 \pm 0.8 \pm 2.7$ MeV]
 - Width fixed to charged $Z_c(4020)$
 - Interference neglect

$Z_c(4430)$ in $B^0 \rightarrow \psi(2S)K\pi$



- First charged charmonium-like particle, reported by Belle
- Babar : reflections of K^* states, but not contradict to Belle
- Belle update results confirmed its existence, J^P is favored 1^+
 - ✓ Four dimensional analysis, $F=(M^2_{K\pi}, M^2_{\psi'\pi}, \theta_{\psi'}, \phi)$
 - ✓ Mass and width are higher than that of previous Belle results
- LHCb established its existence, $J^P=1^+$ unambiguously
 - ✓ Mass and width consistent with Belle latest result

$B^0 \rightarrow J/\psi k \pi$ @ Belle



- New Z_c (4200) is found (J^P = 1⁺) with 7.2σ:

$$M = 4196_{-29-6}^{+31+17} \text{ MeV}/c^2, \Gamma = 370_{-70-85}^{+70+70} \text{ MeV}.$$

- Exclusion levels (J^P=0⁻, 1⁻, 2⁻, 2⁺) : 6.7σ, 7.7σ, 5.2σ, 7.6σ

- Z_c(4430) is also found (4σ),

A new charged charmonium-like particle, Z_c(4200) ?

A new Z_c(4430) decay mode?

Need confirmation!

$$\frac{\mathcal{B}(Z_c(4430)^+ \rightarrow \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \rightarrow J/\psi\pi^+)} \sim 10$$

Summary and outlook

- Y states
 - ✓ New information on the Y's from BaBar and Belle. Y(4660) confirmed, Y(4008) need confirmed
 - ✓ $e+e-\rightarrow\pi+\pi-h_c$ and $\omega\chi_{c0}$ cross section measured by BESIII
 - different line shape observed at $\pi+\pi-h_c$ process, makes situation complicate
- Zc states
 - ✓ Confirmed exotic state with at least four quarks, $Z_c(3900)$, at BESIII & Belle
 - ✓ Observation of charged and neutral Z_c' at BESIII
 - ✓ $Z_c(4430)$ confirmed by LHCb, quantum number favor 1^+

Summary and outlook

- Y(4260), Y(4360) and Y(4660) @ BESIII
 - ✓ All produced in e^+e^- collisions
 - narrow structure above charm threshold
 - Strongly couple to charmonium states
 - ✓ No evidence in open-charm process and R-value scan
Large BESIII R value data sample may confirm/improve
 - ✓ C-even states can be produced from radiative transitions
- ISR & B decay @ Belle, Babar and Belle II
 - ✓ Belle and Babar have remarkable success in quarkonium spectroscopy
 - ✓ No doubt for further success for Belle II with higher luminosities
- ATLAS/CMS/LHCb @ LHC
 - ✓ made great measurement improved results from B-Factory
 - ✓ Promise to be even more fruitful sources after a two-year shutdown for an upgrade