A Review of Heavy Exotic States

Jianming Bian

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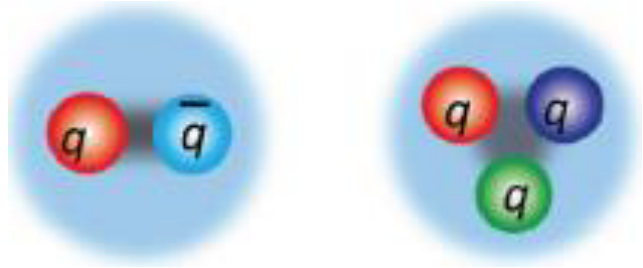
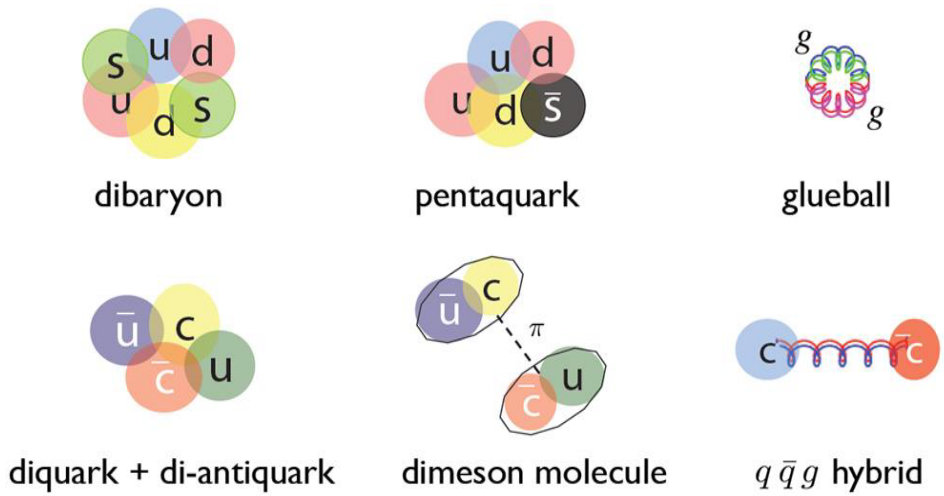
University of Minnesota

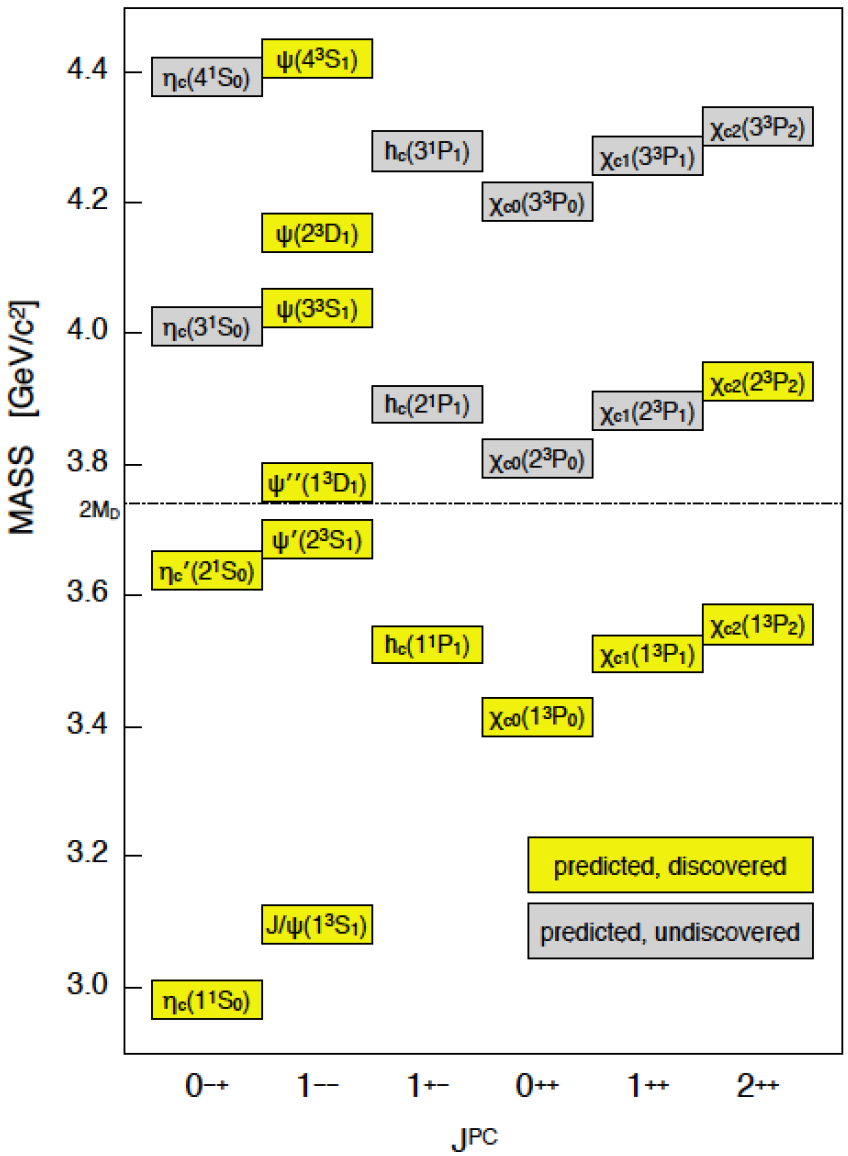
Hadrons： normal & exotic

- In the quark model, hadrons are dominantly bound states of qqbar (mesons) or qqq (baryons)
- But QCD allows hadrons with $N_{quarks} \neq 2, 3$
  - Glueball: $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid: $N_{quarks} = 2$ + excited gluon
  - Multiquark state: $N_{quarks} > 3$
  - Molecule: bound state of 2 or more hadrons
  - …
- It is a long history of searches for these exotic hadrons, however, no solid experimental evidence was found until recent breakthroughs in the charmonium region.





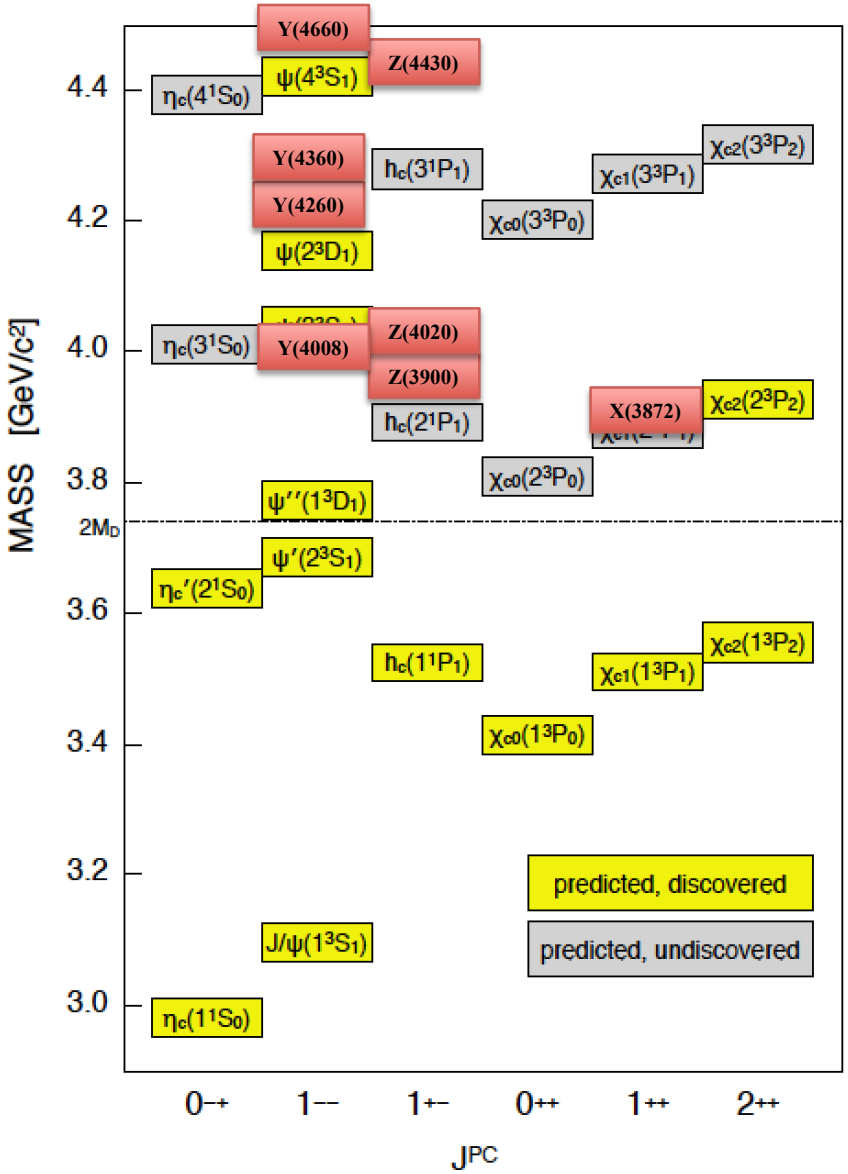
Charmonium spectroscopy



Below open-charm threshold, all states have been observed. Charm anti-charm potential models describe spectrum very well.

Many missing states above open-charm threshold.

There are lots of XYZ states



A number of new states above open-charm threshold.

Charmonium in the final state, but not an obvious charmonium state (charmoniumlike or *XYZ*)

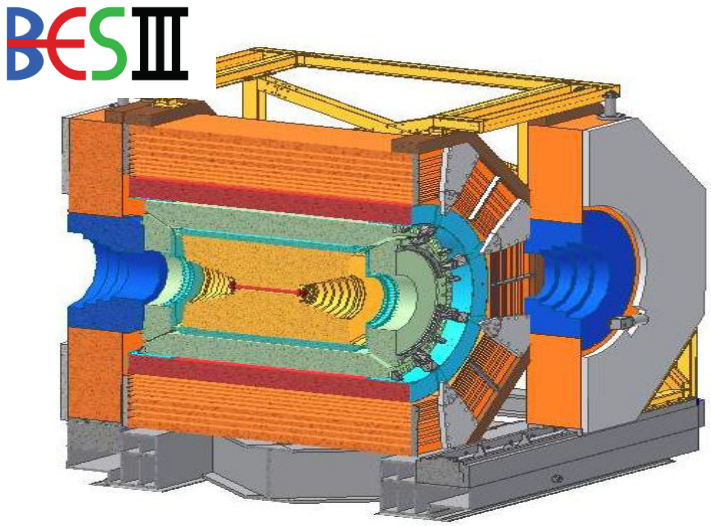
What are they?

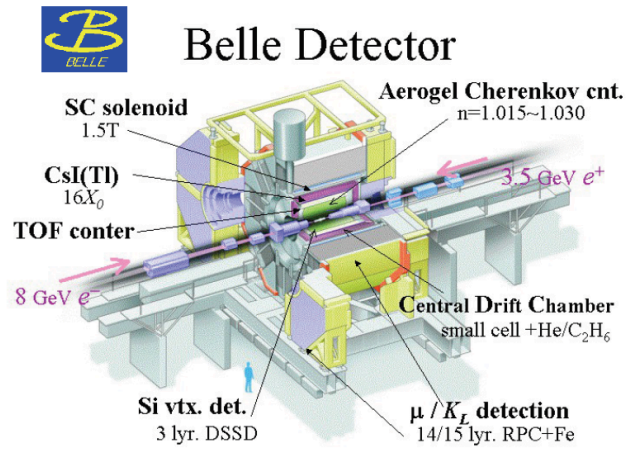
- Charmonium?
- Tetraquark?
- Molecule?
- Hybrid?
- Hadrocharmonium?
- …

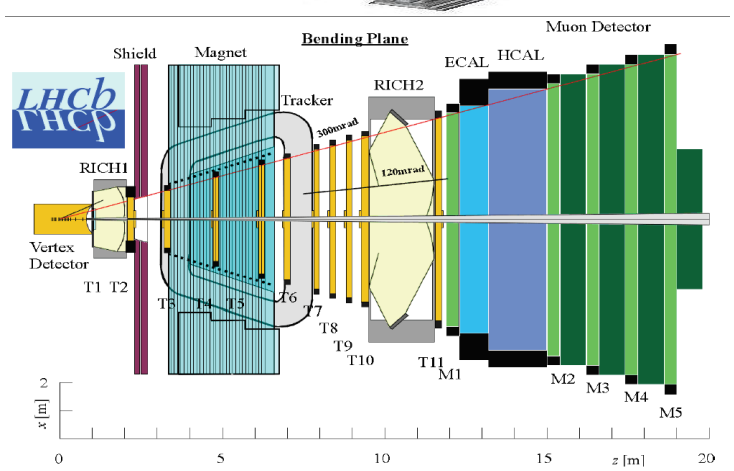
XYZ and Experiments

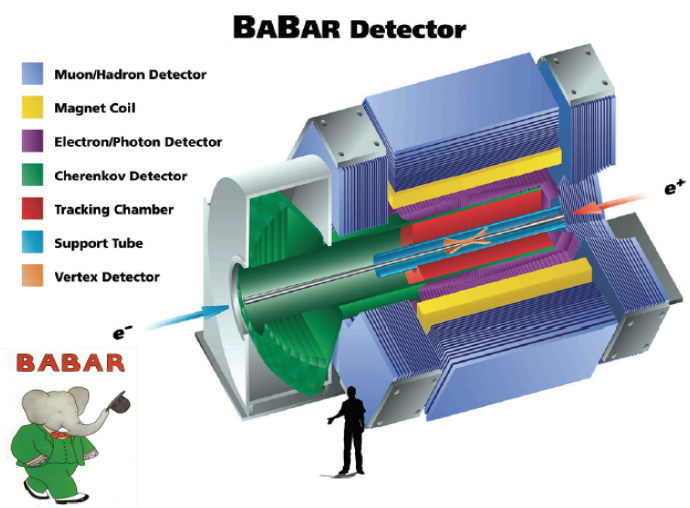
- ***X***: **neutral, in B decays and hadron machines.**
- ***Y***: **neutral, vectors in e^+e^- colliders.**
- ***Z*$^{\pm}$**: **charged quarkonium-like**

+CLEO-c, CDF, CMS…



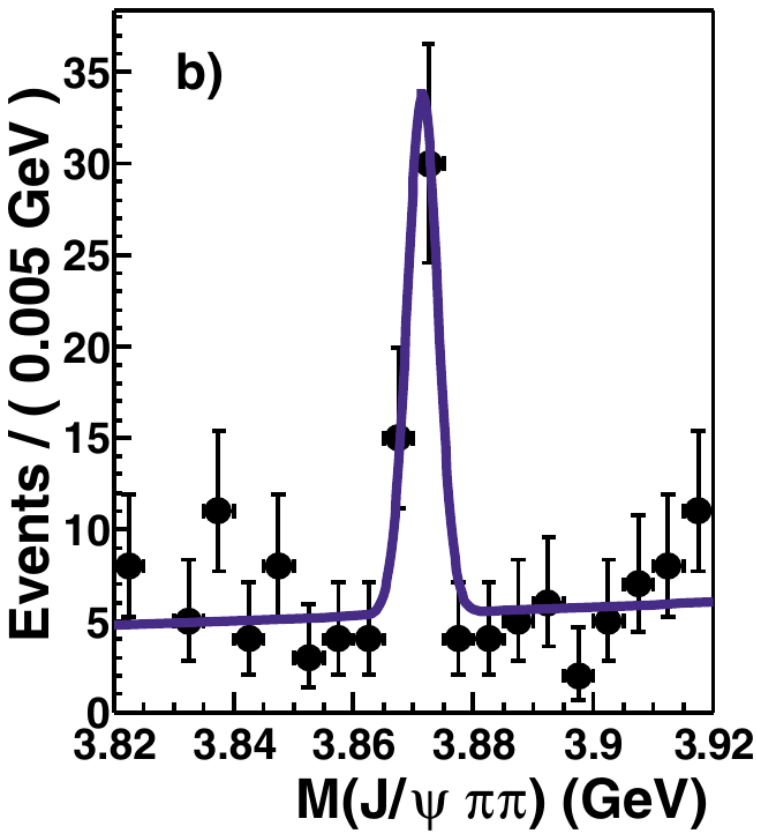






What is the *X*(3872)?

BELLE [PRL 91, 26 (2003)]

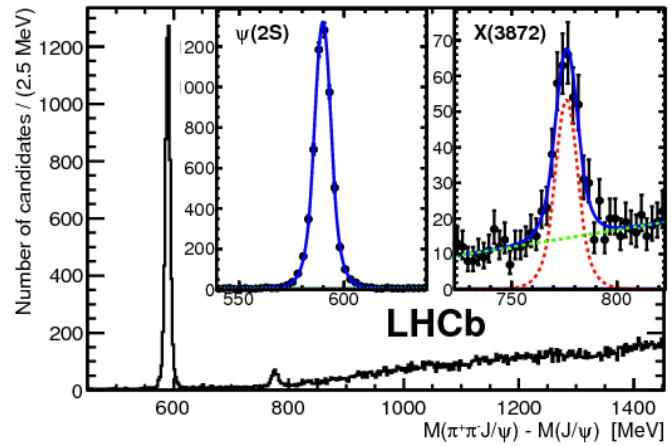


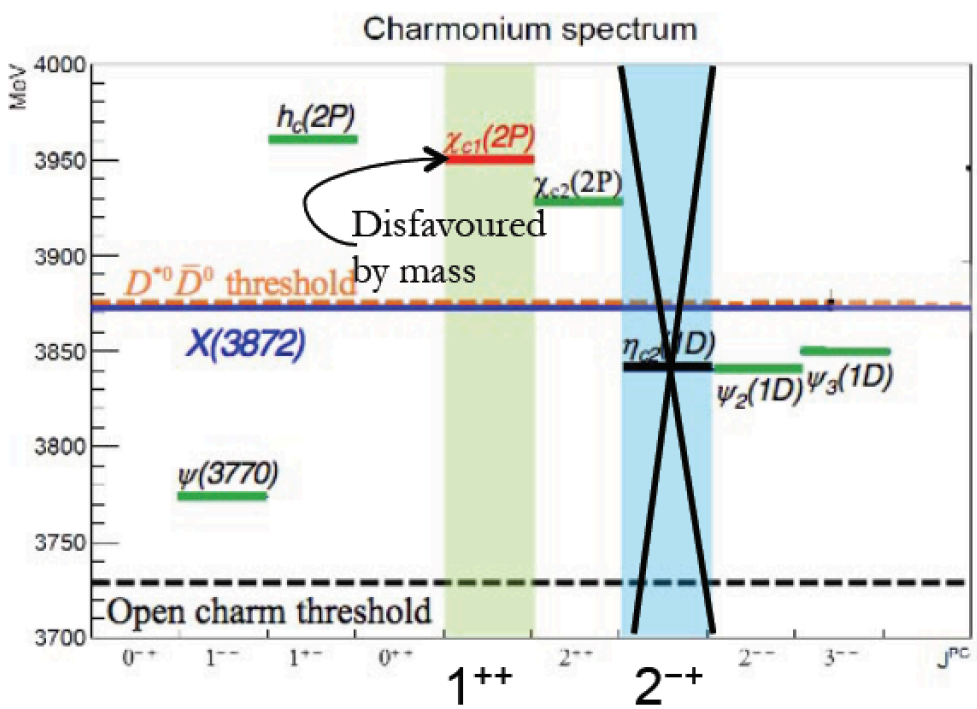
D- or P-wave charmonium?
Molecular state?
Tetraquark?
Molecule + charmonium mixture?

- First observed charmonium-like exotic state is *X(3872)*.
- Observed at Belle in 2003 in the mode $\pi^+\pi^- J/\psi$, confirmed by CDF, D0, BaBar, CMS and LHCb.
- Mass: Very close to $D^0 D^{*0}$ threshold.
- Width: Very narrow (< 1.2 MeV).
- Mass and decay modes are in disagreement with charmonium.
- Produced in
  - *pp* collision
  - *B* decay *(B→KX)*
  - *Y(4260)→γX*(3872) ?

Determination of the *X*(3872) quantum numbers.

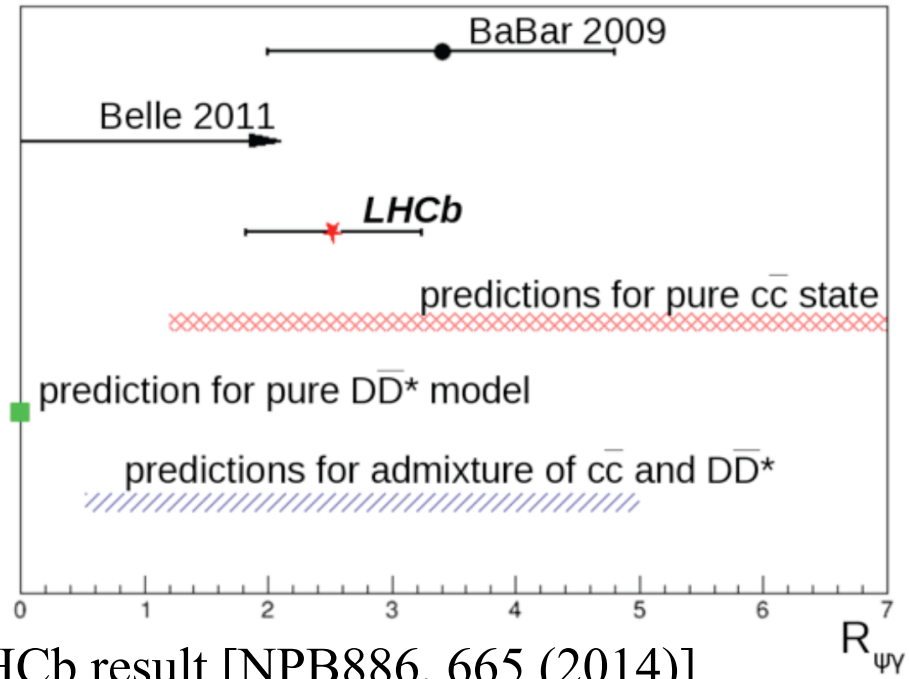
- CDF measurement [PRL 98 132002 (2007)] excluded all J^{PC} except 2^{-+} and 1^{++}.
- LHCb measurement [PRL 110, 222001 (2013)], established $J^{PC} = 1^{++}$.





~~D-wave charmonium?~~
Molecular state?
Tetraquark?
Molecule + charmonium mixture?

Radiative decays of *X*(3872)



~~D-wave charmonium?~~
~~molecular state?~~
Tetraquark?
Molecule + charmonium mixture?

LHCb result [NPB886, 665 (2014)]

$$R_{\psi\gamma} = \frac{\mathcal{B}(\mathrm{X}(3872) \to \psi(2\mathrm{S})\gamma)}{\mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

BaBar result [PRL102 132001 (2009)]

$R_{\psi\gamma}=3.4\pm1.4$

Belle did not see signal [PRL107, 091803 (2011)]

$R_{\psi\gamma}<2.1$ @ 90%CL

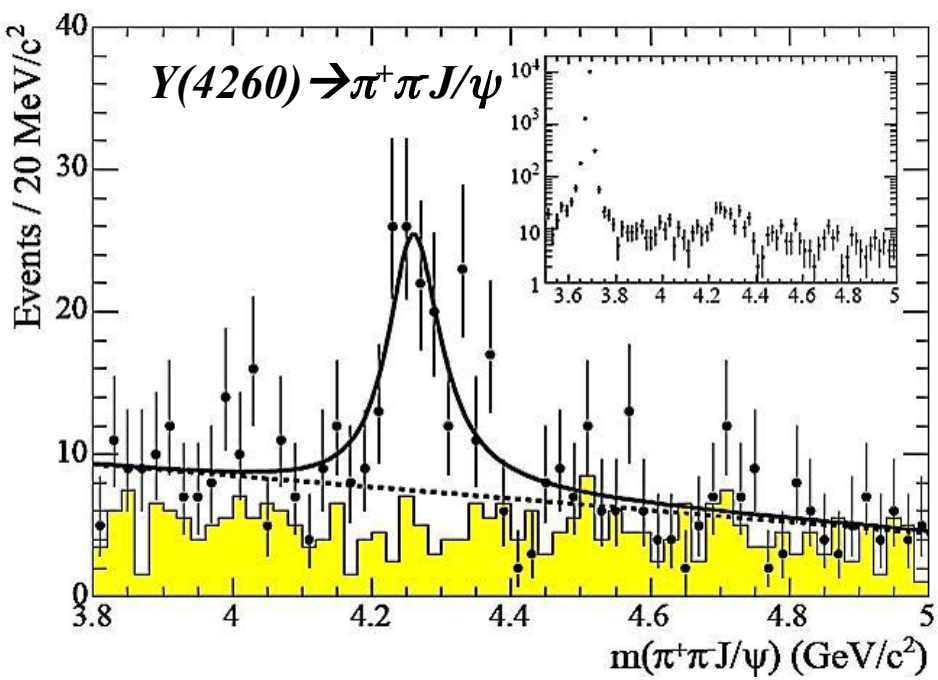
Average:

$$\overline{R} = \frac{\mathcal{B}(X(3872) \to \gamma\psi(2S))}{\mathcal{B}(X(3872) \to \gamma J/\psi)} = 2.31 \pm 0.57$$

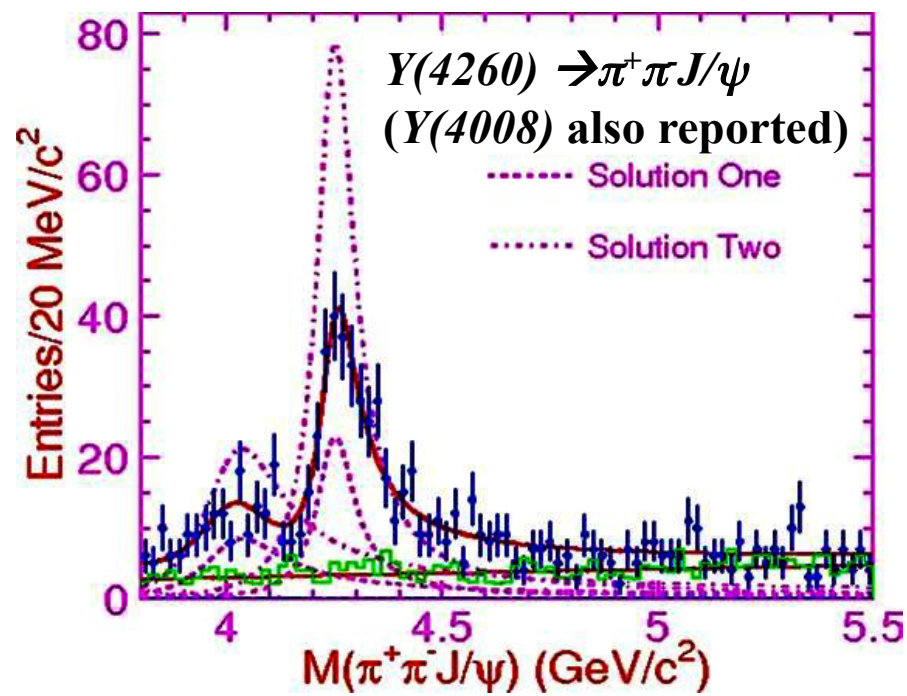
Y-family states

- A family of vectors ($J^{PC}=1^{--}$) observed in e^+e^- colliders.
- In the process $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$, the BaBar experiment observed the $Y(4260)$, then confirmed by CLEO and Belle.
- Properties are different from 1^{--} charmonium: strong coupling to $\pi\pi J/\psi$, no significant enhancement in open charm production.

BaBar: [PRL95, 142001]
273fb-1

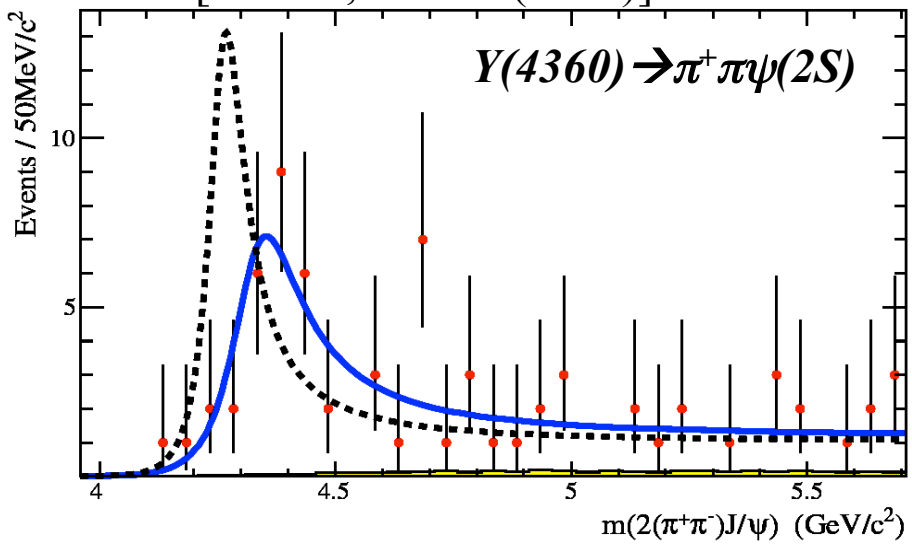


Belle [PRL99, 182004 (2005)]
548fb-1

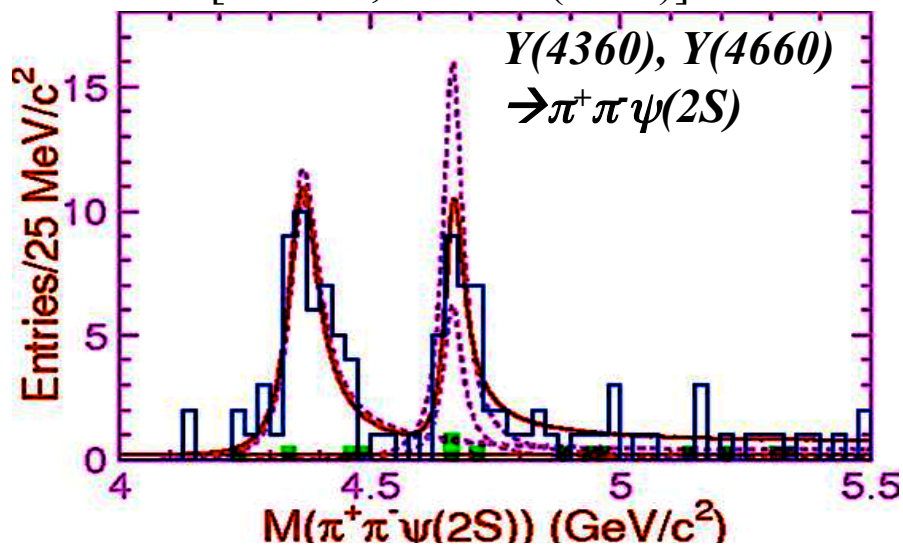


Y-family states

BaBar [PRL95, 142001(2005)] 273fb^{-1}



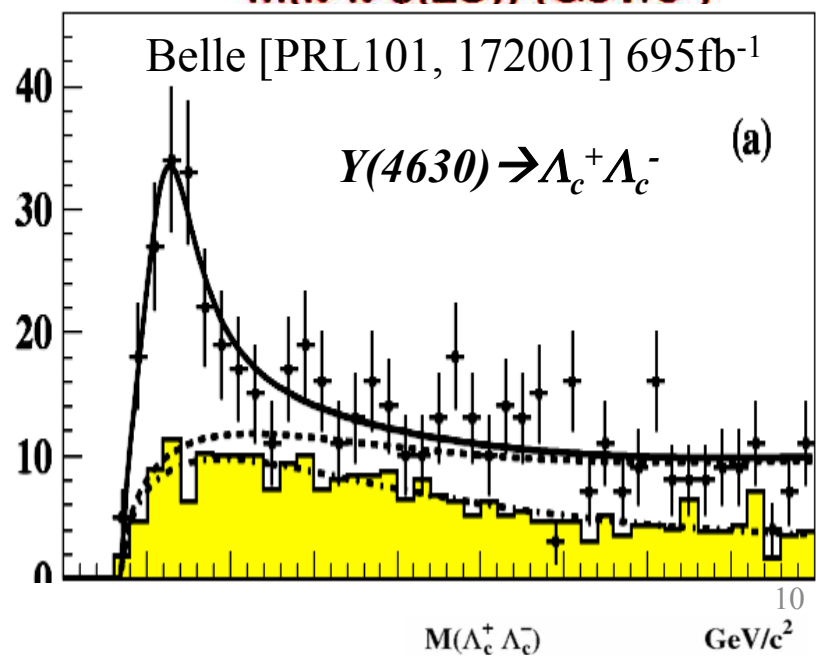
Belle [PRL 99, 142002 (2007)] 673fb^{-1}



Several Y states were observed by Belle and BaBar in $\pi^+\pi J/\psi$, $\pi^+\pi\psi(2S)$ and $\Lambda_c\Lambda_c$ after the discovery of *Y(4260)*.

***Y(4008)* (Belle)**
***Y(4260)* (BaBar, Belle, CLEO)**
***Y(4360)* (BaBar, Belle)**
***Y(4660)* (Belle, BaBar)**
***Y(4630)* (Belle)**

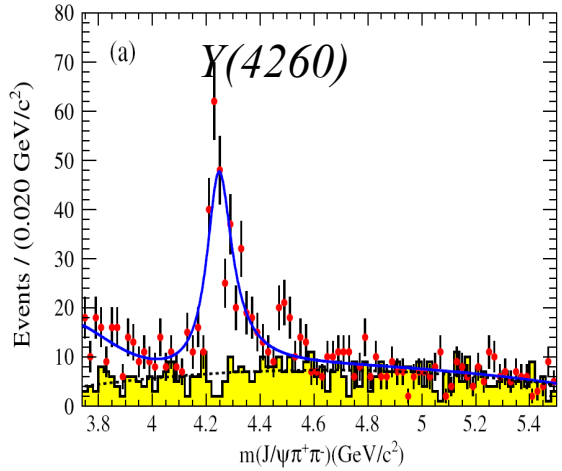
Belle [PRL101, 172001] 695fb^{-1}



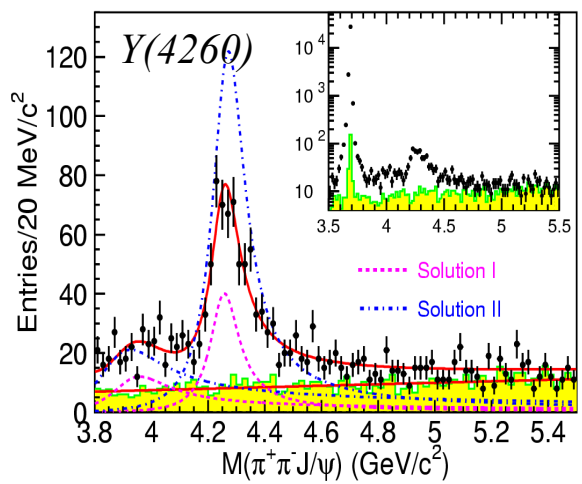
Y-family states

With larger data samples *Y*(4260), *Y*(4360) and *Y*(4660) were confirmed by Belle and BaBar in ISR process.

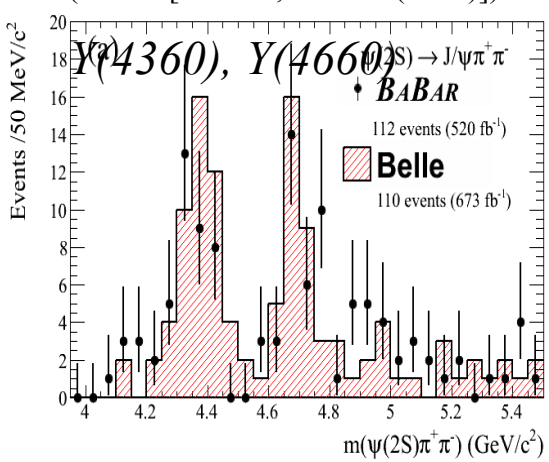
BaBar [PRL 98, 212001 (2007)] 298 fb^{-1}



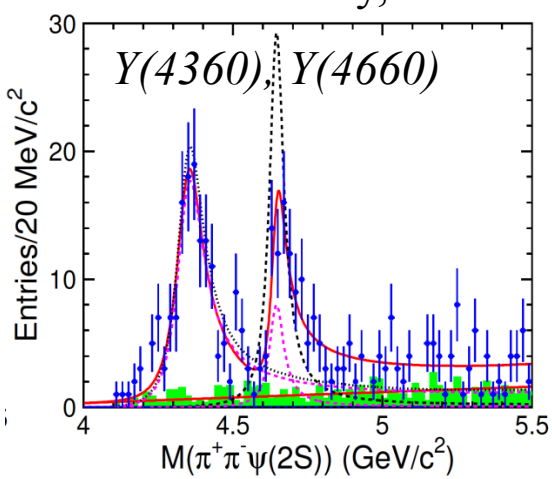
Belle [PRL110,252002 (2013)], 967 fb^{-1}

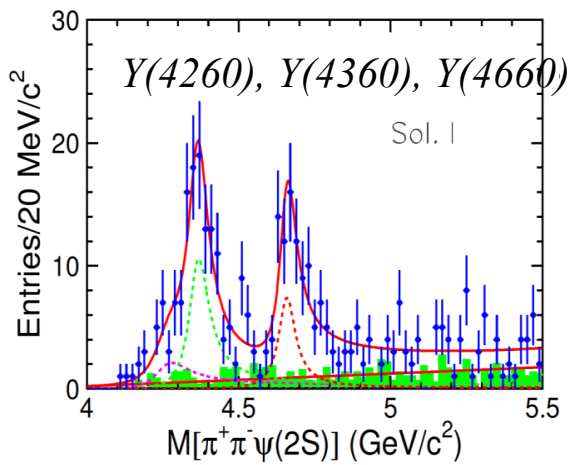


BaBar [PRD 89, 111103 (2014)]
(Belle [PRL 99, 142002 (2007)])



Belle Preliminary, 980 fb^{-1}

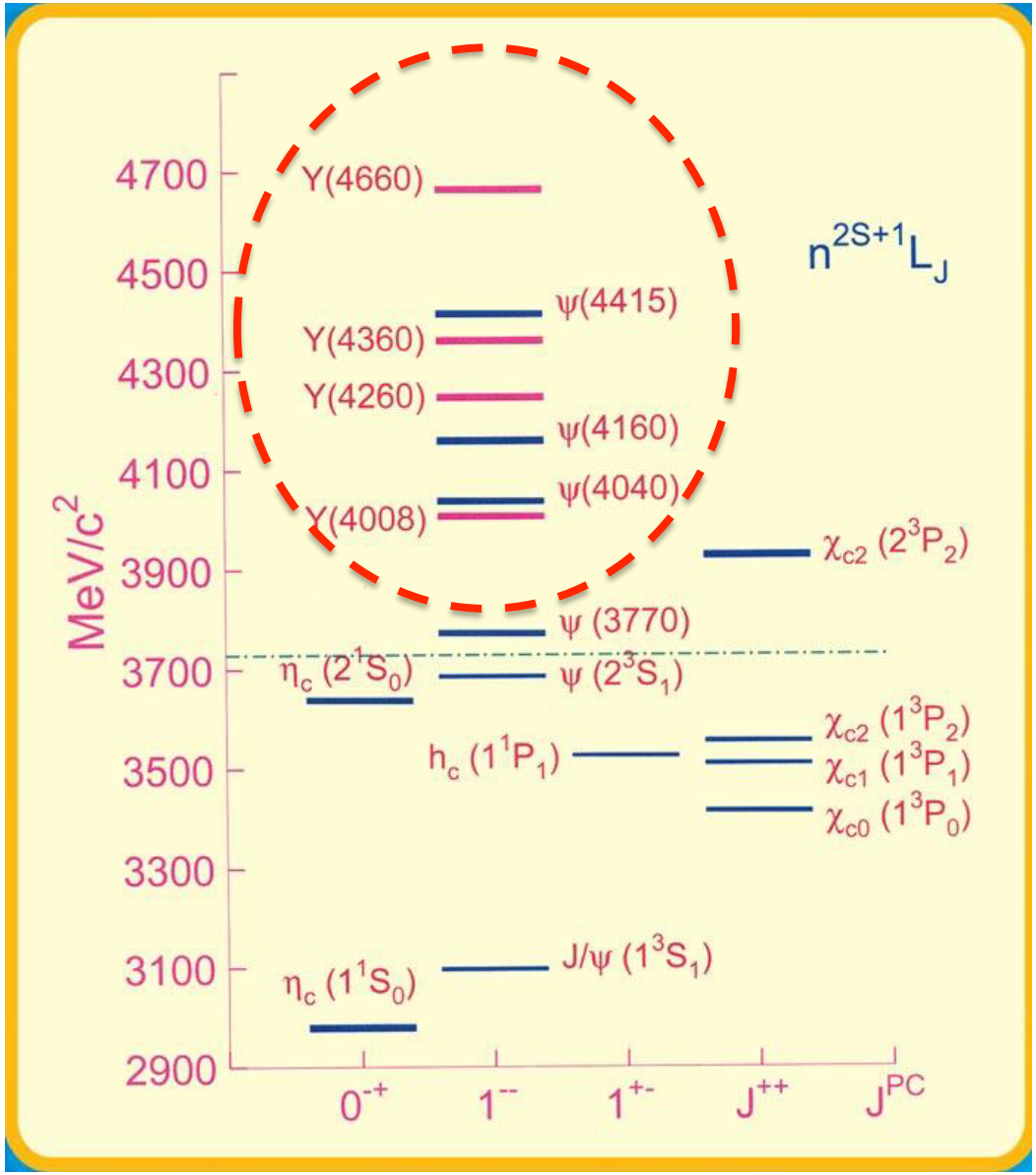




List of Y-family states

State	Mass (MeV/c^2)	Width (MeV/c^2)	Decay mode	Experiment
$Y(4008)$	4008^{+121}_{-49}	226±97	$\pi^+\pi J/\psi$	Belle
$Y(4260)$	4250±9	108±12	$\pi^+\pi J/\psi$ $\pi^0\pi^0 J/\psi$ $K^+K^- J/\psi$	BaBar CLEO Belle
$Y(4360)$	4361±13	74±18	$\pi^+\pi\psi(2S)$	Belle BaBar
$Y(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	$\Lambda_c^+\Lambda_c^-$	Belle
$Y(4660)$	4664±12	48±15	$\pi^+\pi\psi(2S)$	Belle BaBar

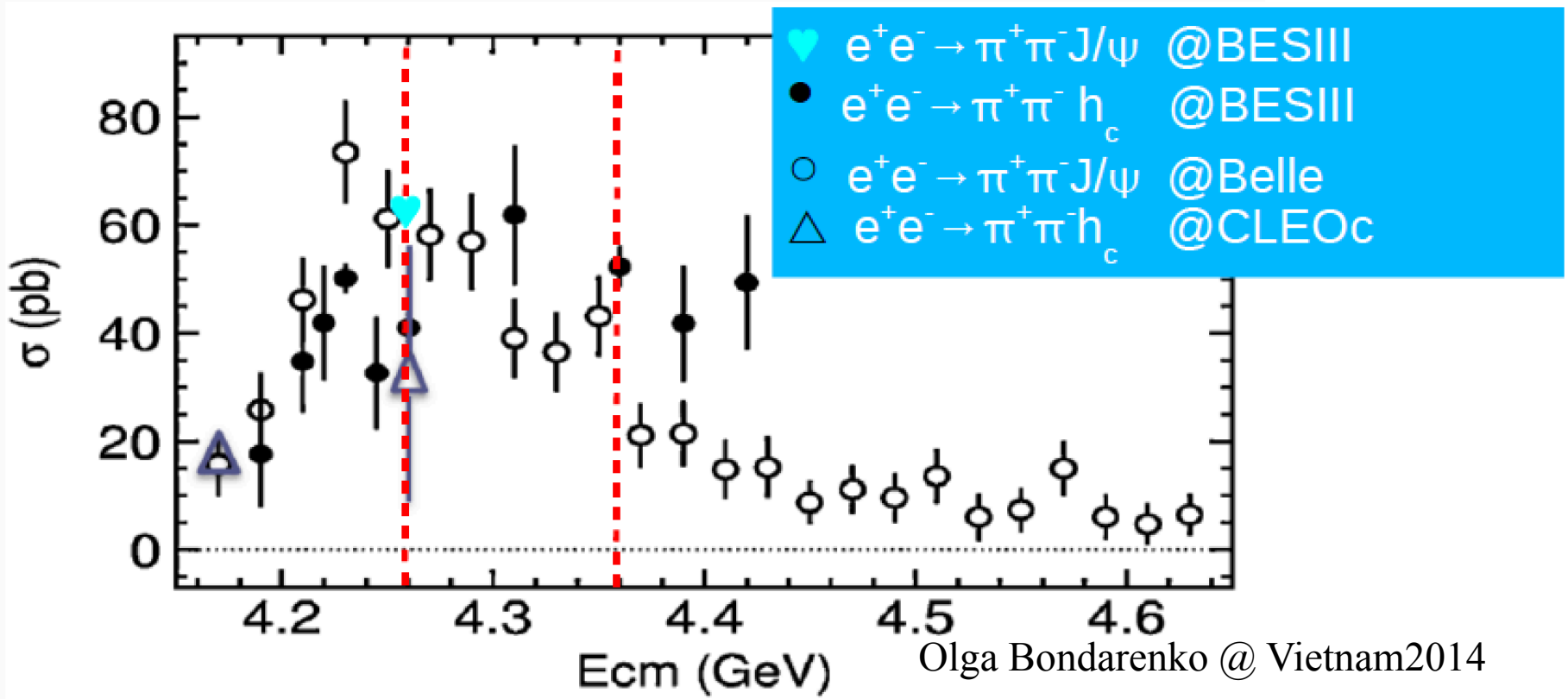
What do we know about Y?



- Between 4 and 4.7 GeV, at most 5 1^{--} states expected in charmonium family (3S, 2D, 4S, 3D, 5S), but 7 particles are observed.
- Hybrids? Molecular states? Hadrocharmonium? Threshold effect? FSI?
- *Y*(4260), *Y*(4360) and *Y*(4660) are similar and narrow.

C. Z. Yuan @ LP2013

Cross sections around *Y*-states region

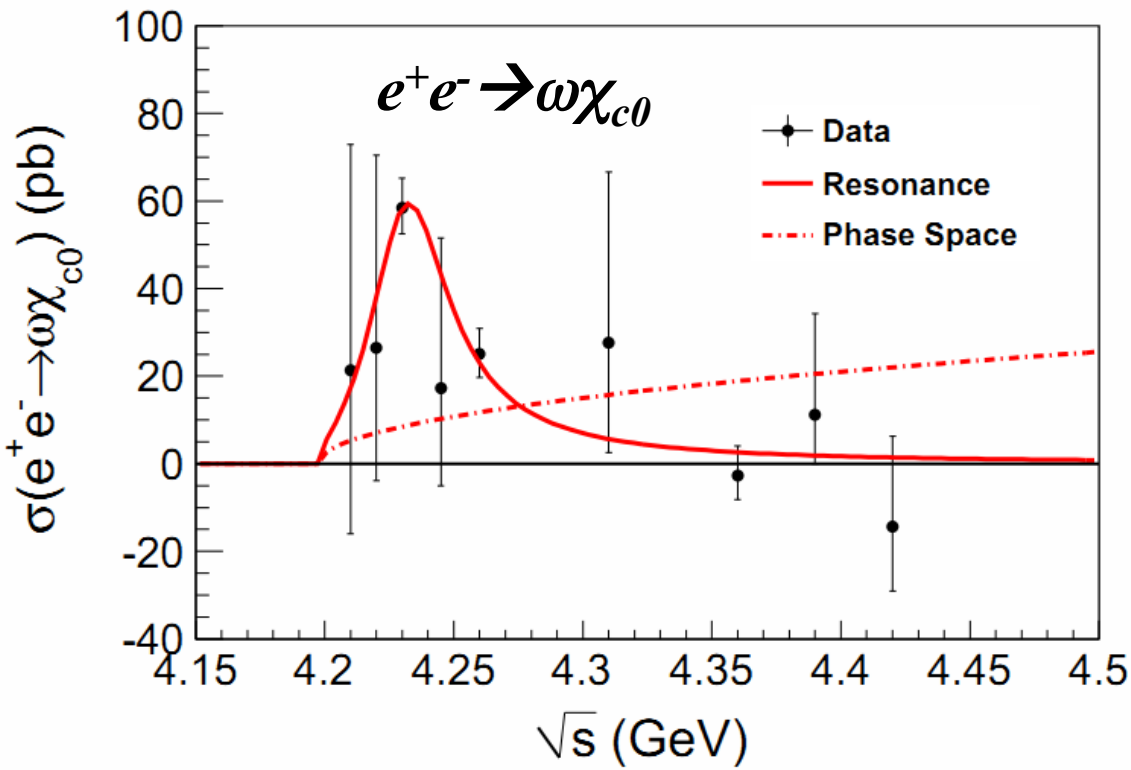


Olga Bondarenko @ Vietnam2014

- Different decay modes have similar cross sections.
- The line shapes seem to be different.
- Correlation with *Y*(4260) or *Y*(4360) is unclear.

Cross sections around *Y*-states region

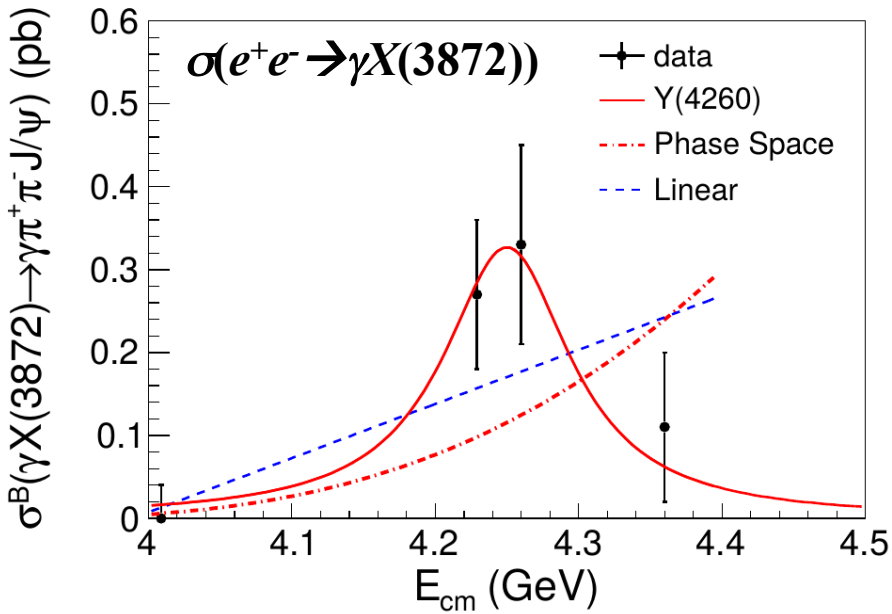
BESIII preliminary

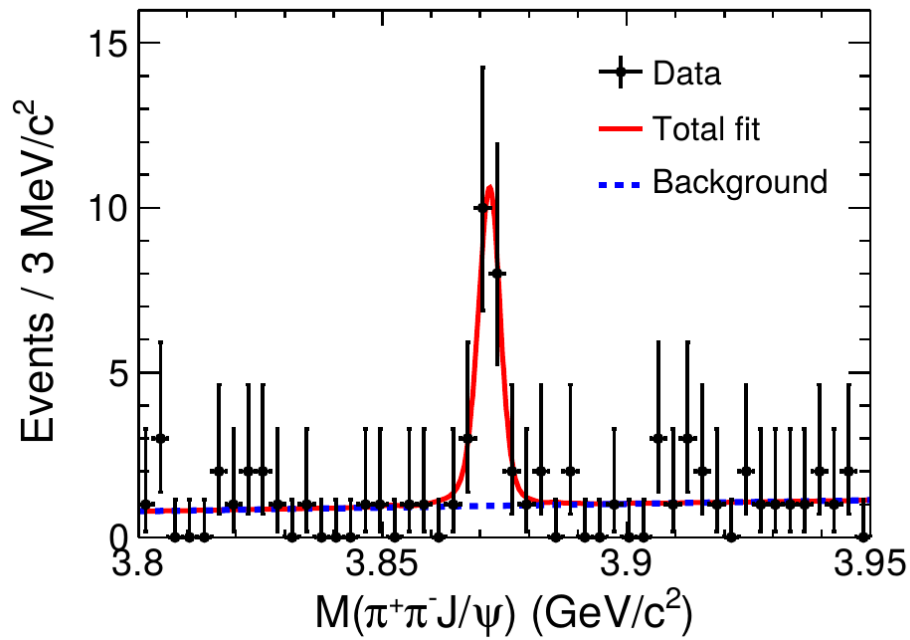


$e^+e^- \rightarrow \omega\chi_{c0}$ are observed at 4230 MeV and 4260 MeV. Signal does not arise from the decays of the *Y*(4260).

Cross sections of $e^+e^- \rightarrow \gamma X(3872)$

BESIII [PRL 112, 092001 (2014)]





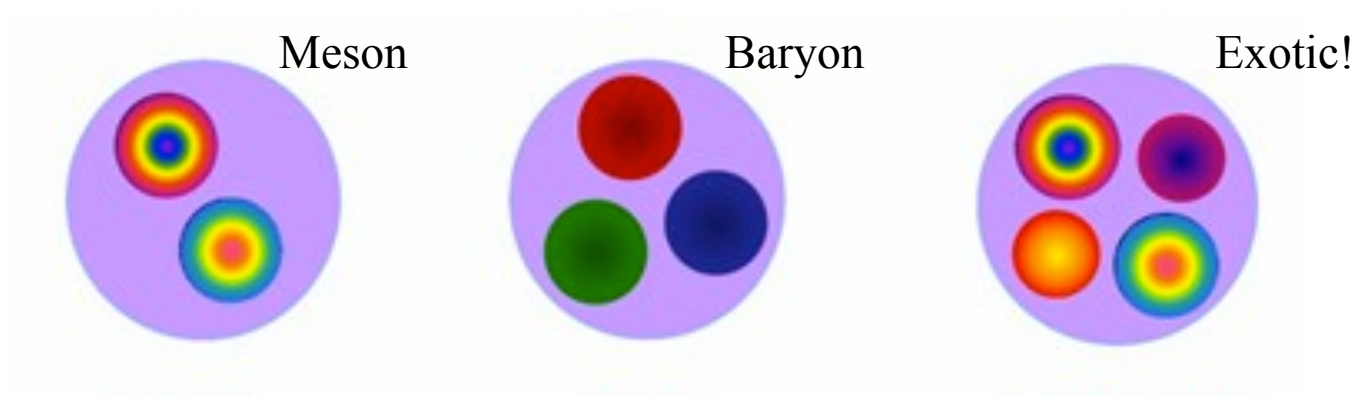
- BESIII observed $e+e- \rightarrow \gamma X(3872)$.
- It seems that $X(3872)$ is from $Y(4260)$.
- $R(B(e^+e^- \rightarrow \gamma X(3872))/B(e^+e^- \rightarrow \pi^+\pi^- J/\psi)) \sim 11\%$, large transition rate.
- Together with $Y(4260) \rightarrow \pi Z_c(3900)$, indicates commonality in the nature of the exotics states $X(3872)$, $Y(4260)$, and $Z_c(3900)$.

$Z_c^{\pm}$: charged charmonium-like states

- $Z_c^{\pm}$ decay to charmonium demonstrates a ccbar pair.
- Electric charge demonstrates two or more light quarks:

$$N_{quark} \geq 4$$

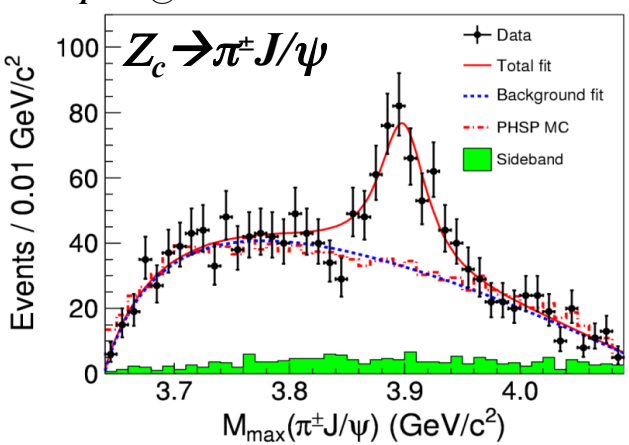
- A clear signature for an exotic hadronic state!



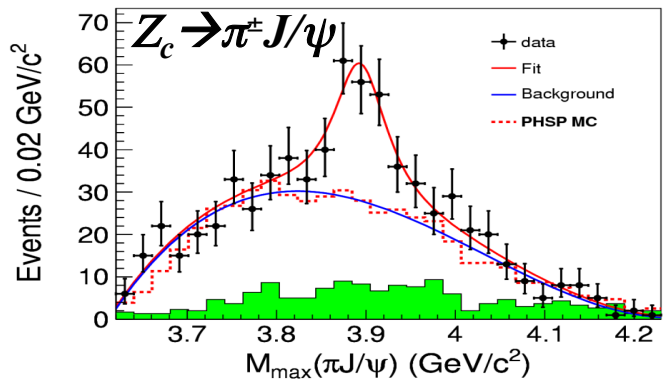
- Search in final states $\pi J/\psi$, πh_c, $\pi\psi(2S)$ $\pi\chi_{cJ}$...

Observation of $Z_c(3900)^{\pm}$ in $e^+e^- \to \pi^+\pi^- J/\psi$

BESIII[PRL 110 252001 (2013)]
525pb-1 @ 4.26GeV



Belle PRL 110 252002 (2013)
967fb-1, in e+e-→$\gamma_{ISR}\pi+\pi-J/\psi$

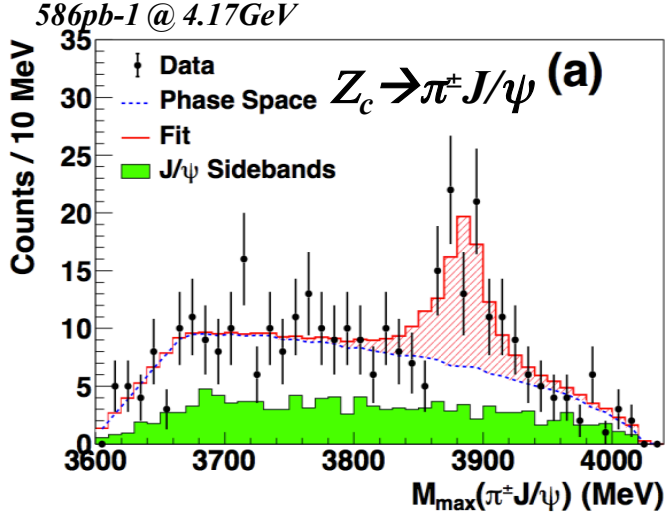


BESIIII
M = 3899.0±3.6±4.9 MeV
Γ= 46±10±20 MeV 307±48 events, >8σ

Belle
M = 3894.5±6.6±4.5 MeV
Γ=63±24±26 MeV
159 ± 49 events, >5.2σ

CLEO-c data
M = 3886±4±2 MeV
Γ= 37±4±8 MeV
81±16 events, >5σ

CLEO-c data [PLB 727 366-370 (2013)]
586pb-1 @ 4.17GeV

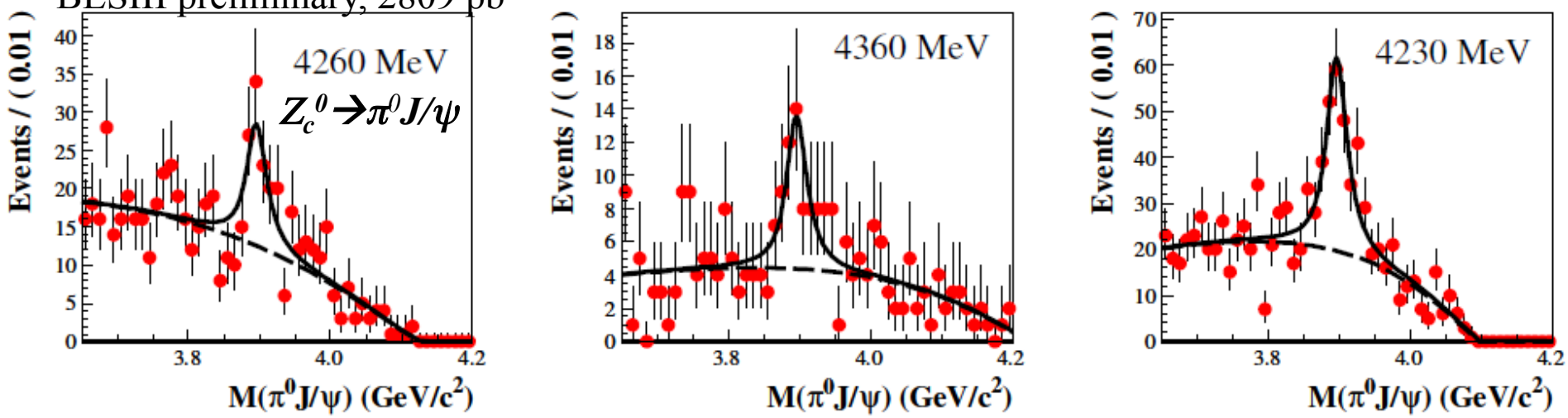


- **$Z_c(3900)^{\pm}$: first confirmed charged charmonium-like states observed in $\pi^+\pi^- J/\psi$ by BESIII, Belle and confirmed in CLEO-c data (NWU group).**

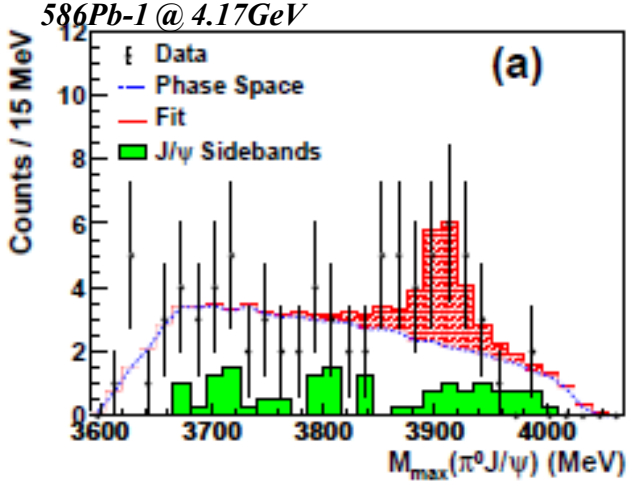
- **Couple to ccbar.**
- **Has electric charge.**
- **At least 4 quarks.**
- **Mass close to DD* threshold.**
- **Molecular state? Tetraquark? Hadrocharmonium? Threshold effect? …**

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

BESIII preliminary, 2809 pb^{-1}

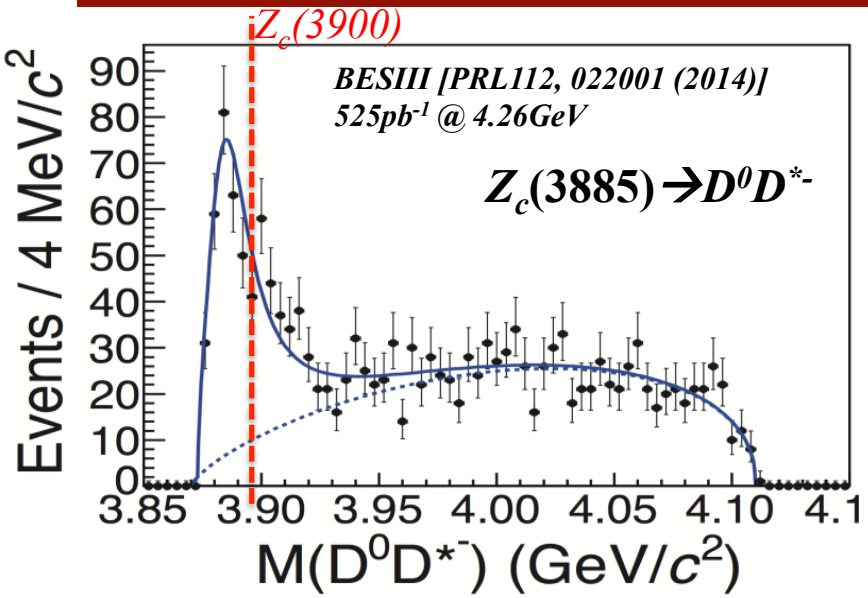


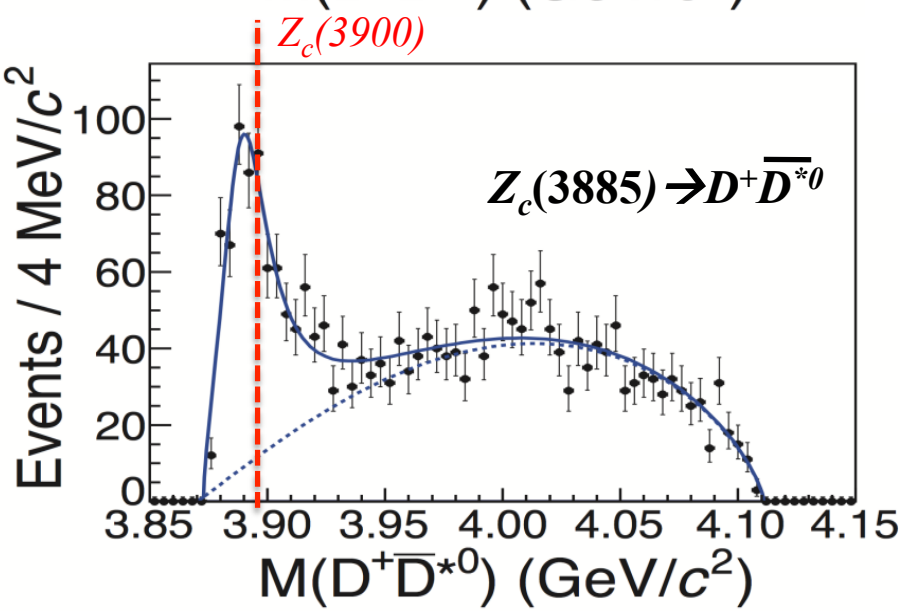
CLEO-c data[PLB 727 , 366-370 (2013)]
586Pb-1 @ 4.17GeV



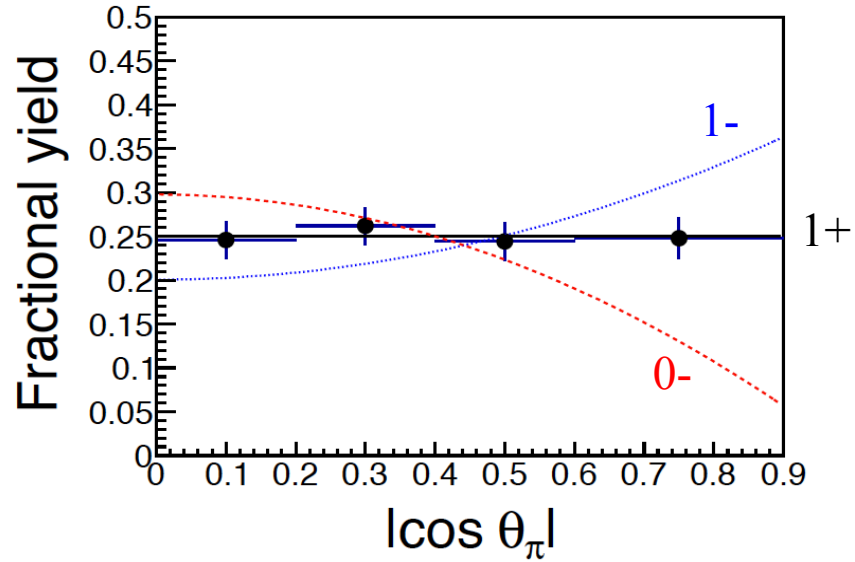
- $Z_c(3900)^0$ is observed clearly at E_{cm}=4230, 4260, 4360MeV by BESIII.
- BESIII preliminary result:
- M= 3894.8±2.3 MeV
- Γ = 29.6±8.2 MeV
- Significance = 10.4 σ
- Interpretation: neutral isospin partner, $Z_c(3900)^0$ observed

$e^+e^- \to \pi^\pm(DD^*)^\pm$ @ 4.26 GeV





π angular distribution indicates that **J^P favors 1+**



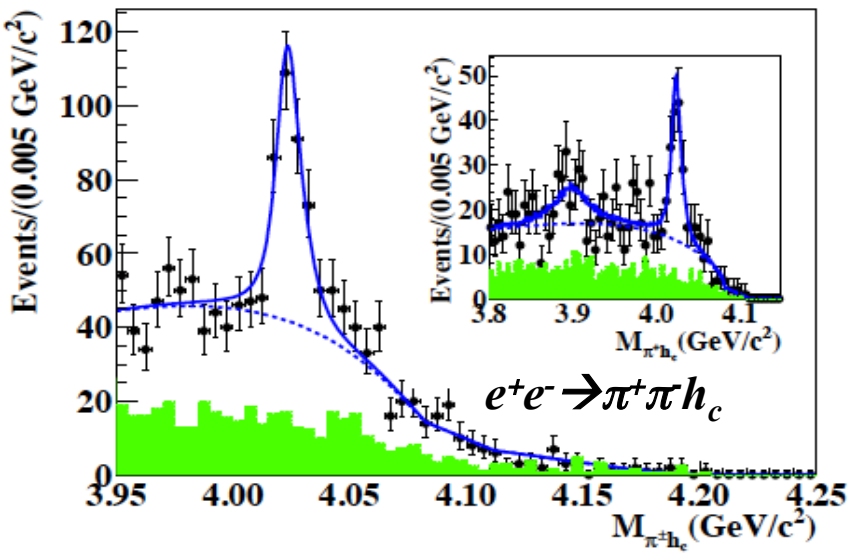
M[Z_c(3885)] = 3883.9±1.5±4.2MeV
Γ[Z_c(3885)] = 24.8±3.3±11.0MeV
2σ/1σ below those of Z_c(3900)

Assuming Z_c(3885) is Z_c(3900):
$\Gamma(DD^*)/\Gamma(\pi J/\psi) = 6.2 \pm 2.9$

Large non-DDbar coupling

Observation of $Z_c(4020)^{\pm}$ in $e^+e^- \to \pi^+\pi^- h_c(1P)$

BESIII [PRL 111 242001 (2013)]



Narrow $\pi^{\pm}h_c$ structure observed

***M = 4022.9±0.8±2.7 MeV**

***Γ= 7.9±2.7±2.6 MeV**

***Significance : 8.9σ**

Hint for $Z_c(3900) \to \pi^{\pm}h_c$?

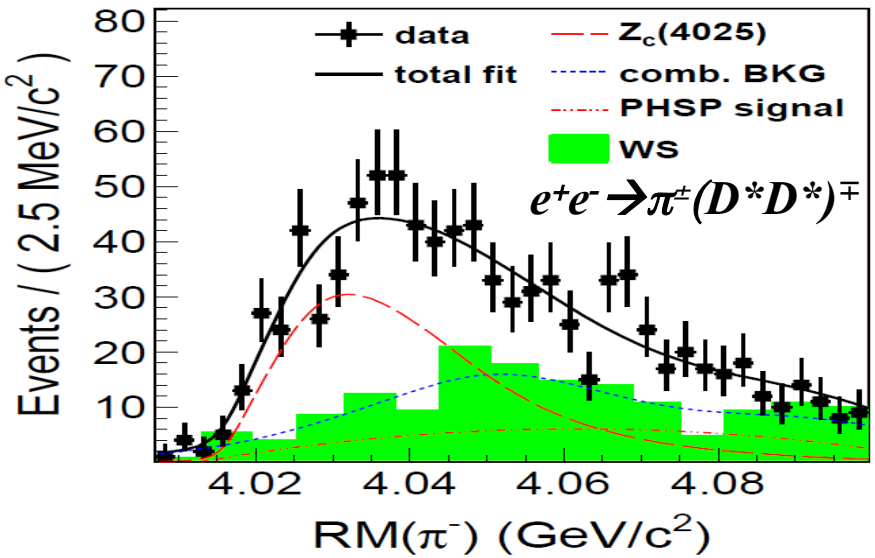
***Significance is only 2.1σ**

$J/\psi(1S)$	$c\bar{c}\uparrow\uparrow$
$h_c(1P)$	$c\bar{c}\uparrow\downarrow$

$$\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- h_c) < 11 \text{ pb}$$

$$\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi) = 13 \pm 5 \text{ pb}$$

BESIII [PRL112, 132001 (2014)]
827pb^{-1} @ 4.26GeV



Deviation from phase space decay

***M = 4026.3±2.6±3.7 MeV**

***Γ = 24.8±5.6±7.7 MeV**

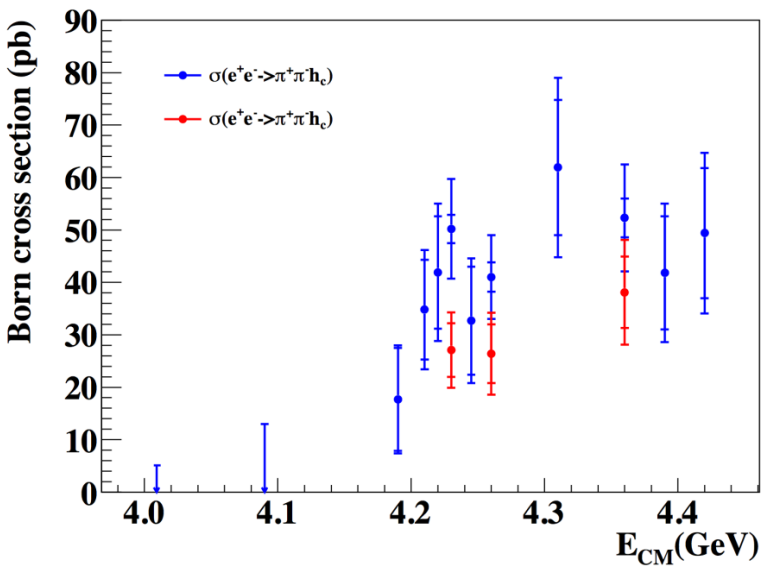
***Significance : 10σ**

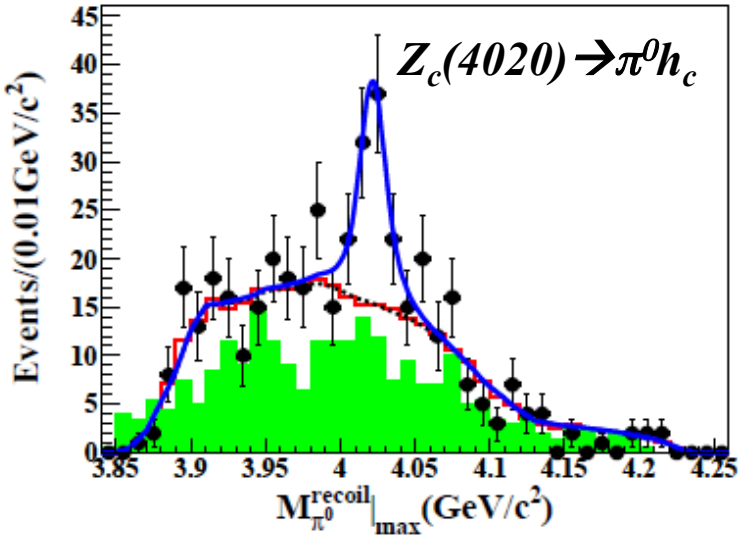
Assuming $Z_c(4025)$ is $Z_c(4020)$

$\Gamma(DD^*)/\Gamma(\pi h_c) = 12\pm5$

Neutral partner of $Z_c(4020)$ in $e^+e^- \rightarrow \pi^0\pi^0 h_c$

BESIII Preliminary





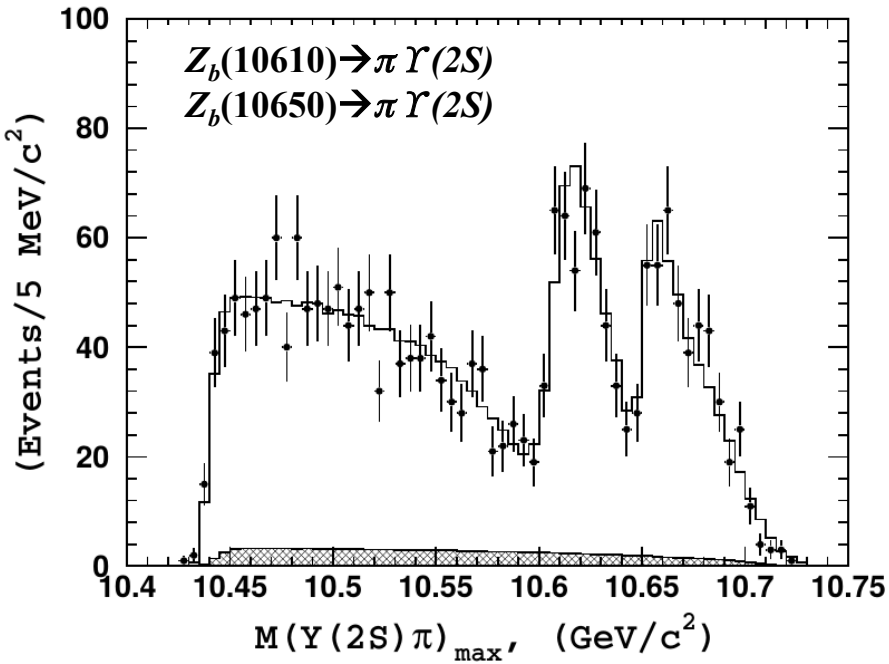
X-sec of $\pi^0\pi^0 h_c$ is about half of charged process, agree with expectation of isospin symmetry

BESIII preliminary Result :
M[Zc(4020)^0] = 4023.6±2.2±3.9 MeV -
M[Zc(4020)$^\pm$] = 4022.9±0.8±2.7 MeV]
-Width fixed to charged $Z_c(4020)$
Significance >5σ

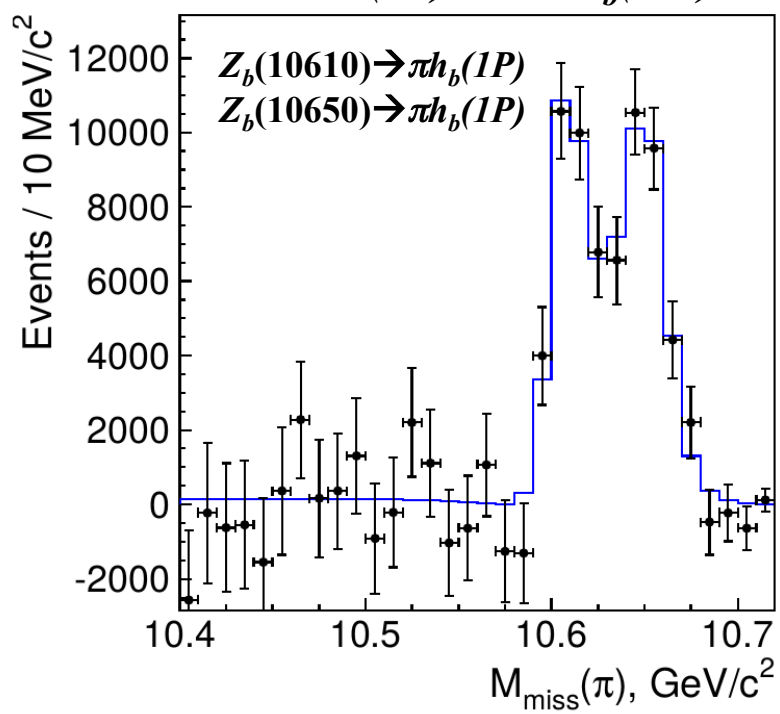
$Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$

Belle [PRL108,122001 (2012)] 121.4 fb^{-1}

$e^+e^- \to \Upsilon(5S) \to \pi^+\pi^- \Upsilon(nS)$



$e^+e^- \to \Upsilon(5S) \to \pi^+\pi^- h_b(mP)$



$Z_b(10610)$ M = 10607.2±2.0 MeV/c^2
Γ = 18.4±2.4 MeV
$J^P = 1^+$

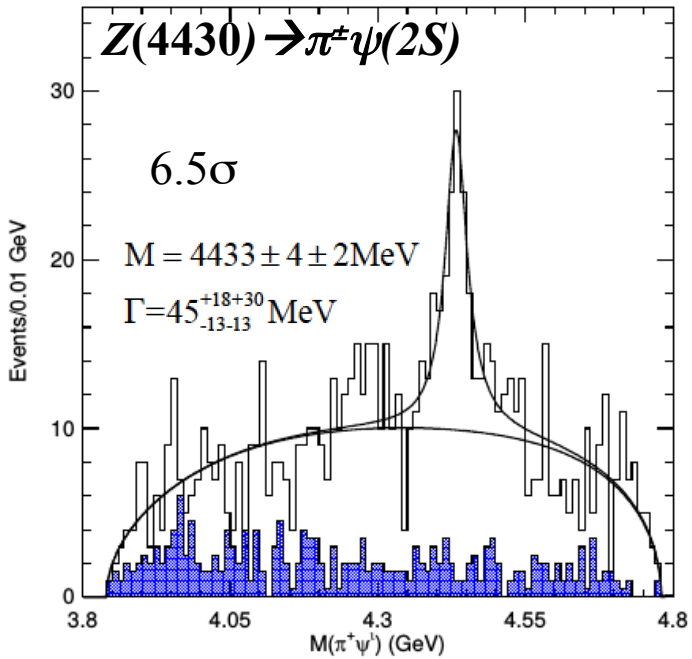
$Z_b(10650)$ M = 10652.2±1.5 MeV/c^2
Γ = 11.5±2.2 MeV
$J^P = 1^+$

Heavy flavor partners of Z_c?

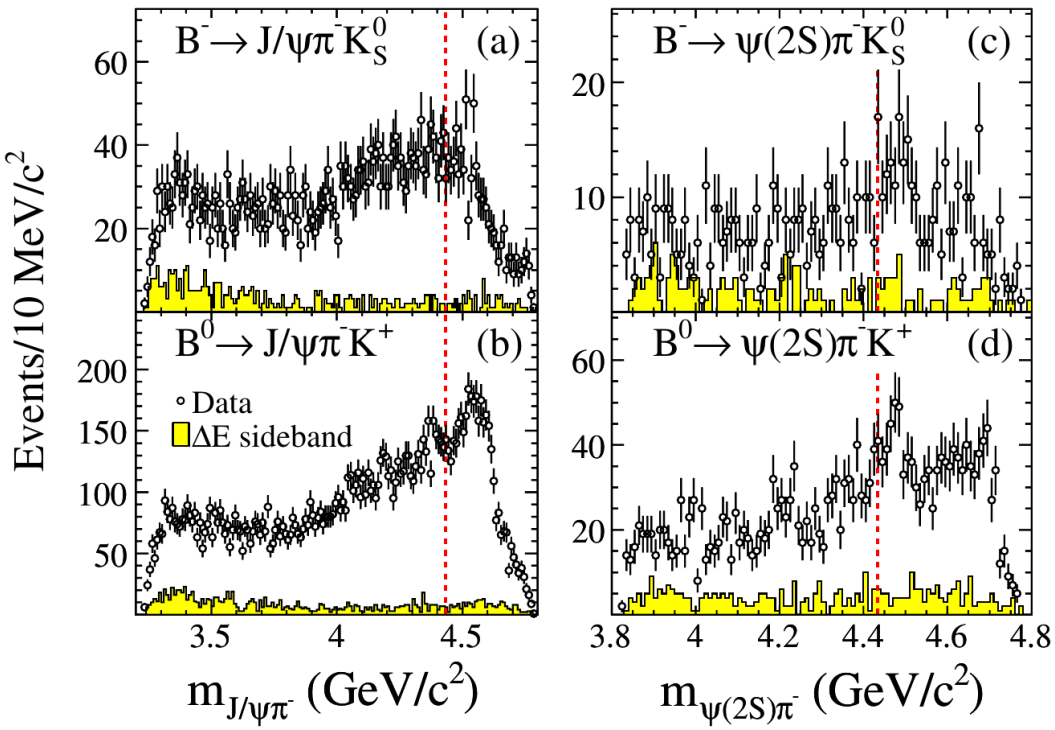
$Z_c \to \pi J/\psi$, (DD^*)
$Z_c' \to \pi h_c(1P)$, (D^*D^*)
$Z_b \to \pi \Upsilon(nS)$, $\pi h_b(mP)$, (BB^*)
$Z_b' \to \pi \Upsilon(nS)$, $\pi h_b(mP)$, (B^*B^*)

$Z(4430)^{\pm}$ in $B^0 \to \psi(2S)K\pi$

Seen by Belle
[PRL100, 142001 (2008)] 605fb^{-1}



Not seen by BaBar
[PRD 79, 112001 (2009)] 413fb-1

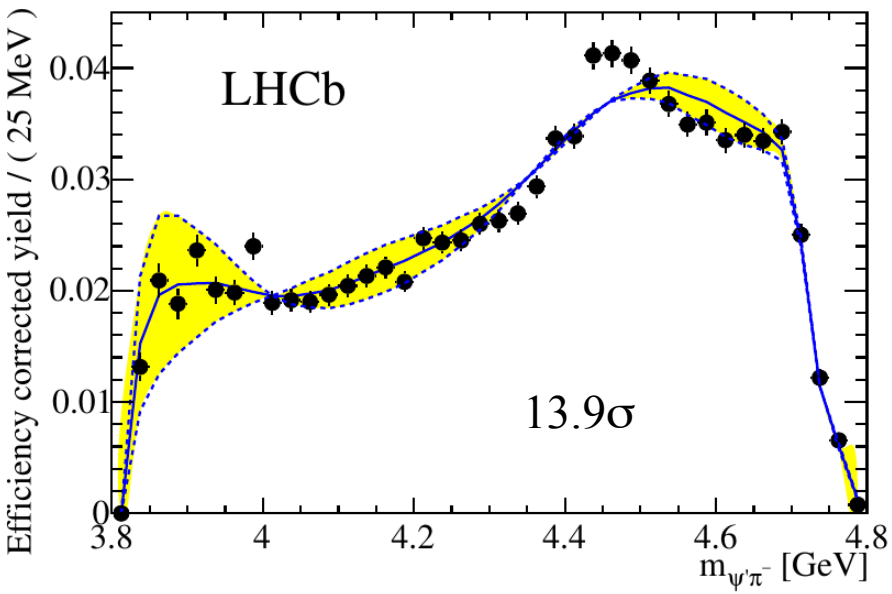


Belle updated results confirmed its existence, $J^p = 1^+$ is favored
[PRD 88, 074026 (2013)] 711fb^{-1}

Belle Z(4430) was the first evidence of a fourquark state in the charmonium sector.

$Z(4430)^{\pm}$ in $B^0 \to \psi(2S)K\pi$

LHCb [PRL112, 222002 (2014)] 3fb^{-1}

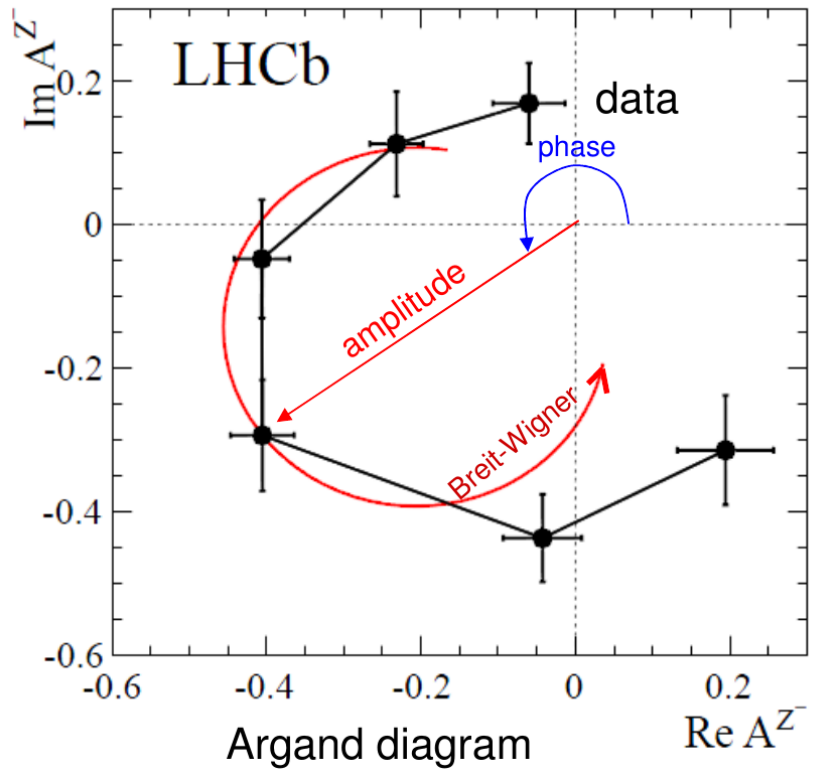


$M = 4475 \pm 7^{+15}_{-25}$ MeV/c^2

$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

$J^P = 1^+$ Measured for the first time

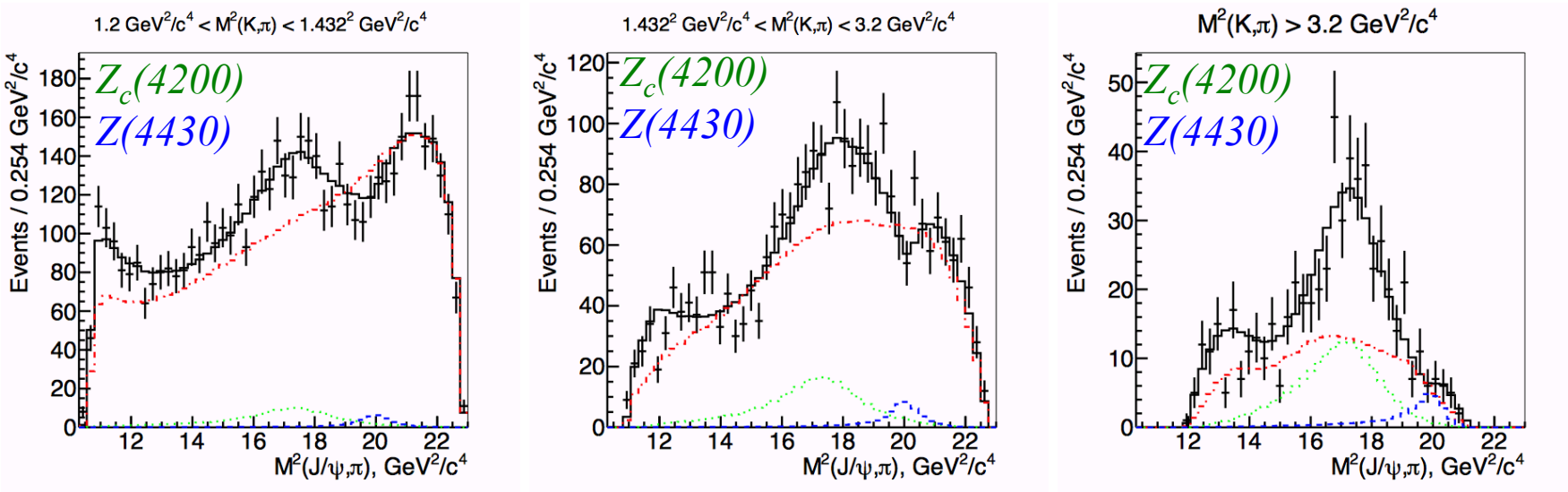
LHCb confirmed Belle results and determined $Z(4430)$ J^P unambiguously.



Fitted values of the Z(4430) amplitude in six $m^2(\psi'\pi^-)$ bins. Argand diagram is consistent with the behavior of resonance.

$Z_c(4200)^{\pm}$ in $B^0 \to J/\psi K\pi$

Belle preliminary [**arXiv:1408.6457 (2014)**], 711 fb^{-1}



Belle observed a new charged charmonium-like state $Z_c(4200)^{\pm}$ in $\pi J/\psi$ with a significance of 6.2 sigma.

$$M = 4196^{+31+17}_{-29-13}\ \mathrm{MeV}/c^2,$$
$$\Gamma = 370^{+70+70}_{-70-132}\ \mathrm{MeV}.$$

List of confirmed Z_c states

State	Mass (MeV/c^2)	Width (MeV/c^2)	Decay mode	J^{PC}	Experiment
$Z_c(3900)^{\pm,0}$	3888.6±2.7	34.7±6.6	$\pi^{\pm} J/\psi\ (DD^*)$	1^+	BESIII, Belle CLEO-c data
$Z_c(4020)^{\pm,0}$	4023.8±2.1	7.9±3.8	$\pi^{\pm} h_c\ (D^*D^*)$	$1^?$	BESIII
$Z(4430)^{\pm}$	4478±21	181±33	$\pi^{\pm}\psi(2S)$	1^+	Belle LHCb

Summary

- Exotic particles, *XYZ*, are found both in charmonium and bottomonium sectors in the last decade. They don't fit into the expected charmonium spectrum.
- J^{PC} of $X(3872)$ has been determined to be 1^{++}.
- Y-states: $Y(4260)$, $Y(4360)$ and $Y(4660)$ are confirmed.
- Four quark states are observed with certainty: $Z_c(3900)$, $Z_c(4020)$, $Z(4430)$, $Z_b(10610)^{\pm}$ and $Z_b(10650)$...

Thank you!