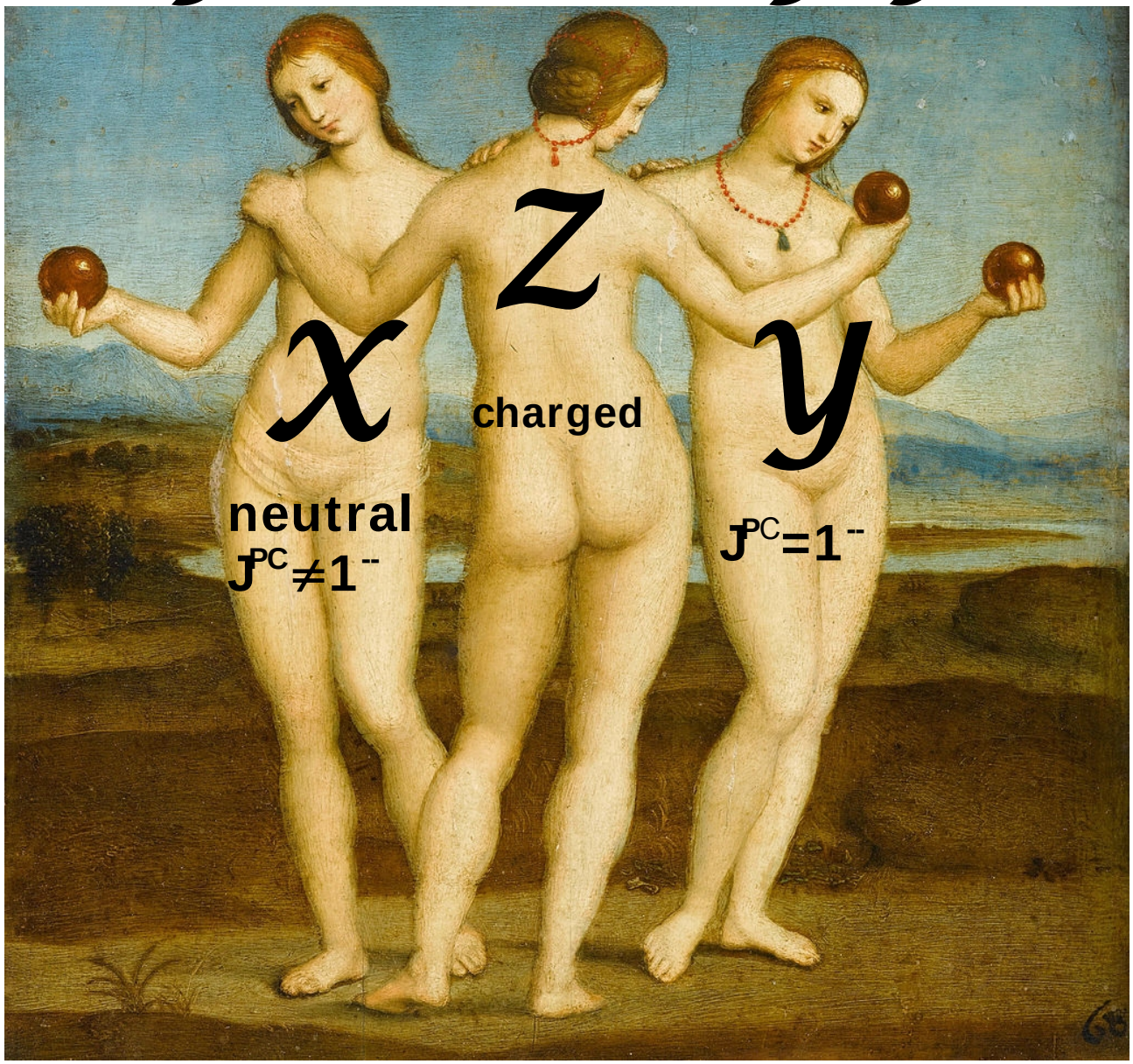
Exotic quarkonium-like spectroscopy

university of groningen

kvi - center for advanced radiation technology

Exotic quarkonium-like spectroscopy



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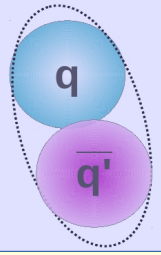
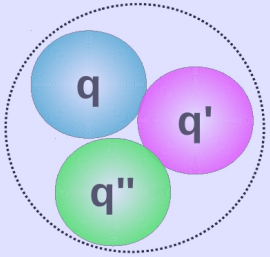
QCD-predicted states

Pions, charmonium, etc



Meson

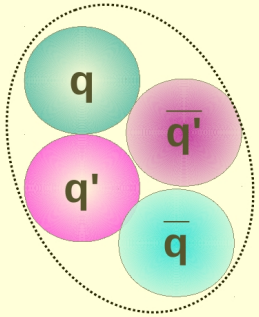


Baryon

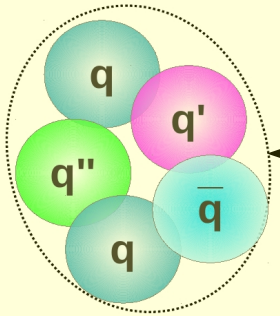
Protons, neutrons, etc

Conventional

?



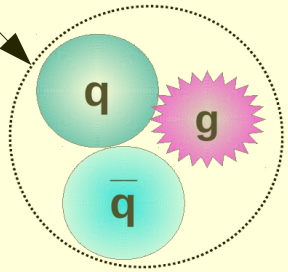
Four-quark state



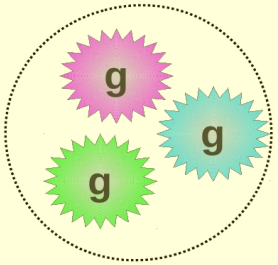
Five-quark state

Pentaquarks?

?



Hybrid

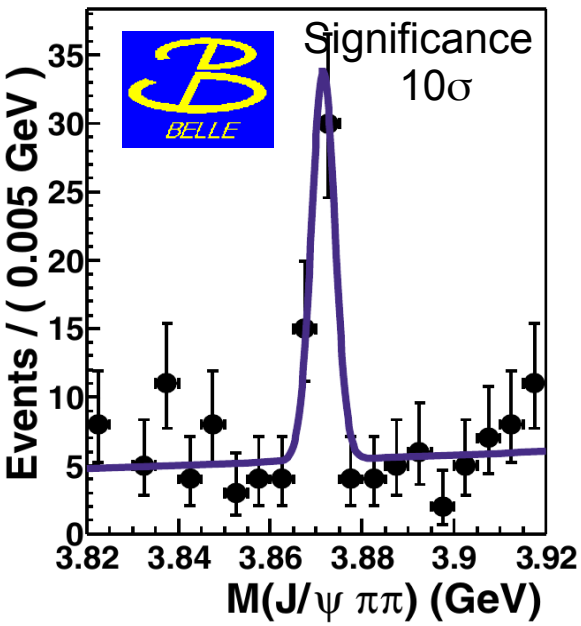


Glueball

Exotic

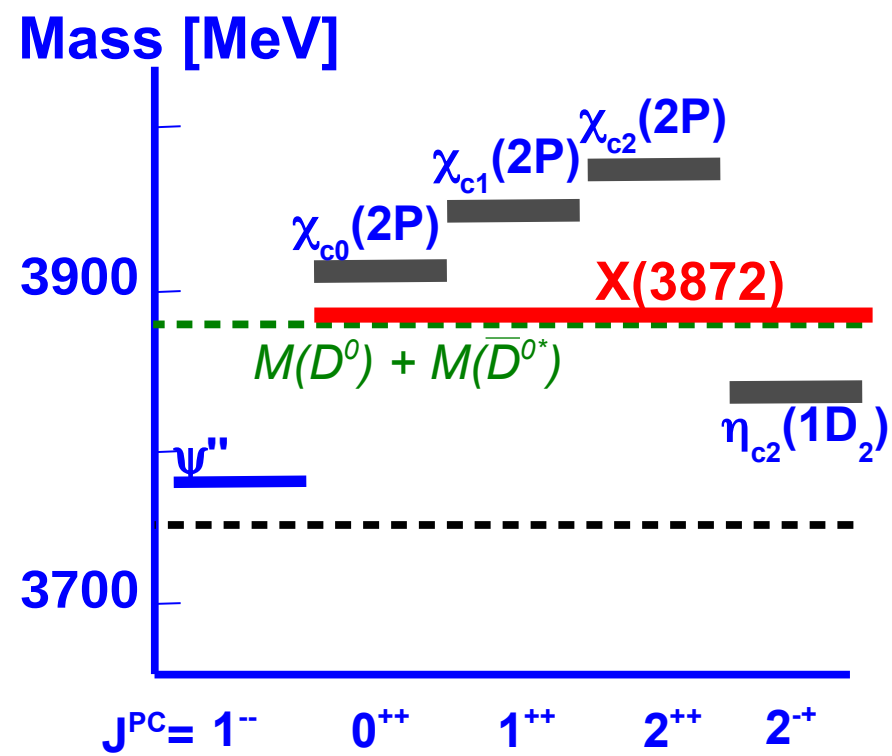
X states: the first encounter

BELLE Collaboration, PRL 91, 26 (2003)



$M = 3872 \pm 0.8$ MeV/c^2

$\Gamma < 2.3$ MeV @90%CL

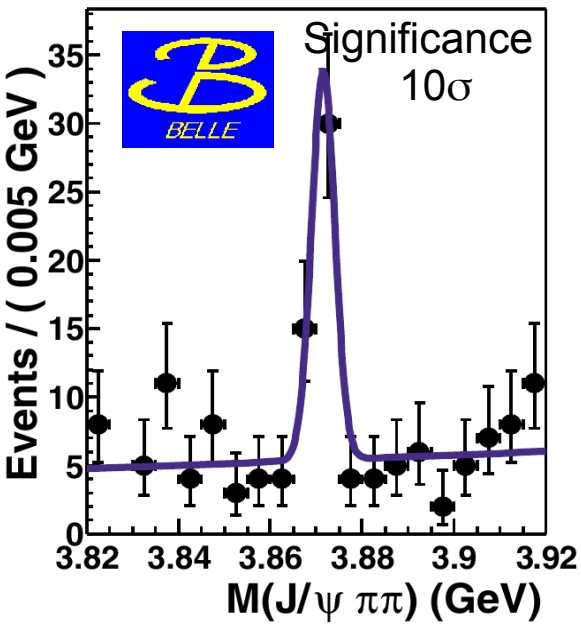


D- or P-wave charmonium?
Molecular state?
Tetraquark?
Molecule + charmonium?

$M(D^0) + M(\bar{D}^{0*}) = 3871.81 \pm 0.36$ MeV

X (3872): some progress

BELLE Collaboration, PRL 91, 26 (2003)



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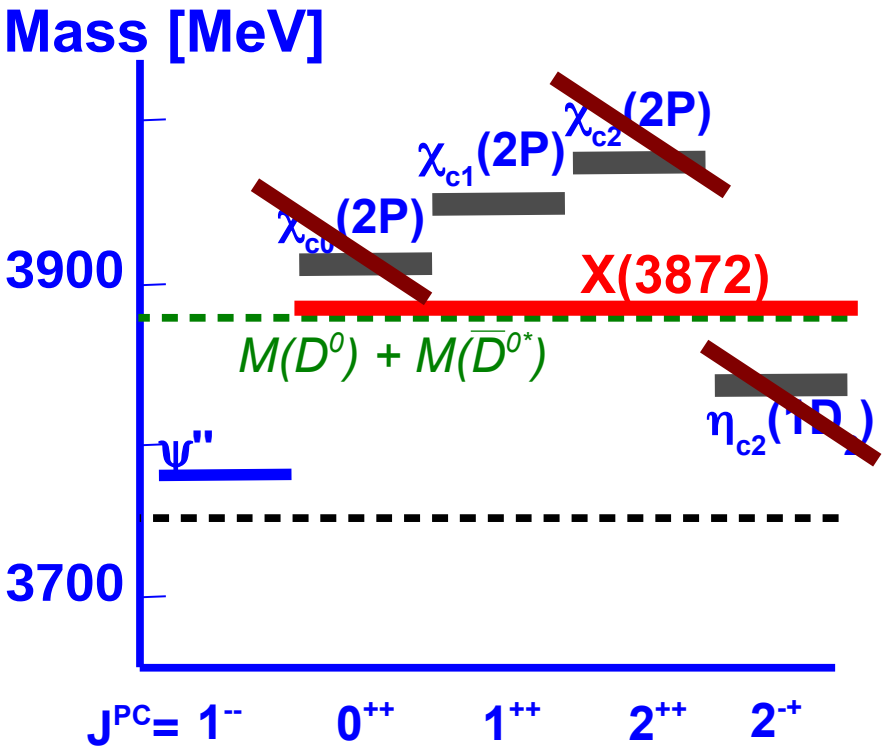


LHCb Collaboration, PRL 110, 222001 (2013)

$B^+ \to X(3872)K^+$

From angular analysis: $J^P = 1^+$

~~D-wave charmonium?~~

Molecular state?

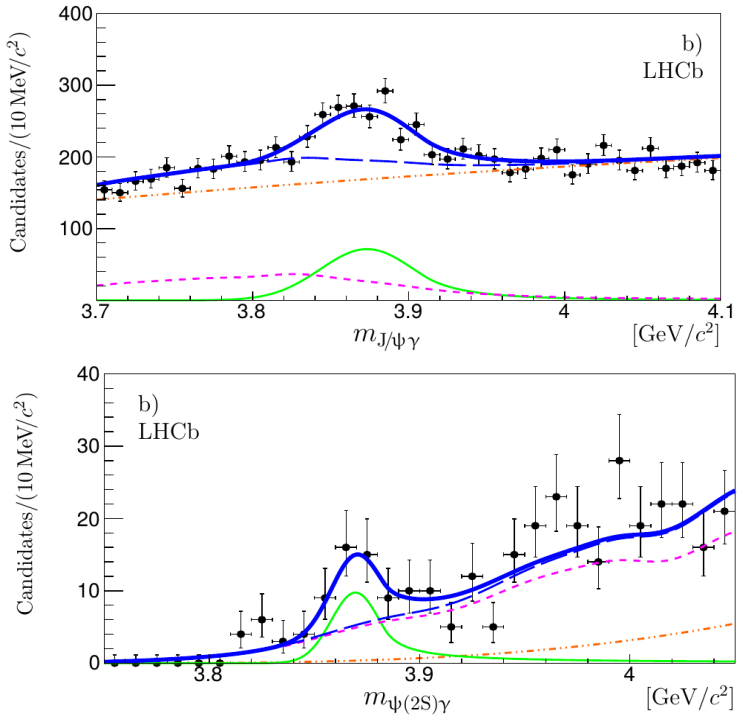
Tetraquark?

Molecule + charmonium?

X(3872): more progress

LHCb Collaboration, CERN-PH-EP-2014-050

$B^+ \to X(3872)K^+$



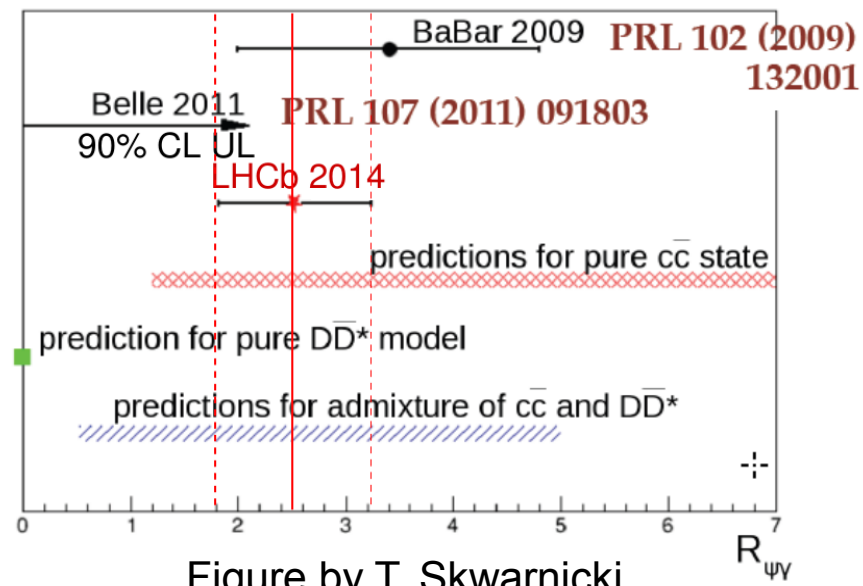


Figure by T. Skwarnicki

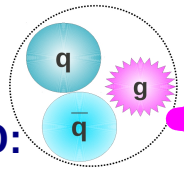
$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

Pure charmonium?
~~Molecular state?~~
Tetraquark?
Molecule + charmonium?

Investigations are going on.
What about BESIII? Hang on!

Y states

List of Y states with measured $J^P = 1^-$

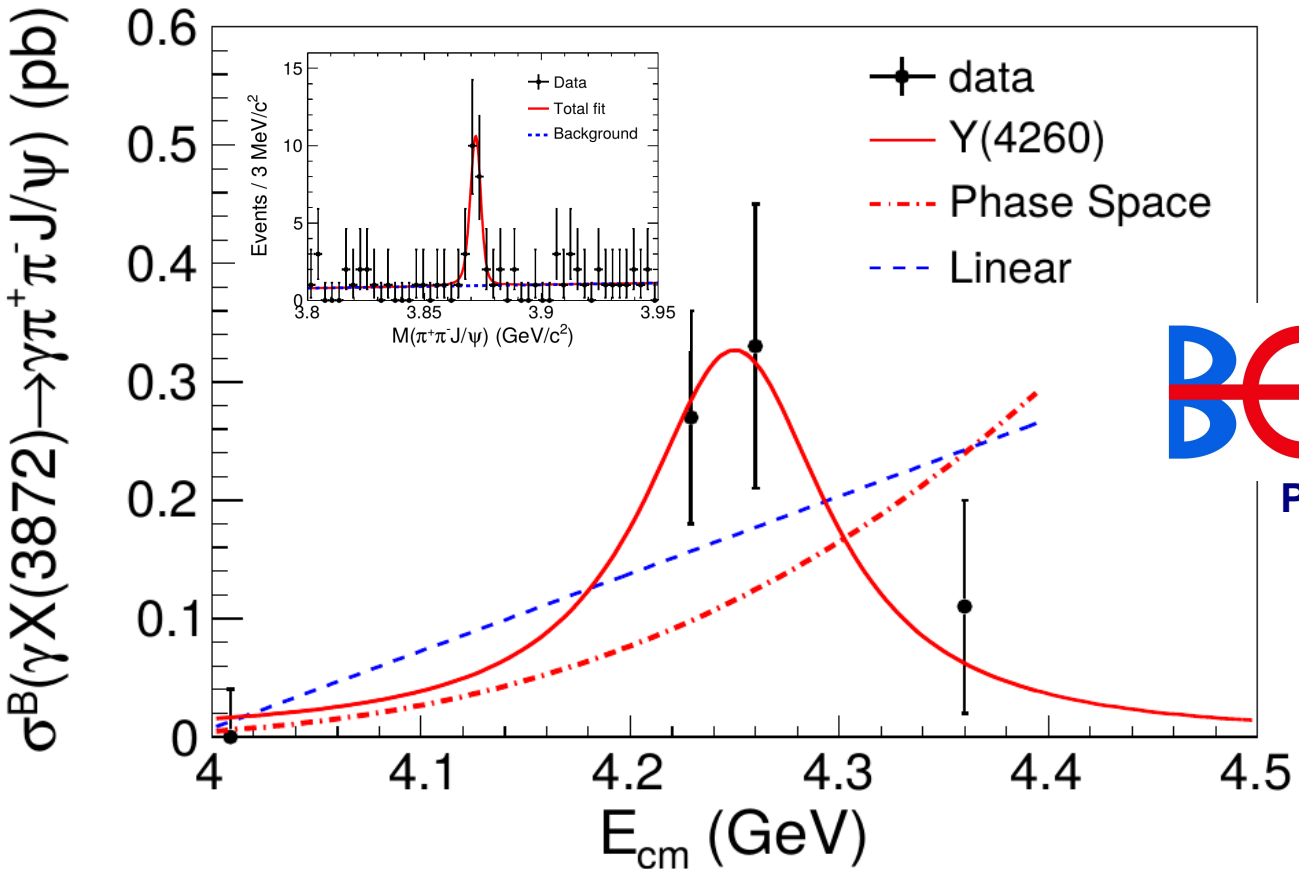


Lattice QCD: JHEP 1207, 126 (2012)

State	Mass, (MeV/c^2)	Width, (MeV)	Decay modes	Seen by
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	$\pi^+\pi^-\psi(2S)$	BaBar, Belle
Y(4630)	4634^{+9}_{-11}	92^{+41}_{-32}	$\Lambda_c^+\Lambda_c^-$	Belle
Y(4660)	4664±12	48±15	$\pi^+\pi^-\psi(2S)$	BaBar, Belle

Currently, the e^+e^- colliders are the leading producers of Y states.

Y States: Connection with X(3872)

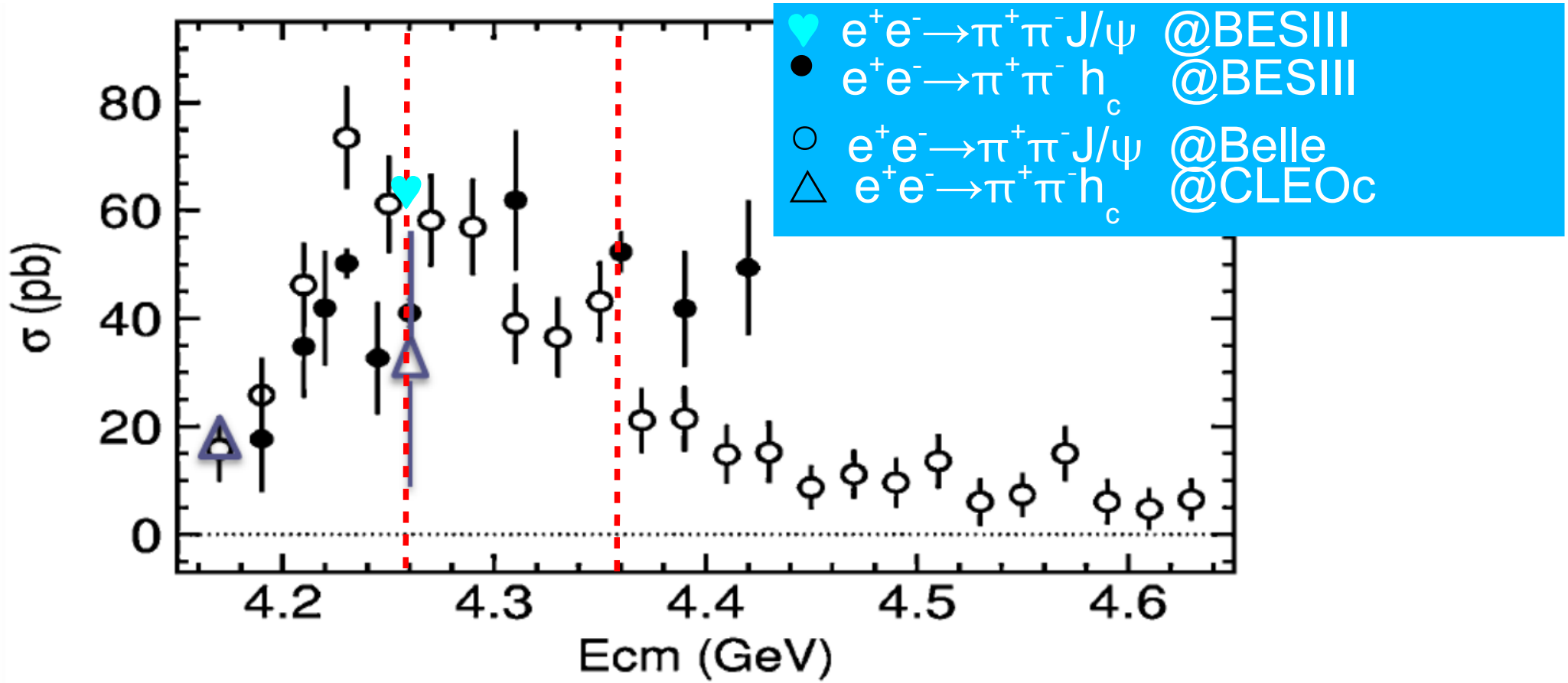


PRL 112, 092001 (2014)

$$\frac{\sigma(e^+e^-\to\gamma X(3872))}{\sigma(e^+e^-\to\pi^+\pi^- J/\psi)} \sim 11\%$$

Y(4260) couples to X(3872)?
May hint to their nature.

Y states

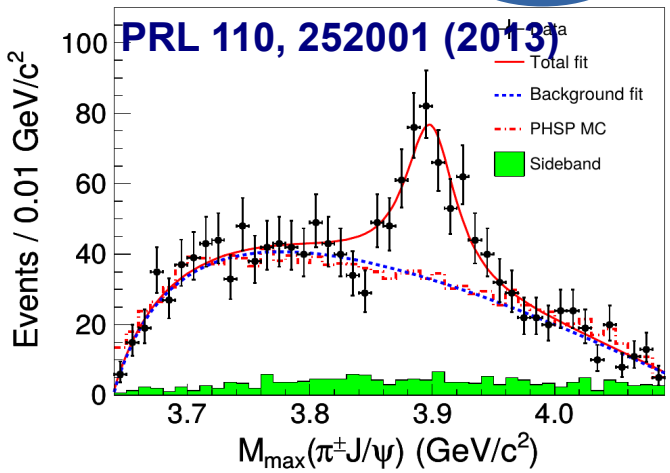


- Different decay modes have similar cross-section.
- The line shapes seem to be different.
- Correlation with Y(4260) or Y(4360) is unclear

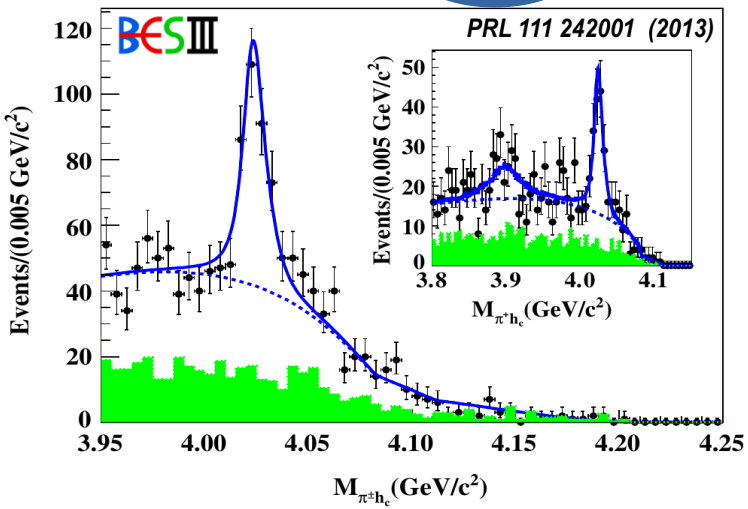
Investigations are going on at BESIII:
More lineshape studies will soon be released

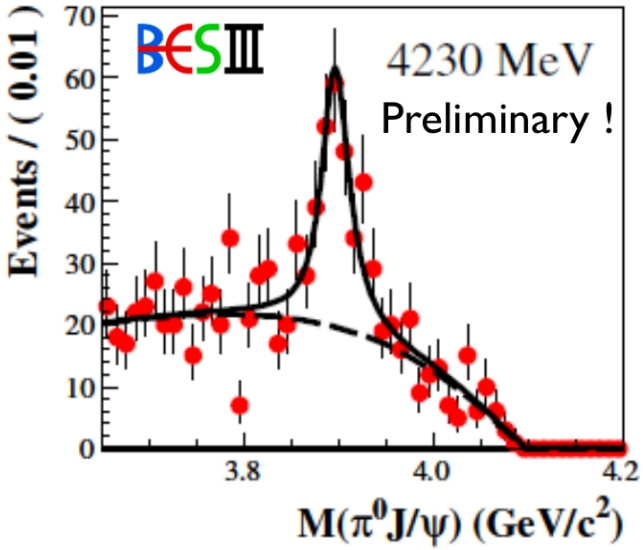
Y States: connection with Z_c

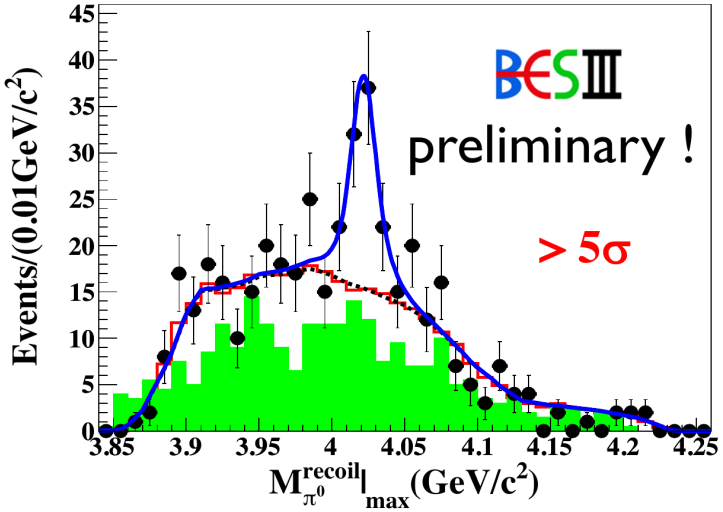
$e^+e^- \to \pi\pi J/\psi$



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







Y(4260) couples to Z states?

Charged charmonium-like

- Strongly coupled to charmonium → contain c and $\bar{c}$.
- Charged → at least four quarks!

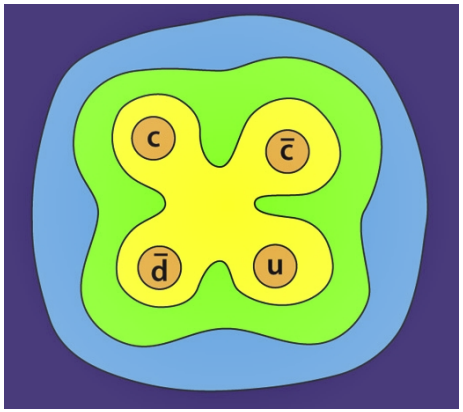


FIG:APS/Alan Stonebraker

List of confirmed Z_c states

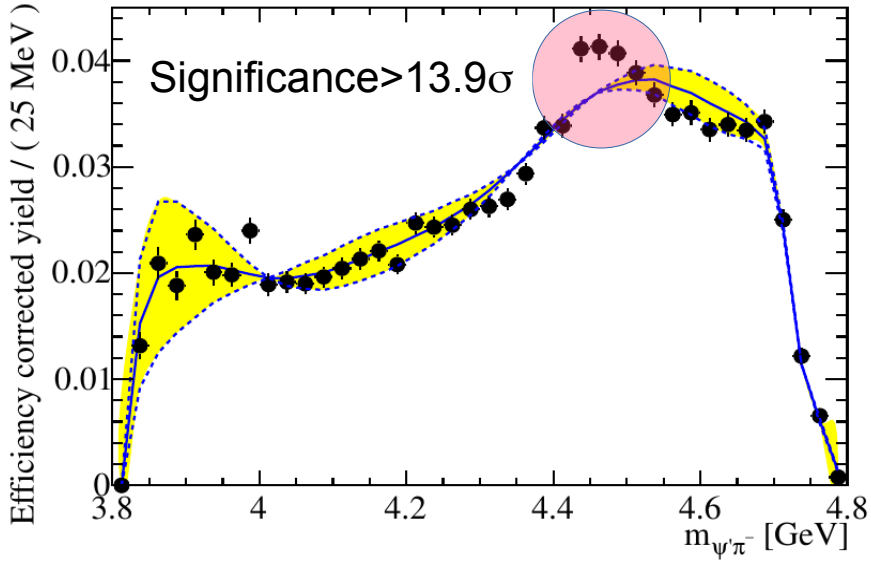
State	Mass, (MeV/c^2)	Width, (MeV)	J^P	Decay modes	Seen by
$Z_c(3900)^{\pm,0}$	3899.0±6.1(BESIII) 3883.9±4.5(BESIII)	46±22(BESIII) 24.8±11.4(BESIII)	1^+	$\pi^{\pm,0}J/\psi$, $(D^*\bar{D})^{\pm}$	BESIII, Belle CLEOc data COMPASS
$Z_c(4020)^{\pm,0}$	4022.9±2.8 4026.3±4.5	7.9±3.8 24.8±9.5	$1^?$	$\pi^{\pm,0}\ h_c$, $(D^*\bar{D}^*)^{\pm}$	BESIII
$Z_c(4430)^{\pm}$	4478±21	181±33	1^+	$\pi^{\pm}\psi(2S)$	Belle, ~~BaBar,~~ LHCb

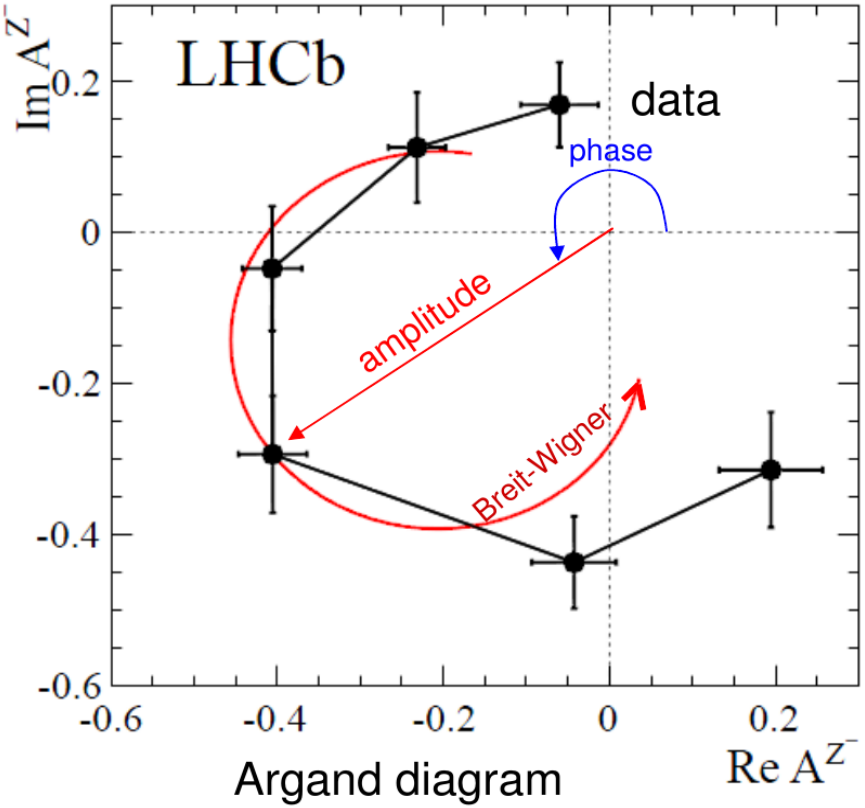
Four-quark states are found!

$Z(4430)^{\pm}$

PRL 112, 222002 (2014)

In $B^0 \to K^+\pi^-\psi(2S)$





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

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

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

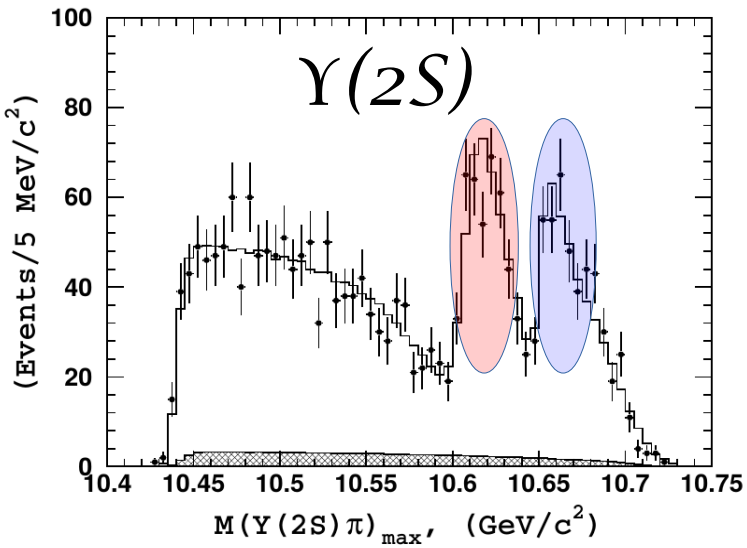
Argand diagram is consistent with the resonant behaviour

Charged bottomonium-like

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

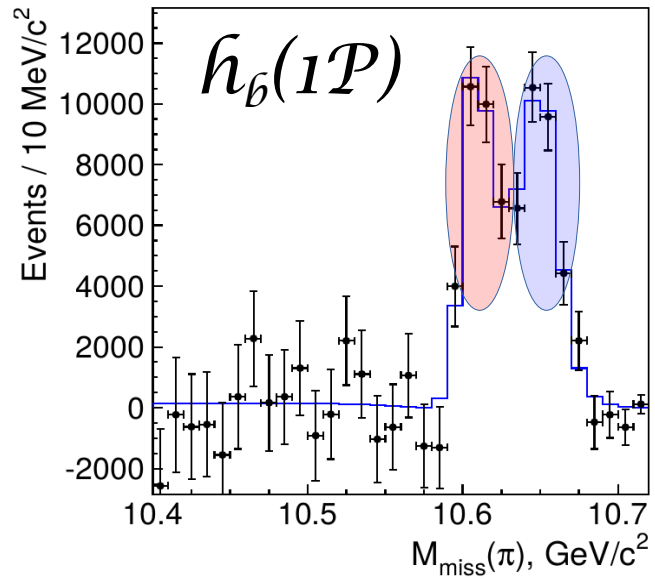
PRL108,122001 (2012)

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



$M = 10607.2 \pm 2.0$ MeV/c^2
$\Gamma = 18.4 \pm 2.4$ MeV
$J^P = 1^+$

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



$M = 10652.2 \pm 1.5$ MeV/c^2
$\Gamma = 11.5 \pm 2.2$ MeV
$J^P = 1^+$

Are they heavy-flavor partners of Z_c?

Summary

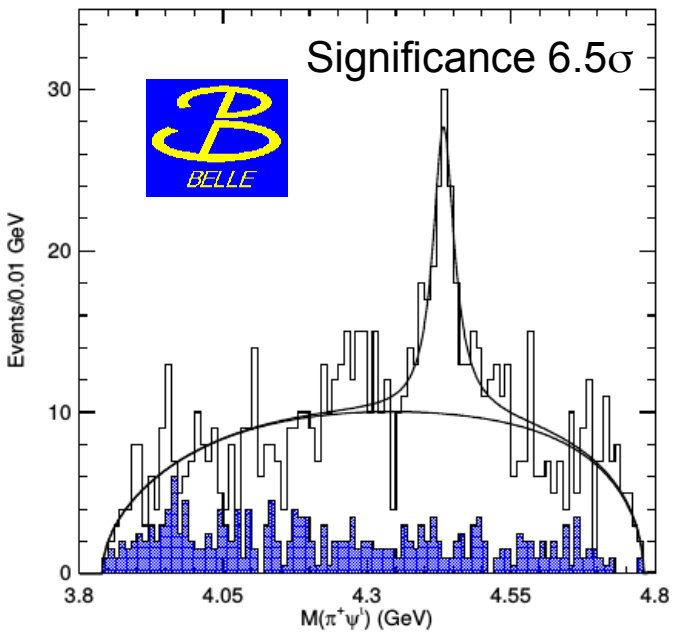
- A whole new class of particles, the XYZ, was found during the last decade both in charmonium and bottomonium sectors.
- The three graces, XYZ, are believed to be exotic QCD states.
- Leptonic and hadronic machines produce X and Z abundantly, while Y states are seen mostly in e^+e^- collisions.
- Studies using hadronic and leptonic machines are complementary:
  - leptonic production mode is good for discoveries,
  - production in hadronic collisions is good for detailed studies.
- A lot of progress has been made during last years, states appear to be related to each other:
  - Y couple to X and Z?
  - There are correlations between $c\bar{c}$- and $b\bar{b}$-like states.
- Soon all the pieces will fall into place!

Elusive $Z(4430)^{\pm}$

The first evidence of the four-quark state in charmonium sector

Seen by BELLE in $B \to K\pi^{\pm}\psi(2S)$

PRL100, 142001 (2008)



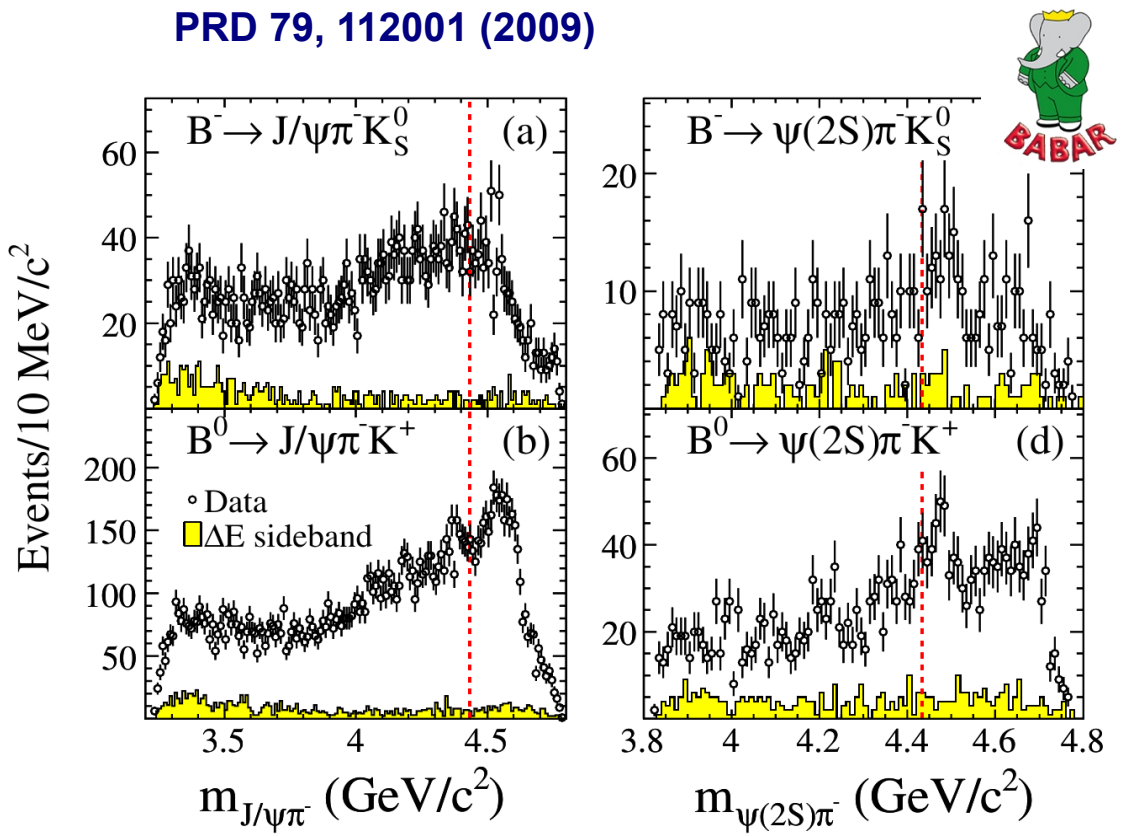
$M = 4433^{+24}_{-18}$ MeV/c^2

$\Gamma = 107^{+135}_{-71}$ MeV

PRD80, 031104 (2009)

Not seen by BaBar in $B \to K\pi^{\pm}\psi(1S,2S)$

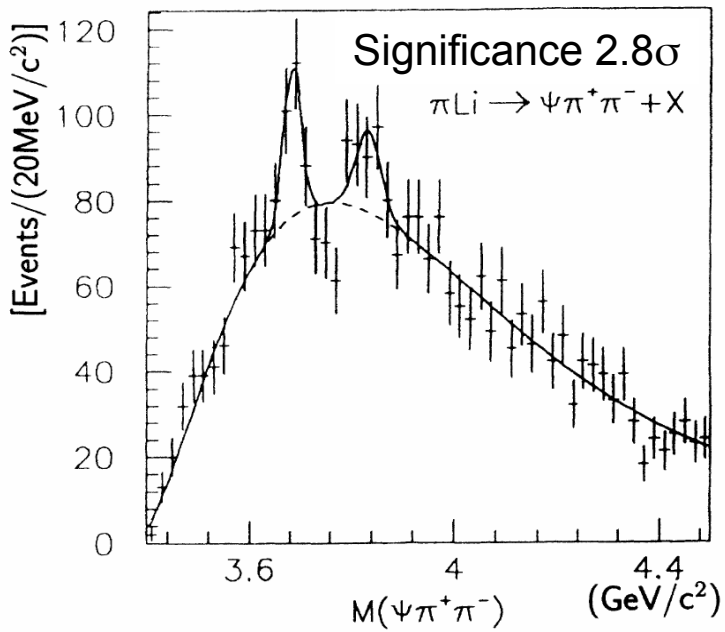
PRD 79, 112001 (2009)



Nice try, but unconfirmed

X states: the first encounter

E705 Collaboration, PRD 50, 4258 (1994)

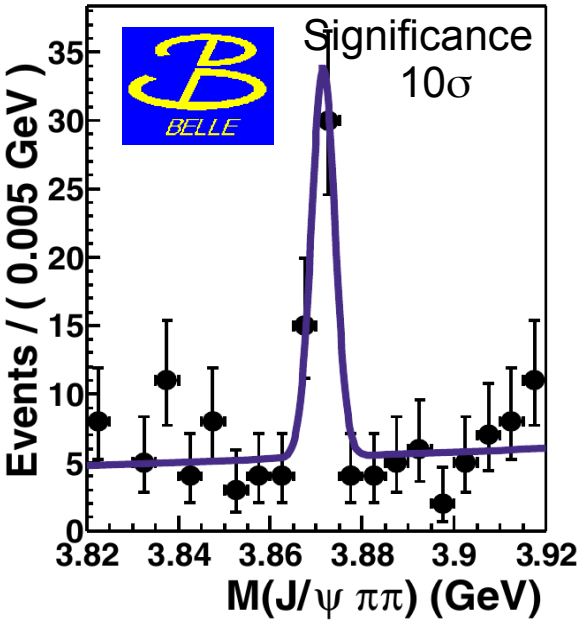


$M = 3836 \pm 13$ MeV/c^2

$\Gamma = 24 \pm 5$ MeV (consistent with detector resolution)

(A lower mass value can be due to an incorrect momentum scale for soft pions.)

BELLE Collaboration, PRL 91, 26 (2003)



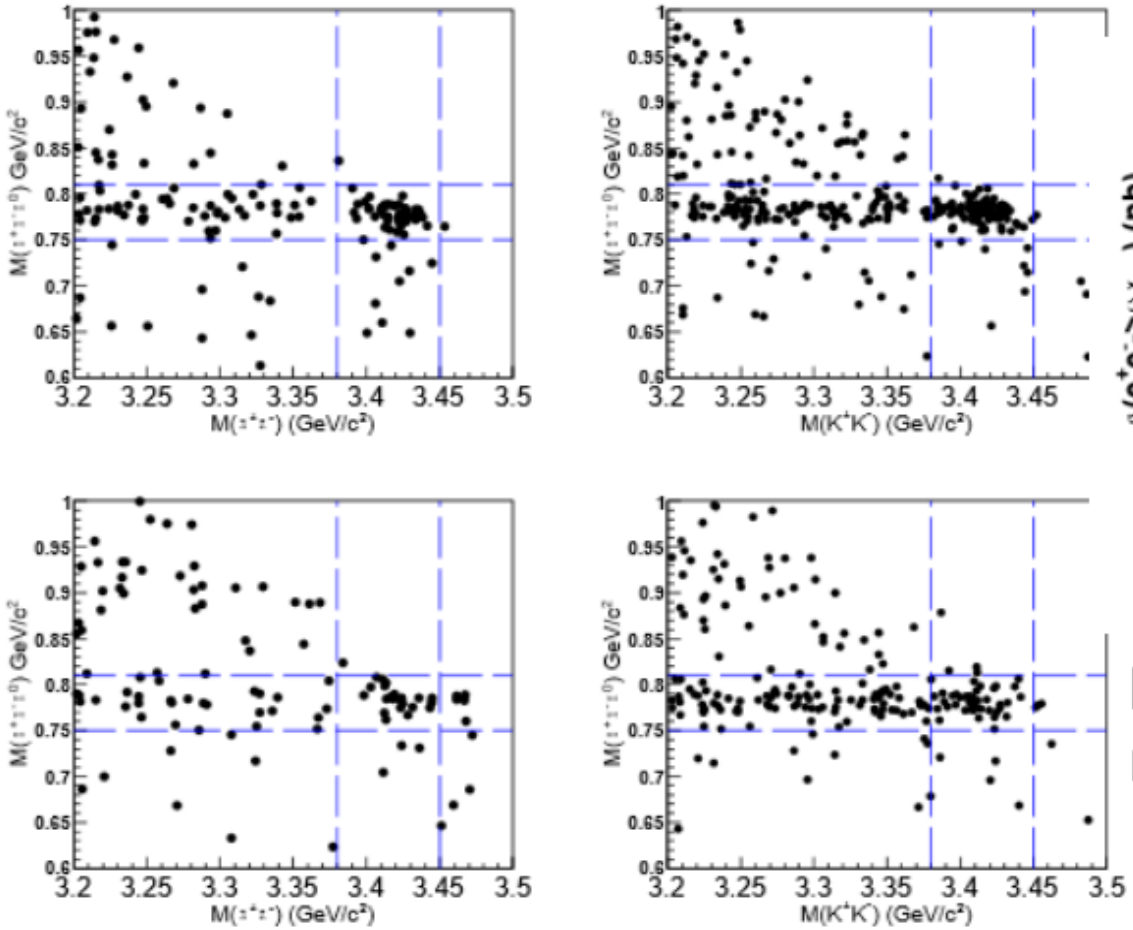
$M = 3872 \pm 0.8$ MeV/c^2

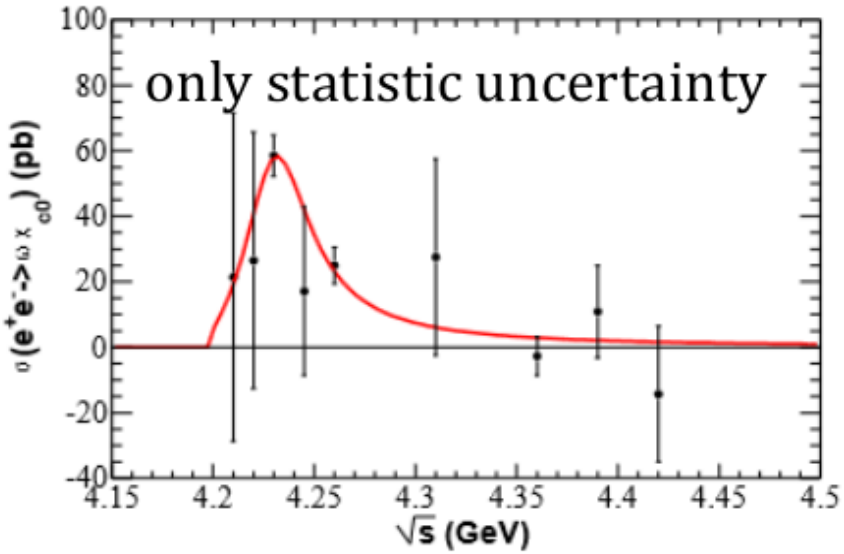
$\Gamma < 2.3$ MeV @90%CL

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

$M(D^0) + M(\bar{D}^{0*}) = 3871.81 \pm 0.36$ MeV

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





Fit with a single BW assumption, mass lower than 4.26 GeV.

No signal of $\omega\chi_{c1}$ or $\omega\chi\_c2$ found.

Disfavor $Y(4260)$ is a $\omega\chi_{c1}$ molecule.

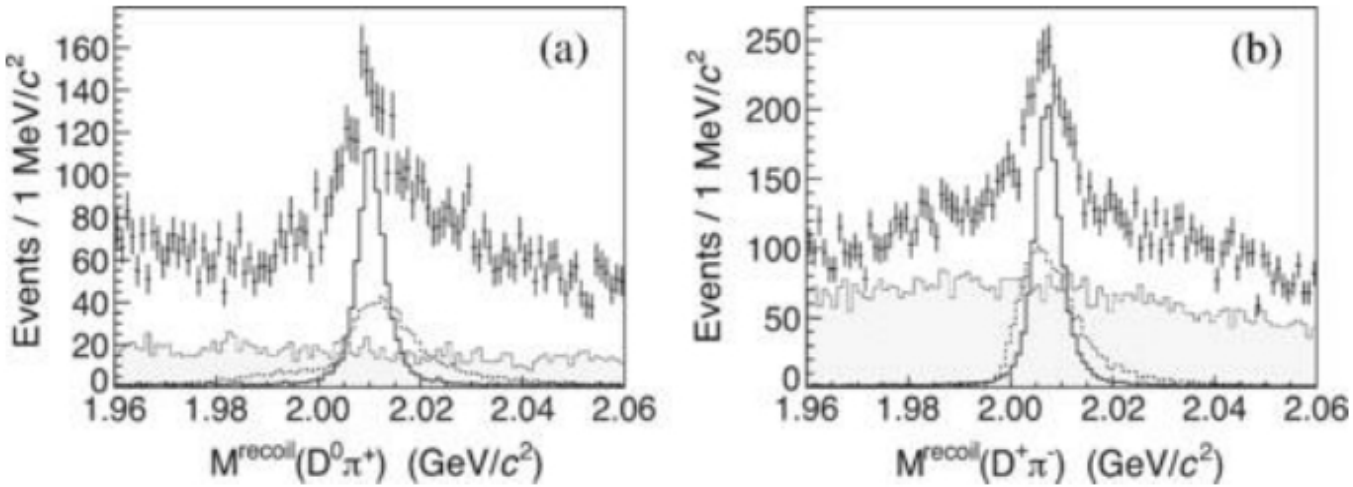
$Z_c(3885)$

Phys. Rev. Lett. 112, 022001

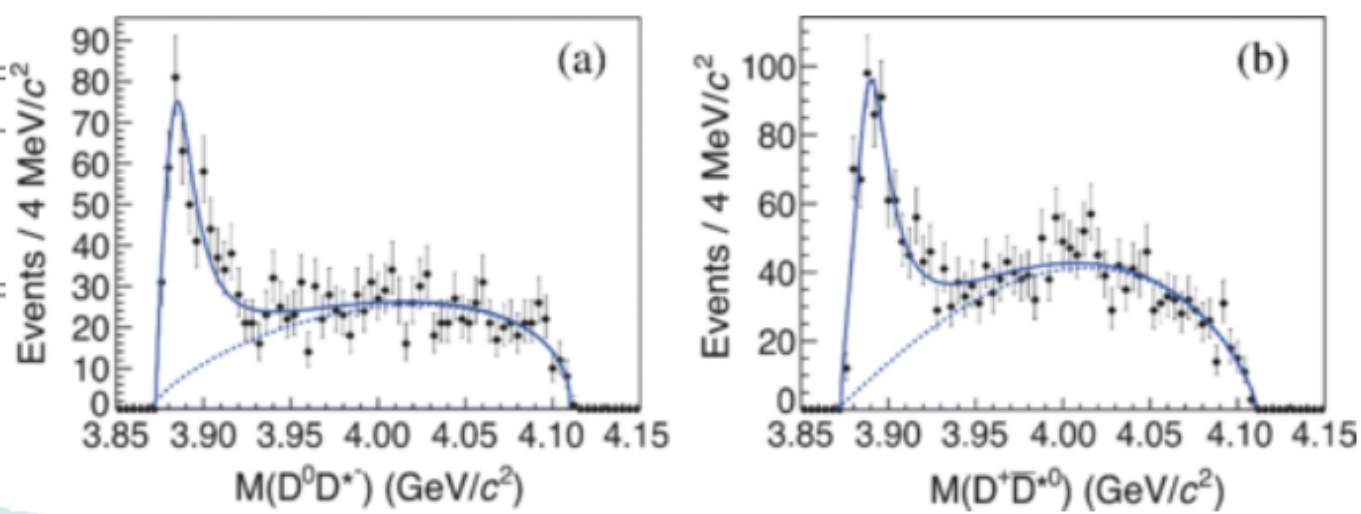
- $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ at 4.26 GeV

BESIII

$\sqrt{s}$=4.26 GeV
$525pb^{-1}$
Favor $J^P = 1^+$



	$Z_c(3885) \to D\bar{D}^*$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$
$\sigma \times \mathcal{B}$ (pb)	$83.5 \pm 6.6 \pm 22.0$

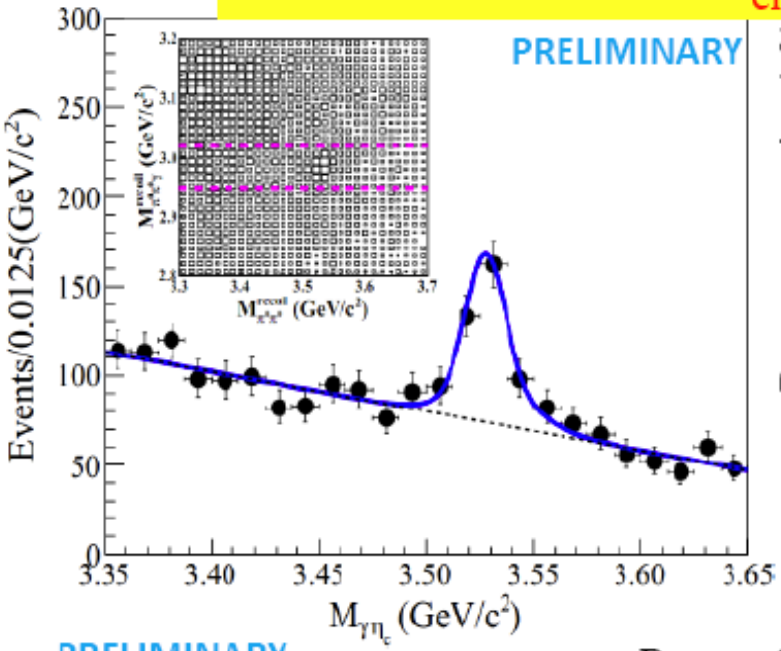


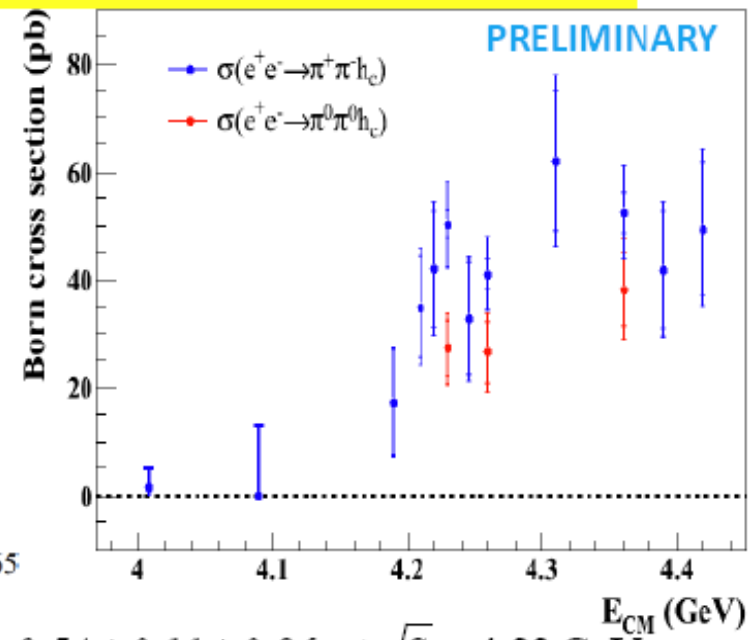
$Z_c(4020)$: neutral

BESIII

Observation of $e^+e^- \to \pi^0\pi^0 h_c(1P)$

Summed results at E_{cm}=4.23, 4.26, 4.36GeV





PRELIMINARY

For $R_{\pi\pi h_c} = \dfrac{\sigma(\text{neutral})}{\sigma(\text{charged})}$,

$R_{\pi\pi h_c} = 0.54 \pm 0.11 \pm 0.06$ at $\sqrt{S} = 4.23$ GeV,

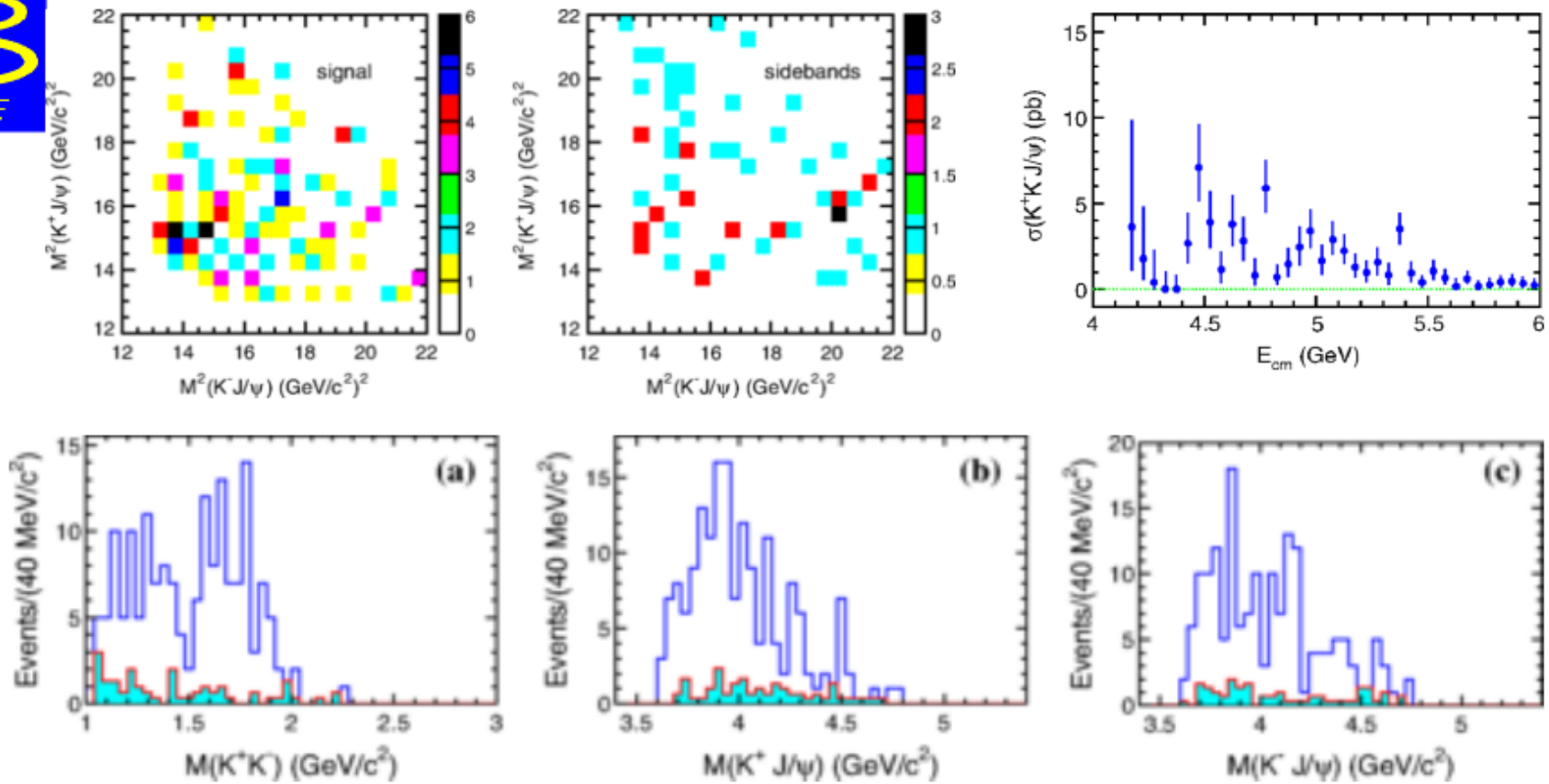
$R_{\pi\pi h_c} = 0.64 \pm 0.14 \pm 0.10$ at $\sqrt{S} = 4.26$ GeV,

$R_{\pi\pi h_c} = 0.73 \pm 0.14 \pm 0.10$ at $\sqrt{S} = 4.36$ GeV,

Z_{cs} search

Phys. Rev. D 89, 72015

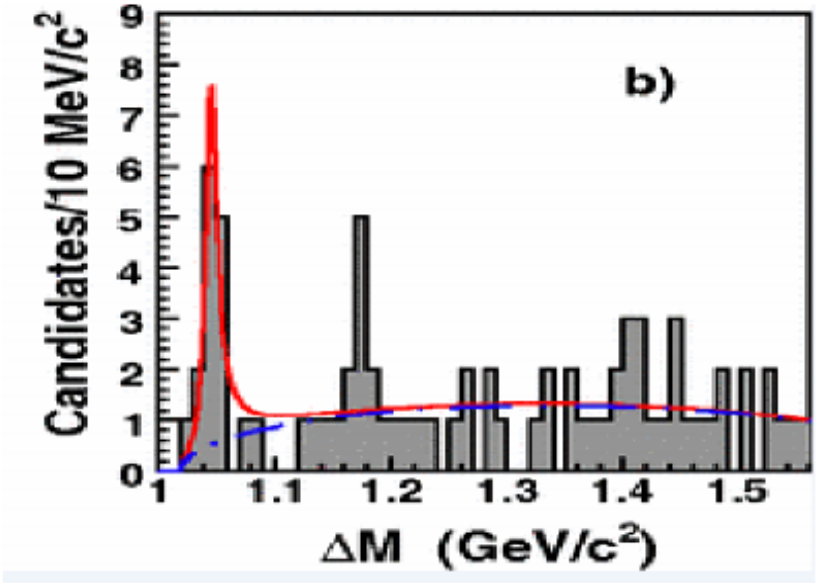
- Belle update K^+K^-J/ψ to Dalitz Plot



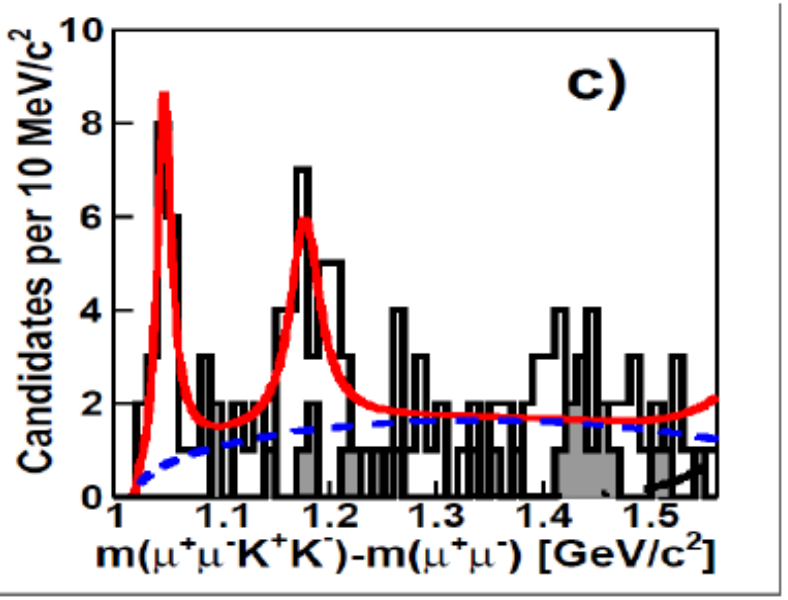
No evident structure in $K^{\pm}J/\psi$ mass distribution under current statistics

First Observations of Y(4140)

PRL 102, 242002 (2009)



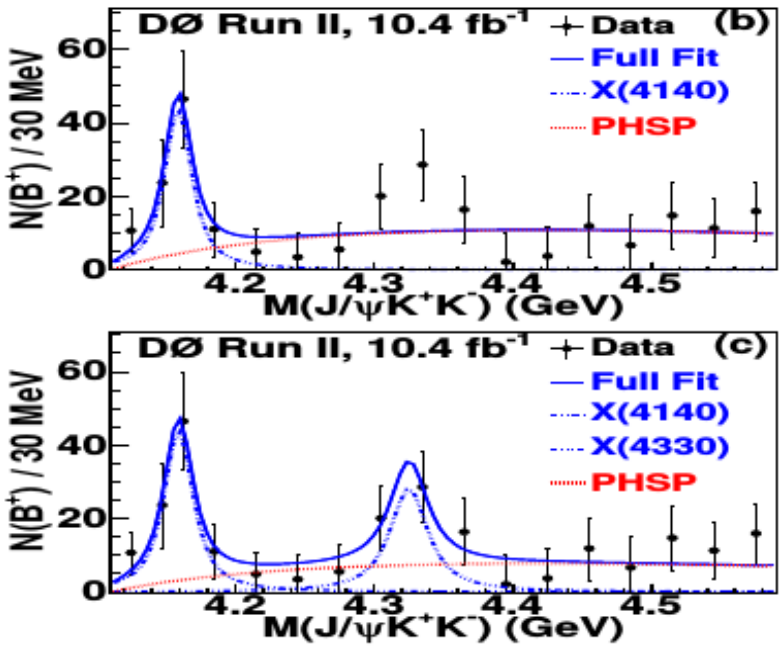
arXiv:1101.6058 (2011)



- 2009, with $2.7fb^{-1}$, first evidence of Y(4140). Significance is 3.8σ.
- 2011, with $6fb^{-1}$, significance of Y(4140) over 5σ and an evidence for a second structure.

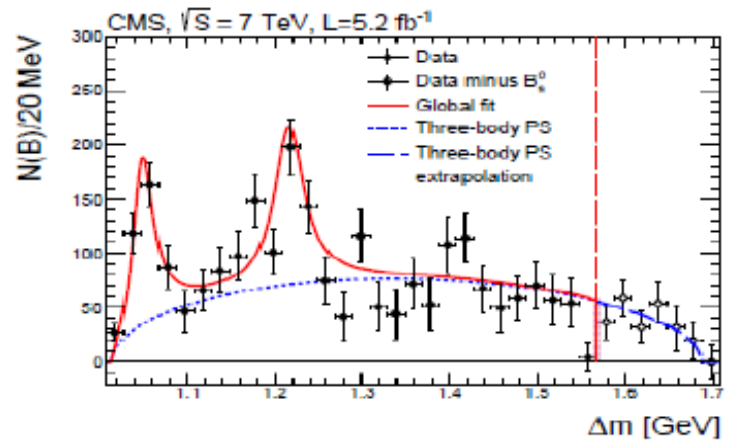
Study on $J/\psi\phi$ Mass Spectrum

D0, PRD 89, 012004 (2014)



- An evidence of 3.1σ is reported for the first peak at D0.

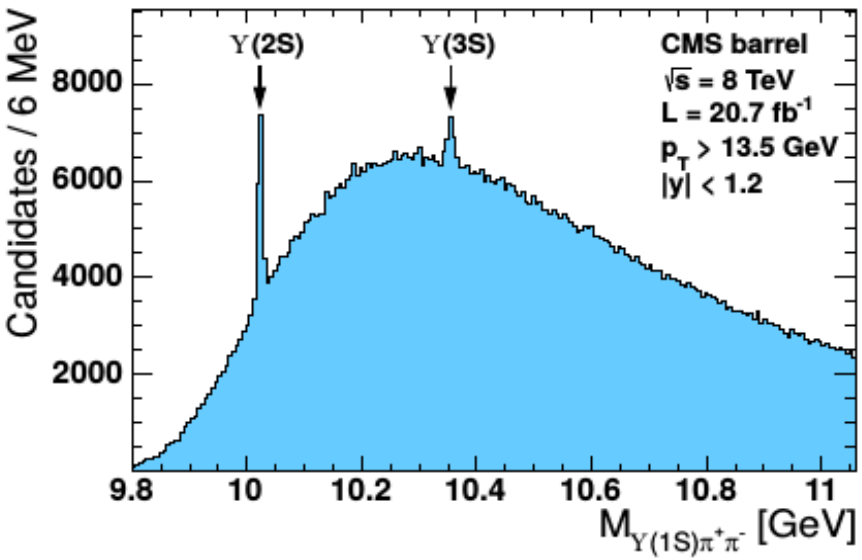
CMS, arXiv:1309.6920 (2013)

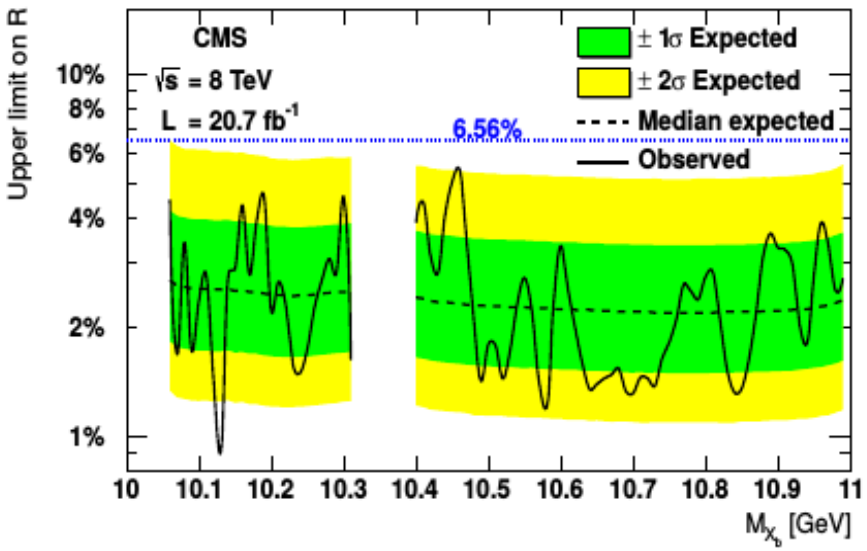


- Y(4140) is observed at CMS exceeding 5 σ.
- Y(4330) is also allowed on the $J/\psi\phi$ mass spectrum of both D0 and CMS.

Search for Bottomonium Partner of X(3872)

$\sqrt{s} = 8$ TeV PLB 727, 57-76 (2013) $\Upsilon(1S)\pi^+\pi^-$





- no evidence for X_b, the X(3872)'s bottomonium counterpart is observed.
- the ratio of the cross section X_b to $\Upsilon(2S)$'s upper limit is set within (0.9-5.4)% at 95% C.L..