Experimental review of charmonium like states

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Outline:

Biased selection!

- $X(3872)$
- $X(3915)$
- $X(4140)$
- $X(4160)$
- $Y(4260)$
- $Y(4360)$
- $Y(4660)$
- $Z_c(3900)$
- $Z_c(4020)$

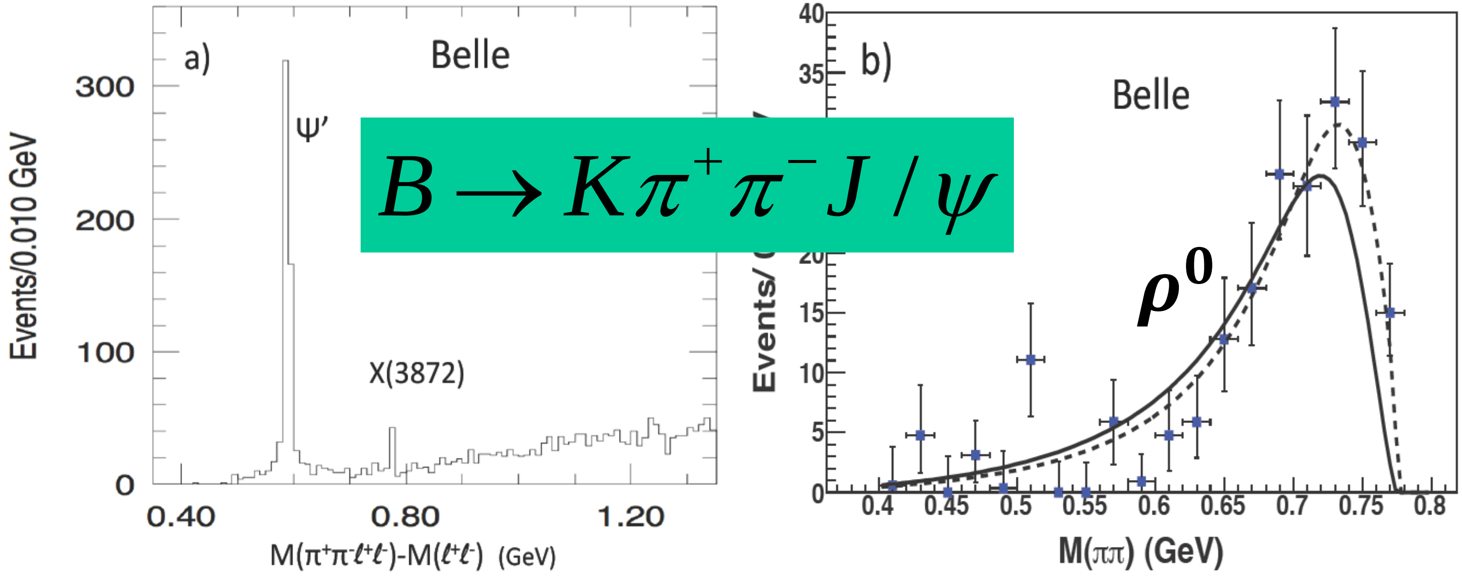
Also see Li-Ming Zhang's talk

See Xiao-Rui Lyu's talk

Not include new $Z_{cs}(3985)^{+-}$

$X(3872)$ or $\chi_{c1}(3872)$, $I^G(J^{PC}) = 0^+(1^{++})$

- Found by Belle (PRL, 91,262001(2003), citation 1917)



- Well established in experiment

$M = 3871.69 \pm 0.17$ MeV

$\Gamma < 1.2$ MeV at 90% CL

$(m_{D^0} + m_{D^{*0}})$-M(X(3872))= -0.01$\pm$0.20 MeV

Babar, Phys. Rev. D71 (2005) 071103
CDF, Phys. Rev. Lett. 93 (2004) 072001
D0, Phys. Rev. Lett. 93 (2004) 162002
Lhcb, Eur. Phys. J. C72 (2012) 1972
CMS, JHEP 04 (2013) 154
ATLAS, JHEP 01 (2017) 117
BESIII, Phys. Rev. Lett. 112 (2014) 092001

$X(3872)$ continued

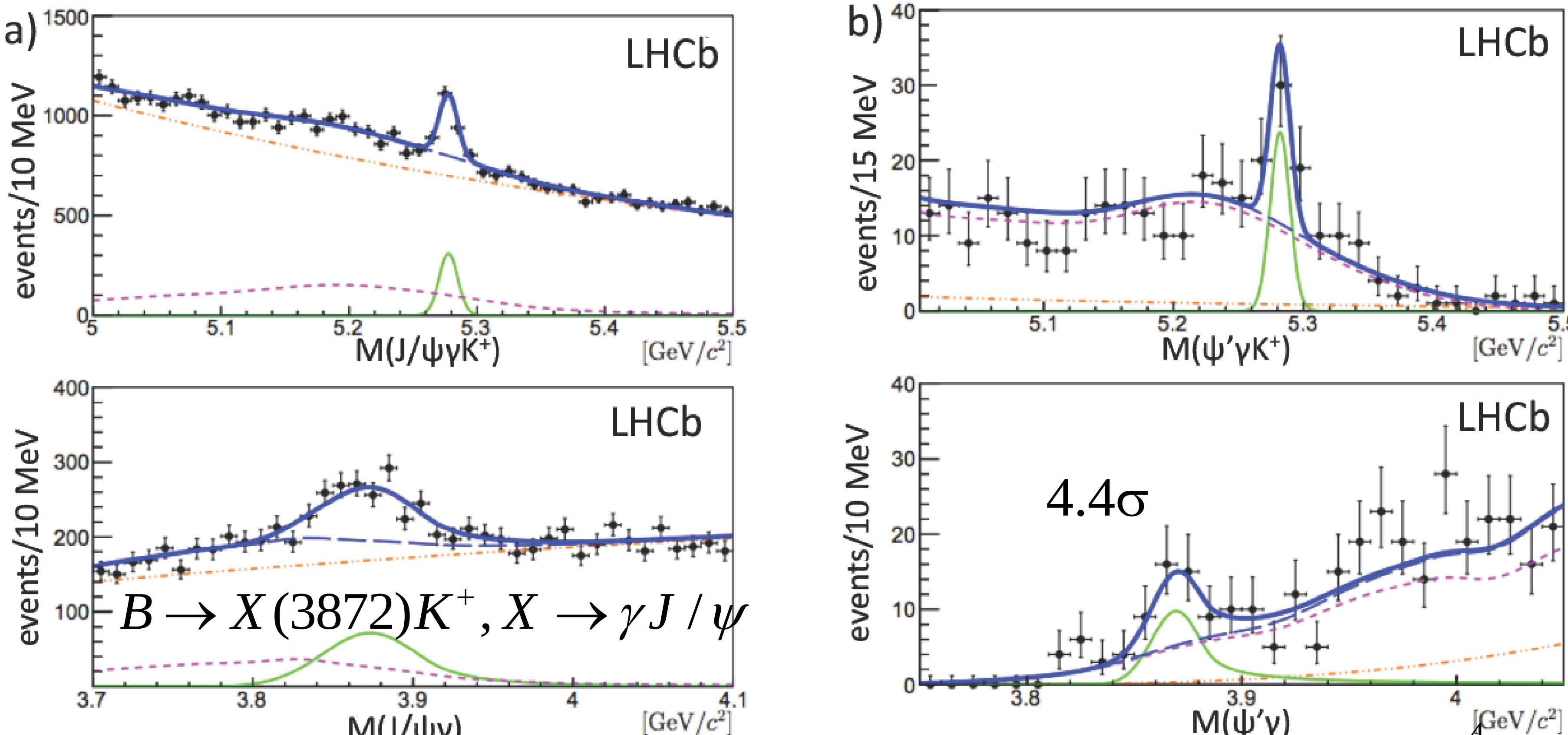
- observed radiative decay $X(3872) \rightarrow \gamma J/\psi$, hence C=+1

Belle, Phys. Rev. Lett. 107 (2011) 091803
Babar, Phys. Rev. D74 (2006) 071101

$$\frac{B(X \to \gamma\psi')}{B(X \to \gamma\psi)} = 2.46 \pm 0.70$$

Favor χ_{c1} !

$B \to X(3872)K^+, X \to \gamma\psi'$

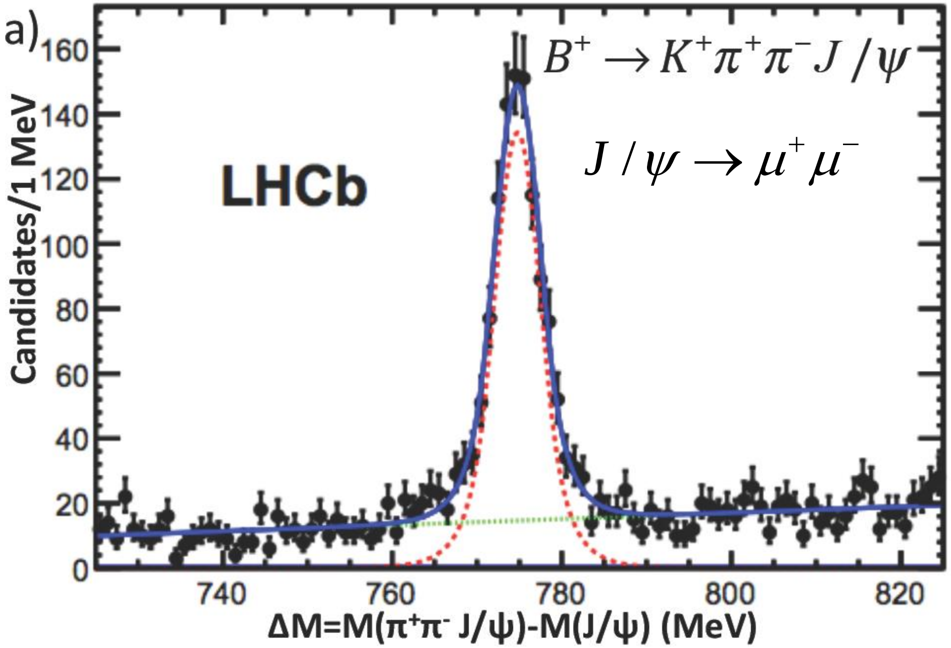


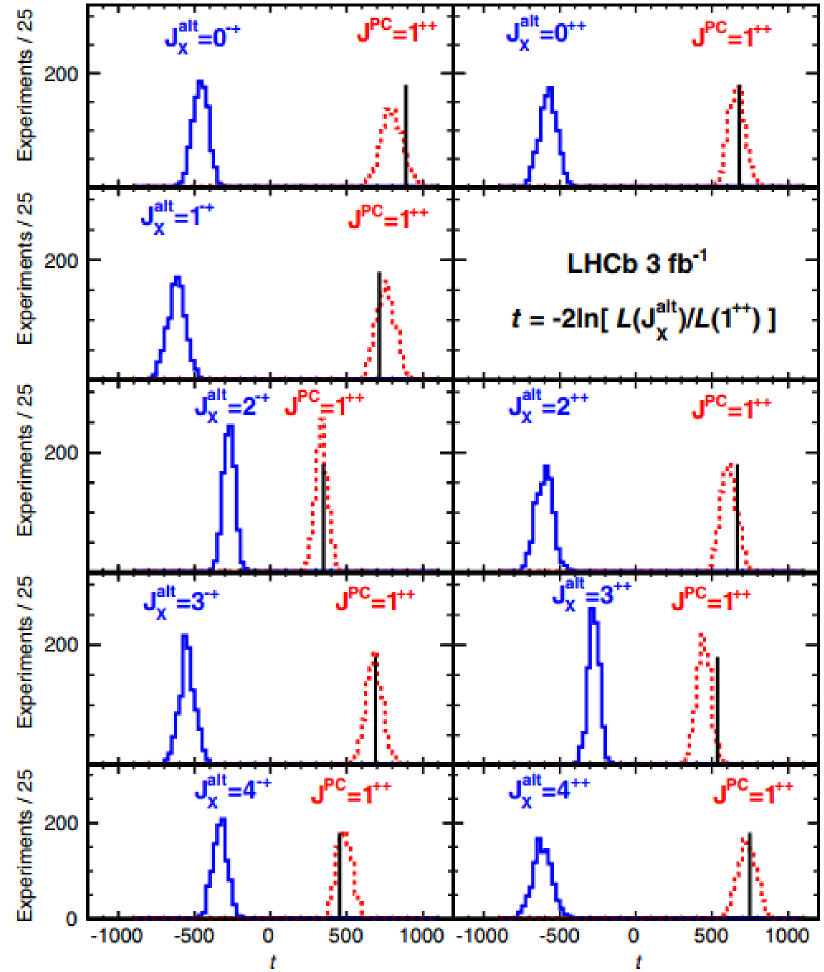
LHCb, Nucl. Phys. B886 (2014) 665

$X(3872)$ continued

- **LHCb determined J^{PC}=1^{++}**

LHCb, Phys. Rev. D92 (2015) 011102,
LHCb, Phys. Rev. Lett. 110 (2013) 222001



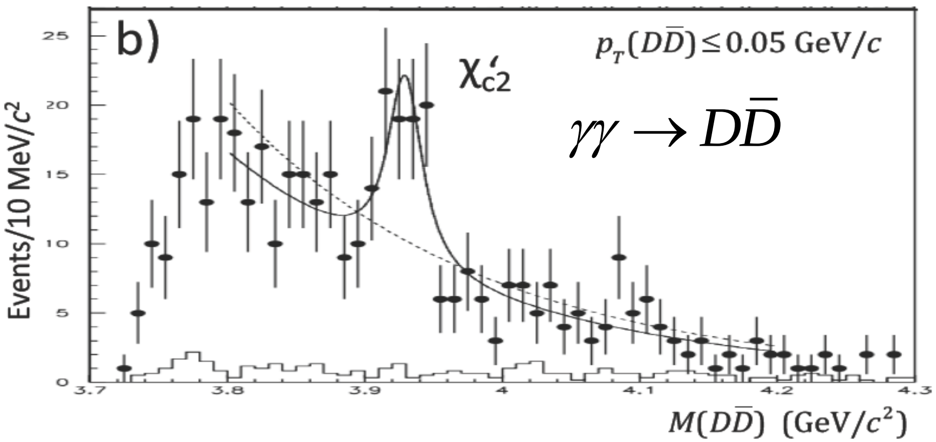


- LHCb Run I, 1011 events
- Data favors for 1^{++}
- J^{PC} = 1^{++} assignment with significance >16σ

$t = -2\ln(\mathcal{L}^{alt}/\mathcal{L}^{++})$

$X(3872)$ continued

- **Problems to assign $X(3872)$ as χ_{c1}' (2^3P_1)**
  - mass



χ_{c2}' candidate

Belle, Phys. Rev. Lett. 96 (2006) 082003

Confirmed by Babar

States	χ_{c1}' (2^3P_1)	χ_{c2}' (2^3P_2)	$\chi_{c1}(1^3P_1)$	$\chi_{c2}(1^3P_2)$
Mass(MeV)	3871.69	3927	3510.6	3556.2
Difference	$\delta M_{2\text{-}1}(2P)=55.3\pm3$ MeV		$\delta M_{2\text{-}1}(1P)=45.5\pm0.1$ MeV	

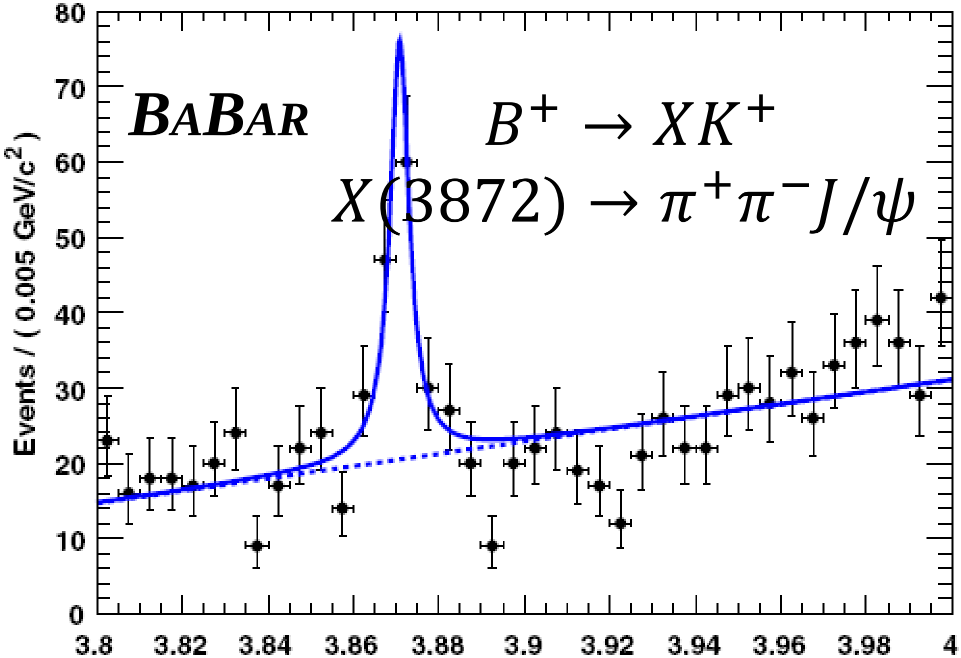
E. J. Eichten, K. Lane, and C. Quigg, PRD73 (2006) 014014

$c\bar{c}$ potential model: $\delta M_{2-1}(n_r P)$ decrease with increasing n_r

$X(3872)$ continued

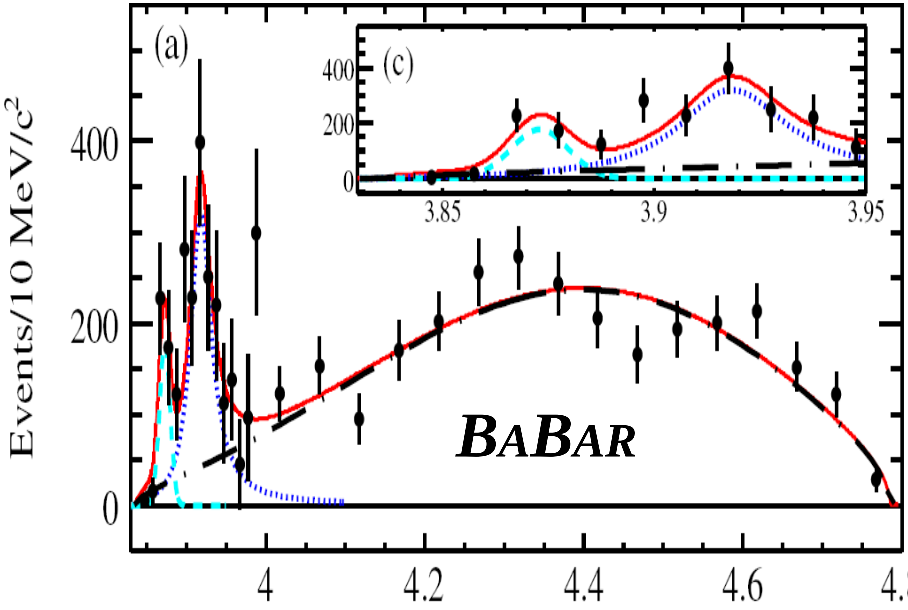
□ Isospin violation

PRD77, 111101(R) (2008)



$m(\pi^+\pi^- J/\psi)$ GeV

PRD82, 011101(R) (2010)



$m(J/\psi\omega)$ GeV

$$m_\rho \sim M_X - M_{J/\psi} = 775 \text{ MeV}$$

$$\frac{B(X \to \omega J/\psi)}{B(X \to \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3$$

$$B(B^0 \to X^- K^+, X^- \to J/\psi \pi^- \pi^0) < 5.4 \times 10^{-6}$$

Babar: Phys.Rev. D71, 031501 (2005)

X(3872) continued

Exotic nature of X(3872)

- Narrow width inconsistent with the $\chi_{c1}{}'$ assignment.

$$1\text{P }\chi_{c1}:\ \Gamma(\chi_{c1}) = 0.84 \pm 0.04 \text{ MeV} < \Gamma(\chi_{c1}{}')$$

- Isospin not precisely defined in molecular picture

decay length: $a = \hbar\,/\,\sqrt{\mu|\delta m|}$ PLB590, 209 (2004)

$D^0\bar{D}^{*0}$ molecule state: scattering length $a \geq 7$ fm
$D^+\bar{D}^{*-}$ molecule state: … ~ 2 fm

- Pure molecular state can not explain [PLB558,189(2004),JPD38,015001(2011)]

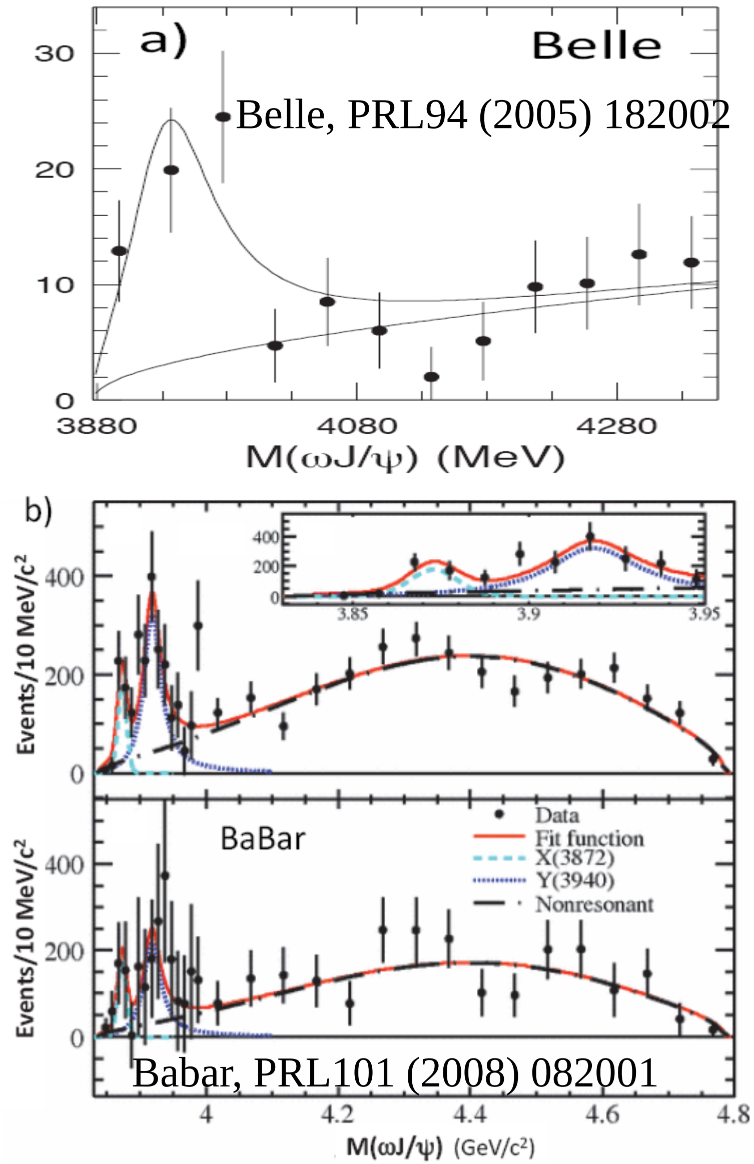
$$B(X \to \gamma\psi')/B(X \to \gamma\psi) = 2.46 \pm 0.70$$

- Commonality in the nature of X (3872) and Y (4260)

$B\big(Y(4260) \to \gamma X(3872)\big)/B(Y(4260) \to \pi^+\pi^- J/\psi) > 0.05$ (BESIII, PRL, 112,092001)

$X(3915)$ [or $\chi_{c0}(3915)$]

- $X(3915)$ in $B \rightarrow K\omega J/\psi$ observed by Belle and Babar



Belle: @275 M $B\bar{B}$

S-wave Breit-Wigner

$$M = 3943 \pm 17 \text{ MeV}$$
$$\Gamma = 87 \pm 24 \text{ MeV}$$

Babar: @467 M $B\bar{B}$

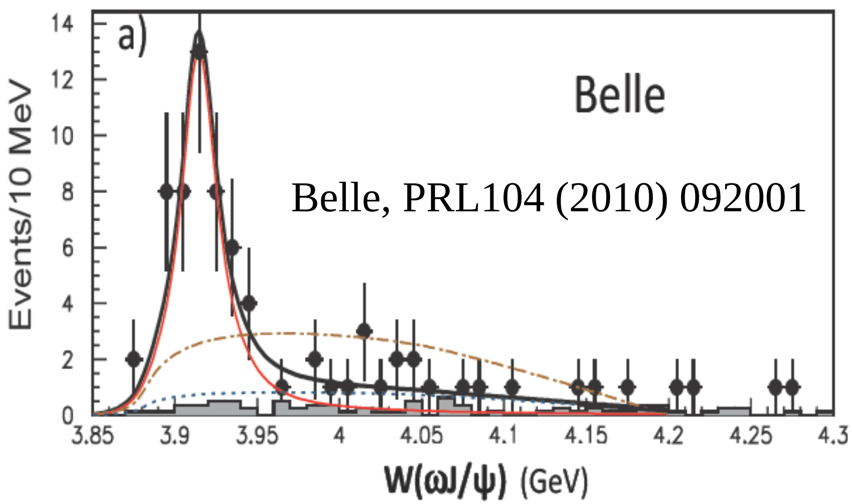
$$M = 3919 \pm 4 \text{ MeV}$$
$$\Gamma = 31 \pm 11 \text{ MeV}$$

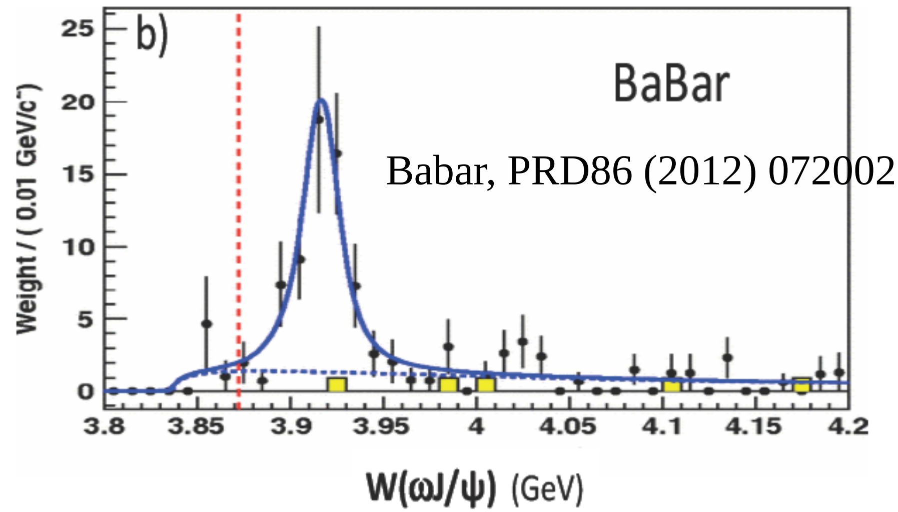
Weighted average:

$$M = 3920 \pm 4 \text{ MeV}$$
$$\Gamma = 41 \pm 10 \text{ MeV}.$$

X(3915)

- $X(3915)$ in $\gamma\gamma \to \omega J/\psi$ reported by Belle and Babar





Weight average:

$$M = 3917.4 \pm 2.4 \text{ MeV} \text{ and } \Gamma = 14 \pm 6 \text{ MeV}$$

PDG 2020:

$$M(X(3915)) = 3918.4 \pm 1.9 \text{ MeV}$$

$$\Gamma(X(3915)) = 20.0 \pm 5.0 \text{ MeV}.$$

$X(3915)$

- Is the $X(3915)$ the χ_{c0}' charmonium state?
  - Data favors $J^{PC}=0^{++}$ in Babar's spin-parity analysis of $\gamma\gamma \to \omega J/\psi$
  - $X(3915)$ as the χ_{c0}' state in PDG 2020
  - But mass splitting is too high

$$\delta M_{2-0}(2P) = 8.8 \pm 3.2\text{MeV}, \ \delta M_{2-0}(1P) = 141.5 \pm 0.3\text{MeV}$$

Quark model: $\delta M_{2\text{-}0}(2P) \sim 35$ MeV

E. J. Eichten, K. Lane, and C. Quigg, PRD69, 094019

  - no $\chi_{c0}' \to D\bar{D}$ observed, but strong coupling to $\omega J/\psi$ (OZI violation)

  - Possible to be $J^{PC}=2^{++}$ [Z.-Y. Zhou, Z. Xiao, and H.-Q. Zhou, PRL115 (2015) 022001)]

$X(3915)$

- If $X(3915)$ to be $\chi_{c2}(2P)$, it would be a controversy

$$\mathcal{B}(B^+ \to K^+\chi_{c2}(1\mathrm{P})) = (1.1 \pm 0.4) \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^+X(3915)) \times \mathcal{B}(X \to \omega J/\psi) = 3.0^{+0.9}_{-0.7} \times 10^{-5}$$

- More data are crucial to resolve the controversy [X*(3860) as χ_{c0}', Belle, 2017]

Is the $X(3915)$ a $c\bar{c}s\bar{s}$ four-quark state?

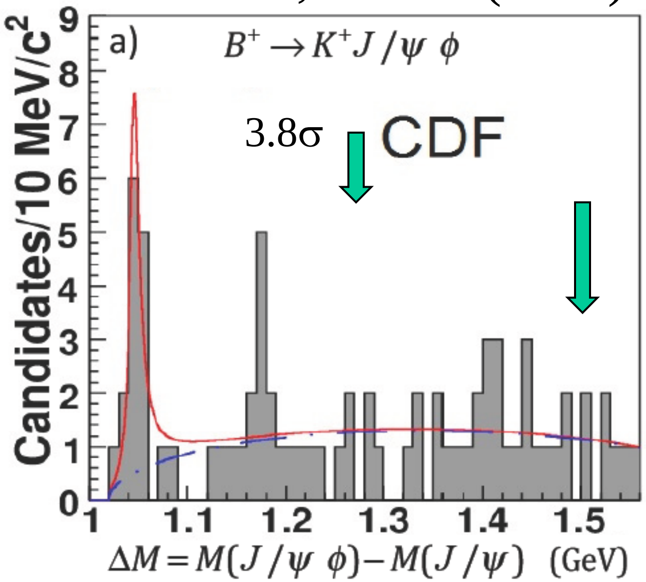
- $2M(D_s) - M(X(3915)) \sim 18\mathrm{MeV}$
- $D_s^+ D_s^-$ molecule-like configuration [PRD91 (2015) 114014], [$\underline{cs}$][cs] tetraquark states [RPD93 (2016) 094024] or mixture of the two.
- Predict the dominant decay $X(3915) \to \eta\eta_c$
- Not observed by Belle [Belle, JHEP 06 (2015) 132]

$$\mathcal{B}(B^+ \to K^+X(3915)) \times \mathcal{B}(X \to \eta\eta_c) < 4.7 \times 10^{-5}.$$

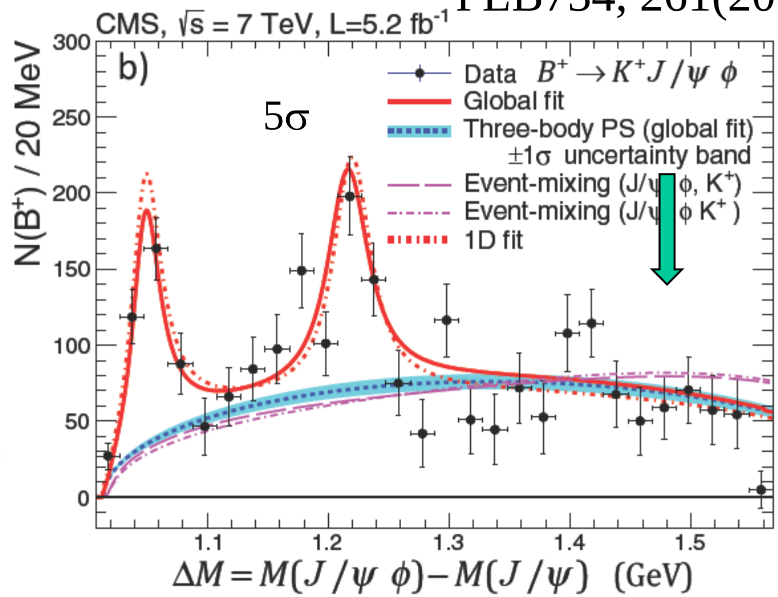
X(4140)

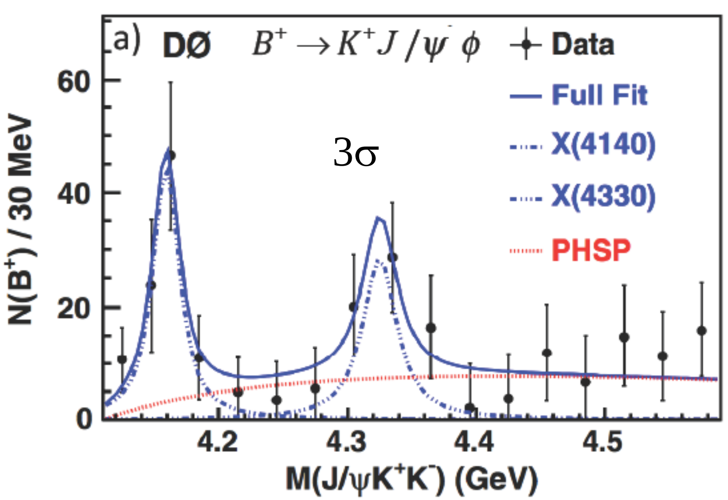
- Evidence for X(4140) was reported by CDF for the first time

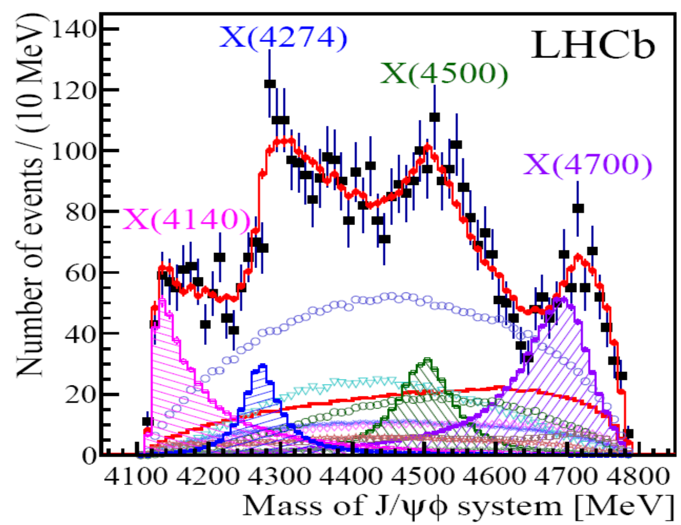
PRL102, 242002(2009)



PLB734, 261(2014)







Run-I
4.3 K
events

$X(4140)$

- Controversial history of $X(4140)$ observation

Year	Experiment luminosity	$B \to J/\psi\phi K$ yield	$X(4140)$ peak Mass [MeV]	Width [MeV]	Significance	Fraction %
2008	CDF 2.7 fb^{-1} (80)	58 ± 10	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8σ	
2009	*Belle (323)*	*325 ± 21*	*4143.0 fixed*	*11.7 fixed*	*1.9σ*	
2011	*CDF 6.0 fb^{-1} (94)*	*115 ± 12*	*$4143.4^{+2.9}_{-3.0} \pm 0.6$*	*$15.3^{+10.4}_{-6.1} \pm 2.5$*	*5.0σ*	*$14.9 \pm 3.9 \pm 2.4$*
2011	LHCb 0.37 fb^{-1} (322)	346 ± 20	4143.4 fixed	15.3 fixed	1.4σ	< 7 @ 90%CL
2013	CMS 5.2 fb^{-1} (81)	2480 ± 160	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0σ	10 ± 3 (stat.)
2013	D0 10.4 fb^{-1} (82)	215 ± 37	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	3.0σ	$21 \pm 8 \pm 4$
2014	BaBar (325)	189 ± 14	4143.4 fixed	15.3 fixed	1.6σ	< 13.3 @ 90%CL
2016	LHCb 3.0 fb^{-1} (49)	4289 ± 151	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	8.4σ	$13.0 \pm 3.2^{+4.8}_{-2.0}$
2015	D0 10.4 fb^{-1} (83)	$p\bar{p} \to J/\psi\phi ...$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	5.7σ (4.7σ)	

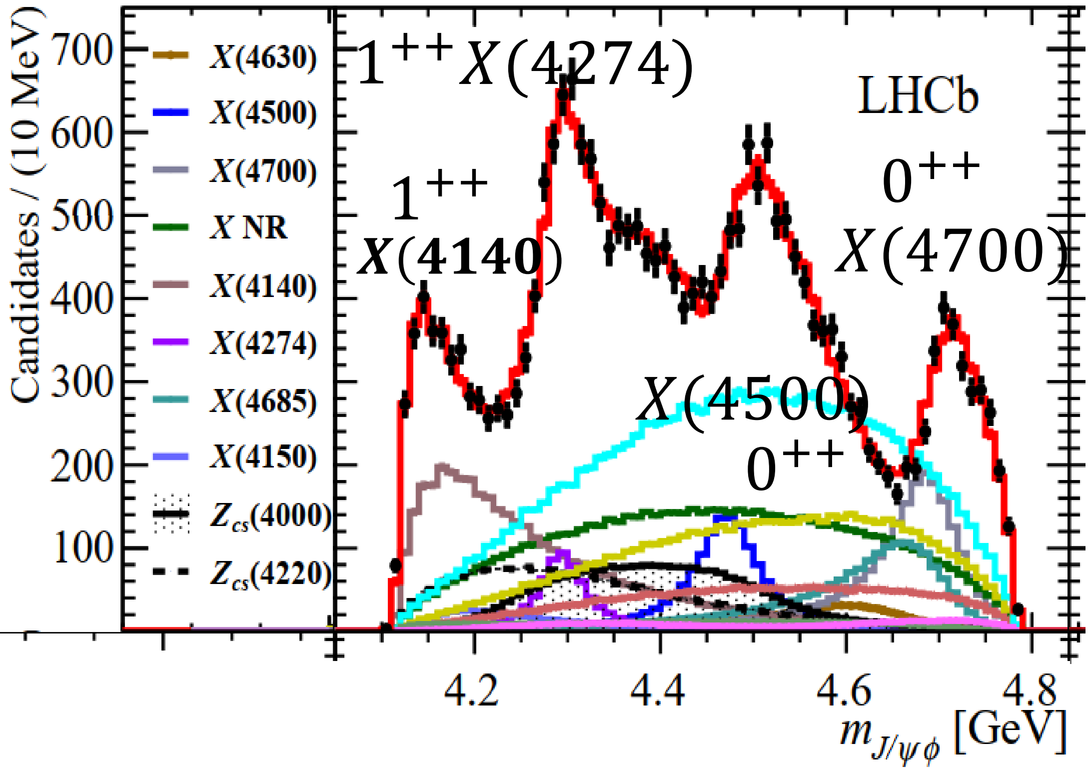
Year	Experiment luminosity	$B \to J/\psi\phi K$ yield	$X(4274-4351)$ peaks(s) Mass [MeV]	Width [MeV]	Significance	Fraction [%]
2011	*CDF 6.0 fb^{-1} (94)*	*115 ± 12*	*$4274.4^{+8.4}_{-6.7} \pm 1.9$*	*$32.3^{+21.9}_{-15.3} \pm 7.6$*	*3.1σ*	
2011	LHCb 0.37 fb^{-1} (322)	346 ± 20	4274.4 fixed	32.3 fixed		< 8 @ 90%CL
2013	CMS 5.2 fb^{-1} (81)	2480 ± 160	$4313.8 \pm 5.3 \pm 7.3$	$38^{+30}_{-15} \pm 16$		
2013	D0 10.4 fb^{-1} (82)	215 ± 37	4328.5 ± 12.0	30 fixed		
2014	BaBar (325)	189 ± 14	4274.4 fixed	32.3 fixed	1.2σ	< 18.1 @ 90%CL
2016	LHCb 3.0 fb^{-1} (49)	4289 ± 151	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	6.0σ	$7.1 \pm 2.5^{+3.5}_{-2.4}$
			$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	6.1σ	$6.6 \pm 2.4^{+3.5}_{-2.3}$
			$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	5.6σ	$12 \pm 5^{+9}_{-5}$
2010	Belle (95)	$\gamma\gamma \to J/\psi\phi$	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$	3.2σ	

$X(4140)$

- LHCb amplitude analysis [LHCb, arXiv: 2103.01803]

LHCb Run I + II data events

- 24.2 K decays from $B^+ \rightarrow J/\psi\phi K^+$
- The mode including K^* six X resonances, two Zcs.
- $X(4140)$, 16σ
  $M = 4118 \pm 11^{+19}_{-36}$ MeV
  $\Gamma = 162 \pm 21^{+24}_{-49}$ MeV
  $J^{PC}=1^{++}$, >13 σ
- Rule out 0^{++} and 2^{++} $D_s^* \bar{D}_s^*$ molecular models



PRD80 (2009) 017502
PRD80 (2009) 054019
PLB678 (2009) 186

EPJC64 (2009) 297
J.PG37 (2010) 025005
PRD80 (2009) 114013

$X(4140)$ continued

- Charmonium assignments for the $J/\psi\phi$ states?

$X(4140)$ and $X(4274)$ as candidate of $\chi_{c1}(3P)$ state

Eur. Phys. J. C76 (2016) 671
Phys. Rev. D80 (2009) 014012
Phys. Rev. D94 (2016) 074007

Decay widths to DD^*, D^*D^*, $D_sD_s^*$ to be 30MeV to 58 MeV

Phys. Rev. D72 (2005) 054026,
Phys. Rev. D94 (2016) 114018,
Eur. Phys. J. C76(2016) 671

$X(4500)$ and $X(4700)$ as candidates of $\chi_{c0}(4P)$ and $\chi_{c0}(5P)$ state,

Phys. Rev. D94 (2016) 074007,
Phys. Rev. D94 (2016) 114018

Exotic features in experiments:

- No observation in $B \to D^{(*)}_{(s)} D^{(*)}_{(s)} K$
- No observation in $B \to J/\psi \omega K$

X(4140) continued

- $X(4140)$ as $\chi_{c1}(2P)$ candidate $I^G(J^{PC}) = 0^+(1^{++})$ (PDG2020)

$$M = 4146.8 \pm 2.4\ \text{MeV}, \Gamma = 22^{+8}_{-7}\ \text{MeV}$$

- No cusp account for the mass

- $D_s^* D_s^*$ molecular state or hybrid charmonium state with $J^{PC}=1^{-+}$ Phys. Lett.B679 (2009) 228, Eur. Phys. J. C63 (2009) 115

- Tetraquark model predict $J^{PC}=1^{++}$ for $X(4140)$, but different to 1^{++} for next higher energy state

Phys. Rev. D93 (2016) 094024,
Phys. Rev. D79 (2009) 077502,
Int. J. Mod. Phys. A30 (2015) 1550004,
Int. J. Mod. Phys. A30 (2015) 1550186

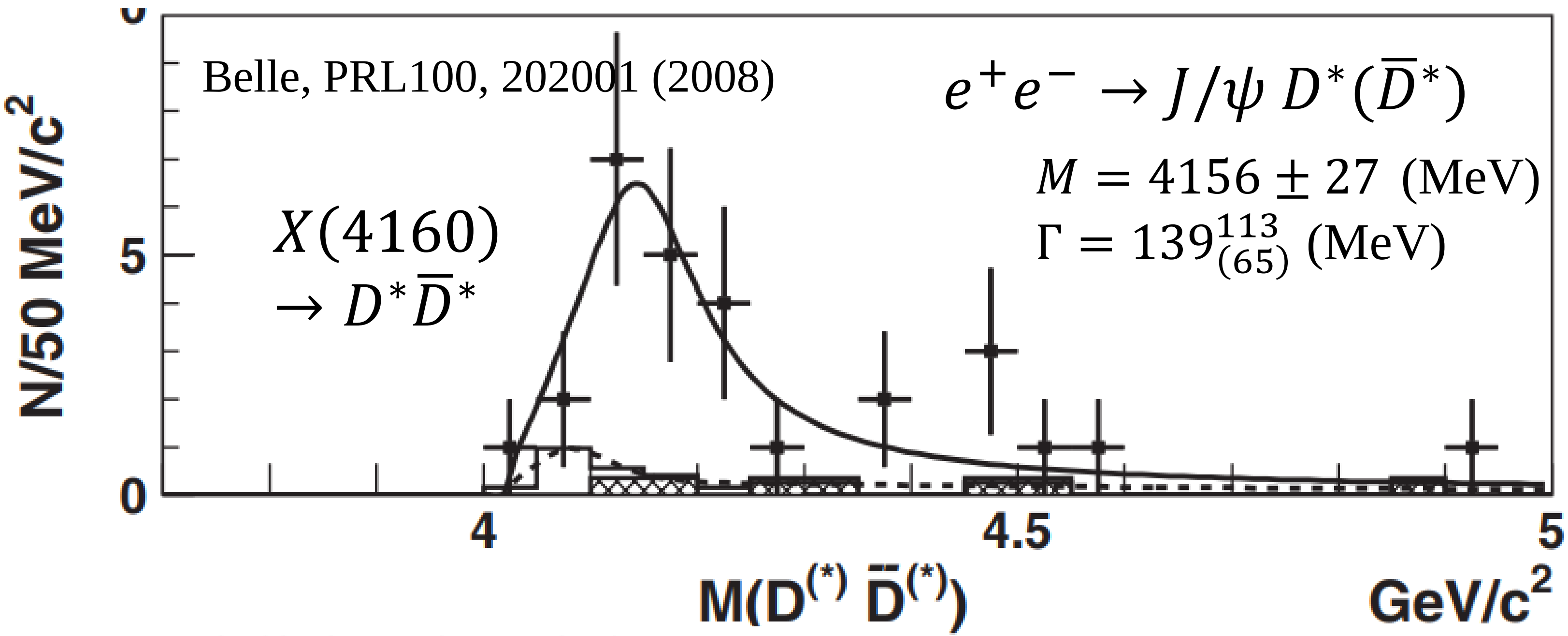
An exception: J. Phys. G37 (2010) 075017

1^{++}: M=4195, 4356 MeV

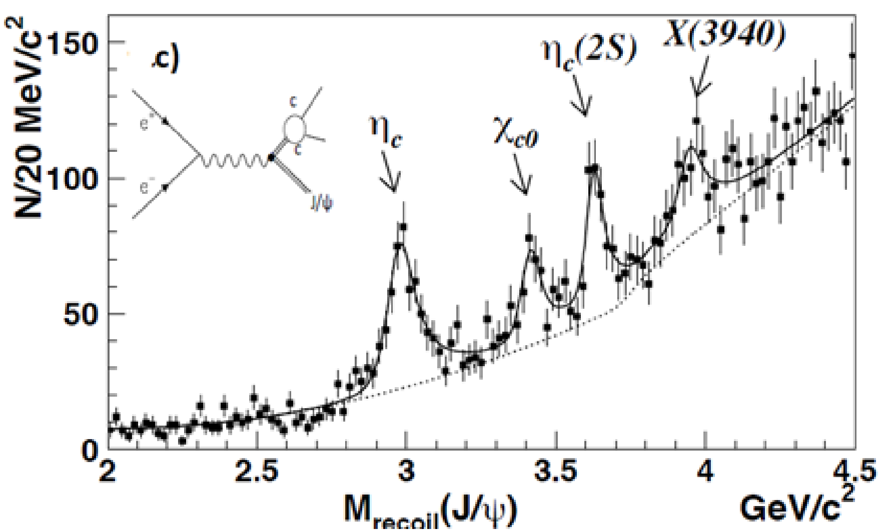
- Lattice QCD found no evidence for 1^{++} tetraquark state below 4.2 GeV

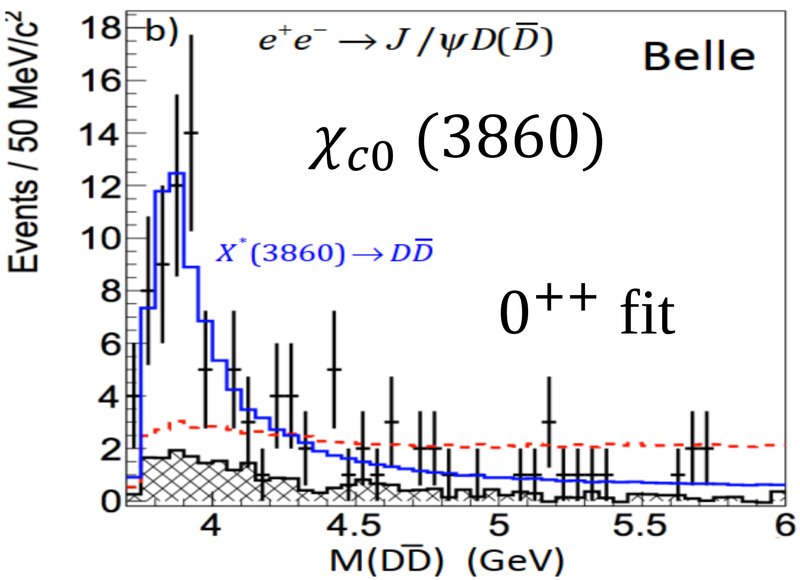
Phys. Rev. D92 (2015) 034501

$X(4160)$ [J^{PC} =?$^{??}$]



double charmonium production





$X(4160)$ [J^{PC} =?$^{??}$]

- $X(4160)$ produced from $e^+e^- \to J/\psi\ (c\bar{c})$, favor $J = 0$, C+
- 0^{++} or 0^{-+} allow the decay $X(4160) \to D^*\,\bar{D}^*$, but 0^{-+} not allow $X(4160) \to D\bar{D}$ due to spin-parity violation
- not seen $X(4160) \to D\bar{D}$

  support: 0^{-+}
- To assign X(3940) as $\eta_c(3S)$ and $X(4160)$ as $\eta_c(4S)$

  $\psi(3S) = \psi(4040)$

  $\psi(4S) = \psi(4415)$

  charmonium mass splitting $n_r^3S - n_r^1S$

$$M(\psi') - M(\eta'_c) = 47.2 \pm 1.2 \text{ MeV}$$

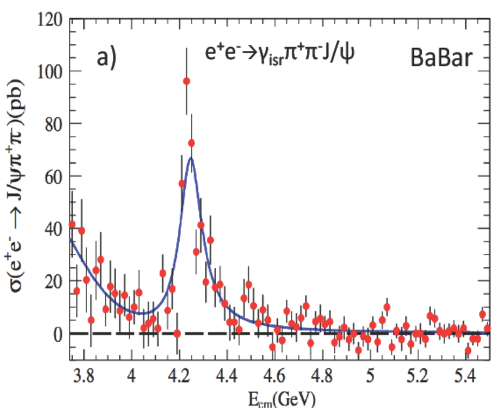
$$M(\psi(3S)) - M(X(3940)) \sim 100 \text{ MeV}$$

$$M(\psi(4S)) - M(X(4160)) \sim 250 \text{ MeV}$$

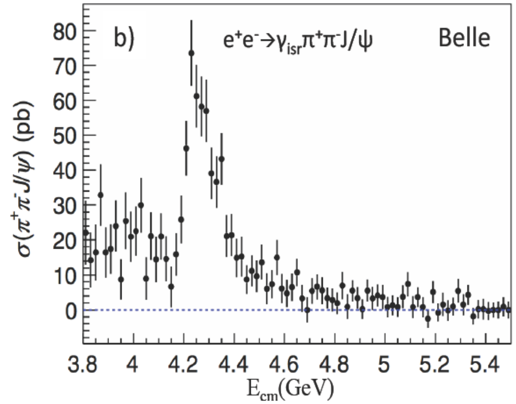
Conflict with potential model: mass splitting decrease with increasing n_r.

- $Y(4260)$ observed in $e^+e^- \rightarrow \gamma_{ISR}\, \pi^+\pi^- J/\psi$ by Babar

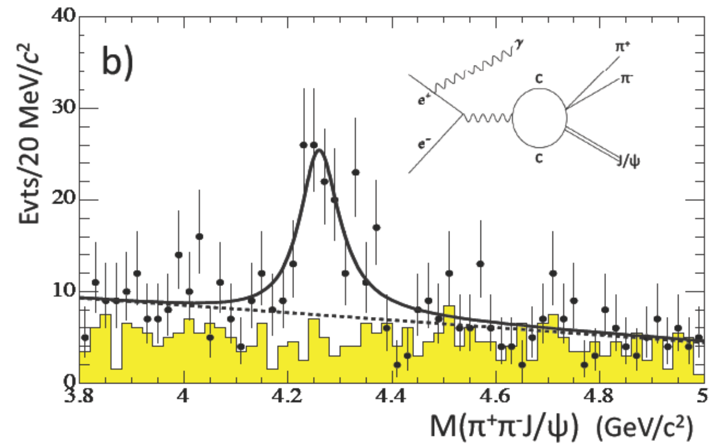
Babar, PRD86 (2012) 051102



Belle, PRL110 (2013) 252002



Babar. PRL95 (2005) 142001



- Cross section around $Y(4260)$ measured

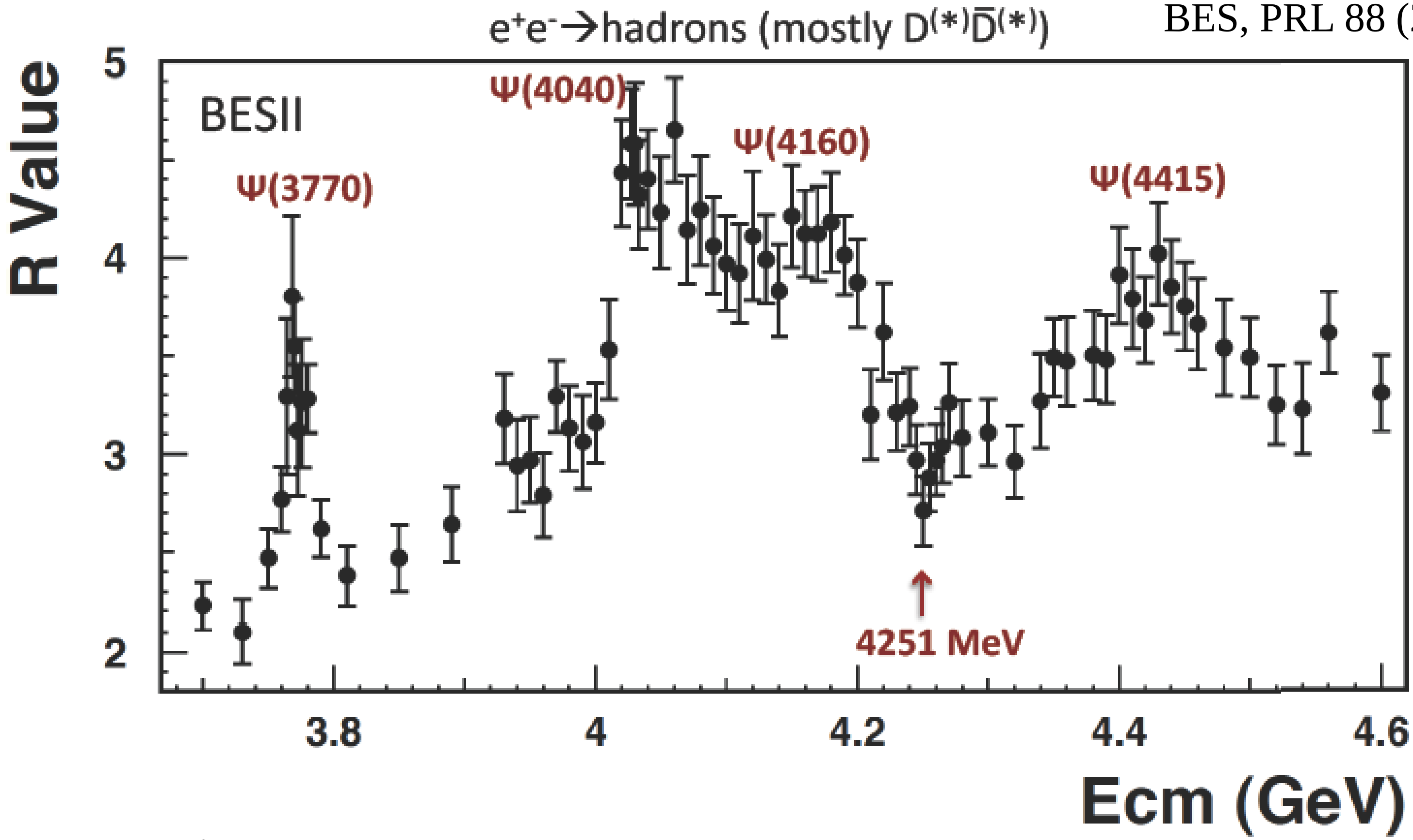
Weighted average over Babar, Belle and CLEO results:

$$M(Y(4260)) = 4251 \pm 9 \text{ MeV}$$
$$\Gamma(Y(4260)) = 120 \pm 12 \text{ MeV}.$$

Y(4260) continued

- *Y*(4260) as muti-quark meson or $c\underline{c}$-gluon hybrid

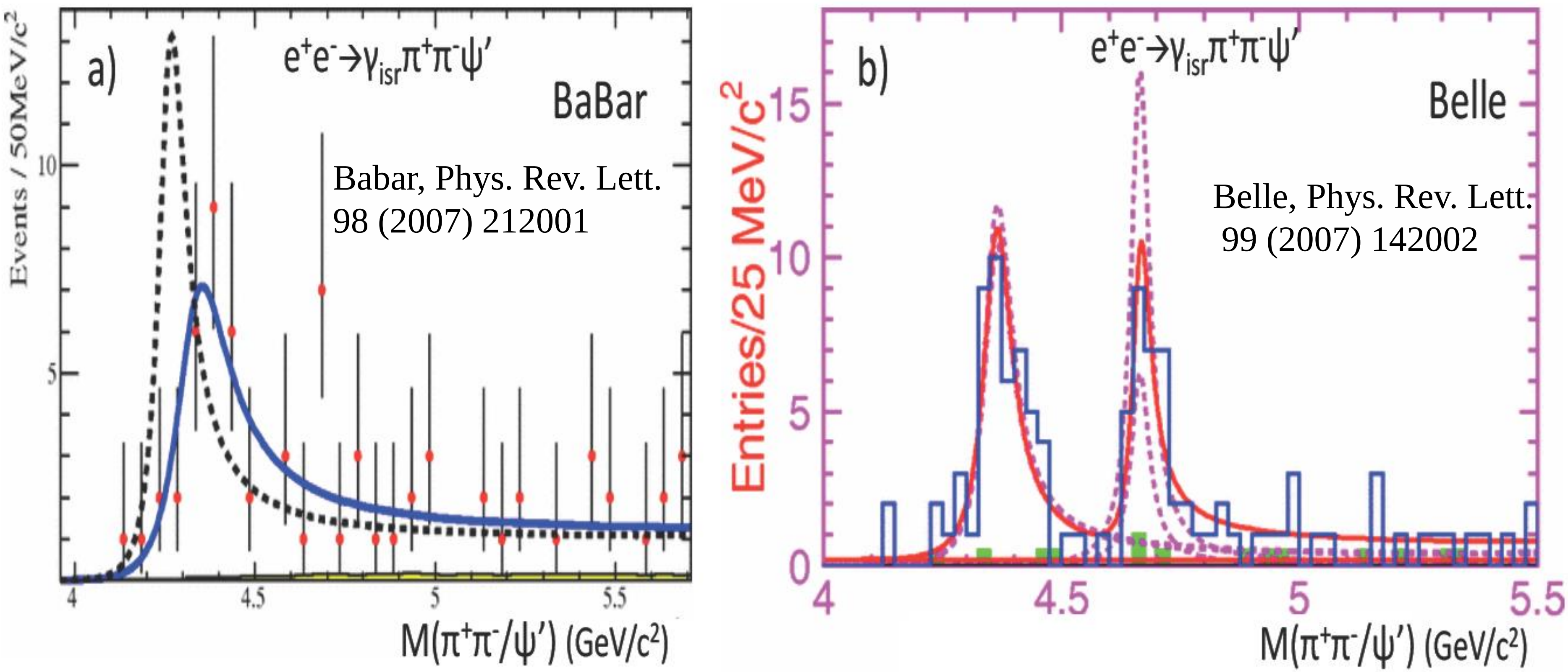
BES, PRL 88 (2002) 101802



Exotic state

Eur. Phys. J. C71 (2011) 1534
PRD89 (2014) 114010
PRD89 (2014), 116005

Y(4360) and *Y*(4660)



$$M(Y(4360)) = 4346 \pm 6 \text{ MeV} \qquad M(Y(4660)) = 4643 \pm 9 \text{ MeV}$$

$$\Gamma(Y(4360)) = 102 \pm 12 \text{ MeV}. \qquad \Gamma(Y(4660)) = 72 \pm 11 \text{ MeV}.$$

BESIII as a "*Y*(4360)-factory"

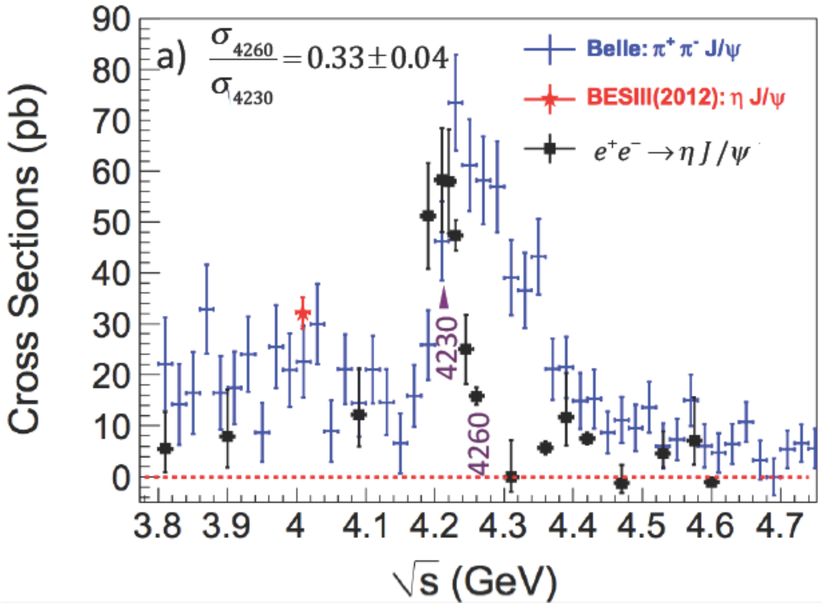
- ISR experiments vs. scan experiments

2013: 1092 pb^{-1} at **4.23 GeV**
826 pb^{-1} at **4.26 GeV**
540 pb^{-1} at **4.36 GeV**

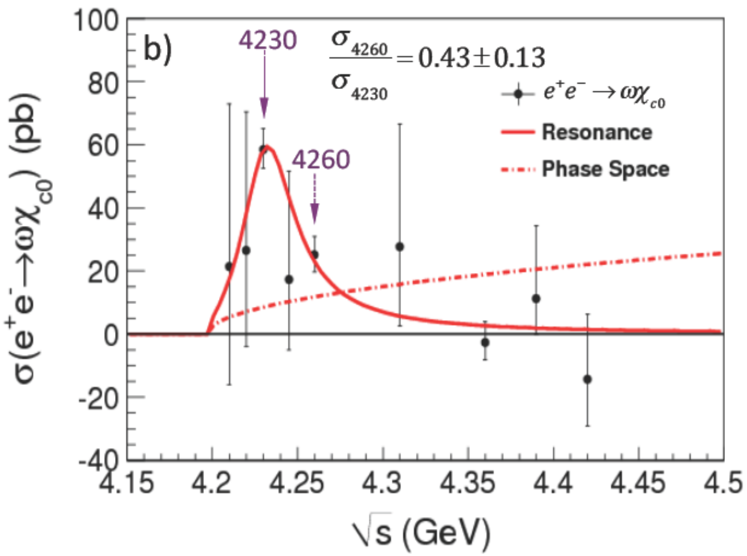
2014: 1029 pb^{-1} at **4.42 GeV**
110 pb^{-1} at **4.47 GeV**
110 pb^{-1} at **4.53 GeV**
48 pb^{-1} at **4.575 GeV**
567 pb^{-1} at **4.6 GeV**

2017. 500/pb each for 7 energy points between 4.19~4.28 GeV

BESIII, PRD91 (2015) 112005



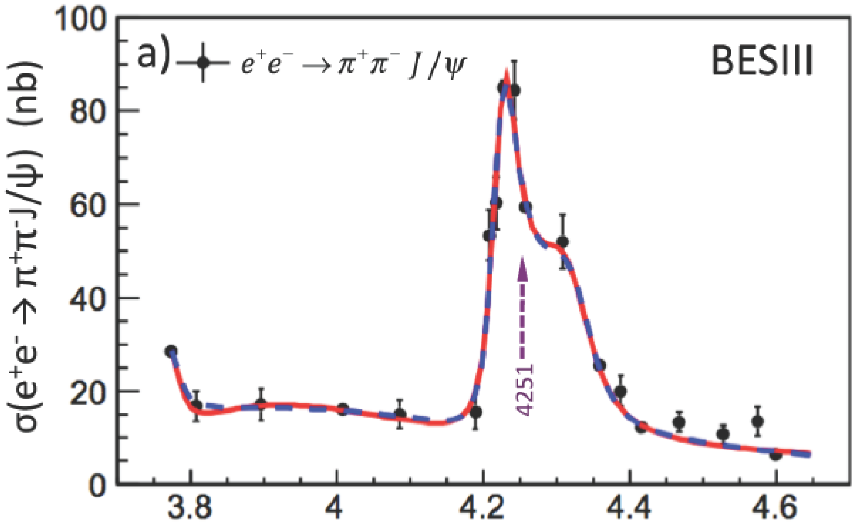
BESIII, PRL114 (2015) 092003

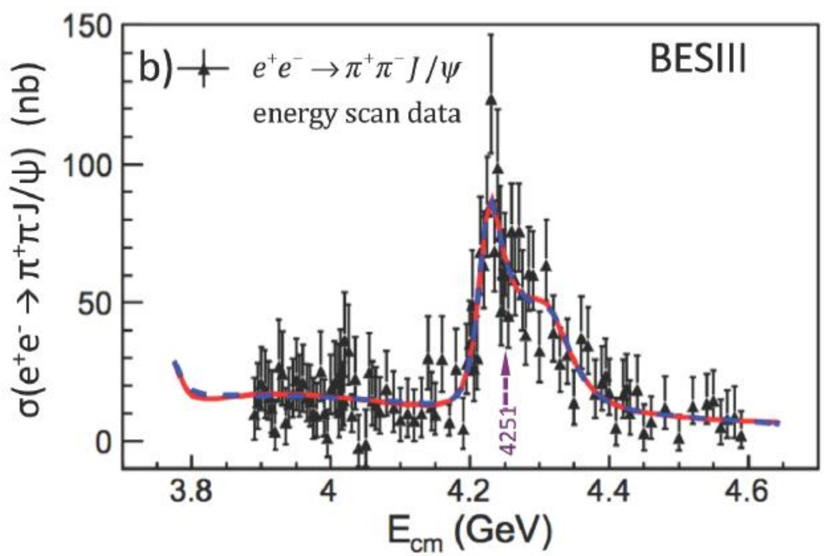


BESIII as a "Y(4360)-factory" (continued)

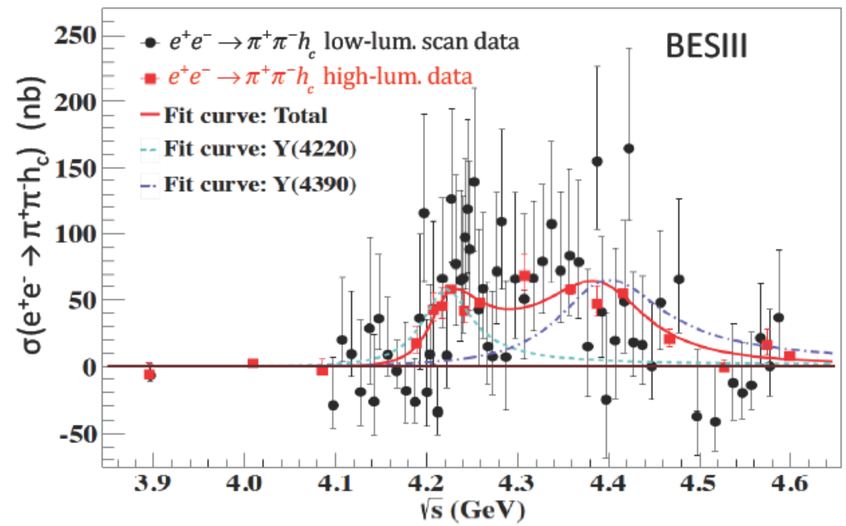
- Narrow structure around $Y(4260)$

BESIII, PRL118 (2017) 092001,





BESIII, PRL, 118 (2017) 092002



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

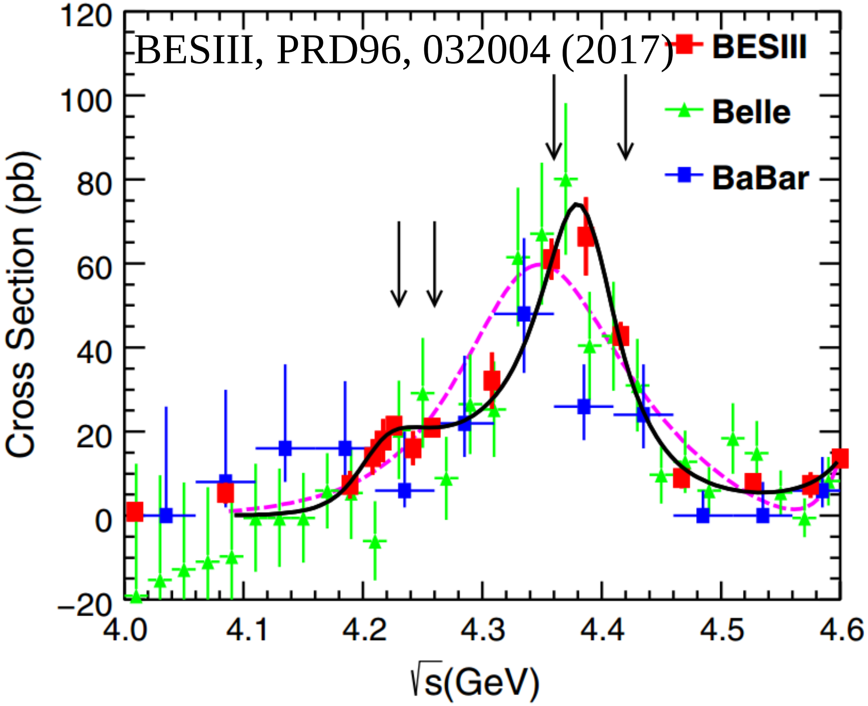
$$M_1 = 4222 \pm 4 \text{ MeV} \quad \Gamma_1 = 44 \pm 5 \text{ MeV}$$
$$M_2 = 4320 \pm 13 \text{ MeV} \quad \Gamma_2 = 101^{+27}_{-22} \text{ MeV},$$

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

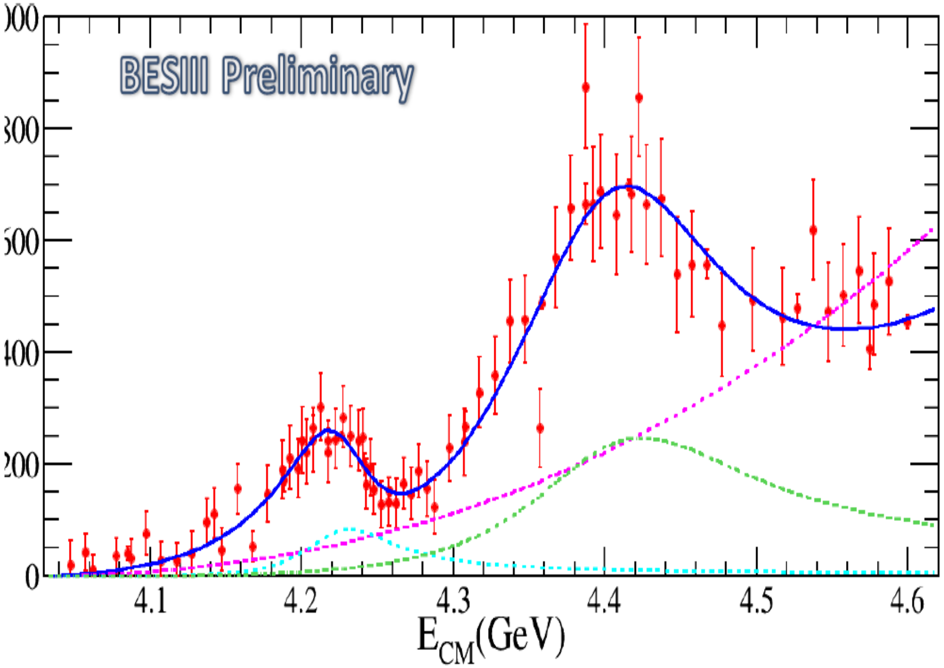
$$M_1 = 4218 \pm 4 \text{ MeV} \quad \Gamma_1 = 66 \pm 9 \text{ MeV}$$
$$M_2 = 4392 \pm 6 \text{ MeV} \quad \Gamma_2 = 140 \pm 16 \text{ MeV}$$

BESIII as a "Y(4360)-factory" (continued)

$e^+e^- \to \pi^+\pi^-\psi(3686)$



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



Process	M_1 (MeV/c^2)	Γ_1 (MeV)	M_2 (MeV/c^2)	Γ_2 (MeV)
$e^+e^- \to \omega\chi_{c0}$	$4230 \pm 8 \pm 6$	$38 \pm 12 \pm 2$ [37]		
$e^+e^- \to \pi^+\pi^- J/\psi$	$4220.0 \pm 3.1 \pm 1.4$	$44.1 \pm 4.3 \pm 2.0$	$4320.0 \pm 10.4 \pm 7.0$	$101.4^{+25.3}_{-19.7} \pm 10.2$[9]
$e^+e^- \to \pi^+\pi^- h_c$	$4218.4^{+5.5}_{-4.5} \pm 0.9$	$66.0^{+12.3}_{-8.3} \pm 0.4$	$4391.5^{+6.3}_{-6.8} \pm 1.0$	$139.5^{+16.2}_{-20.6} \pm 0.6$ [10]
$e^+e^- \to \pi^+ D^0 D^{*-} + c.c$	$4224.8 \pm 5.6 \pm 4.0$	$72.3 \pm 9.1 \pm 0.9$	$4400.1 \pm 9.3 \pm 2.1$	$181.7 \pm 16.9 \pm 7.4$ [38]
$e^+e^- \to \pi^+\pi^-\psi(3686)$	$4209.5 \pm 7.4 \pm 1.4$	$80.1 \pm 24.6 \pm 2.9$	$4383.8 \pm 4.2 \pm 0.8$	$84.2 \pm 12.5 \pm 2.1$

Status of $Y(4260), Y(4230)[I^G(J^{PC}) = 0^-(1^{--})]$

- ISR measurement unreliable, should replace with scan ones.

  PDG2020:
  $Y(4260)$: $M = 4209 \sim 4259$ MeV, $\Gamma = 73 \sim 134$ MeV

  Average with BESIII measurements $\pi^+\pi^- J/\psi(\psi'), \pi^+\pi^- \mathrm{h_c}, \omega\chi_{c0}$

  PDG: $M(Y(4230)) = 4220 \pm 15$ MeV
  $\Gamma(Y(4230)) = 44 \pm 9$ MeV

- $D\bar{D}_1(2420)$ bound state [PRL111,132003(2013), PRD79, 014001(2009)]

  Bind energy increase from 27.4 → 35 MeV, large than that estimated with Yukawa meson-exchange force

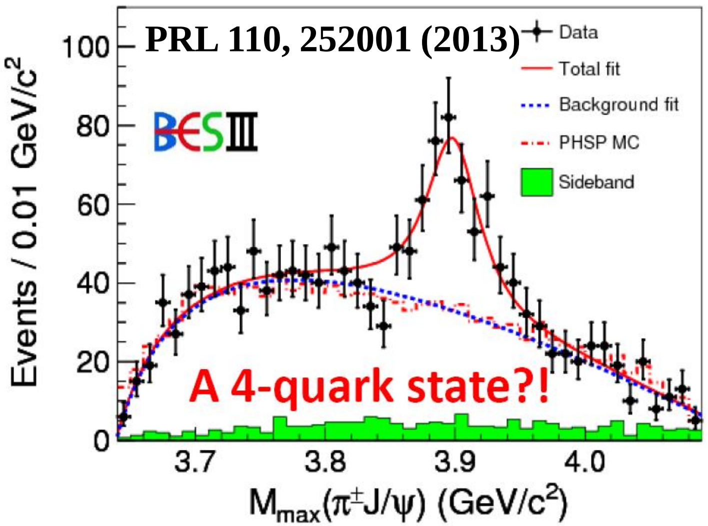
- $c\bar{c}$-gluon hybrid meson [PLB625,212(2005), PLB628,215(2005), PLB631,164(2005)]

- Lattice QCD [JHEP07,126(2012)]

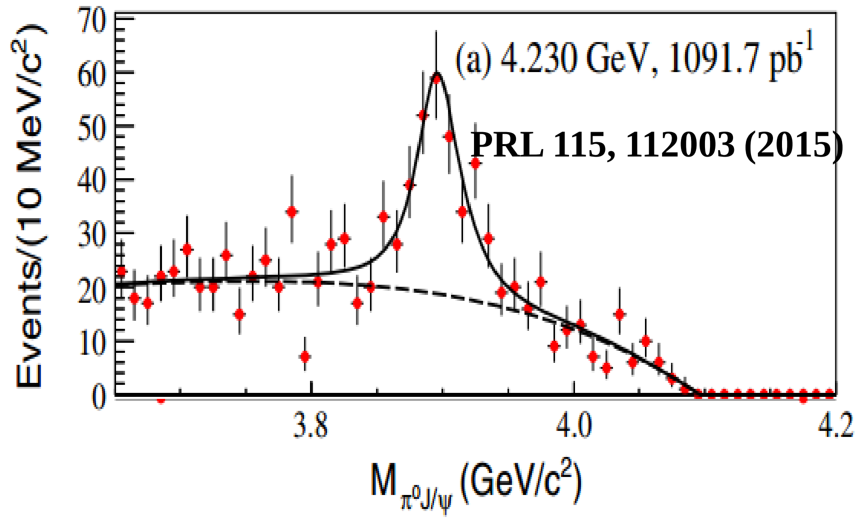
  1^{--} hybrid state: $M = 4285 \pm 14$ MeV

Observation of Zc(3900): $I^G(J^{PC}) = 1^+(1^{+-})$

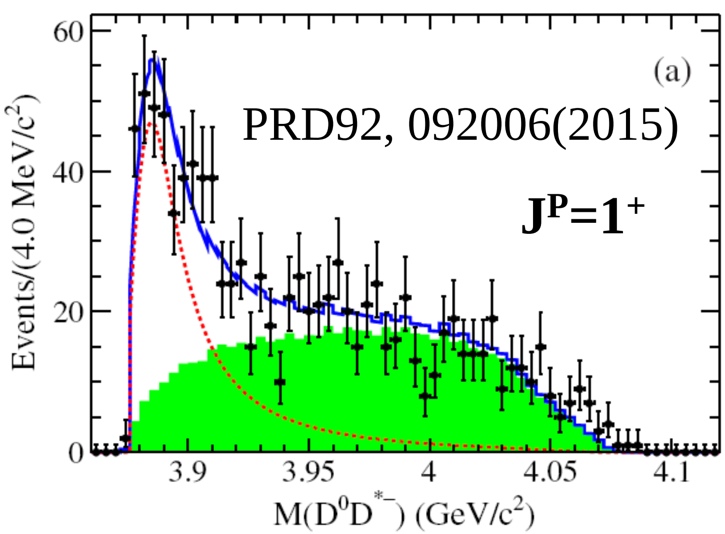
$$Z_c(3900)^{\pm} : e^+e^- \to \pi^+\pi^- J/\psi$$



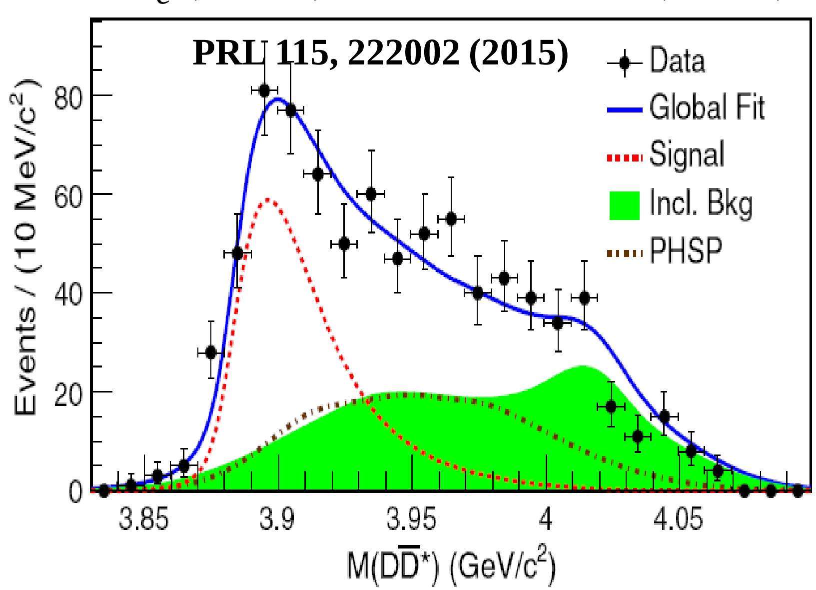
$$Z_c(3900)^0 : e^+e^- \to \pi^0\pi^0 J/\psi$$



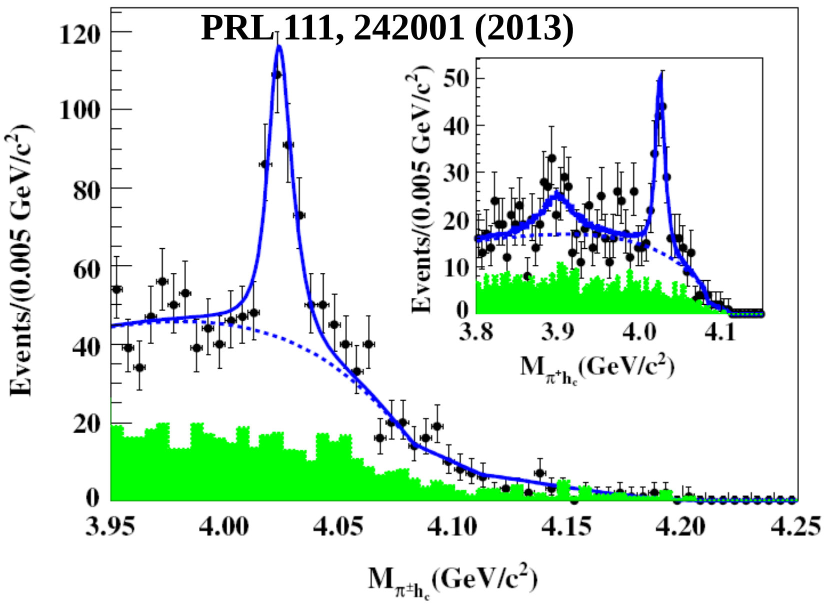
$$Z_c(3900)^{\pm} : e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$$



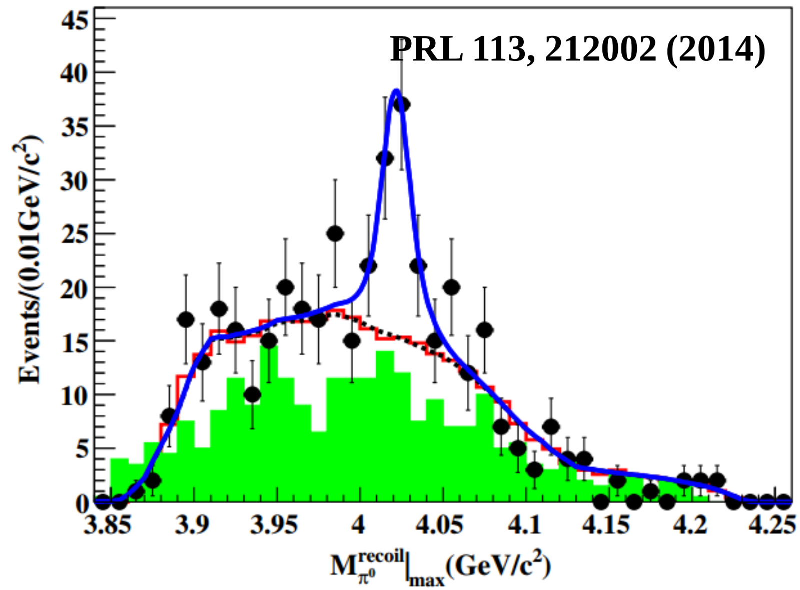
$$Z_c(3900)^0 : e^+e^- \to \pi^0(D\bar{D}^*)^0$$



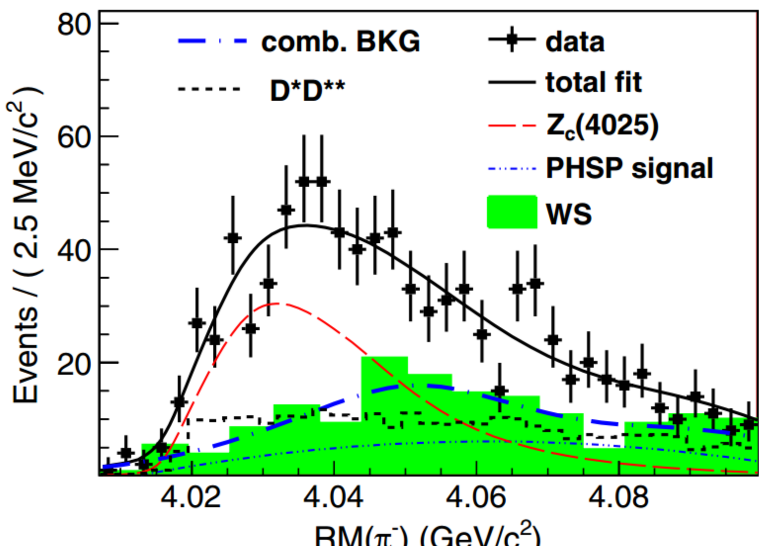
$Z_c(4020)^{\pm} : e^+e^- \to \pi^+\pi^- h_c$



$Z_c(4020)^0 : e^+e^- \to \pi^0\pi^0 h_c$

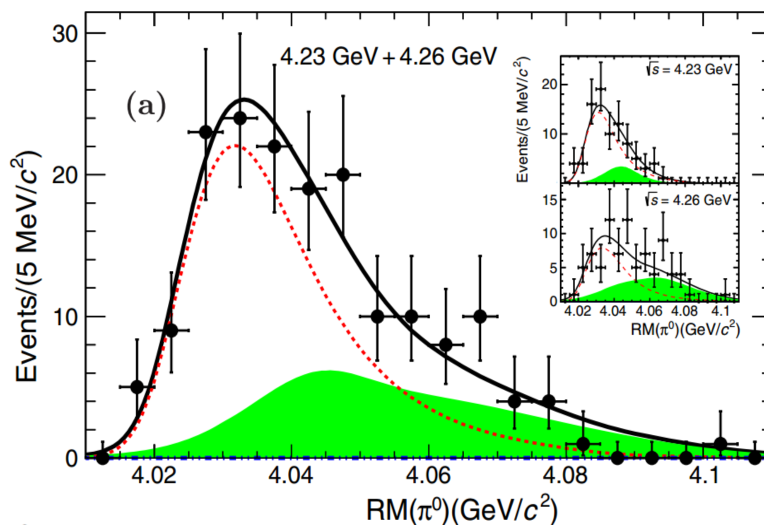


$Z_c(4025)^{\pm} : e^+e^- \to \pi^{\pm}(D^*\bar{D}^*)^{\mp}$



PRL 112, 132001 (2014)

$Z_c(4025)^0 : e^+e^- \to \pi^0(D^*\bar{D}^*)^0$



PRL 115, 182002 (2015)

Open issues for Z_c states

- Are the *Z*c(3900) and *Z*c(3885) same state?
  - 2σ difference in masses, and width of Zc(3885) is about half of that Zc(3900). The two have $J^P=1^+$
  - Zc(3900) as a tetraquark state, Zc(3885) as molecular state
    Z.G.Wang and J.X.Zhang, Eur. Phys. J. C (2018) 78:14
  - PDG2020: one state with a 35±7 MeV width
- Are the *Z*c(4020) and *Z*c(4025) same state?
  - J^P unknown
  - PDG2020: average of mass and width

$$M = 4024.1 \pm 1.9 \text{ MeV}$$
$$\Gamma = 13 \pm 5 \text{ MeV}$$

Open issues for Z_c states

- Lineshape parameterization
  - Breit-Wigner or Flatte-like formula in experiments
  - Unitarized for coupled channel analysis

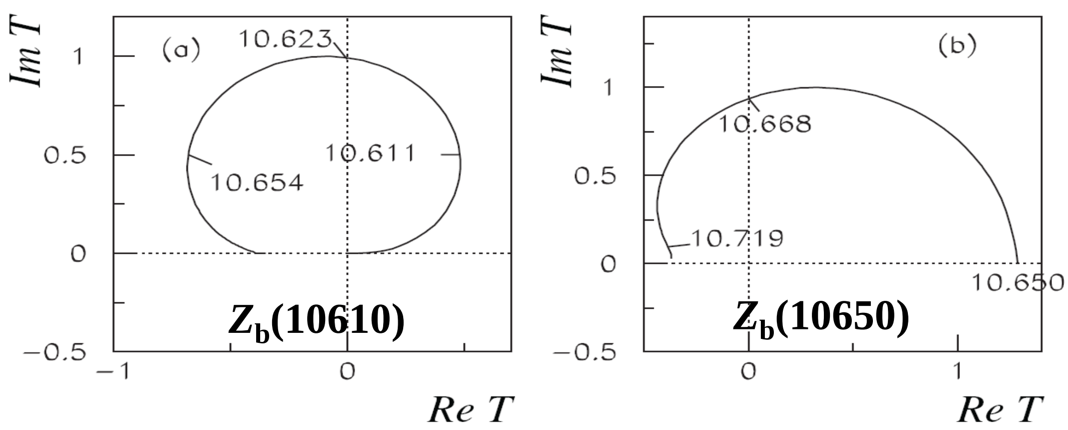
W. Qin, S.R. Xie, and Q.Zhao, PRD94, 054035 (2016)
M. Cleven, Q. Wang, F.K. Guo, C. Hanhart, U-G. Meibner, Q.Zhao, PRD90, 074039 (2014)
Q.R. Gong, Z.H. Guo, C. Meng, G.Y. Tang, Y.F. Wang and H.Q. Zheng, PRD94, 114019(2016)

- Phase shift model independent measurement
  - Lattice QCD predictions

CLQCD, PRD92 054507 (2015)
CLQCD, PRD89 094506 (2014)

- Argand plot due to cusp

D.V.Bugg, EPL96 (2011) , 11002

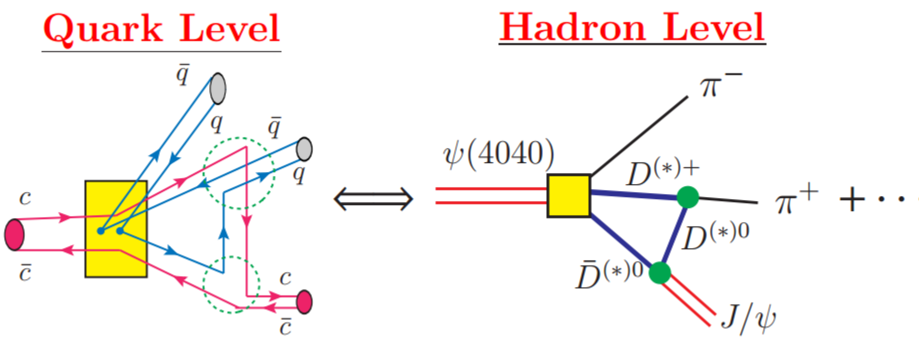


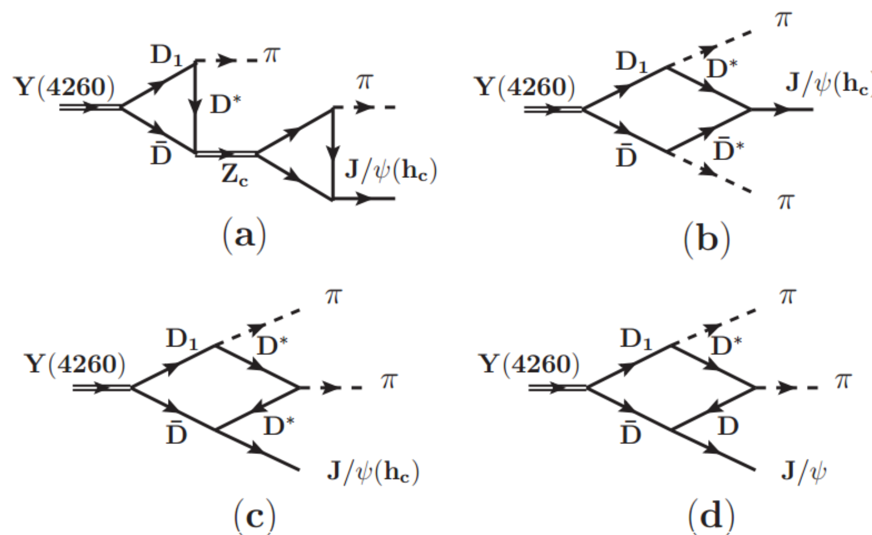
Open issues for Z_c states

- Production model test

Q.Wang, C. Hanhart, Q.Zhao, PRL111 (2013),132003

D.Y. Chen, X. Liu, PRD**84 (2011) 034032**





- Couple channel analysis in experiment

$$Zc(3900/3885)^{\pm}:\ e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}, \pi^+\pi^- J/\psi, \pi^+\pi^- h_c$$

$$Zc(4020/4025)^{\pm}:\ e^+e^- \to \pi^{\pm}(D^*\bar{D}^*)^{\mp}, \pi^+\pi^- J/\psi, \pi^+\pi^- h_c$$

Summary

From 2003, a large number of exotic charmonium like states were observed tau-charm and B-factory and LHC experiment, and more than 20 states are well established. They are characterized by

- ✓ Decays to open charm are suppressed
- ✓ Decays to hidden charm are enhanced

  -- Large apparent OZI-rule violations
- ✓ They are relatively narrow, some are near thresholds
- ✓ Figure out the underlying structure, more efforts need both from experimental and theoretical community.

Thanks for you attention