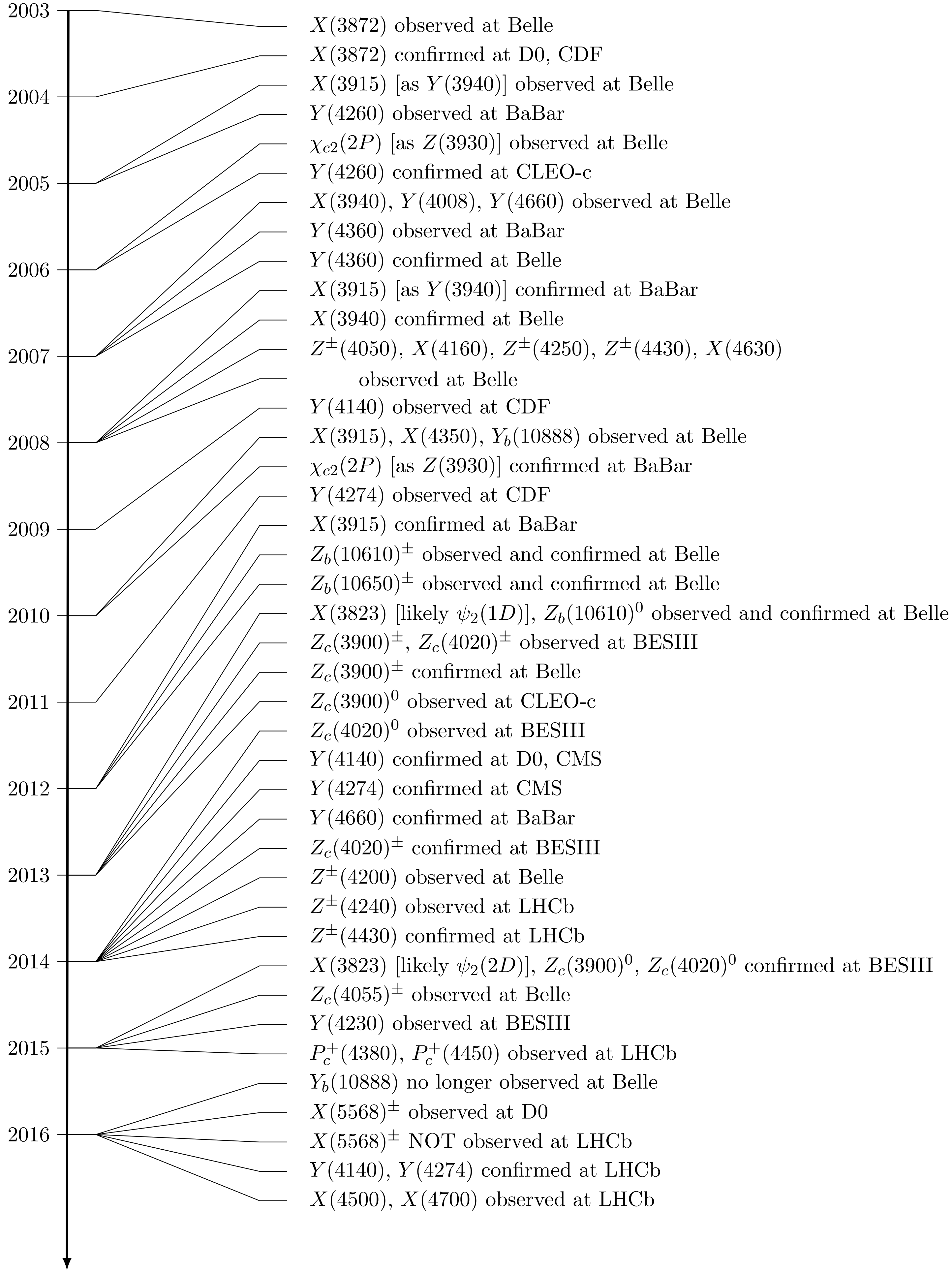
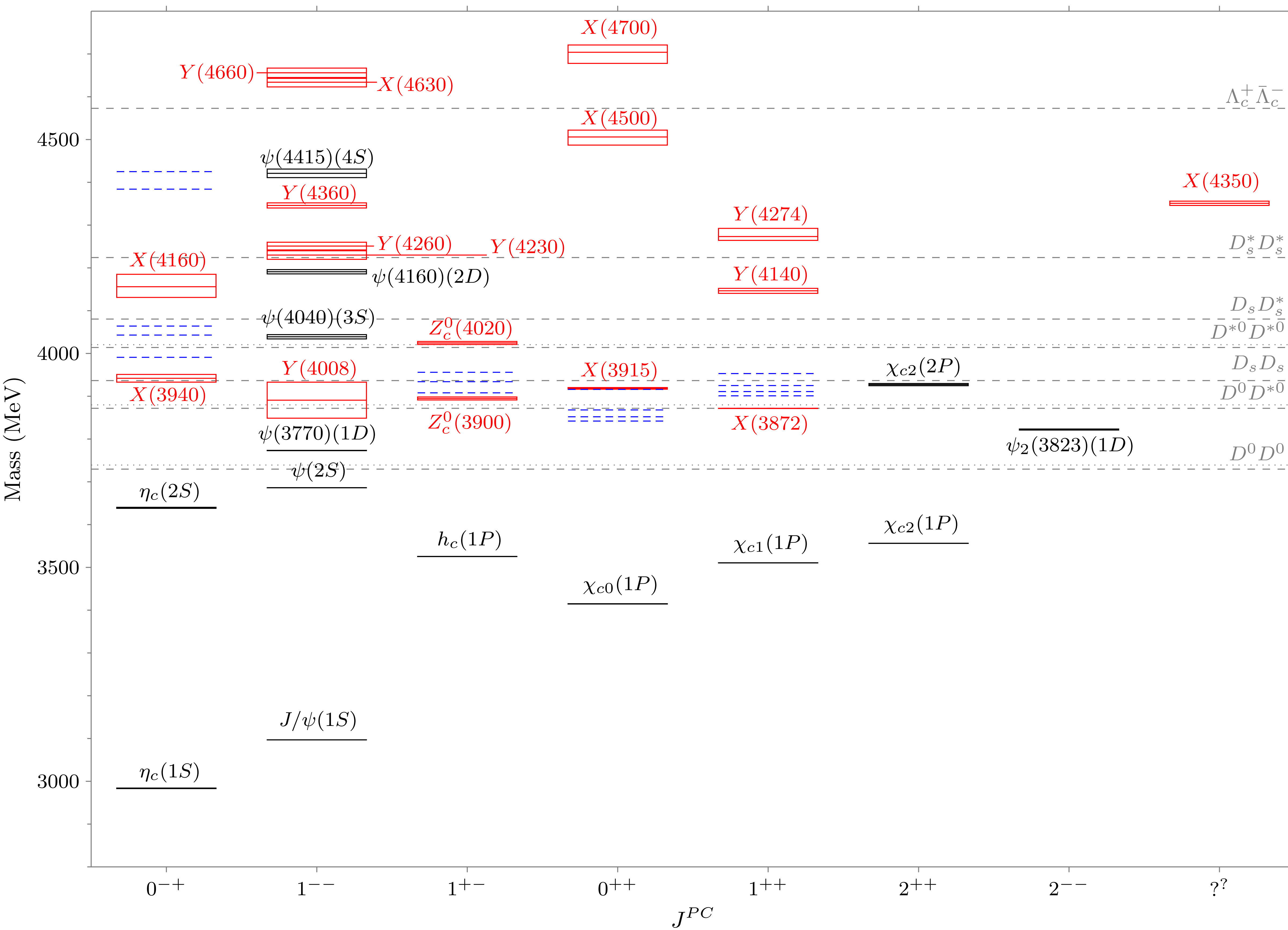
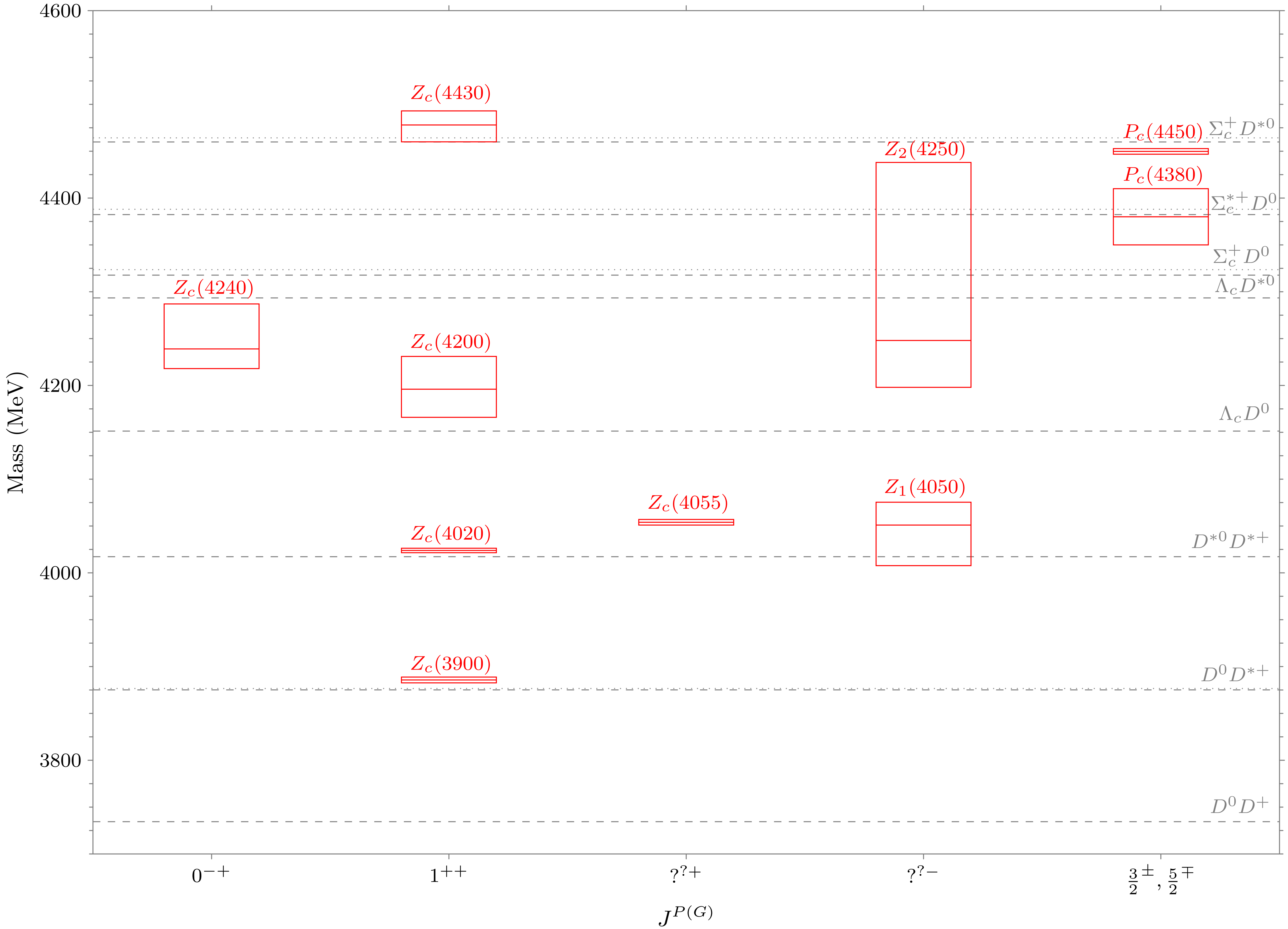

2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
$X(3872)$ observed at Belle
$X(3872)$ confirmed at D0, CDF
$X(3915)$ [as $Y(3940)$] observed at Belle
$Y(4260)$ observed at BaBar
$\chi_{c2}(2P)$ [as $Z(3930)$] observed at Belle
$Y(4260)$ confirmed at CLEO-c
$X(3940)$, $Y(4008)$, $Y(4660)$ observed at Belle
$Y(4360)$ observed at BaBar
$Y(4360)$ confirmed at Belle
$X(3915)$ [as $Y(3940)$] confirmed at BaBar
$X(3940)$ confirmed at Belle
$Z^{\pm}(4050)$, $X(4160)$, $Z^{\pm}(4250)$, $Z^{\pm}(4430)$, $X(4630)$ observed at Belle
$Y(4140)$ observed at CDF
$X(3915)$, $X(4350)$, $Y_b(10888)$ observed at Belle
$\chi_{c2}(2P)$ [as $Z(3930)$] confirmed at BaBar
$Y(4274)$ observed at CDF
$X(3915)$ confirmed at BaBar
$Z_b(10610)^{\pm}$ observed and confirmed at Belle
$Z_b(10650)^{\pm}$ observed and confirmed at Belle
$X(3823)$ [likely $\psi_2(1D)$], $Z_b(10610)^0$ observed and confirmed at Belle
$Z_c(3900)^{\pm}$, $Z_c(4020)^{\pm}$ observed at BESIII
$Z_c(3900)^{\pm}$ confirmed at Belle
$Z_c(3900)^0$ observed at CLEO-c
$Z_c(4020)^0$ observed at BESIII
$Y(4140)$ confirmed at D0, CMS
$Y(4274)$ confirmed at CMS
$Y(4660)$ confirmed at BaBar
$Z_c(4020)^{\pm}$ confirmed at BESIII
$Z^{\pm}(4200)$ observed at Belle
$Z^{\pm}(4240)$ observed at LHCb
$Z^{\pm}(4430)$ confirmed at LHCb
$X(3823)$ [likely $\psi_2(2D)$], $Z_c(3900)^0$, $Z_c(4020)^0$ confirmed at BESIII
$Z_c(4055)^{\pm}$ observed at Belle
$Y(4230)$ observed at BESIII
$P_c^+(4380)$, $P_c^+(4450)$ observed at LHCb
$Y_b(10888)$ no longer observed at Belle
$X(5568)^{\pm}$ observed at D0
$X(5568)^{\pm}$ NOT observed at LHCb
$Y(4140)$, $Y(4274)$ confirmed at LHCb
$X(4500)$, $X(4700)$ observed at LHCb



$X(4700)$
$Y(4660)$
$X(4630)$
$\Lambda_c^+\bar{\Lambda}_c^-$
$X(4500)$
4500
$\psi(4415)(4S)$
$Y(4360)$
$X(4350)$
$Y(4274)$
$Y(4260)$
$Y(4230)$
$D_s^*D_s^*$
$X(4160)$
$\psi(4160)(2D)$
$Y(4140)$
$\psi(4040)(3S)$
$D_sD_s^*$
$Z_c^0(4020)$
$D^{*0}D^{*0}$
4000
$Y(4008)$
$X(3915)$
$\chi_{c2}(2P)$
D_sD_s
$X(3940)$
D^0D^{*0}
$Z_c^0(3900)$
$X(3872)$
$\psi(3770)(1D)$
$\psi_2(3823)(1D)$
D^0D^0
$\psi(2S)$
$\eta_c(2S)$
$h_c(1P)$
$\chi_{c2}(1P)$
$\chi_{c1}(1P)$
3500
$\chi_{c0}(1P)$
$J/\psi(1S)$
$\eta_c(1S)$
3000
Mass (MeV)
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
2^{--}
$?^?$
J^{PC}



4600
4400
4200
4000
3800
Mass (MeV)
$Z_c(4430)$
$\Sigma_c^+ D^{*0}$
$P_c(4450)$
$Z_2(4250)$
$P_c(4380)$
$\Sigma_c^{*+} D^0$
$\Sigma_c^+ D^0$
$Z_c(4240)$
$\Lambda_c D^{*0}$
$Z_c(4200)$
$\Lambda_c D^0$
$Z_c(4055)$
$Z_1(4050)$
$Z_c(4020)$
$D^{*0} D^{*+}$
$Z_c(3900)$
$D^0 D^{*+}$
$D^0 D^+$
0^{-+}
1^{++}
$?^{?+}$
$?^{?-}$
$\frac{3}{2}^{\pm}, \frac{5}{2}^{\mp}$
$J^{P(G)}$

Experiment	Highlights	Accelerator	Years	Institute	Production
BaBar	$Y(4260)$ [28] $Y(4360)$ [103]	PEP-II	1999–2008	SLAC (Menlo Park, California, USA)	e^+e^- annihilation ($E_{\rm CM} \approx 10$ GeV): $e^+e^- \to B\bar{B}$; $B \to KX$ $e^+e^- \to Y_b$ $e^+e^- \to \pi Z_b$ $e^+e^-(\gamma_{\rm ISR}) \to Y$ $e^+e^-(\gamma_{\rm ISR}) \to \pi Z_c$ $e^+e^- \to J/\psi + X$ $\gamma\gamma \to X$
Belle	$X(3872)$ [4] $Y(3940)$ [101] $X(3915)$ [160] $Z_c(4430)$ [29, 131, 132] $Z_b(10610)$, $Z_b(10650)$ [154, 156, 157] $Y_b(10888)$ [145, 146]	KEKB	1998–2010	KEK (Tsukuba, Japan)	
Belle II	Upcoming continuation of Belle	SuperKEKB	2018–		
CLEO-c	$Y(4260)$ [137] $\pi^+\pi^- h_c$ [171]	CESR-c	2003–2008	Cornell U. (Ithaca, New York, USA)	e^+e^- annihilation ($E_{\rm CM} \approx 4$ GeV): $e^+e^- \to Y$ $e^+e^- \to \pi Z$ $e^+e^- \to \gamma X$
BESIII	$Z_c(3900)$ [21, 148] $Z_c(4020)$ [150, 152] $Y(4230)$ [143] $X(3872)$ [49]	BEPCII	2008–	IHEP (Beijing, China)	
CDF	$Y(4140)$ [121] $Y(4274)$ [127] $X(3872)$ [172, 173, 166]	Tevatron	1985–2011	Fermilab (Batavia, Illinois, USA)	$p\bar{p}$ collisions ($E_{\rm CM} \approx 2$ TeV): $p\bar{p} \to X$ + any $p\bar{p} \to B$ + any; $B \to KX$
D0	$X(3872)$ [165] $Y(4140)$ [168] $X(5568)$ [169]				
ATLAS	$\chi_b(3P)$ [174]	LHC	2010–	CERN (Geneva, Switzerland)	pp collisions ($E_{\rm CM} = 7, 8, 13$ TeV): $pp \to X$ + any $pp \to B$ + any; $B \to KX$ $pp \to \Lambda_b$ + any; $\Lambda_b \to KP_c$
CMS	$X(3872)$ [27] $Y(4140)$, $Y(4274)$ [125]				
LHCb	$Z_c(4430)$ [133, 134] $X(3872)$ [104] $P_c(4380)$, $P_c(4450)$ [34] $Y(4140)$, $Y(4274)$ [120, 126]				
COMPASS	photoproduction [175] $a_1(1420)$ [176]	SPS	2002-2011		μ/π beam on N target ($p_{beam} \approx 160, 200$ GeV) $\pi N \to XN$ $\gamma N \to XN$
$\bar{\rm P}$ANDA	Upcoming	HESR		GSI (Darmstadt, Germany)	$\bar{p}$ beam on p target ($p_{beam} \approx 1.5$–15 GeV): $p\bar{p} \to X$ $p\bar{p} \to X$ + any
GlueX	Beginning (searches for light quark hybrid mesons)	CEBAF	2016–	Jefferson Lab (Newport News, Virginia, USA)	γ beam on p target ($E_{beam} \le 11$ GeV): $\gamma p \to Xp$
CLAS12					

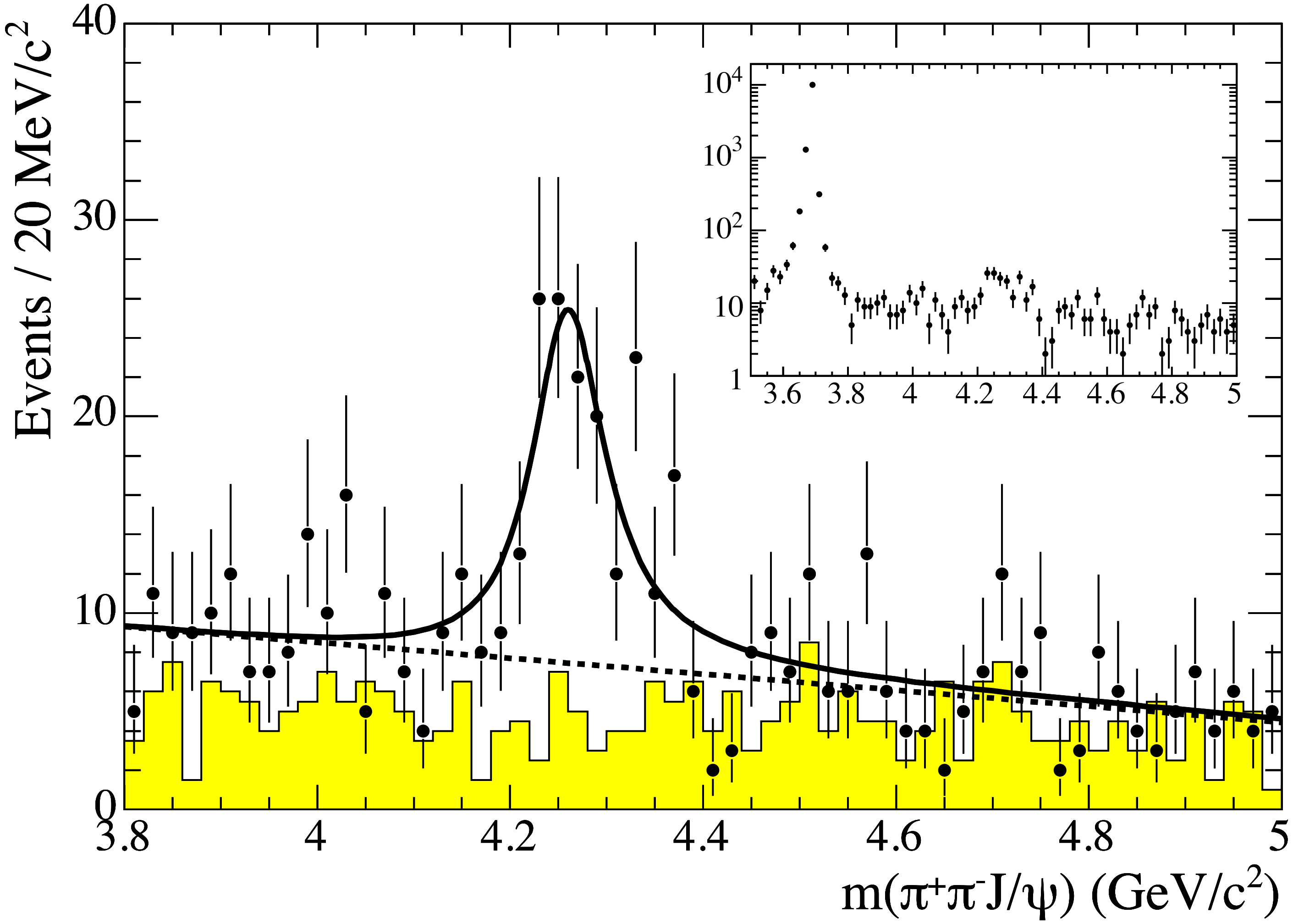
Process	Production	Decay	Particle
B and Λ_b Decays	$B \to K + X$	$X \to \pi^+\pi^- J/\psi$ [4, 104, 105, 106, 107, 108, 109] $X \to D^{*0}\bar{D}^0$ [110, 111, 112] $X \to \gamma J/\psi$ [113, 114, 115, 116] $X \to \gamma\psi(2S)$ [113, 115]	$X(3872)$
		$X \to \omega J/\psi$ [101, 117, 118]	$X(3872)$ $Y(3940)$
		$X \to \gamma\chi_{c1}$ [119]	$X(3823)$
		$X \to \phi J/\psi$ [120, 121, 122, 123, 124, 125, 126, 127]	$Y(4140)$ $Y(4274)$ $X(4500)$ $X(4700)$
	$B \to K + Z$	$Z \to \pi^\pm \chi_{c1}$ [128, 129]	$Z_1(4050)$ $Z_2(4250)$
		$Z \to \pi^\pm J/\psi$ [43, 130]	$Z_c(4200)$ $Z_c(4430)$
		$Z \to \pi^\pm \psi(2S)$ [29, 130, 131, 132, 133, 134]	$Z_c(4240)$ $Z_c(4430)$
	$B \to K\pi + X$	$X \to \pi^+\pi^- J/\psi$ [135]	$X(3872)$
	$\Lambda_b \to K + P_c$	$P_c \to pJ/\psi$ [34]	$P_c(4380)$ $P_c(4450)$
e^+e^- Annihilation	$e^+e^- \to Y$	$Y \to \pi\pi J/\psi$ [22, 28, 136, 137, 138, 139]	$Y(4008)$ $Y(4260)$
		$Y \to \pi\pi\psi(2S)$ [103, 140, 141, 142]	$Y(4360)$ $Y(4660)$
		$Y \to \omega\chi_{c0}$ [143]	$Y(4230)$
		$Y \to \Lambda_c\bar{\Lambda}_c$ [144]	$X(4630)$
		$Y \to \pi\pi\Upsilon(1S, 2S, 3S)$ [145, 146] $Y \to \pi\pi h_b(1P, 2P)$ [147]	$Y_b(10888)$
	$e^+e^- \to \pi + Z$	$Z \to \pi J/\psi$ [21, 22, 30, 31] $Z \to D^*\bar{D}$ [32, 148, 149]	$Z_c(3900)$
		$Z \to \pi h_c$ [150, 151] $Z \to D^*\bar{D}^*$ [152, 153]	$Z_c(4020)$
		$Z \to \pi^\pm\psi(2S)$ [142]	$Z_c(4055)$
		$Z \to \pi\Upsilon(1S, 2S, 3S)$ [154, 155, 156] $Z \to \pi h_b(1P, 2P)$ [154]	$Z_b(10610)$ $Z_b(10650)$
		$Z \to B\bar{B}^*$ [157]	$Z_b(10610)$
		$Z \to B^*\bar{B}^*$ [157]	$Z_b(10650)$
	$e^+e^- \to \gamma + X$	$X \to \pi^+\pi^- J/\psi$ [49]	$X(3872)$
	$e^+e^- \to \pi^+\pi^- + X$	$X \to \gamma\chi_{c1}$ [158]	$X(3823)$
	$e^+e^- \to J/\psi + X$	$X \to D\bar{D}^*$ [38, 159]	$X(3940)$
		$X \to D^*\bar{D}^*$ [38]	$X(4160)$
$\gamma\gamma$ Collisions	$\gamma\gamma \to X$	$X \to \omega J/\psi$ [160, 161]	$X(3915)$
		$X \to D\bar{D}$ [162, 163]	$Z(3930)$
		$X \to \phi J/\psi$ [164]	$X(4350)$
Hadron Collisions	pp or $p\bar{p} \to X+$ anything	$X \to \pi^+\pi^- J/\psi$ [26, 165, 166, 167]	$X(3872)$
		$X \to \phi J/\psi$ [168]	$Y(4140)$
		$X \to B_s\pi^\pm$ [169]	$X(5568)$

Y(4260)

Y(4260)

B. Aubert [BaBar], hep-ex/0506081

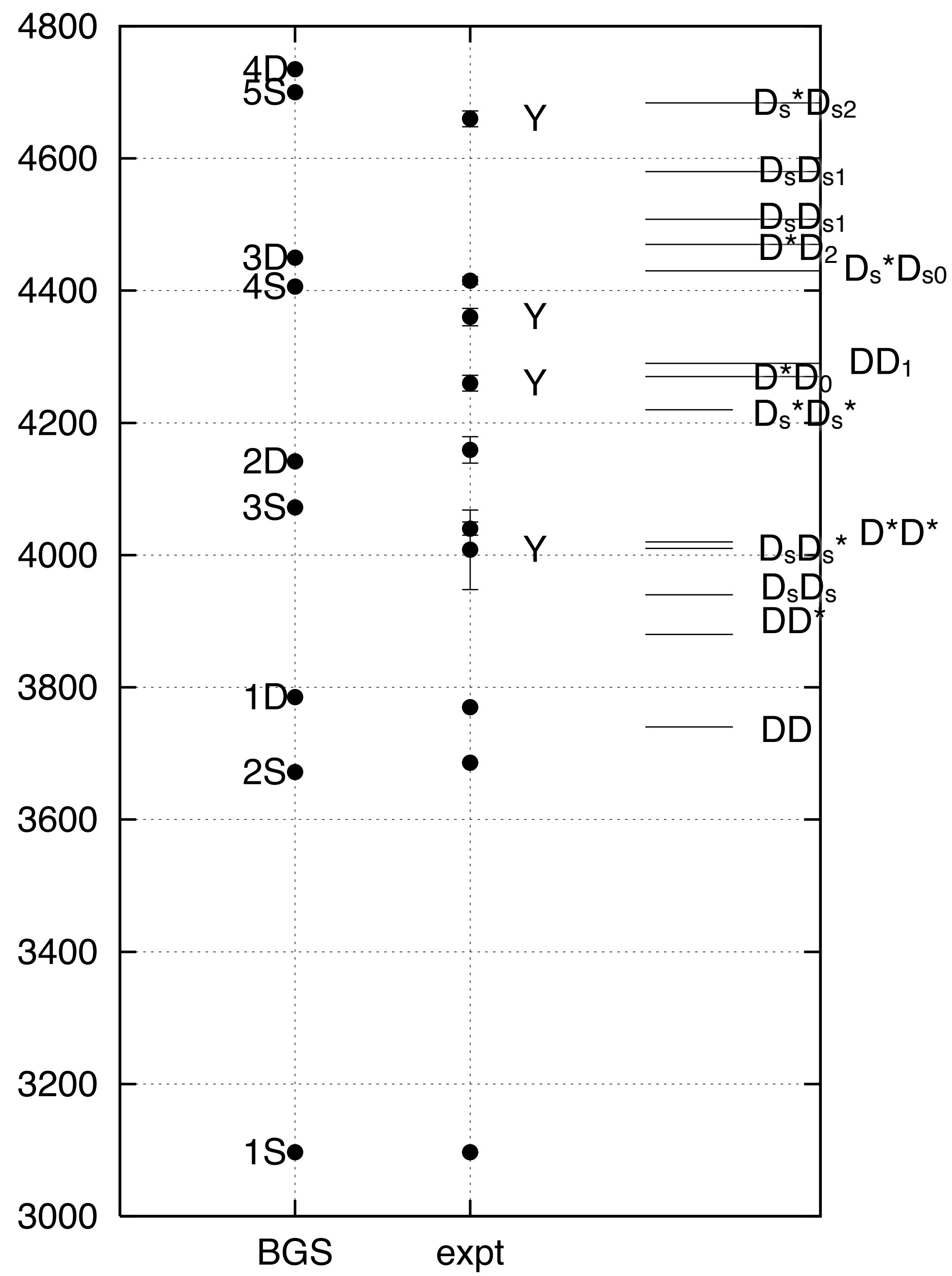
$$e^+e^- \to \gamma_{\rm ISR}\pi\pi J/\psi$$



$$\Gamma = 50 - 90$$

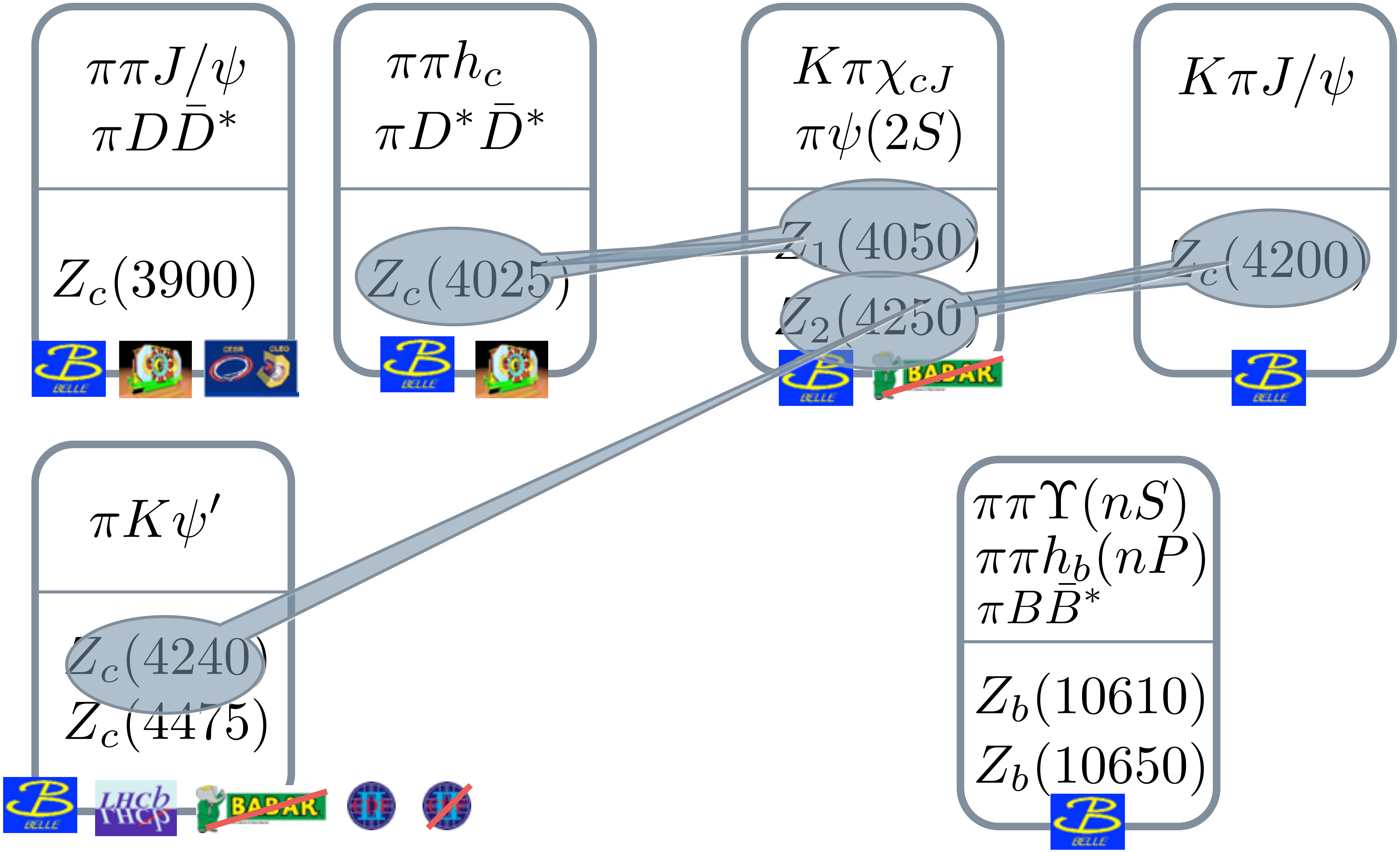
Y(4260)

Charmonium Vectors



Z(4430)

Four-quark States

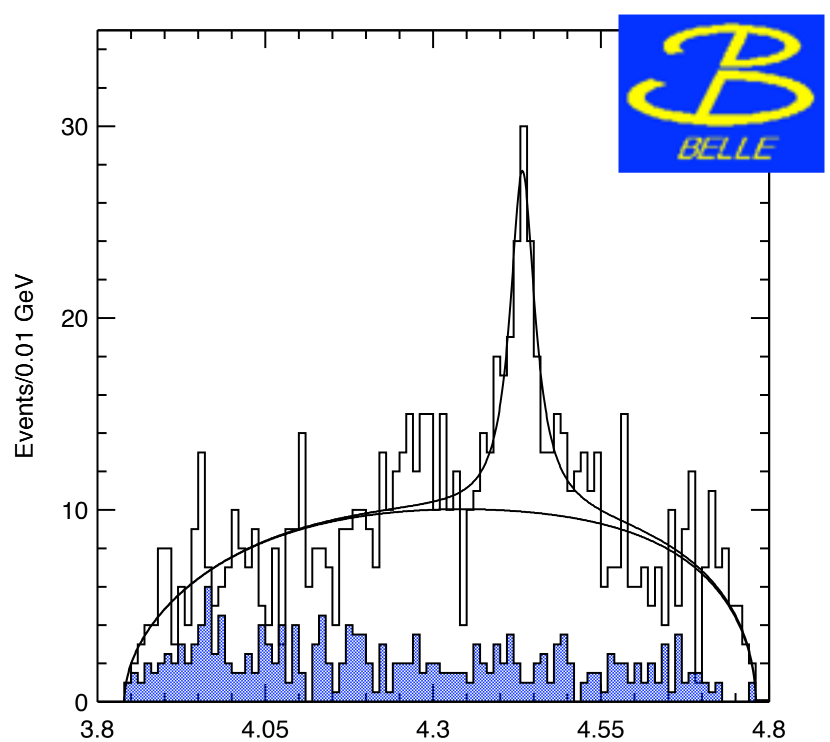


$Z^+(4430)$

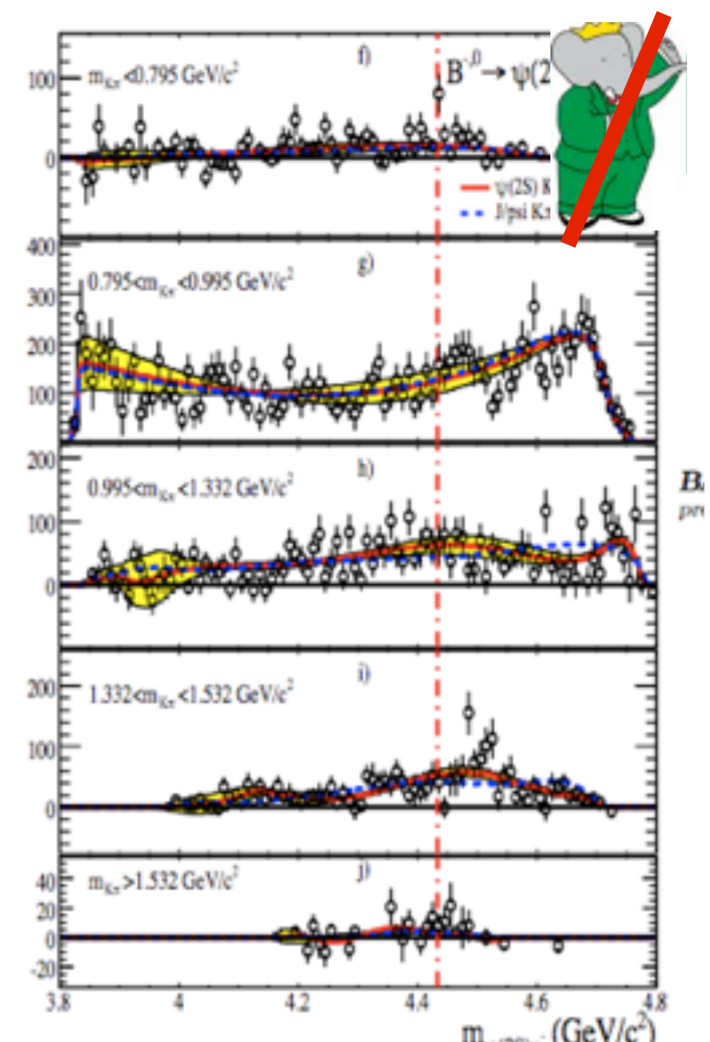
$B \to K\pi^+\psi'$

$$M = 4443^{+24}_{-18}$$
$$\Gamma = 107^{+113}_{-71}$$
$$J^{PC} = ?$$

.manifestly exotic
.not confirmed by BaBar



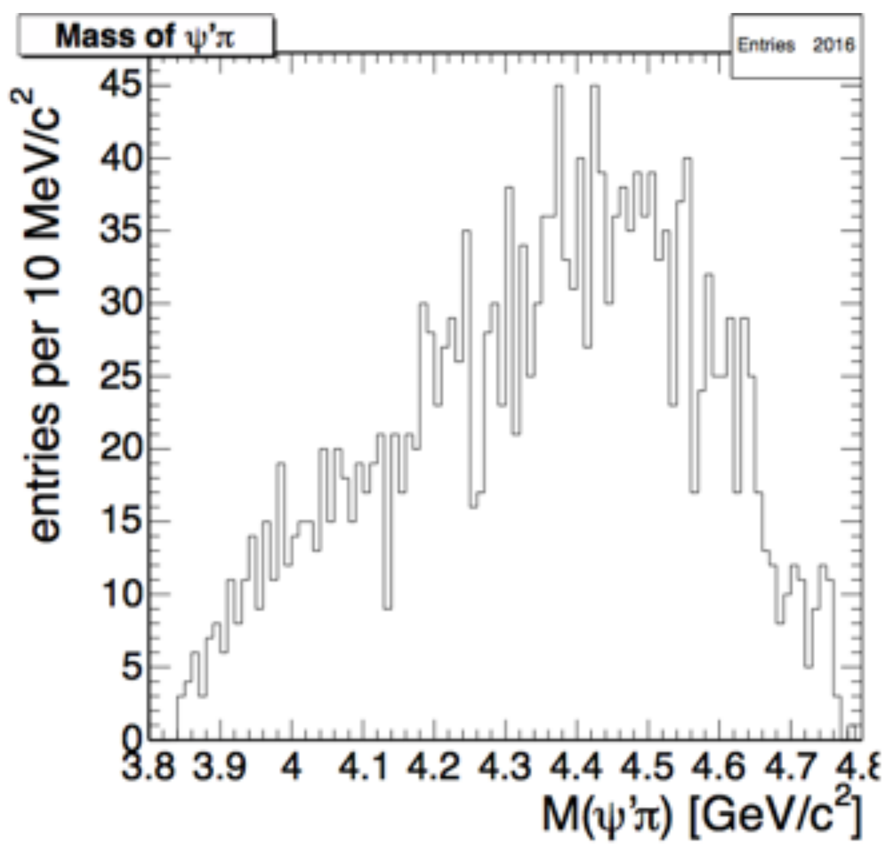
S.-K Choi et al. [Belle] 0708.1790



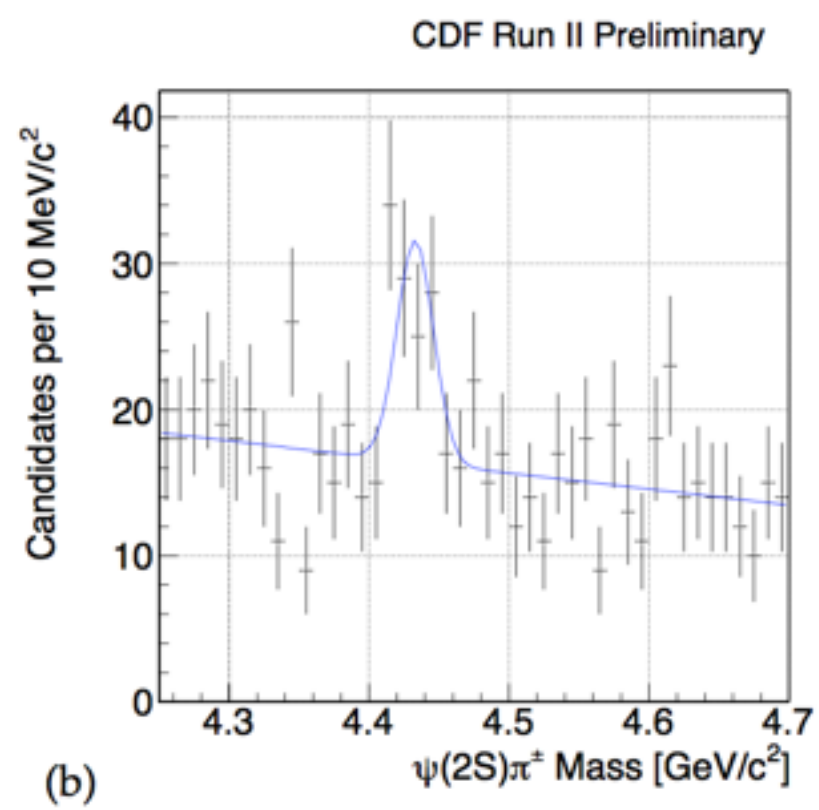
Mokhtar. 0810.1073

$Z^+(4430)$

pp -> B B(pi K psi')

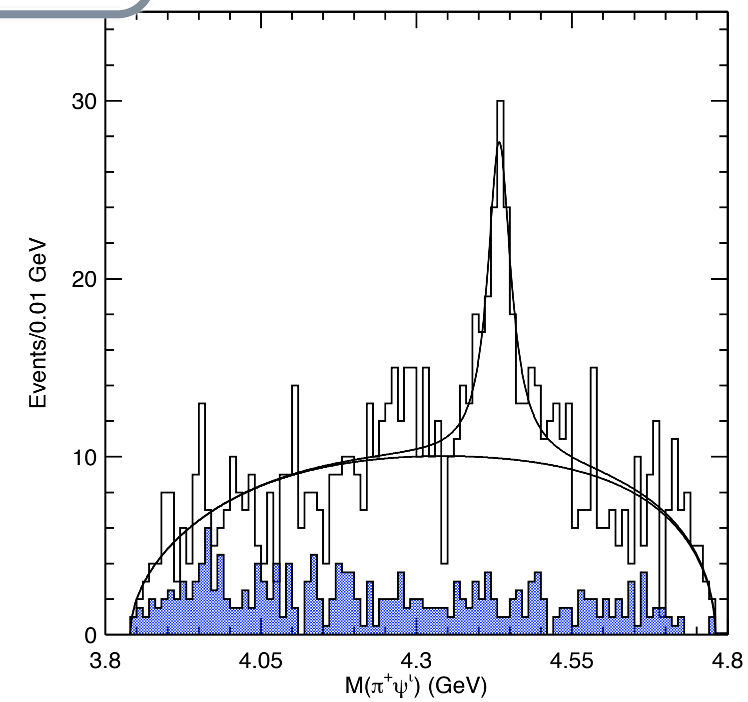


prompt production

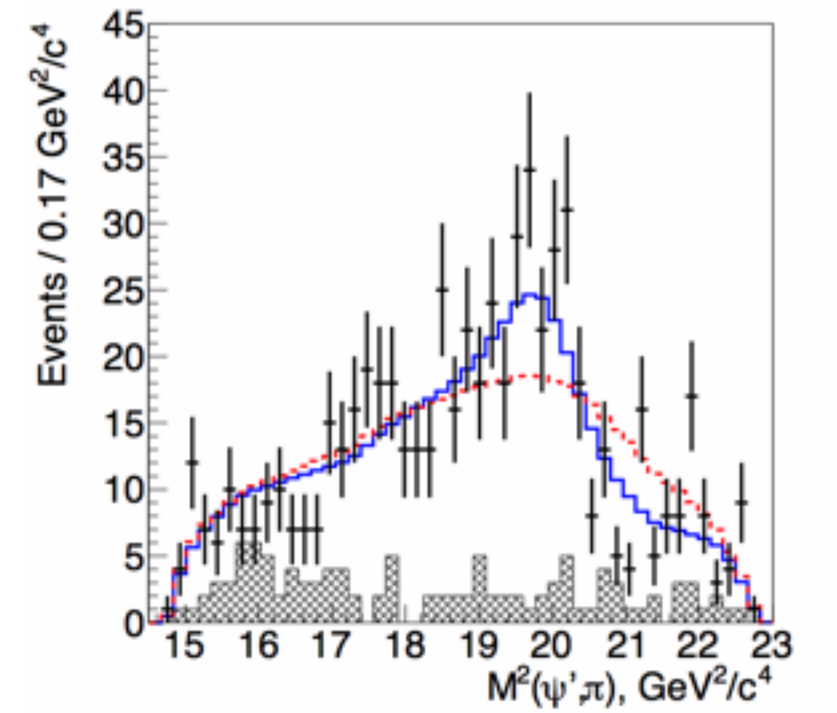


F. Rubbo, Torino thesis

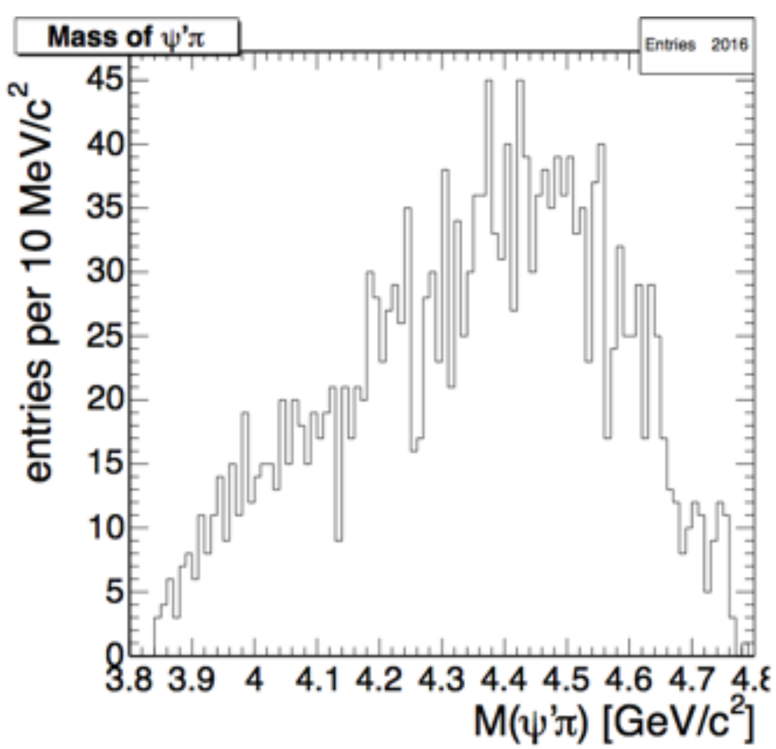
$Z^+(4430)$



Belle original

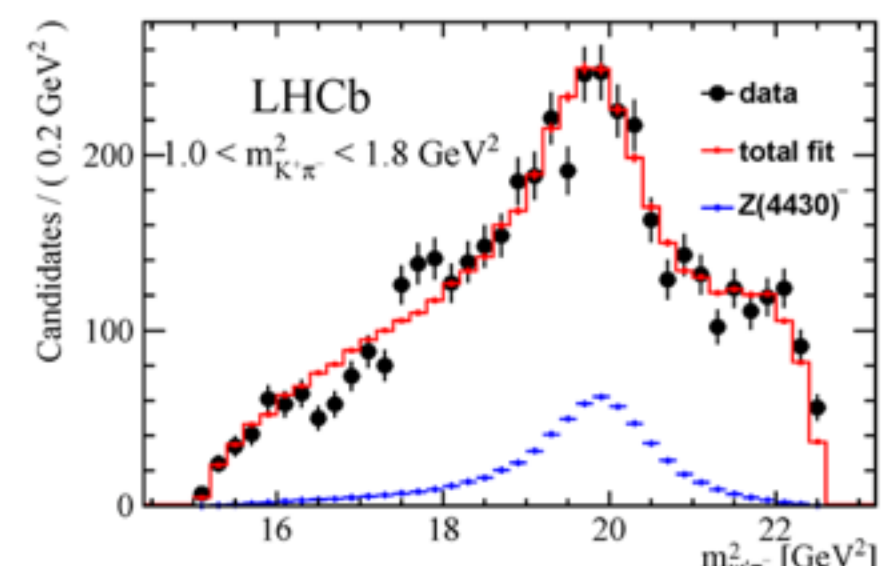


Belle re-analysis
1306.4894



F. Rubbo, Torino thesis

CDF

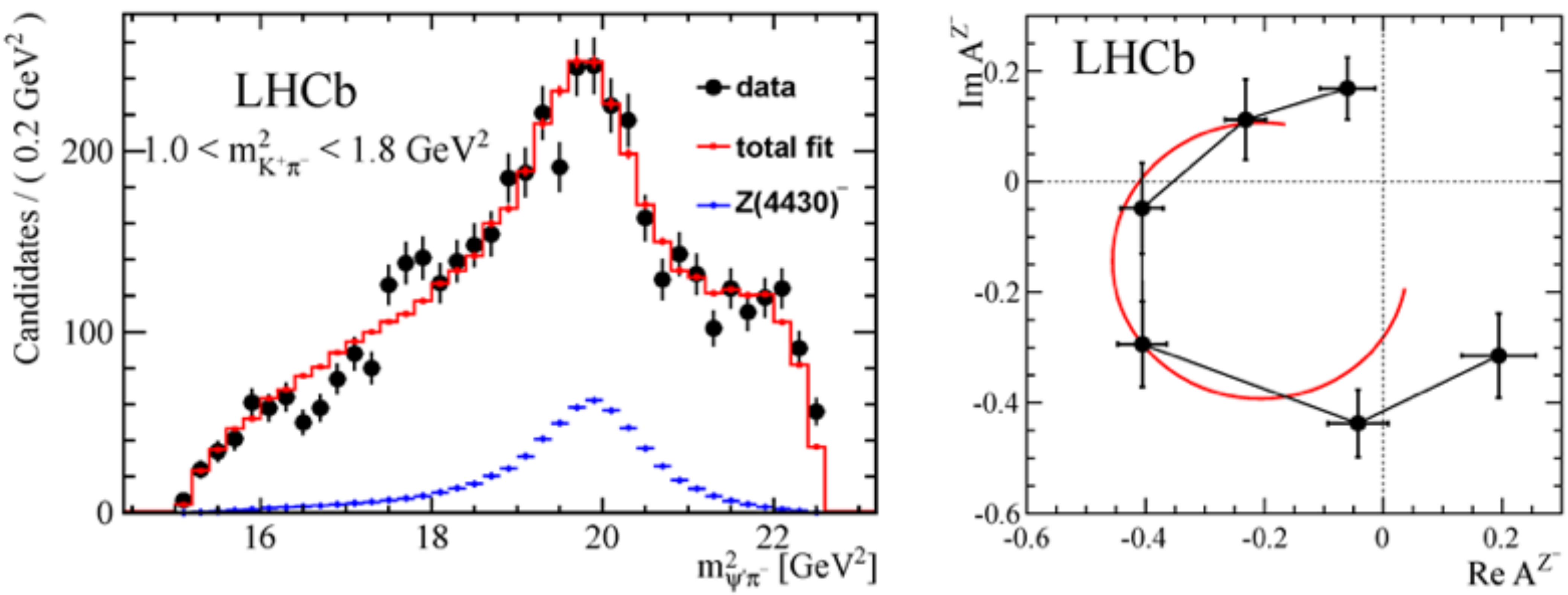


LHCb

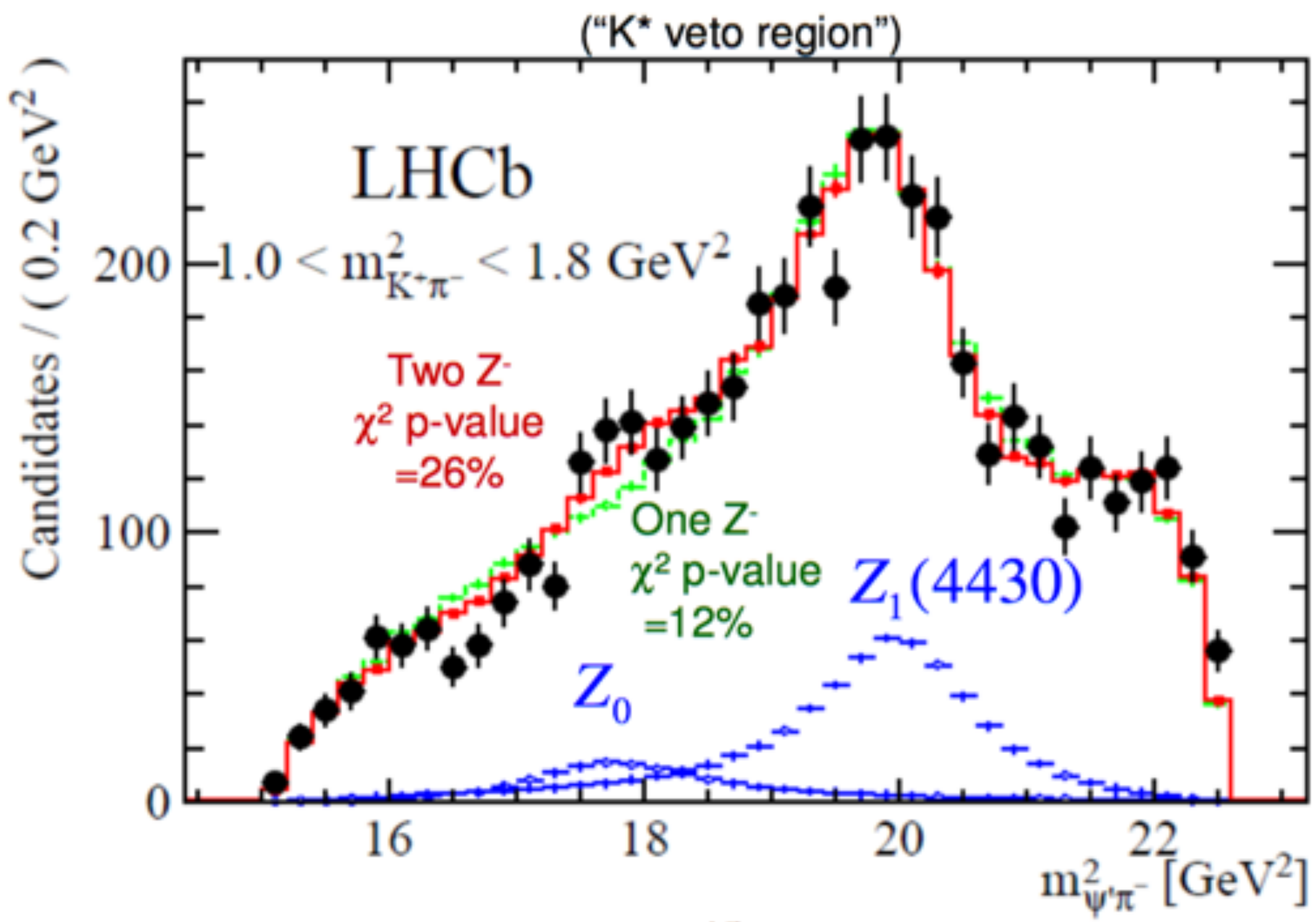
$Z^+(4430)$

.confirmed by LHCb

$J^P = 1^+$



Z(4240) [?]



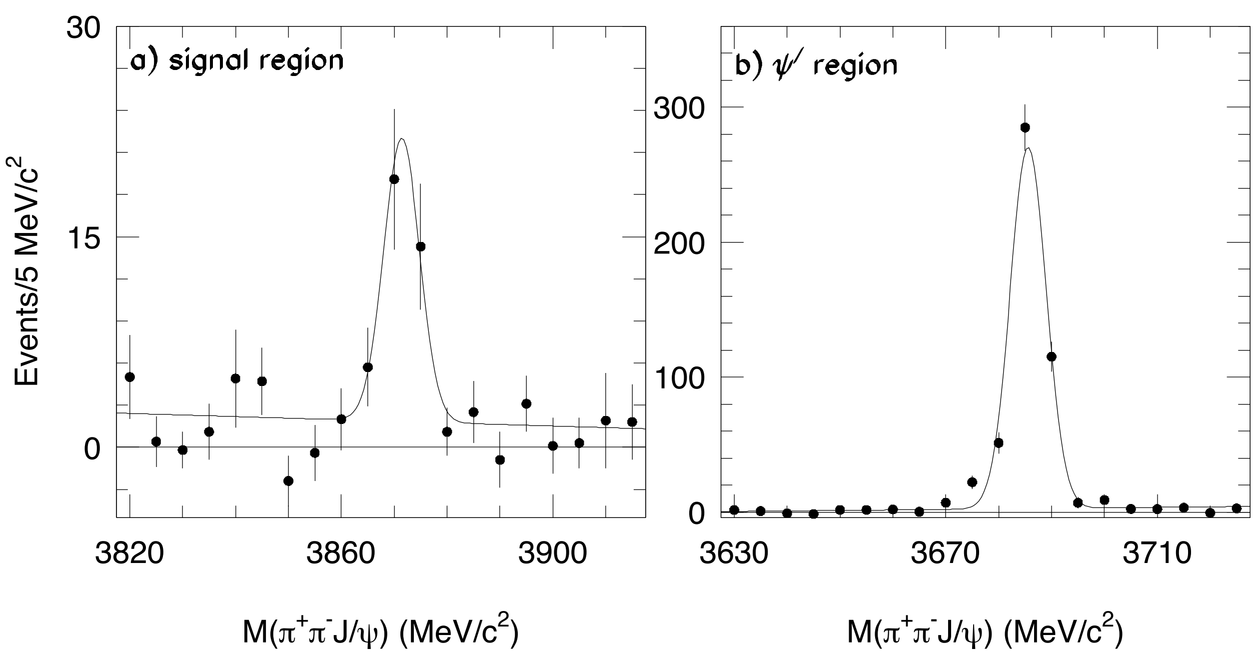
$$M(Z_0) = 4239 \pm 18^{+45}_{-10} \text{ MeV}$$

$$\Gamma(Z_0) = 220 \pm 47^{+108}_{-74} \text{ MeV}$$

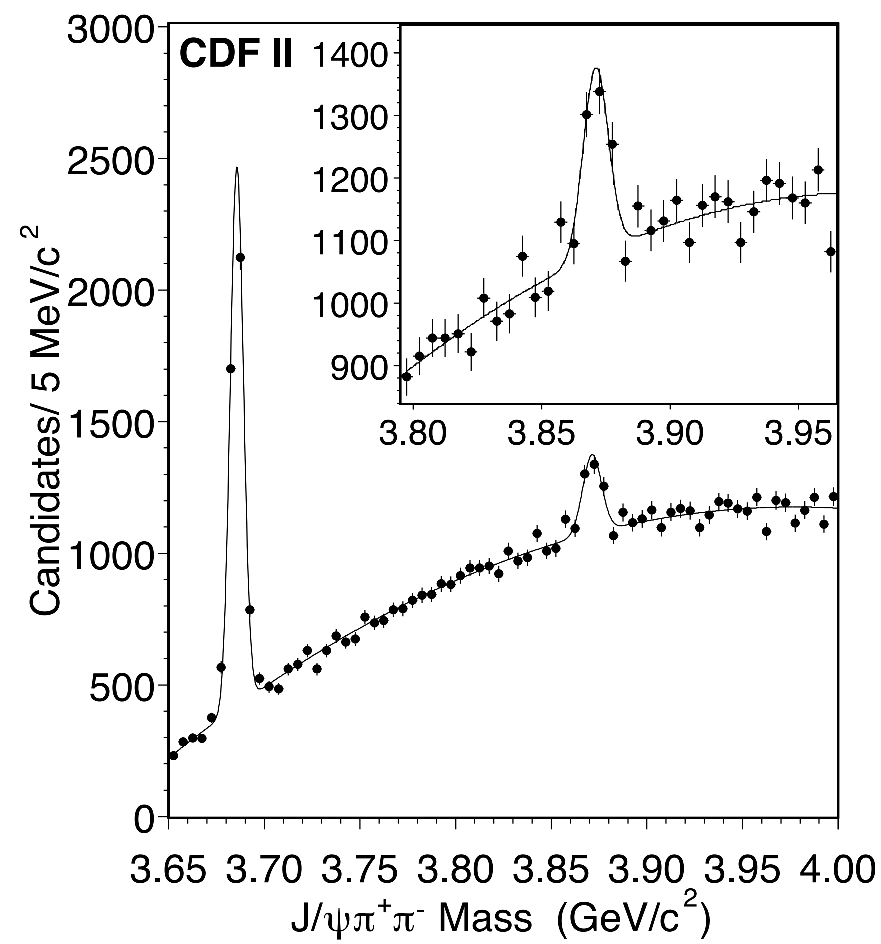
X(3872)

X(3872)

$$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$$



S.-K. Choi (Belle), hep-ex/0309032

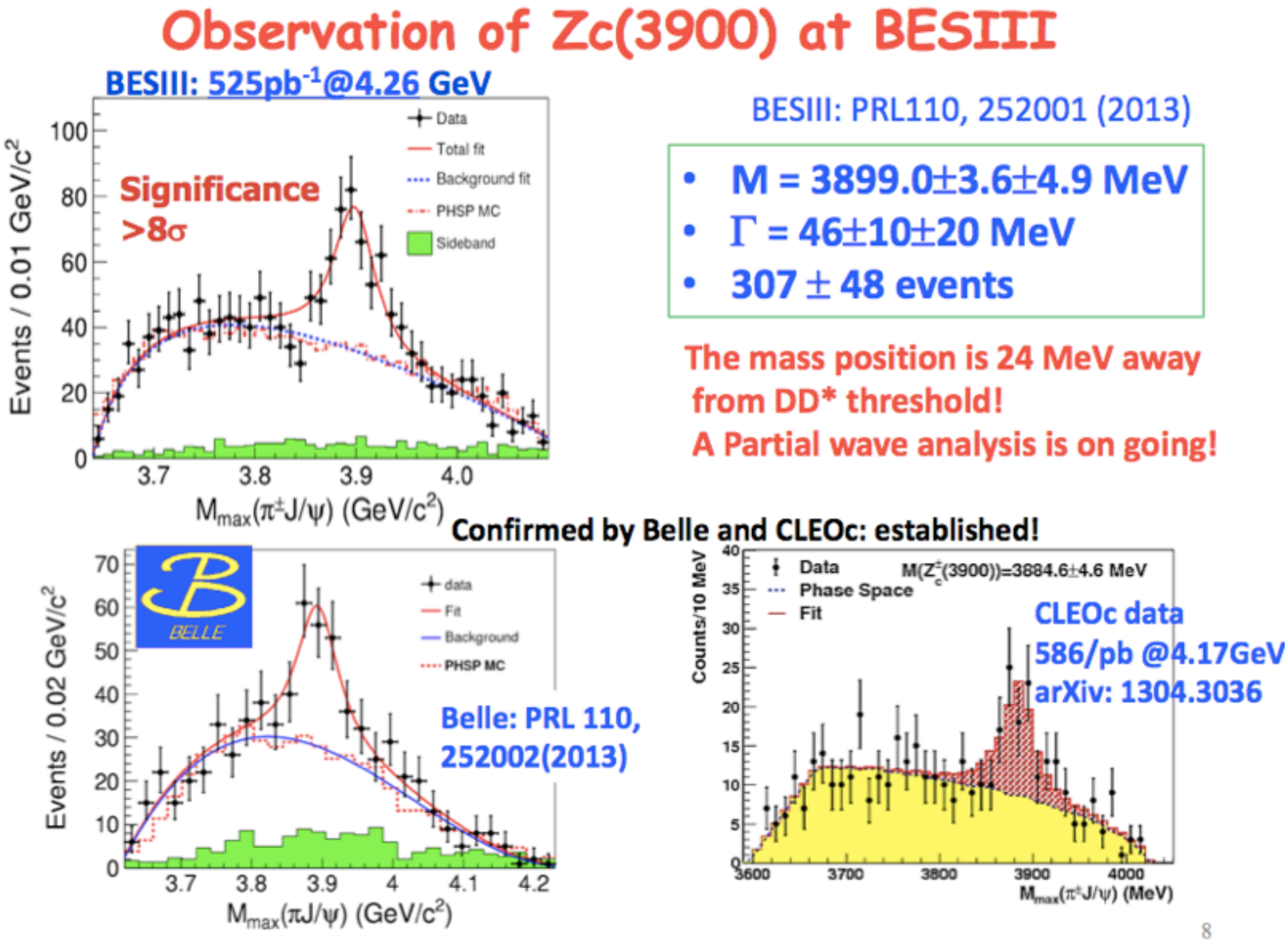


D. Acosta (CDF) hep-ex/0312021

B. Aubert (Babar) hep-ex/0402025

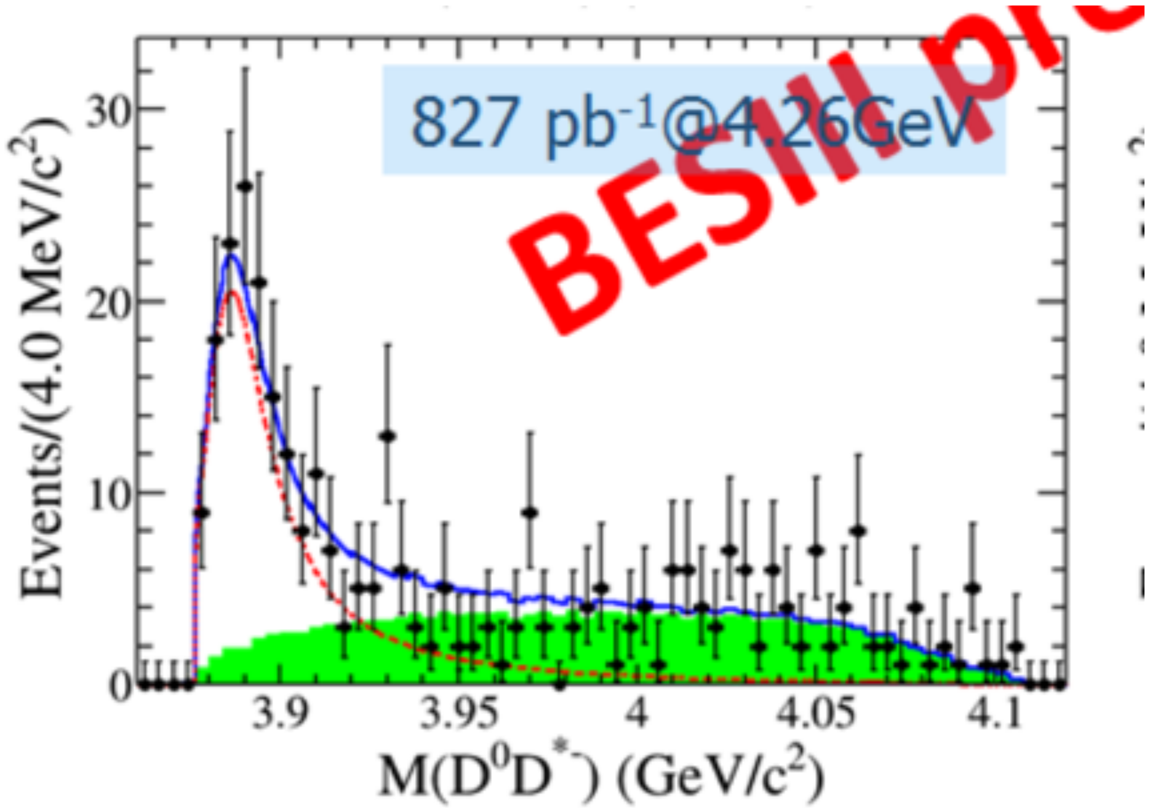
Zc and Zb

$Z_c(3900)$



Shuangshi Feng [BESIII] H13

Zc(3900)



Wolfgang Gradl, "Bound States in QCD", St Goar, Mar 24-27, 2015

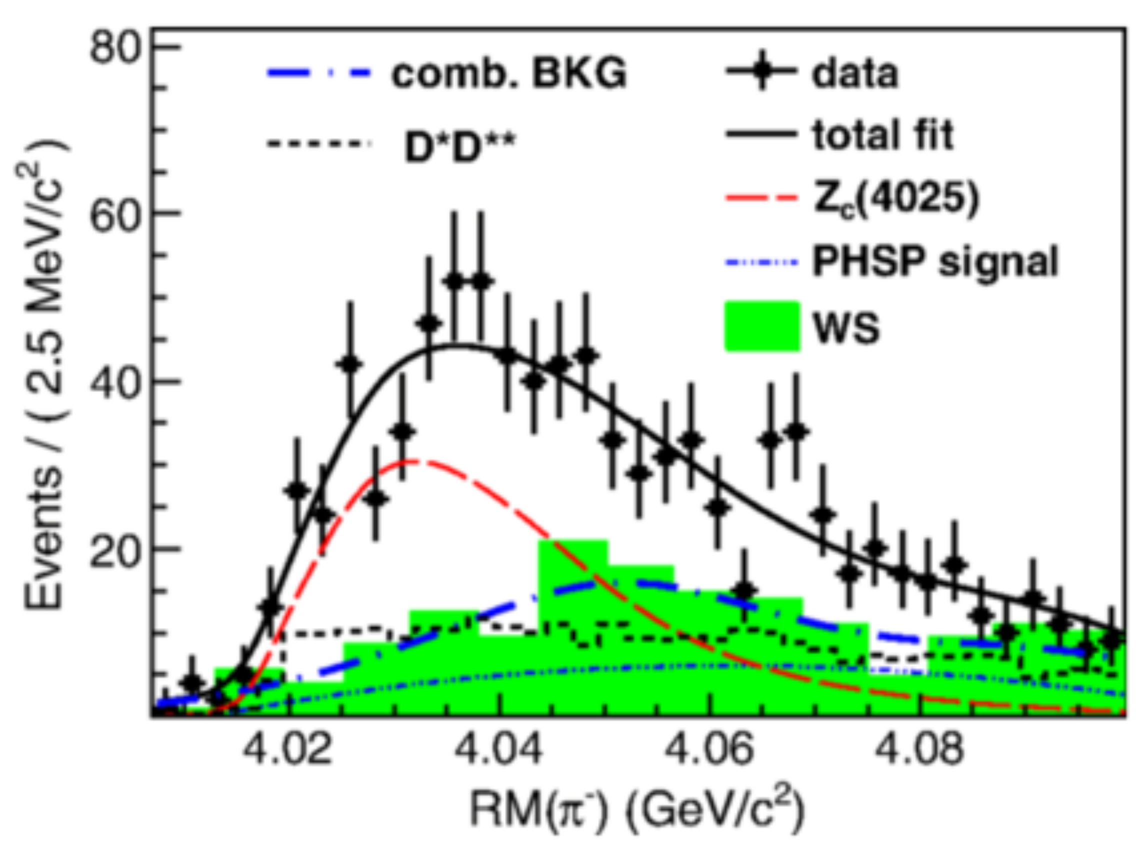
New BESIII result with all three particles identified.
Much smaller background.

$Z_c(4025)$

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

$$M = 4026.3 \pm 2.6 \pm 3.7$$

$$\Gamma = 24.8 \pm 5.6 \pm 7.7$$

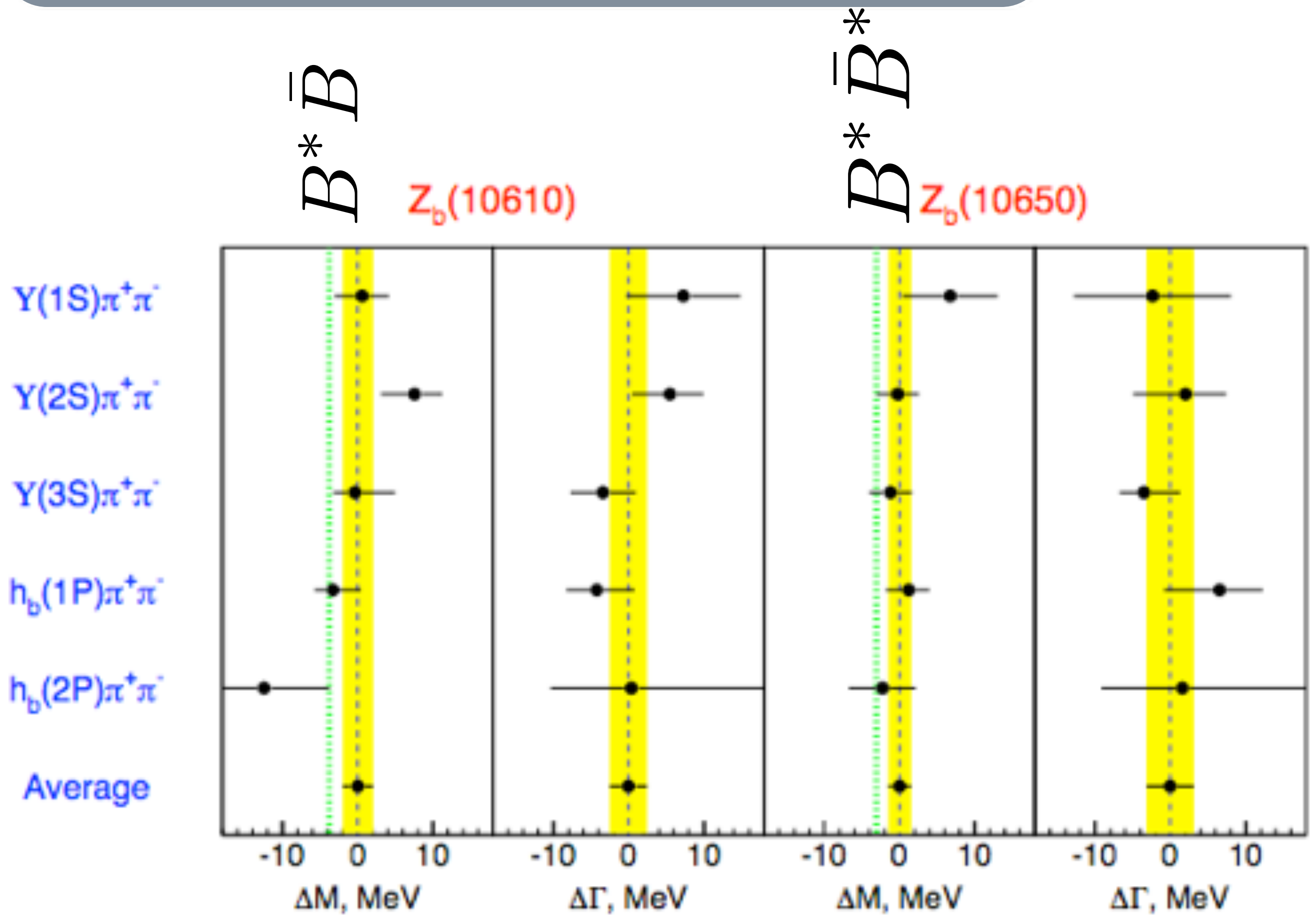


BESIII Phys. Rev. Lett. 112, 132001 (2014)

$Z_b^+(10610) \quad Z_b^+(10650)$

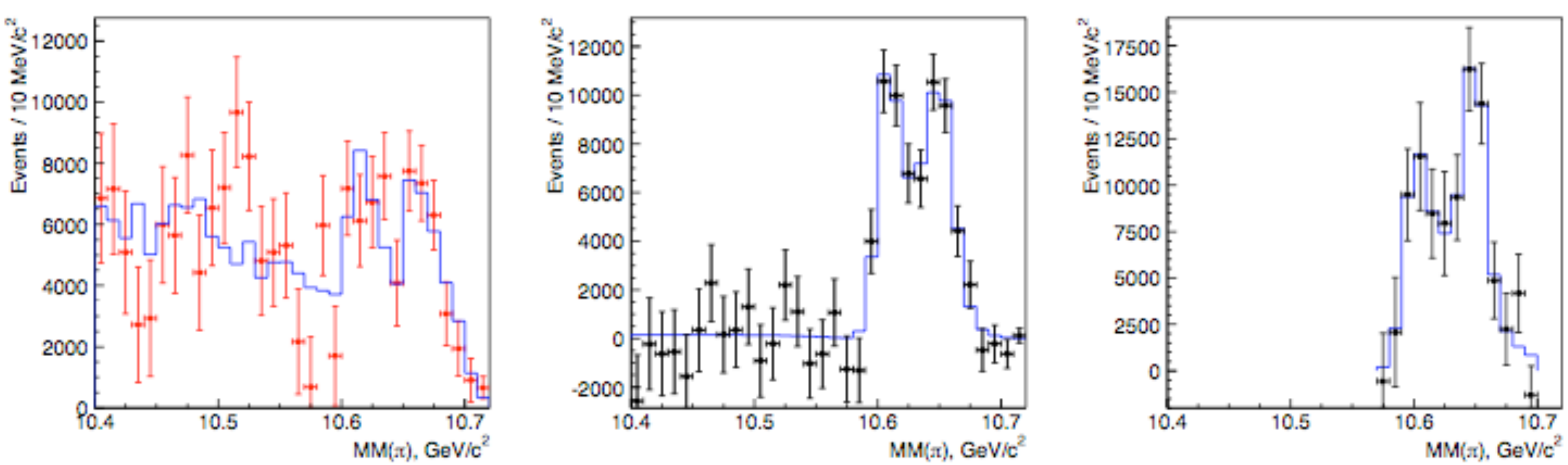
Adachi et al. [Belle] 1105.4583

$$I^G J^P = 1^+ 1^+$$



$$\Upsilon(5S) \to \pi\pi\Upsilon(nS)$$

$\Upsilon(2S)$ $\quad h_b(1P)$ $\quad h_b(2P)$



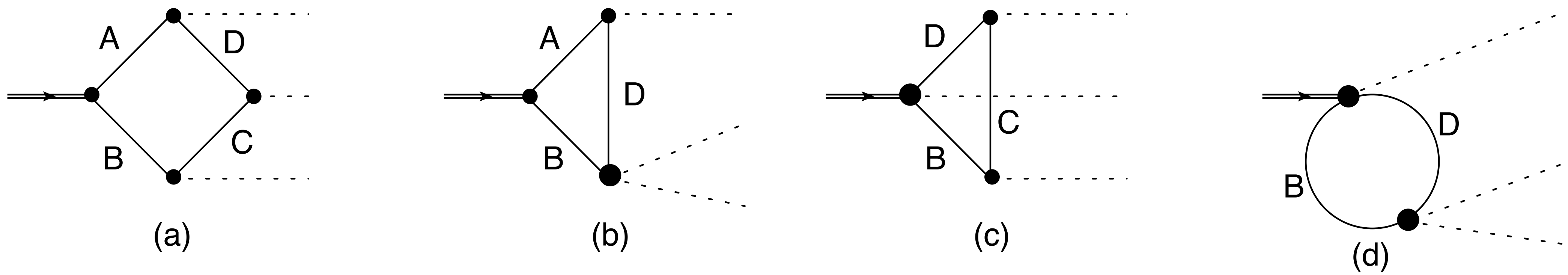
Loops Create Cusps

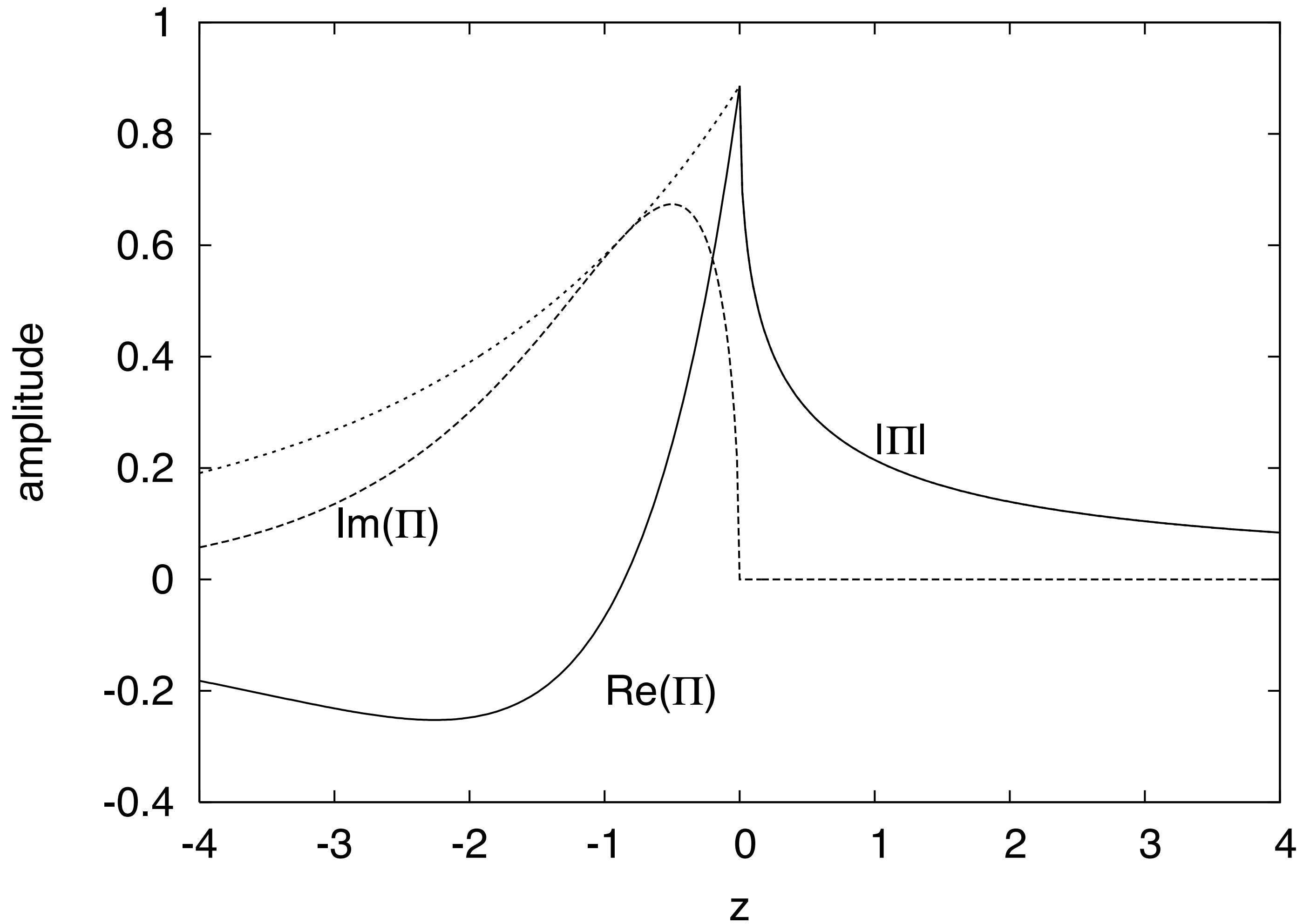
E.P. Wigner, Phys. Rev. 73 (1948) 1002

D. V. Bugg, Europhys. Lett. 96, 11002 (2011)

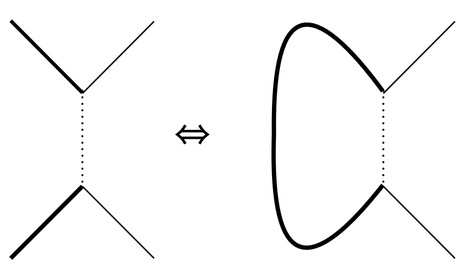
D. V. Bugg, Int. J. Mod. Phys. A 24, 394 (2009)

E.S. Swanson, arXiv:1409.3291



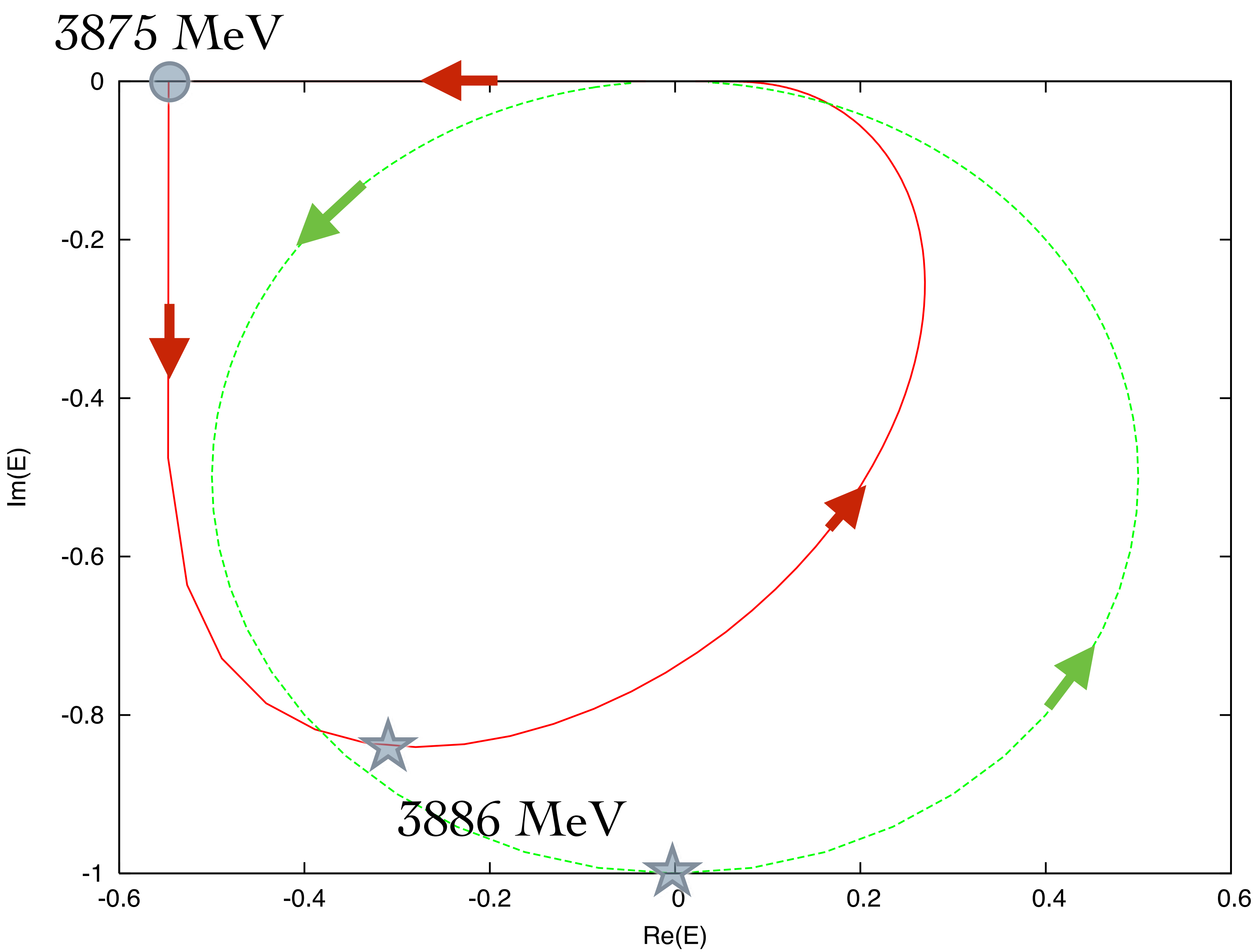


and are related to thresholds

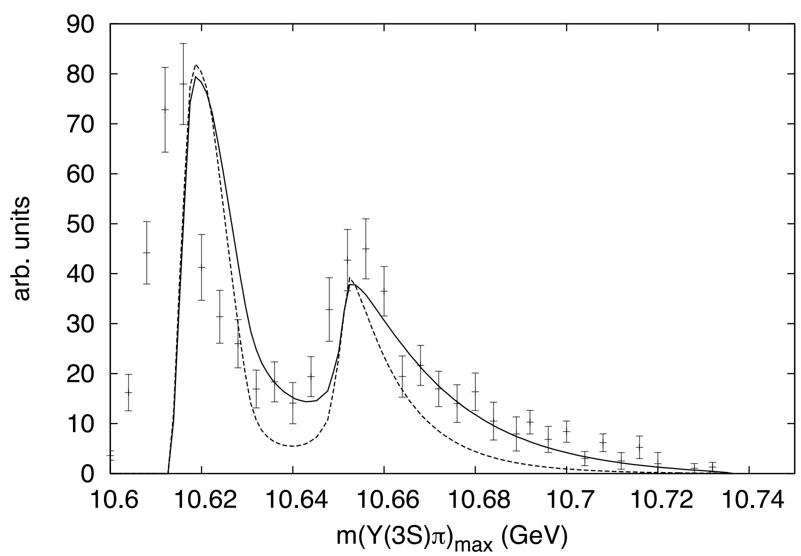


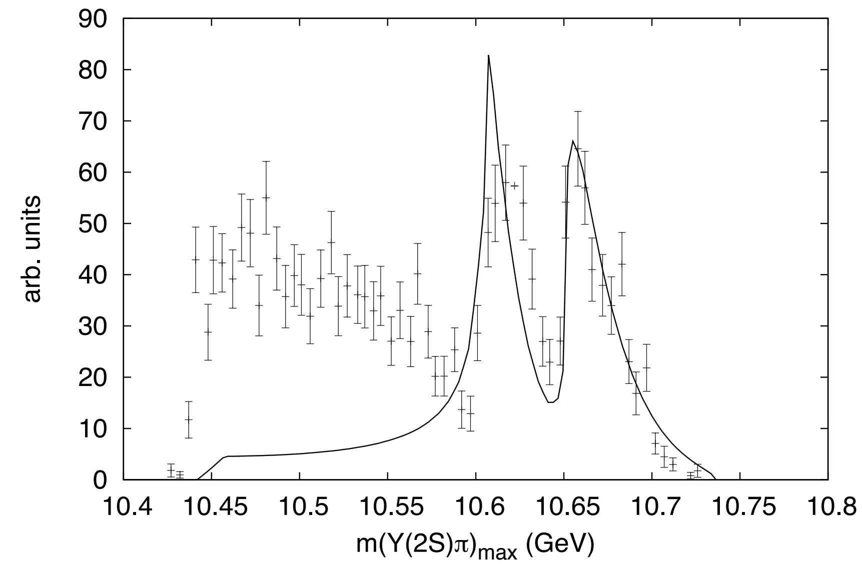
Modelling the Zs — Cusps

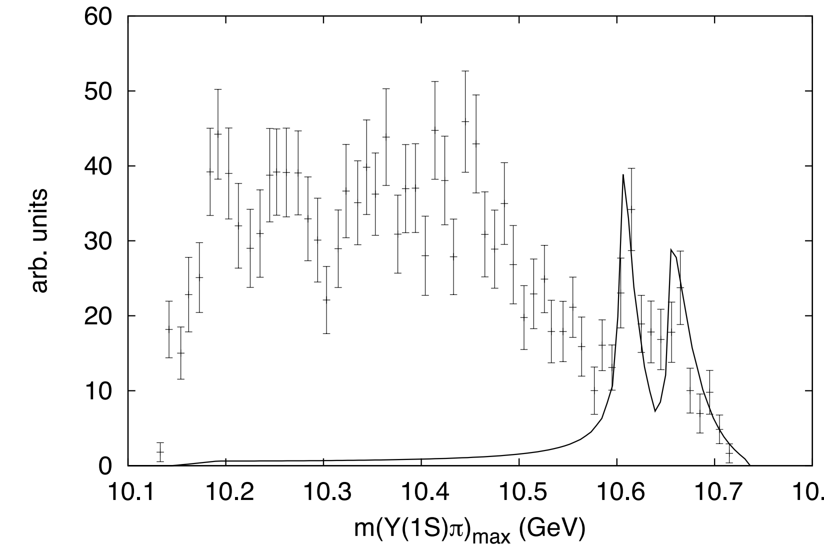
phase motion

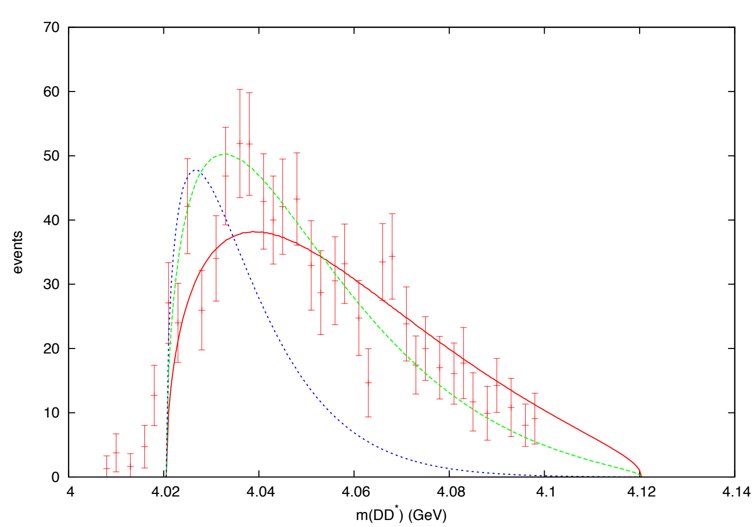


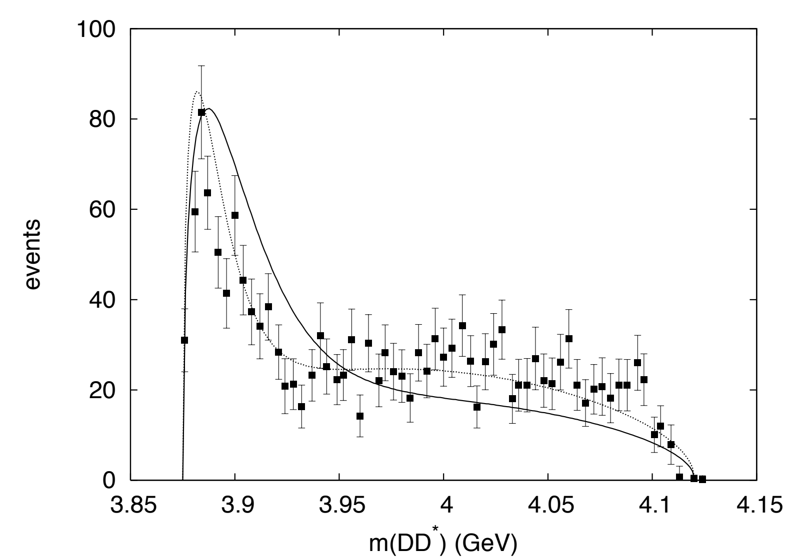
Modelling the Zs — Cusps

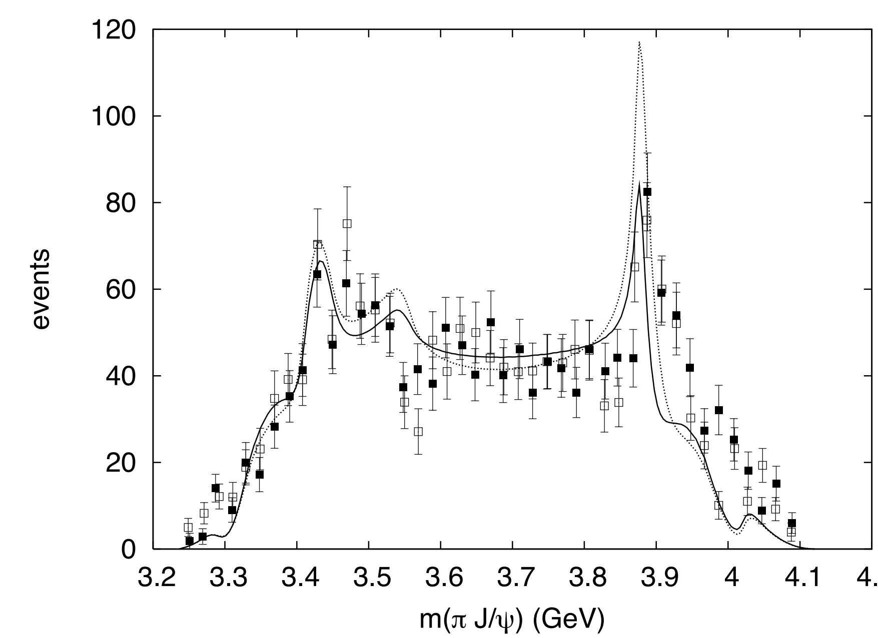








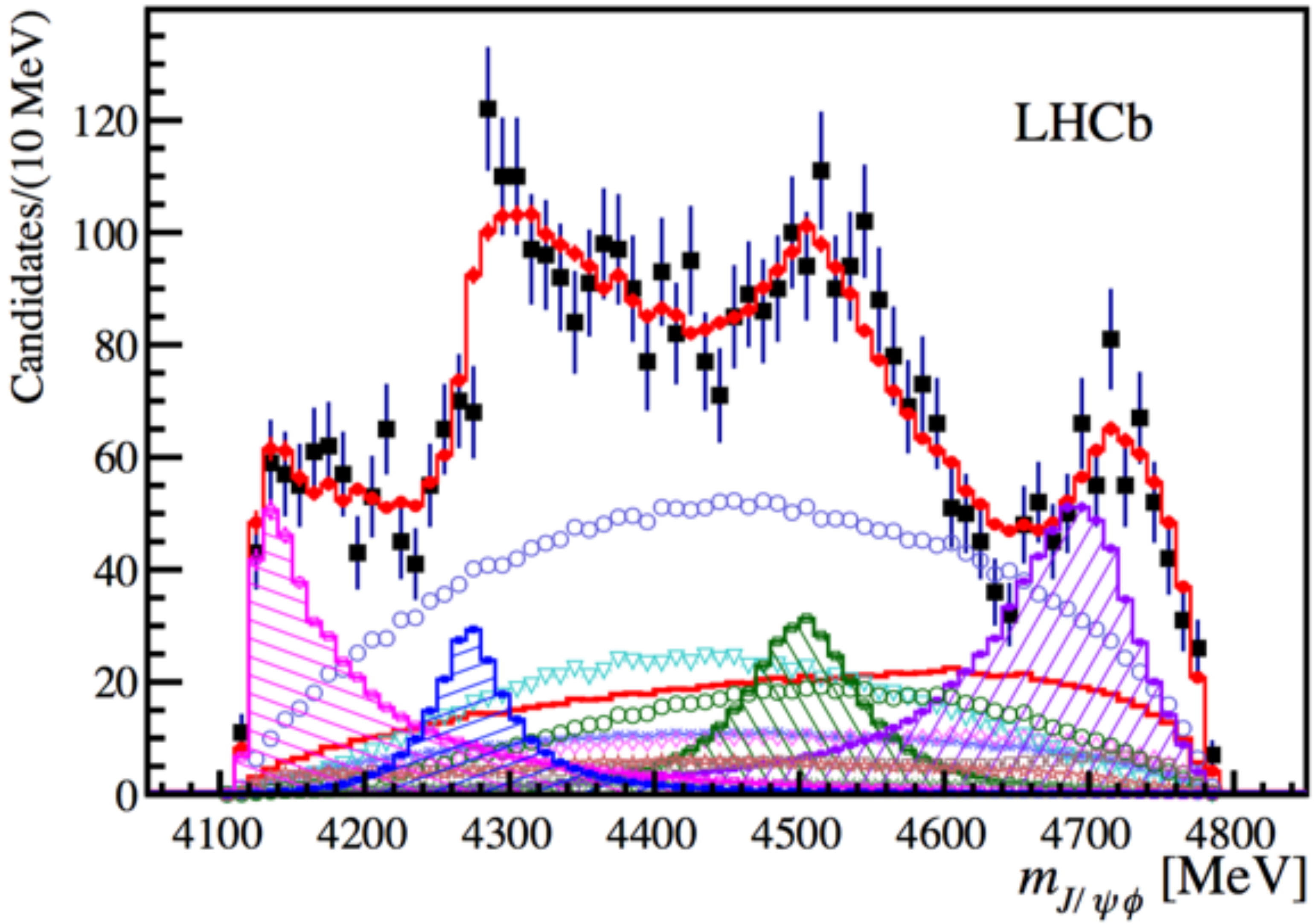




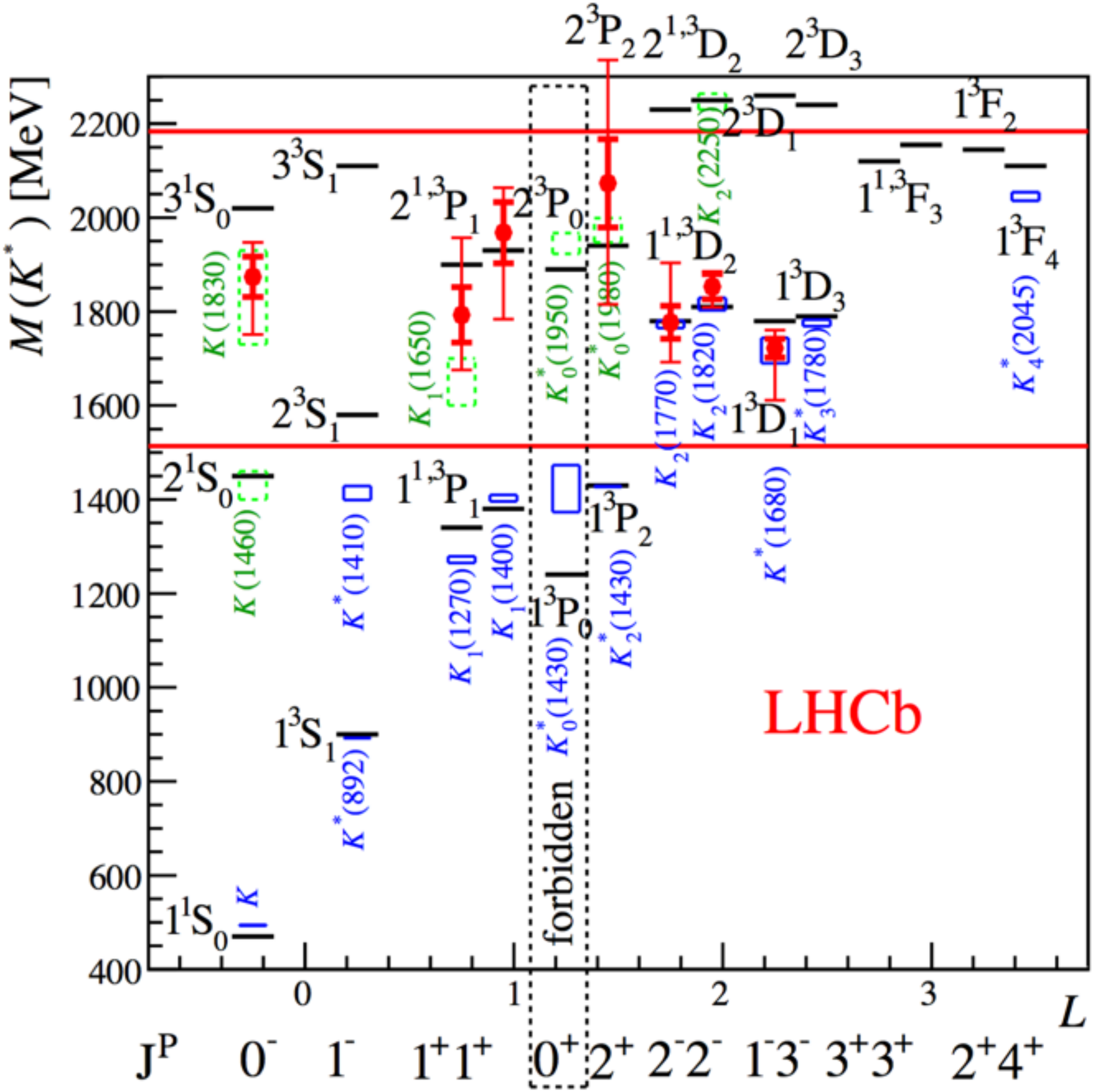
LHCb 4X

arXiv:1606.07895v1

$B \to K J/\psi \phi$



State	Mass (unct.) [MeV]	Width (unct.) [MeV]	J^{PC}
$Y(4140)$	4165.5(5,3)	83(21,16)	1^{++}
$Y(4274)$	4273.3(8,11)	56(11,10)	1^{++}
$X(4500)$	4506(11,13)	92(21,21)	0^{++}
$X(4700)$	4704(10,19)	120(31,35)	0^{++}



red: LHCb fit
black GI
blue: PDG
green: unconfirmed

X(5568)

<- with “cone” cut

V without cut

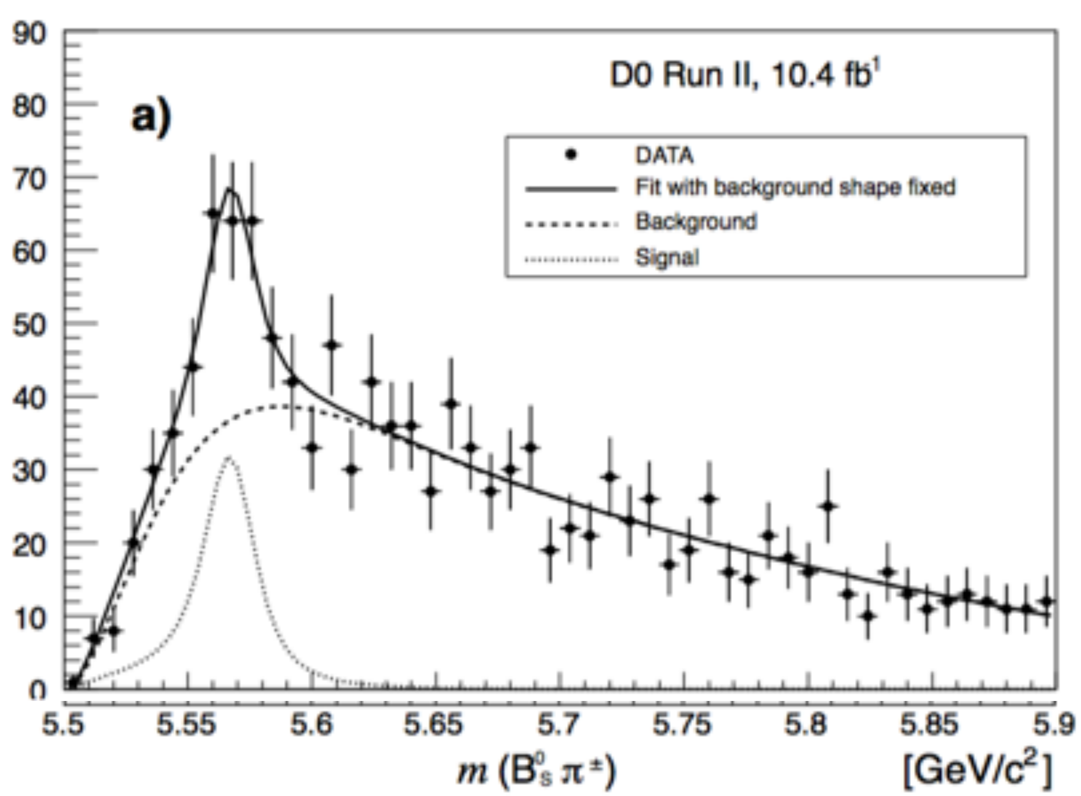
Seen by D0 in $X(5568) \to B_s^0 \pi^{\pm}$

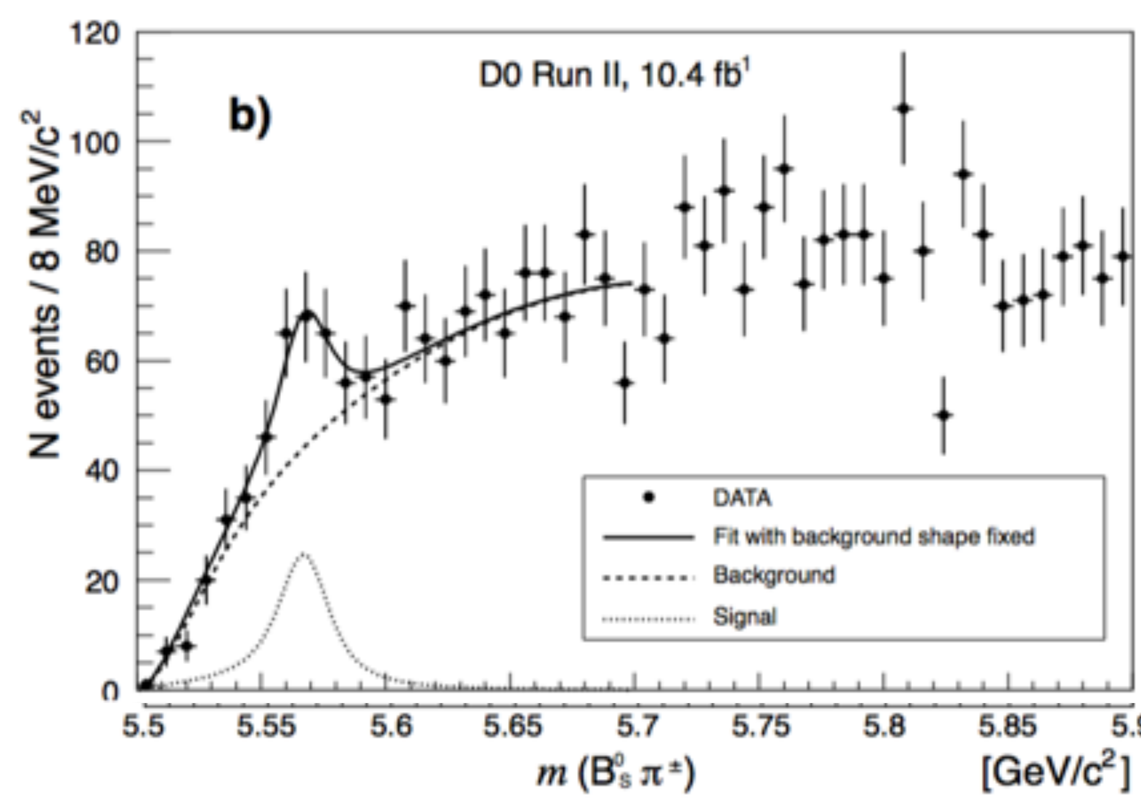
V. M. Abazov et al. (D0 Collaboration) Phys. Rev. Lett. **117**,022003

$$m = 5567.8 \pm 2.9^{+0.9}_{-1.9}$$

$$\Gamma = 21.9 \pm 6.4\,^{+5.0}_{-2.5}$$

$su\bar{b}\bar{d}$ (the first example of such an open flavour exotic!)





New Pentaquarks

$P_c(4450)$
$P_c(4380)$

$$\Lambda_b^0 \to J/\psi K^- p$$

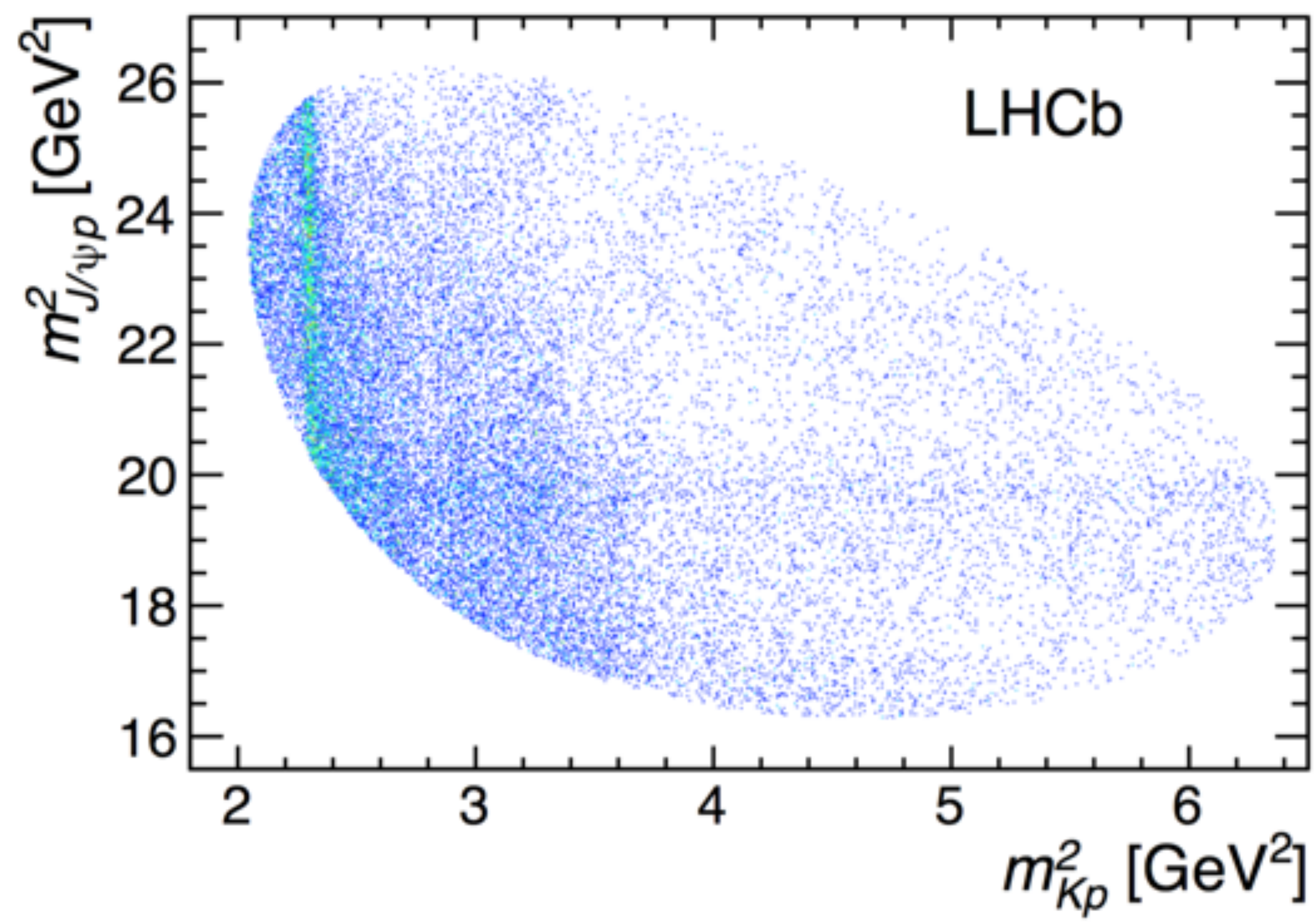
$P_c(4450)$ $\Gamma = 39 \pm 5 \pm 19\ \text{MeV}$

$P_c(4380)$ $\Gamma = 205 \pm 18 \pm 86\ \text{MeV}$

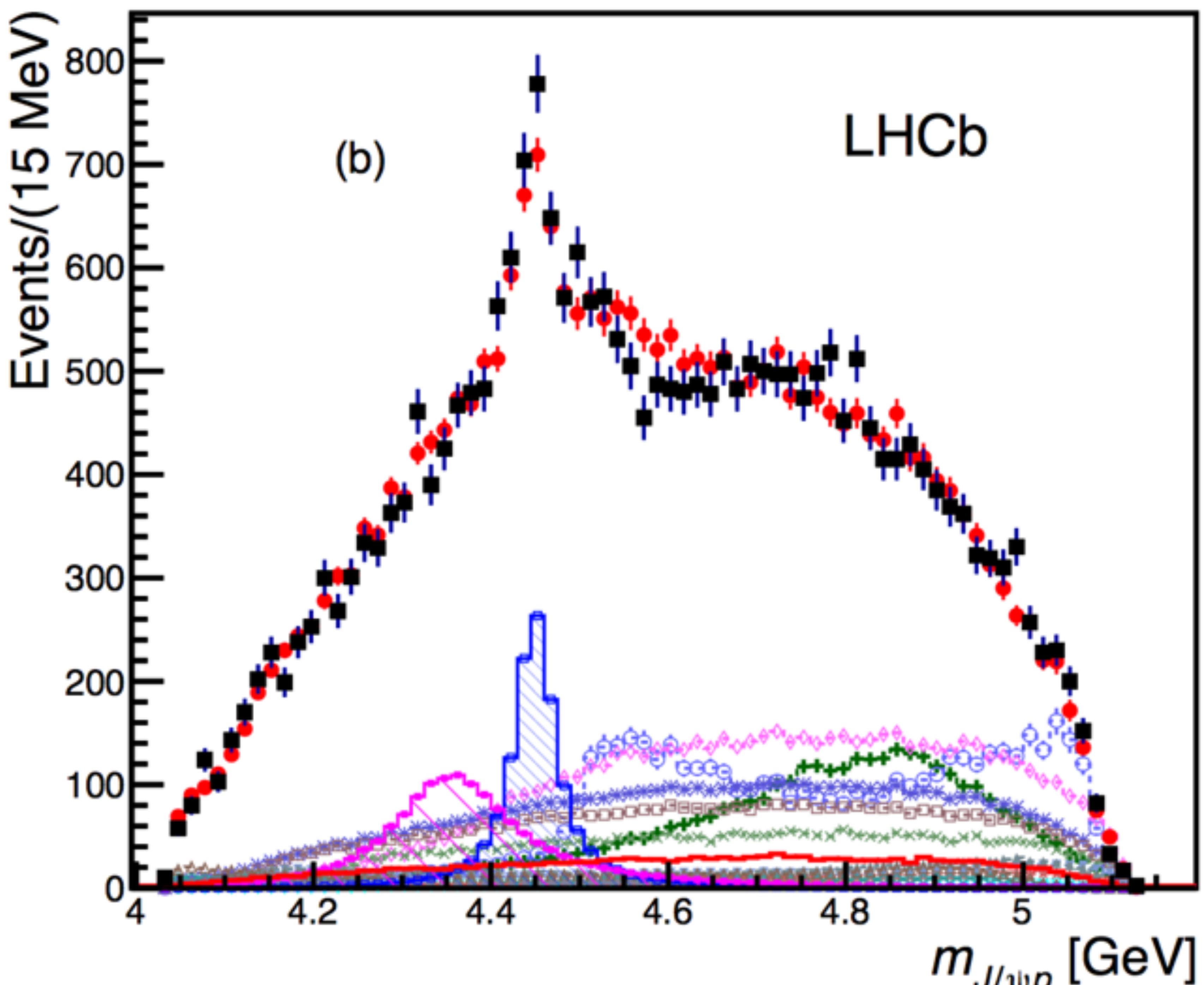
LHCb 1507.03414v2

$$J^P = \frac{3}{2}^{\pm}$$

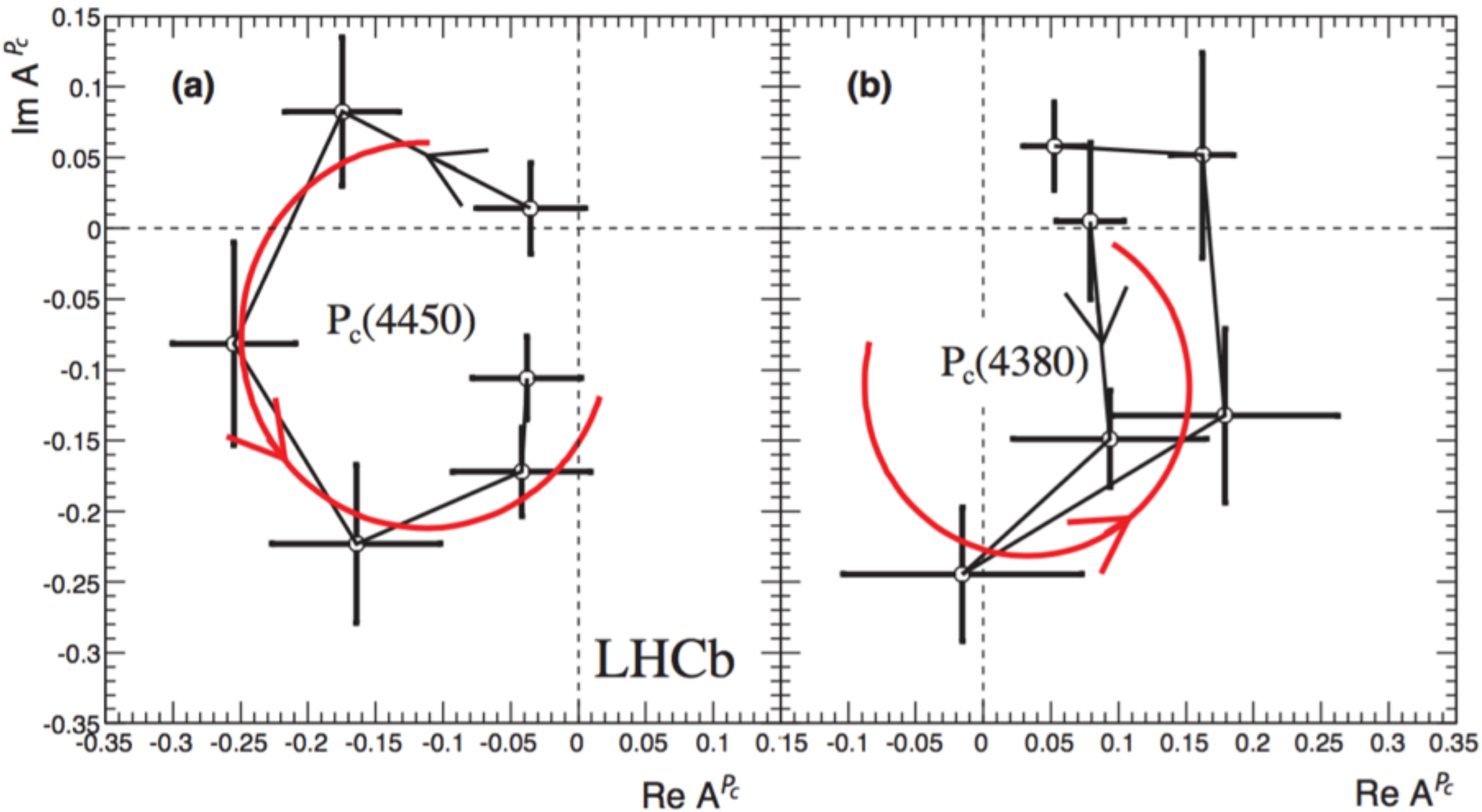
$$J^P = \frac{5}{2}^{\mp}$$



$P_c(4450)$
$P_c(4380)$



$P_c(4450)$
$P_c(4380)$

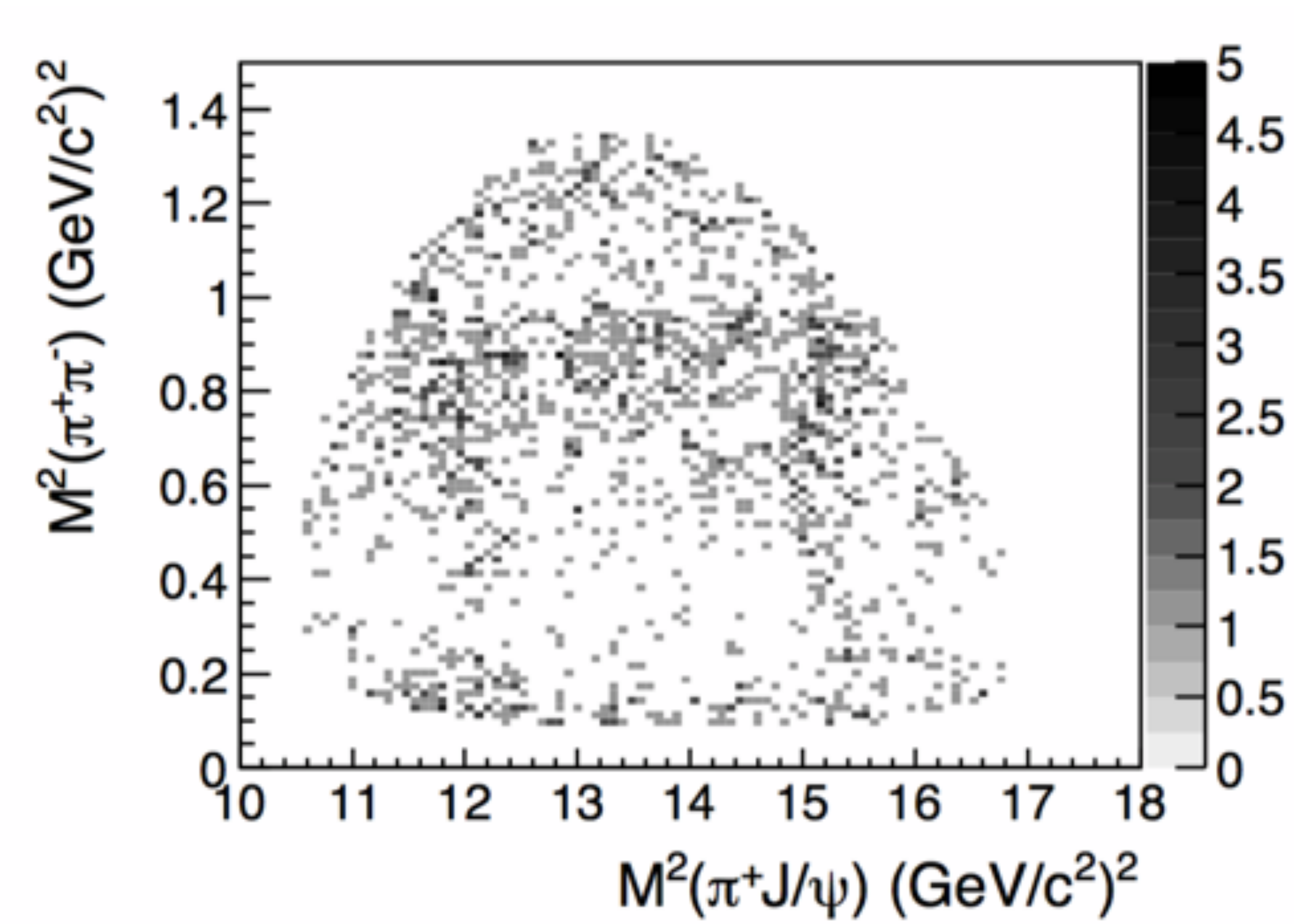


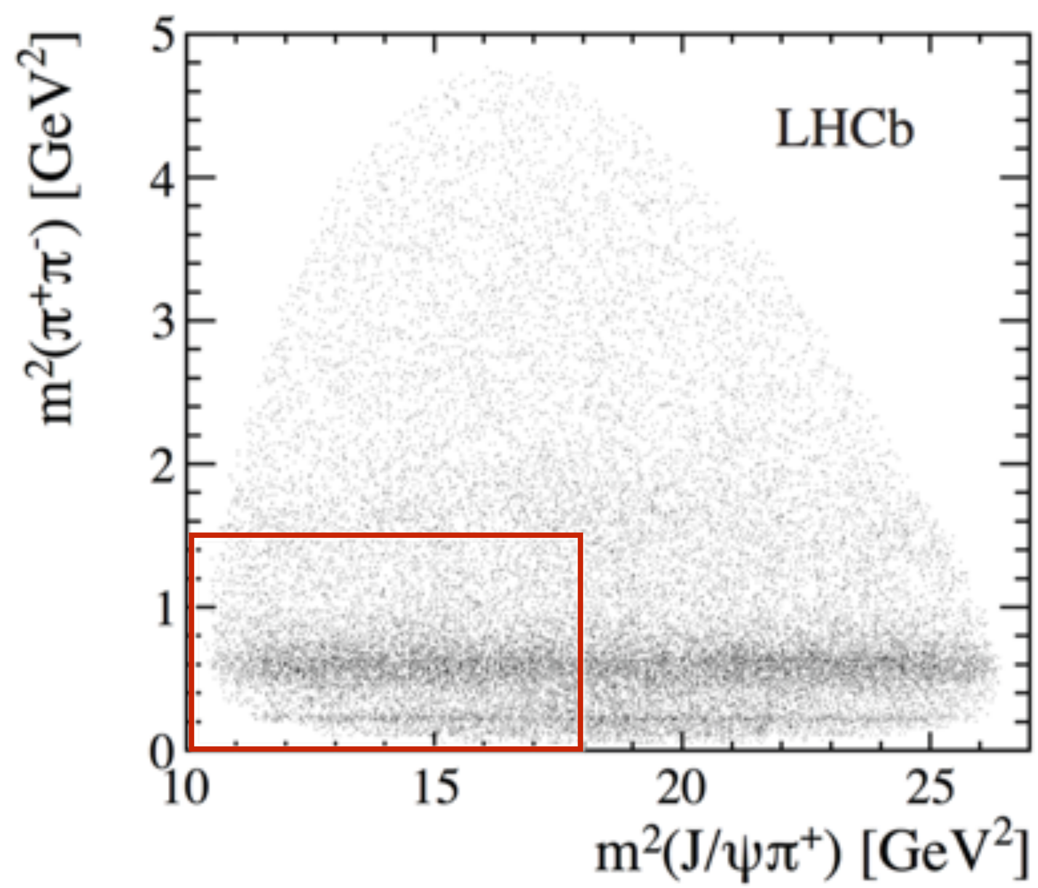
Observations

Why do ee and b decay production modes differ?

$Y(4260) \to \pi^+\pi^- J/\psi$

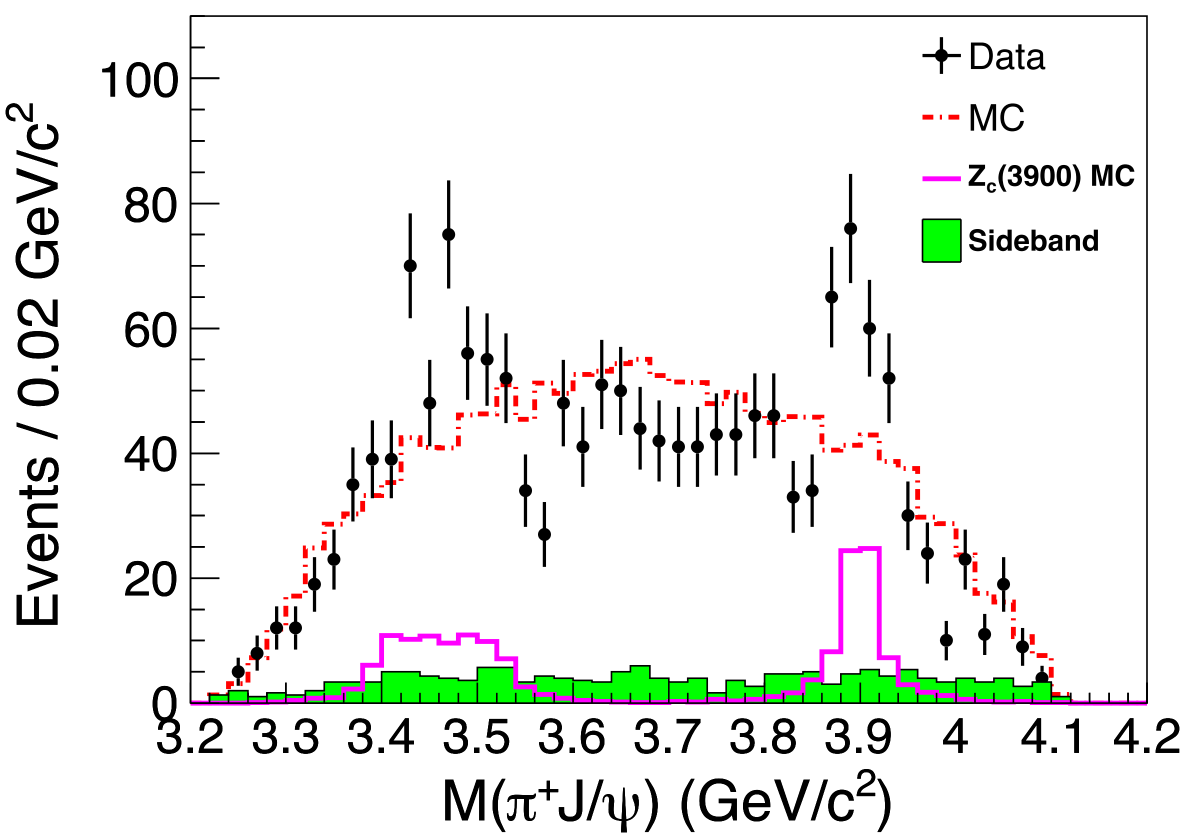
$B_0 \to \pi^+\pi^- J/\psi$





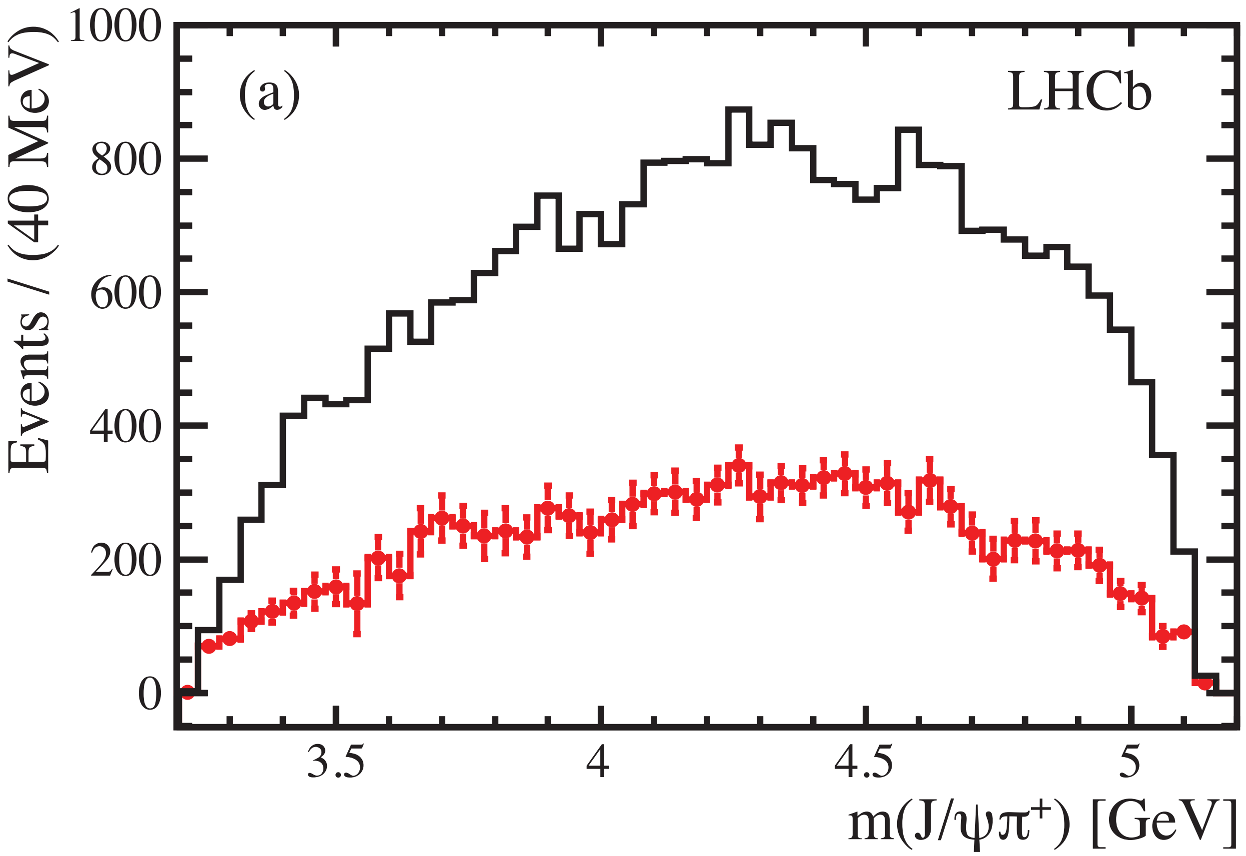
Why do ee and b decay production modes differ?

$Y(4260) \to \pi^+\pi^- J/\psi$



BESIII

$B_0 \to \pi^+\pi^- J/\psi$



LHCb

R. Aaij et al. [LHCb Collaboration], Phys. Rev. D 90, 012003 (2014).

Why does “radial filtering” happen?

$$e^+e^- \to Y(4360) \to \pi^+\pi^-\psi(2S)$$
$$Y(4660)$$

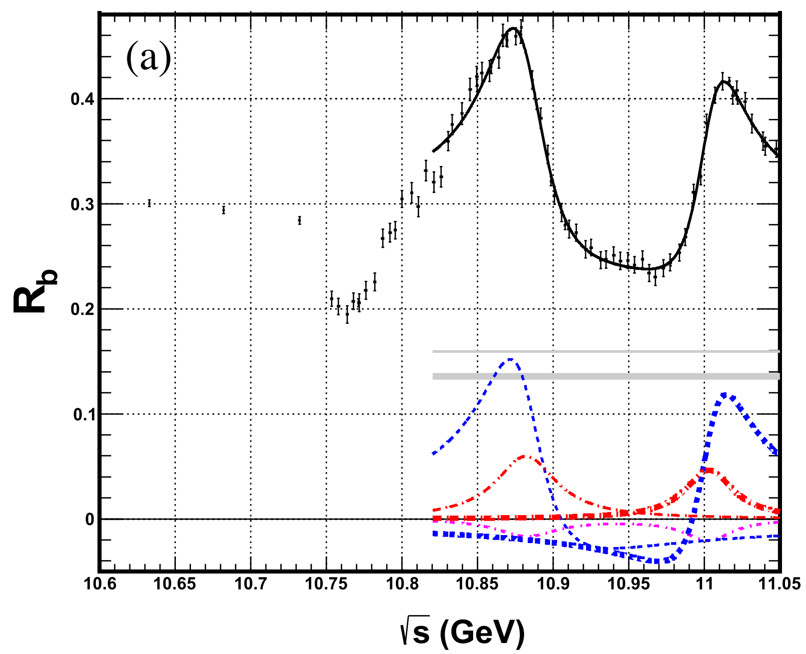
$$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$$

$$e^+e^- \to \pi^\pm Z_c(4055);\ \ Z_c(4055) \to \pi^\mp\psi(2S)$$

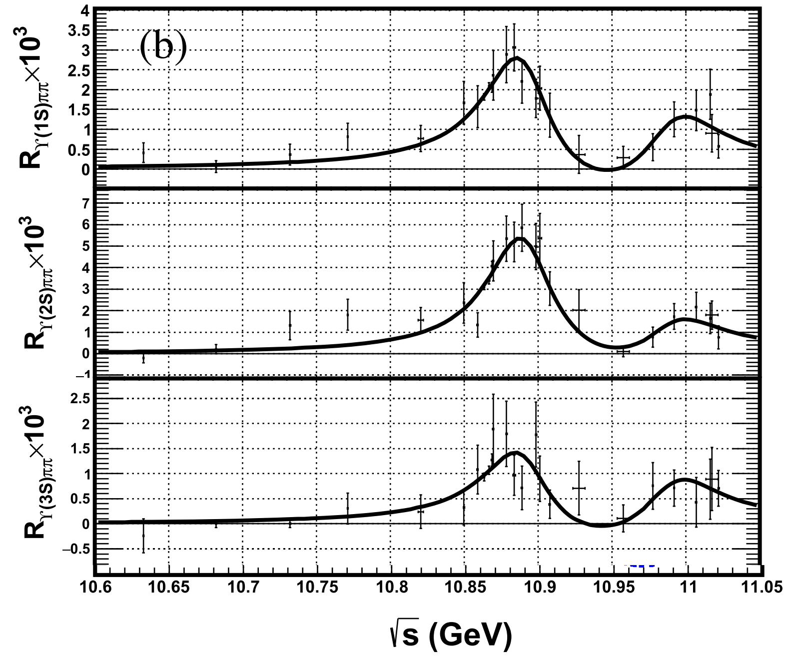
$$B \to K Z_c(4475); Z_c(4475) \to \pi^\pm\psi(2S)$$
$$Z_c(4240)$$

$$B \to K Z_c(4200); Z_c(4200) \to \pi^\pm J/\psi$$

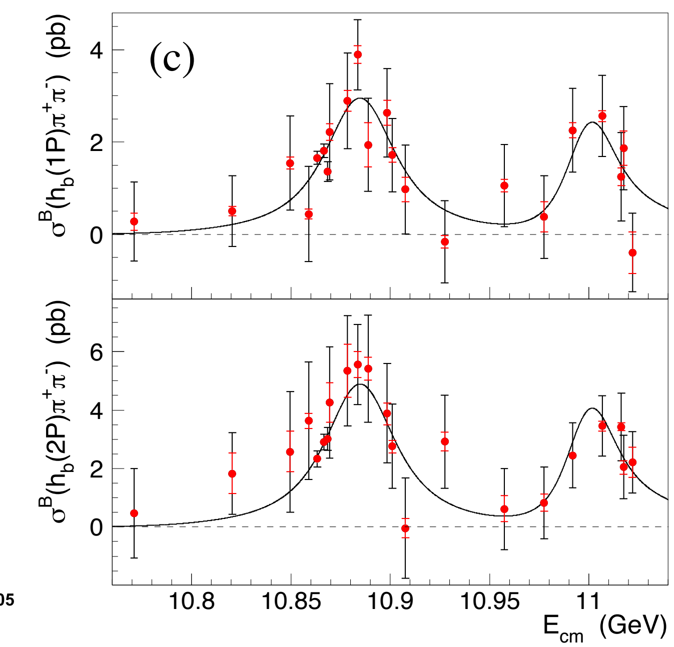
R_b



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

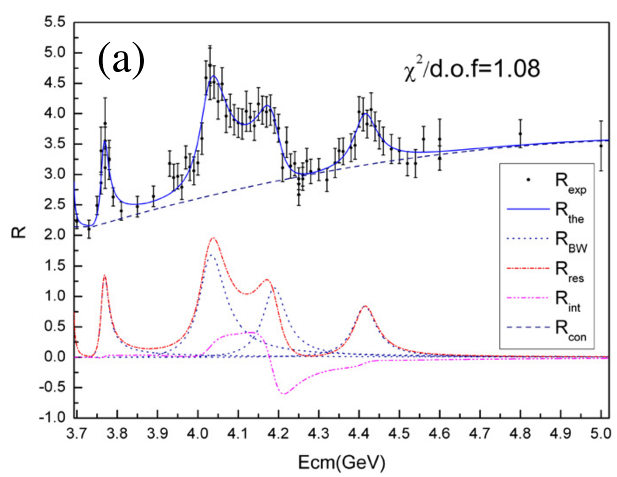


$e^+e^- \to \pi^+\pi^- h_b$

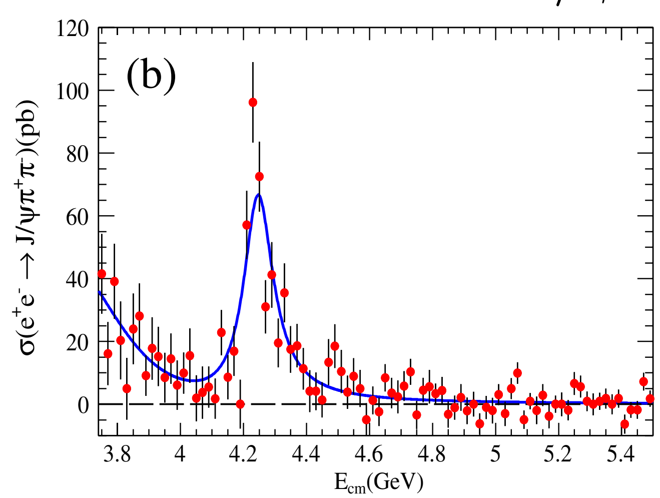


Contrast ee -> bb where the Upsilon(4S) and (5S) are clearly visible to cc:

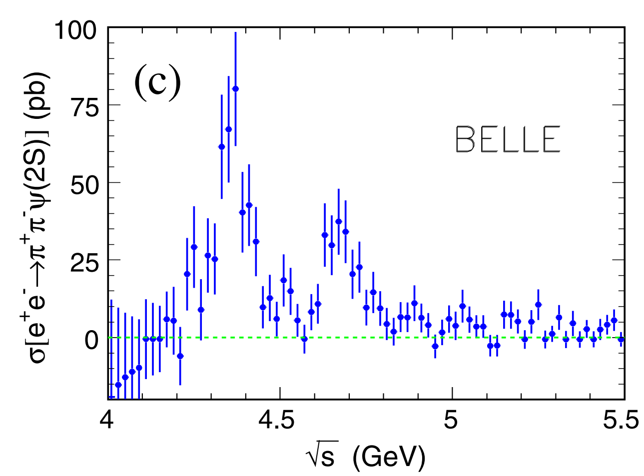
R_c



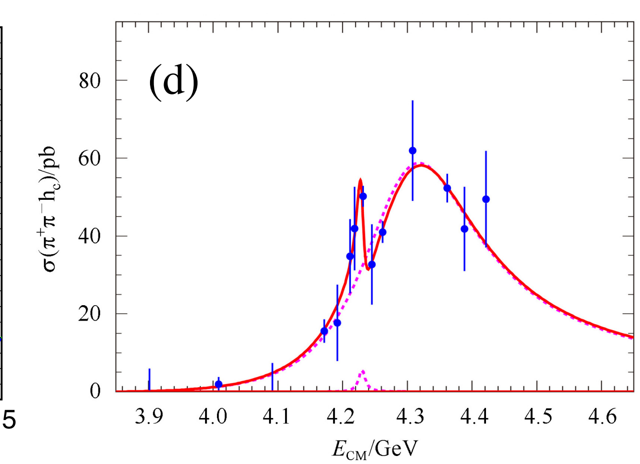
$e^+e^- \to \pi^+\pi^- J/\psi$



$e^+e^- \to \pi^+\pi^-\psi(2S)$



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



Conclusions

- X(3872): likely a $c\bar{c} - \bar{D}D^*$ mixture (not a cusp!)
- Y(4260): our best candidate for a hybrid; expect many more!
- Zc(4475): 4q exotic? Much to be understood with this (and related?) states.
- 4X: more exotics/cusps?
- X(5568): likely dead.
- Pc(4450) +Pc(4380): actual pentaquarks? Again, much remains to be understood.

- Why do ee and B decays differ?
- Why are states associated with radial excitations?

Conclusions

- there are a lot of new states, not all of them are 'real'!
- cusp effects can be important and should be accounted for when modelling
- it appears likely (?) that the Z_b and Z_c states are kinematical
- cusps appear above threshold with fixed properties such as widths and phases
- channel-dependent widths, masses, and production characteristics are a clue!
- nonrelativistic separable model fits the data well and is internally consistent.

Conclusions

- search for new classes of exotics: hexaquarks, double heavies, eg $cc\bar{u}\bar{d}$; exotic J^{PC}
- search for new decay modes of exotics
- clarify conventional $c\bar{c}$ in 3.8-4.0 GeV range. Zc(3930) = ?
  . $\chi_{c2}(2P)$: should be able to observe a DD* decay mode
- understand the e^+e^- charm cross sections better
- compare $p\bar{p}$ to e^+e^- production (via PANDA); photoproduction at COMPASS
- full amplitude analysis a la LHCb, more sophisticated models than isobar?

Heavy-Quark QCD Exotica

R.F. Lebed, R.E. Mitchell, and E.S. Swanson, to appear in Prog. Part. Nucl. Phys.

arXiv:1610.04528

Issues and Opportunities with Exotic Hadrons

R. Briceno et al., Chin. Phys. C40, 042001 (2016).

arXiv:1511.06779

The hidden-charm pentaquark and tetraquark states

Hua-Xing Chen, Wei Chen, Xiang Liu, Shi-Lin Zhu

arXiv:1601.02092