Experimental Aspects of Heavy Quark Exotica:
A Brief Tour of the XYZ

Ryan Mitchell
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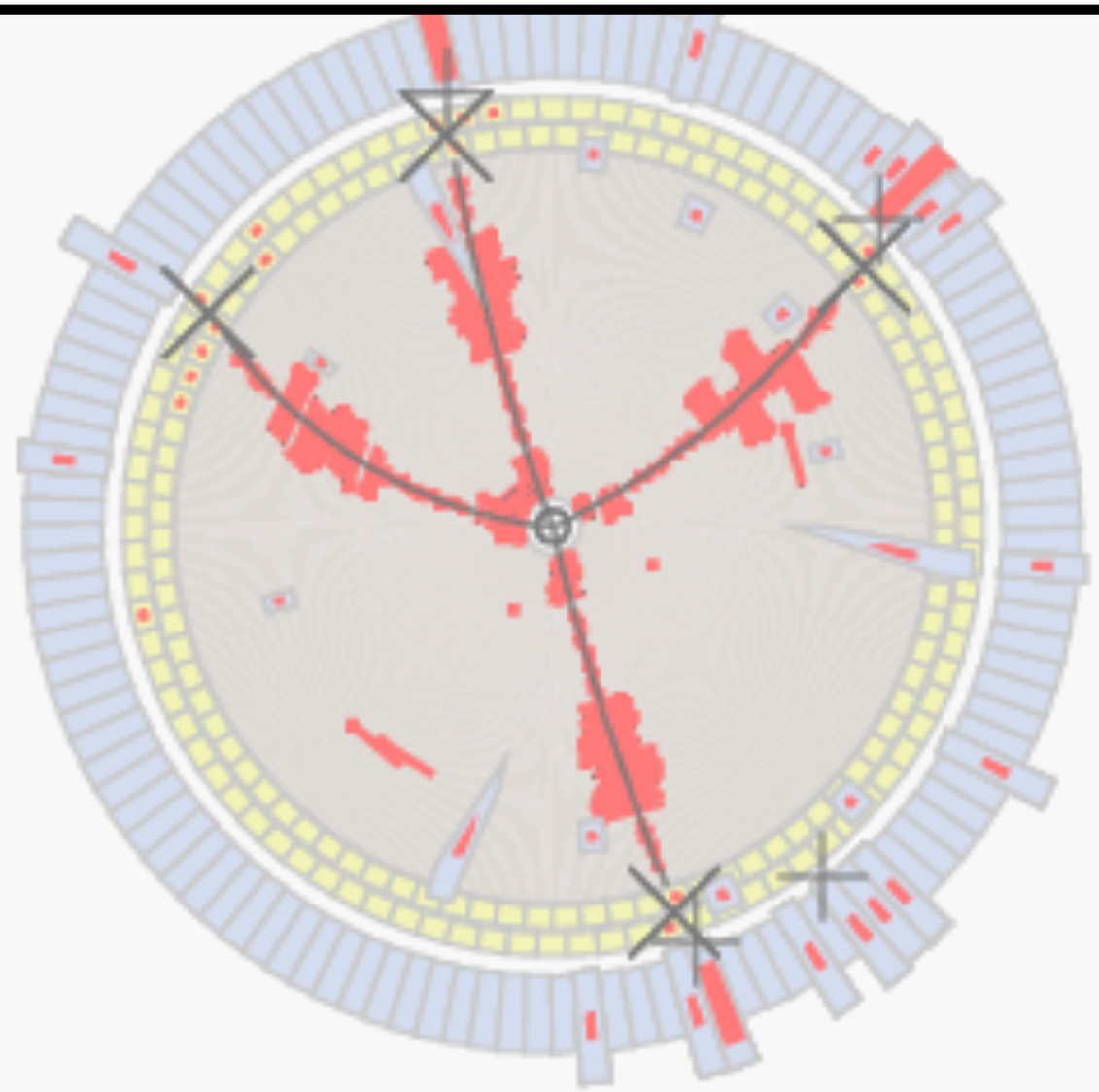
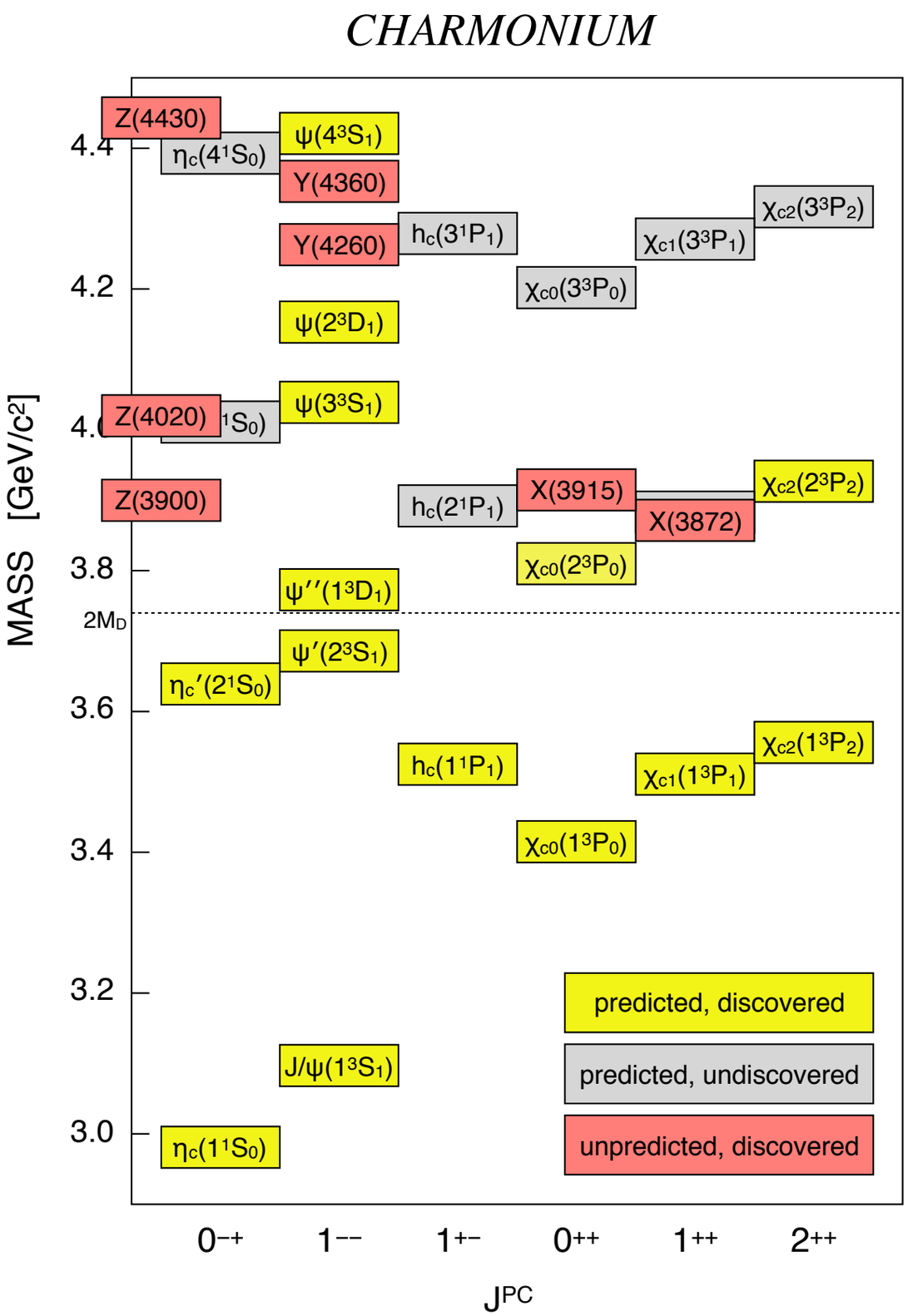
XIIIth Quark Confinement and the Hadron Spectrum
Maynooth, Ireland, August 2, 2018



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

Introduction to Heavy Quark Exotica



Q: What are heavy quark exotica?

A: Phenomena in the heavy quark sector that do not easily fit into the naive quark model picture of mesons and baryons.

Q: Why are they interesting?

A: They can be used to explore novel phenomena in QCD:

hybrid mesons, tetraquarks, pentaquarks, molecules, hadroquarkonium, thresholds

Q: Why are they called XYZ?

A: Mostly historical reasons.

But now there are patterns:

Z: electrically charged (I = 1).

Y: $J^{PC} = 1^{--}$, made directly in e^+e^-.

X: whatever is leftover.

But there are many exceptions!

[And the PDG has now renamed them by IJ^{PC}.]

Q: How many have been found?

A: Many.

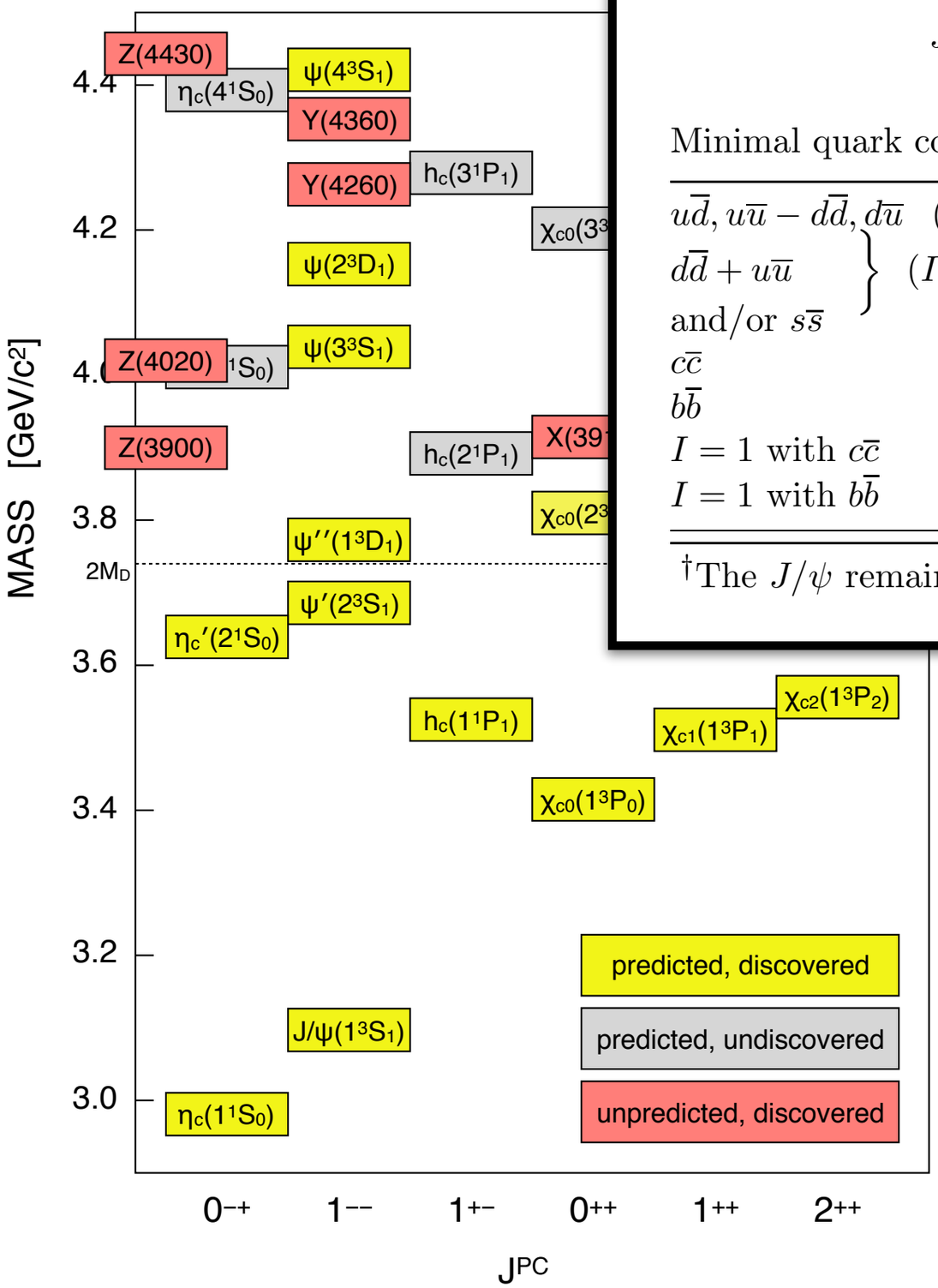
Introd

Table 8.1: Symbols for mesons with strangeness and heavy-flavor quantum numbers equal to zero. States that do not yet appear in the RPP are listed in parentheses.

$J^{PC} =$	$\begin{cases} 0^{-+} \\ 2^{-+} \\ \vdots \end{cases}$	1^{+-} 3^{+-} $\vdots$	1^{--} 2^{--} $\vdots$	0^{++} 1^{++} $\vdots$
Minimal quark content				
$u\bar{d}, u\bar{u} - d\bar{d}, d\bar{u}$ $(I = 1)$	π	b	ρ	a
$d\bar{d} + u\bar{u}$ and/or $s\bar{s}$ $\Big\}$ $(I = 0)$	η, η'	h, h'	ω, ϕ	f, f'
$c\bar{c}$	η_c	h_c	$\psi^\dagger$	χ_c
$b\bar{b}$	η_b	h_b	Υ	χ_b
$I = 1$ with $c\bar{c}$	(Π_c)	Z_c	R_c	(W_c)
$I = 1$ with $b\bar{b}$	(Π_b)	Z_b	(R_b)	(W_b)

†The J/ψ remains the J/ψ.

CHARMONI



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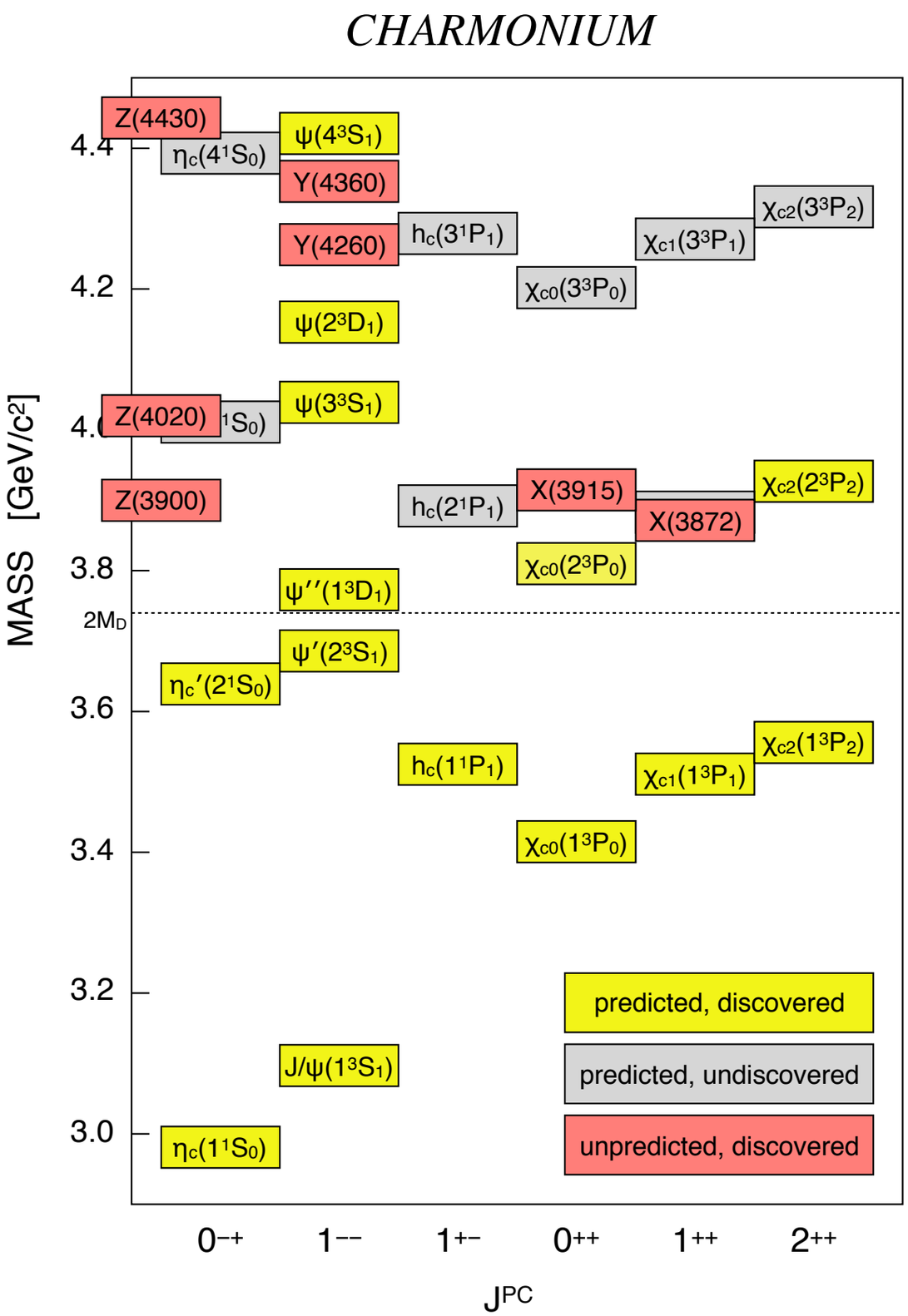
Introduction to Heavy Quark Exotica



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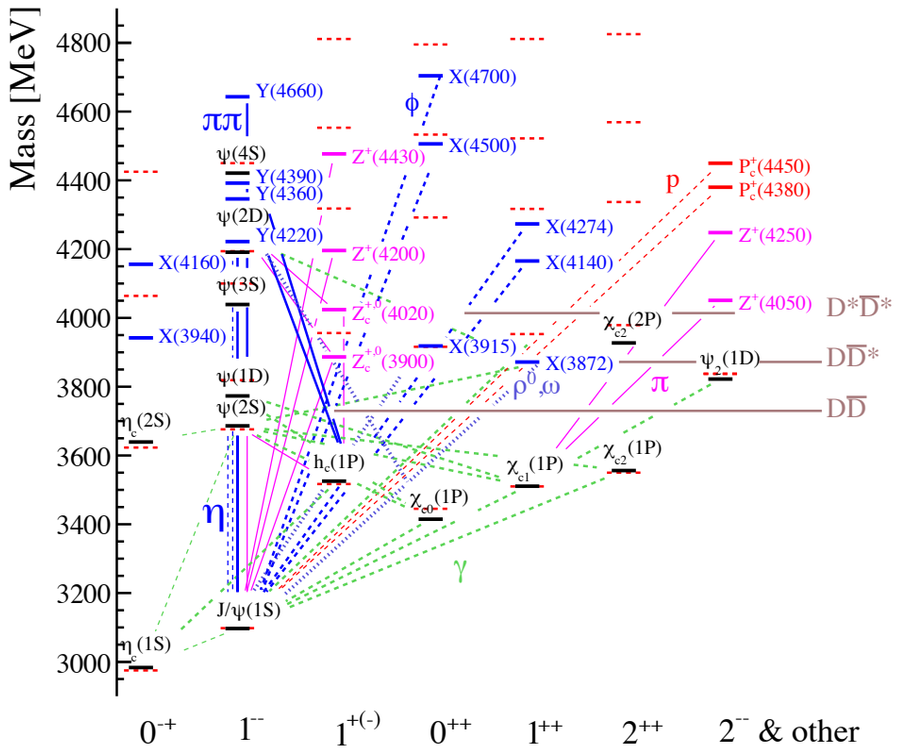
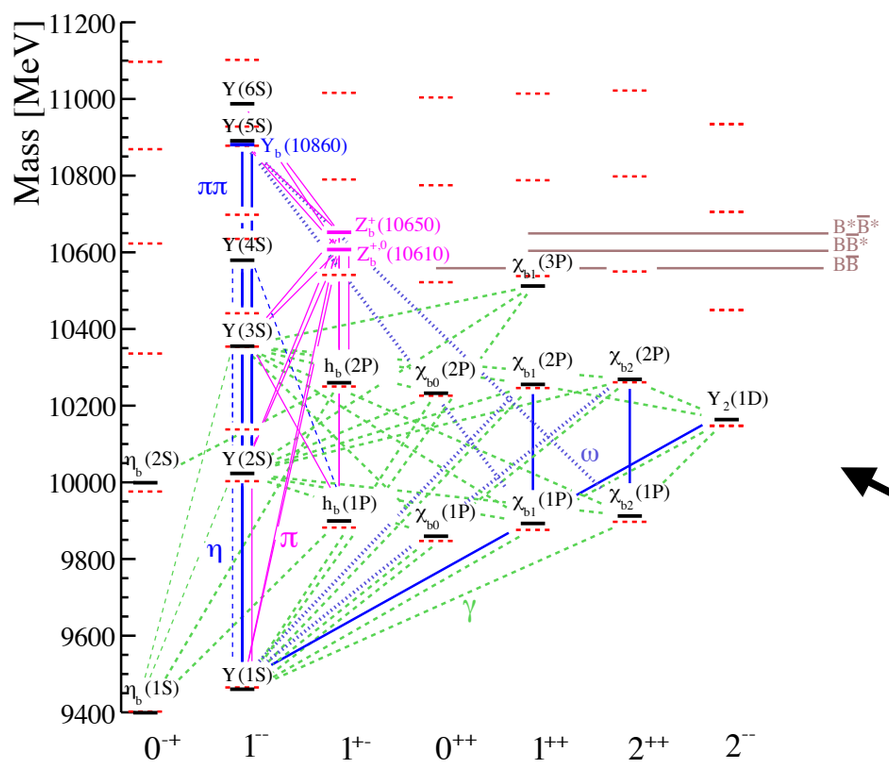
2016-2018 Review Articles on Heavy Quark Exotica





(1) **The hidden-charm pentaquark and tetraquark states**
Hua-Xing Chen, Wei Chen, Xiang Liu, Shi-Lin Zhu
Physics Reports 639, 1-121 (2016) [arXiv:1601.02092]

(2) **Heavy-Quark QCD Exotica**
Richard F. Lebed, Ryan E. Mitchell, Eric S. Swanson
Progress in Particle and Nuclear Physics 93, 143–194 (2017) [arXiv:1610.04528]

(3) **Multiquark Resonances**
A. Esposito, A. Pilloni, A.D. Polosa
Physics Reports 668, 1-97 (2017) [arXiv:1611.07920]

(4) **Hadronic Molecules**
Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, Qian Wang, Qiang Zhao, and Bing-Song Zou
Reviews of Modern Physics 90, 015004 (2018) [arXiv:1705.00141]

(5) **Exotics: Heavy Pentaquarks and Tetraquarks**
Ahmed Ali, Jens Sören Lange, Sheldon Stone
Progress in Particle and Nuclear Physics 97, 123–198 (2017) [arXiv:1706.00610]

(6) **Nonstandard Heavy Mesons and Baryons: Experimental Evidence**
Stephen Lars Olsen, Tomasz Skwarnicki, Daria Zieminska
Reviews of Modern Physics 90, 015003 (2018) [arXiv:1708.04012]

2016-2018 Review Articles on Heavy Quark Exotica

(2) **Heavy-Quark QCD Exotica**
Richard F. Lebed, Ryan E. Mitchell, Eric S. Swanson
Progress in Particle and Nuclear Physics 93, 143–194 (2017)
[arXiv:1610.04528]

Particle	$I^G J^{PC}$	Mass [MeV]	Width [MeV]	Production and Decay
$X(3823)$ $(\psi_2(1D))$	(0^-2^{--})	3822.2 ± 1.2 [176]	< 16	$B \to KX$; $X \to \gamma\chi_{c1}$ $e^+e^- \to \pi^+\pi^- X$; $X \to \gamma\chi_{c1}$
$X(3872)$	0^+1^{++}	3871.69 ± 0.17 [176]	< 1.2	$B \to KX$; $X \to \pi^+\pi^- J/\psi$ $B \to KX$; $X \to D^{*0}\bar{D}^0$ $B \to KX$; $X \to \gamma J/\psi, \gamma\psi(2S)$ $B \to KX$; $X \to \omega J/\psi$ $B \to K\pi X$; $X \to \pi^+\pi^- J/\psi$ $e^+e^- \to \gamma X$; $X \to \pi^+\pi^- J/\psi$ pp or $p\bar{p} \to X$ + any.; $X \to \pi^+\pi^- J/\psi$
$Z_c(3900)$	1^+1^{+-}	3886.6 ± 2.4 [176]	28.1 ± 2.6	$e^+e^- \to \pi Z$; $Z \to \pi J/\psi$ $e^+e^- \to \pi Z$; $Z \to D^*\bar{D}$
$X(3915)$	0^+0^{++}	3918.4 ± 1.9 [176]	20 ± 5	$\gamma\gamma \to X$; $X \to \omega J/\psi$
$Y(3940)$				$B \to KX$; $X \to \omega J/\psi$
$Z(3930)$ $(\chi_{c2}(2P))$	0^+2^{++}	3927.2 ± 2.6 [176]	24 ± 6	$\gamma\gamma \to Z$; $Z \to D\bar{D}$
$X(3940)$		$3942^{+7}_{-6} \pm 6$ [41]	$37^{+26}_{-15} \pm 8$	$e^+e^- \to J/\psi + X$; $X \to D\bar{D}^*$
$Y(4008)$	1^{--}	$3891 \pm 41 \pm 12$ [23]	$255 \pm 40 \pm 14$	$e^+e^- \to Y$; $Y \to \pi^+\pi^- J/\psi$
$Z_c(4020)$	$1^+?^{?-}$	4024.1 ± 1.9 [176]	13 ± 5	$e^+e^- \to \pi Z$; $Z \to \pi h_c$ $e^+e^- \to \pi Z$; $Z \to D^*\bar{D}^*$
$Z_1(4050)$	$1^-?^{?+}$	$4051 \pm 14^{+20}_{-41}$ [133]	82^{+21+47}_{-17-22}	$B \to KZ$; $Z \to \pi^\pm\chi_{c1}$
$Z_c(4055)$	$1^+?^{?-}$	$4054 \pm 3 \pm 1$ [148]	$45 \pm 11 \pm 6$	$e^+e^- \to \pi^\mp Z$; $Z \to \pi^\pm\psi(2S)$
$Y(4140)$	0^+1^{++}	$4146.5 \pm 4.5^{+4.6}_{-2.8}$ [125]	$83 \pm 21^{+21}_{-14}$	$B \to KY$; $Y \to \phi J/\psi$ pp or $p\bar{p} \to Y$ + any.; $Y \to \phi J/\psi$
$X(4160)$		$4156^{+25}_{-20} \pm 15$ [41]	$139^{+111}_{-61} \pm 21$	$e^+e^- \to J/\psi + X$; $X \to D^*\bar{D}^*$
$Z_c(4200)$	1^+1^{+-}	4196^{+31+17}_{-29-13} [46]	$370^{+70+70}_{-70-132}$	$B \to KZ$; $Z \to \pi^\pm J/\psi$
$Y(4230)$	0^-1^{--}	$4230 \pm 8 \pm 6$ [149]	$38 \pm 12 \pm 2$	$e^+e^- \to Y$; $Y \to \omega\chi_{c0}$
$Z_c(4240)$	1^+0^{--}	$4239 \pm 18^{+45}_{-10}$ [138]	$220 \pm 47^{+108}_{-74}$	$B \to KZ$; $Z \to \pi^\pm\psi(2S)$
$Z_2(4250)$	$1^-?^{?+}$	$4248^{+44+180}_{-29-35}$ [133]	$177^{+54+316}_{-39-61}$	$B \to KZ$; $Z \to \pi^\pm\chi_{c1}$
$Y(4260)$	0^-1^{--}	4251 ± 9 [176]	120 ± 12	$e^+e^- \to Y$; $Y \to \pi\pi J/\psi$
$Y(4274)$	0^+1^{++}	$4273.3 \pm 8.3^{+17.2}_{-3.6}$ [125]	$52 \pm 11^{+8}_{-11}$	$B \to KY$; $Y \to \phi J/\psi$
$X(4350)$	$0^+?^{?+}$	$4350.6^{+4.6}_{-5.1} \pm 0.7$ [170]	$13^{+18}_{-9} \pm 4$	$\gamma\gamma \to X$; $X \to \phi J/\psi$
$Y(4360)$	1^{--}	4346 ± 6 [176]	102 ± 10	$e^+e^- \to Y$; $Y \to \pi^+\pi^-\psi(2S)$
$Z_c(4430)$	1^+1^{+-}	4478^{+15}_{-18} [176]	181 ± 31	$B \to KZ$; $Z \to \pi^\pm J/\psi$ $B \to KZ$; $Z \to \pi^\pm\psi(2S)$
$X(4500)$	0^+0^{++}	$4506 \pm 11^{+12}_{-15}$ [125]	$92 \pm 21^{+21}_{-20}$	$B \to KX$; $X \to \phi J/\psi$
$X(4630)$	1^{--}	4634^{+8+5}_{-7-8} [150]	92^{+40+10}_{-24-21}	$e^+e^- \to X$; $X \to \Lambda_c\bar{\Lambda}_c$
$Y(4660)$	1^{--}	4643 ± 9 [176]	72 ± 11	$e^+e^- \to Y$; $Y \to \pi^+\pi^-\psi(2S)$
$X(4700)$	0^+0^{++}	$4704 \pm 10^{+14}_{-24}$ [125]	$120 \pm 31^{+42}_{-33}$	$B \to KX$; $X \to \phi J/\psi$
$P_c(4380)$		$4380 \pm 8 \pm 29$ [35]	$205 \pm 18 \pm 86$	$\Lambda_b \to KP_c$; $P_c \to pJ/\psi$
$P_c(4450)$		$4449.8 \pm 1.7 \pm 2.5$ [35]	$39 \pm 5 \pm 19$	$\Lambda_b \to KP_c$; $P_c \to pJ/\psi$
$X(5568)$		$5567.8 \pm 2.9^{+0.9}_{-1.9}$ [175]	$21.9 \pm 6.4^{+5.0}_{-2.5}$	$p\bar{p} \to X$ + anything; $X \to B_s\pi^\pm$
$Z_b(10610)$	1^+1^{+-}	10607.2 ± 2.0 [176]	18.4 ± 2.4	$e^+e^- \to \pi Z$; $Z \to \pi\Upsilon(1S, 2S, 3S)$ $e^+e^- \to \pi Z$; $Z \to \pi h_b(1P, 2P)$ $e^+e^- \to \pi Z$; $Z \to B\bar{B}^*$
$Z_b(10650)$	1^+1^{+-}	10652.2 ± 1.5 [176]	11.5 ± 2.2	$e^+e^- \to \pi Z$; $Z \to \pi\Upsilon(1S, 2S, 3S)$ $e^+e^- \to \pi Z$; $Z \to \pi h_b(1P, 2P)$ $e^+e^- \to \pi Z$; $Z \to B^*\bar{B}^*$
$Y_b(10888)$	0^-1^{--}	10891 ± 4 [176]	54 ± 7	$e^+e^- \to Y$; $Y \to \pi\pi\Upsilon(1S, 2S, 3S)$ $e^+e^- \to Y$; $Y \to \pi\pi h_b(1P, 2P)$

organized by mass

2016-2018 Review Articles on Heavy Quark Exotica

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[arXiv:1610.04528]

Process	Production	Decay	Particle
B and Λ_b Decays	$B \to K + X$	$X \to \pi^+\pi^- J/\psi$ [4, 109, 110, 111, 112, 113, 114] $X \to D^{*0}\bar{D}^0$ [115, 116, 117] $X \to \gamma J/\psi$ [118, 119, 120, 121] $X \to \gamma\psi(2S)$ [118, 120]	$X(3872)$
		$X \to \omega J/\psi$ [106, 122, 123]	$X(3872)$ $Y(3940)$
		$X \to \gamma\chi_{c1}$ [124]	$X(3823)$
		$X \to \phi J/\psi$ [125, 126, 127, 128, 129, 130, 131, 132]	$Y(4140)$ $Y(4274)$ $X(4500)$ $X(4700)$
	$B \to K + Z$	$Z \to \pi^\pm\chi_{c1}$ [133, 134]	$Z_1(4050)$ $Z_2(4250)$
		$Z \to \pi^\pm J/\psi$ [46, 135]	$Z_c(4200)$ $Z_c(4430)$
		$Z \to \pi^\pm\psi(2S)$ [30, 135, 136, 137, 138, 139]	$Z_c(4240)$ $Z_c(4430)$
	$B \to K\pi + X$	$X \to \pi^+\pi^- J/\psi$ [140]	$X(3872)$
	$\Lambda_b \to K + P_c$	$P_c \to pJ/\psi$ [35]	$P_c(4380)$ $P_c(4450)$
e^+e^- Annihilation	$e^+e^- \to Y$	$Y \to \pi\pi J/\psi$ [23, 29, 141, 142, 143, 144, 145]	$Y(4008)$ $Y(4260)$
		$Y \to \pi\pi\psi(2S)$ [108, 146, 147, 148]	$Y(4360)$ $Y(4660)$
		$Y \to \omega\chi_{c0}$ [149]	$Y(4230)$
		$Y \to \Lambda_c\bar{\Lambda}_c$ [150]	$X(4630)$
		$Y \to \pi\pi\Upsilon(1S, 2S, 3S)$ [151, 152] $Y \to \pi\pi h_b(1P, 2P)$ [153]	$Y_b(10888)$
	$e^+e^- \to \pi + Z$	$Z \to \pi J/\psi$ [22, 23, 31, 32] $Z \to D^*\bar{D}$ [33, 154, 155]	$Z_c(3900)$
		$Z \to \pi h_c$ [156, 157] $Z \to D^*\bar{D}^*$ [158, 159]	$Z_c(4020)$
		$Z \to \pi^\pm\psi(2S)$ [148]	$Z_c(4055)$
		$Z \to \pi\Upsilon(1S, 2S, 3S)$ [160, 161, 162] $Z \to \pi h_b(1P, 2P)$ [160]	$Z_b(10610)$ $Z_b(10650)$
		$Z \to B\bar{B}^*$ [163]	$Z_b(10610)$
		$Z \to B^*\bar{B}^*$ [163]	$Z_b(10650)$
	$e^+e^- \to \gamma + X$	$X \to \pi^+\pi^- J/\psi$ [52]	$X(3872)$
	$e^+e^- \to \pi^+\pi^- + X$	$X \to \gamma\chi_{c1}$ [164]	$X(3823)$
	$e^+e^- \to J/\psi + X$	$X \to D\bar{D}^*$ [41, 165]	$X(3940)$
		$X \to D^*\bar{D}^*$ [41]	$X(4160)$
$\gamma\gamma$ Collisions	$\gamma\gamma \to X$	$X \to \omega J/\psi$ [166, 167]	$X(3915)$
		$X \to D\bar{D}$ [168, 169]	$Z(3930)$
		$X \to \phi J/\psi$ [170]	$X(4350)$
Hadron Collisions	pp or $p\bar{p} \to X+$ anything	$X \to \pi^+\pi^- J/\psi$ [27, 171, 172, 173]	$X(3872)$
		$X \to \phi J/\psi$ [174]	$Y(4140)$
		$X \to B_s\pi^\pm$ [175]	$X(5568)$

organized by production

2016-2018 Review Articles on Heavy Quark Exotica

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Richard F. Lebed, Ryan E. Mitchell, Eric S. Swanson
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[arXiv:1610.04528]

Experiment	Highlights	Accelerator	Years	Institute	Production
BaBar	$Y(4260)$ [29] $Y(4360)$ [108]	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] $Y(3940)$ [106] $X(3915)$ [166] $Z_c(4430)$ [30, 136, 137] $Z_b(10610)$, $Z_b(10650)$ [160, 162, 163] $Y_b(10888)$ [151, 152]	KEKB	1998–2010	KEK (Tsukuba, Japan)	
Belle II	Upcoming continuation of Belle	SuperKEKB	2018–		
CLEO-c	$Y(4260)$ [142] $\pi^+\pi^- h_c$ [177]	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	$Z_c(3900)$ [22, 154] $Z_c(4020)$ [156, 158] $Y(4230)$ [149] $X(3872)$ [52]	BEPCII	2008–	IHEP (Beijing, China)	
CDF	$Y(4140)$ [126] $Y(4274)$ [132] $X(3872)$ [178, 179, 172]	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	$X(3872)$ [171] $Y(4140)$ [174] $X(5568)$ [175]				
ATLAS	$\chi_b(3P)$ [180]	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	$X(3872)$ [28] $Y(4140)$, $Y(4274)$ [130]				
LHCb	$Z_c(4430)$ [138, 139] $X(3872)$ [109] $P_c(4380)$, $P_c(4450)$ [35] $Y(4140)$, $Y(4274)$ [125, 131]				
COMPASS	photoproduction [181] $a_1(1420)$ [182]	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 ($E_{beam} \leq 11$ GeV): $\gamma p \to Xp$
CLAS12					

organized by experiment

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A. Glossary of Exotic States

A.1. $X(3823)$ (*or* $\psi_2(1D)$)

The $X(3823)$ was discovered by the Belle Collaboration in 2013 in the reaction $B \to KX$ with $X \to \gamma\chi_{c1}$ [124]. The BESIII Collaboration later found a peak consistent with the $X(3823)$ produced in $e^+e^- \to \pi^+\pi^- X$, again with $X \to \gamma\chi_{c1}$ [164]. The $X(3823)$ is likely the $\psi_2(1D)$ state of charmonium. See Sec. 2.6 for more detail.

A.2. $X(3872)$

Accidentally discovered by the Belle Collaboration in 2003 in the reaction $B \to KX$ with $X \to \pi^+\pi^- J/\psi$ [4], the $X(3872)$ was both the first of the XYZ states to be discovered and is the one that has been most studied. Nevertheless, like most of the XYZ states, there is no interpretation that is universally agreed upon. It has been produced in decays of the B meson [4, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 140], in hadronic collisions [27, 28, 171, 172, 173, 178], and perhaps in radiative decays of the $Y(4260)$ [52]. Besides $\pi^+\pi^- J/\psi$, it has also been seen to decay to $\omega J/\psi$ [122], $D^*\bar{D}$ [115, 116, 117], $\gamma J/\psi$ [118, 119, 120, 121], and $\gamma\psi(2S)$ [118, 120]. Its unusual features include a mass that is currently indistinguishable from the $D^{*0}\bar{D}^0$ threshold (the current mass difference is 0.01 ± 0.18 MeV) and a narrow width (< 1.2 MeV). It is has no isospin partners and has $J^{PC} = 1^{++}$. See Sec. 2.3 for more discussion of its experimental properties.

A.3. $Z_c(3900)$

The $Z_c(3900)$ was simultaneously discovered in 2013 by the BESIII and Belle Collaborations in the process $e^+e^- \to \pi^\mp Z_c^\pm$ with $Z_c^\pm \to \pi^\pm J/\psi$. For the BESIII observation [22], the center-of-mass energy was fixed to 4.26 GeV. Belle [23] used initial-state radiation to cover the energy region from 4.15 to 4.45 GeV, corresponding to the region of the $Y(4260)$. It is not yet clear whether the production of the $Z_c(3900)$ is associated with the $Y(4260)$. The $Z_c(3900)$ has since been seen in decays to $\pi^0 J/\psi$ [31, 32] (Z_c^0) and in $D^*\bar{D}$ (both charged and neutral) [33, 154, 155]. It has only been produced in the reaction $e^+e^- \to \pi Z_c$. See Sec. 2.5.4 for more experimental details.

A.4. $X(3915)$ (*or* $\chi_{c0}(2P)$)

The $X(3915)$ was first seen by the Belle Collaboration in 2010 in the process $\gamma\gamma \to X$ with $X \to \omega J/\psi$ [166]. It was later confirmed by the BaBar Collaboration [167]. It appears as a clear peak with little background. Its J^{PC} is likely 0^{++}, so there is some possibility that it is the $\chi_{c0}(2P)$ state of charmonium, although this assignment is controversial. See Sec. 2.6 for more discussion.

[OUTLINE] A Tour through the XYZ

[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Z_c(4430)

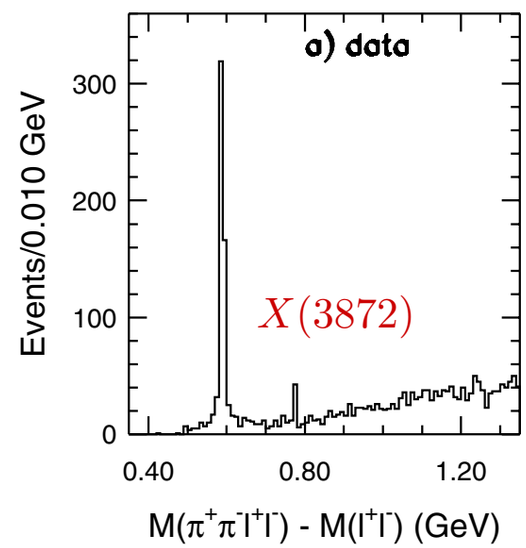
[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the χ_{cJ}(2P).

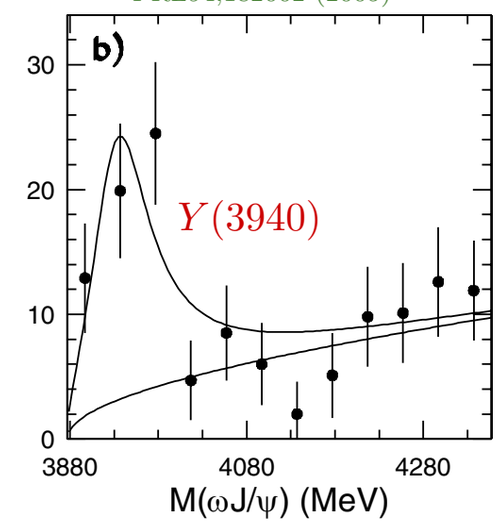
[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e^+e^- cross sections ("Y states").
Peaks in their decays ("Z states").

[Part IV: Z_c(4430)]
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in Λ_b decays.

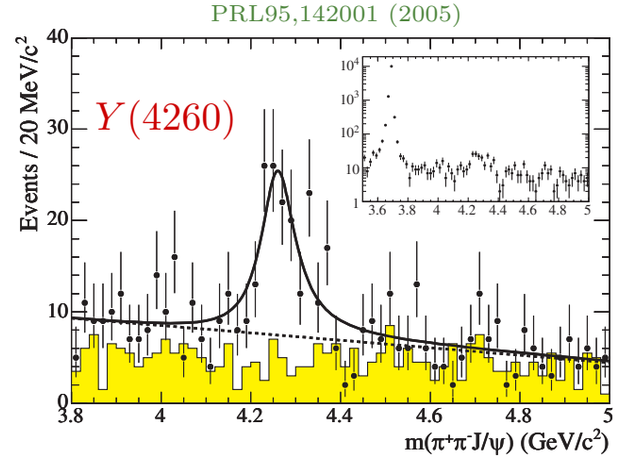
$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle
PRL91,262001 (2003)



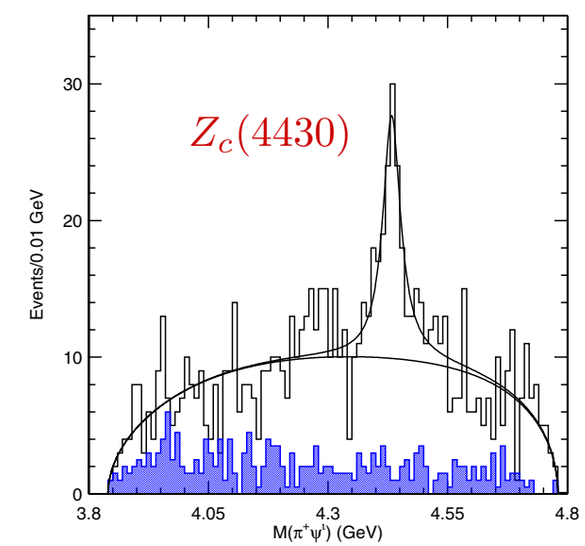
$B \to KX; X \to \omega J/\psi$ at Belle
PRL94,182002 (2005)



$e^+e^- \to Y; Y \to \pi^+\pi^- J/\psi$ at BaBar
PRL95,142001 (2005)

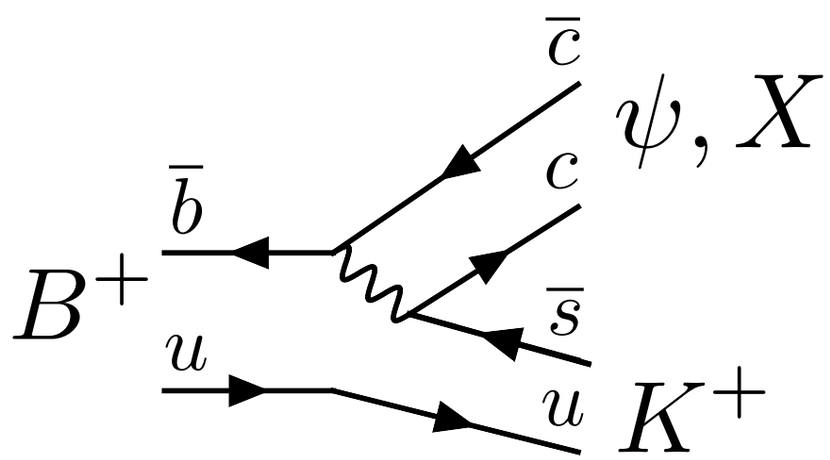


$B \to KZ; Z \to \pi^\pm\psi(2S)$ at Belle
PRL100,142001 (2008)



[PRELIM: Four Foundational Discoveries] X(3872)

Year:	*Search for this:*	*Find this:*
2003	$B \to K\psi(2S)$ ↳ $\pi^+\pi^- J/\psi$	$B \to K\psi(2S)$, **X(3872)** ↳ $\pi^+\pi^- J/\psi$



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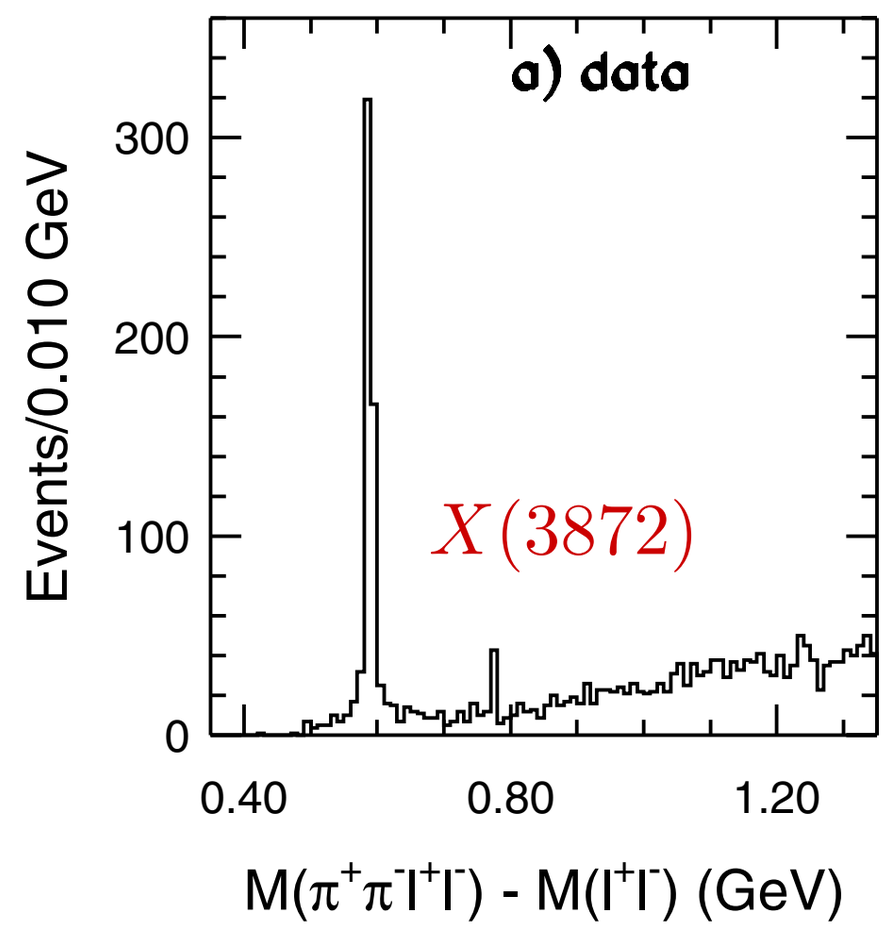
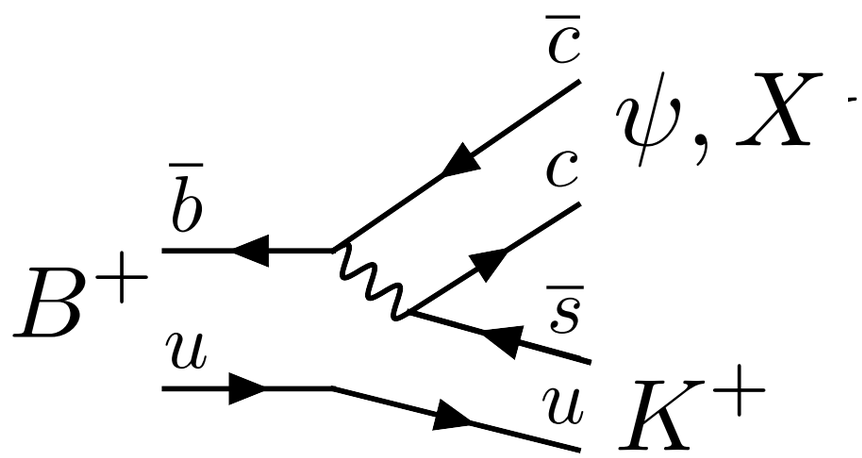
PRL91,262001 (2003)



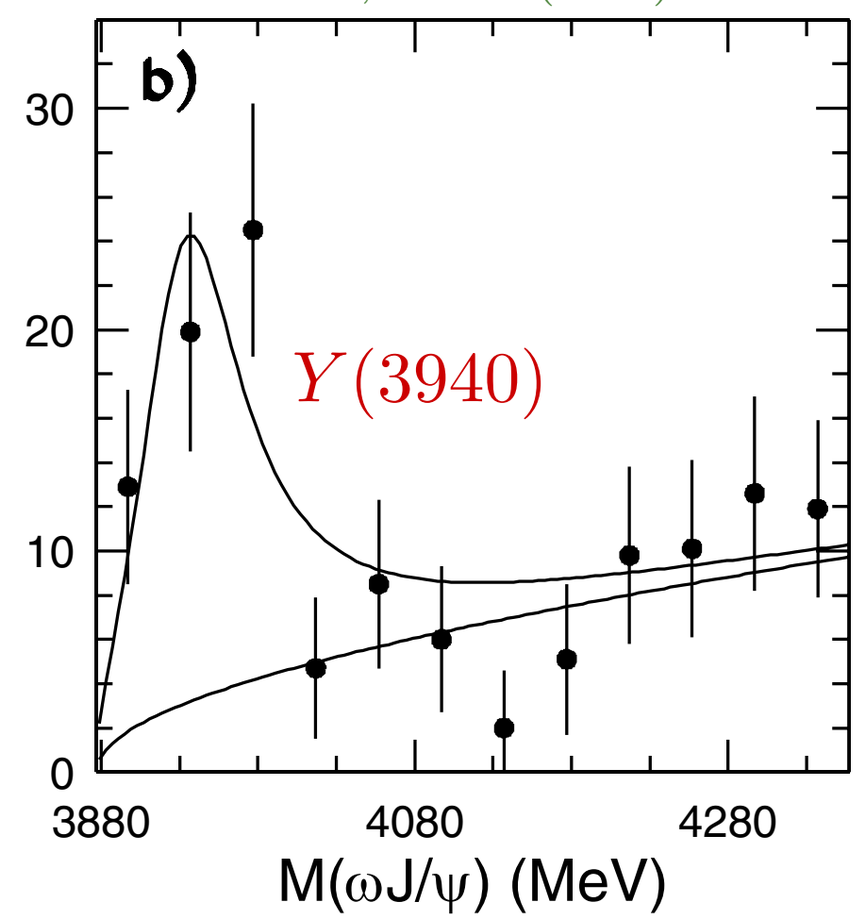
[PRELIM: Four Foundational Discoveries] Y(3940)

Year:	*Search for this:*	*Find this:*
2005	B → KX(3872) ↳ ωJ/ψ	B → K**Y(3940)** ↳ ωJ/ψ



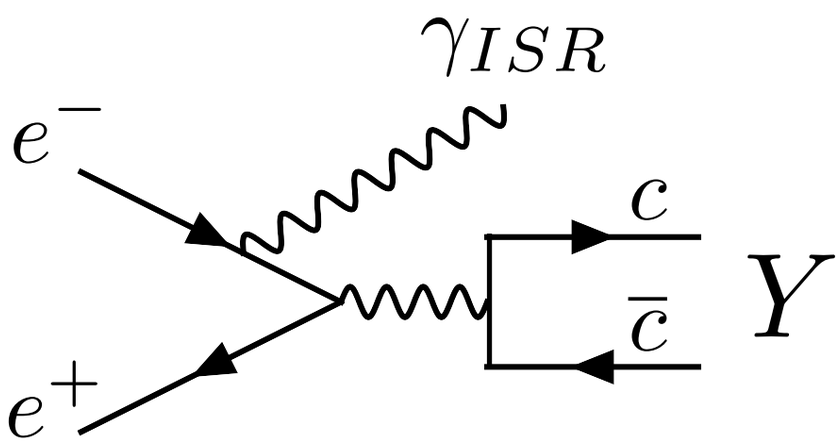
$B \to KX; X \to \omega J/\psi$ at Belle

PRL94,182002 (2005)



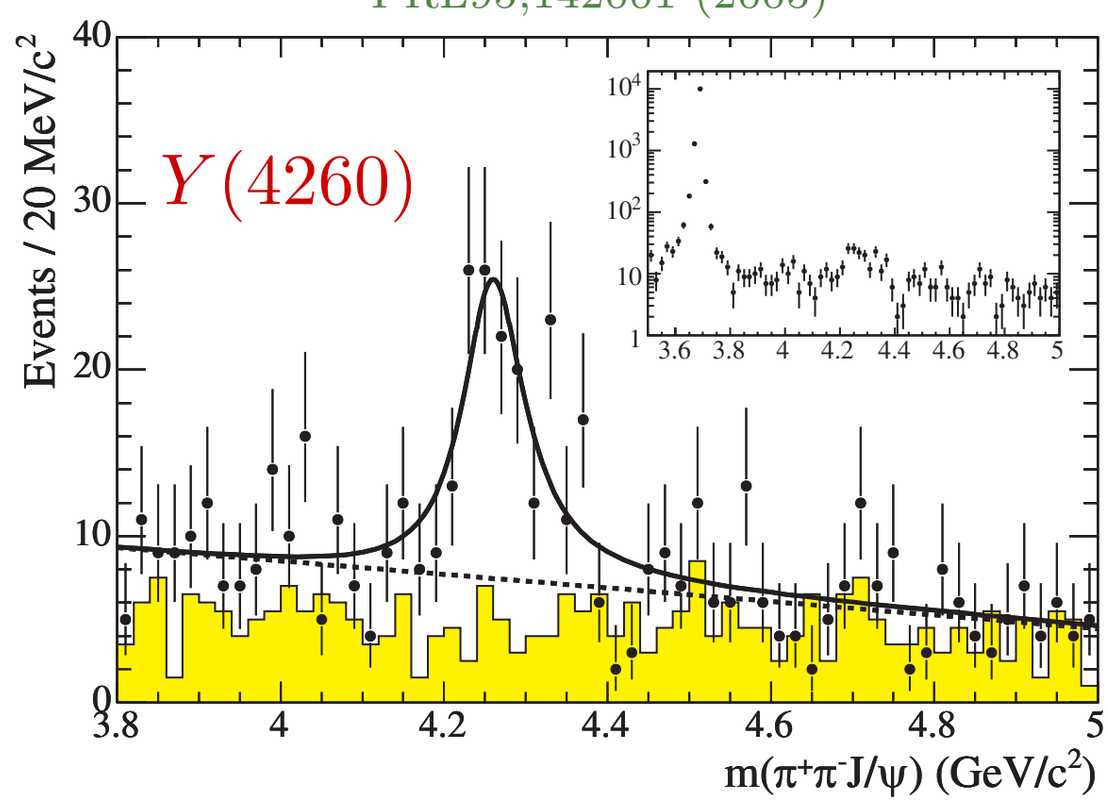
[PRELIM: Four Foundational Discoveries] Y(4260)

Year:	*Search for this:*	*Find this:*
2005	$e^+e^- \to X(3872)$ ↳ $\pi^+\pi^- J/\psi$	$e^+e^- \to$ **Y(4260)** ↳ $\pi^+\pi^- J/\psi$



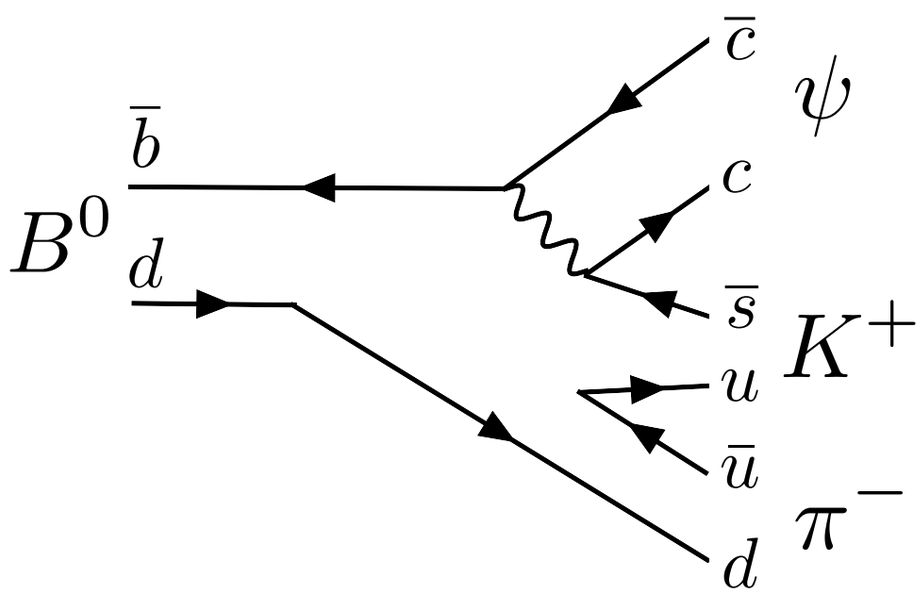
$e^+e^- \to Y; Y \to \pi^+\pi^- J/\psi$ at BaBar

PRL95,142001 (2005)



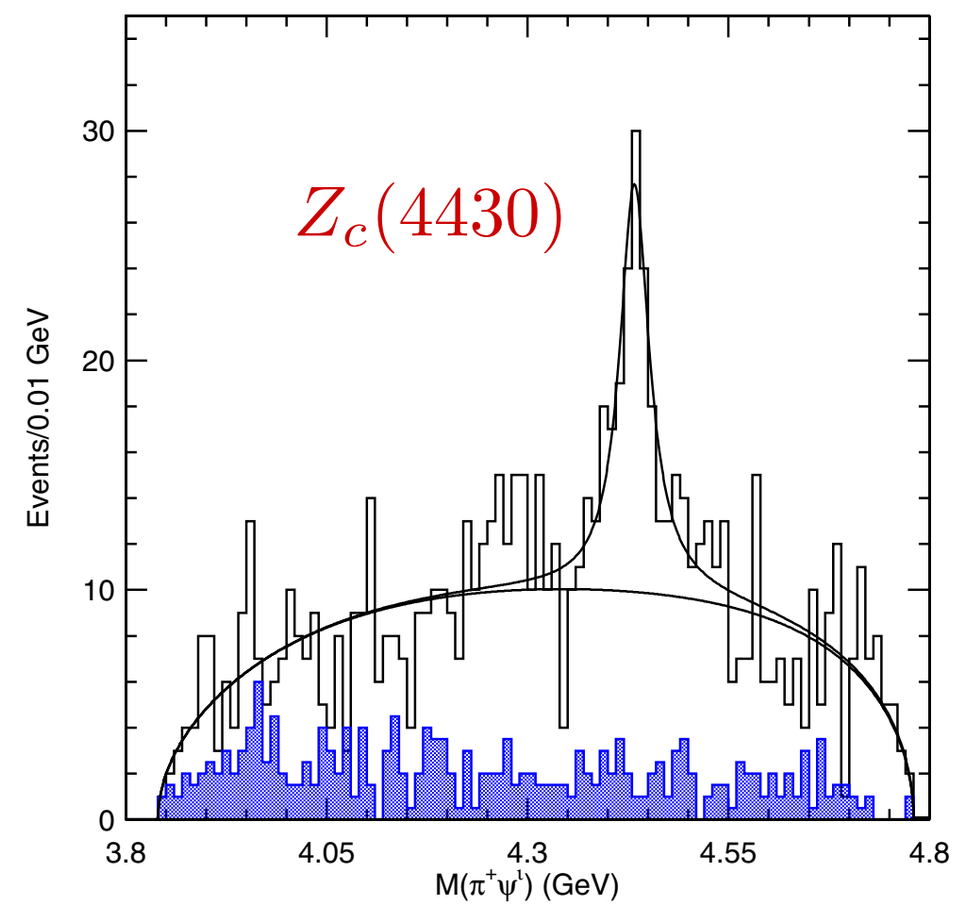
[PRELIM: Four Foundational Discoveries] $Z_c(4430)$

Year:	*Search for this:*	*Find this:*
2008	$B \to K\pi^{\pm}\psi(2S)$	$B \to K\mathbf{Z_c(4430)^{\pm}}$ ↳ $\pi^{\pm}\psi(2S)$



$B \to KZ; Z \to \pi^{\pm}\psi(2S)$ at Belle

PRL100,142001 (2008)



[OUTLINE] A Tour through the XYZ

[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Z_c(4430)

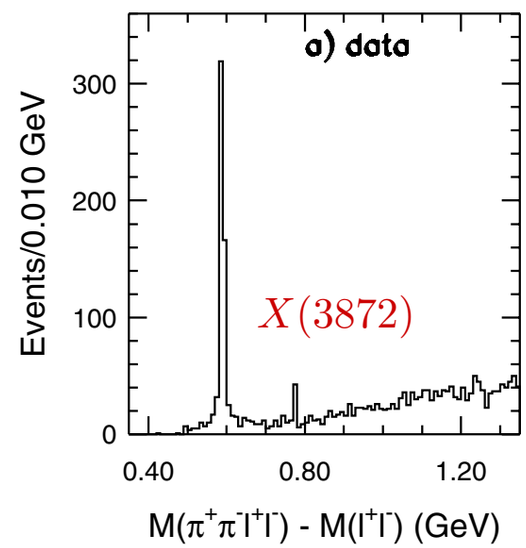
[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the χ_{cJ}(2P).

[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e^+e^- cross sections ("Y states").
Peaks in their decays ("Z states").

[Part IV: Z_c(4430)]
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in Λ_b decays.

$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle
PRL91,262001 (2003)



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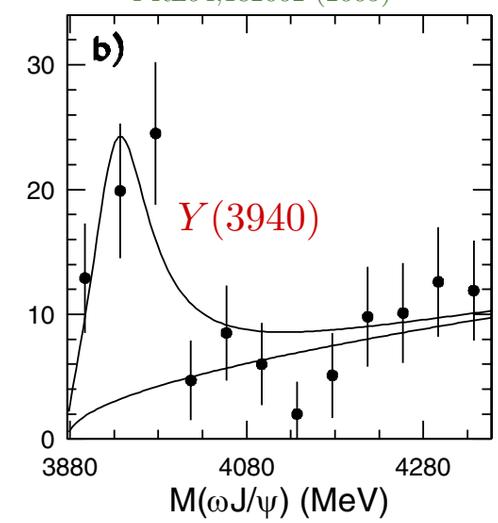
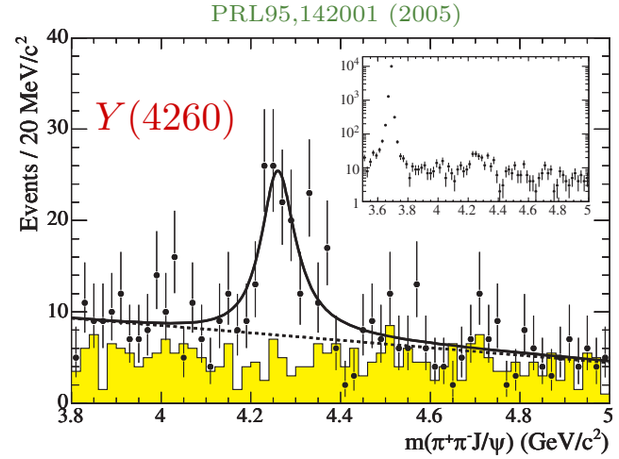
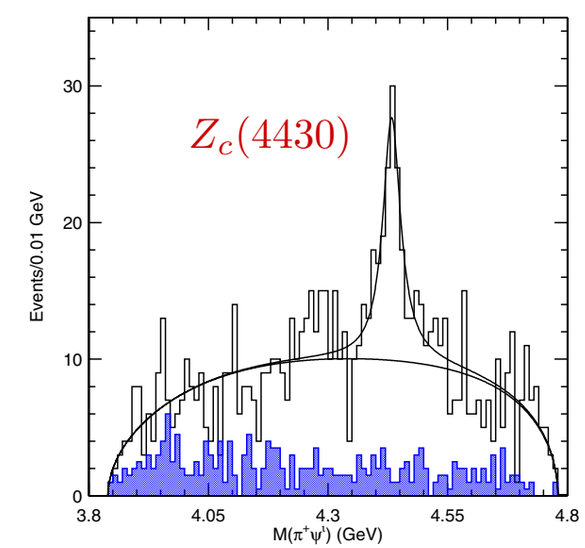
PRL94,182002 (2005)



$e^+e^- \to Y; Y \to \pi^+\pi^- J/\psi$ at BaBar
PRL95,142001 (2005)



$B \to KZ; Z \to \pi^\pm\psi(2S)$ at Belle
PRL100,142001 (2008)



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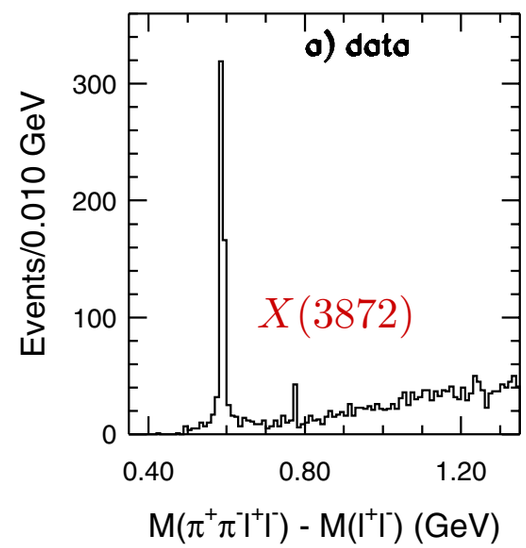
Peaks in Λ_b decays.

$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle
PRL91,262001 (2003)



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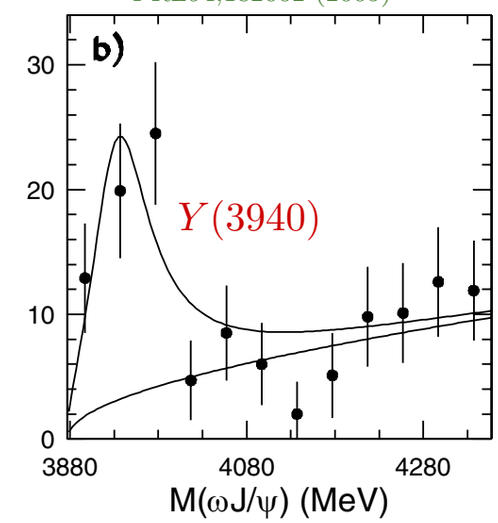
PRL94,182002 (2005)



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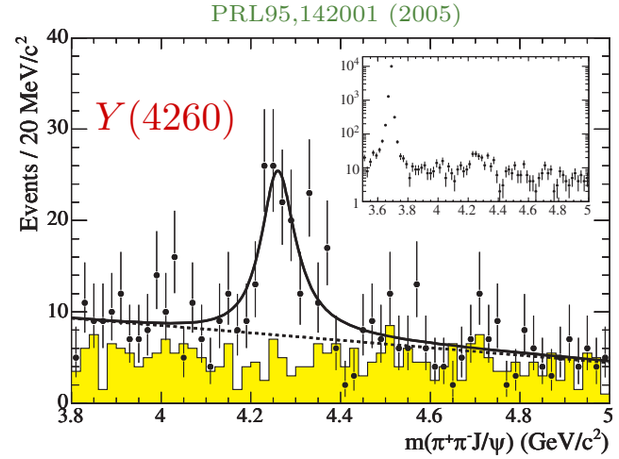
PRL95,142001 (2005)



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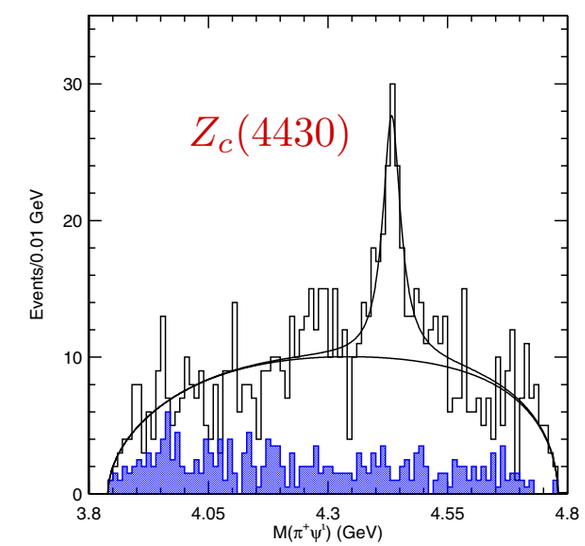
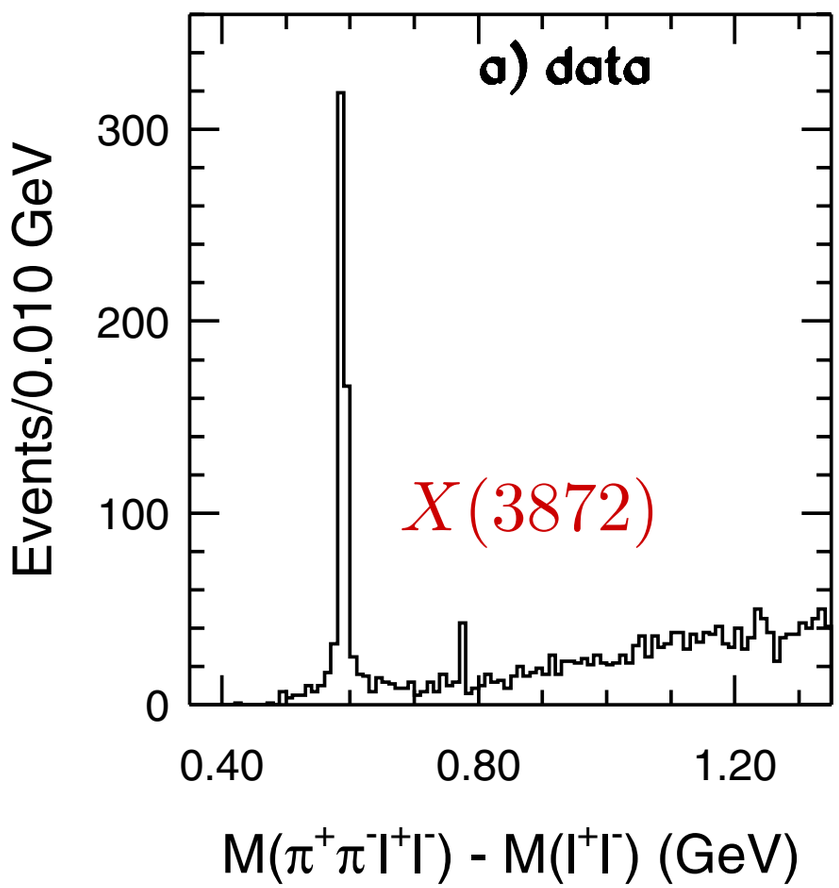
PRL100,142001 (2008)



[PART I: X(3872)] What happened?

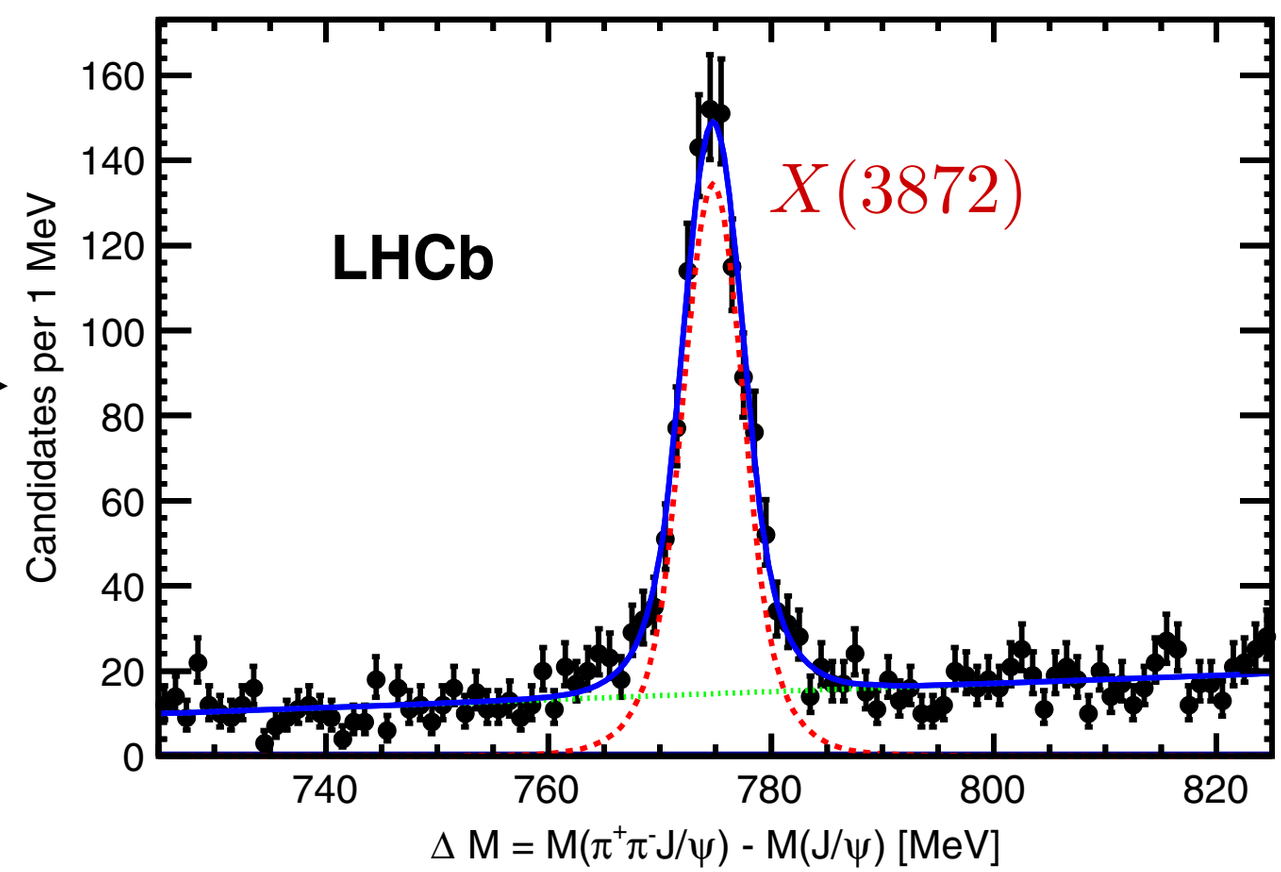
$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle

PRL91,262001 (2003)



$B \to KX; X \to \pi^+\pi^- J/\psi$ at LHCb

PRD92,011102 (2015)



More statistics!!
More experimental details.

[PART I: X(3872)] Experimental Details

Properties:

1. Its mass is *really* close to the D^0D^{*0} threshold.

$$M(X) - M(D^0\bar{D}^{*0}) = 0.01 \pm 0.18 \text{ MeV}$$

2. It's narrow.

$$\Gamma(X) < 1.2 \text{ MeV}$$

3. It has no isospin partners.
4. It has $J^{PC} = 1^{++}$.

Decays:

5. It decays to $\rho J/\psi$.
6. It has radiative decays to J/ψ and $\psi(2S)$.

$$\frac{B(X\to\gamma\psi(2S))}{B(X\to\gamma J/\psi)} = 2.6 \pm 0.6$$

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

8. It decays to D^0D^{*0}.

$$\frac{B(X\to D^0\bar{D}^{*0})}{B(X\to\pi^+\pi^- J/\psi)} = 9.2 \pm 2.9$$

9. There are lower limits on its branching fractions.

$$B(X \to \pi^+\pi^- J/\psi) > 3.2\%$$

Production:

10. It is produced in B decays.
11. It is produced in hadron collisions.

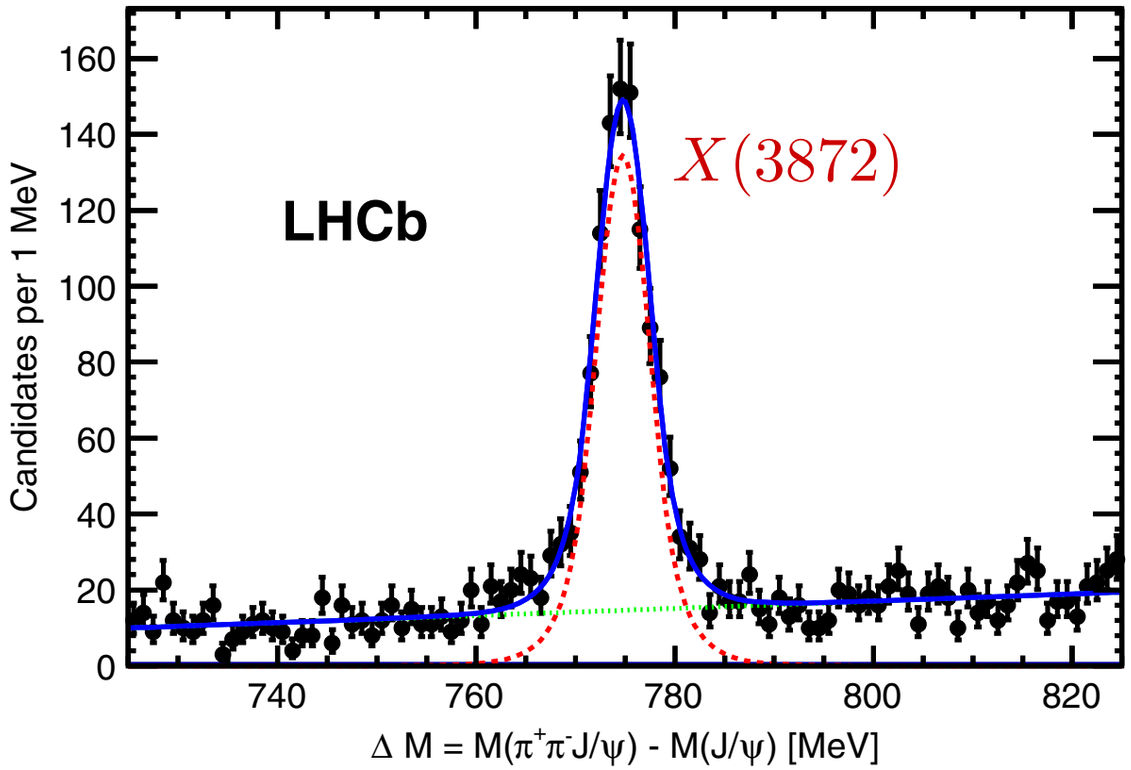
$$\frac{\sigma(pp\to X \ + \ \text{anything})\times B(X\to\pi^+\pi^- J/\psi)}{\sigma(pp\to\psi(2S) \ + \ \text{anything})\times B(\psi(2S)\to\pi^+\pi^- J/\psi)}$$

$$= 0.0656 \pm 0.0029 \pm 0.0065 \quad \text{(CMS)}$$

12. It's produced in $e^+e^- \to \gamma X(3872)$, maybe through the Y(4260).
13. It might be produced in photoproduction.

$B \to KX; X \to \pi^+\pi^- J/\psi$ at LHCb

PRD92,011102 (2015)



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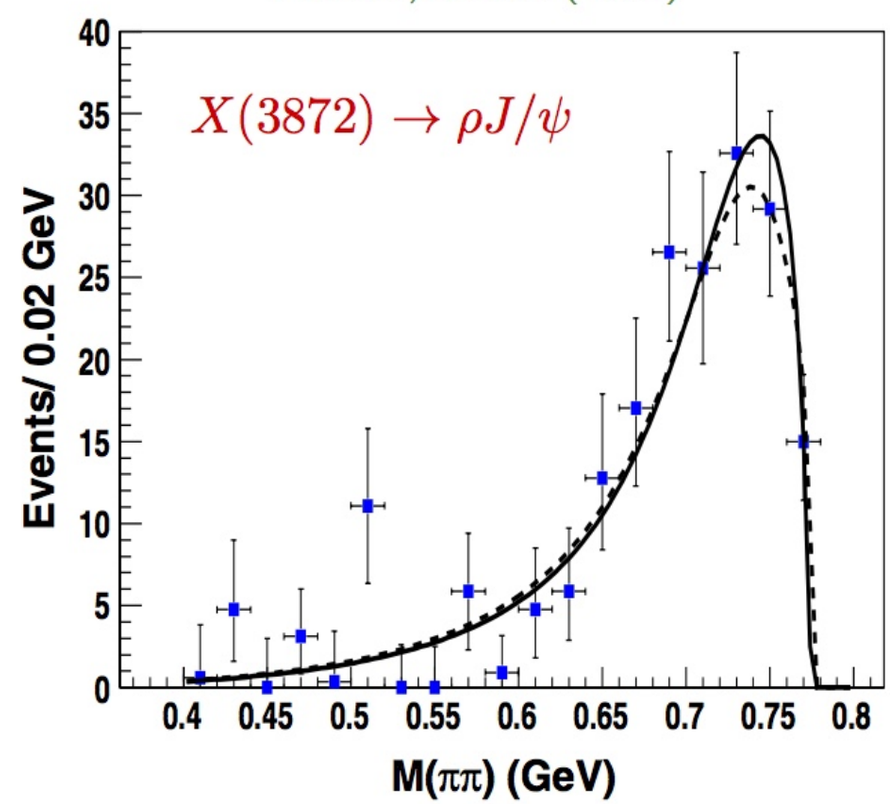
$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle

PRD84,052004 (2011)



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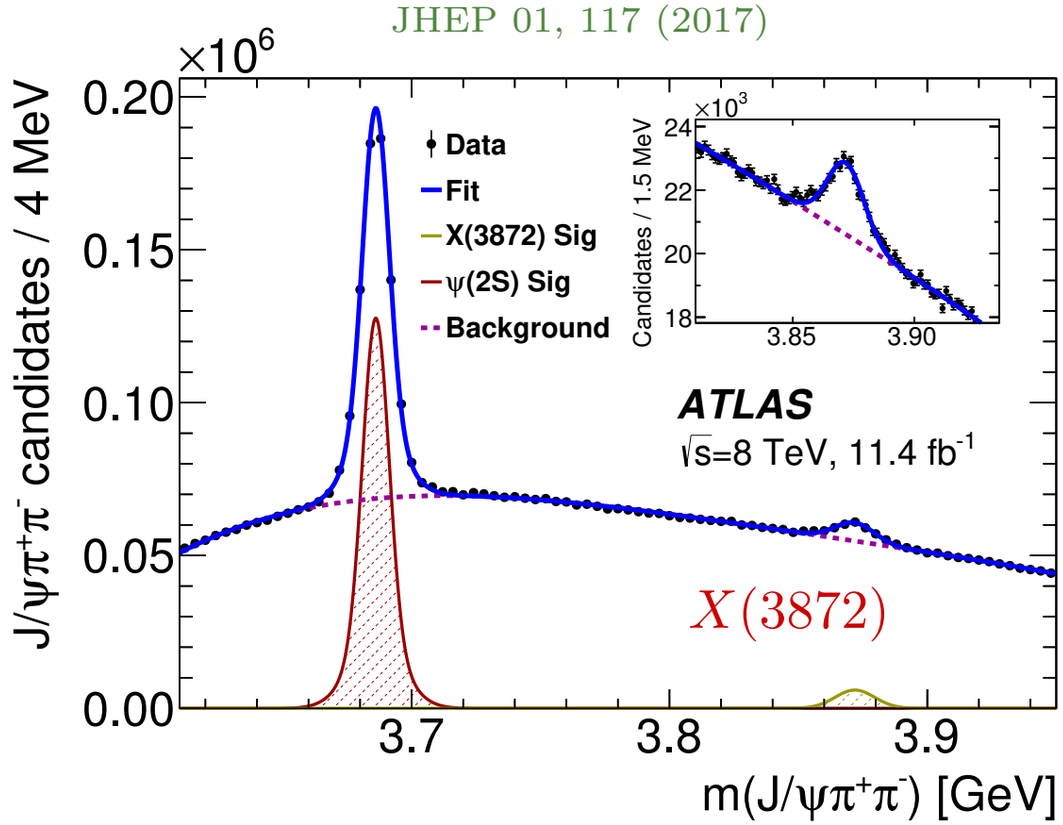
$pp \to X+$ anything; $X \to \pi^+\pi^- J/\psi$ at ATLAS

JHEP 01, 117 (2017)



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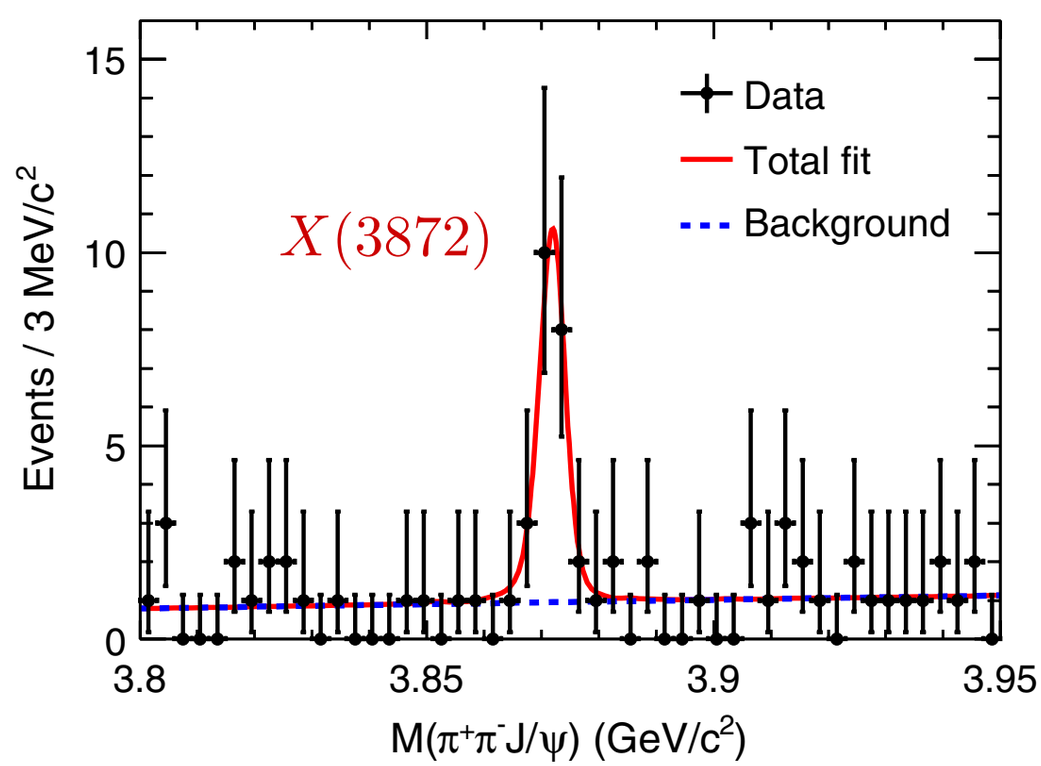
13. It might be produced in photoproduction.

$e^+e^- \to \gamma X;\ X \to \pi^+\pi^- J/\psi$ at BESIII

PRL 112, 092001 (2014)



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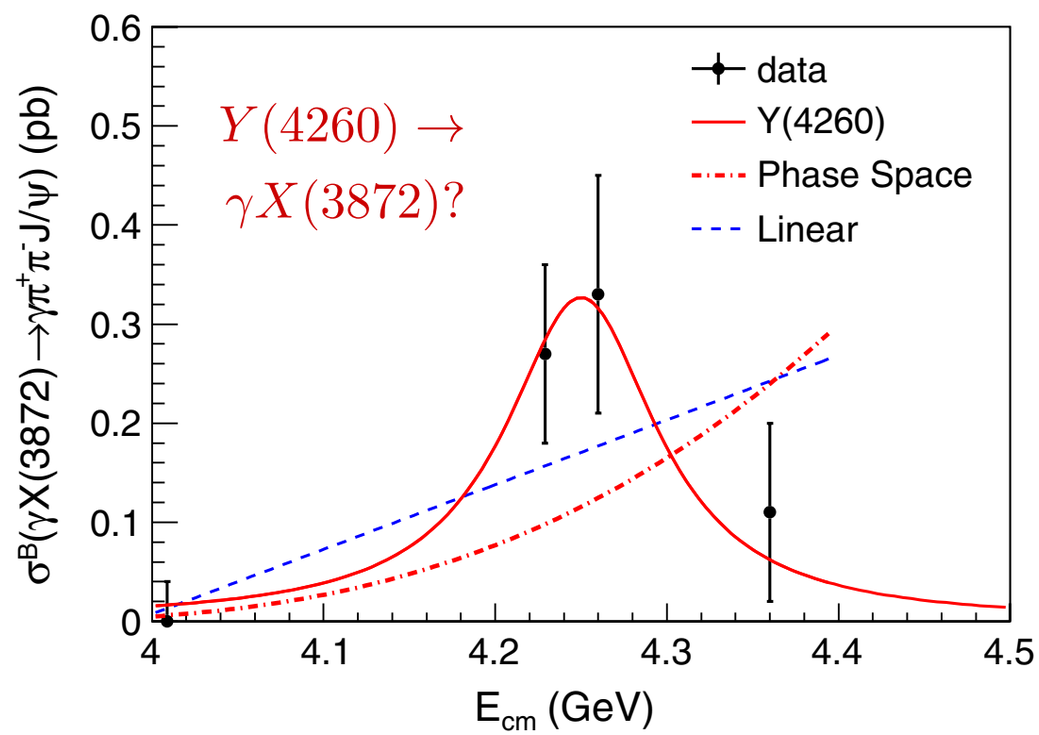
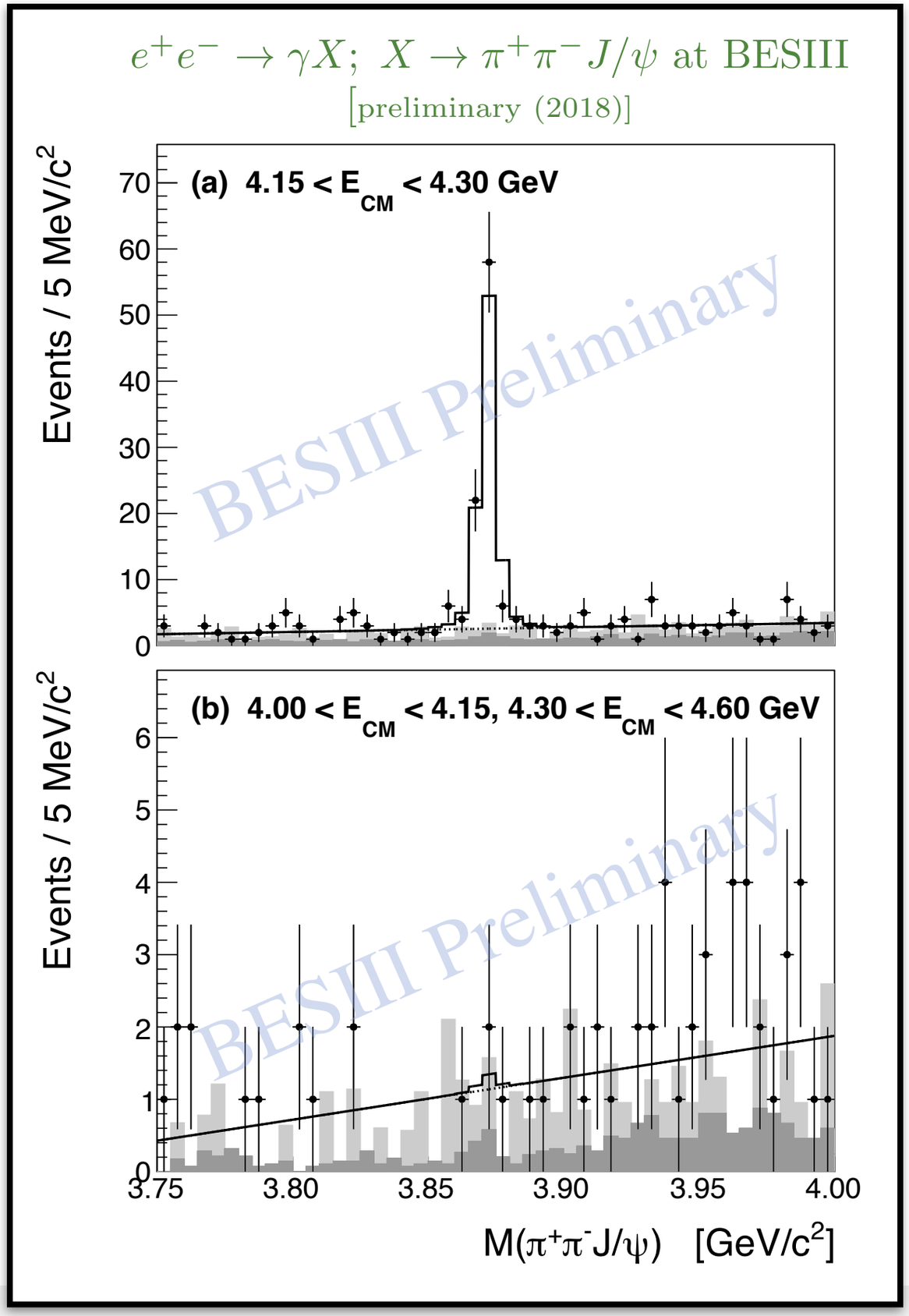
$e^+e^- \to \gamma X;\ X \to \pi^+\pi^- J/\psi$ at BESIII

PRL 112, 092001 (2014)



[PART I: X(3872)] Experimental Details



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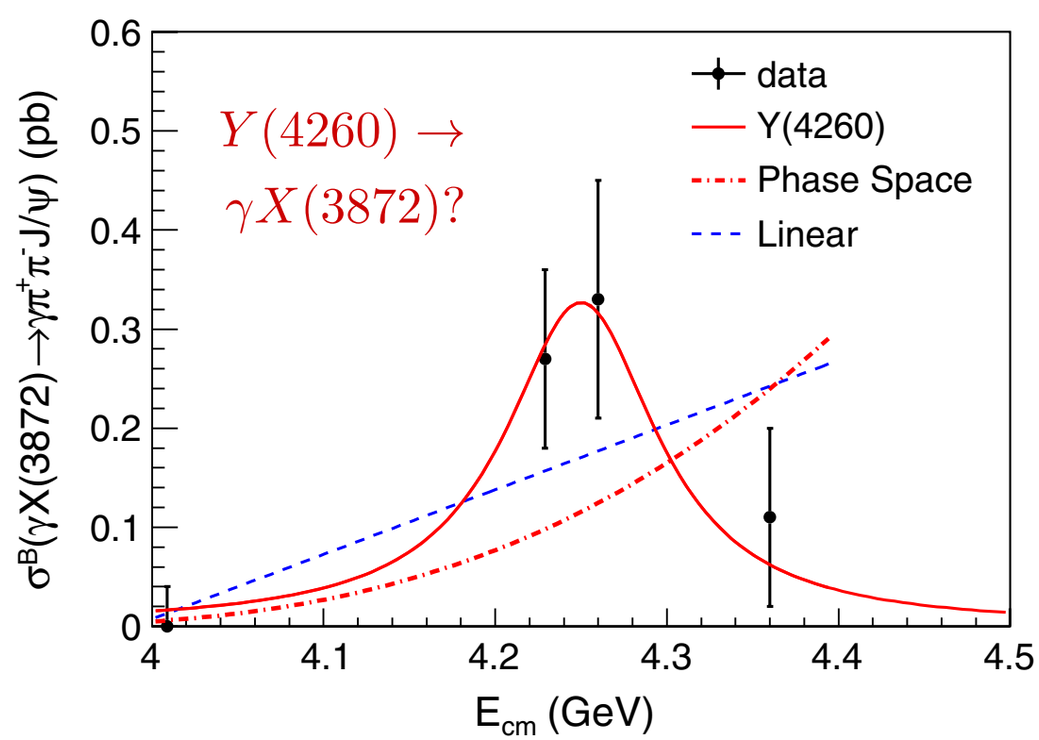
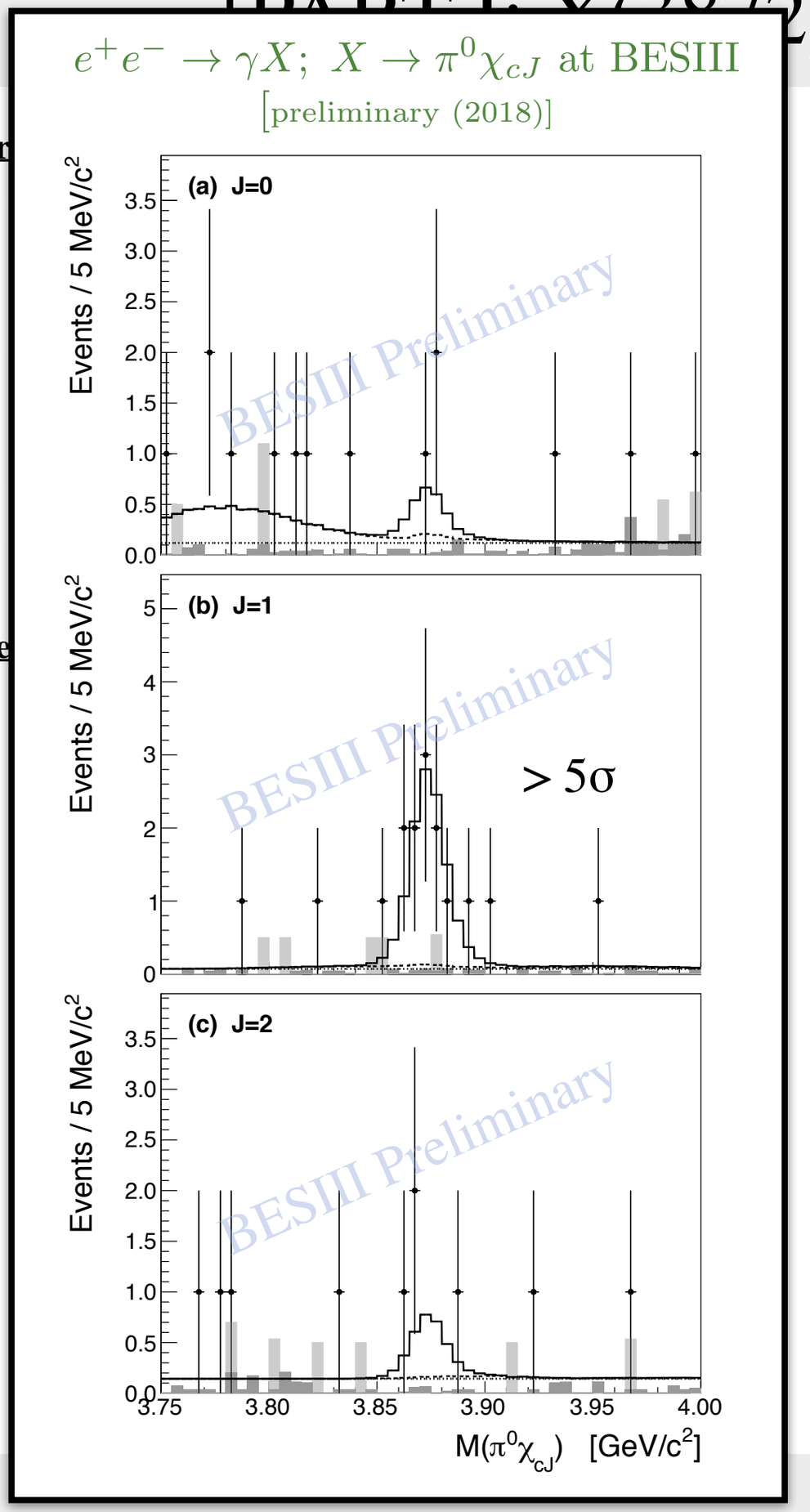


[PART I: X(3872)] Experimental Details



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6.

7.

8.

9.

Production:

10. It is produced in B decays.
11. It is produced in hadron collisions.

$$\frac{\sigma(pp\to X\ +\ \text{anything})\times B(X\to\pi^+\pi^- J/\psi)}{\sigma(pp\to\psi(2S)\ +\ \text{anything})\times B(\psi(2S)\to\pi^+\pi^- J/\psi)}$$

$$= 0.0656 \pm 0.0029 \pm 0.0065 \quad \text{(CMS)}$$

12. It's produced in $e^+e^- \to \gamma X(3872)$, maybe through the Y(4260).
13. It might be produced in photoproduction.

NEW:

$R_J = B(X \to \pi^0\chi_{cJ}) / B(X \to \pi^+\pi^- J/\psi)$:

$R_0 < 19$ (90% U.L.)

$R_1 = 0.88^{+0.31}_{-0.26} \pm 0.14$

$R_2 < 1.0$ (90% U.L.)

c.f. Dubynskiy, Voloshin, PRD 77, 014013 (2008)

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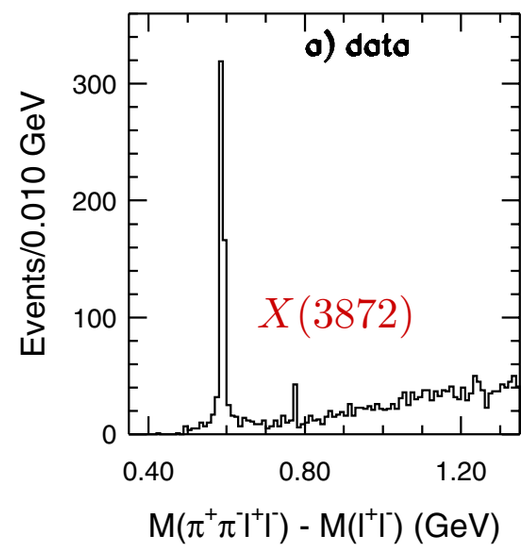
PRL91,262001 (2003)



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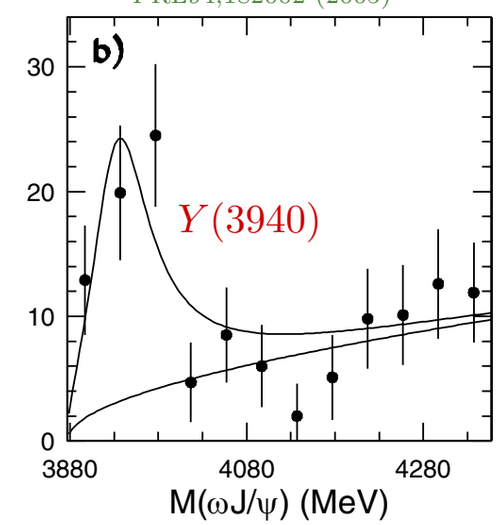

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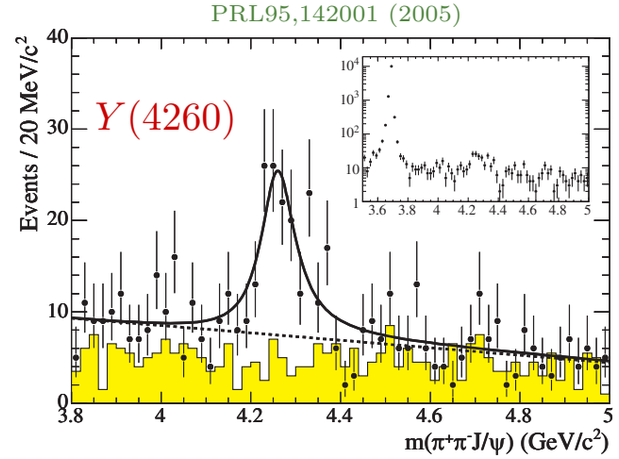

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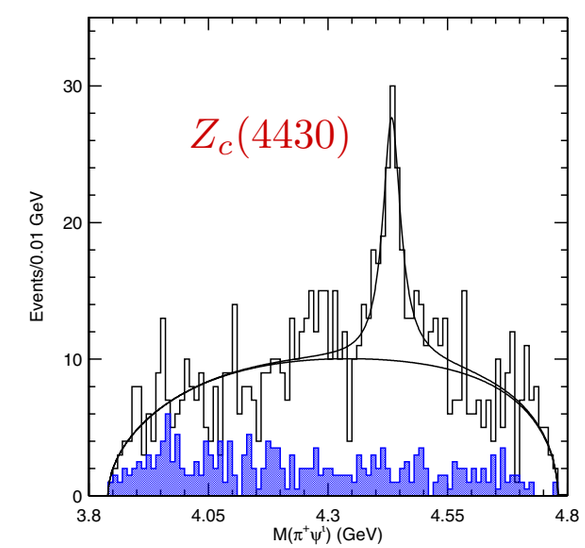
PRL100,142001 (2008)



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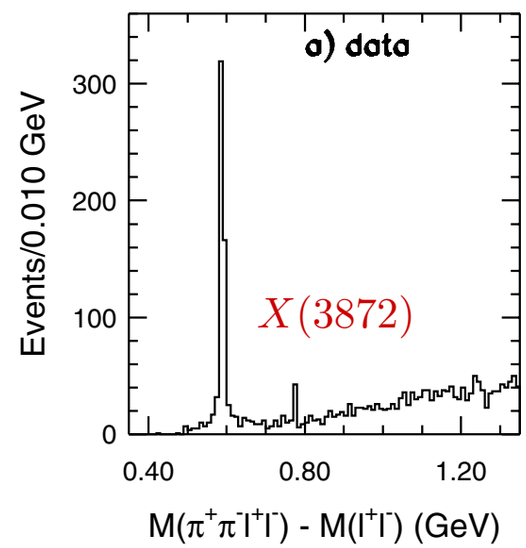

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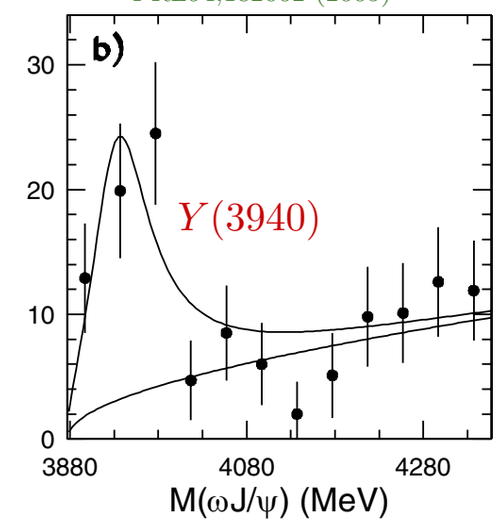

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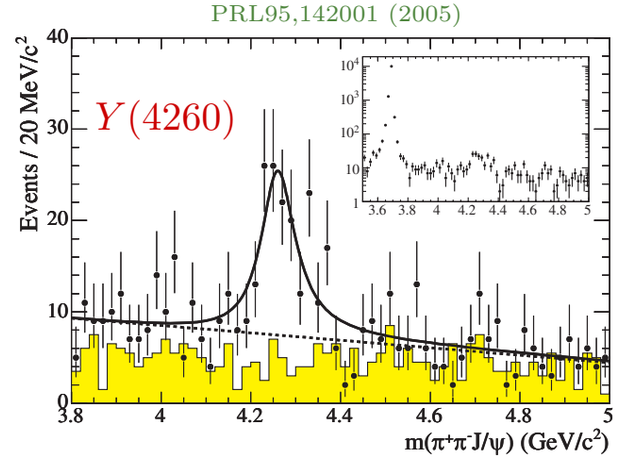

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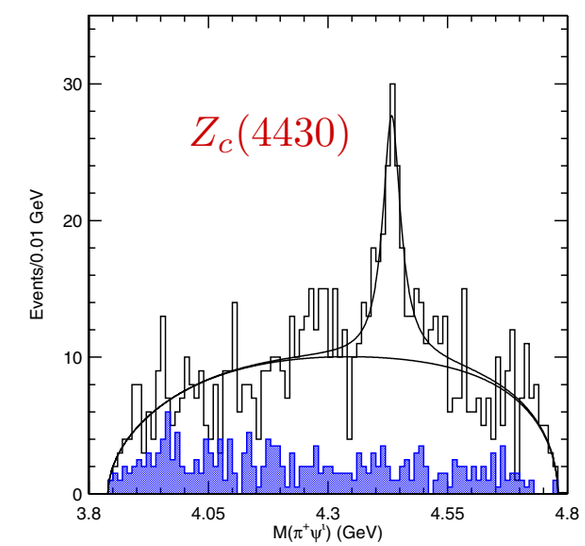
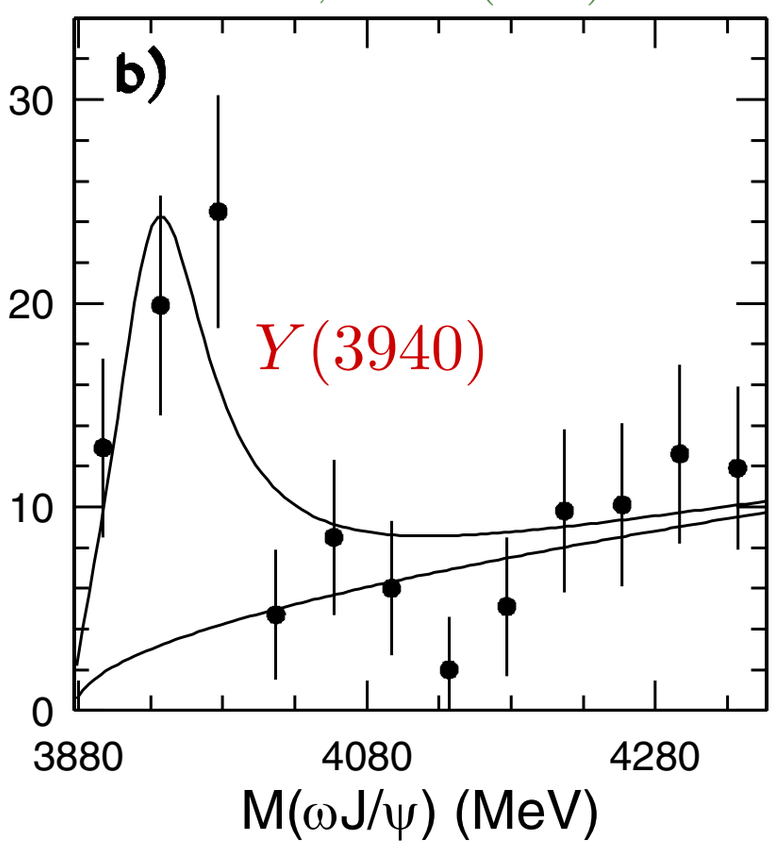


[PART II: Y(3940)] What happened?

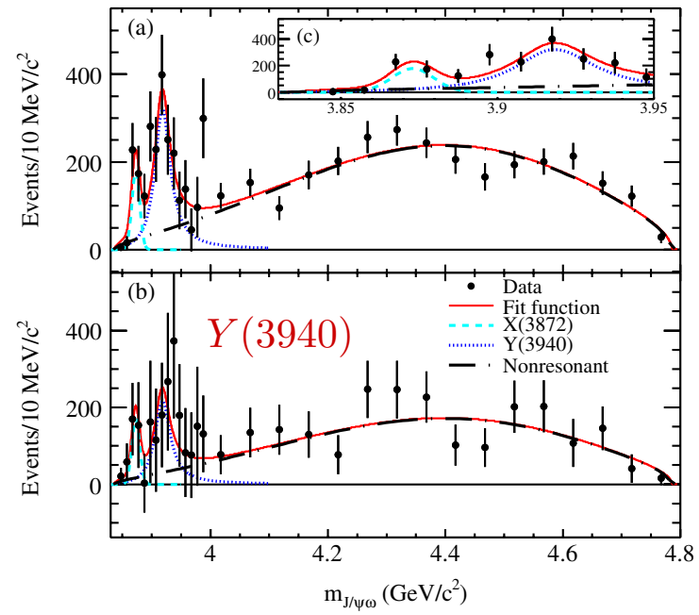
$B \to KX; X \to \omega J/\psi$ at Belle

PRL94,182002 (2005)



$B \to KX; X \to \omega J/\psi$ at BaBar

PRD82,011101 (2010)

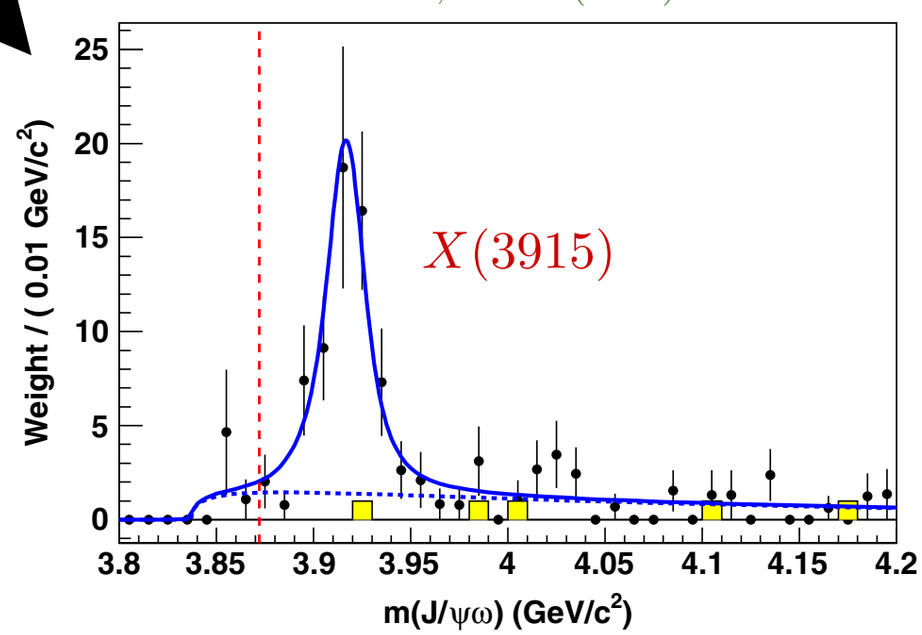


It was confirmed.

Its mass shifted to ~3915 MeV/c².

$\gamma\gamma \to X; X \to \omega J/\psi$ at BaBar

PRD86,072002 (2012)

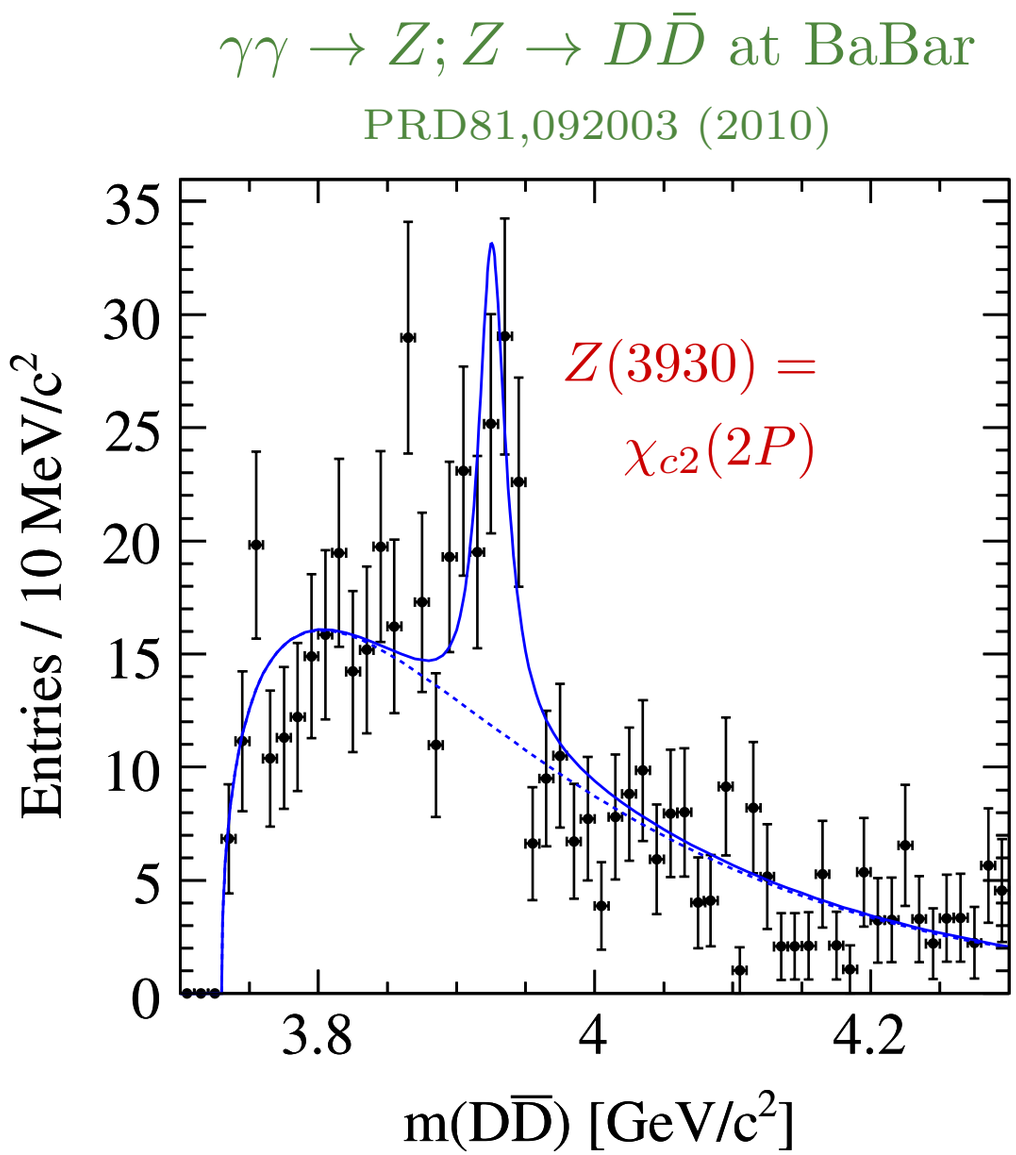


It was found in γγ collisions with $J^{PC} = 0^{++}$

Its name changed to X(3915).

Does X(3915) = $\chi_{c0}(2P)$??

[PART II: Y(3940)] Where is the $\chi_{c0}(2P)$?



Studies of $\gamma\gamma \to DD$ show the $\chi_{c2}(2P)$, but where is the $\chi_{c0}(2P)$?

Problems with X(3915)/Y(3940) = $\chi_{c0}(2P)$:

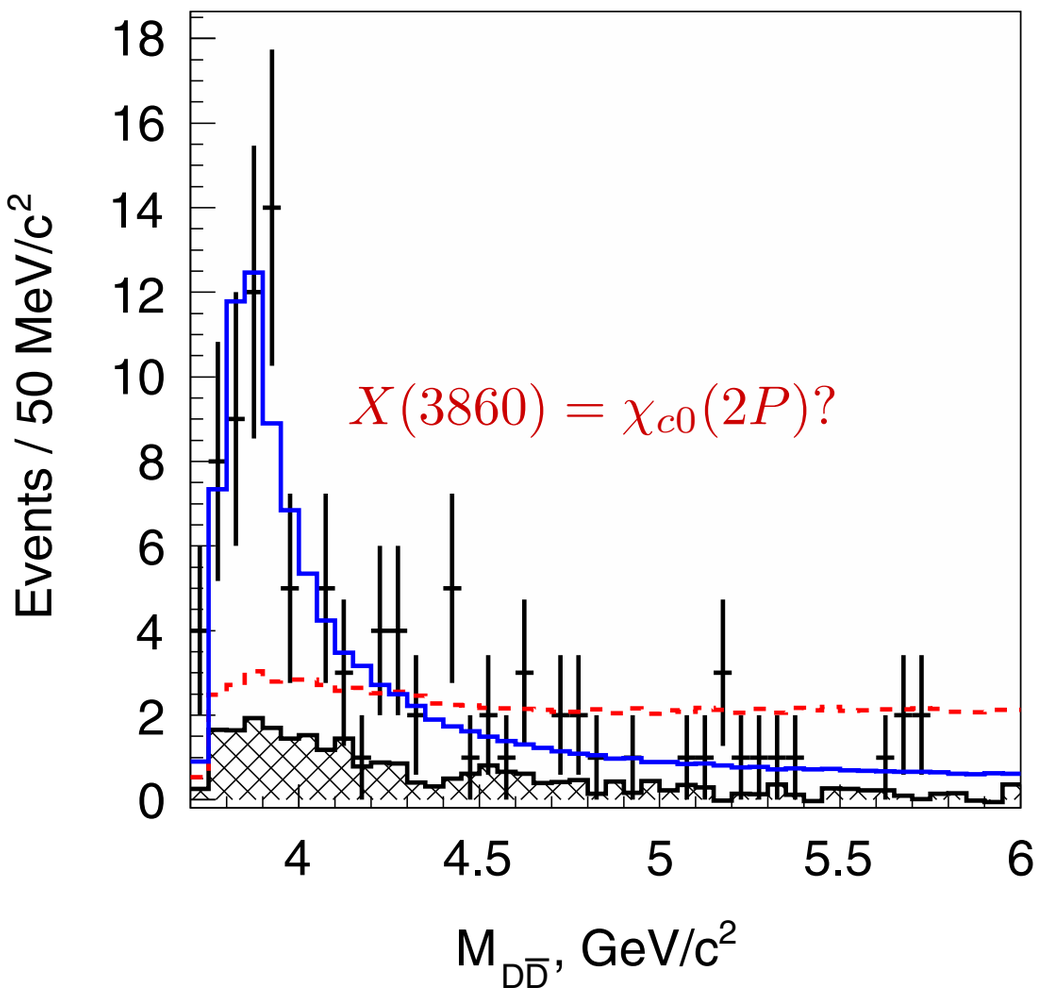
* why isn't it in DD?
* why is the $\chi_{c0}(2P)/\chi_{c2}(2P)$ mass splitting so small?

Possible partial solution:
perhaps the $\chi_{c0}(2P)$ is broad.

[PART II: Y(3940)] Where is the $\chi_{c0}(2P)$?

$e^+e^- \to J/\psi X;\ X \to D\bar{D}$ at Belle

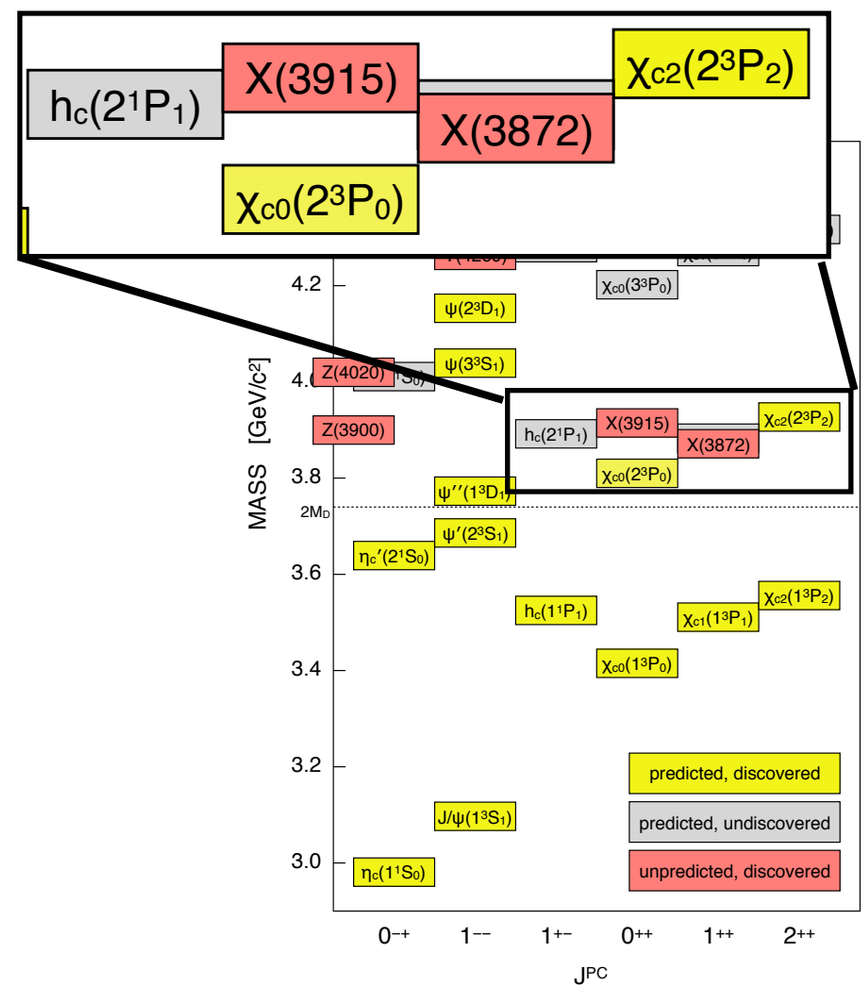
PRD 95, 112003 (2017)



Candidate $\chi_{c0}(2P)$ found in $e^+e^- \to J/\psi(DD)$ [0^{++} favored].

Mass and width makes sense.

But then **what is the X(3915)**/Y(3940)??



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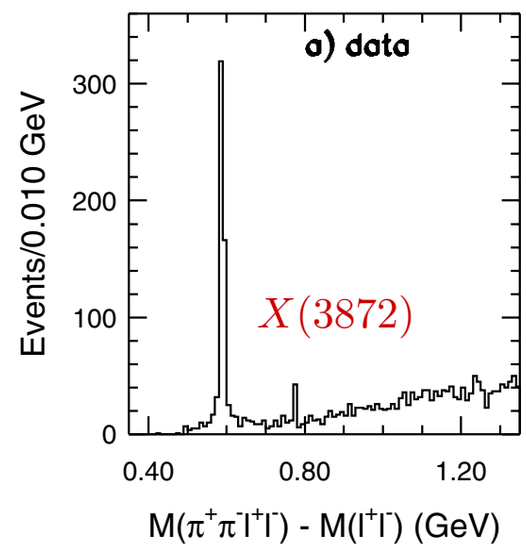

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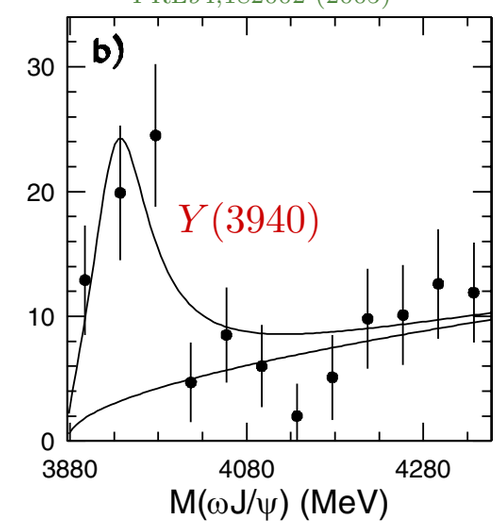

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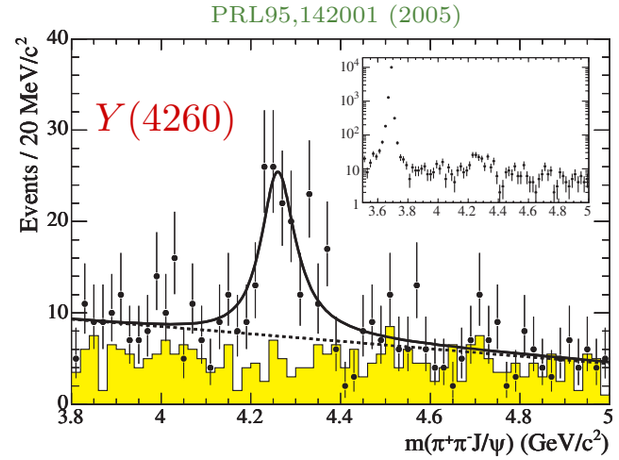
PRL95,142001 (2005)



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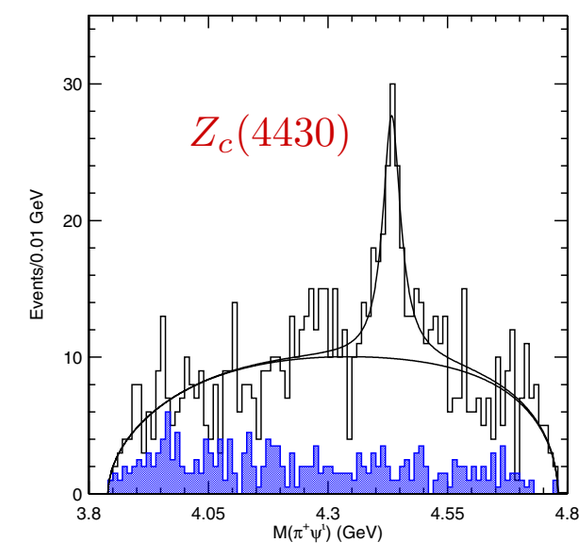
PRL100,142001 (2008)



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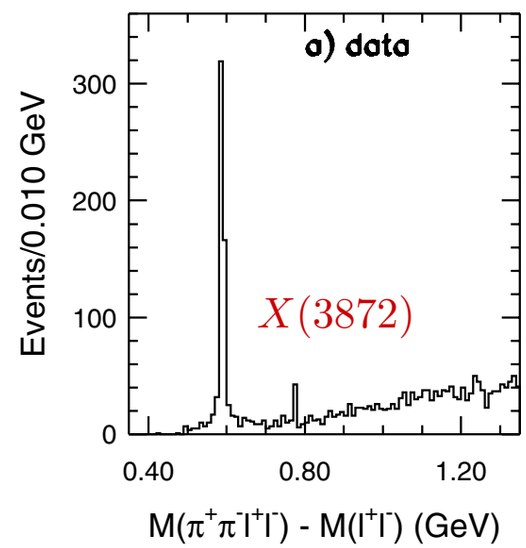

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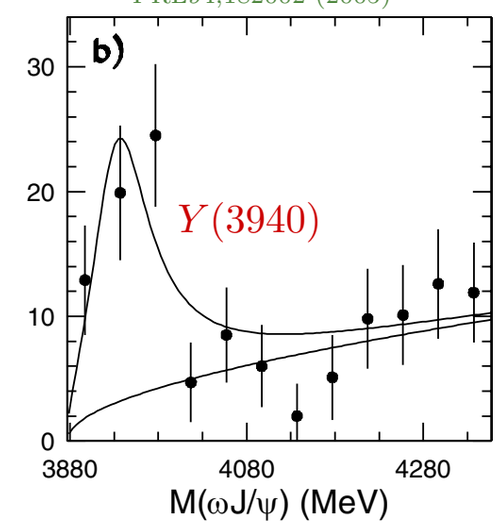

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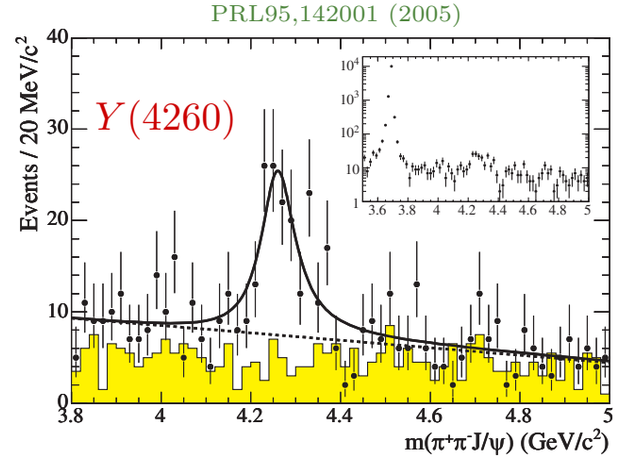

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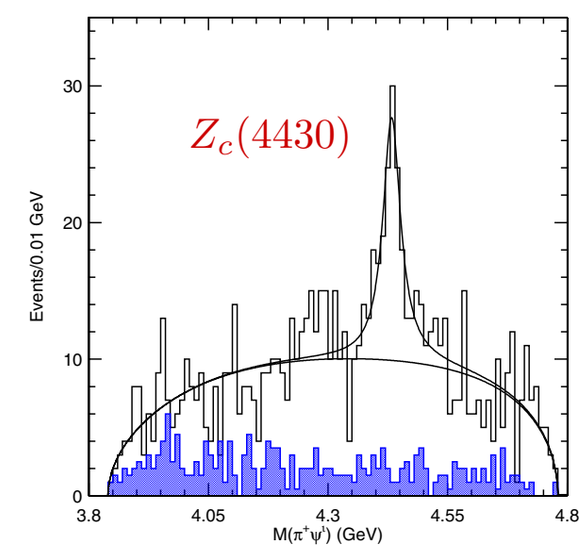
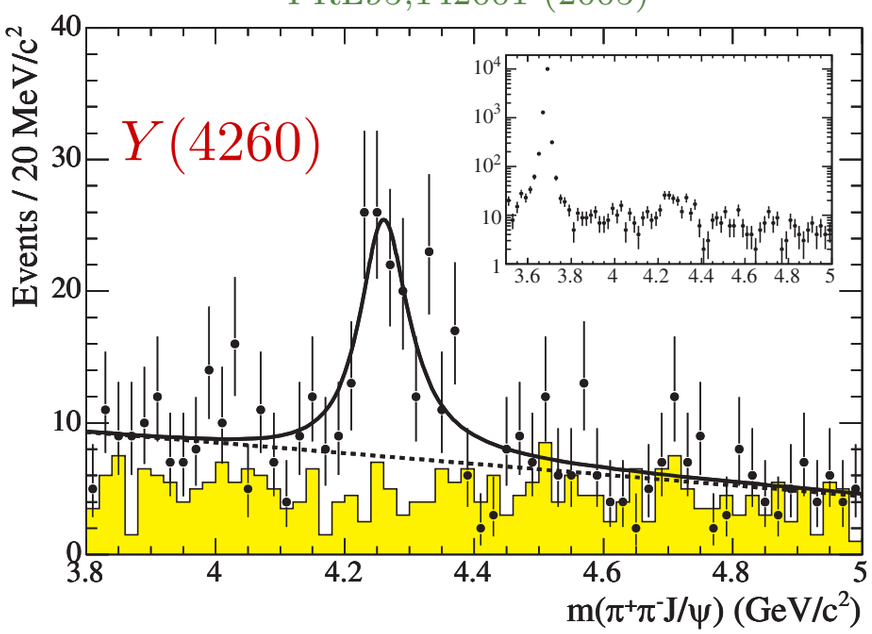


[PART III: Y(4260)] What happened?

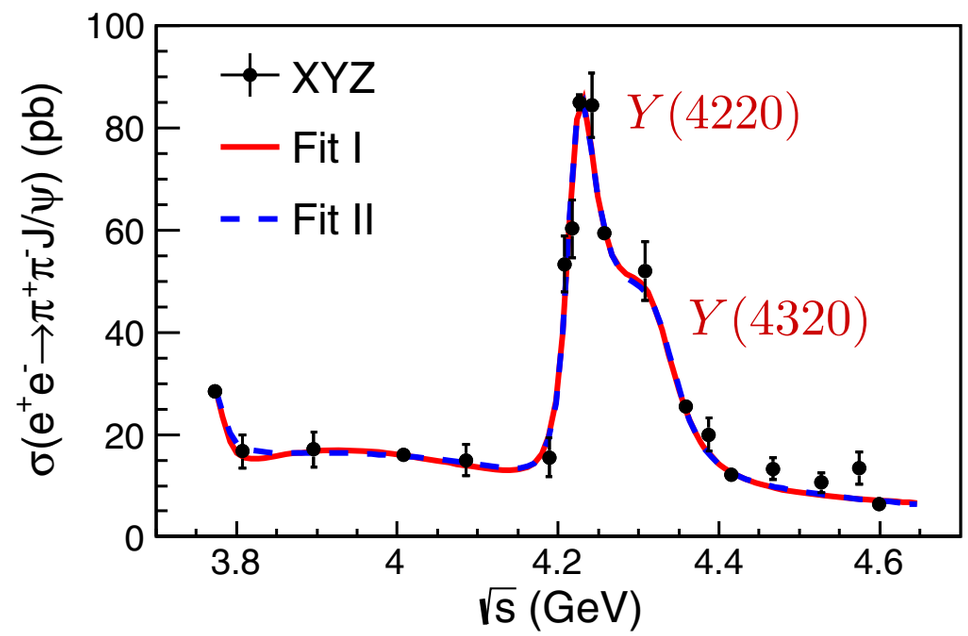
$e^+e^- \to Y; Y \to \pi^+\pi^- J/\psi$ at BaBar

PRL95,142001 (2005)



$e^+e^- \to Y; Y \to \pi^+\pi^- J/\psi$ at BESIII

PRL118,092001 (2017)



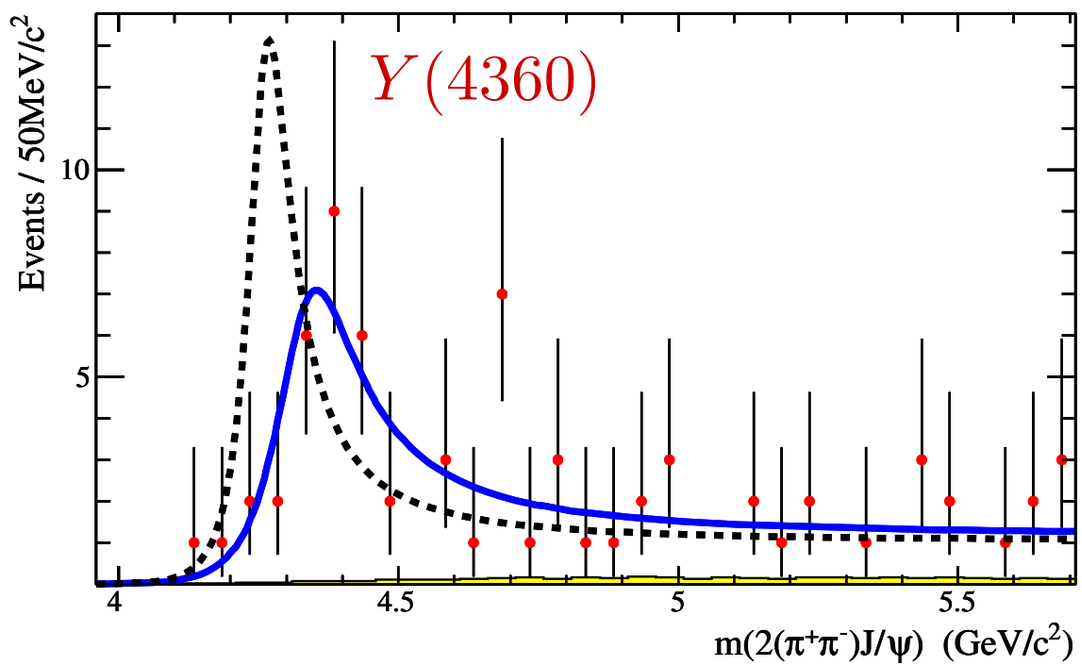
The Y(4260) is not a simple peak.

Important Note: Old and new data are consistent!!

[PART III: Y(4260)] Peaks in e⁺e⁻ cross sections ("Y")

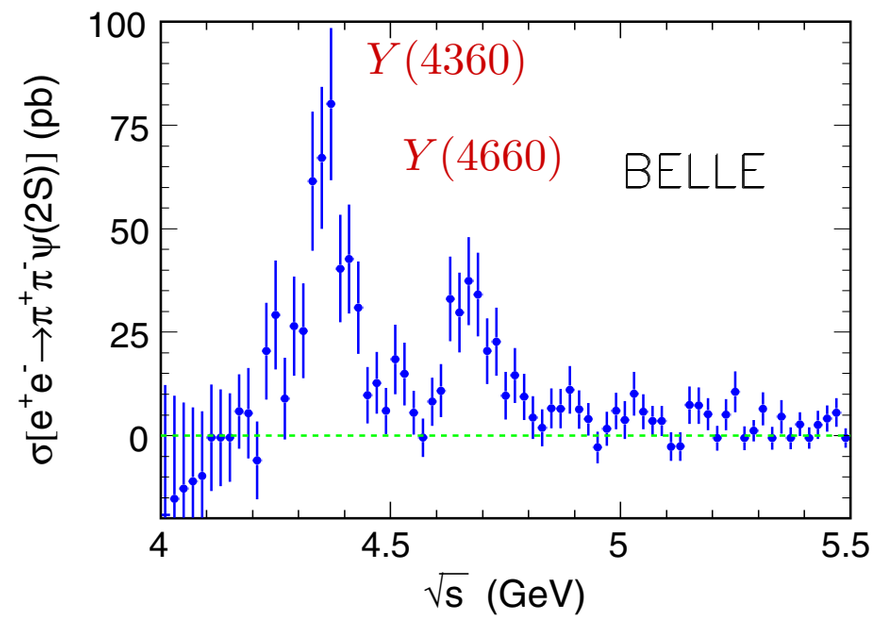
$e^+e^- \to Y; Y \to \pi^+\pi^-\psi(2S)$ at BaBar

PRL98,212001 (2007)



$e^+e^- \to Y; Y \to \pi^+\pi^-\psi(2S)$ at Belle

PRD91,112007 (2015)



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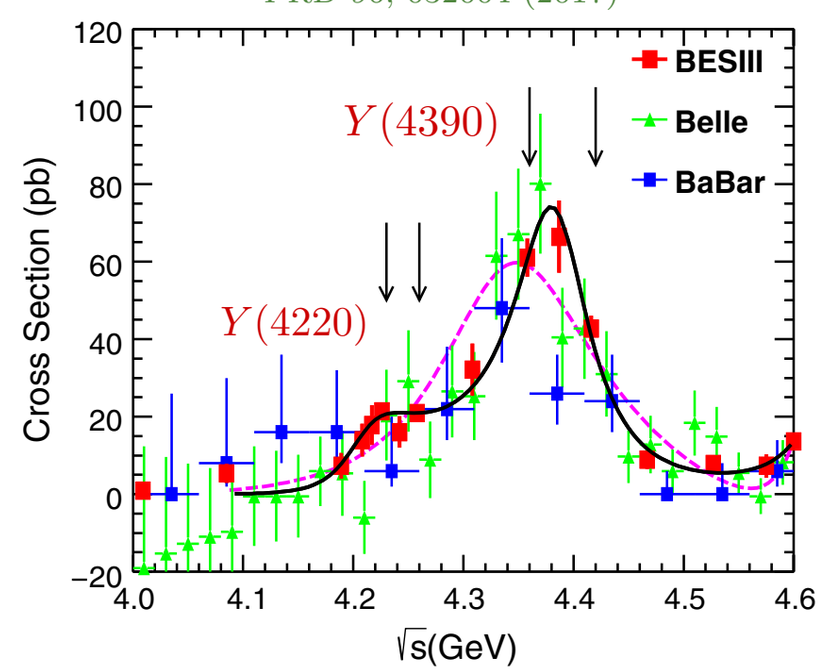
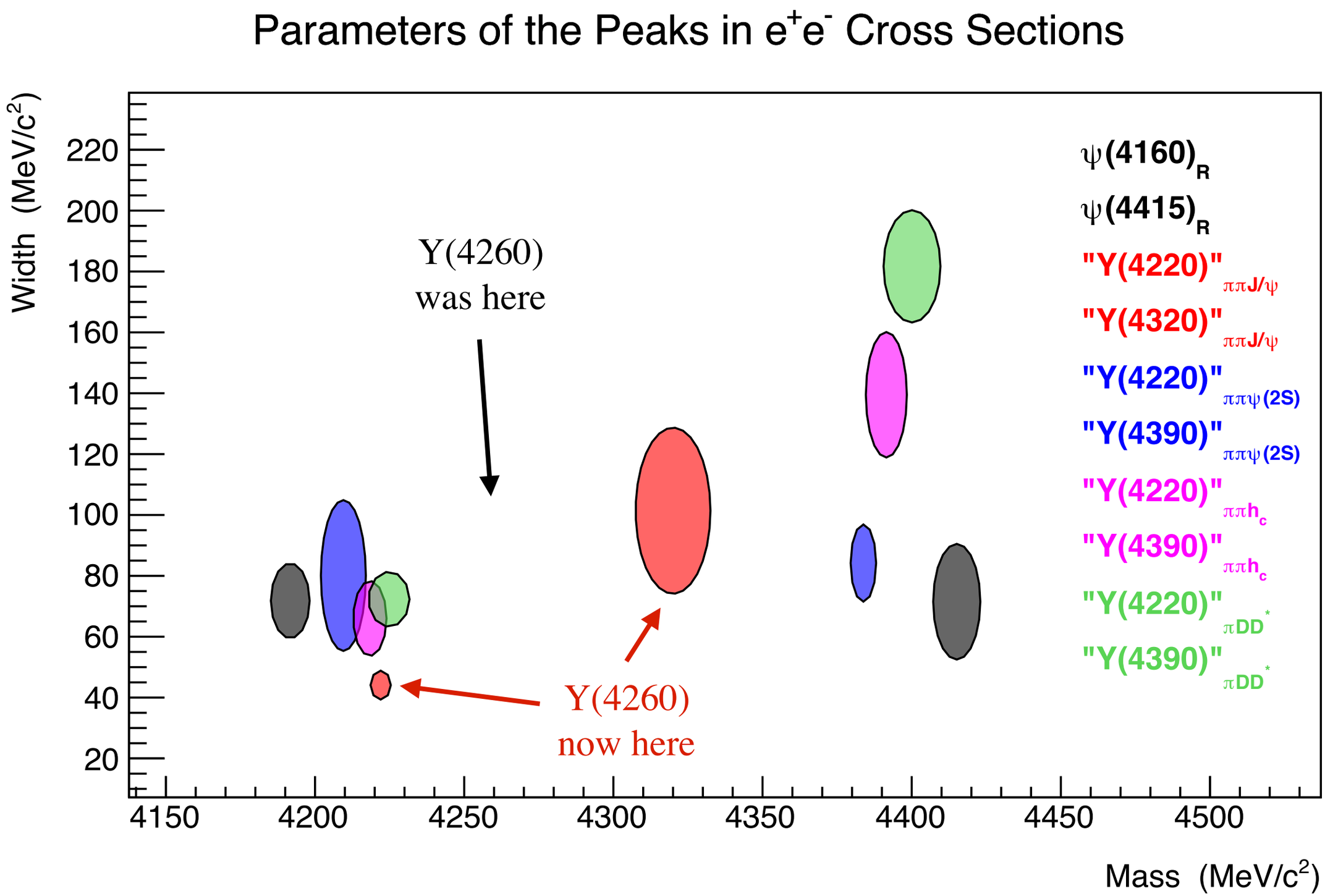
PRD 96, 032004 (2017)



The Y(4360) is not a simple peak.

[PART III: Y(4260)] Peaks in e^+e^- cross sections ("Y")

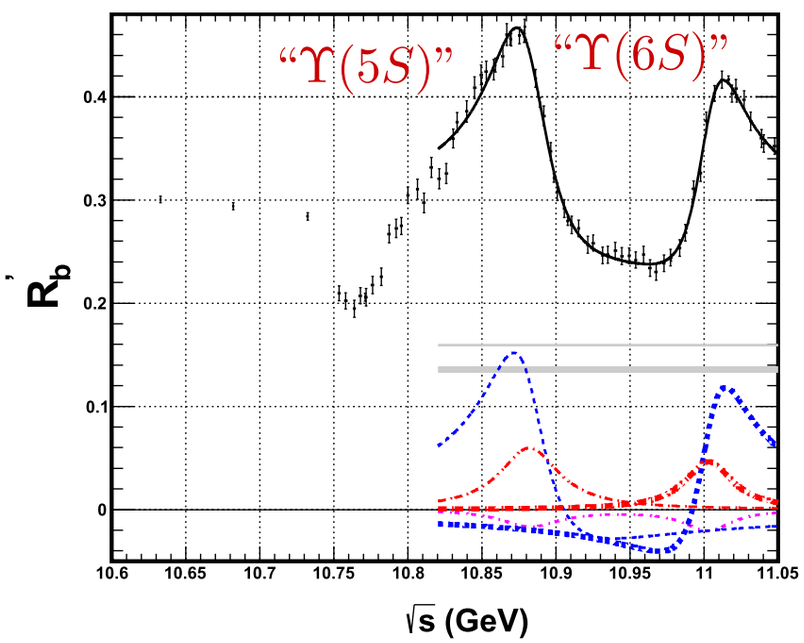


Important Note: Masses and widths (and numbers of peaks) depend on parametrization!! A global analysis is needed.

[PART III: Y(4260)] Peaks in e⁺e⁻ cross sections ("Y")

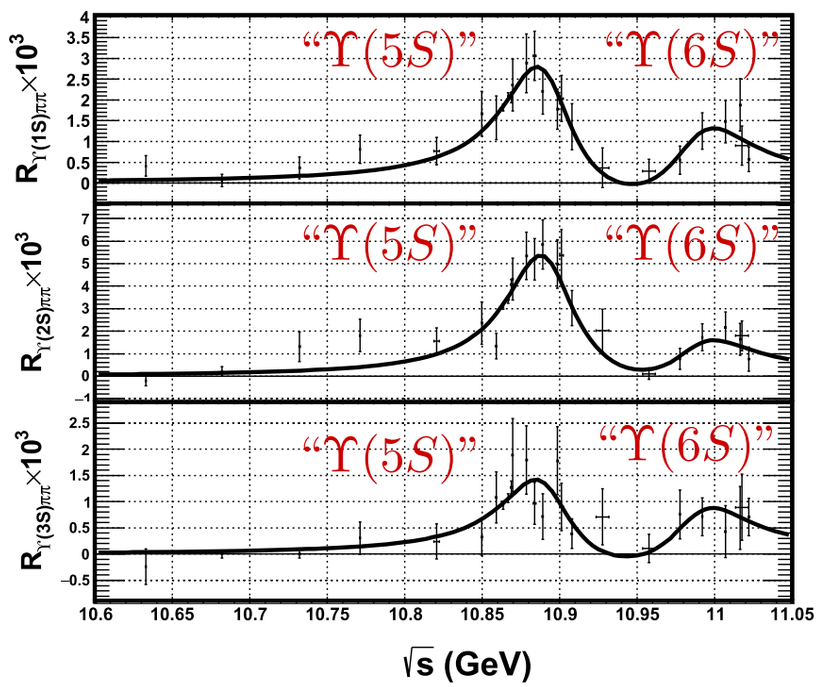
$e^+e^- \to$ Hadrons at Belle

PRD93,011101 (2016)



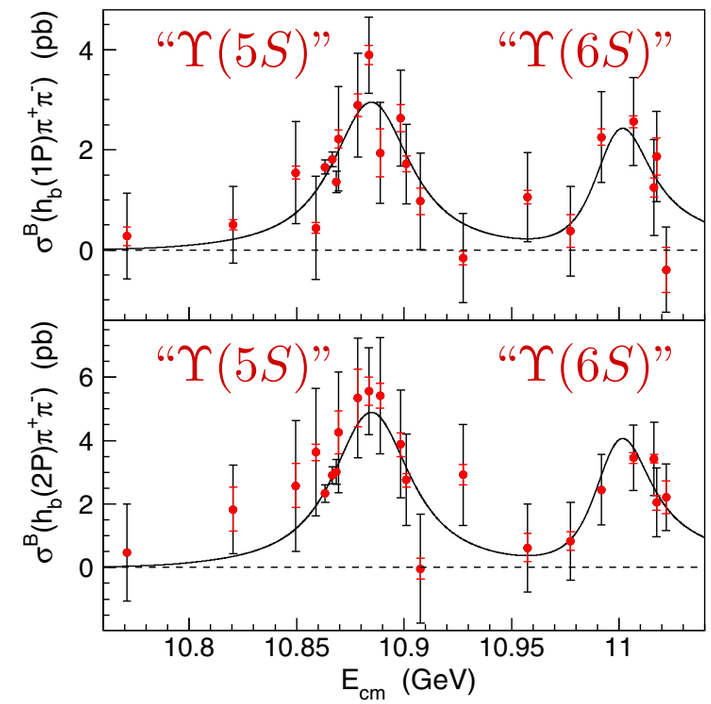
$e^+e^- \to \pi^+\pi^-\Upsilon(1S, 2S, 3S)$ at Belle

PRD93,011101 (2016)



$e^+e^- \to \pi^+\pi^- h_b(1P, 2P)$ at Belle

PRL117,142001 (2016)

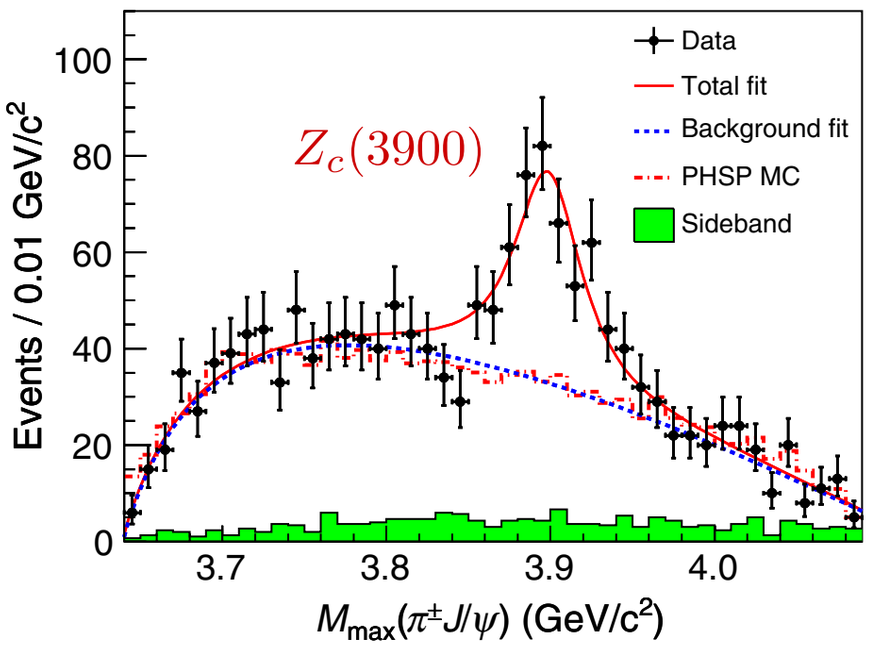


The e⁺e⁻ cross sections above open-bottom threshold are more orderly.

[PART III: Y(4260)] Peaks in "Y" decays ("Z_c")

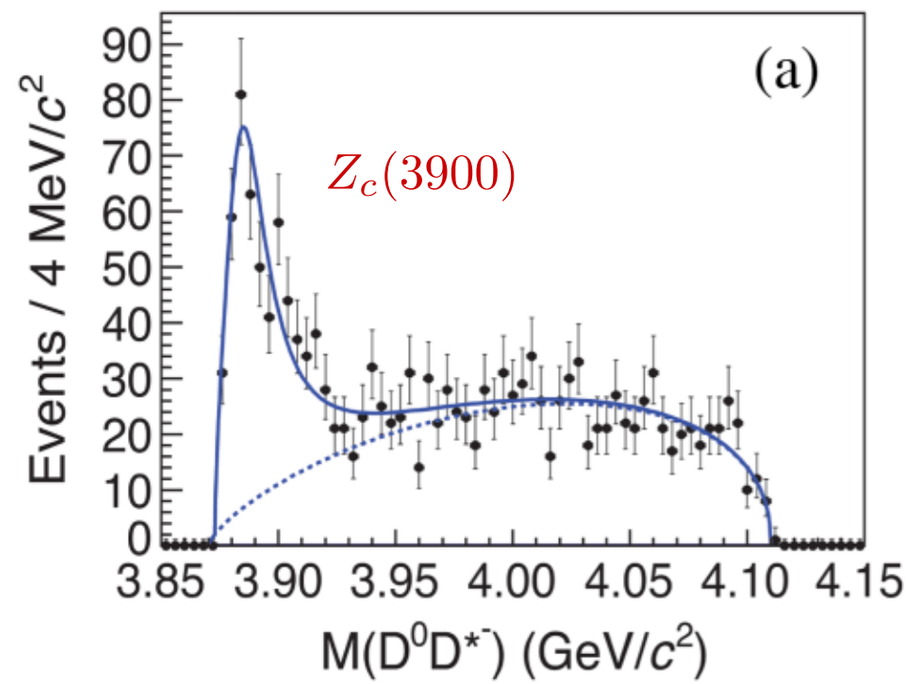
$e^+e^- \to \pi^\pm Z; Z \to \pi^\mp J/\psi$ at BESIII

PRL110,252001 (2013)



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

PRL112,022001 (2014)



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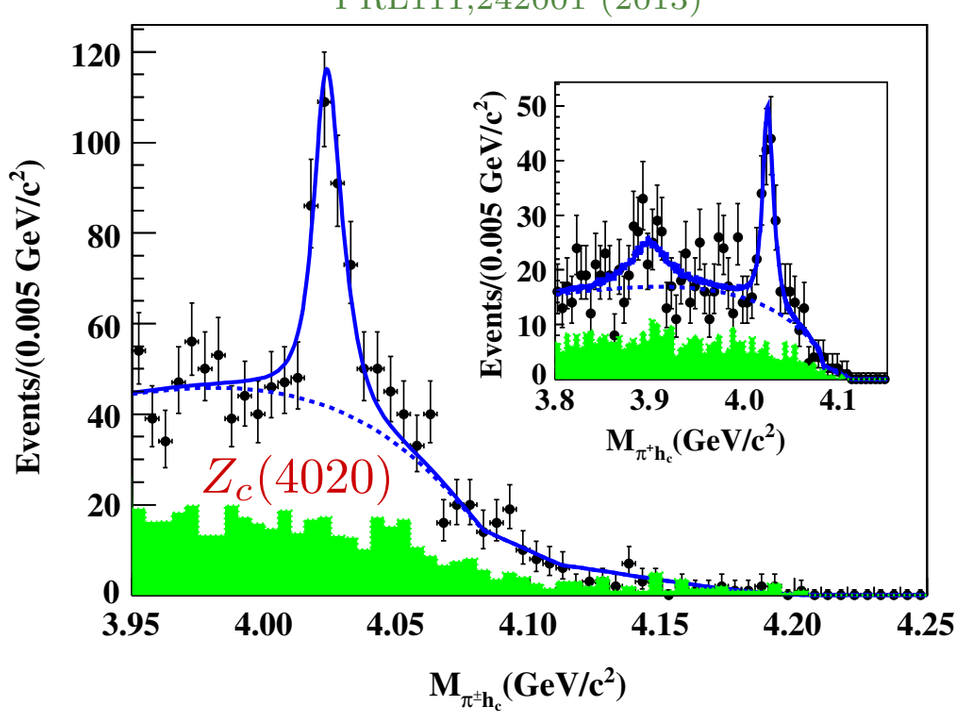
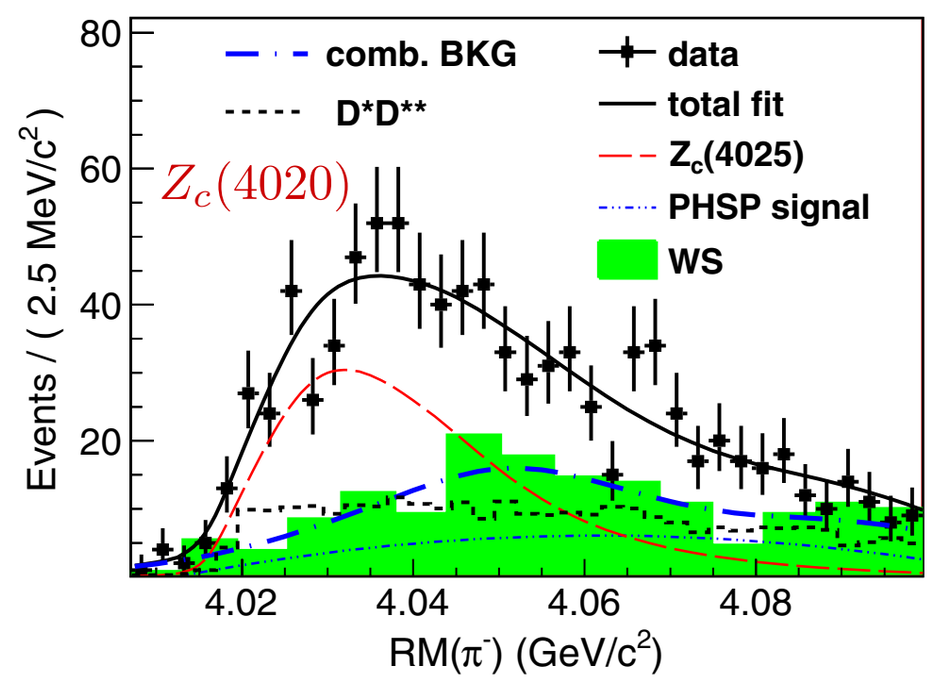
PRL111,242001 (2013)



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

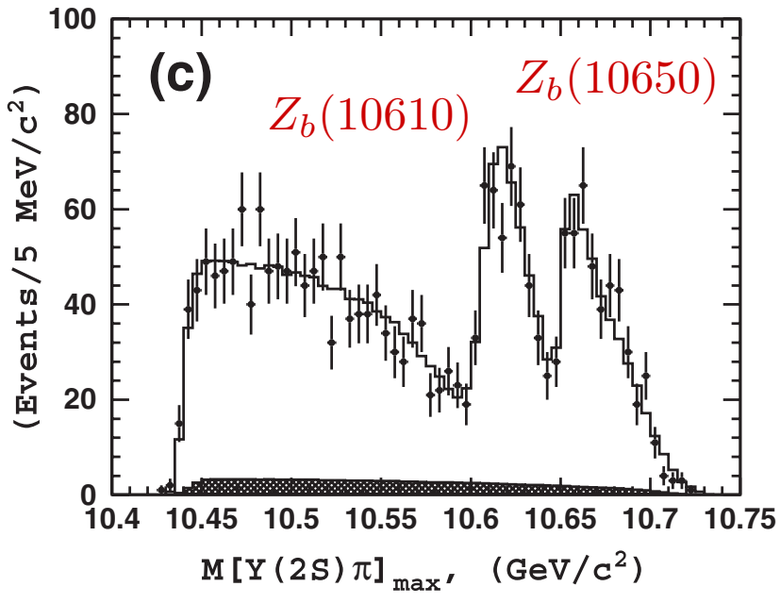
PRL112,132001 (2014)



[PART III: Y(4260)] Peaks in "Y" decays ("Z_b")

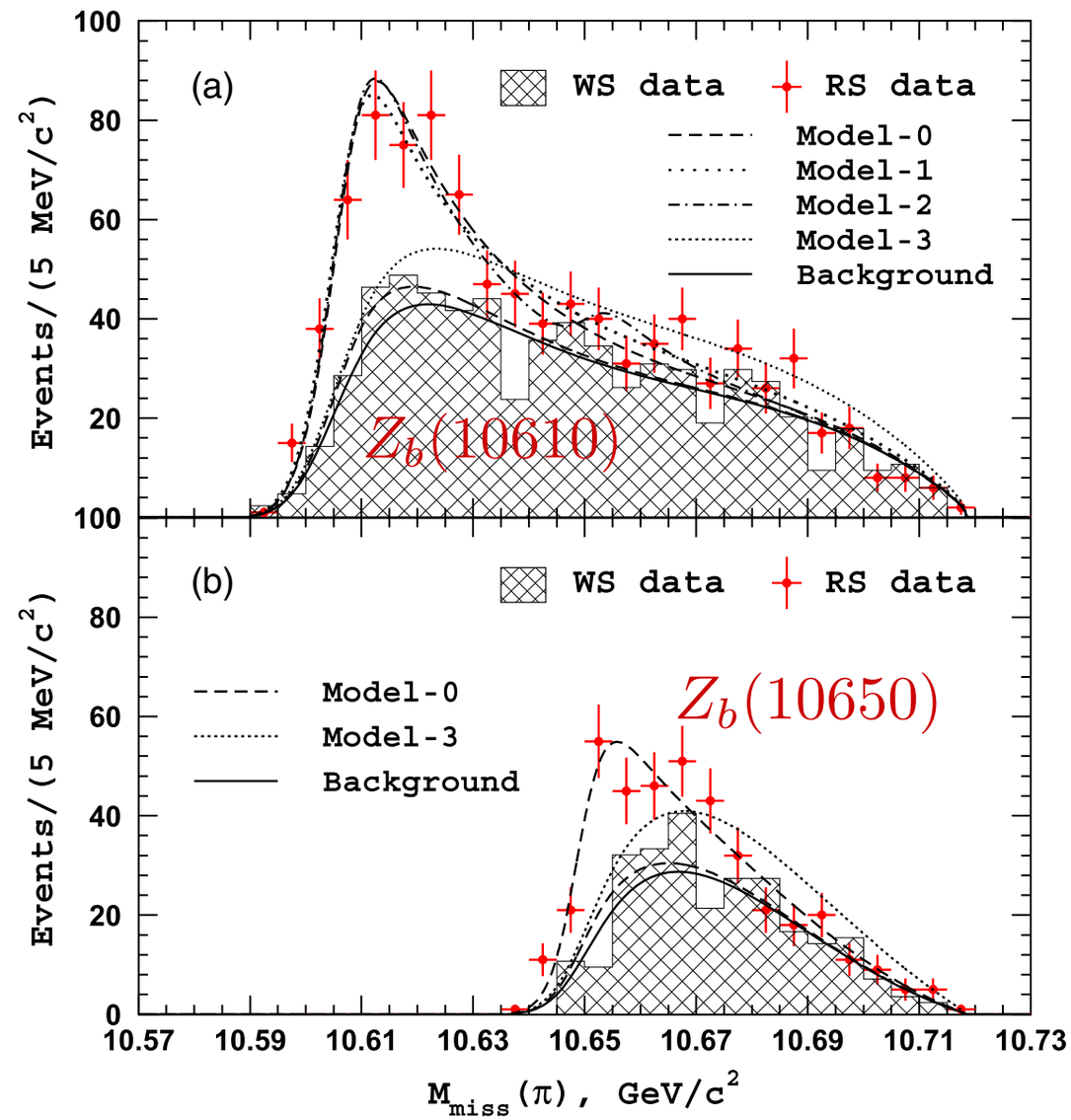
$e^+e^- \to \pi^\pm Z; Z \to \pi^\mp \Upsilon(1S, 2S, 3S)$ at Belle

PRL108,122001 (2012)



$e^+e^- \to \pi^\pm Z; Z \to (B^{(*)}\bar{B}^*)^\mp$ at Belle

PRL116,212001 (2016)



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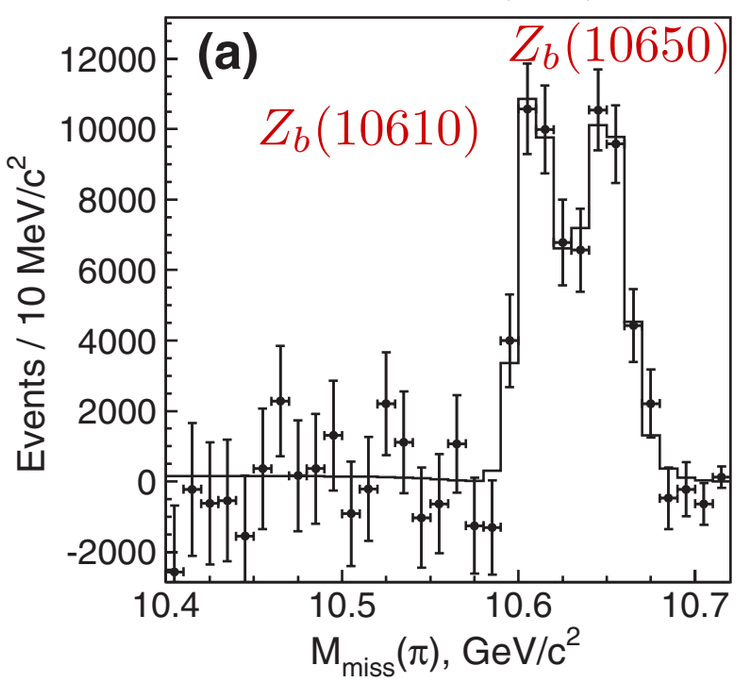
PRL108,122001 (2012)



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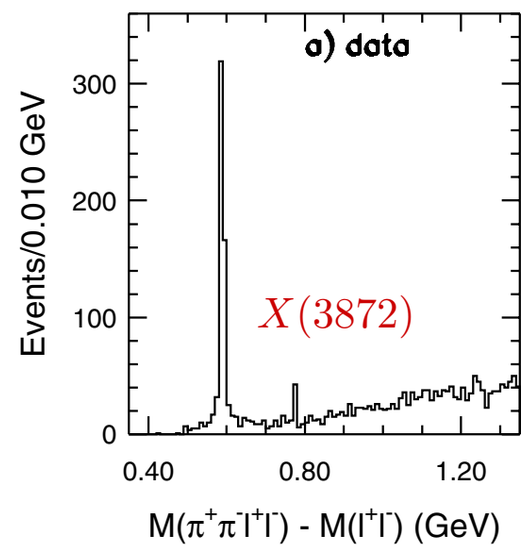

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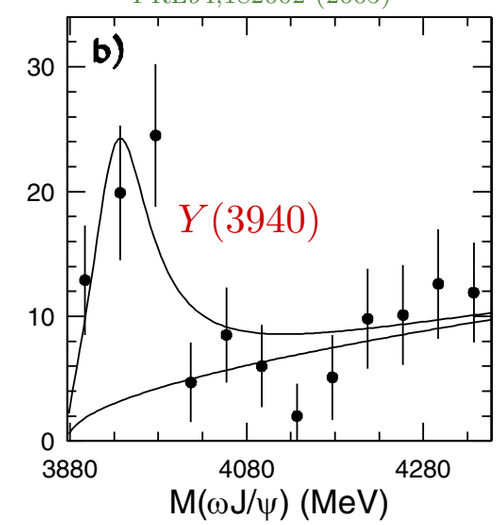
PRL94,182002 (2005)



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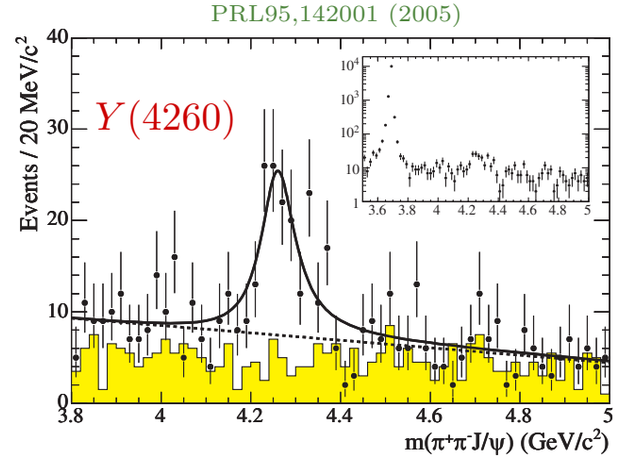

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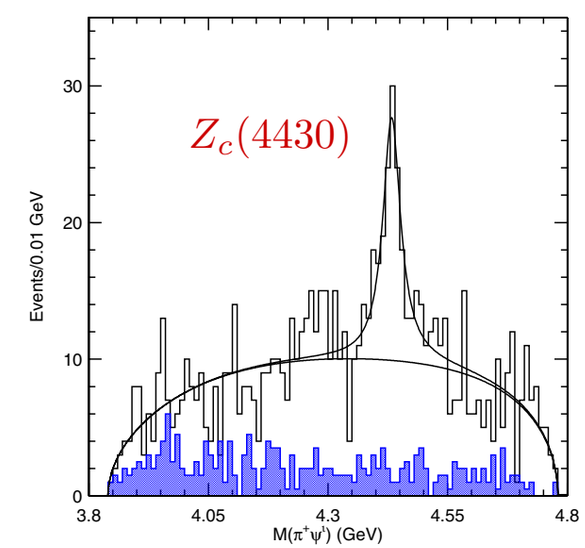

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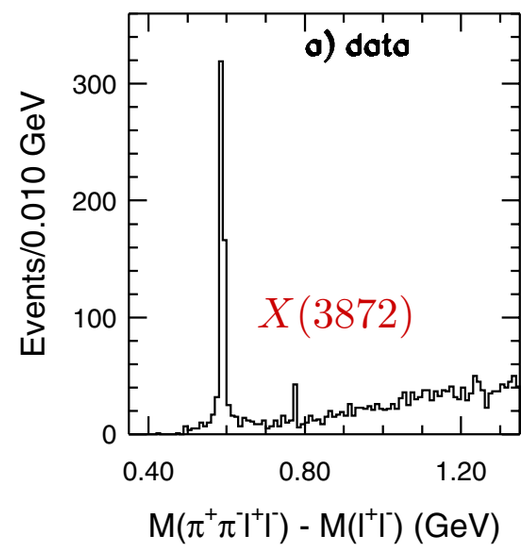

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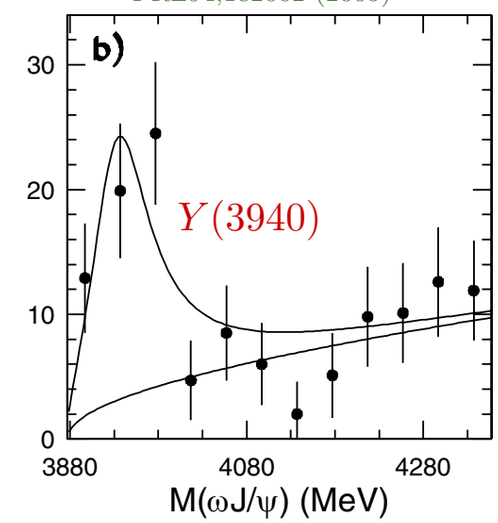

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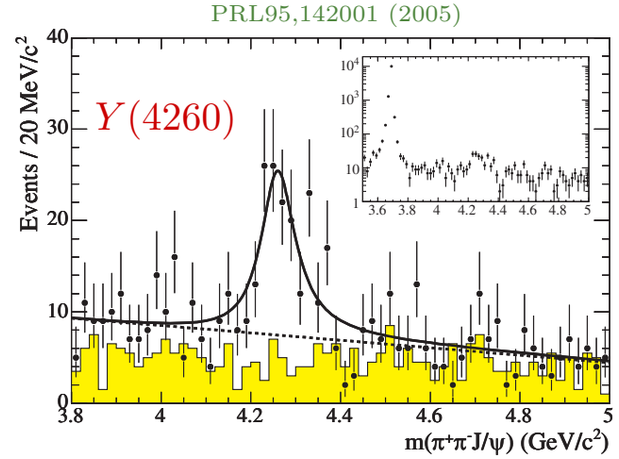

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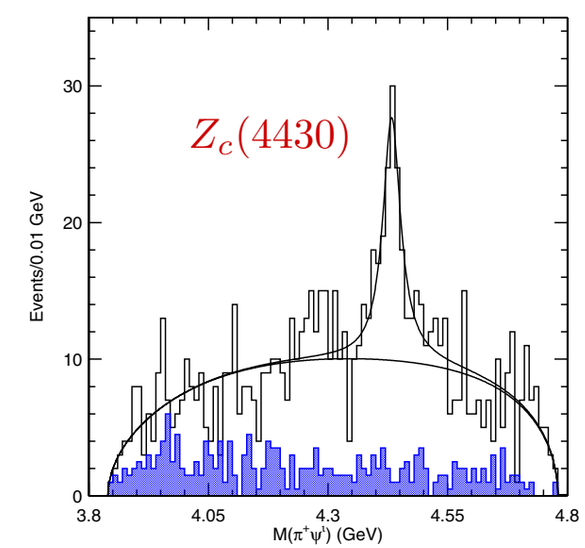
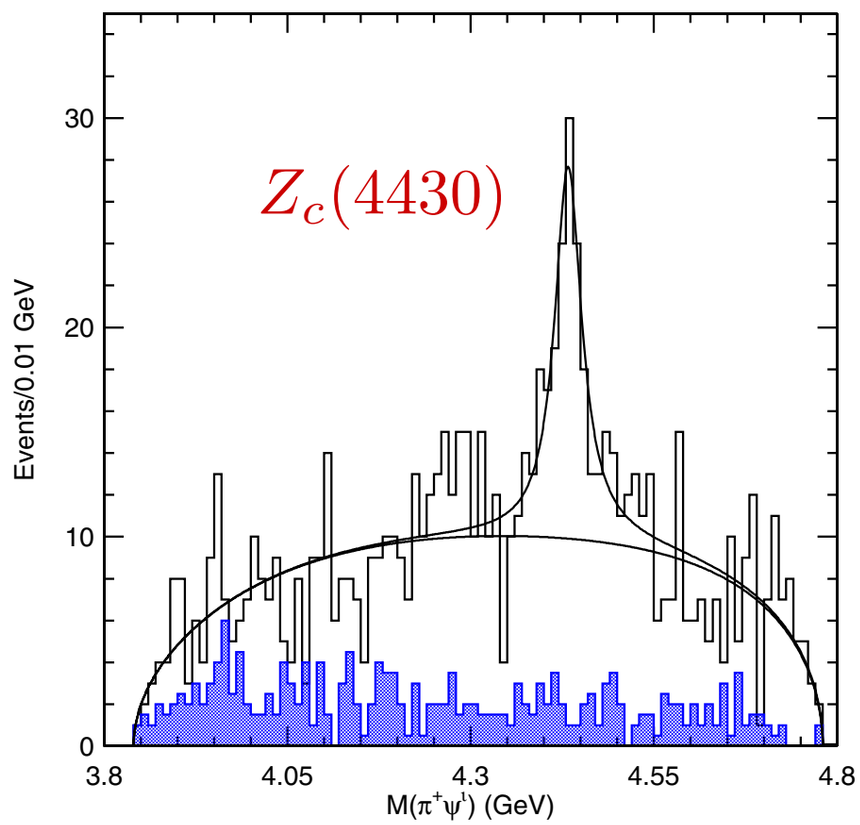


[PART IV: $Z_c(4430)$] What happened?

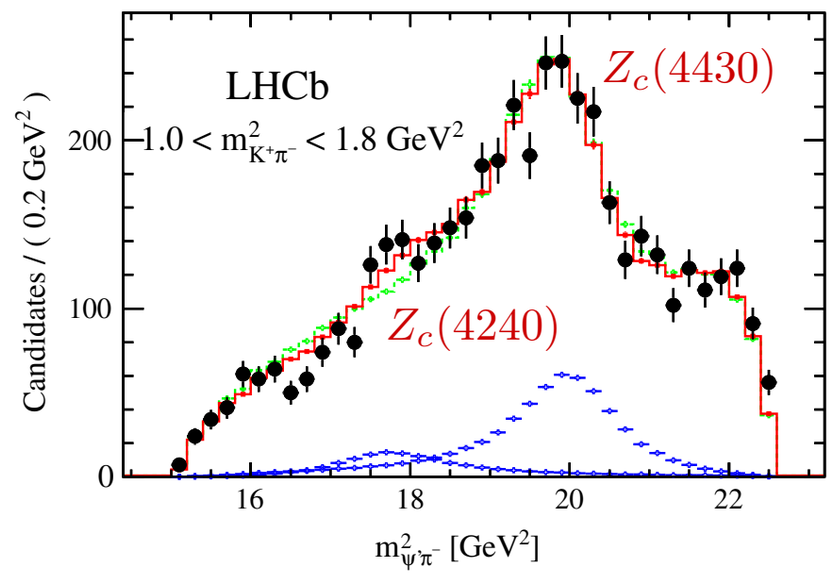
$B \to KZ; Z \to \pi^{\pm}\psi(2S)$ at Belle

PRL100,142001 (2008)



$B \to KZ; Z \to \pi^{\pm}\psi(2S)$ at LHCb

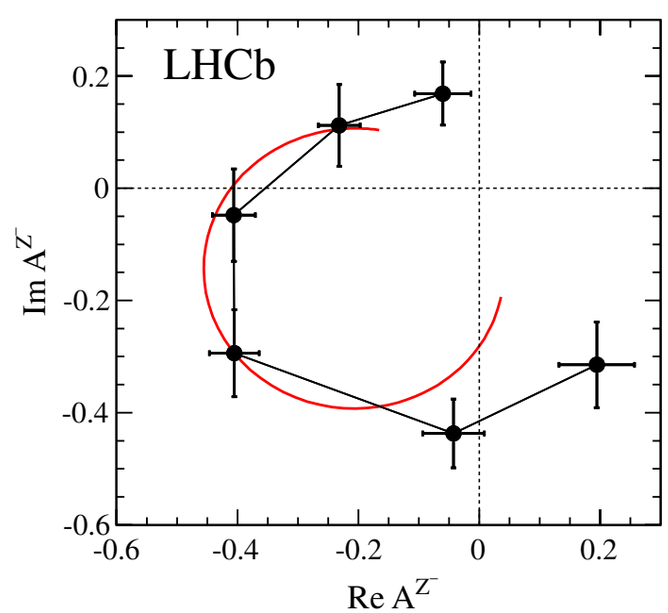
PRL112,222002 (2014)



It was confirmed by LHCb.

$B \to KZ; Z \to \pi^{\pm}\psi(2S)$ at LHCb

PRL112,222002 (2014)

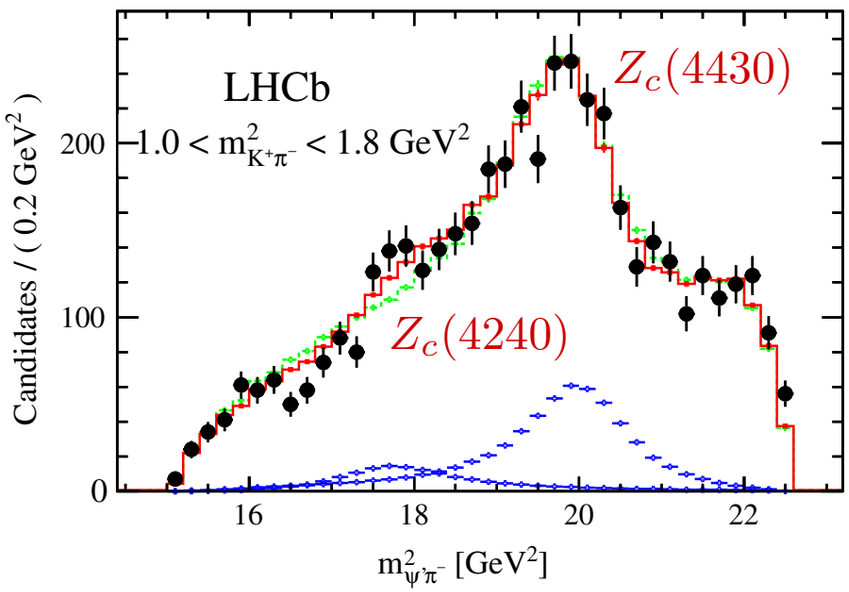


Its phase motion was measured.

[PART IV: $Z_c(4430)$] Peaks in B decays

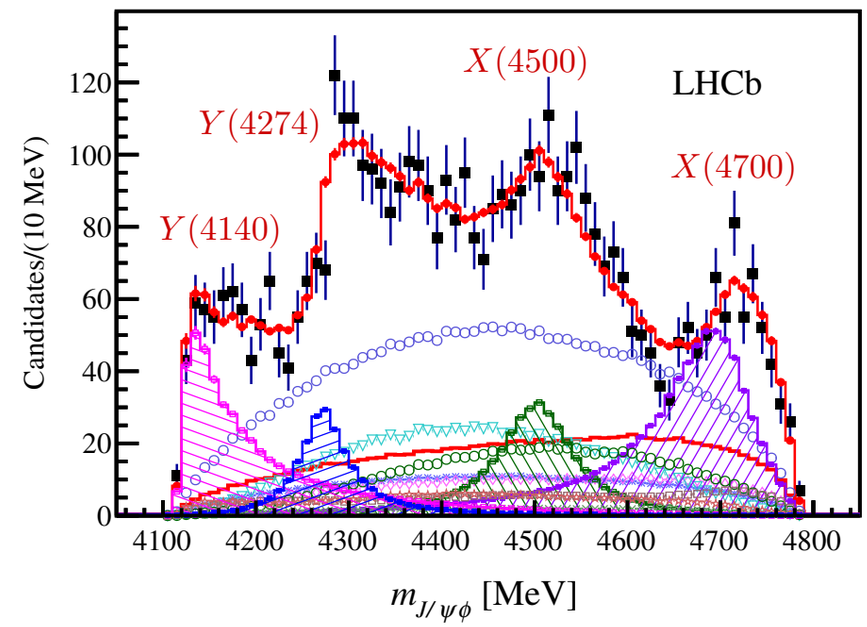
$B \to KZ; Z \to \pi^{\pm}\psi(2S)$ at LHCb

PRL112,222002 (2014)



$B \to KX; X \to \phi J/\psi$ at LHCb

PRL118,022003 (2017)



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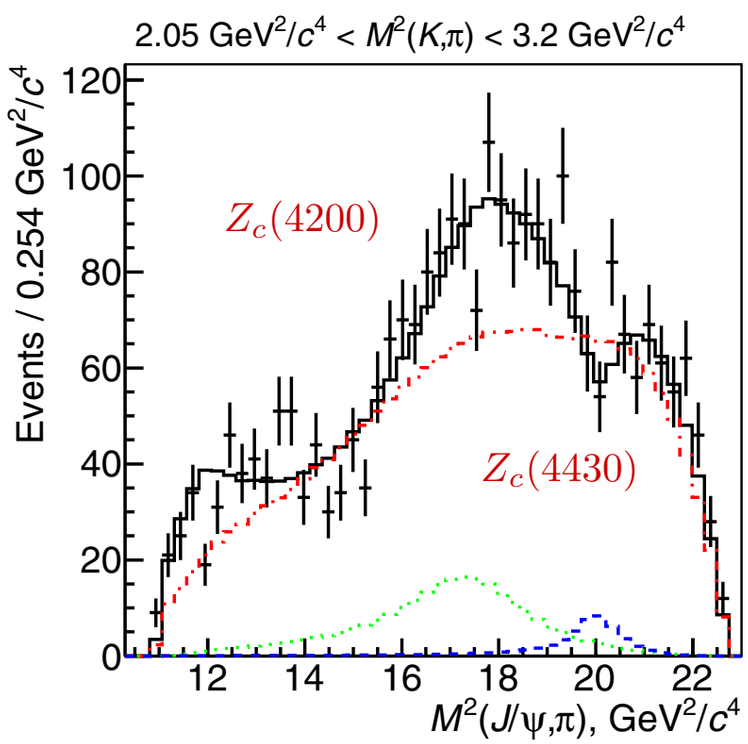
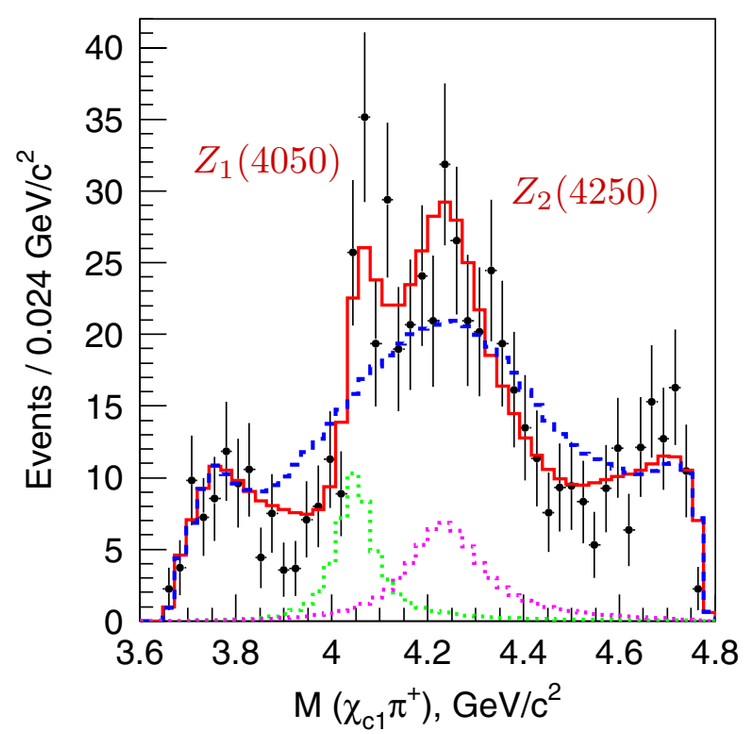
PRD90,112009 (2014)



$B \to KZ; Z \to \pi^{\pm}\chi_{c1}$ at Belle

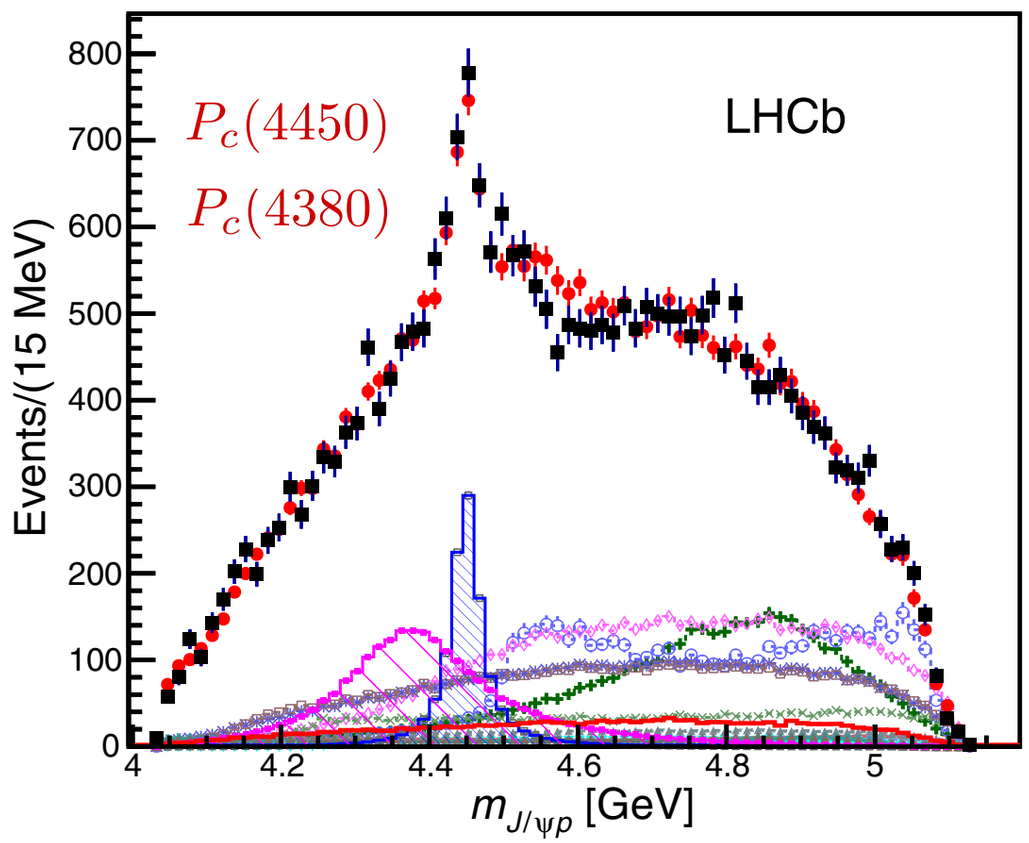
PRD78,072004 (2008)



[PART IV: $Z_c(4430)$] Peaks in Λ_b decays

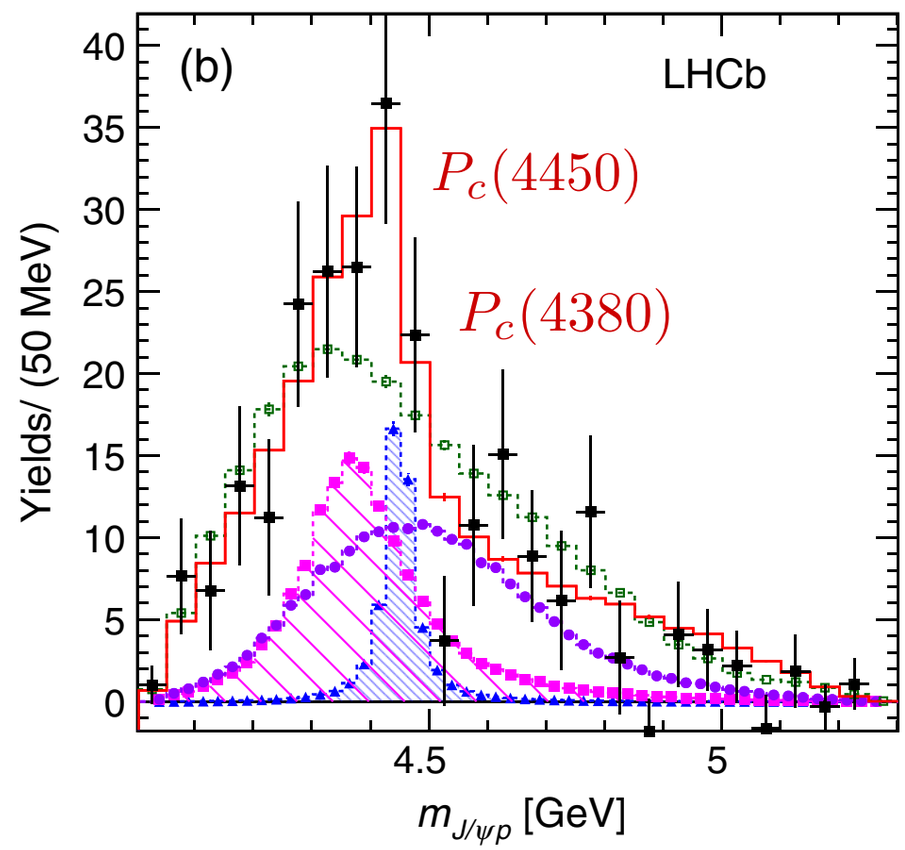
$\Lambda_b \to KP; P \to pJ/\psi$ at LHCb

PRL115,072001 (2015)



$\Lambda_b \to \pi P;\ P \to pJ/\psi$ at LHCb

PRL 117, 082003 (2016)



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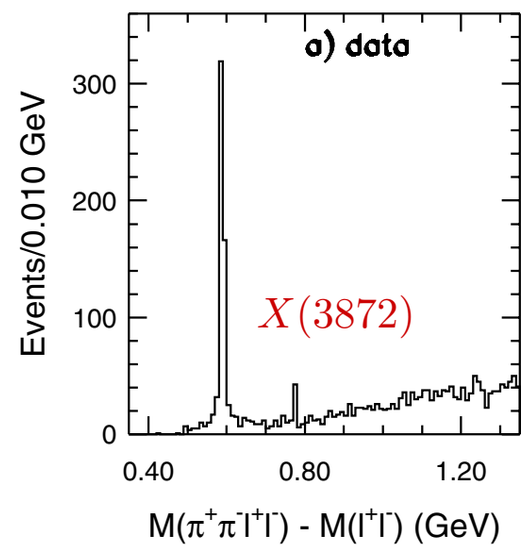

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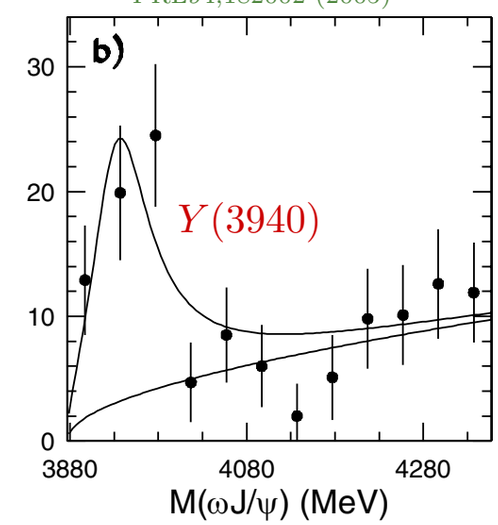

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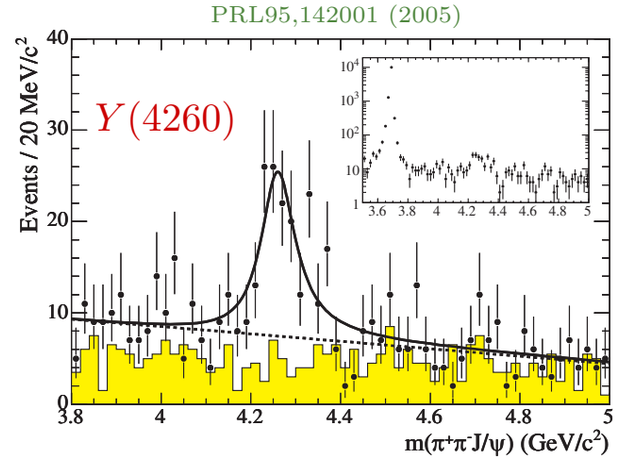

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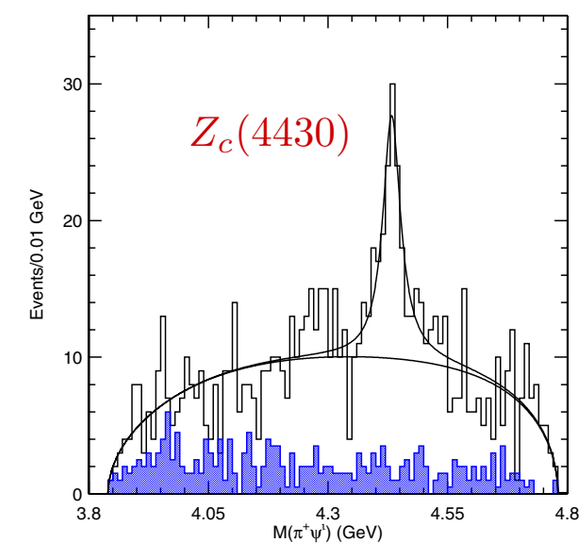

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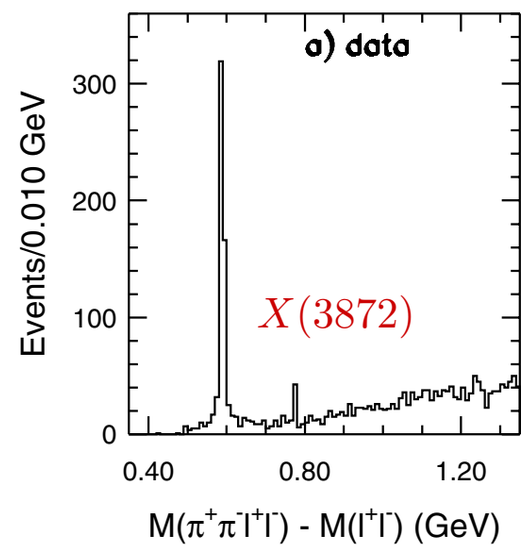

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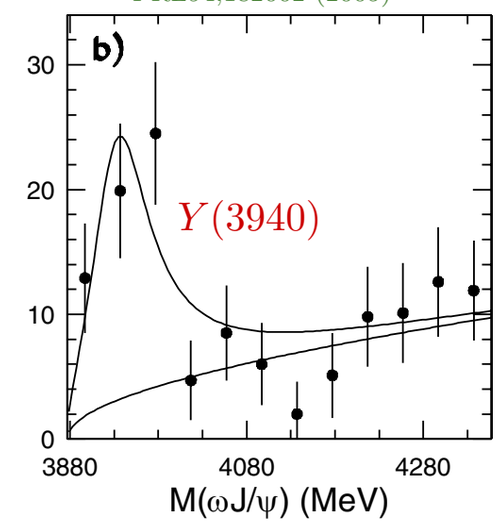

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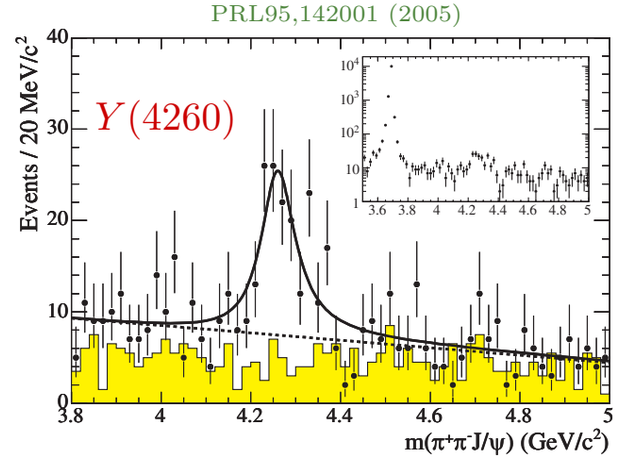

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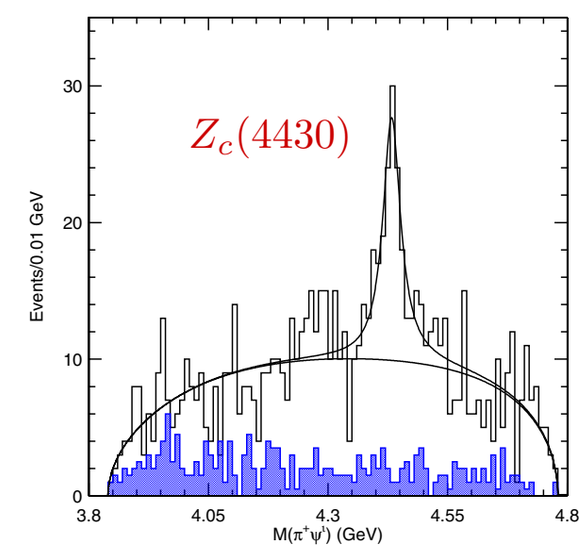
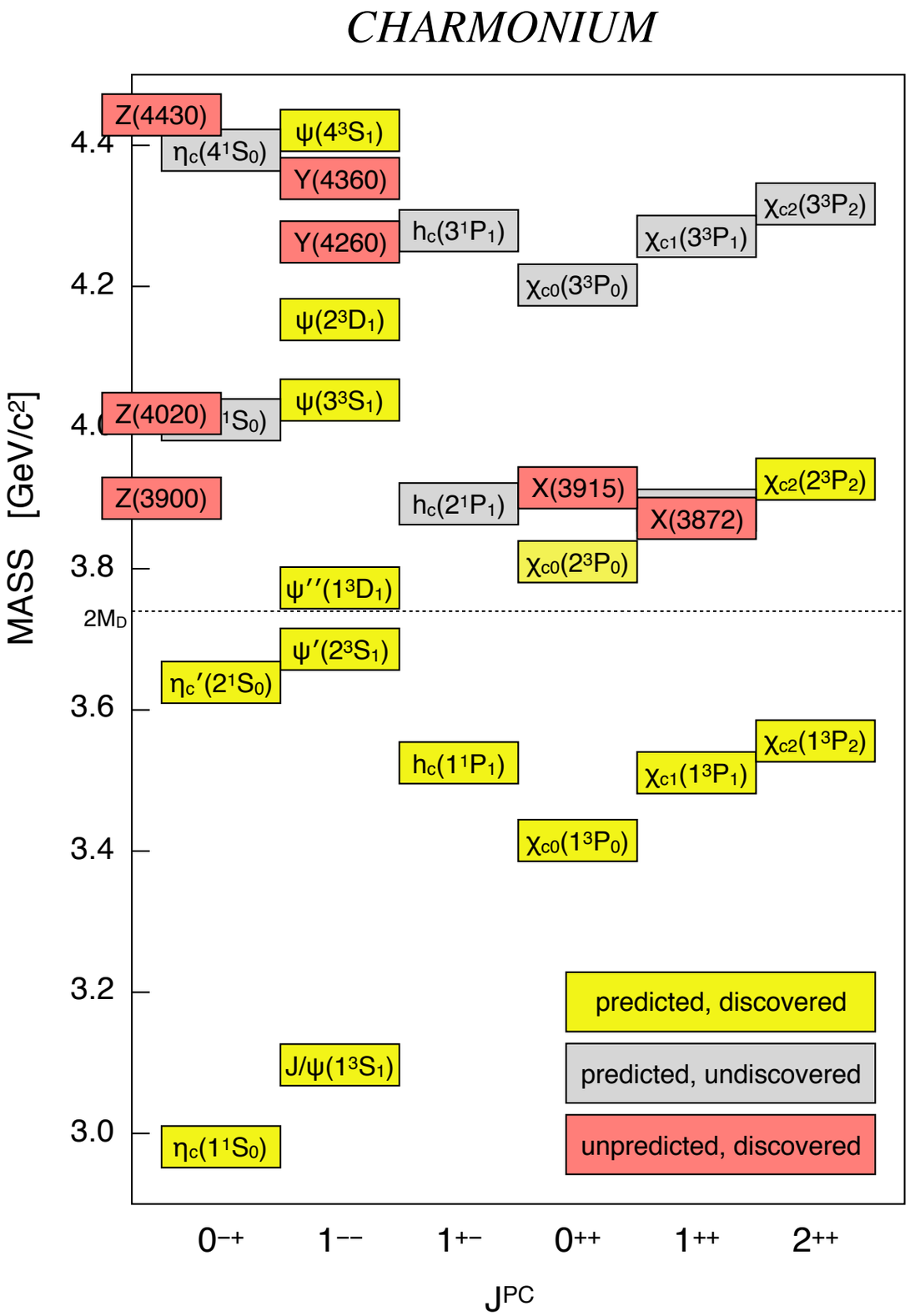


Closing Thoughts on the Future of Heavy Quark Exotica



(1) The field is characterized by:

* experimental results that are unexpected…
  … but robust.
* theoretical developments that are unsettled…
  … but productive.
* many avenues left to explore.

(2) The flow of experimental results will not end:

* BESIII and LHC experiments will continue.
* Belle II will soon be producing results.

(3) Further progress will require more interchange between experiment and theory.

(4) New production mechanisms need to be explored (e.g. PANDA, COMPASS).

(5) We should also test ideas beyond charmonium and bottomonium (e.g. GlueX, LHC).

We are making progress!