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

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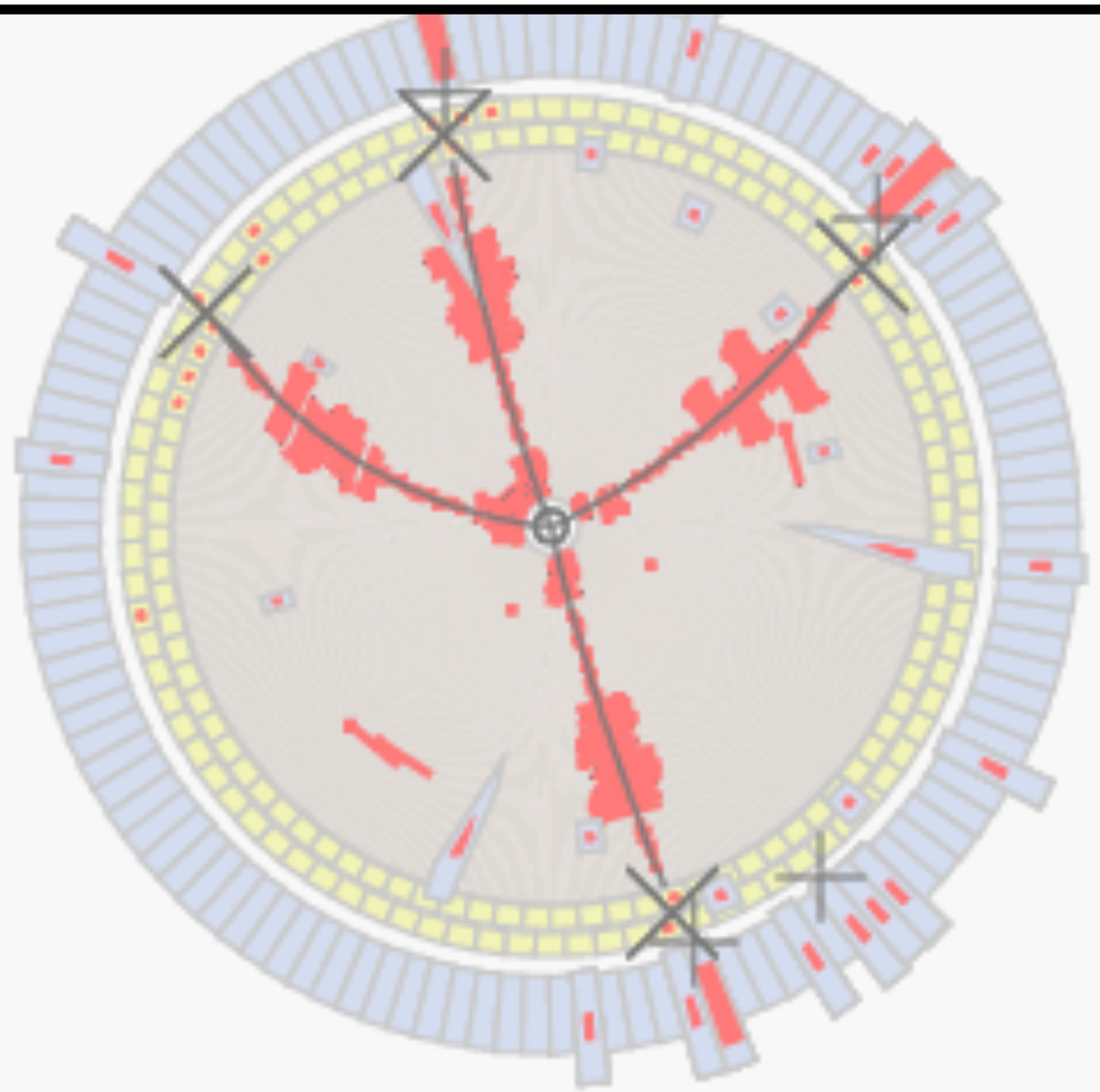
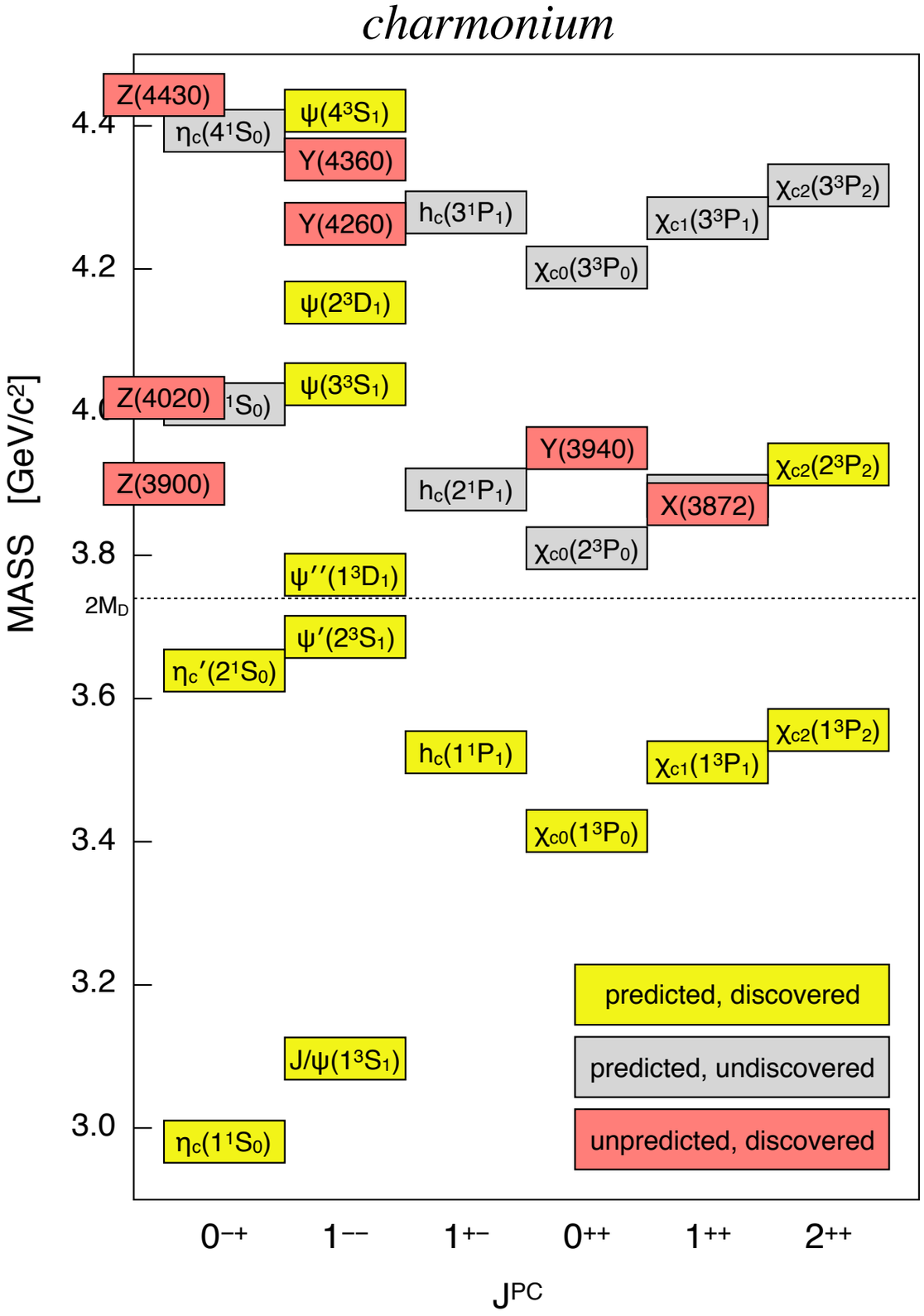


$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

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!

[The PDG will soon name them by IJ^{PC}.]

Q: How many have been found?

A: Many.

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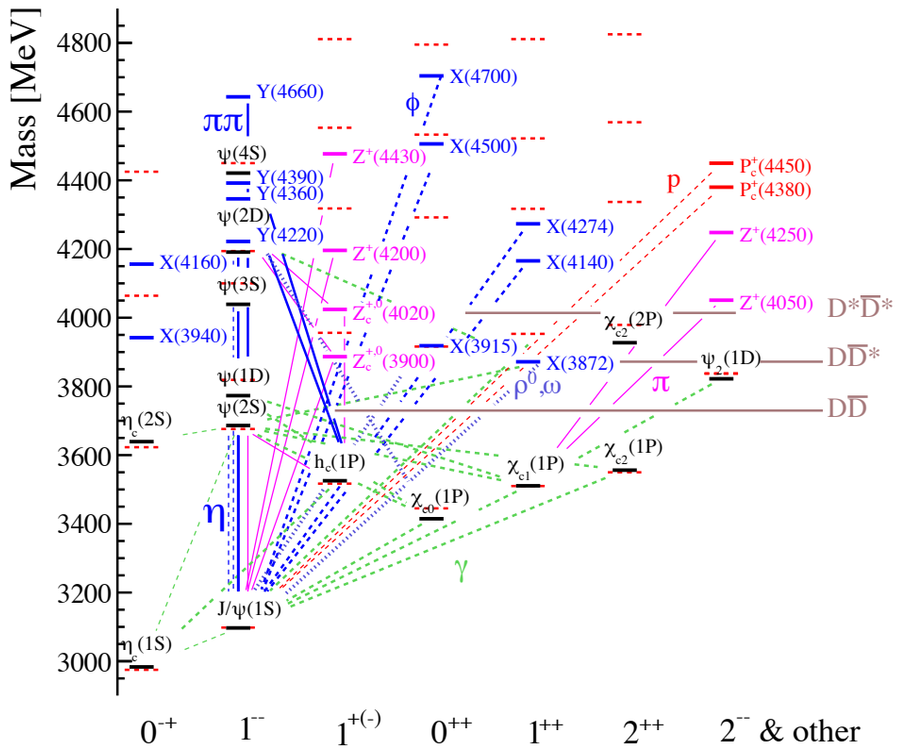

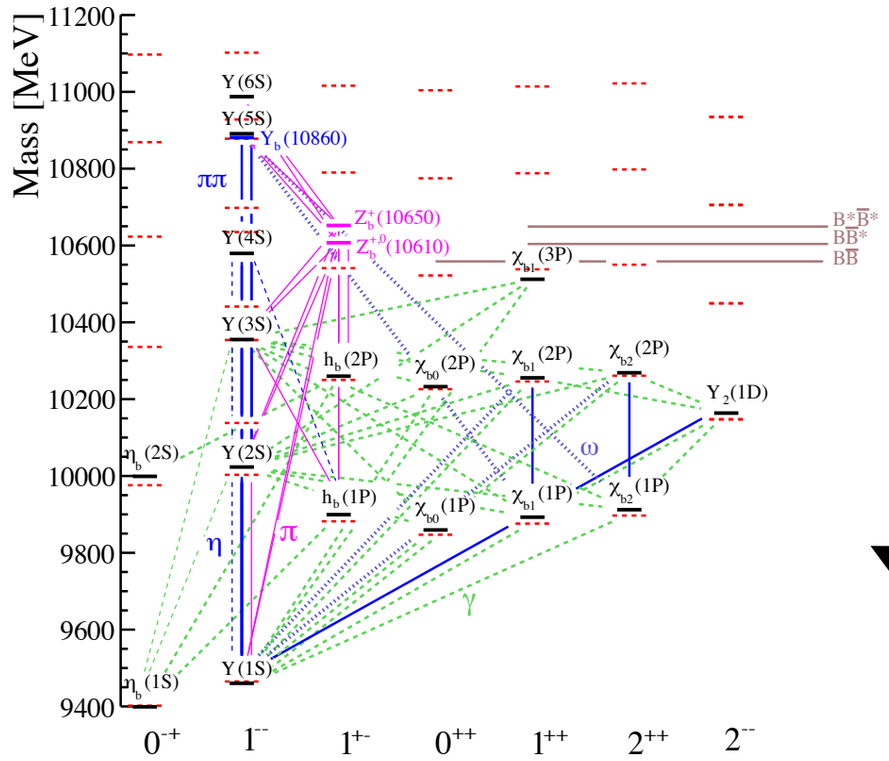

(1) **The hidden-charm pentaquark and tetraquark states**
Hua-Xing Chen, Wei Chen, Xiang Liu, Shi-Lin Zhu
Physics Reports 639, 1-121 (2016) [arXiv:1601.02092]

(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
[arXiv:1705.00141]

(5) **Exotics: Heavy Pentaquarks and Tetraquarks**
Ahmed Ali, Jens Sören Lange, Sheldon Stone
[arXiv:1706.00610]

(6) **Non-Standard Heavy Mesons and Baryons, an Experimental Review**
Stephen Lars Olsen, Tomasz Skwarnicki, Daria Zieminska
[arXiv:1708.04012]

2016-2017 Review Articles on Heavy Quark Exotica

(2) **Heavy-Quark QCD Exotica**
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[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	$e^+e^- \to Y;\ Y \to \pi\pi\Upsilon(1S, 2S, 3S)$ $e^+e^- \to Y;\ Y \to \pi\pi h_b(1P, 2P)$

2016-2017 Review Articles on Heavy Quark Exotica

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Progress in Particle and Nuclear Physics 93, 143–194 (2017)
[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]	$X(5568)$

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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					

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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)

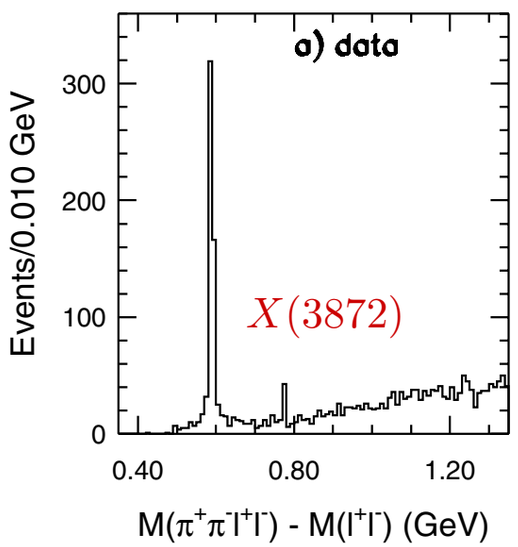
[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
The ongoing search for the χ_{c0}(2P).

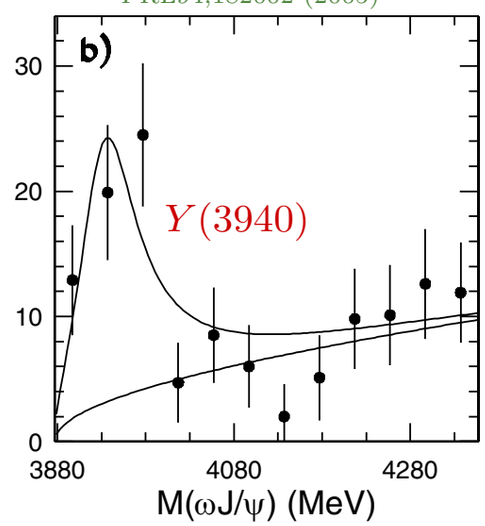
[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e^+e^- cross sections ("Y states").
Peaks in their decays ("Z states").

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

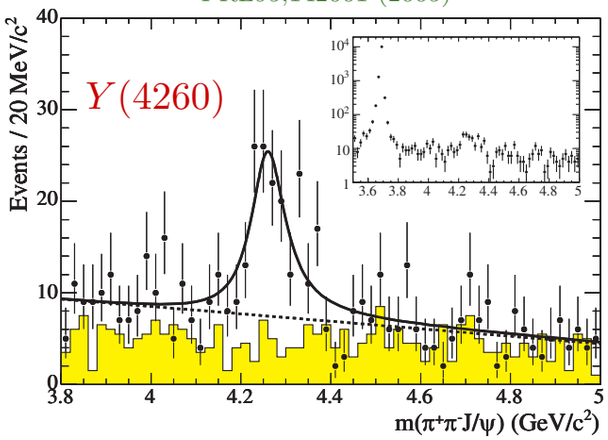
$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle
PRL91,262001 (2003)



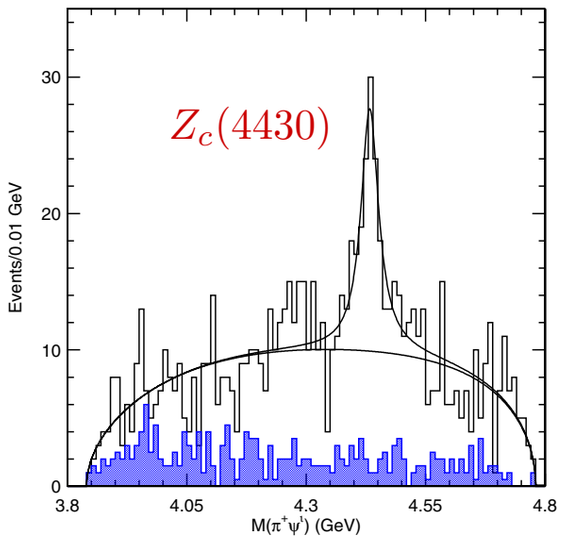
$B \to KX; X \to \omega J/\psi$ at Belle
PRL94,182002 (2005)



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

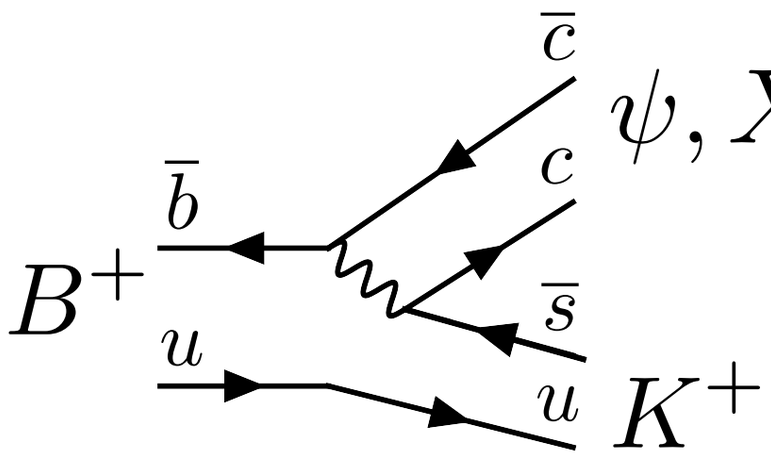


$B \to KZ; Z \to \pi^\pm \psi(2S)$ at Belle
PRL100,142001 (2008)



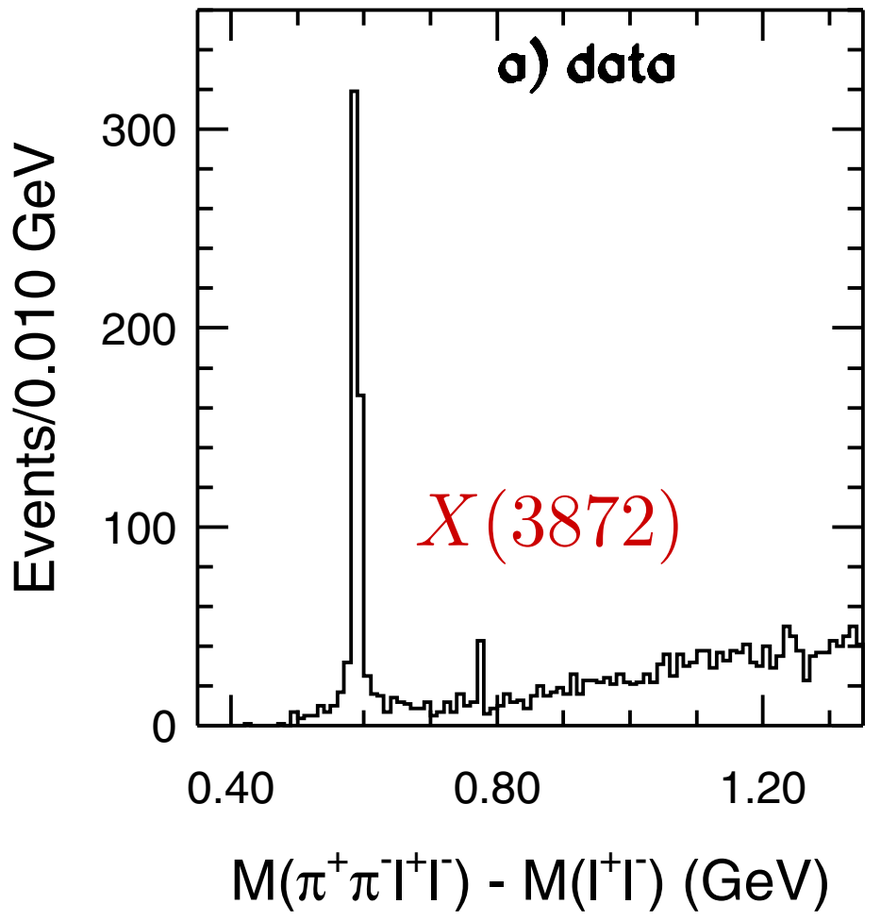
[PRELIM: Four Foundational Discoveries] X(3872)

Year:	*Search for this:*	*Find this:*
2003	B → Kψ(2S) ↳ π⁺π⁻J/ψ	B → Kψ(2S), **X(3872)** ↳ π⁺π⁻J/ψ



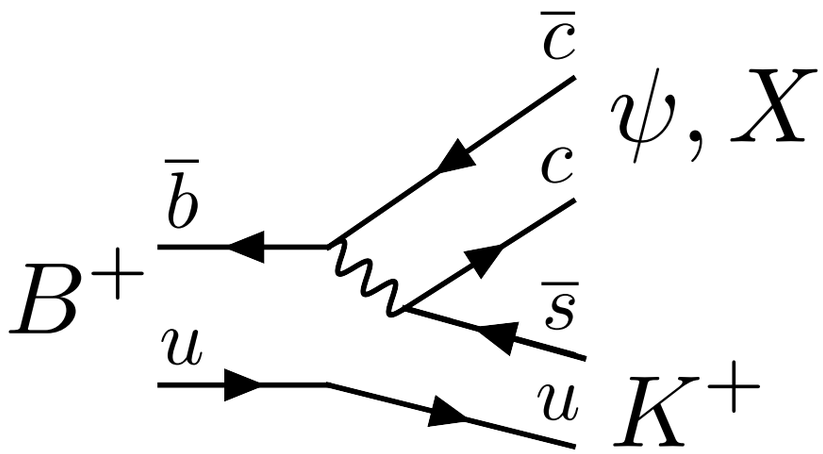
$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle

PRL91,262001 (2003)



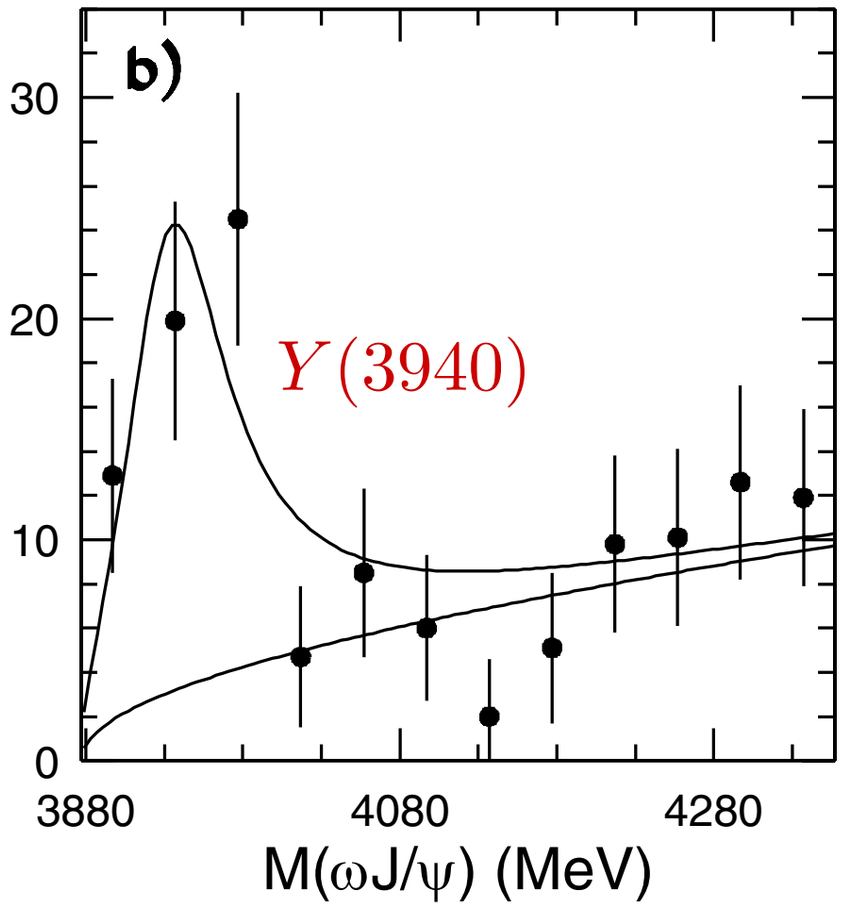
[PRELIM: Four Foundational Discoveries] Y(3940)

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



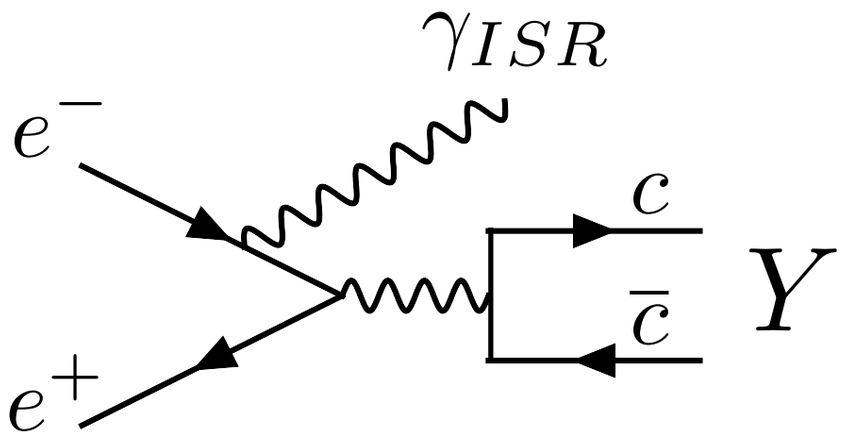
$B \to KX; X \to \omega J/\psi$ at Belle

PRL94,182002 (2005)



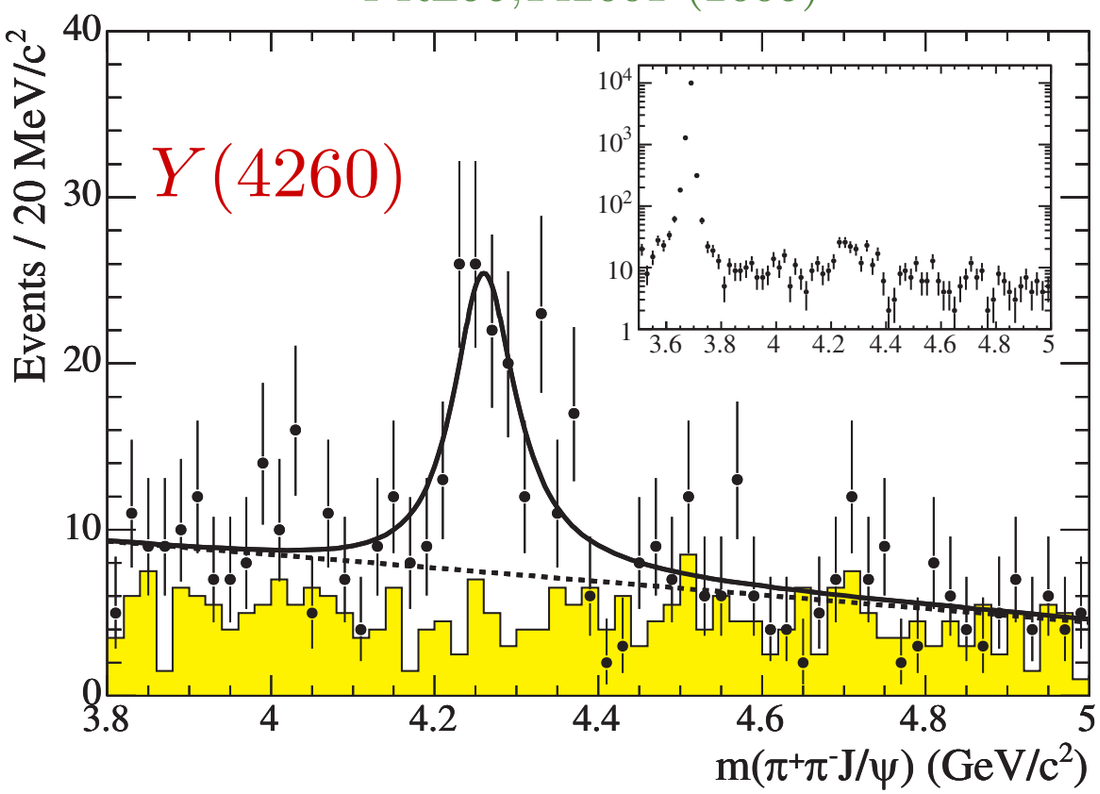
[PRELIM: Four Foundational Discoveries] Y(4260)

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



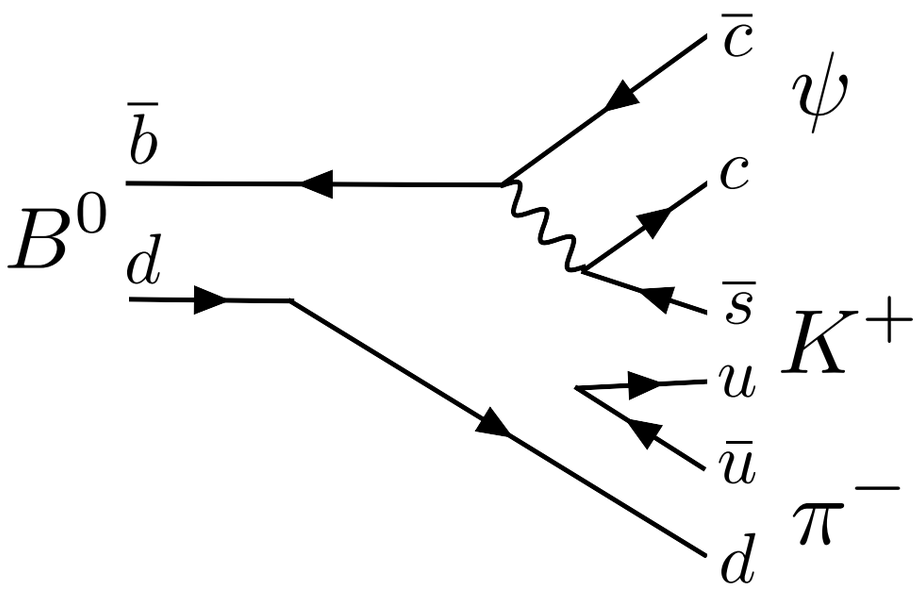
$e^+e^- \to Y; Y \to \pi^+\pi^- J/\psi$ at BaBar

PRL95,142001 (2005)



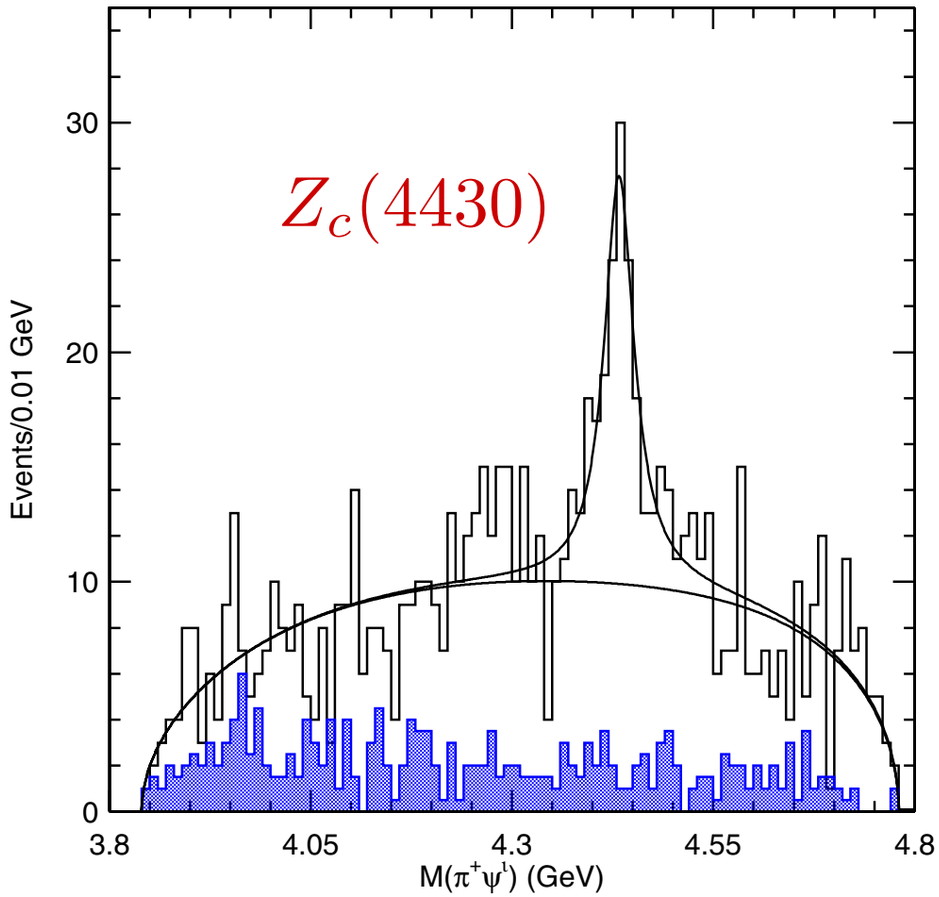
[PRELIM: Four Foundational Discoveries] $Z_c(4430)$

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



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

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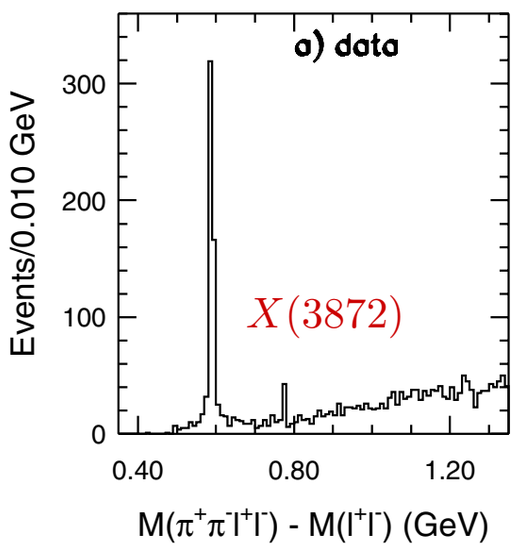
What happened to the Y(3940)?
The ongoing search for the $\chi_{c0}(2P)$.

[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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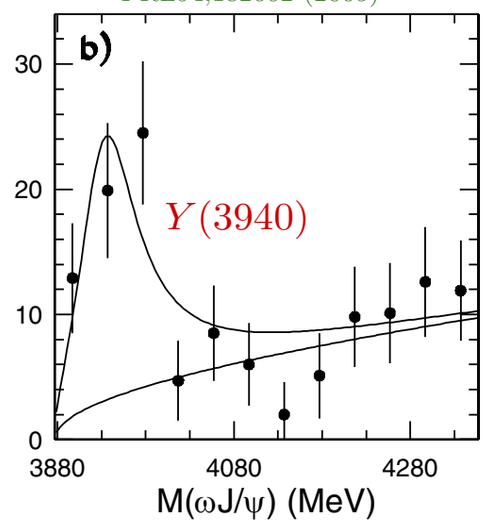

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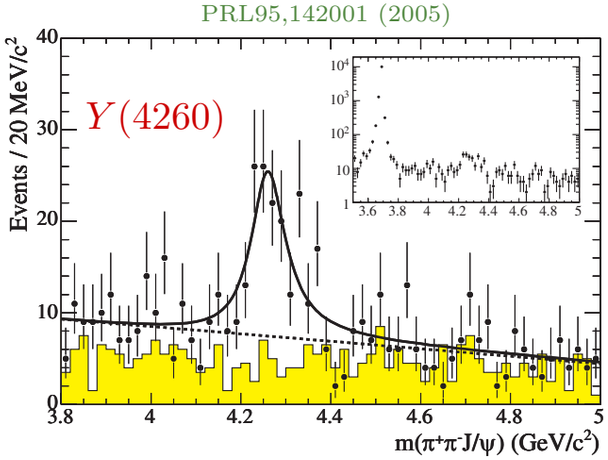

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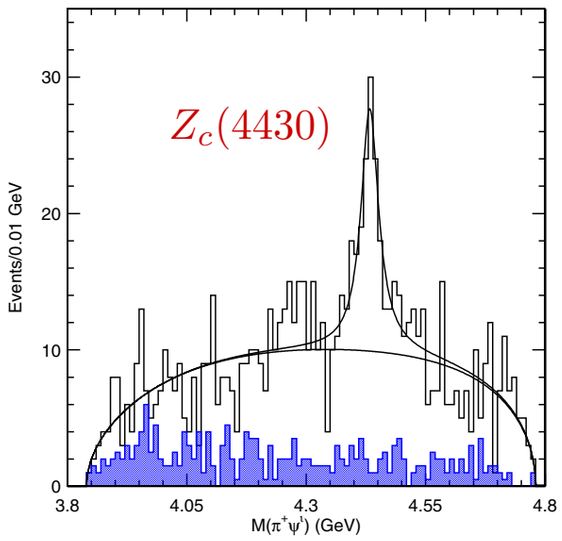

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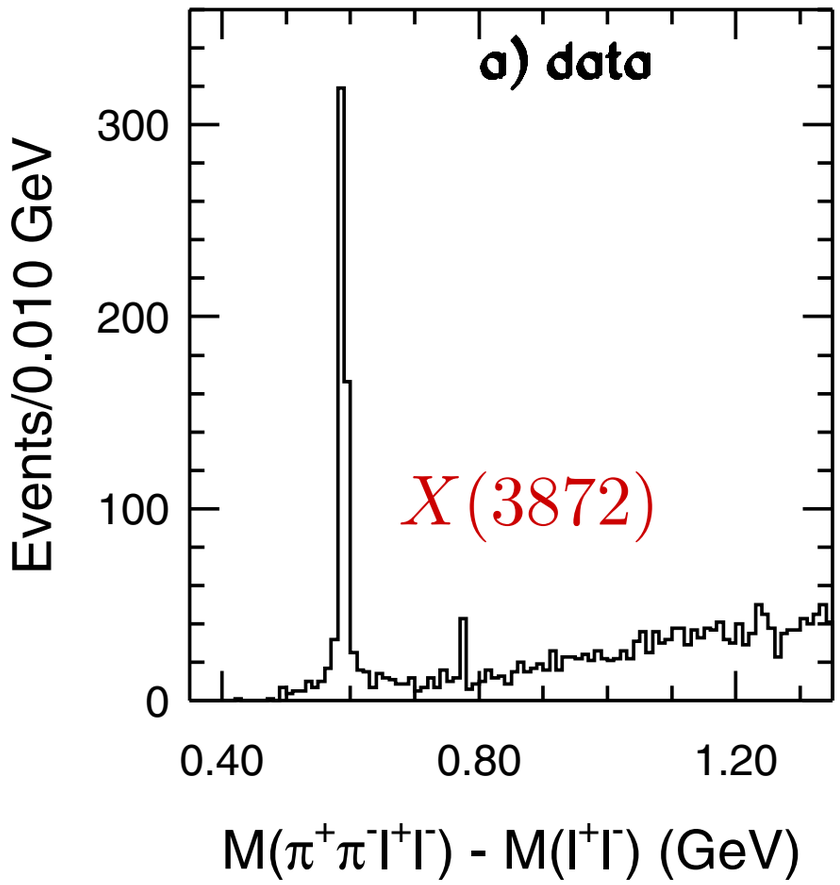
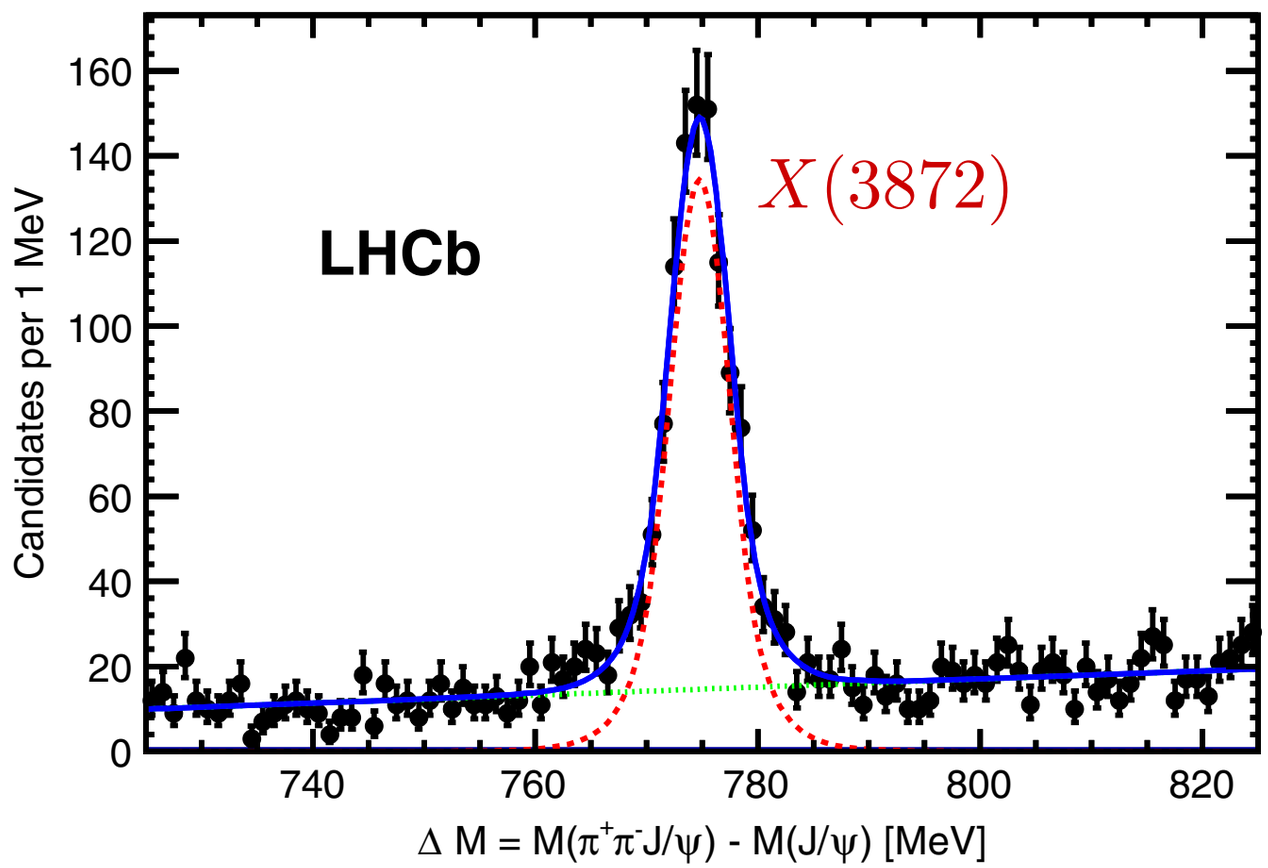
$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle

PRL91,262001 (2003)



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

PRD92,011102 (2015)



More statistics!!

More experimental details.

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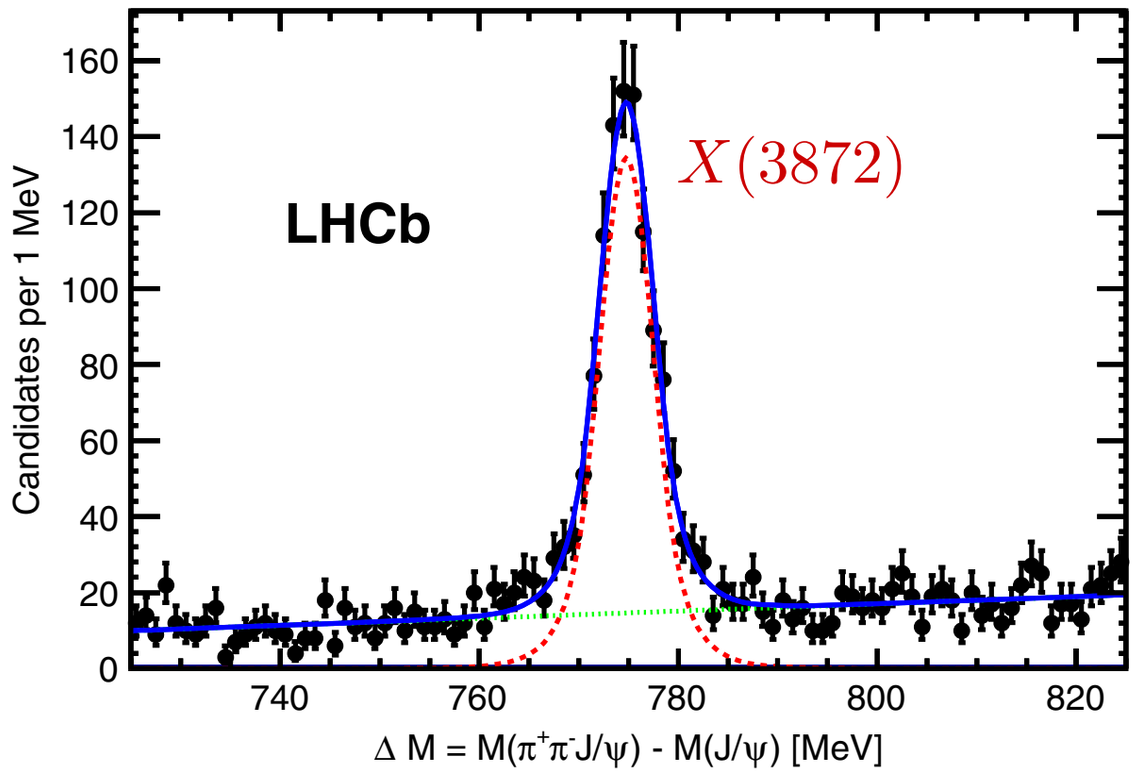
PRD92,011102 (2015)



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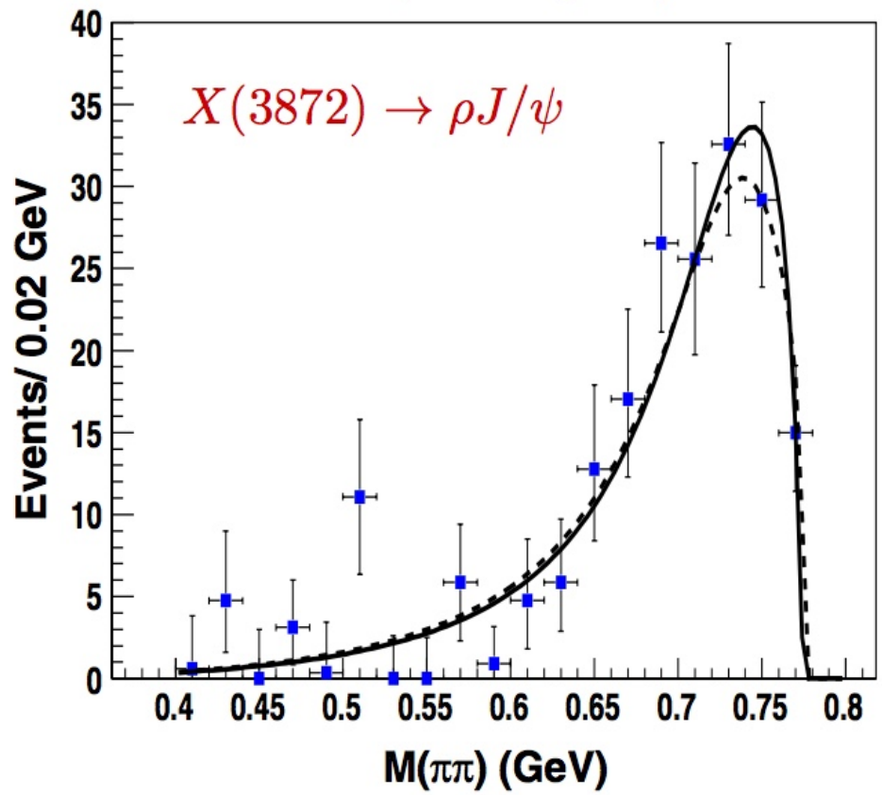
PRD84,052004 (2011)



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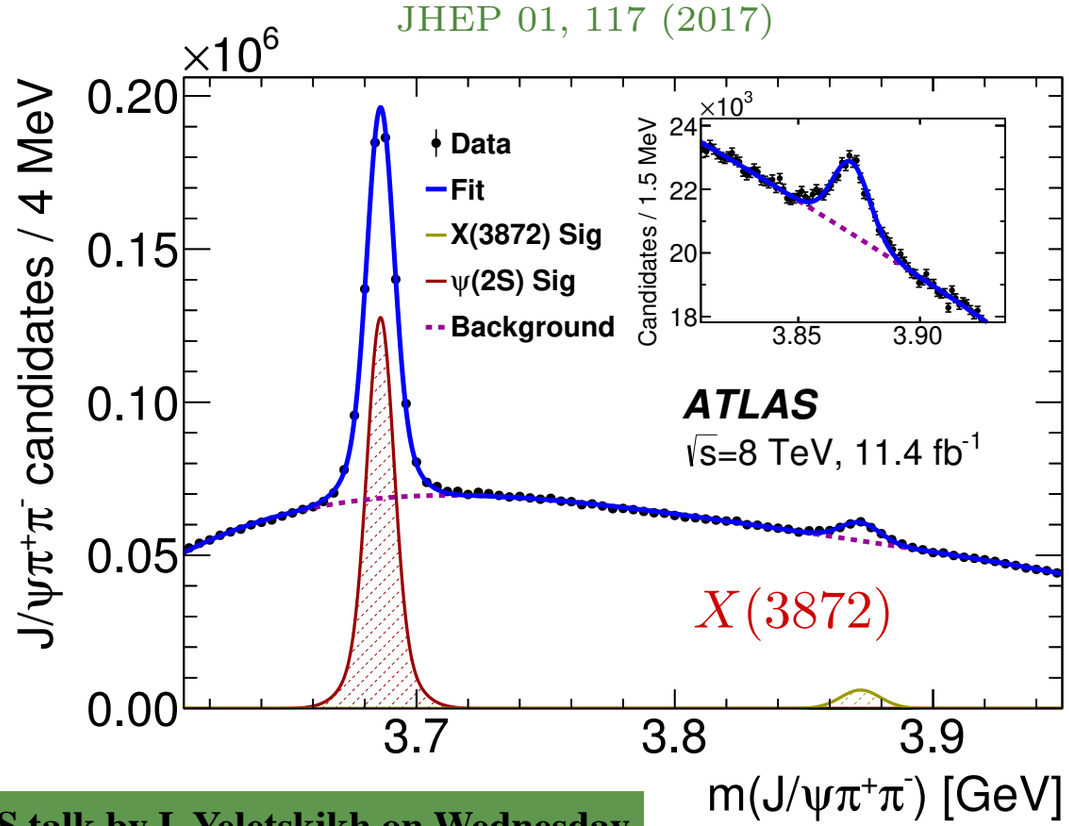
JHEP 01, 117 (2017)



ATLAS talk by I. Yeletskikh on Wednesday

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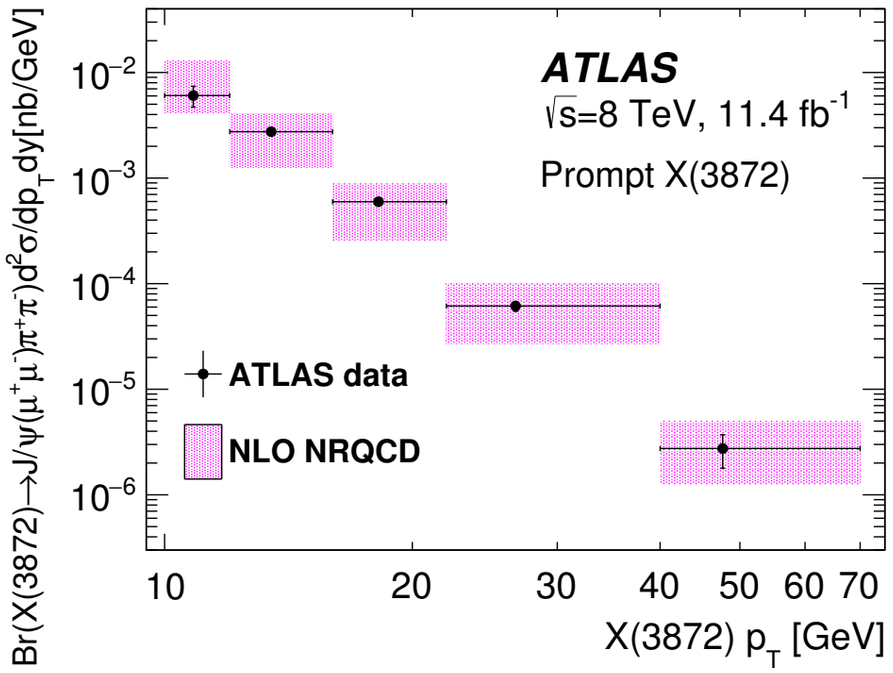
JHEP 01, 117 (2017)



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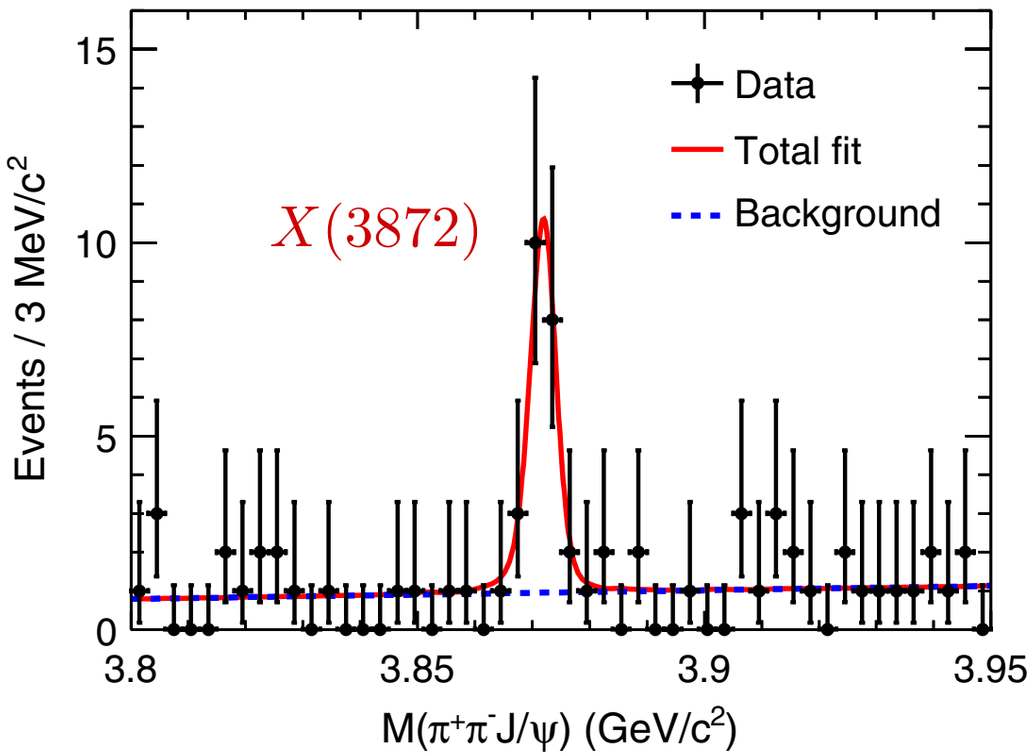
$e^+e^- \to \gamma X;\ X \to \pi^+\pi^- J/\psi$ at BESIII

PRL 112, 092001 (2014)



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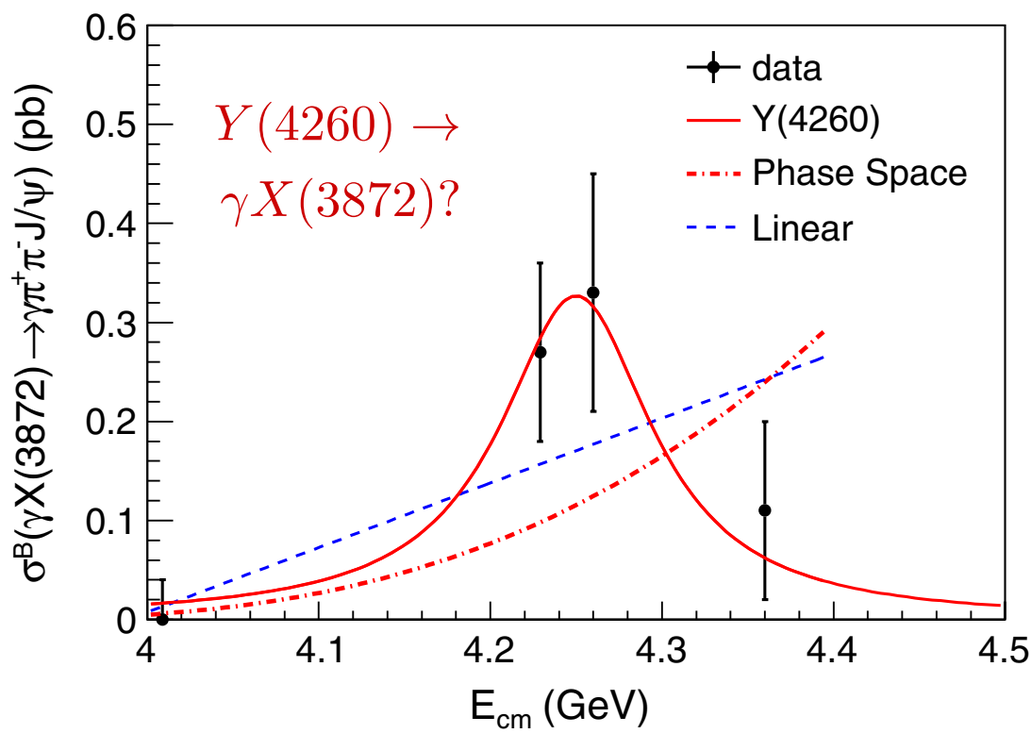
PRL 112, 092001 (2014)



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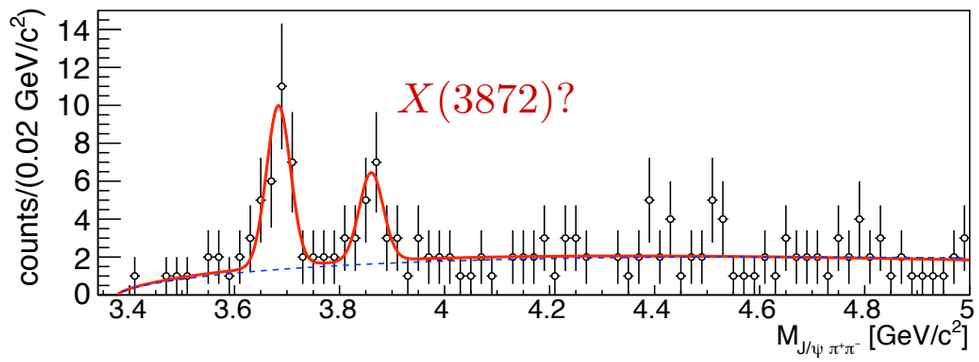
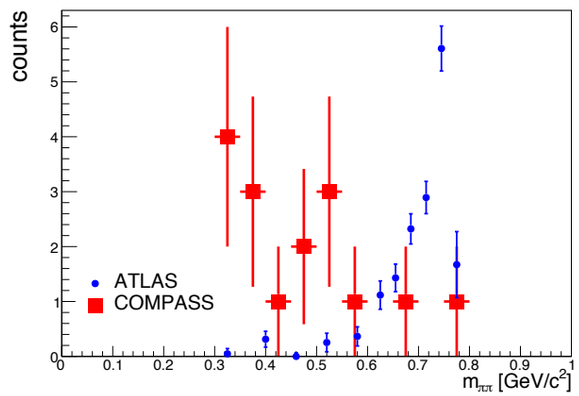
$\gamma^* N \to X\pi^\pm N'; X \to \pi^+\pi^- J/\psi$ at COMPASS

arXiv:1707.01796 (2017)





COMPASS talk by A. Guskov on Friday

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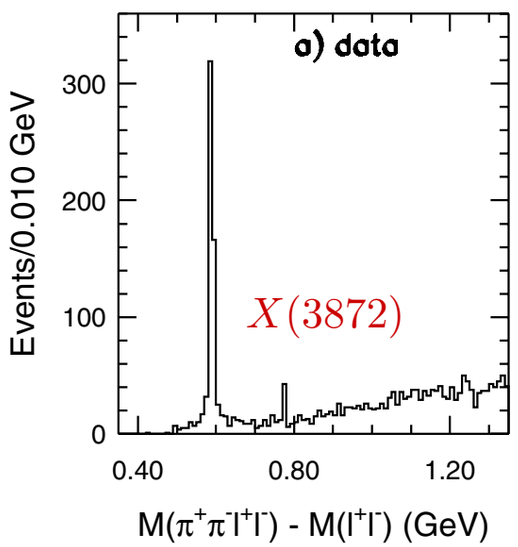

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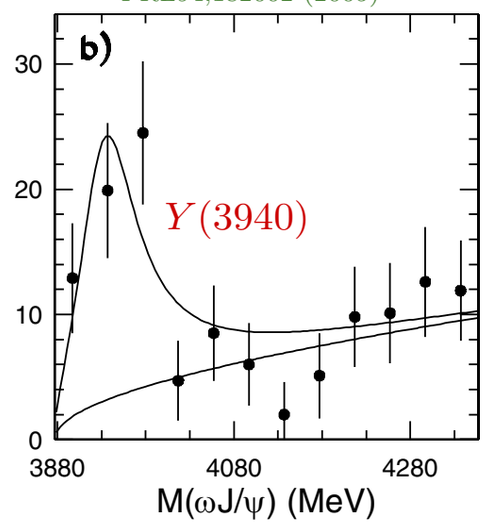

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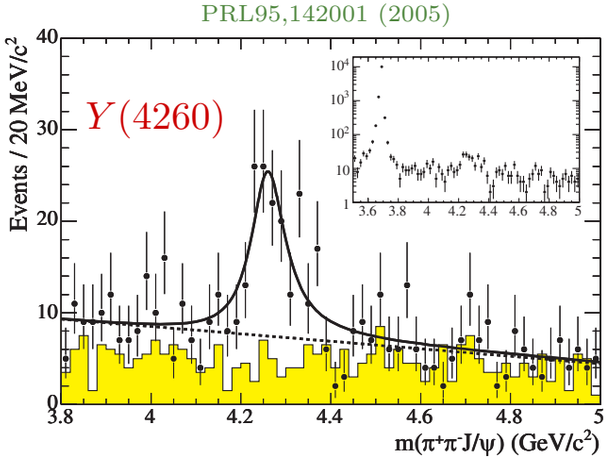

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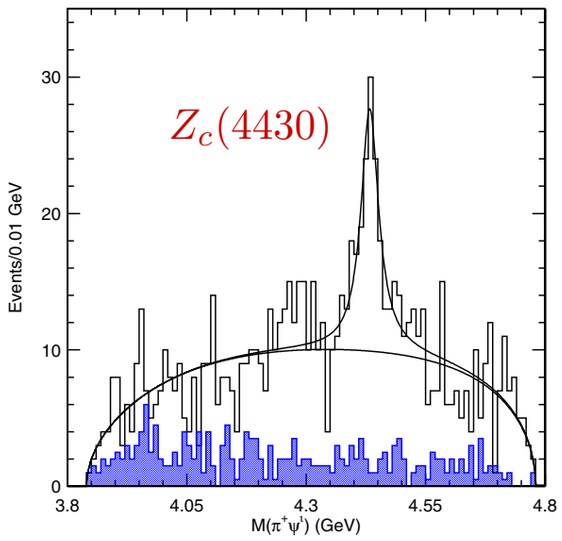

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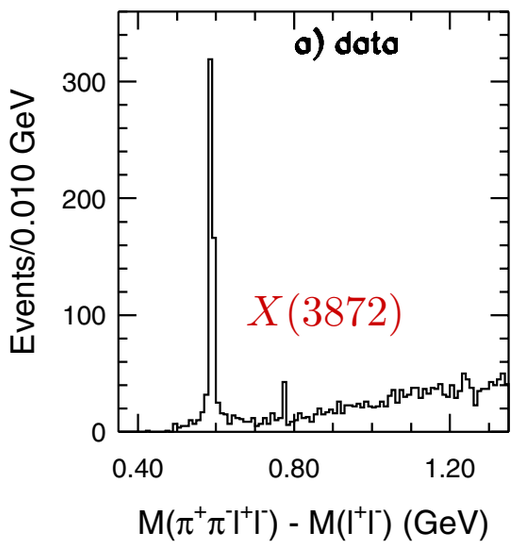
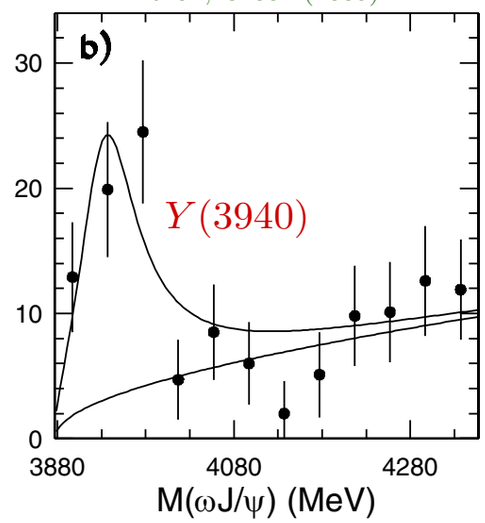
The ongoing search for the $\chi_{c0}(2P)$.

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



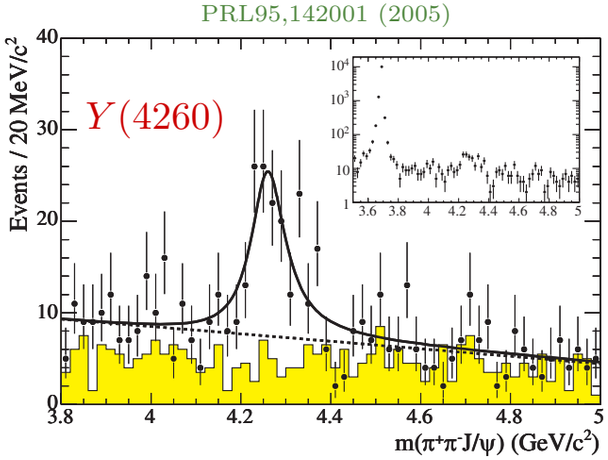
$B \to KX; X \to \omega J/\psi$ at Belle
PRL94,182002 (2005)



[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.

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



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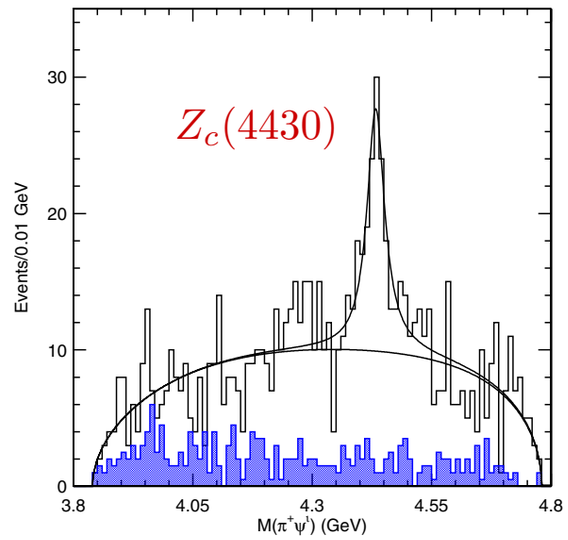
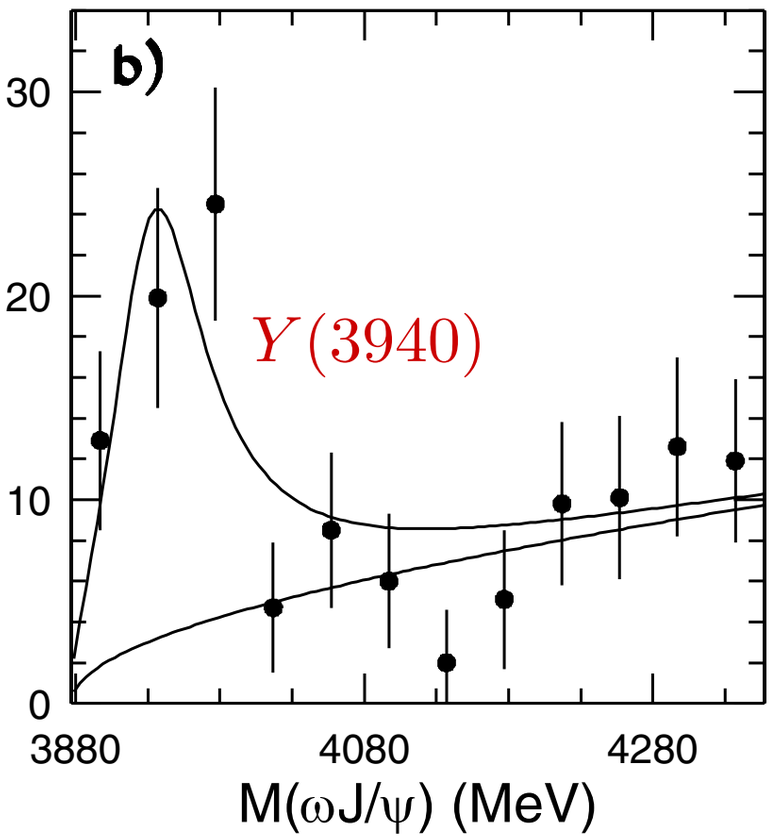


[PART II: Y(3940)] What happened?

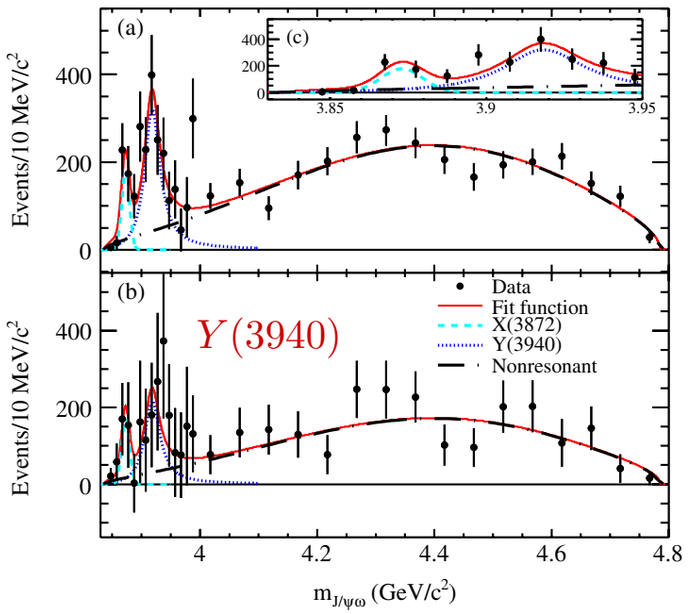
$B \to KX; X \to \omega J/\psi$ at Belle

PRL94,182002 (2005)



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

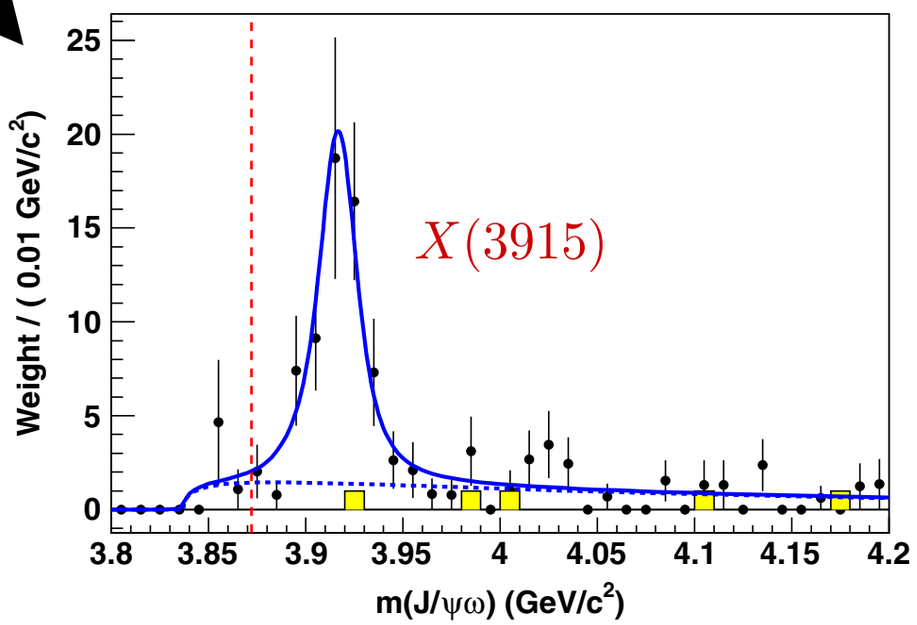
PRD82,011101 (2010)



Its mass shifted to ~3915 MeV/c².

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

PRD86,072002 (2012)

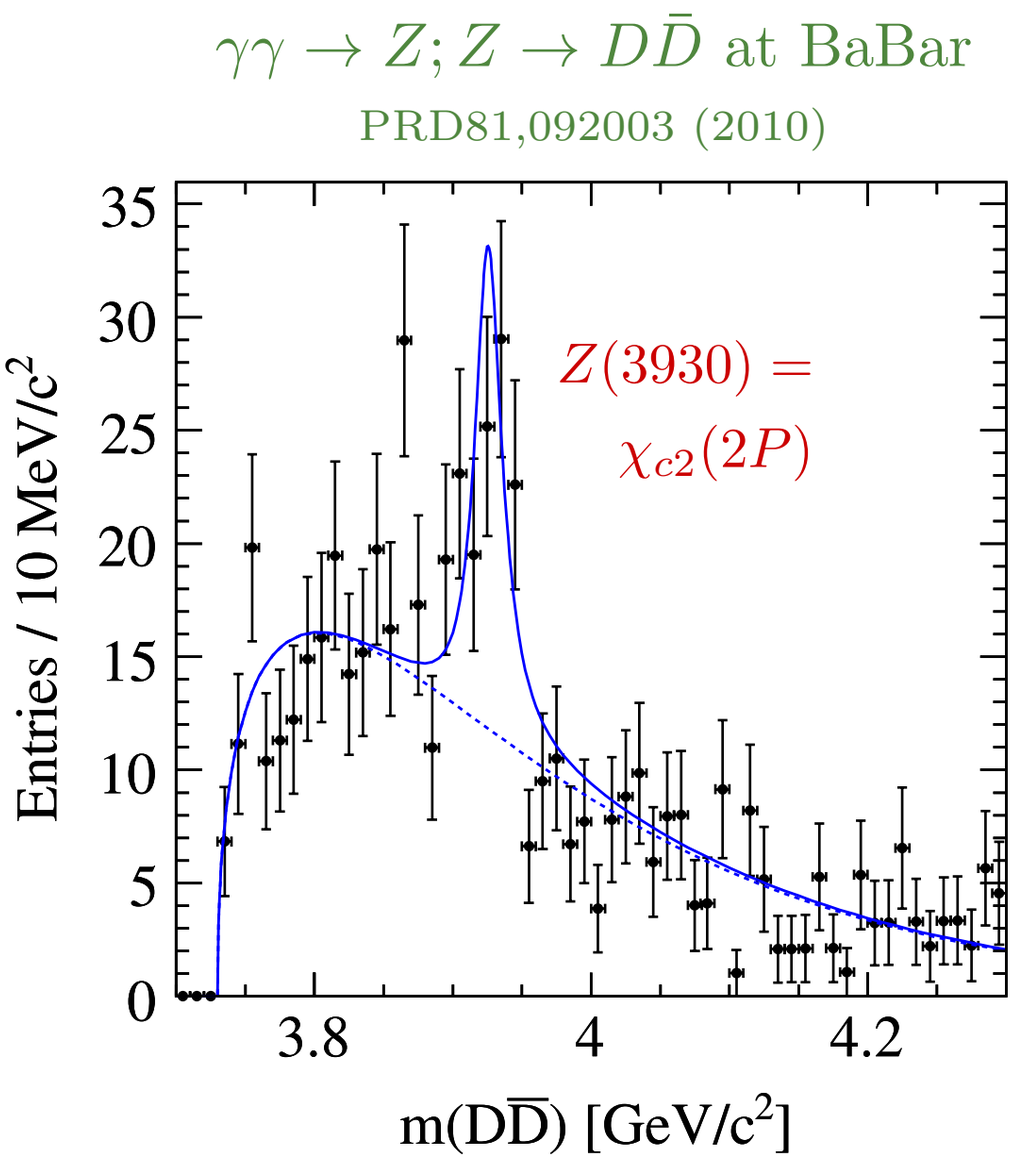


It was found in γγ collisions with $J^{PC} = 0^{++}$.

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) = $\chi_{c0}(2P)$:

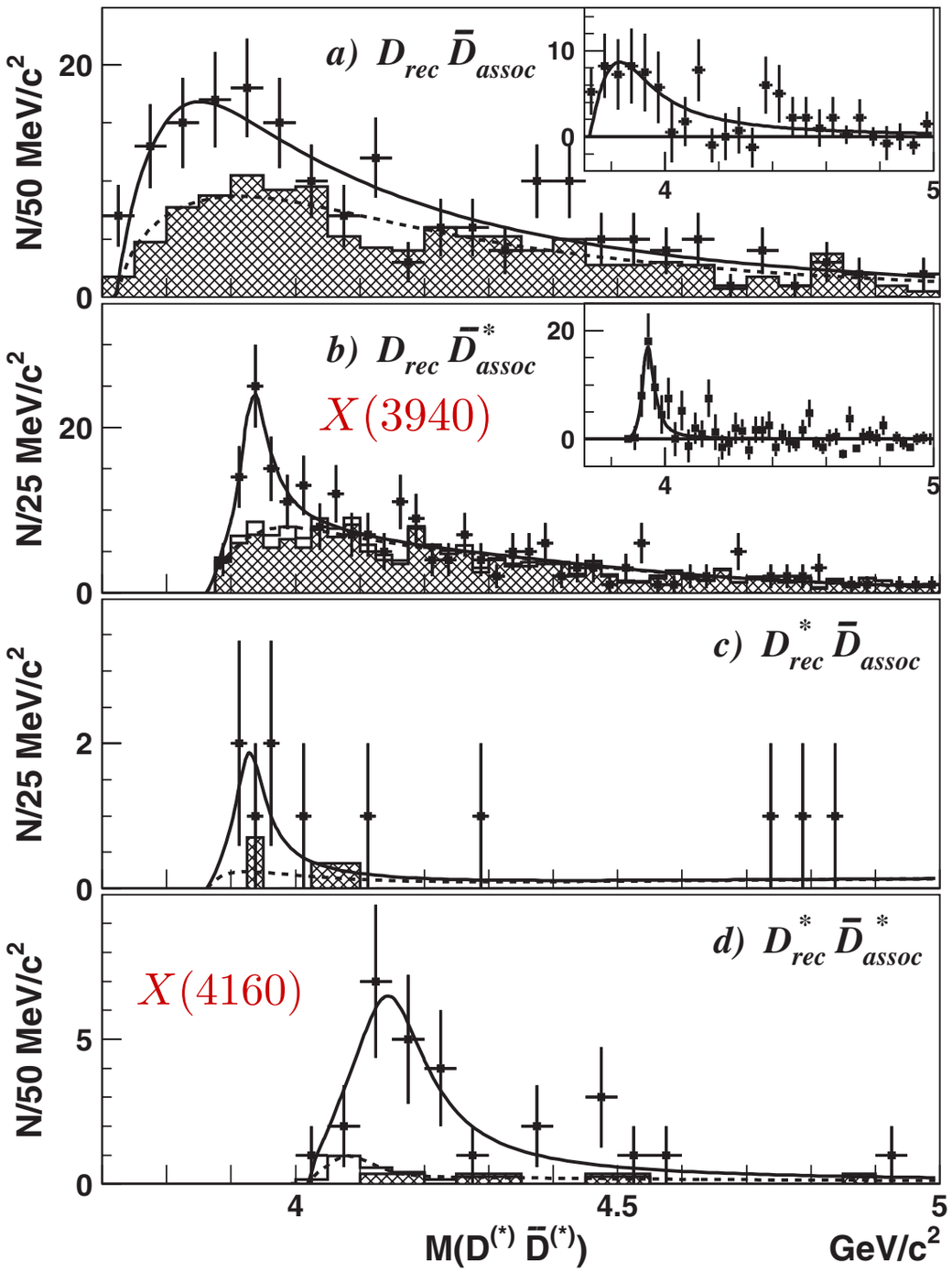
* why isn't it in DD?
* why is the $\chi_{c0}(2P)/\chi_{c2}(2P)$ mass splitting so small?

Possible solution: the broad part includes the $\chi_{c0}(2P)$.

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

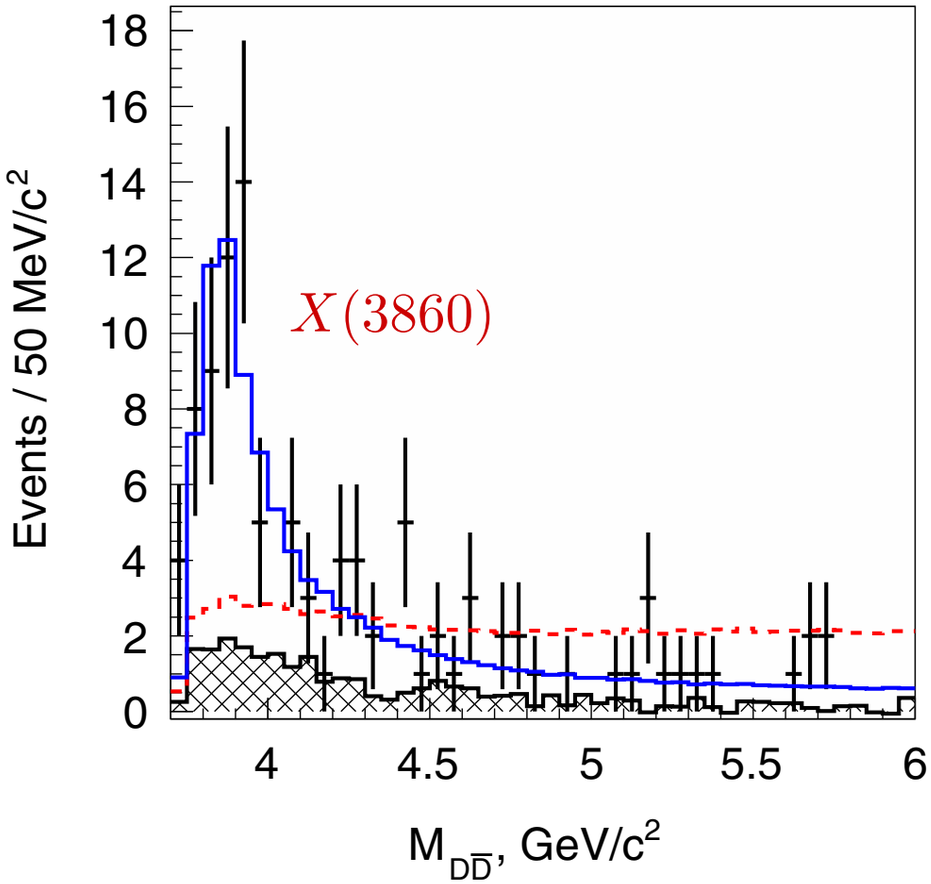
$e^+e^- \to J/\psi X; X \to D^{(*)}\bar{D}^{(*)}$ at Belle

PRL100,202001 (2008)



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

PRD 95, 112003 (2017)



Reanalysis of $e^+e^- \to J/\psi(DD)$ shows a new X(3860), with 0^{++} favored.

If the X(3860) is the $\chi_{c0}(2P)$,
what is the X(3915)/Y(3940)??
Also, what are the X(3940) and X(4160)??

Belle talk by S. Eidelman on Thursday

[OUTLINE] A Tour through the XYZ

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

[Part I: X(3872)]
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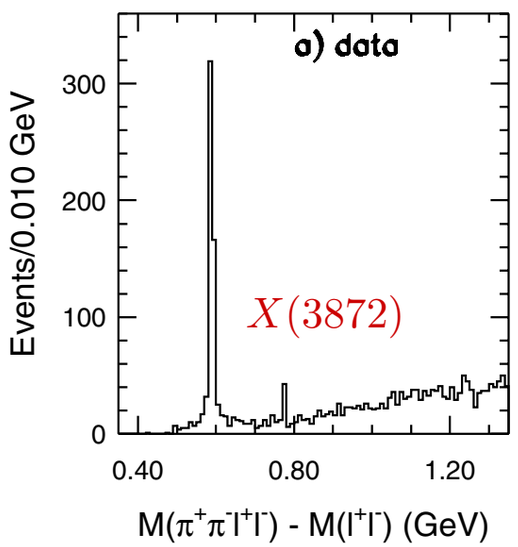

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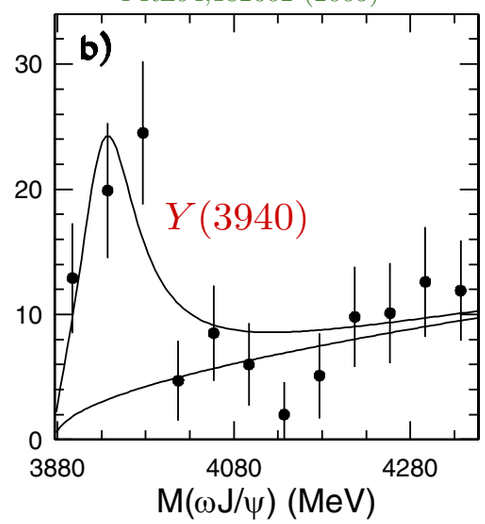

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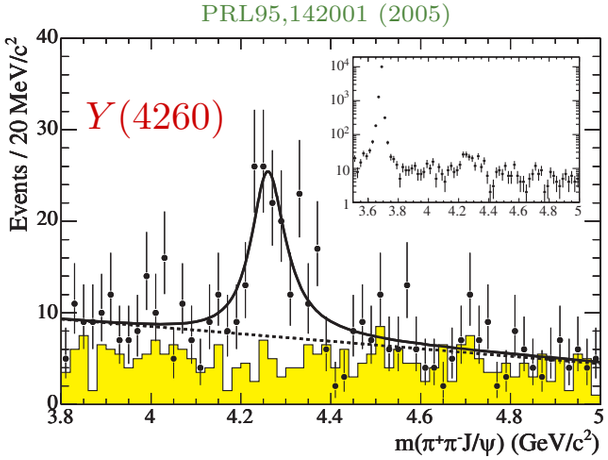
PRL95,142001 (2005)



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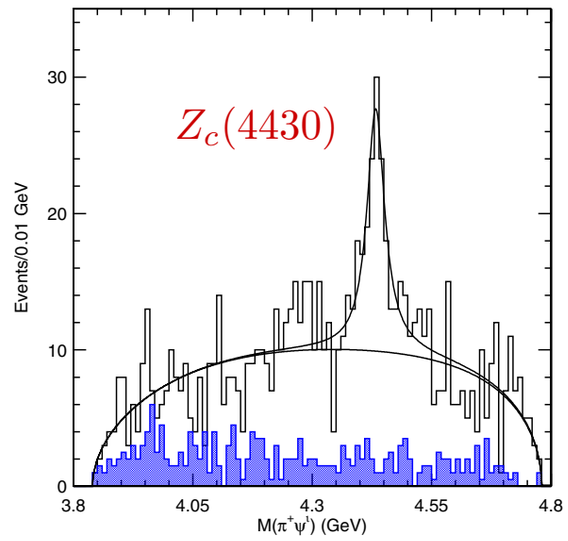

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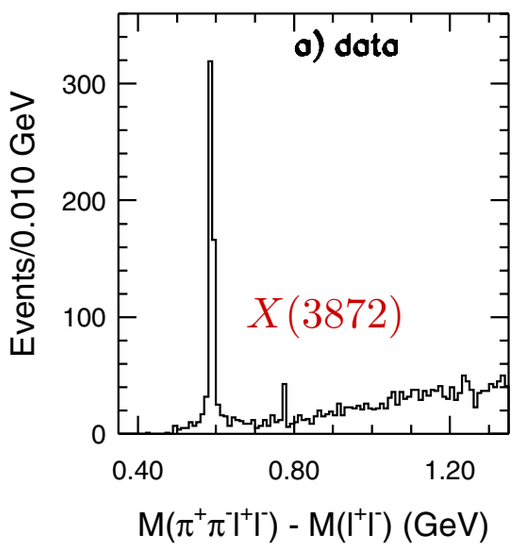

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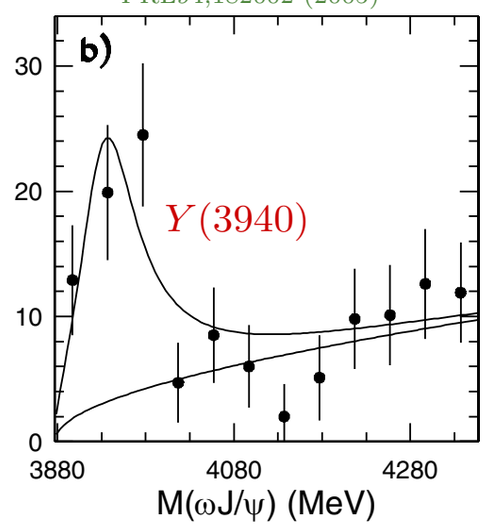

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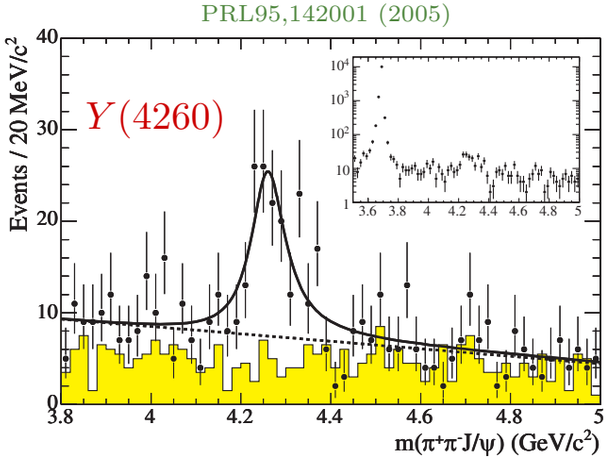
PRL95,142001 (2005)



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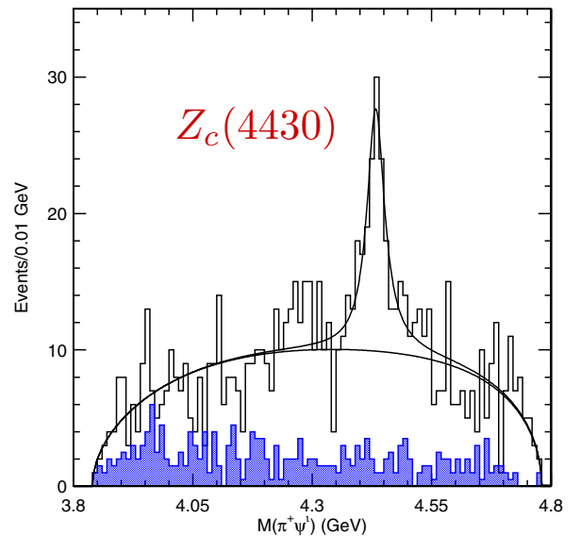
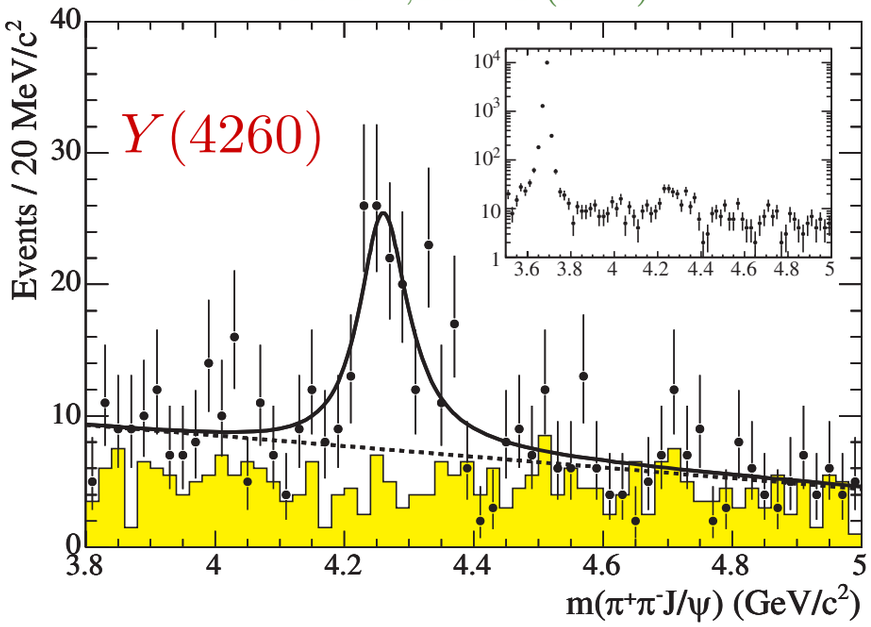


[PART III: Y(4260)] What happened?

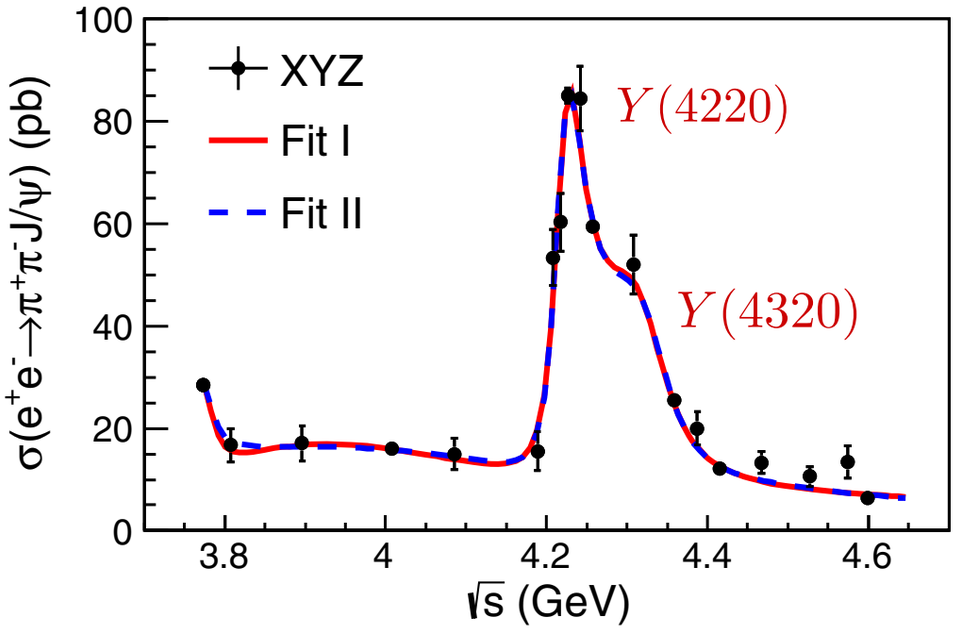
$e^+e^- \to Y; Y \to \pi^+\pi^- J/\psi$ at BaBar

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.

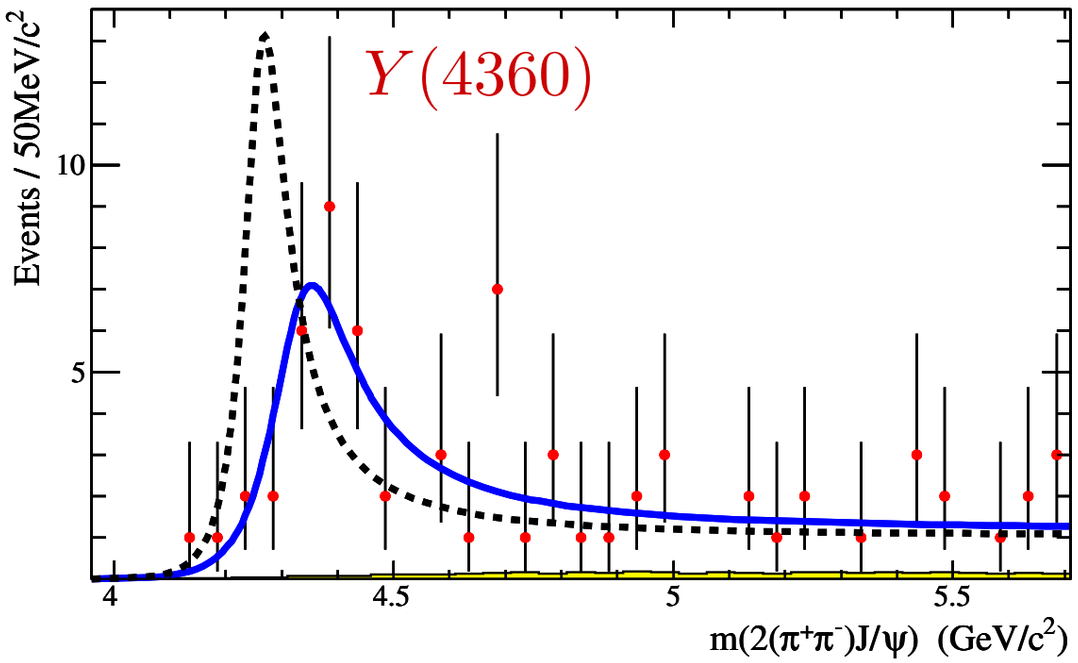
BESIII talk by Ke Li on Tuesday

Important Note: Old and new data are consistent!!

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

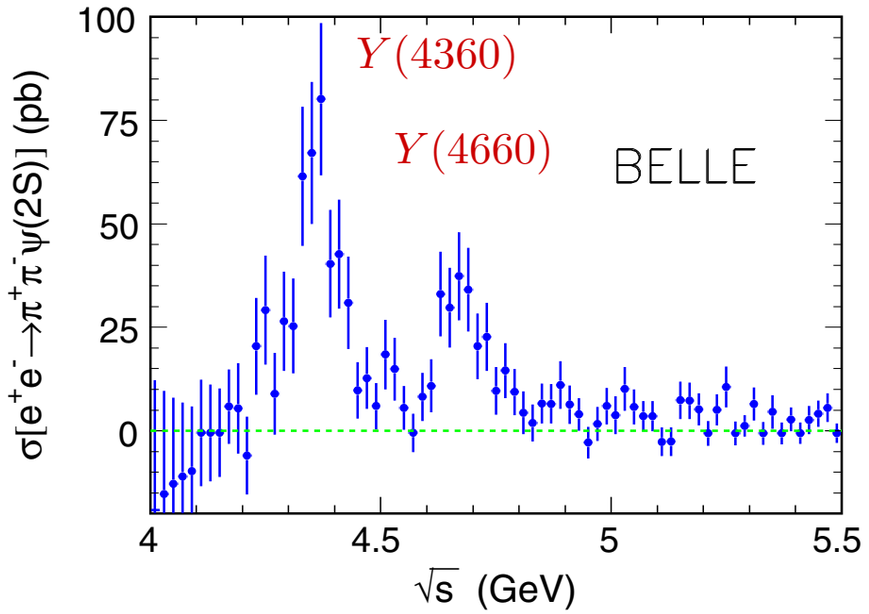
$e^+e^- \to Y; Y \to \pi^+\pi^-\psi(2S)$ at BaBar

PRL98,212001 (2007)



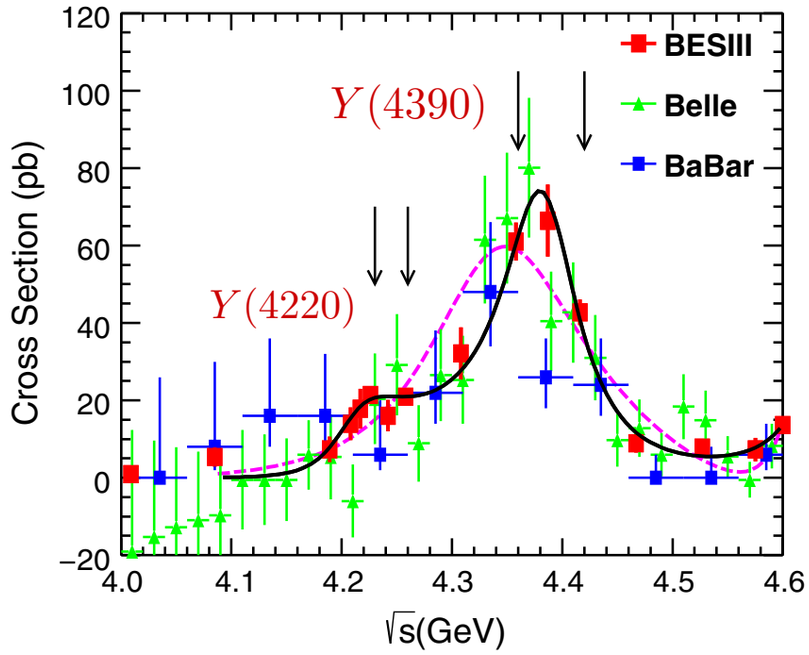
$e^+e^- \to Y; Y \to \pi^+\pi^-\psi(2S)$ at Belle

PRD91,112007 (2015)



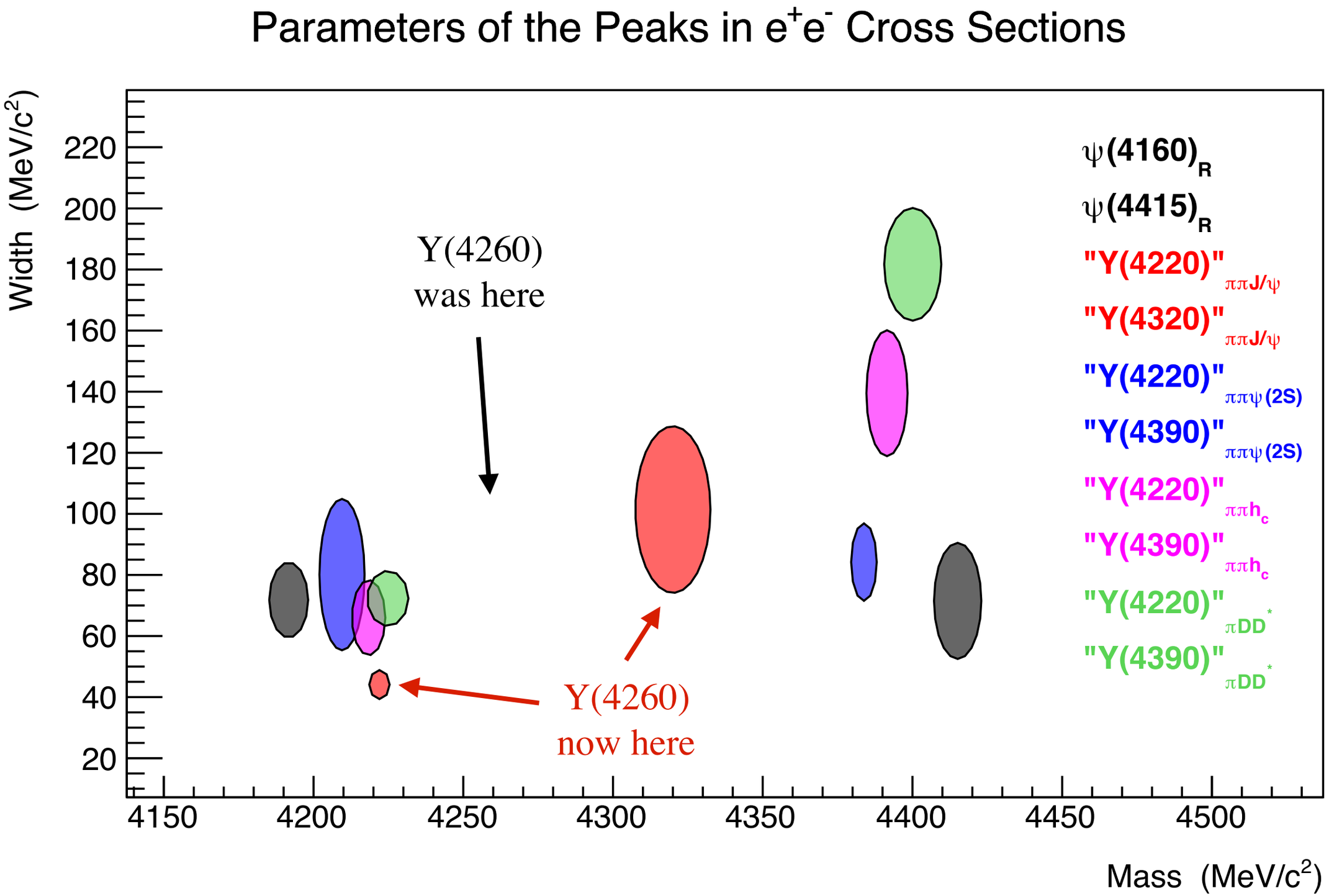
$e^+e^- \to Y;\ Y \to \pi^+\pi^-\psi(2S)$ at BESIII

PRD 96, 032004 (2017)



BESIII talk by Ke Li on Tuesday

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

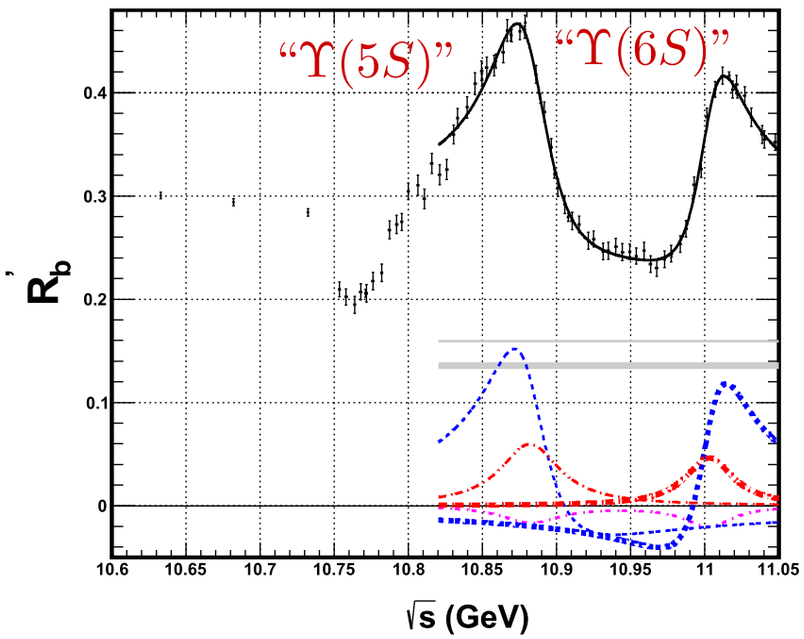


Important Note: Masses and widths (and numbers of peaks) depend on parametrization!! A global analysis is needed.

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

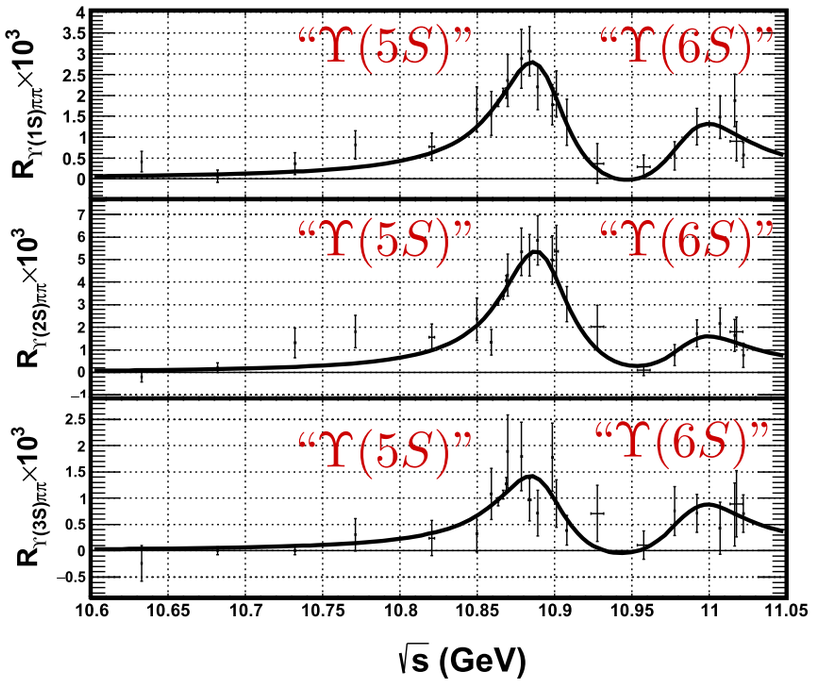
$e^+e^- \to$ Hadrons at Belle

PRD93,011101 (2016)



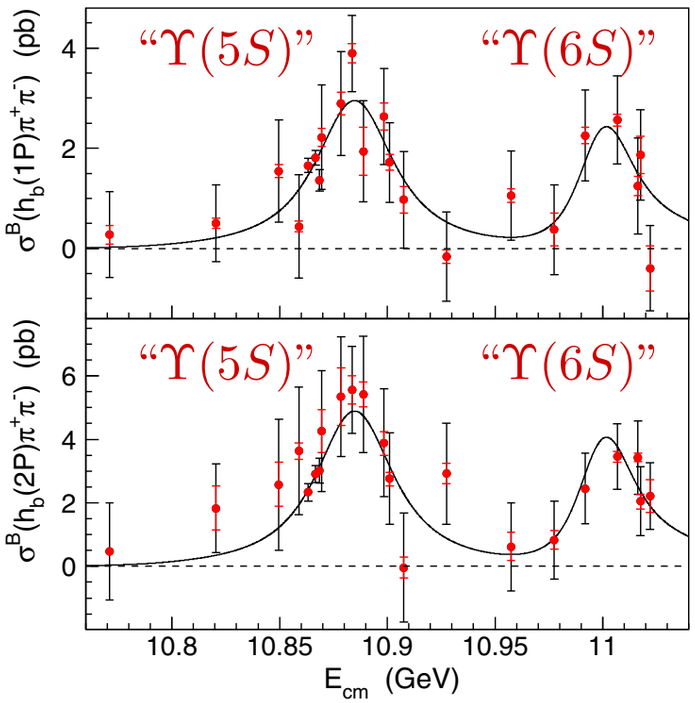
$e^+e^- \to \pi^+\pi^-\Upsilon(1S,2S,3S)$ at Belle

PRD93,011101 (2016)



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

PRL117,142001 (2016)

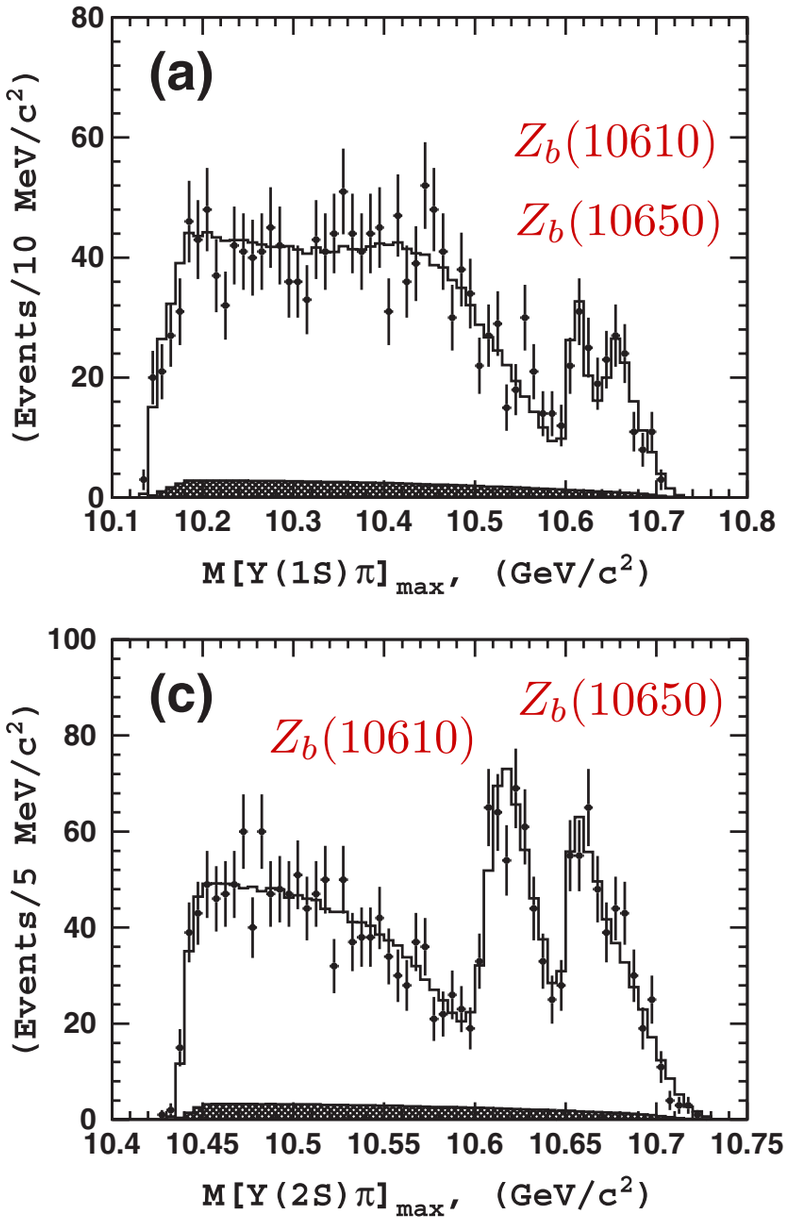


Belle talk by Junhao Yin on Wednesday

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

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

PRL108,122001 (2012)



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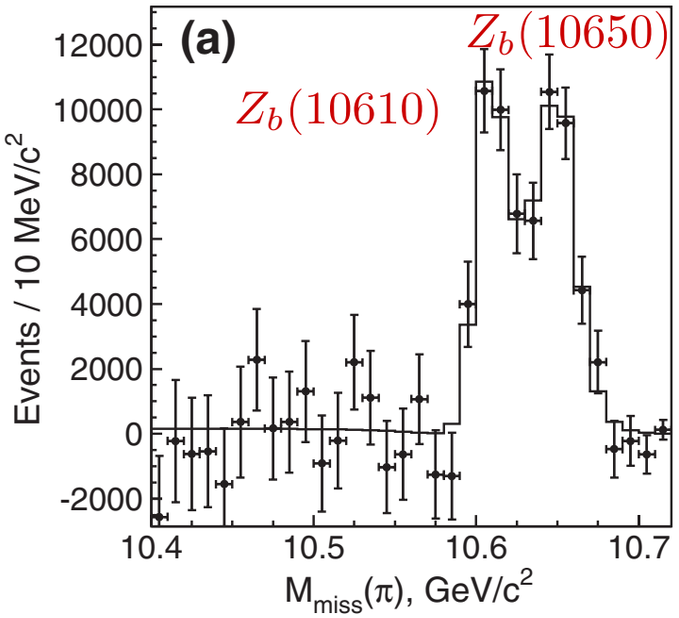
PRL108,122001 (2012)



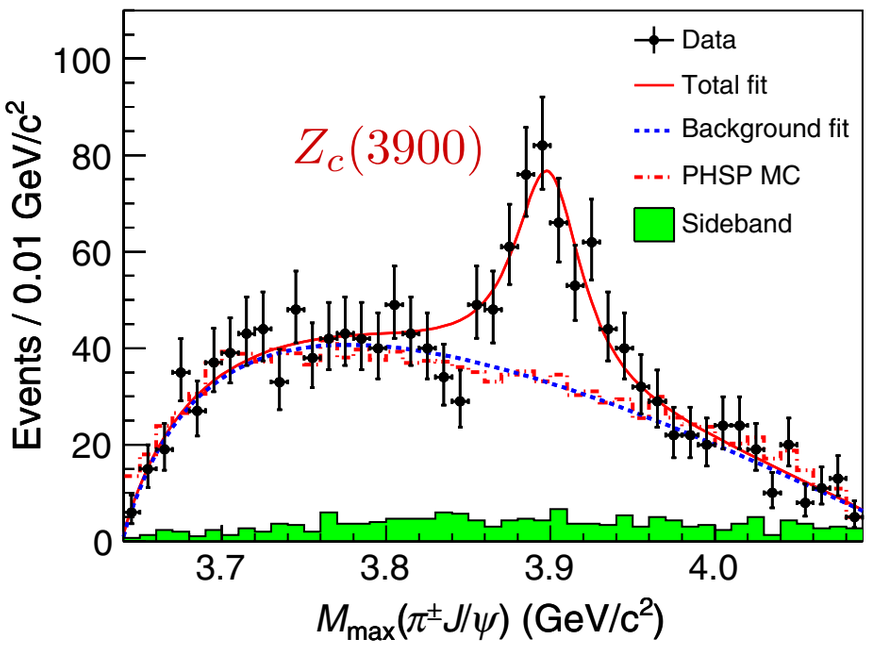
$e^+e^- \to \pi^\pm Z; Z \to (B^{(*)}\bar{B}^*)^\mp$ at Belle

PRL116,212001 (2016)

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

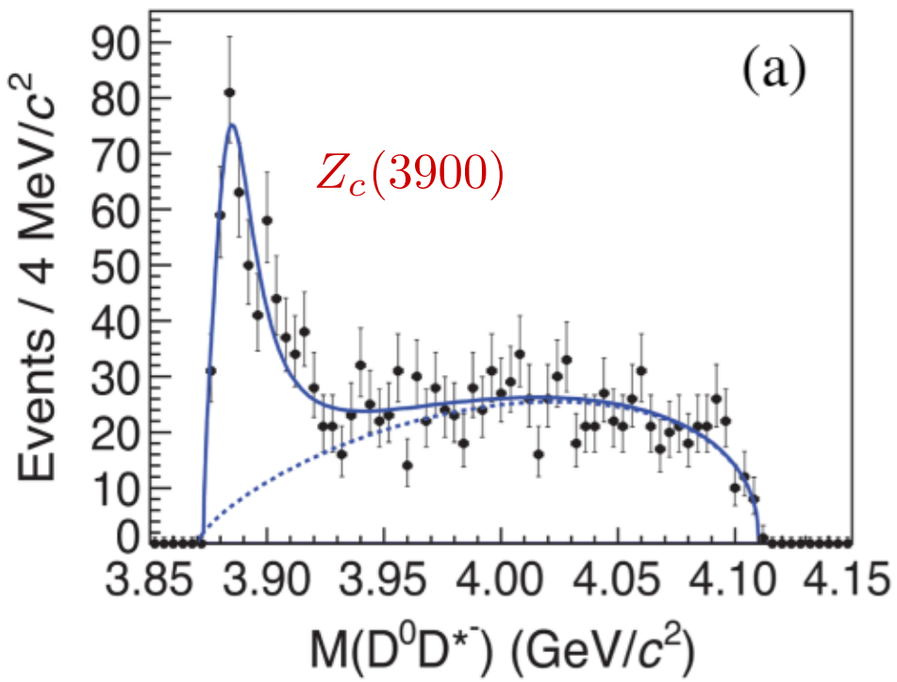
$e^+e^- \to \pi^\pm Z; Z \to \pi^\mp J/\psi$ at BESIII

PRL110,252001 (2013)



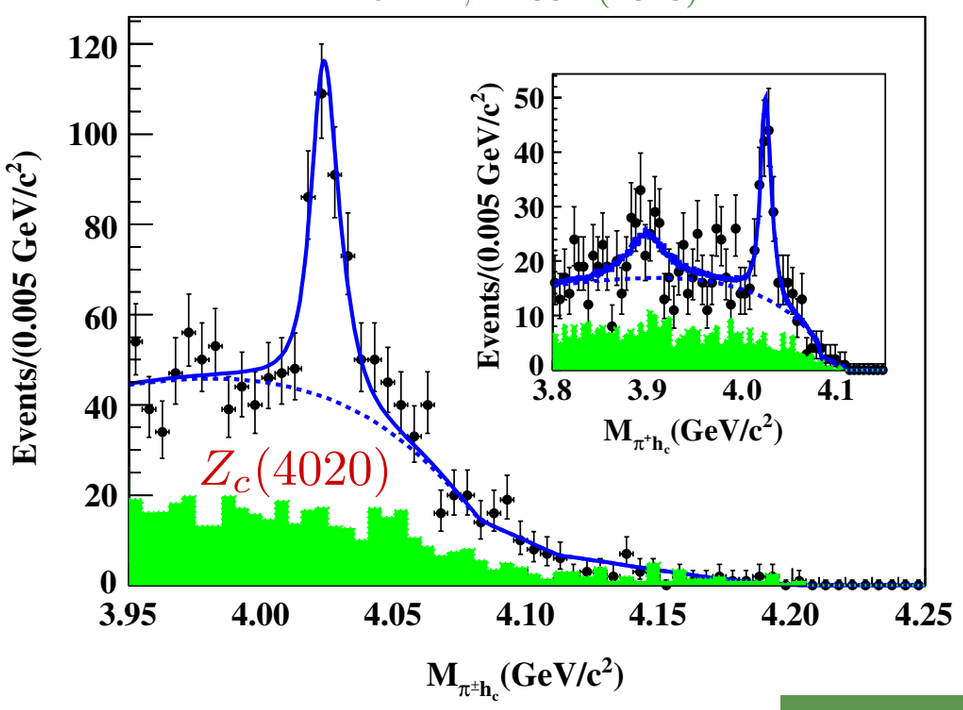
$e^+e^- \to \pi^\pm Z; Z \to (D\bar{D}^*)^\mp$ at BESIII

PRL112,022001 (2014)



$e^+e^- \to \pi^\pm Z; Z \to \pi^\mp h_c(1P)$ at BESIII

PRL111,242001 (2013)



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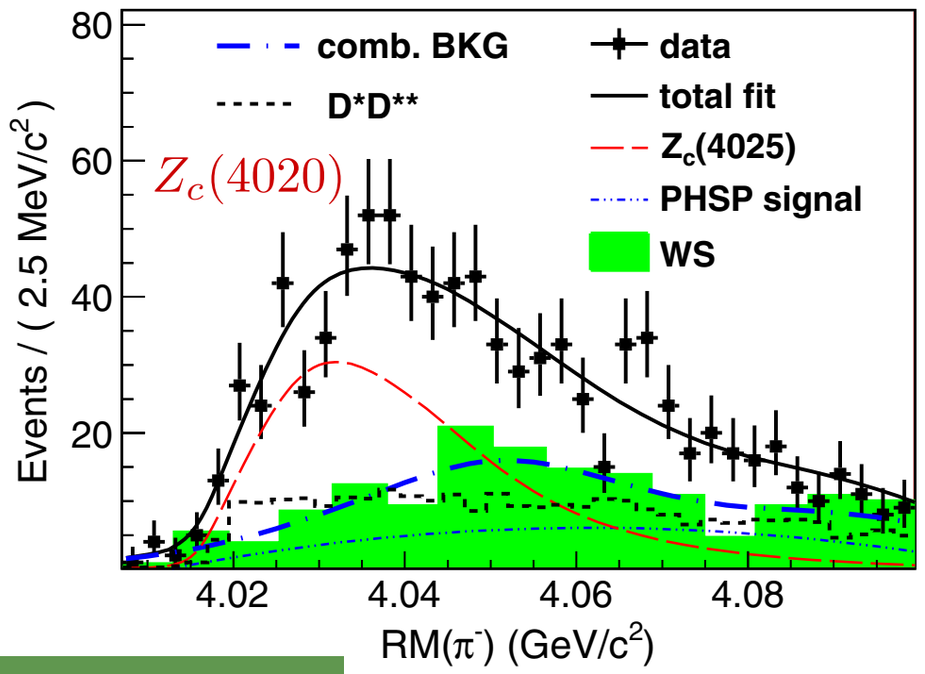
PRL112,132001 (2014)



BESIII talk by Peirong Li on Tuesday

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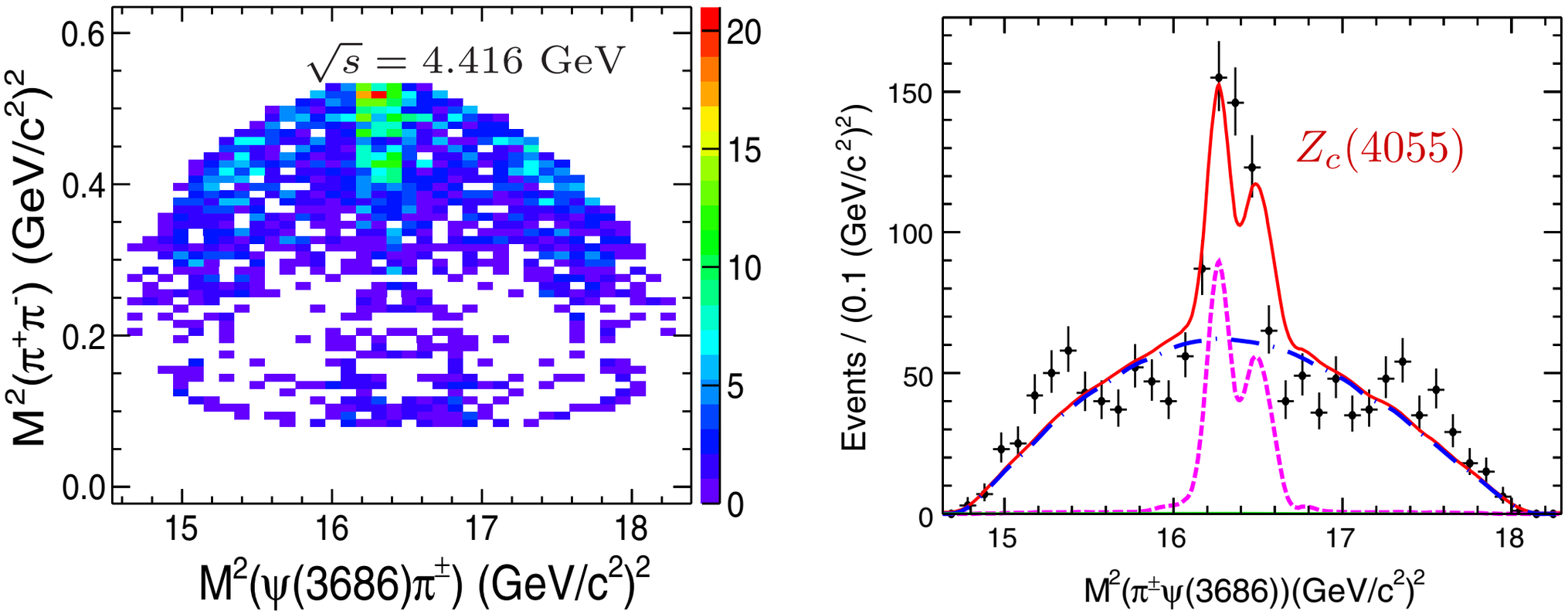
PRD 96, 032004 (2017)



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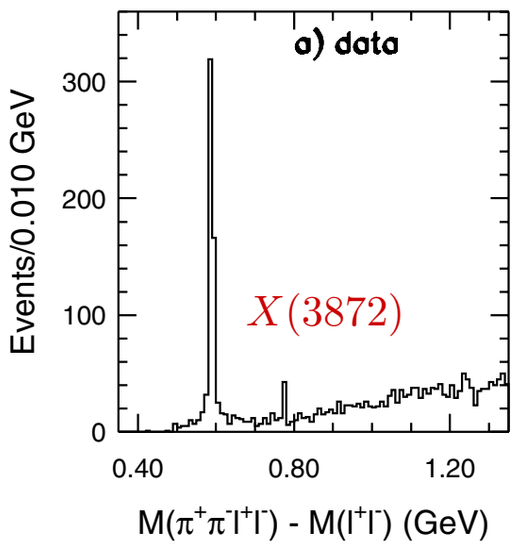

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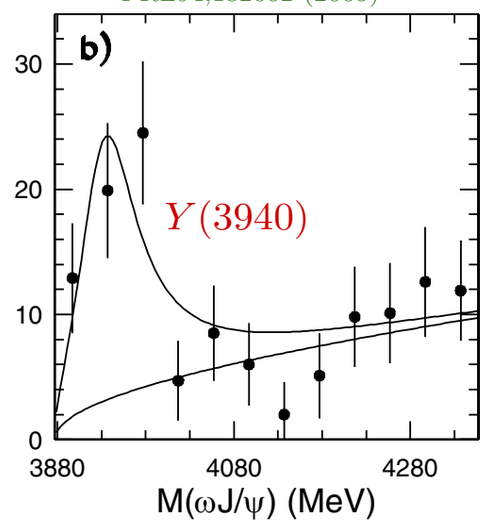

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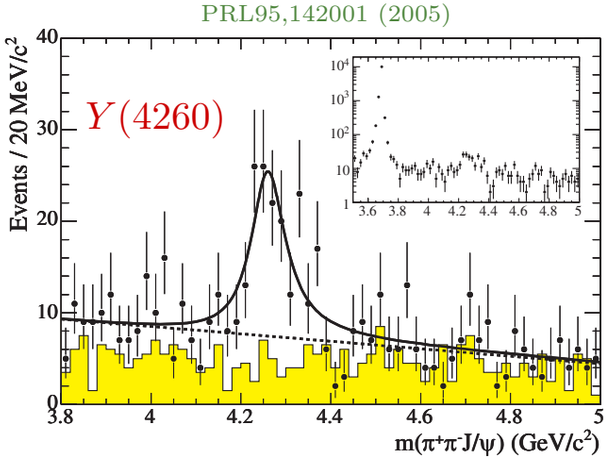

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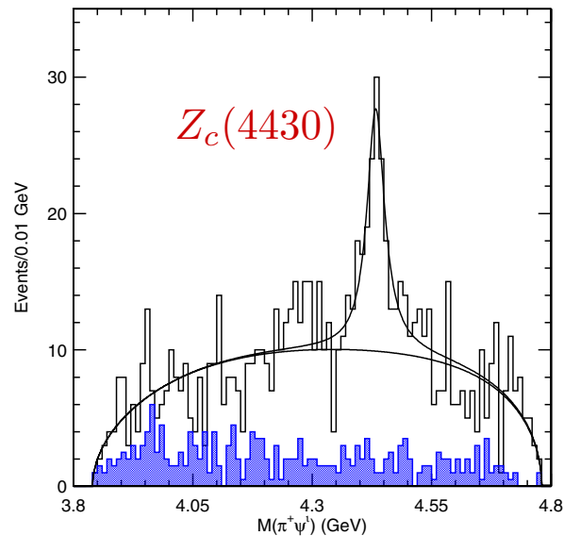

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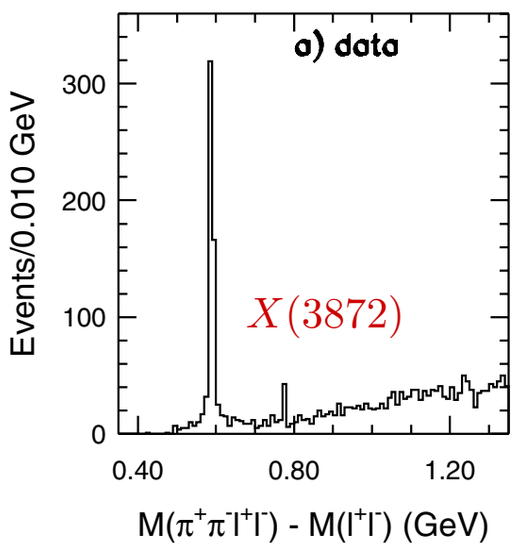

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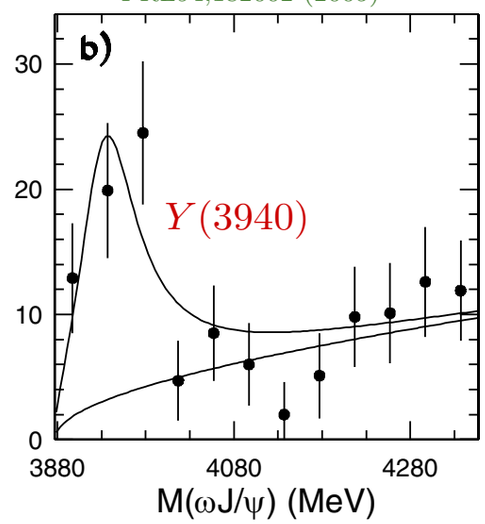

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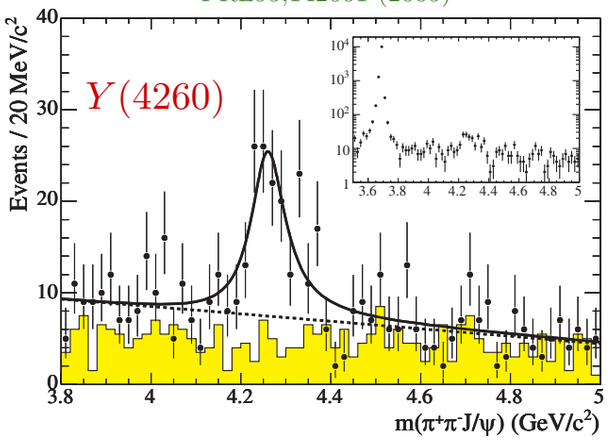
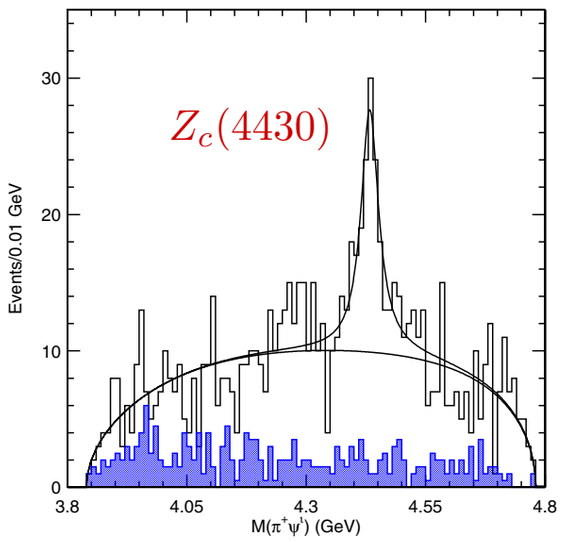
PRL95,142001 (2005)



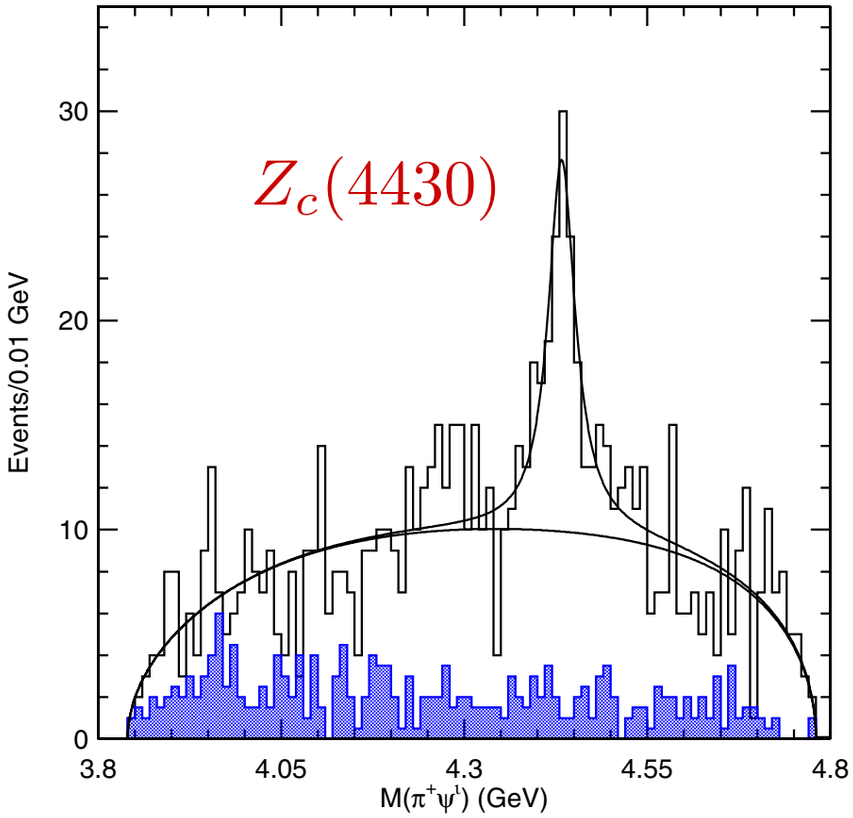
$B \to KZ; Z \to \pi^\pm\psi(2S)$ at Belle
PRL100,142001 (2008)



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

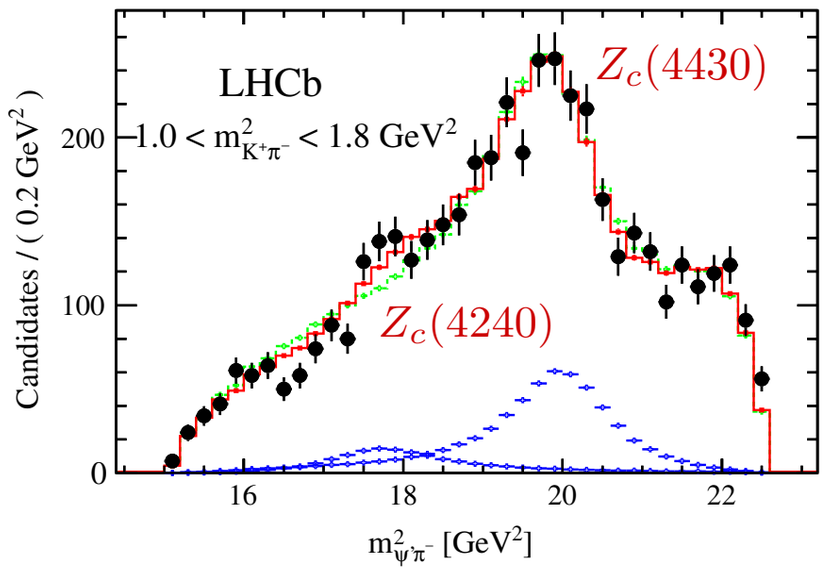
$B \to KZ; Z \to \pi^{\pm}\psi(2S)$ at Belle

PRL100,142001 (2008)



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

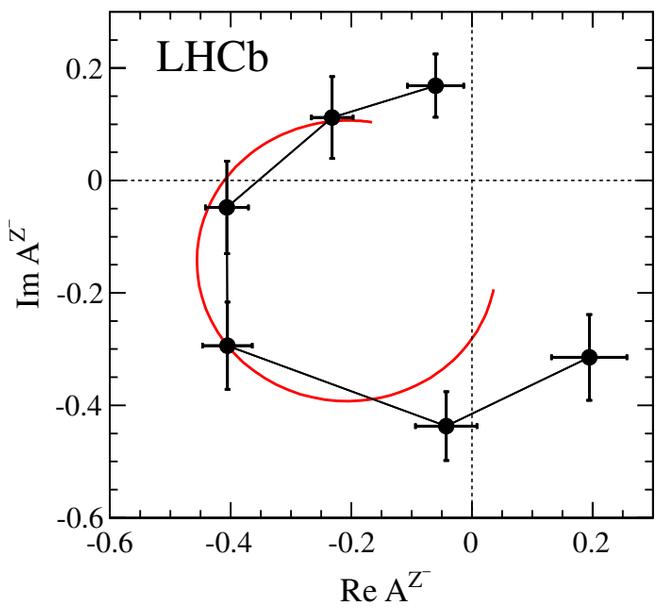
PRL112,222002 (2014)



confirmed by LHCb

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

PRL112,222002 (2014)

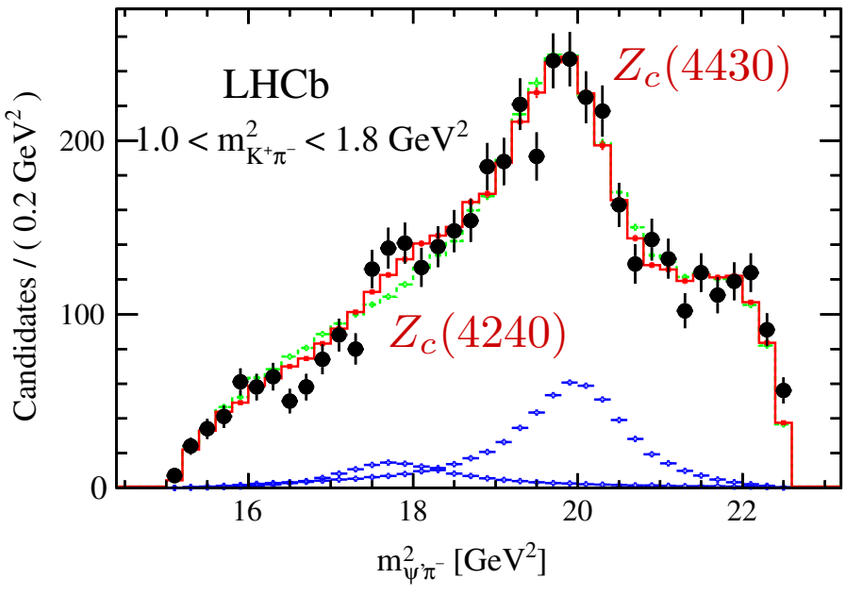


phase motion measured

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

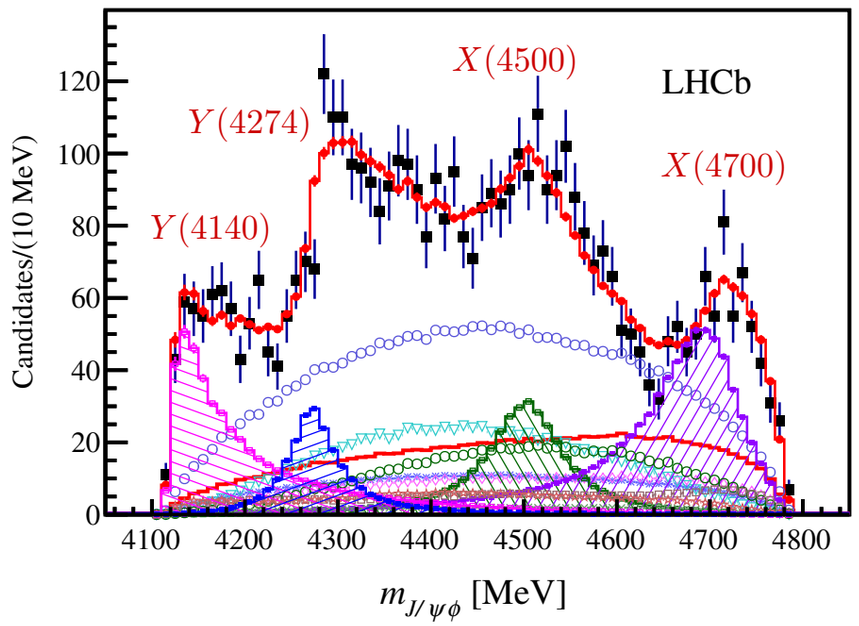
$B \to KZ; Z \to \pi^{\pm}\psi(2S)$ at LHCb

PRL112,222002 (2014)



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

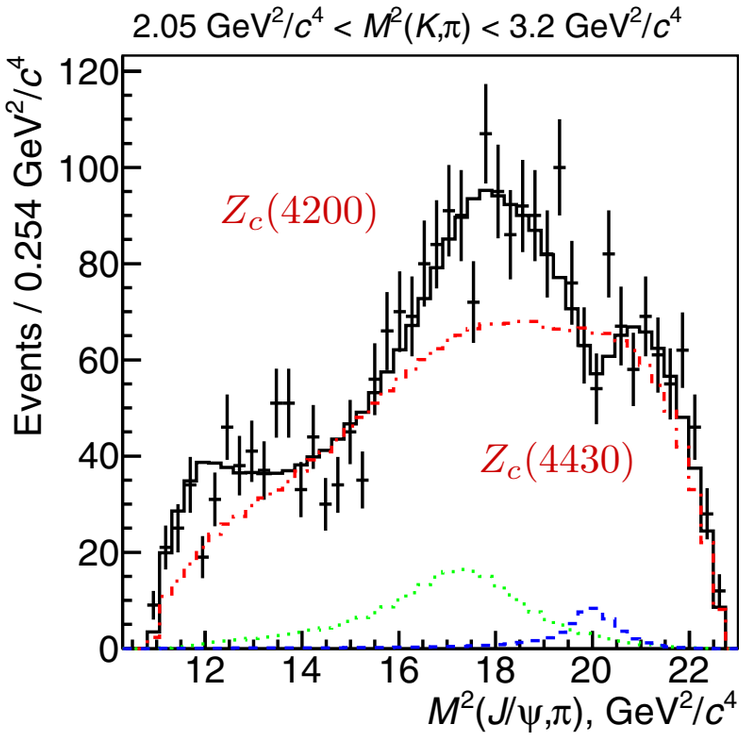
PRL118,022003 (2017)



LHCb talk by M. Pappagallo on Monday

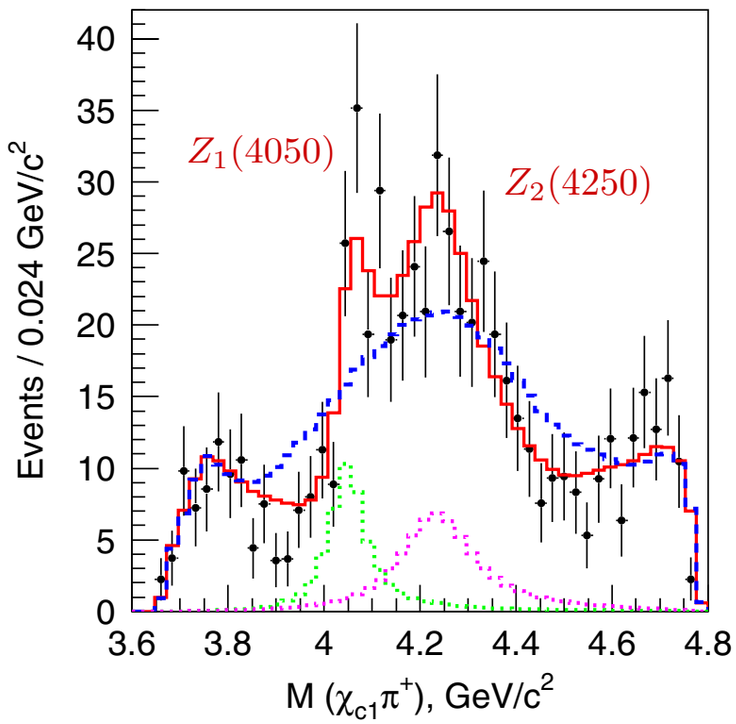
$B \to KZ; Z \to \pi^{\pm}J/\psi$ at Belle

PRD90,112009 (2014)



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

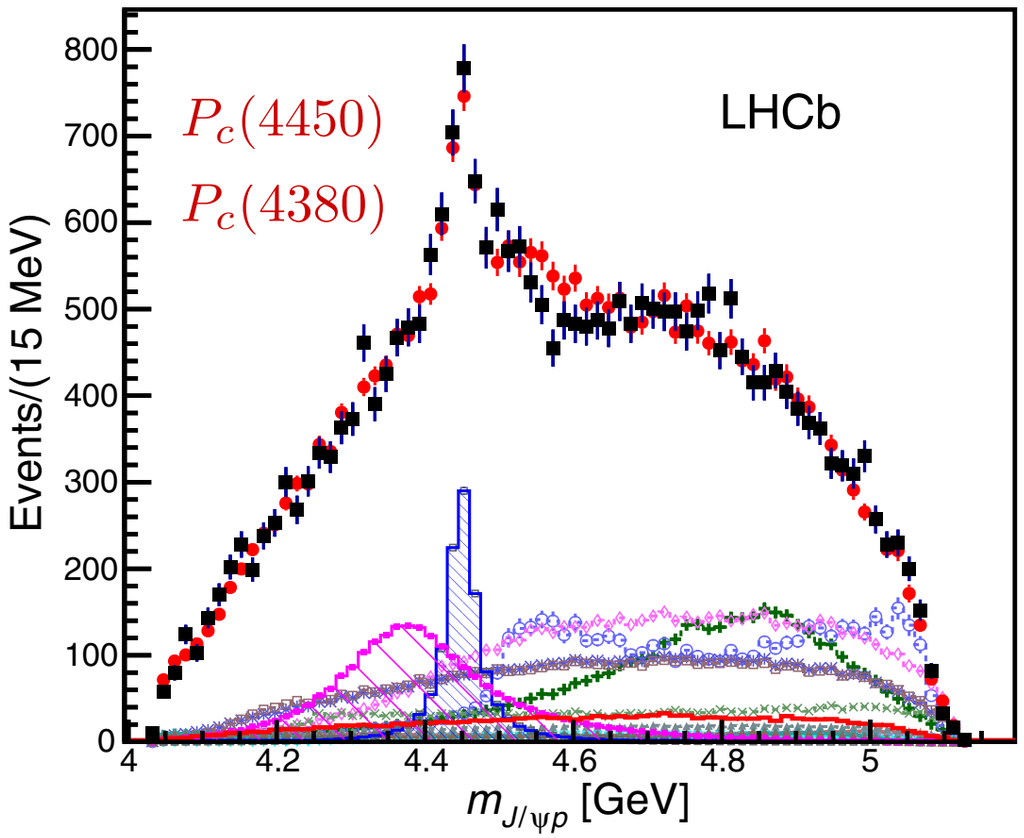
PRD78,072004 (2008)



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

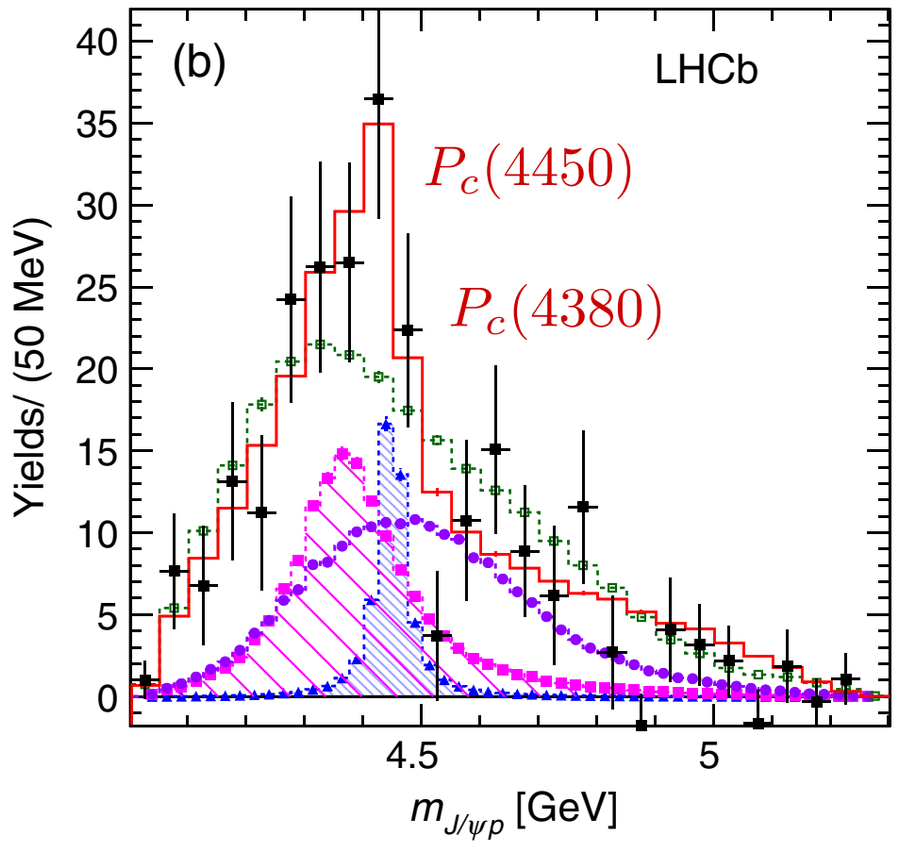
$\Lambda_b \to KP; P \to pJ/\psi$ at LHCb

PRL115,072001 (2015)



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

PRL 117, 082003 (2016)



Baryon talk by S. Neubert on Monday

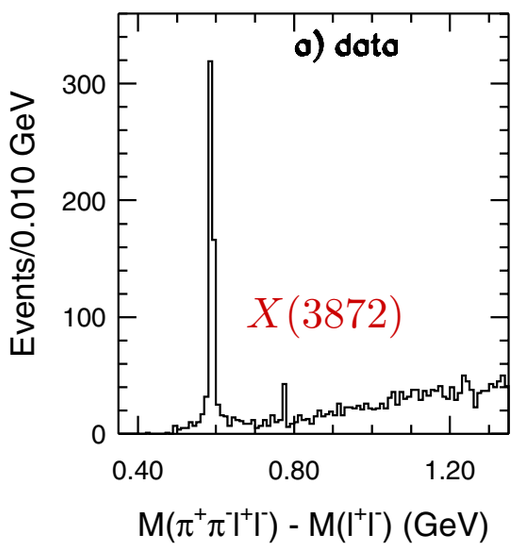
[OUTLINE] A Tour through the XYZ

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

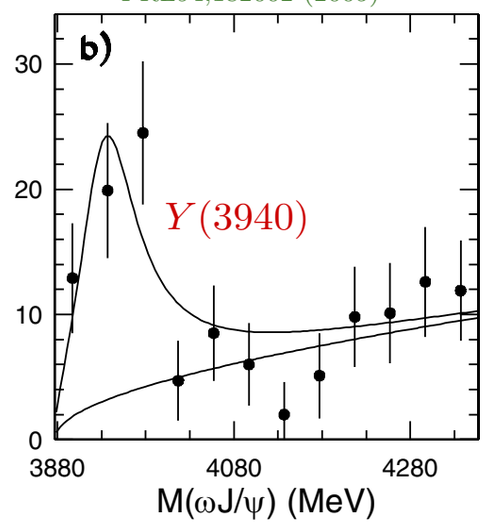
[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
The ongoing search for the χ_{c0}(2P).

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



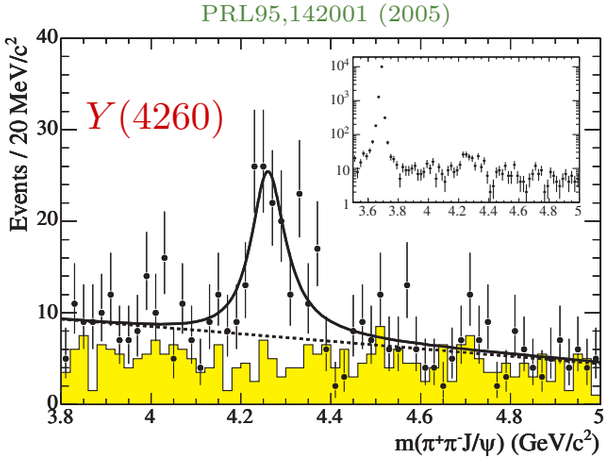
$B \to KX; X \to \omega J/\psi$ at Belle
PRL94,182002 (2005)



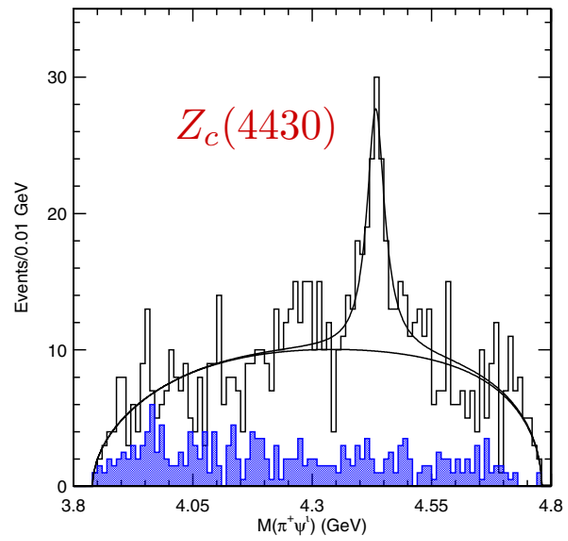
[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e^+e^- cross sections ("Y states").
Peaks in their decays ("Z states").

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

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



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



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[Part III: Y(4260)]
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[Part IV: Z_c(4430)]
What happened to the $Z_c(4430)$?
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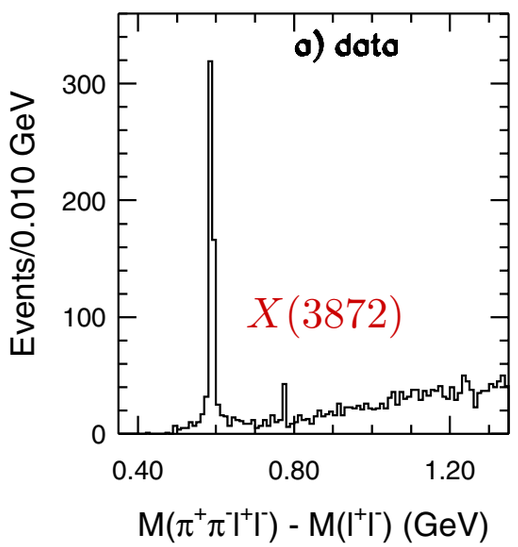
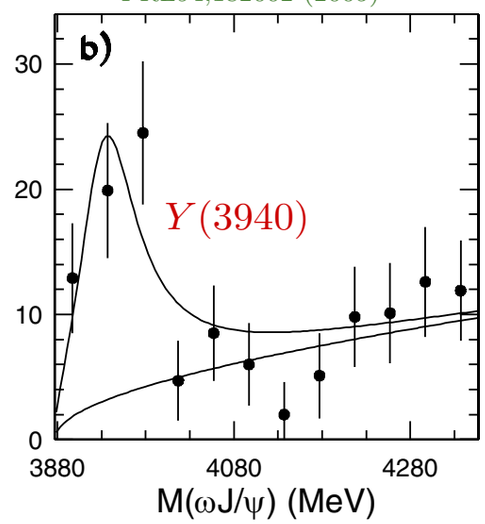
Peaks in Λ_b decays.

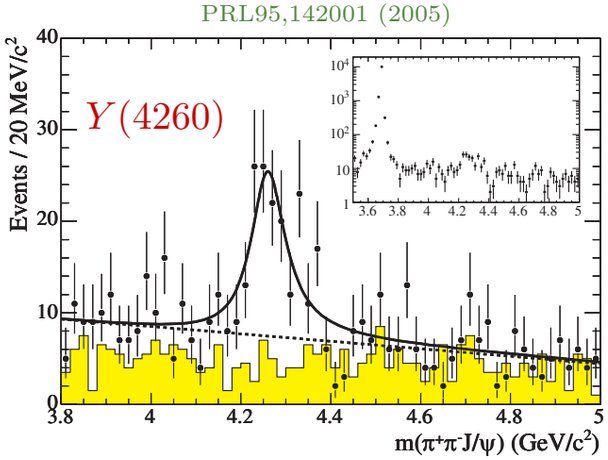
$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle
PRL91,262001 (2003)



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



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



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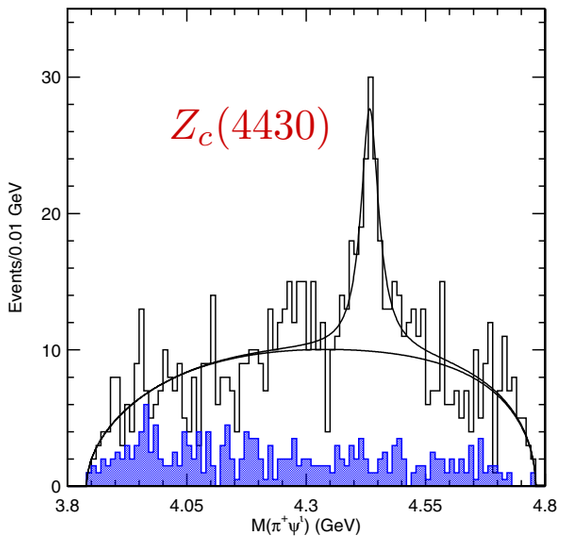

Closing Thoughts on the Future of Heavy Quark Exotica

(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 has no end in sight:
BESIII and LHC experiments will continue…
Belle II will soon be online…

(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!