HUGS 2021 Lectures on:
Experimental Meson Spectroscopy

LECTURE IV. Exotic Mesons

- IVA. Exotic Meson Identification
- IVB. Exotic Charmonium
- IVC. Exotic Bottomonium
- IVD. Exotic Light Quark Mesons

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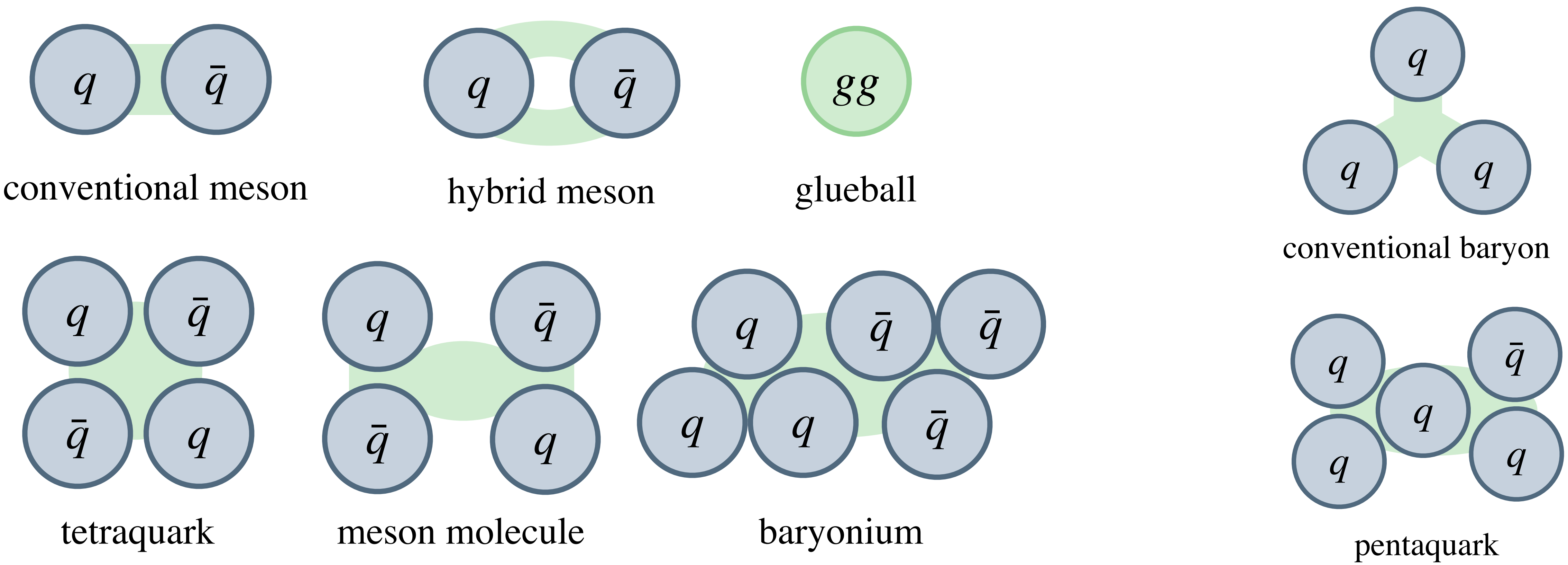
IVA. Exotic Meson Identification

A variety of color-singlet meson states are allowed, in principle:

MESONS **BARYONS**



All non-$q\bar{q}$ mesons and all non-qqq baryons are "exotic"

(note: sometimes "exotic" is reserved for non-$q\bar{q}$ J^{PC}, like 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, $\ldots$).

IVA. Exotic Meson Identification

Exotic mesons can be distinguished from conventional mesons in at least four ways:

1. unusual properties
   e.g. $X(3872)$

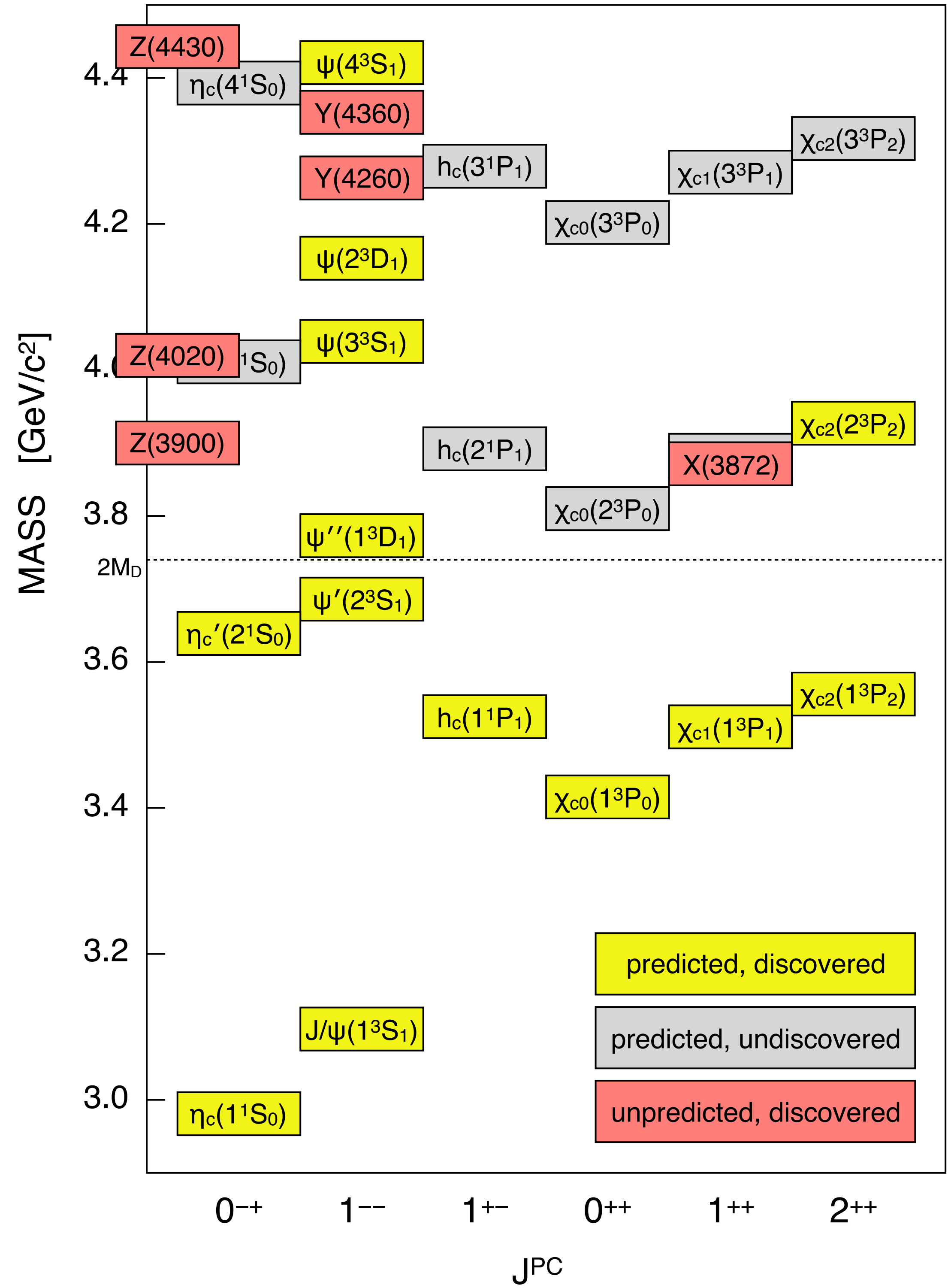
2. overpopulation
   e.g. $Y(4260)$, $Y(4360)$

3. exotic flavor
   e.g. $Z_c(3900)$, $Z_c(4020)$

4. exotic J^{PC}
   e.g. $\pi_1(1600)$

major caveat: an exotic hadron must also be a hadron (as opposed to a scattering artifact, for example)

Charmonium



This talk: charmonium, bottomonium, light quark mesons.

IVB. Exotic Charmonium

Physics Reports 873 (2020) 1–154

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The *XYZ* states: Experimental and theoretical status and perspectives

Nora Brambilla[l,m], Simon Eidelman[b,k,h], Christoph Hanhart[f,*], Alexey Nefediev[h,i,j], Cheng-Ping Shen[e,a,**], Christopher E. Thomas[d], Antonio Vairo[l], Chang-Zheng Yuan[g,c]

REVIEWS OF MODERN PHYSICS, VOLUME 90, JANUARY–MARCH 2018

Nonstandard heavy mesons and baryons: Experimental evidence

Stephen Lars Olsen[*]

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Progress in Particle and Nuclear Physics 93 (2017) 143–194

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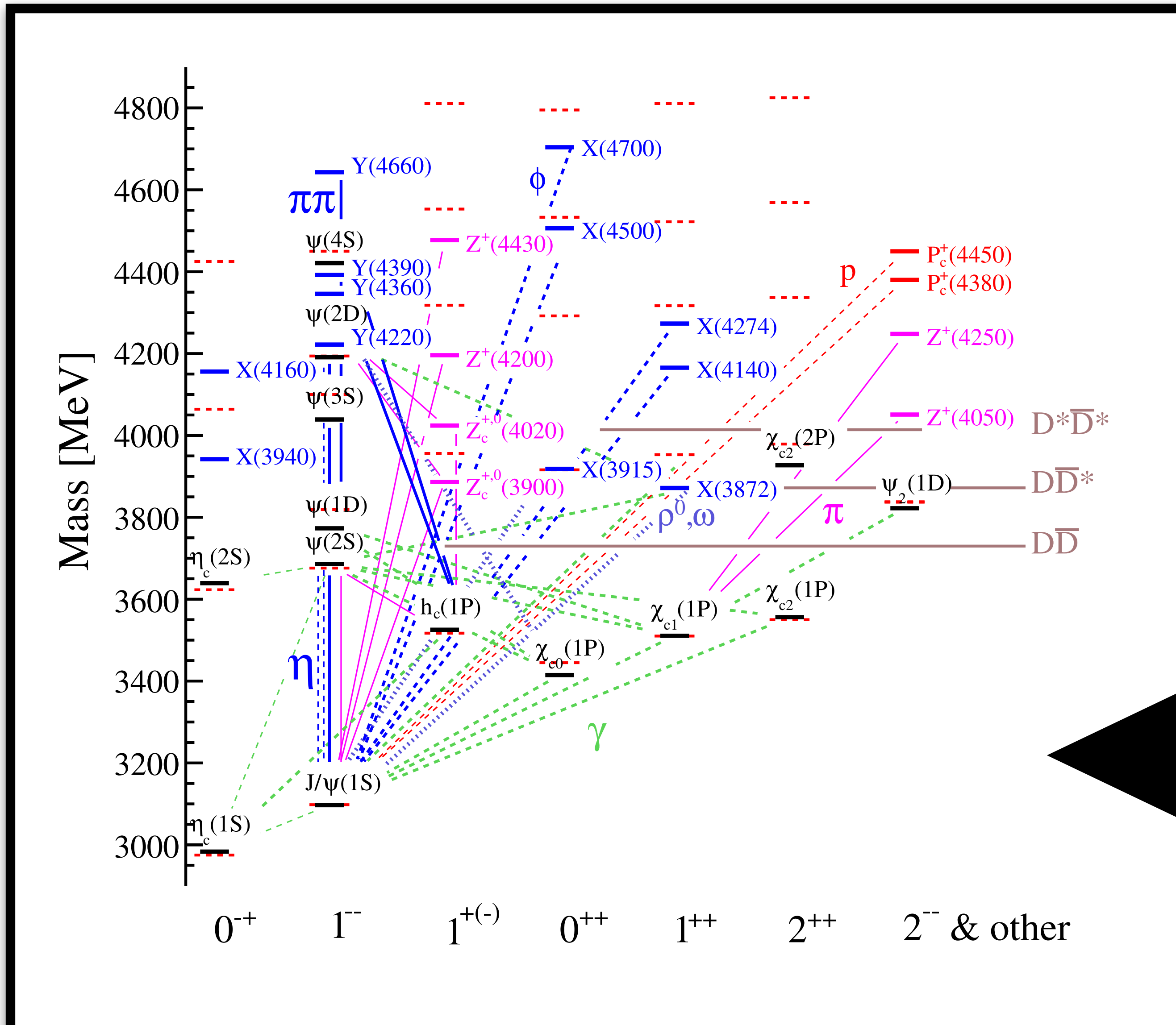
Review

Heavy-quark QCD exotica

Richard F. Lebed[a,*], Ryan E. Mitchell[b], Eric S. Swanson[c]

IVB. Exotic Charmonium



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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]	$120 \pm 31^{+42}_{-33}$	$B \to KX;\ X \to \phi J/\psi$

IVB. Exotic Charmonium

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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.

IVB. Exotic Charmonium

The basics of exotic charmonium (or “charmoniumlike” states):

$\chi_{c1}(3872)$
aka $X(3872)$

$\psi(4230)$ and $\psi(4360)$
aka Y(4260) and Y(4360)

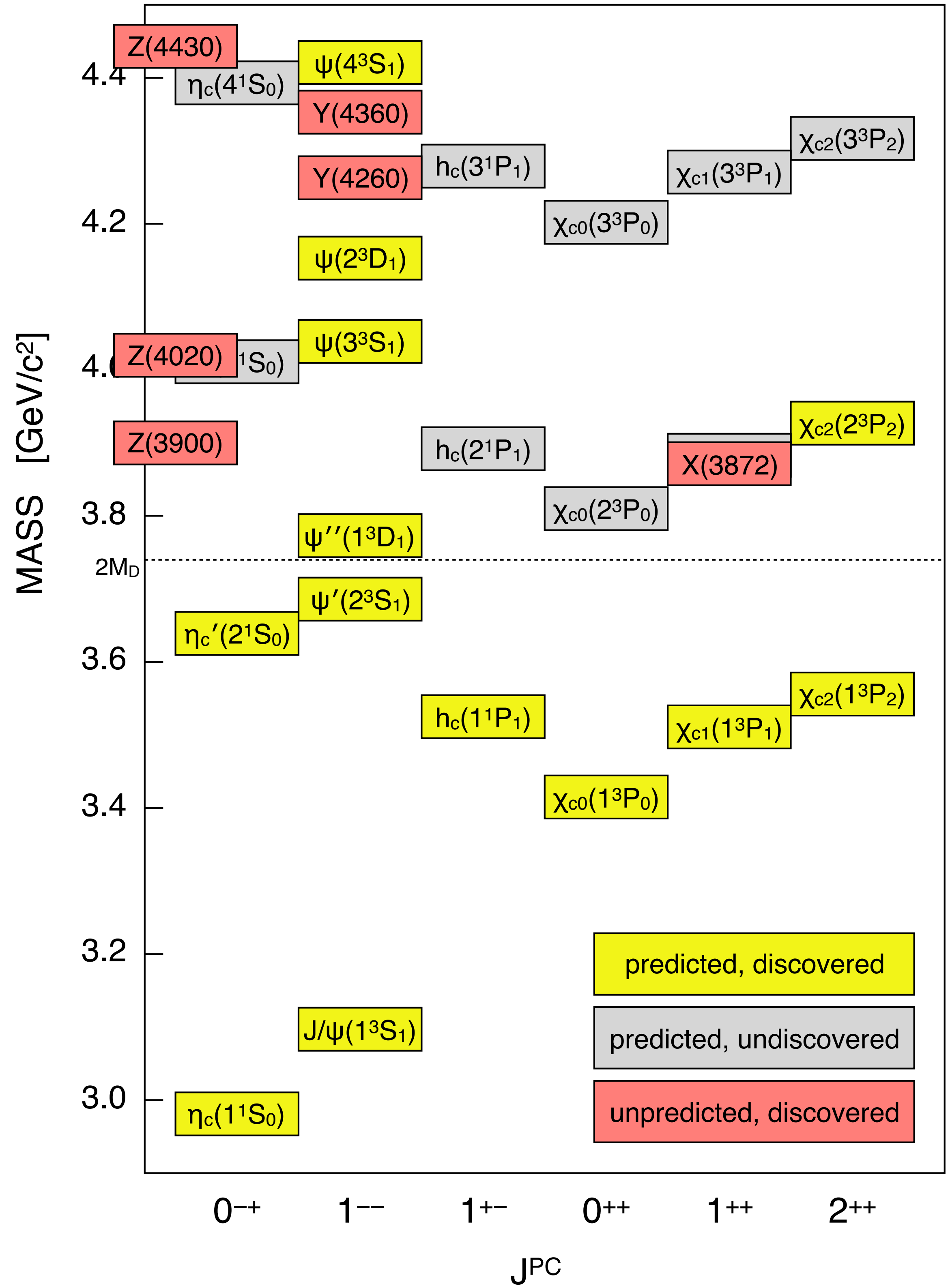
$Z_c(3900)$ and $Z_c(4020)$

Z_c mesons in B decays

Original names (still commonly used):

Y: mesons made directly in e^+e^-
Z: “charmonium” with $I \neq 0$.
X: everything else

Charmonium



IVB. Exotic Charmonium

PDG names:

$J^{PC} = \{$	0^{-+}, 2^{-+}, $\vdots$	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 $s\bar{s}$ $(I = 0)$	η, η'	h, h'	ω, ϕ	f, f'
$c\bar{c}$	η_c	h_c	ψ	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)

Original names (still commonly used):

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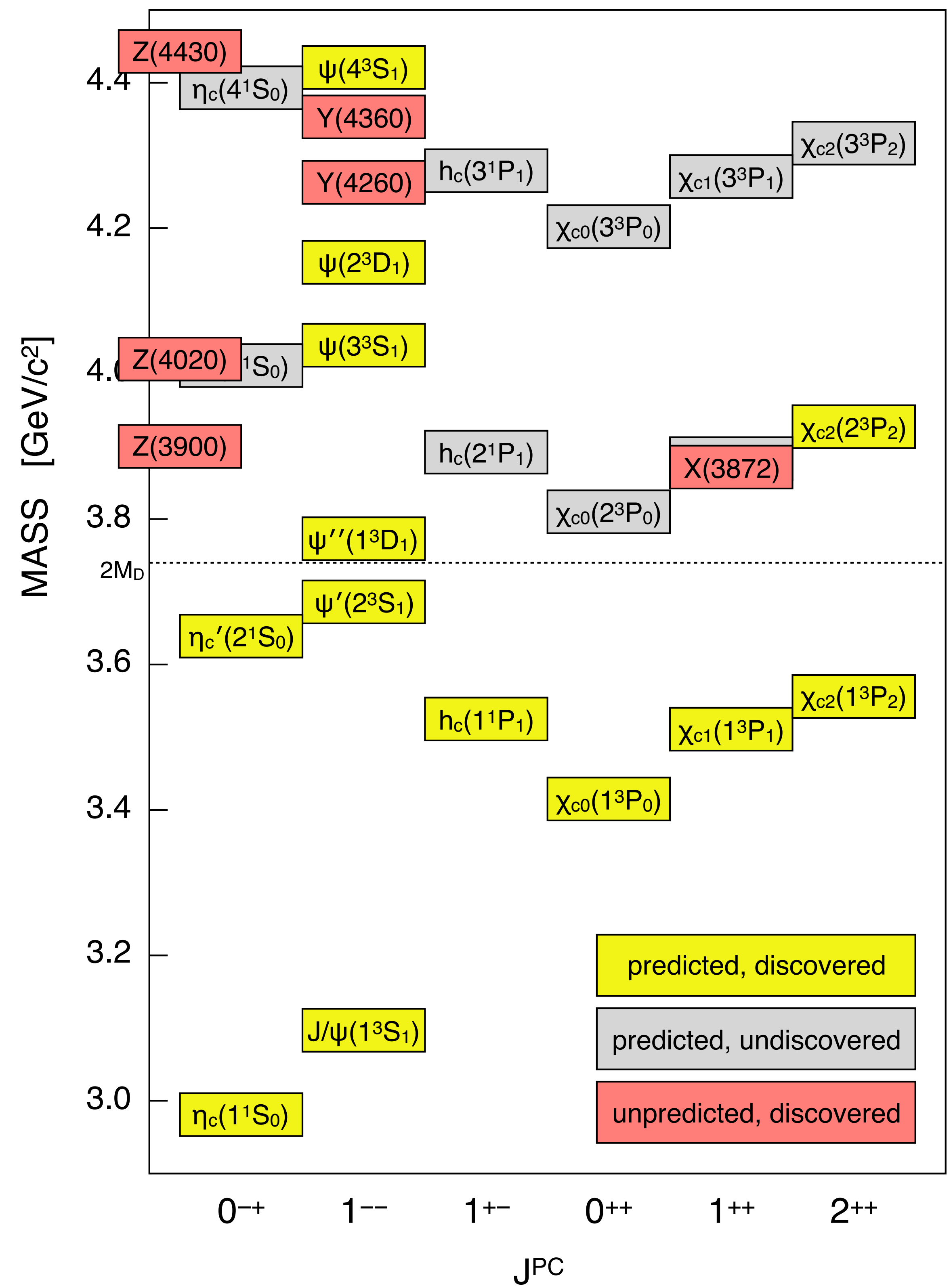


IVB. Exotic Charmonium: X(3872)

properties of the
$\chi_{c1}(3872)$ aka $X(3872)$:

(1) discovered at Belle in 2003
in $B \to K(\pi^+\pi^- J/\psi)$

(2) isoscalar but decays to $\rho J/\psi$
$\Longrightarrow$ large isospin violation

(3) $J^{PC} = 1^{++}$

(4) produced in $e^+e^- \to \gamma X$
in a narrow range of e^+e^- energies

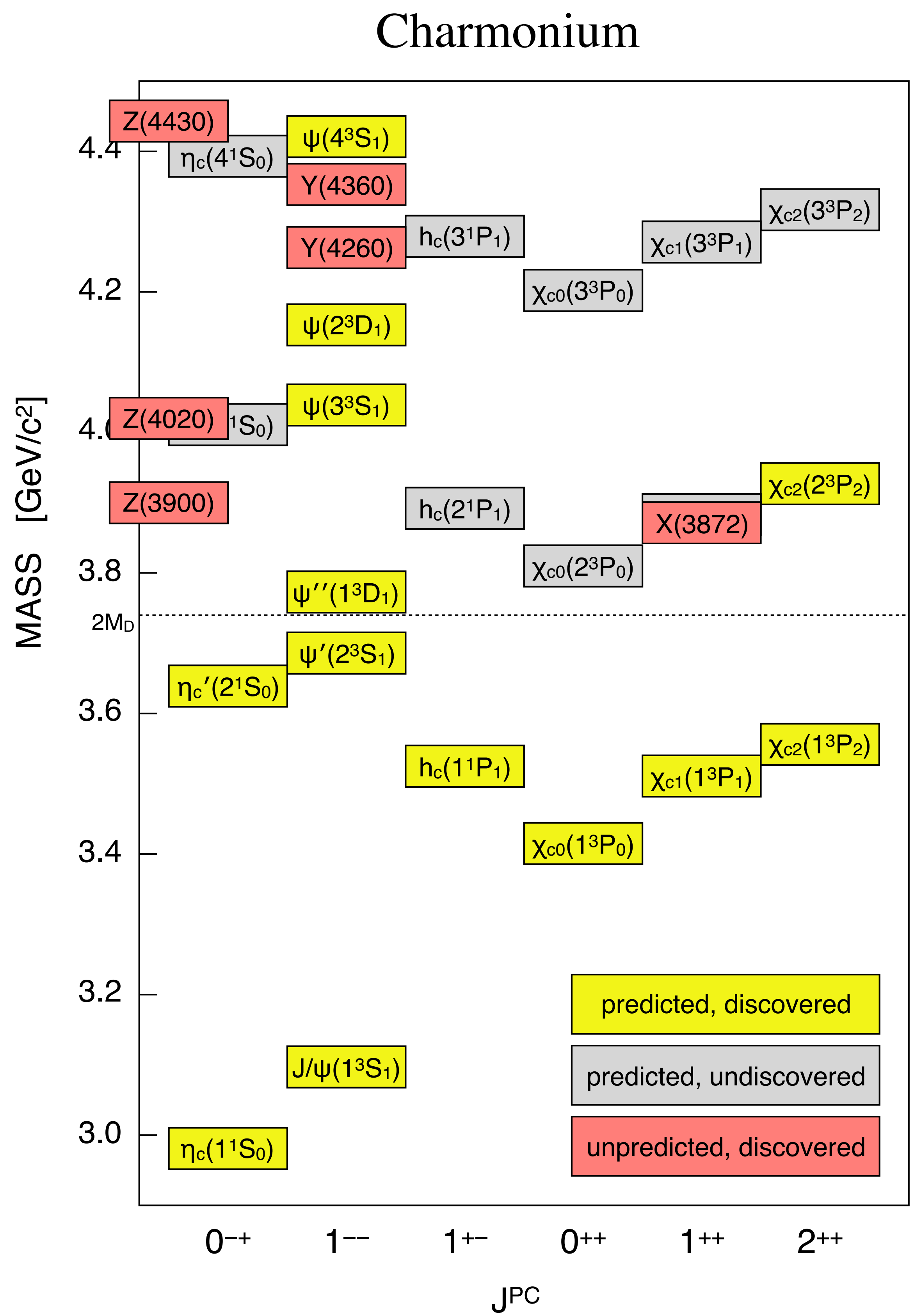
(5) a variety of decays have
been discovered

(6) mass is extremely
close to $D^0\bar{D}^{*0}$ threshold

(7) width is extremely narrow

(8) inconsistent with
quark model expectations
for the $\chi_{c1}(2P)$

(9) production may
hold clues to it's internal structure



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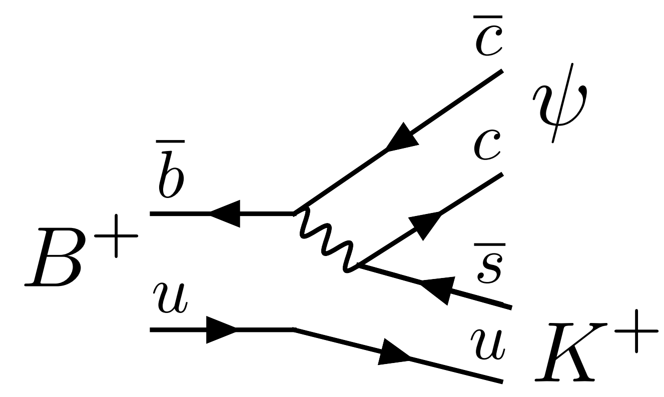
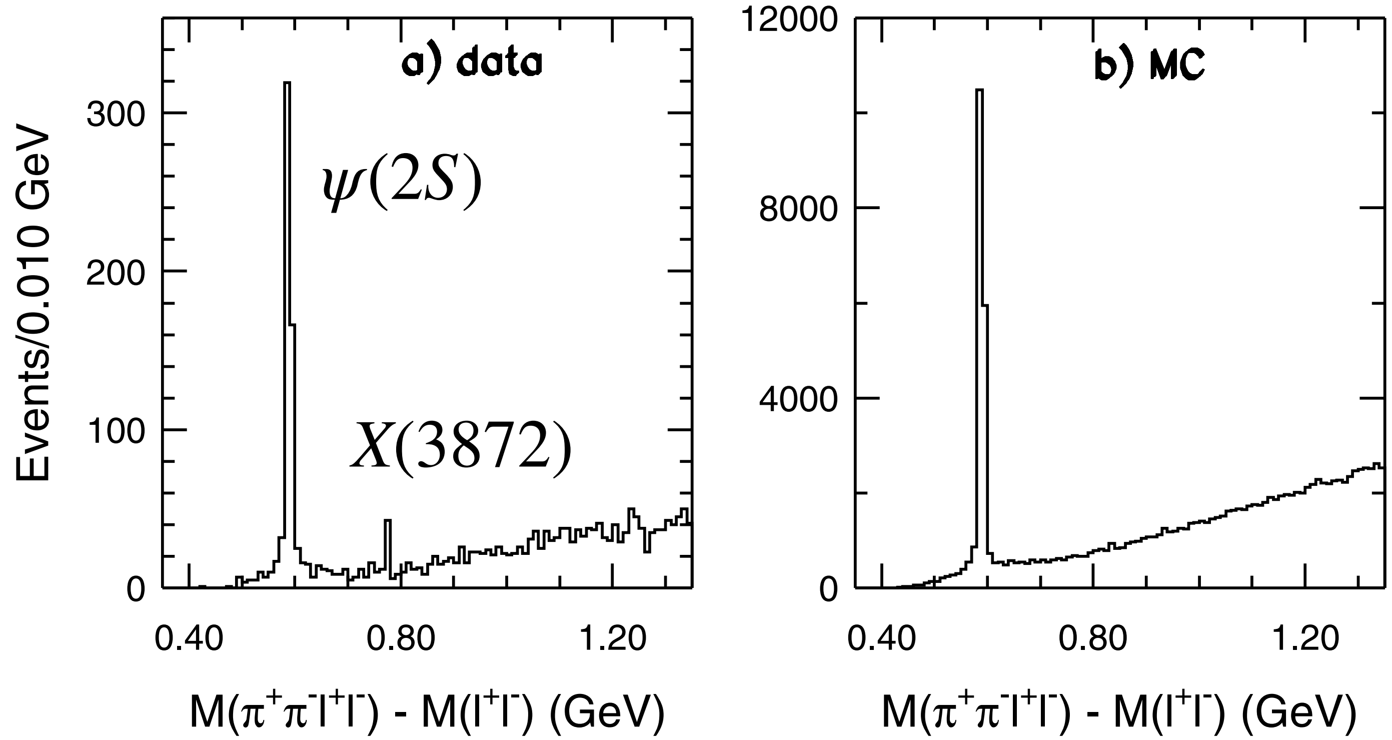
B decays at Belle, BaBar, LHCb, etc.



VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

Observation of a Narrow Charmoniumlike State in Exclusive $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$ Decays

(Belle Collaboration)



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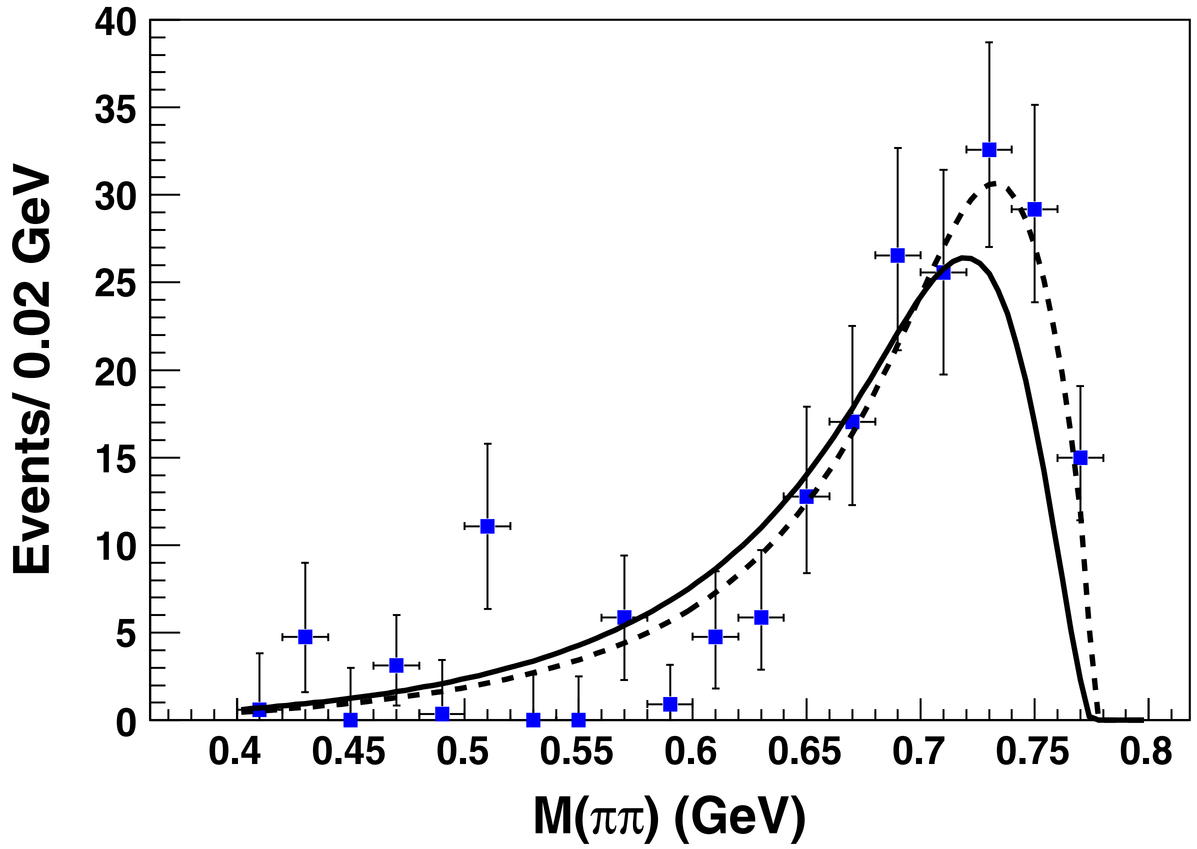
Belle found $B^+ \to K^+X^0$ but not $B^+ \to K^0X^+$, which you would expect if I = 1.

PHYSICAL REVIEW D **84,** 052004 (2011)

Bounds on the width, mass difference and other properties of $X(3872) \to \pi^+\pi^- J/\psi$ decays

(The Belle Collaboration)



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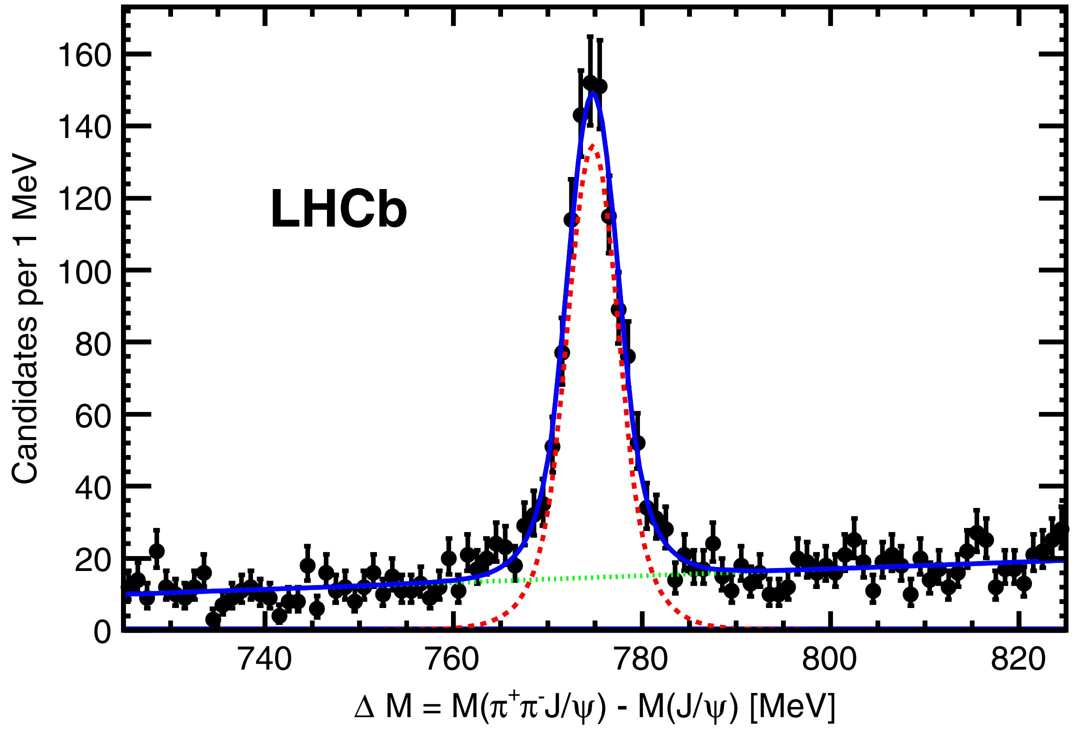
PHYSICAL REVIEW D **92,** 011102(R) (2015)

Quantum numbers of the $X(3872)$ state and orbital angular momentum in its $\rho^0 J/\psi$ decay

R. Aaij *et al.**
(LHCb Collaboration)



Perform an amplitude analysis using the decay chain:

$$B^+ \to X(3872)K^+$$
$$X(3872) \to \rho^0 J/\psi$$
$$\rho^0 \to \pi^+\pi^-$$
$$J/\psi \to \mu^+\mu^-$$

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Angular distribution:

$$\sum_{\Delta\lambda_\mu=-1,+1} \Big| \sum_{\lambda_{J/\psi},\lambda_\rho=-1,0,+1} A_{\lambda_{J/\psi},\lambda_\rho}\, D^{J_X}_{0,\lambda_{J/\psi}-\lambda_\rho}(0,\theta_X,0)^* \, D^1_{\lambda_\rho,0}(\Delta\phi_{X,\rho},\theta_\rho,0)^*\, D^1_{\lambda_{J/\psi},\Delta\lambda_\mu}(\Delta\phi_{X,J/\psi},\theta_{J/\psi},0)^* \Big|^2$$

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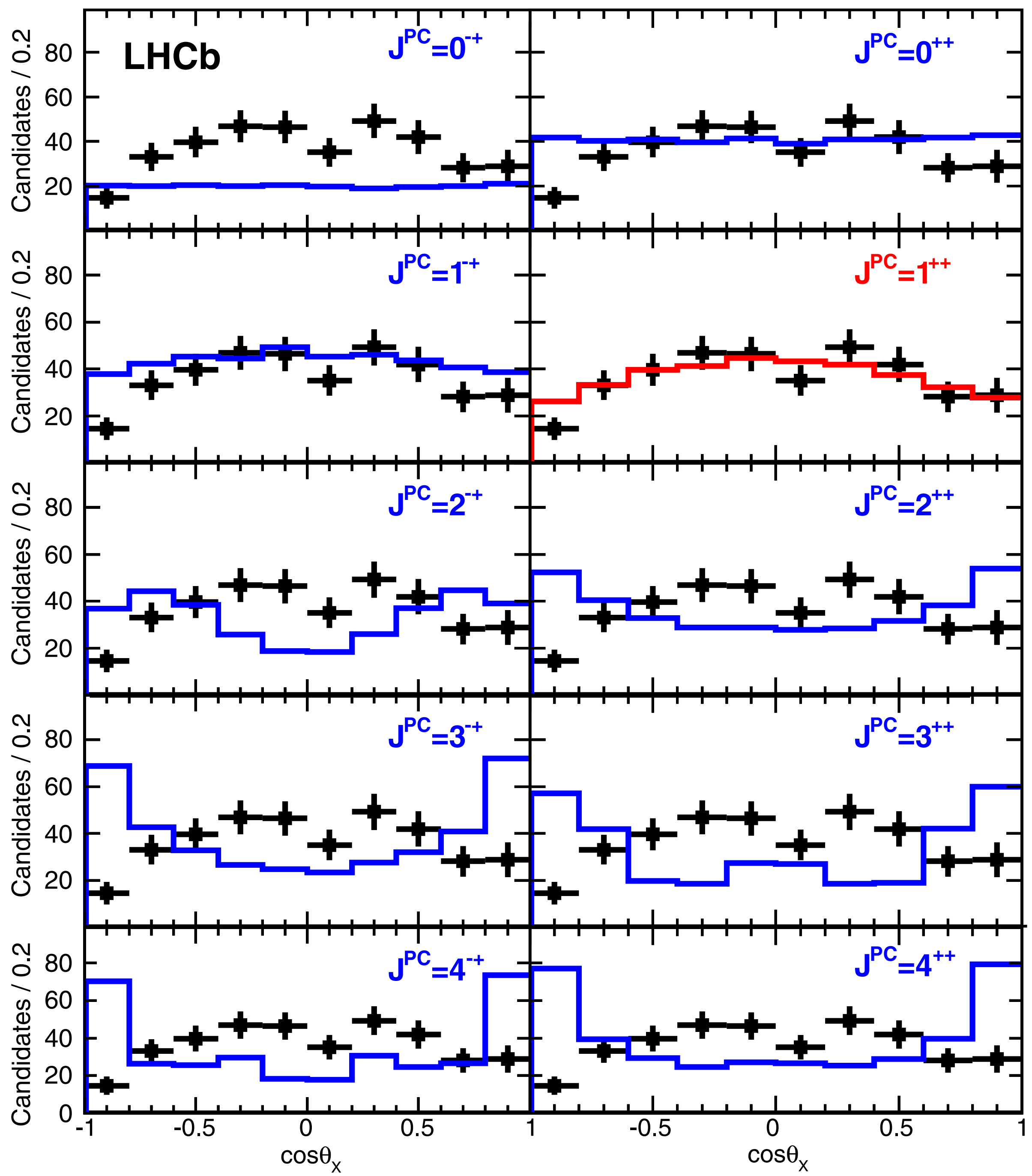

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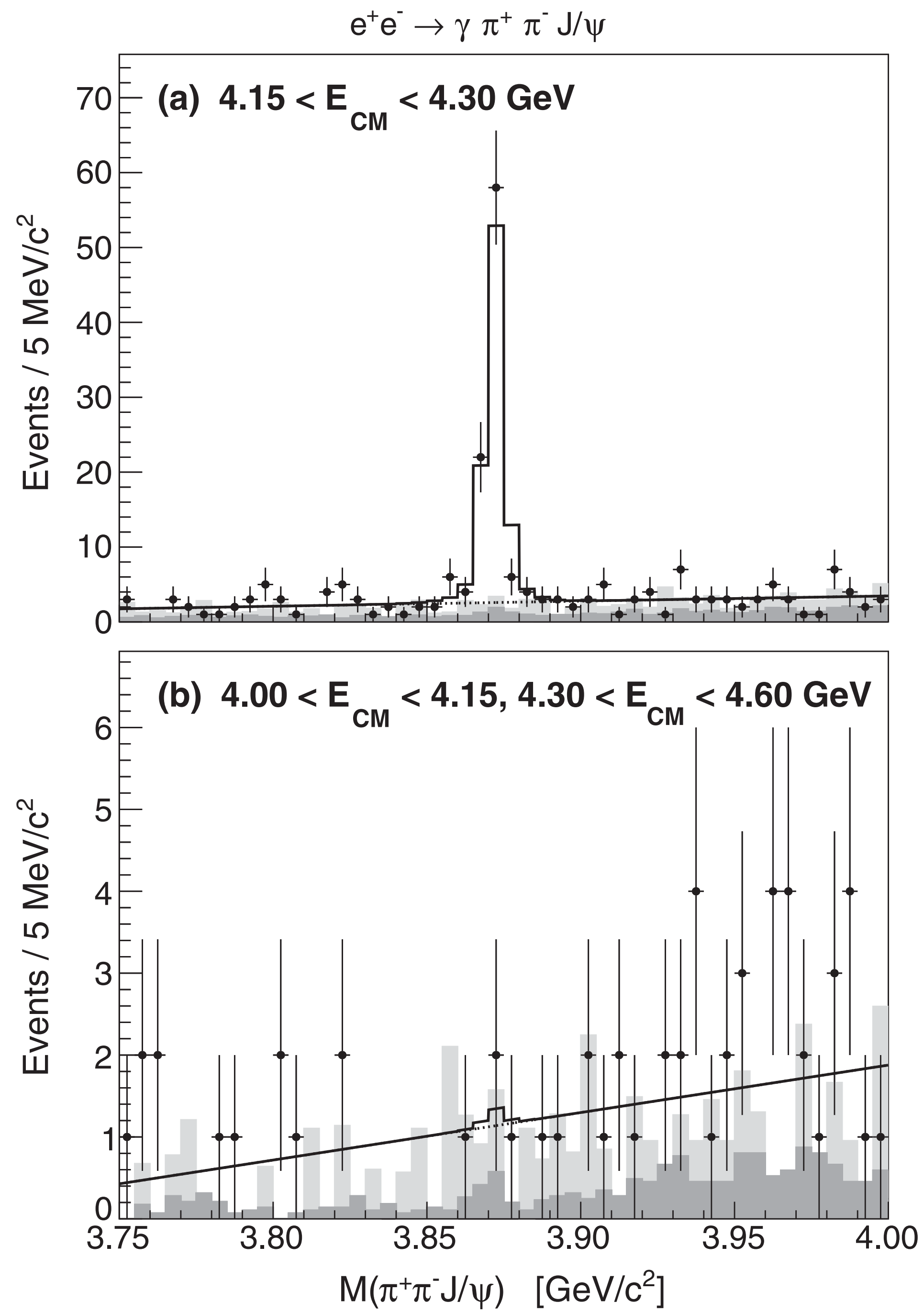
PHYSICAL REVIEW LETTERS **122,** 202001 (2019)

Observation of the Decay $X(3872) \to \pi^0\chi_{c1}(1P)$

(BESIII Collaboration)



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$\Longrightarrow$ large isospin violation

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PHYSICAL REVIEW LETTERS **124,** 242001 (2020)

Study of Open-Charm Decays and Radiative Transitions of the $X(3872)$

(BESIII Collaboration)

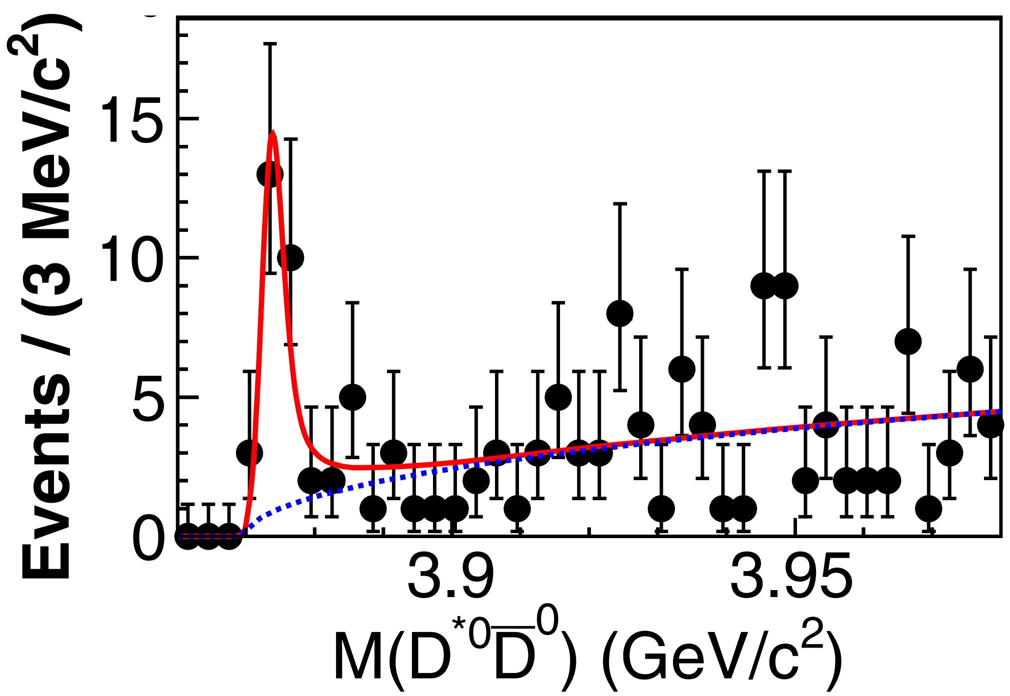

TABLE I. Relative branching ratios and UL on branching ratios compared with $X(3872) \to \pi^+\pi^- J/\psi$ [18,27], where systematic uncertainties have been taken into account.

Mode	Ratio	UL
$\gamma J/\psi$	0.79 ± 0.28	$\cdots$
$\gamma\psi'$	-0.03 ± 0.22	< 0.42
$\gamma D^0\bar{D}^0$	0.54 ± 0.48	< 1.58
$\pi^0 D^0\bar{D}^0$	-0.13 ± 0.47	< 1.16
$D^{*0}\bar{D}^0$ + c.c.	11.77 ± 3.09	$\cdots$
γD^+D^-	$0.00^{+0.48}_{-0.00}$	< 0.99
$\omega J/\psi$	$1.6^{+0.4}_{-0.3} \pm 0.2$ [18]	$\cdots$
$\pi^0\chi_{c1}$	$0.88^{+0.33}_{-0.27} \pm 0.10$ [27]	$\cdots$

IVB. Exotic Charmonium: X(3872)

properties of the
$\chi_{c1}(3872)$ aka $X(3872)$:

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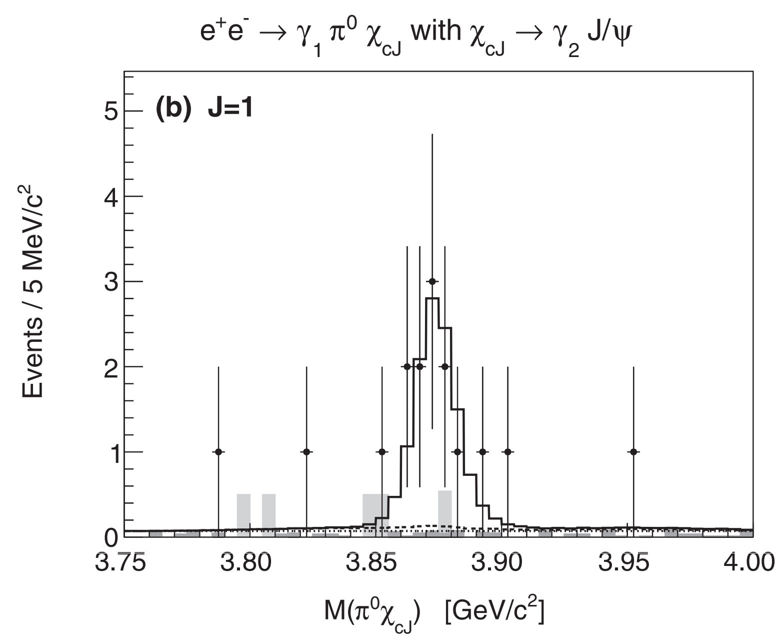
PHYSICAL REVIEW LETTERS **122,** 202001 (2019)

Observation of the Decay $X(3872) \to \pi^0\chi_{c1}(1P)$

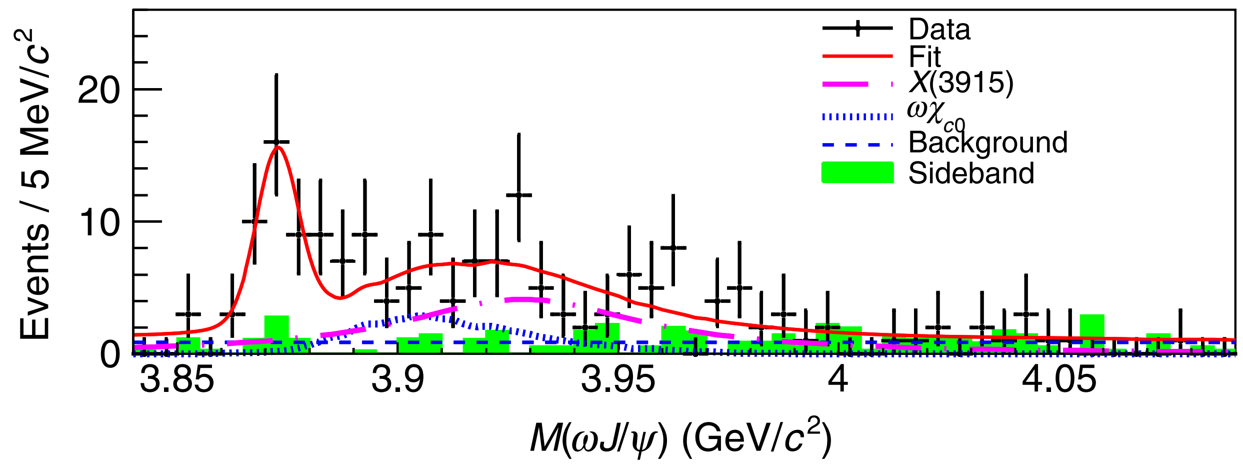
(BESIII Collaboration)



PHYSICAL REVIEW LETTERS **122,** 232002 (2019)

Study of $e^+e^- \to \gamma\omega J/\psi$ and Observation of $X(3872) \to \omega J/\psi$

(BESIII Collaboration)



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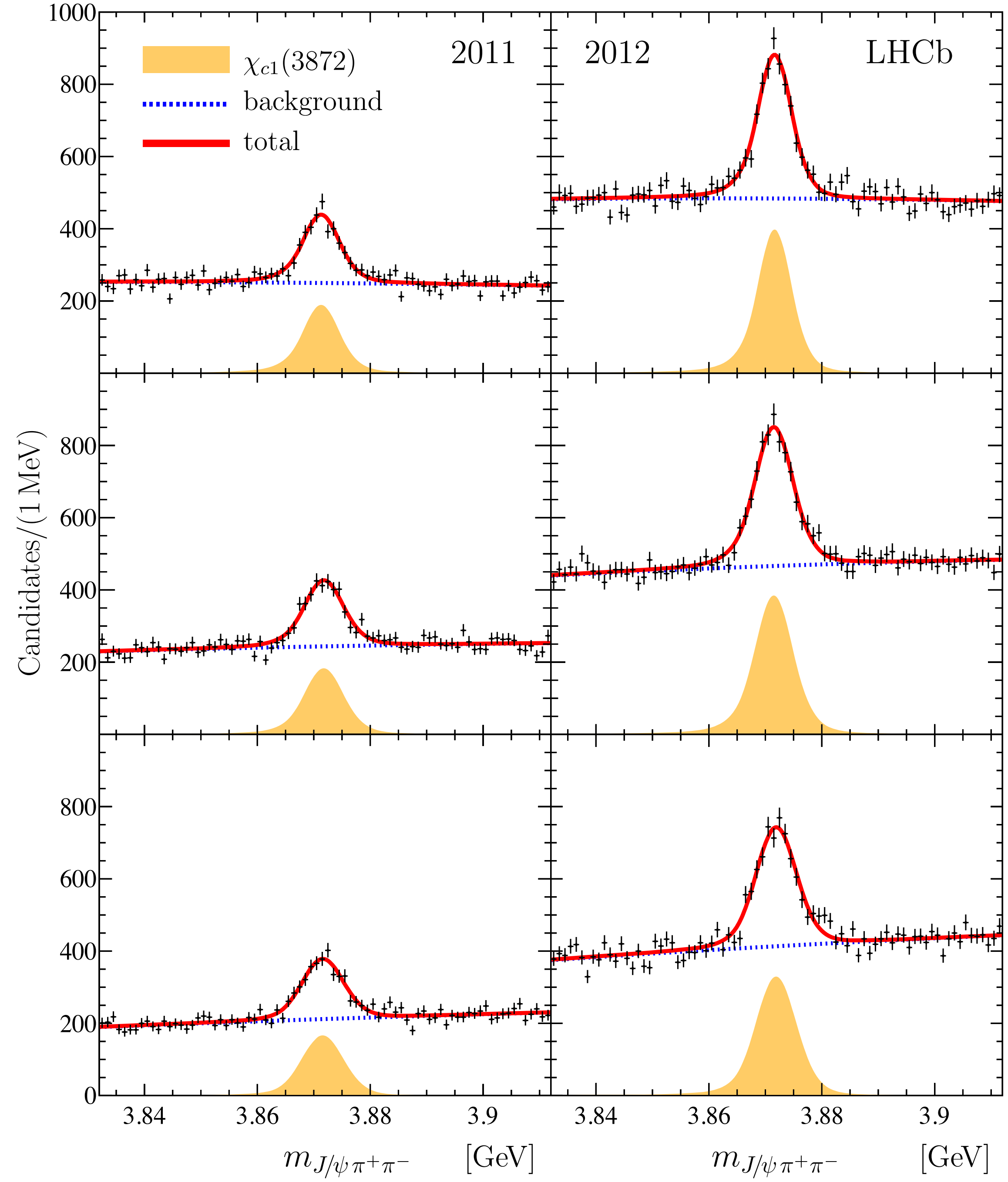
PHYSICAL REVIEW D **102,** 092005 (2020)

Study of the lineshape of the $\chi_{c1}(3872)$ state

R. Aaij *et al.*[*]
(LHCb Collaboration)



increasing $\pi^+\pi^-$ momentum

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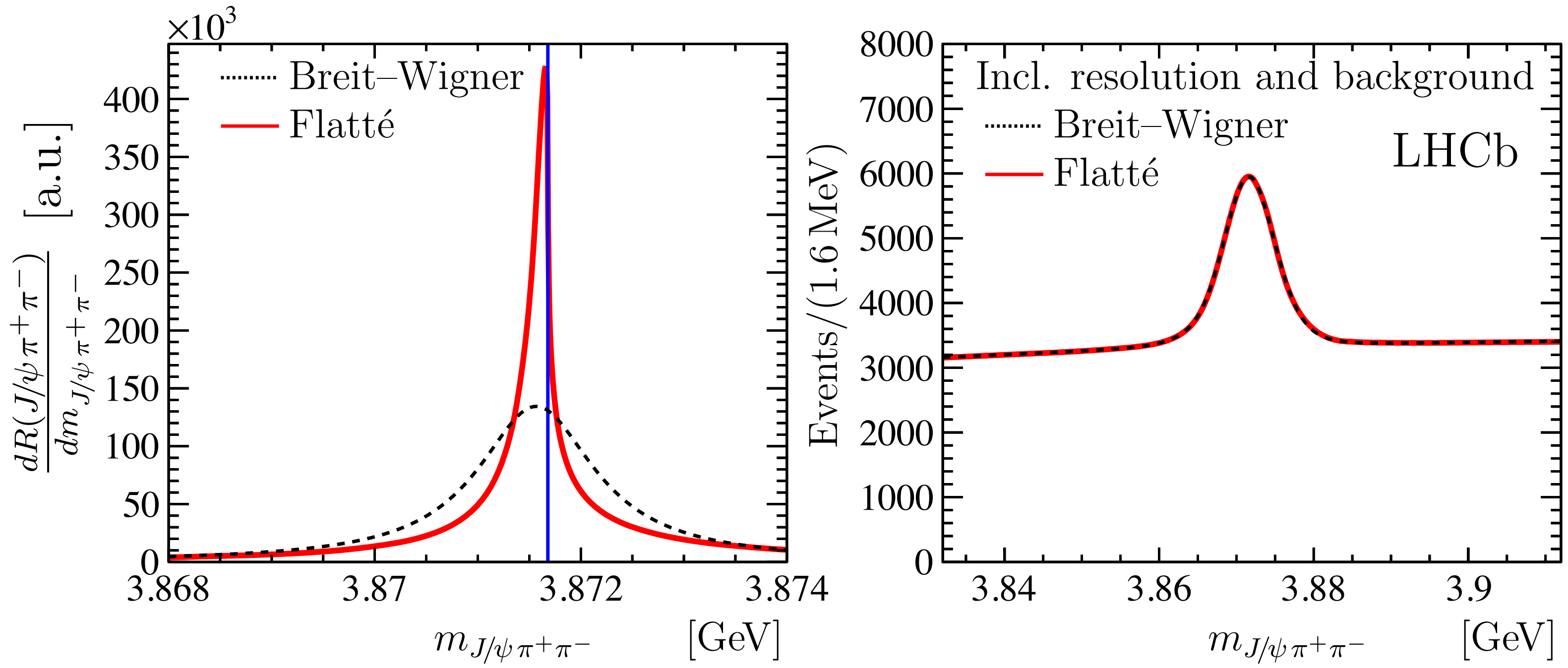

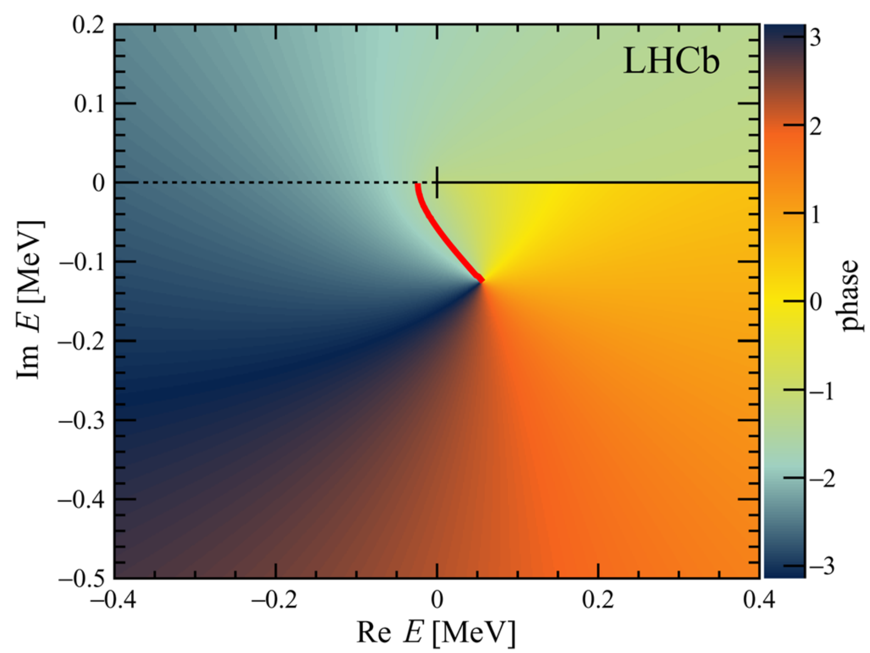

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PHYSICAL REVIEW D **72,** 054026 (2005)

Higher charmonia

T. Barnes,[1,*] S. Godfrey,[2,†] and E. S. Swanson[3,‡]

Multiplet	State	Expt.	Input (NR)	Theor. NR	Theor. GI
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	$\eta_c'(2^1S_0)$	3637.7 ± 4.4	3638	3630	3623
3S	$\psi(3^3S_1)$	4040 ± 10	4040	4072	4100
	$\eta_c(3^1S_0)$			4043	4064
4S	$\psi(4^3S_1)$	4415 ± 6	4415	4406	4450
	$\eta_c(4^1S_0)$			4384	4425
1P	$\chi_2(1^3P_2)$	3556.18 ± 0.13	3556	3556	3550
	$\chi_1(1^3P_1)$	3510.51 ± 0.12	3511	3505	3510
	$\chi_0(1^3P_0)$	3415.3 ± 0.4	3415	3424	3445
	$h_c(1^1P_1)$	see text		3516	3517
2P	$\chi_2(2^3P_2)$			3972	3979
	$\chi_1(2^3P_1)$			3925	3953
	$\chi_0(2^3P_0)$			3852	3916
	$h_c(2^1P_1)$			3934	3956

Meson	State	Mode	Γ_{thy} (MeV)
$\chi_2(3972)$	2^3P_2	DD	42
		DD*	37
		D_sD_s	0.7
		total	80
$\chi_1(3925)$	2^3P_1	DD*	165

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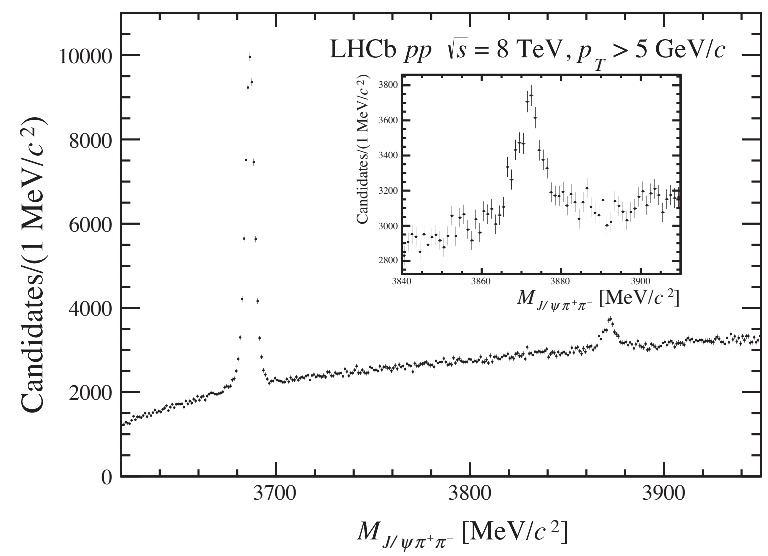
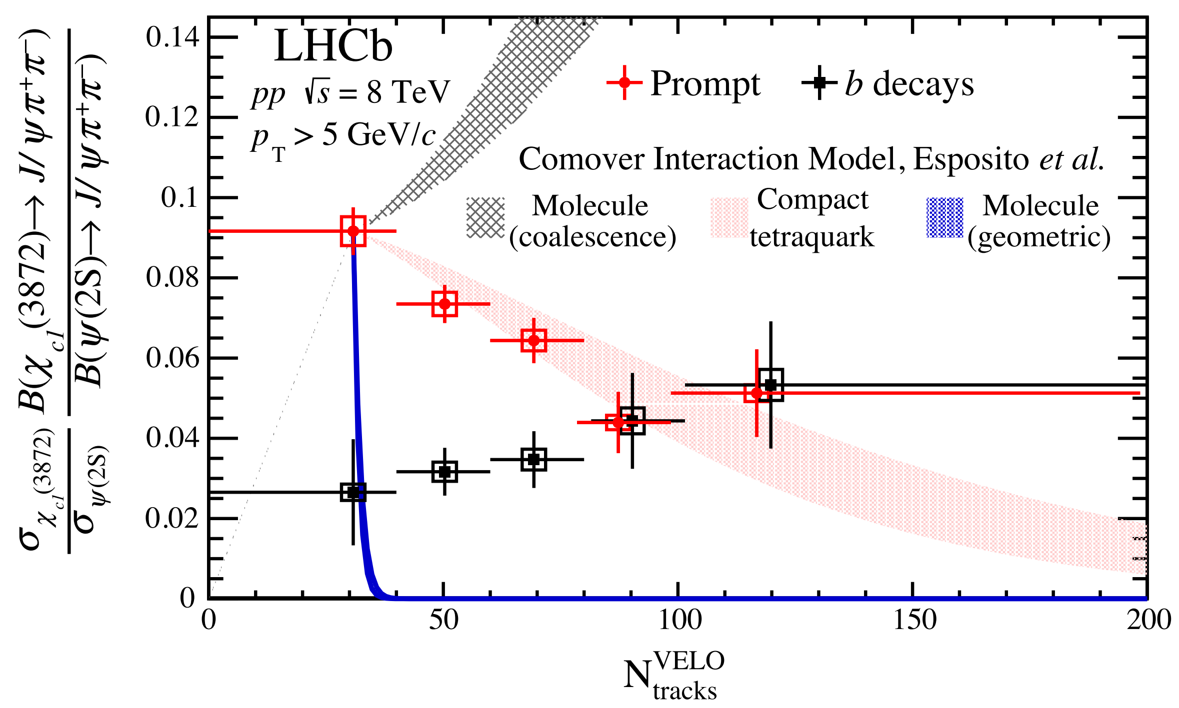
PHYSICAL REVIEW LETTERS **126,** 092001 (2021)

Observation of Multiplicity Dependent Prompt $\chi_{c1}(3872)$ and $\psi(2S)$ Production in pp Collisions

R. Aaij *et al.**
(LHCb Collaboration)





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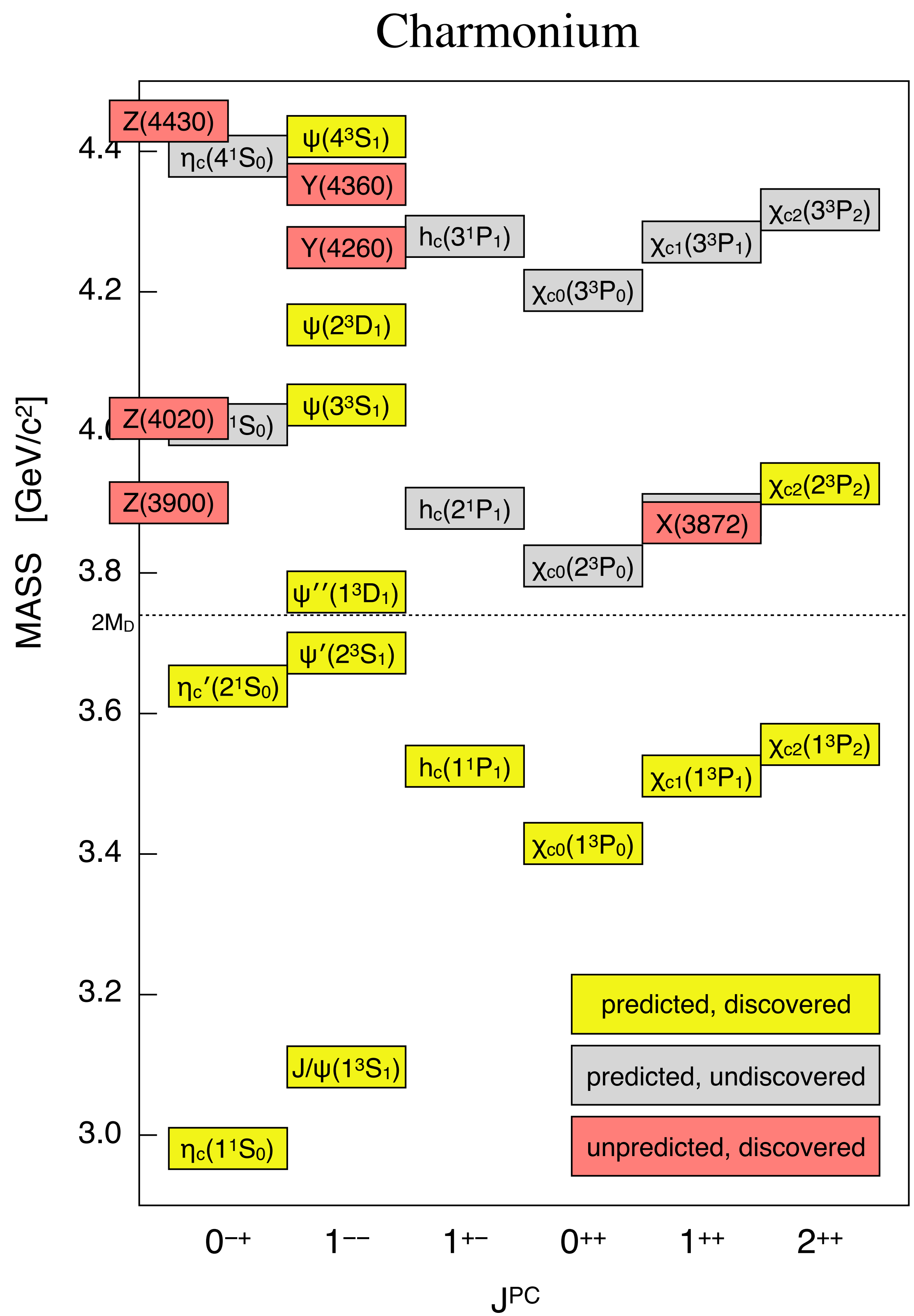

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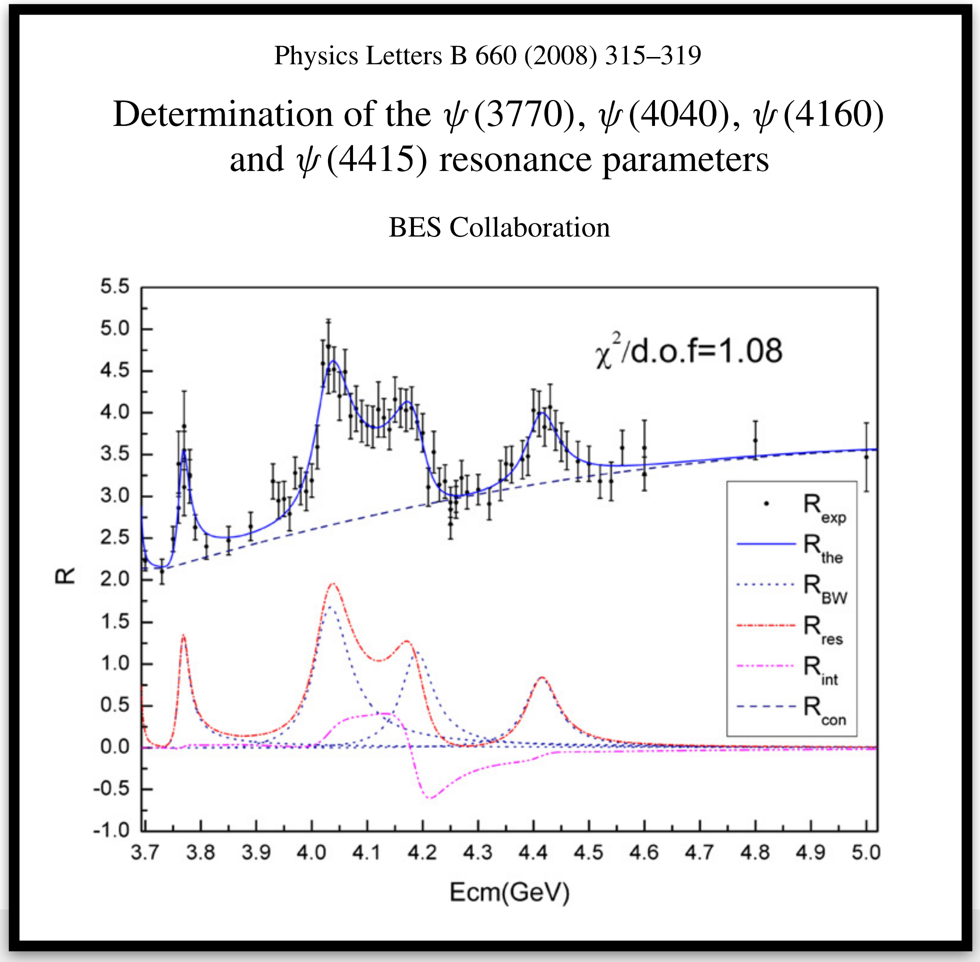
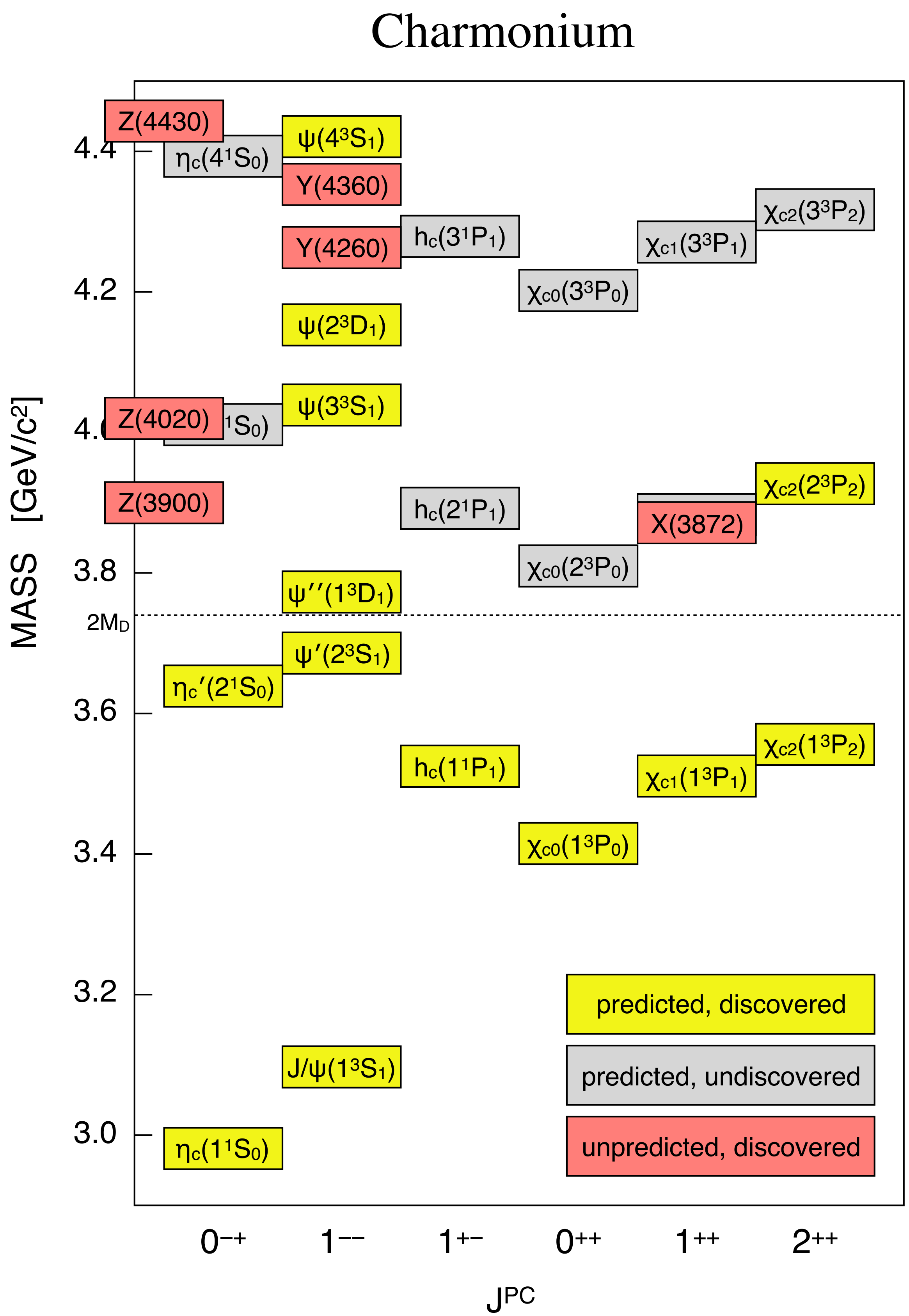

Physics Letters B 660 (2008) 315–319

Determination of the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ resonance parameters

BES Collaboration



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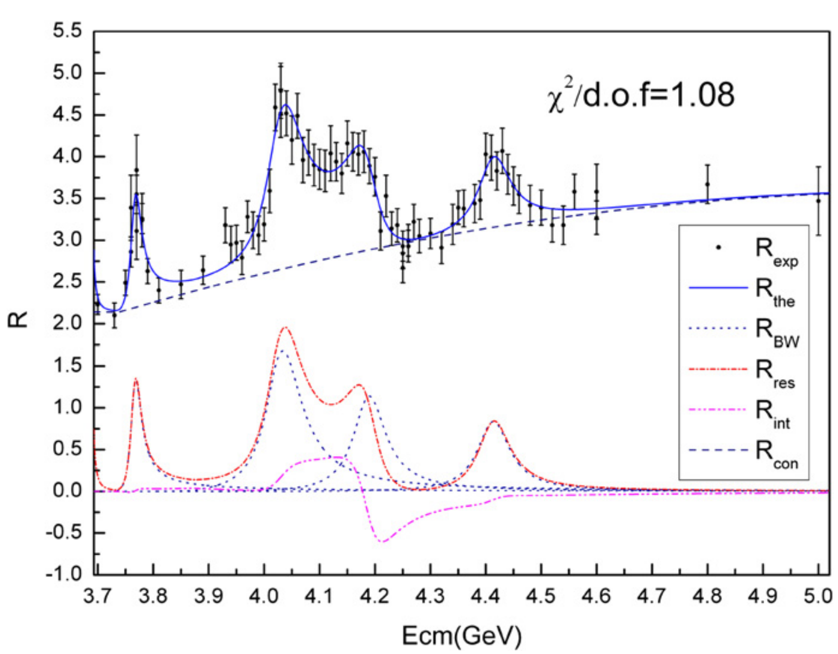

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	$\chi_1(3^3P_1)$			4271	4317
	$\chi_0(3^3P_0)$			4202	4292
	$h_c(3^1P_1)$			4279	4318
1D	$\psi_3(1^3D_3)$			3806	3849
	$\psi_2(1^3D_2)$			3800	3838
	$\psi(1^3D_1)$	3769.9 ± 2.5	3770	3785	3819
	$\eta_{c2}(1^1D_2)$			3799	3837
2D	$\psi_3(2^3D_3)$			4167	4217
	$\psi_2(2^3D_2)$			4158	4208
	$\psi(2^3D_1)$	4159 ± 20	4159	4142	4194
	$\eta_{c2}(2^1D_2)$			4158	4208

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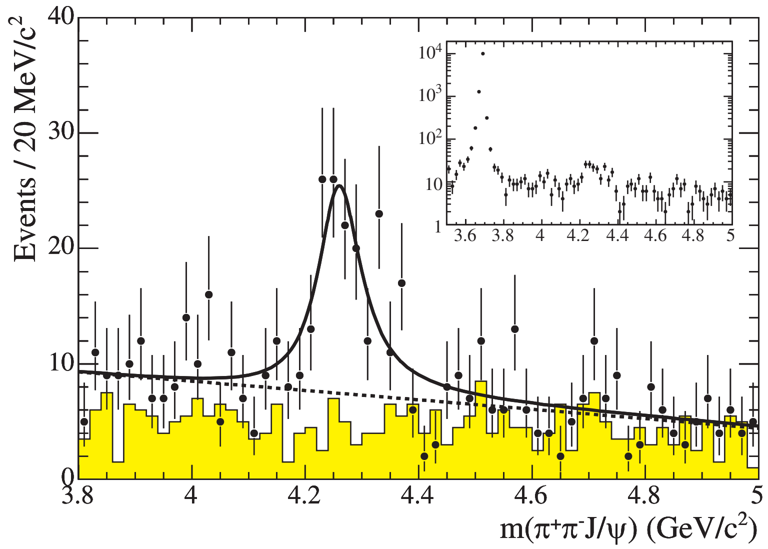
PRL **95,** 142001 (2005) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2005

Observation of a Broad Structure in the $\pi^+\pi^- J/\psi$ Mass Spectrum around 4.26 GeV/c^2

(BABAR Collaboration)



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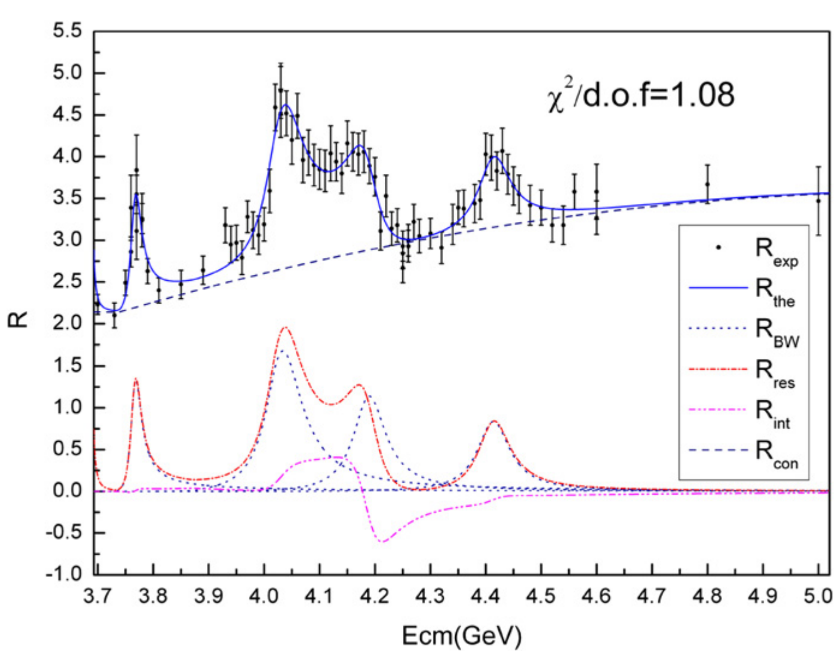

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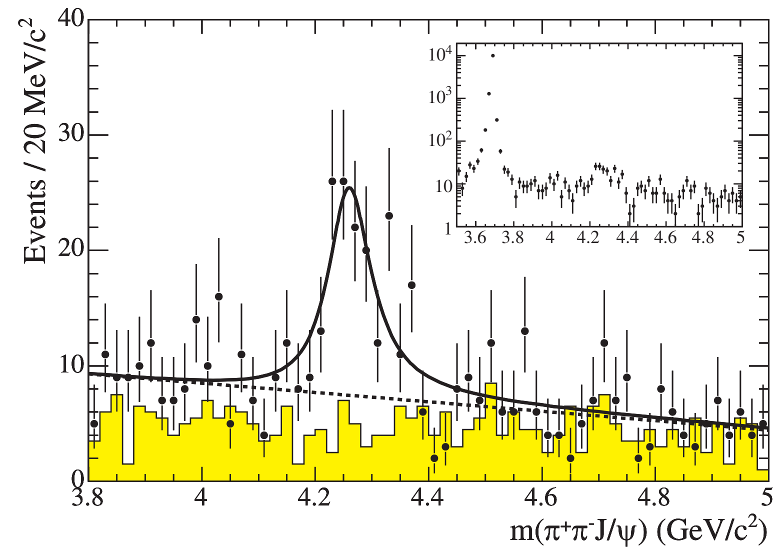

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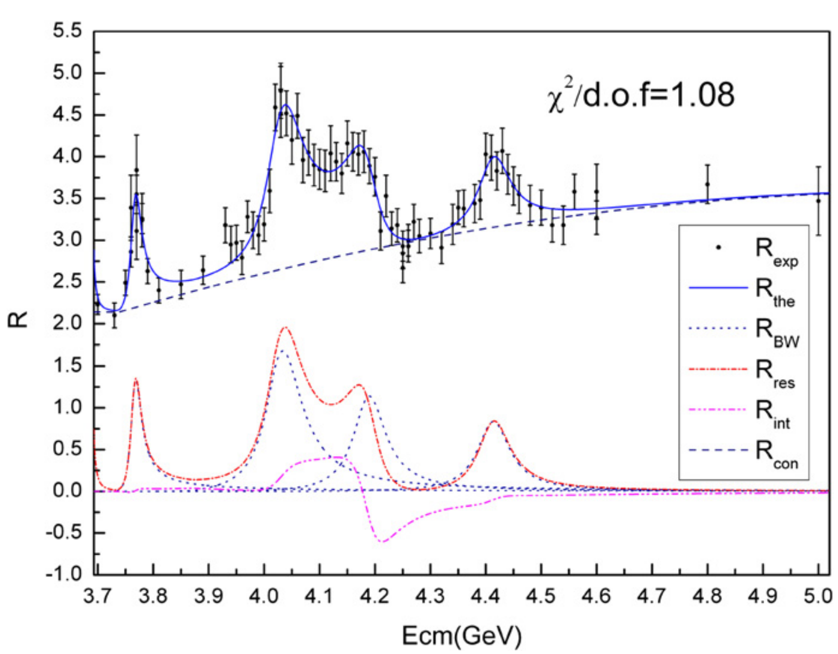
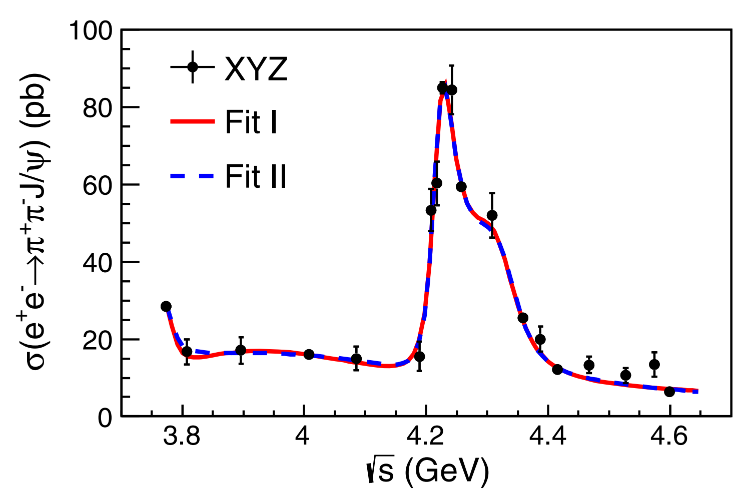


PRL **118,** 092001 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

Precise Measurement of the $e^+e^- \to \pi^+\pi^- J/\psi$ Cross Section at Center-of-Mass Energies from 3.77 to 4.60 GeV

(BESIII Collaboration)



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PRL **98,** 212001 (2007) PHYSICAL REVIEW LETTERS week ending 25 MAY 2007

Evidence of a Broad Structure at an Invariant Mass of 4.32 GeV/c^2 in the Reaction $e^+e^- \to \pi^+\pi^-\psi(2S)$ Measured at *BABAR*

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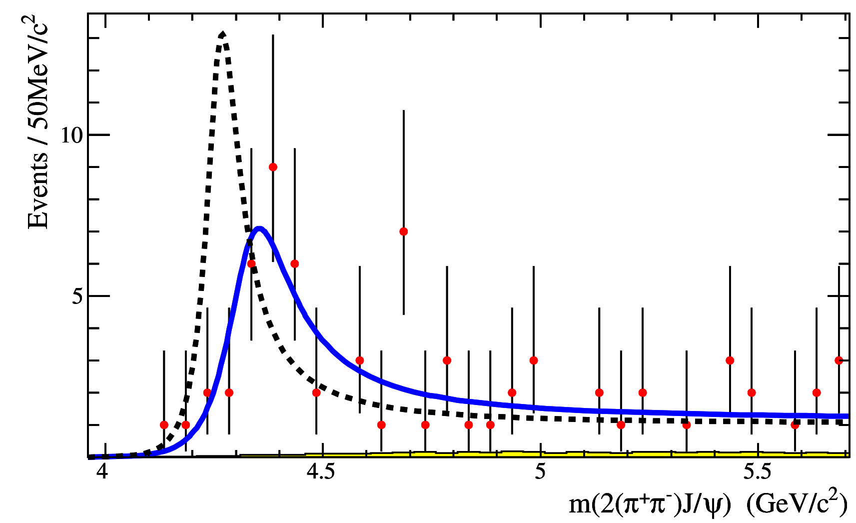

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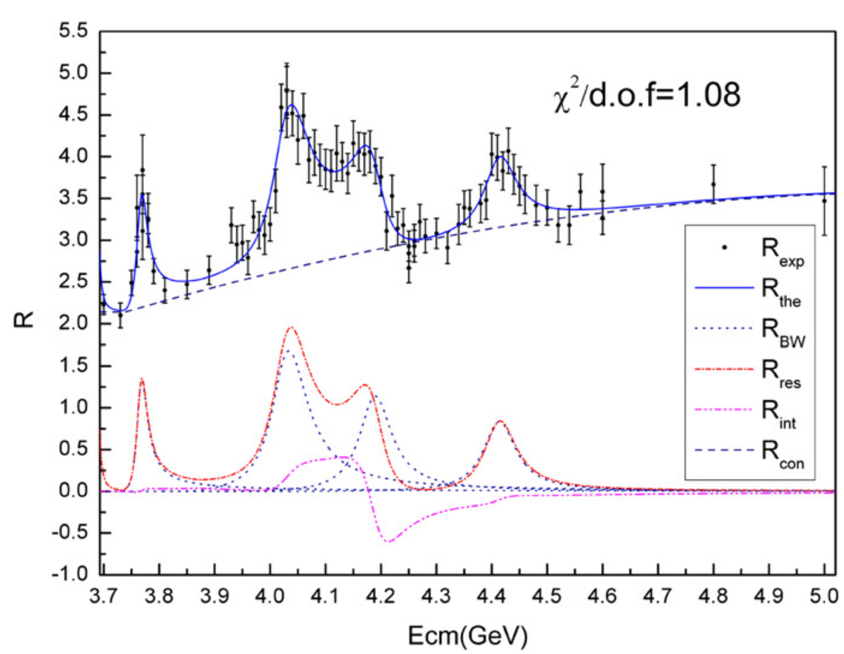

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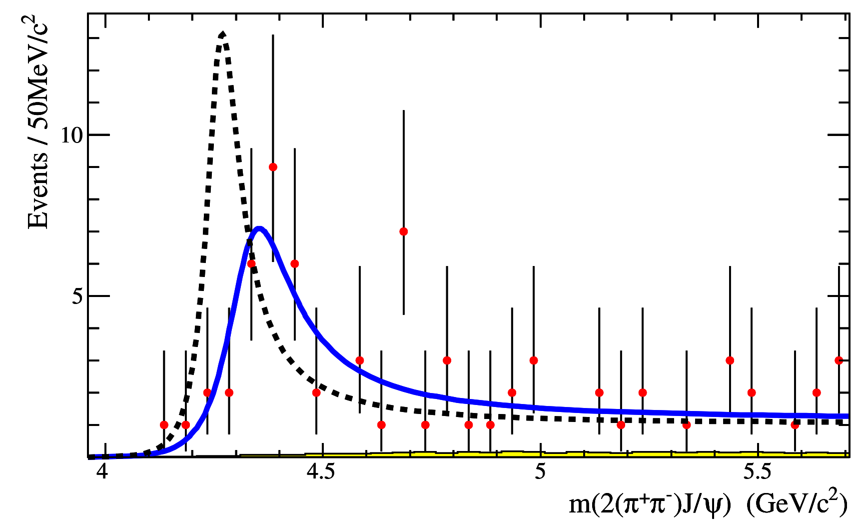

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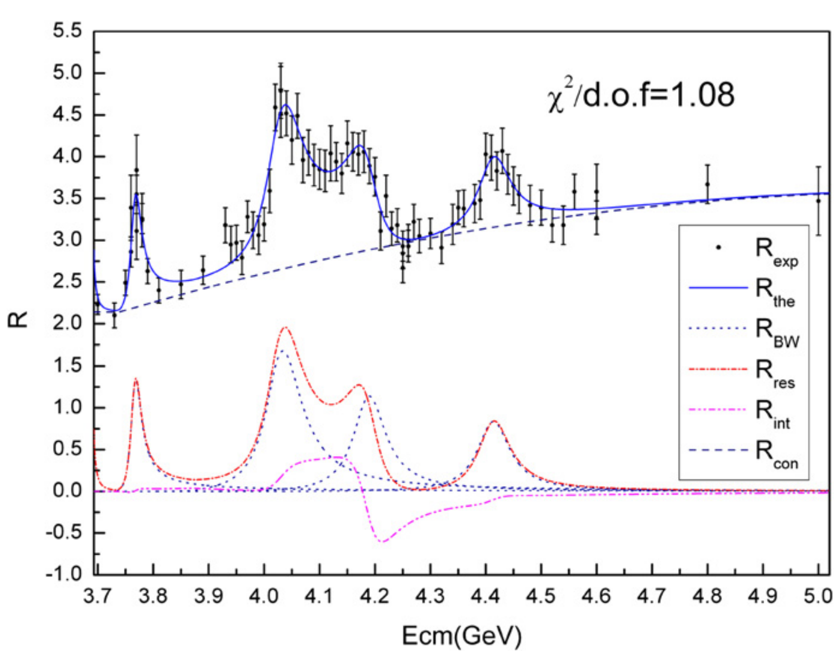
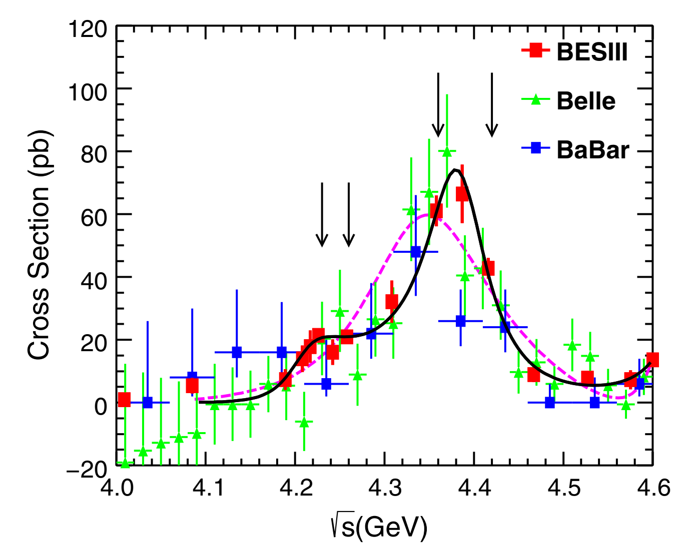


PHYSICAL REVIEW D 96, 032004 (2017)

Measurement of $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ from 4.008 to 4.600 GeV and observation of a charged structure in the $\pi^\pm\psi(3686)$ mass spectrum

(BESIII Collaboration)



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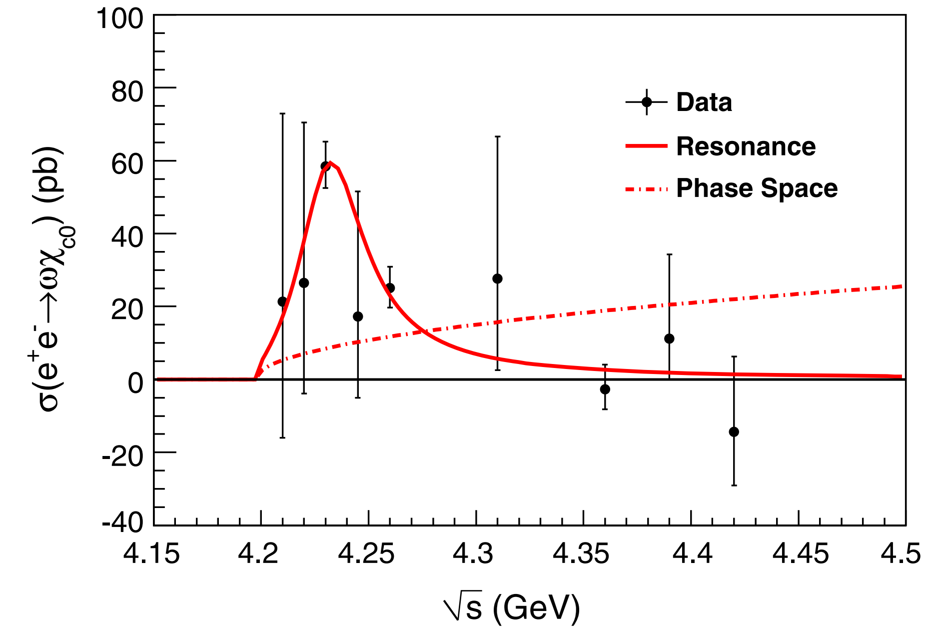
PRL **114**, 092003 (2015) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2015

Study of $e^+e^- \to \omega\chi_{cJ}$ at Center of Mass Energies from 4.21 to 4.42 GeV

(BESIII Collaboration)



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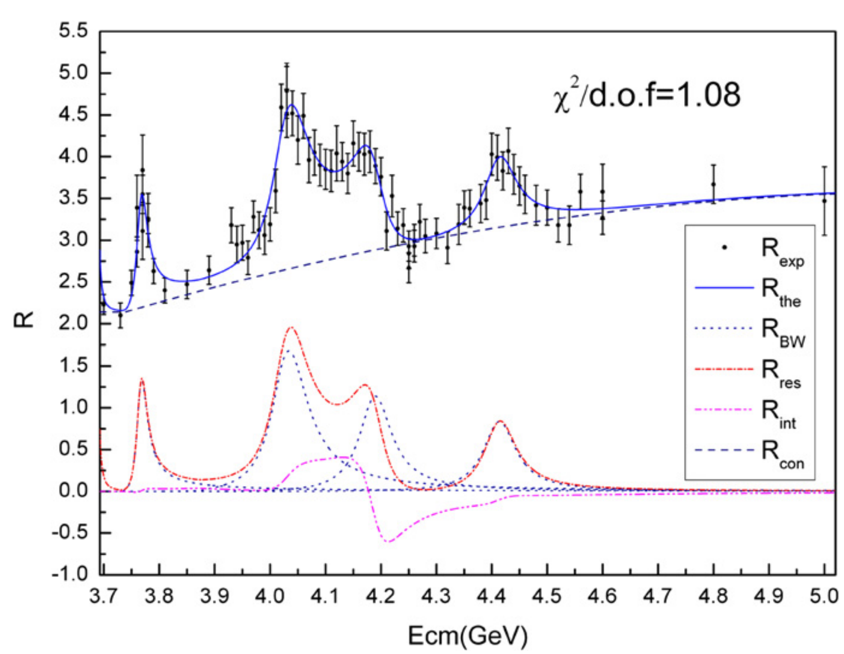

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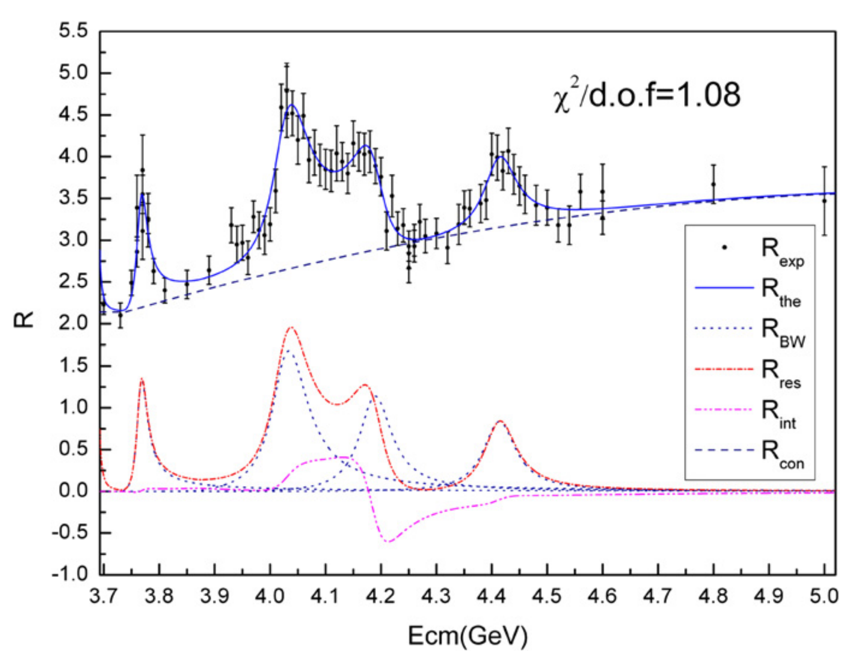
(5) seen in $e^+e^- \to \eta J/\psi$

(6) masses and widths are highly reaction-dependent

Physics Letters B 660 (2008) 315–319

Determination of the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ resonance parameters

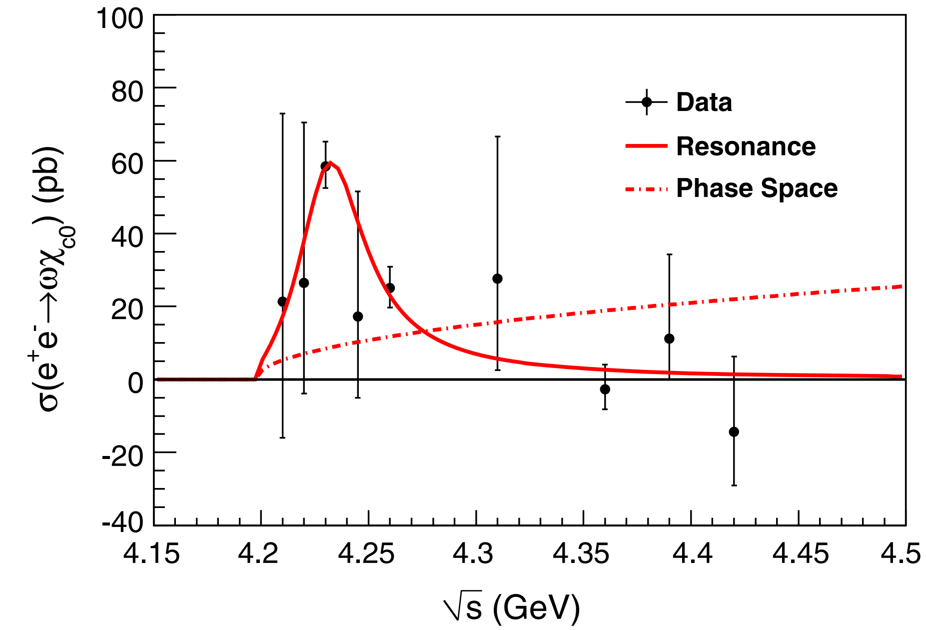
BES Collaboration



PRL **114,** 092003 (2015) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2015

Study of $e^+e^- \to \omega\chi_{cJ}$ at Center of Mass Energies from 4.21 to 4.42 GeV

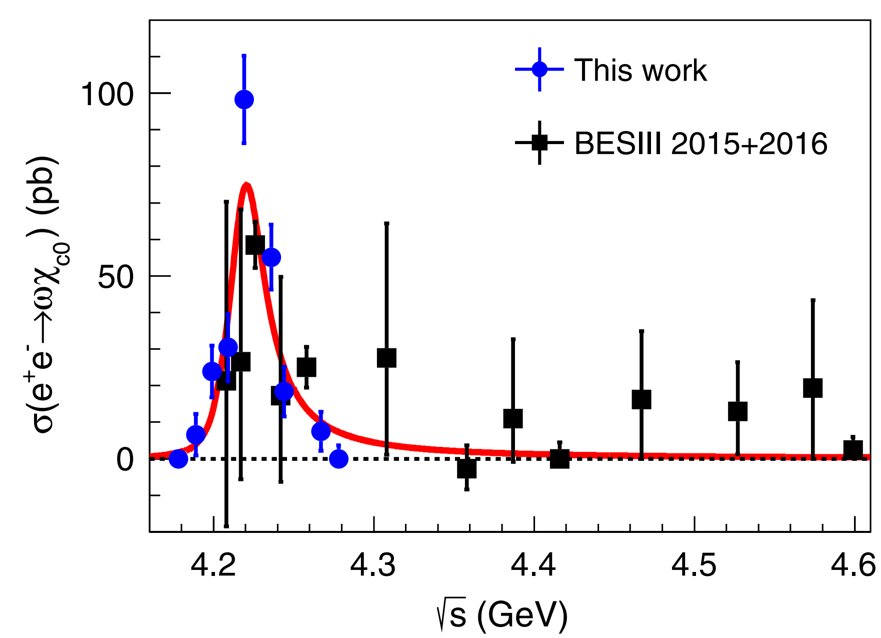
(BESIII Collaboration)



PHYSICAL REVIEW D **99,** 091103(R) (2019)

Cross section measurements of $e^+e^- \to \omega\chi_{c0}$ from $\sqrt{s} = 4.178$ to 4.278 GeV

(BESIII Collaboration)



IVB. Exotic Charmonium: Y(4260) + other Y

properties of the $\psi(4230)$ and $\psi(4360)$ (aka $Y(4260)$ and $Y(4360)$):

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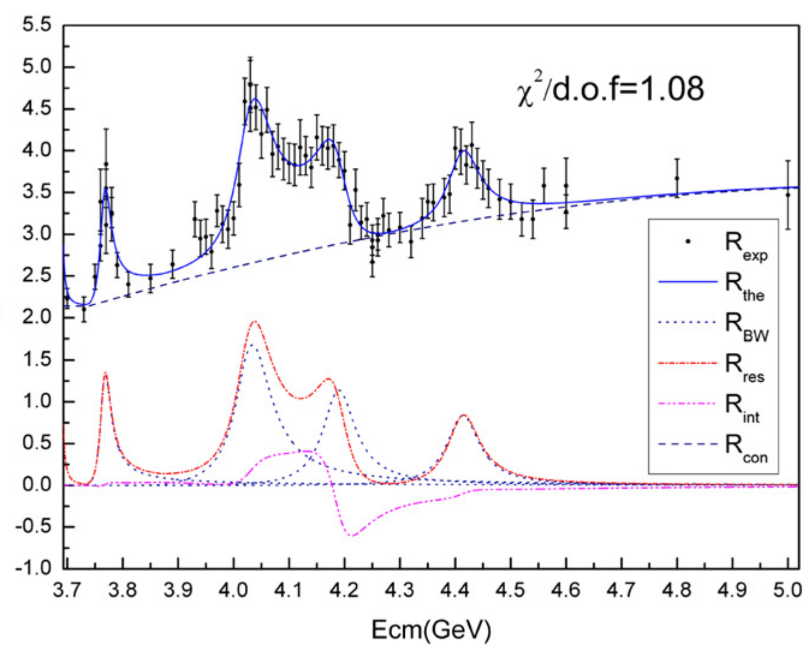

Physics Letters B 660 (2008) 315–319

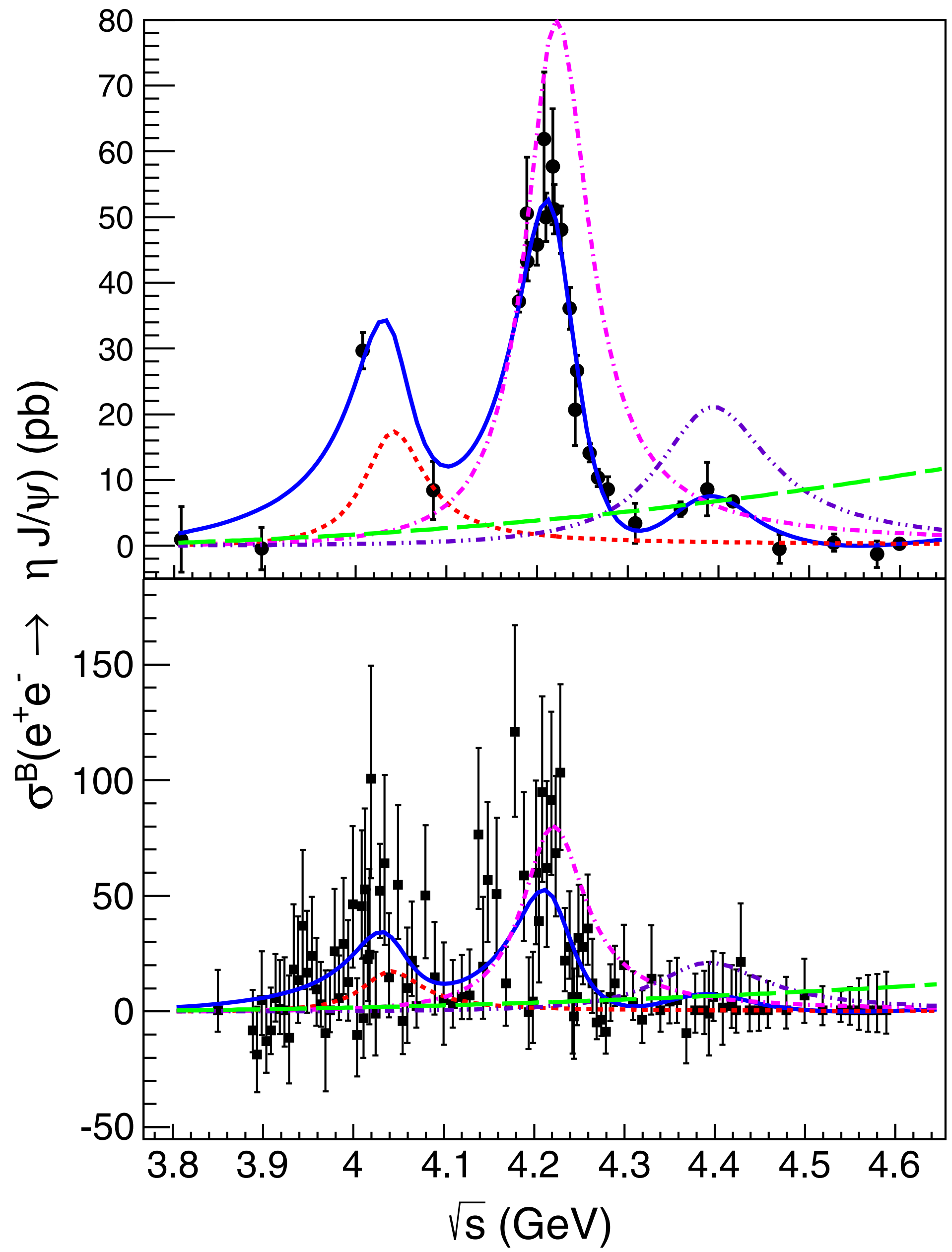
Determination of the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ resonance parameters

BES Collaboration

PHYSICAL REVIEW D **102,** 031101(R) (2020)

Observation of the $Y(4220)$ and $Y(4390)$ in the process $e^+e^- \to \eta J/\psi$

(BESIII Collaboration)



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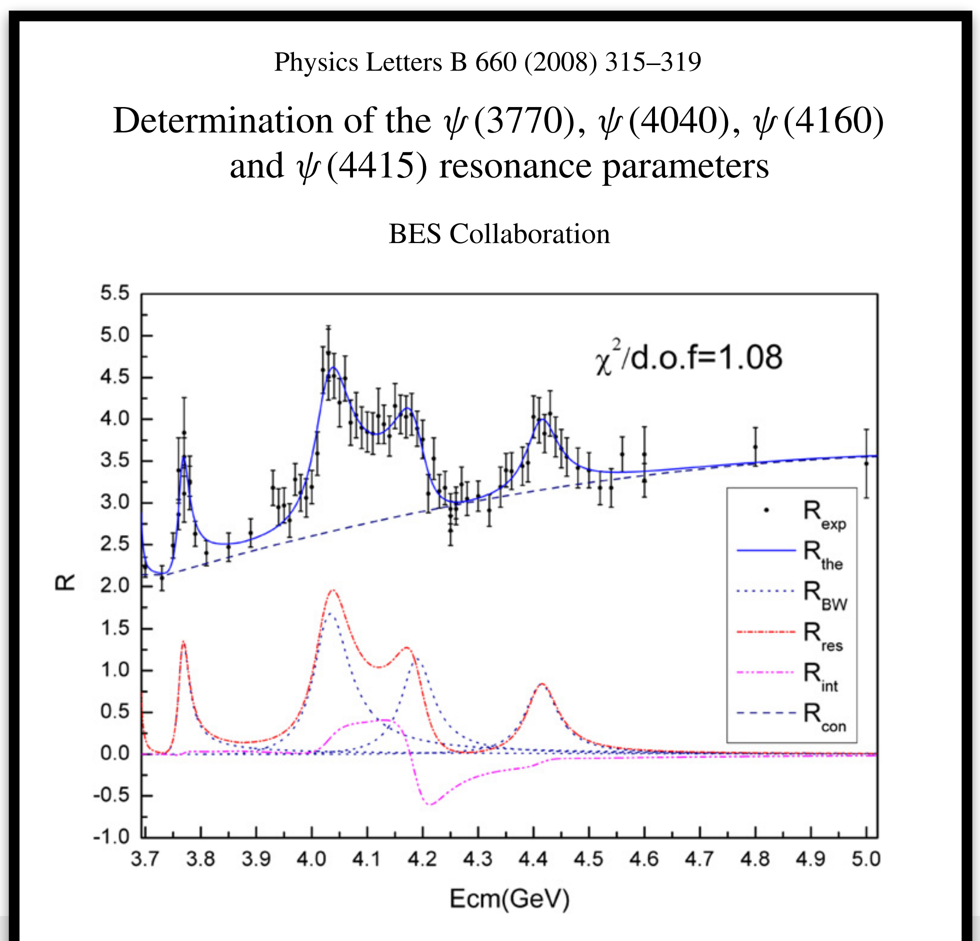
Physics Letters B 660 (2008) 315–319

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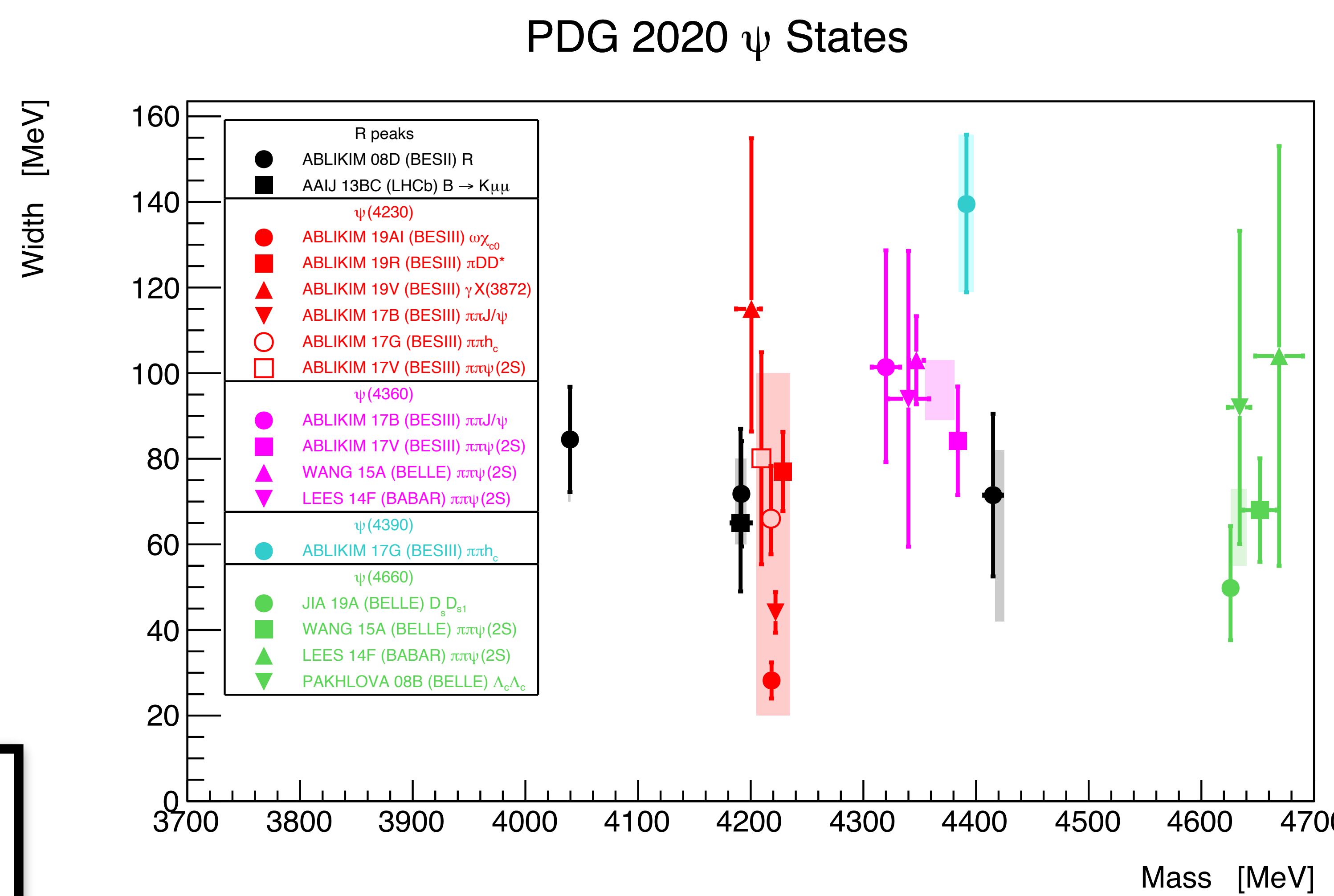
BES Collaboration



PDG 2020 $c\bar{c}$ States Above Open-Flavor Threshold

• $\psi(3770)$	$0^-(1^{--})$	• $\psi(4040)$	$0^-(1^{--})$	~~$\psi(4260)$~~	~~$0^-(1^{--})$~~
• $\psi_2(3823)$	$0^-(2^{--})$	$X(4050)^\pm$	$1^-(?^{?+})$	• $\chi_{c1}(4274)$	$0^+(1^{++})$
• $\psi_3(3842)$	$0^-(3^{--})$	$X(4055)^\pm$	$1^+(?^{?-})$	$X(4350)$	$0^+(?^{?+})$
$\chi_{c0}(3860)$	$0^+(0^{++})$	$X(4100)^\pm$	$1^-(?^{??})$	• $\psi(4360)$	$0^-(1^{--})$
• $\chi_{c1}(3872)$	$0^+(1^{++})$	• $\chi_{c1}(4140)$	$0^+(1^{++})$	$\psi(4390)$	$0^-(1^{--})$
• $Z_c(3900)$	$1^+(1^{+-})$	• $\psi(4160)$	$0^-(1^{--})$	• $\psi(4415)$	$0^-(1^{--})$
• $X(3915)$	$0^+(0/2^{++})$	$X(4160)$	$?^?(?^{??})$	• $Z_c(4430)$	$1^+(1^{+-})$
• $\chi_{c2}(3930)$	$0^+(2^{++})$	$Z_c(4200)$	$1^+(1^{+-})$	$\chi_{c0}(4500)$	$0^+(0^{++})$
$X(3940)$	$?^?(?^{??})$	• $\psi(4230)$	$0^-(1^{--})$	• $\psi(4660)$	$0^-(1^{--})$
• $X(4020)^\pm$	$1^+(?^{?-})$	$R_{c0}(4240)$	$1^+(0^{--})$	$\chi_{c0}(4700)$	$0^+(0^{++})$
		$X(4250)^\pm$	$1^-(?^{?+})$		

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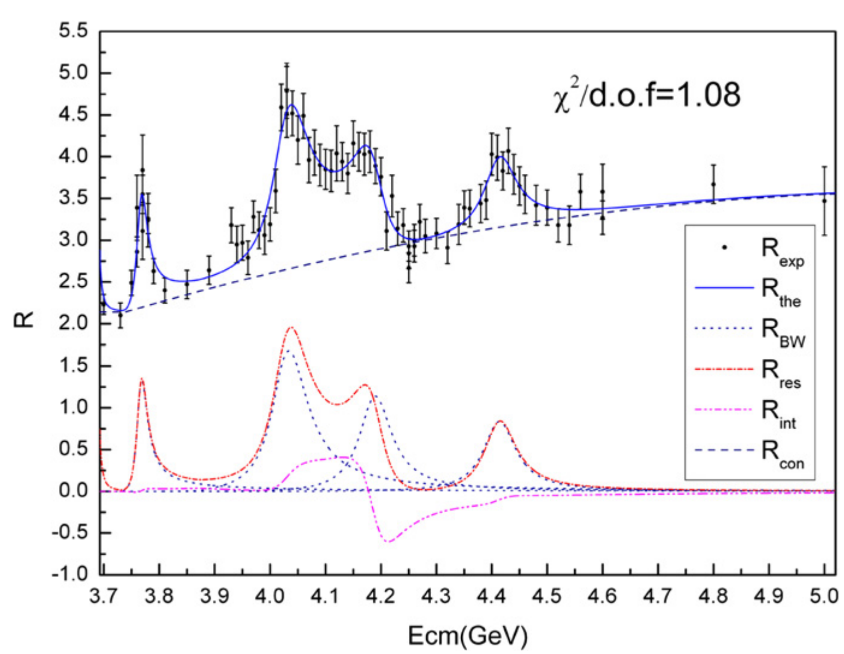
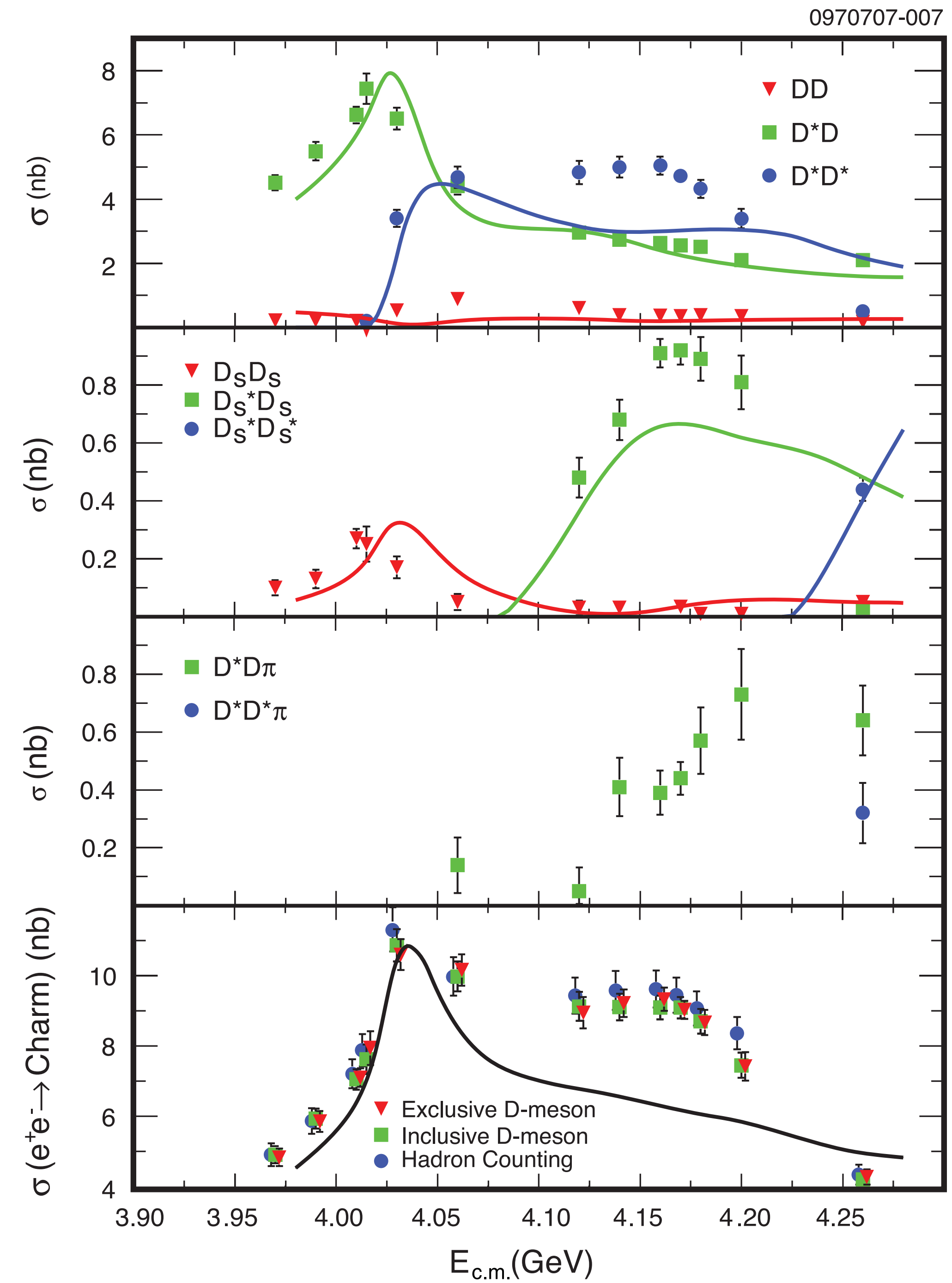


PHYSICAL REVIEW D **80,** 072001 (2009)

Measurement of charm production cross sections in e^+e^- annihilation at energies between 3.97 and 4.26 GeV

(CLEO Collaboration)



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Physics Letters B 660 (2008) 315–319

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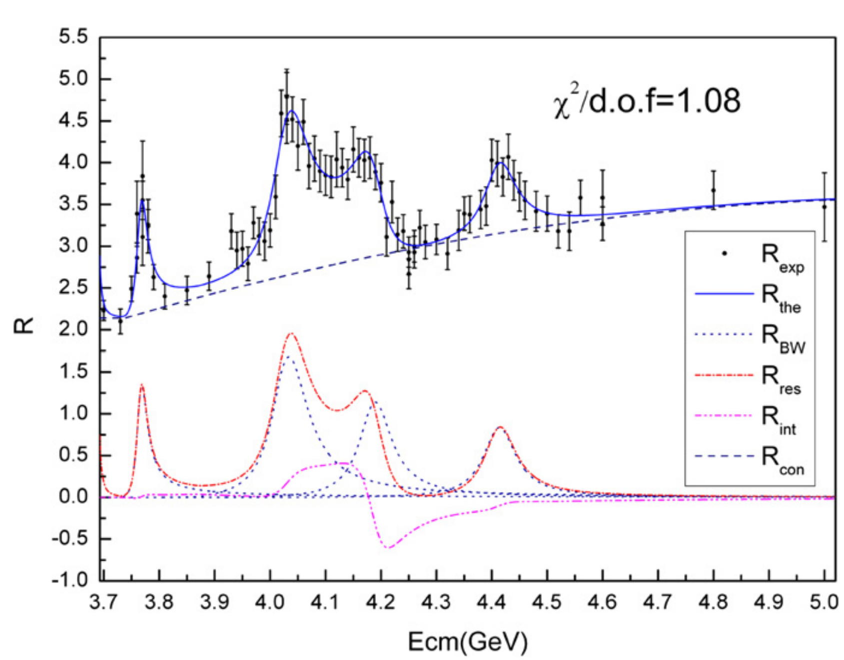
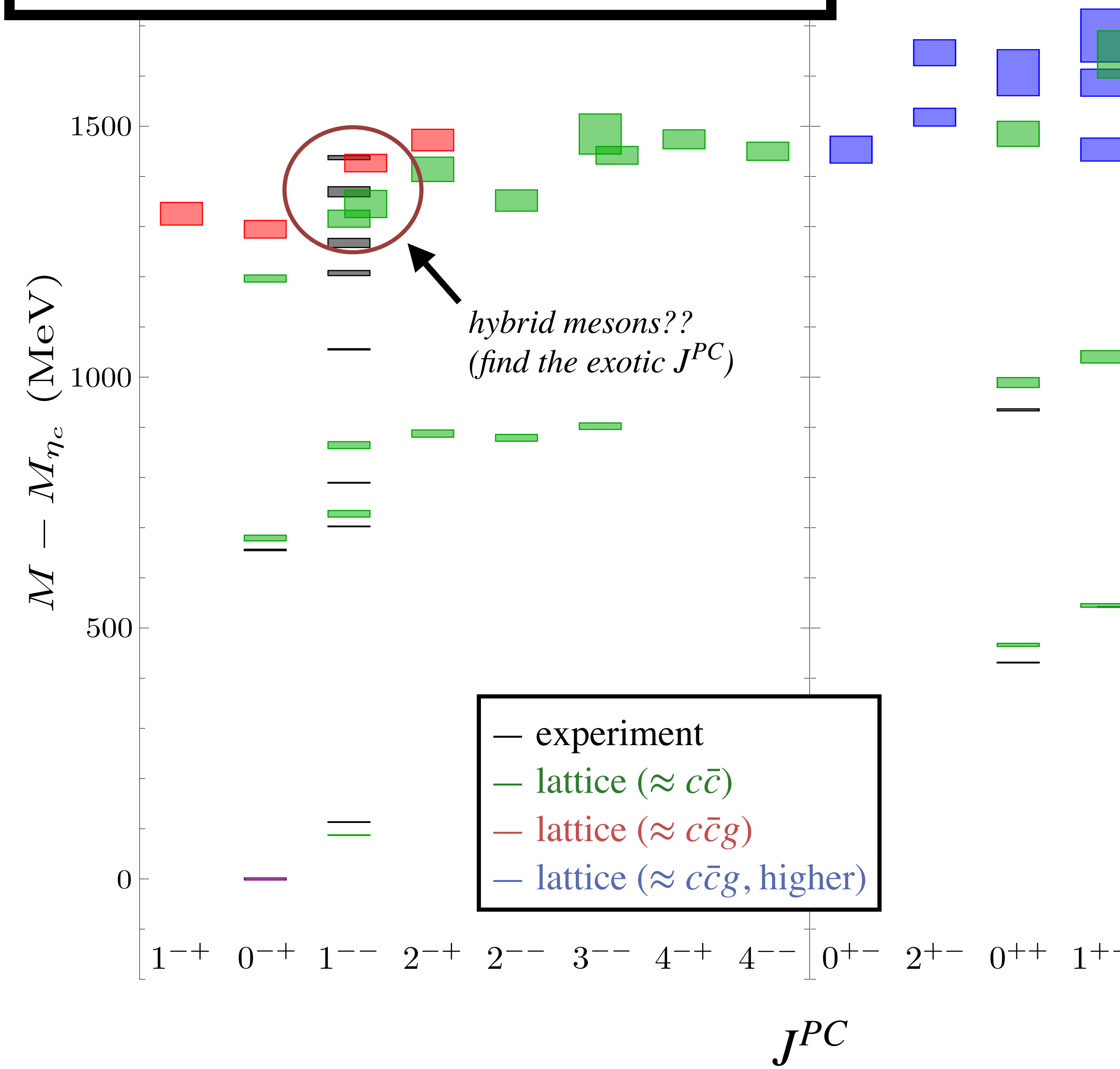


JHEP12(2016)089

Excited and exotic charmonium, D_s and D meson spectra for two light quark masses from lattice QCD

Gavin K.C. Cheung,[a] Cian O'Hara,[b] Graham Moir,[a] Michael Peardon,[b] Sinéad M. Ryan,[b] Christopher E. Thomas[a] and David Tims[b]
(For the Hadron Spectrum Collaboration)



IVB. Exotic Charmonium: $Z_c(3900)$ and $Z_c(4020)$

properties of the
$Z_c(3900)$ and $Z_c(4020)$:

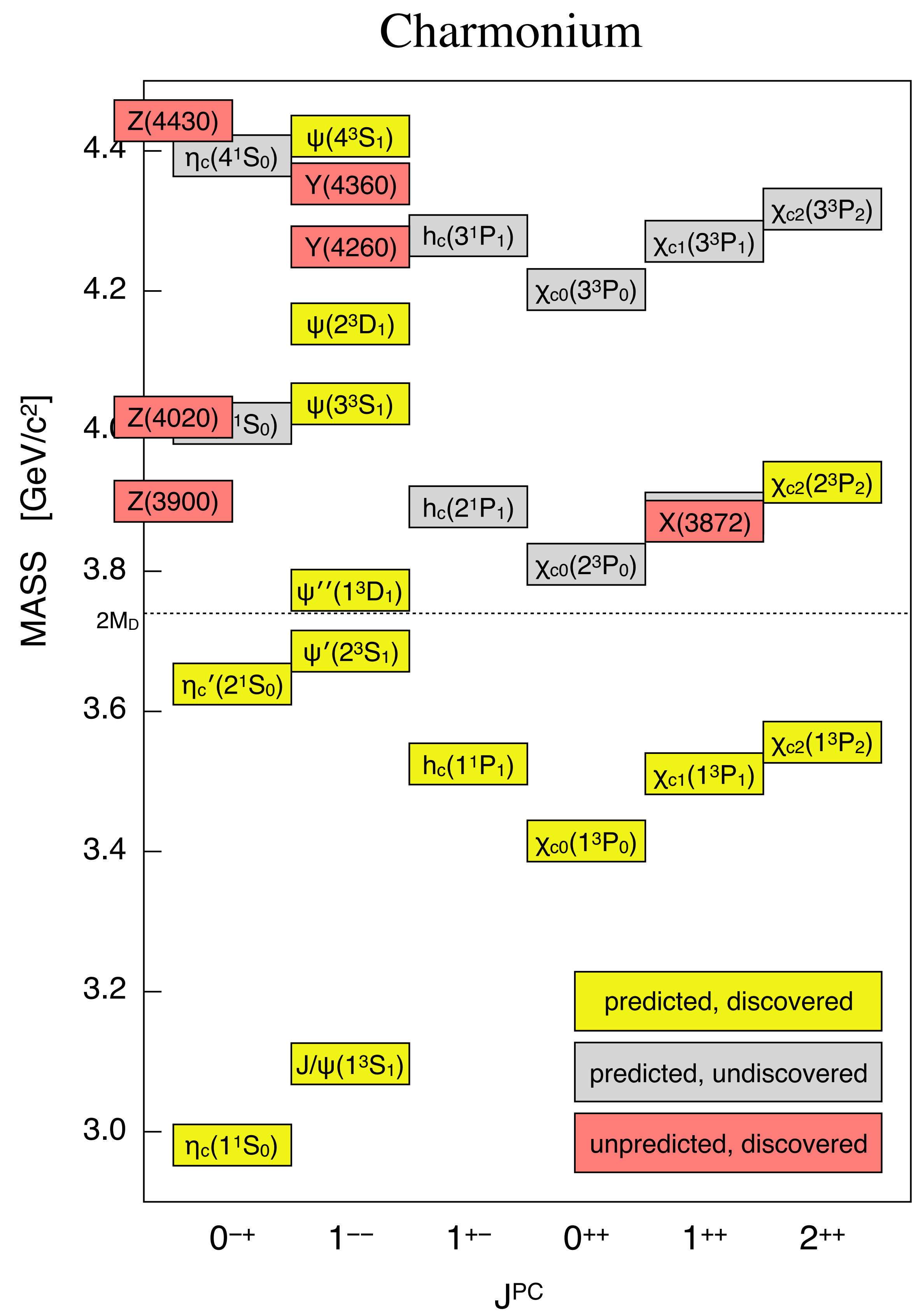
(1) isovector states so clearly not $c\bar{c}$

(2) seen in $Z_c(3900) \rightarrow \pi J/\psi$

(3) seen in $Z_c(4020) \rightarrow \pi h_c(1P)$

(4) close to open-charm thresholds

(5) interpretation depends on lineshapes



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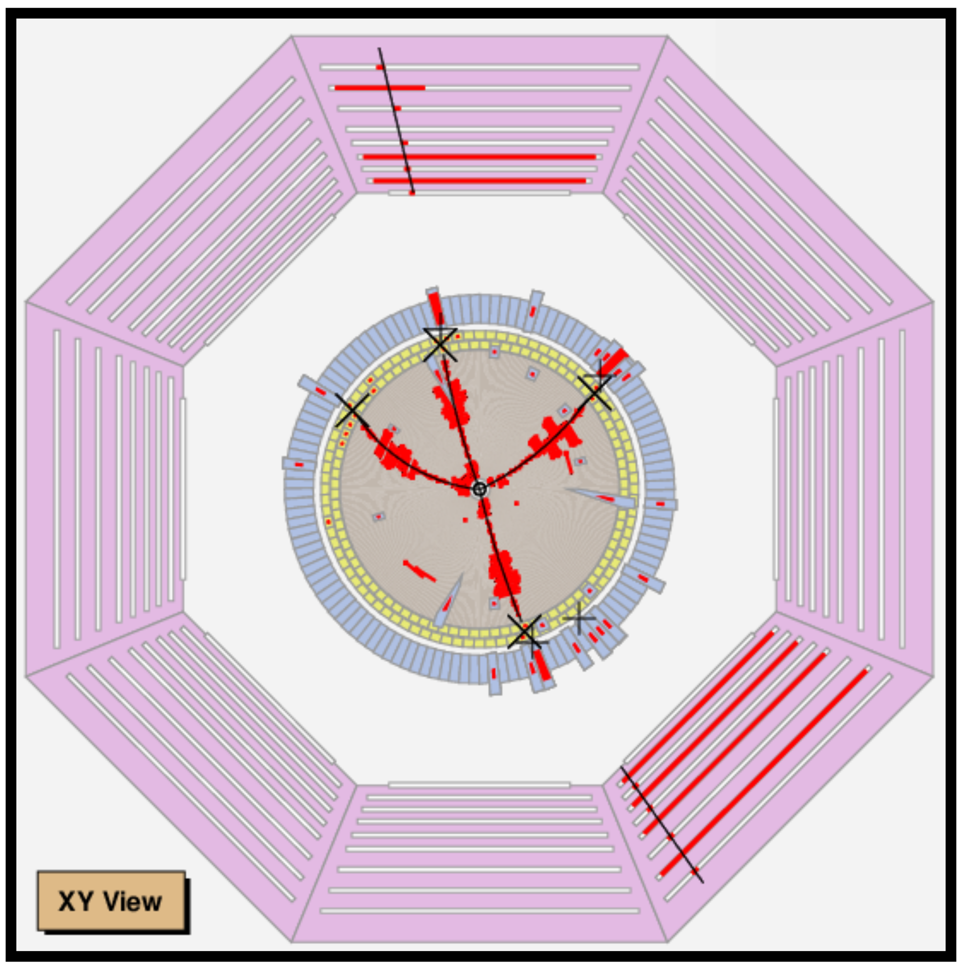
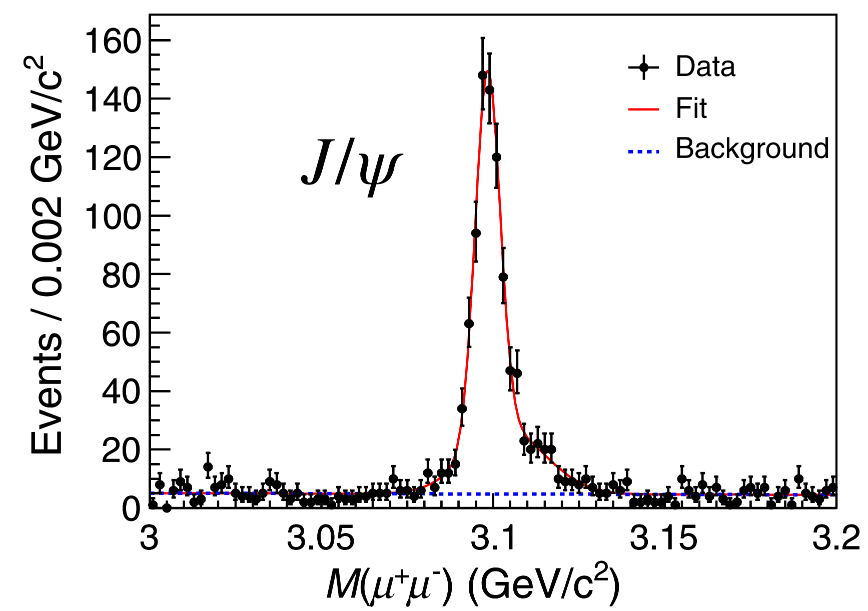
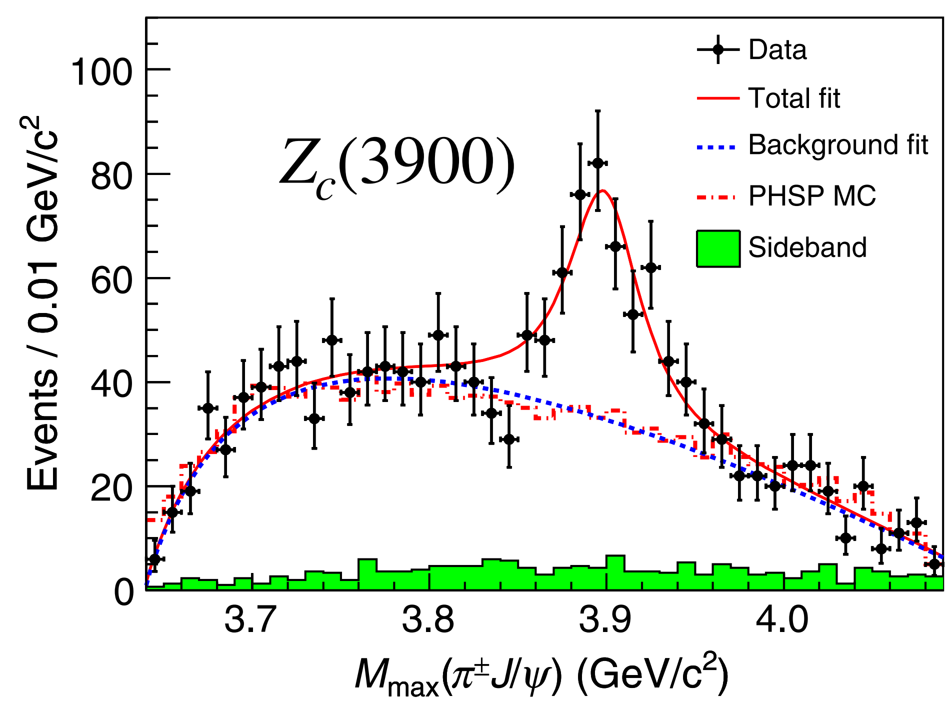


Selected for a Viewpoint in *Physics*
PRL **110**, 252001 (2013) PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV

(BESIII Collaboration)





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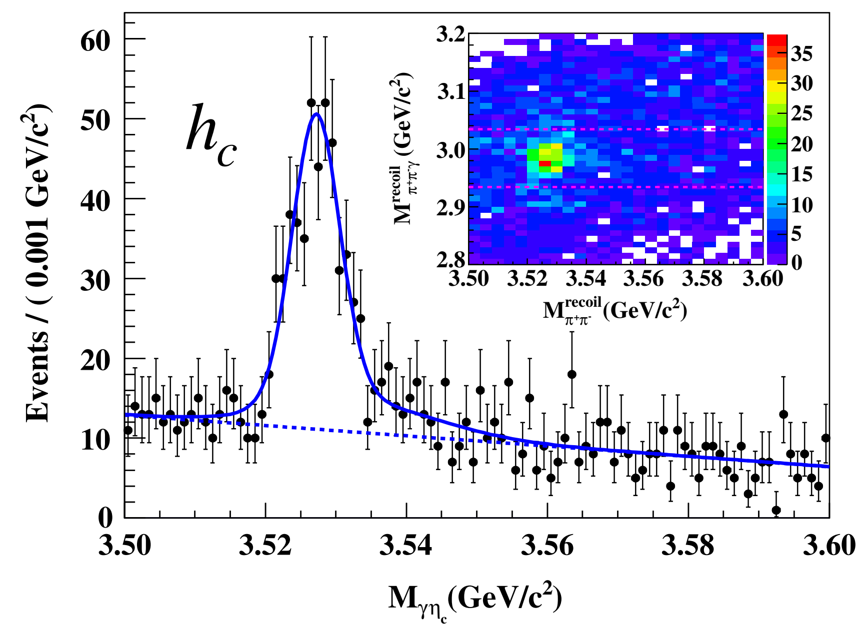
(4) close to open-charm thresholds

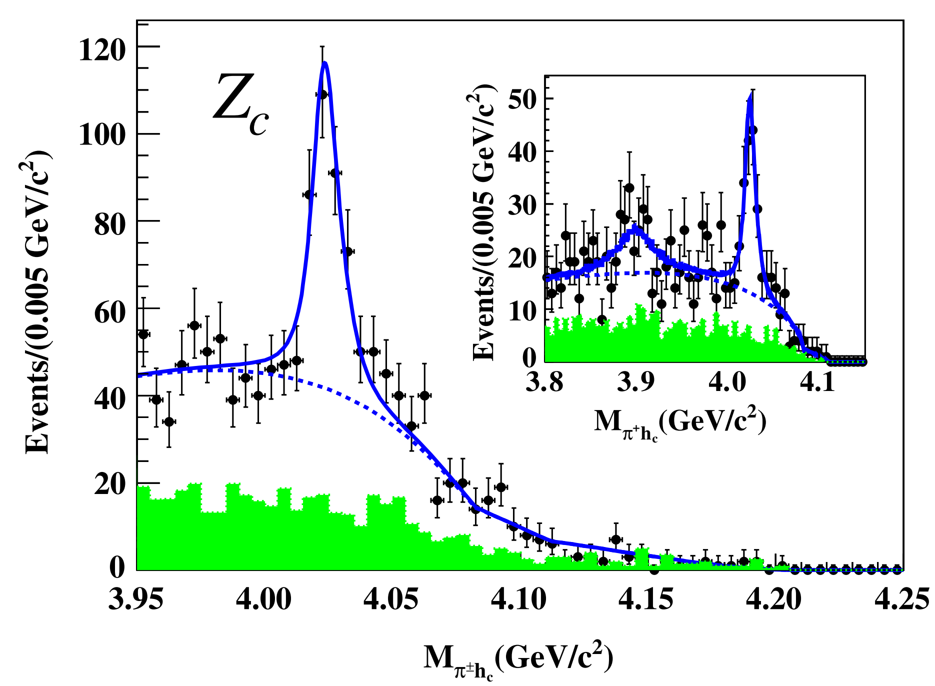
(5) interpretation depends on lineshapes

PRL **111,** 242001 (2013) PHYSICAL REVIEW LETTERS week ending 13 DECEMBER 2013

Observation of a Charged Charmoniumlike Structure $Z_c(4020)$ and Search for the $Z_c(3900)$ in $e^+e^- \to \pi^+\pi^- h_c$

(BESIII Collaboration)





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(5) interpretation depends on lineshapes

$$M(D) + M(D^*) \approx 3872 - 3879 \text{ MeV}$$

$$M(D^*) + M(D^*) \approx 4014 - 4020 \text{ MeV}$$

PRL **111,** 242001 (2013) PHYSICAL REVIEW LETTERS week ending 13 DECEMBER 2013

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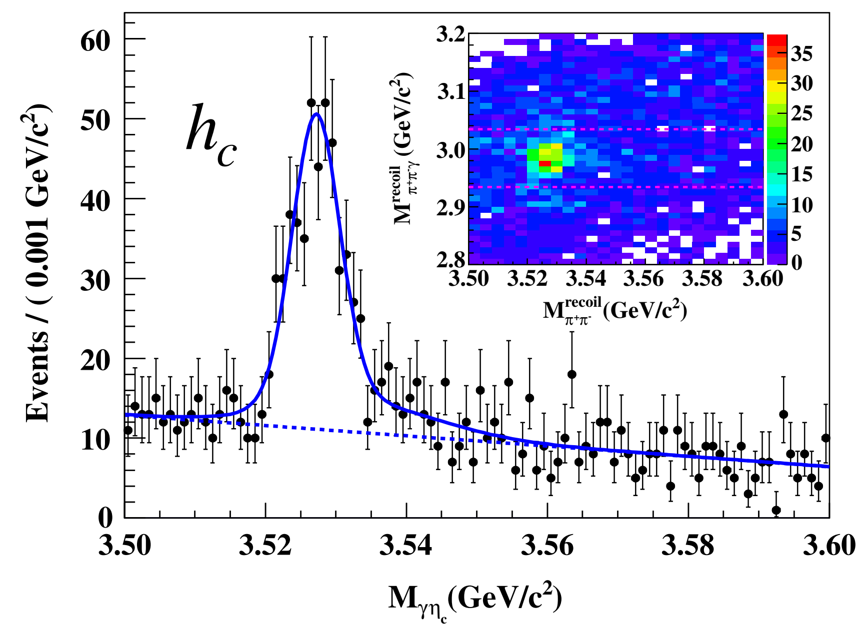

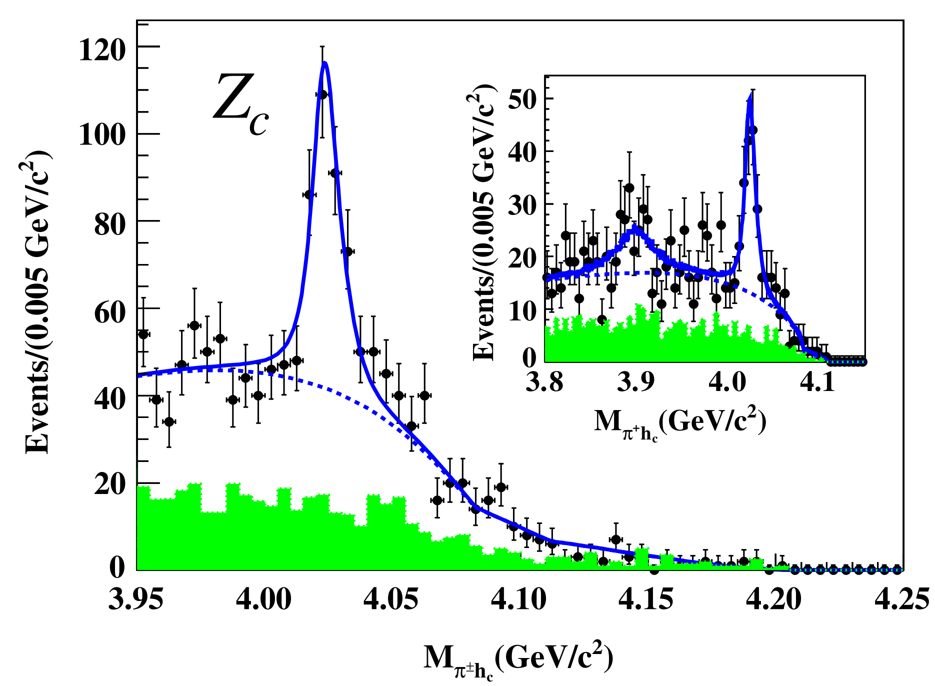

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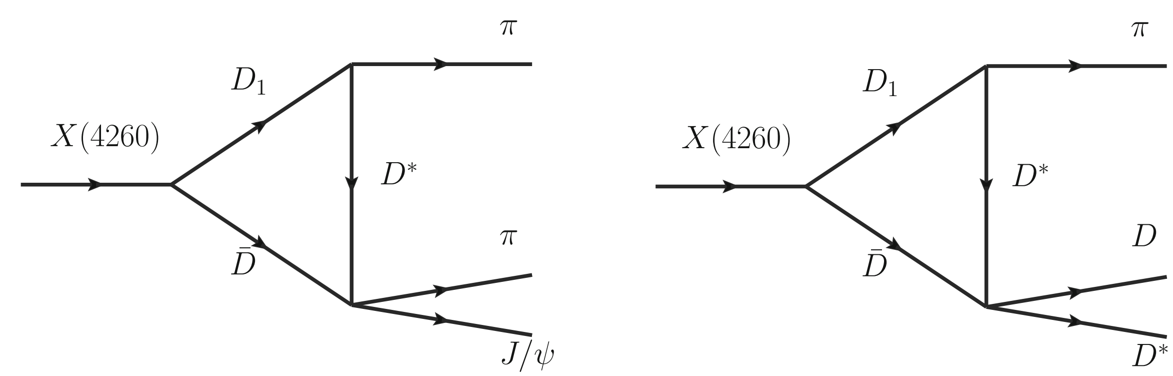
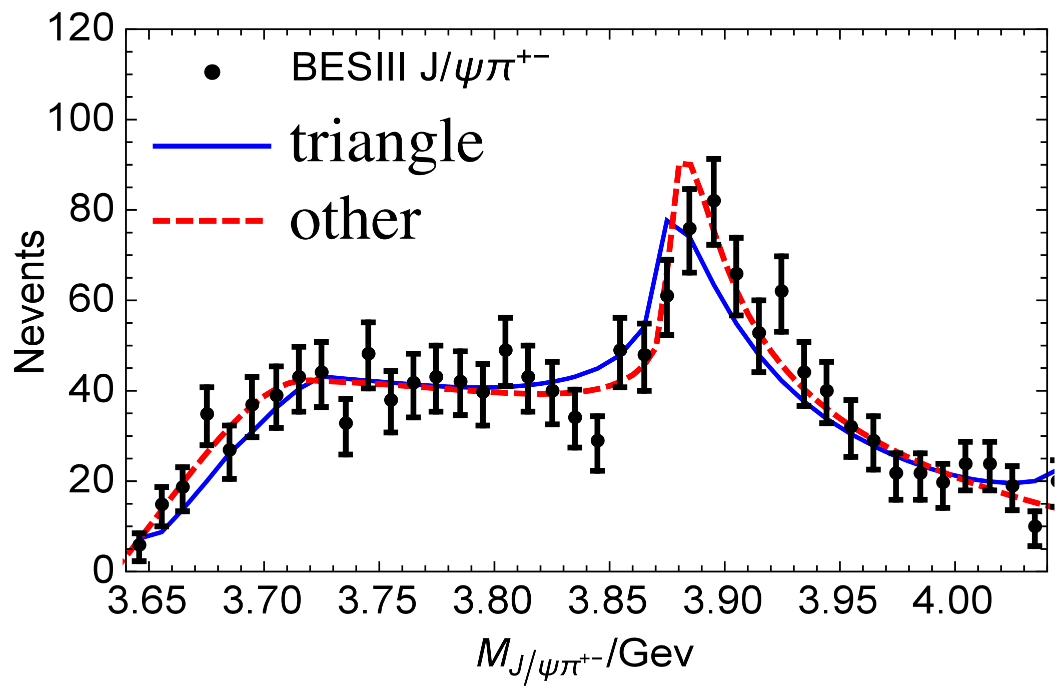
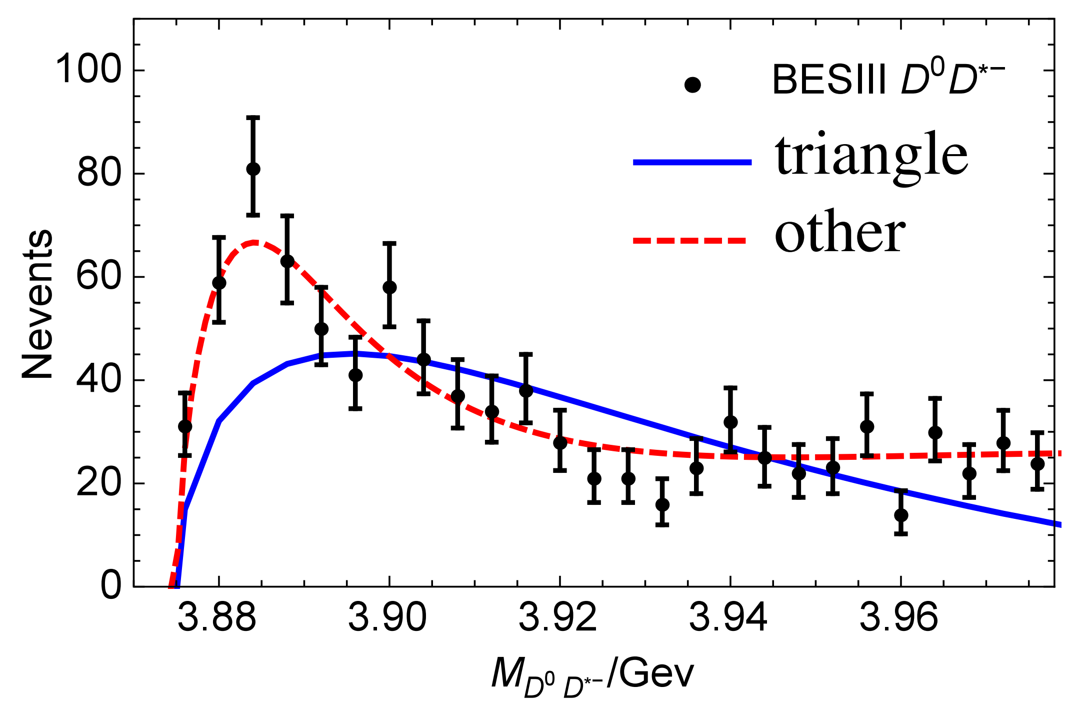
Eur. Phys. J. C (2018) 78:276
https://doi.org/10.1140/epjc/s10052-018-5690-7
THE EUROPEAN PHYSICAL JOURNAL C
CrossMark
Regular Article - Theoretical Physics

The $Z_c(3900)$ peak does not come from the "triangle singularity"

Qin-Rong Gong[1], Jing-Long Pang[1], Yu-Fei Wang[1], Han-Qing Zheng[1,2,a]







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Physics Letters B 772 (2017) 200–209

Contents lists available at ScienceDirect

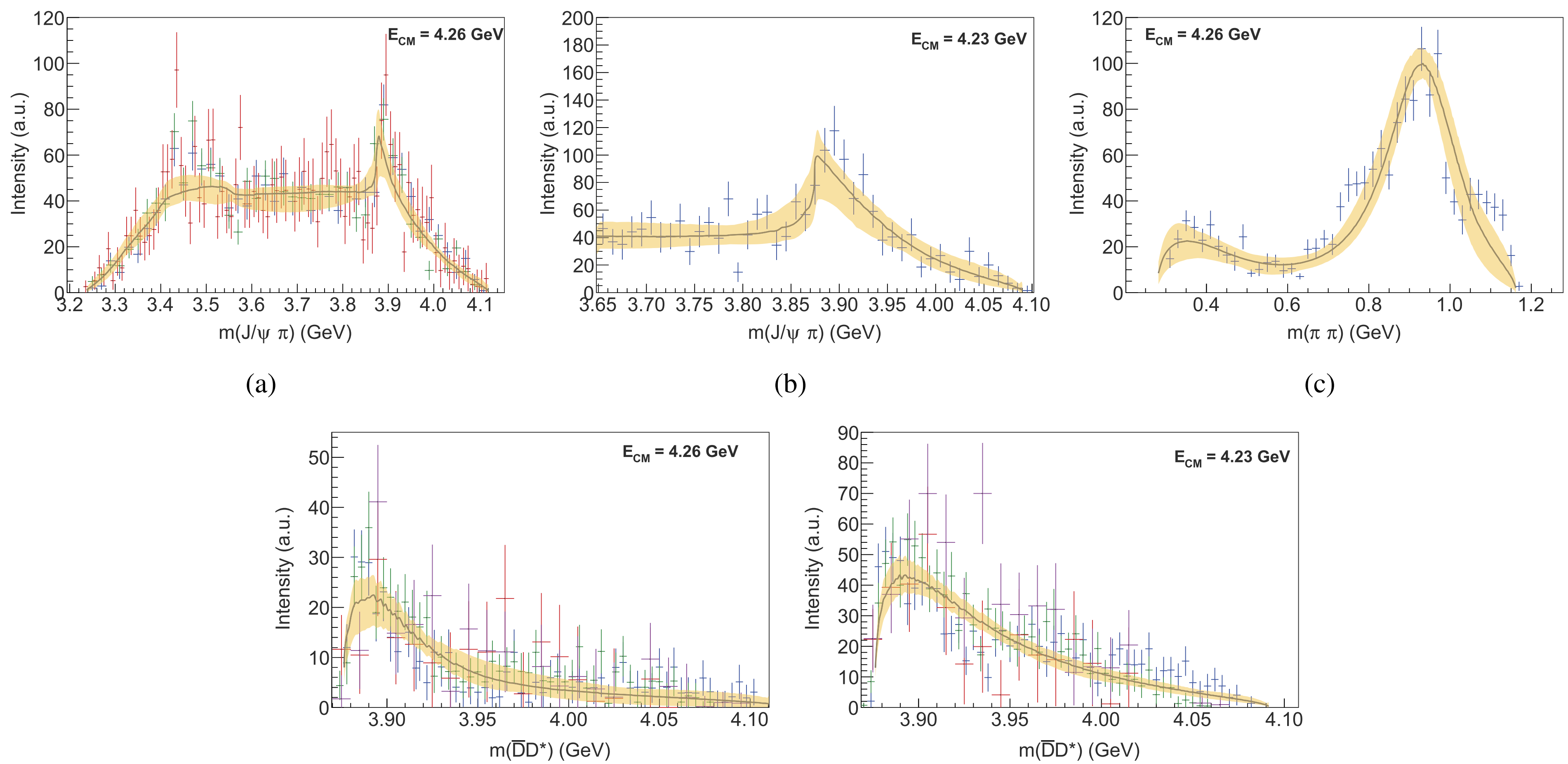
Physics Letters B

www.elsevier.com/locate/physletb

Amplitude analysis and the nature of the $Z_c(3900)$

A. Pilloni [a,*], C. Fernández-Ramírez [b], A. Jackura [c,d], V. Mathieu [c,d], M. Mikhasenko [e], J. Nys [f], A.P. Szczepaniak [a,c,d]

JPAC Collaboration



IVB. Exotic Charmonium: Z_c from B decays

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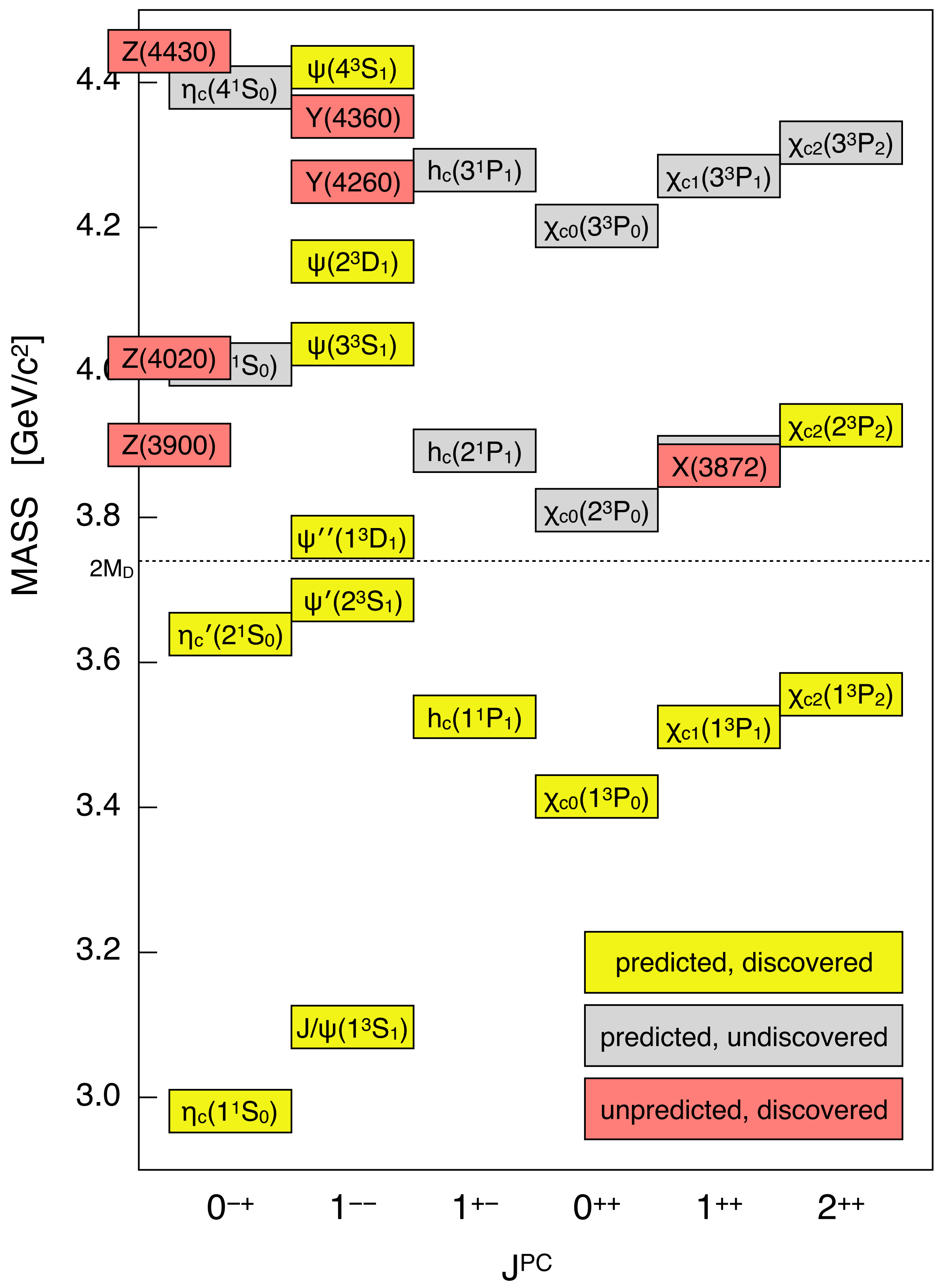
(1) different from those seen in e^+e^- (??)

(2) structure in $B \to K\pi J/\psi$

(3) structure in $B \to K\phi J/\psi$

Charmonium



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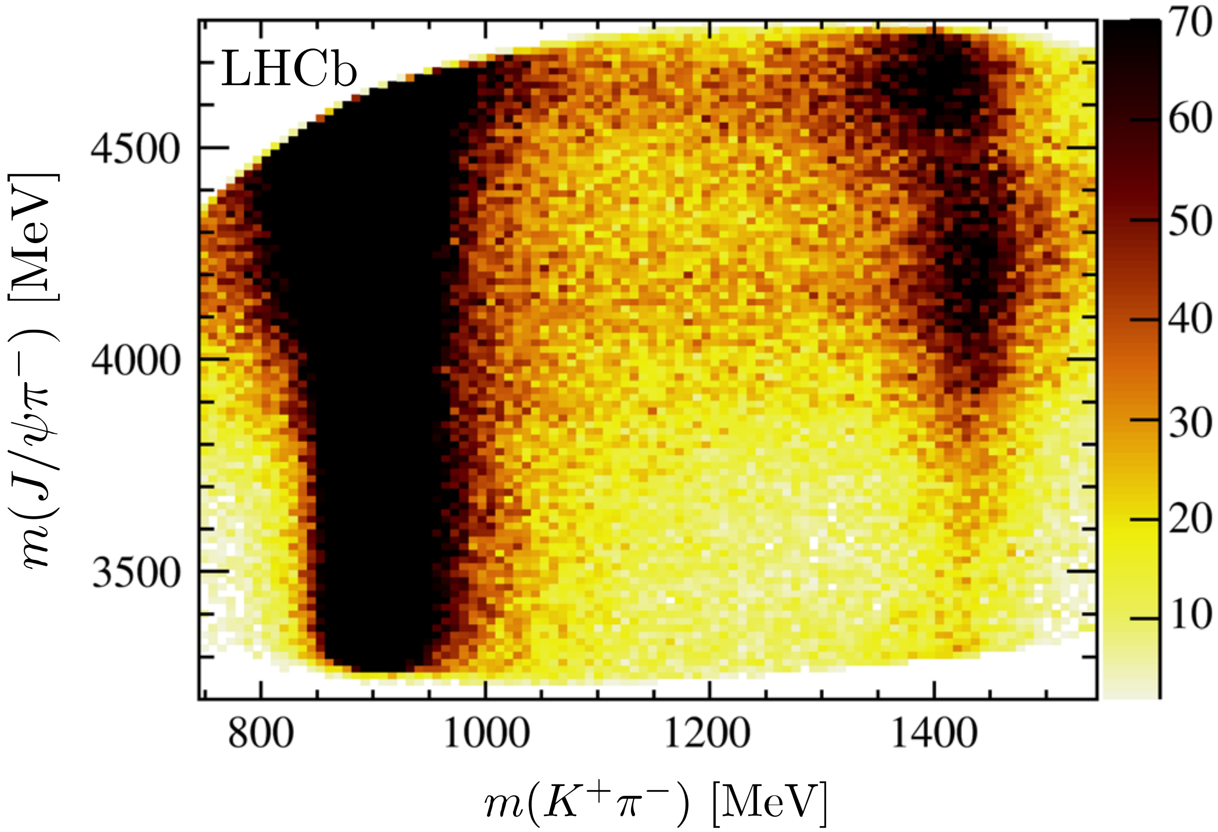
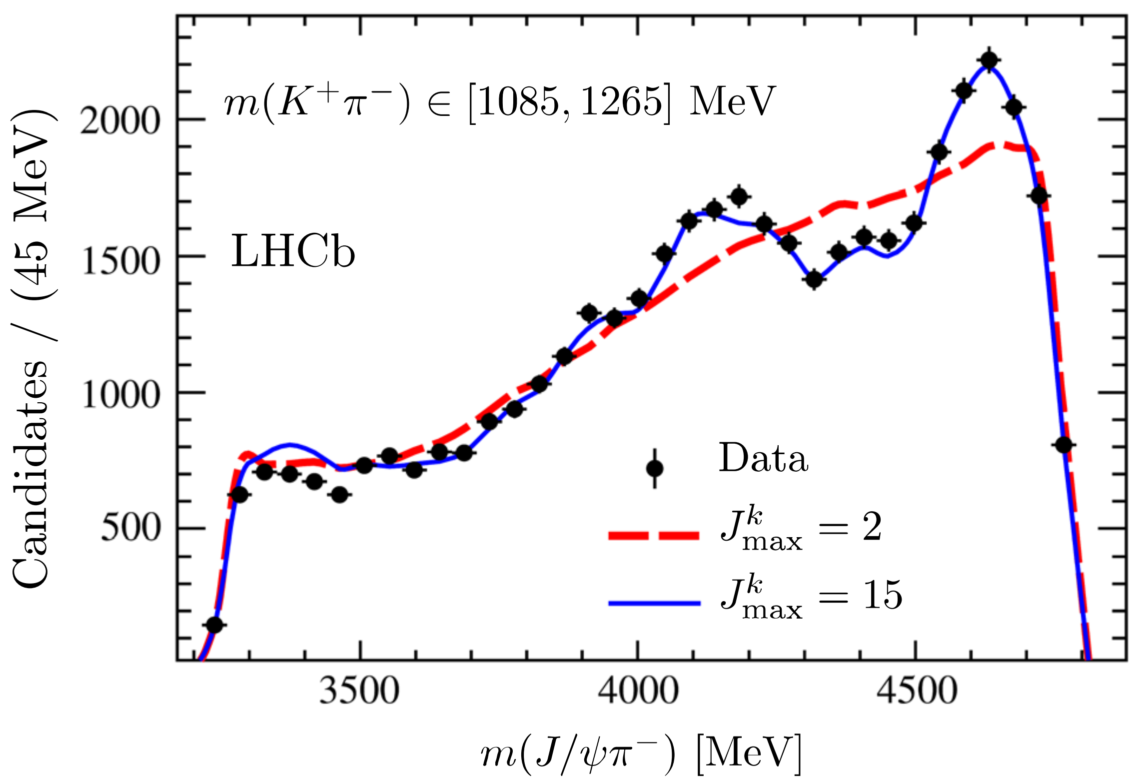
PHYSICAL REVIEW LETTERS **122,** 152002 (2019)

Model-Independent Observation of Exotic Contributions to $B^0 \to J/\psi K^+\pi^-$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)





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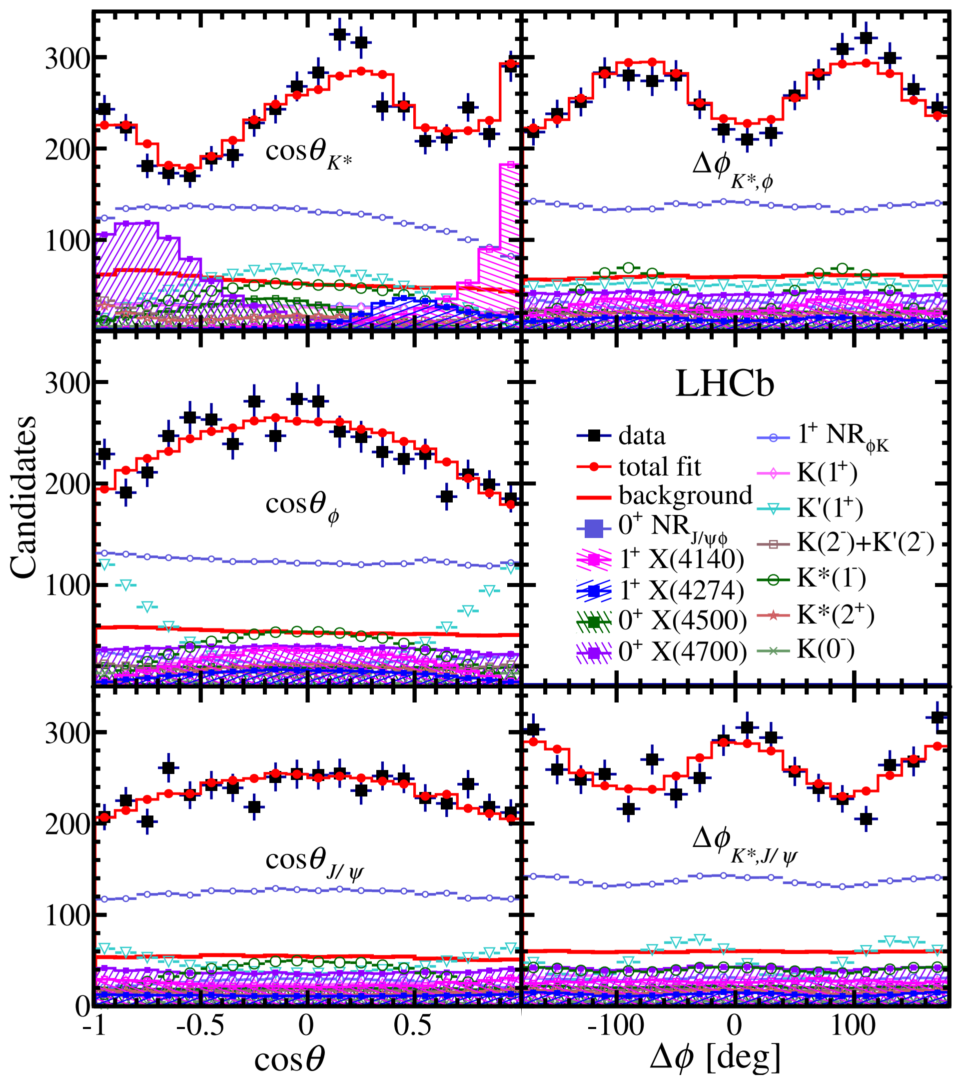
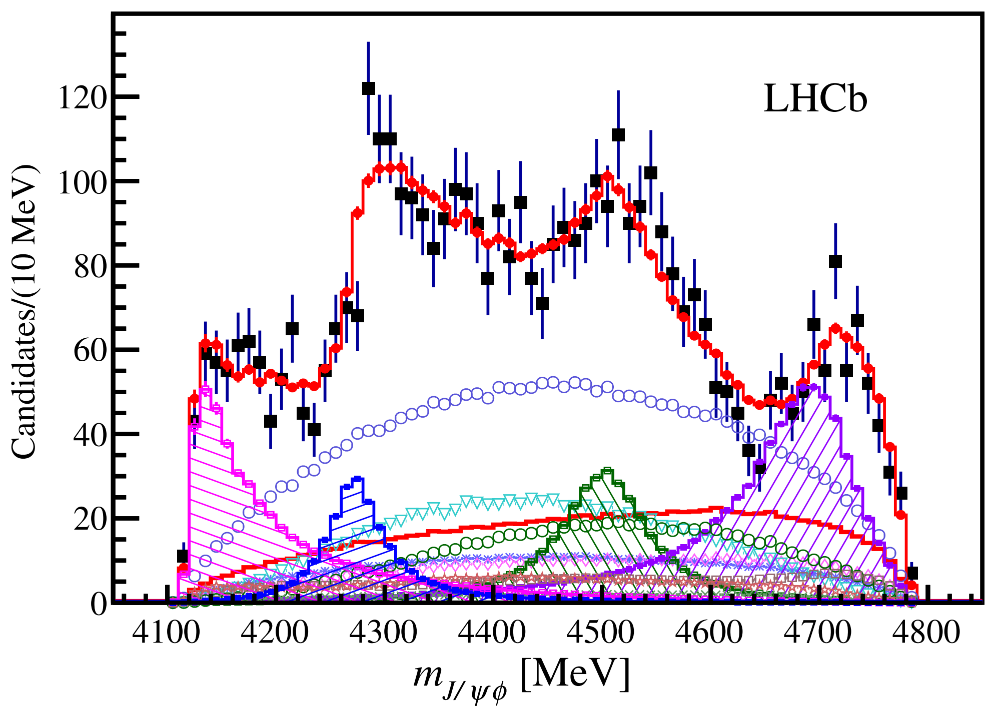
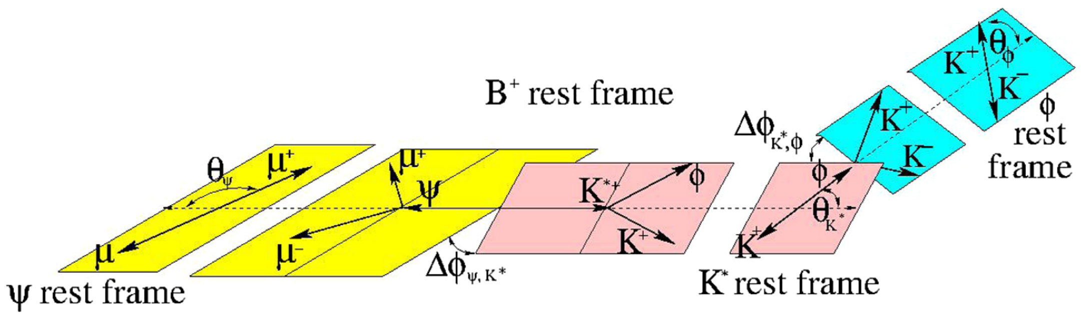
PHYSICAL REVIEW D **95,** 012002 (2017)

Amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays

R. Aaij *et al.*[*]
(LHCb Collaboration)







(good reference for amplitude analysis)

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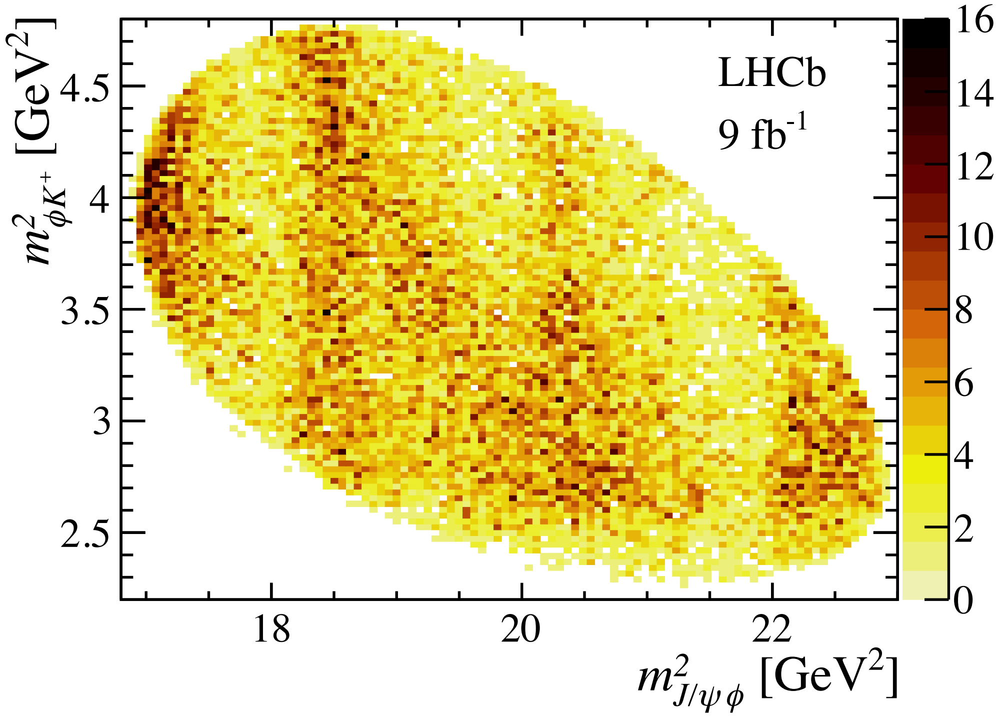
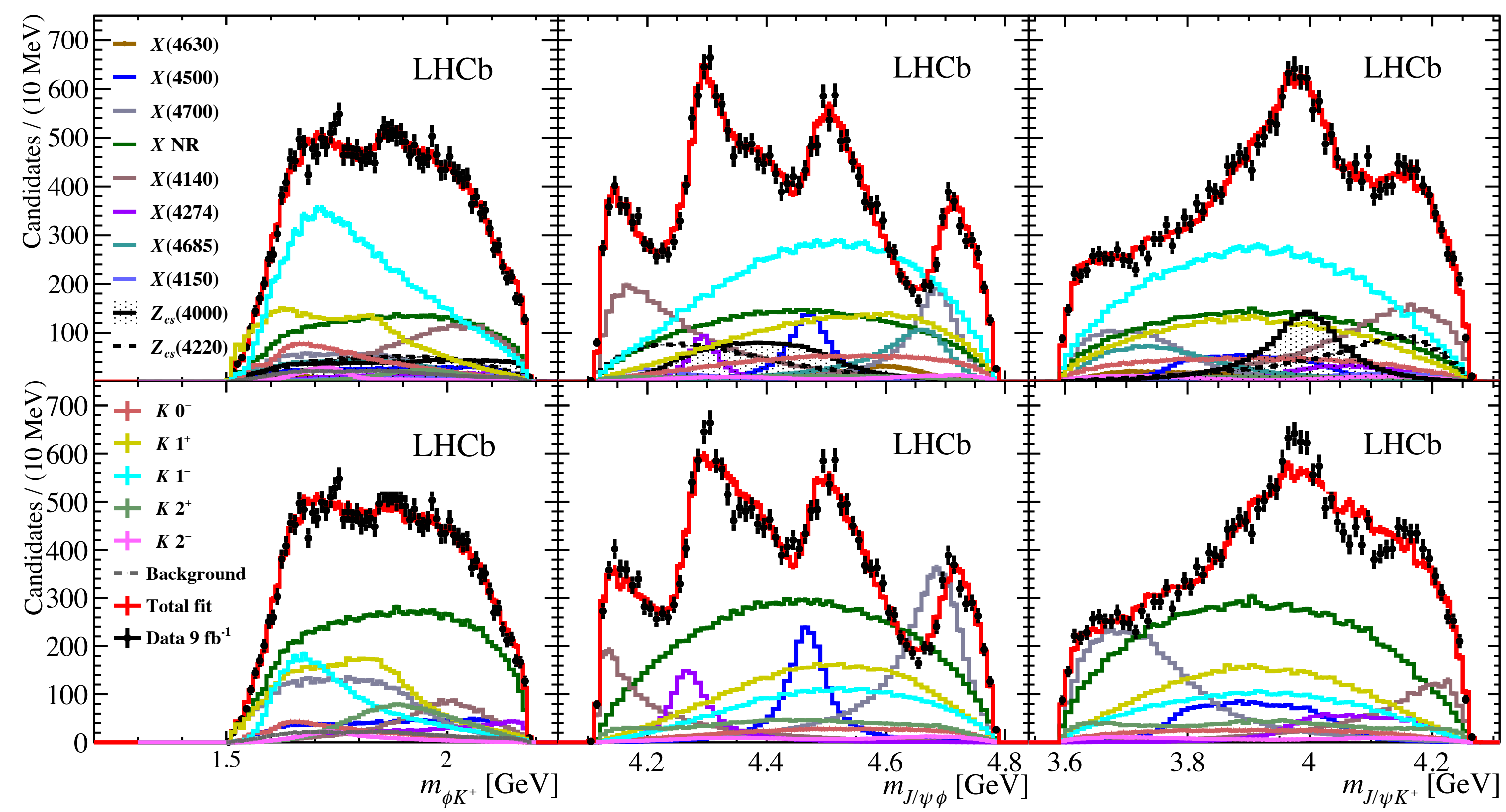
Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

arXiv:2103.01803v1 [hep-ex] 2 Mar 2021

LHCb collaboration†





CERN COURIER MAY/JUNE 2021

HADRON SPECTROSCOPY

LHCb observes four new tetraquarks

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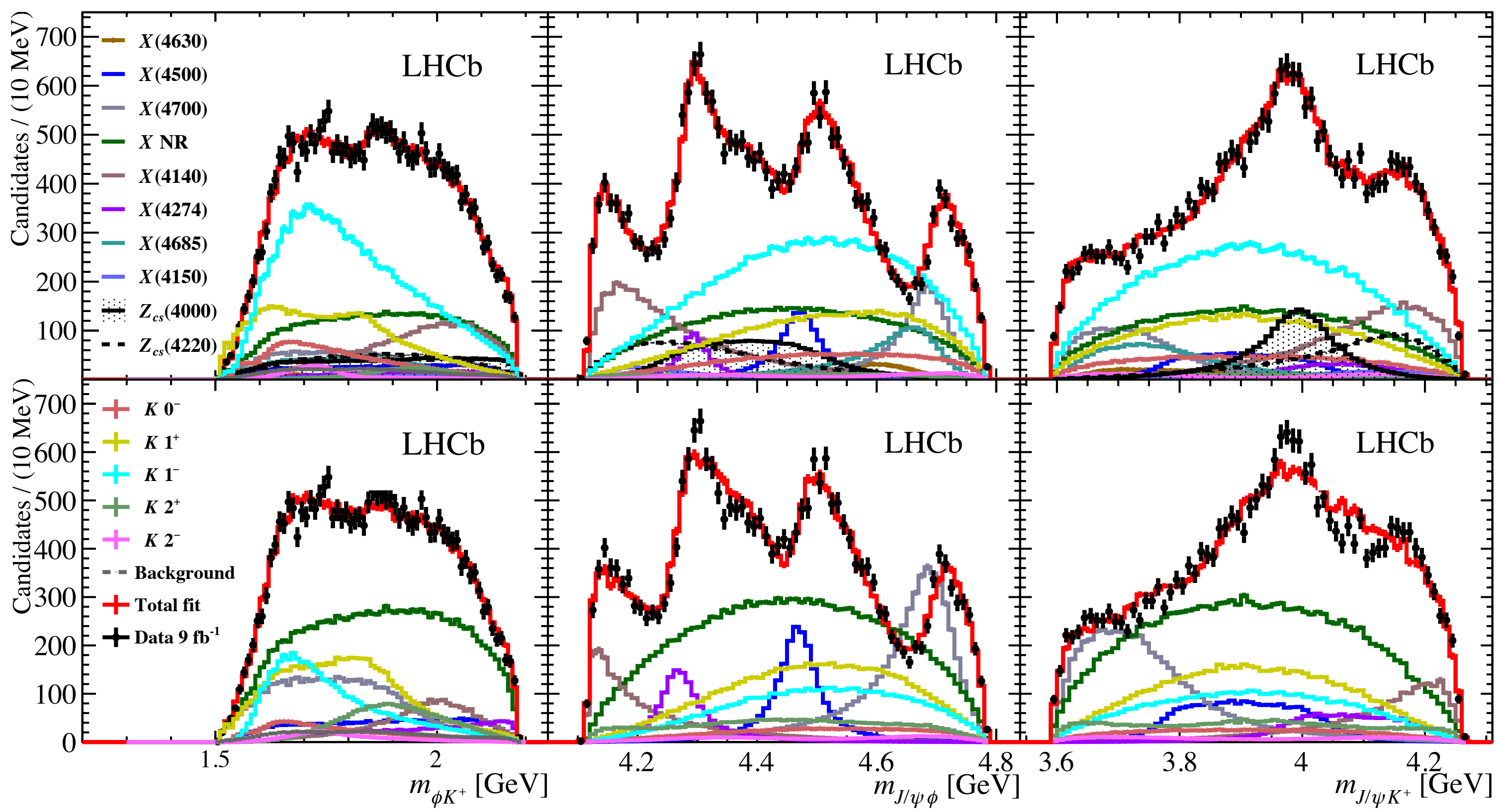
Contribution		Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
	All $K(1^+)$				$25 \pm 4^{+6}_{-15}$
2^1P_1	$K(1^+)$	4.5 (4.5)	$1861 \pm 10^{+16}_{-46}$	$149 \pm 41^{+231}_{-23}$	
2^3P_1	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37^{+124}_{-48}$	$276 \pm 50^{+319}_{-159}$	
1^3P_1	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3^{+3}_{-11}$
	All $K(2^-)$				$2.1 \pm 0.4^{+2.0}_{-1.1}$
1^1D_2	$K_2(1770)$	7.9 (8.0)	1773	186	
1^3D_2	$K_2(1820)$	5.8 (5.8)	1816	276	
	All $K(1^-)$				$50 \pm 4^{+10}_{-19}$
1^3D_1	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2^{+35}_{-8}$
2^3S_1	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5^{+11}_{-17}$
	$K(2^+)$				
2^3P_2	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22^{+194}_{-31}$	$318 \pm 82^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
	$K(0^-)$				
2^1S_0	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2^{+1.0}_{-3.8}$
	$X(2^-)$				
	$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
	$X(1^-)$				
	$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
	All $X(0^+)$				$20 \pm 5^{+14}_{-7}$
	$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
	$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
	$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
	All $X(1^+)$				$26 \pm 3^{+8}_{-10}$
	$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
	$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
	$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
	All $Z_{cs}(1^+)$				$25 \pm 5^{+11}_{-12}$
	$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
	$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

arXiv:2103.01803v1 [hep-ex] 2 Mar 2021

LHCb collaboration†



CERN COURIER MAY/JUNE 2021

HADRON SPECTROSCOPY

LHCb observes four new tetraquarks

IVB. Exotic Charmonium

The basics of exotic charmonium
(or "charmoniumlike" states):

$\chi_{c1}(3872)$
aka $X(3872)$

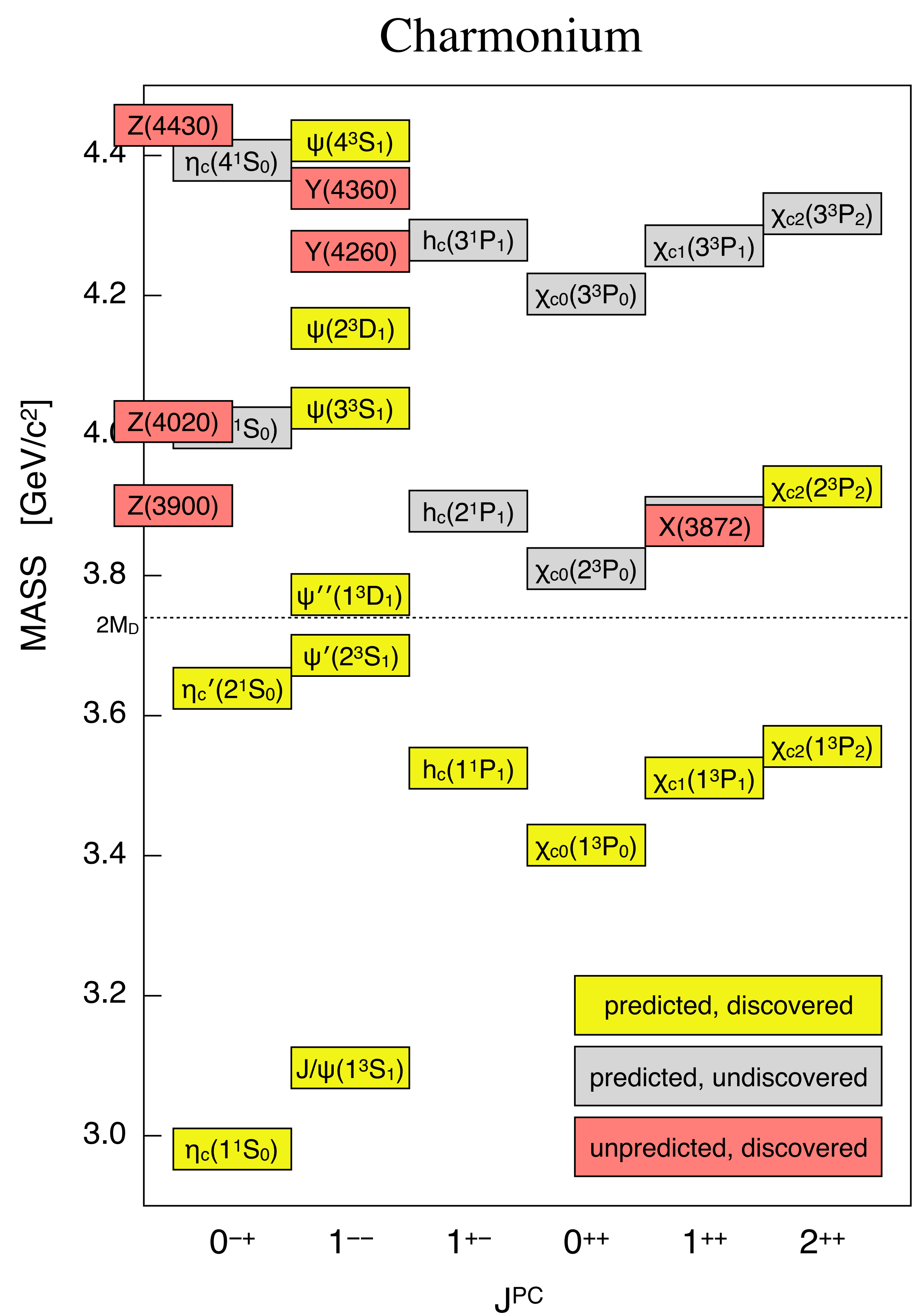
$\psi(4230)$ and $\psi(4360)$
aka Y(4260) and Y(4360)

$Z_c(3900)$ and $Z_c(4020)$

Z_c mesons in B decays

Original names (still commonly used):

Y: mesons made directly in e^+e^-
Z: "charmonium" with $I \neq 0$.
X: everything else



IVC. Exotic Bottomonium

The basics of exotic charmonium
(or "charmoniumlike" states):

$\chi_{c1}(3872)$ aka $X(3872)$	→	no bottomonium X(3872)
$\psi(4230)$ aka Y(4230) (previously Y(4260))	→	similar Υ states (Y_b)
$Z_c(3900)$ and $Z_c(4020)$	→	similar Z states (Z_b)
Z_c mesons in B decays	→	no top mesons

Original names (still commonly used):

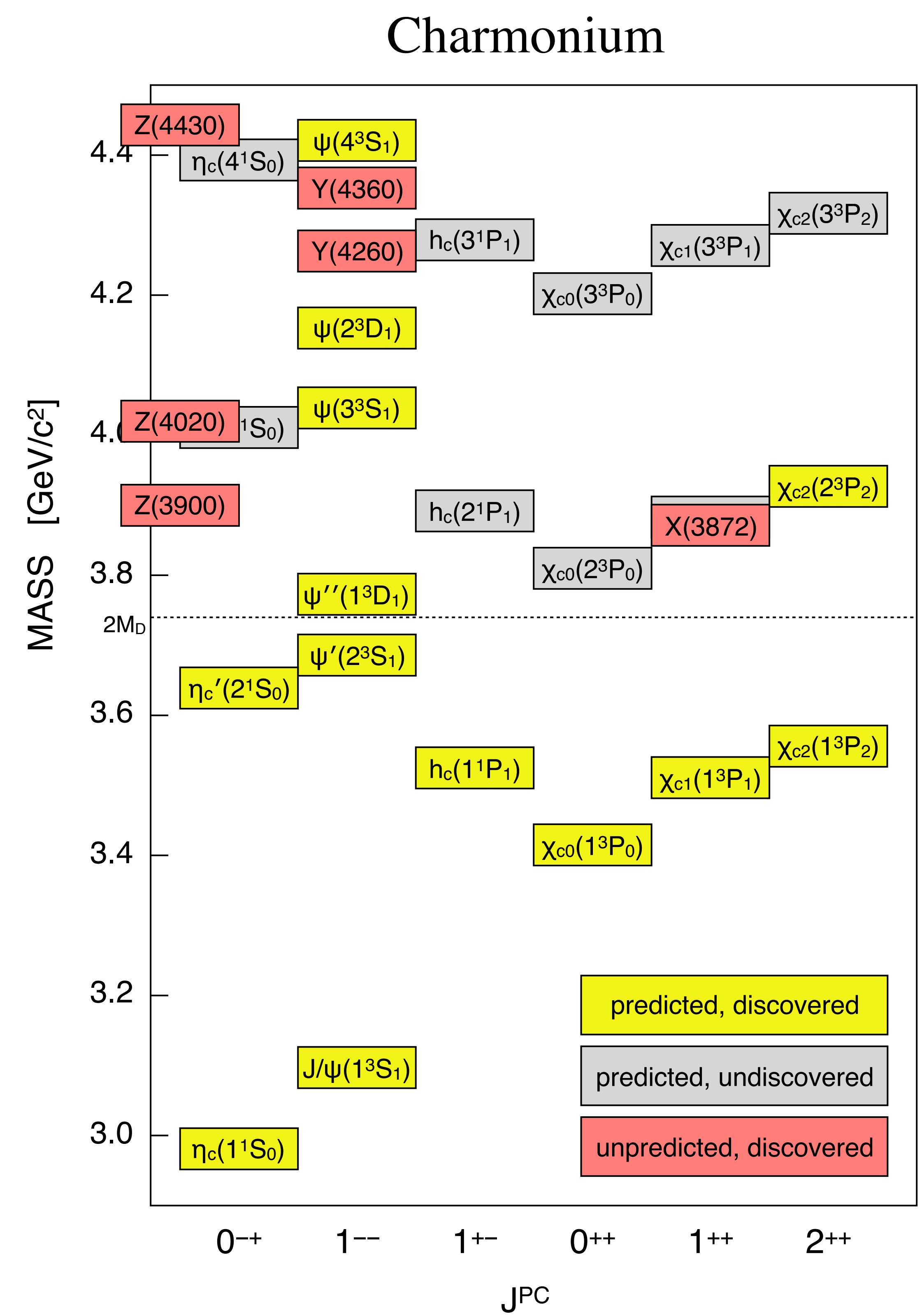
Y: mesons made directly in e^+e^-
Z: "charmonium" or "bottomonium" with $I \neq 0$.
X: everything else

IVA. Exotic Meson Identification

Exotic mesons can be distinguished from conventional mesons in at least four ways:

1. unusual properties
   e.g. $X(3872)$
2. overpopulation
   e.g. $Y(4260)$, $Y(4360)$
3. exotic flavor
   e.g. $Z_c(3900)$, $Z_c(4020)$
4. exotic J^{PC}
   e.g. $\pi_1(1600)$

major caveat: an exotic hadron must also be a hadron (as opposed to a scattering artifact, for example)



This talk: charmonium, bottomonium, light quark mesons.

IVD. Exotic Light Quark Mesons

Exotic mesons can be distinguished from conventional mesons in at least four ways:

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   e.g. $X(3872)$
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   e.g. $Y(4260)$, $Y(4360)$
3. exotic flavor
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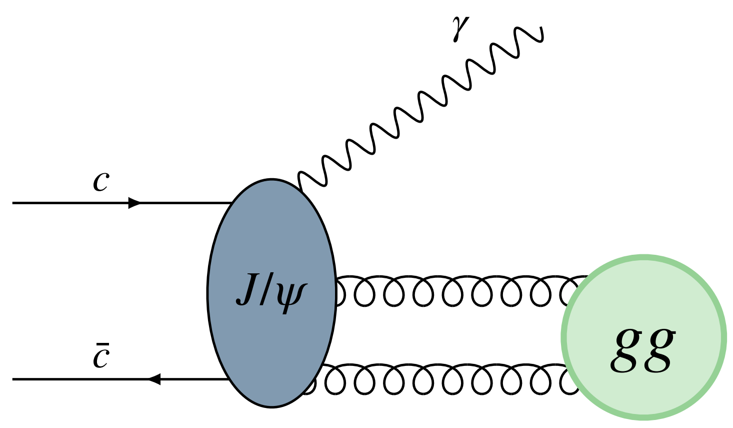
Light Quark Mesons:

glueballs

* lightest is expected to have $J^{PC} = 0^{++}$
* traditionally expected in J/ψ radiative decays



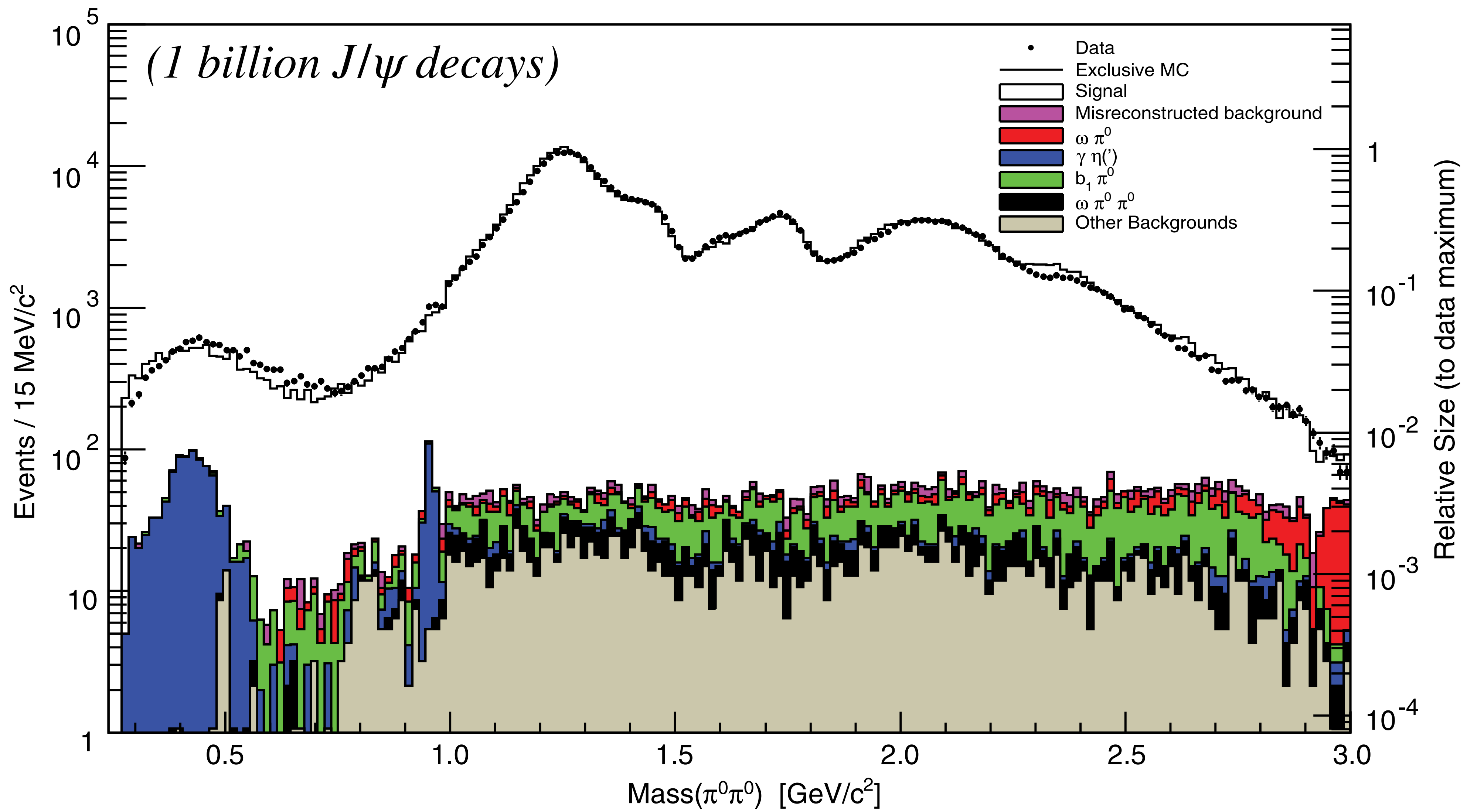
mesons with exotic J^{PC}

* expect hybrid mesons with $J^{PC} = 1^{-+}$ (η_1, π_1)
* perhaps produce these with photoproduction
* (also expected in heavy quark systems)

PHYSICAL REVIEW D **92**, 052003 (2015)

Amplitude analysis of the $\pi^0\pi^0$ system produced in radiative J/ψ decays

(BESIII Collaboration)
A. P. Szczepaniak,[19,53,54] and P. Guo[19,53]



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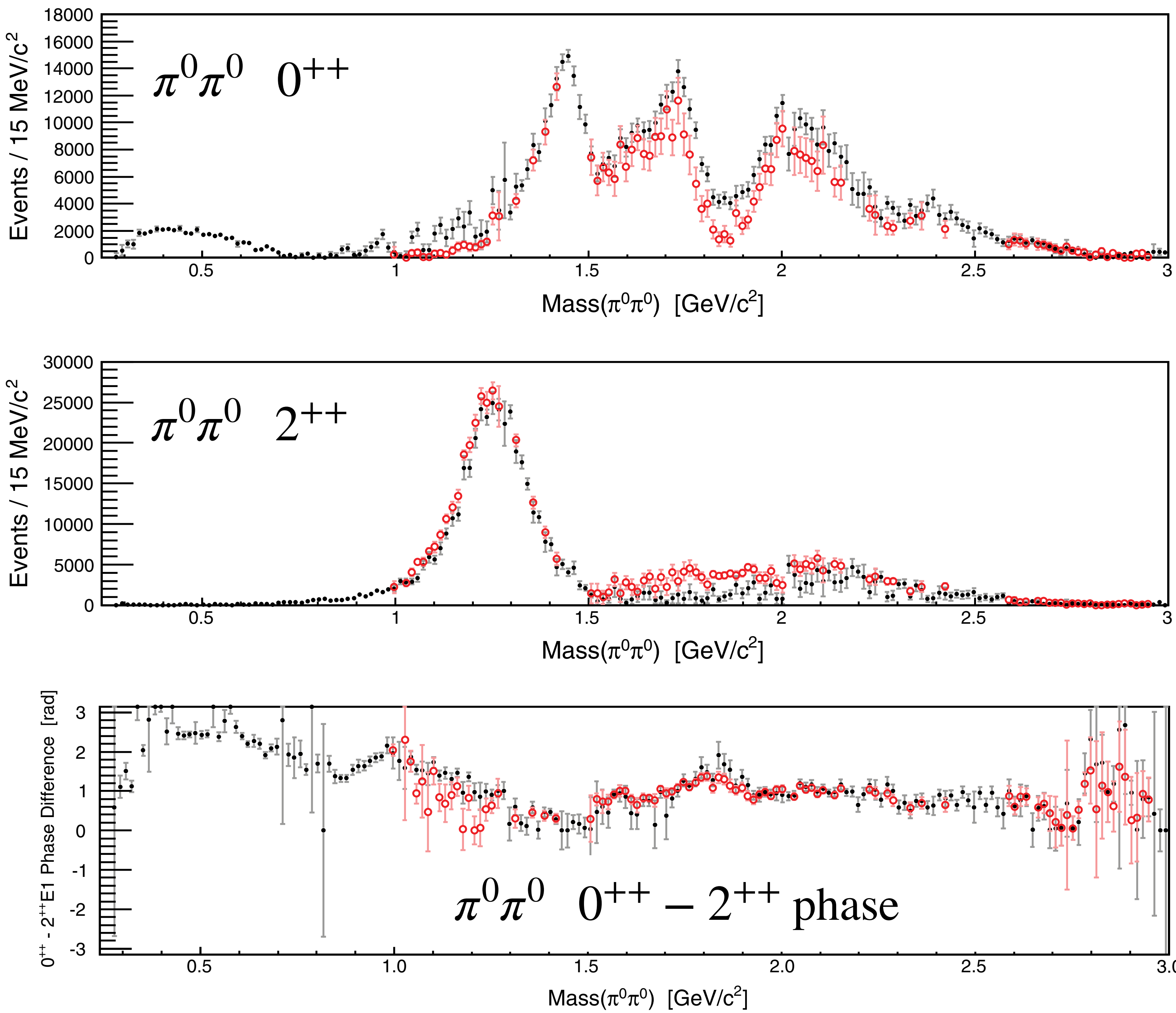

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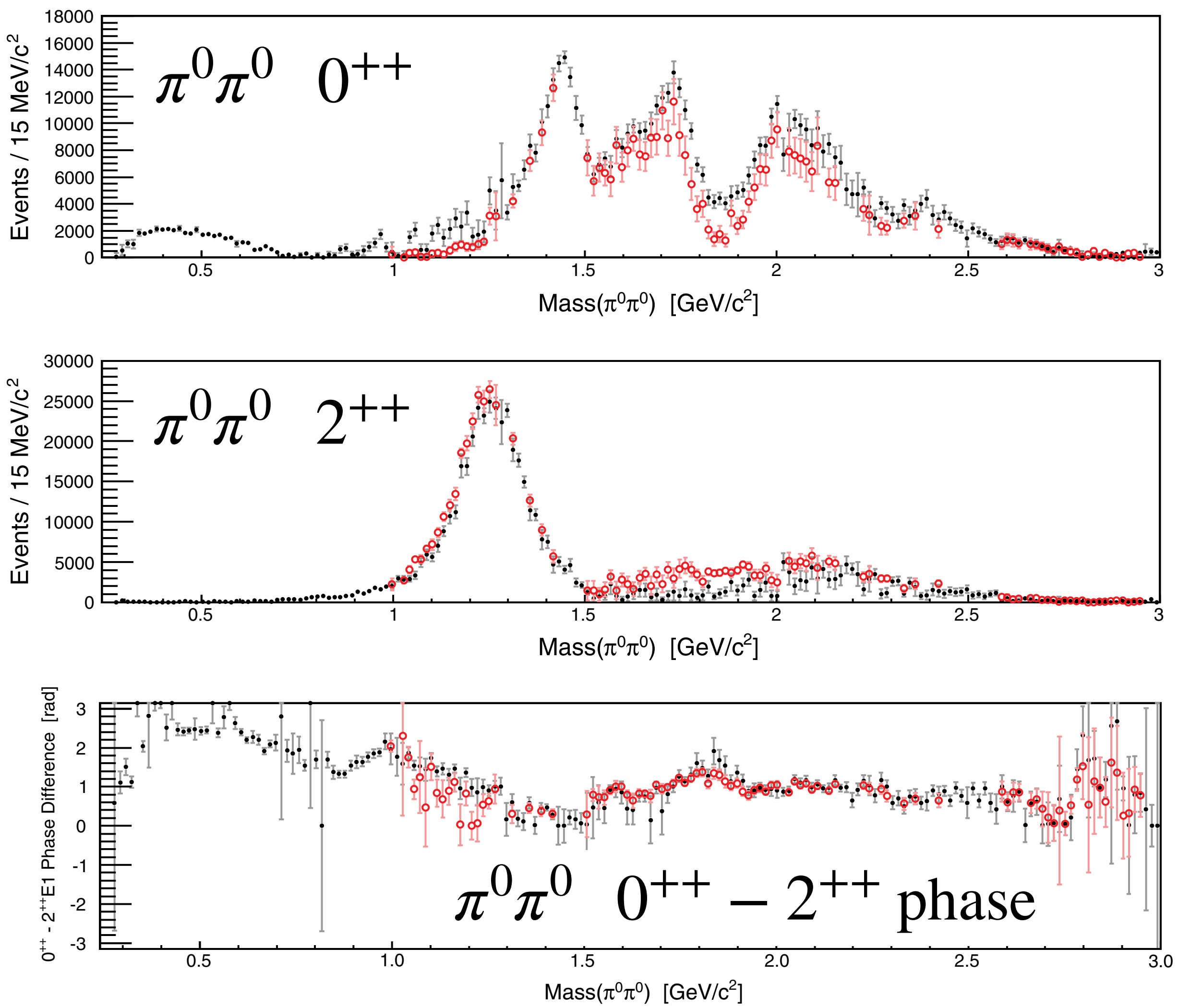
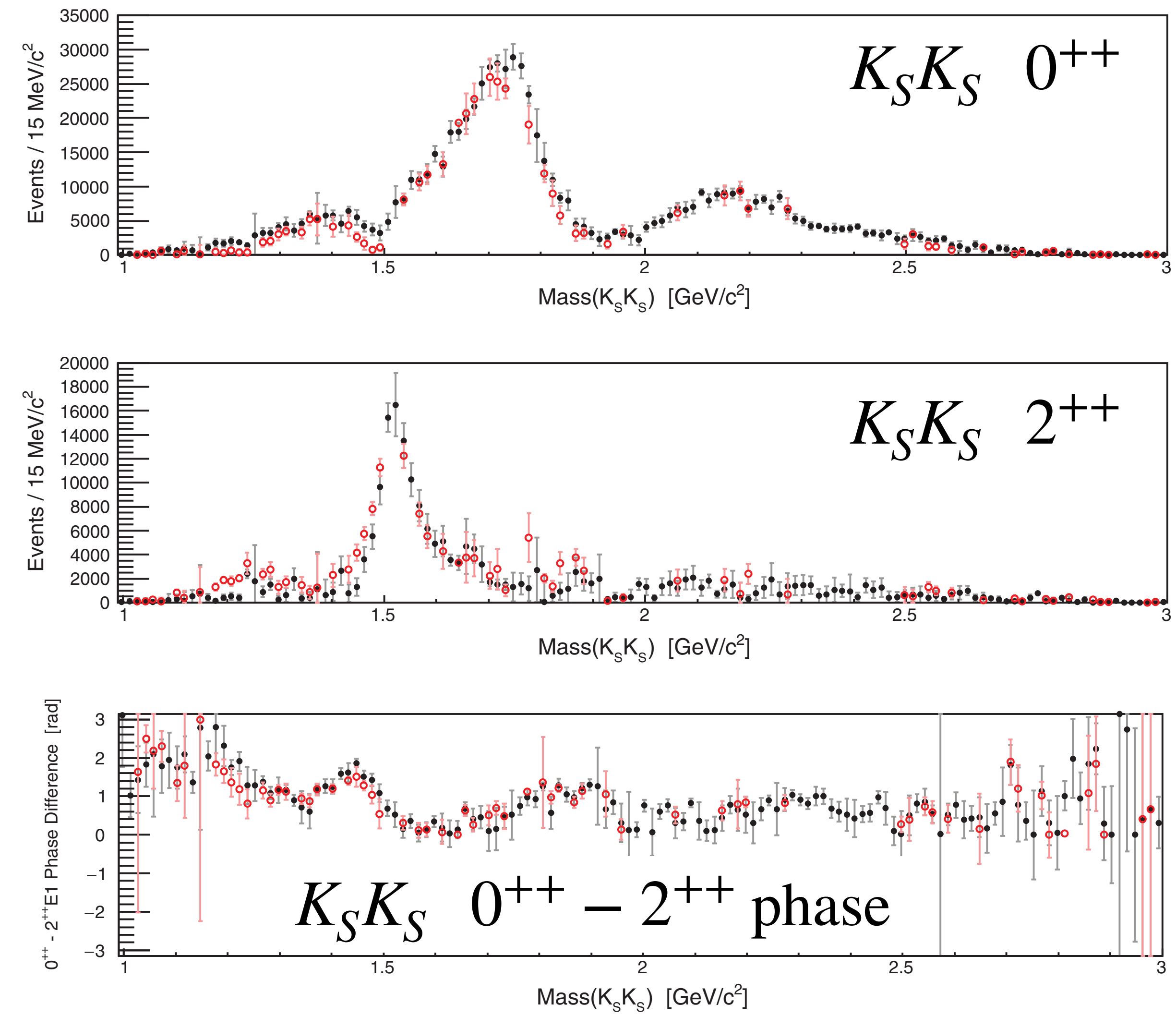


PHYSICAL REVIEW D **98,** 072003 (2018)

Amplitude analysis of the K_SK_S system produced in radiative J/ψ decays

(BESIII Collaboration)

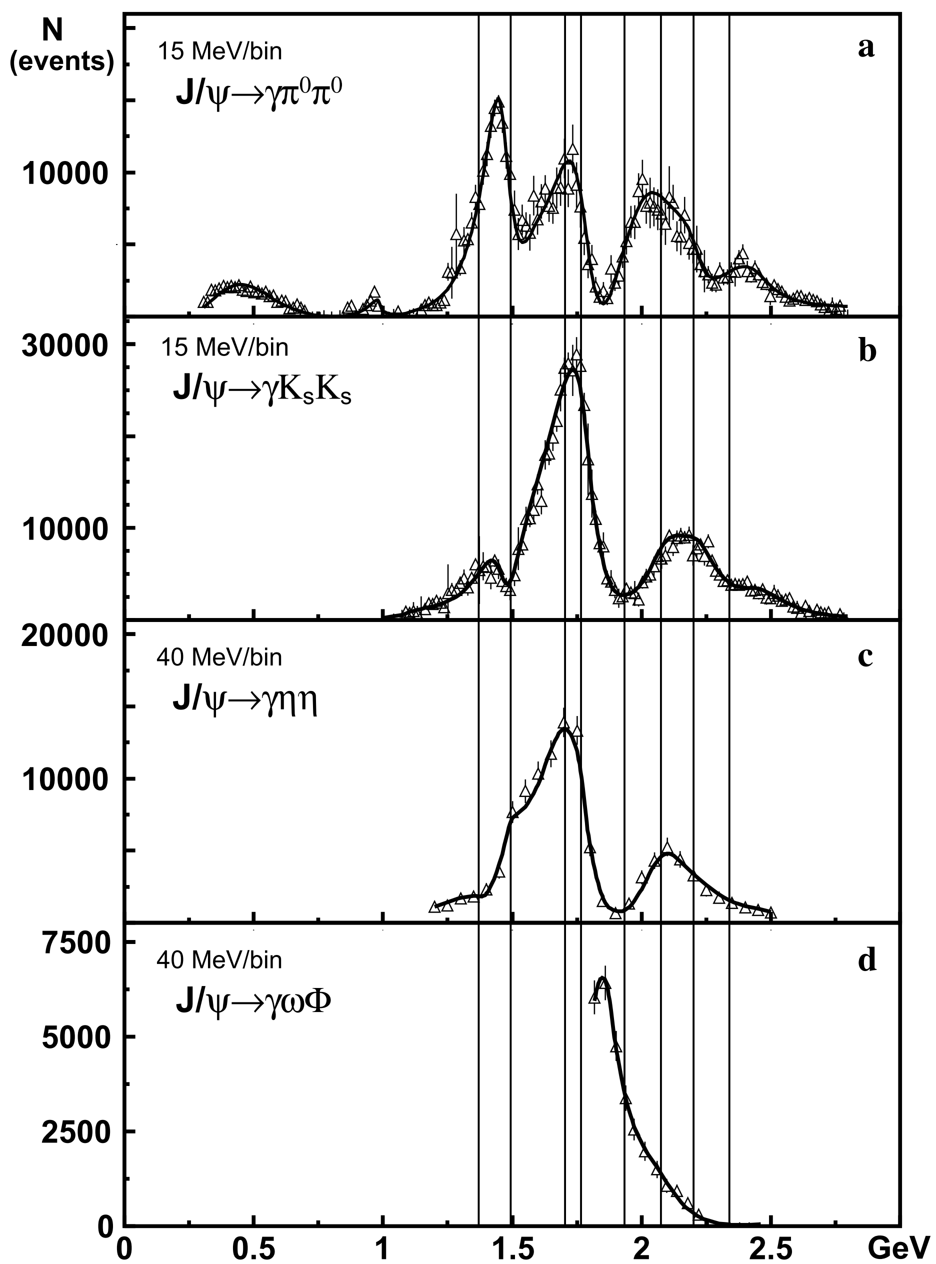


IVD. Exotic Light Quark Mesons

Physics Letters B 816 (2021) 136227

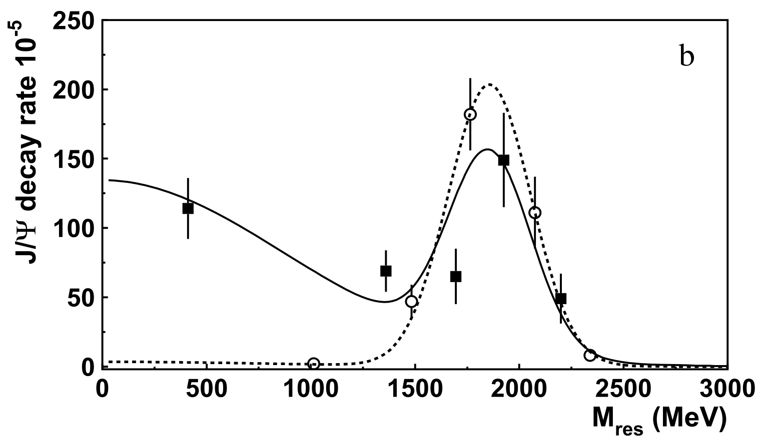
Scalar isoscalar mesons and the scalar glueball from radiative J/ψ decays

A.V. Sarantsev [a,b], I. Denisenko [c], U. Thoma [a], E. Klempt [a,*]



10 f_0 states! but no explicit glueball?

Name	$f_0(500)$	$f_0(1370)$	$f_0(1710)$	$f_0(2020)$	$f_0(2200)$
M [MeV]	410±20	1370±40	1700±18	1925±25	2200±25
	400→550	1200→1500	1704±12	1992±16	2187±14
Γ [MeV]	480±30	390±40	255±25	320±35	150±30
	400→700	100→500	123±18	442±60	~200
Name	$f_0(980)$	$f_0(1500)$	$f_0(1770)$	$f_0(2100)$	$f_0(2330)$
M [MeV]	1014±8	1483 ± 15	1765±15	2075±20	2340±20
	990±20	1506±6		2086^{+20}_{-24}	~2330
Γ [MeV]	71±10	116±12	180±20	260±25	165±25
	10→100	112±9		284^{+60}_{-32}	250±20



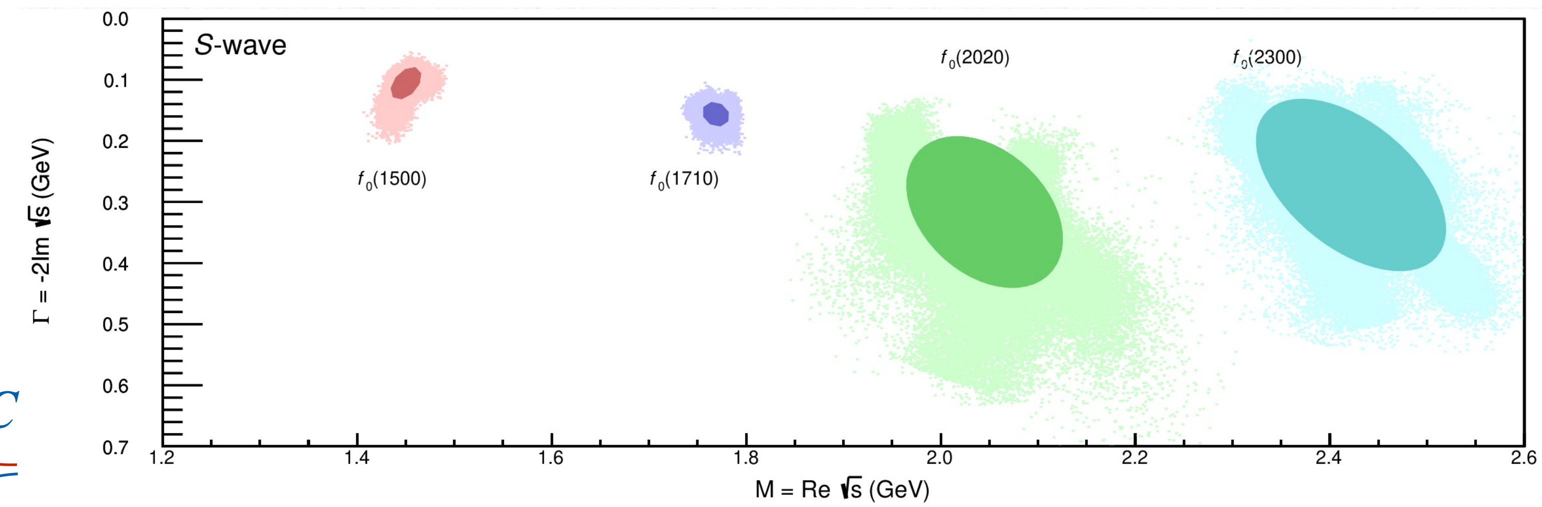
maybe the glueball is apparent in the J/ψ couplings??

IVD. Exotic Light Quark Mesons

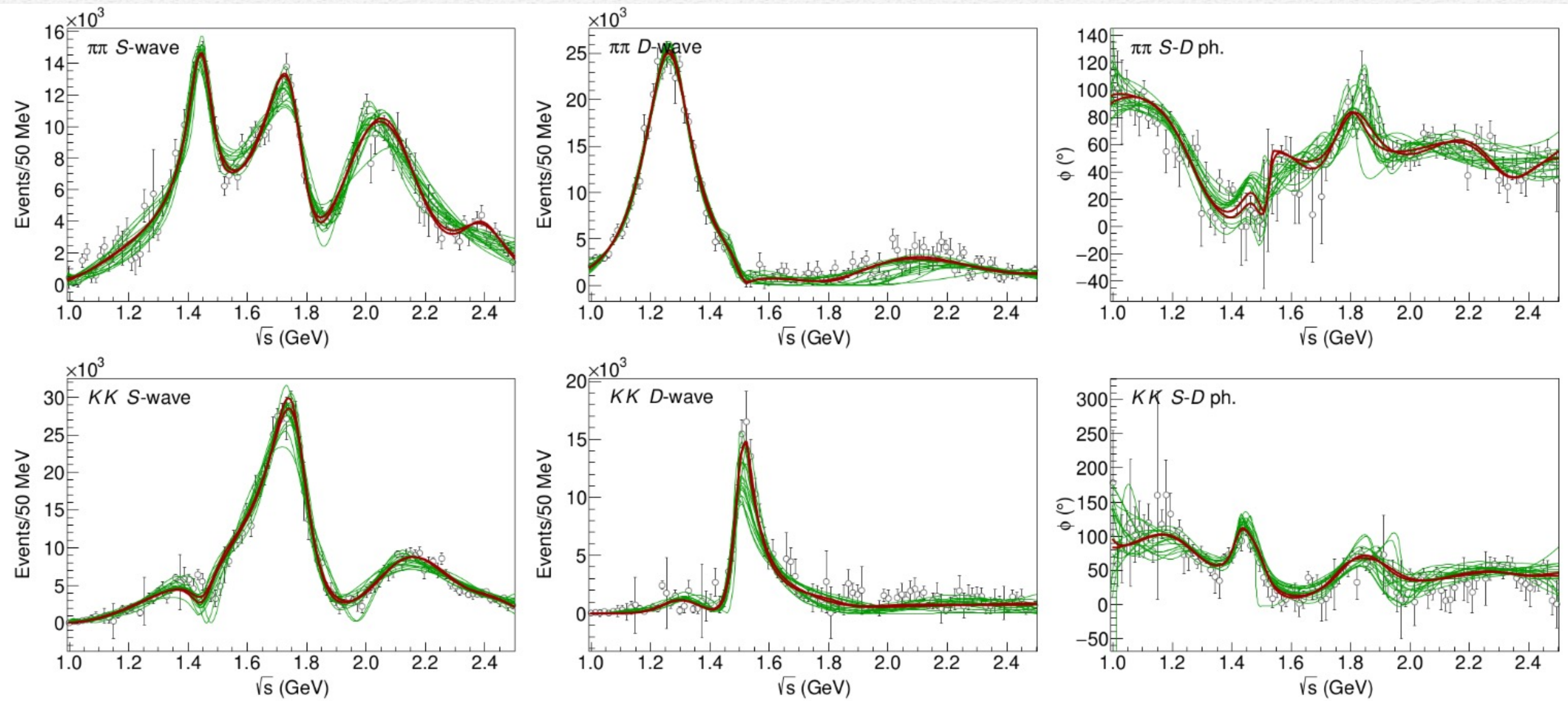
Amplitude analysis for/from charmonia

Alessandro Pilloni

CHARM2021, Mexico City, May 31st, 2021



Rodas, AP, in preparation



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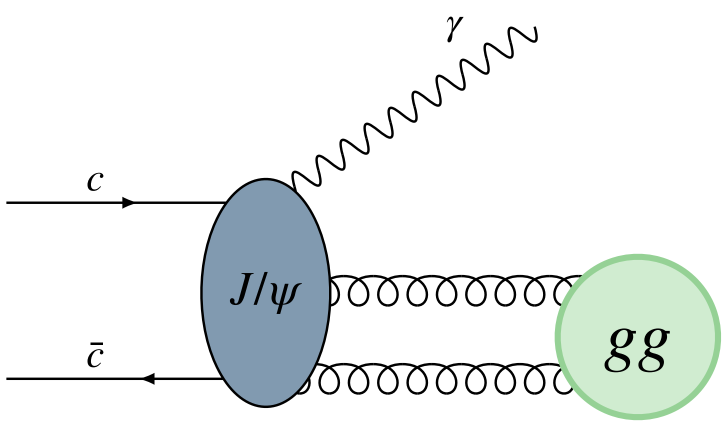

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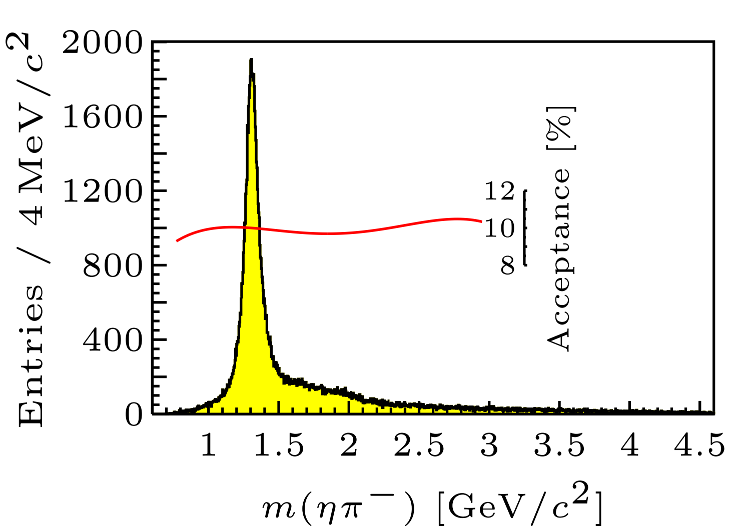
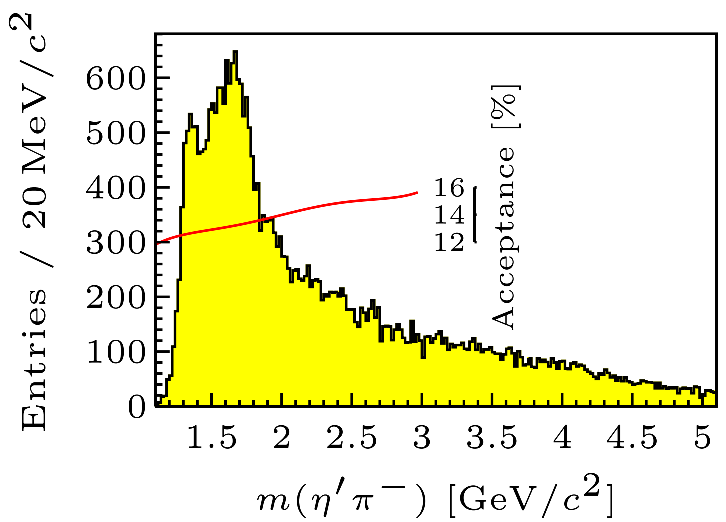
* (also expected in heavy quark systems)

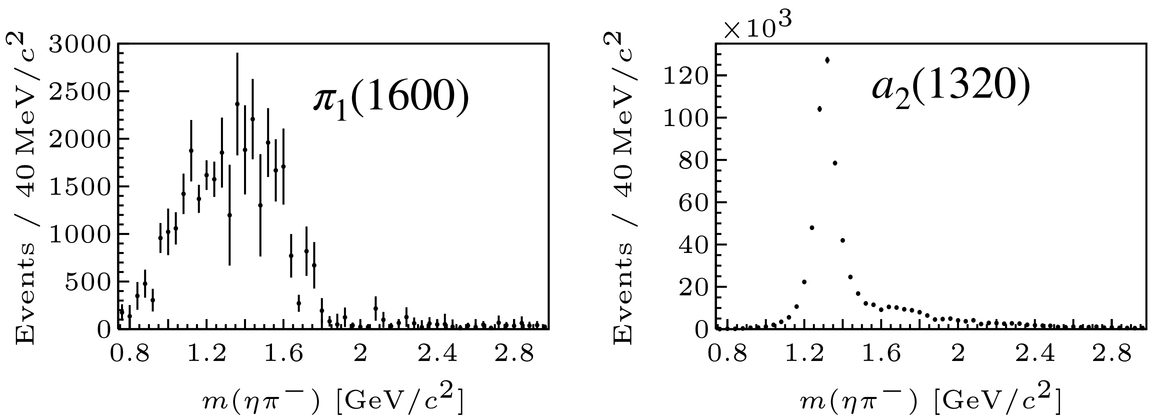
Physics Letters B 740 (2015) 303–311

Odd and even partial waves of $\eta\pi^-$ and $\eta'\pi^-$ in $\pi^- p \to \eta^{(\prime)}\pi^- p$ at 191 GeV/c

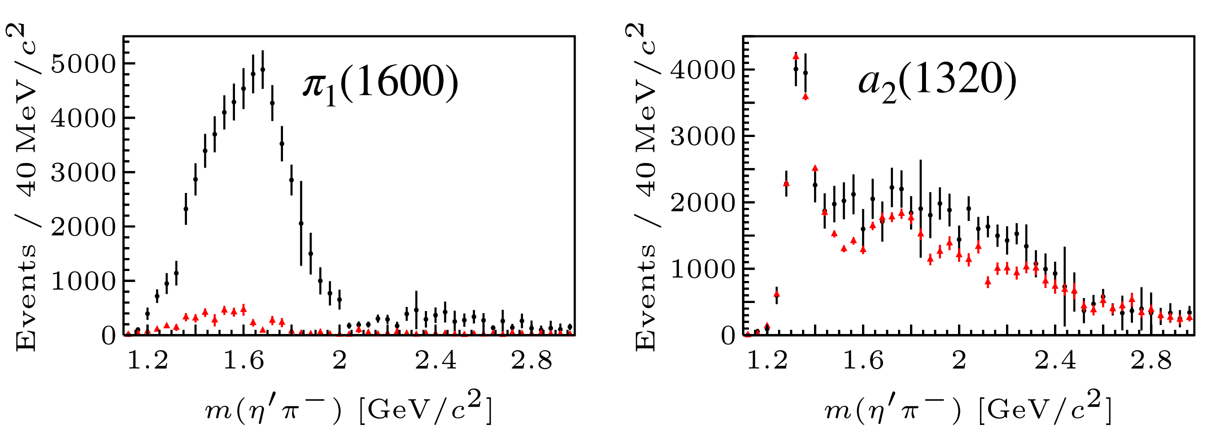
COMPASS Collaboration







(a) P-wave, $L = 1$ (b) D-wave, $L = 2$



(a) P-wave, $L = 1$ (b) D-wave, $L = 2$

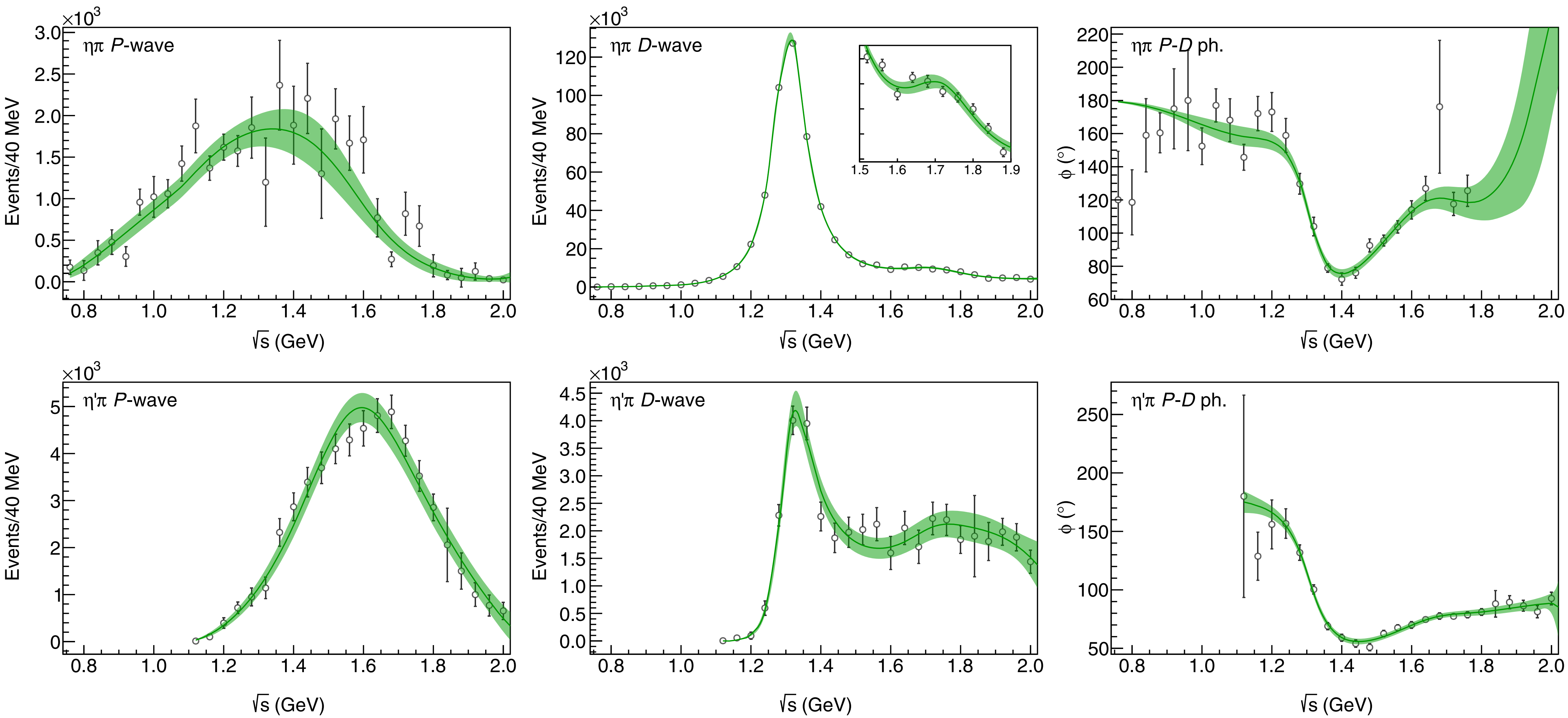
IVA. Exotic Meson Identification

PHYSICAL REVIEW LETTERS **122,** 042002 (2019)

Determination of the Pole Position of the Lightest Hybrid Meson Candidate

A. Rodas,[1,*] A. Pilloni,[2,3,†] M. Albaladejo,[2,4] C. Fernández-Ramírez,[5] A. Jackura,[6,7] V. Mathieu,[2] M. Mikhasenko,[8] J. Nys,[9] V. Pauk,[10] B. Ketzer,[8] and A. P. Szczepaniak[2,6,7]

(Joint Physics Analysis Center)



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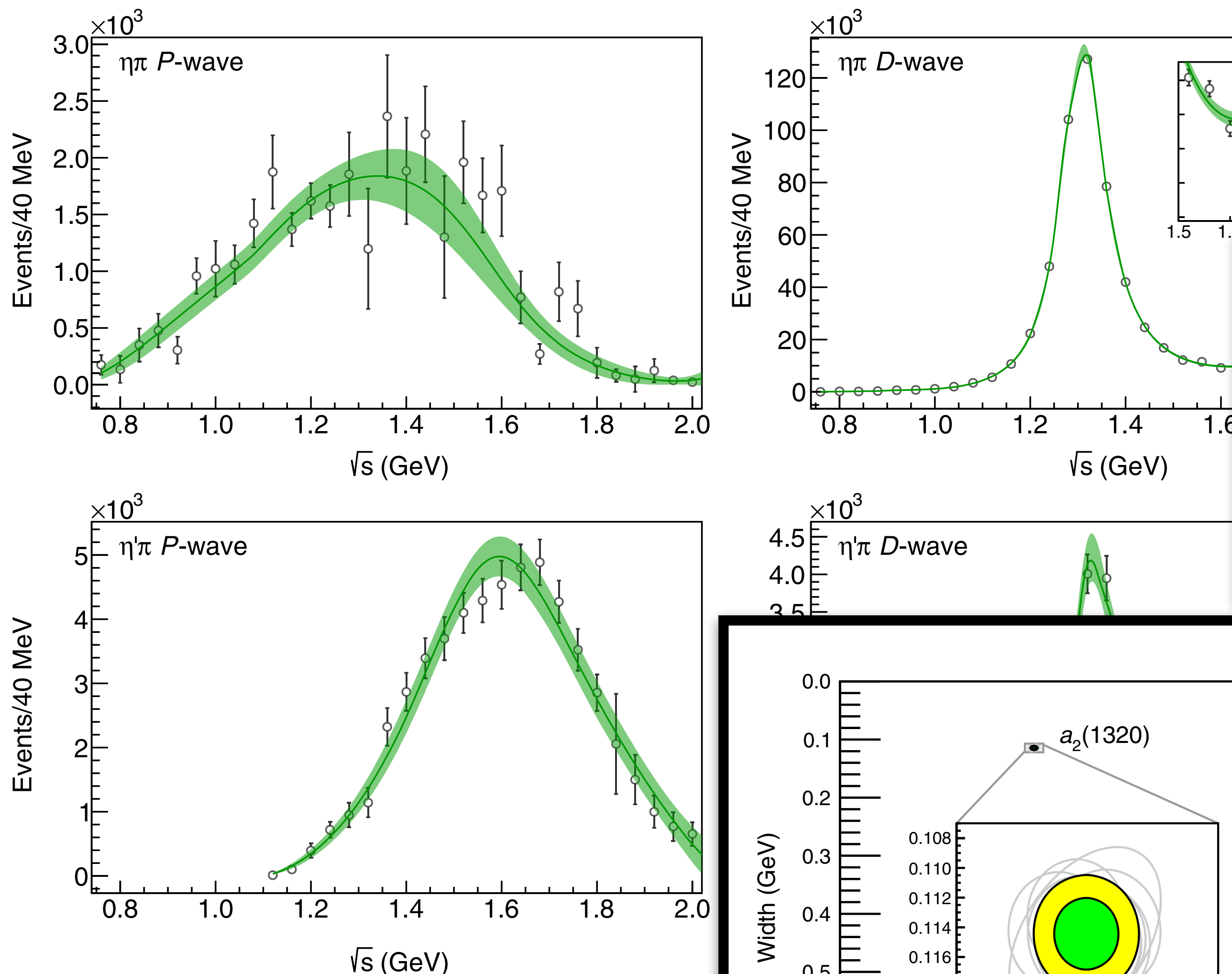
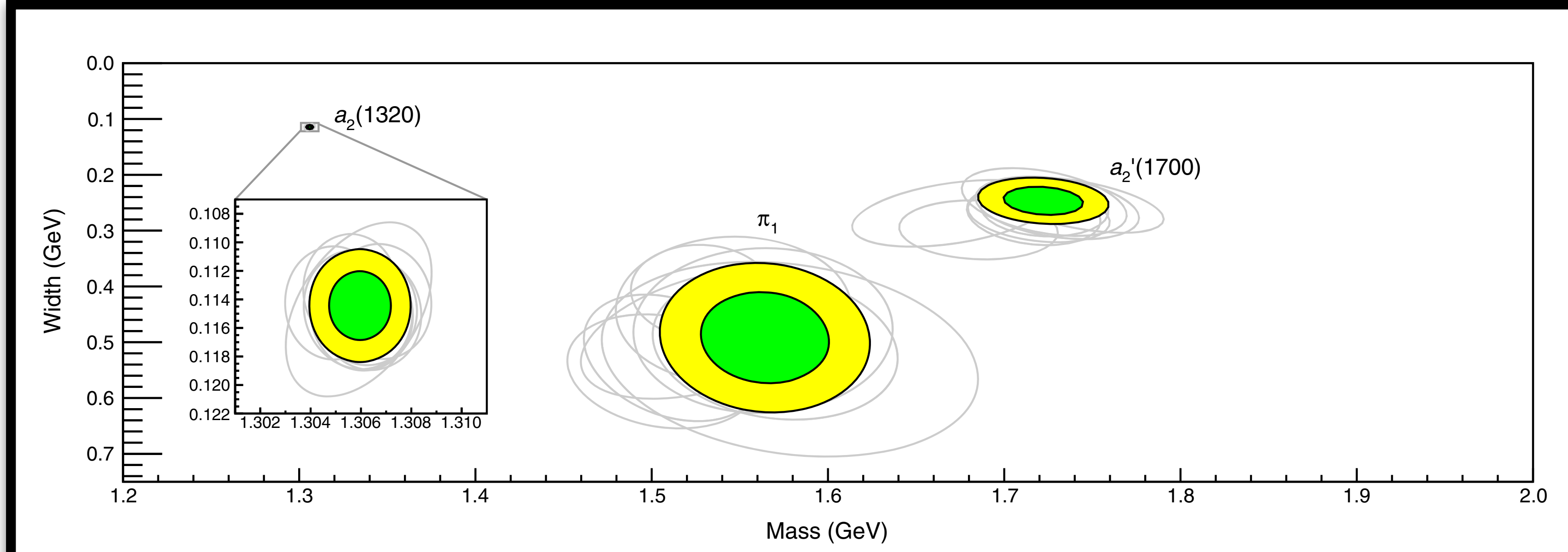


Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$



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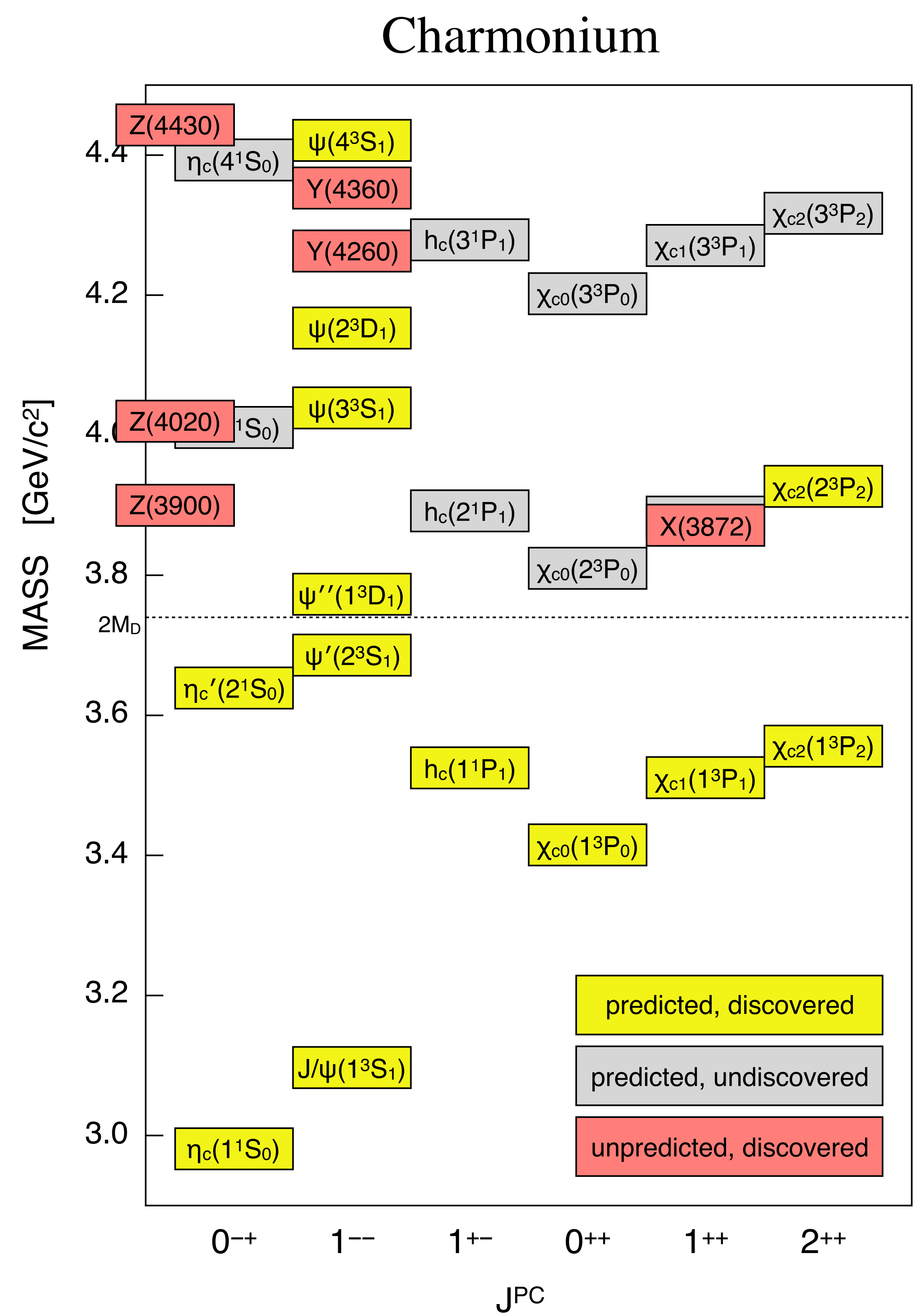

This talk: charmonium, bottomonium, light quark mesons.

HUGS 2021 Lectures on:
Experimental Meson Spectroscopy

LECTURE IV. Exotic Mesons

IVA. Exotic Meson Identification

IVB. Exotic Charmonium

IVC. Exotic Bottomonium

IVD. Exotic Light Quark Mesons

Ryan Mitchell
Senior Scientist
Indiana University
(*remitche@indiana.edu*)

HUGS 2021 Lectures on:
Experimental Meson Spectroscopy

LECTURE IV. Exotic Mesons

Exotic mesons (and baryons) can offer new insight into quark and gluon interactions.

Many exotic meson candidates exist and many more are being discovered.

The field is active, but there are currently very few firm conclusions.

Ryan Mitchell
Senior Scientist
Indiana University
(remitche@indiana.edu)

IV