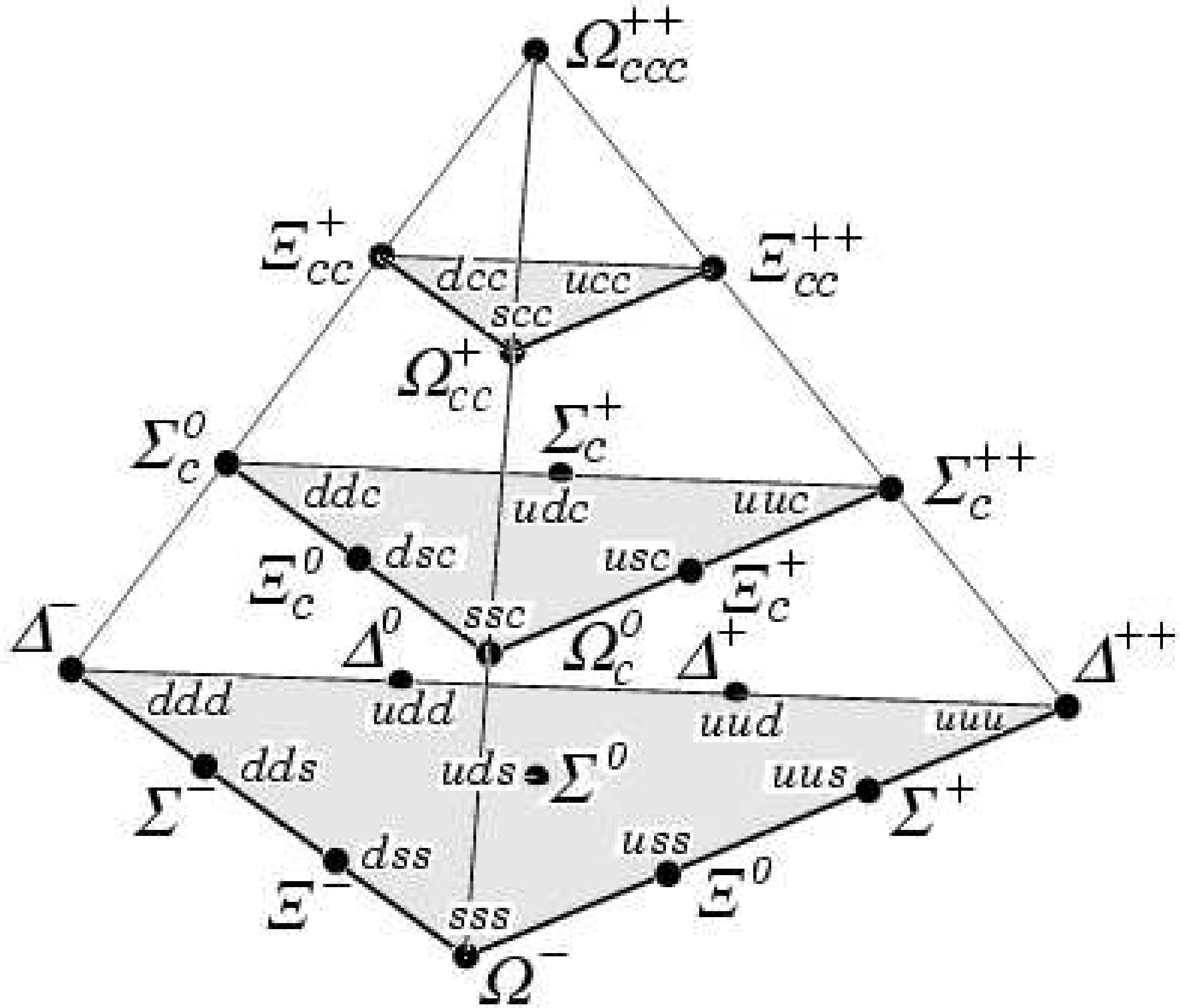
Oct, 2016

Heavy Exotic Conundrums

Eric Swanson

"hadrons are simple"



"hadrons are irreducible complexity"

theoretical issues

gluonics

hybrids
glueballs
strong decays

vacuum structure

chiral symmetry breaking
confinement
instantons/vortices/monopoles

short range interactions

gluon exchange
pion exchange
instantons
coupled channels

long range interactions

pomeron exchange
pion exchange
gluonic multipoles
coupled channels
confinement
emergence of nuclear physics

states

$\pi_1(1400)$
$f_0(1500)$
$\Theta^+(1530)$
$\pi_1(1600)$
$\pi(1800)$
$\pi_1(2015)$
$\xi(2230)$
H

$D_s(2317)$
$D_{sJ}(2630)$
$D_s^*(2700)$
$D_{sJ}(2860)$

B_c

h_c
η_c'
$X(3872)$
$Z_c(3900)$
$G(3900)$
$X(3915)$
$X(3940)$
χ_{c2}'
$Y(4008)$
$Z_1(4050)$
$Y(4140)$
$X(4160)$

$Z_2(4250)$
$Y(4260)/Y(4360)$
$Y(4274)$
$Y(4320)$
$X(4350)$
$Z^+(4430)$
$X(4630)$
$Y(4660)$

η_b
$\chi_{bJ}(3P)$
$Z_b^+(10610)$
$Z_b^+(10650)$
$Y_b(10888)$

states

h_c

η_c'

$X(3872)$

$Z_c(3900)$

$G(3900)$

$X(3915)$

$X(3940)$

χ_{c2}'

$Y(4008)$

$Z_1(4050)$

$Y(4140)$

$X(4160)$

$Z_2(4250)$

$Y(4260)/Y(4360)$

$Y(4274)$

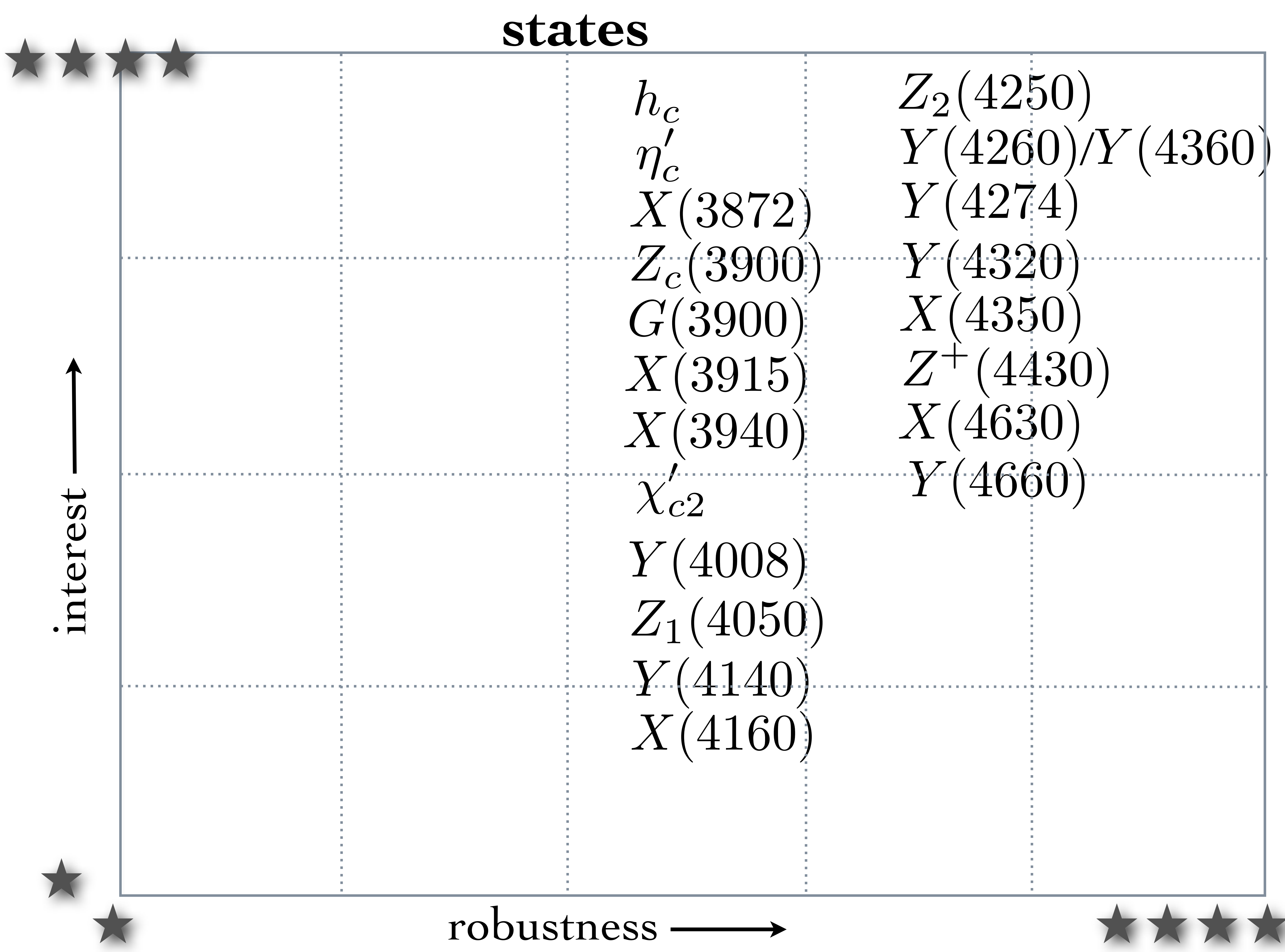
$Y(4320)$

$X(4350)$

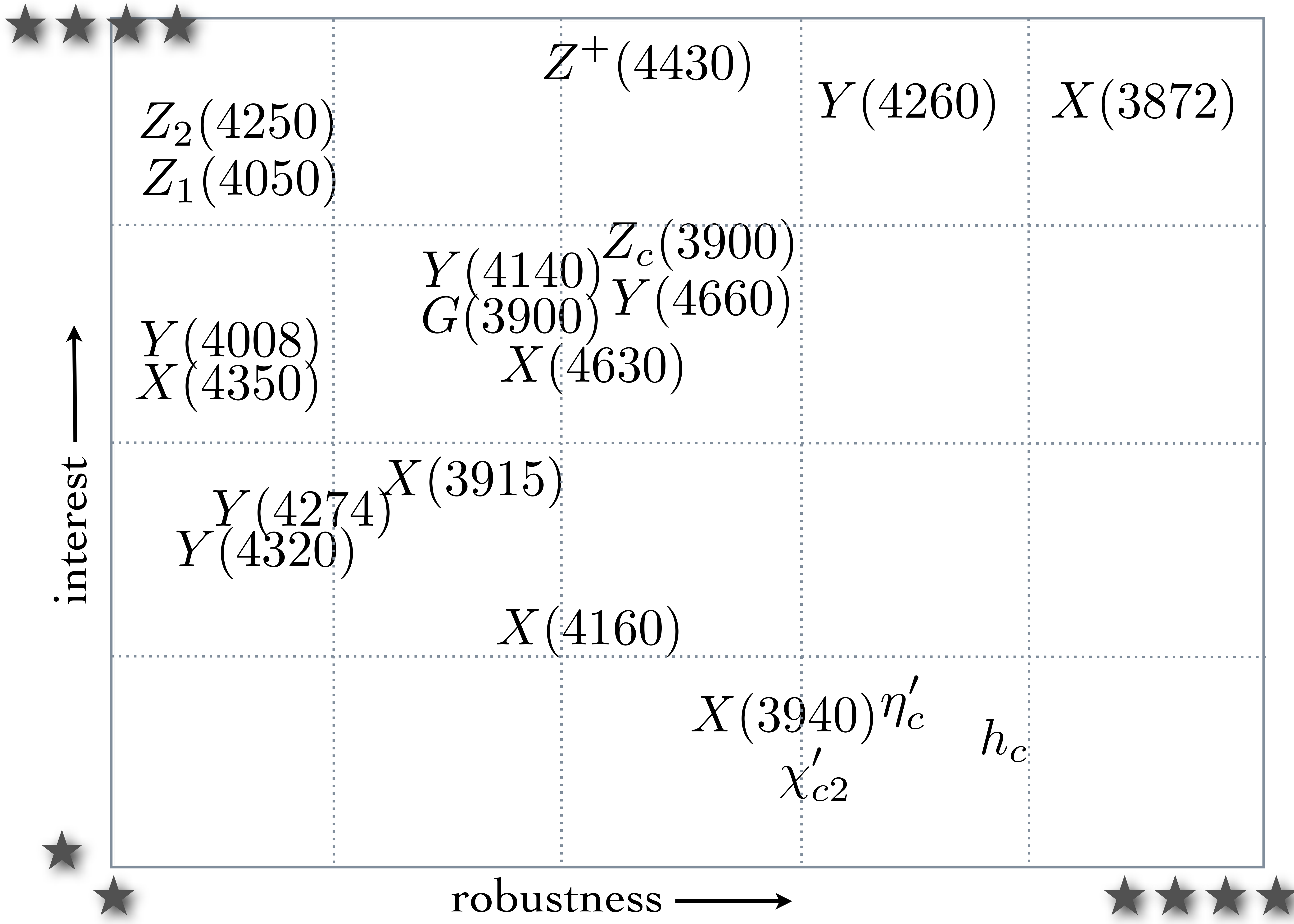
$Z^+(4430)$

$X(4630)$

$Y(4660)$



states
h_c
η_c'
$X(3872)$
$Z_c(3900)$
$G(3900)$
$X(3915)$
$X(3940)$
χ_{c2}'
$Y(4008)$
$Z_1(4050)$
$Y(4140)$
$X(4160)$
$Z_2(4250)$
$Y(4260)/Y(4360)$
$Y(4274)$
$Y(4320)$
$X(4350)$
$Z^+(4430)$
$X(4630)$
$Y(4660)$
interest
robustness



$Z^+(4430)$
$Y(4260)$
$X(3872)$
$Z_2(4250)$
$Z_1(4050)$
$Z_c(3900)$
$Y(4140)$
$Y(4660)$
$G(3900)$
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$X(4630)$
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$Y(4320)$
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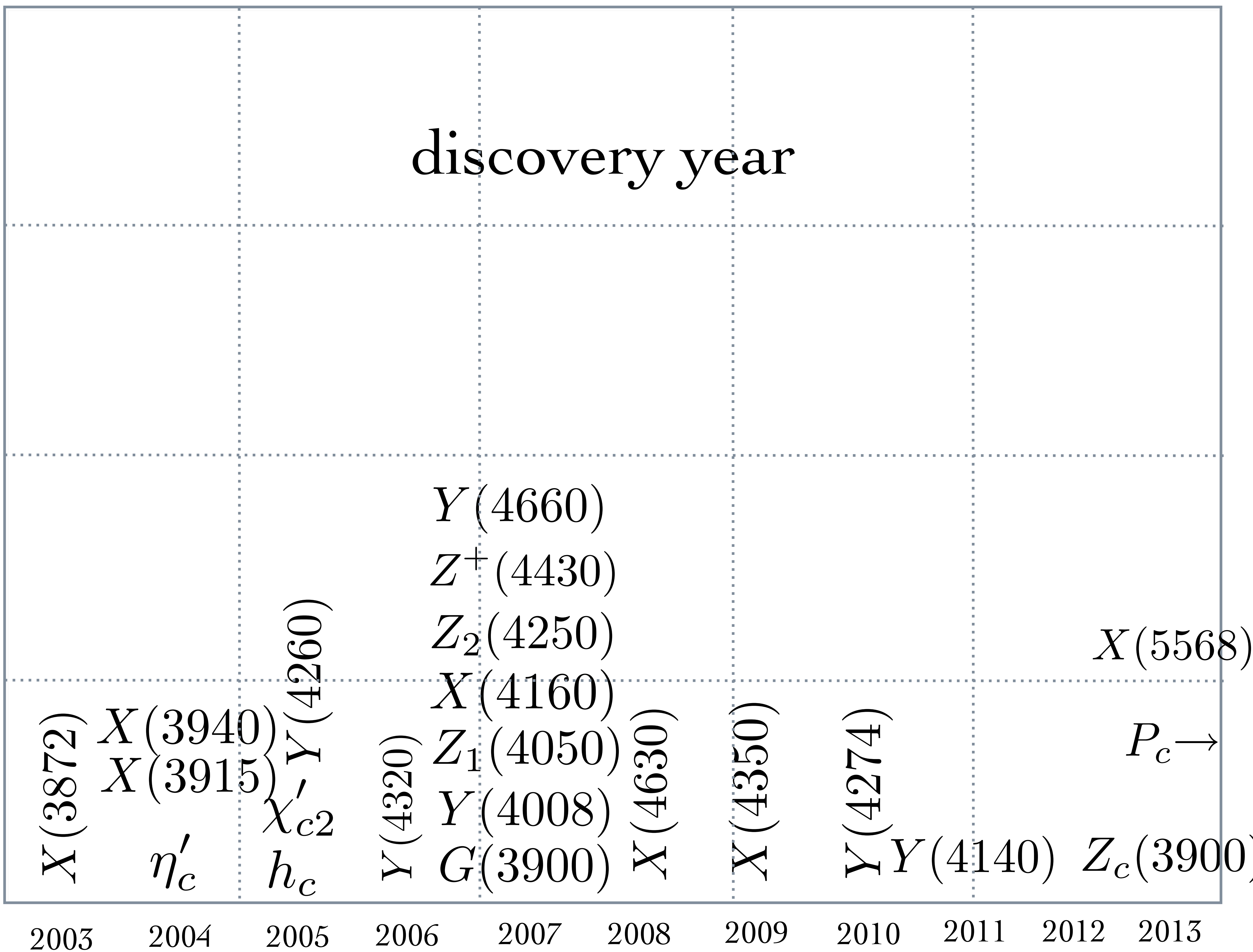
$X(3940)$
η_c'
h_c
χ_{c2}'
interest
robustness

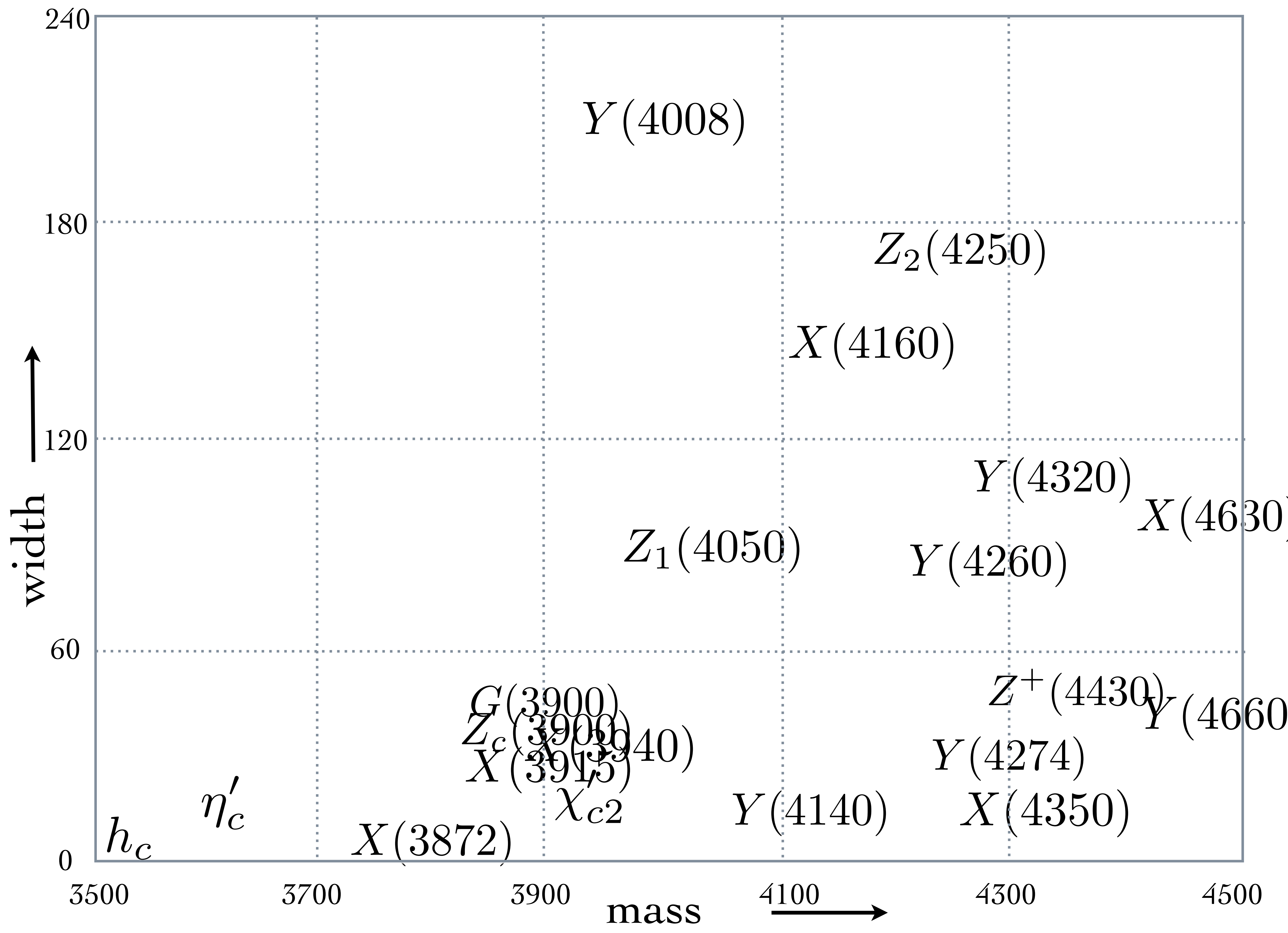


discovery year
X(3872)
X(3940)
X(3915)
η'c
Y(4260)
χ'c2
hc
Y(4320)
Y(4660)
Z+(4430)
Z2(4250)
X(4160)
Z1(4050)
Y(4008)
G(3900)
X(4630)
X(4350)
Y(4274)
Y(4140)
X(5568)
Pc→
Zc(3900)
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013

discovery experiment

$Y(4660)$
$X(4630)$
$Z^+(4430)$
$X(4350)$
$Z_2(4250)$
$X(4160)$
$Z_1(4050)$
$Y(4008)$
$X(3940)$

$Y(4320)$ $X(3915)$
$Y(4260)$ $X(3872)$ $Y(4274)$ η_c'
$G(3900)$ χ_{c2}' $Z_c(3900)$ $Y(4140)$ h_c $X(5568)$ P_c



240
180
120
60
0
width
3500
3700
3900
4100
4300
4500
mass
Y(4008)
Z_2(4250)
X(4160)
Y(4320)
X(4630)
Z_1(4050)
Y(4260)
Z^+(4430)
Y(4660)
G(3900)
Z_c(3900)
X(3940)
Y(4274)
X(3915)
η'_c
χ_c2
Y(4140)
X(4350)
h_c
X(3872)

production mode

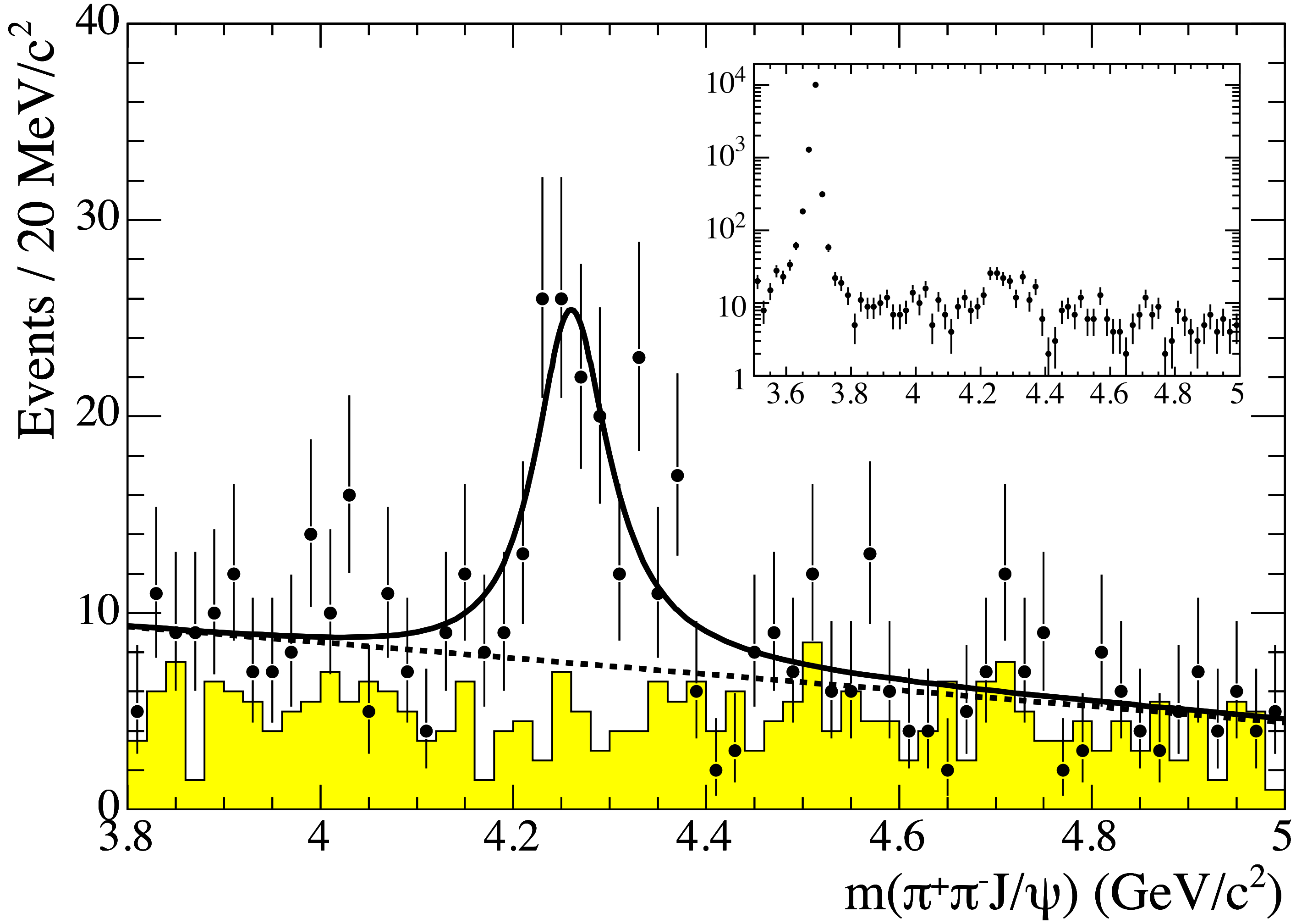
$B \to KX$	$e^+e^- \to \gamma X$	$e^+e^- \to e^+e^- X$	$e^+e^- \to J/\psi X$
$Z^+(4430)$			h_c ($\psi' \to KX$; $X \to \gamma\eta_c$)
η_c'			
$Y(4274)$	$Y(4660)$		
$Z_2(4250)$	$X(4630)$		
$Y(4140)$	$Y(4320)$		
$Z_1(4050)$	$Y(4260)$		$Z_c(3900)$
$X(3915)$	$Y(4008)$	χ_{c2}'	$X(4160)$
$X(3872)$	$G(3900)$	$X(4350)$	$X(3940)$
$X \to \phi J/\psi$	$X \to \pi\pi J/\psi$	$X \to \phi J/\psi$	$X \to \bar{D}D^*$
$X \to \pi\chi_{c1}$	$X \to \pi\pi\psi'$	$X \to D\bar{D}$	$X \to \pi\pi$
$X \to \pi\pi J/\psi$	$X \to \Lambda\bar{\Lambda}$		
$X \to \omega J/\psi$	$X \to \bar{D}D$		
$X \to KK\pi$			
$X \to \pi^+\psi'$			

Y(4260)

Y(4260)

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

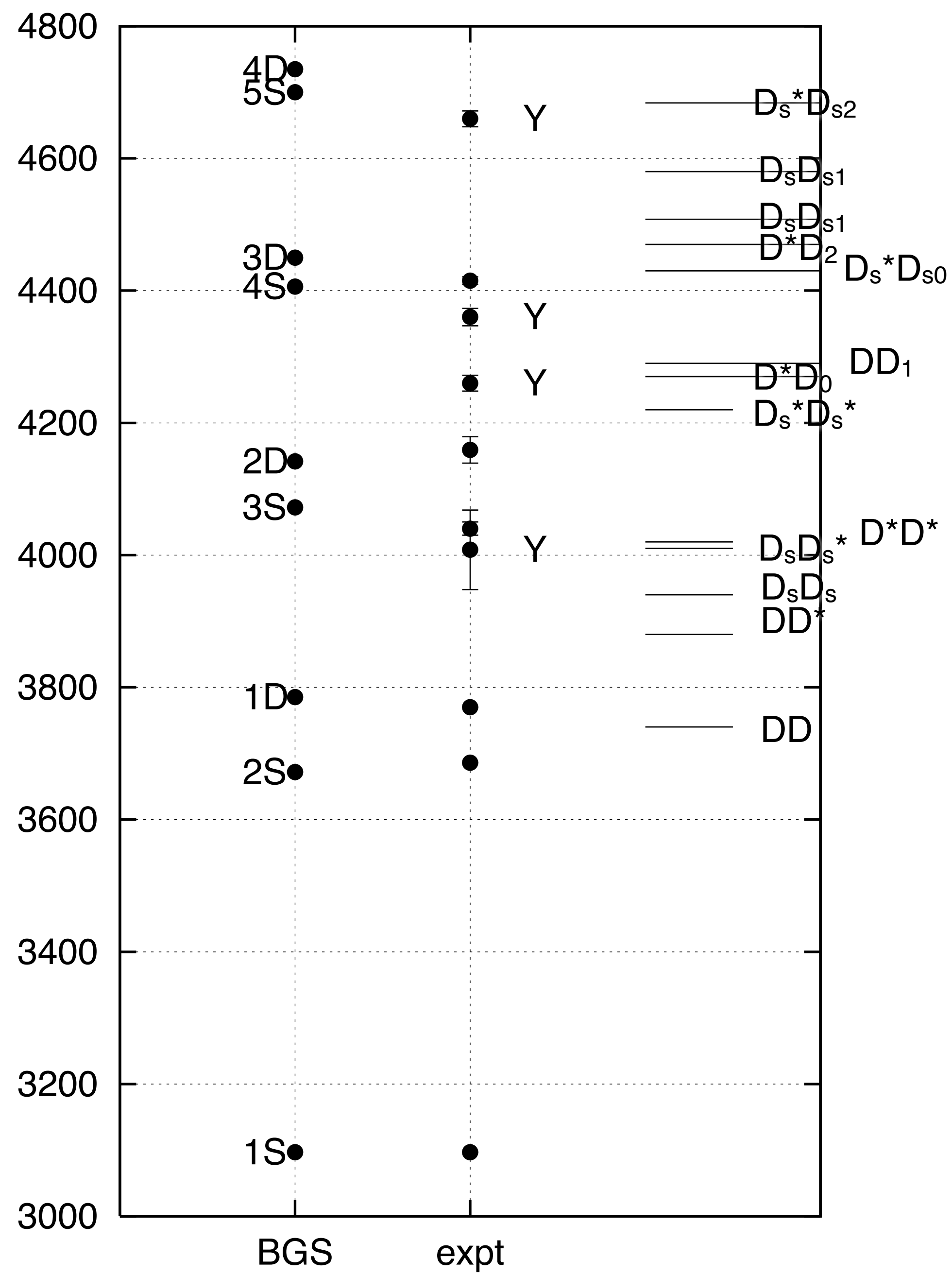
$$e^+e^- \to \gamma_{\rm ISR}\pi\pi J/\psi$$



$$\Gamma = 50 - 90$$

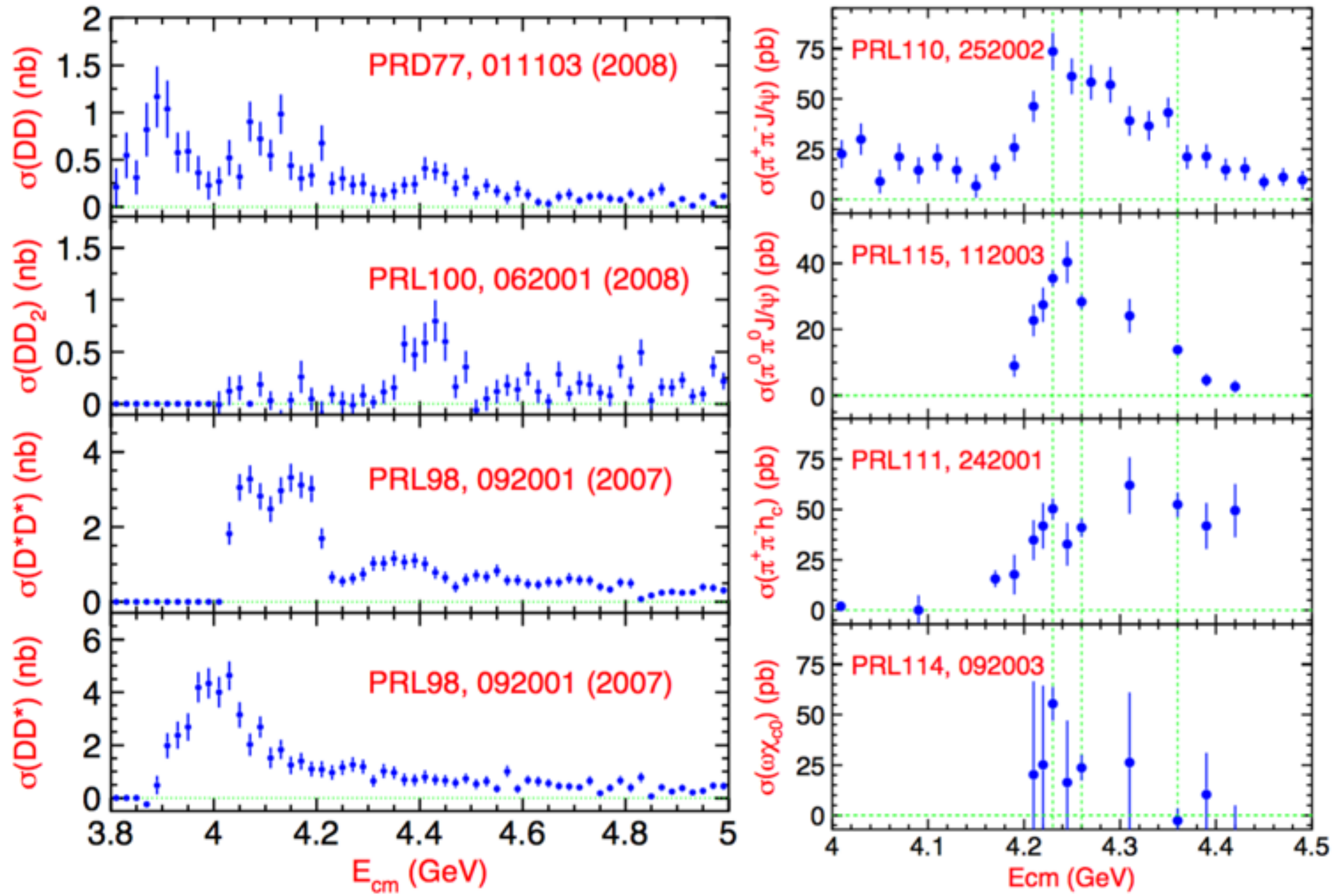
Y(4260)

Charmonium Vectors



Y(4260)

Y is is dip in R. Note the mess in the exclusive channels.



Y(4260)

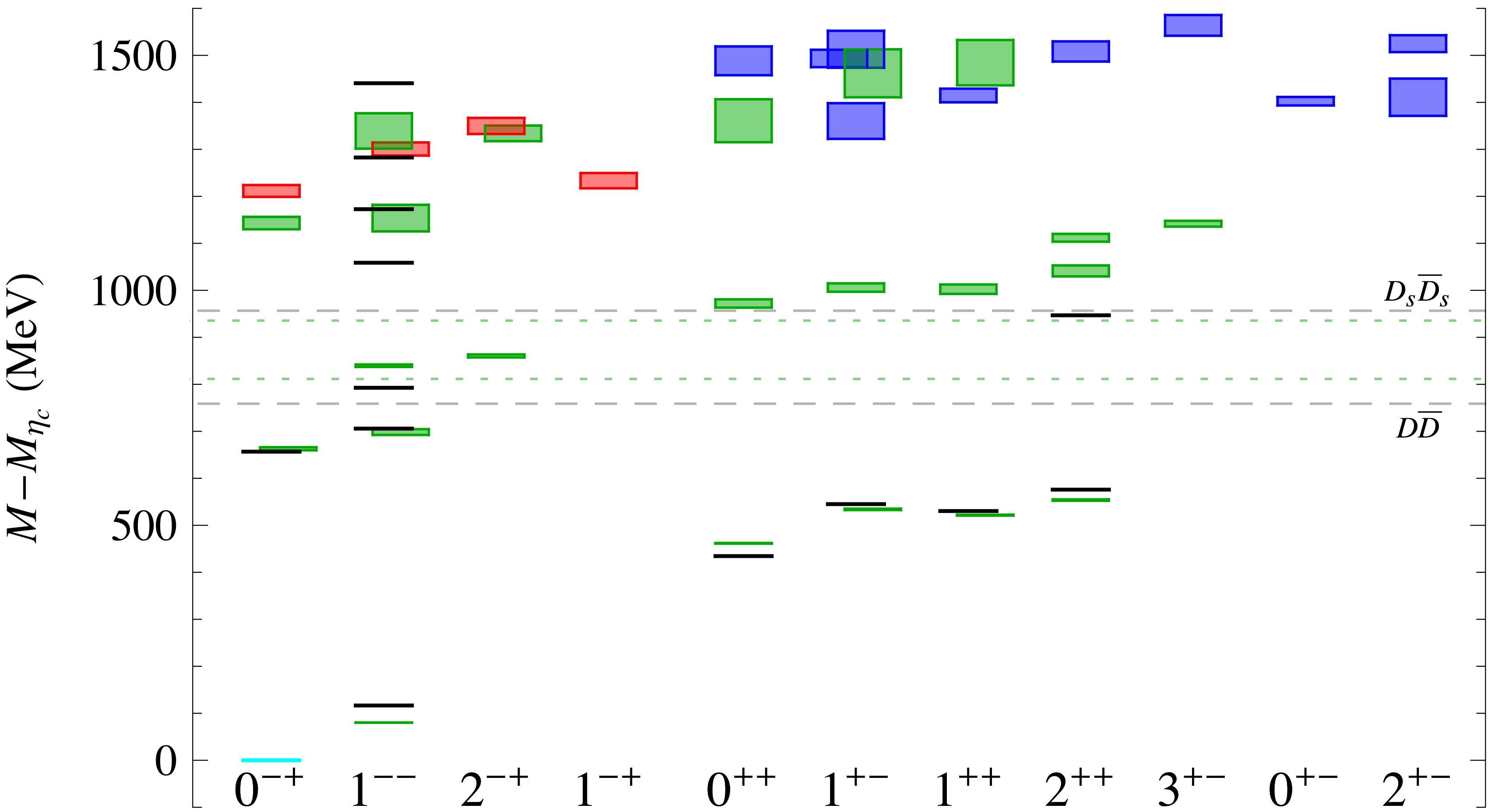
Llanes-Estrada, hep-ph/0507035

- no available vector (4S=4415, 2D=4159)

S-L Zhu, hep-ph/0507025
Close & Page, hep-ph/0507199

- vector hybrid [at 4400]?
- the first vector S-wave open charm channel is at 4285 ($D\bar{D}_1'$) or 4309 ($D\bar{D}_1$): a cusp? a molecule?
- a very good candidate for a hybrid meson! [But note the expected suppressed coupling to ee]

JHC charmonia spectrum



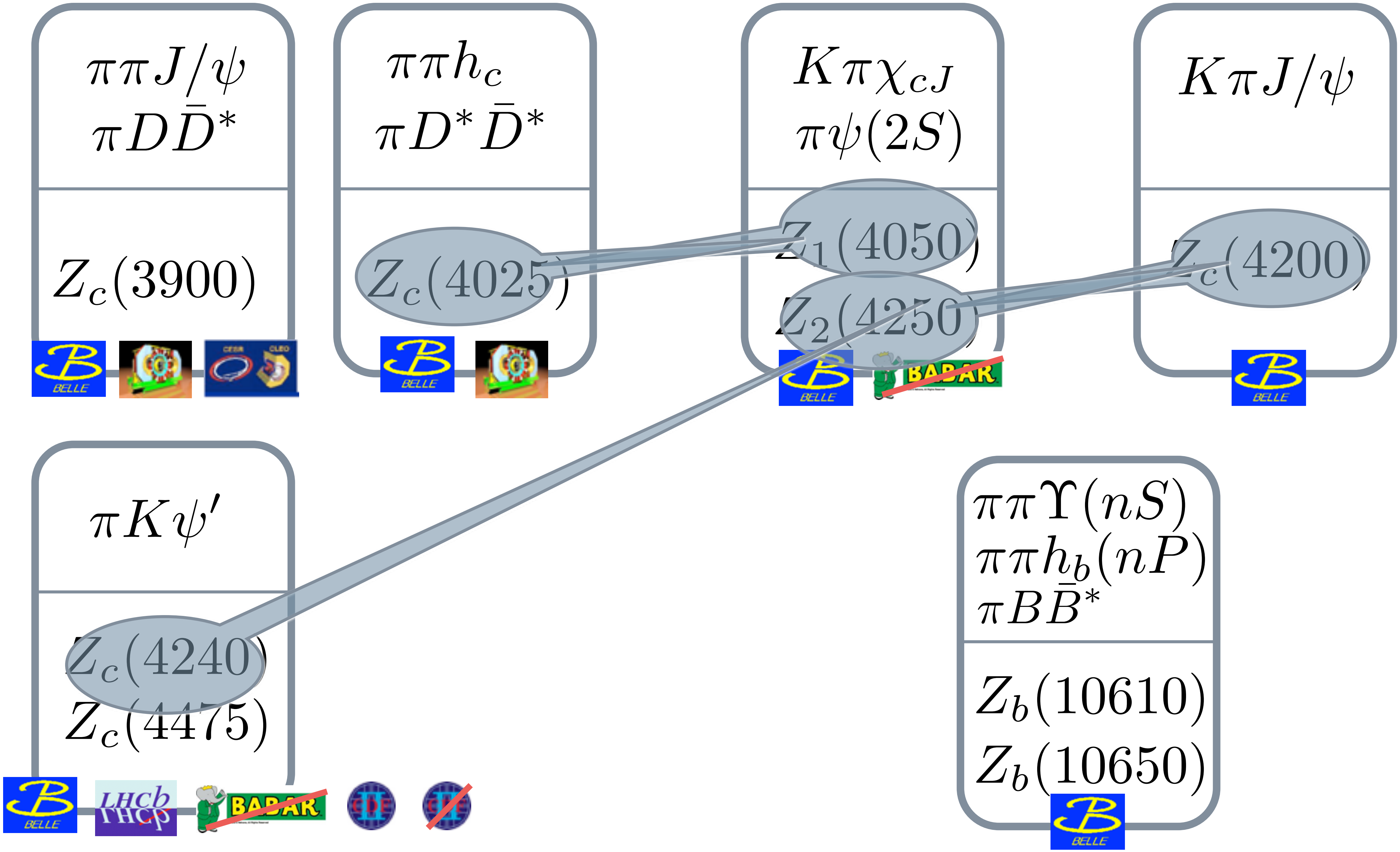
JHC charmonia spectrum

J^{PC}	Mass (MeV)	
0^{-+}	4195(13)	
1^{-+}	4217(16)	
1^{--}	4285(14)	
2^{-+}	4334(17)	
1^{+-}	4344(38)	4477(30)
0^{+-}	4386(9)	
2^{+-}	4395(40)	4509(18)
1^{++}	4399(14)	
0^{++}	4472(30)	
2^{++}	4492(21)	
3^{+-}	4548(22)	

part of an expected S-wave multiplet made with a 1+- chromomagnetic gluon

Z(4430)

Four-quark States



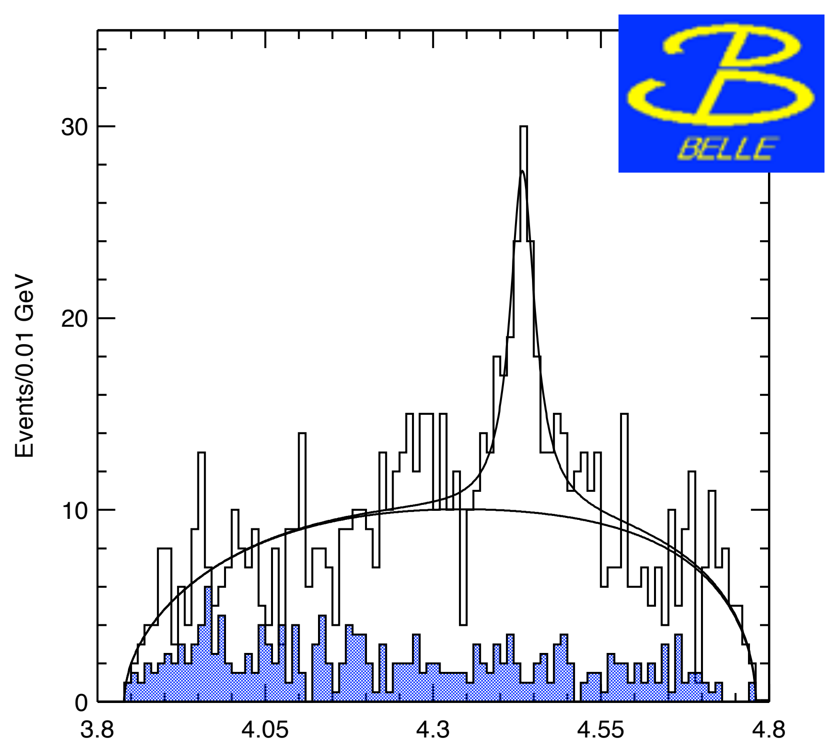
$$Z^+(4430)$$

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

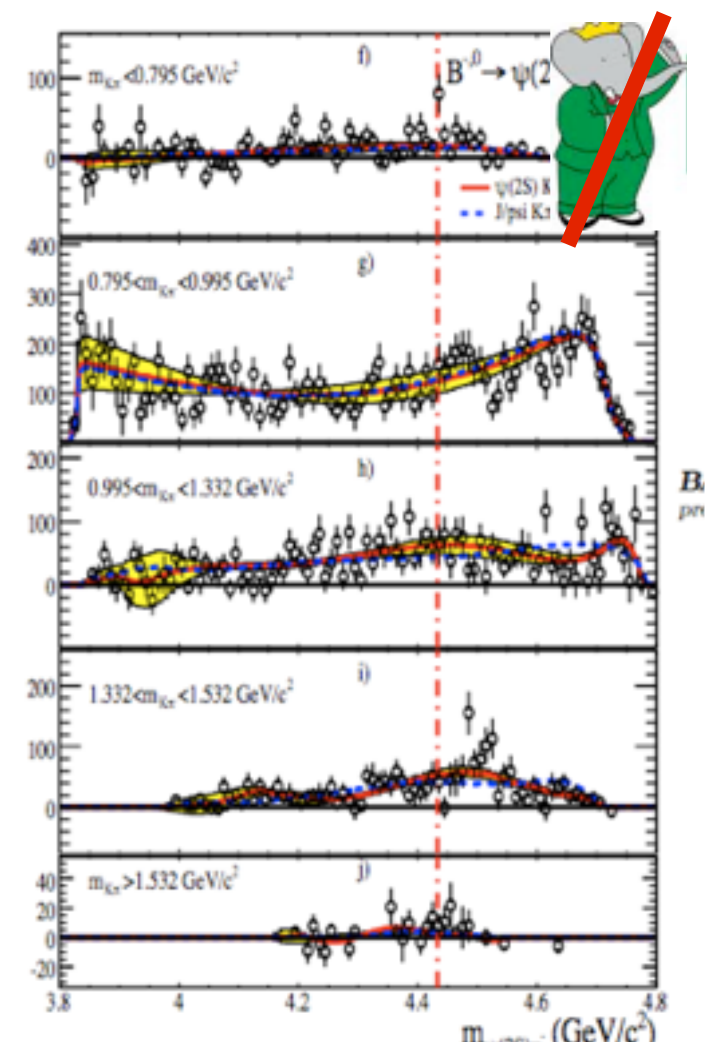
$$M = 4443^{+24}_{-18}$$
$$\Gamma = 107^{+113}_{-71}$$
$$J^{PC} = ?$$

.manifestly exotic

.not confirmed by BaBar



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

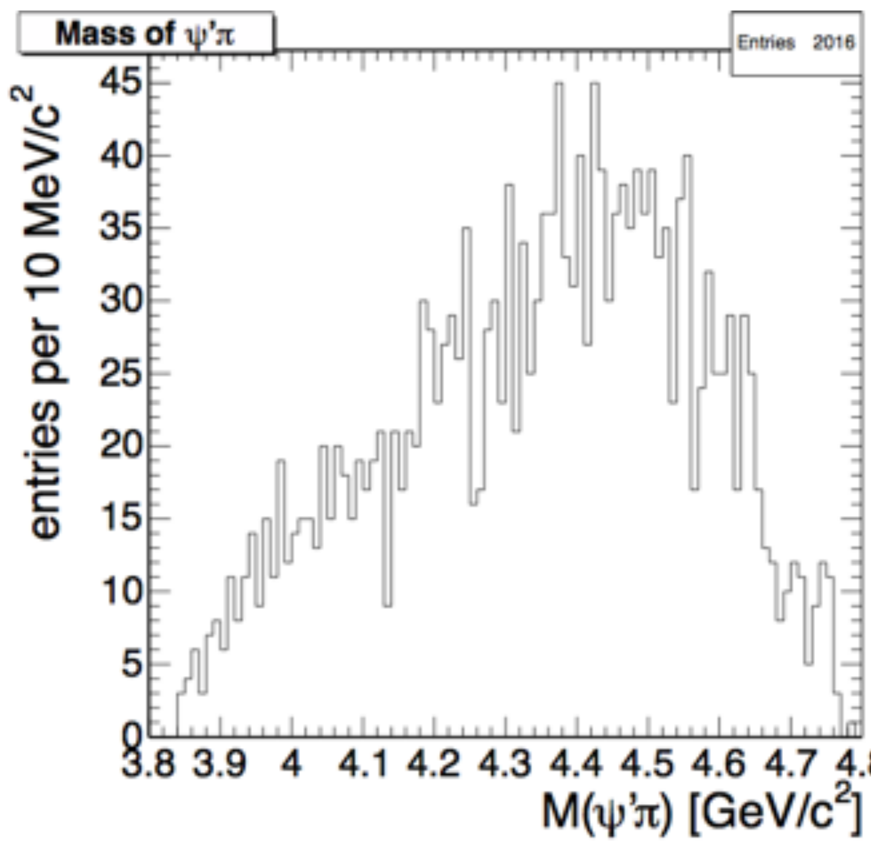


Mokhtar, 0810.1073

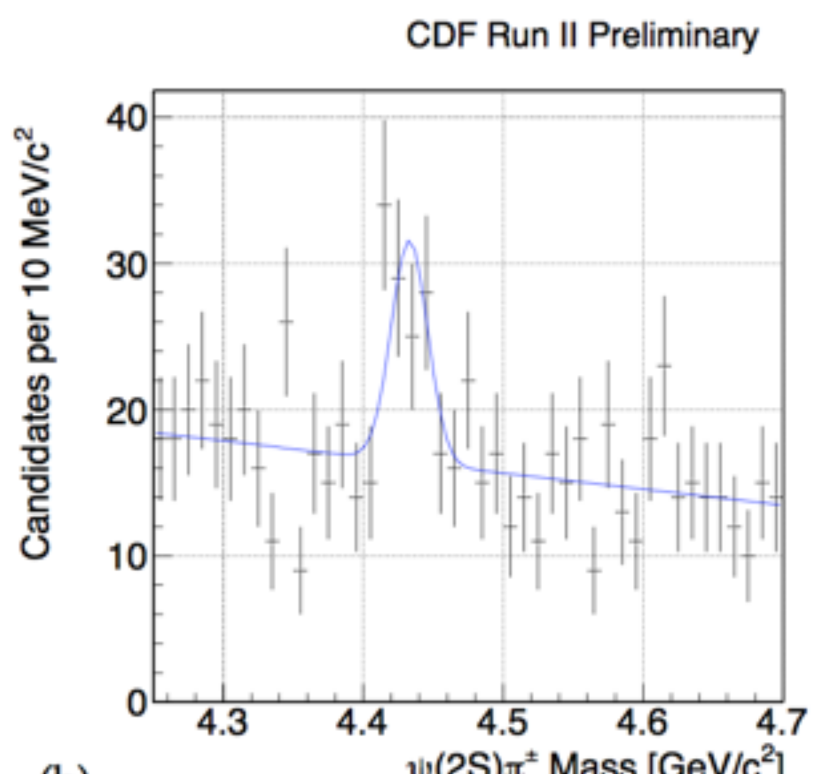
$Z^+(4430)$

seen and not seen at CDF

pp -> B B(pi K psi')



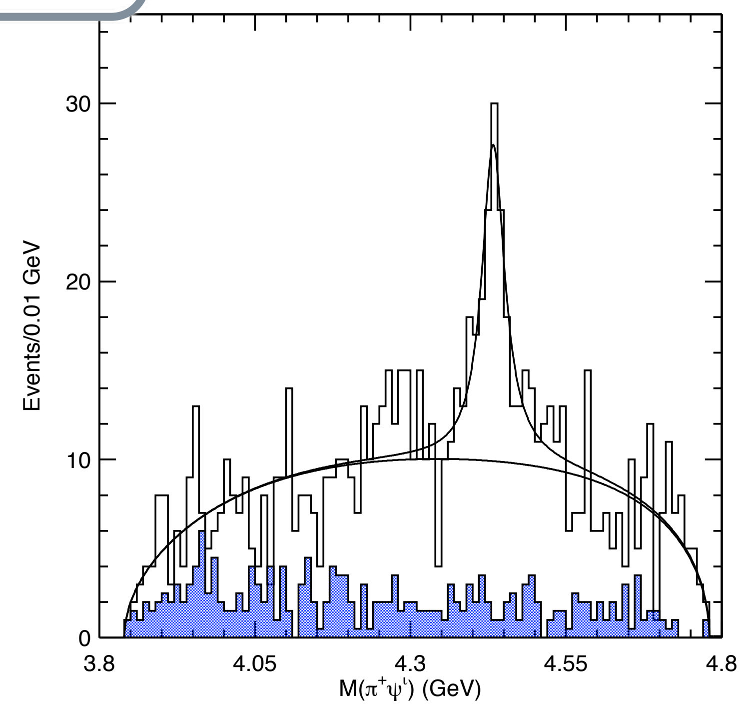
prompt production



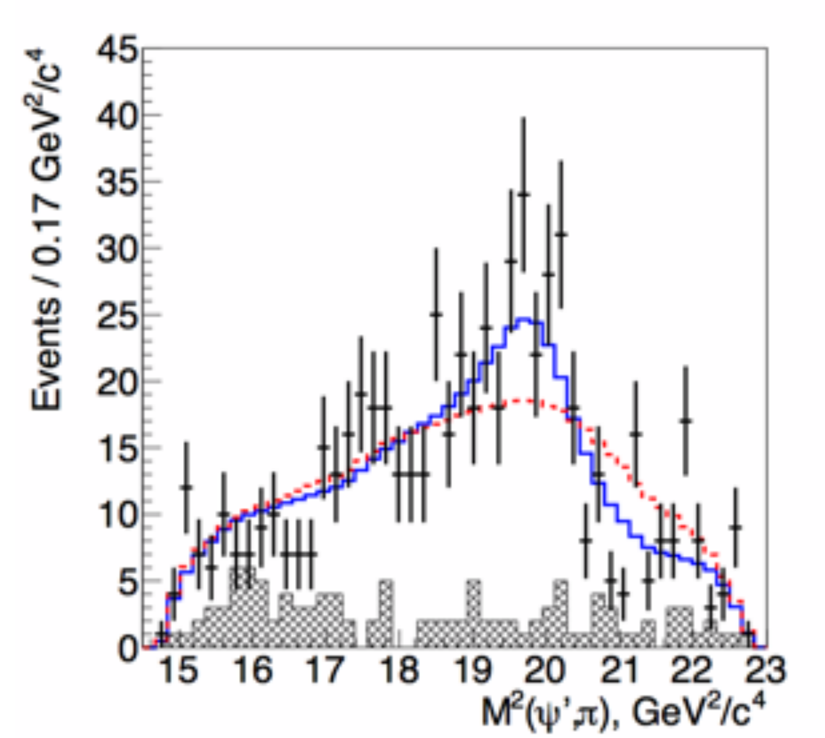
(b)

F. Rubbo, Torino thesis

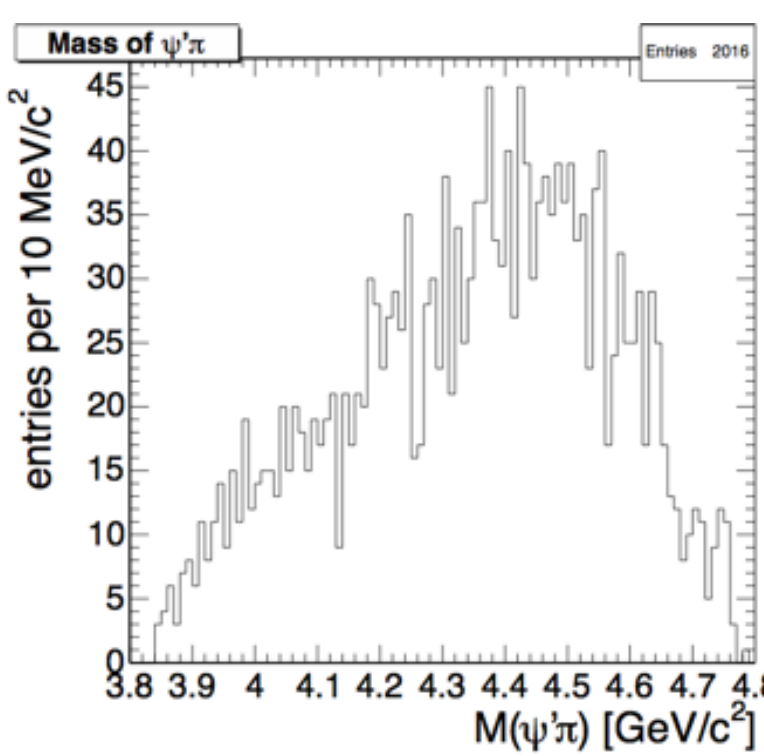
$Z^+(4430)$



Belle original

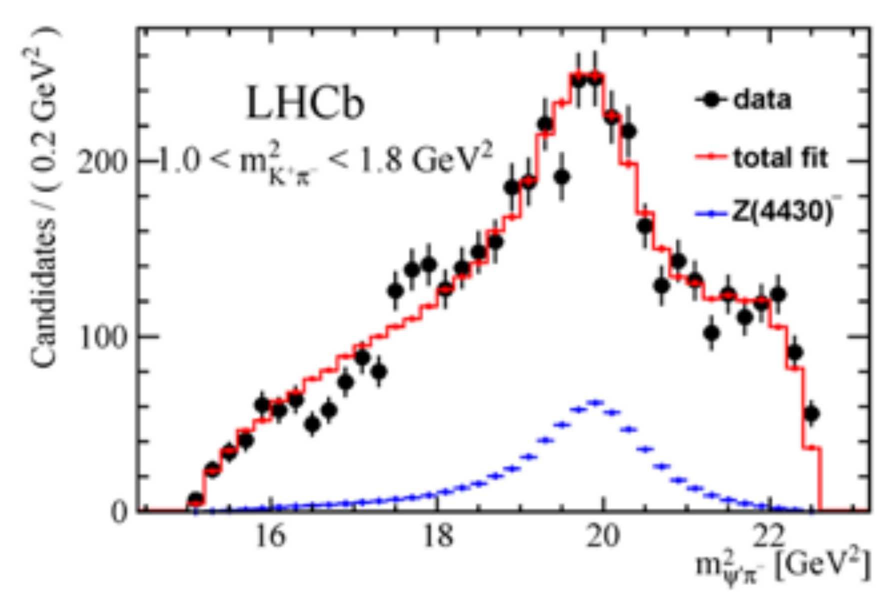


Belle re-analysis
1306.4894



F. Rubbo, Torino thesis

CDF

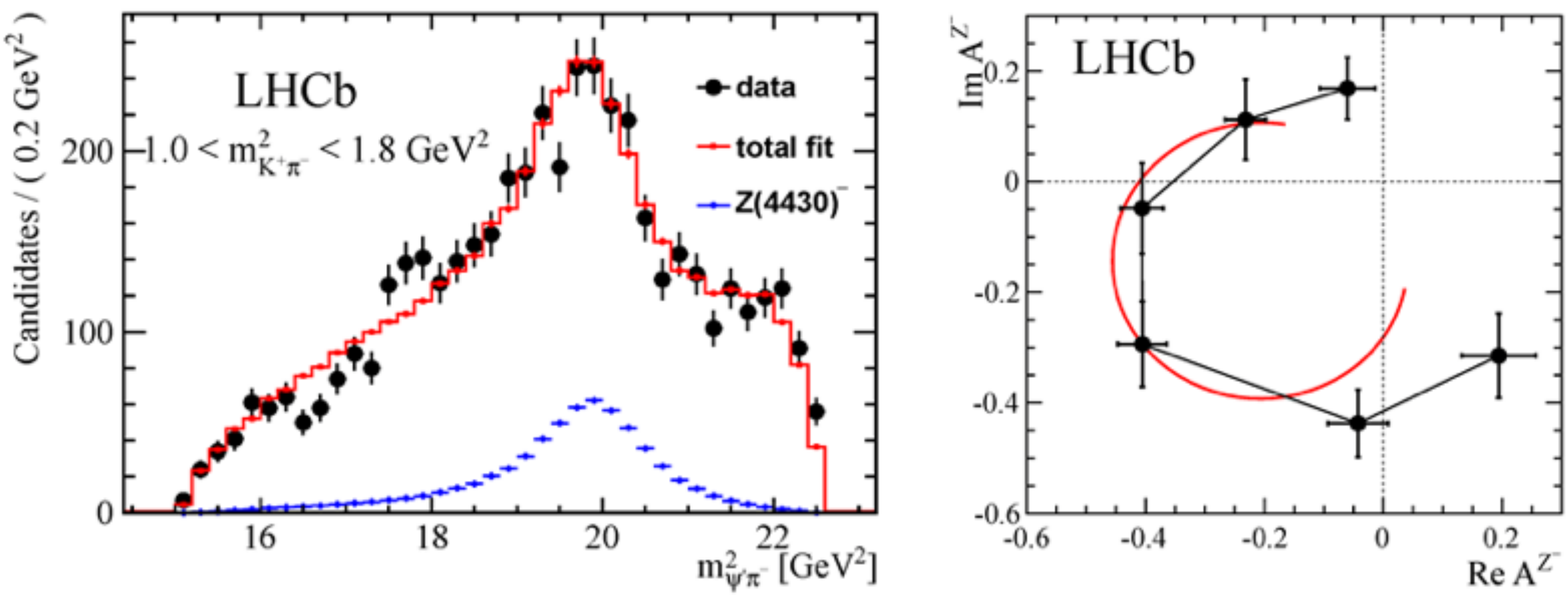


LHCb

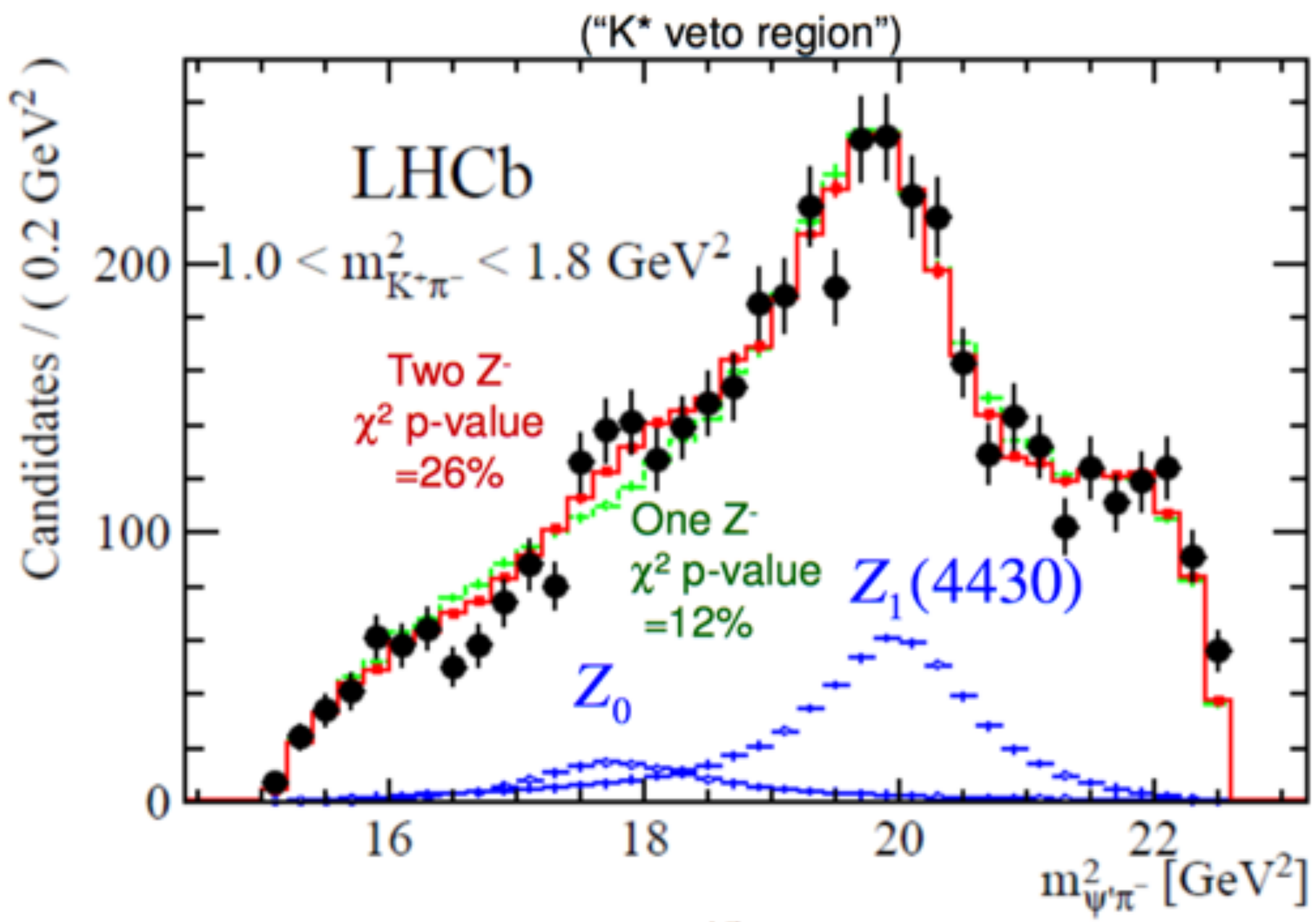
$Z^+(4430)$

.confirmed by LHCb

$J^P = 1^+$



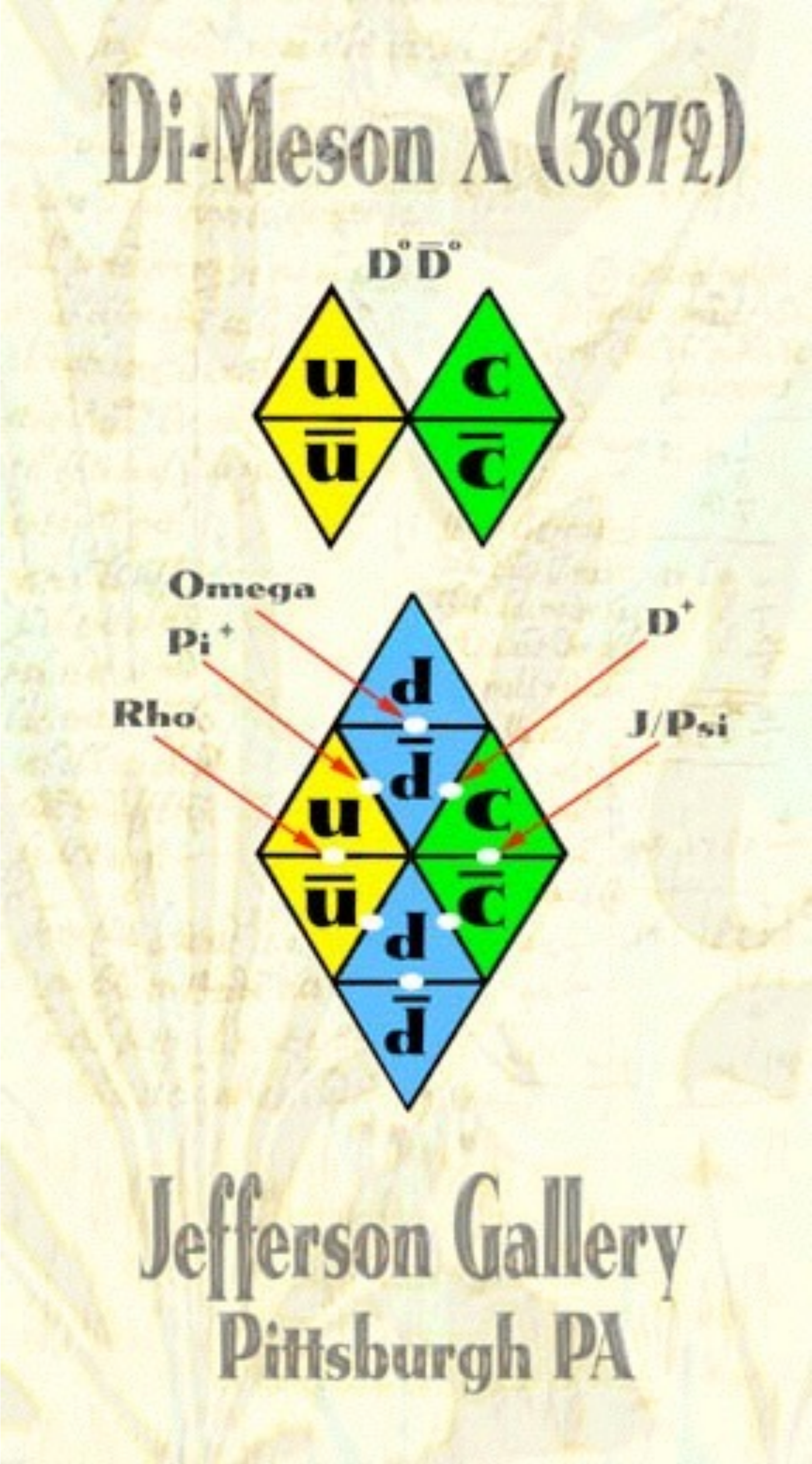
Z(4240) [?]



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

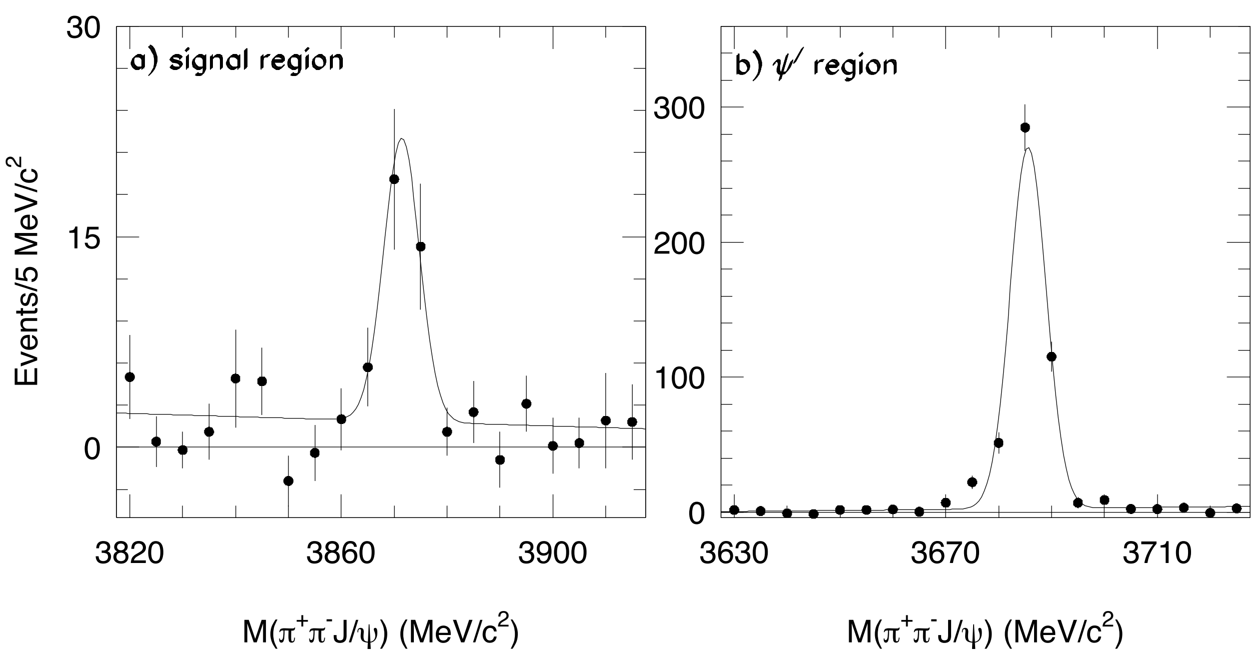
$$\Gamma(Z_0) = 220 \pm 47^{+108}_{-74}\ \text{MeV}$$

X(3872)

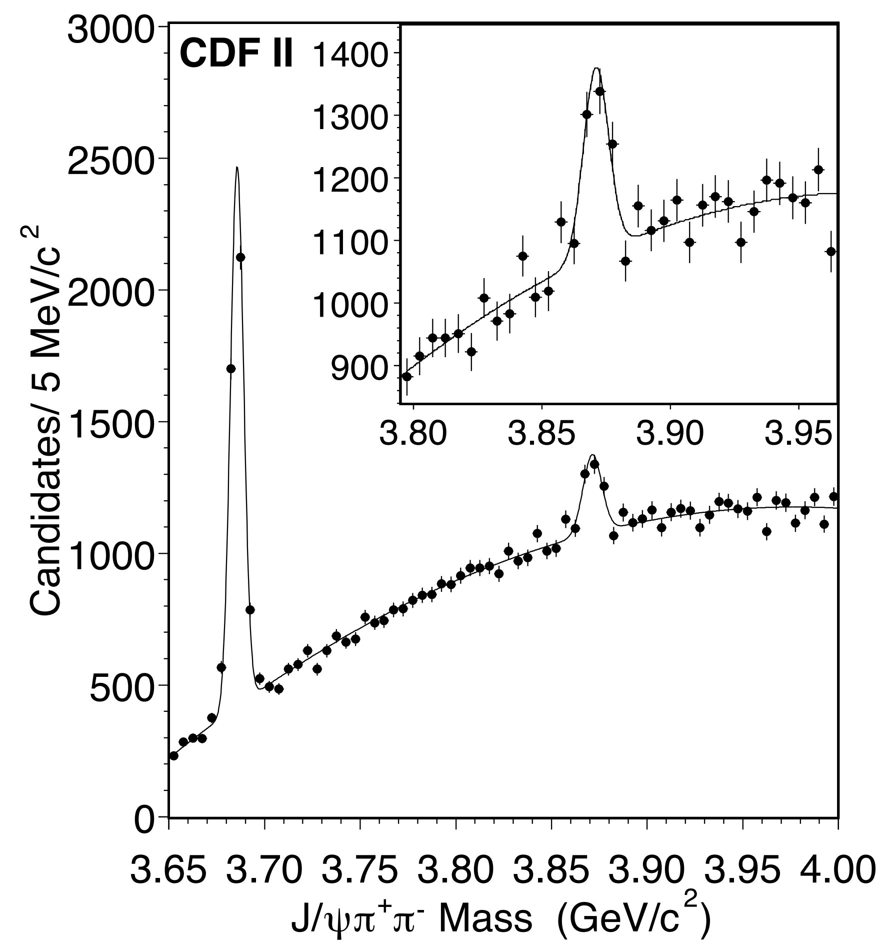

Di-Meson X (3872)
D°D̄°
u
ū
c
c̄
Omega
Pi⁺
Rho
D⁺
J/Psi
d
d̄
d
u
ū
c
c̄
d
d̄
Jefferson Gallery
Pittsburgh PA

X(3872)

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



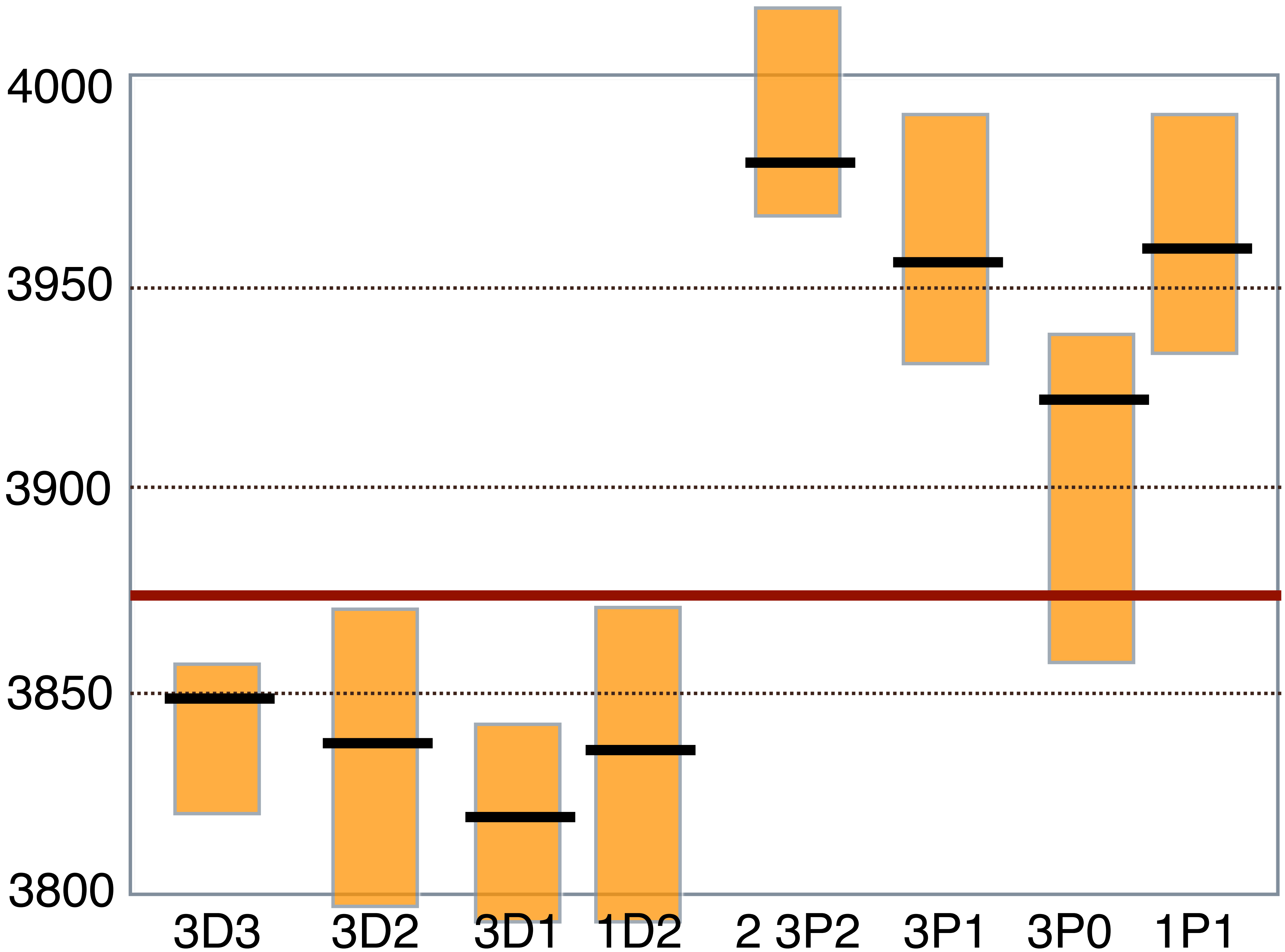
S.-K. Choi (Belle), hep-ex/0309032

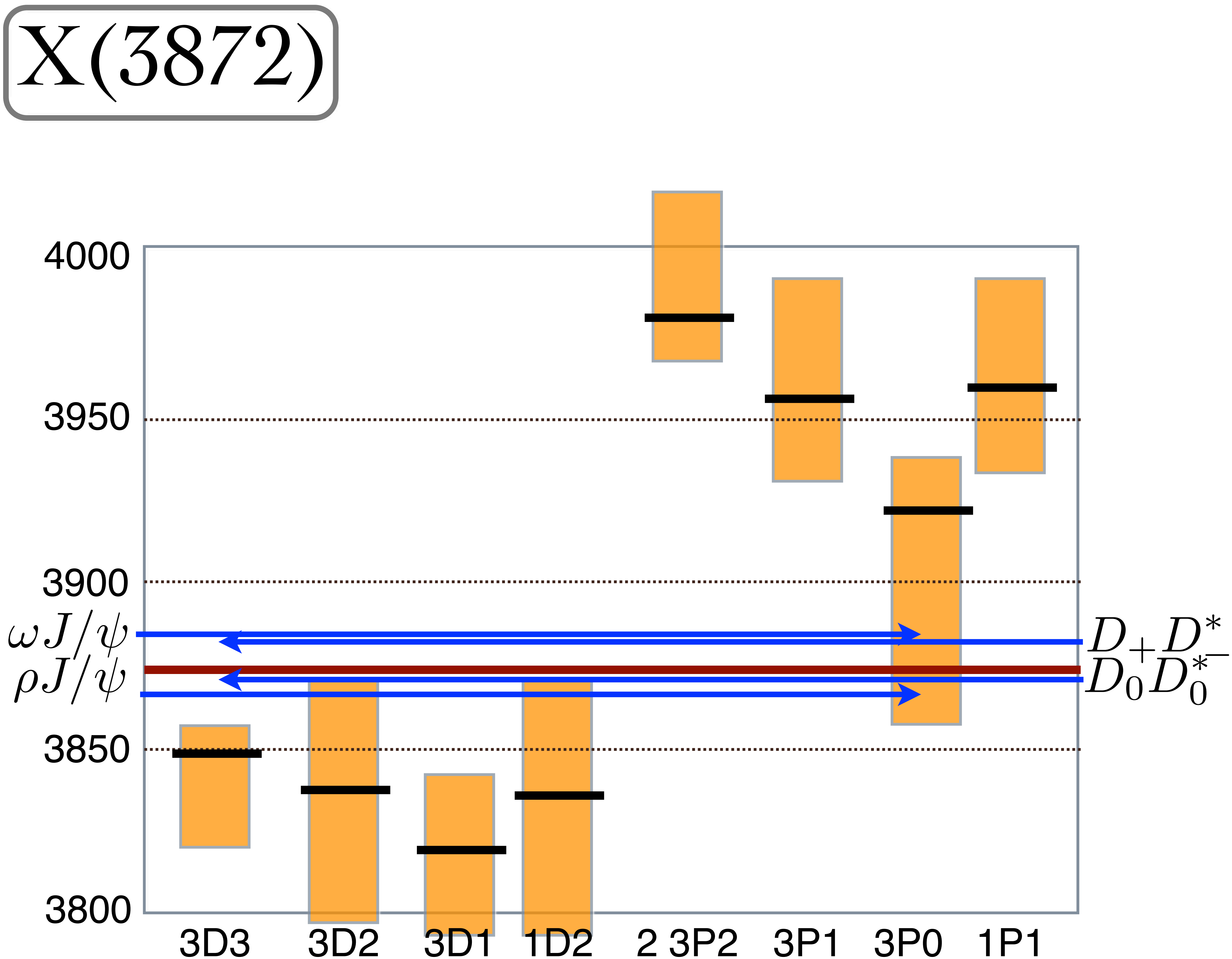


D. Acosta (CDF) hep-ex/0312021

B. Aubert (Babar) hep-ex/0402025

X(3872)





X(3872)
4000
3950
3900
$\omega J/\psi$
$\rho J/\psi$
3850
3800
$D_+ D^*_-$
$D_0 D^*_0$
3D3
3D2
3D1
1D2
2 3P2
3P1
3P0
1P1

X(3872)

ESS, PLB588, 189 (2004)

- model the X(3872) as a $D\bar{D}^*$ bound state with $\omega J/\psi$ and $\rho J/\psi$ components.

- we need a microscopic model:

$$\mathcal{L} = \frac{1}{2}\int d^3x d^3y\, \psi^\dagger \psi V(x-y)\psi^\dagger\psi + \int d^4x \bar{\psi}\gamma^\mu\gamma_5\tau^a\psi\partial_\mu\pi^a$$

constituent quark interaction   quark-pion interaction

X(3872)

Predictions:

- $J^{PC} = 1^{++}$
- only one bound state
- strong isospin mixing
- decay to pi pi pi J/psi
- $X \to \gamma J/\psi \gg X \to \gamma \psi(2S)$

X(3872)

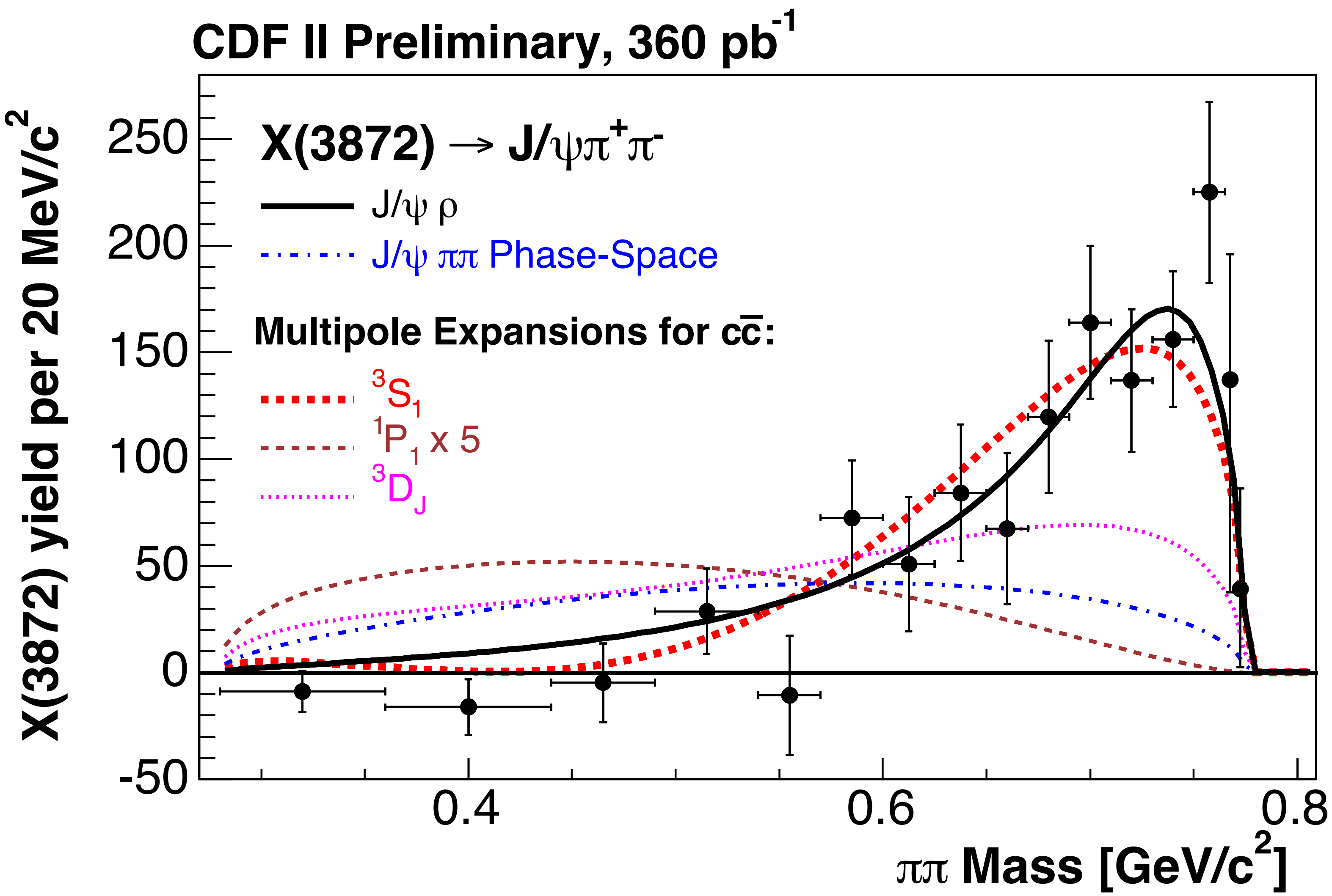
decay widths

weak binding $\rightarrow$ use free space decay widths to estimate dissociation decay modes

	D^{0*}	D^{0*}	D^{-*}	D^{-*}	D^{-*}	ρ	ρ/ω	ω	ρ/ω
B_E (MeV)	$D^0\bar{D}^0\pi^0$	$D^0\bar{D}^0\gamma$	$D^+D^-\pi^0$	$(D^+\bar{D}^0\pi^-+\text{c.c})/\sqrt{2}$	$D^+D^-\gamma$	$\pi^+\pi^-J/\psi$	$\pi^+\pi^-\gamma J/\psi$	$\pi^+\pi^-\pi^0 J/\psi$	$\pi^0\gamma J/\psi$
0.7	67	38	5.1	4.7	0.2	1290	12.9	720	70
1.0	66	36	6.4	5.8	0.3	1215	12.1	820	80
2.0	57	32	9.5	8.6	0.4	975	9.8	1040	100
3.8	52	28	12.5	11.4	0.6	690	6.9	1190	115
6.1	46	26	15.0	13.6	0.7	450	4.5	1270	120
9.0	43	24	16.9	15.3	0.8	285	2.9	1280	125
12.7	38	22	18.5	16.7	0.9	180	1.8	1240	120

$$\frac{\Gamma(\hat{\chi} \to \pi\pi\pi J/\psi)}{\Gamma(\hat{\chi} \to \pi\pi J/\psi)} = 0.56$$

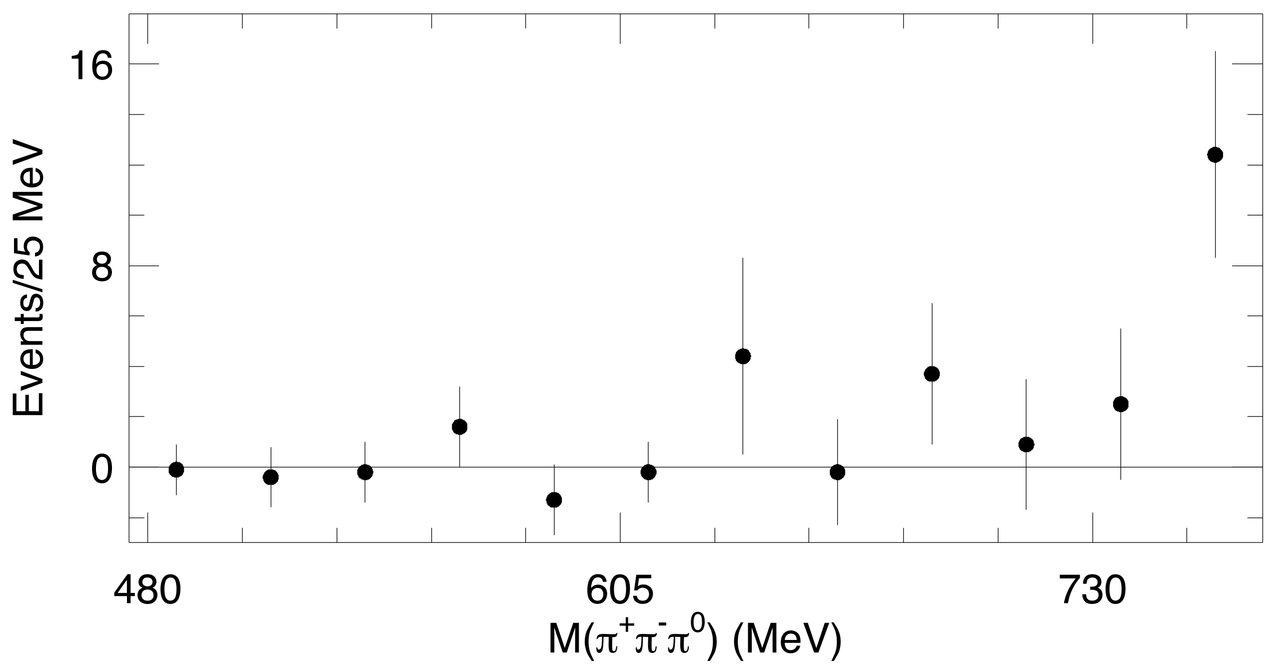
X(3872)



CDF II Preliminary, 360 pb^{-1}
X(3872) → J/ψπ$^+$π$^-$
J/ψ ρ
J/ψ ππ Phase-Space
Multipole Expansions for c$\bar{c}$:
$^3S_1$
$^1P_1$ x 5
^3D_J
X(3872) yield per 20 MeV/c^2
250
200
150
100
50
0
-50
0.4
0.6
0.8
ππ Mass [GeV/c^2]

X(3872)

$$X \to 3\pi J/\psi$$



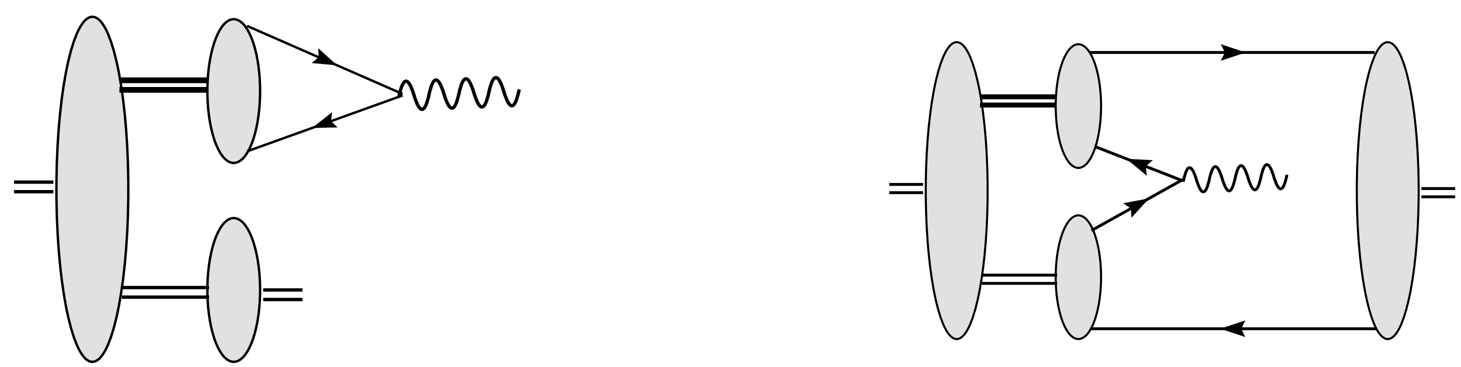
Abe et al [Belle], hep-ex/0505037

[confirmed by BaBar]

X(3872)

ESS, PLB598, 197 (04)

EM Transitions



mode	m_f (MeV)	q (MeV)	$\Gamma[c\bar{c}]$ (keV) [B&G]	$\Gamma[c\bar{c}]$ (keV) [A]	$\Gamma[c\bar{c}]$ (keV) [B]	$\Gamma[\hat{\chi}_{c1}]$ (keV)
$\gamma J/\psi$	3097	697	11	71	139	8
$\gamma\psi'(2^3S_1)$	3686	182	64	95	94	0.03
$\gamma\psi''(1^3D_1)$	3770	101	3.7	6.5	6.4	0
$\gamma\psi_2(1^3D_2)$	3838	34	0.5	0.7	0.7	0

X(3872)

three problems

- prompt production similar to psi(2S)
- X to gamma psi(2S)/psi = 2.6(6)
- X to D0D0*/pipiJ/psi = 9.2(2.9)

X(3872)

X-χ mixing

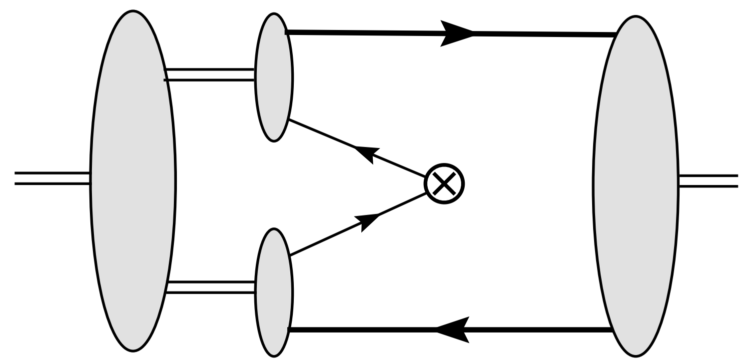


Table 1: $X - \chi_{c1}$ Mixing.

state	E_B (MeV)	a (fm)	Z_{00}	a_χ (MeV)	prob
χ_{c1}	0.1	14.4	93%	94	5%
	0.5	6.4	83%	120	10%
χ'_{c1}	0.1	14.4	93%	60	100%
	0.5	6.4	83%	80	$>100\%$

X(3872)

Other Molecules

no MM mixtures

state	J^{PC}	channels	mass (MeV)	E_B
$D^*\bar{D}^*$	0^{++}	$^1S_0$, $^5D_0$	4019	1.0
$B\bar{B}^*$	0^{-+}	$^3P_0$	10543	61
$B\bar{B}^*$	1^{++}	$^3S_1$, $^3D_1$	10561	43
$B^*\bar{B}^*$	0^{++}	$^1S_0$, $^5D_0$	10579	71
$B^*\bar{B}^*$	0^{-+}	$^3P_0$	10588	62
$B^*\bar{B}^*$	1^{+-}	$^3S_1$, $^3D_1$	10606	44
$B^*\bar{B}^*$	2^{++}	$^1D_2$, $^5S_2$, $^5D_2$, $^5G_2$	10600	50

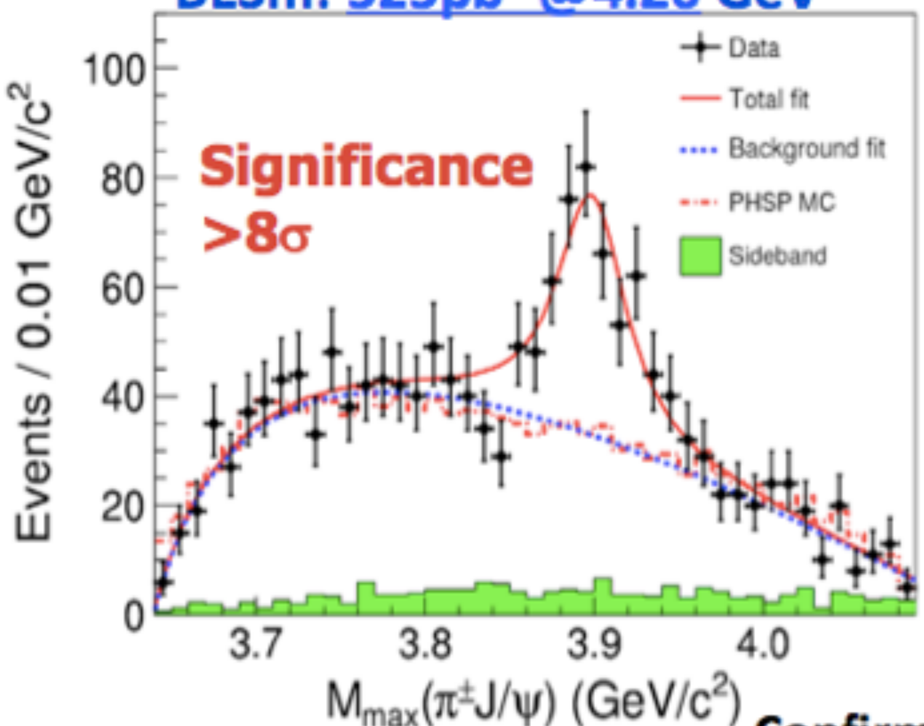
Zc and Zb

$Z_c(3900)$

ee (4260) -> pi pi psi

Observation of Zc(3900) a

BESIII: 525pb^{-1}@4.26 GeV

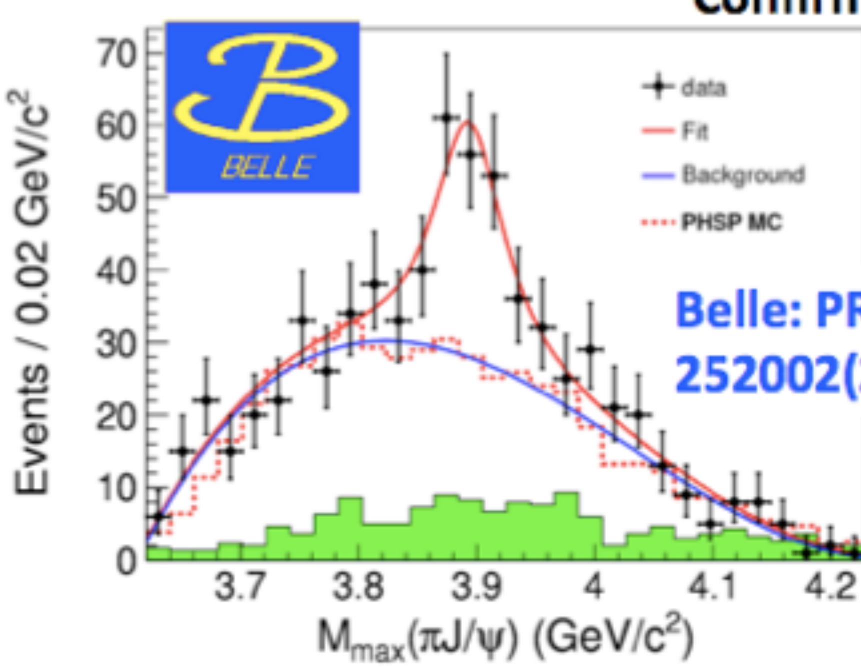


BESIII: PRL110, 252001 (2013)

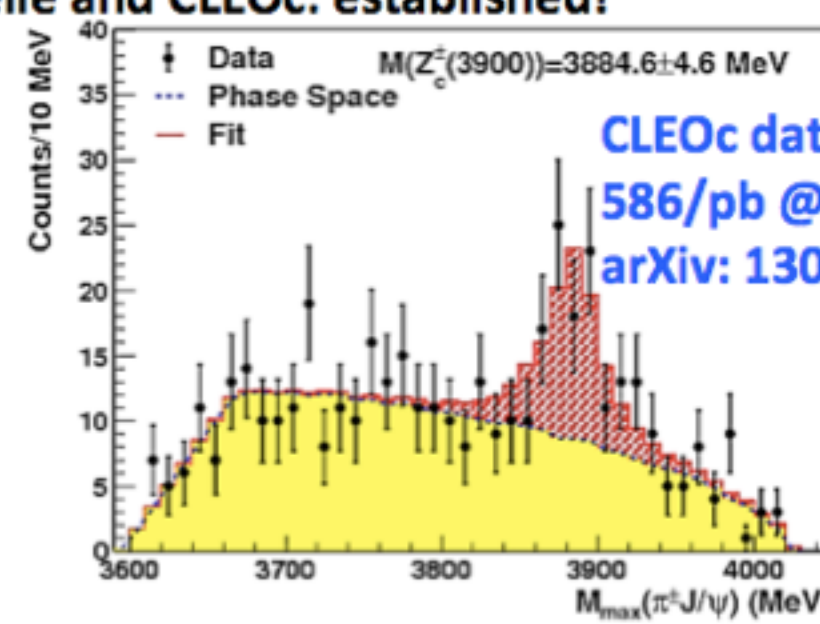
- M = 3899.0±3.6±4.9 MeV
- Γ = 46±10±20 MeV
- 307 ± 48 events

The mass position is 24 MeV away from DD* threshold!
A Partial wave analysis is on going!

Confirmed by Belle and CLEOc: established!



Belle: PRL 110, 252002(2013)



CLEOc data
586/pb @4.17GeV
arXiv: 1304.3036

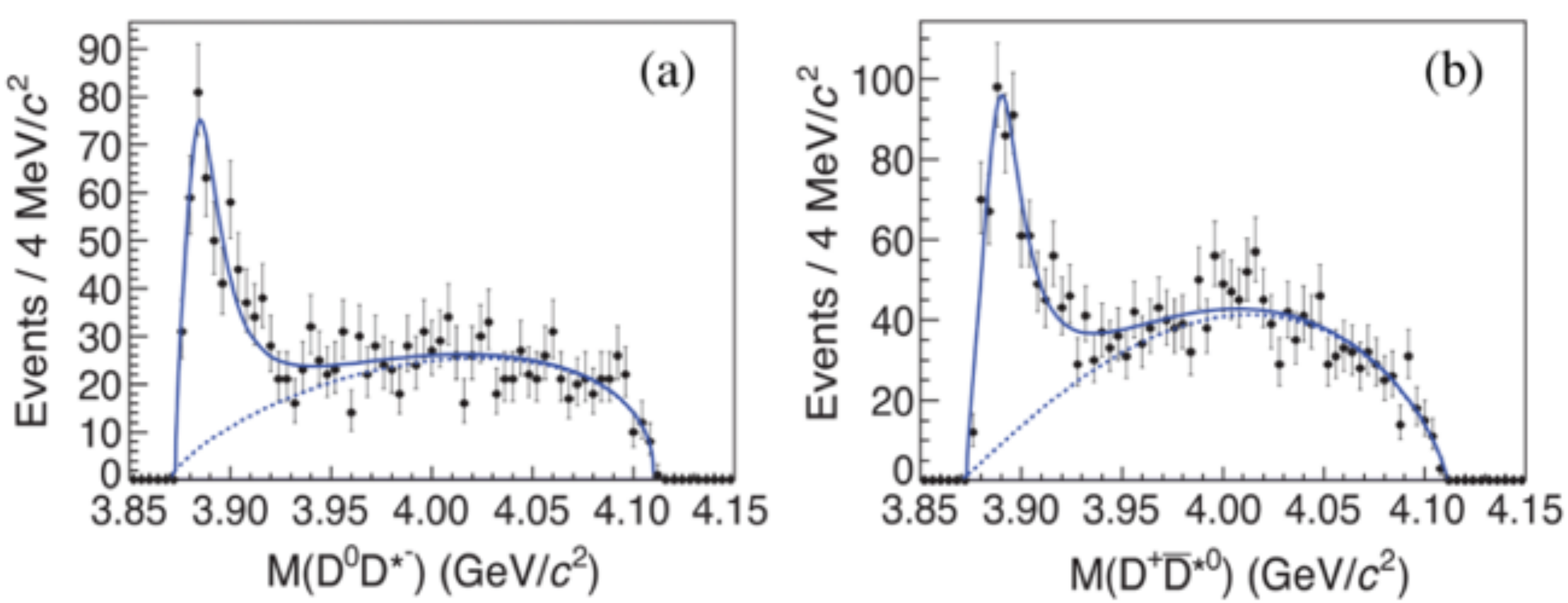
Shuangshi Feng [BESIII] H13

$Z_c(3900)$

$e^+e^- \to \pi D\bar{D}^*$ $\sqrt{s} = 4.26$

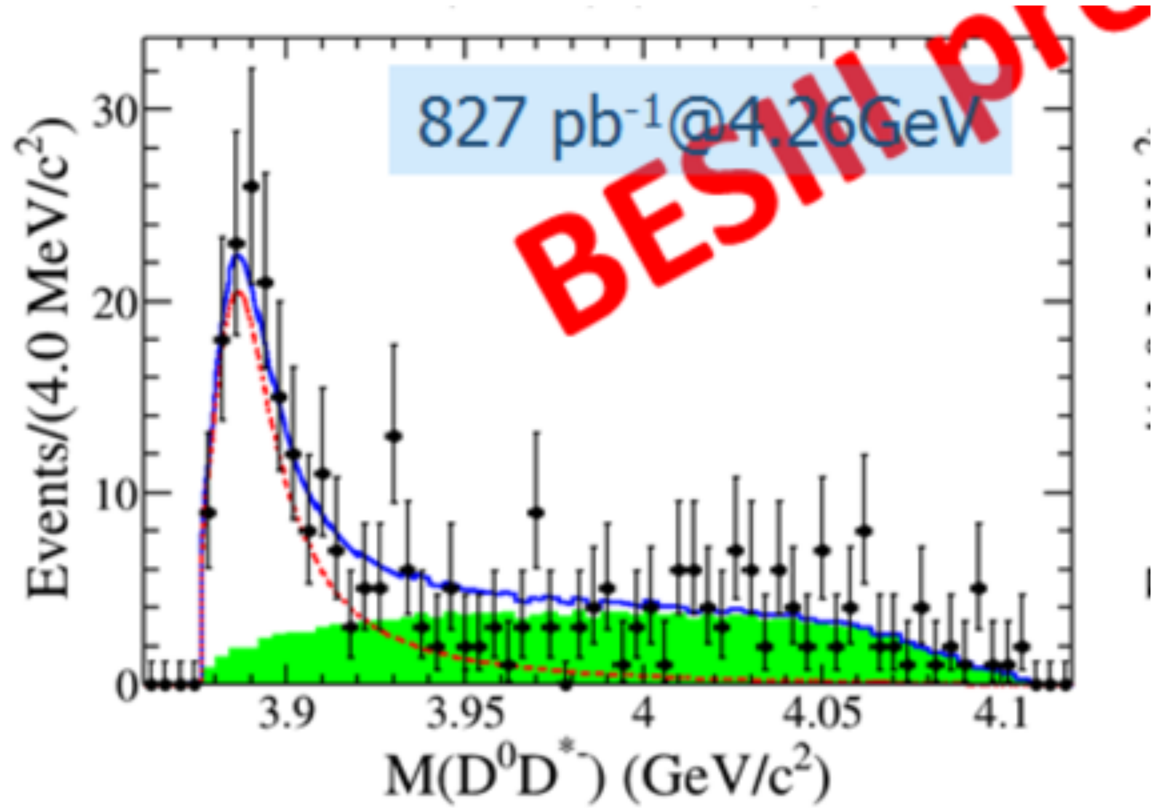
$M = 3883.9 \pm 1.5 \pm 4.2$

$\Gamma = 24.8 \pm 3.3 \pm 11.0$



BESIII PRL112 022001 (14)

Zc(3900)



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

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

$Z_c(4025)$

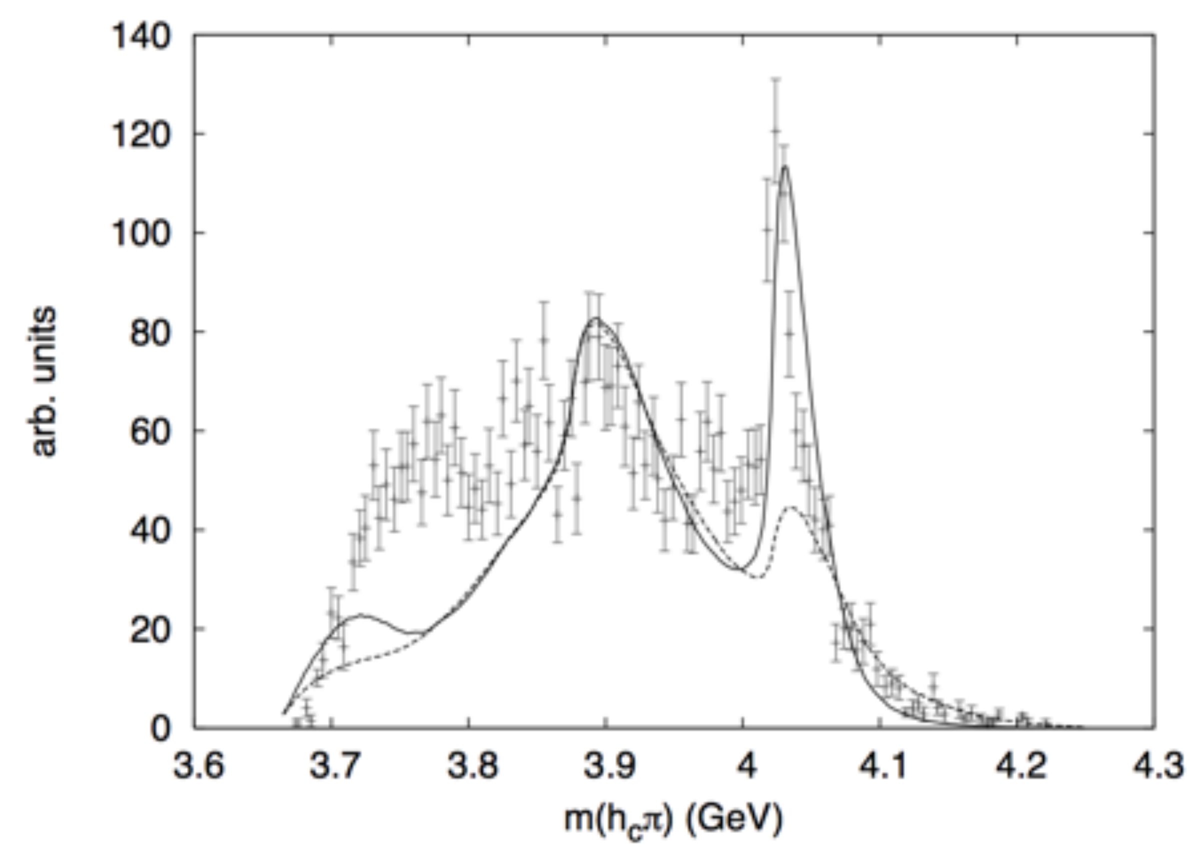
$$e^+e^- \to \pi^+\pi^- h_c$$

sums 13 different ee energy values

"no significant Zc(3900) observed"

$$M = 4022.9 \pm 0.8 \pm 2.7$$

$$\Gamma = 7.9 \pm 2.7 \pm 2.6$$



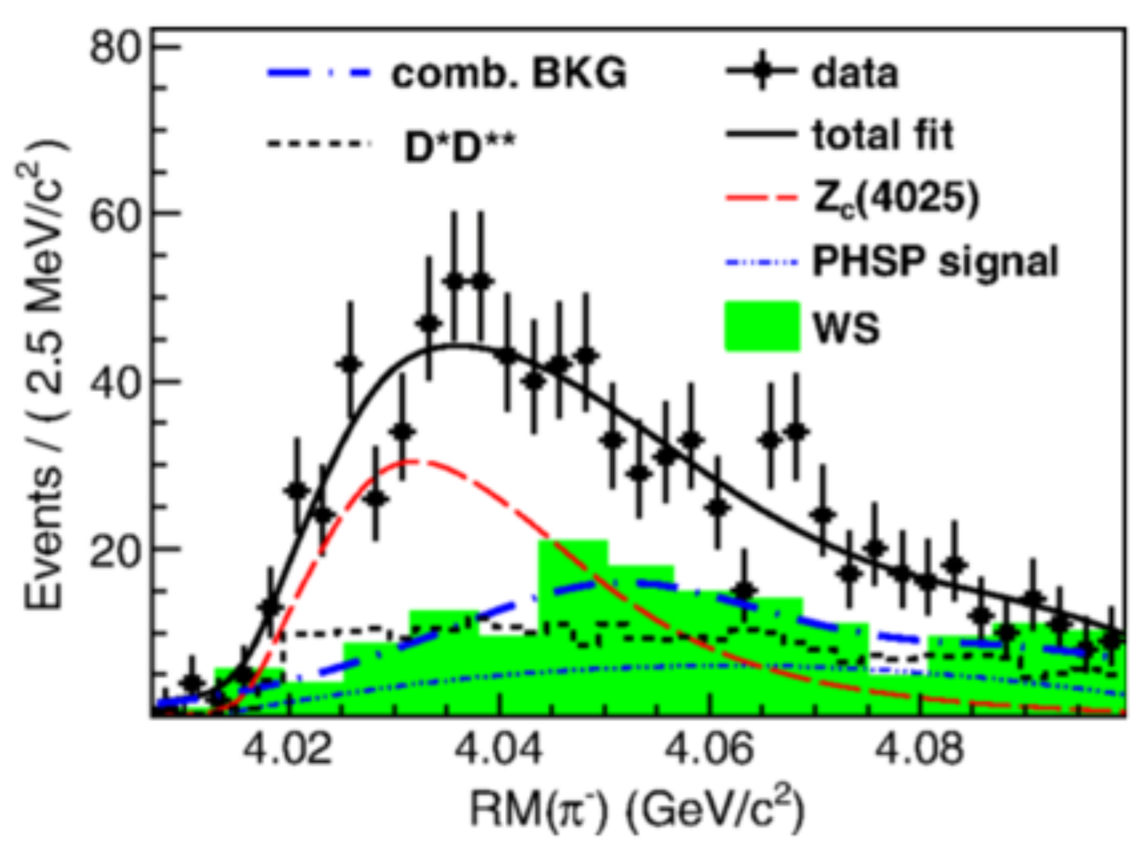
BESIII Phys. Rev. Lett. 111, 242001 (2013).

$$Z_c(4025)$$

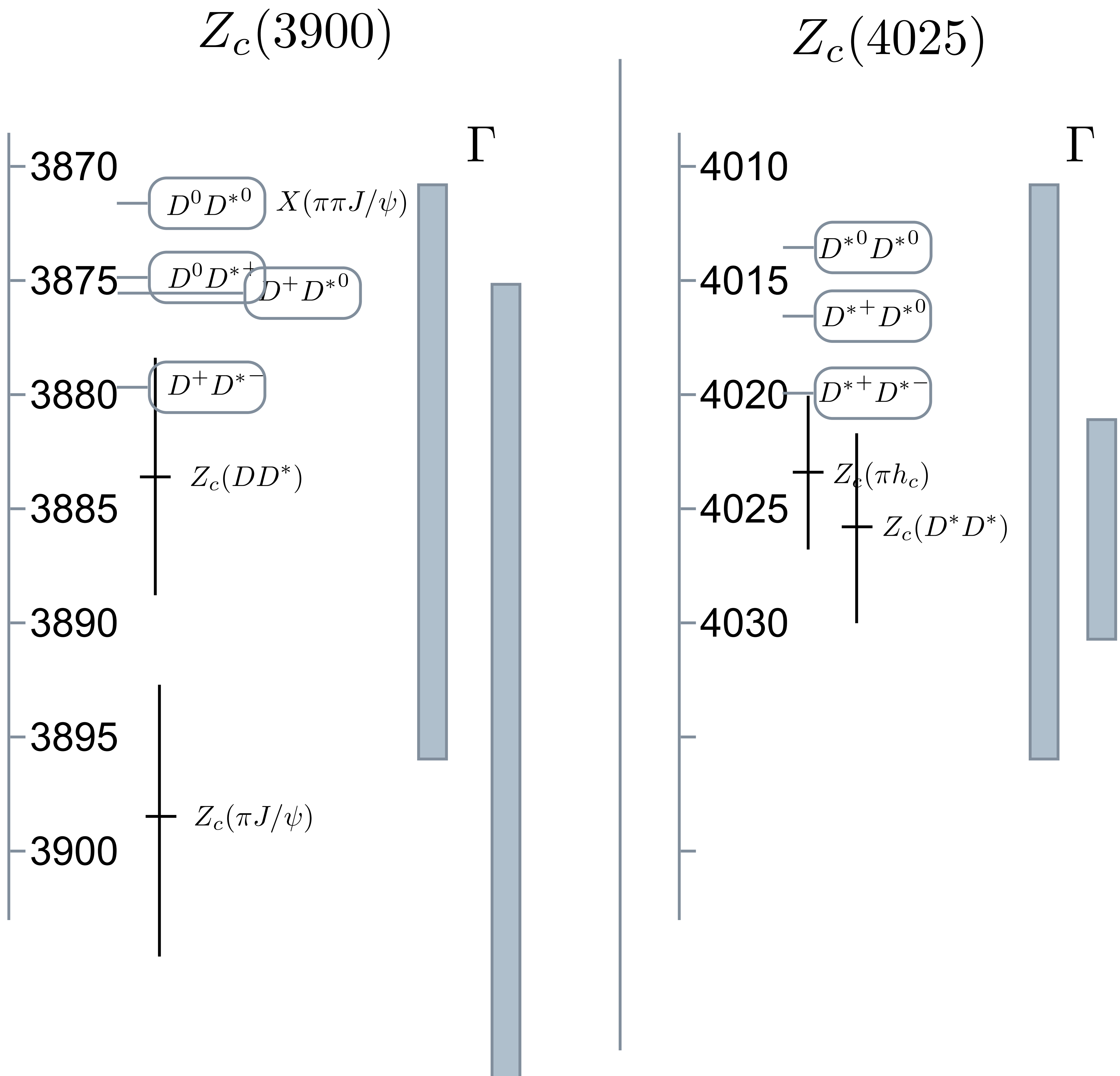
$$e^+e^- \rightarrow (D^*\bar{D}^*)^{\pm}\pi^{\mp}$$

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

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



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

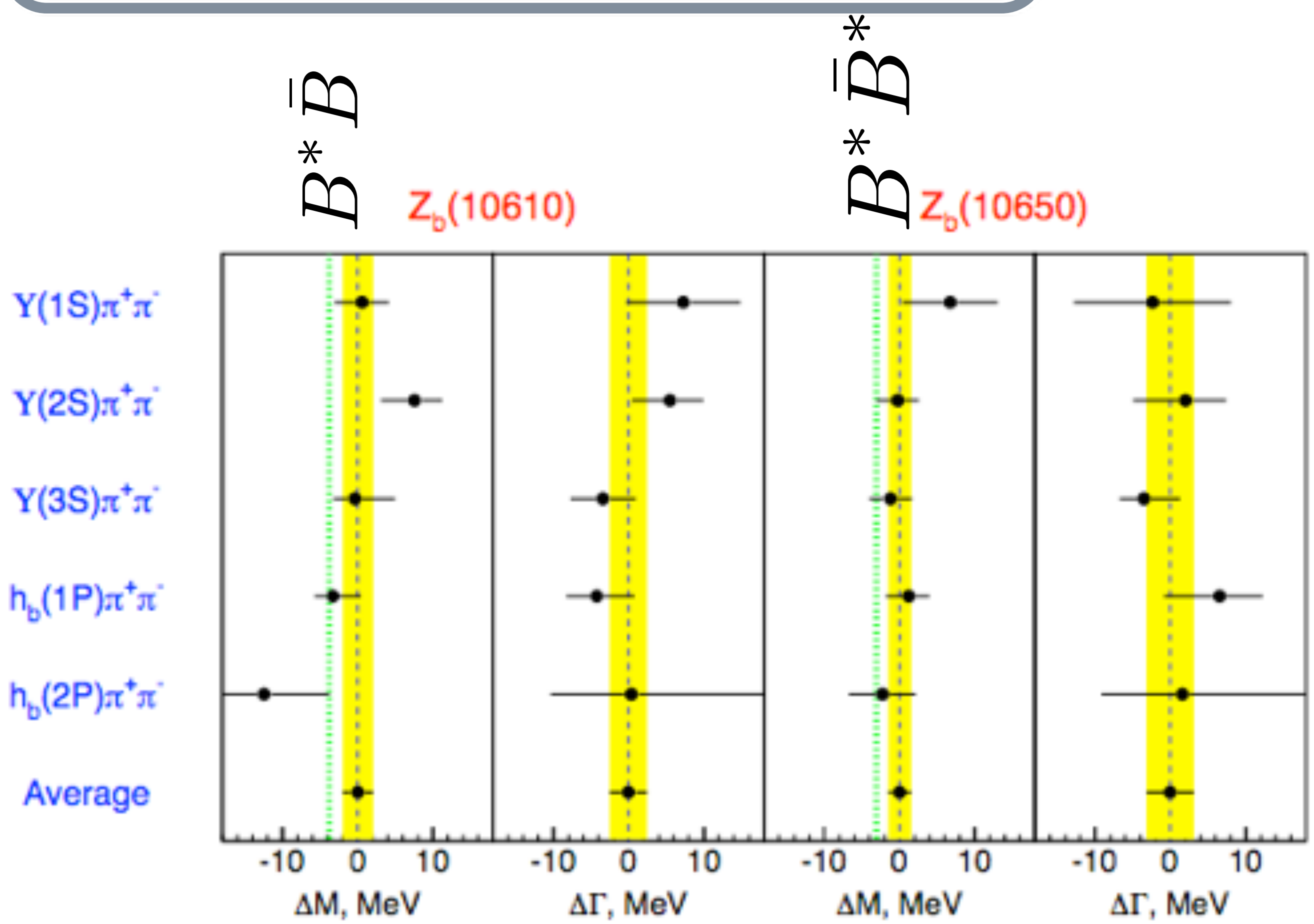


$Z_c(3900)$
$Z_c(4025)$
Γ
Γ
3870
3875
3880
3885
3890
3895
3900
$D^0 D^{*0}$
$X(\pi\pi J/\psi)$
$D^0 D^{*+}$
$D^+ D^{*0}$
$D^+ D^{*-}$
$Z_c(DD^*)$
$Z_c(\pi J/\psi)$
4010
4015
4020
4025
4030
$D^{*0} D^{*0}$
$D^{*+} D^{*0}$
$D^{*+} D^{*-}$
$Z_c(\pi h_c)$
$Z_c(D^* D^*)$

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

Adachi et al. [Belle] 1105.4583

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



1+1+ B*B* is 5D1 and mildly attractive so likely a channel opening effect

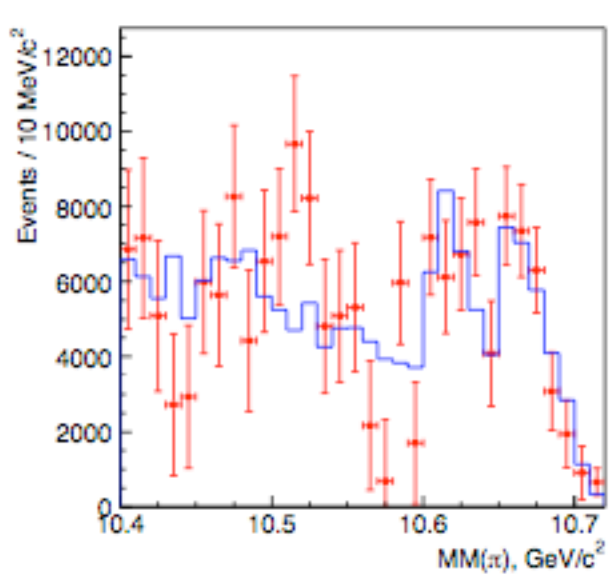
isovector 1++ BB* is repulsive

note that both states are above threshold

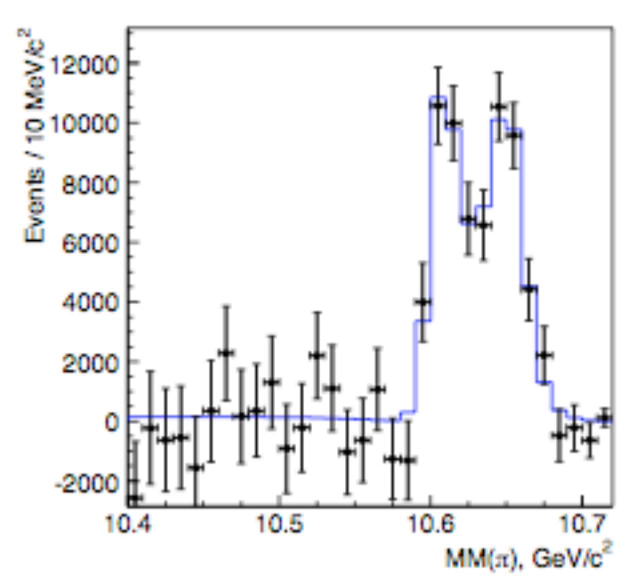
narrow (15 MeV)

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

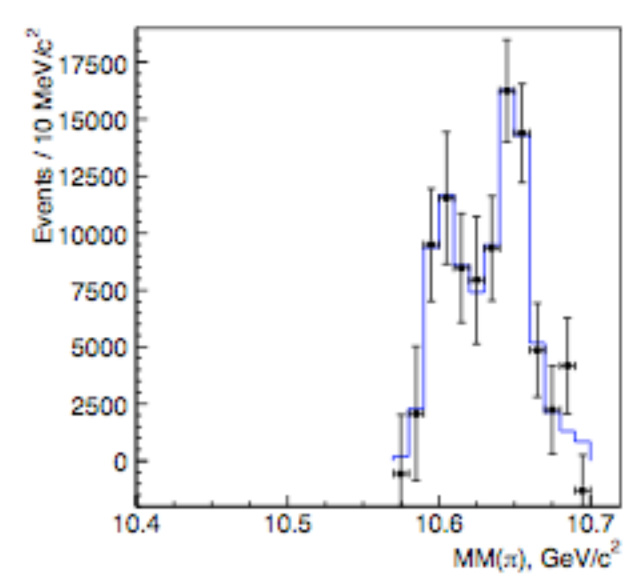
$\Upsilon(2S)$



$h_b(1P)$



$h_b(2P)$



Zc(3900)
Zc(4025)

Ideas:

From SPIRE HEP Database (21st, Apr):

1. Tetraquarks
- arXiv:1110.1333, 1303.6857
- arXiv:1304.0345, 1304.1301

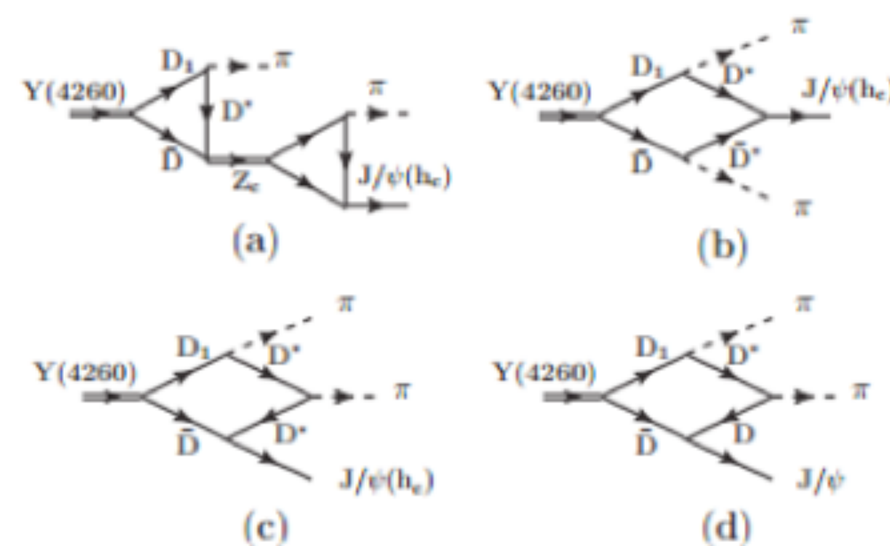
2. Hadronic molecules
- arXiv:1303.6608, 1304.2882, 1304.1850

3. Four quark state (1 or 2)
- arXiv:1304.0380

4. Meson loop
- arXiv:1303.6355
- arXiv:1304.4458

5. ISPE model
- arXiv:1303.6842

6. ...

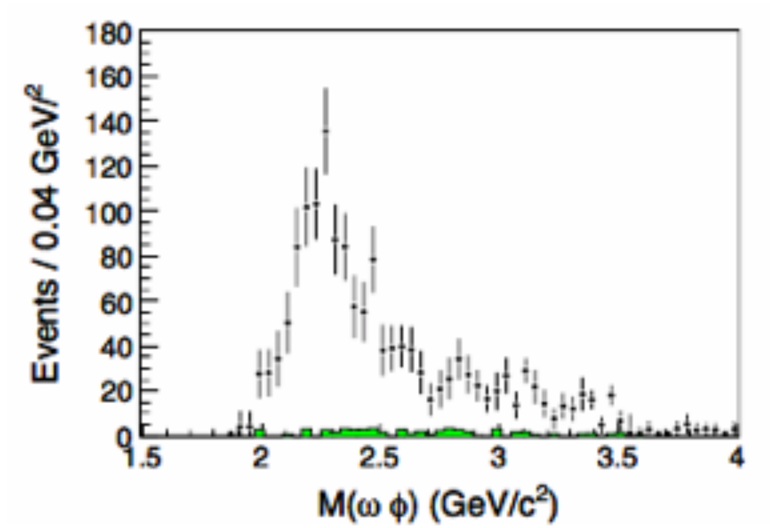


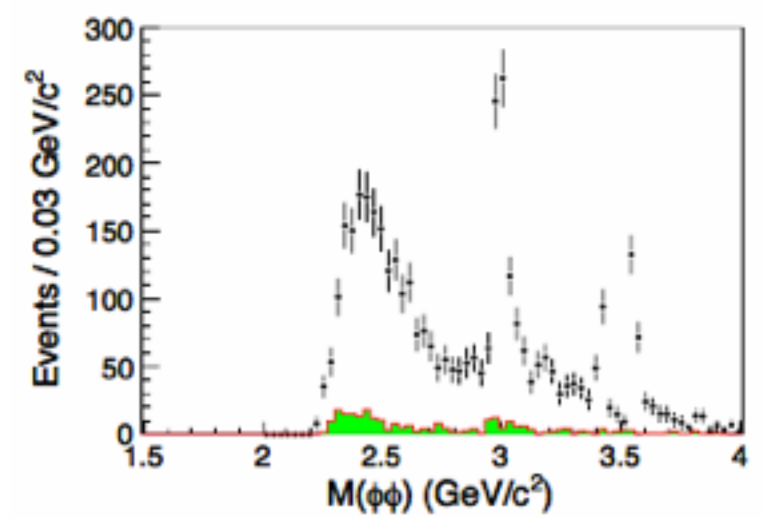
Meson loop

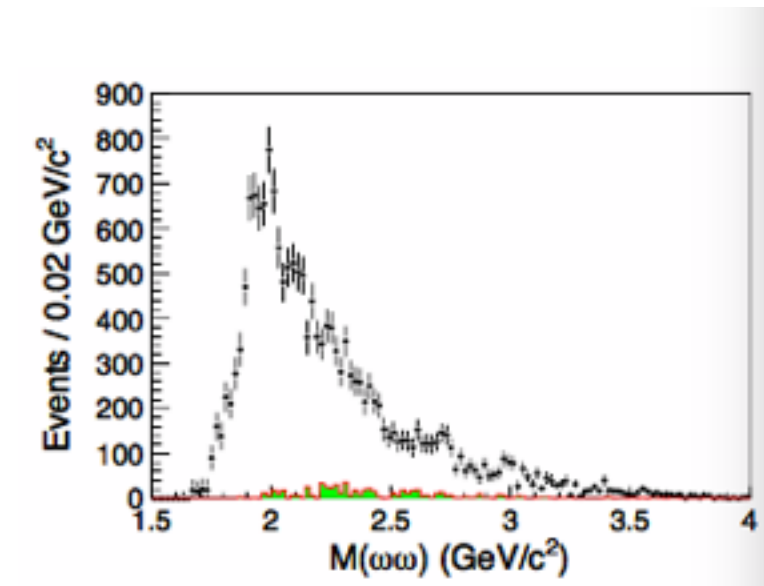
Modelling the Zs

- It seems foolish to ignore that the Z_cs and Z_bs are just above related thresholds.
- Threshold enhancements are common in hadronic interactions

threshold enhancements







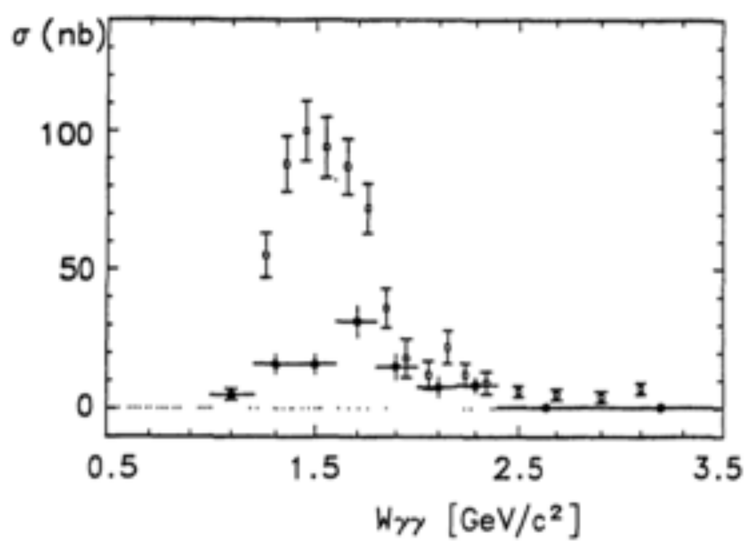
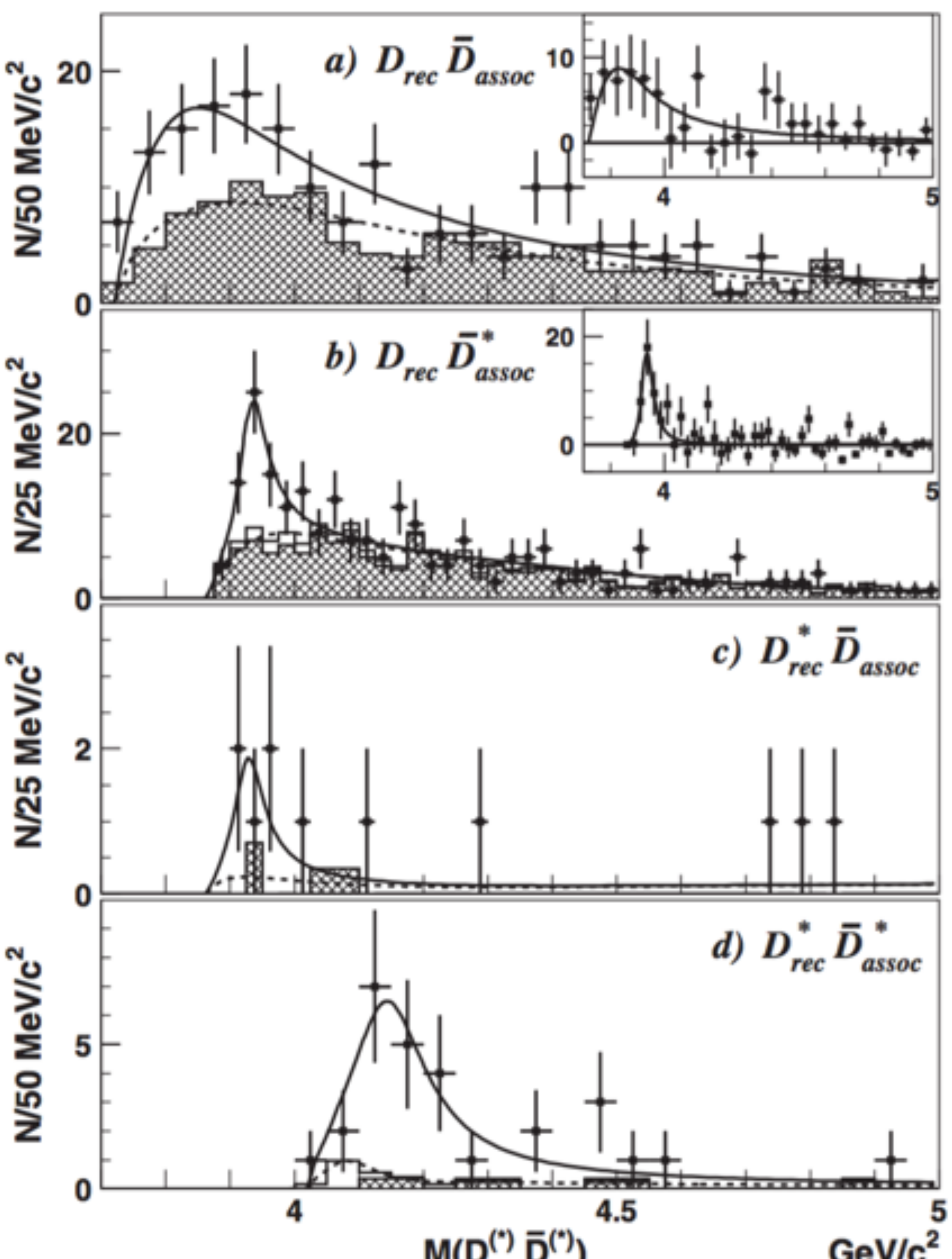


Figure 5.2: Comparison of the $\gamma\gamma \to \rho\rho$ measured cross sections. The reaction $\gamma\gamma \to \rho^0\rho^0$ is presented as squares and is the measurement by PLUTO [11] and the reaction $\gamma\gamma \to \rho^+\rho^-$ as full dots.

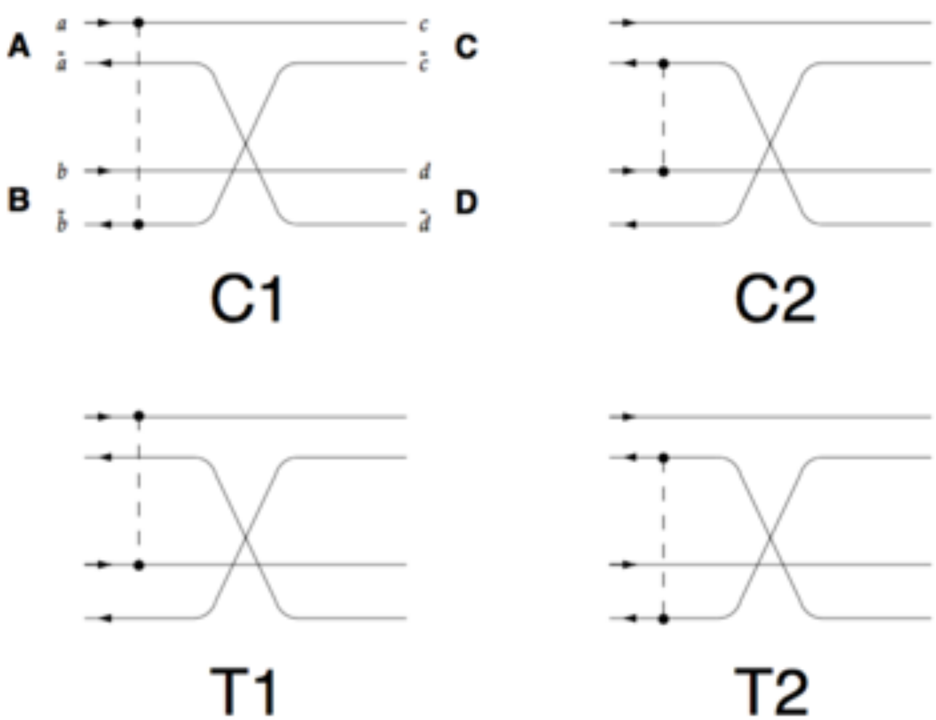
threshold enhancements

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



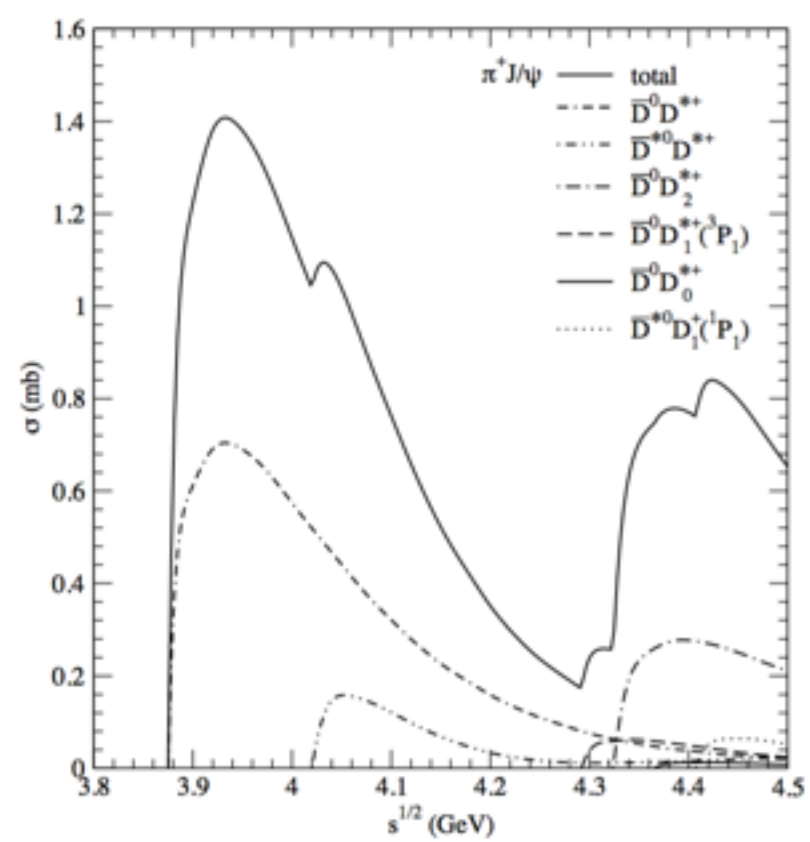
[Belle] PRL100, 202001 (08)

threshold enhancements

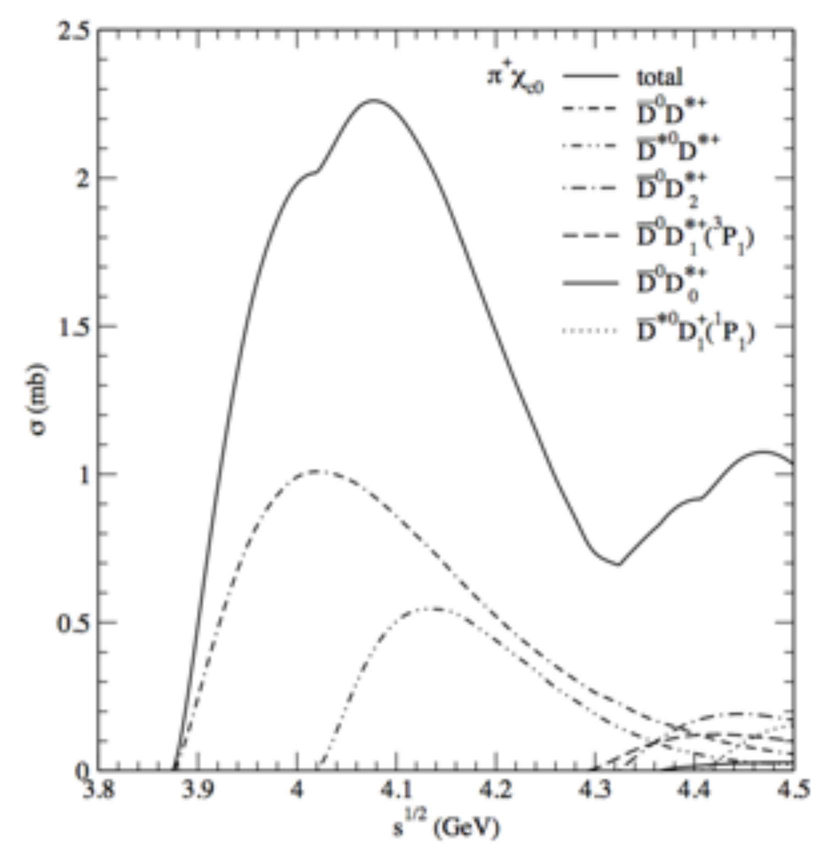


A Quark Model Example

S-wave



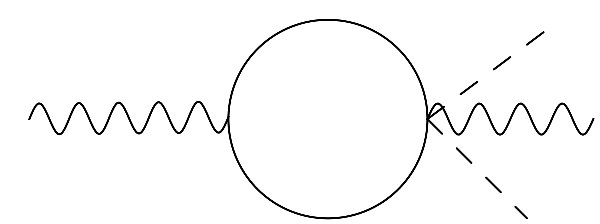
P-wave



Modelling the Zs — Cusps

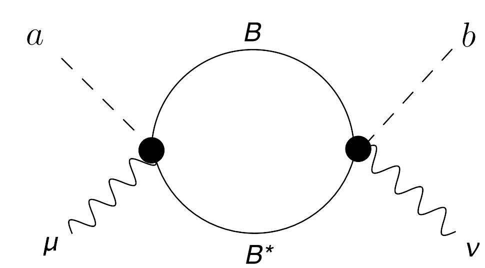
Q: how does Y(5S) couple to Yππ?

$$\Upsilon(5S) \to \text{ hidden bottom} = 3.8\%$$



$$\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)} = 57.3\%$$

$$\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi = 8.3\%$$



$$\Upsilon(5S) \to \Upsilon(nS)\pi\pi < 7.8 \cdot 10^{-3}$$

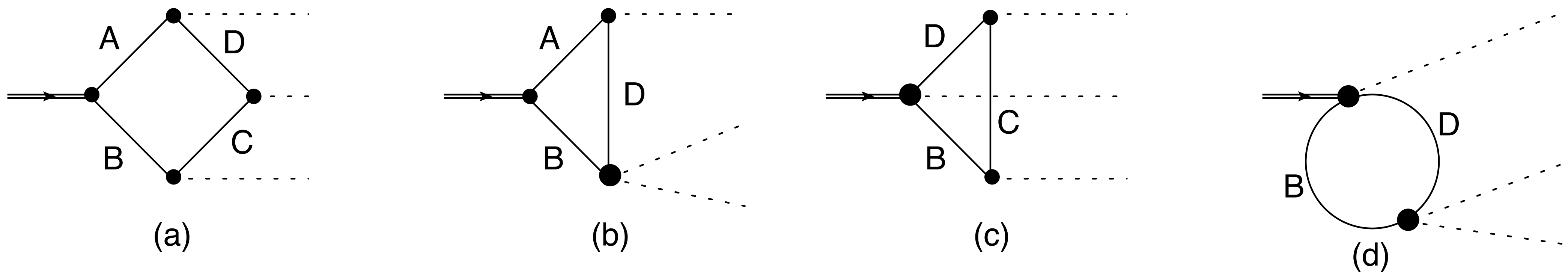
Loops Create Cusps

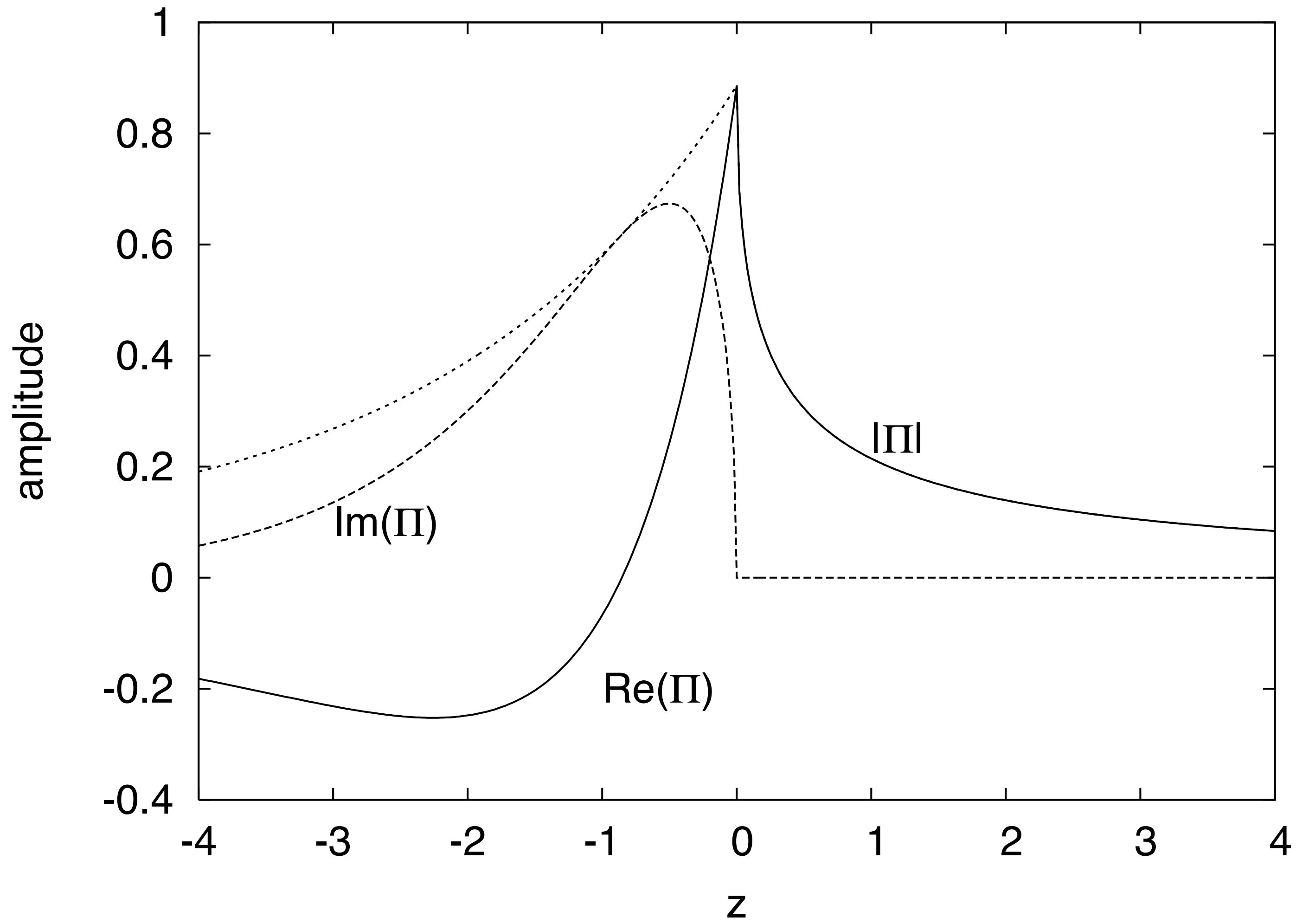
E.P. Wigner, Phys. Rev. 73 (1948) 1002

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

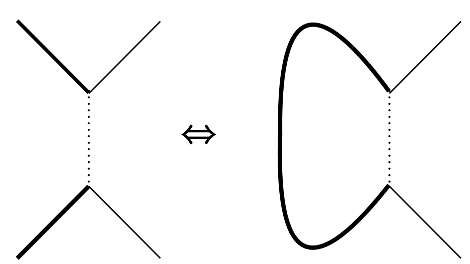
D. V. Bugg, Int. J. Mod. Phys. A 24, 394 (2009)

E.S. Swanson, arXiv:1409.3291





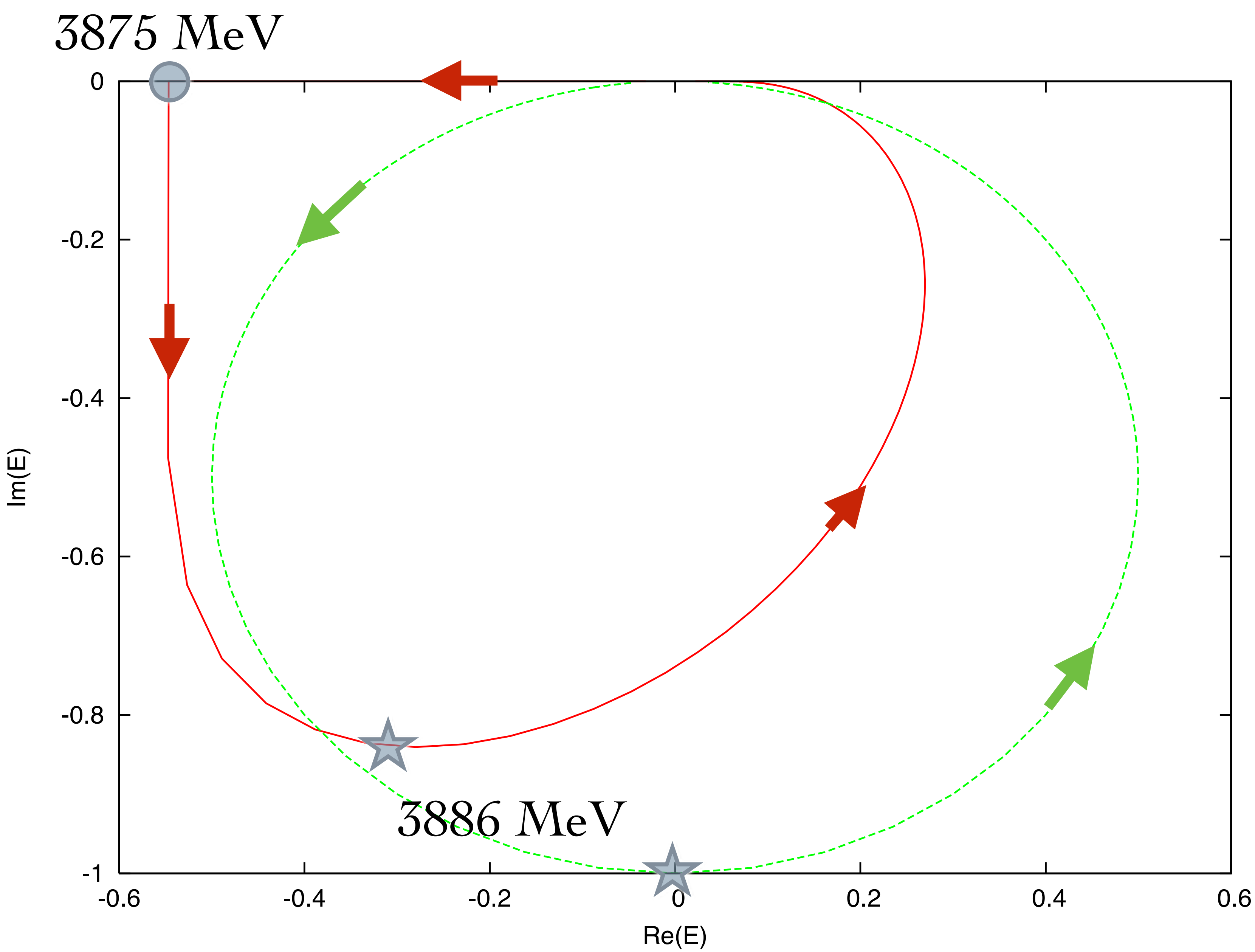
and are related to thresholds



Modelling the Zs — Cusps

this is -BW
and 80*loop
both ‘resoanance’ locations at 3886 =
11 MeV above threshold

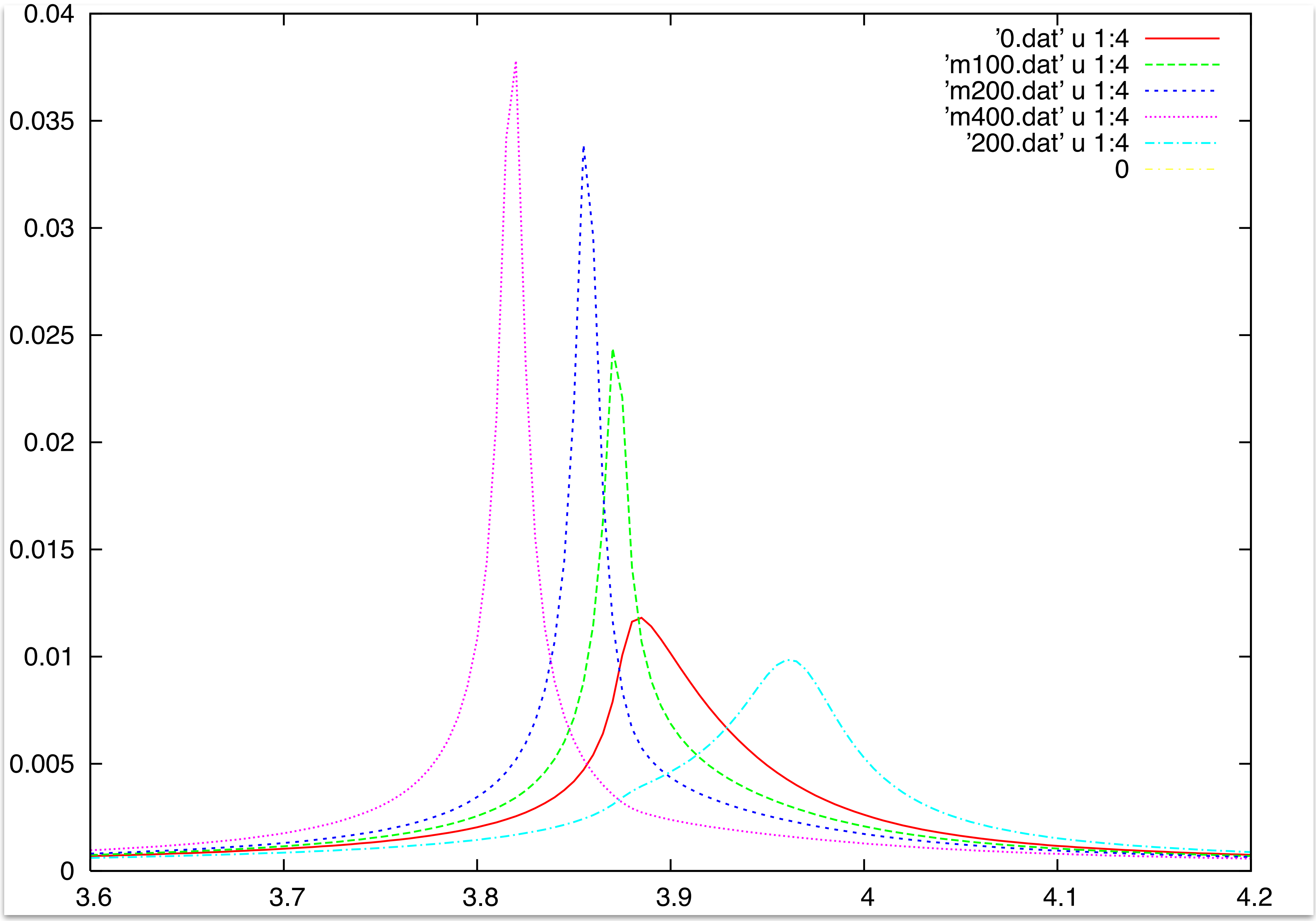
phase motion



Modelling the Zs — Cusps

track pole while doing this!!!
need to couple pi psi to get a resonance

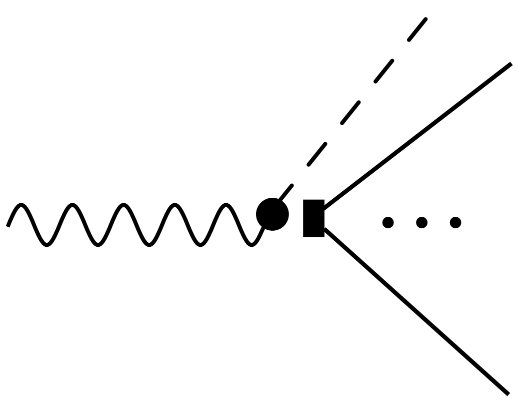
effect of the bubble sum



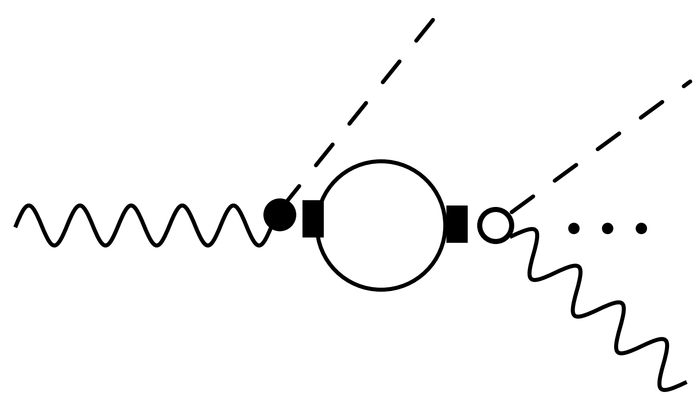
E.S. Swanson, arXiv:1504.07952

Modelling the Zs — Cusps

Attempt a "microscopic" cusp model
[separable nonrelativistic model; solve exactly]
[iterate all bubbles]



$Y(4260) \to \pi D\bar{D}^*$

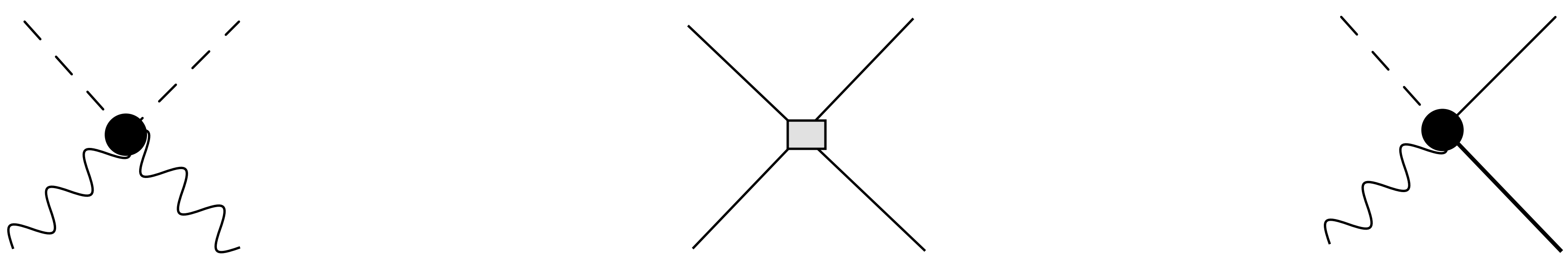


$Y(4260) \to \pi\pi J/\psi$

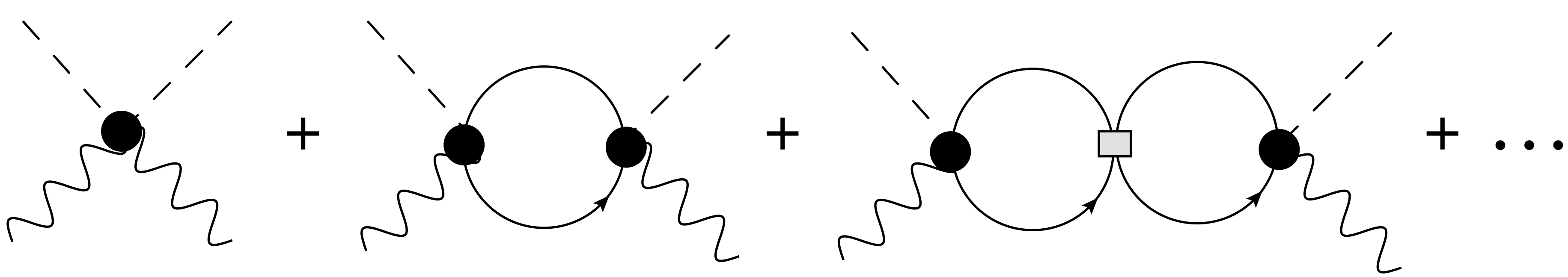
$$g_{DD^*} \cdot \exp(-\lambda(s_{\pi Y})/\beta^2_{\pi Y}) \exp(-\lambda(s_{DD^*})/\beta^2_{DD^*})$$

More Detailed Modelling

Model the vertices so that more processes can be described.



Now we need to build the 'self energy'

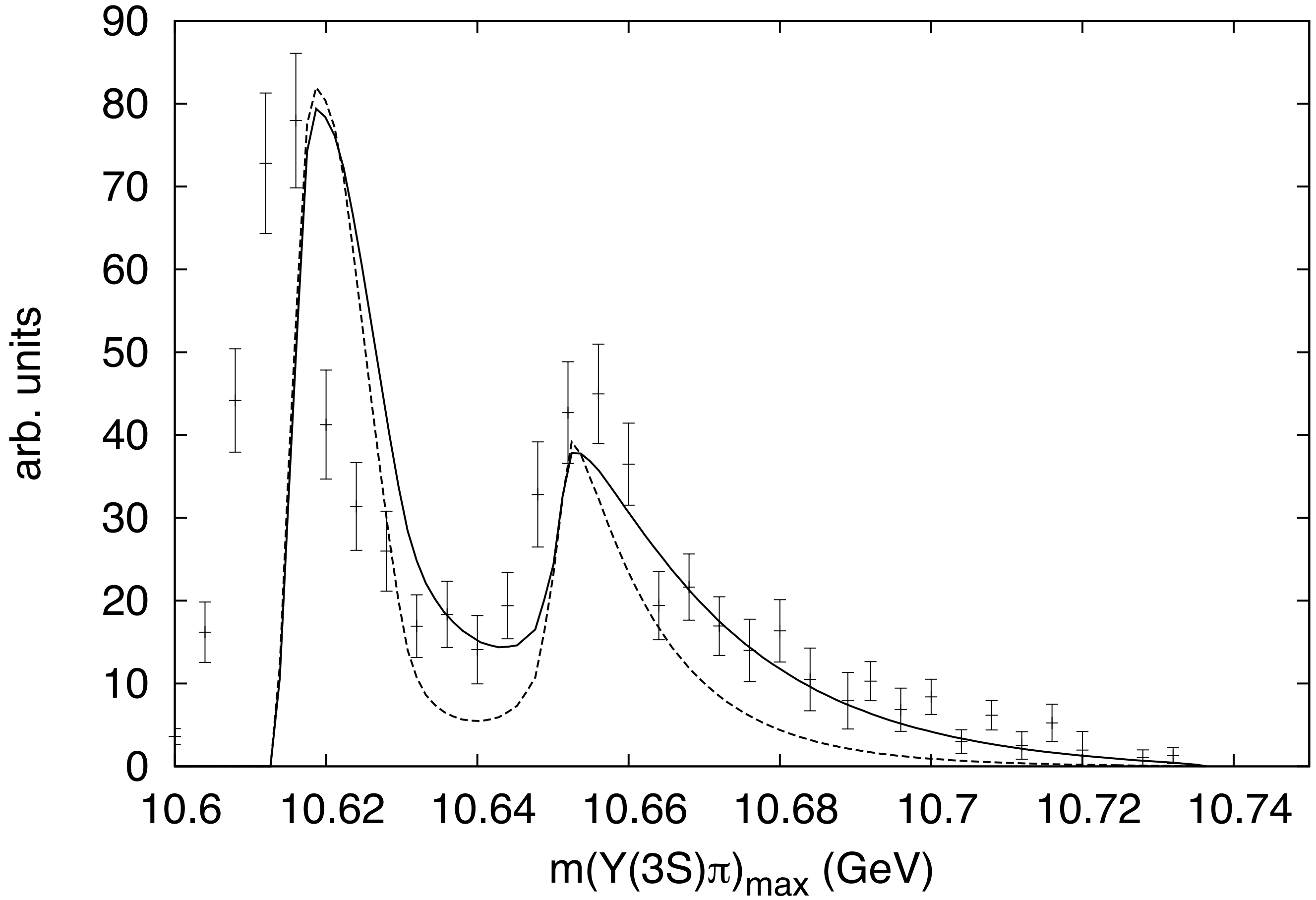


Modelling the Zs — Cusps

fix couplings and scales with Y(3S) — relatively little pipi dynamics. Get Y(2S) with same couplings! Y(1S) requires 70% smaller coupling BB*:piY(1S)

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

Zb(10610), Zb(10650)



$$\beta_{\alpha i} = 0.7 \text{ GeV}$$

$$g^2_{\Upsilon(nS)BB^*} = 0.9 \cdot g^2_{\Upsilon(nS)B^*B^*}$$

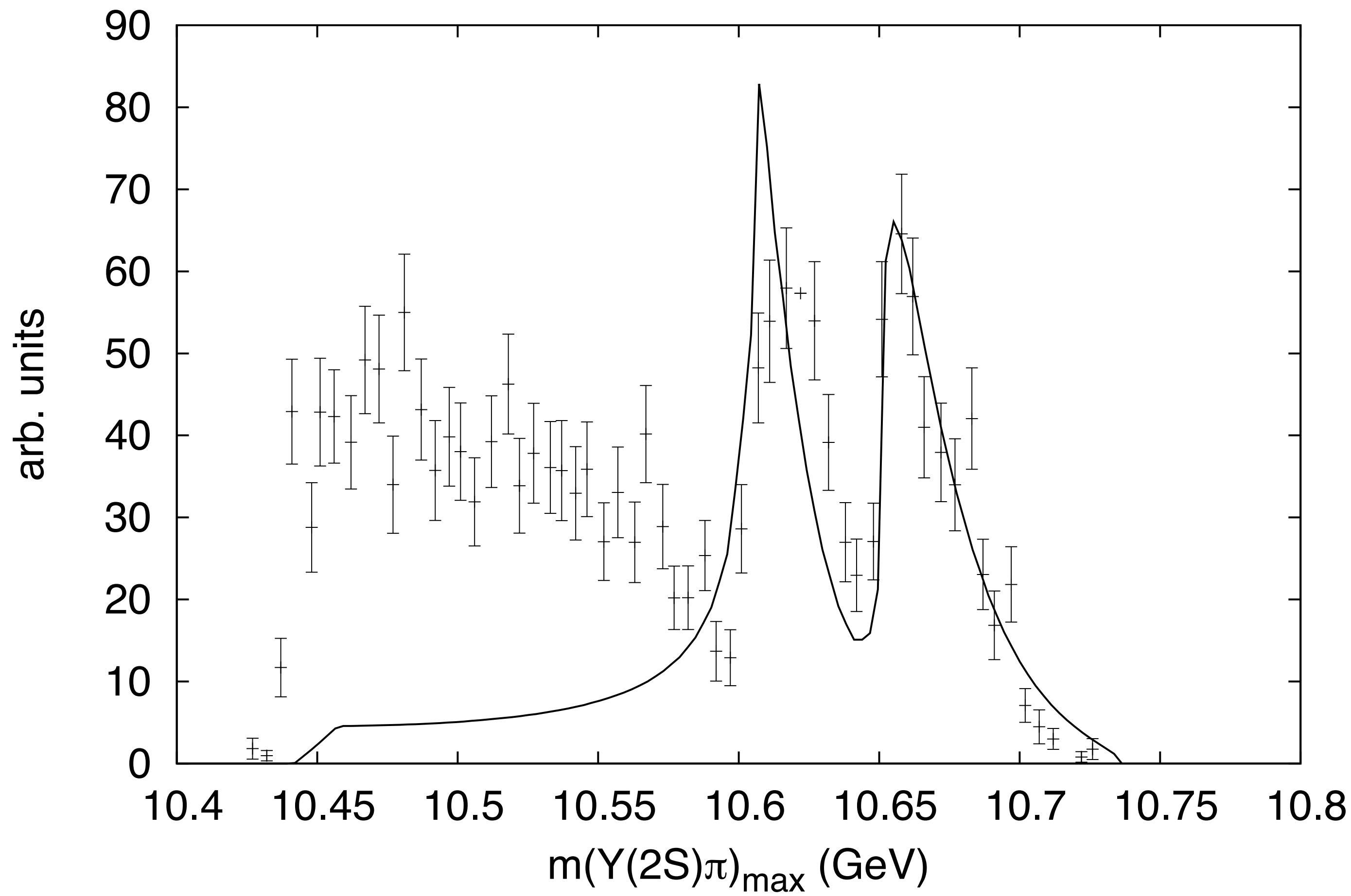
Adachi et al. [Belle Collaboration], arXiv:1105.4583 [hep-ex];

Garmash et al. [Belle Collaboration], arXiv:1403.0992 [hep-ex].

Modelling the Zs — Cusps

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

Zb(10610), Zb(10650)



same couplings used!

Adachi et al. [Belle Collaboration], arXiv:1105.4583 [hep-ex];

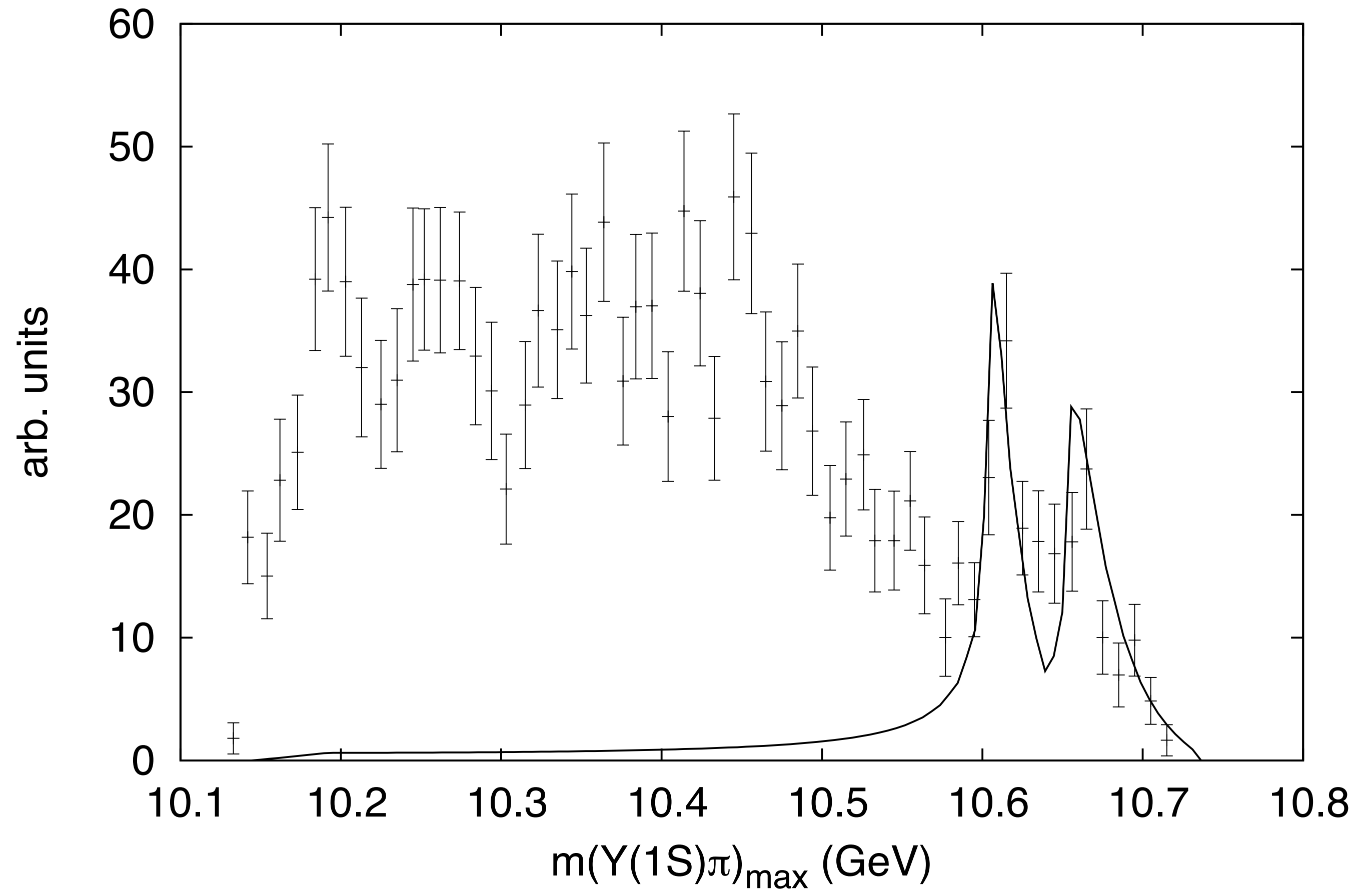
Garmash et al. [Belle Collaboration], arXiv:1403.0992 [hep-ex].

Modelling the Zs — Cusps

fix couplings and scales with Y(3S) — relatively little pipi dynamics. Get Y(2S) with same couplings! Y(1S) requires 70% smaller coupling BB*:piY(1S)

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

Zb(10610), Zb(10650)



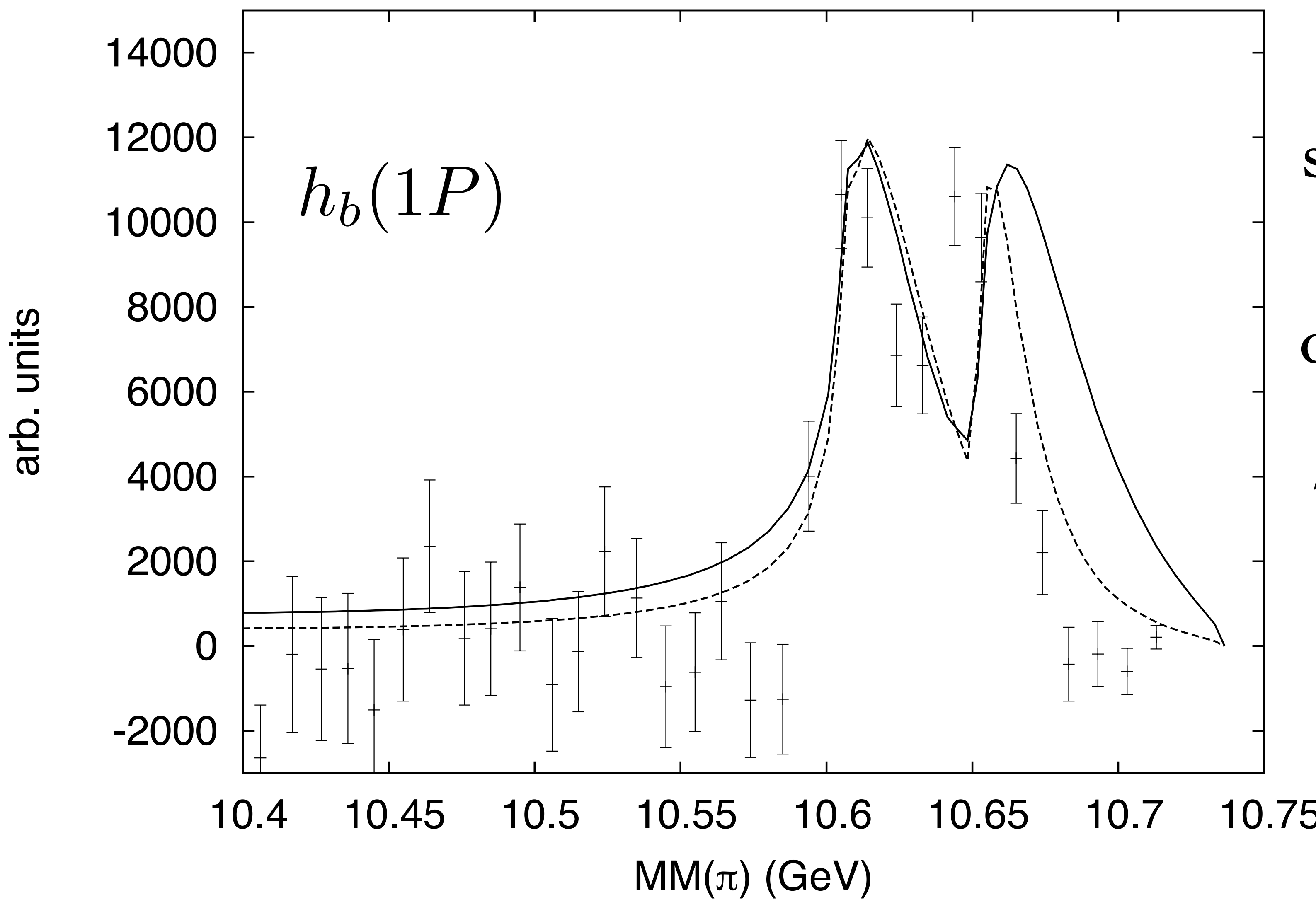
30% smaller coupling required

Adachi et al. [Belle Collaboration], arXiv:1105.4583 [hep-ex];

Garmash et al. [Belle Collaboration], arXiv:1403.0992 [hep-ex

Modelling the Zs — Cusps

$$\Upsilon(5S) \to h_b(nP)\pi\pi$$ Zb(10610), Zb(10650)



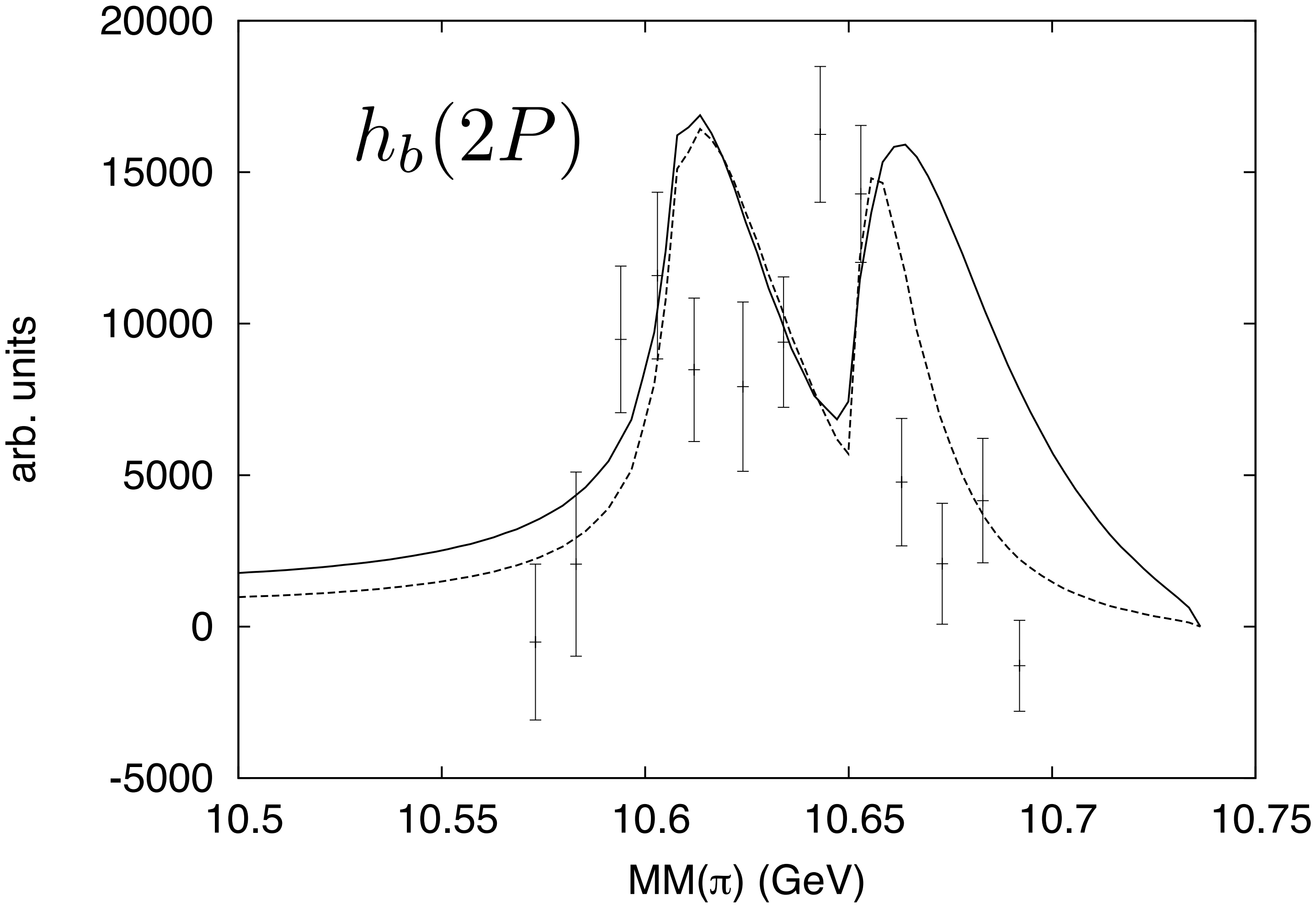
solid line: same as above

dashed line:

$$\beta_{BB^*} = 0.7 \text{ GeV}, \ \beta_{B^*B^*} = 0.4 \text{ GeV}$$
$$g^2_{BB^*} = 0.5\, g^2_{B^*B^*}$$

Modelling the Zs — Cusps

$$\Upsilon(5S) \to h_b(nP)\pi\pi$$ Zb(10610), Zb(10650)



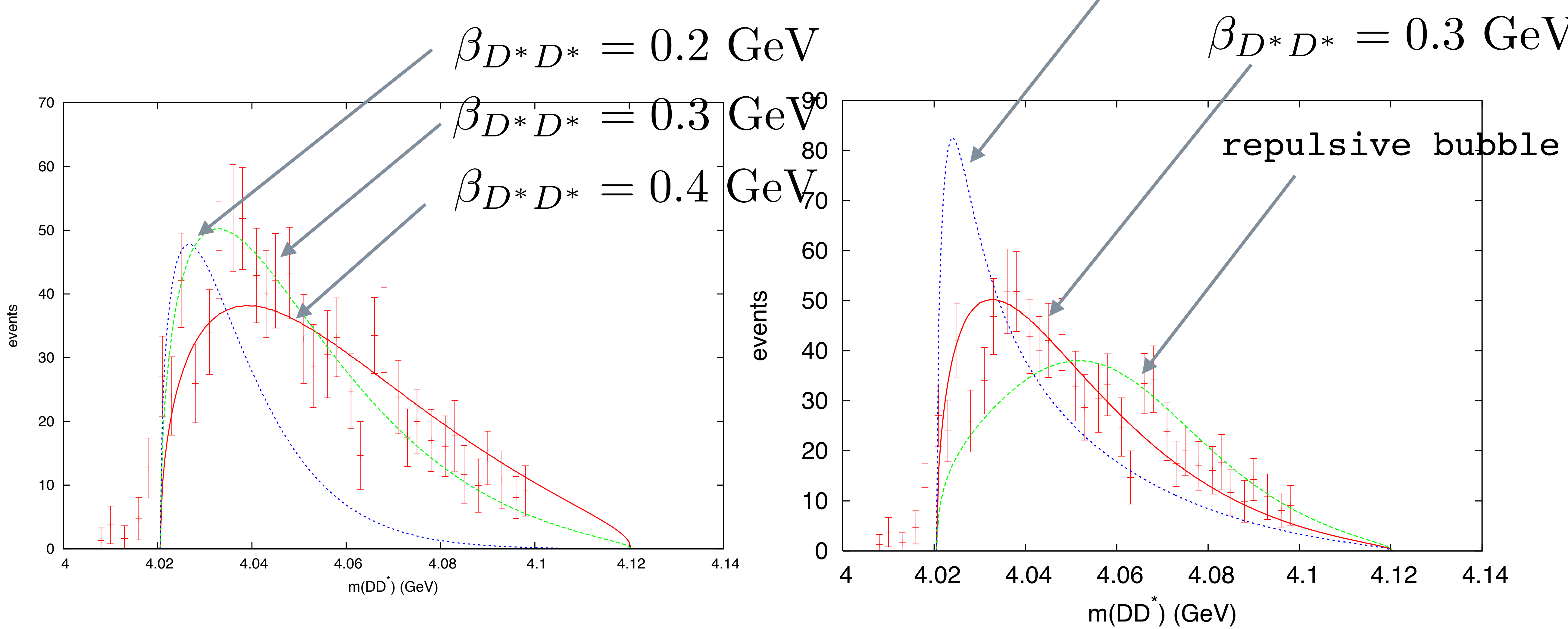
solid line: same as above

dashed line:

$$\beta_{BB^*} = 0.7 \text{ GeV}, \ \beta_{B^*B^*} = 0.4 \text{ GeV}$$
$$g^2_{BB^*} = 0.5\, g^2_{B^*B^*}$$

Modelling the Zs — Cusps

fit the pi Y: D*D* vertex



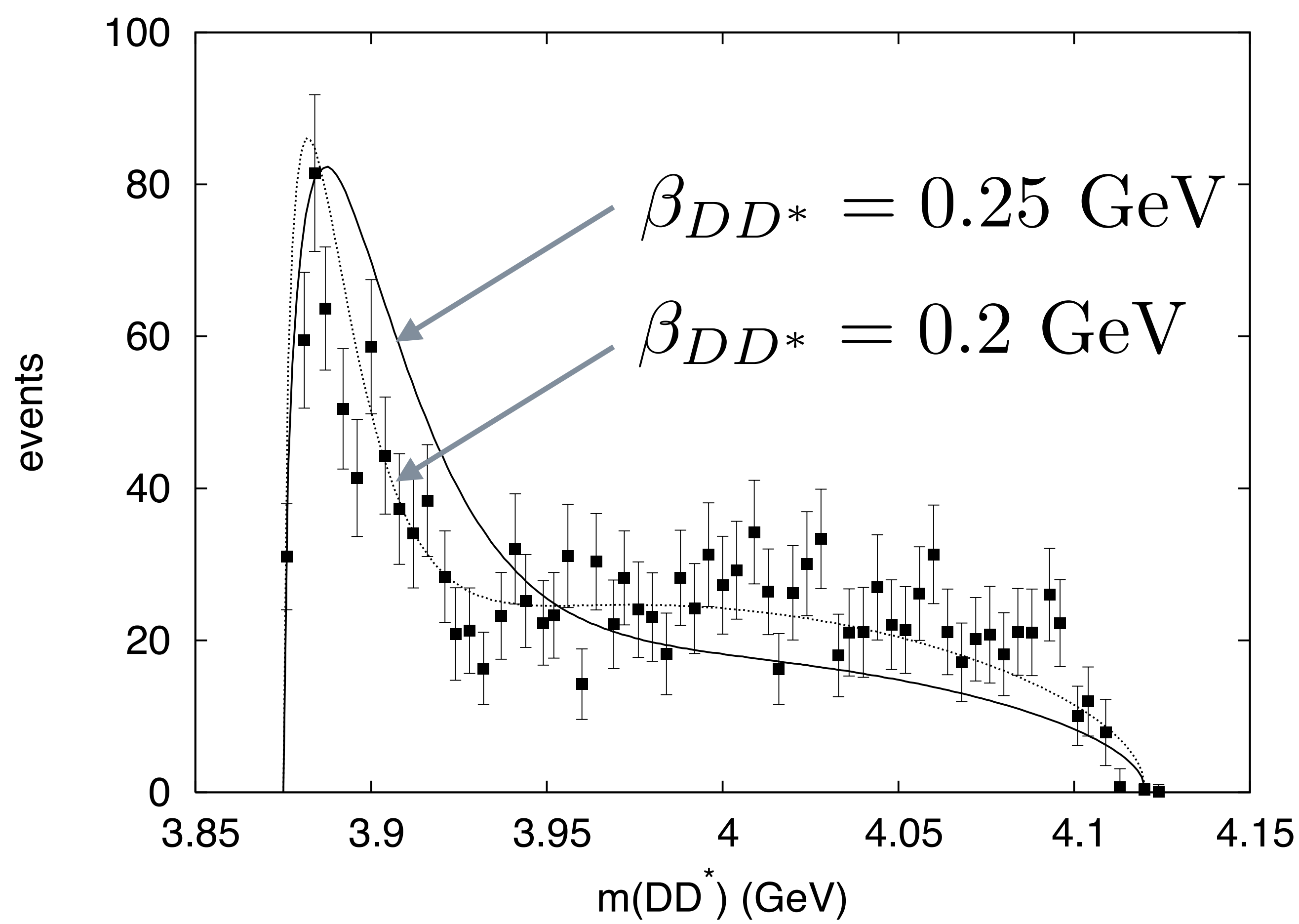
no evidence for π D* dynamics, background, or bubble

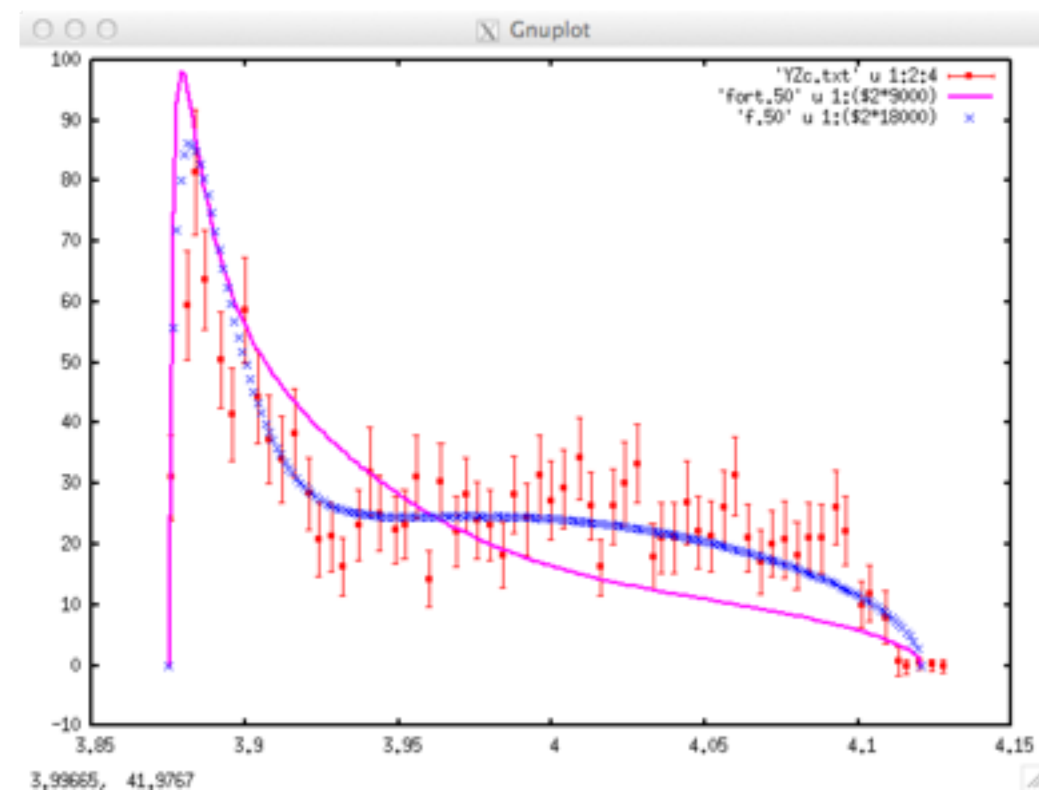
Modelling the Zs — Cusps

note that only pi and D are reconstructed, D* is inferred => lots of room for incoherent background

Pink curve: wider beta, compensate with attractive bubble => ruins shape

fit the pi Y: DD* vertex



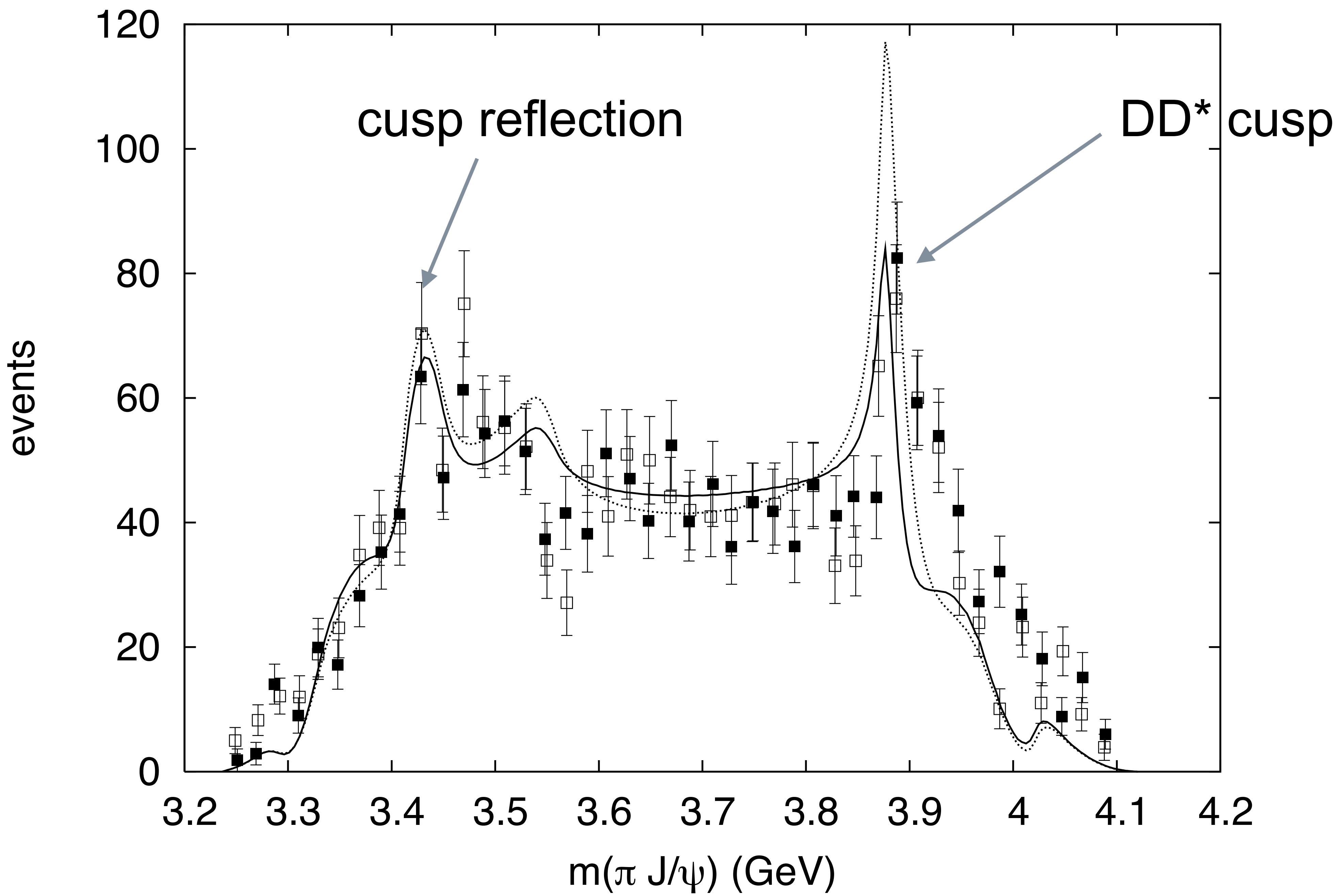


no evidence for bubble

evidence for incoherent background

Modelling the Zs — Cusps

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



BESIII

Modelling the Zs — Cusps

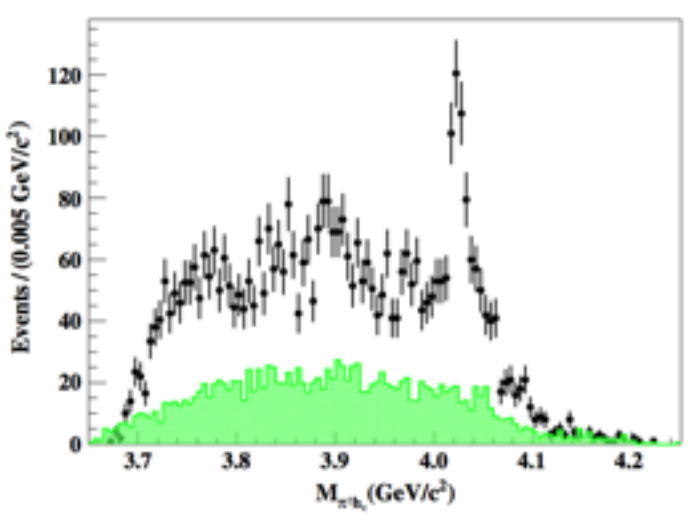
M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 111, 242001 (2013).

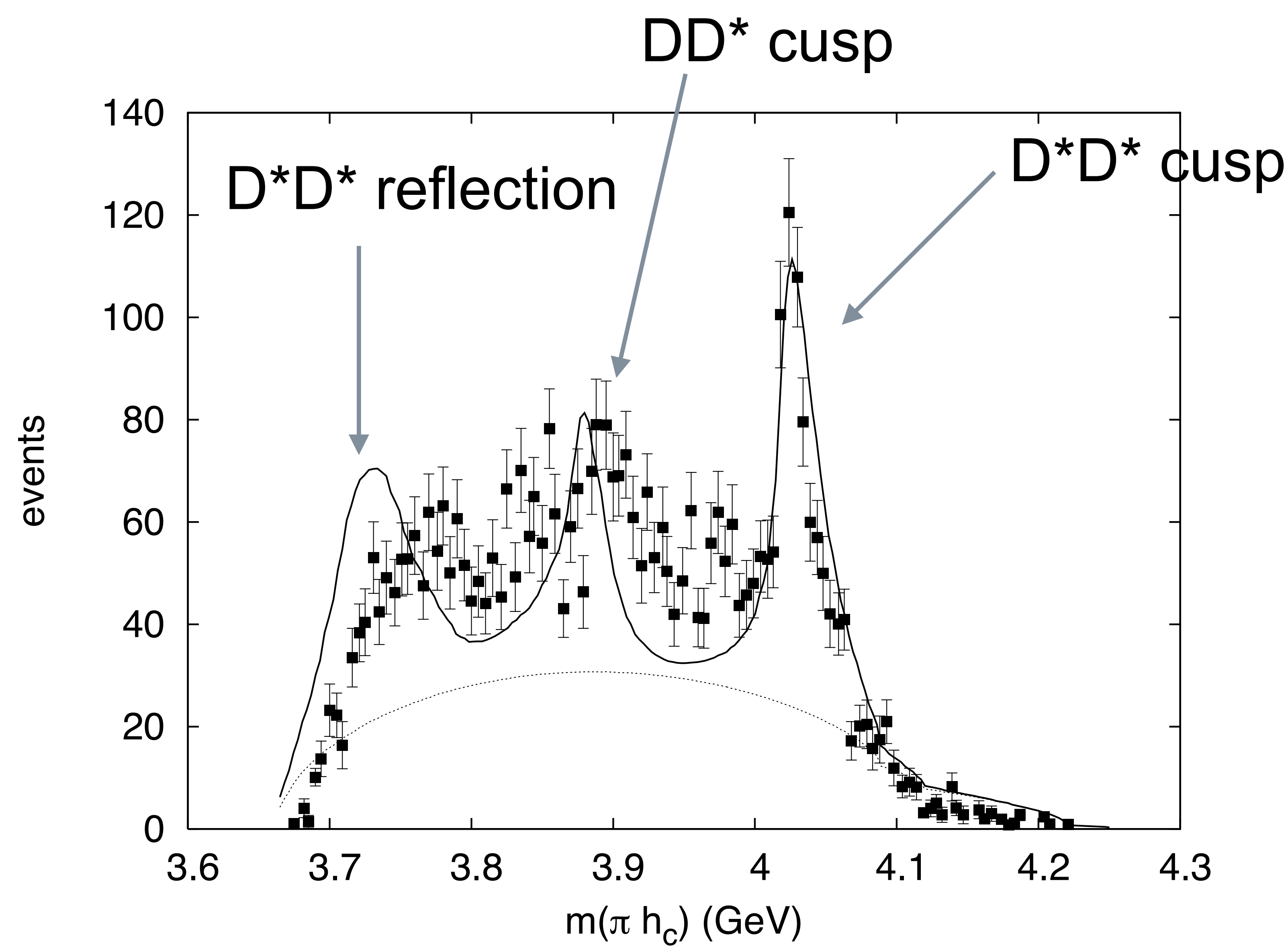
$$e^+e^- \to \pi^+\pi^- h_c$$

sums 13 different ee energy values

"no significant Zc(3900) observed"

[incoherent background only]





Modelling the Zs — Issues with Cusps

other cusp channels?

- $\Upsilon(5S) \to K\bar{K}\Upsilon(nS)$

$B\bar{B}_s^* + B^*\bar{B}_s$	10695
$B^*\bar{B}_s^*$	10745

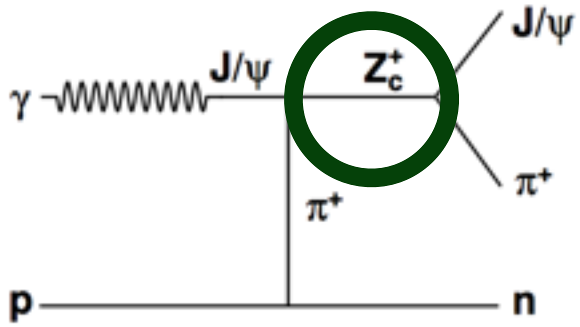
- $e^+e^- \to K\bar{K}J/\psi$

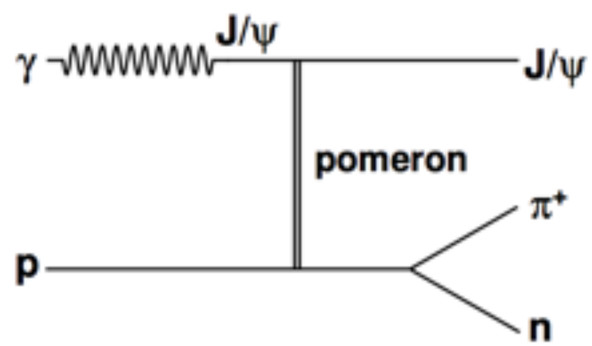
$D\bar{D}_s^* + D^*\bar{D}_s$	3980
$D^*\bar{D}_s^*$	4120

Modelling the Zs — Issues with Cusps

assumed a dipole form factor -> not much suppression at this high CoM energy

COMPASS



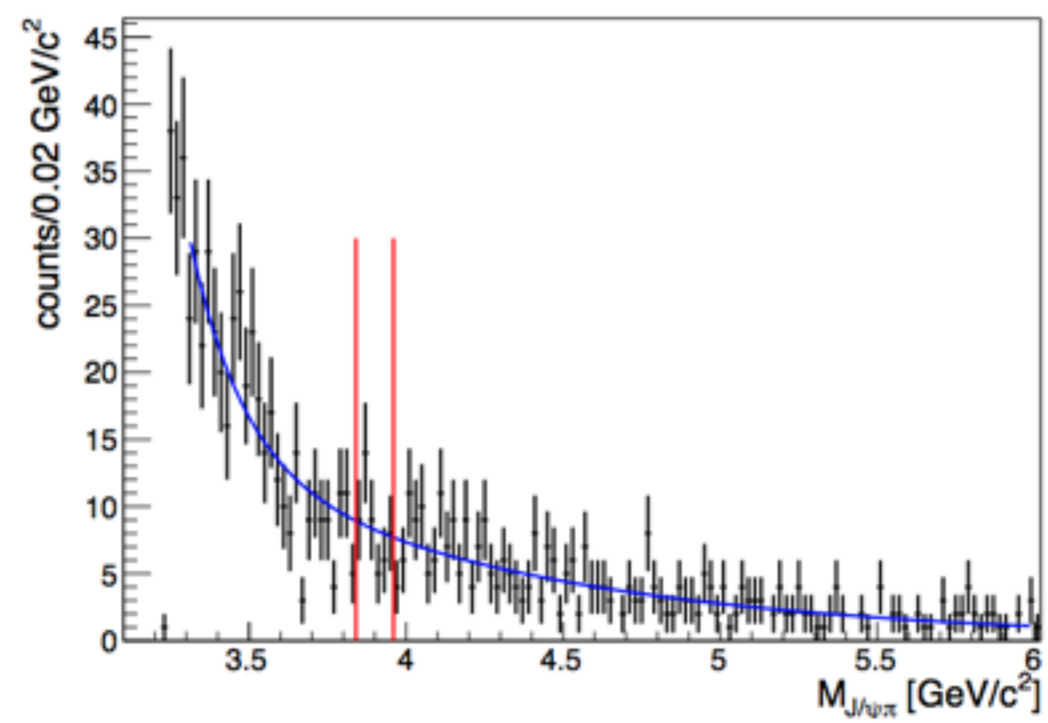


$$\sqrt{s_{\gamma N}} = 7 \text{ GeV}$$

$$\exp(-\lambda(s_{\gamma N}, m_\psi^2, m_\pi^2)/(4 s_{\gamma N}\beta^2) \approx$$

$$\exp(-(s_{\gamma N} - m_\psi^2)^2/(4 s_{\gamma N}\beta^2) \approx$$

$$\exp(-88)$$



C. Adolph et al. [COMPASS] arXiv:1407.6186v1

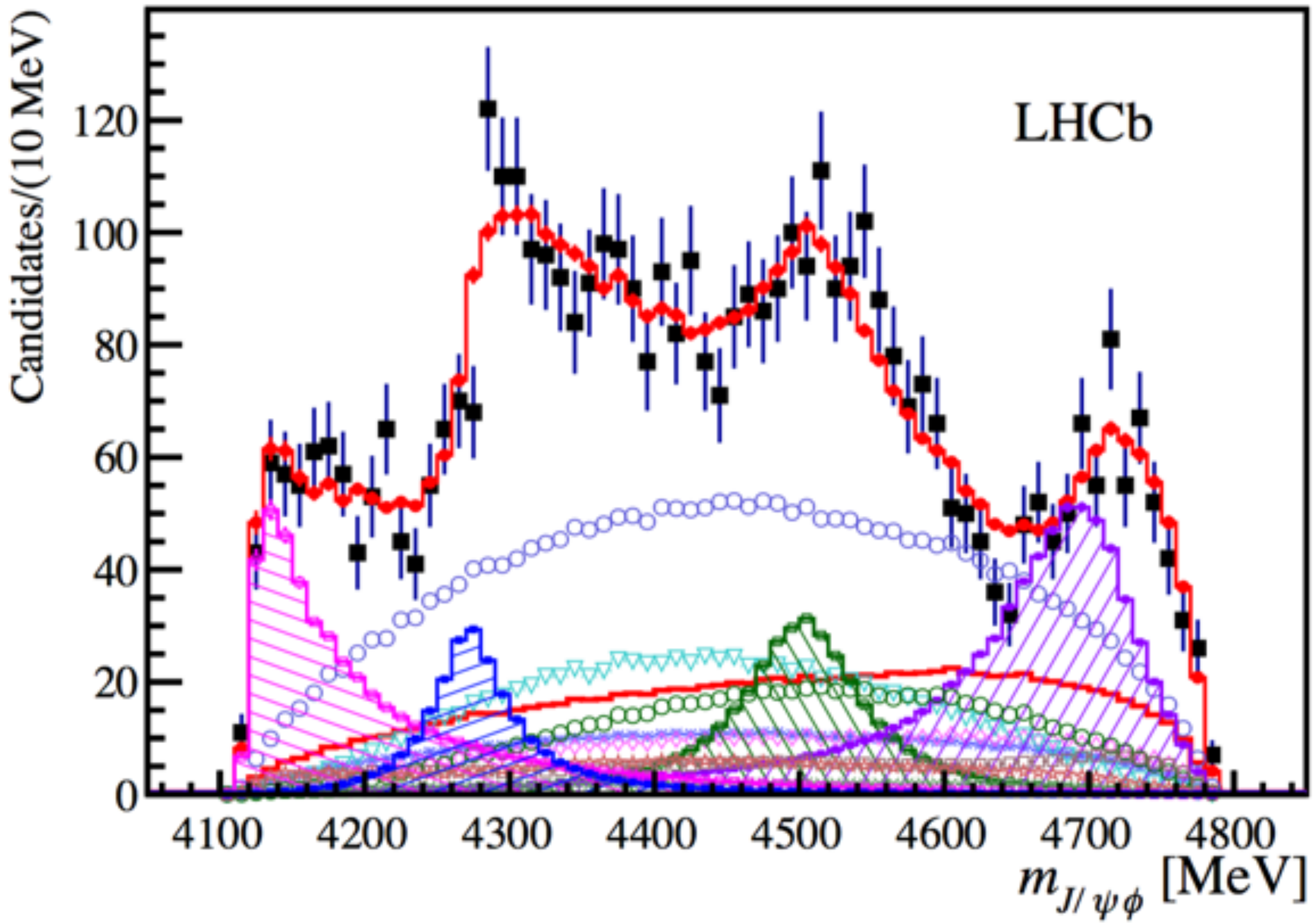
LHCb 4X

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

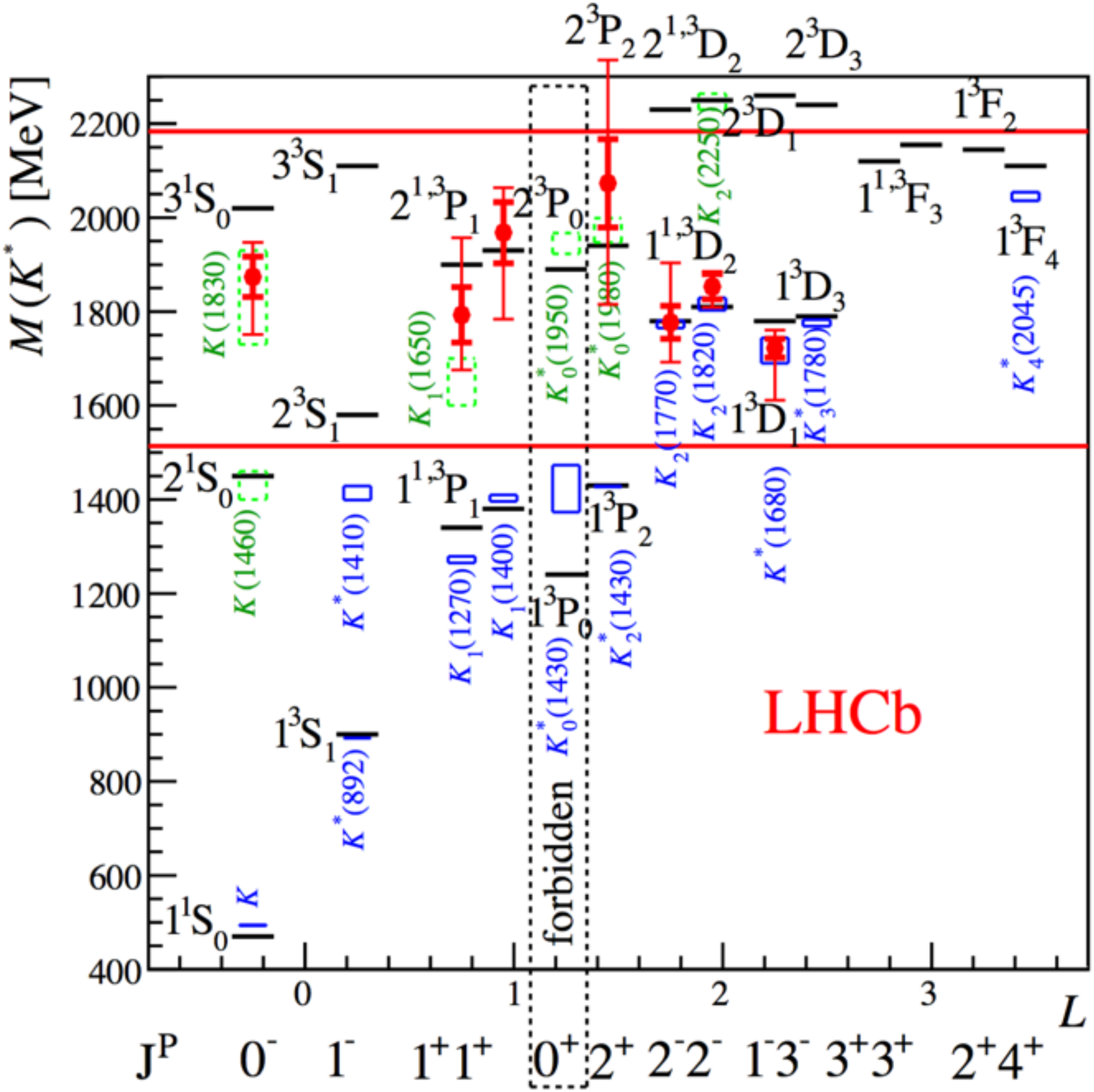
Year	Experiment luminosity	$B \to J/\psi\phi K$ yield	$X(4274-4351)$ peaks(s) Mass [MeV]	Width [MeV]	Sign.	Fraction [%]
2011	*CDF 6.0 fb^{-1}* [28]	*115 ± 12*	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32.3^{+21.9}_{-15.3} \pm 7.6$	3.1σ	
2011	LHCb 0.37 fb^{-1} [21]	346 ± 20	4274.4 fixed	32.3 fixed		< 8 @ 90%CL
2013	CMS 5.2 fb^{-1} [25]	2480 ± 160	$4313.8 \pm 5.3 \pm 7.3$	$38^{+30}_{-15} \pm 16$		
2013	D0 10.4 fb^{-1} [26]	215 ± 37	4328.5 ± 12.0	30 fixed		
2014	BaBar [24]	189 ± 14	4274.4 fixed	32.3 fixed	1.2σ	< 18.1 @ 90%CL
2010	Belle [31]	$\gamma\gamma \to J/\psi\phi$	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$	3.2σ	

arXiv:1606.07895v1

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



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



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

LHCb fit the lowest state with my cusp model:

The value of β_0 obtained by the fit to the data is 297 ± 20 MeV, in agreement with 300 MeV used by Swanson [44]. A fit with this parameterization (3 free parameters: β_0 plus the S-wave complex helicity coupling) has a better likelihood than the BW fit by 1.6σ for the default model (8 parameters in the $X(4140)$ BW parameterization), and better by 3σ when only S-wave couplings are allowed (4 parameters), providing an indication that the $X(4140)$ structure may not be a bound state that can be described by the BW formula.

X(5568)

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

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

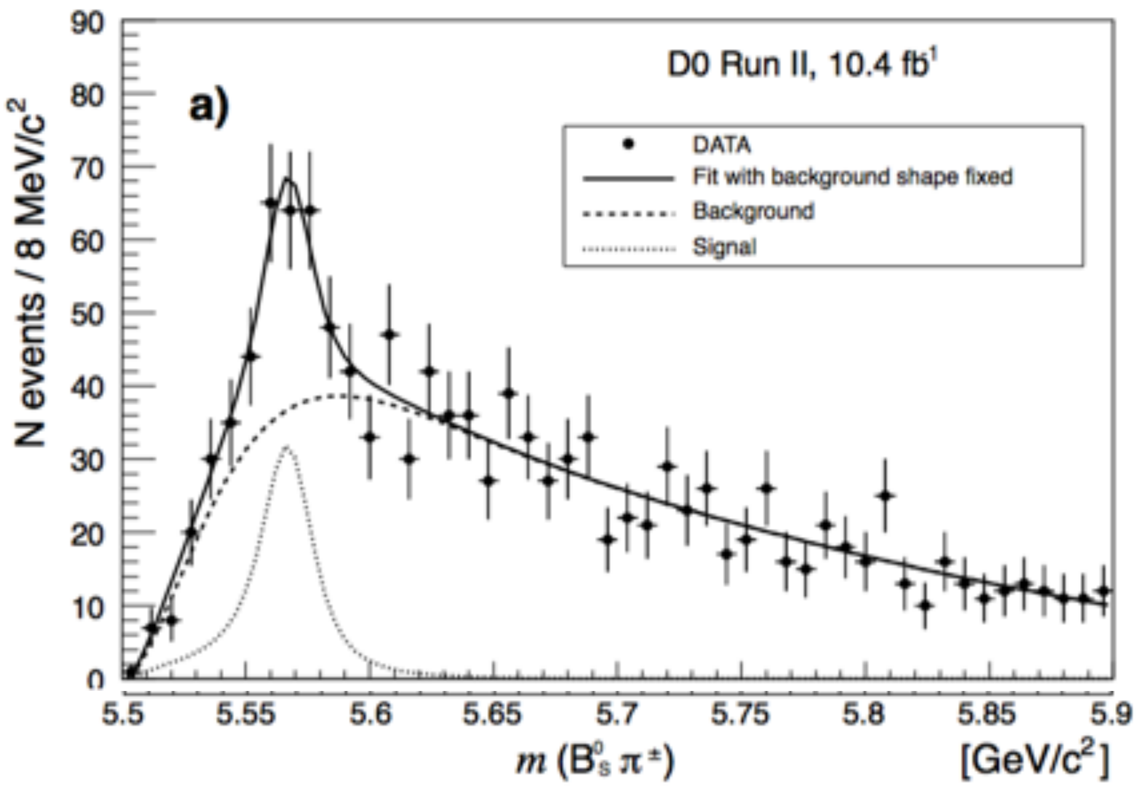
$$m = 5567.8 \pm 2.9^{+0.9}_{-1.9}$$

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

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

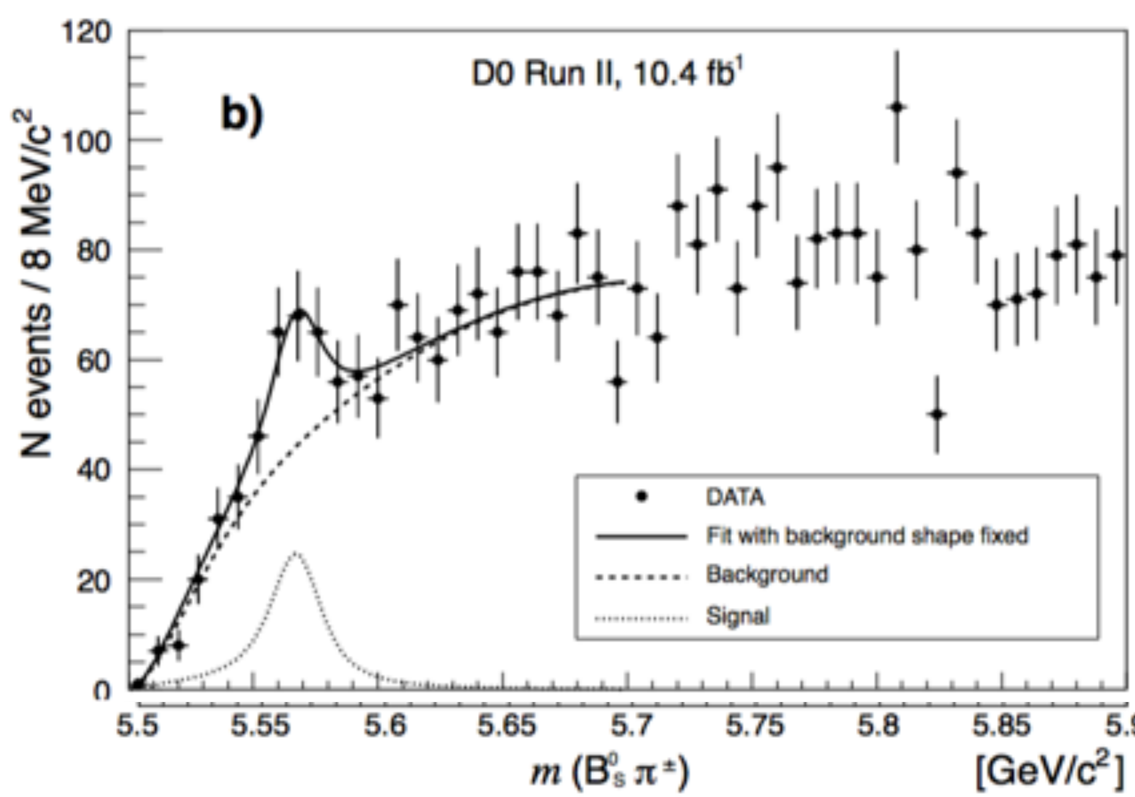
they may have missed a gamma, in which case it goes to Bs*pi, and has a higher mass

$$X(5568 + 48.6) \to B_s^* \gamma \pi^\pm$$



<- with “cone” cut

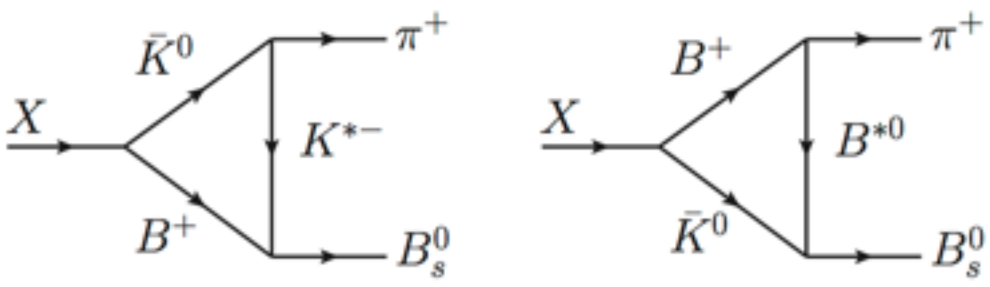
V without cut



ideas:

C.-J. Xiao, D.-Y. Chen, arXiv:1603.00228.

BK molecule (mass = 5777)

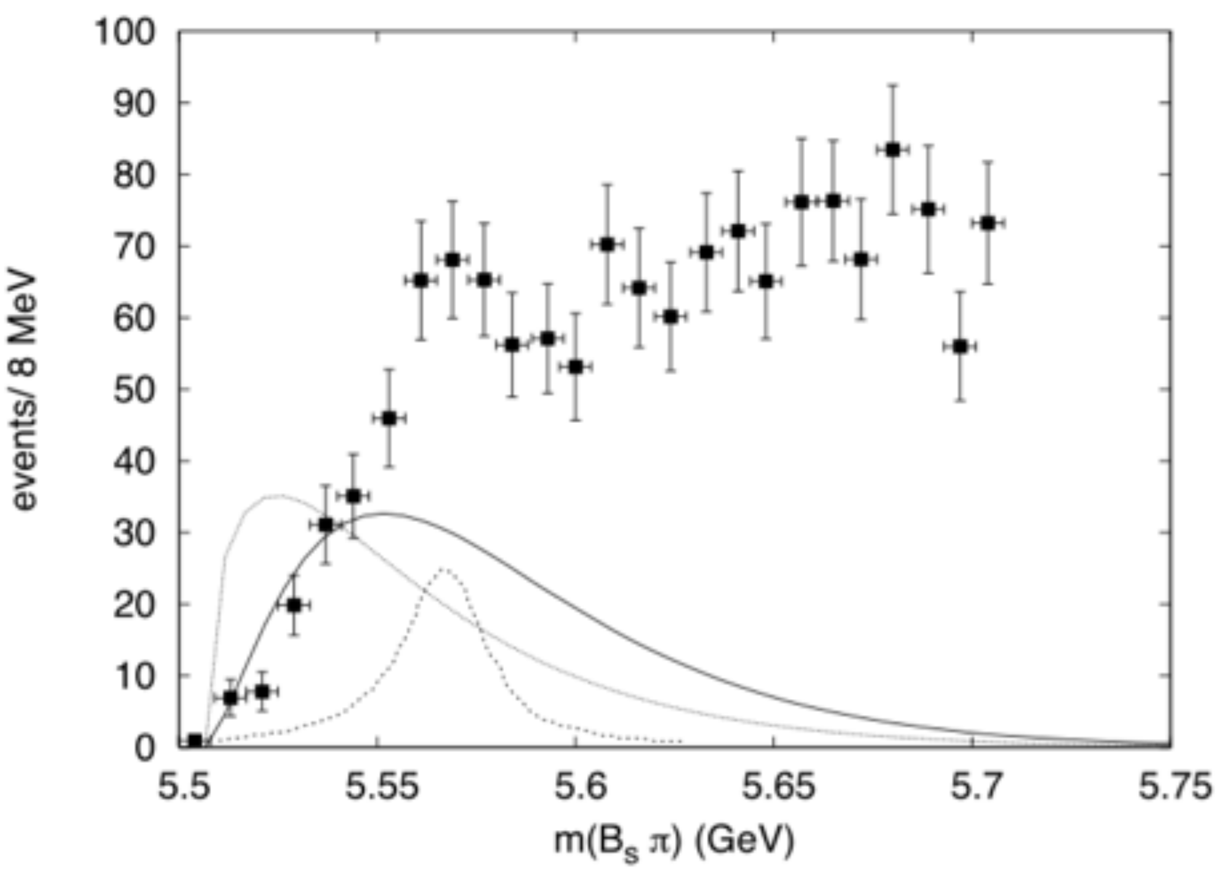


E.E. Kolomeitsev, M.F.M. Lutz, Phys. Lett. B 582 (2004) 39.

exotic flavour in a unitarised chiral model.
but mass 180 MeV greater than observed

T.J. Burns and E.S. Swanson, Phys. Lett. B760, 627 (2016).

check threshold enhancement…



check cusps…

only nearby threshold is $B_s^* \pi$ at 5555 MeV

Can fit data BUT

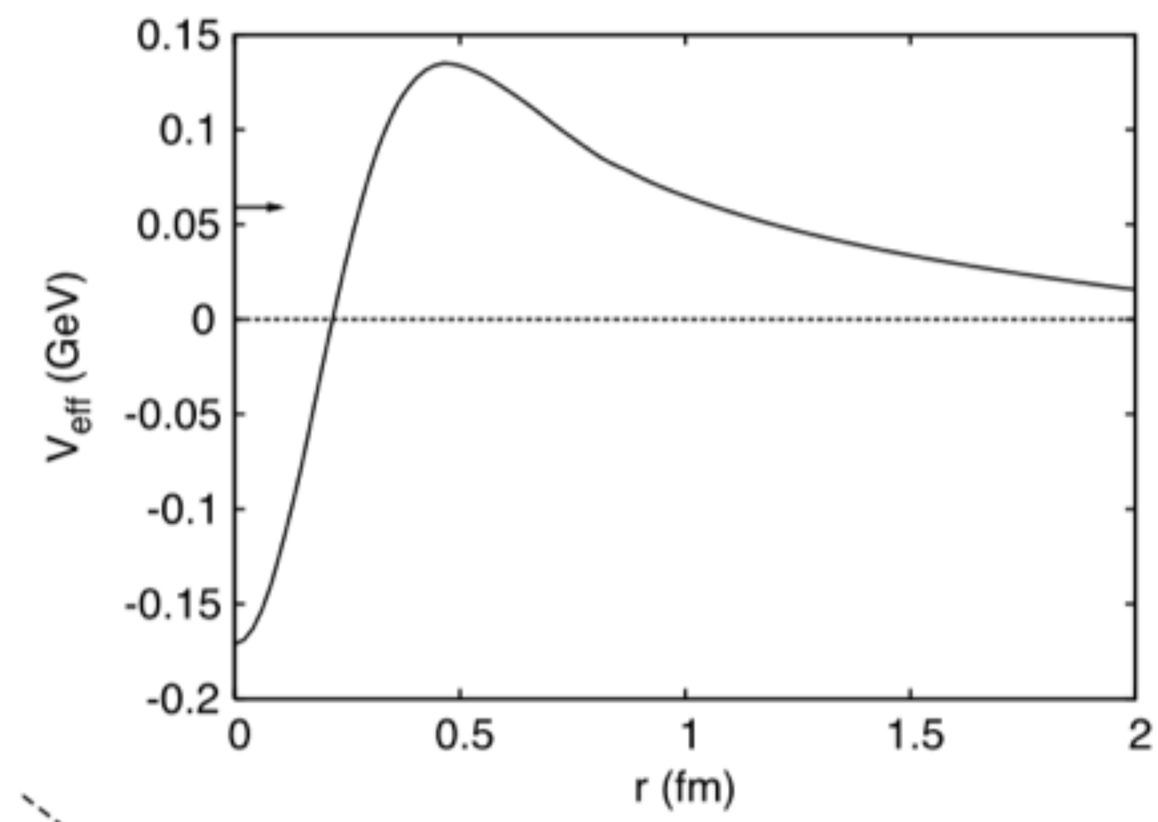
- require P-wave rescattering
- hadronic bubble scale = 50 MeV (typical is 300)
- weird process ($BK \leftrightarrow B_s \pi$ is more natural)
- expect a neutral analogue state

check molecules…

Natural system is $BK \leftrightarrow B_s\pi$

arrow is location of resonance req'd. A good old fashioned Gamov-Gurney-Condon tunneling resonance.

Find attraction, but not enough



tetraquark models…

S.S. Agaev, K. Azizi, H. Sundu, Phys. Rev. D 93 (2016) 074024.
W. Chen, H.-X. Chen, X. Liu, T.G. Steele, S.-L. Zhu, arXiv:1602.08916.
Z.-G. Wang, arXiv:1602.08711.
C.M. Zanetti, M. Nielsen, K.P. Khemchandani, Phys. Rev. D 93 (2016) 096011.

W. Wang, R. Zhu, arXiv:1602.08806.
Y.-R. Liu, X. Liu, S.-L. Zhu, Phys. Rev. D 93 (2016) 074023.
F. Stancu, arXiv:1603.03322.

L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, Phys. Rev. D 89 (2014) 114010.

R.F. Lebed, A.D. Polosa, Phys. Rev. D 93 (2016) 094024.
A. Ali, L. Maiani, A.D. Polosa, V. Riquer, arXiv:1604.01731 [hep-ph].

Tetraquark scenarios

The bsu baryons Ξ_b and Ξ_b^* have masses of 5794 MeV and 5945 MeV.

$$H = \sum_k m_k + \sum_{ij} \alpha_{ij} S_i \cdot S_j$$

Estimate constituent masses with spin averaged B/B* and K/K* masses.

Get $\sum_k m_k = 6146 \text{ MeV}$

So need abnormally light quarks or large spin splittings.

Tetraquark scenarios

Ambiguity: double spectrum by including the other colour combination?

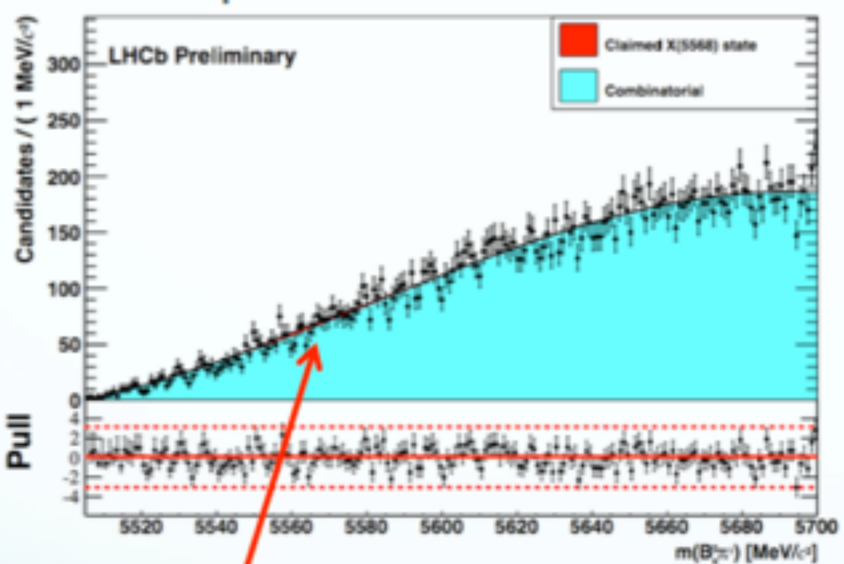
$(qq)_{\bar{3}}\,(\bar{b}\bar{s})_{3}$ $(qq)_{6}\,(\bar{b}\bar{s})_{\bar{6}}$

Spin interactions between quarks or diquarks?

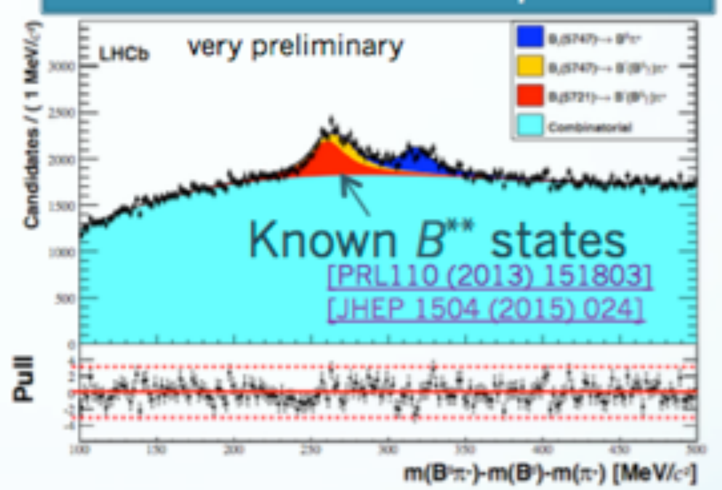
Hot result: new tetraquark from LHCb?

[LHCb-CONF-2016-004]
in preparation

- Add pion:



Cross-check with $B^0\pi$ spectrum



- No peak observed at 5568 MeV. Cannot confirm D0 peak.
  - UL cross section ratio ~1%

$$\rho_X^{\mathrm{LHCb}} \equiv \frac{\sigma(pp \to X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \to B_s^0\pi)}{\sigma(pp \to B_s^0 + \text{anything})}$$

- More details in Moriond QCD

New Pentaquarks

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

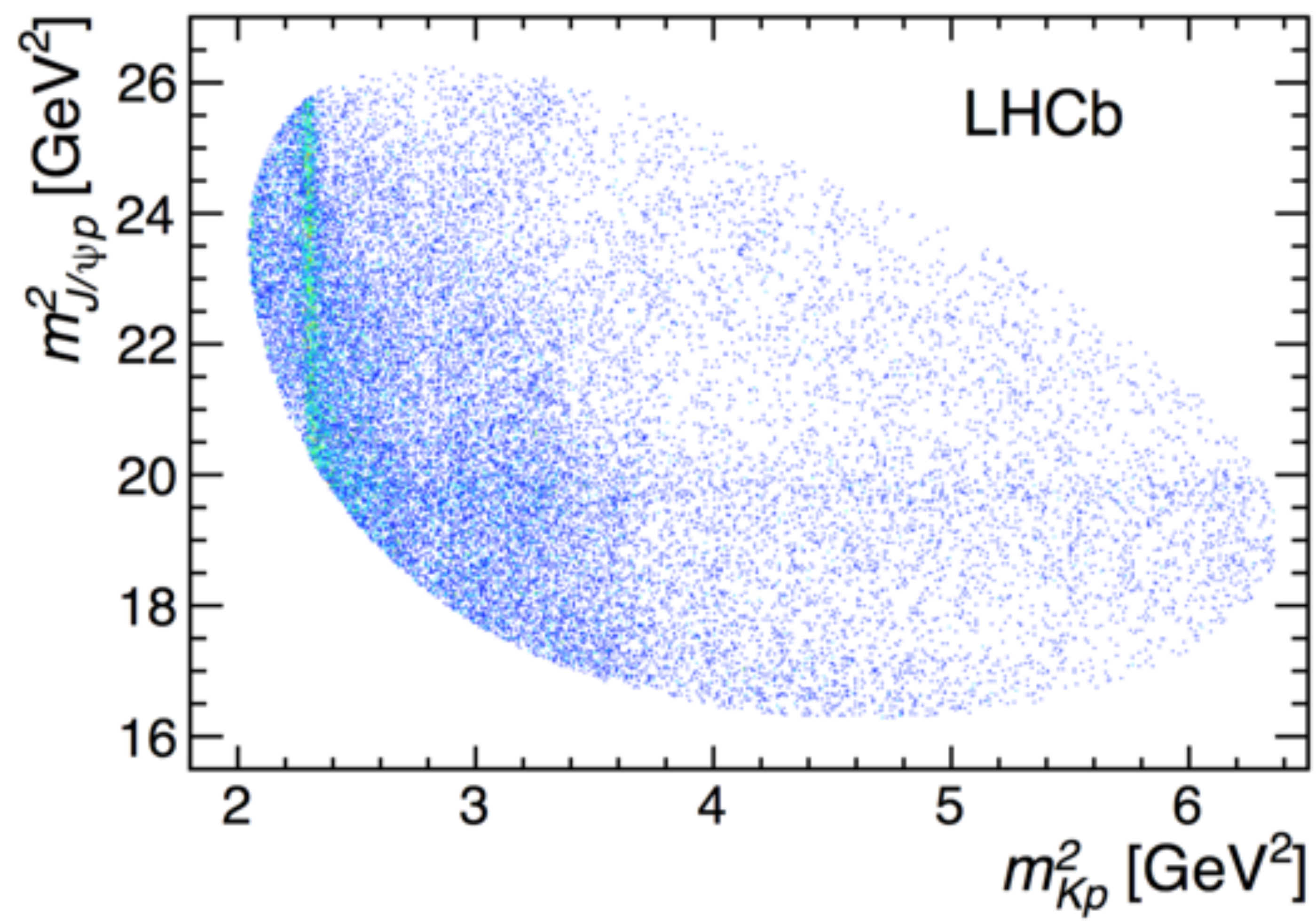
$$\Lambda_b^0 \to J/\psi K^- p$$

$P_c(4450)$ $\Gamma = 39 \pm 5 \pm 19$ MeV
$P_c(4380)$ $\Gamma = 205 \pm 18 \pm 86$ MeV

LHCb 1507.03414v2

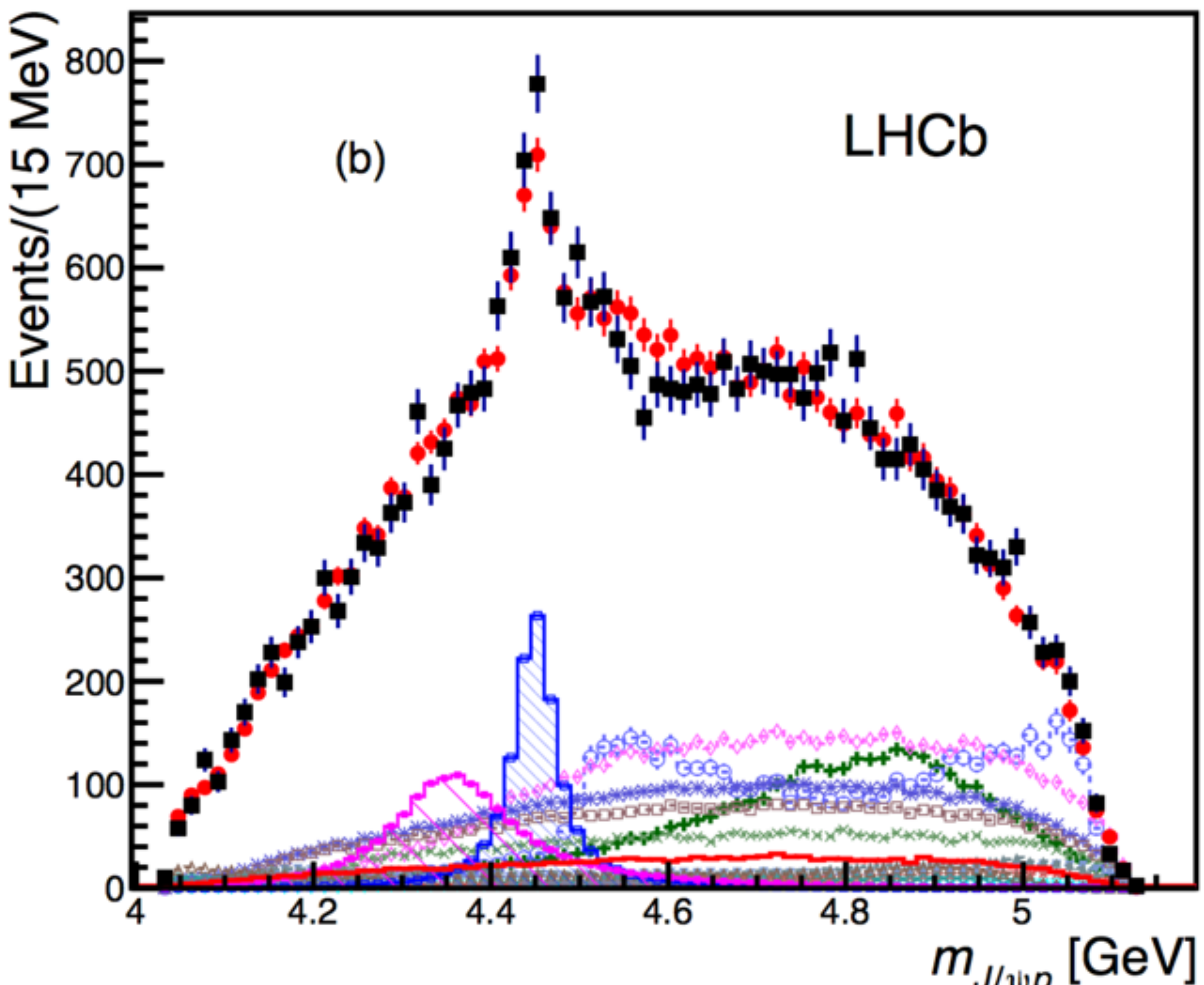
$$J^P = \frac{3}{2}^{\pm}$$

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

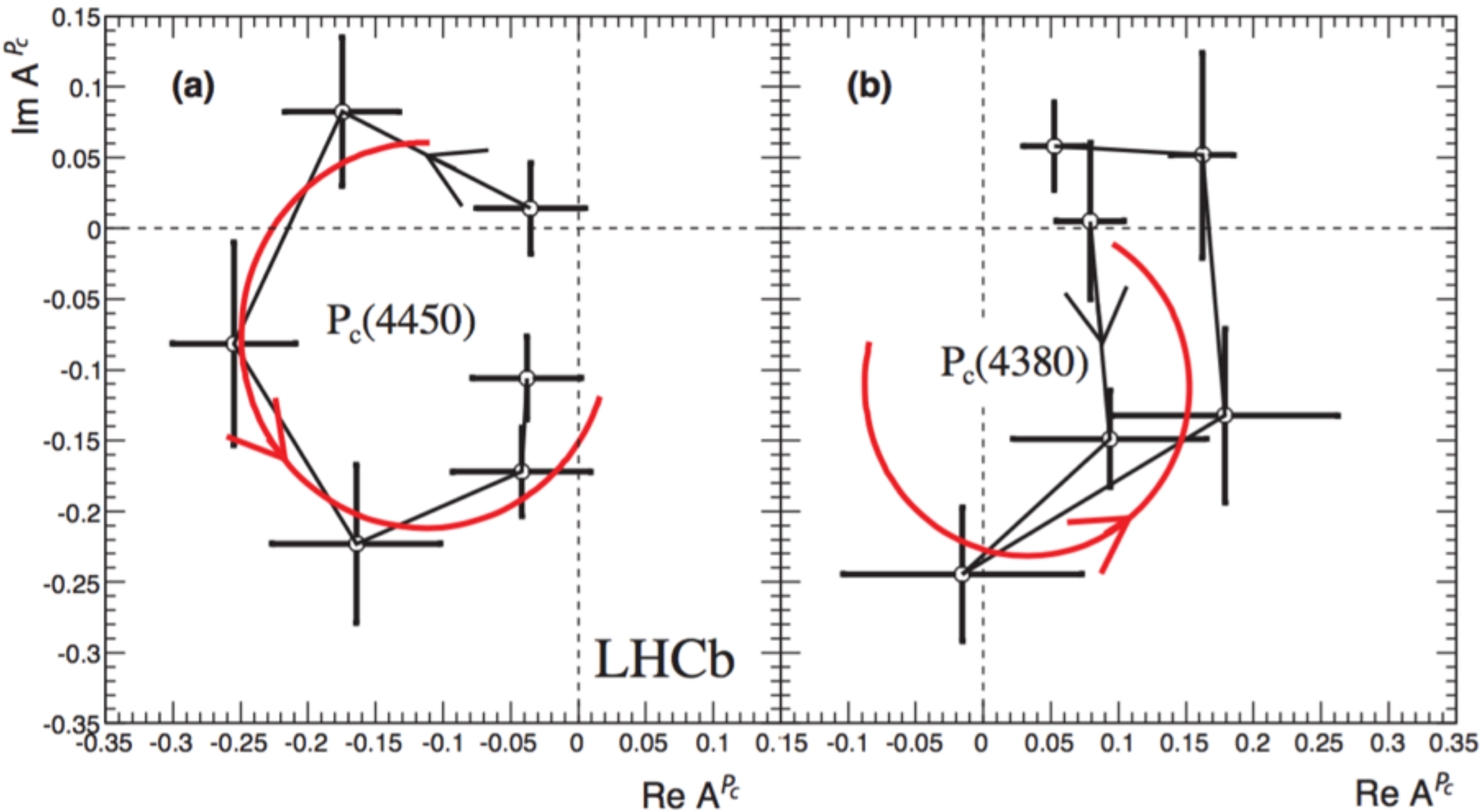


$P_c(4450)$
$P_c(4380)$

blue = 4450
purple = 4380



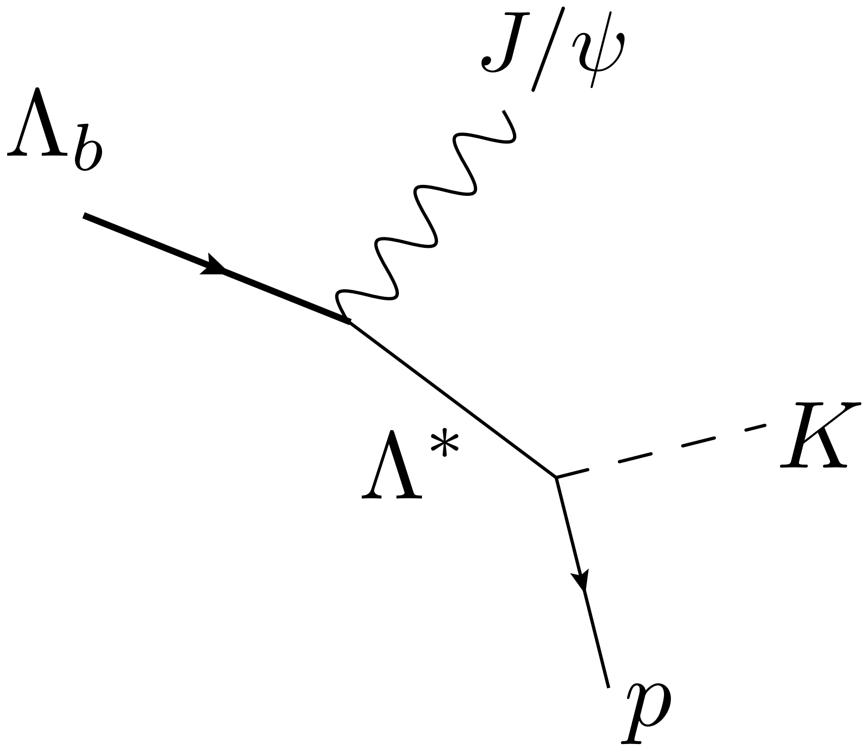
$P_c(4450)$
$P_c(4380)$

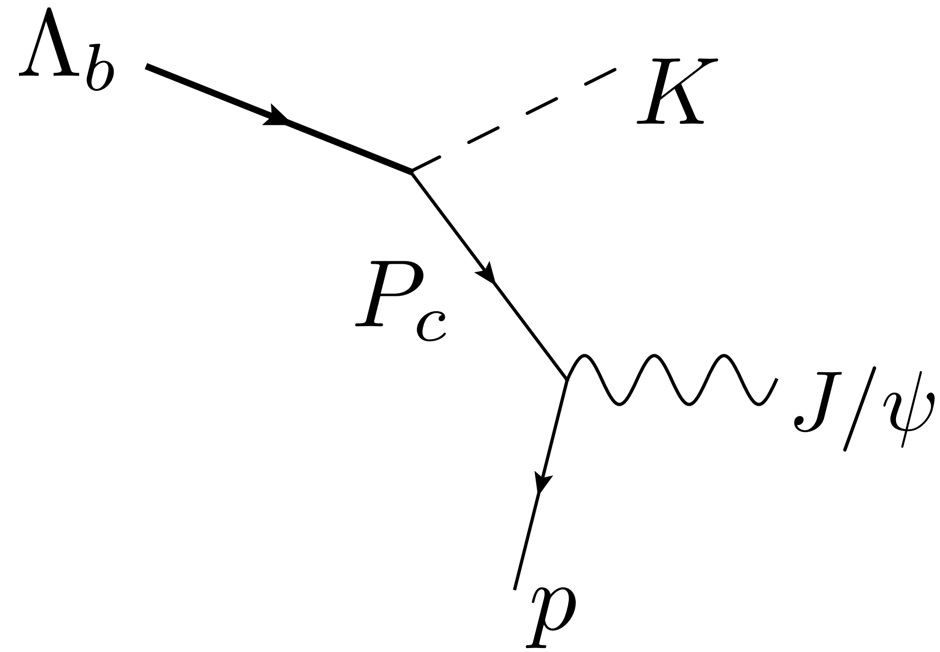


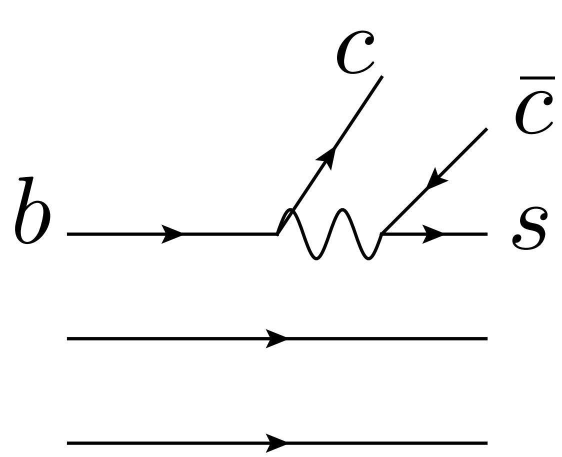
T.J. Burns & E.S. Swanson, in progress

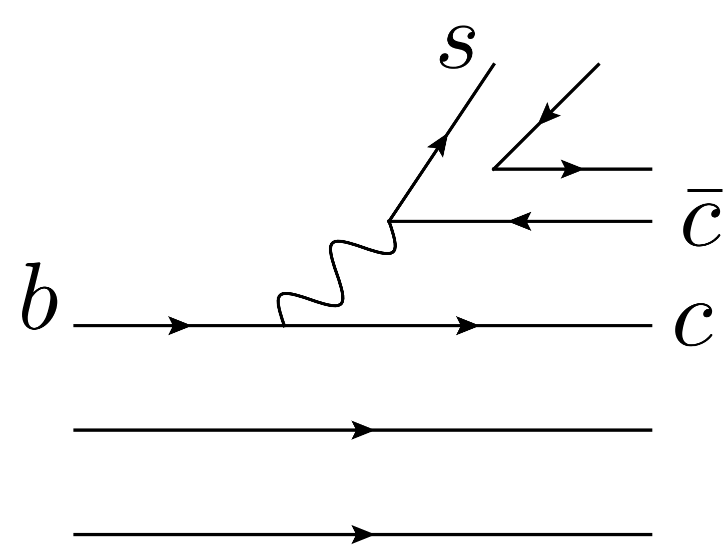
		$P_c(4380)^+$	$P_c(4450)^+$
Mass		$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width		$205 \pm 18 \pm 86$	$35 \pm 5 \pm 19$
Assignment 1		$3/2^-$	$5/2^+$
Assignment 2		$3/2^+$	$5/2^-$
Assignment 3		$5/2^+$	$3/2^-$
Assignment 4		$5/2^-$	$3/2^+$
$\Sigma_c^{*+}\bar{D}^0$	$(udc)(u\bar{c})$	4382.3 ± 2.4	
$\Sigma_c^{+}\bar{D}^{*0}$	$(udc)(u\bar{c})$		4459.9 ± 0.5
$\Lambda_c^{+}(1P)\bar{D}^0$	$(udc)(u\bar{c})$		4457.09 ± 0.35
$\chi_{c1}p$	$(udu)(c\bar{c})$		4448.93 ± 0.07

Production Mechanisms (tree)

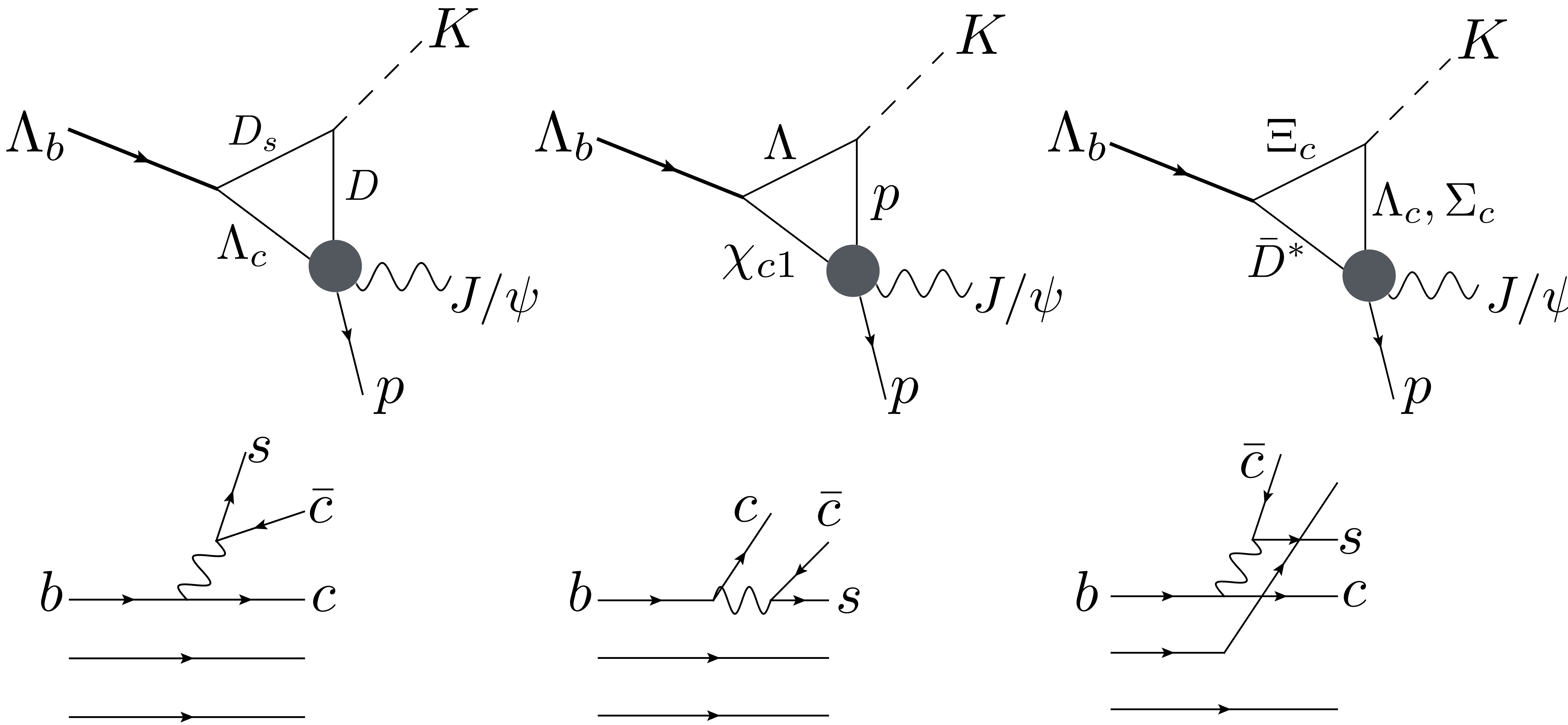








Production Mechanisms (loop)



1/N 1/N

A huge number of possible cusp thresholds!

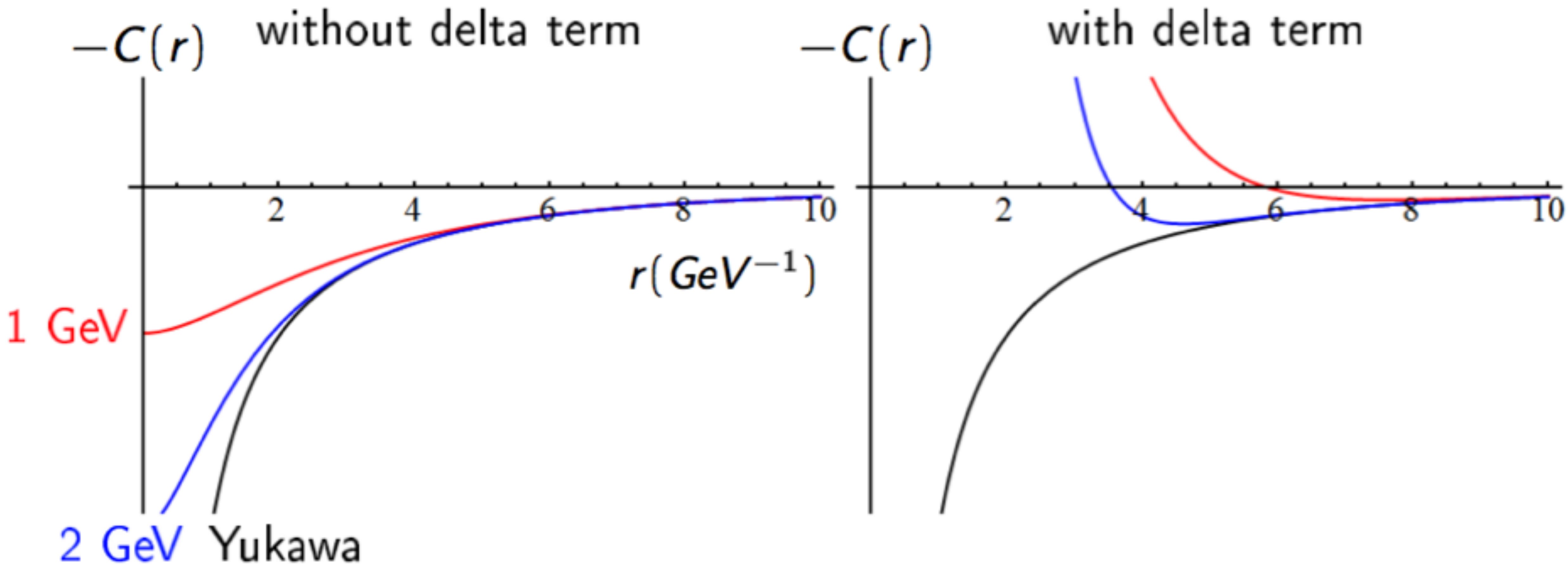
And still need to account for the final state interactions!

Q: can the final state interactions select/enhance an intermediate state?

For point-like constituents:

$$C(r) = \frac{g^2 m^3}{12\pi f_\pi^2}\left(\frac{e^{-mr}}{mr} - \frac{4\pi}{m^3}\delta^3(\vec{r})\right)$$

For extended hadrons, use dipole form factors with cutoff Λ. The limit $\Lambda \to \infty$ recovers the point-like case.



diagonal only

Potential without the delta term.
(Deuteron binding requires $\Lambda = 0.8$ GeV.)

	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\frac{1}{2}\left(\frac{1}{2}^-\right)$	✓	✓	✓		$+16/3$	$+20/3$
$\frac{1}{2}\left(\frac{3}{2}^-\right)$		✓		✓	$-8/3$	$+8/3$
$\frac{1}{2}\left(\frac{5}{2}^-\right)$						-4
$\frac{3}{2}\left(\frac{1}{2}^-\right)$			✓		$-8/3$	$-10/3$
$\frac{3}{2}\left(\frac{3}{2}^-\right)$				✓	$+4/3$	$-4/3$
$\frac{3}{2}\left(\frac{5}{2}^-\right)$						$+2$

$\Sigma_c^* \bar{D}^*$ $1/2(5/2^-)$

$$\Sigma_c^{*+} \bar{D}^{*0} = 4524.4 \pm 2.4$$
$$\Sigma_c^{*++} D^{*-} = 4528.2 \pm 0.7$$

Mixed isopsin:
$|P\rangle = \cos\phi|\frac{1}{2}, \frac{1}{2}\rangle + \sin\phi|\frac{3}{2}, \frac{1}{2}\rangle$

Decays:
$\rightarrow J/\psi p$: D-wave, spin flip
Reason for absence at LHCb?

$\rightarrow J/\psi \Delta$: S-wave, spin cons.
$\Longrightarrow$ $I = 3/2$ decay enhanced.

$\Xi_c^* \bar{D}^*$ $0(5/2^-)$

$$\Xi_c^{*0} \bar{D}^{*0} = 4652.9 \pm 0.6$$
$$\Xi_c^{*+} D^{*-} = 4656.2 \pm 0.7$$

Mixed isopsin:
$|P\rangle = \cos\phi|0, 0\rangle + \sin\phi|1, 0\rangle$

Decays:
$\rightarrow J/\psi \Lambda$: D-wave, spin flip
e.g. $\Lambda_b^0 \rightarrow J/\psi \Lambda \eta$, $J/\psi \Lambda \phi$

$\rightarrow J/\psi \Sigma^*$: S-wave, spin cons.
$\Longrightarrow$ $I = 1$ decay enhanced.

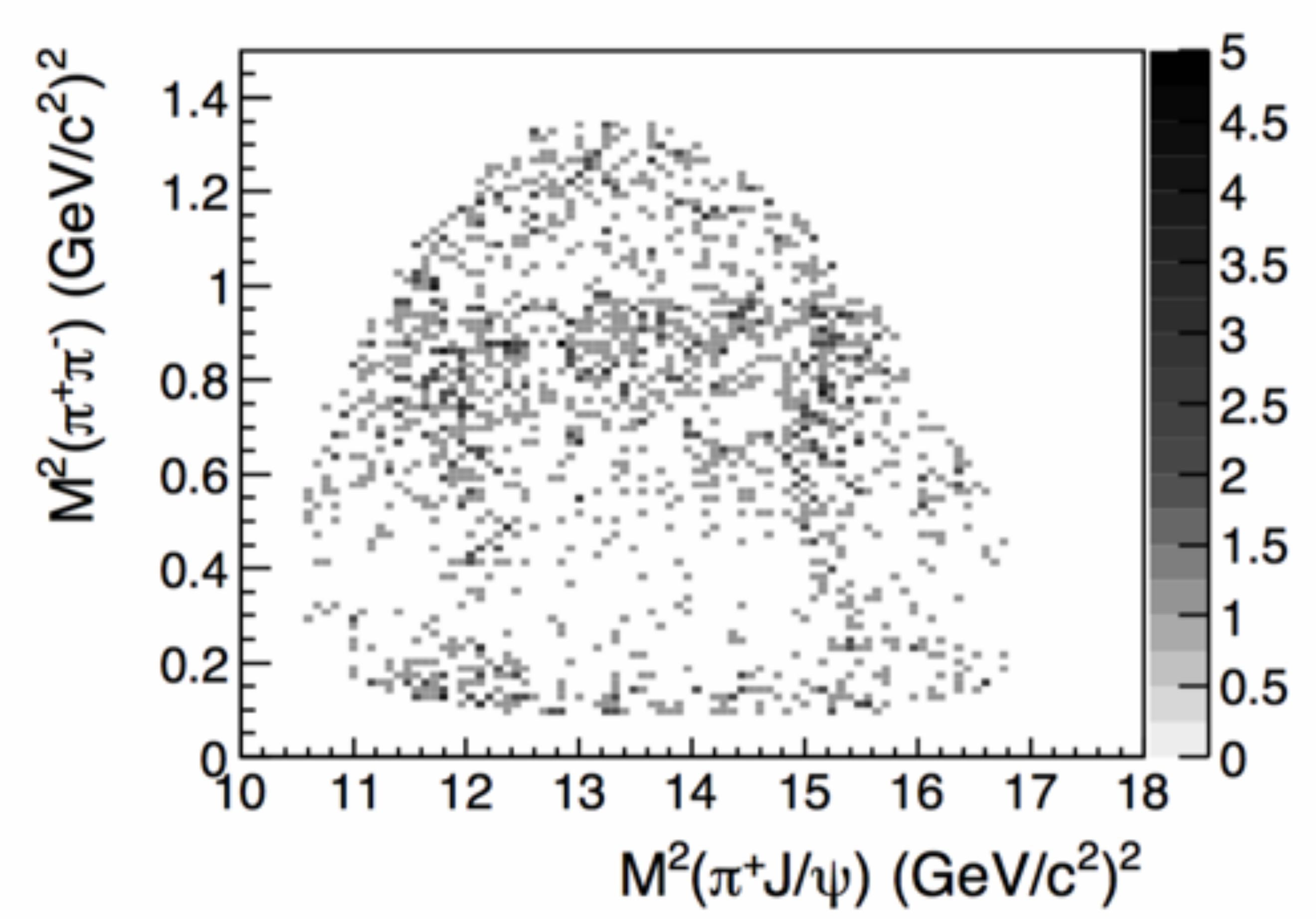
Observations

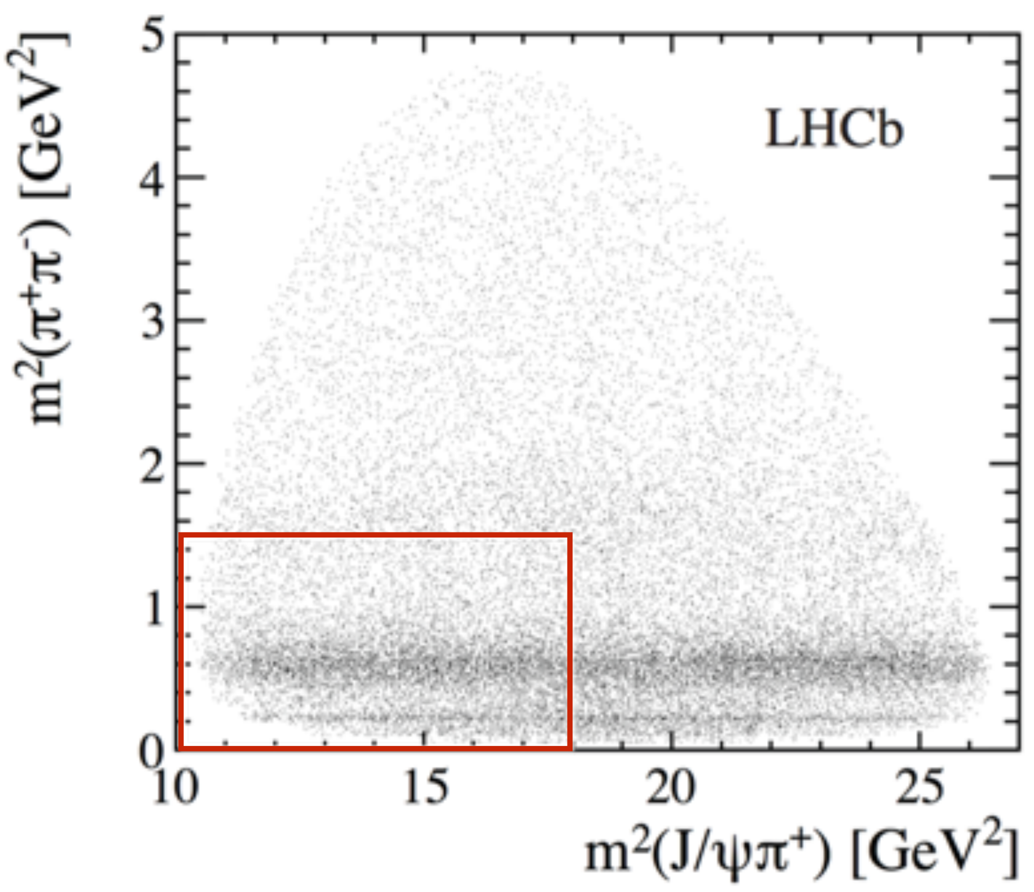
Why do ee and b decay production modes differ?

goes in PV mode in P-wave (pi Zc)_P

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

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



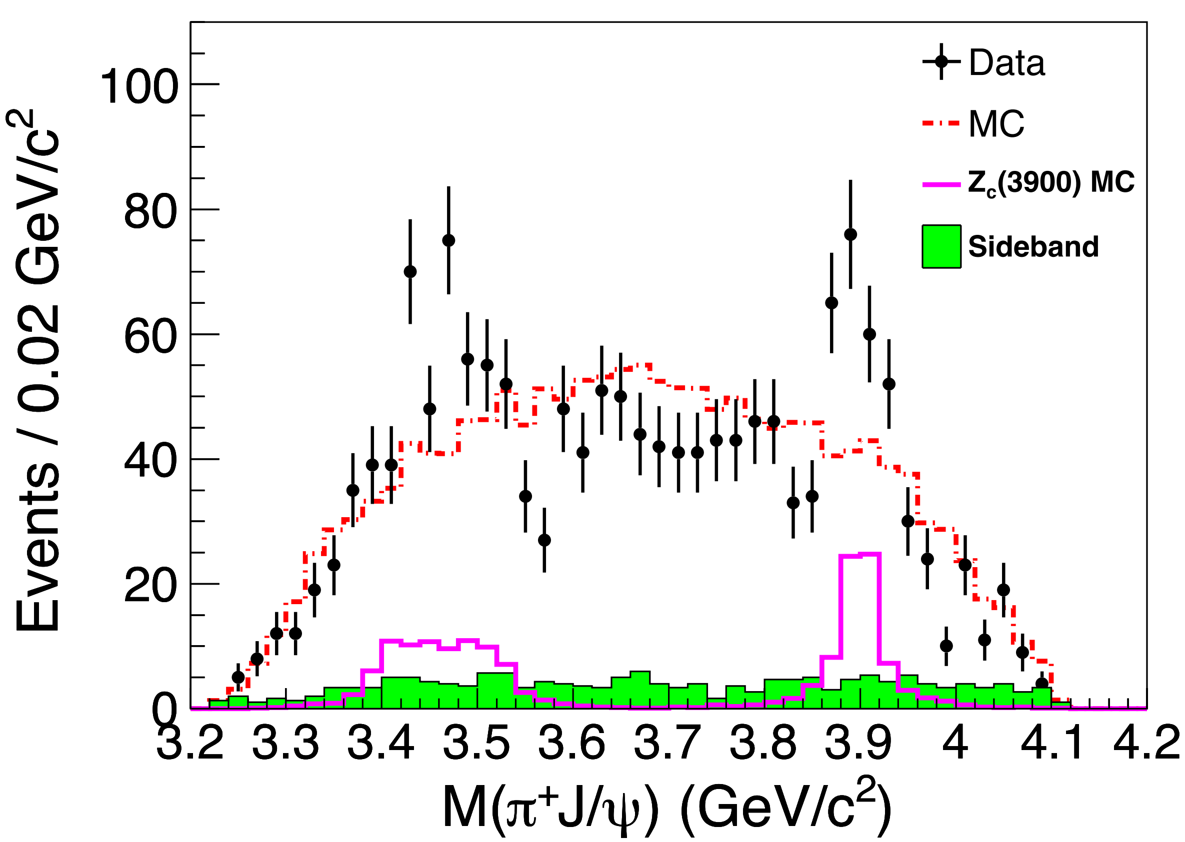


Why do ee and b decay production modes differ?

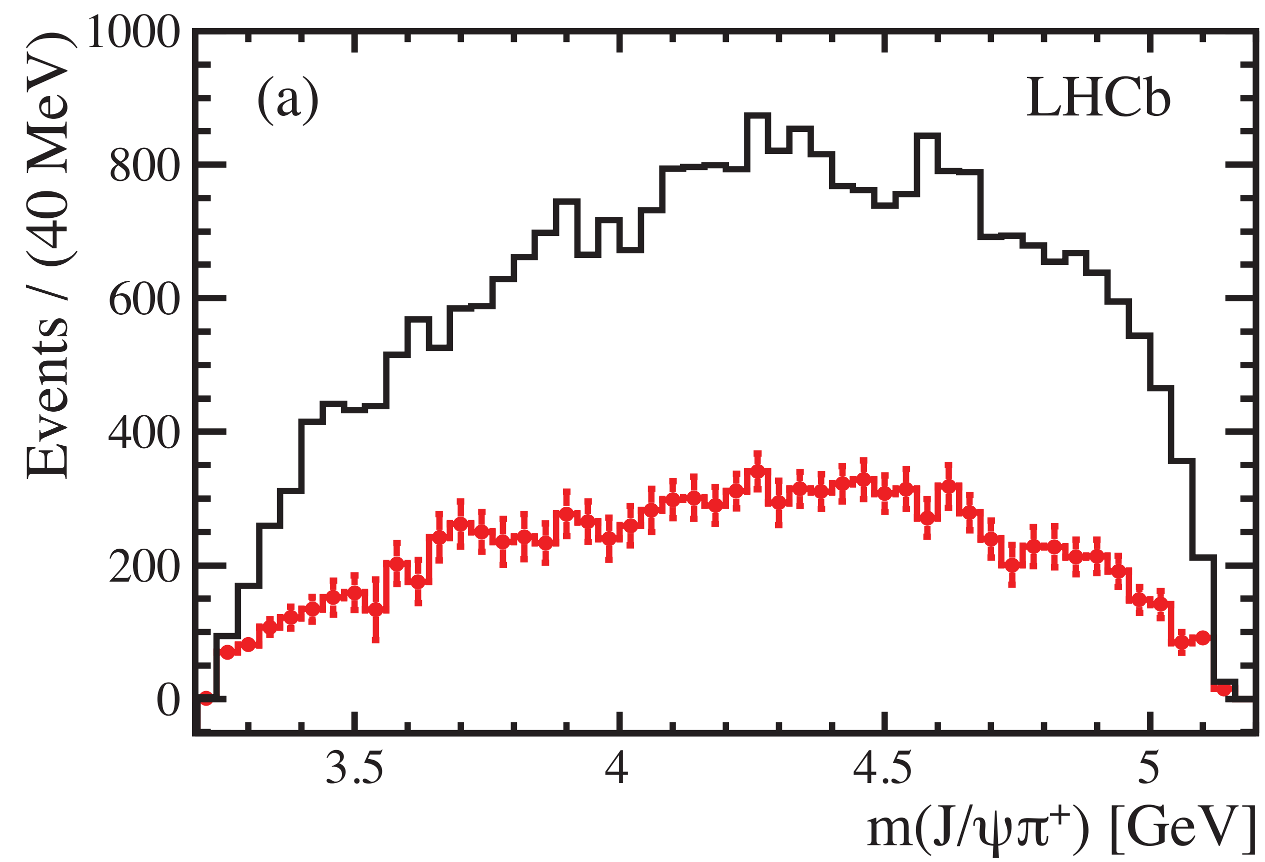
B : pi Zc goes in PV P-wave:

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

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



BESIII



LHCb

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

Why does "radial filtering" happen?

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

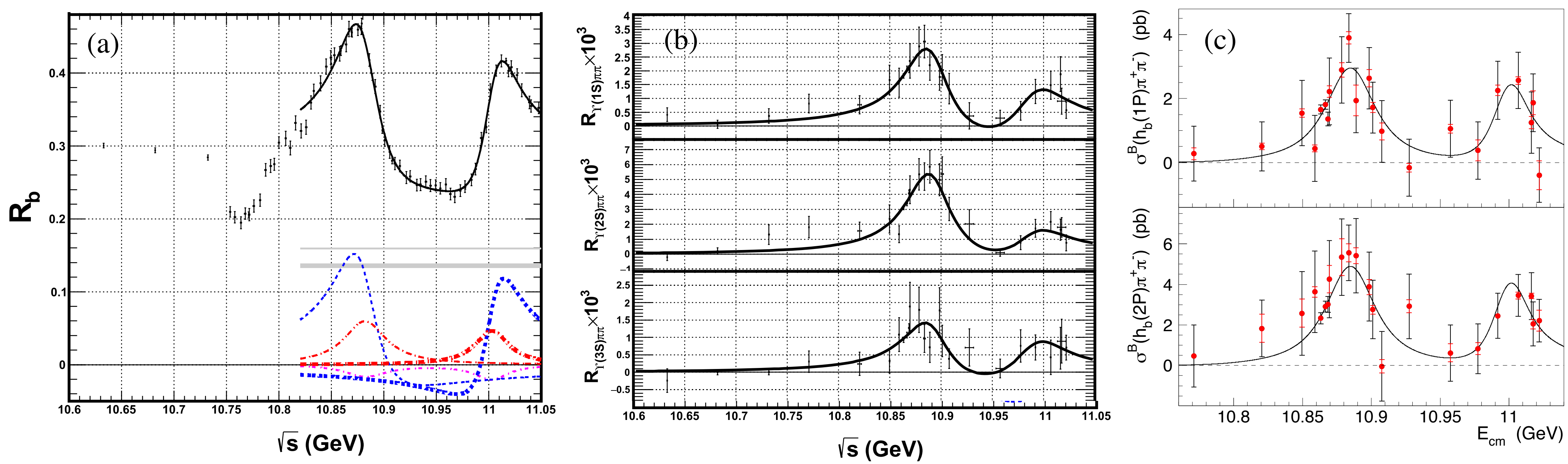
$$e^+e^- \rightarrow Y(4260) \rightarrow \pi^+\pi^- J/\psi$$

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

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

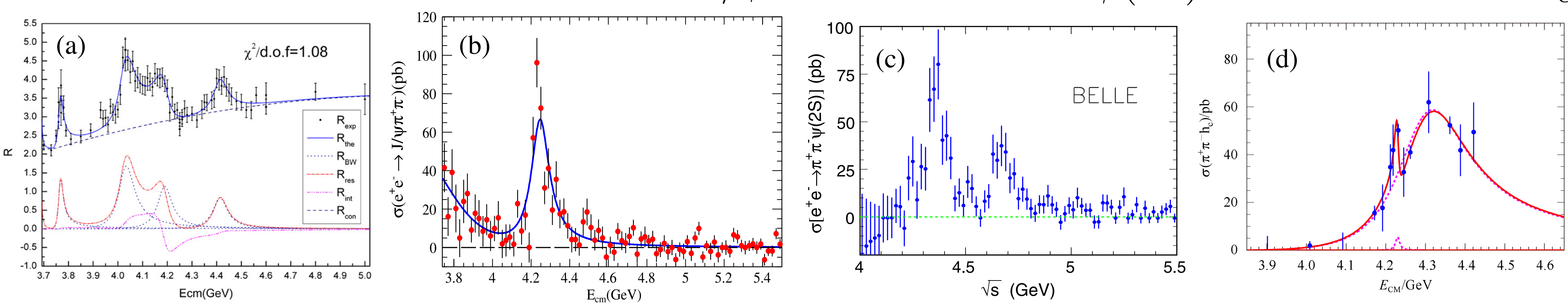
$$B \rightarrow K Z_c(4200); Z_c(4200) \rightarrow \pi^\pm J/\psi$$

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



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

R_c $\quad e^+e^- \to \pi^+\pi^- J/\psi$ $\quad e^+e^- \to \pi^+\pi^-\psi(2S)$ $\quad e^+e^- \to \pi^+\pi^- h_c$



Conclusions

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

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

Conclusions

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

Conclusions

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

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