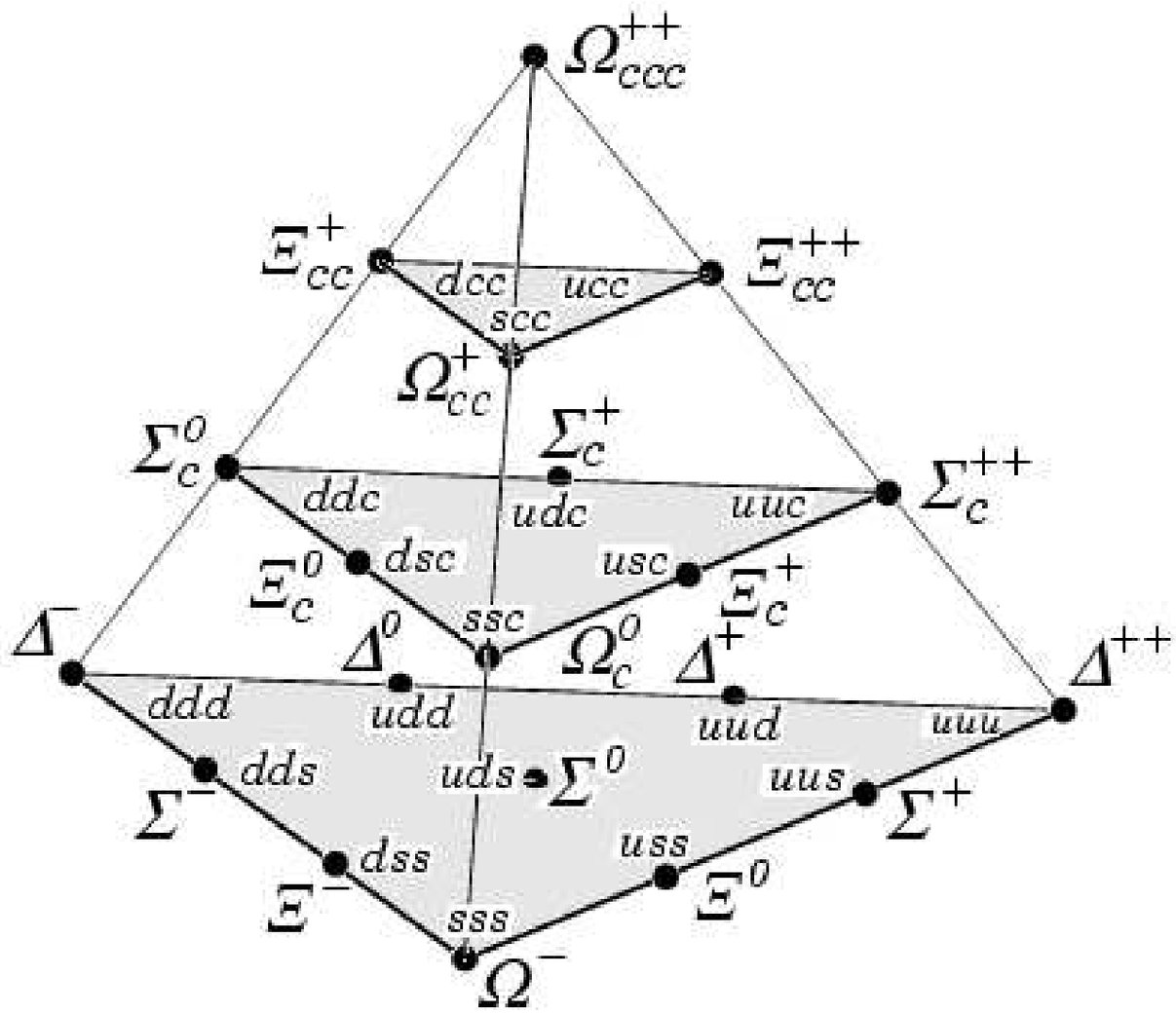
Exotic Hadrons

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

Overview

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}'
$Y(4008)$
$Z_1(4050)$
$Y(4140)$
$X(4160)$

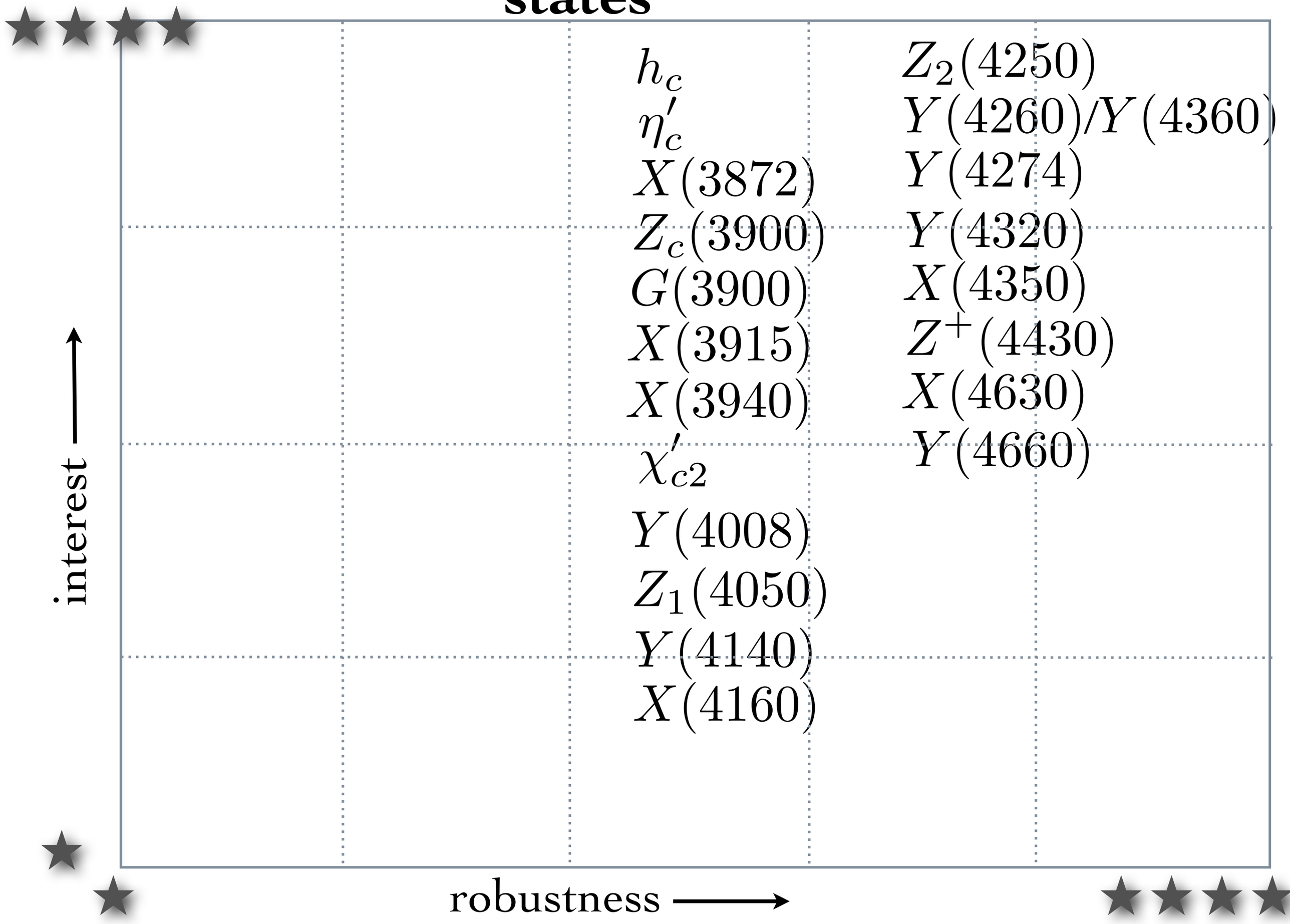
$Z_2(4250)$
$Y(4260)/Y(4360)$
$Y(4274)$
$Y(4320)$
$X(4350)$
$Z^+(4430)$
$X(4630)$
$Y(4660)$

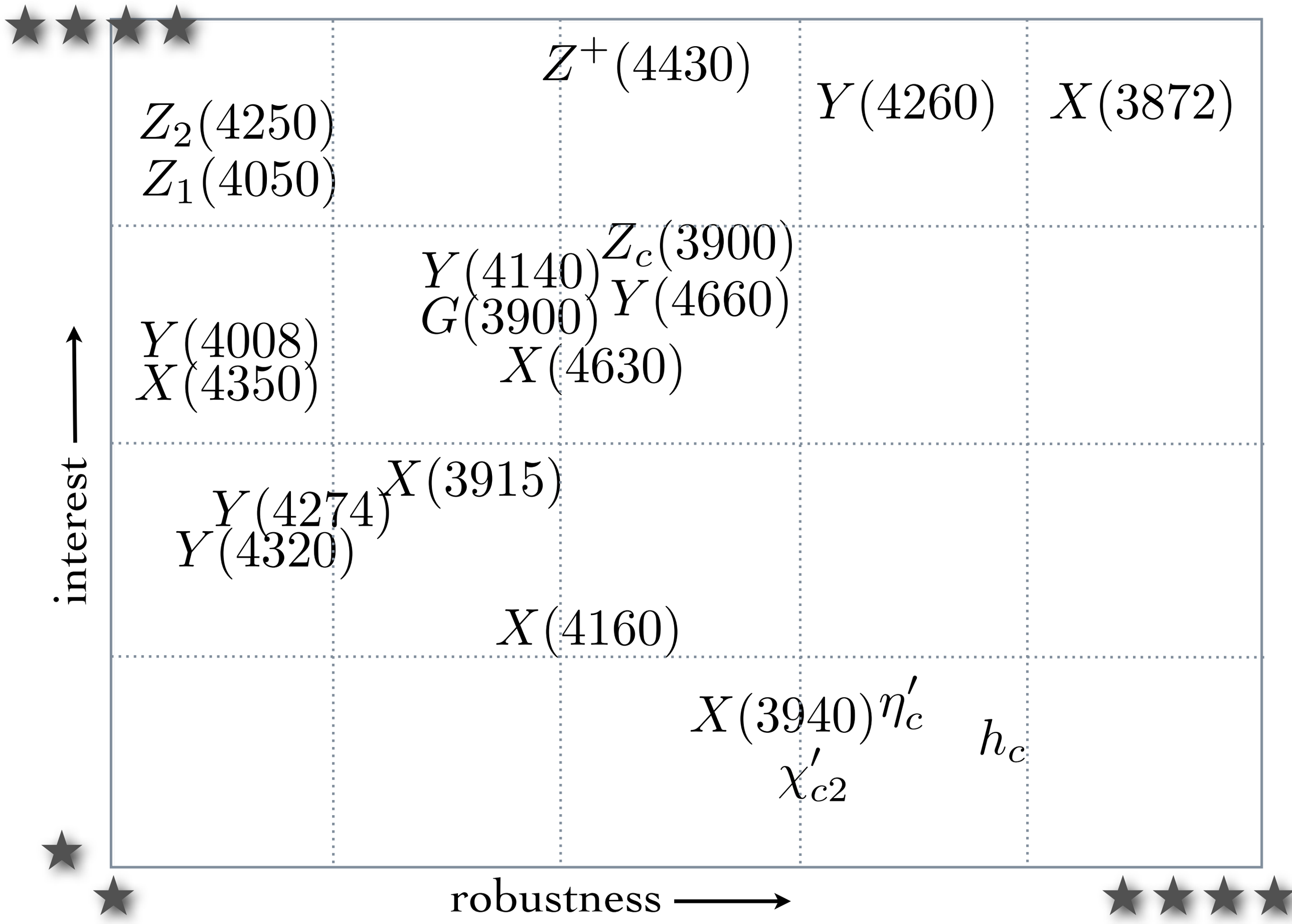
η_b
$\chi_{bJ}(3P)$
$Z_b^+(10610)$
$Z_b^+(10650)$
$Y_b(10888)$

states

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

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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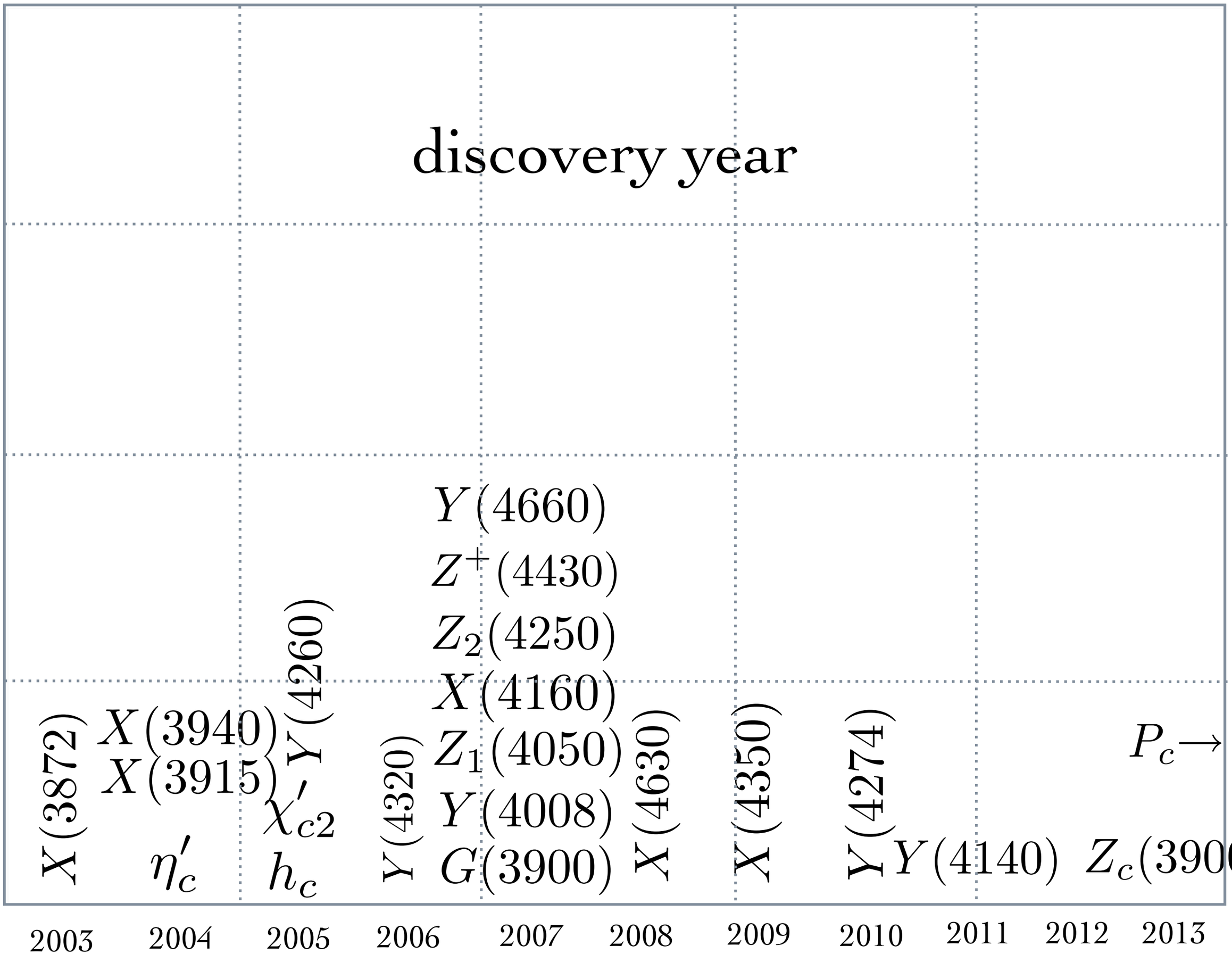
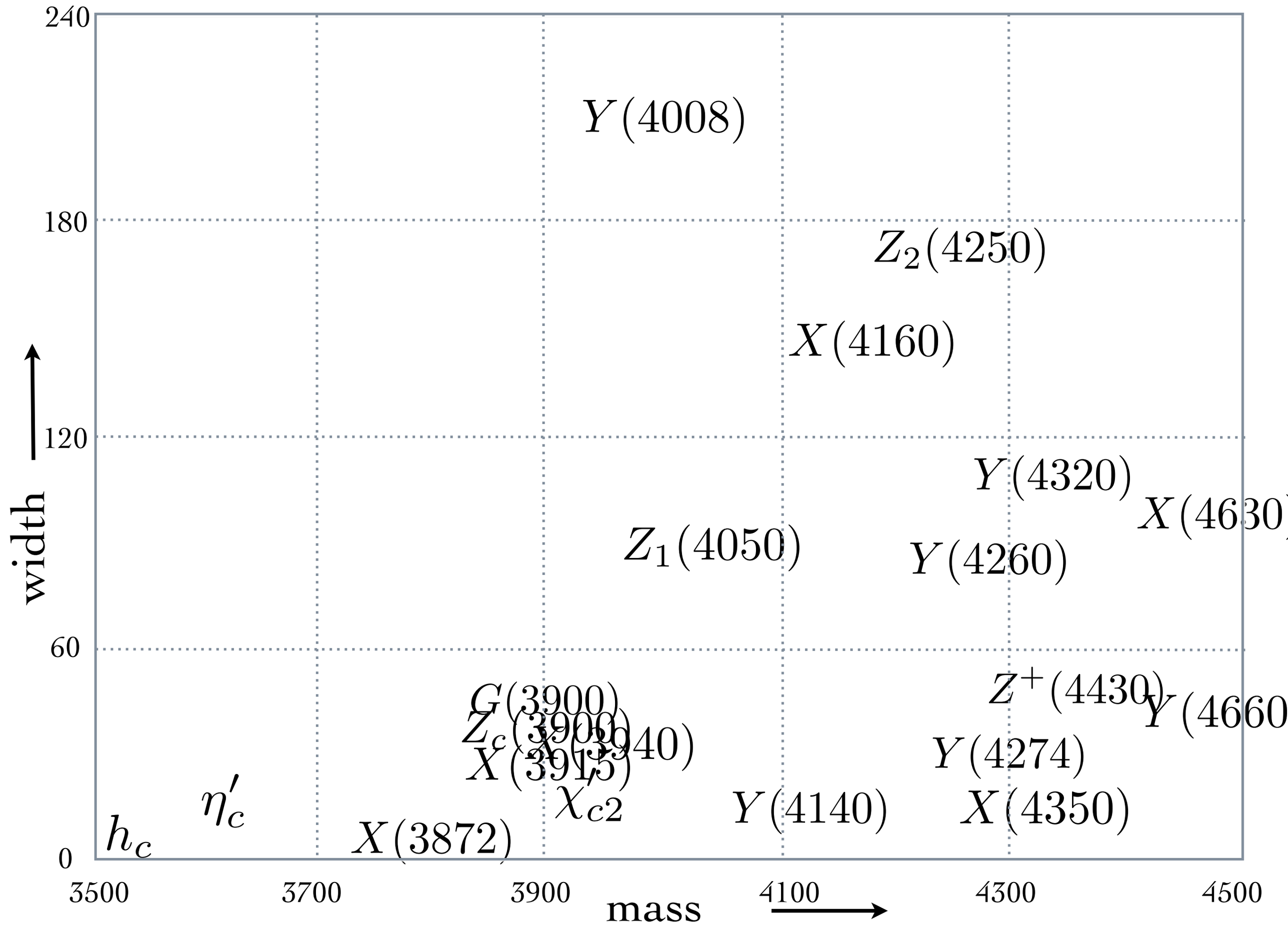
$X(3915)$
$Y(4274)$
$Y(4320)$
$X(4160)$
$X(3940)$
η_c'
h_c
χ_{c2}'
interest
robustness


discovery year
$Y(4660)$
$Z^+(4430)$
$Z_2(4250)$
$X(4160)$
$Z_1(4050)$
$Y(4008)$
$G(3900)$
$X(3872)$
$X(3940)$
$X(3915)$
η_c'
$Y(4260)$
χ_{c2}'
h_c
$Y(4320)$
$X(4630)$
$X(4350)$
$Y(4274)$
$Y(4140)$
$P_c \rightarrow$
$Z_c(3900)$
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013

discovery experiment

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

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

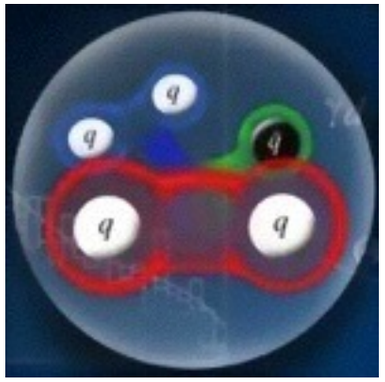

240
180
120
60
0
width
3500
3700
3900
4100
4300
4500
mass
$Y(4008)$
$Z_2(4250)$
$X(4160)$
$Y(4320)$
$X(4630)$
$Z_1(4050)$
$Y(4260)$
$Z^+(4430)$
$Y(4660)$
$G(3900)$
$Z_c(3900)$
$X(3940)$
$X(3915)$
$Y(4274)$
χ_{c2}
$Y(4140)$
$X(4350)$
η_c'
h_c
$X(3872)$

production mode

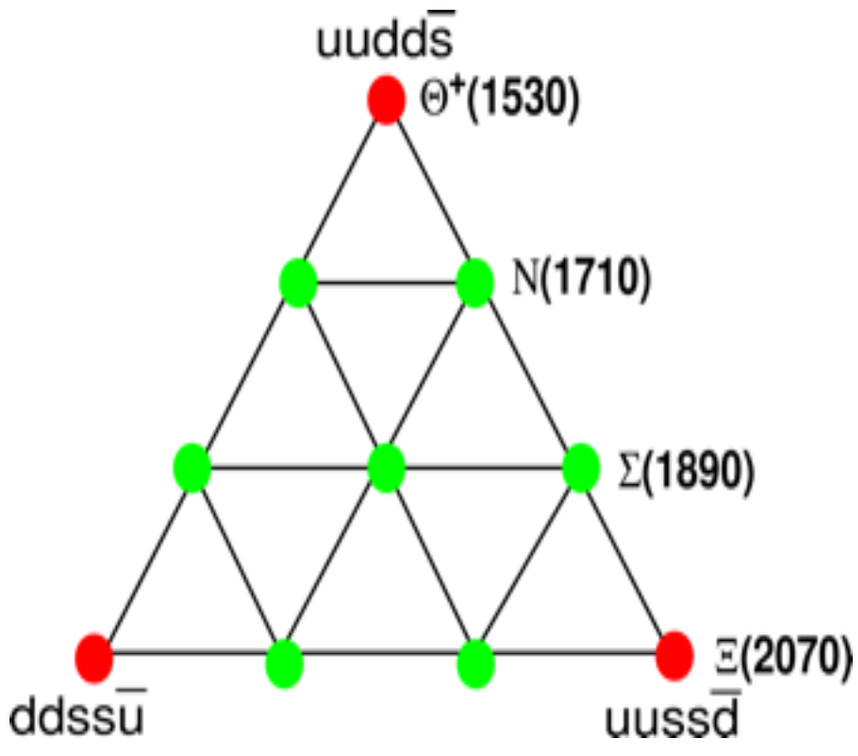
$Z^+(4430)$			h_c
η_c'			$\psi' \to KX$
$Y(4274)$	$Y(4660)$		$X \to \gamma\eta_c$
$Z_2(4250)$	$X(4630)$		
$Y(4140)$	$Y(4320)$		
$Z_1(4050)$	$Y(4260)$		$Z_c(3900)$
$X(3915)$	$Y(4008)$	χ_{c2}'	$X(4160)$
$X(3872)$	$G(3900)$	$X(4350)$	$X(3940)$
$B \to KX$	$e^+e^- \to \gamma X$	$e^+e^- \to e^+e^- X$	$e^+e^-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

Novel States

$\Theta^+(1530)$



1997: Diakonov, Petrov, Polyakov suggest that an exotic baryon decuplet exists based on a chiral soliton model.



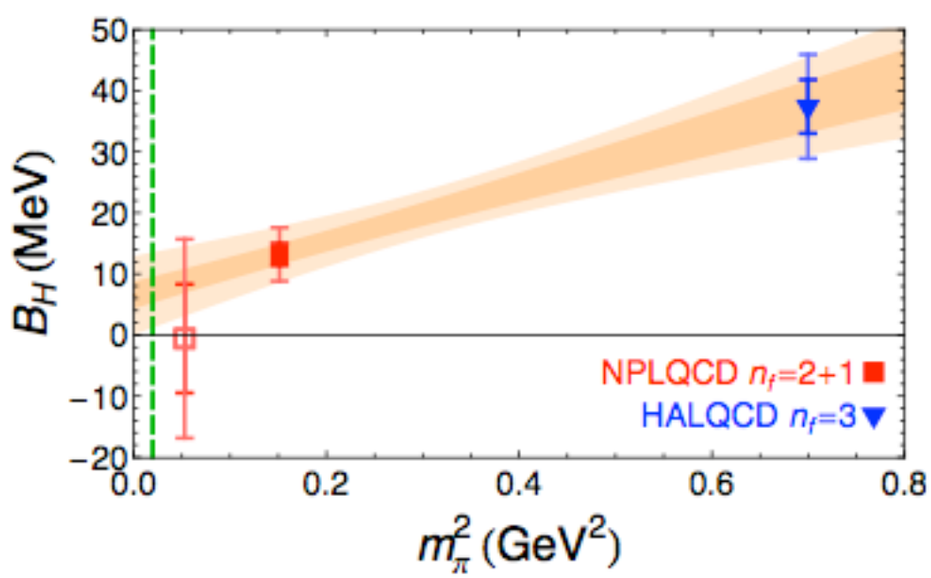
Experiment	Search Reaction	θ^+	Ξ_5	θ_c	Reference
ALEPH	Hadronic Z decays	$\Downarrow$	$\Downarrow$	$\Downarrow$	[19]
BaBar	$e^+e^- \to \Upsilon(4S)$	$\Downarrow$	$\Downarrow$	–	[20]
BELLE	$KN \to PX$	$\Downarrow$	–	$\Downarrow$	[21]
BES	$e^+e^- \to J/\psi(\psi(2S) \to \theta\bar{\theta}$	$\Downarrow$	–	$\Downarrow$	[22]
CDF	$p\bar{p} \to PX$	$\Downarrow$	$\Downarrow$	$\Downarrow$	[23]
COMPASS	$\mu^+(^6LiD) \to PX$	$\Downarrow$	$\Downarrow$	–	[24]
DELPHI	Hadronic Z decays	$\Downarrow$	–	–	[25]
E690	$pp \to PX$	$\Downarrow$	$\Downarrow$	–	[26]
FOCUS	$\gamma p \to PX$	$\Downarrow$	$\Downarrow$	$\Downarrow$	[27]
HERA-B	$pA \to PX$	$\Downarrow$	$\Downarrow$	–	[28]
HyperCP	$(\pi^+, K^+, p)Cu \to PX$	$\Downarrow$	–	–	[29]
LASS	$K^+p \to K^+n\pi^+$	$\Downarrow$	–	–	[30]
L3	$\gamma\gamma \to \theta\bar{\theta}$	$\Downarrow$	–	–	[25, 31]
PHENIX	$AuAu \to PX$	$\Downarrow$	–	–	[32]
SELEX	$(\pi, p, \Sigma)p \to PX$	$\Downarrow$	–	–	[33]
SPHINX	$pC(N) \to \theta^+C(N)$	$\Downarrow$	–	–	[34]
WA89	$\Sigma^-N \to PX$	–	$\Downarrow$	–	[36]
ZEUS	$ep \to PX$	$\Uparrow$	$\Downarrow$	$\Downarrow$	[16, 37, 38]

Dzierba, Meyer, Szczepaniak, hep-ex/0412077

D. Diaokonv, V. Petrov, and M.V. Polyakov, Z.Phys. A359 (1997) 305-314

H

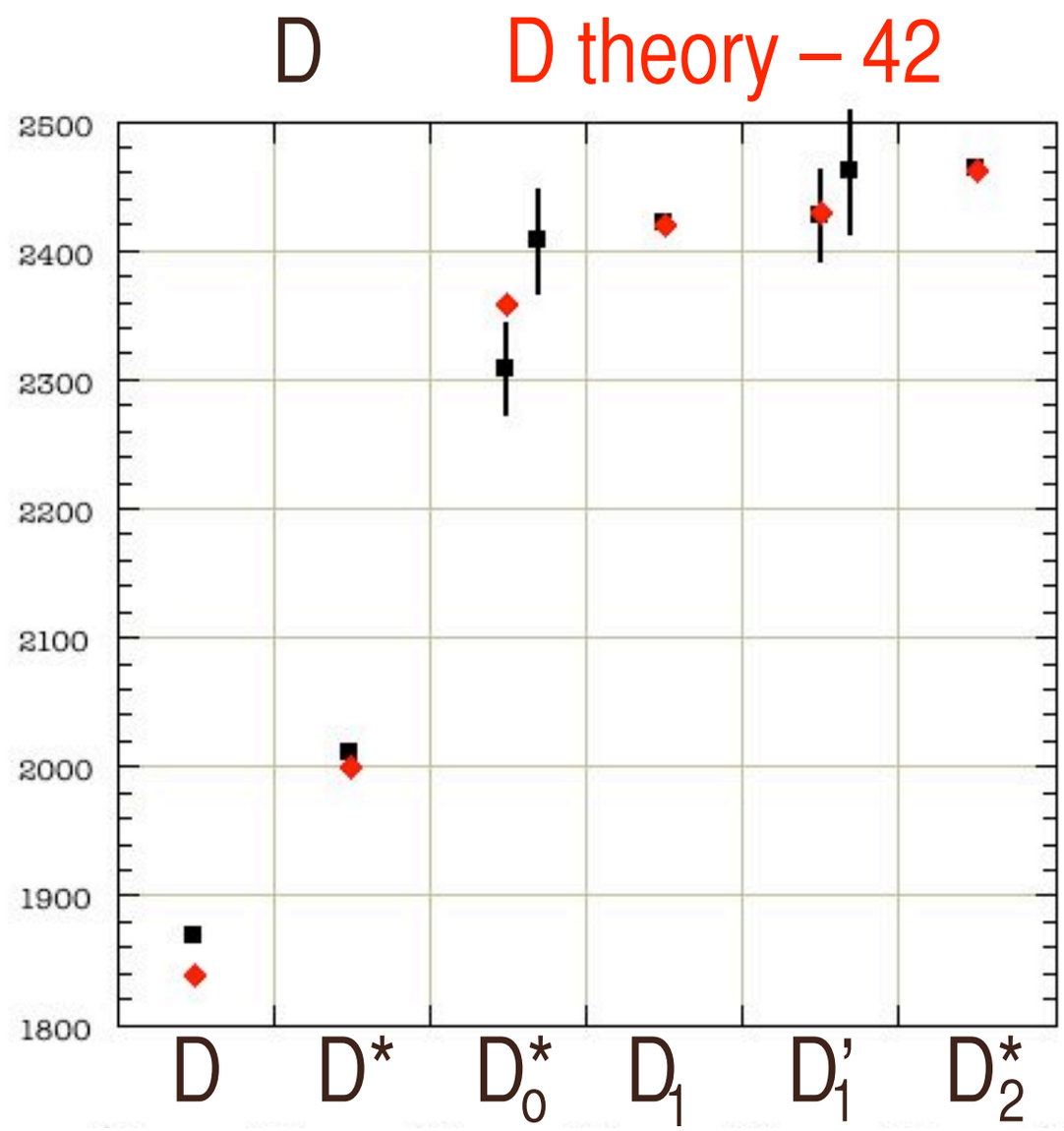
1977: Bob Jaffe suggests that a udsuds state will be strongly bound based on the MIT bag model.



NPLQCD, S. Beane, et al,1103.2821

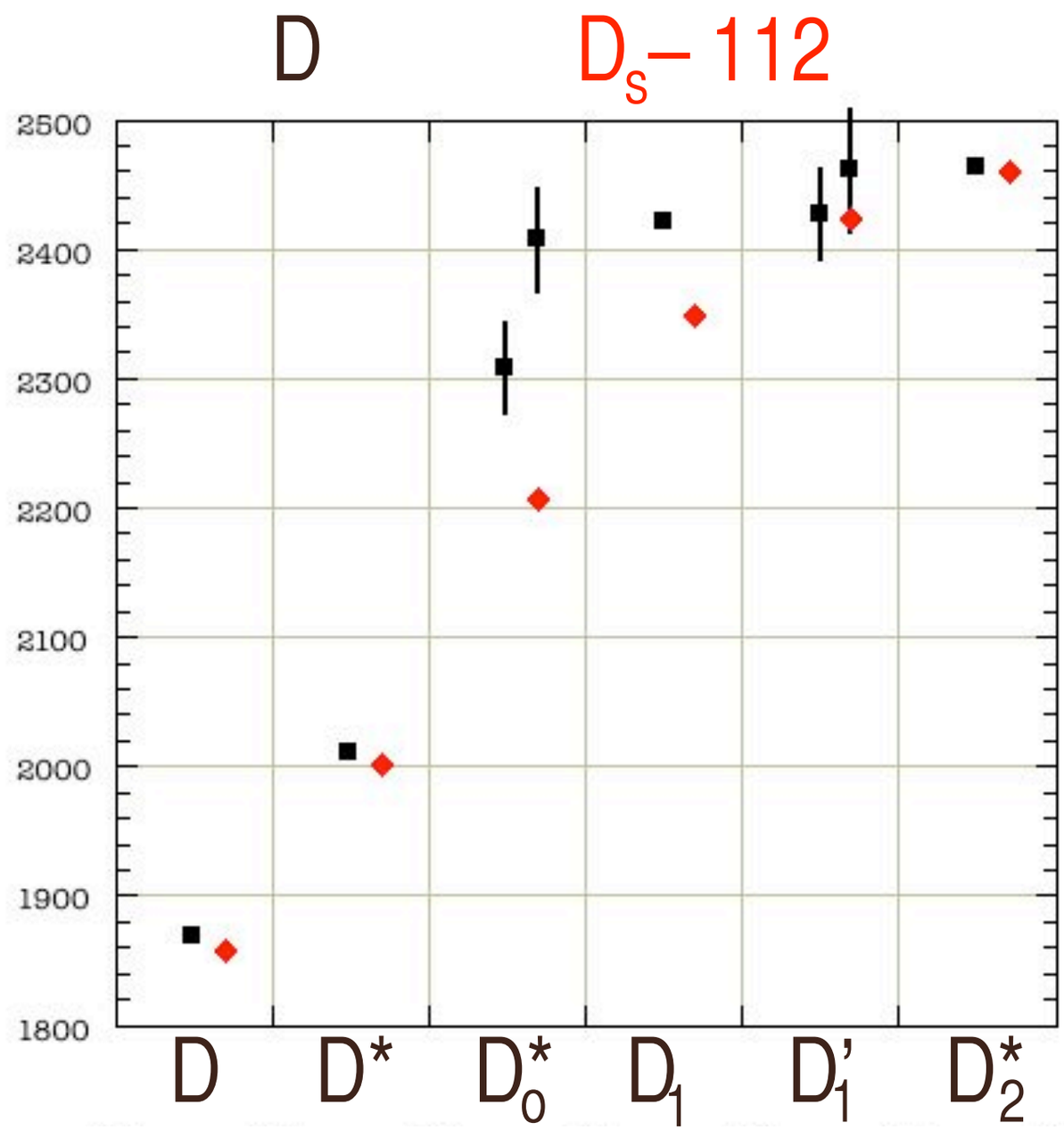
$D_s(2317)$

D Spectrum



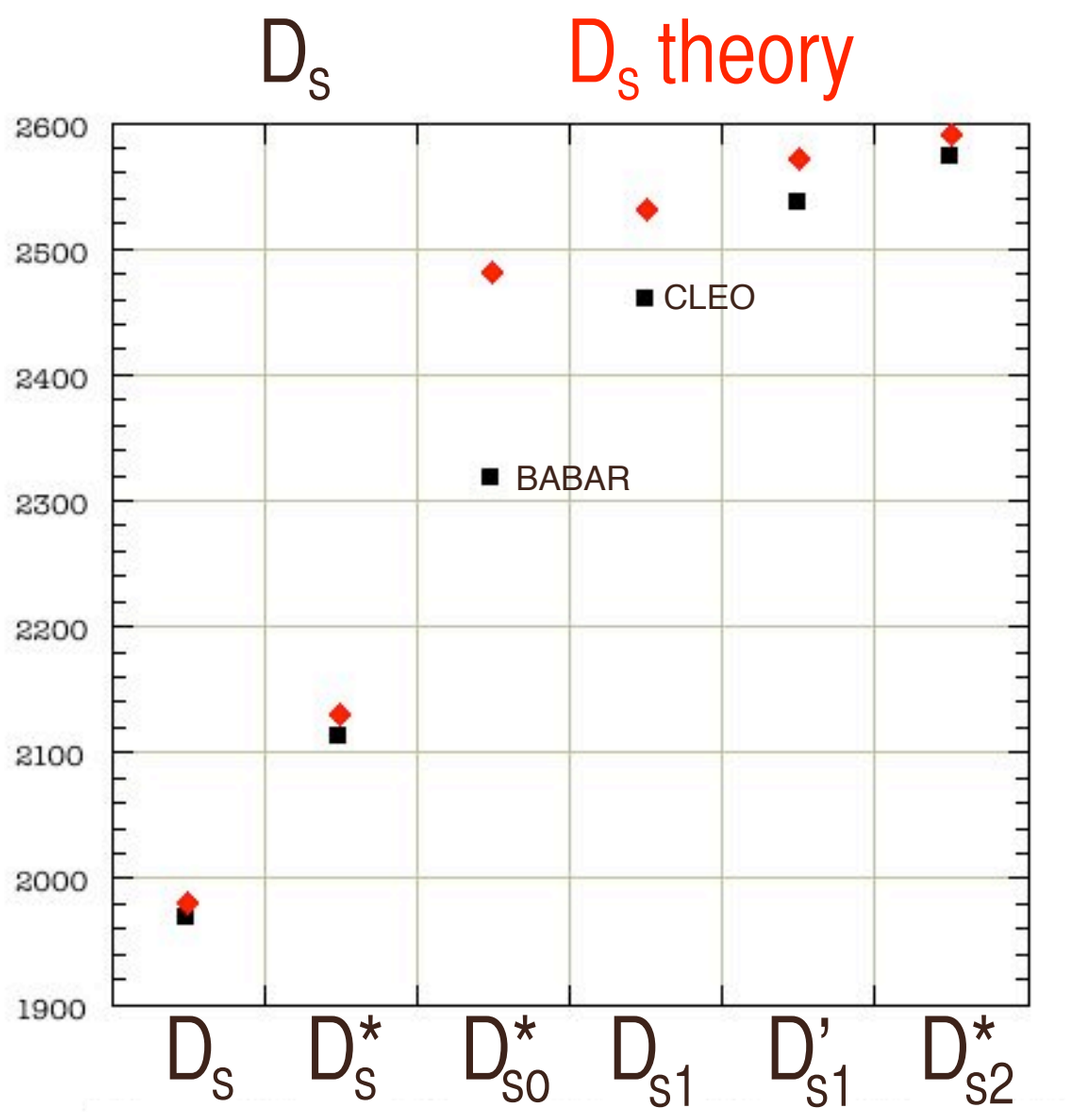
$D_s(2317)$

D vs D_s Spectrum



$D_s(2317)$

D_s Spectrum vs Theory



Godfrey & Isgur,PRD32, 189 (85)

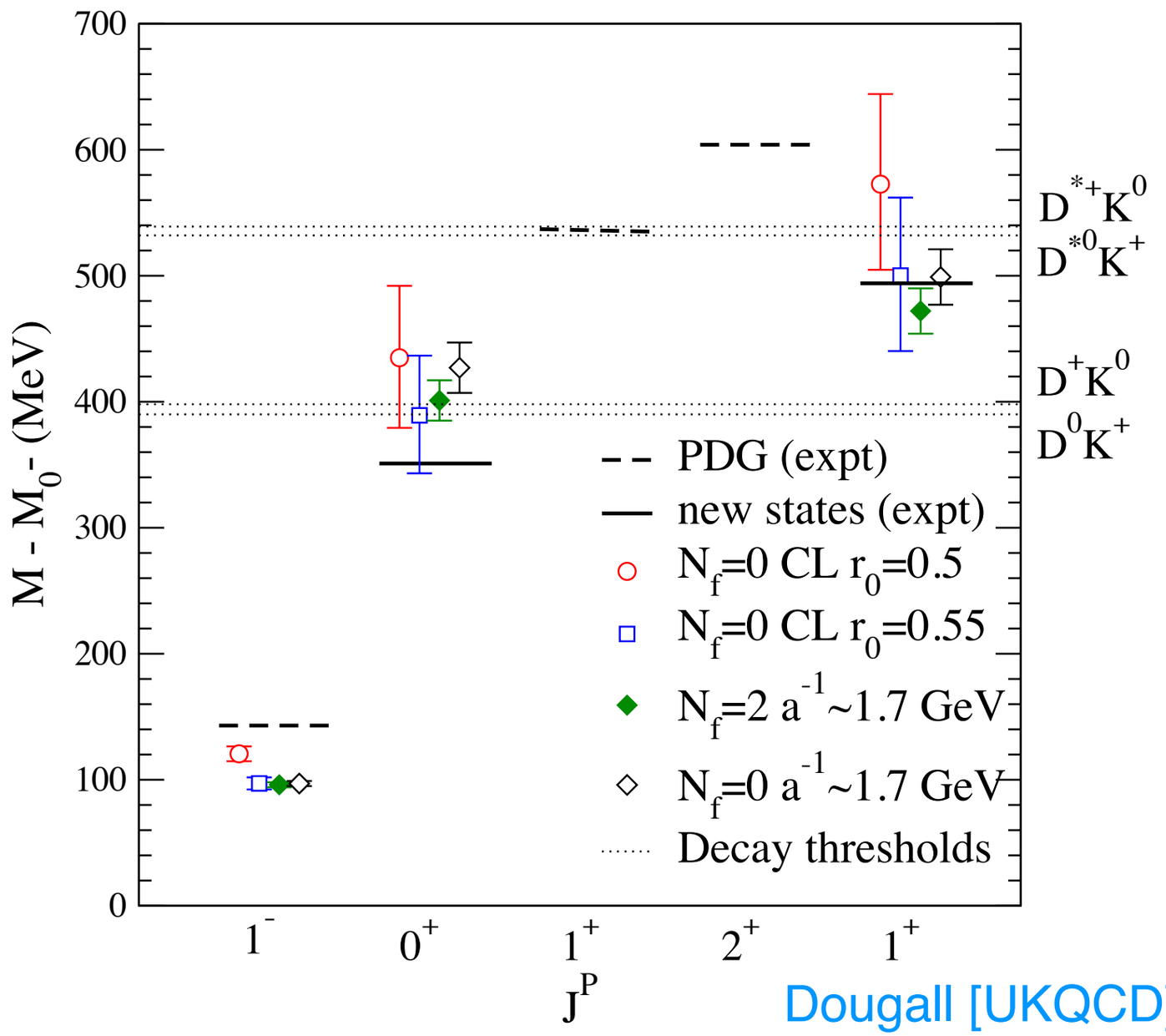
BABAR, PRL90, 242001 (03)

CLEO, PRD68, 032002 (03)

Close & ESS, hep-ph/ 0505206

$D_s(2317)$

The Lattice Weighs In on D_s



Dougall [UKQCD], hep-lat/0307001
Bali, hep-ph/0305209

Lang et al., arXiv:1403.8103

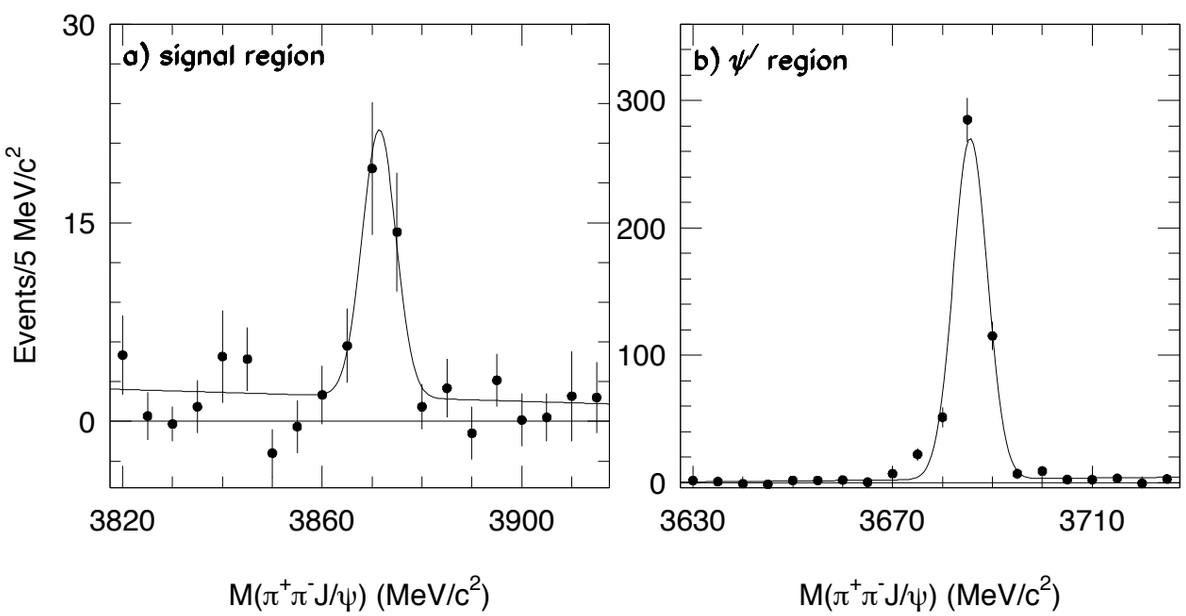
$D_s(2317)$

Some Ideas:

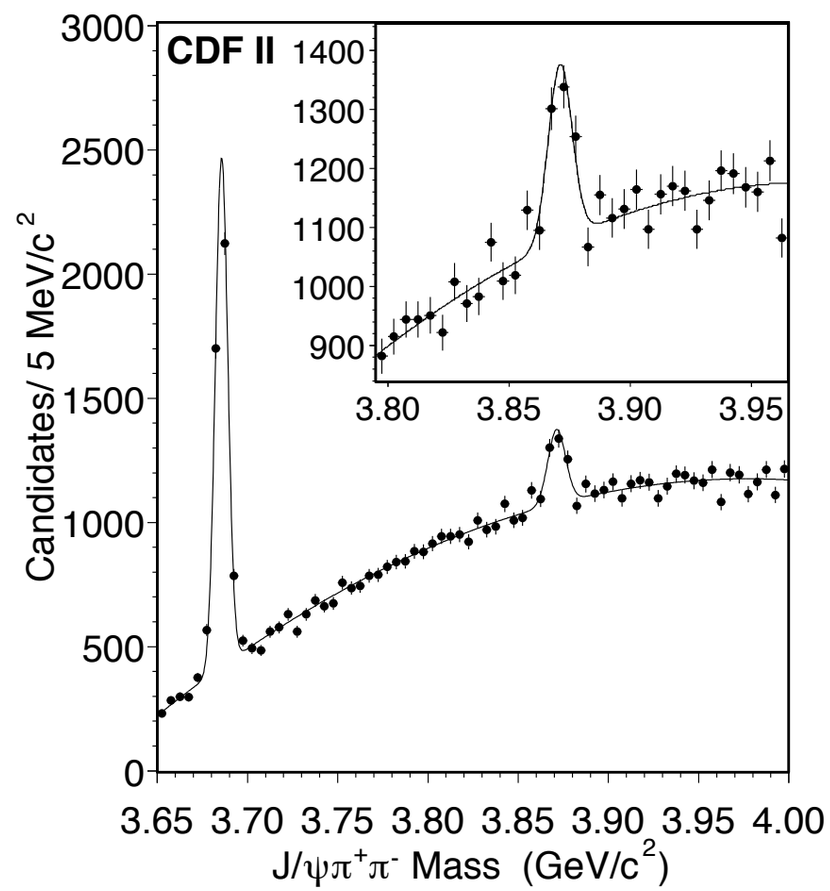
- DK molecule. T. Barnes, F. Close, H. Lipkin, PRD68, 054006 (03)
- $D_s\pi$ molecule A. Szczepaniak, PLB567, 23 (03)
- spin-orbit + tensor splitting. B. Cahn & J. Jackson, PRD68, 037502 (03).
- $q\bar{q}$ + $q\bar{q}q\bar{q}$ mixing. T. Browder, S. Pakvasa, A. Petrov, PLB578, 365 (04)
- $q\bar{q}$ mixing with DK,D*K*. D. Hwang & D-W Kim, hep-ph/0408154
- flavour-dependent potential O. Lakhina and E.S. Swanson, PLB650, 159 (07)

X(3872)

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



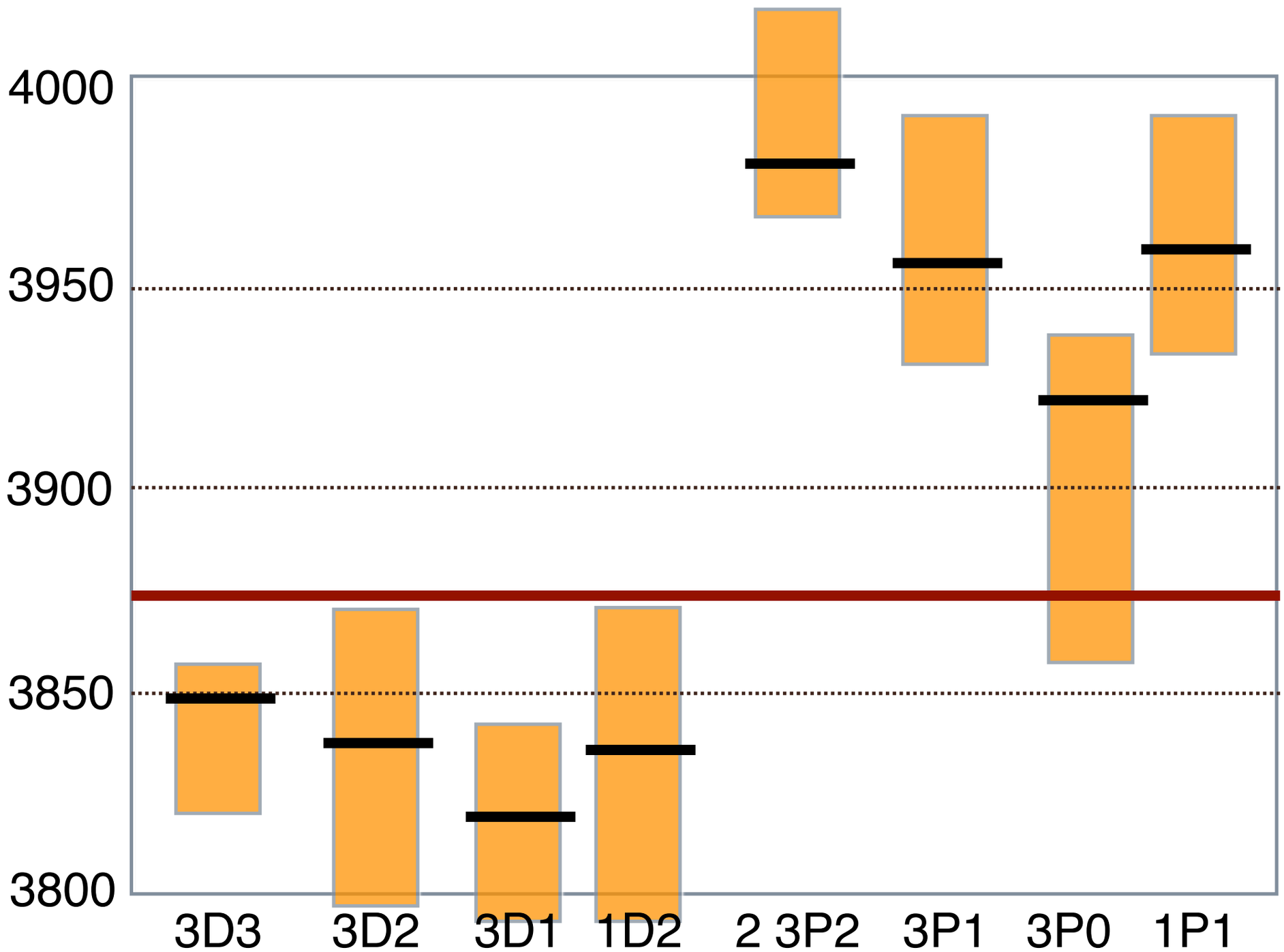
S.-K. Choi (Belle), hep-ex/0309032



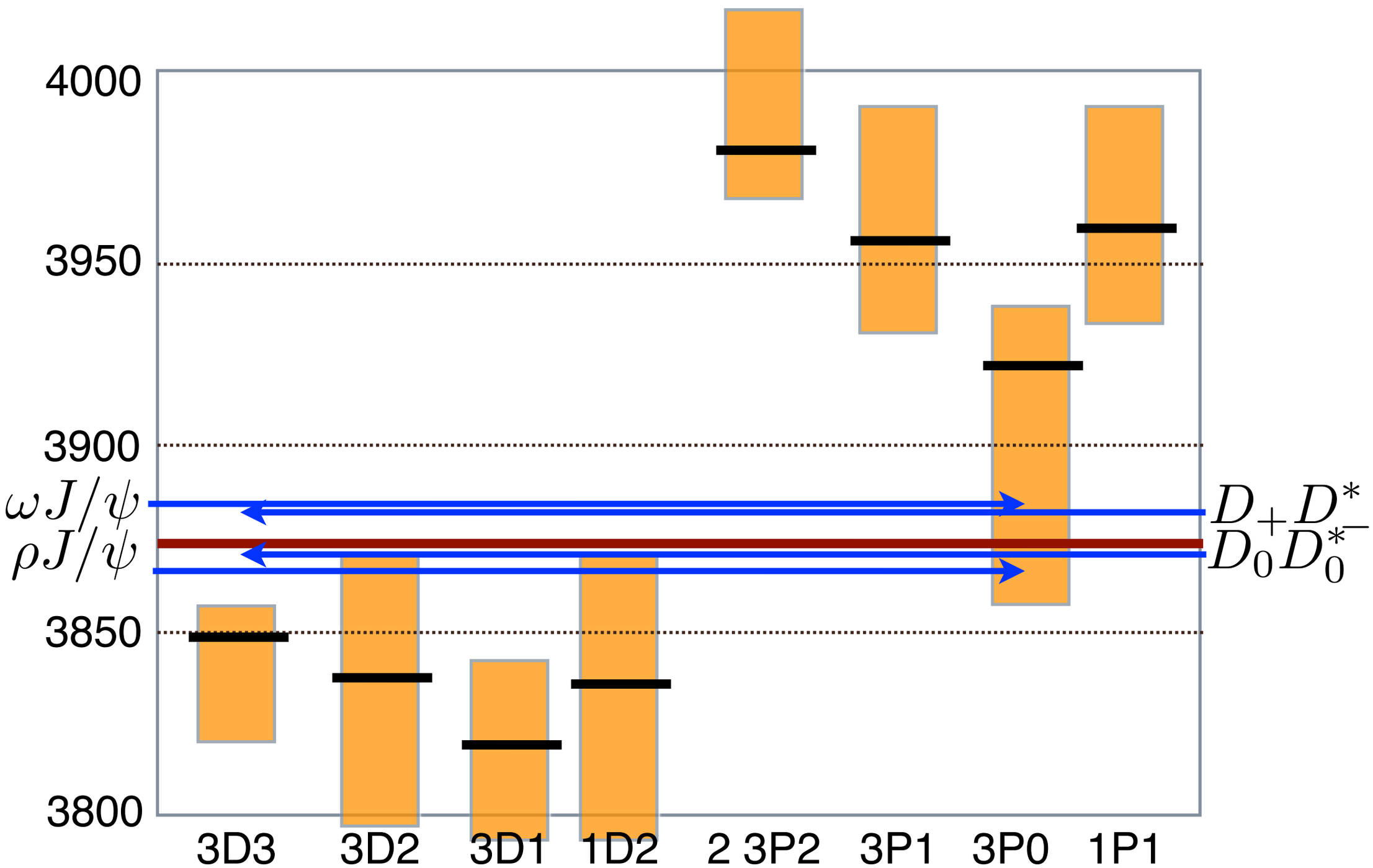
D. Acosta (CDF) hep-ex/0312021

B. Aubert (Babar) hep-ex/0402025

X(3872)



X(3872)


4000
3950
3900
3850
3800
$\omega J/\psi$
$\rho J/\psi$
$D_+ D_-^*$
$D_0 D_0^*$
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)

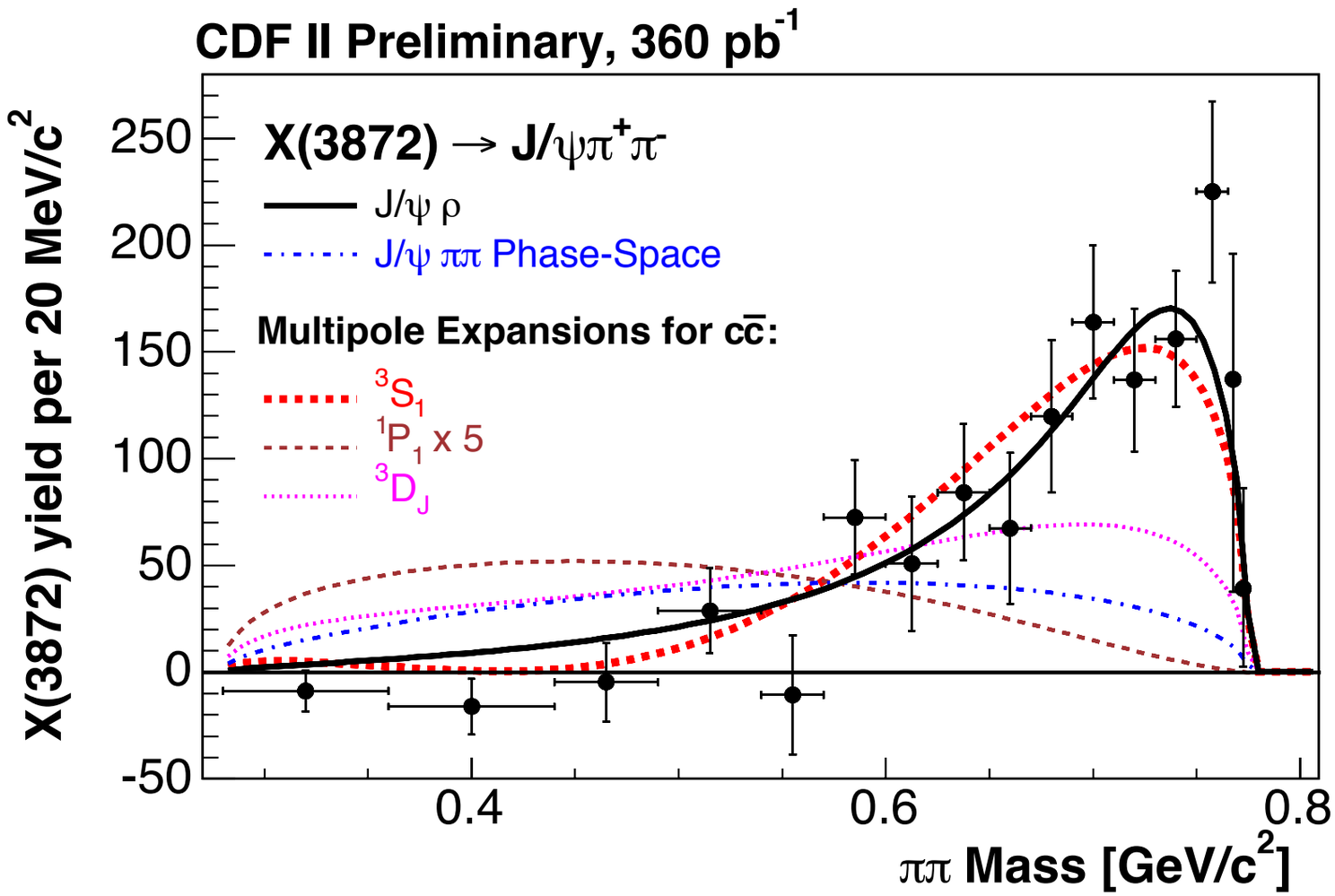
decay widths

weak binding → use free space decay widths to estimate dissociation decay modes

B_E (MeV)	$D^{0*}\bar{D}^0\pi^0$	$D^{0*}\bar{D}^0\gamma$	$D^{-*}D^+\pi^0$	$D^{-*}(D^+\bar{D}^0\pi^-+\text{c.c})/\sqrt{2}$	$D^{-*}D^+\gamma$	$\rho\pi^+\pi^-J/\psi$	$\rho/\omega\pi^+\pi^-\gamma J/\psi$	$\omega\pi^+\pi^-\pi^0J/\psi$	$\rho/\omega\pi^0\gamma J/\psi$
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

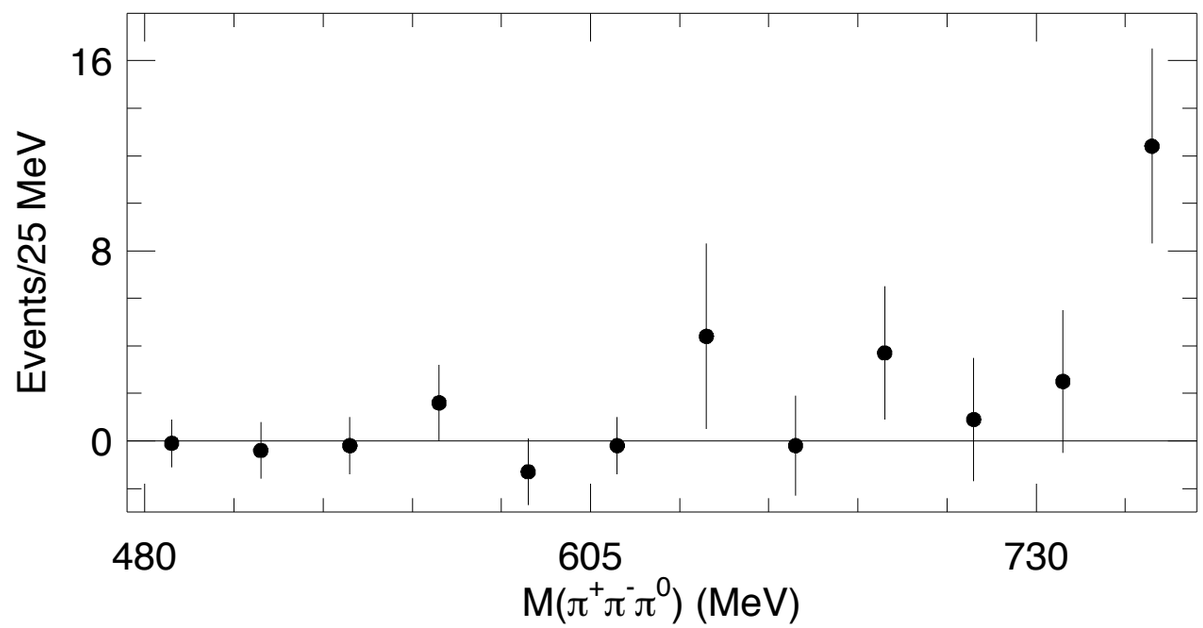
$$\frac{\Gamma(\hat{\chi} \to \pi\pi\pi J/\psi)}{\Gamma(\hat{\chi} \to \pi\pi J/\psi)} = 0.56$$

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
ππ Mass [GeV/c^2]
250
200
150
100
50
0
-50
0.4
0.6
0.8

X(3872)

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



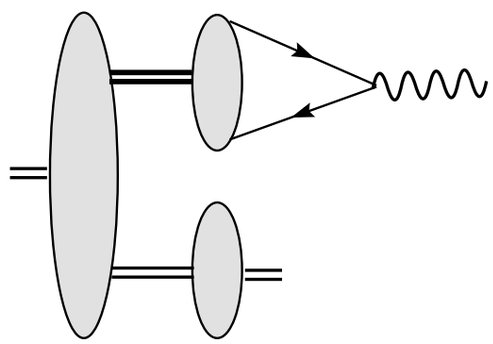
Abe et al [Belle], hep-ex/0505037

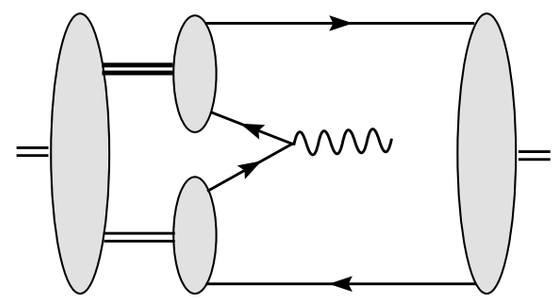
[confirmed by BaBar]

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)

X-χ mixing

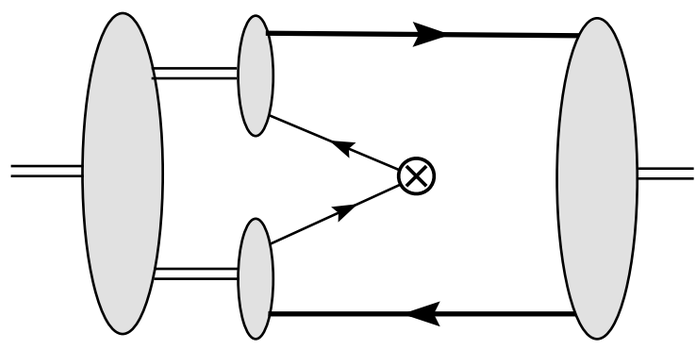


Table 1: $X - \chi_{c1}$ Mixing.

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

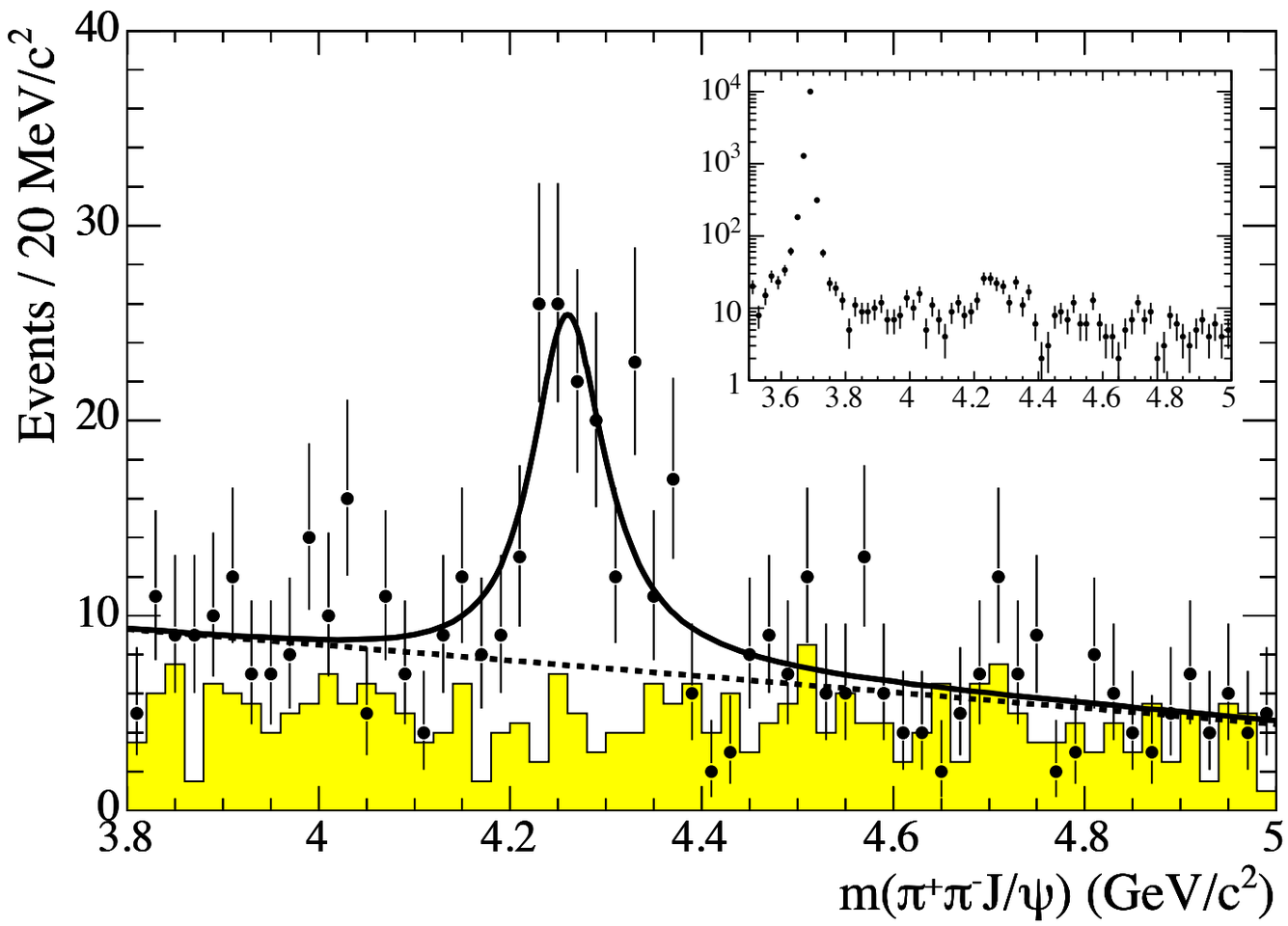
no MM mixtures

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

Y(4260)

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

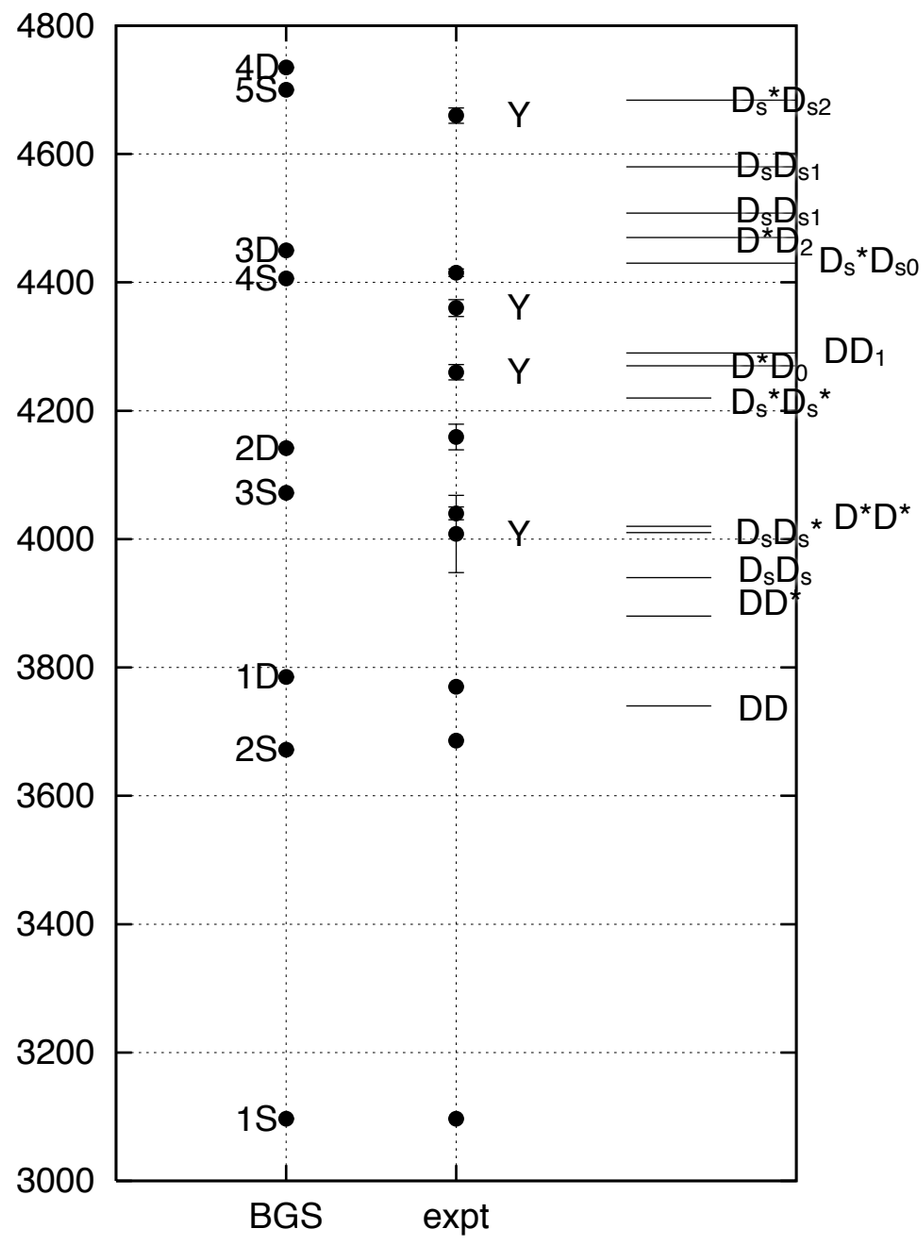
$$e^+e^- \to \gamma_{\rm ISR}\pi\pi J/\psi$$



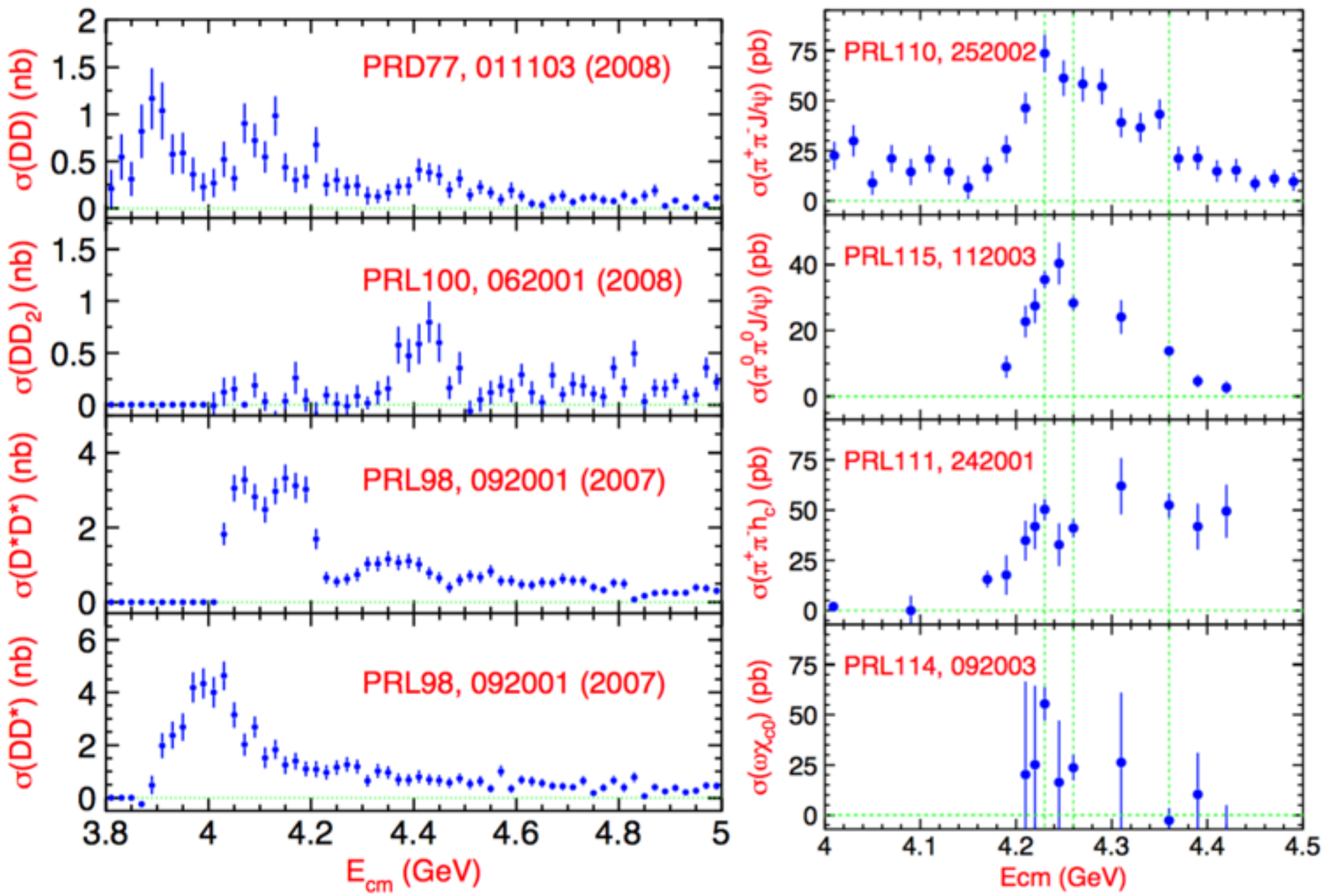
$$\Gamma = 50 - 90$$

Y(4260)

Charmonium Vectors



Y(4260)


PRD77, 011103 (2008)
PRL100, 062001 (2008)
PRL98, 092001 (2007)
PRL98, 092001 (2007)
σ(DD) (nb)
σ(DD2) (nb)
σ(D*D*) (nb)
σ(DD*) (nb)
Ecm (GeV)
PRL110, 252002
PRL115, 112003
PRL111, 242001
PRL114, 092003
σ(π+π-J/ψ) (pb)
σ(π0π0J/ψ) (pb)
σ(π+π-hc) (pb)
σ(ωχc0) (pb)
Ecm (GeV)

Y(4260)

Llanes-Estrada, hep-ph/0507035

- no available vector (4S=4415, 2D=4159)
- vector hybrid [at 4400]?

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

- 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]

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

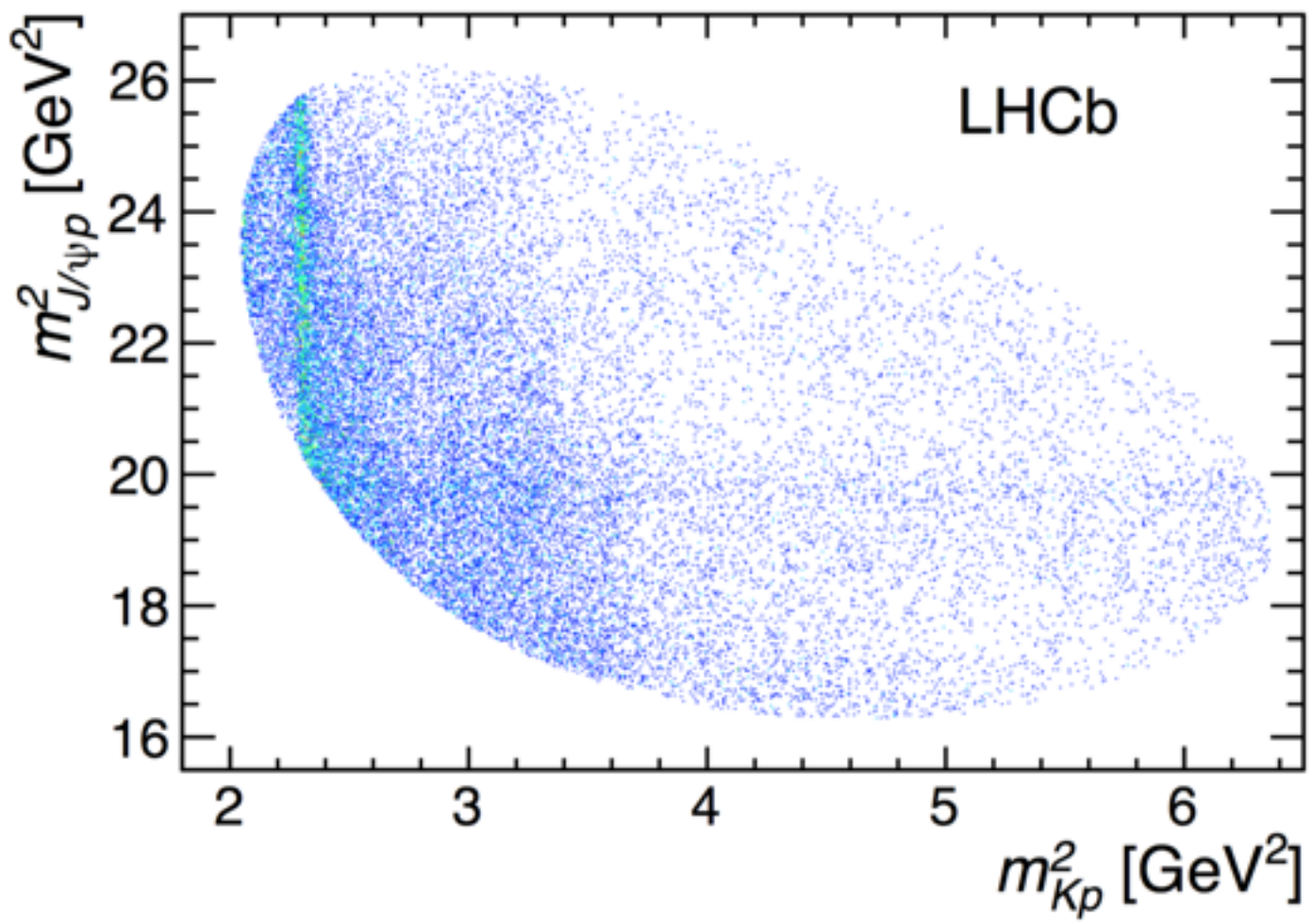
$$\Lambda_b^0 \to J/\psi K^- p$$

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

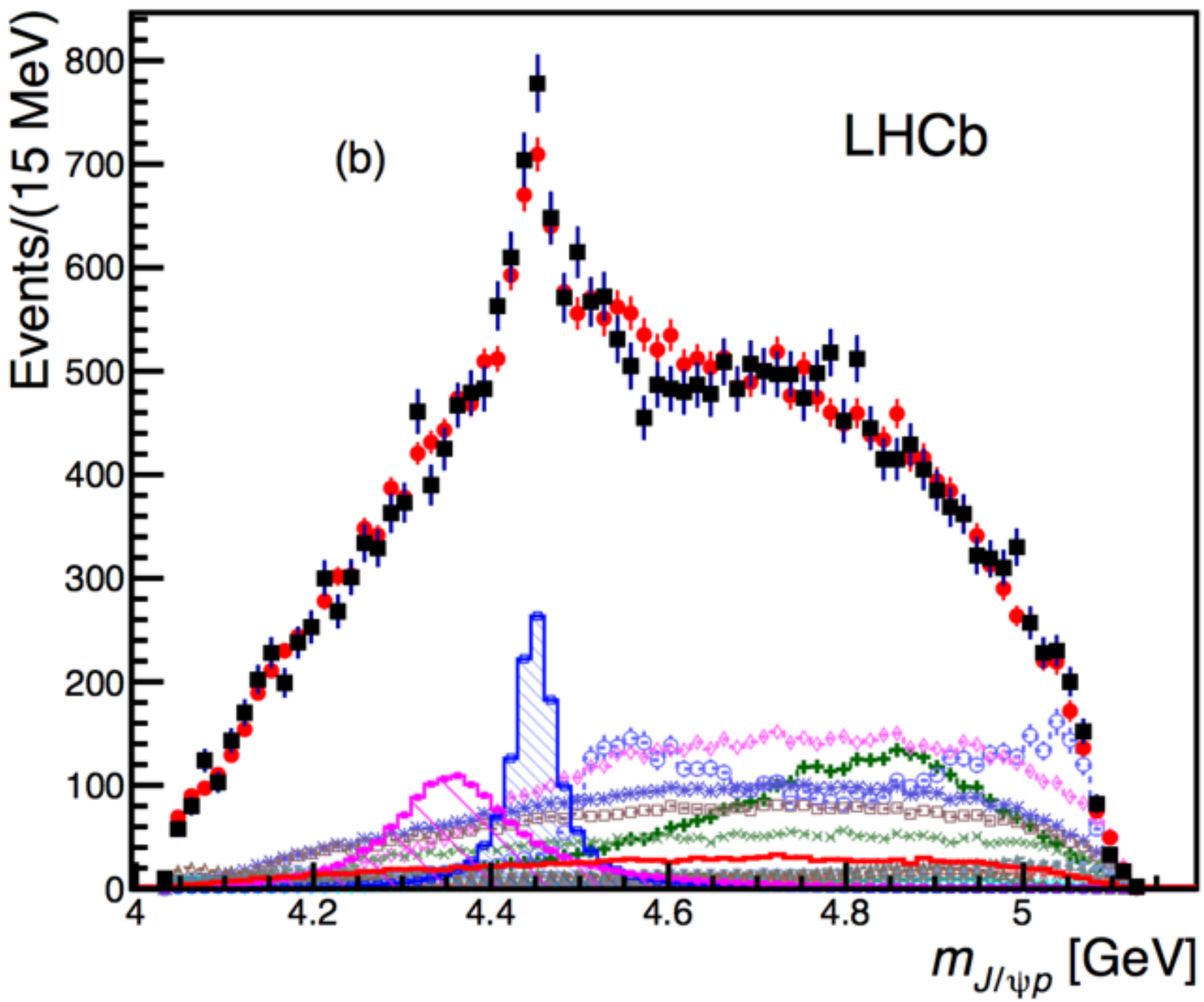
LHCb 1507.03414v2

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

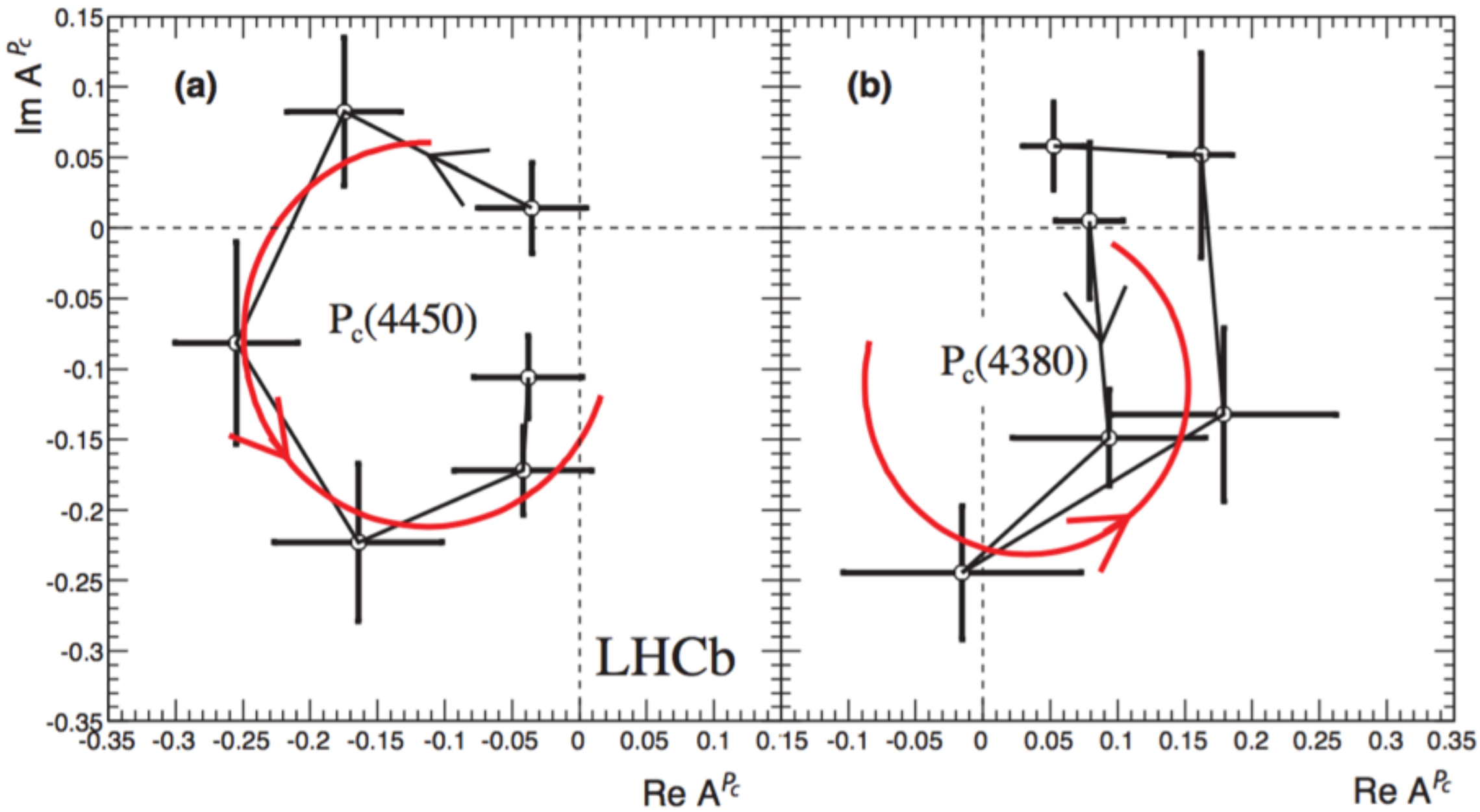
$$J^P = \frac{5}{2}^{\mp}$$



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



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



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

		$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$	$\frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{5}{2}^+$
	Ass. 1		P_c (4380				P_c^*(4450
	Ass. 2			P_c^*		P_c	
	Ass. 3		P_c^*				P_c
$I = \frac{1}{2}$	$\Lambda_c \bar{D}$	S	D	D	P	P	F
	$\Lambda_c \bar{D}^*$	SD	SD	D	P	PF	PF
	$\Lambda_c(2595)\bar{D}$	P	P	F	S	D	D
$I = \frac{1}{2}, \frac{3}{2}$	$\Sigma_c \bar{D}$	S	D	D	P	P	F
	$\Sigma_c^* \bar{D}$	D	SD	D	P	PF	PF
	$\Sigma_c \bar{D}^*$	SD	SD	D	P	PF	PF
	$\Sigma_c^* \bar{D}^*$	SD	SD	SD	PF	PF	PF
$I = \frac{1}{2}$	$J/\psi N$	SD	SD	D	P	PF	PF
	$\eta_c N$	S	D	D	P	P	F
	$\chi_{c1} N$	P	PF	PF	SD	SD	D
	$\chi_{c0} N$	P	P	F	S	D	D
	$J/\psi N(1440)$	SD	SD	D	P	PF	PF
	$J/\psi N(1520)$	PF	PF	PF	SD	SD	SD
$I = \frac{3}{2}$	$J/\psi \Delta$	SD	SD	SD	PF	PF	PF
	$\eta_c \Delta$	D	SD	D	P	PF	PF

T. J. Burns arXiv:1509.02460v1 [hep-ph]

Four-quark States

$\pi\pi J/\psi$ $\pi D\bar{D}^*$
$Z_c(3900)$

$\pi\pi h_c$ $\pi D^*\bar{D}^*$
$Z_c(4025)$

$K\pi\chi_{cJ}$ $\pi\psi(2S)$
$Z_1(4050)$ $Z_2(4250)$

$K\pi J/\psi$
$Z_c(4200)$

$\pi K\psi'$
$Z_c(4240)$ $Z_c(4475)$

$\pi\pi\Upsilon(nS)$ $\pi\pi h_b(nP)$ $\pi B\bar{B}^*$
$Z_b(10610)$ $Z_b(10650)$

Four-quark States

Four-electron States

1946: Wheeler suggests that Ps_2 might be bound

Wheeler, J. A. Polyelectrons. Ann. NY Acad. Sci. 48, 219–238 (1946).

1946: Ore proves it is unbound

1947: Hylleraas & Ore prove it is bound

Hylleraas, E. A. & Ore, A. Binding energy of the positronium molecule. Phys. Rev.71, 493–496 (1947).

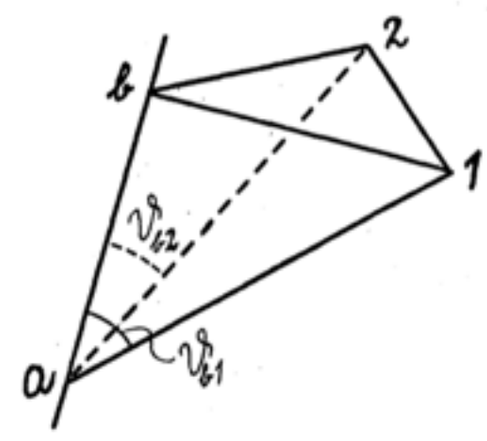


FIG. 1. Coordinate system for the positronium molecule.

2007: Ps_2 is observed

Cassidy, D.B.; Mills, A.P. (Jr.) (2007). "The production of molecular positronium". Nature 449 (7159): 195–197

Four-quark States

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma_\mu D^\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \rightarrow$$

$$[\frac{1}{2}(\nabla_1^2 + \nabla_2^2 + \nabla_3^2 + \nabla_4^2) + \frac{E}{4} + V]\Psi = 0$$

$$V = \frac{1}{r_{1a}} + \frac{1}{r_{2b}} + \frac{1}{r_{1b}} + \frac{1}{r_{2a}} - \frac{1}{r_{12}} - \frac{1}{r_{ab}}$$

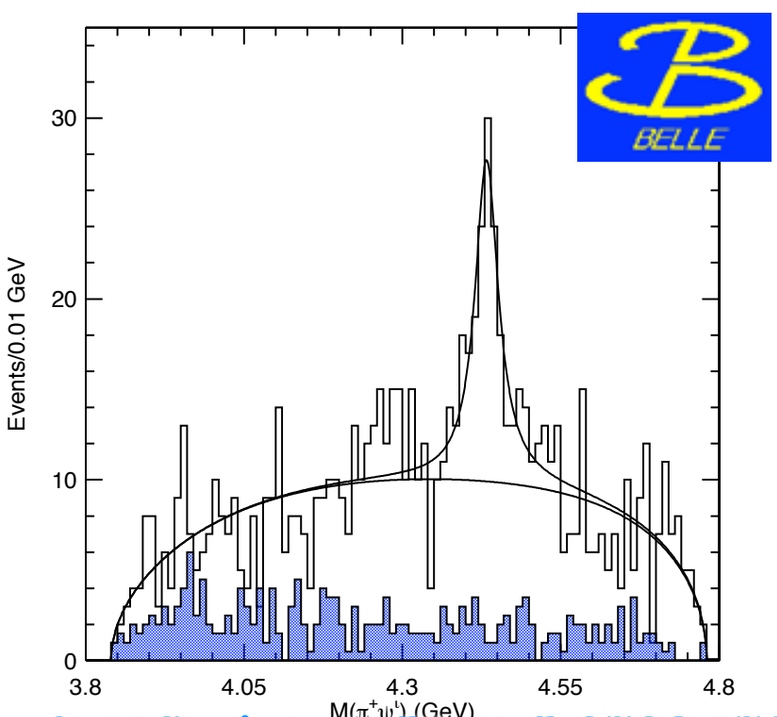
$$\mathcal{L}_{QCD} = \bar{\psi}_i(i\gamma_\mu D^\mu_{ij} - m\,\delta_{ij})\psi_j - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a \rightarrow$$

$$Z^+(4430)$$

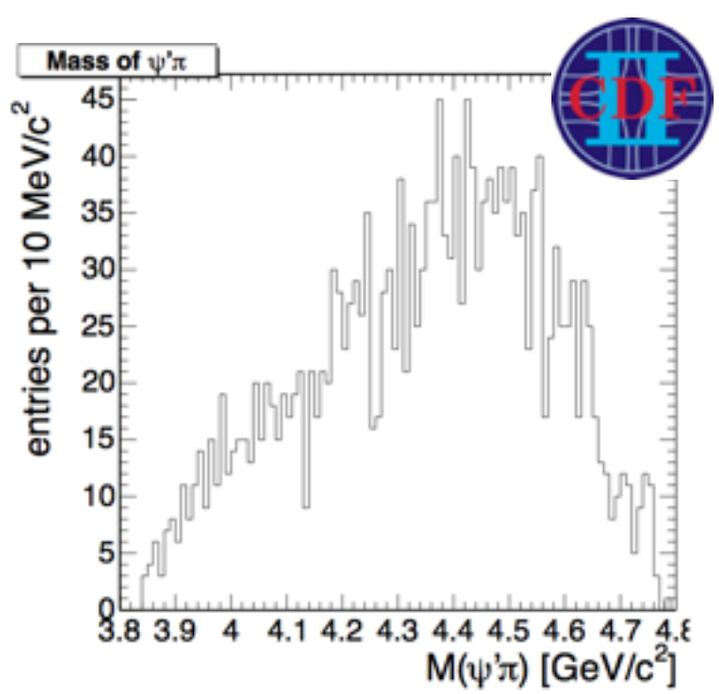
$$B \to K\pi^+\psi'$$

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

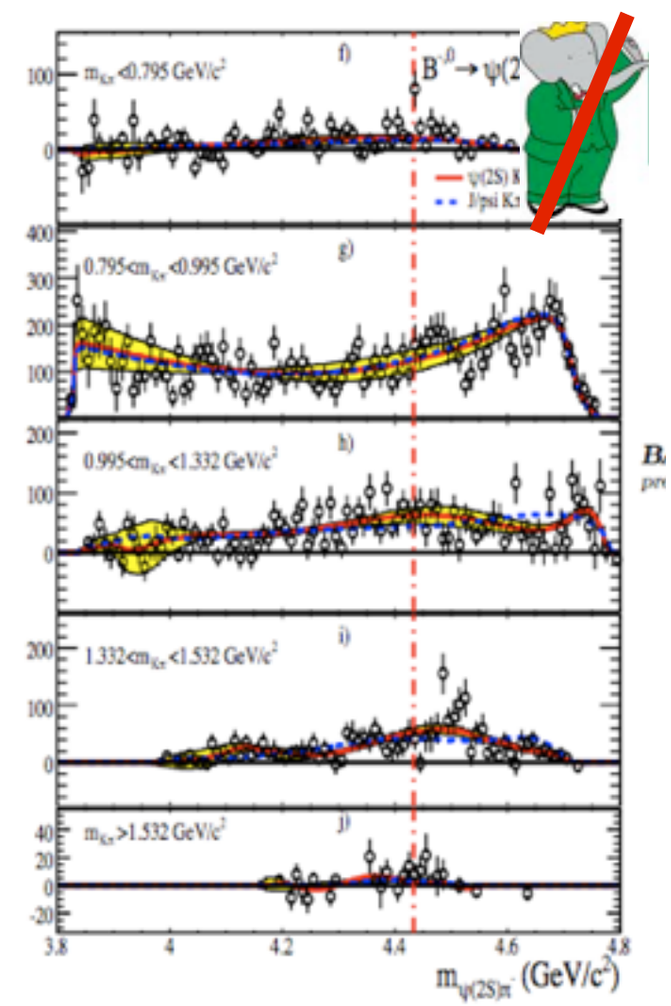
.manifestly exotic
.not confirmed by BaBar



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

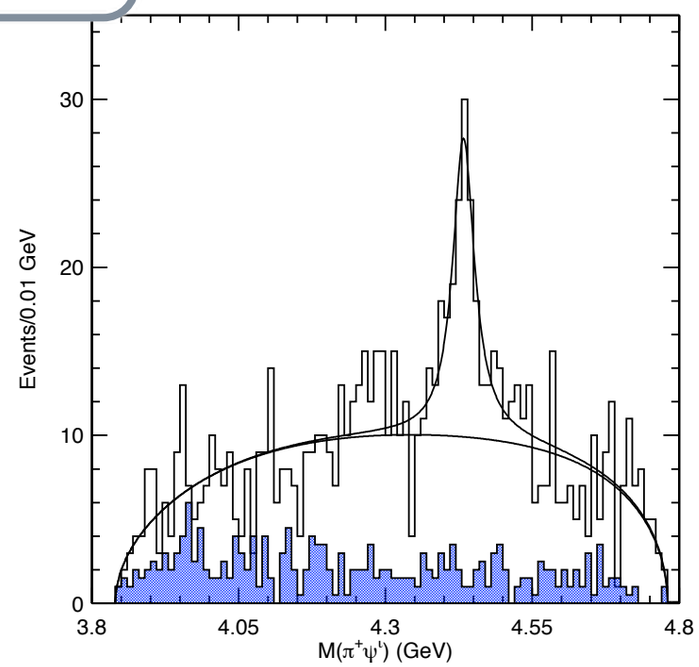


F. Rubbo, Torino thesis

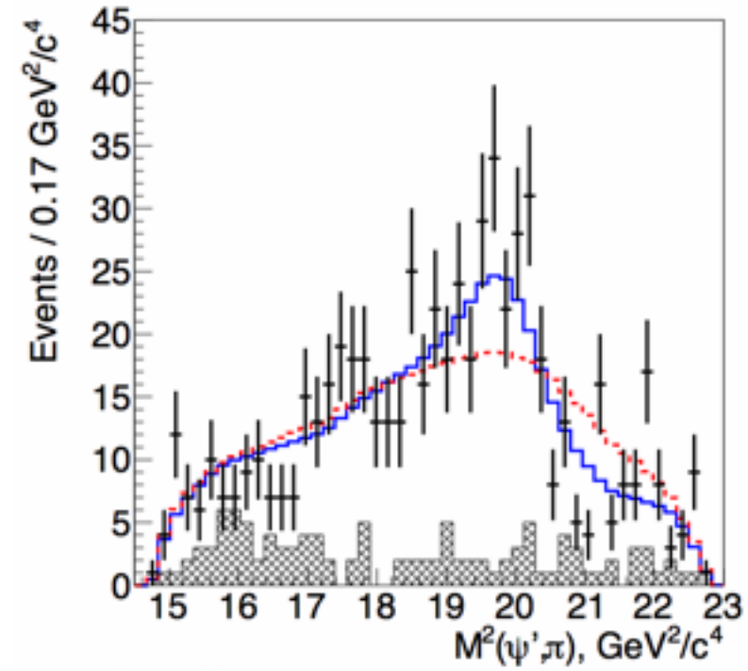


Mokhtar, 0810.1073

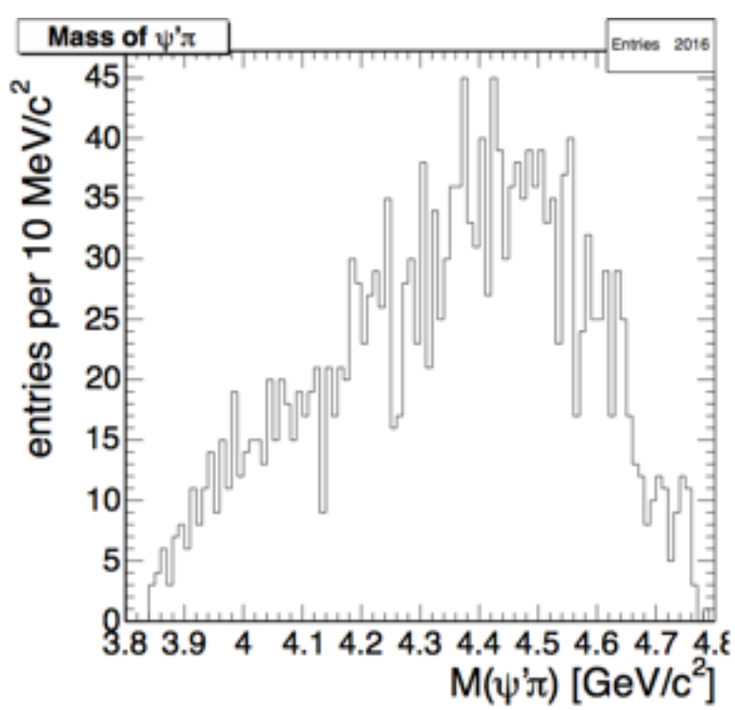
$Z^+(4430)$



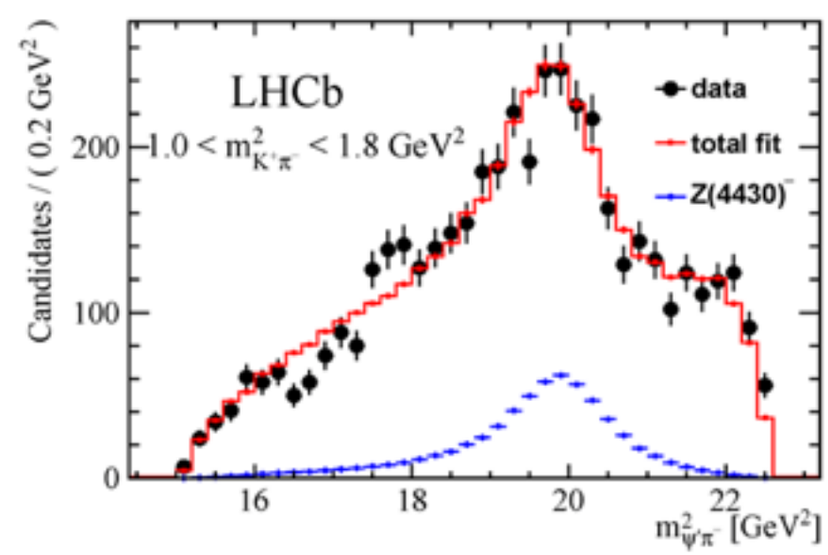
Belle original



Belle re-analysis
1306.4894



CDF

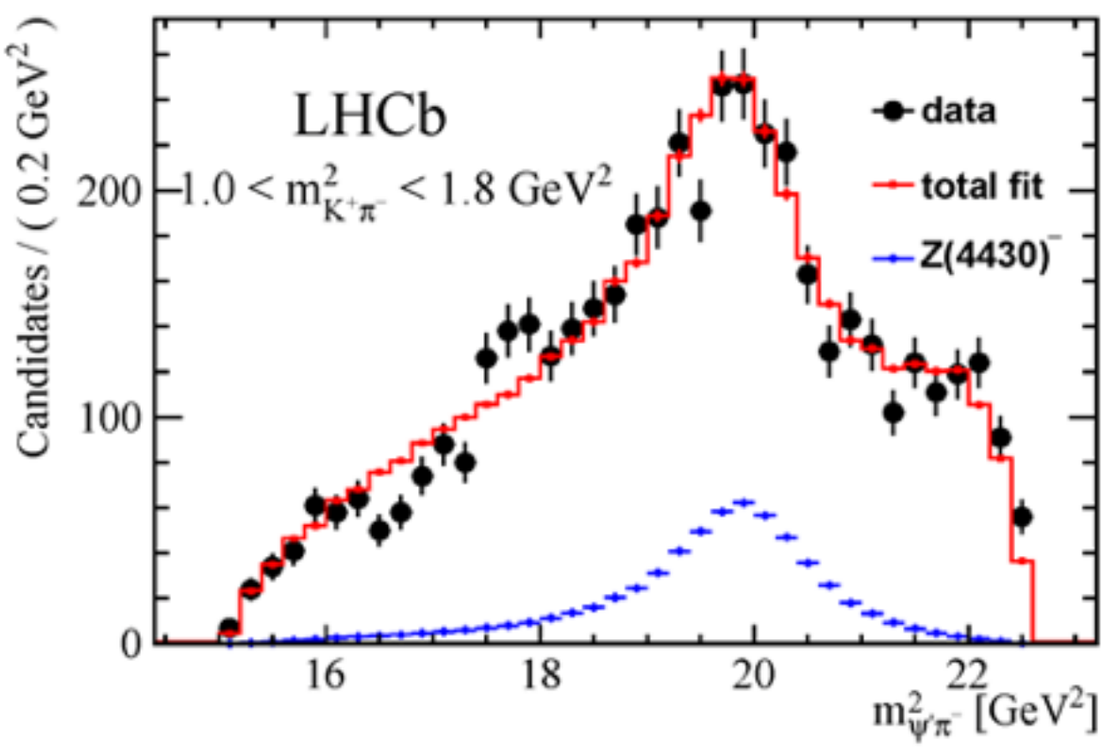


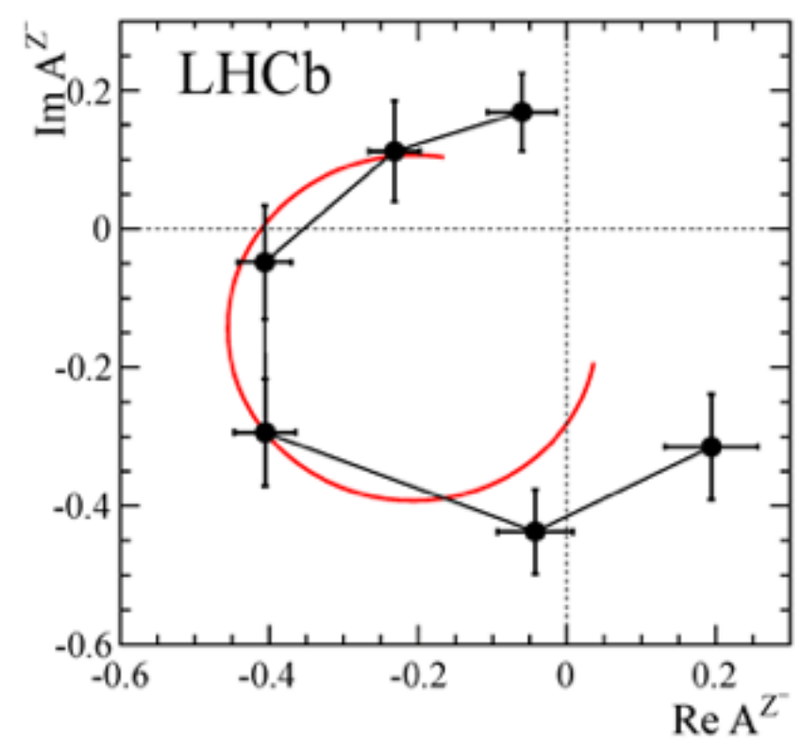
LHCb

$Z^+(4430)$

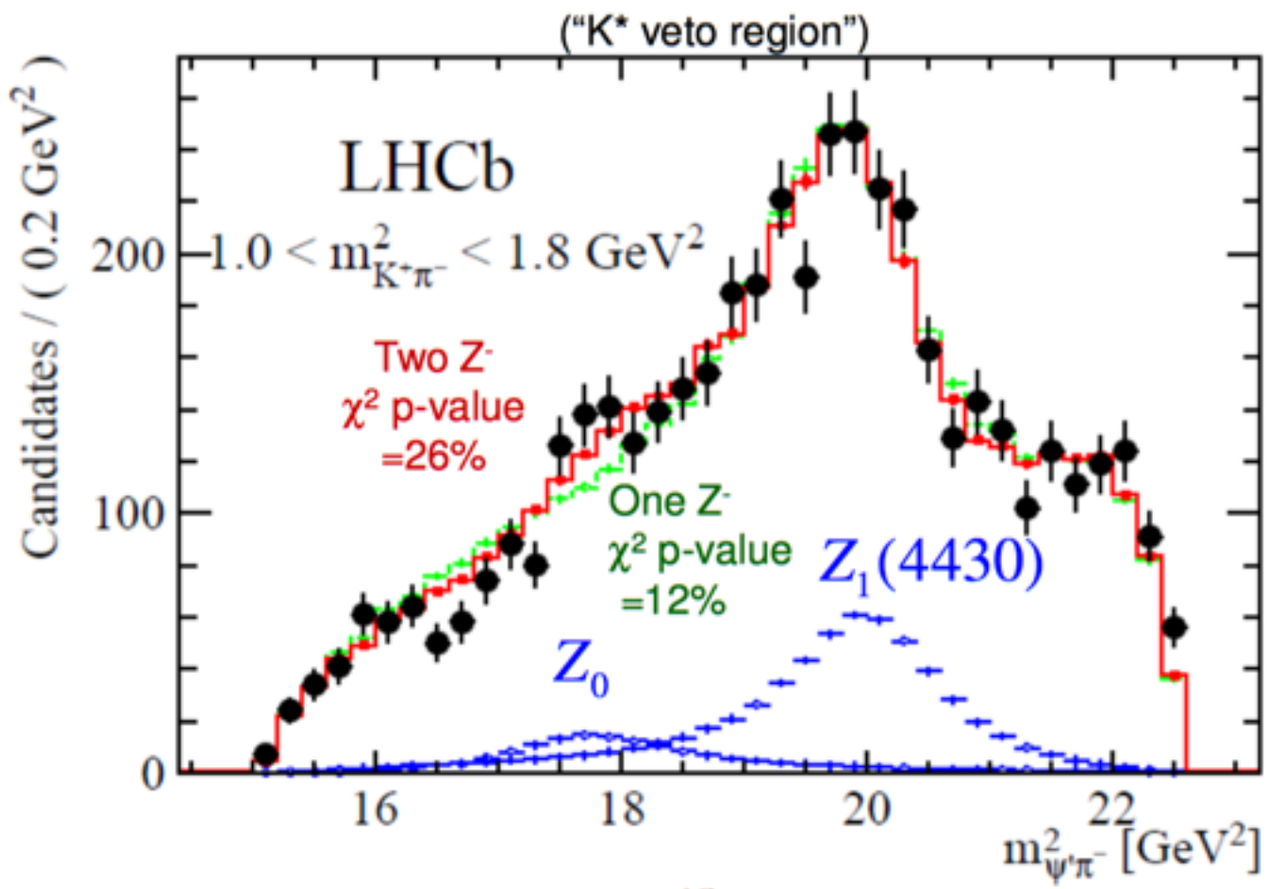
.confirmed by LHCb

$J^P = 1^+$





Z(4240) [?]



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

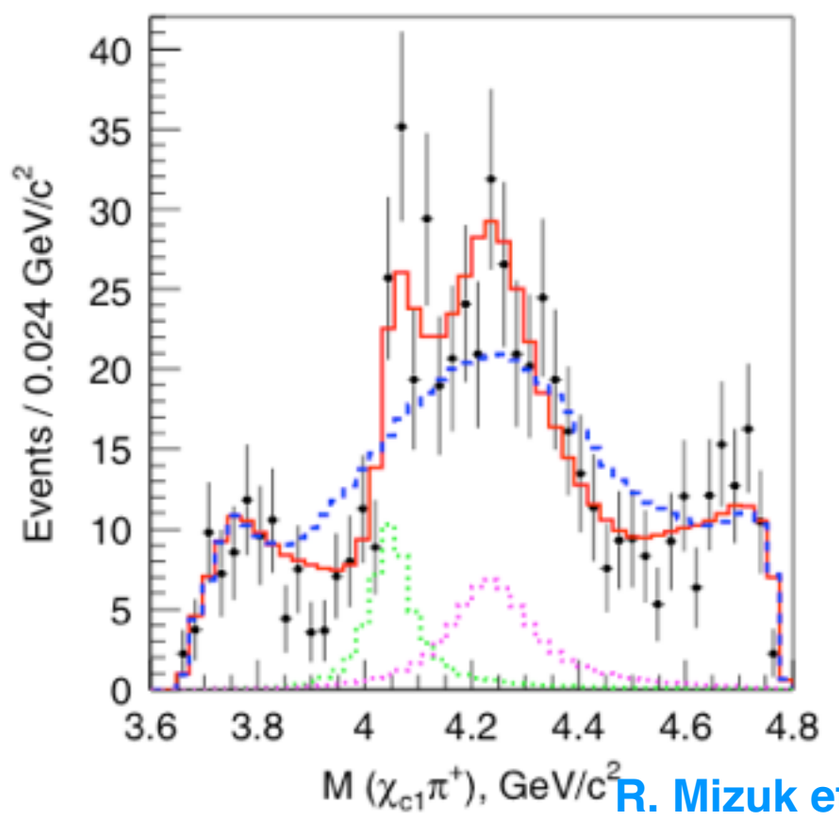
$$\Gamma(Z_0) = 220 \pm 47^{+108}_{-74} \text{ MeV}$$

$Z_1(4050)$
$Z_2(4250)$

$B \to ZK \to \chi_{c1}\pi K$

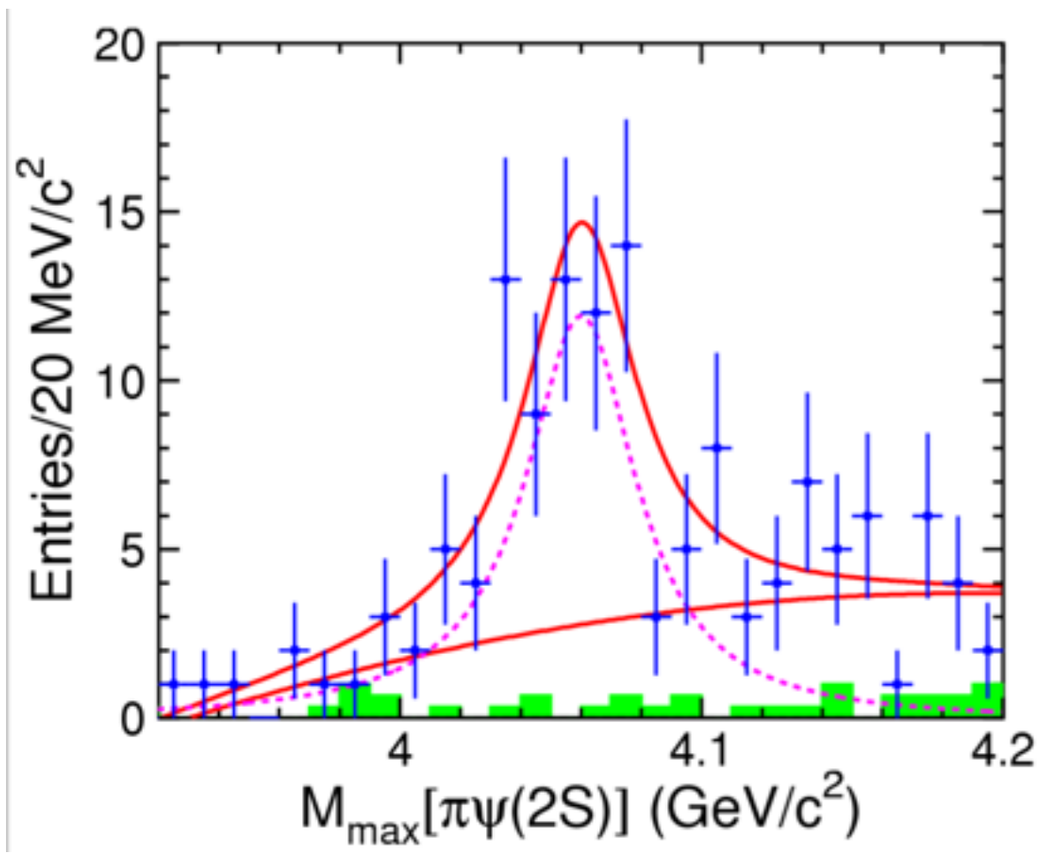
$M = 4051(30)$
$\Gamma = 82(51)$
$M = 4248^{+185}_{-45}$
$\Gamma = 177^{+113}_{-72}$
$J^{PC} = ?$

.manifestly exotic
.dubious



R. Mizuk et al. [Belle], PRD76, 072004 (08)

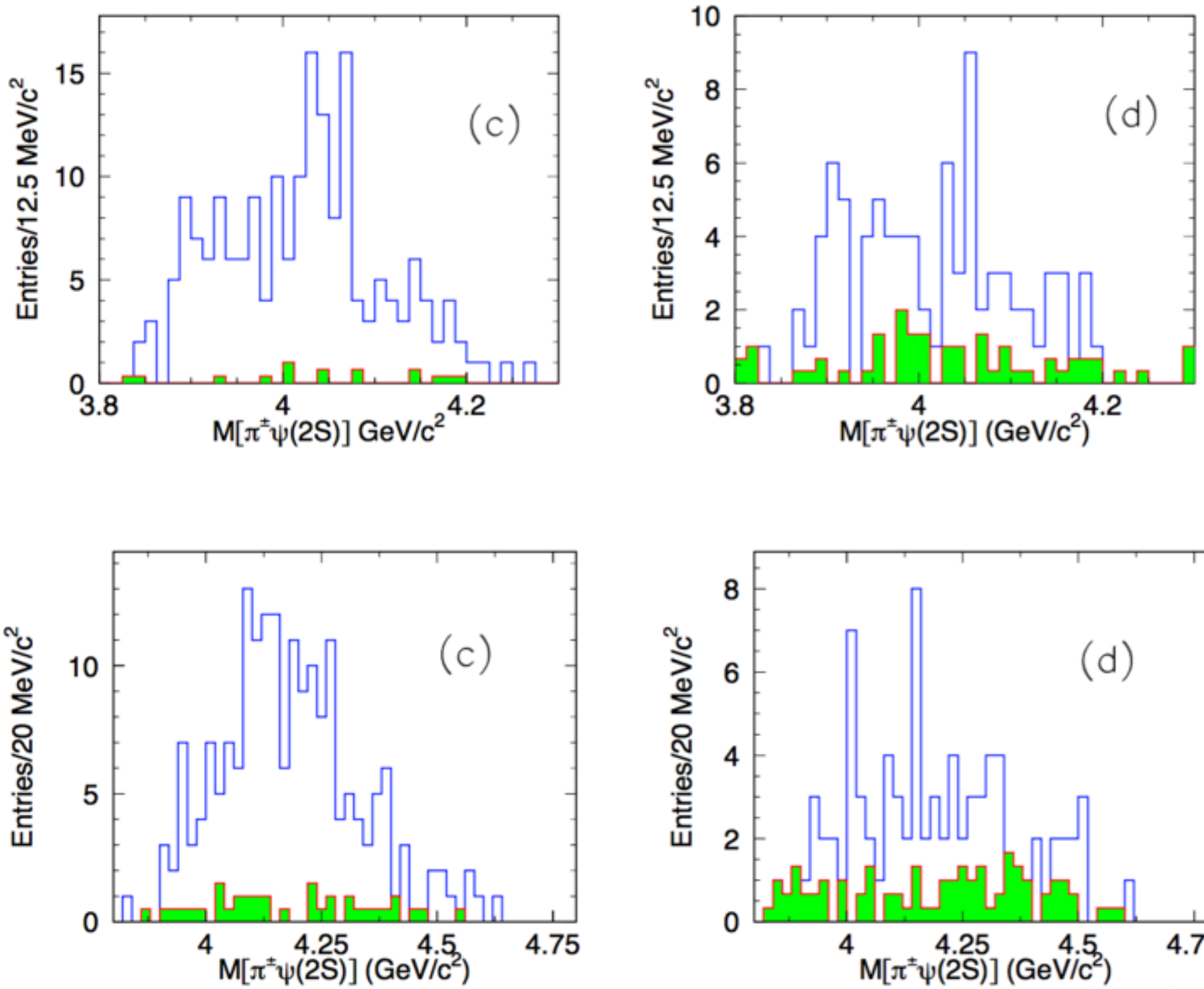
$Z_1(4050)$



from Y(4360)

[Belle] 1410.7641

$Z_1(4050)$



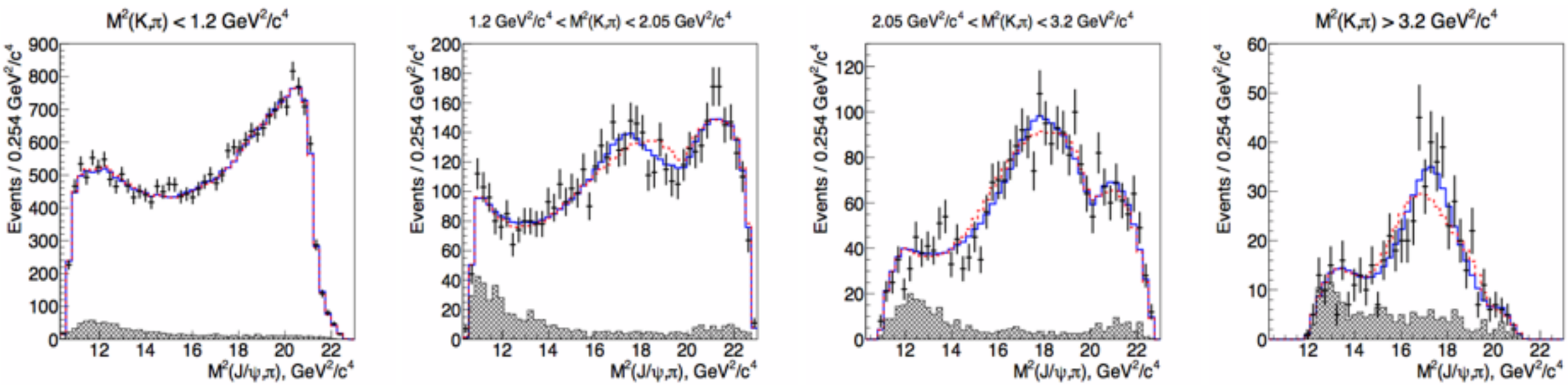
Y(4360)

Y(4660)

[Belle] 1410.7641

$Z_c(4200)$

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

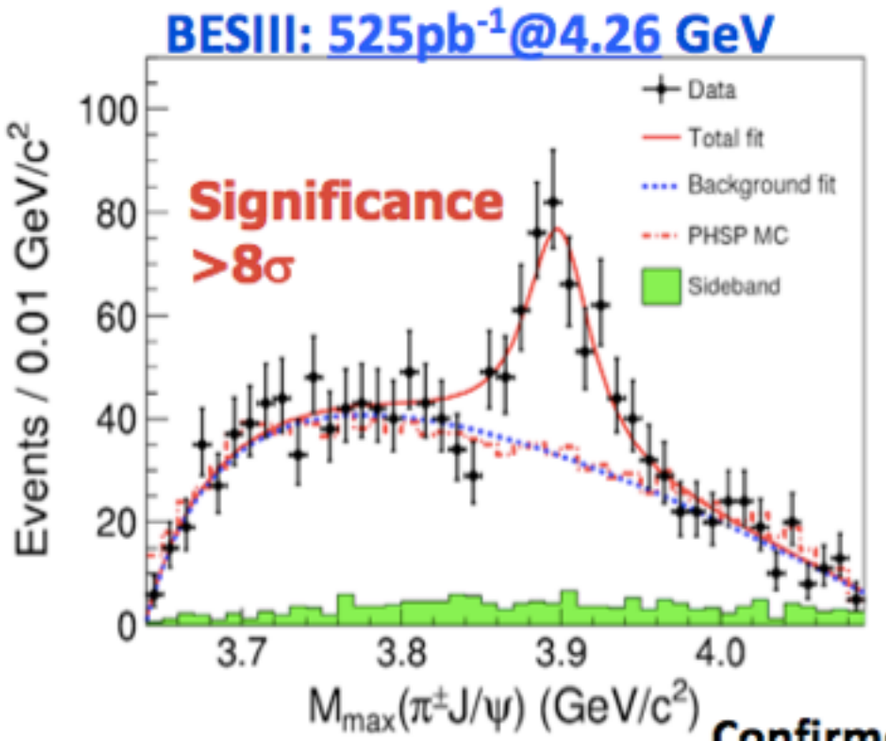


dotted: without Zc(4200)

K. Chilikin et al. [Belle] 1408.6457

$Z_c(3900)$

Observation of Zc(3900) at BESIII

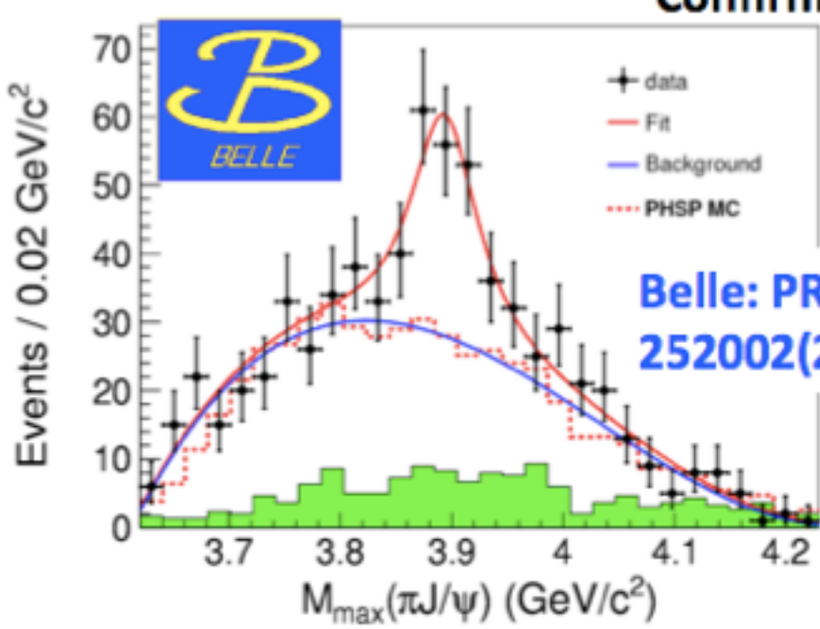


BESIII: PRL110, 252001 (2013)

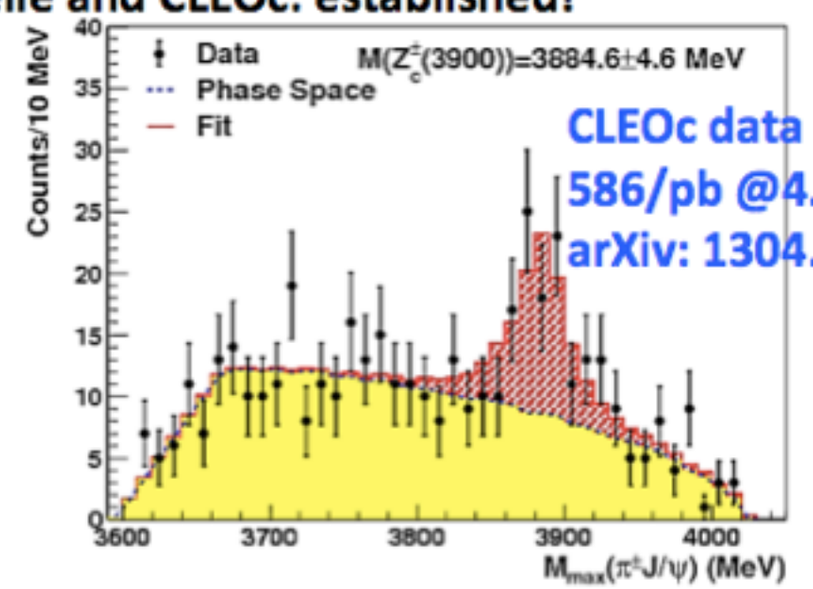
- M = 3899.0±3.6±4.9 MeV
- Γ = 46±10±20 MeV
- 307 ± 48 events

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

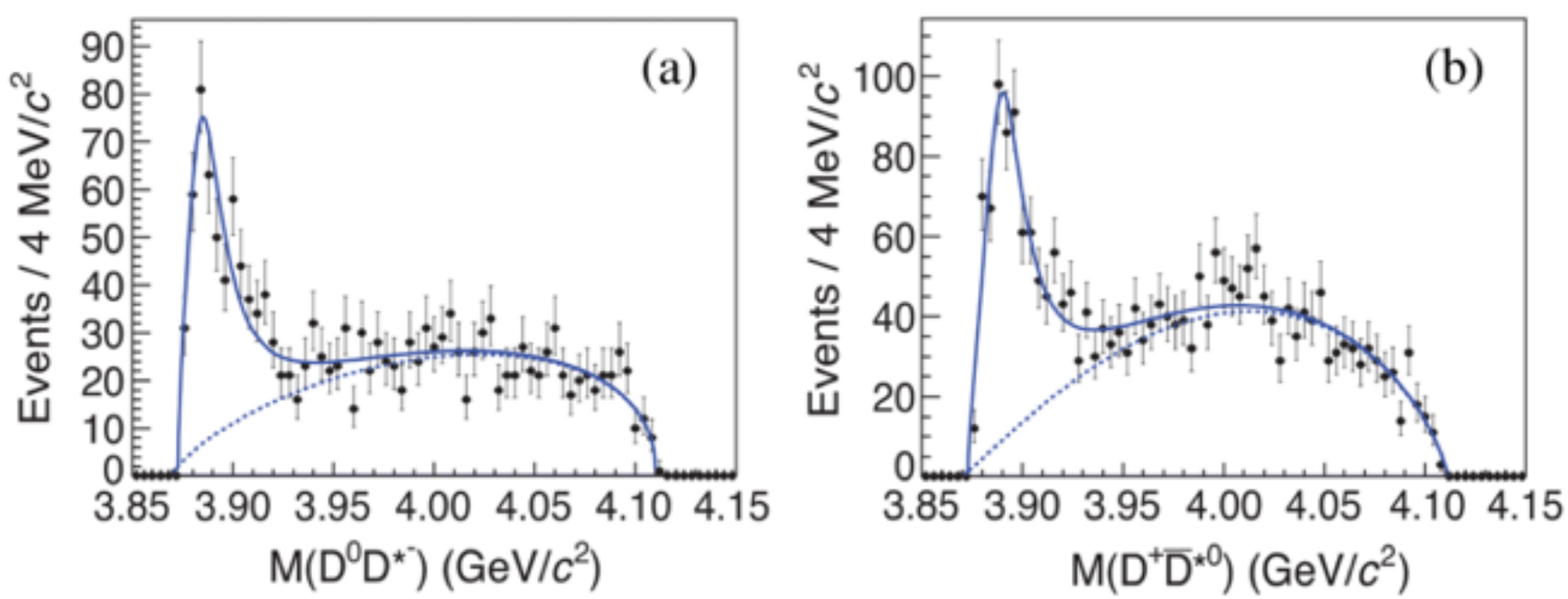
Shuangshi Feng [BESIII] H13

$Z_c(3900)$

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

$$M = 3883.9 \pm 1.5 \pm 4.2$$

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



BESIII PRL112 022001 (14)

$Z_c(4025)$

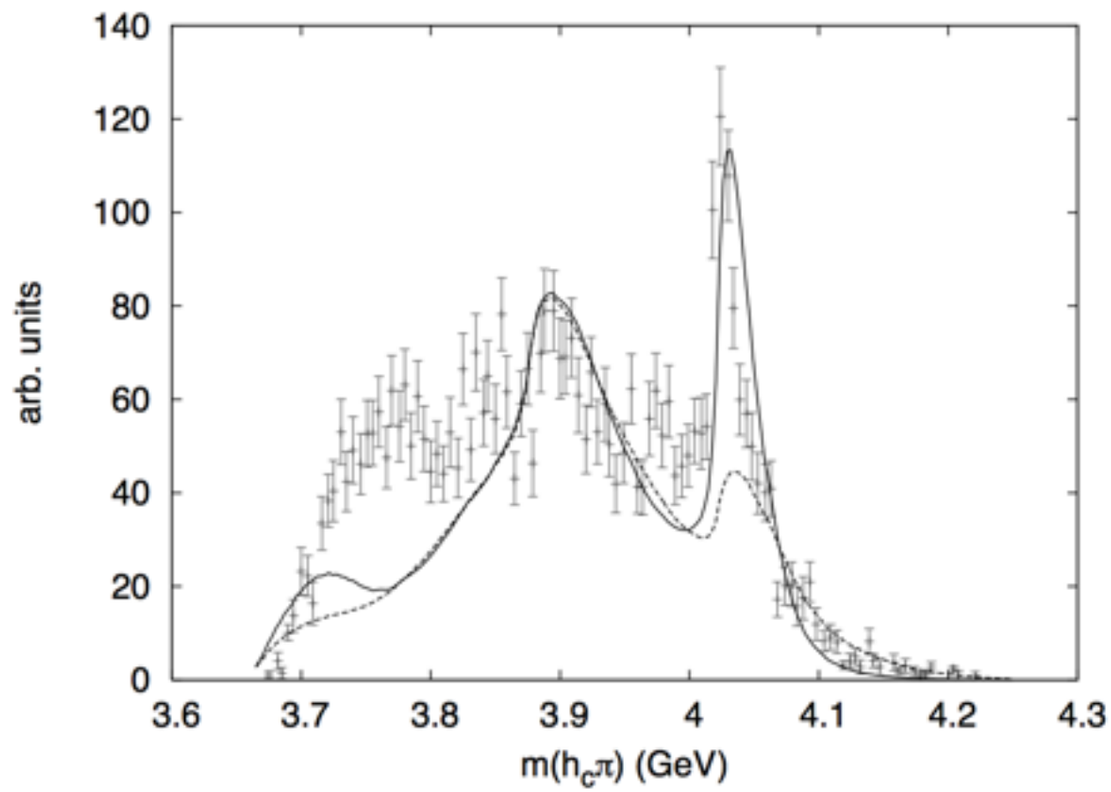
$e^+e^- \to \pi^+\pi^- h_c$

sums 13 different ee energy values

"no significant Zc(3900) observed"

$M = 4022.9 \pm 0.8 \pm 2.7$

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



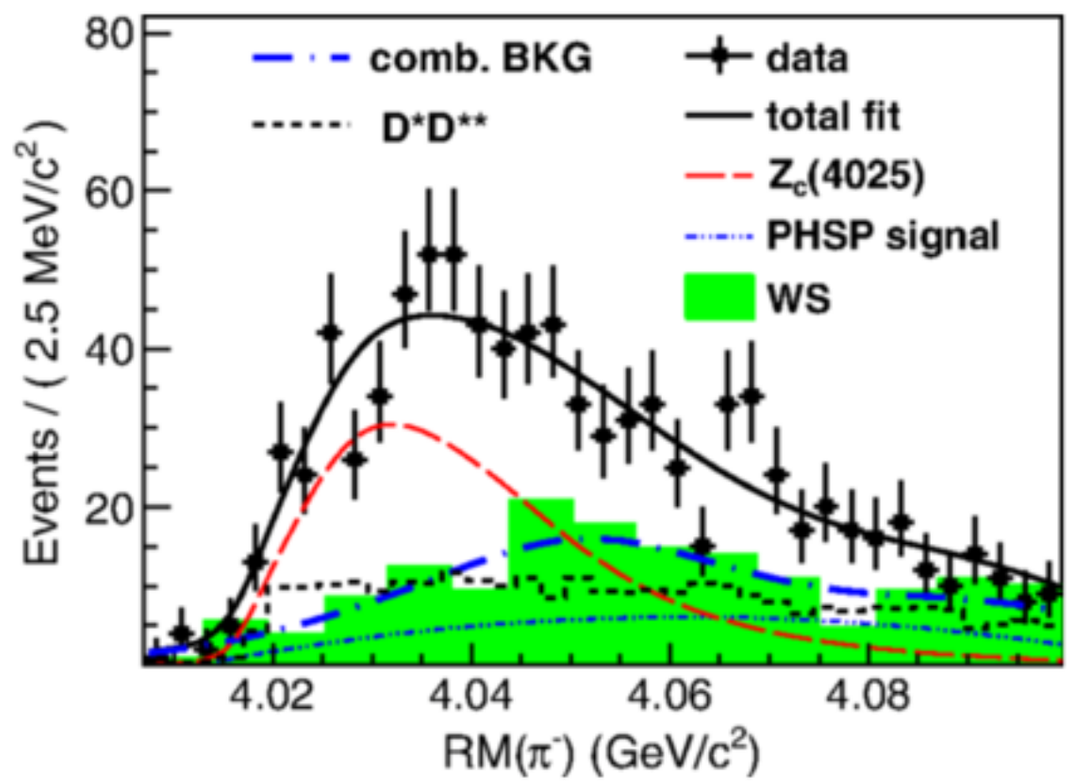
BESIII Phys. Rev. Lett. 111, 242001 (2013).

$Z_c(4025)$

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

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

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



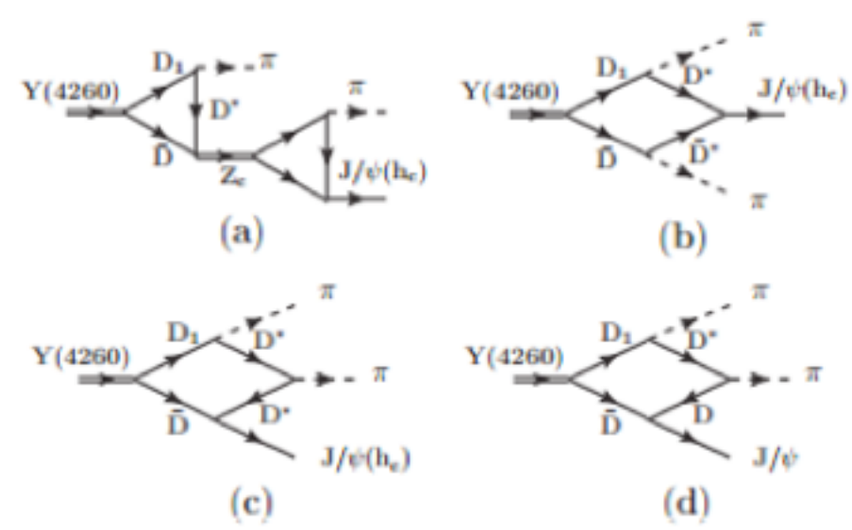
BESIII Phys. Rev. Lett. 112, 132001 (2014)

Zc(3900)
Zc(4025)

Theory

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. ...

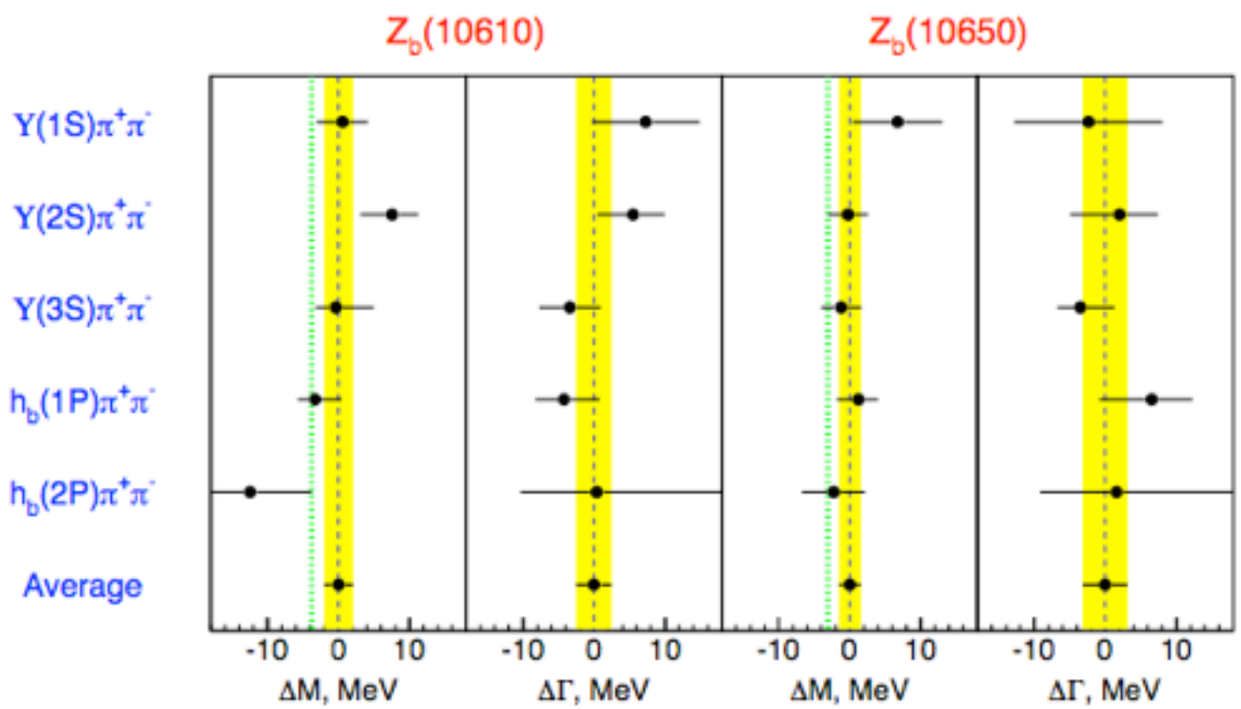


Meson loop

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

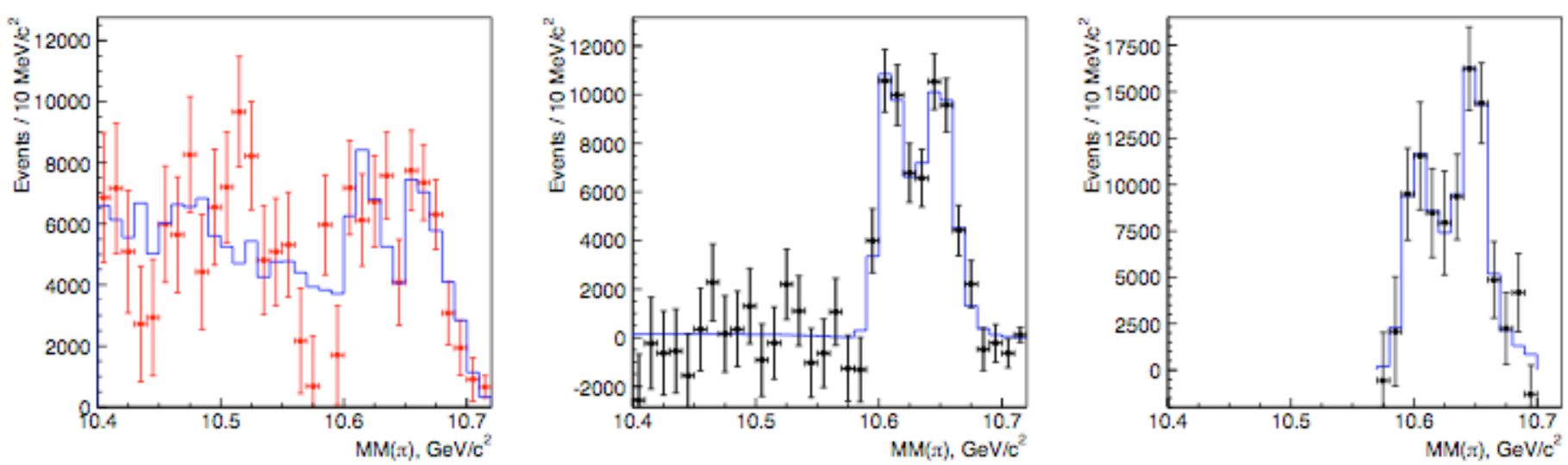
Adachi et al. [Belle] 1105.4583

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

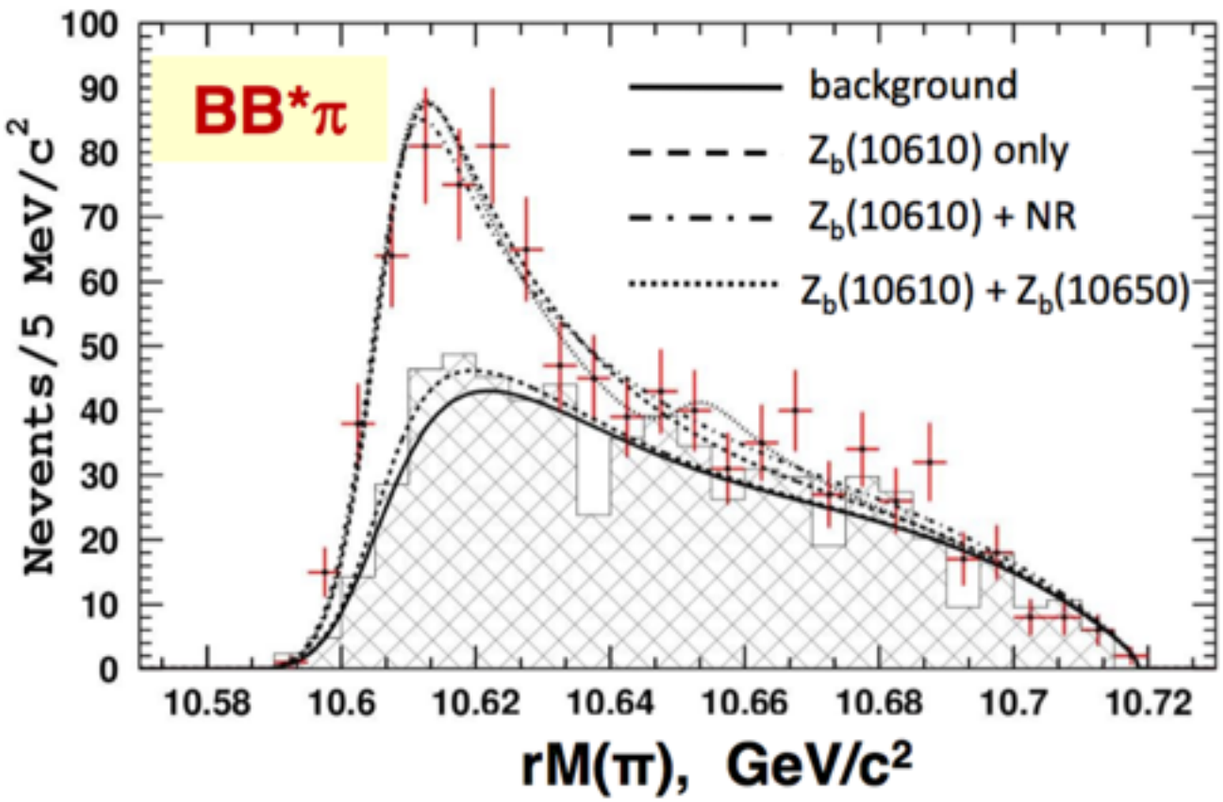


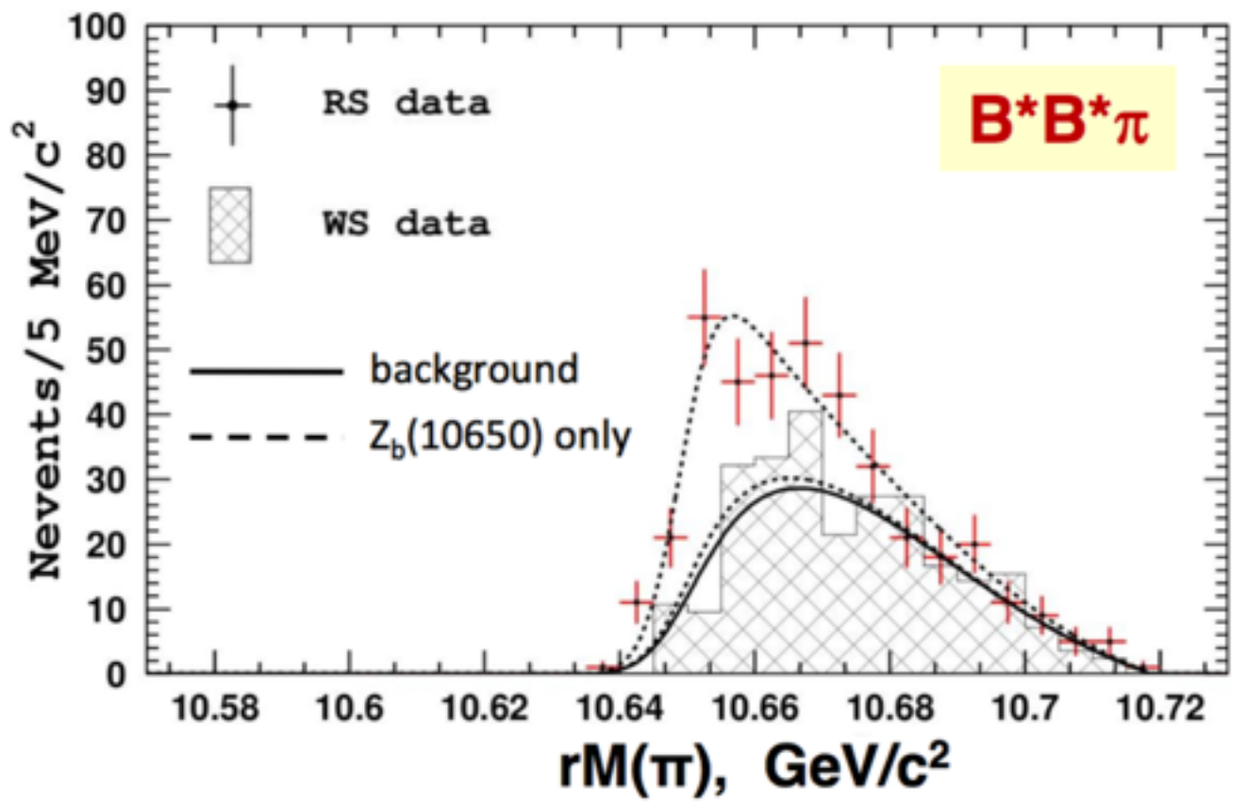
$$\Upsilon(5S) \to \pi\pi\Upsilon(nS)$$

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



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



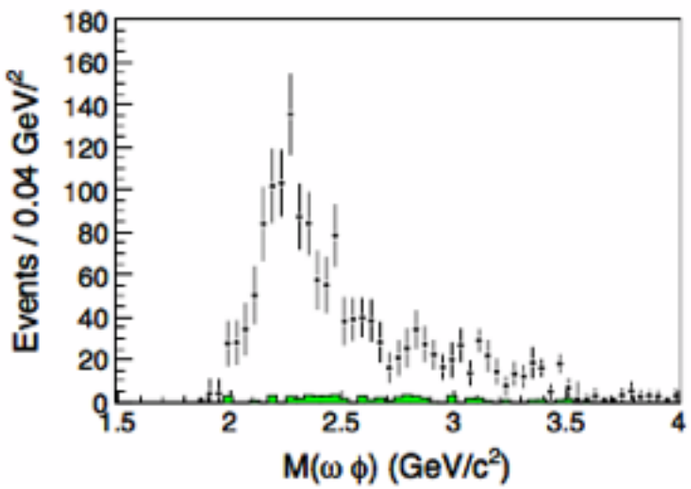


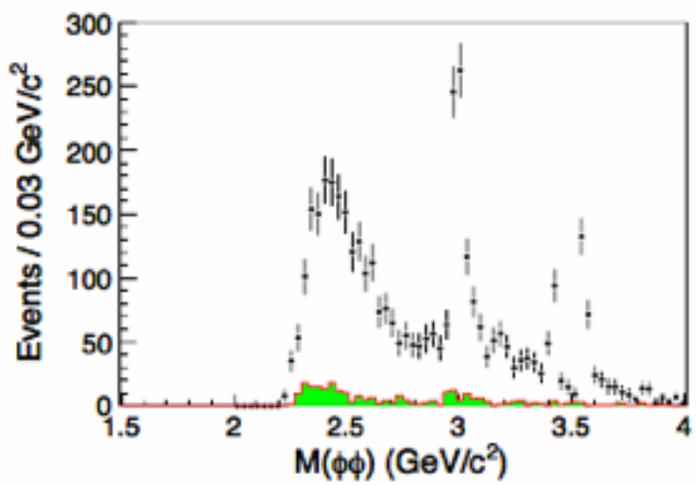
[Belle] preliminary [C.-Z. Yuan, INT Nov 2015]

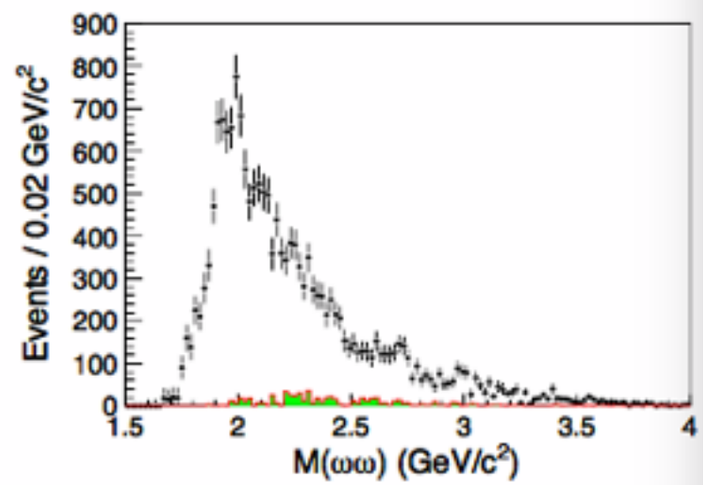
Modelling the Zs

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

Modelling the Zs







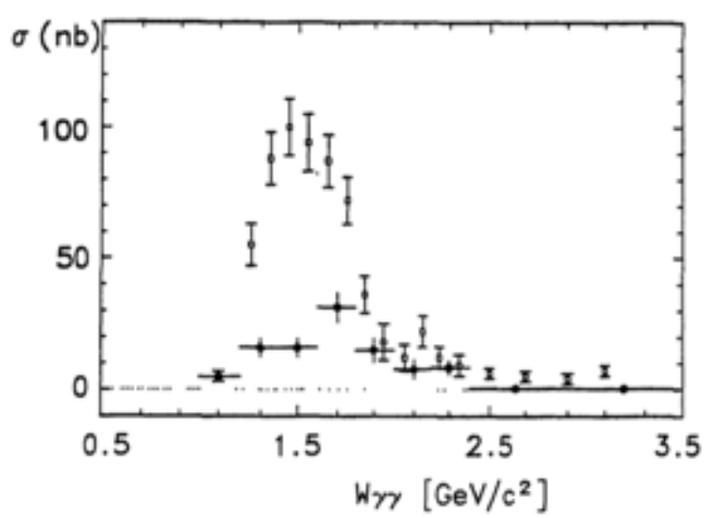
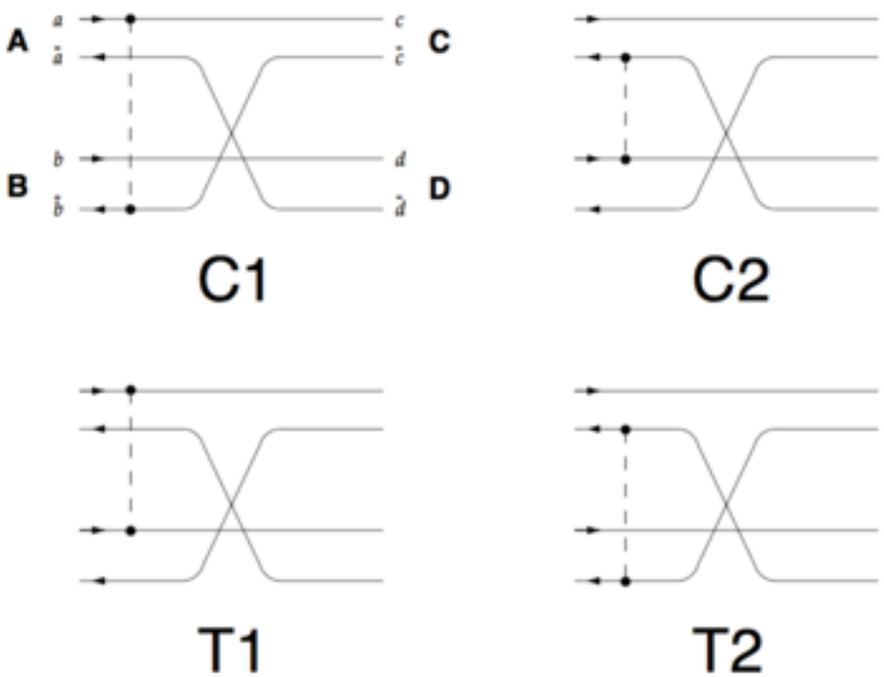


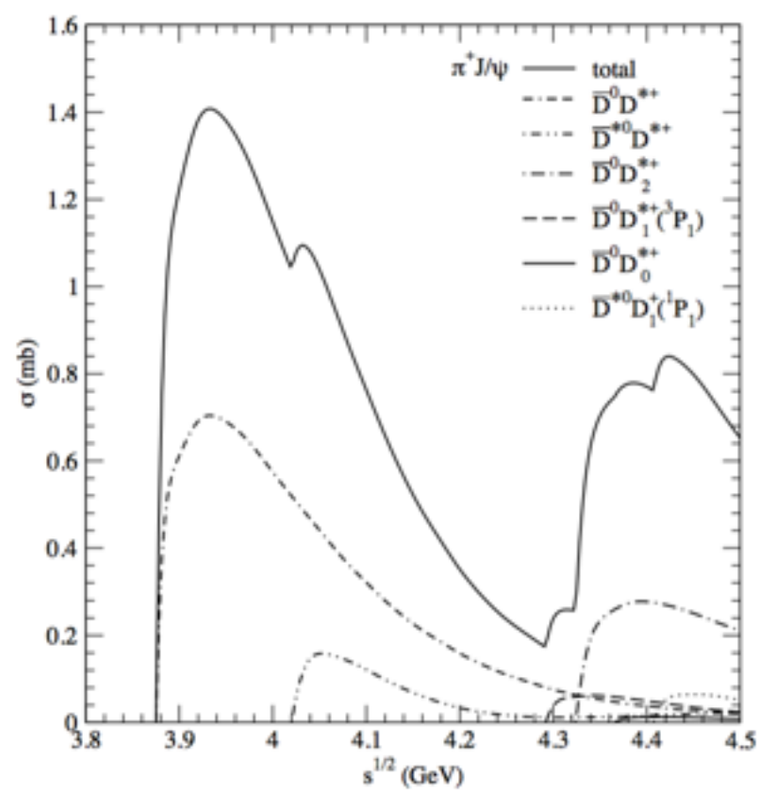
Figure 5.2: Comparison of the $\gamma\gamma \to \rho\rho$ measured cross sections. The reaction $\gamma\gamma \to \rho^0\rho^0$ is presented as squares and is the measurement by PLUTO [11] and the reaction $\gamma\gamma \to \rho^+\rho^-$ as full dots.

Modelling the Zs

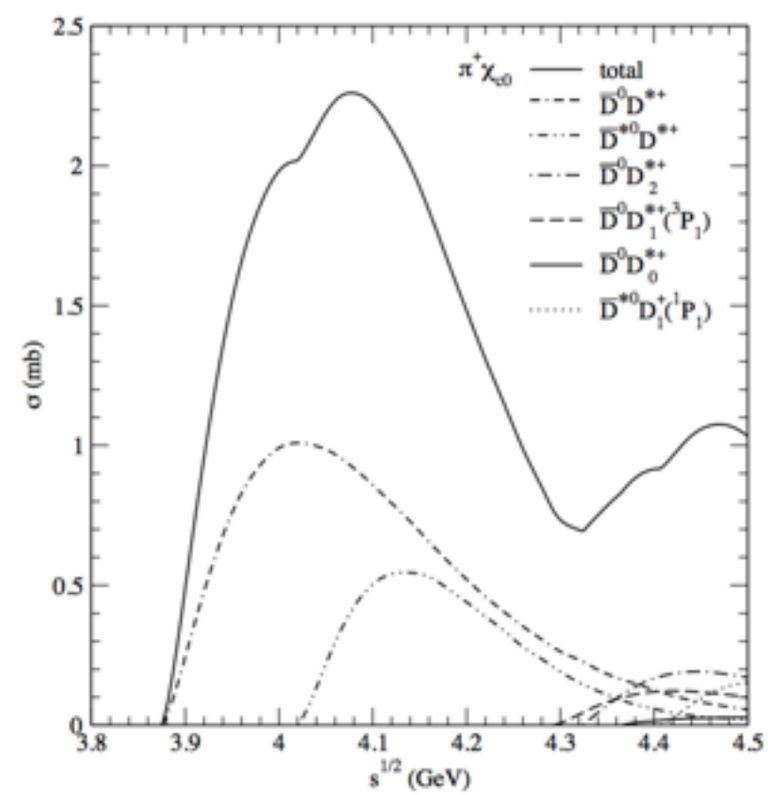


A Quark Model Example

S-wave



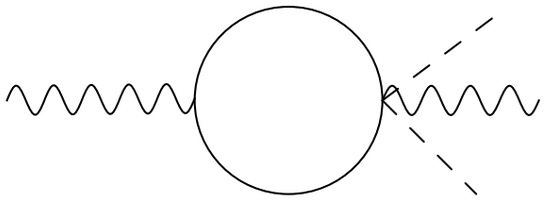
P-wave



Modelling the Zs — Cusps

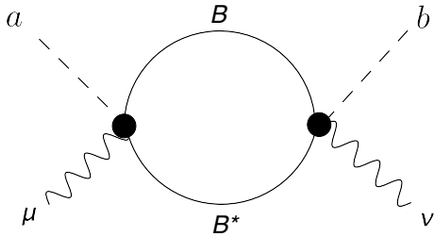
Q: how does Υ(5S) couple to Υππ?

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



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

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



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

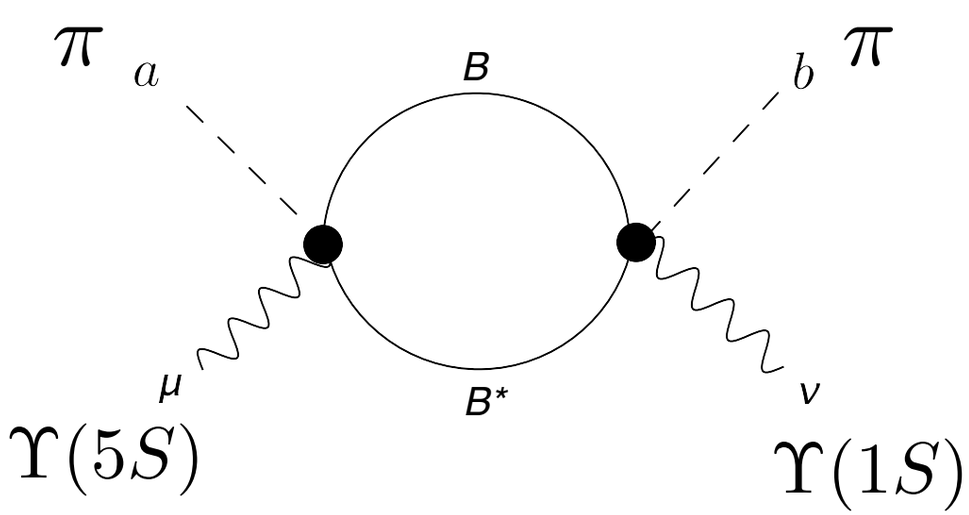
Modelling the Zs — Cusps

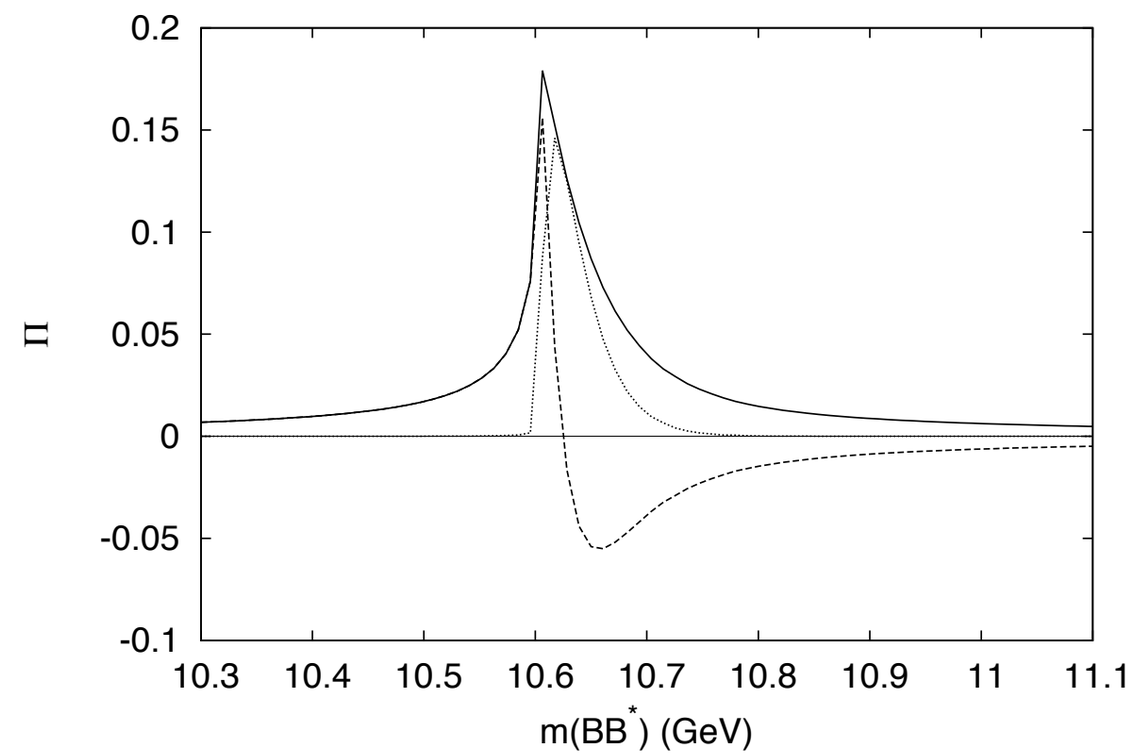
E.P. Wigner, Phys. Rev. 73 (1948) 1002

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



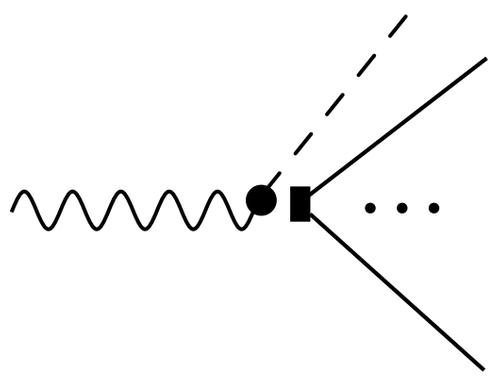


[NB: this exhibits phase motion!]

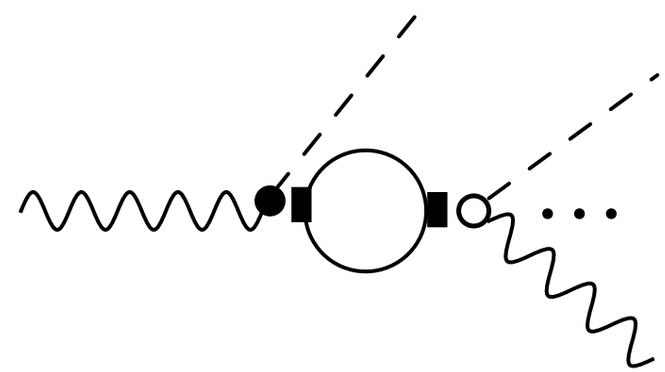
E.S. Swanson, arXiv:1504.07952

Modelling the Zs — Cusps

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



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



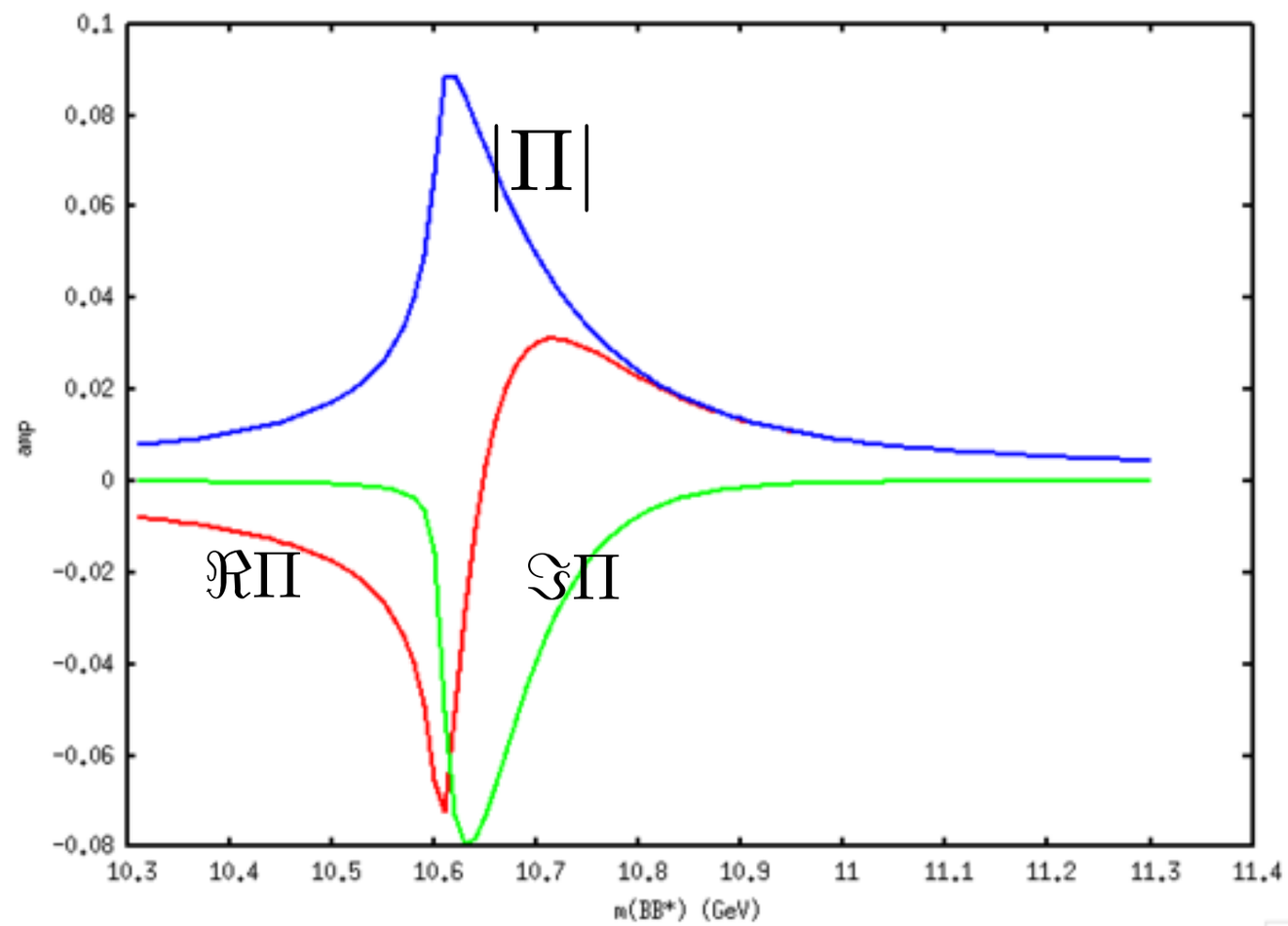
$Y(4260) \to \pi\pi J/\psi$

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

Modelling the Zs — Cusps

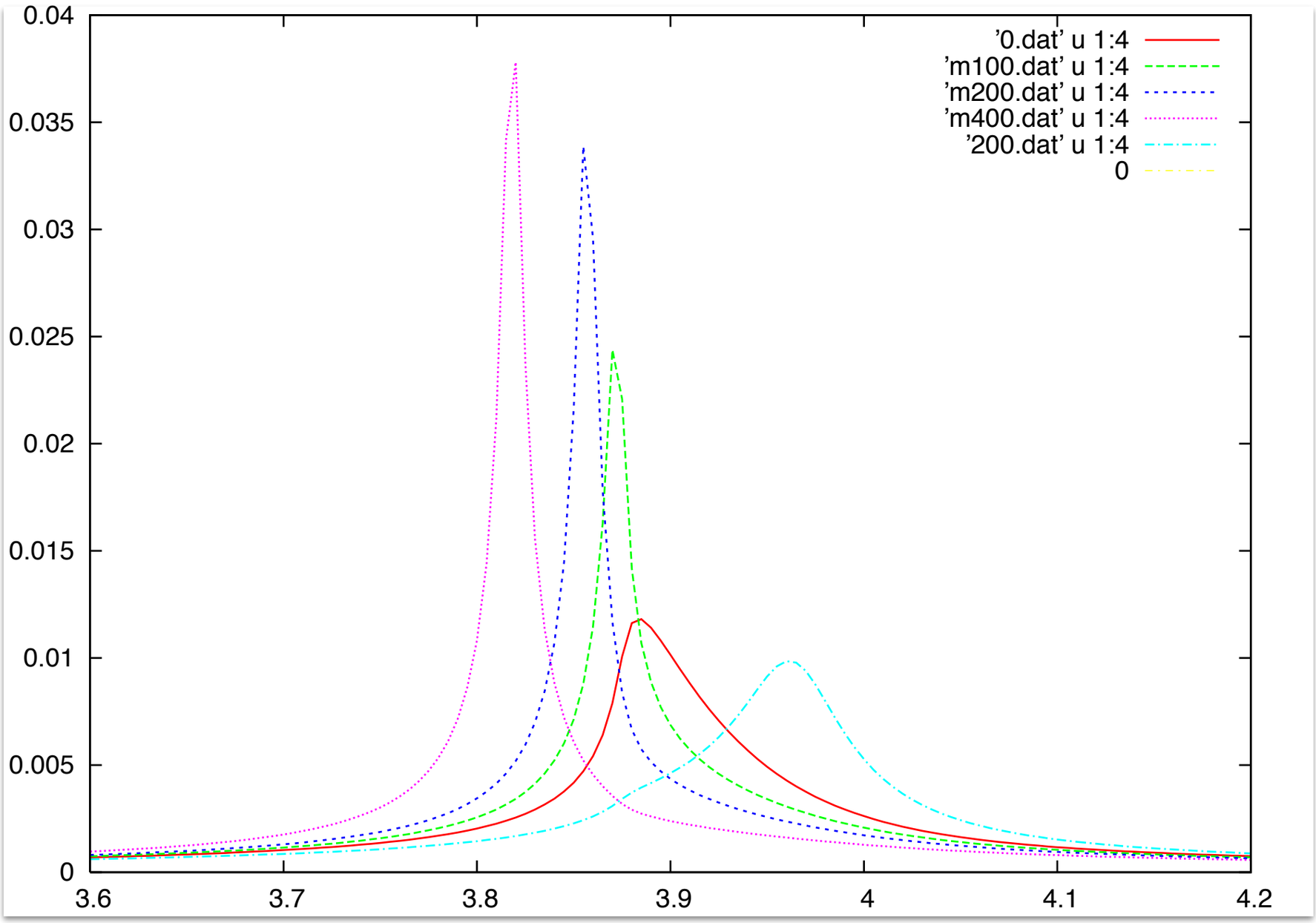
$$\Pi = \int \frac{d^3q}{(2\pi)^3} \frac{\mathrm{e}^{-q^2/\Lambda^2}}{E - m_B - m_{B^*} - q^2/2\mu + i\epsilon}$$

$\Lambda = 0.5$ GeV



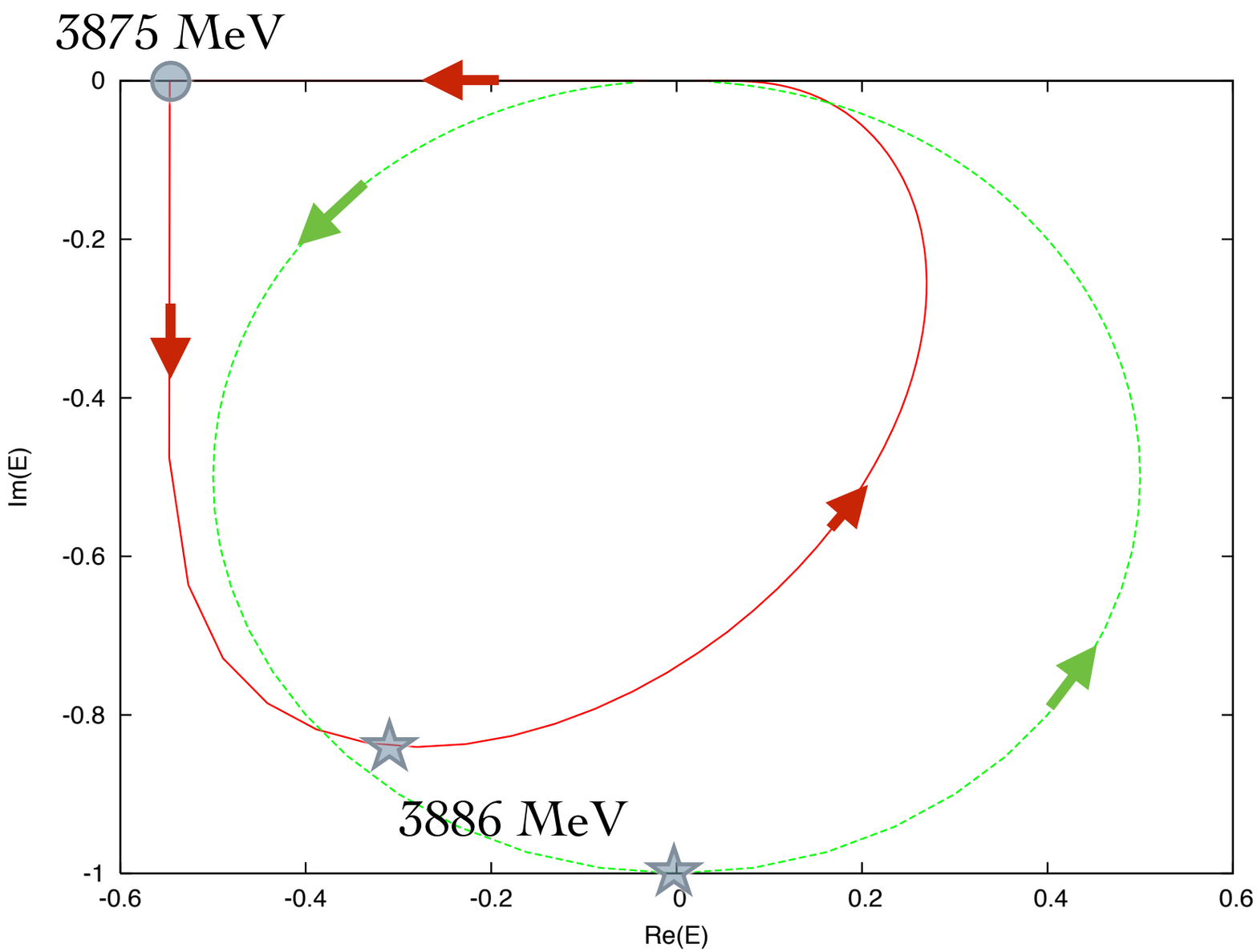
Modelling the Zs — Cusps

effect of the bubble sum



Modelling the Zs — Cusps

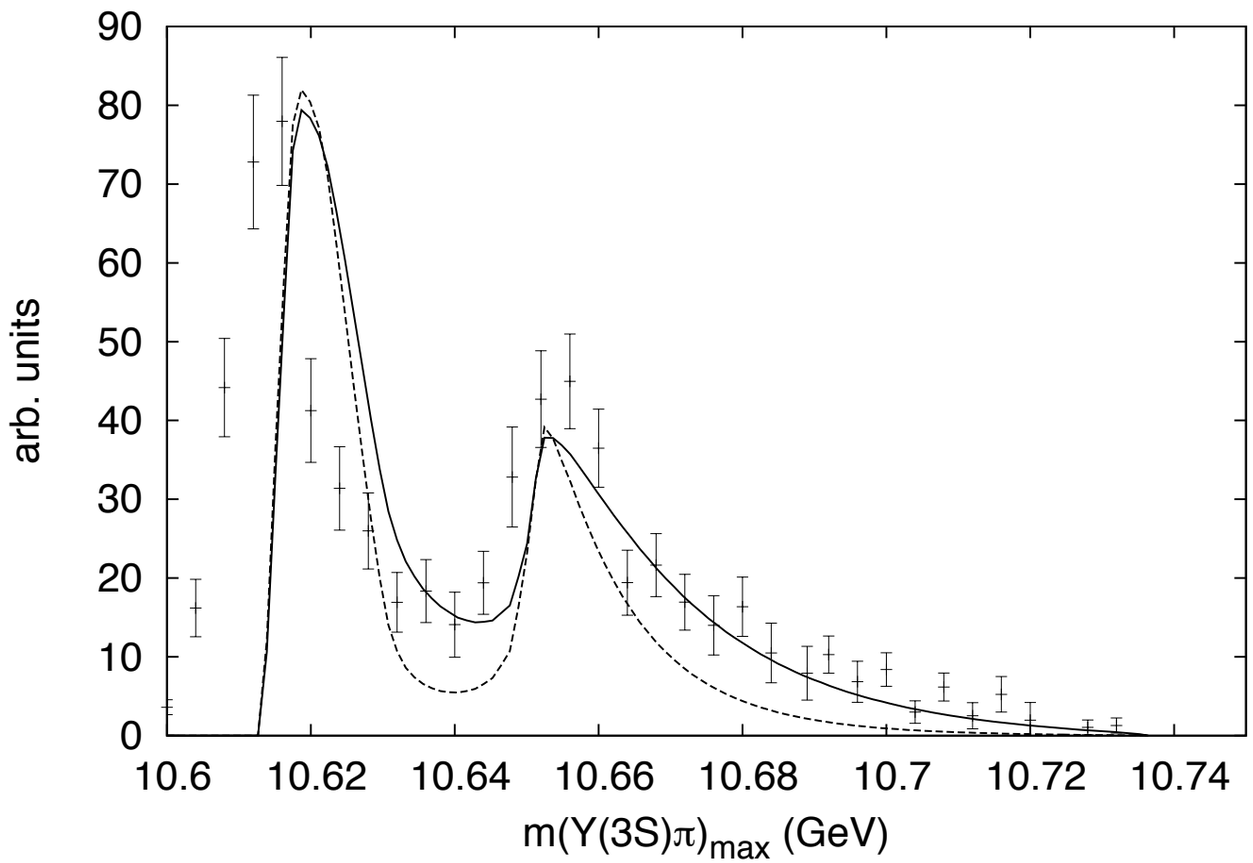
phase motion



Modelling the Zs — Cusps

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

Zb(10610), Zb(10650)



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

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

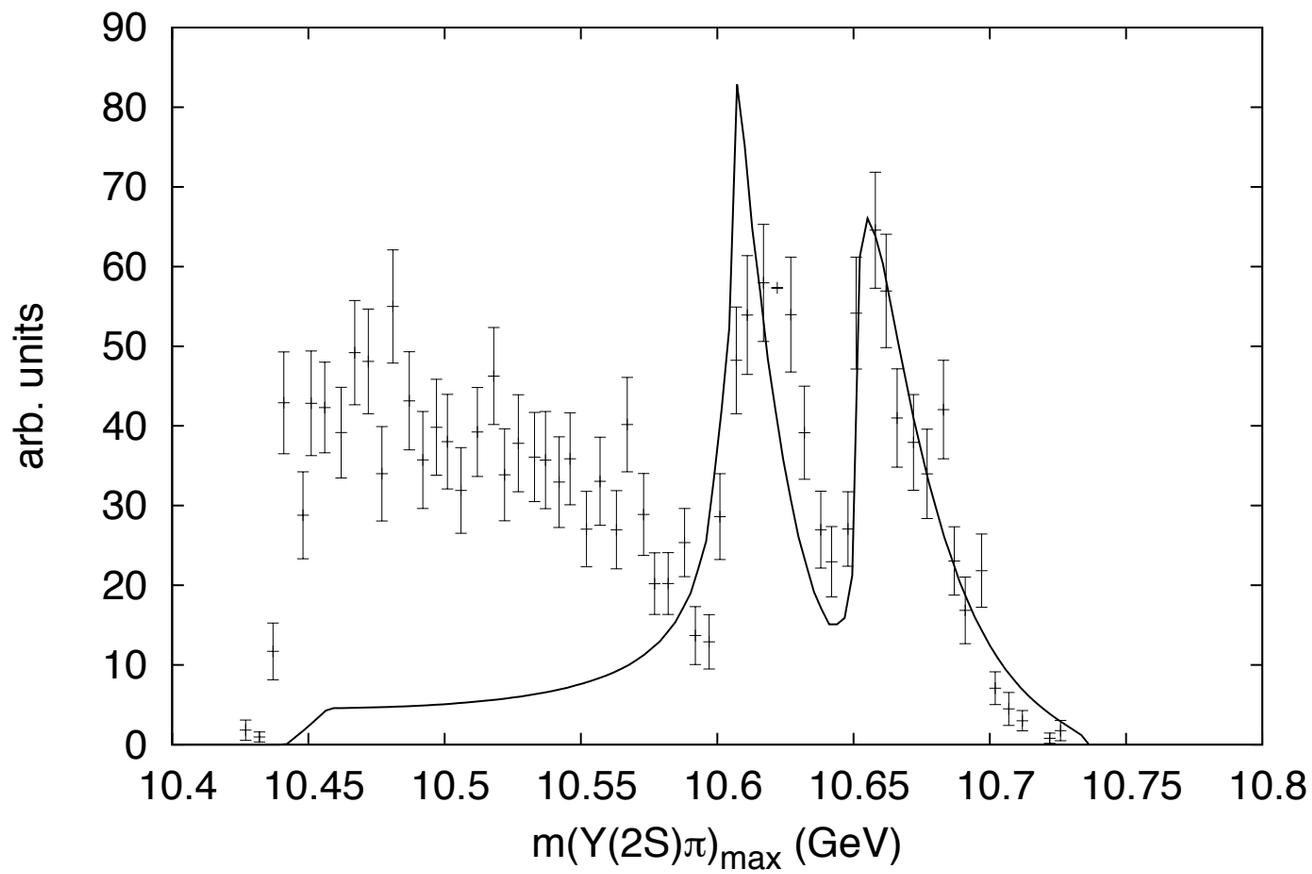
Adachi et al. [Belle Collaboration], arXiv:1105.4583 [hep-ex];

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!

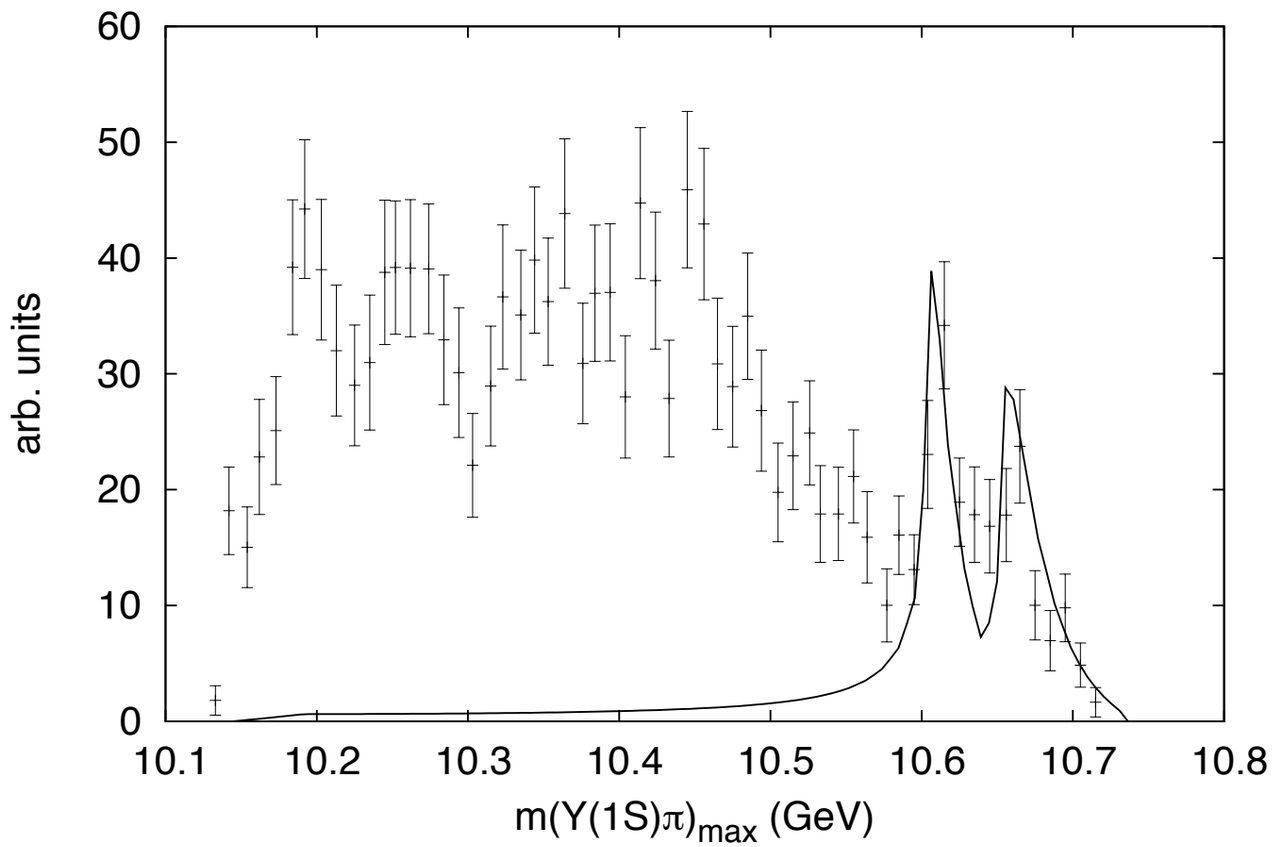
Adachi et al. [Belle Collaboration], arXiv:1105.4583 [hep-ex];

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

Modelling the Zs — Cusps

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

Zb(10610), Zb(10650)



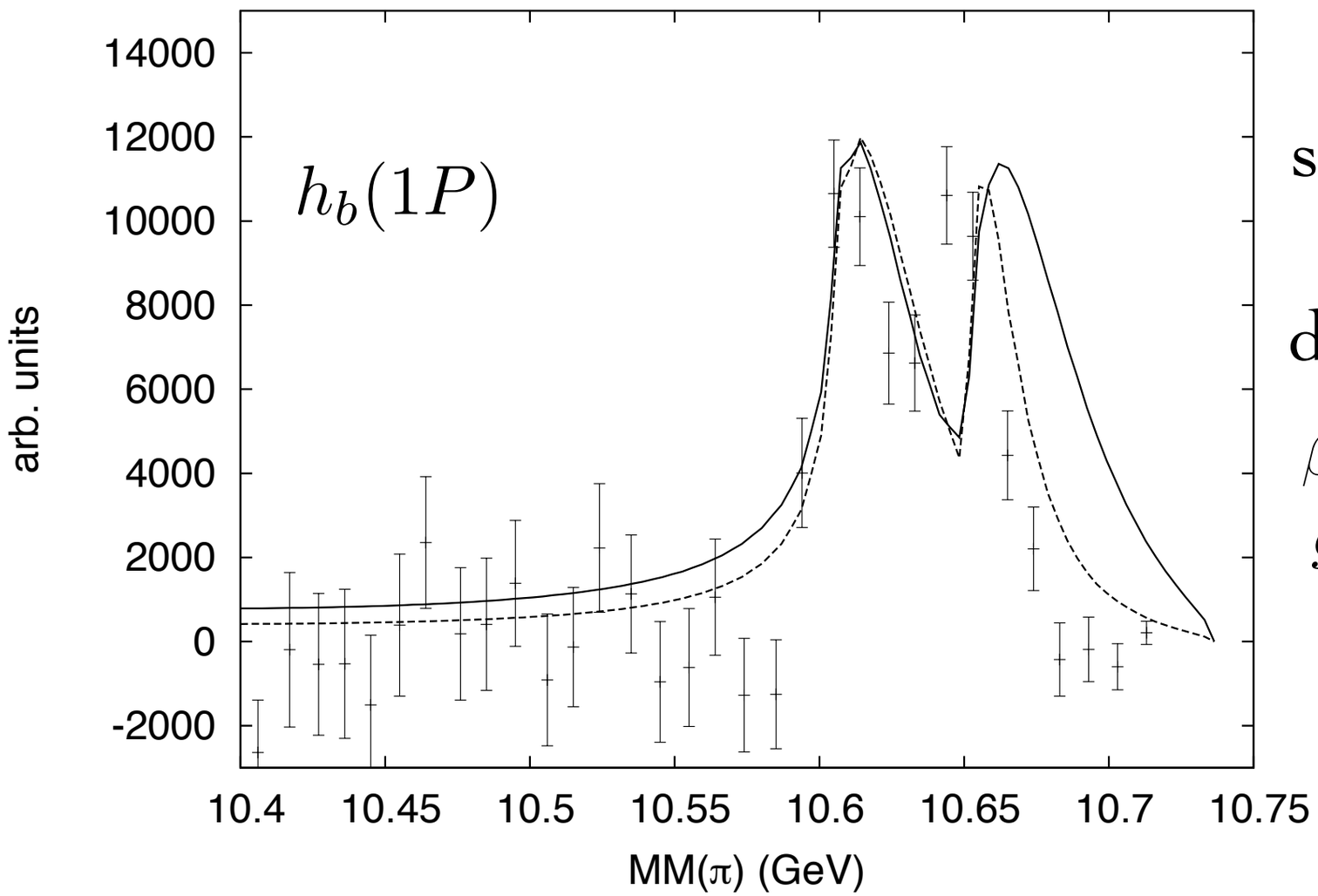
30% smaller coupling required

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

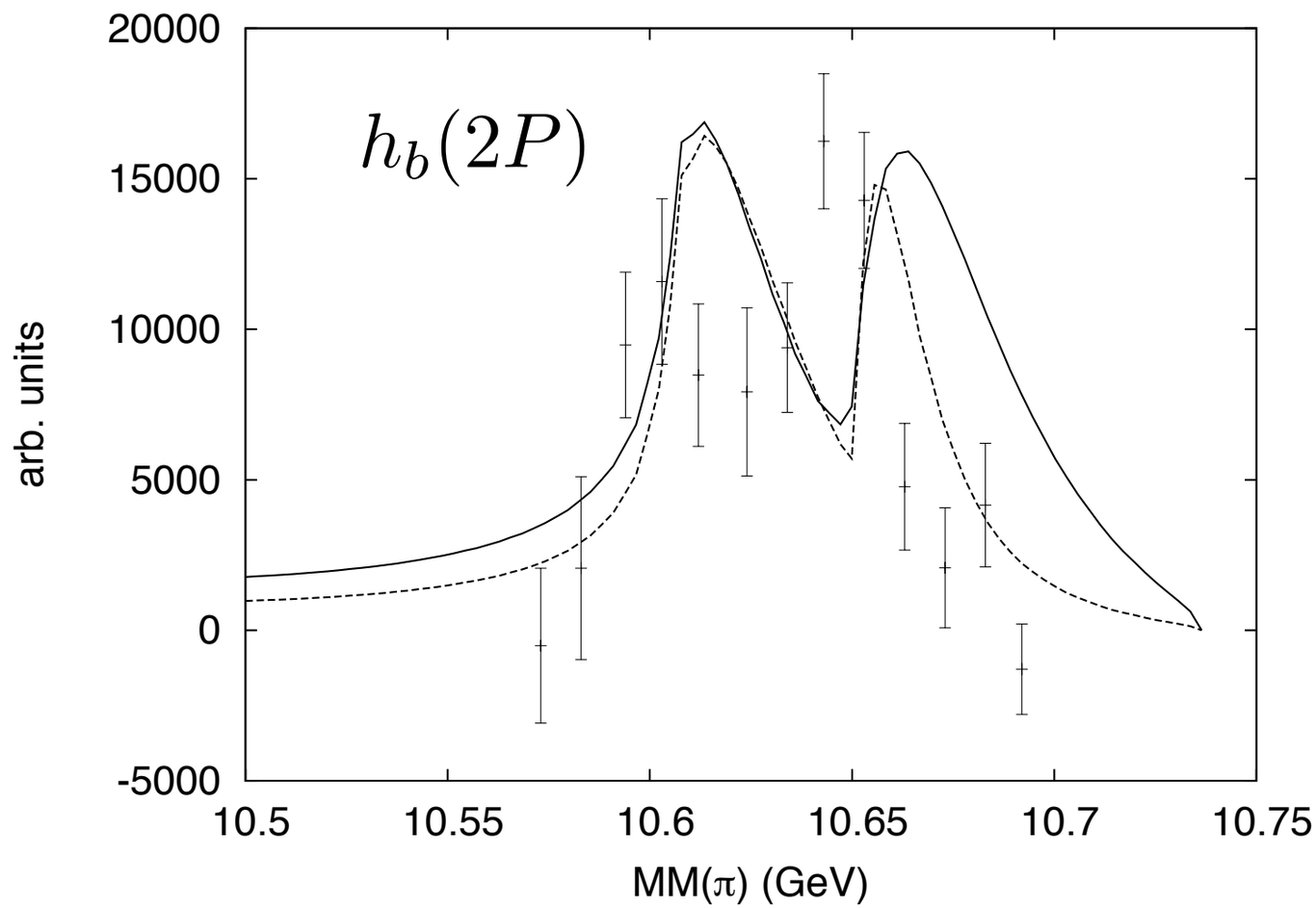
dashed line:

$\beta_{BB^*} = 0.7$ GeV, $\beta_{B^*B^*} = 0.4$ 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

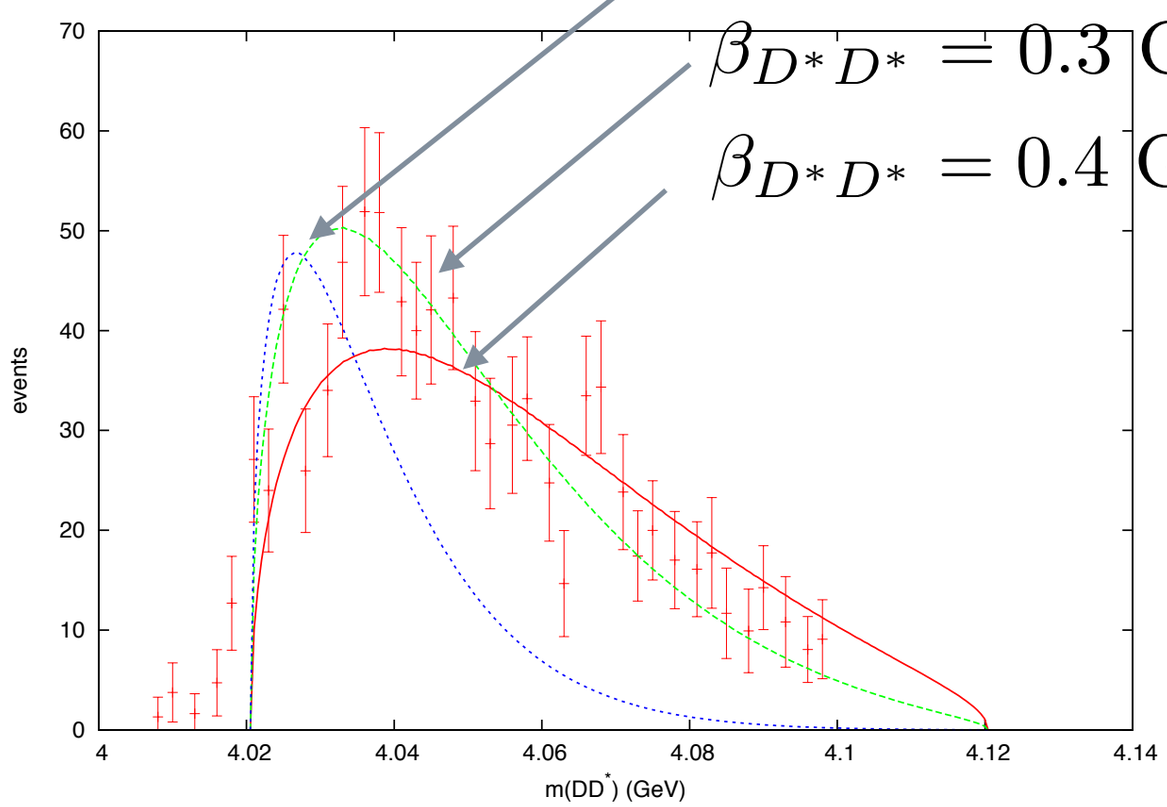
fit the pi Y: D*D* vertex

attractive bubble

$\beta_{D^*D^*} = 0.2$ GeV

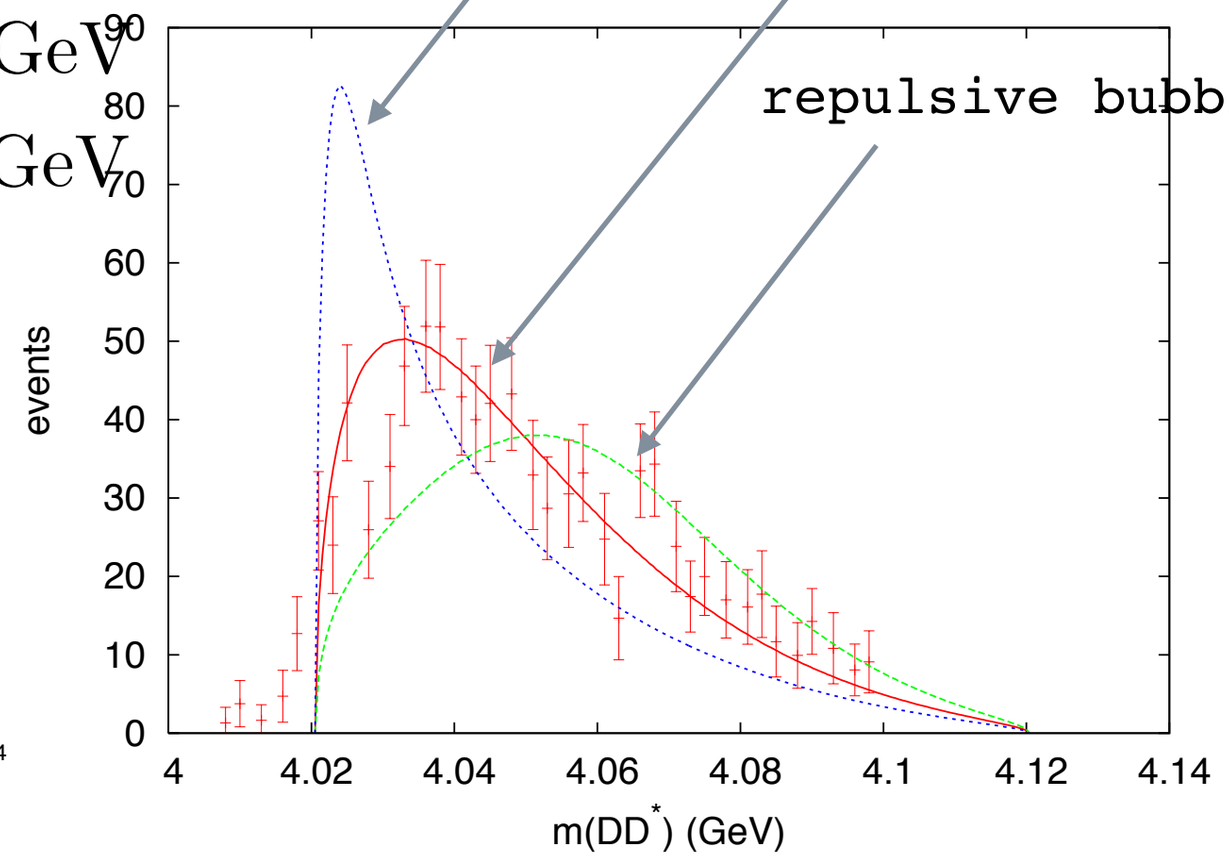
$\beta_{D^*D^*} = 0.3$ GeV

$\beta_{D^*D^*} = 0.4$ GeV



$\beta_{D^*D^*} = 0.3$ GeV

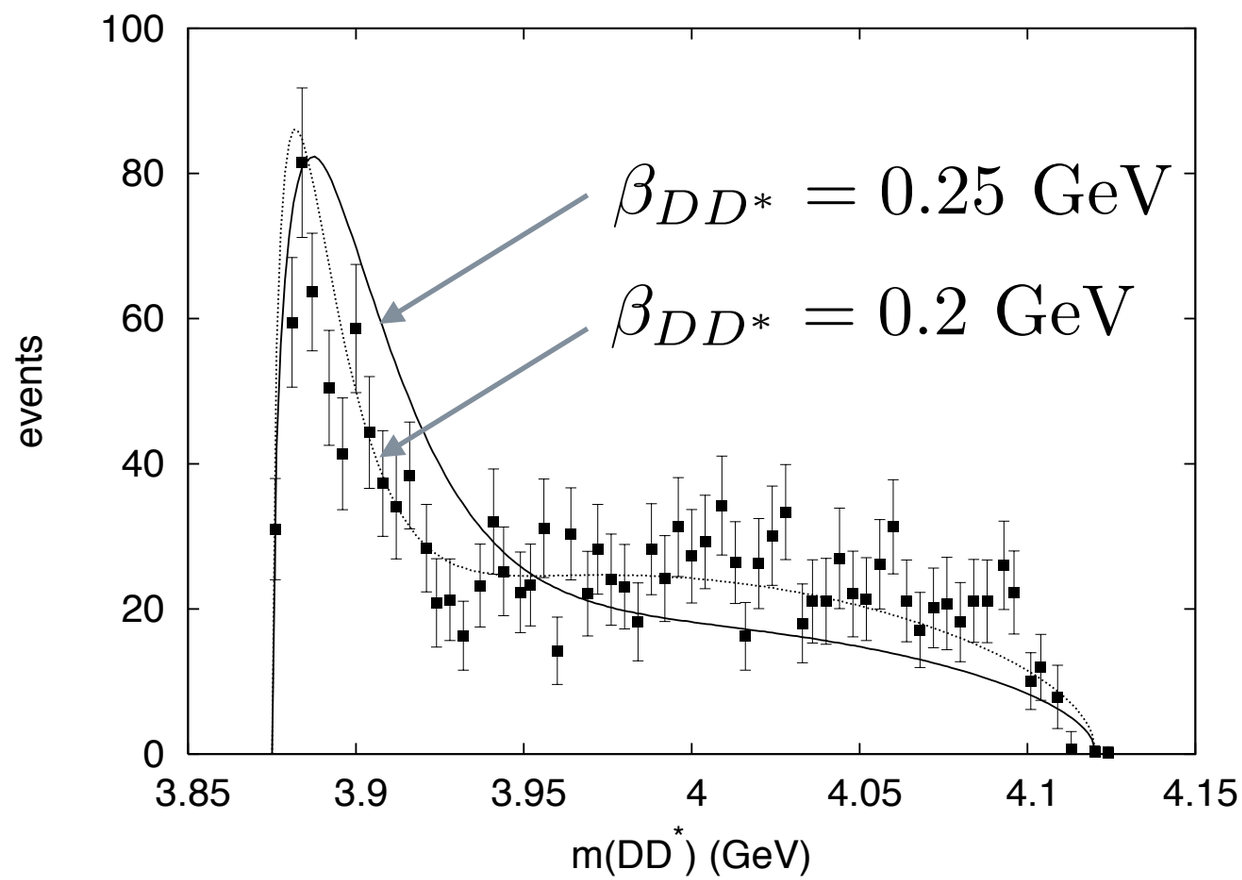
repulsive bubble

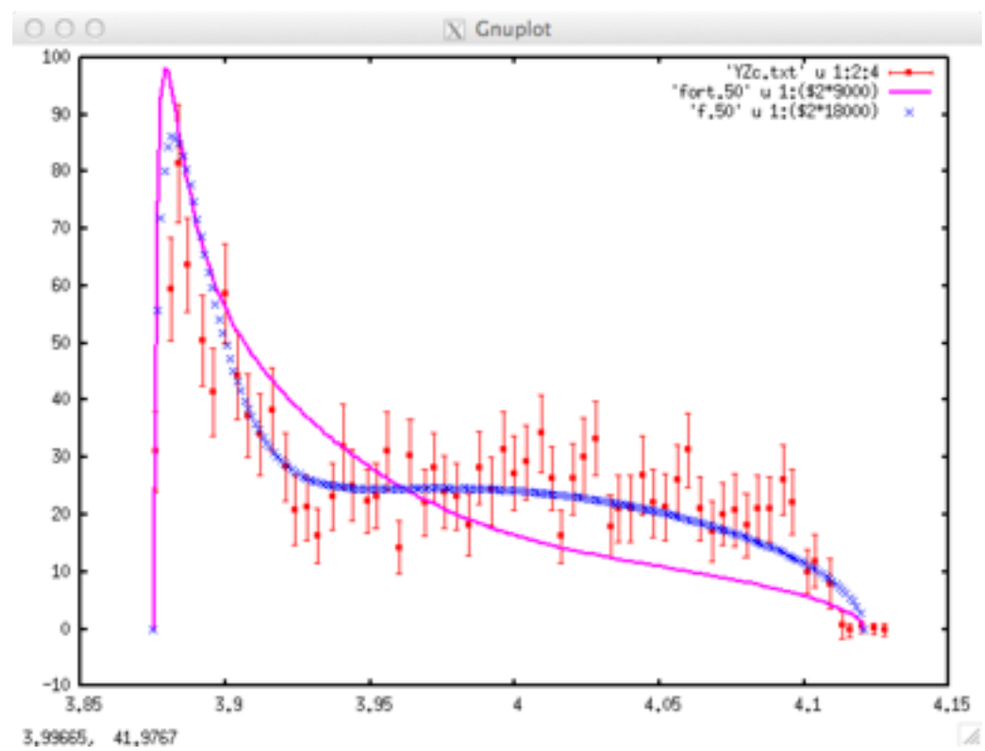


no evidence for π D* dynamics, background, or bubble

Modelling the Zs — Cusps

fit the pi Y: DD* vertex



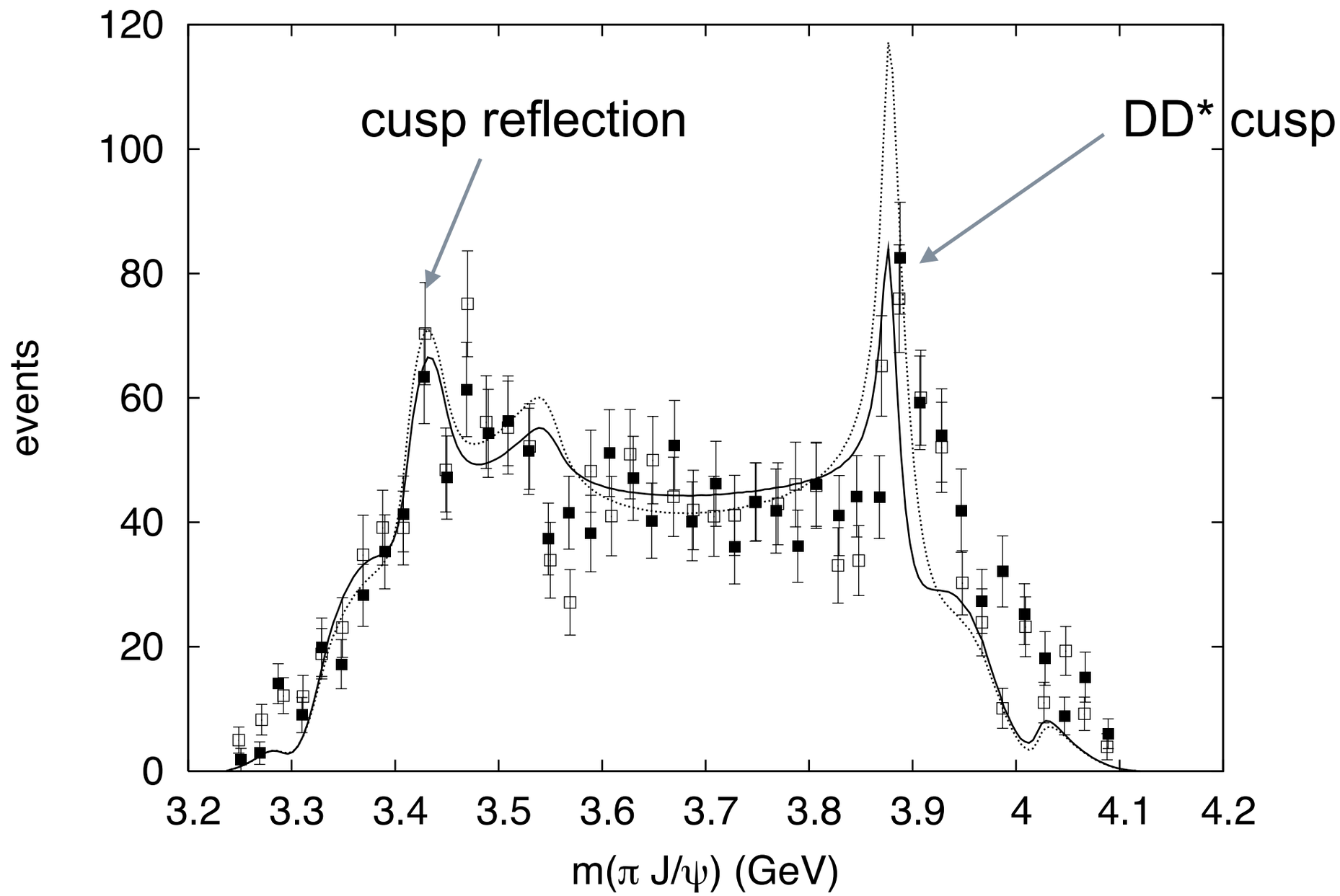


no evidence for bubble

evidence for incoherent background

Modelling the Zs — Cusps

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



BESIII

Modelling the Zs — Cusps

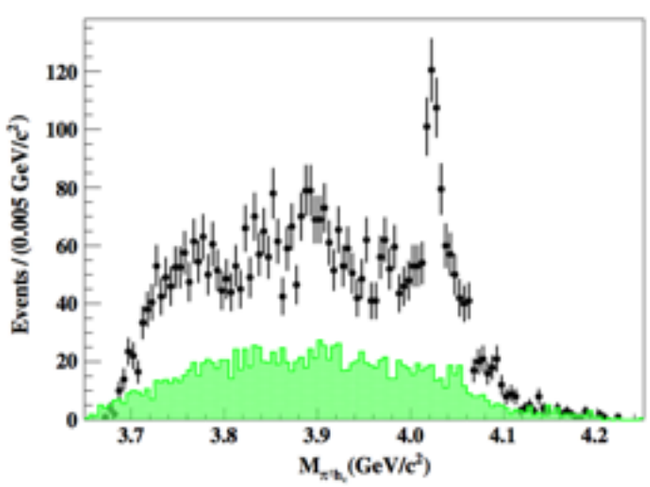
M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 111, 242001 (2013).

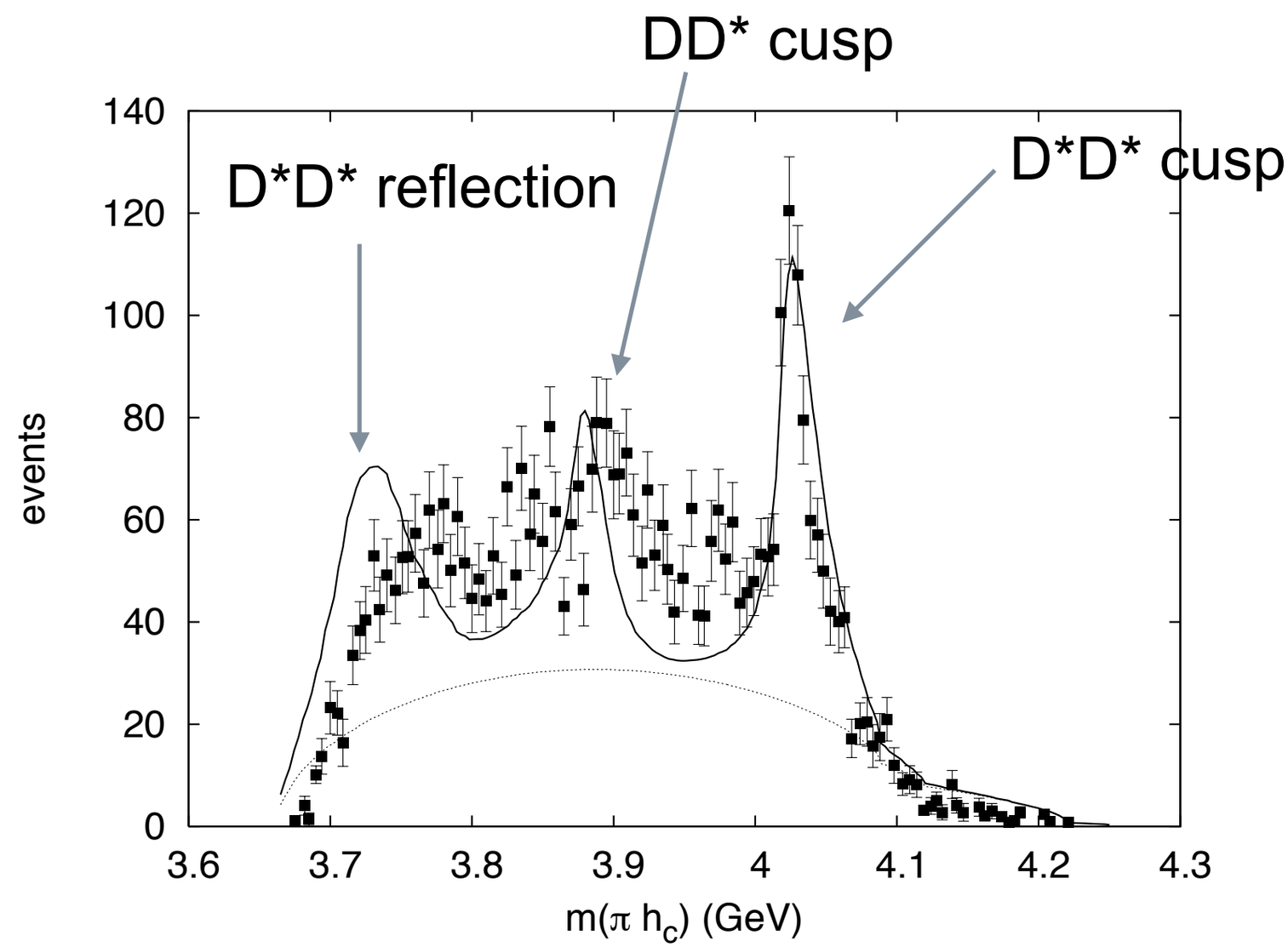
$e^+e^- \to \pi^+\pi^- h_c$

sums 13 different ee energy values

"no significant Zc(3900) observed"

[incoherent background only]





Modelling the Zs — Issues with Cusps

- this should happen a lot (?)
- what is going on with B decays?

Modelling the Zs — Issues with Cusps

other cusp channels?

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

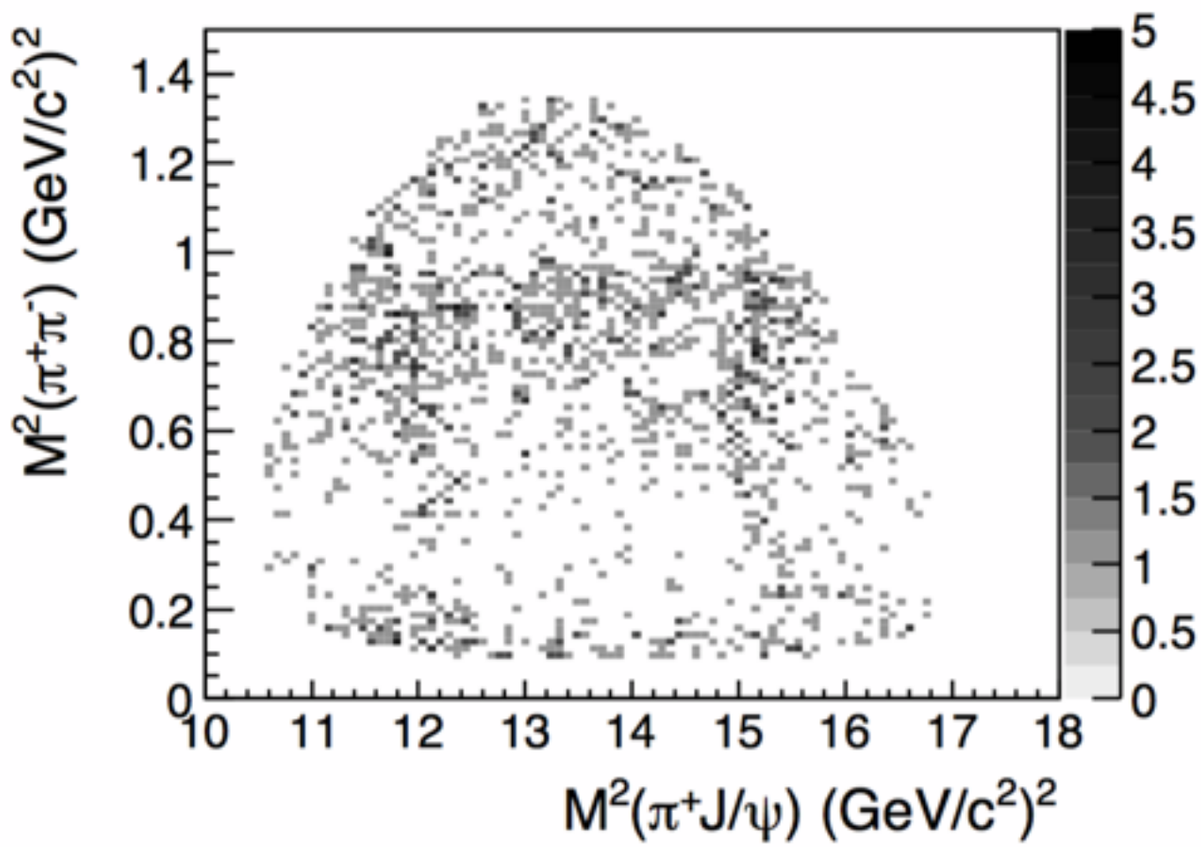
$B\bar{B}_s^* + B^*\bar{B}_s$	10695
$B^*\bar{B}_s^*$	10745

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

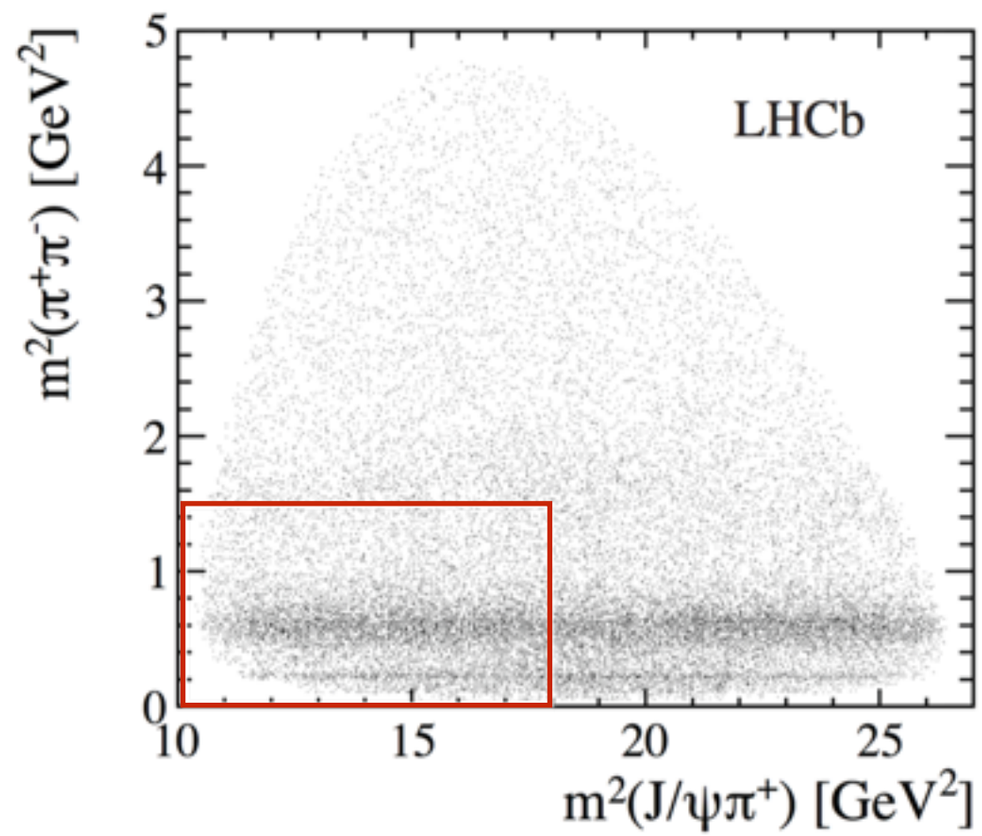
$D\bar{D}_s^* + D^*\bar{D}_s$	3980
$D^*\bar{D}_s^*$	4120

Modelling the Zs — Issues with Cusps

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

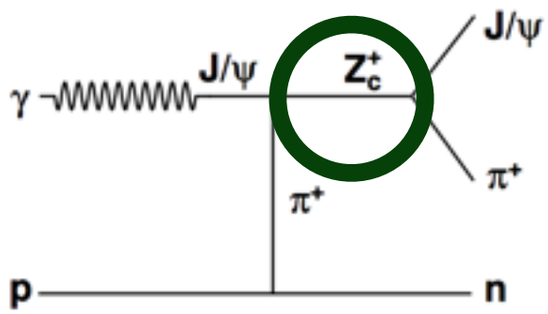


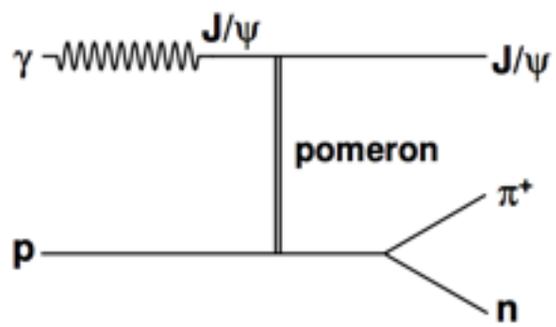
$B_0 \to \pi^+\pi^- J/\psi$



Modelling the Zs — Issues with Cusps

COMPASS



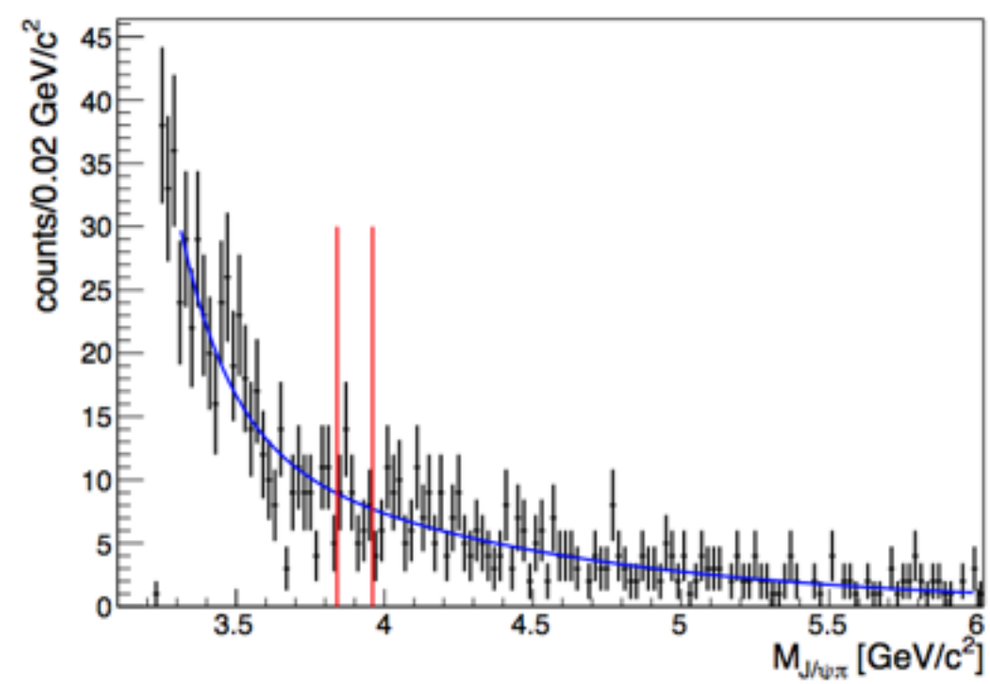


$$\sqrt{s_{\gamma N}} = 7 \text{ GeV}$$

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

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

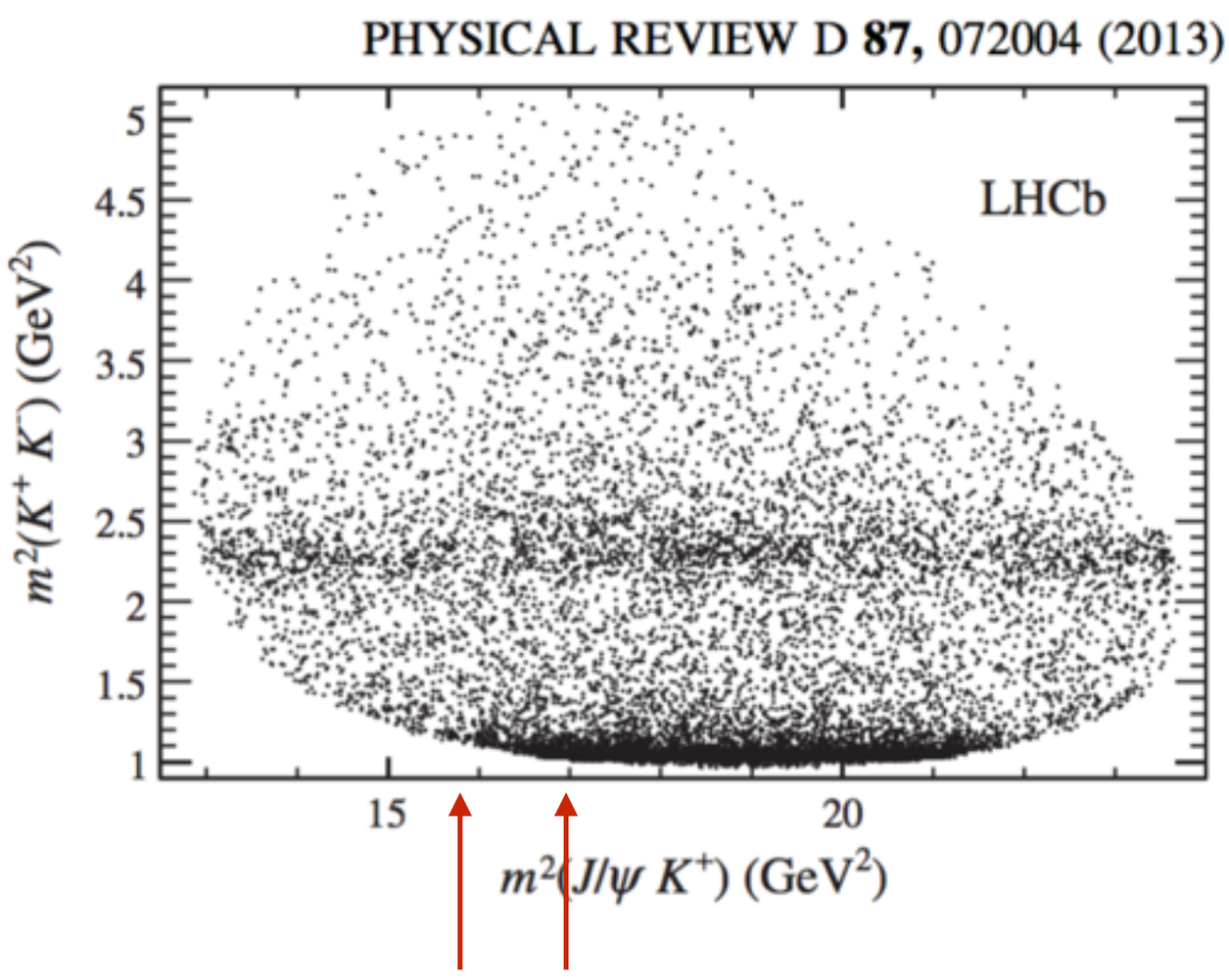
$$\exp(-88)$$



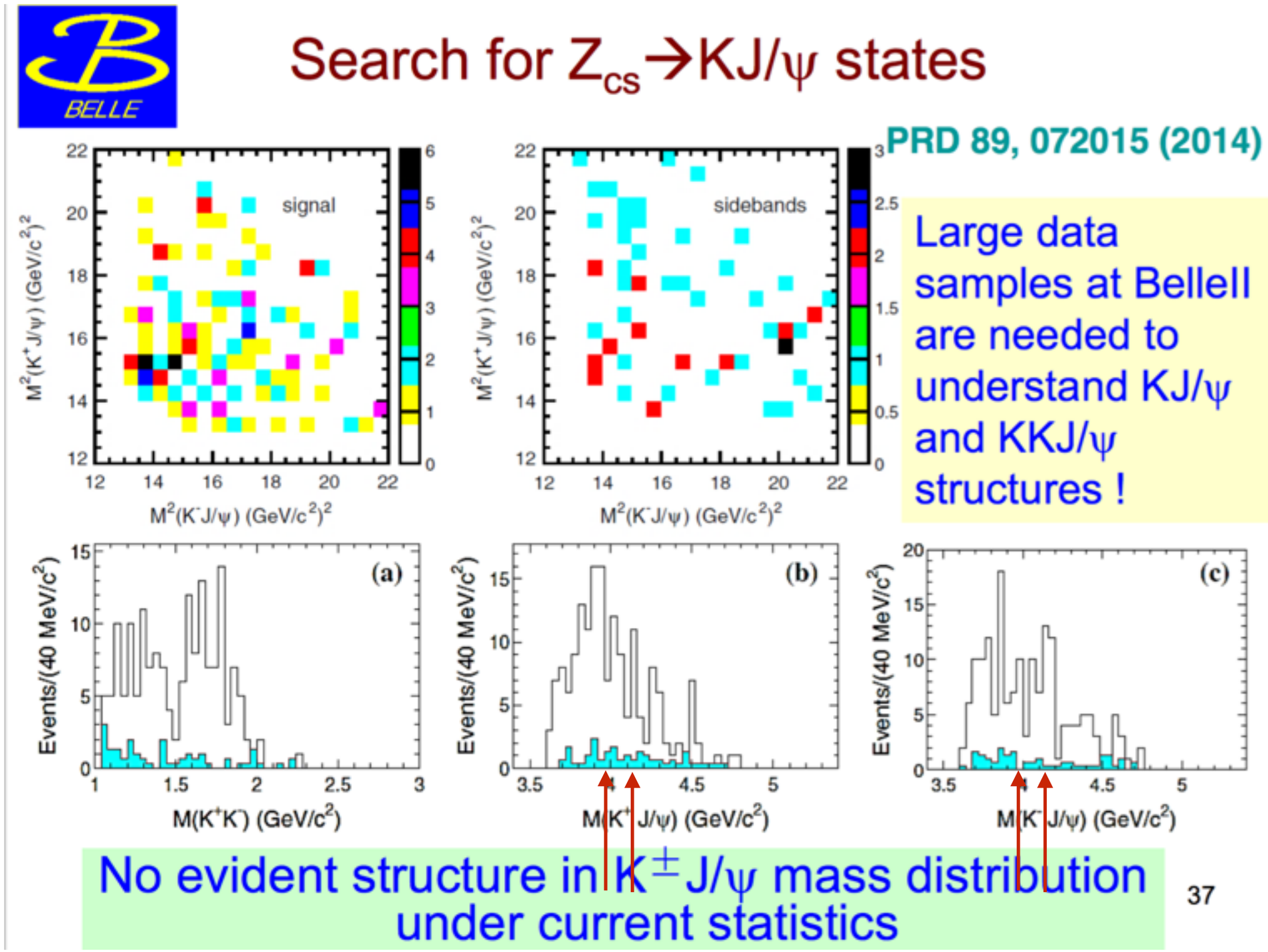
C. Adolph et al. [COMPASS] arXiv:1407.6186v1

Modelling the Zs — Issues with Cusps

$$\bar{B}_s^0 \to K^+ K^- J/\psi$$



Modelling the Zs — Issues with Cusps



Are We Learning Anything?

Are We Learning Anything?

- As we probe higher in the spectrum the constituent quark picture must fail: gluonic and light quark (continuum mixing) become important.

- Y(4260) → gluonics?
- X(3872) → nearby thresholds in the spectrum+ residual interactions (mixed molecule)
- Zs → cusp effects
- many others → noise?
- pentaquark → ?? (actual pq, coupled channels?, molecule?)
- Zc(4475) → ??

Are We Learning Anything?

- It seems likely that QCD phenomenology is in an evolutionary phase, rather than revolutionary (& Kuhn must wait).
- As is traditional, data must be collected until patterns are discerned.
- One difference from tradition is the ever-increasing utility of lattice gauge theory computations.

✠ ÆRIC MEC HEHT GEWYRCAN