[217-125 Yukawa Institute Feb, 201

Cusps, Resonances, and Exotic Charmonia

Eric Swanson

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

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

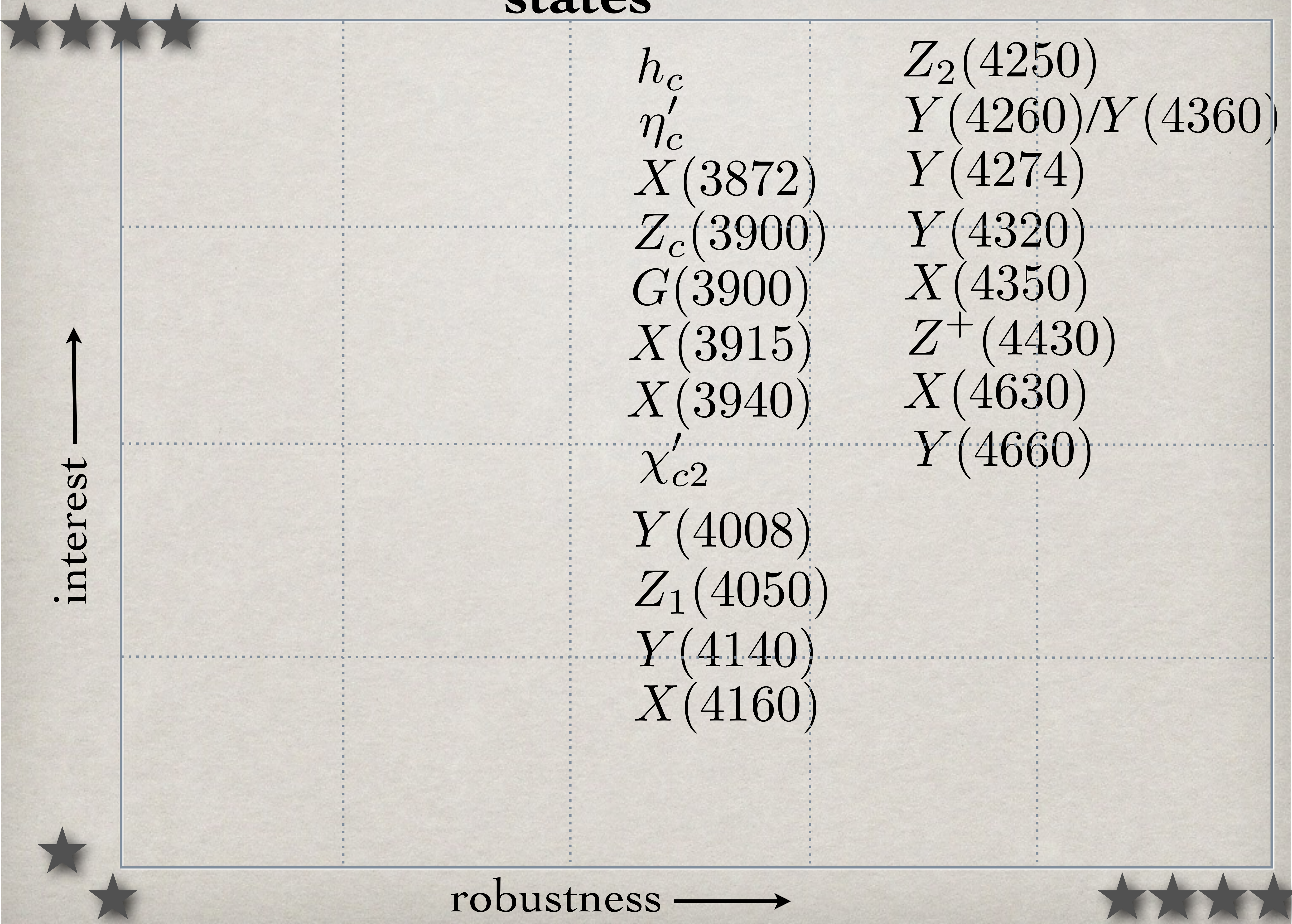
η_b
$\chi_{bJ}(3P)$
$Z_b^+(10610)$
$Z_b^+(10650)$
$Y_b(10888)$

states

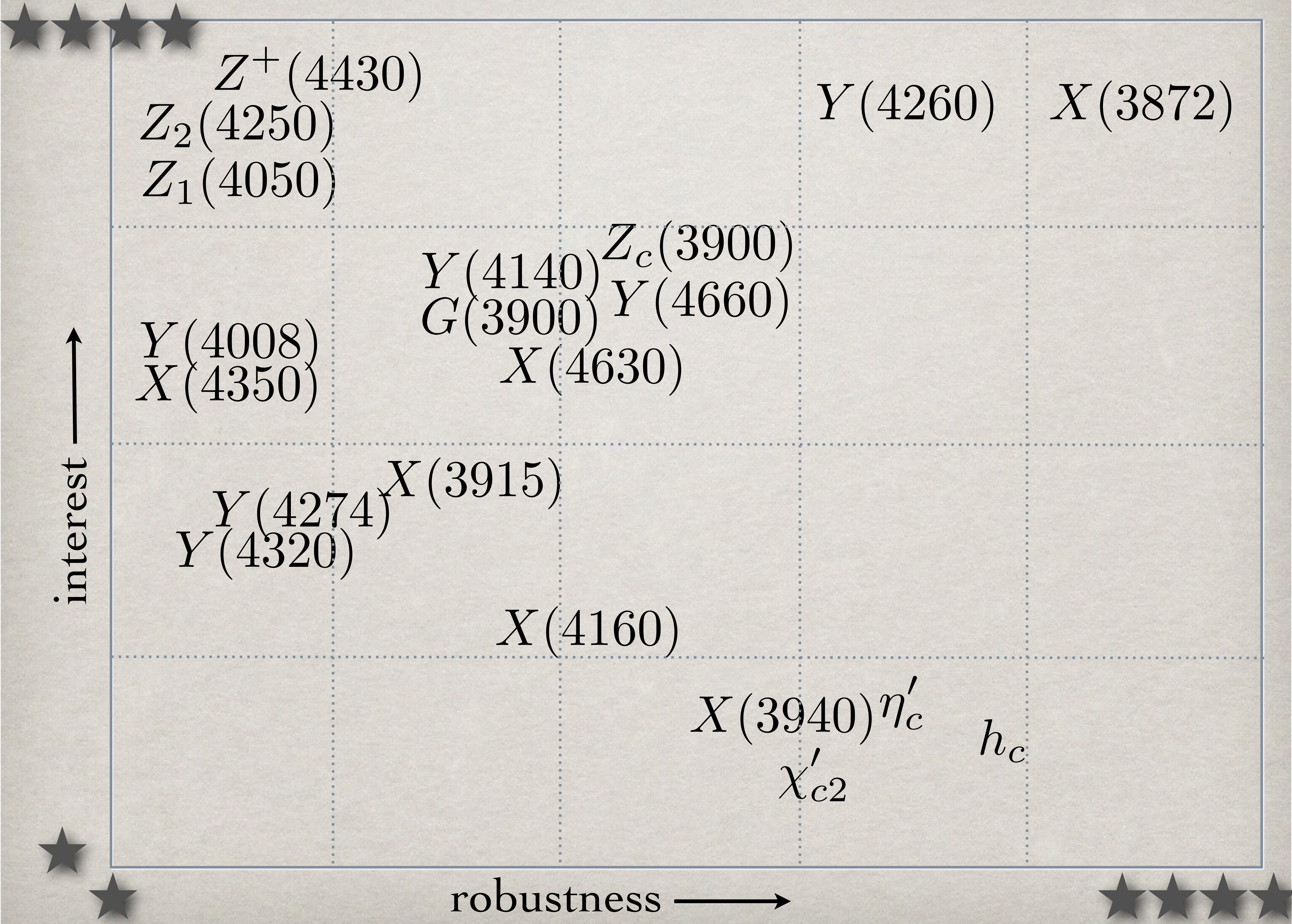
h_c
η_c'
$X(3872)$
$Z_c(3900)$
$G(3900)$
$X(3915)$
$X(3940)$
χ_{c2}'
$Y(4008)$
$Z_1(4050)$
$Y(4140)$
$X(4160)$

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

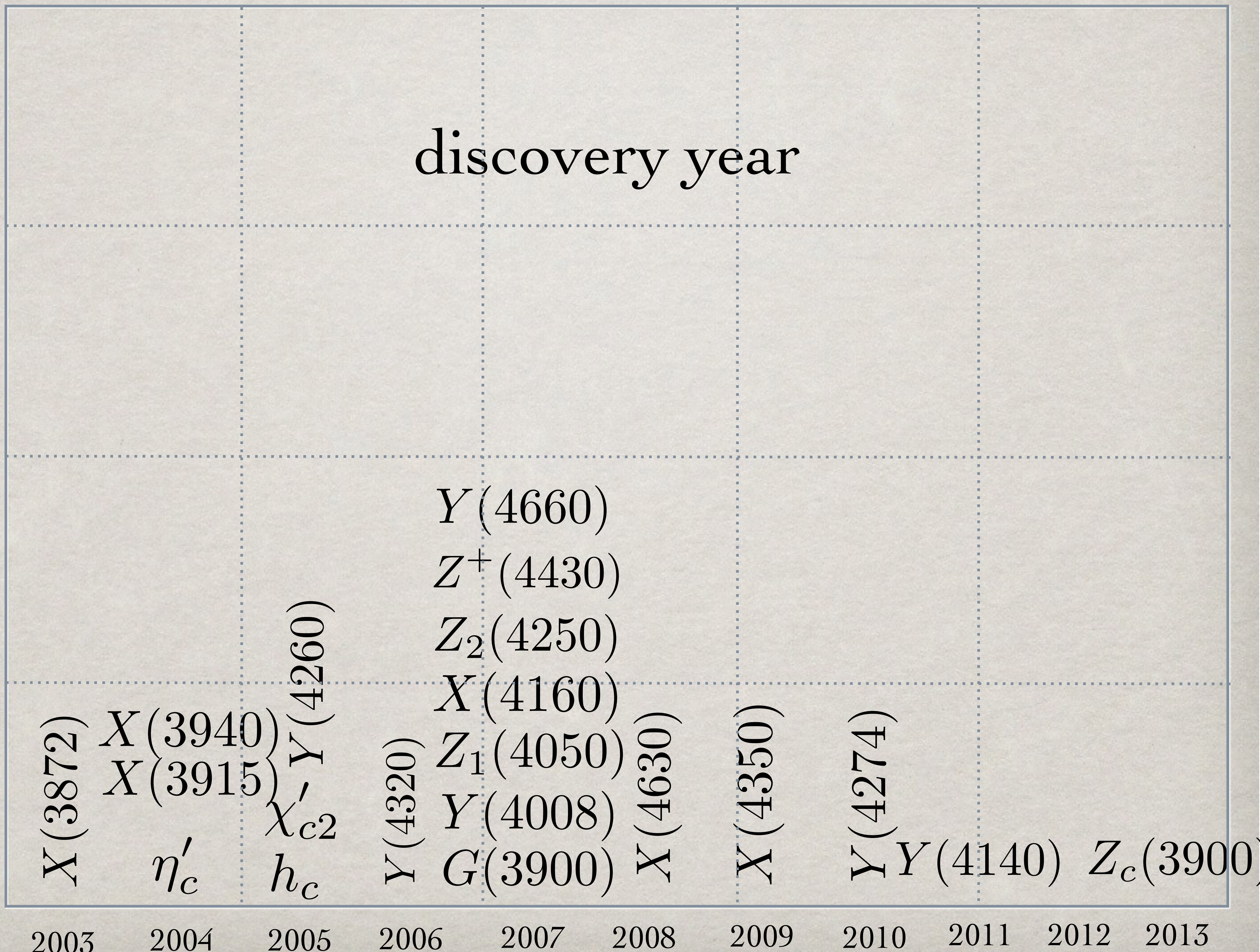
states



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



$Z^+(4430)$
$Z_2(4250)$
$Z_1(4050)$
$Y(4260)$
$X(3872)$
$Z_c(3900)$
$Y(4140)$
$Y(4660)$
$G(3900)$
$Y(4008)$
$X(4630)$
$X(4350)$
$X(3915)$
$Y(4274)$
$Y(4320)$
$X(4160)$
$X(3940)$
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)
Zc(3900)
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013

discovery experiment

$Y(4660)$

$X(4630)$

$Z^+(4430)$

$X(4350)$

$Z_2(4250)$

$X(4160)$

$Z_1(4050)$

$Y(4008)$

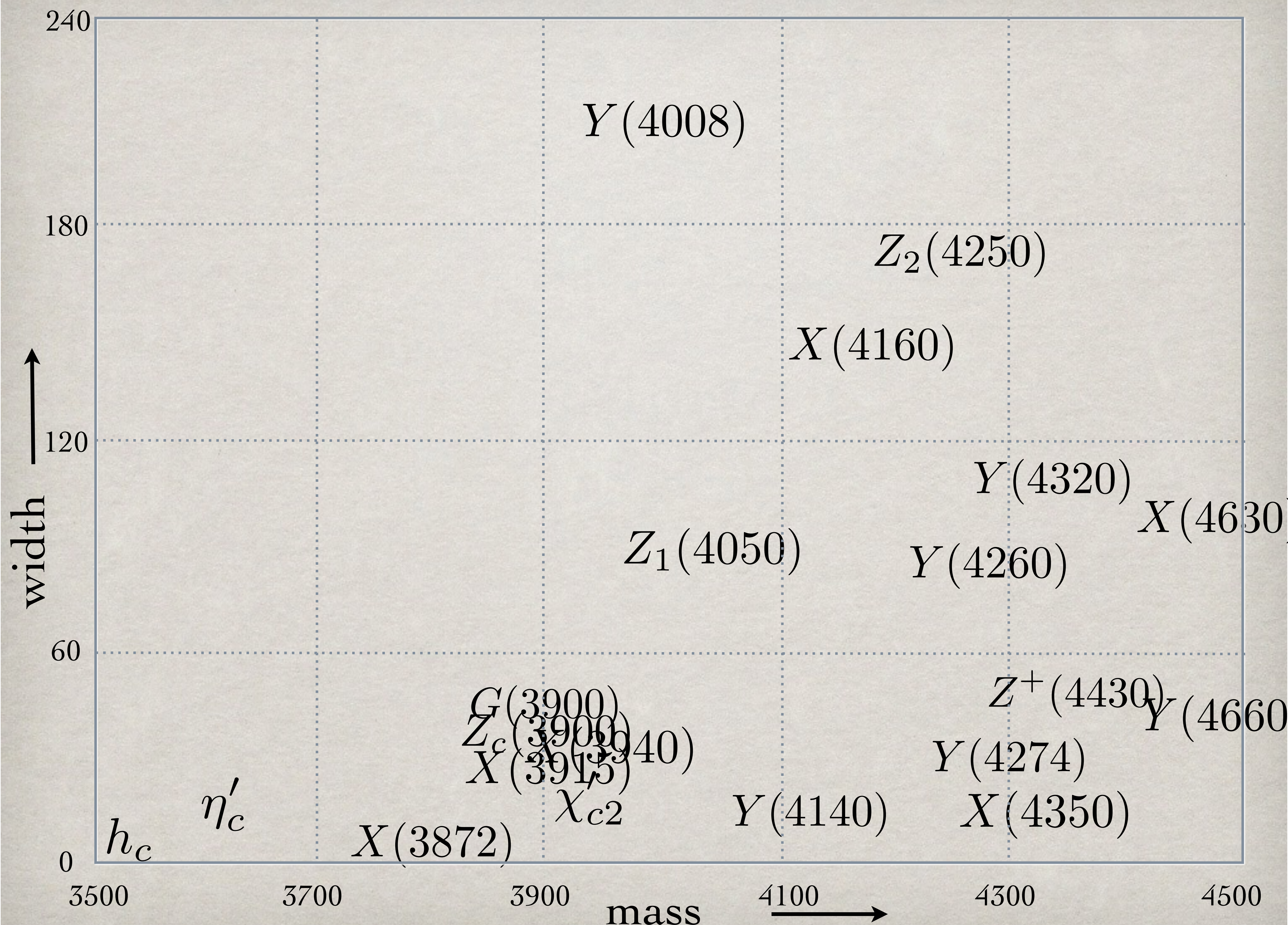
$X(3940)$

$Y(4320)$ $X(3915)$

$Y(4260)$ $X(3872)$ $Z_c(3900)$ $Y(4274)$ η_c'

$G(3900)$ χ_{c2}' $Y(4140)$ h_c

ATLAS EXPERIMENT BABAR BELLE CDF CESR CLEO DØ LHCb



240
180
120
60
0
width
3500
3700
3900
4100
4300
4500
mass
$Y(4008)$
$Z_2(4250)$
$X(4160)$
$Y(4320)$
$X(4630$
$Z_1(4050)$
$Y(4260)$
$Z^+(4430)$
$Y(4660$
$G(3900)$
$Z_c(3900)$
$X(3940)$
$X(3915)$
$Y(4274)$
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
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}'	$X(4160)$
$X(3872)$	$G(3900)$	$X(4350)$	$X(3940)$
$X \to \phi J/\psi$	$X \to \pi\pi J/\psi$	$X \to \phi J/\psi$	$X \to \bar{D}D^*$
$X \to \pi\chi_{c1}$	$X \to \pi\pi\psi'$	$X \to D\bar{D}$	$X \to \pi\pi$
$X \to \pi\pi J/\psi$	$X \to \Lambda\bar{\Lambda}$		
$X \to \omega J/\psi$	$X \to \bar{D}D$		
$X \to KK\pi$			
$X \to \pi^+\psi'$			

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

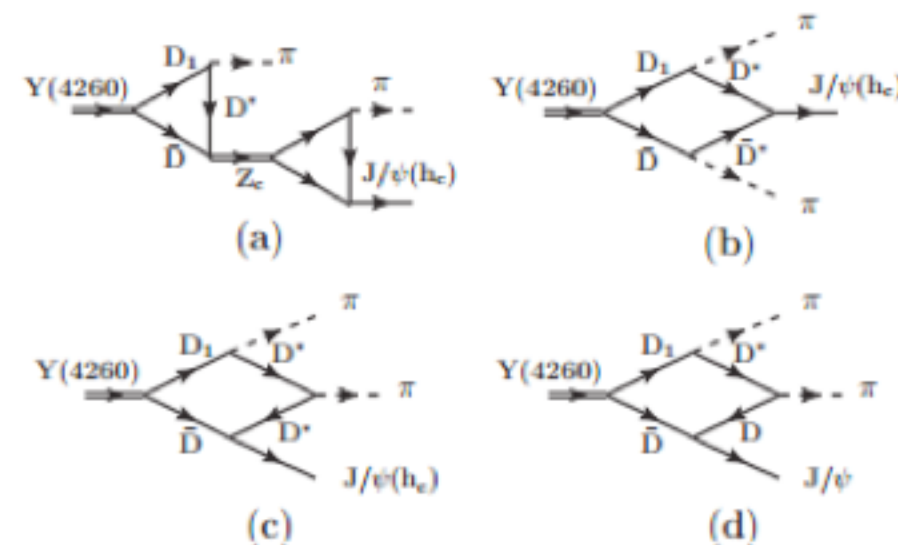
4. Meson loop

- arXiv:1303.6355
- arXiv:1304.4458

5. ISPE model

- arXiv:1303.6842

6. ...



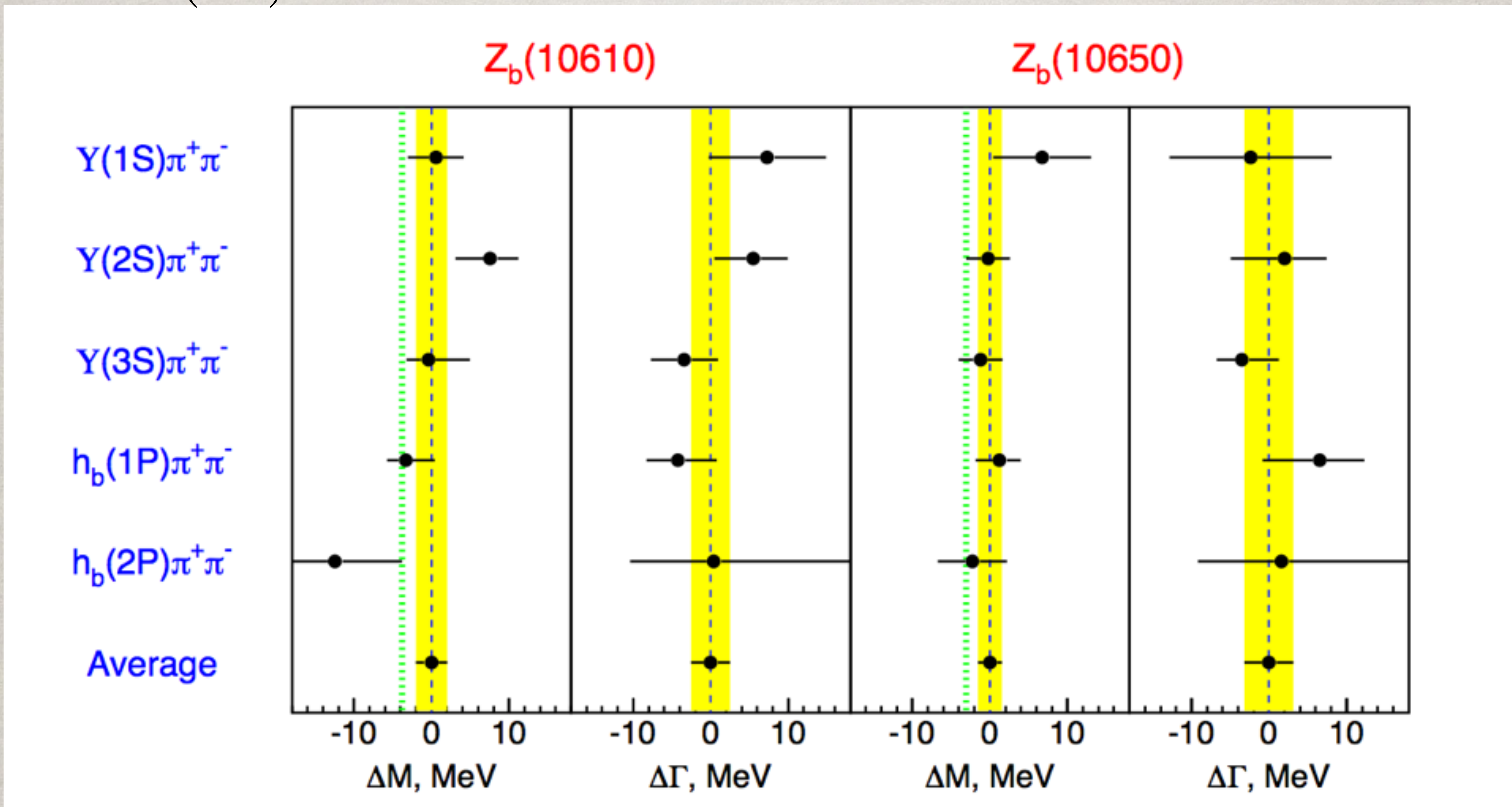
Meson loop

Charged Exotics (bb)

[Belle] , arXiv:1105.4583

[Belle] , arXiv:1403.0992

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



$M = 10608.4 \pm 2.0 \quad \Gamma = 15.6 \pm 2.5$

$M = 10653.2 \pm 1.5 \quad \Gamma = 14.4 \pm 3.2$

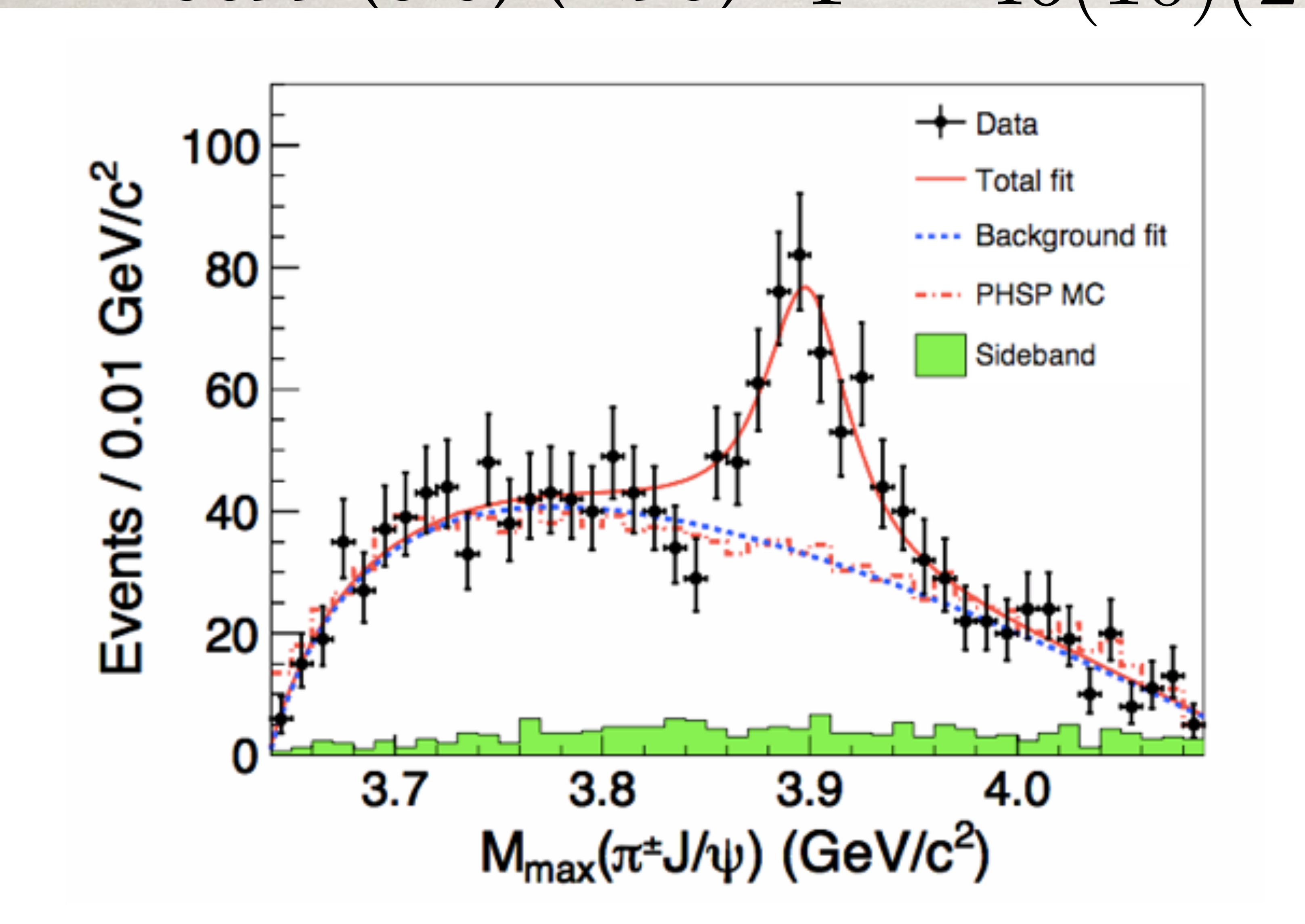
Charged Exotics (cc) Zc(3900)

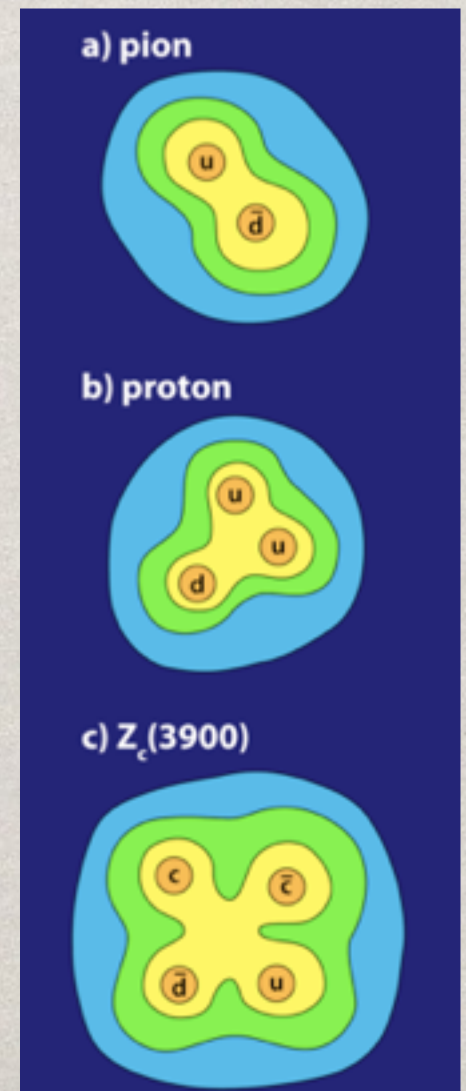
M. Ablikim et al. [BESIII], PRL (13)

A.Q. Lin et al. [Belle], PRL (13)

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

M = 3899 (3.6) (4.98) $\Gamma = 46(10)(20)$



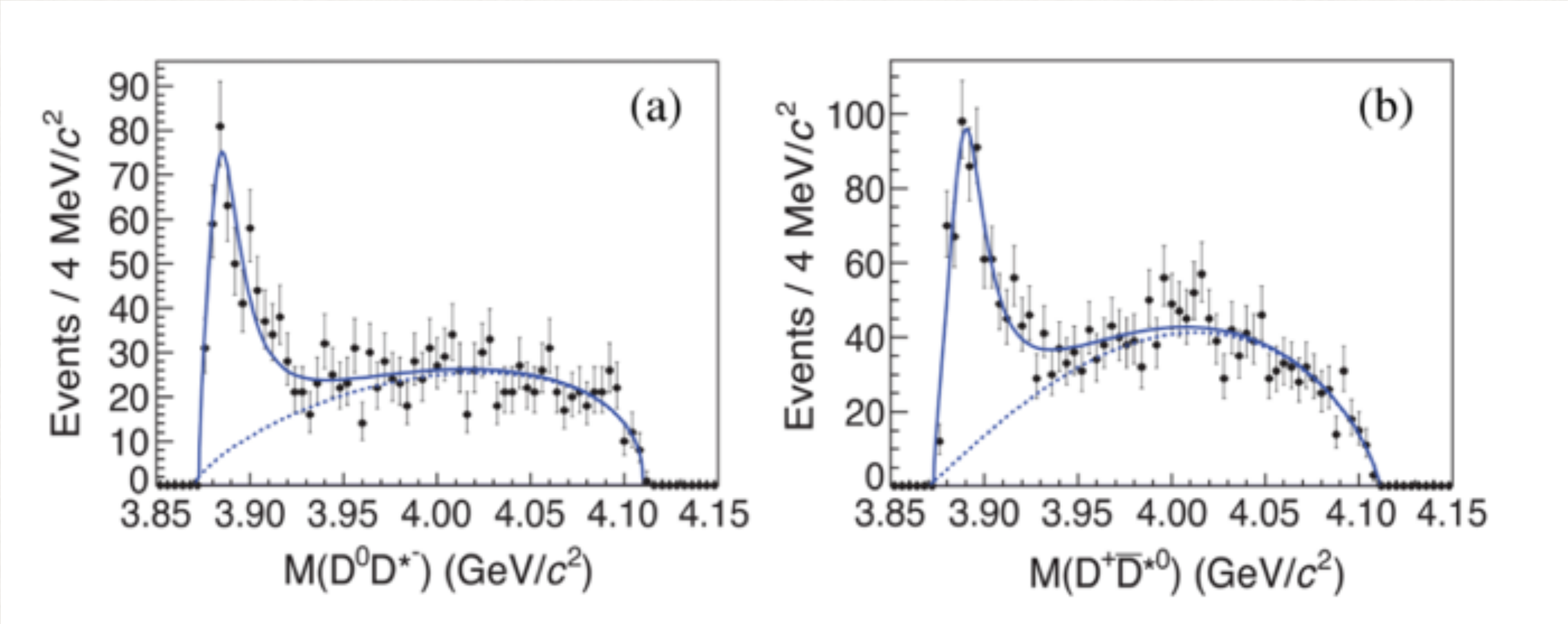


Charged Exotics (cc) Zc(3900)

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

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

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



BESIII PRL112 022001 (14)

Charged Exotics (cc) $Z_c(4025)$

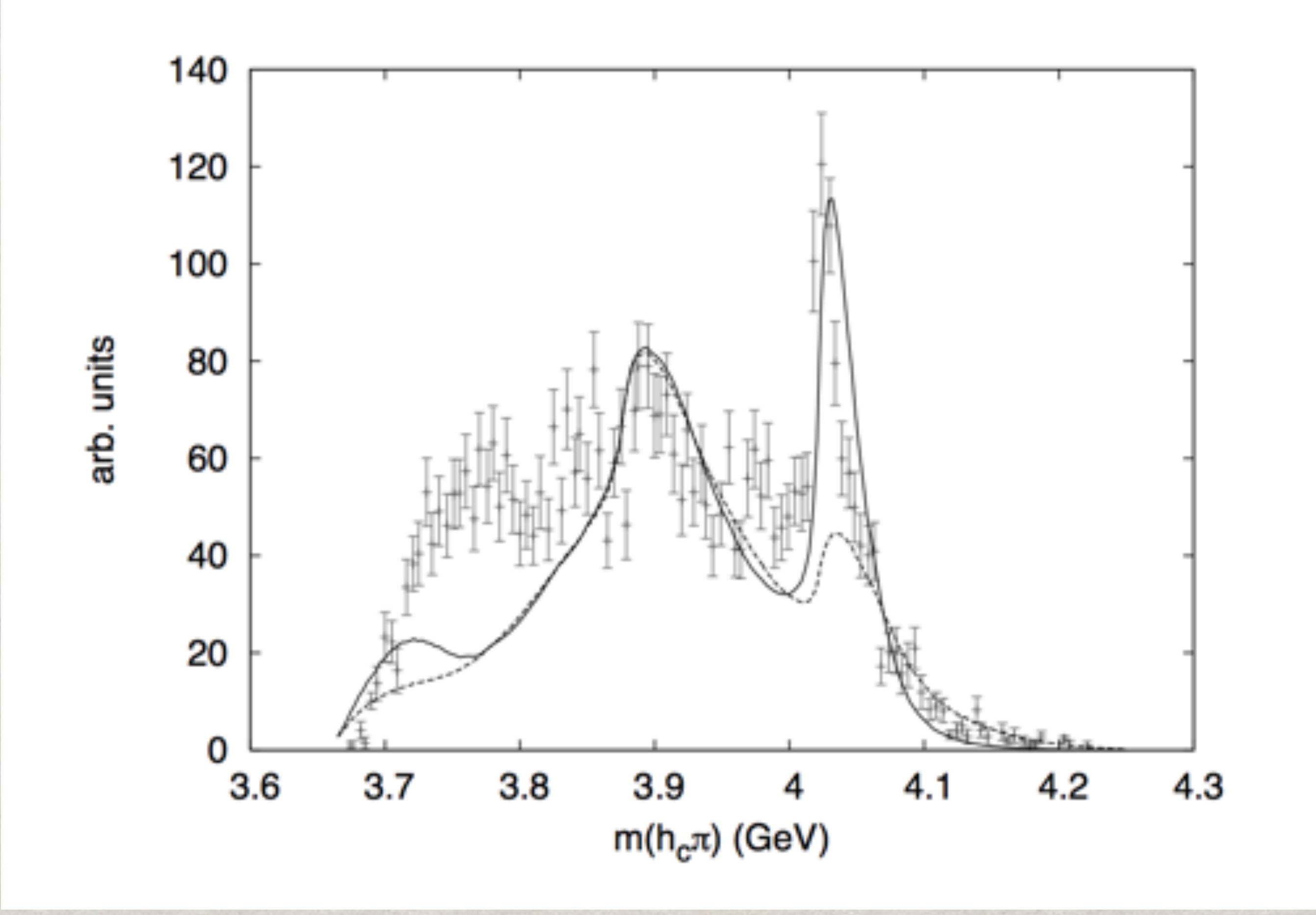
$e^+e^- \to \pi^+\pi^- h_c$

sums 13 different ee energy values

"no significant Zc(3900) observed"

$M = 4022.9 \pm 0.8 \pm 2.7$

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



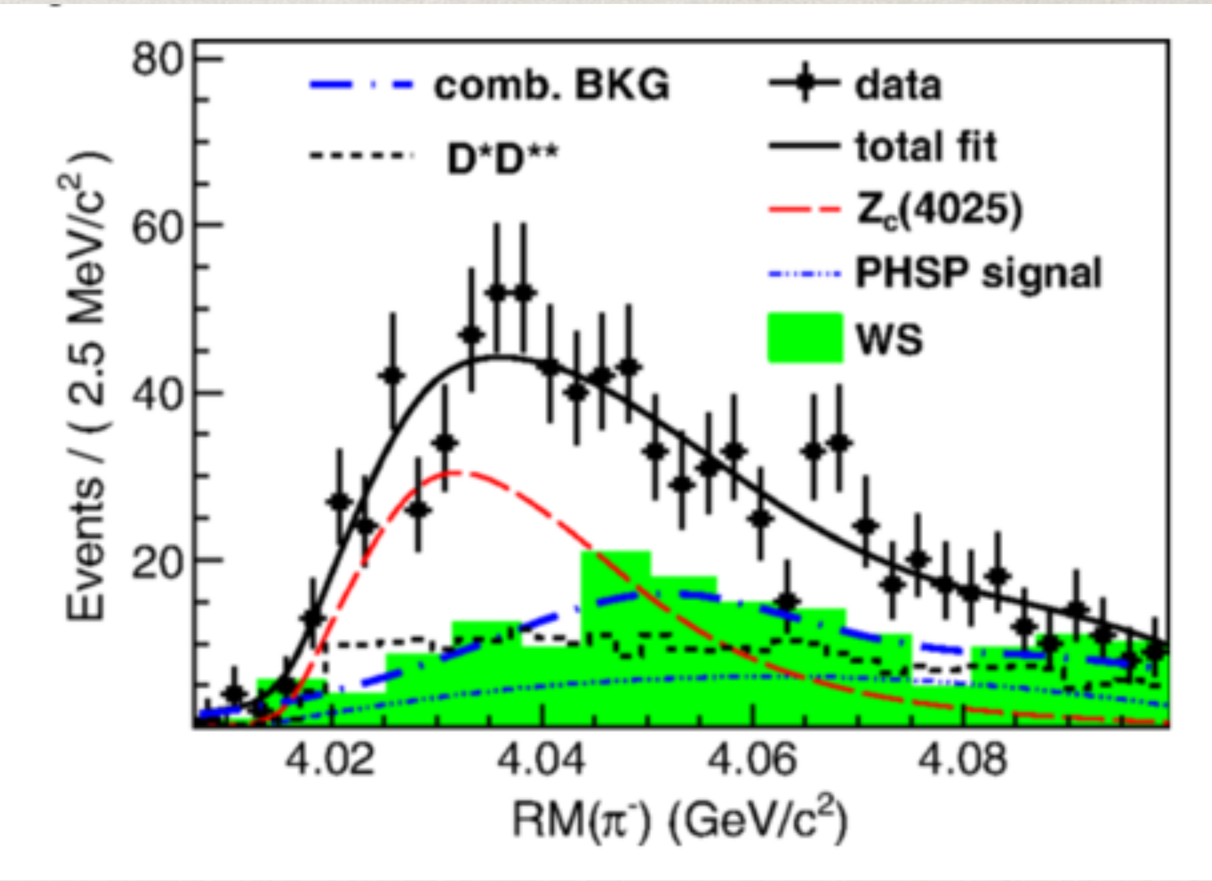
BESIII Phys. Rev. Lett. 111, 242001 (2013).

Charged Exotics (cc) $Z_c(4025)$

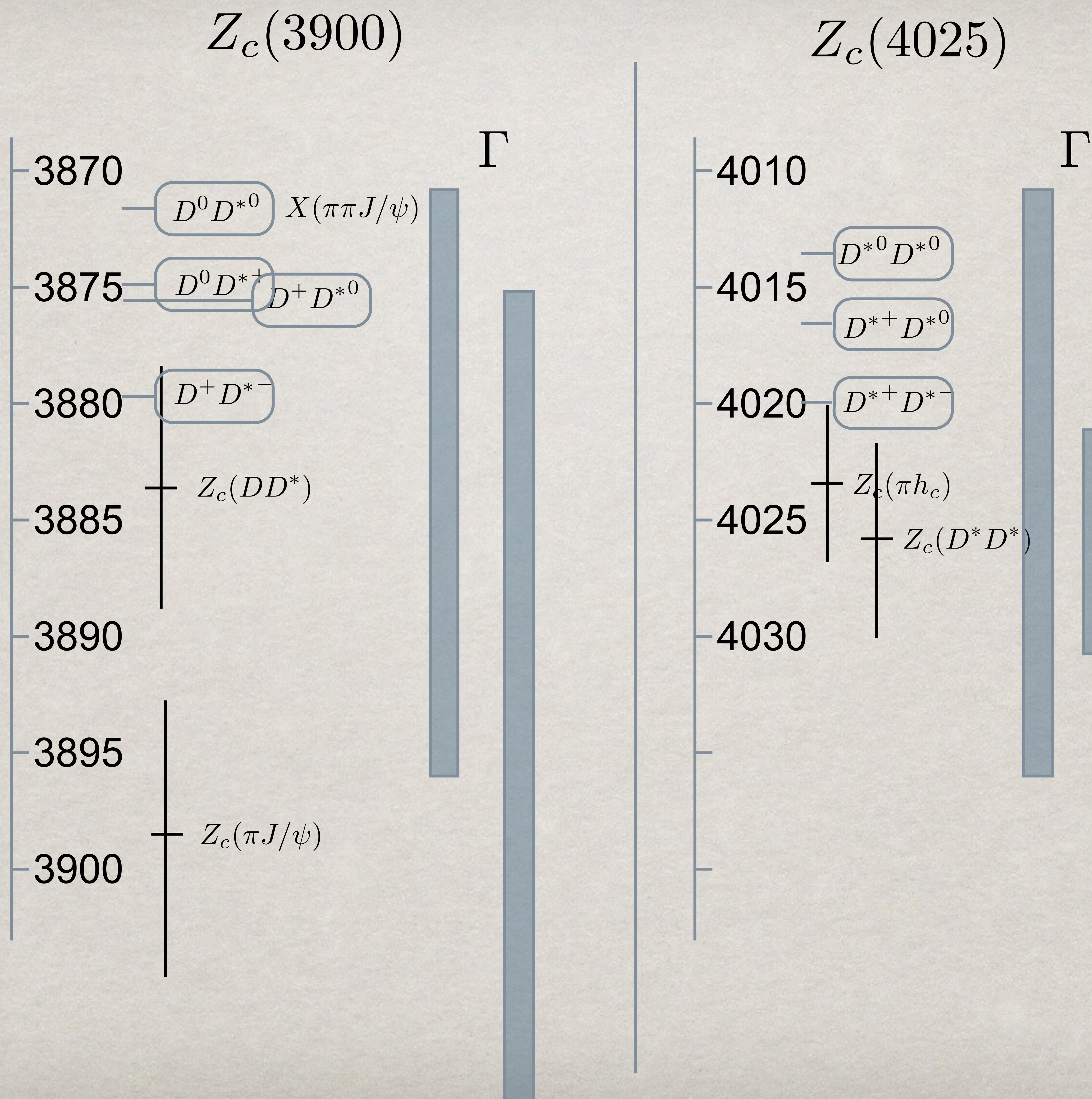
$$e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$$

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

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



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



$Z_c(3900)$
$Z_c(4025)$
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
$D^{*0} D^{*0}$
$D^{*+} D^{*0}$
$D^{*+} D^{*-}$
$Z_c(\pi h_c)$
$Z_c(D^* D^*)$

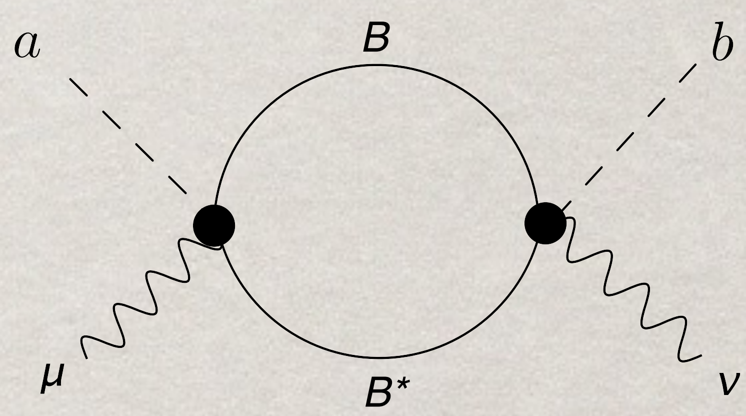
A Cusp Model for the Charged Exotics

E.S. Swanson, arXiv:1409.3291

Cusp Model

Opening channels lead to 'cusps' in amplitudes

$$\mathrm{Im}\Pi_{\alpha\beta}(s) = \sum_i k_i^{1+\ell_{\alpha i}+\ell_{\beta i}} F_{\alpha i}(s) F_{\beta i}(s)$$



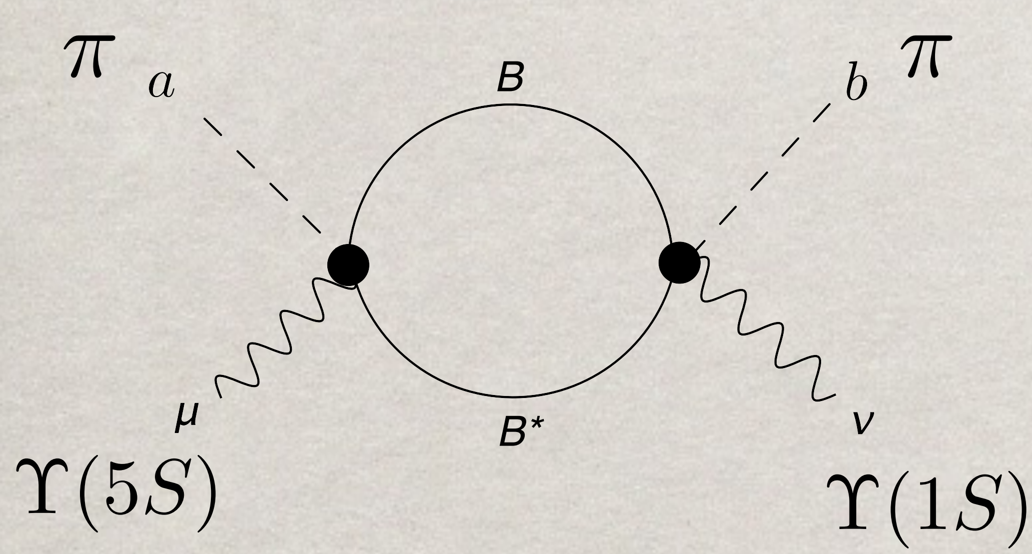
$$F_{\alpha i} = g_{\alpha i} \exp(-s/2\beta_{\alpha i}^2)$$

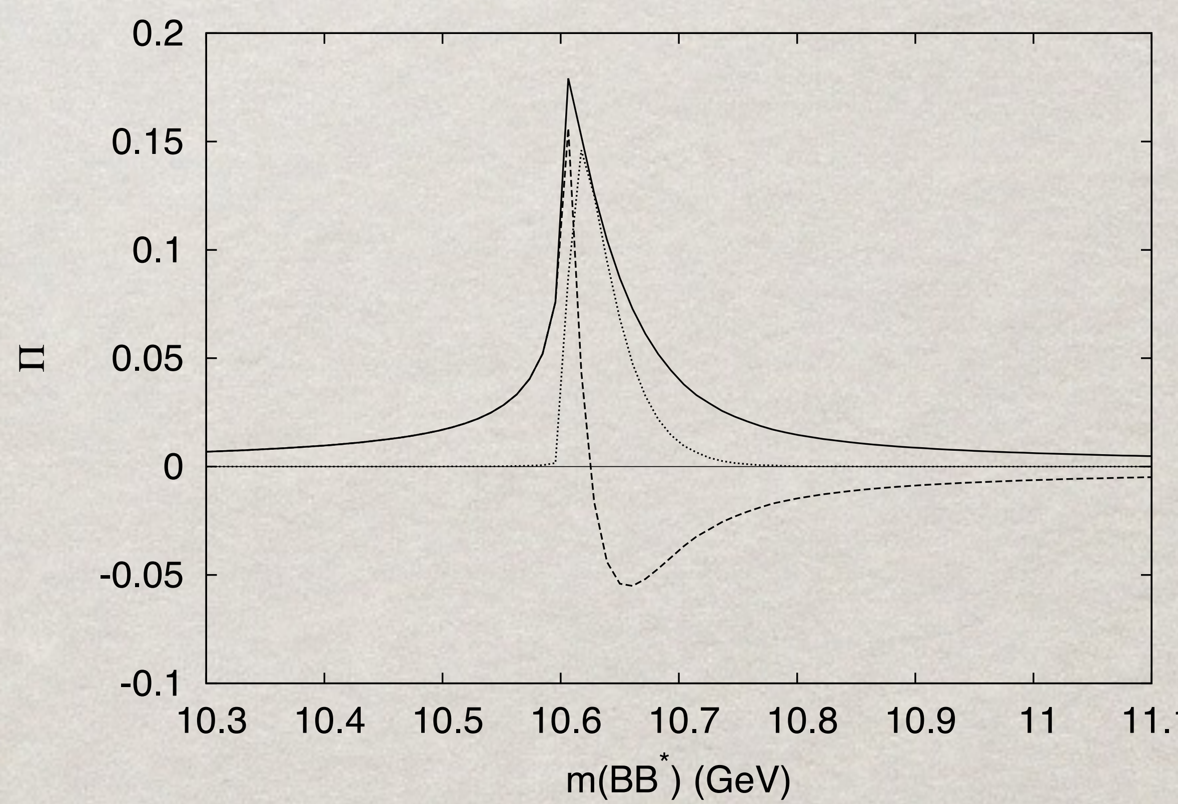
$$k_i^2 = \frac{(s-(m_{1i}+m_{2i})^2)\,(s-(m_{1i}-m_{2i})^2)}{4s}$$

$$\Pi_{\alpha\beta}(s) = \frac{1}{\pi}\int_{s_{th}}^{\infty} ds' \, \frac{\mathrm{Im}\Pi_{\alpha\beta}(s')}{s'-s-i\epsilon}$$

Cusp Model

Opening channels lead to ‘cusps’ in amplitudes





[NB: this exhibits phase motion!]

Cusp Model

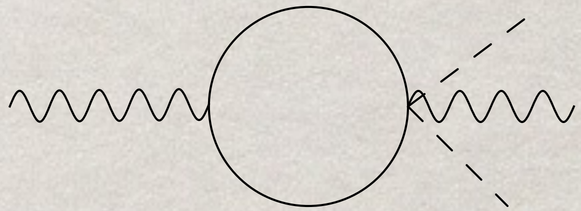
Q: how does Y(5S) couple to Yππ?

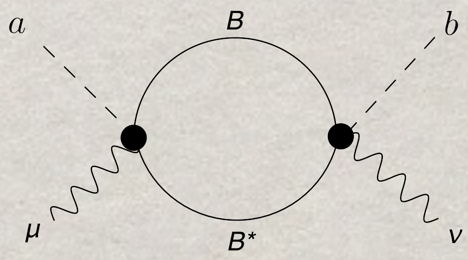
$$\Upsilon(5S) \to \text{ hidden bottom} = 3.8\%$$

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

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

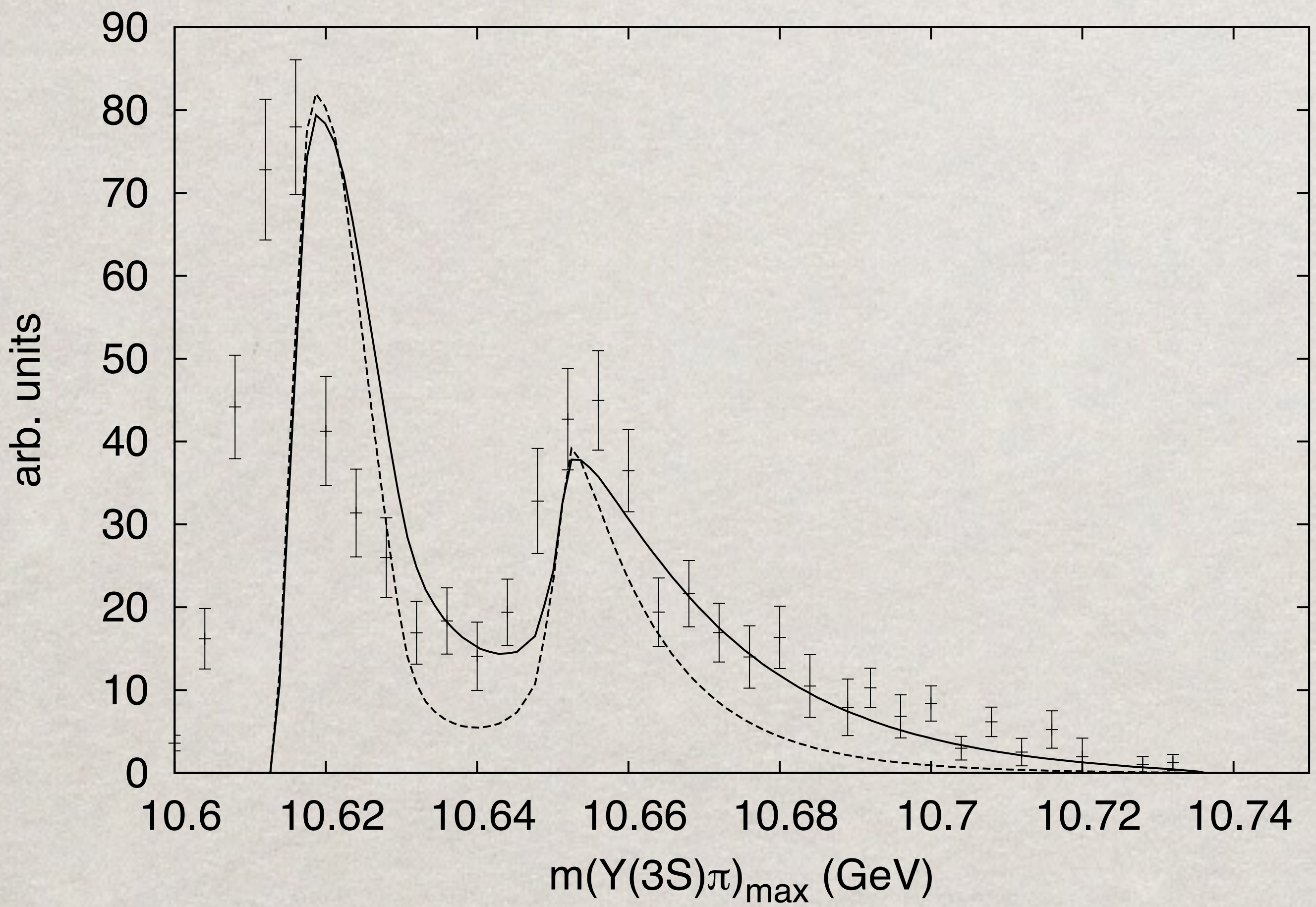
$$\Upsilon(5S) \to \Upsilon(nS)\pi\pi < 7.8 \cdot 10^{-3}$$





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

Zb(10610), Zb(10650)



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

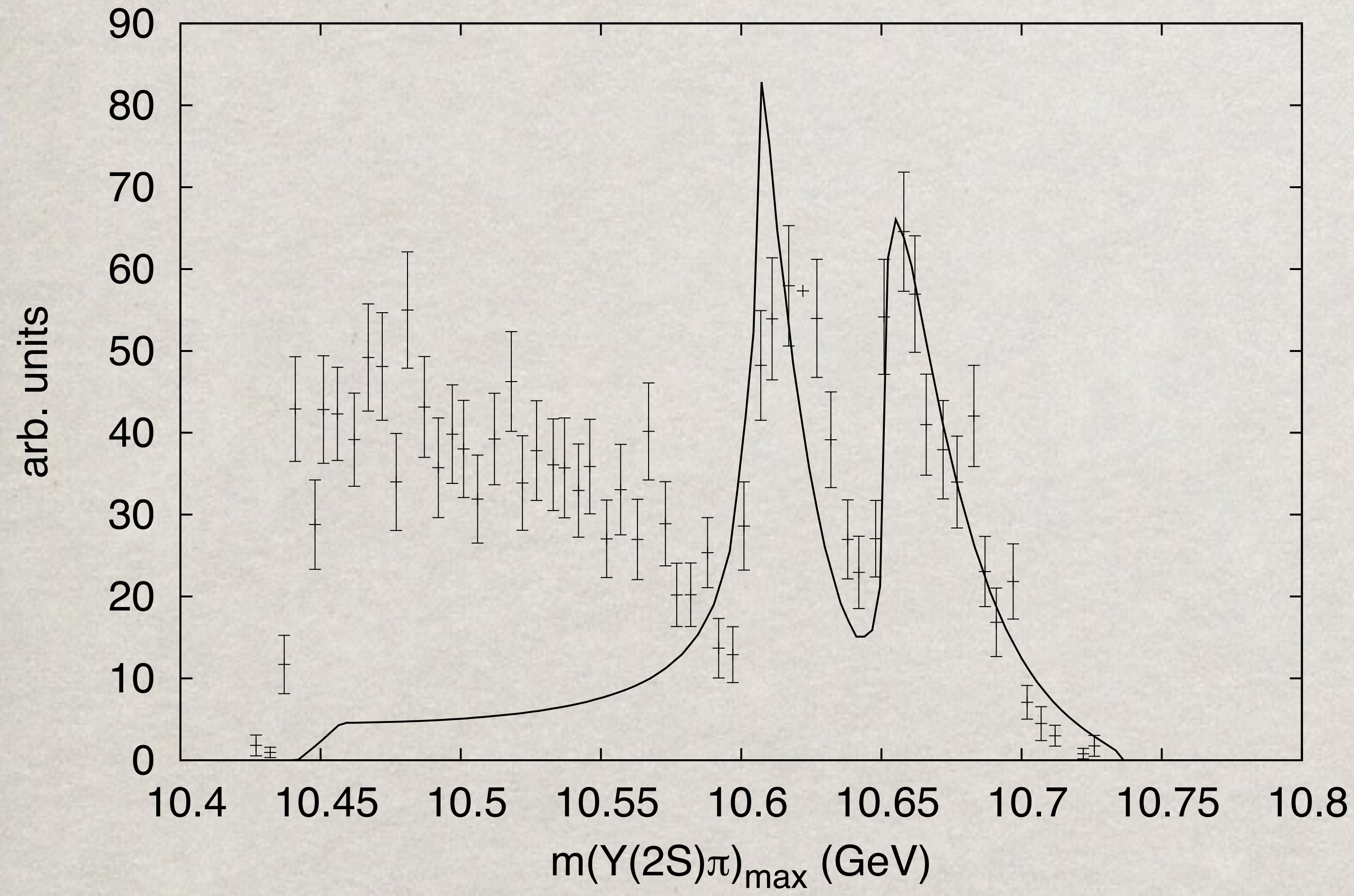
$$g^2_{\Upsilon(nS)BB^*} = 0.9 \cdot g^2_{\Upsilon(nS)B^*B^*}$$

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

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

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

Zb(10610), Zb(10650)



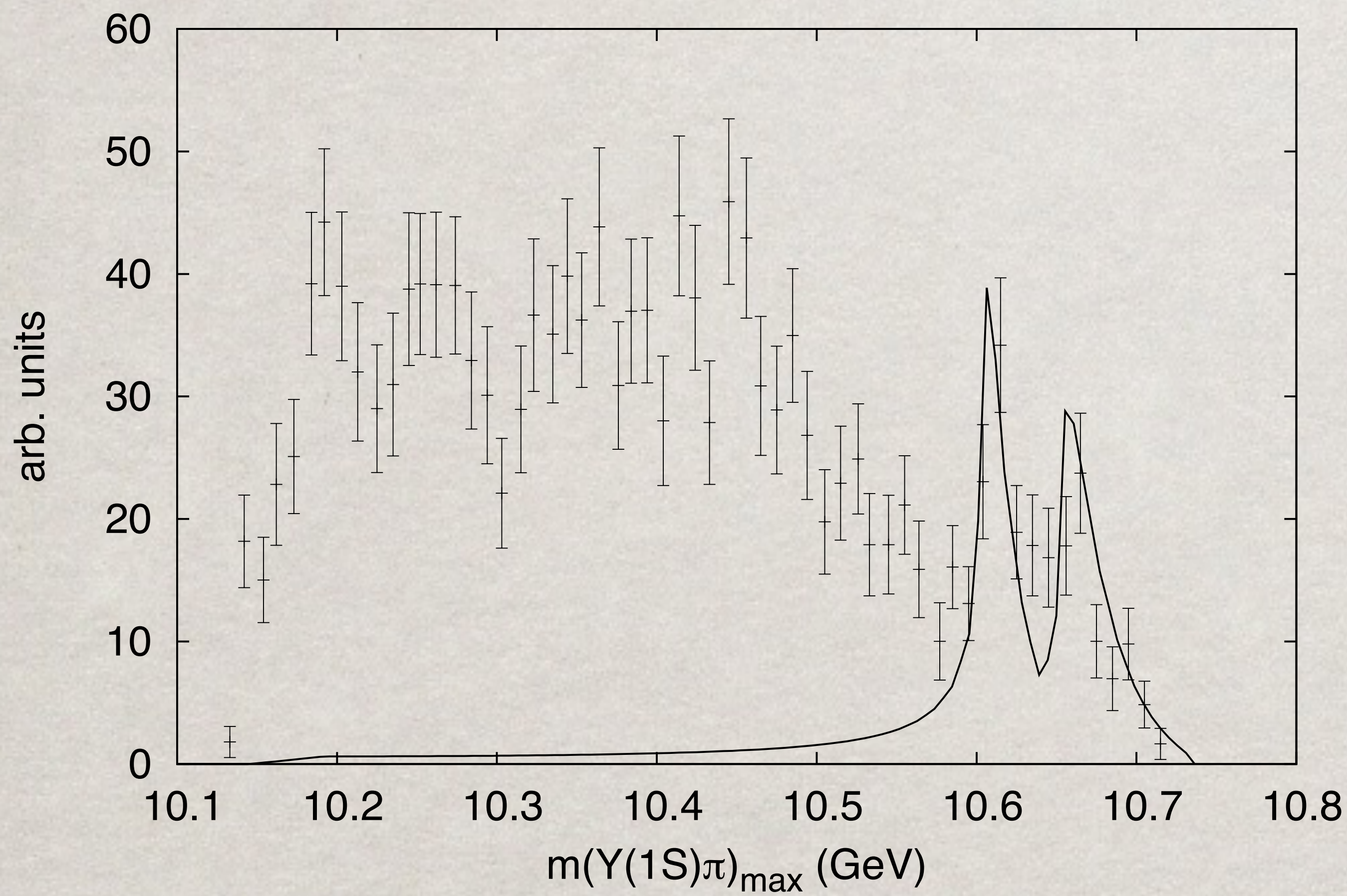
same couplings used!

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

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

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

Zb(10610), Zb(10650)



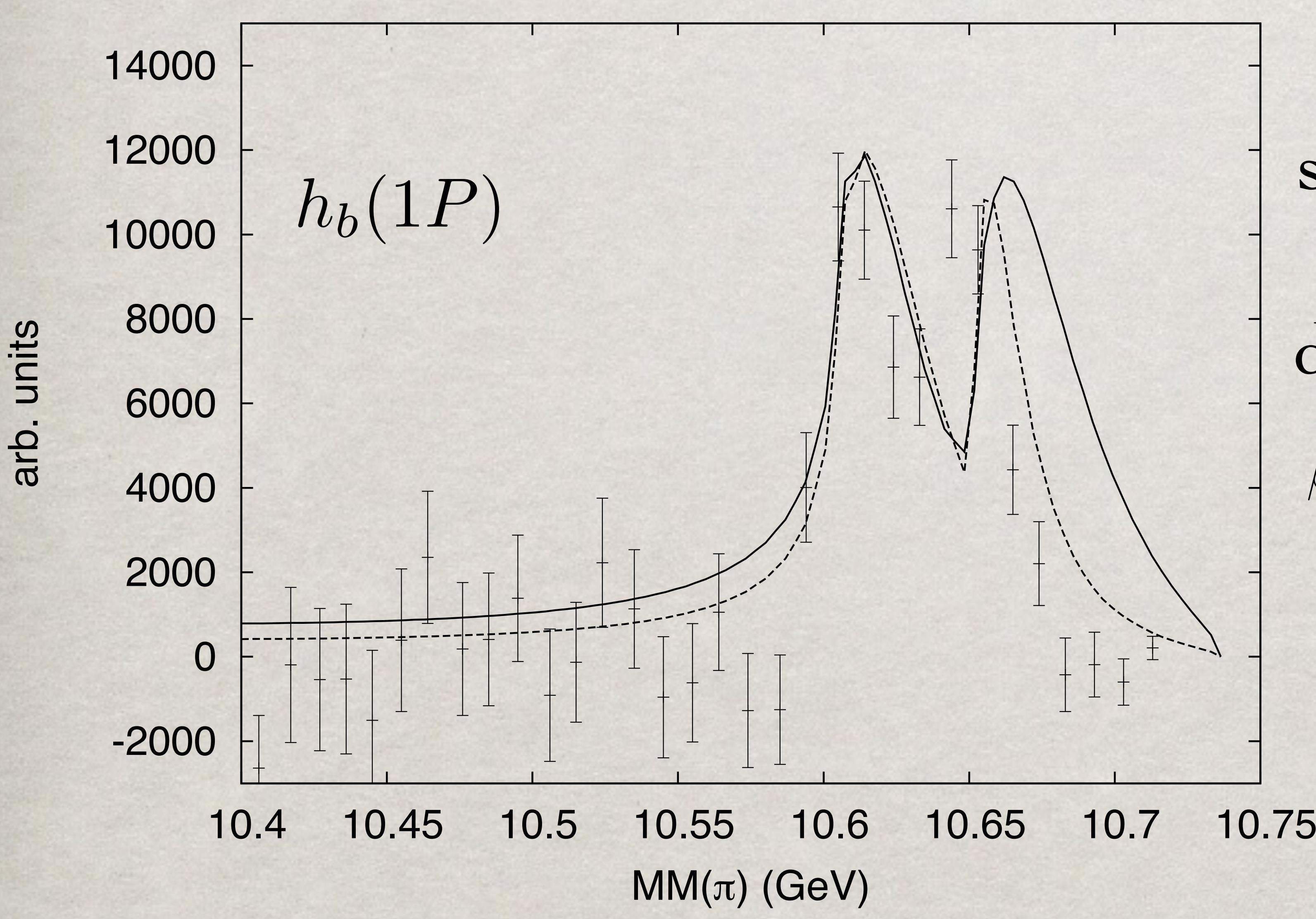
30% smaller coupling required

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

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

Cusp Model $\Upsilon(5S) \to h_b(nP)\pi\pi$

Zb(10610), Zb(10650)



solid line: same as above

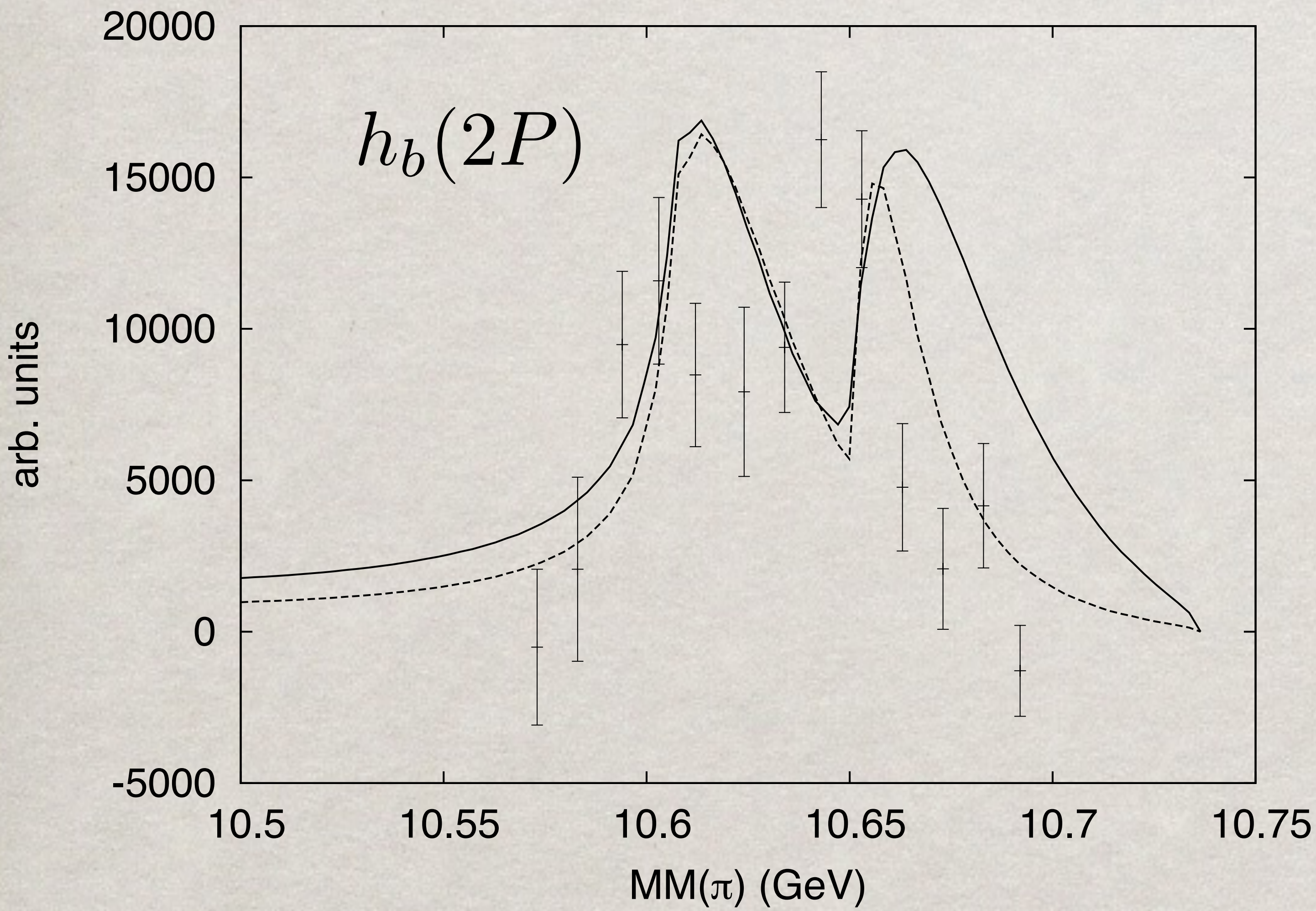
dashed line:

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

$g^2_{BB^*} = 0.5\, g^2_{B^*B^*}$

Cusp Model $\Upsilon(5S) \to h_b(nP)\pi\pi$

Zb(10610), Zb(10650)



solid line: same as above

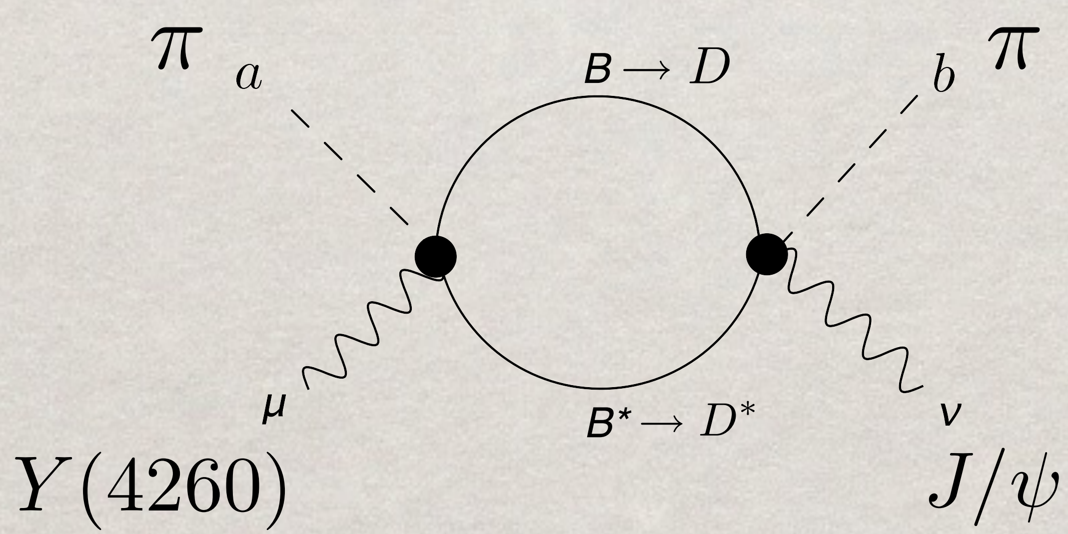
dashed line:

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

Cusp Model

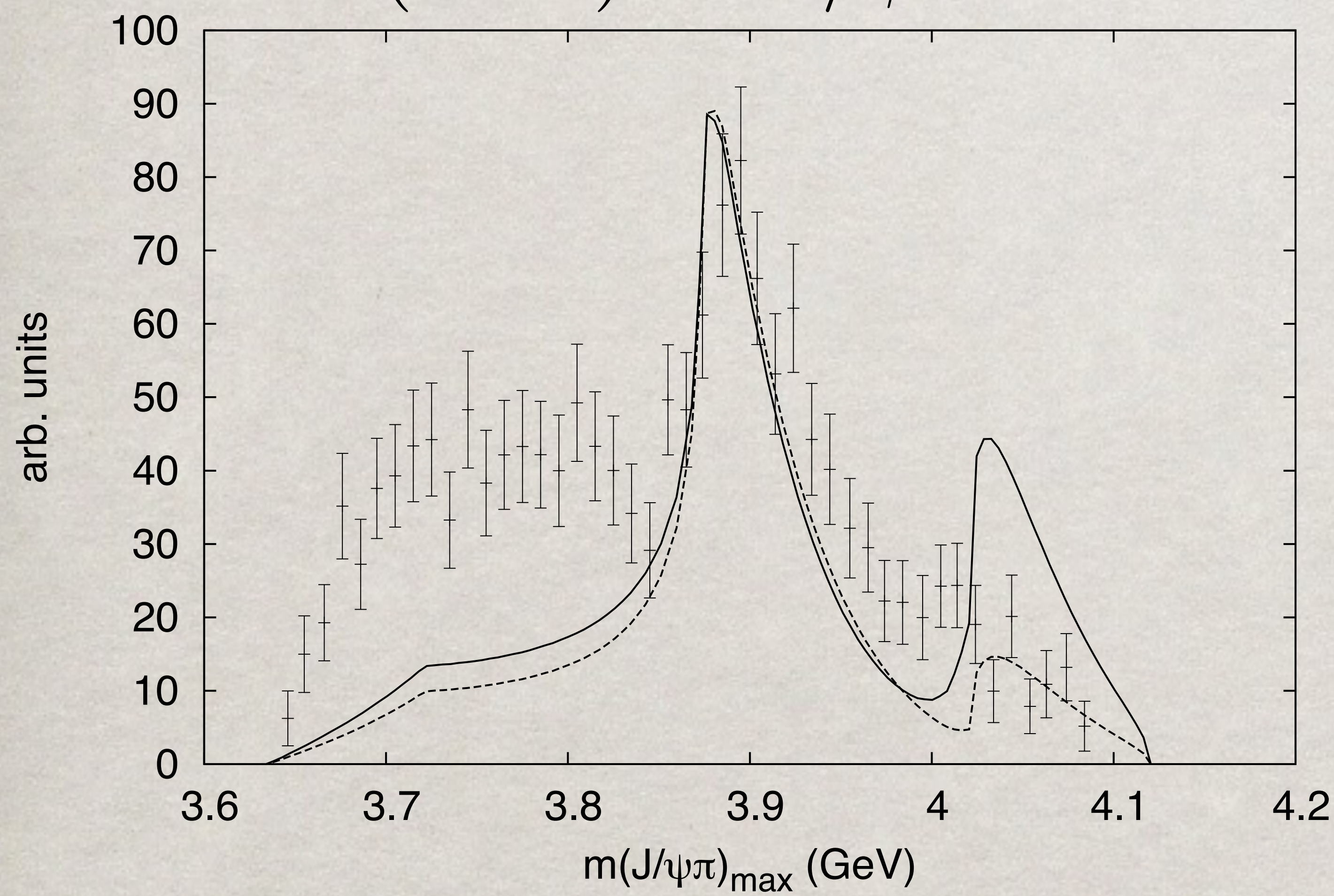
Zc(3900)

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



Cusp Model

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



Zc(3900)

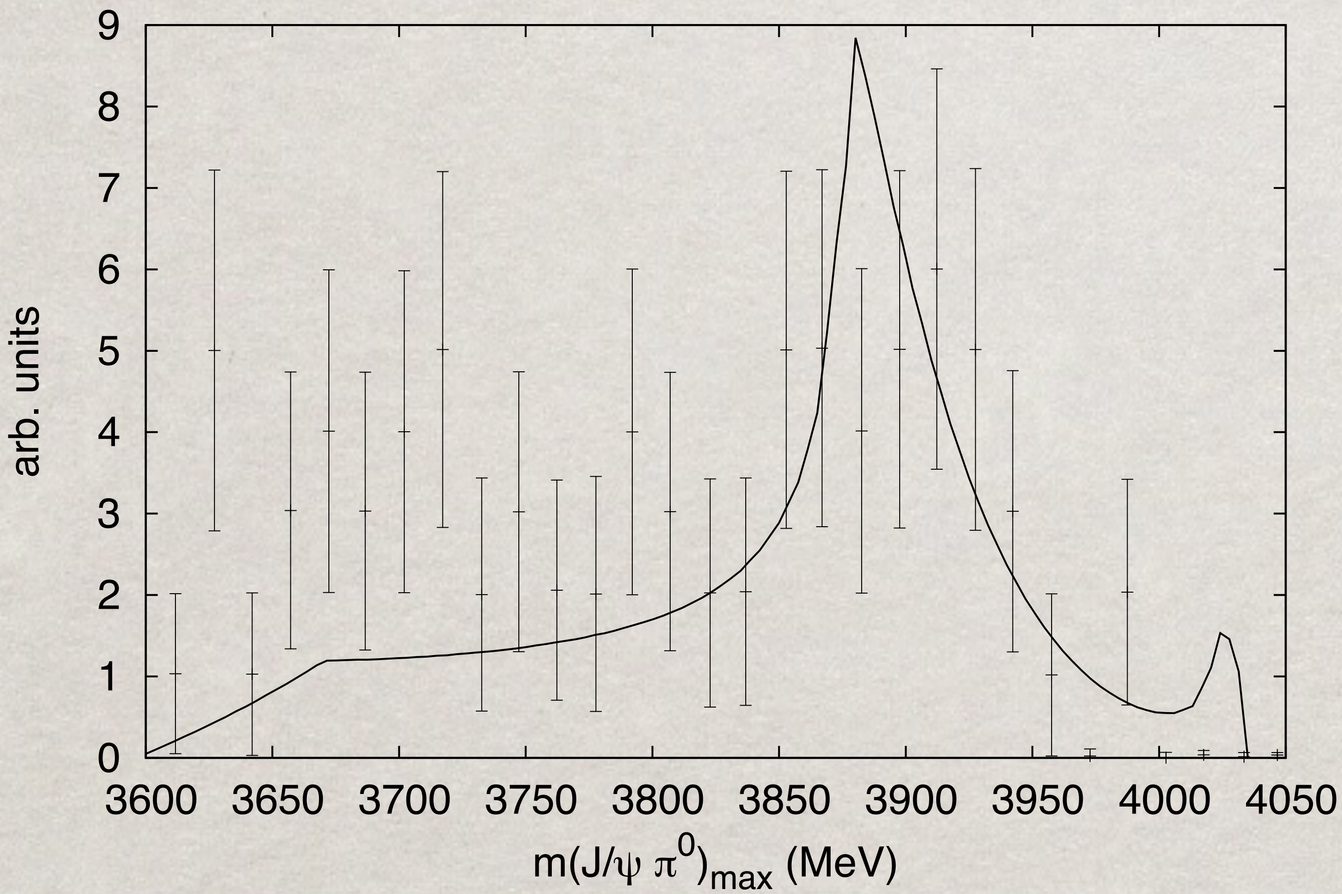
solid line: same as above

dashed line: reduced D*D* coupling

M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 110, 252001 (2013);

Cusp Model

Zc(3900)



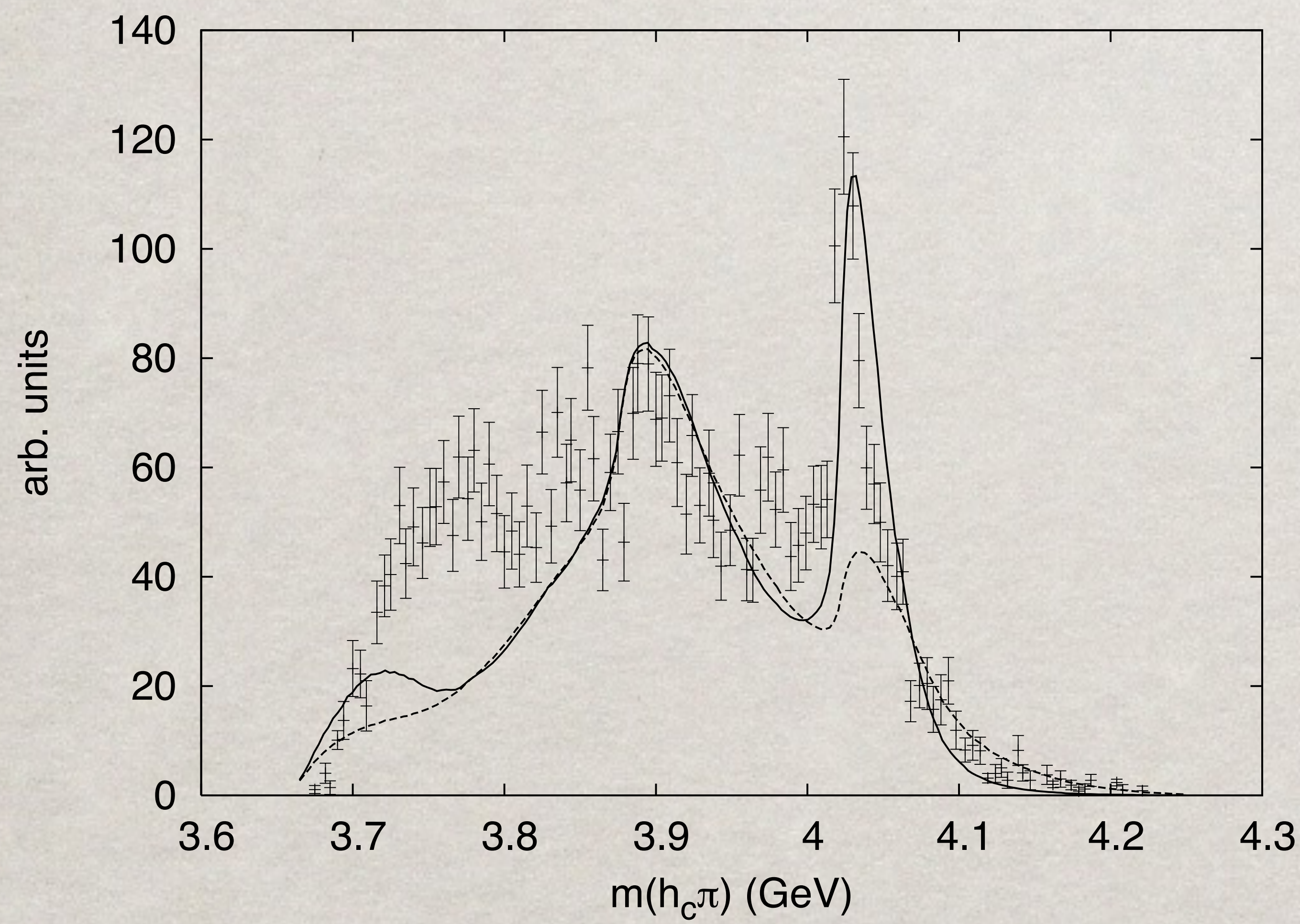
solid line: same as above

T. Xiao, S. Dobbs, A. Tomaradze and K. K. Seth, Phys. Lett. B 727, 366 (2013).

Cusp Model

Zc(4020)

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



scan in 13 values of sqrt(s)

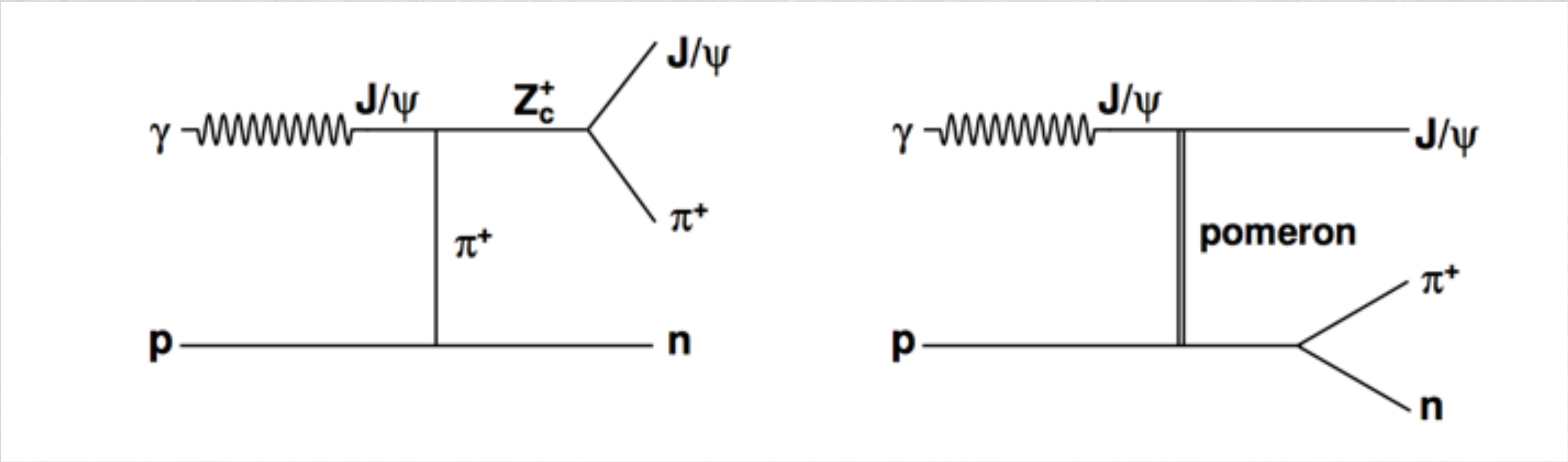
dashed line: same as above

solid line: same as $\Upsilon(5S) \to h_b(nP)\pi\pi$

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

Cusp Model

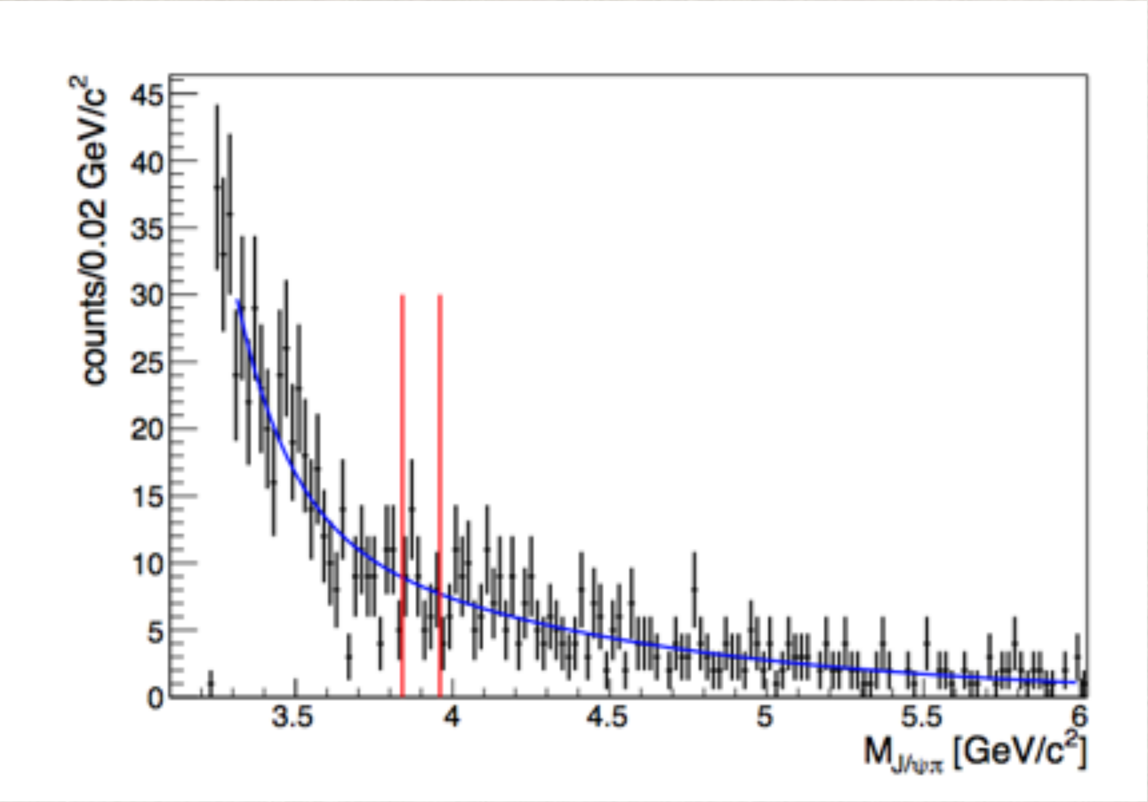
missing exotics…



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

Cusp Model

missing exotics…



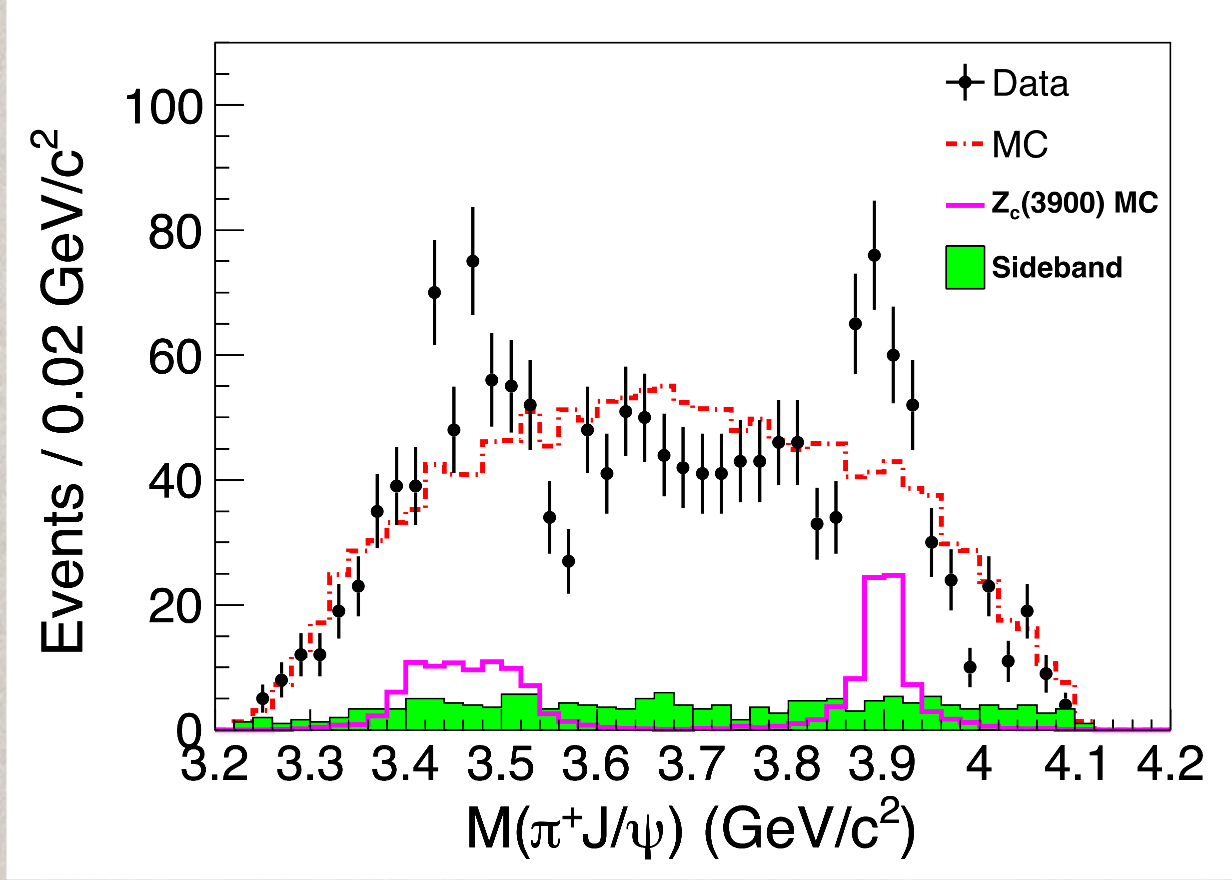
no signal, as expected in the cusp model

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

Cusp Model

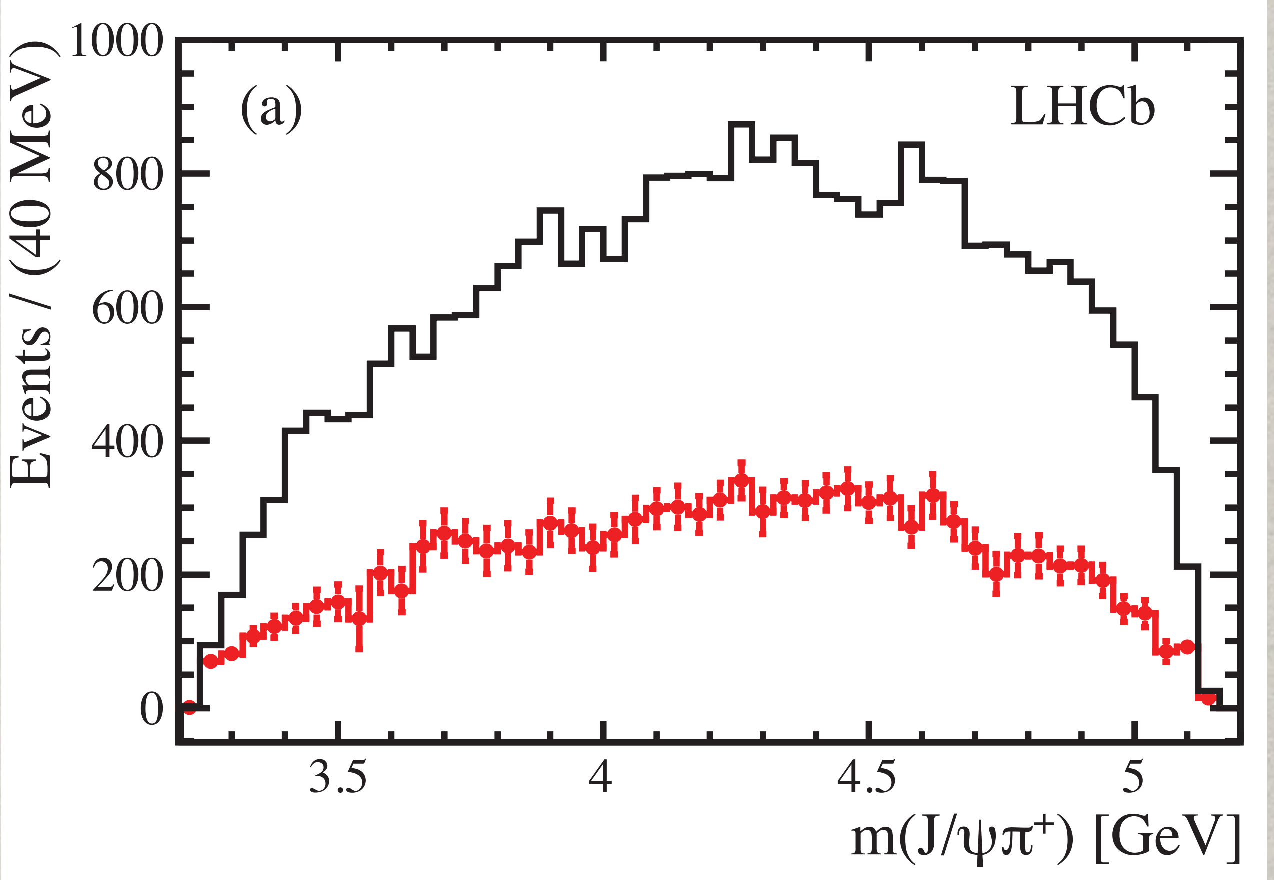
missing exotics...

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



BESIII

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



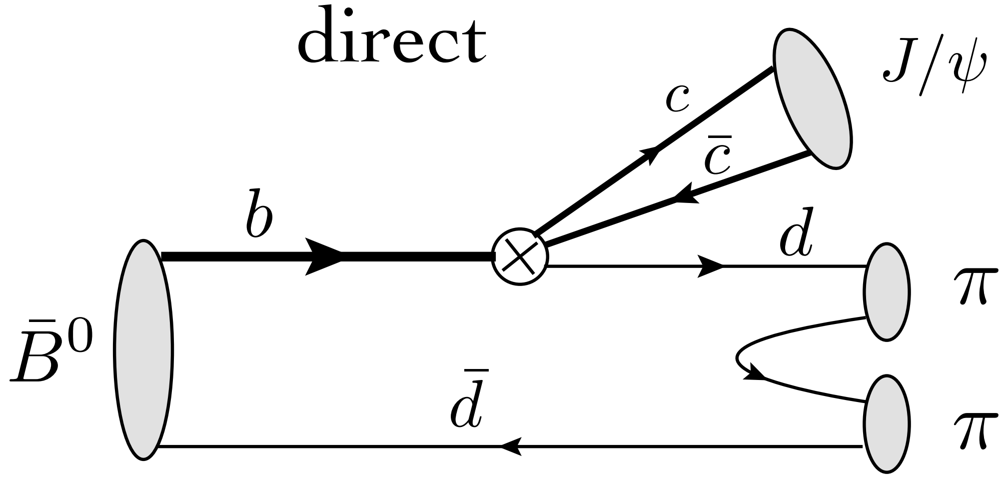
LHCb

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

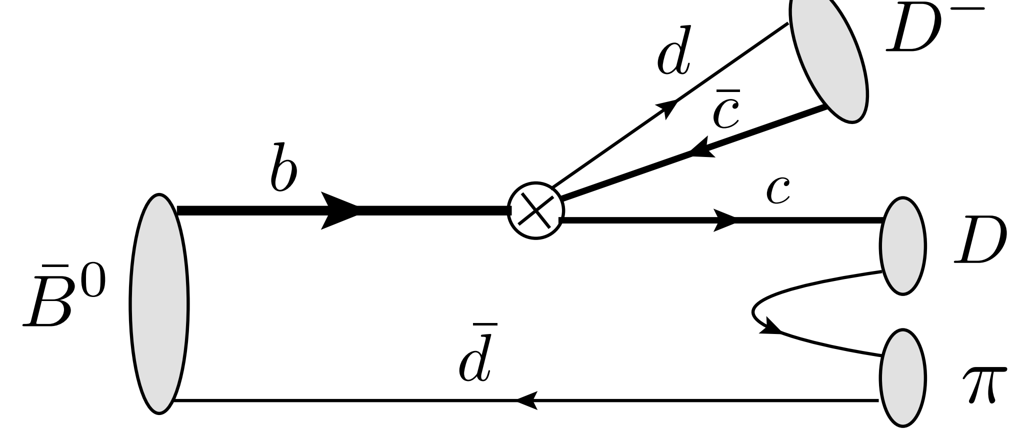
Cusp Model

missing exotics…

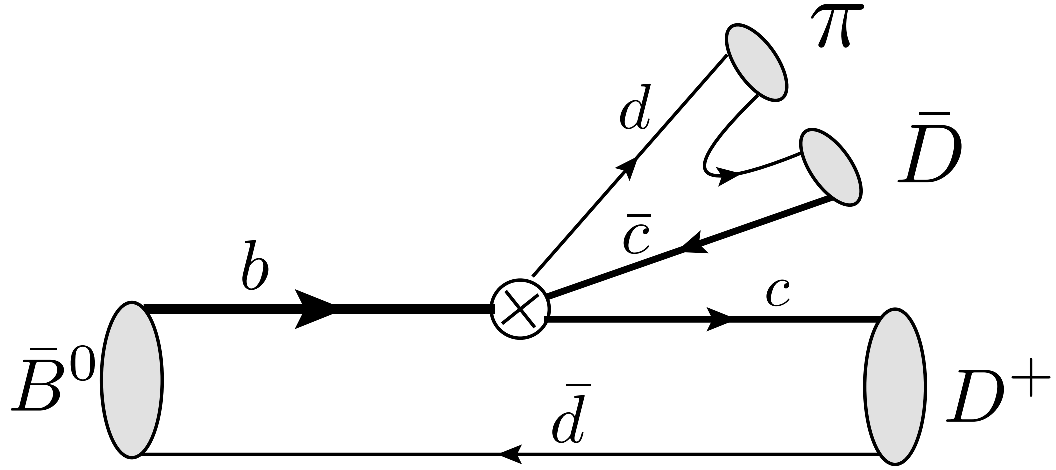
direct



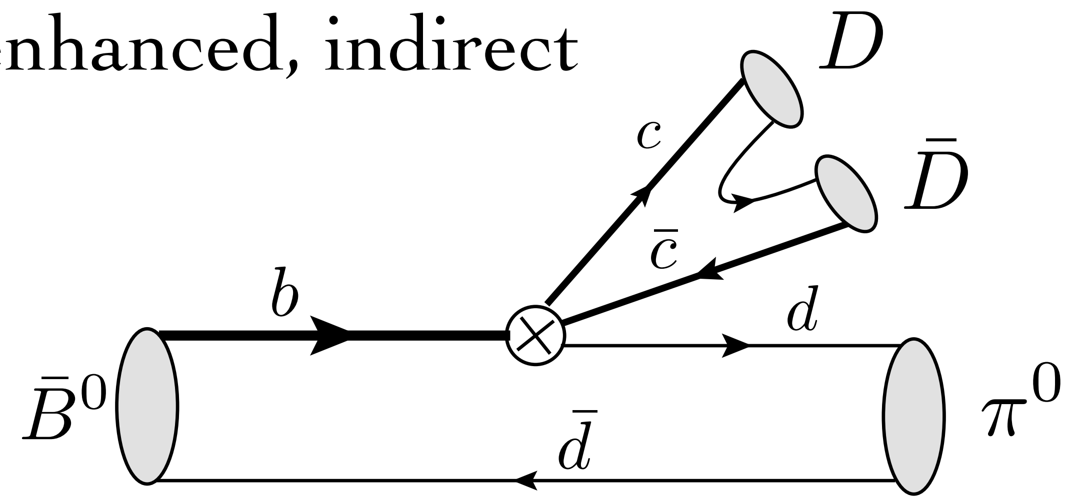
colour enhanced, indirect I



colour enhanced, indirect II



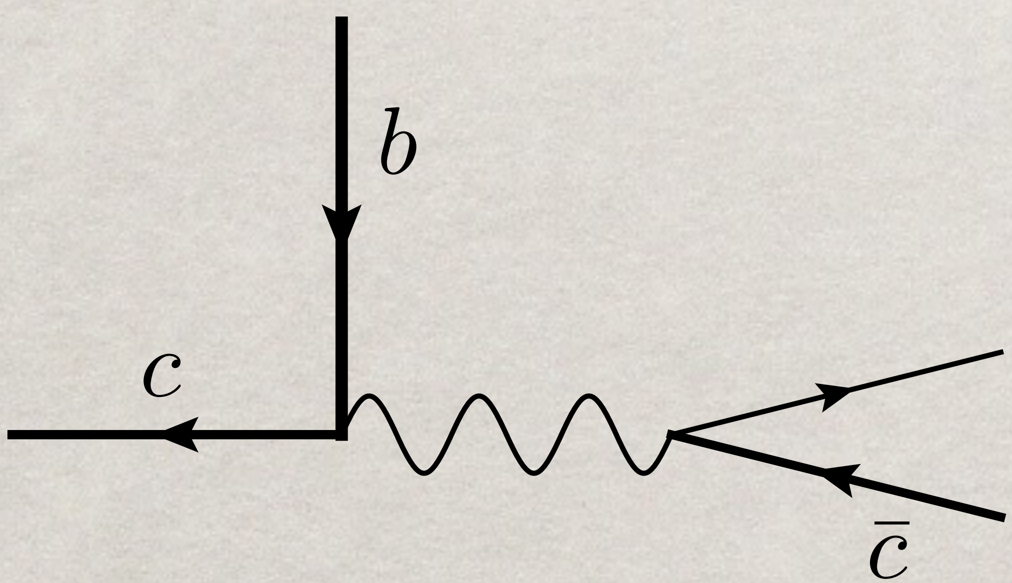
colour suppressed, wavefunction enhanced, indirect



Cusp Model

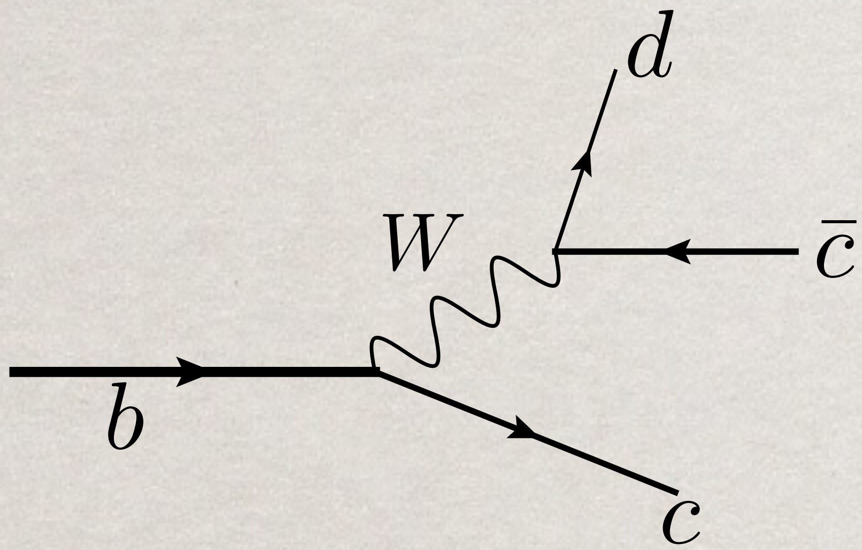
missing exotics…

the direct process is suppressed to the small odds of back to back charm quarks making a J/psi



Cusp Model

missing exotics…



in more detail…

$$\rho(m_{c\bar{c}}) = \int \overline{|\mathcal{M}|^2}(m_{c\bar{c}}, m_{d\bar{c}})\, dm^2_{d\bar{c}}$$

$$\bar{p} = \frac{\int_0^{\sqrt{m_b^2/4 - m_c^2}} \rho(p) p\, dp}{\int_0^{\sqrt{m_b^2/4 - m_c^2}} \rho(p)\, dp}$$

$$\mathcal{P}(\bar{p}) \doteq \int_{\bar{p}}^{\infty} d^3q\, |\psi(q)|^2$$

$\mathcal{P}(0.92) = 25\%$

Cusp Model

missing exotics…

the wavefunction penalty is confirmed in the data

$B \to X$	Bf
D^*D^*	$8 \cdot 10^{-4}$
DD^*	$4 \cdot 10^{-4}$
DD	$4 \cdot 10^{-4}$
$\psi\pi$	$4 \cdot 10^{-5}$
$\psi\rho$	$5 \cdot 10^{-5}$
$\psi\pi\pi$	$4 \cdot 10^{-5}$

Cusp Model

missing exotics…

no penalty for extra light quarks

$B \to X$	Bf
$D\pi^+$	$2.7 \cdot 10^{-3}$
$D^0\pi^+\pi^-$	$8 \cdot 10^{-4}$
$D^-\pi^+\pi^+\pi^-$	$6 \cdot 10^{-3}$
ψK	$8.2 \cdot 10^{-4}$
$\psi K\pi$	$1.2 \cdot 10^{-3}$
$\psi\pi^0$	$1.7 \cdot 10^{-5}$
$\psi\pi^+\pi^-$	$4 \cdot 10^{-5}$

Cusp Model   missing exotics…

direct => wavefunction suppressed
colour enhanced, indirect I, II => rescattering suppressed
colour suppressed, wavefunction enhanced => < rescattering suppressed

The first three must be weak since the Zc is not seen by LHCb in B -> psi pi+ pi- .

The same happens in Bs -> psi K+ K- , which 'should' see a 3980 (DsD* + DDs*) and a 4215 (DsDs*).

We conclude that either the direct diagram or the rescattering wavefunction enhanced diagram dominates.

If the latter dominates then cusp states should be visible in

$$B^0 \to \pi^0\pi^0 J/\psi \qquad B^\pm \to \pi^\pm\pi^0 J/\psi \qquad B_s \to \pi\varphi J/\psi$$

Cusp Model

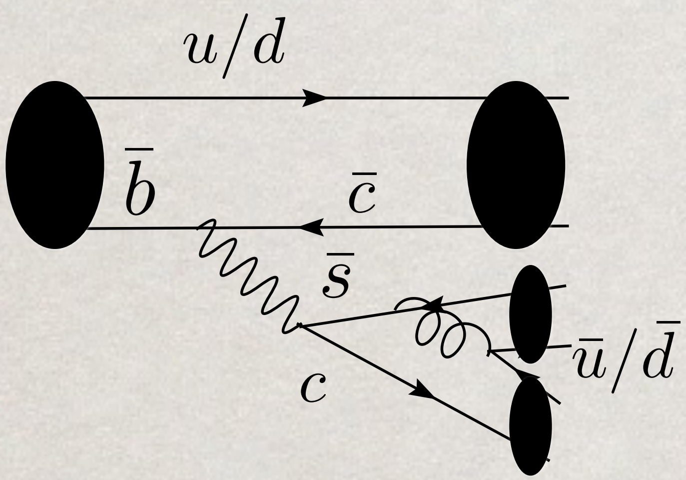
Cusp Diagnostics

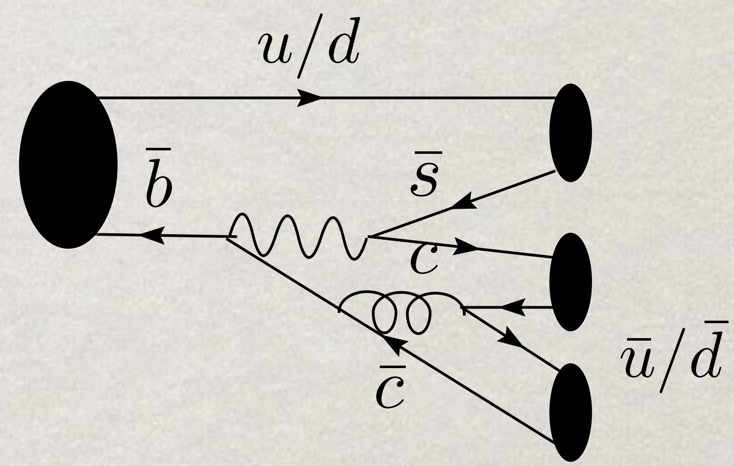
- lie just above thresholds
- S-wave quantum numbers
- partner states of similar width — widths will depend on channel
- the reaction $\Upsilon(5S) \to K\bar{K}\Upsilon(nS)$ should reveal "states" at 10695 ($B\bar{B}_s^* + B^*\bar{B}_s$) and 10745 ($B^*\bar{B}_s^*$)

(if the wavefunction enhanced rescattering diagram contributes)

Cusp Model

Application to X(3872)





colour enhanced, II
rescattering suppressed

$$B^+ \to K^+ D^0 \bar{D}^0$$
$$B^+ \to K^0 D^+ D^0$$

$$B^0 \to K^0 D^- D^+$$
$$B^0 \to K^+ D^- D^0$$

colour suppressed
rescattering enhanced

$$B^+ \to K^+ D^0 \bar{D}^0$$
$$B^+ \to K^+ D^+ D^-$$

$$B^0 \to K^0 D^+ D^-$$
$$B^0 \to K^0 D^0 \bar{D}^0$$

Cusp Model

Application to X(3872)

colour enhanced
rescattering suppressed

$$B^+ \to K^+ D^0 \bar{D}^0$$

$$B^+ \to K^0 D^+ D^0$$

$$B^0 \to K^0 D^- D^+$$

$$B^0 \to K^+ D^- D^0$$

colour suppressed
rescattering enhanced

$$B^+ \to K^+ D^0 \bar{D}^0$$

$$B^+ \to K^+ D^+ D^-$$

$$B^0 \to K^0 D^+ D^-$$

$$B^0 \to K^0 D^0 \bar{D}^0$$

$$\frac{Br(B^0 \to K^0 X)}{Br(B^+ \to K^+ X)} = \left| \frac{N_c Z_{+-} + \gamma Z_{00} + \gamma Z_{+-}}{N_c Z_{00} + \gamma Z_{00} + \gamma Z_{+-}} \right|^2 \approx \left| \frac{\gamma}{N_c + \gamma} \right|^2$$

Cusp Model

Application to X(3872)

$$\frac{Br(B^0 \to K^0 X)}{Br(B^+ \to K^+ X)} = \left| \frac{N_c Z_{+-} + \gamma Z_{00} + \gamma Z_{+-}}{N_c Z_{00} + \gamma Z_{00} + \gamma Z_{+-}} \right|^2 \approx \left| \frac{\gamma}{N_c + \gamma} \right|^2$$

$$\frac{Br(B^0 \to K^0 X)}{Br(B^+ \to K^+ X)} = \; 0.50 \pm 0.30 \pm 0.05$$

Thus $\gamma \approx 7^{+17}_{-4.6}$

Cusp Model

Application to X(3872)

colour enhanced
rescattering suppressed

$$B^+ \to K^+ D^0 \bar{D}^0$$

$$\boxed{B^+ \to K^0 D^+ D^0}$$

$$B^0 \to K^0 D^- D^+$$

$$\boxed{B^0 \to K^+ D^- D^0}$$

colour suppressed
rescattering enhanced

$$B^+ \to K^+ D^0 \bar{D}^0$$

$$B^+ \to K^+ D^+ D^-$$

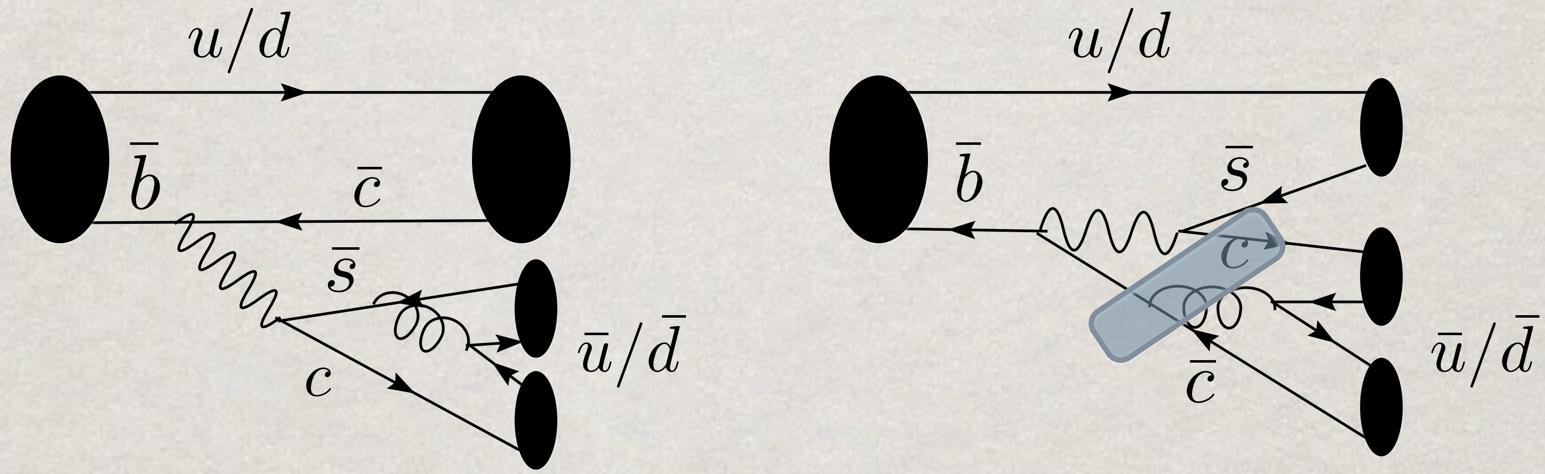
$$B^0 \to K^0 D^+ D^-$$

$$B^0 \to K^0 D^0 \bar{D}^0$$

An X^+ or X^- should be made with approximately the same strength as the X. These modes are not seen ⇒ X has no charge-partners, and X is not a cusp effect.

Cusp Model

Application to X(3872)



Note that the rescattering enhanced diagram goes through a χ'_{c1} explaining the large production seen, if this state has a large overlap with the X.

Cusp Model

Application to X(3872)

X-χ mixing

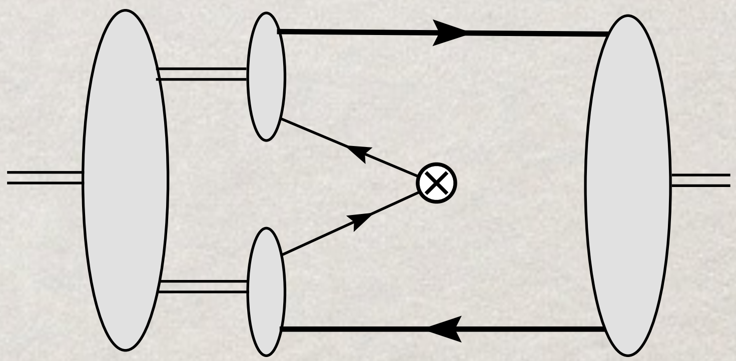


Table 1: $X - \chi_{c1}$ Mixing.

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	$> 100\%$

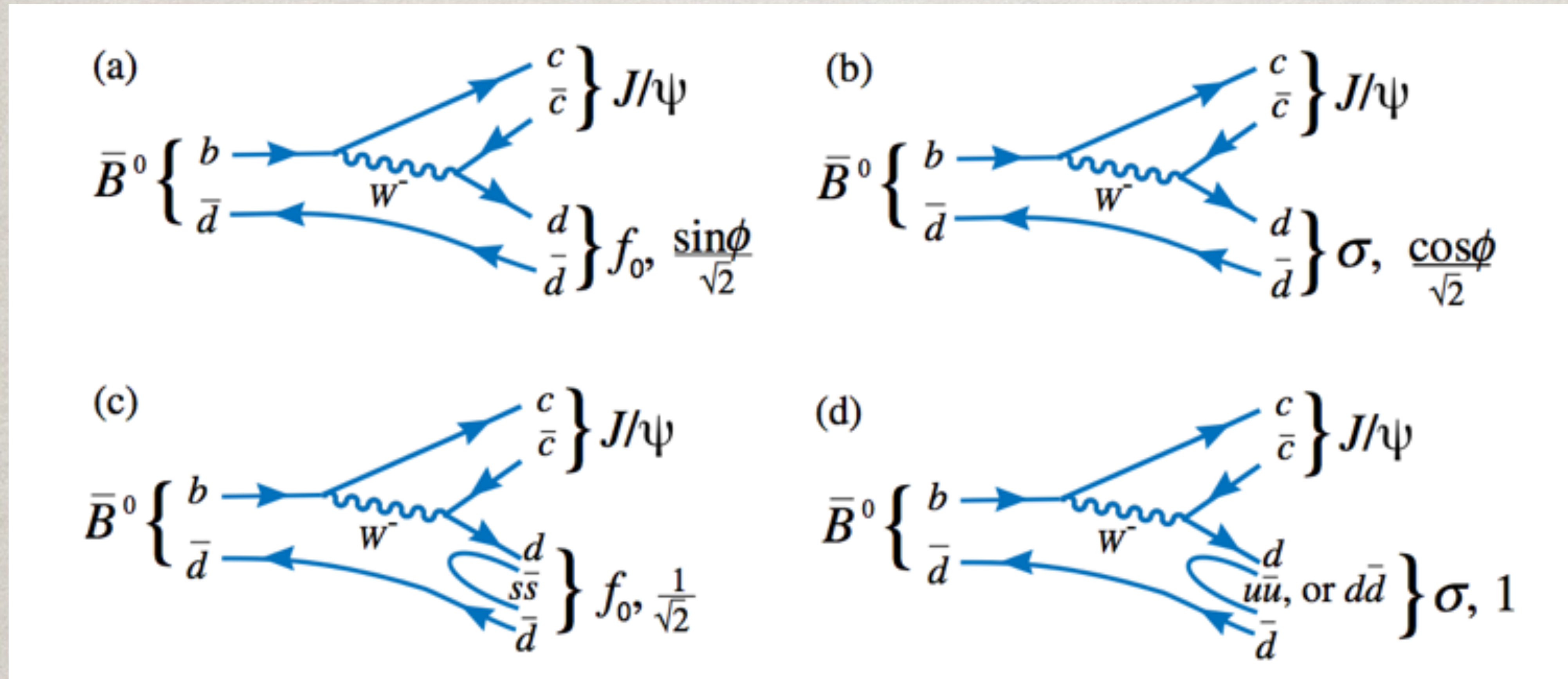
Comments on $B \to \pi\pi J/\psi$

$B_d \to J/\psi X(d\bar{d})$ is a flavour filter for the state X

Stone and Zhang have claimed that this can be used to distinguish qq and tetraquark models for the light isoscalar scalars.

S. Stone and L. Zhang, PRL111, 062001 (2013)

Comments on $B \to \pi\pi J/\psi$



qq

tetraquark

$$|f_0\rangle = \cos\phi|s\bar{s}\rangle + \sin\phi|n\bar{n}\rangle$$

$$|\sigma\rangle = -\sin\phi|s\bar{s}\rangle + \cos\phi|n\bar{n}\rangle$$

$$|f_0\rangle = \frac{1}{\sqrt{2}}([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}])$$

$$|\sigma\rangle = [ud][\bar{u}\bar{d}]$$

Comments on $B \to \pi\pi J/\psi$

$$r \equiv \frac{Br(\bar{B}^0 \to J/\psi f_0)}{Br(\bar{B}^0 \to J/\psi \sigma)} \frac{\Phi(500)}{\Phi(980)} \qquad \frac{\Phi(500)}{\Phi(980)} = 1.25$$

$$r = (1.1^{+1.2+6.0}_{-0.7-0.7}) \times 10^{-2} < 0.098 \text{ at } 90\% \text{ C.L.}$$

which is 8 sigma away from the tetraquark prediction of r=1/2.

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

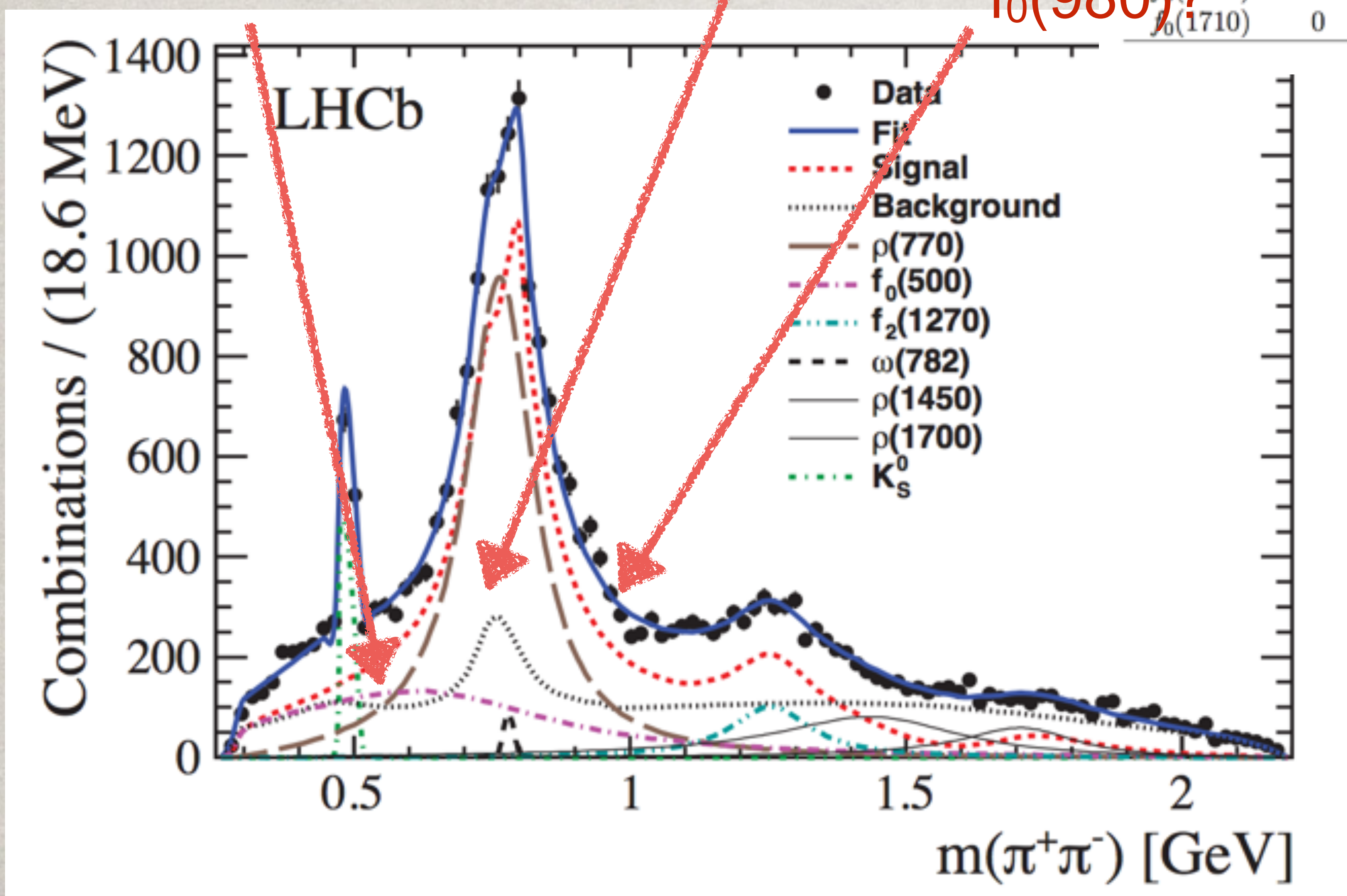
Comments on $B \to \pi\pi J/\psi$

Resonance	Spin	Helicity	Resonance formalism	Mass (MeV)	Width (MeV)
$\rho(770)$	1	$0, \pm 1$	BW	775.49 ± 0.34	149.1 ± 0.8
$f_0(500)$	0	0	BW	513 ± 32	335 ± 67
$f_2(1270)$	2	$0, \pm 1$	BW	1275.1 ± 1.2	$185.1^{+2.9}_{-2.4}$
$\omega(782)$	1	$0, \pm 1$	BW	782.65 ± 0.12	8.49 ± 0.08
$f_0(980)$	0	0	Flatté	–	–
$\rho(1450)$	1	$0, \pm 1$	BW	1465 ± 25	400 ± 60
$\rho(1700)$	1	$0, \pm 1$	BW	1720 ± 20	250 ± 100
$f_0(1500)$	0	0	BW	1461 ± 3	124 ± 7
$f_0(1710)$	0	0	BW	1720 ± 6	135 ± 8

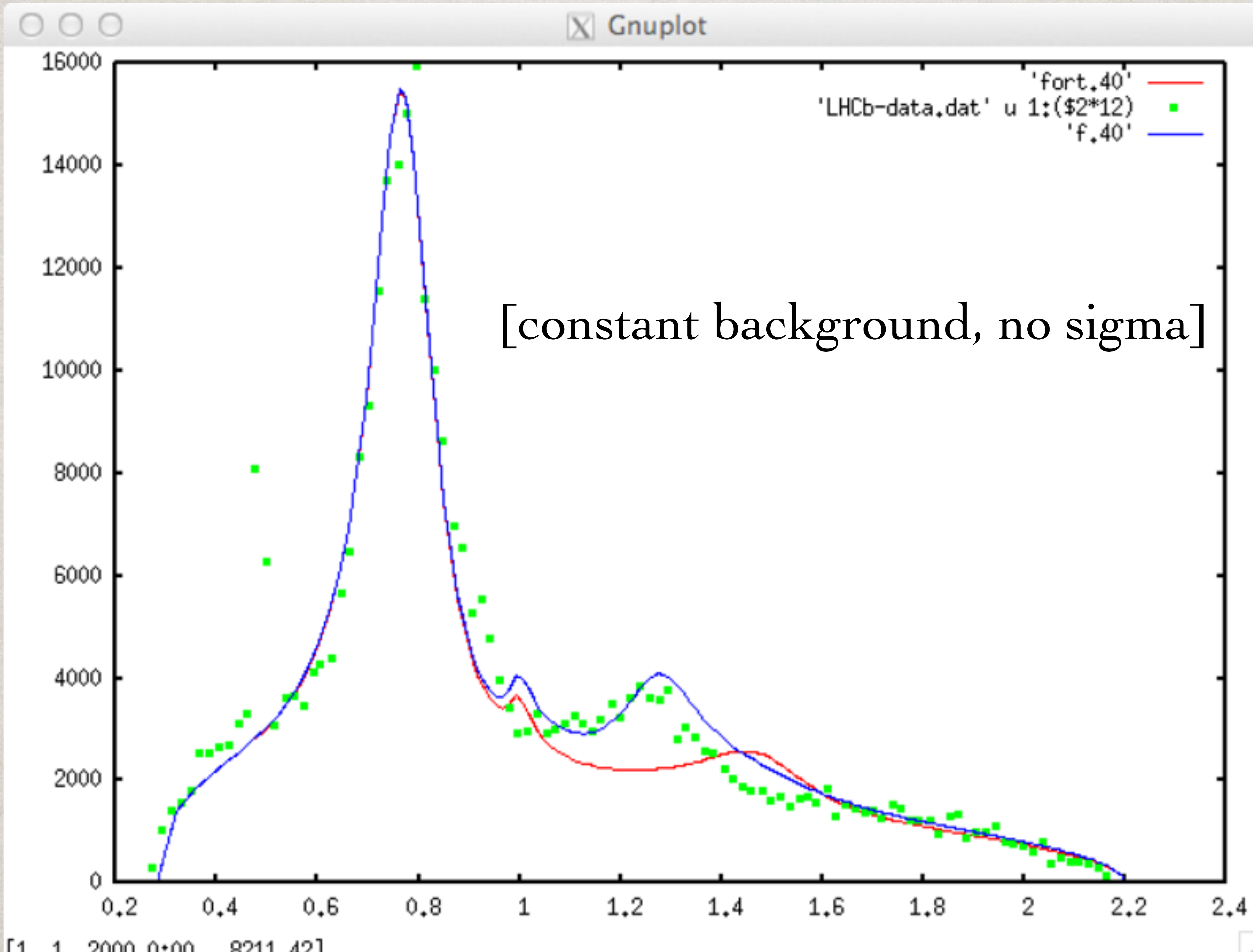
σ?

background?

$f_0(980)$?



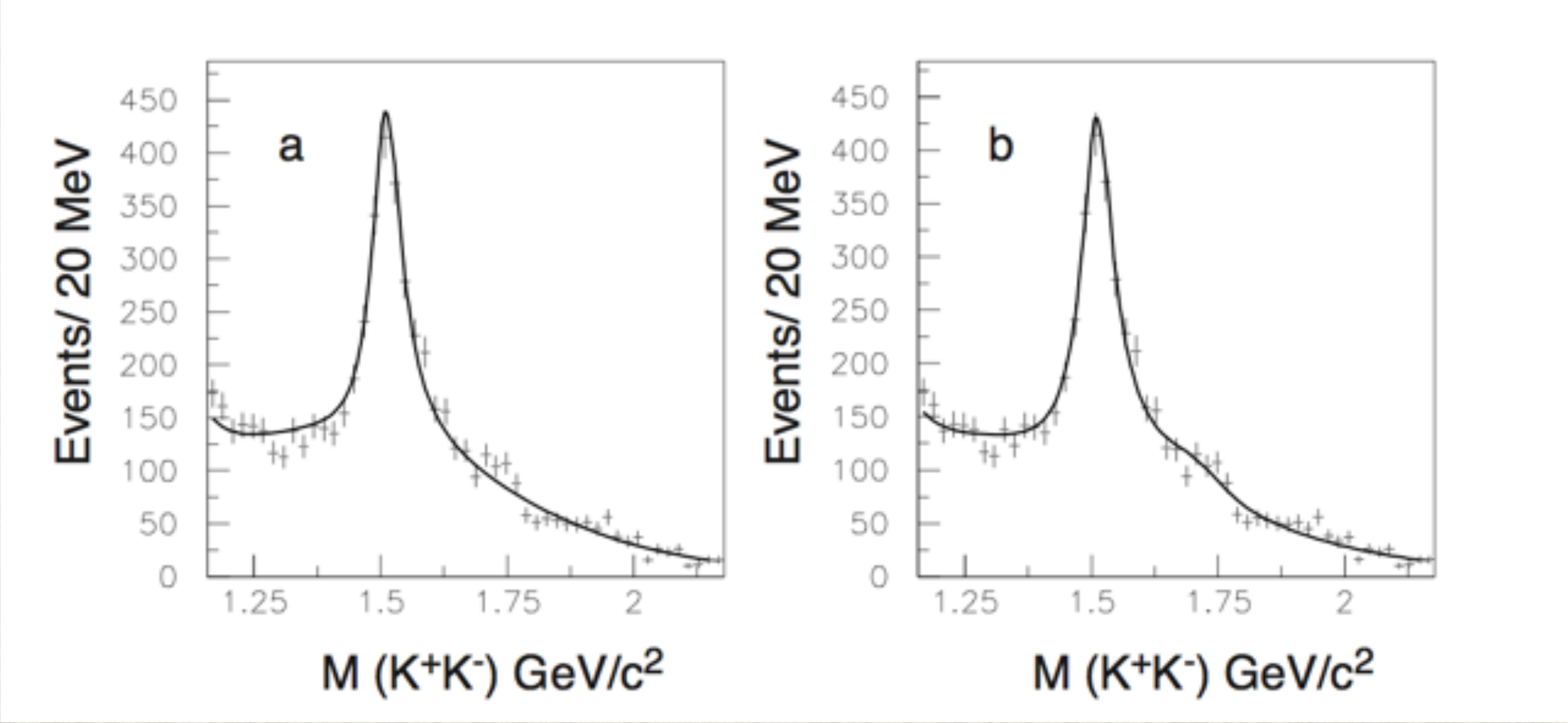
Comments on $B \to \pi\pi J/\psi$



[constant background, no sigma]

Comments on $B \to \pi\pi J/\psi$

Close and Kirk have plotted LHCb data for B(s) -> psi 2(pi) and psi 4(pi) with WA102 parameters and find good agreement. Thus there is no need for the exotic conclusions of LHCb.

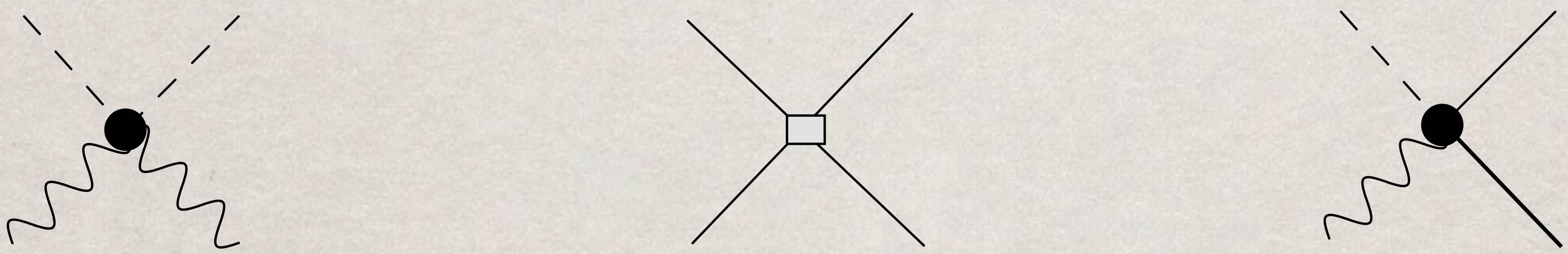


[(b) has the f0(1710) as obtained by WA102]

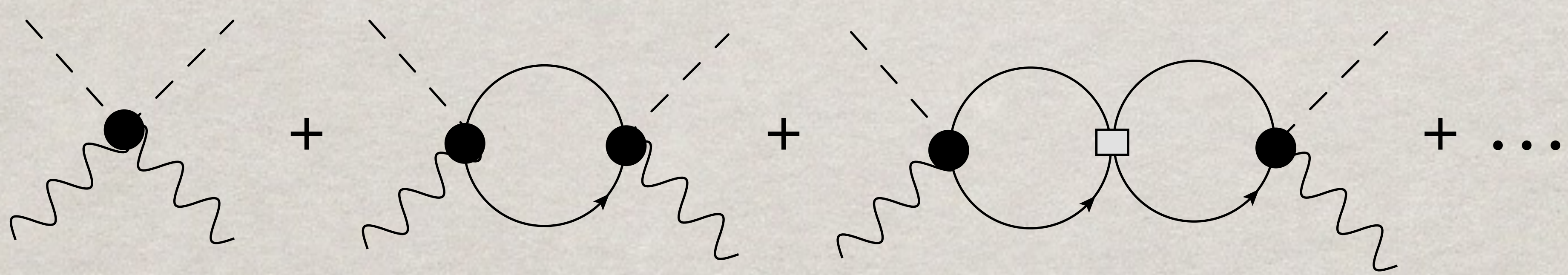
F. Close and A. Kirk, in progress

More Detailed Modelling

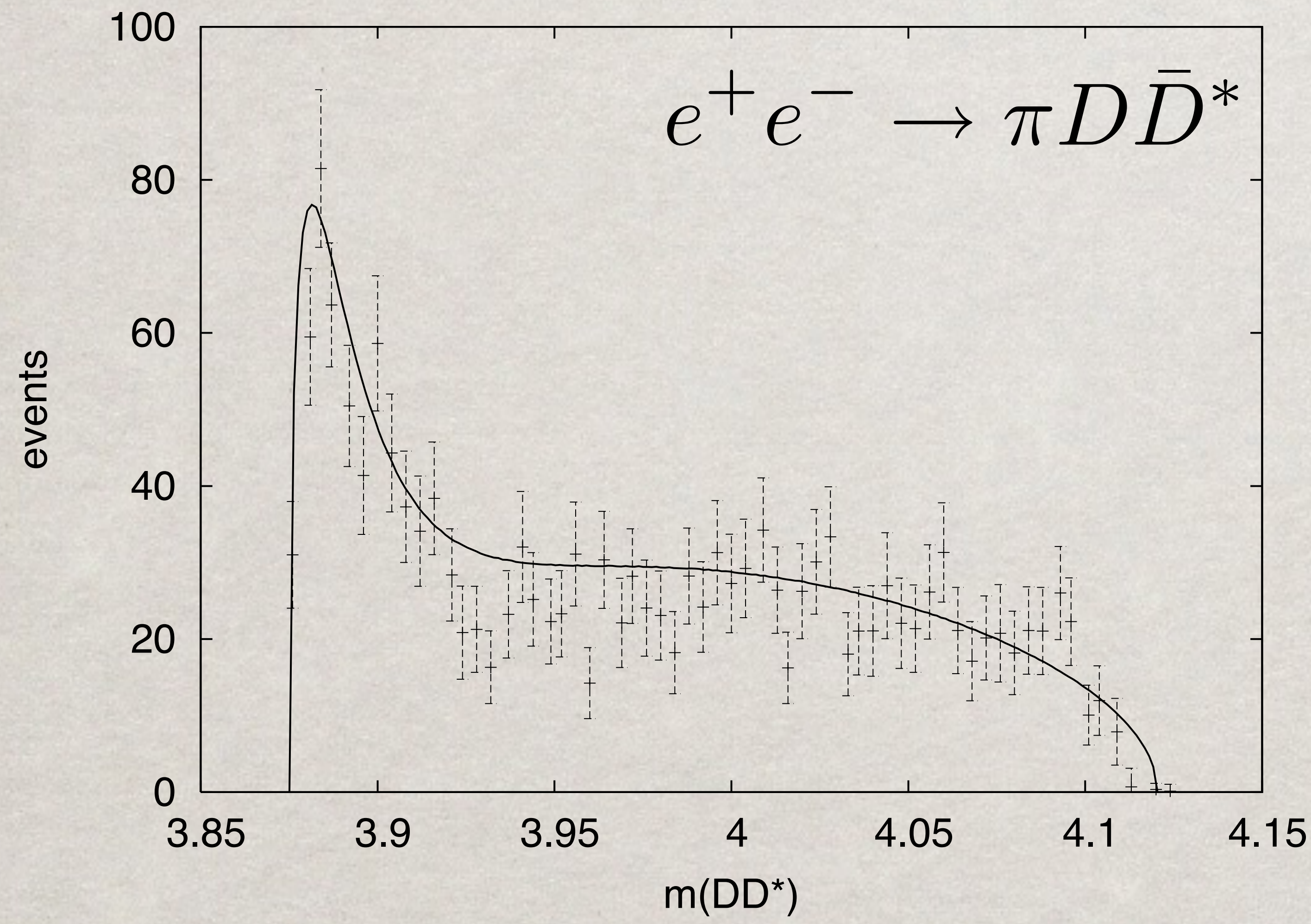
Model the vertices so that more processes can be described.

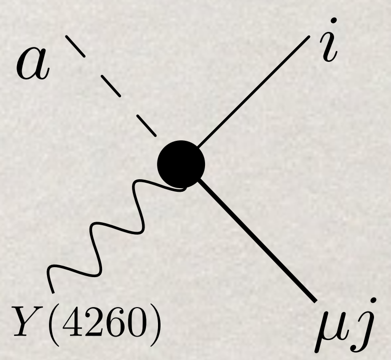


Now we need to build the 'self energy'



More Detailed Modelling



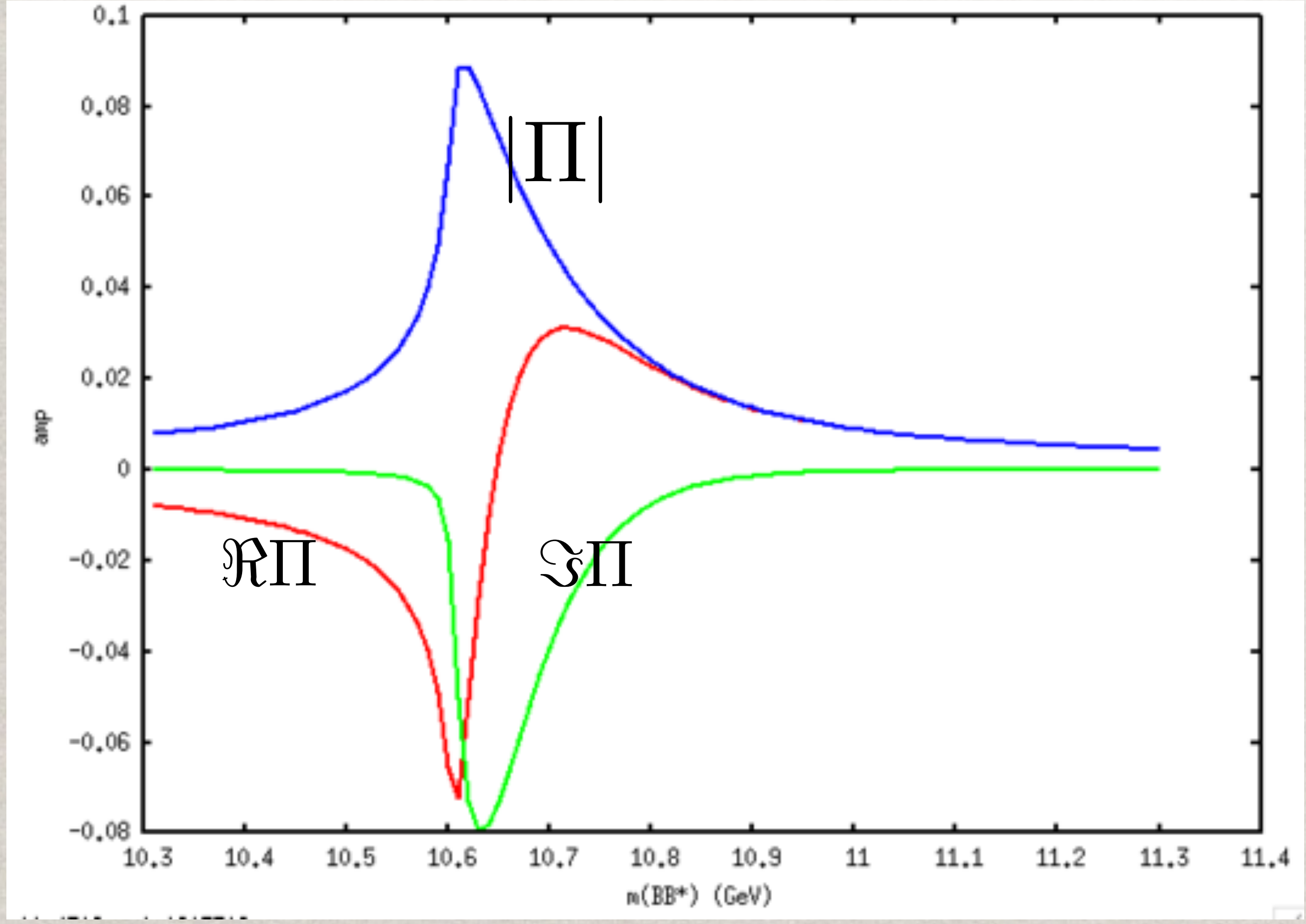


M. Ablikim et al [BESIII] PRL 112, 022001 (2014)

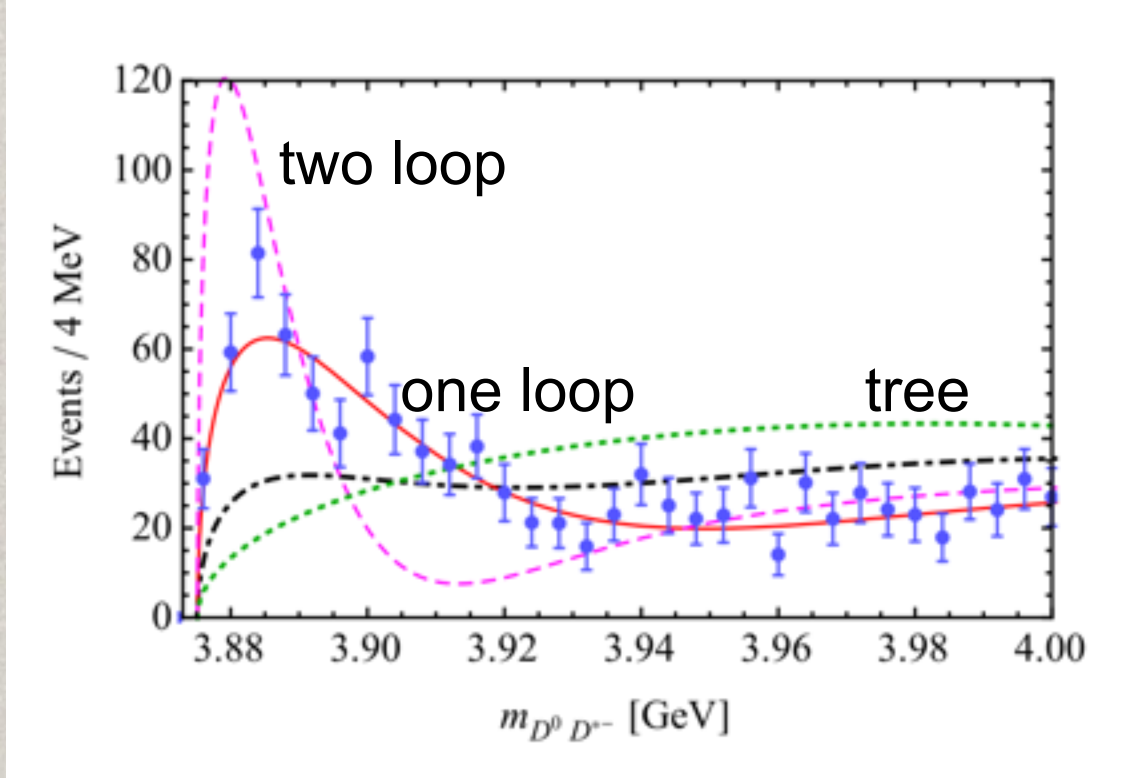
More Detailed Modelling

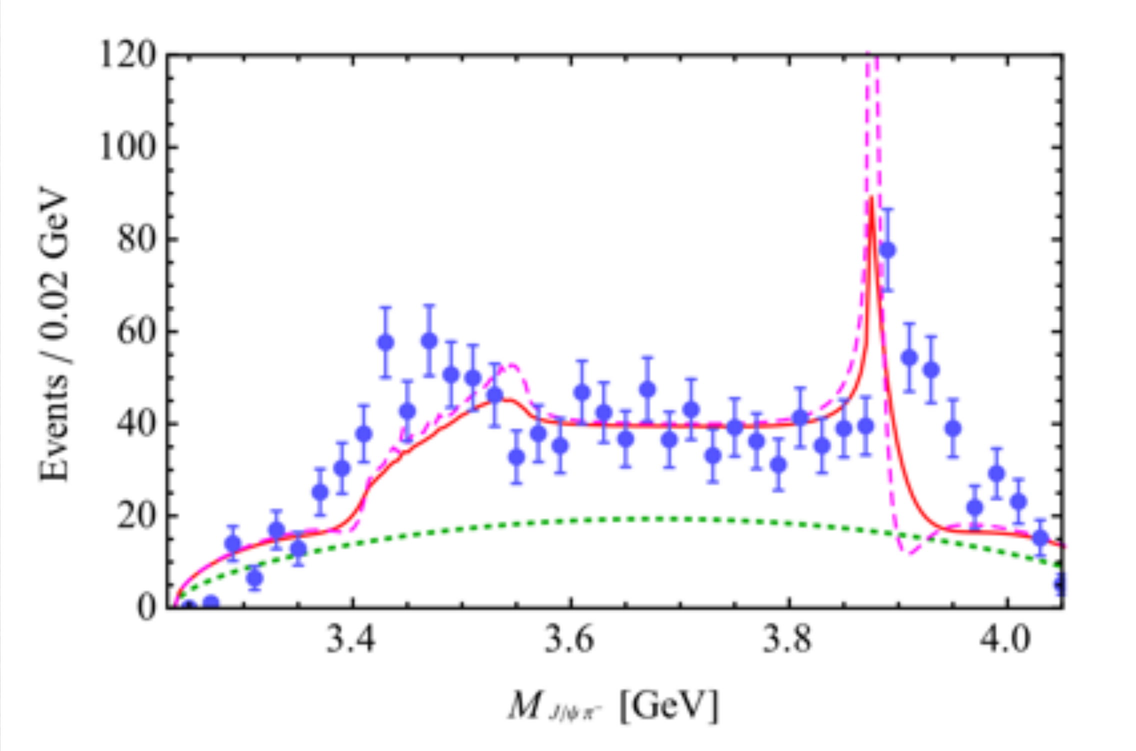
$$\Pi = \int \frac{d^3q}{(2\pi)^3} \frac{e^{-q^2/\Lambda^2}}{E - m_B - m_{B^*} - q^2/2\mu + i\epsilon}$$

$\Lambda = 0.5$ GeV



More Detailed Modelling





Hanhart et al. claim that the strength of the vertex requires bubble summation, which generates a pole.

F.-K. Guo et al. arXiv: 1411.5584

More Detailed Modelling

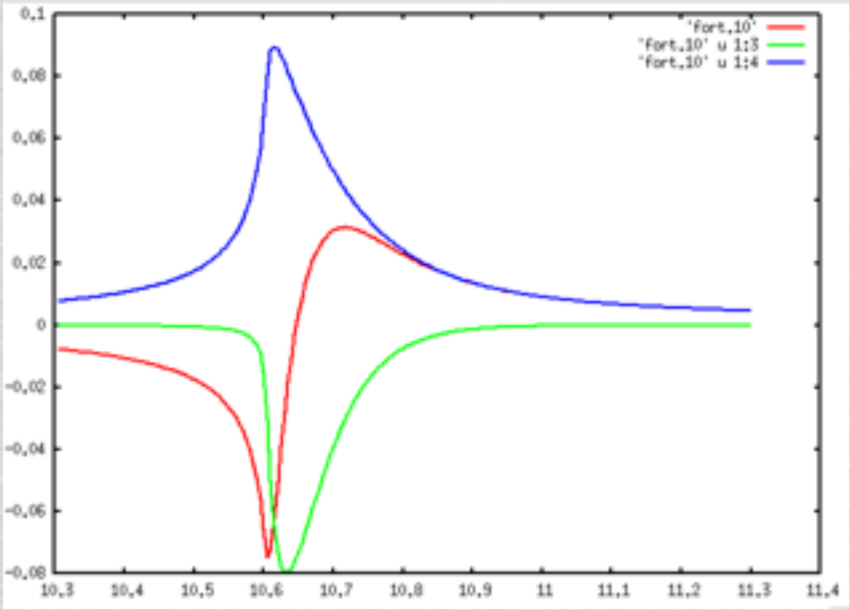
Hanhart et al. claim that the strength of the vertex requires bubble summation, which generates a pole.

But:

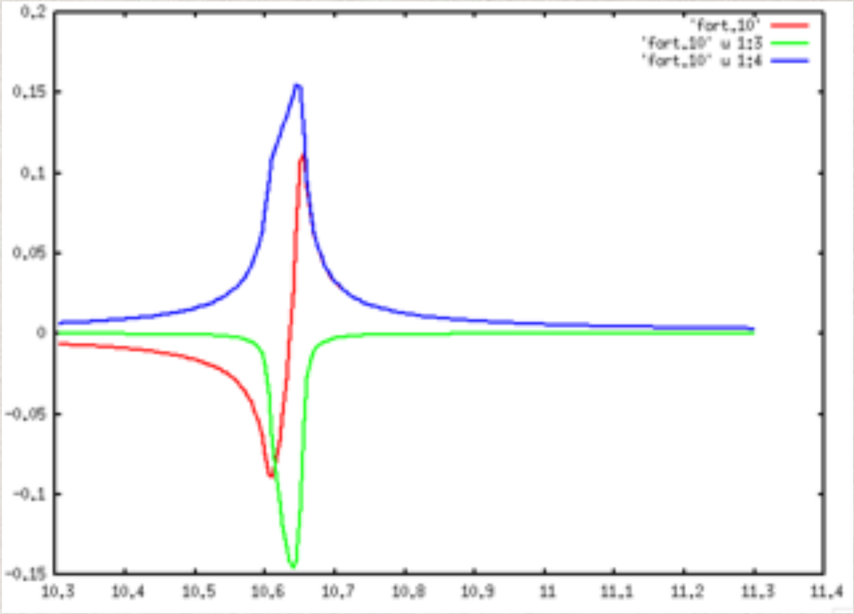
(i) a constant vertex
(ii) didn't show full sum (?)
(iii) assumed I modelled the loop, rather than the sum
(iv) choice of the regulator makes a *big* difference
(v) their regulated bubble model corresponds to my iterated vertex
(vi) knowing cross section normalization will help to pin down models

F.-K. Guo et al. arXiv: 1411.5584

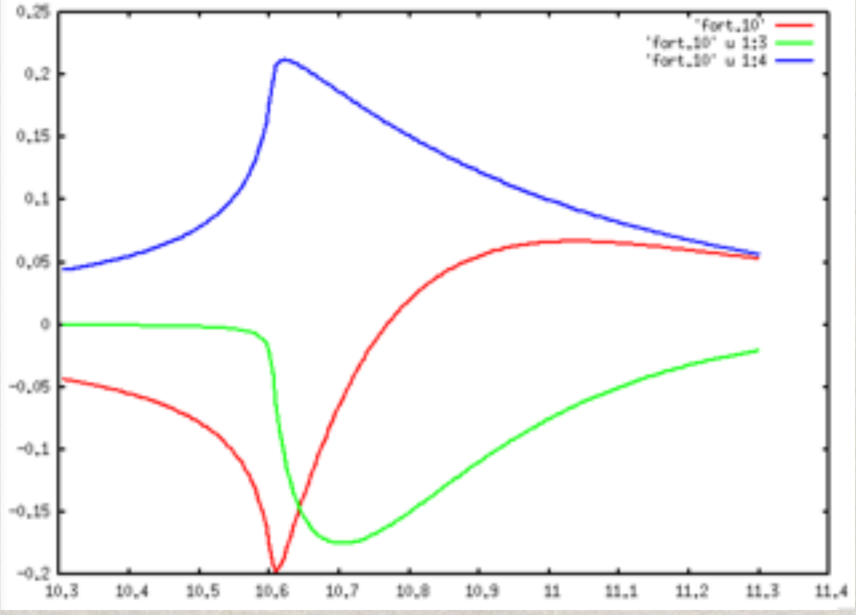
More Detailed Modelling



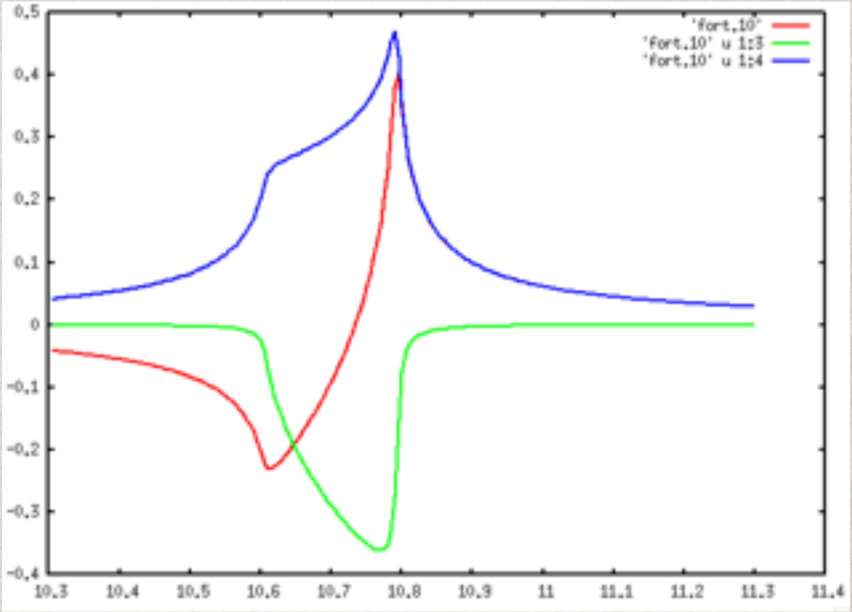
exponential Lambda=0.5



cut off Lambda=0.5



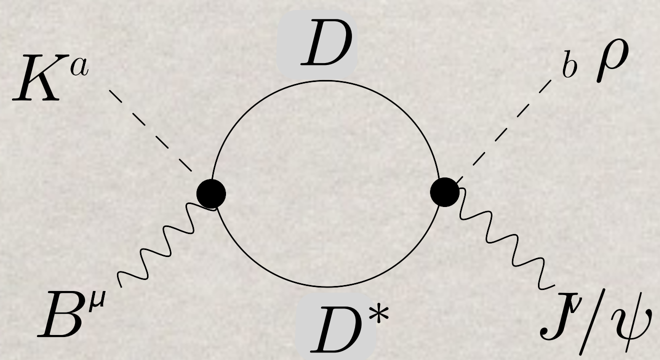
exponential Lambda=1.0

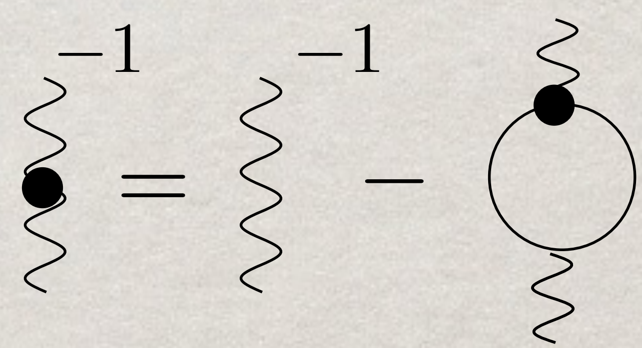


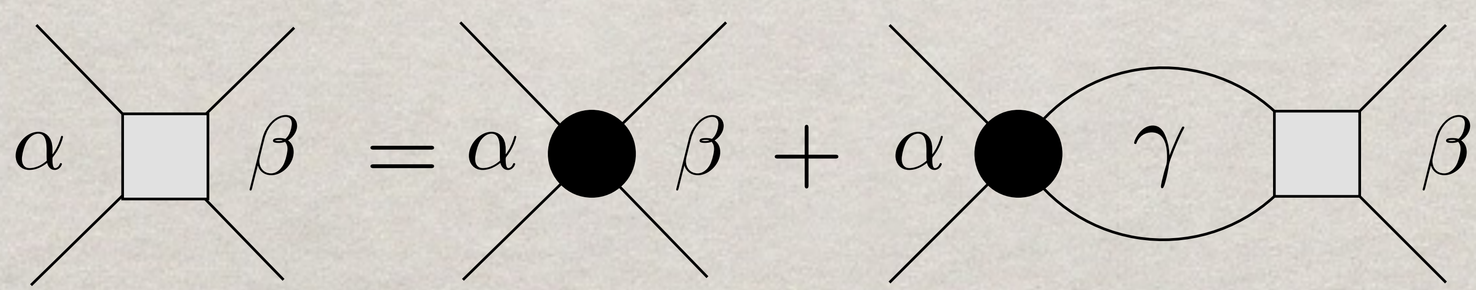
cut off Lambda=1.0

More Detailed Modelling - to do

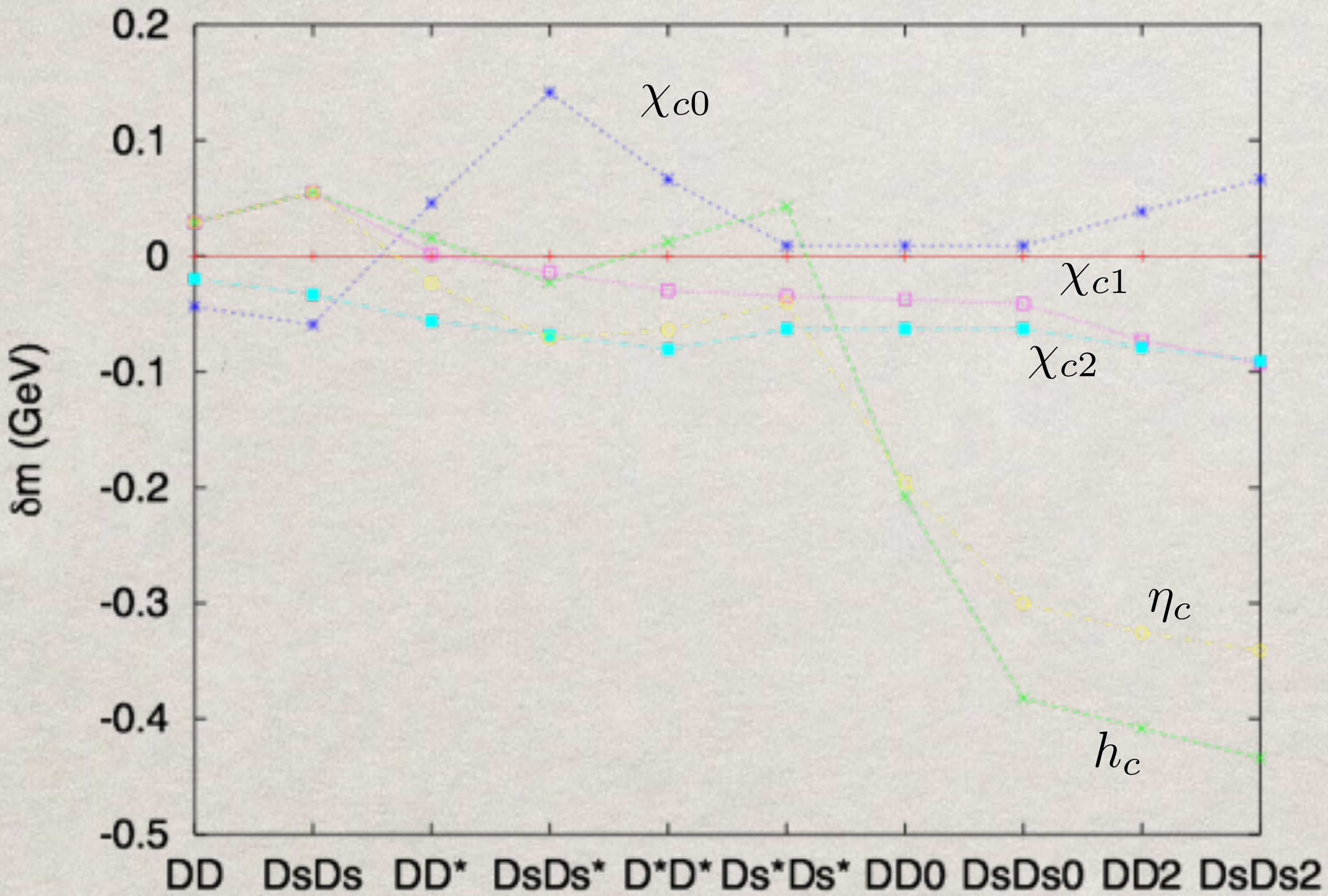
- model vertices in a reasonable way and perform bubble sums
- compare to D D* pi and pi pi J/psi
- examine the X(3872): interplay of cusp, possible bound state dynamics, and mixing with cc states







More Detailed Modelling - to do



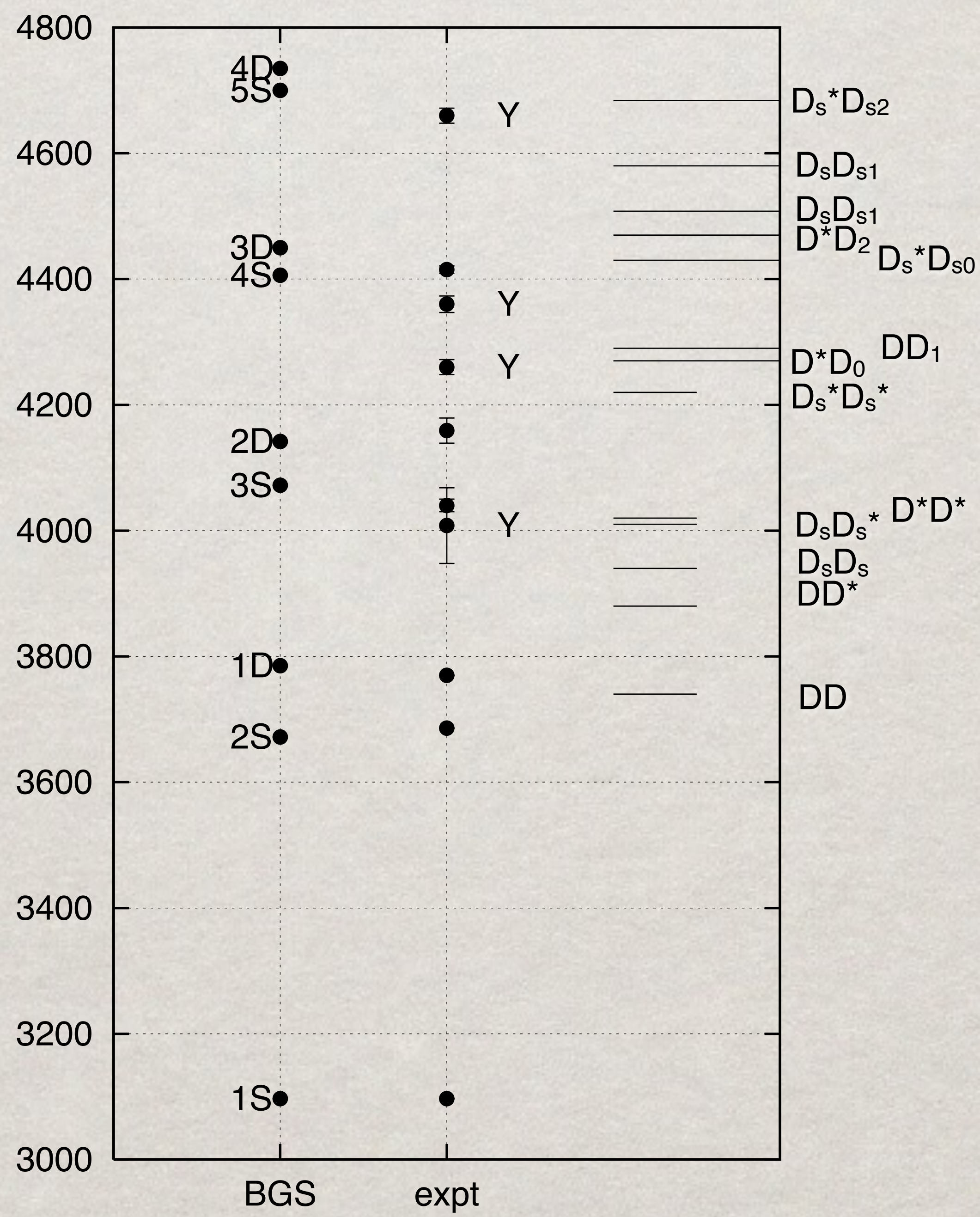
Need to correctly renormalise the bare model (in this case, the constituent quark model)

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!
- there is much subtlety in this game!

✢ ÆRIC MEC HEHT GEWYRCAN

Charmonium Hybrids



Diquarks and the new Charmonia

Maiani, Piccinini,Polosa, Riquer; PRD71, 014028 (2005)

Bigi, Maiani, Piccinini,Polosa, Riquer; PRD72, 114016 (2005)

Maiani, Riquer, Piccinini, Polosa; PRD72, 031502 (2005)

Maiani, Polosa, Riquer; PRL99, 182003 (2007)

Maiani, Polosa, Riquer; arXiv:0708.3997

$$M([cq]_S) = 1933$$
$$M([cq]_V) = 1933$$

Assume a spin-spin interaction

$$
\begin{aligned}
|0^{++}\rangle &= |[cq]_S[\bar{c}\bar{q}]_S; J=0\rangle \\
|0^{++\prime}\rangle &= |[cq]_V[\bar{c}\bar{q}]_V; J=0\rangle \\
|1^{++}\rangle &= \frac{1}{\sqrt{2}}\left(|[cq]_S[\bar{c}\bar{q}]_V; J=1\rangle + |[cq]\right. \\
|1^{+-}\rangle &= \frac{1}{\sqrt{2}}\left(|[cq]_S[\bar{c}\bar{q}]_V; J=1\rangle - |[cq]\right. \\
|1^{+-\prime}\rangle &= |[cq]_V[\bar{c}\bar{q}]_V; J=1\rangle \\
|2^{++}\rangle &= |[cq]_V[\bar{c}\bar{q}]_V; J=2\rangle
\end{aligned}
$$