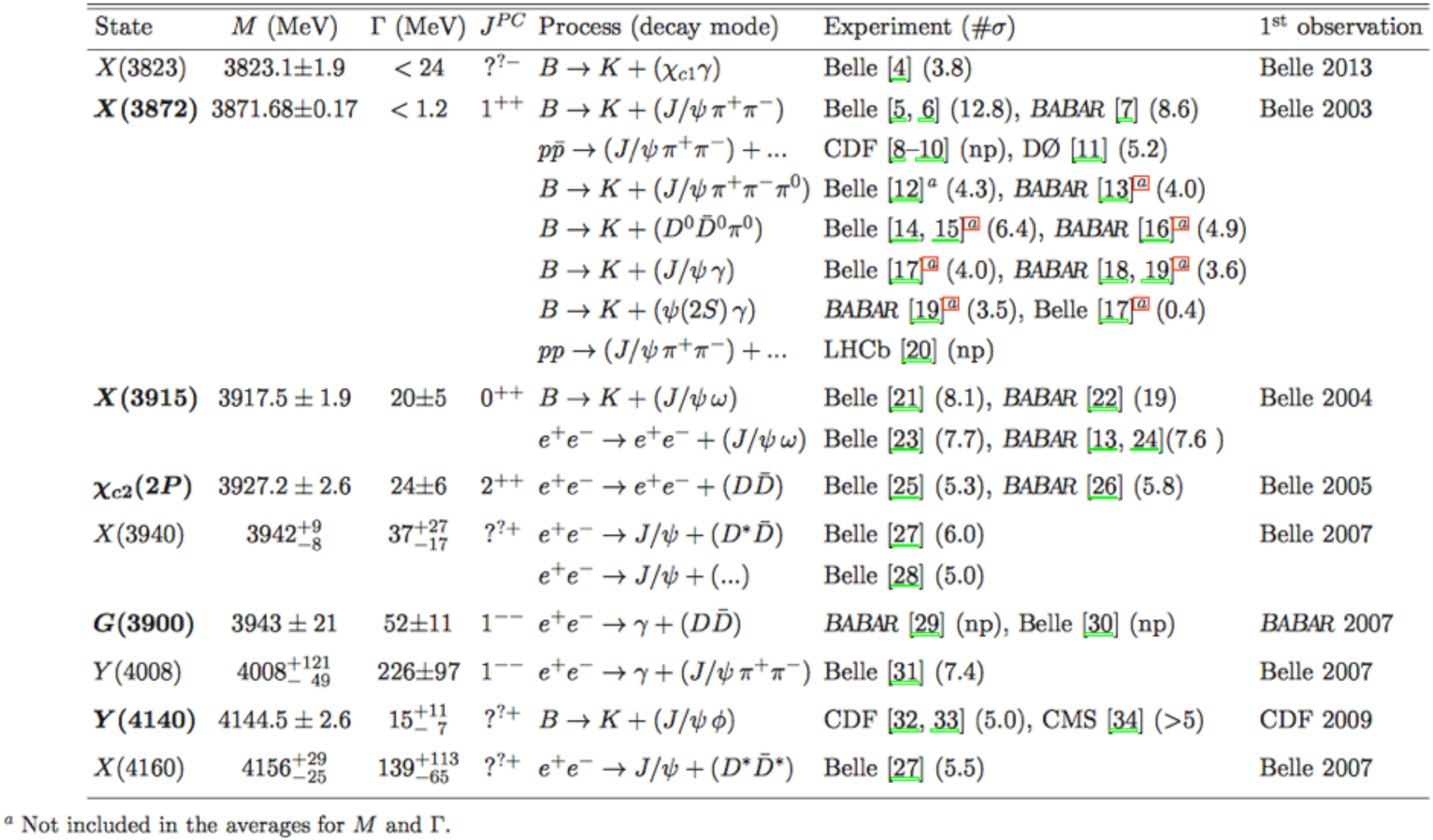
Multiquark Resonances

AD Polosa
CERN and Sapienza University of Rome

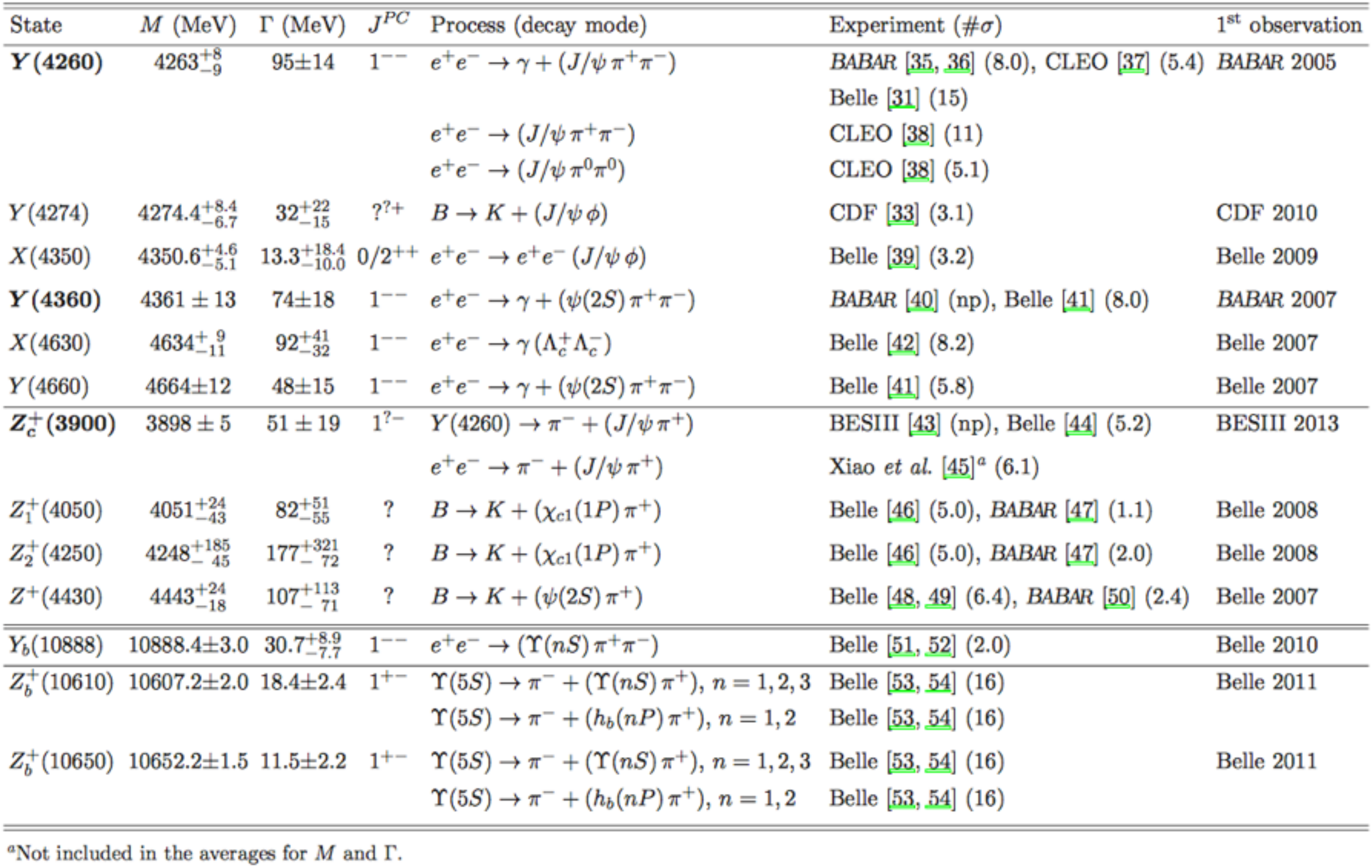
Since 2003/4 new Charmonium-Like States



State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1st observation
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K + (\chi_{c1}\gamma)$	Belle [4] (3.8)	Belle 2013
$\boldsymbol{X(3872)}$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [5, 6] (12.8), *BABAR* [7] (8.6)	Belle 2003
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + \ldots$	CDF [8–10] (np), DØ [11] (5.2)	
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [12][a] (4.3), *BABAR* [13][a] (4.0)	
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [14, 15][a] (6.4), *BABAR* [16][a] (4.9)	
				$B \to K + (J/\psi\,\gamma)$	Belle [17][a] (4.0), *BABAR* [18, 19][a] (3.6)	
				$B \to K + (\psi(2S)\,\gamma)$	*BABAR* [19][a] (3.5), Belle [17][a] (0.4)	
				$pp \to (J/\psi\,\pi^+\pi^-) + \ldots$	LHCb [20] (np)	
$\boldsymbol{X(3915)}$	3917.5 ± 1.9	20 ± 5	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle [21] (8.1), *BABAR* [22] (19)	Belle 2004
				$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle [23] (7.7), *BABAR* [13, 24](7.6)	
$\boldsymbol{\chi_{c2}(2P)}$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [25] (5.3), *BABAR* [26] (5.8)	Belle 2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27] (6.0)	Belle 2007
				$e^+e^- \to J/\psi + (\ldots)$	Belle [28] (5.0)	
$\boldsymbol{G(3900)}$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	*BABAR* [29] (np), Belle [30] (np)	*BABAR* 2007
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle [31] (7.4)	Belle 2007
$\boldsymbol{Y(4140)}$	4144.5 ± 2.6	15^{+11}_{-7}	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [32, 33] (5.0), CMS [34] (>5)	CDF 2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi + (D^*\bar{D}^*)$	Belle [27] (5.5)	Belle 2007

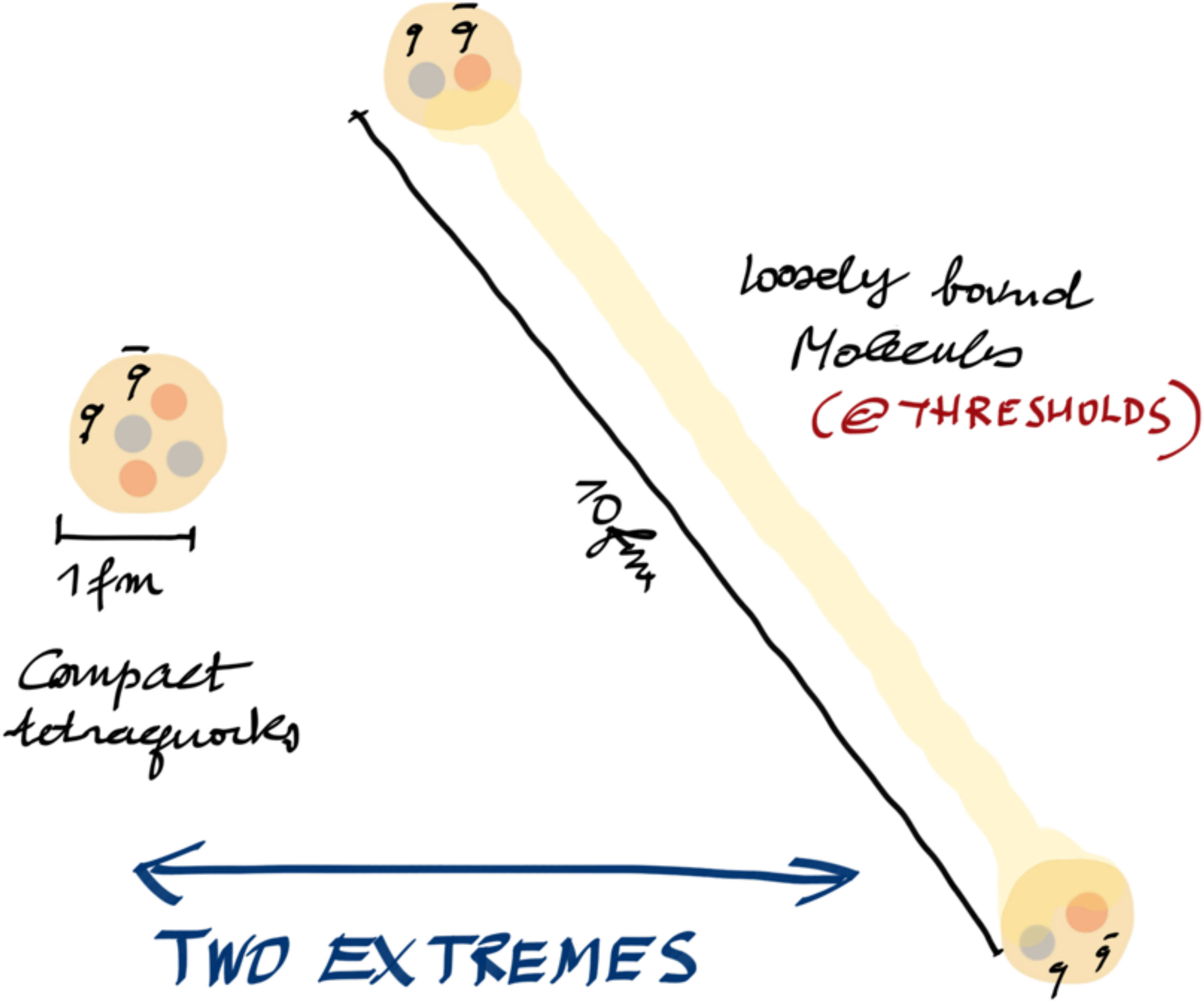
[a] Not included in the averages for M and Γ.

New Charmonium & Bottomonium Like States



State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1st observation
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	*BABAR* [35, 36] (8.0), CLEO [37] (5.4)	*BABAR* 2005
					Belle [31] (15)	
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [38] (11)	
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [38] (5.1)	
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [33] (3.1)	CDF 2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [39] (3.2)	Belle 2009
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	*BABAR* [40] (np), Belle [41] (8.0)	*BABAR* 2007
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [42] (8.2)	Belle 2007
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	Belle [41] (5.8)	Belle 2007
$Z_c^+(3900)$	3898 ± 5	51 ± 19	$1^{?-}$	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [43] (np), Belle [44] (5.2)	BESIII 2013
				$e^+e^- \to \pi^- + (J/\psi\,\pi^+)$	Xiao *et al.* [45][a] (6.1)	
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle [46] (5.0), *BABAR* [47] (1.1)	Belle 2008
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle [46] (5.0), *BABAR* [47] (2.0)	Belle 2008
$Z^+(4430)$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K + (\psi(2S)\,\pi^+)$	Belle [48, 49] (6.4), *BABAR* [50] (2.4)	Belle 2007
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [51, 52] (2.0)	Belle 2010
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle [53, 54] (16)	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle [53, 54] (16)	
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle [53, 54] (16)	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle [53, 54] (16)	

[a] Not included in the averages for M and Γ.


q $\bar{q}$
$\bar{q}$
q
1fm
Compact tetraquarks
10fm
loosely bound Molecules
(@THRESHOLDS)
q $\bar{q}$
TWO EXTREMES

~ 2004

DIQUARK-ANTIDIQUARK

MAIANI, PICCININI, 2004
POLOSA, RIQUER

[HEAVY-LIGHT DIQUARK]

JAFFE & WILCZEK 2003

[LIGHT DIQUARKS FOR PENTAQUARK]

CHARGED STATES PREDICTED

PENTAQUARK BARYONS EXPECTED !

MOLECULES

BRAATEN
[LOOSELY BOUND]

VOLOSHIN
[HADROCHARMONIUM]

CLOSE
KOU, PENE
[HYBRIDS]

SWANSON
[CUSP EFFECTS]

TÖRNQVIST 1994!
[DEUSON]

CHARGED STATES UNDESIRABLE

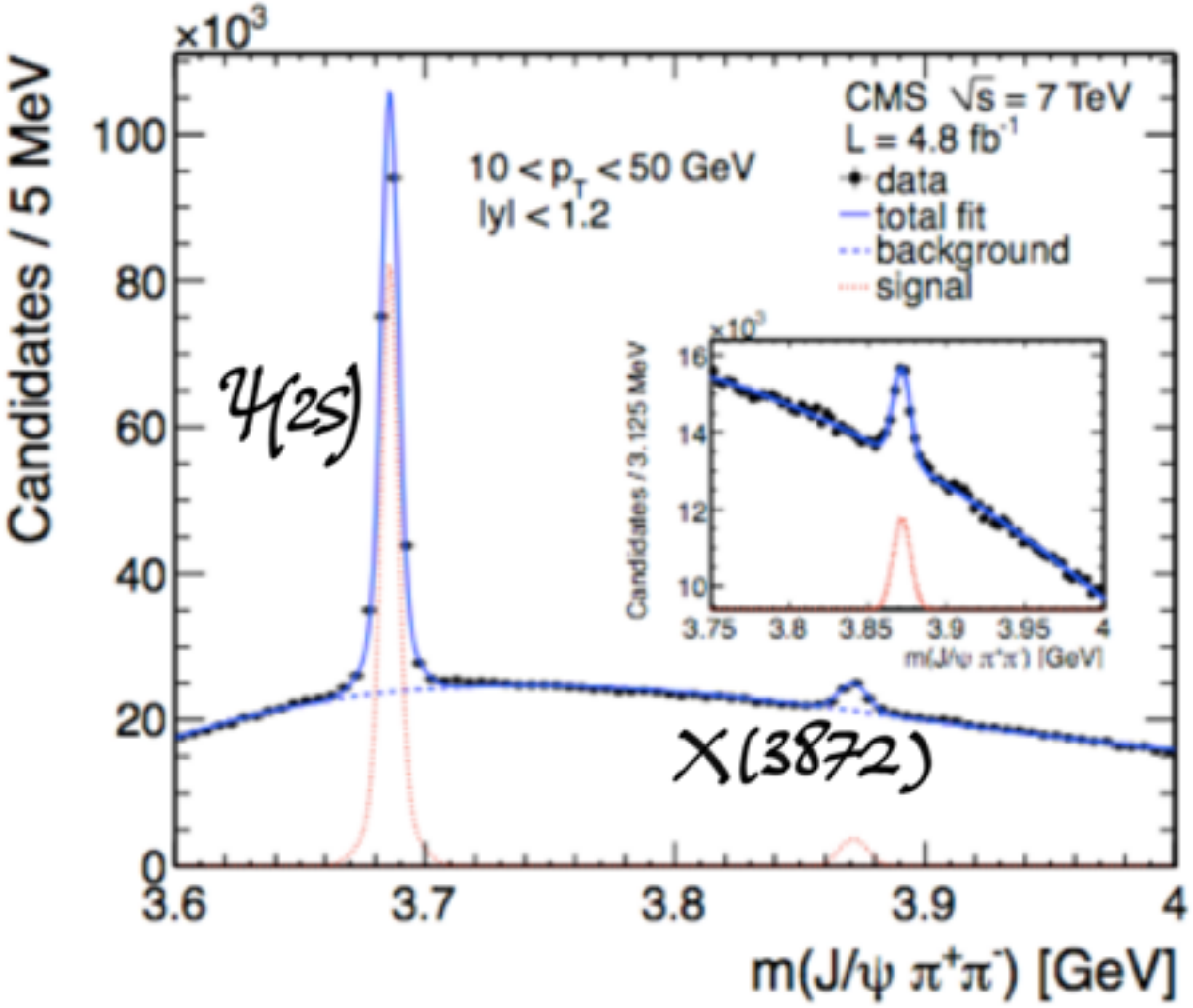
X(3872)

DISCOVERED BY BELLE IN 2003
CONFIRMED BY BaBar, DØ, CDF, CMS, LHCb & ATLAS!

4 $pp \rightarrow X(3872)$ @CMS

4 Measurement of the cross section ratio

PROMPT PRODUCTION



high $p_\perp$

Figure 1: The $J/\psi\pi^+\pi^-$ invariant-mass spectrum for $10 < p_T < 50$ GeV and $|y| < 1.2$. The lines represent the signal-plus-background fits (solid), the background-only (dashed), and the signal-only (dotted) components. The inset shows an enlargement of the X(3872) mass region.

INTERESTING FACTS ABOUT 'X'

1. $J^{PC} = 1^{++}$

2. The largest BR is

$$X \to \bar{D}^0 D^{*0}$$

and $M_X \equiv M_{D^0} + M_{D^{*0}}$!

3. ... but it was discovered in another channel

$$X \to J/\psi\, \rho^0$$

and $M_X \equiv M_{J/\psi} + M_{\rho^0}$!!

What about $X^\pm \to J/\psi\, \rho^\pm$? Never observed_

4. $X \to J/\psi\, \omega$

& $$\frac{BR(X \to J/\psi\, \rho^0)}{BR(X \to J/\psi\, \omega)} \simeq 1$$

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MOLECULAR MODELS

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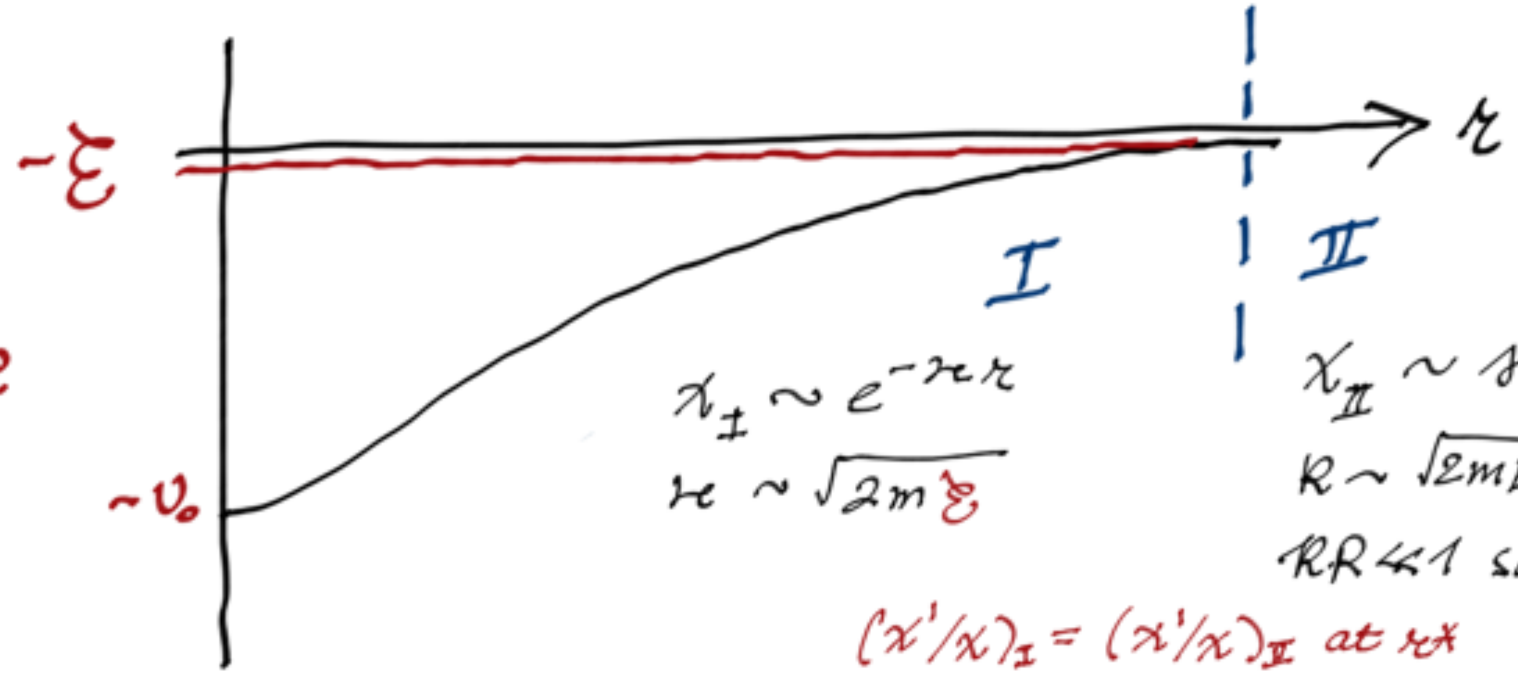
4. $X \to J/\psi\,\omega$

& $$\frac{BR(X \to J/\psi\,\rho^0)}{BR(X \to J/\psi\,\omega)} \simeq 1$$

A $D^0 D^{*0}$ MOLECULE?

Suppose that there is an attractive potential $U(r)$ between D^0 and D^{*0} : two-body problem



$\varepsilon \ll U_0$

$\chi_I \sim e^{-\kappa r}$

$\kappa \sim \sqrt{2m\varepsilon}$

$\chi_{II} \sim \sin(kr+\delta_0)$

$k \sim \sqrt{2mE}$, $E = T+U$

$kR \ll 1$ SLOW PART.

$(\chi'/\chi)_I = (\chi'/\chi)_{II}$ at r^*

$\cot\delta_0 = -\sqrt{\varepsilon/E}$

From scattering theory at low energies

$$f(D^0 D^{*0} \to D^0 D^{*0}) = -\frac{1}{\sqrt{2m}} \frac{\sqrt{\varepsilon} - i\sqrt{E}}{\varepsilon + E}$$

A $D^0 D^{*0}$ MOLECULE?

$$f(\underset{\underset{a}{\shortparallel}}{D^0}\underset{\underset{b}{\shortparallel}}{D^{*0}} \to \underset{\underset{c}{\shortparallel}}{X} \to D^0 D^{*0}) = -\frac{g^2}{8\pi(M_a+M_b)} \frac{1}{(p_a+p_b)^2 - M_c^2}$$

$$M_c \simeq M_a + M_b - \mathcal{E}$$

$$(p_a+p_b)^2 \simeq (M_a+M_b+T)^2$$

$$f(ab \to c \to ab) \simeq -\frac{1}{16\pi(m_a+m_b)^2}\, g^2 \frac{1}{\mathcal{E}+T} \qquad (1)$$

cfr. w/ what found before

$$f(ab \to ab) = -\frac{1}{\sqrt{2m}} \frac{\sqrt{\mathcal{E}} - i\sqrt{E}}{\mathcal{E}+E} \qquad (2)$$

allowing some initial/final state interaction: $\underline{T \to E}$
and considering the point $\underline{E = -\mathcal{E}}$

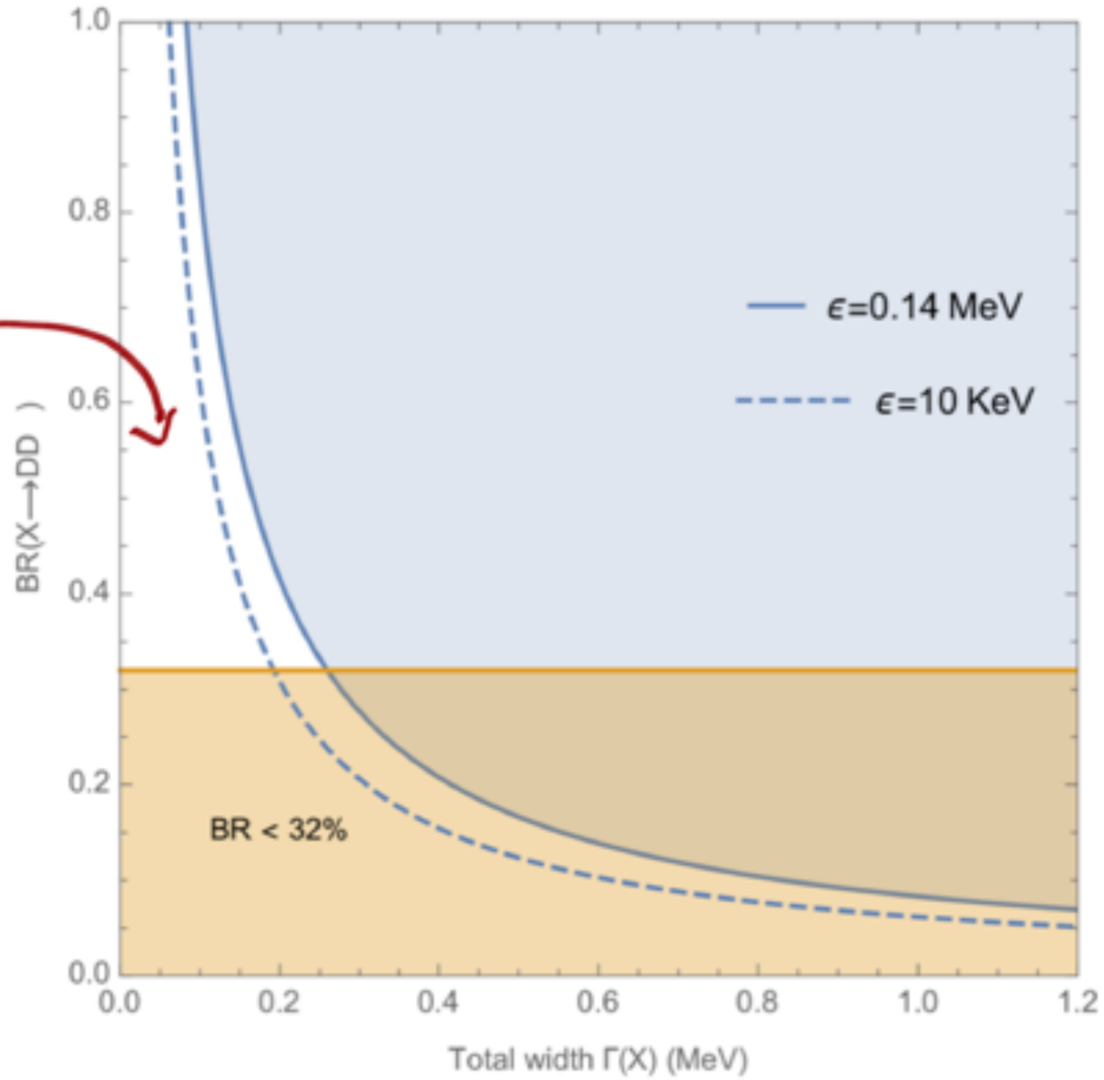
A $D^0 D^{*0}$ MOLECULE?

Comparing (1) and (2) we get

$$\mathcal{E} = \frac{g^4}{512\,\pi^2}\,\frac{m^5}{m_a^4\, m_b^4}$$

Consider now that

$$\mathcal{B}(X\to DD^*)\,\Gamma(X\to All) \equiv \Gamma(X\to DD^*) \sim g^2 \sim \mathcal{E}$$



X somewhere here.

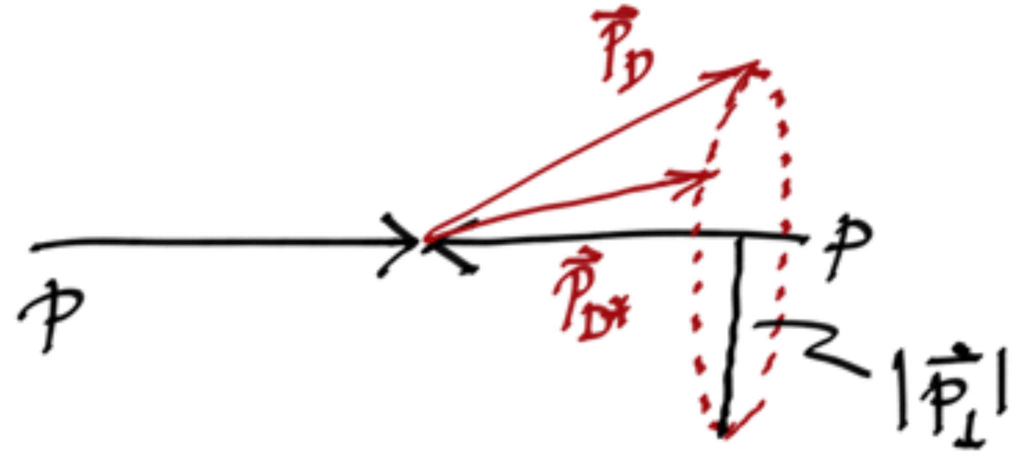
ADP, PLB746 (2015)

A $D^0 D^{*0}$ MOLECULE?

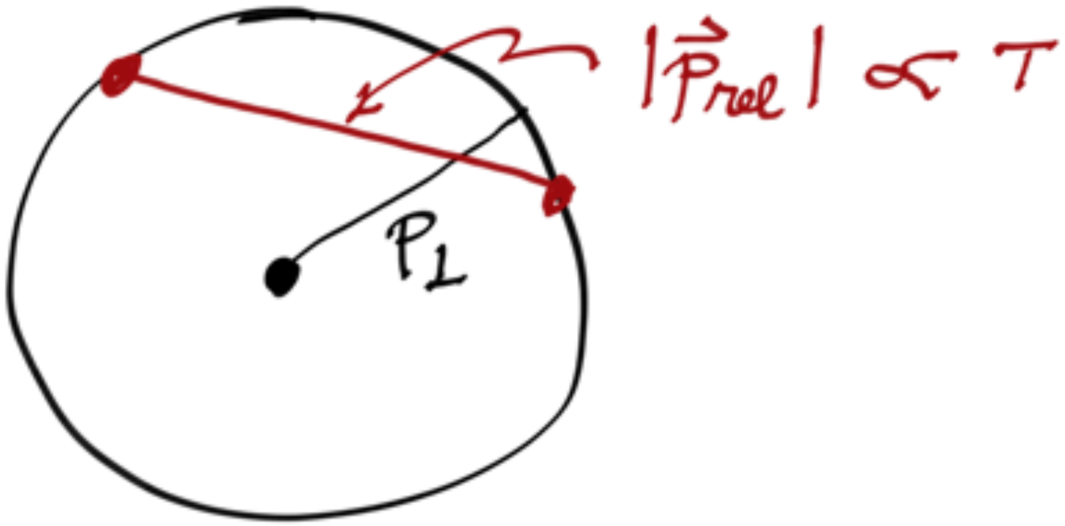
The previous arguments rely on $T \simeq 0$

What is T (barycentric energy of DD^* after subtraction of rest masses)

in pp collisions at LHC with HIGH $P_\perp$ CUTS?



$(|\vec{p}_D| \simeq |\vec{p}_{D^*}|)$



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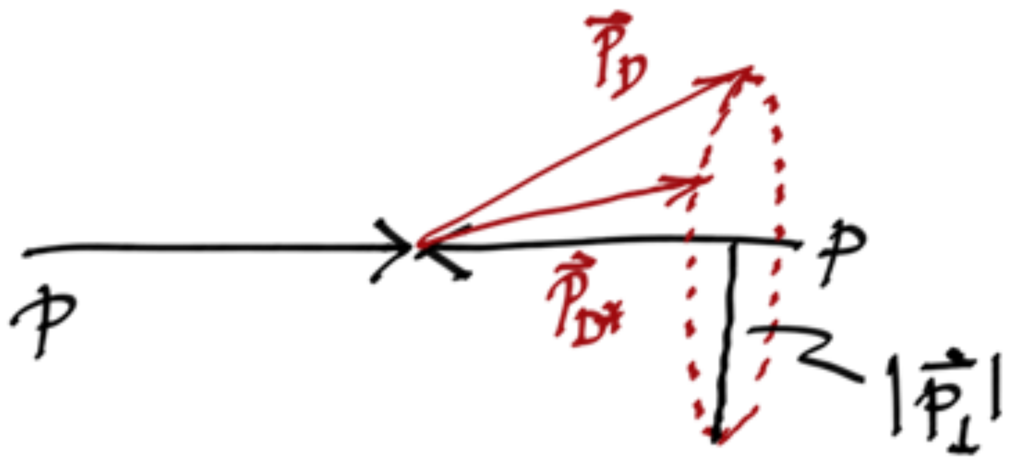
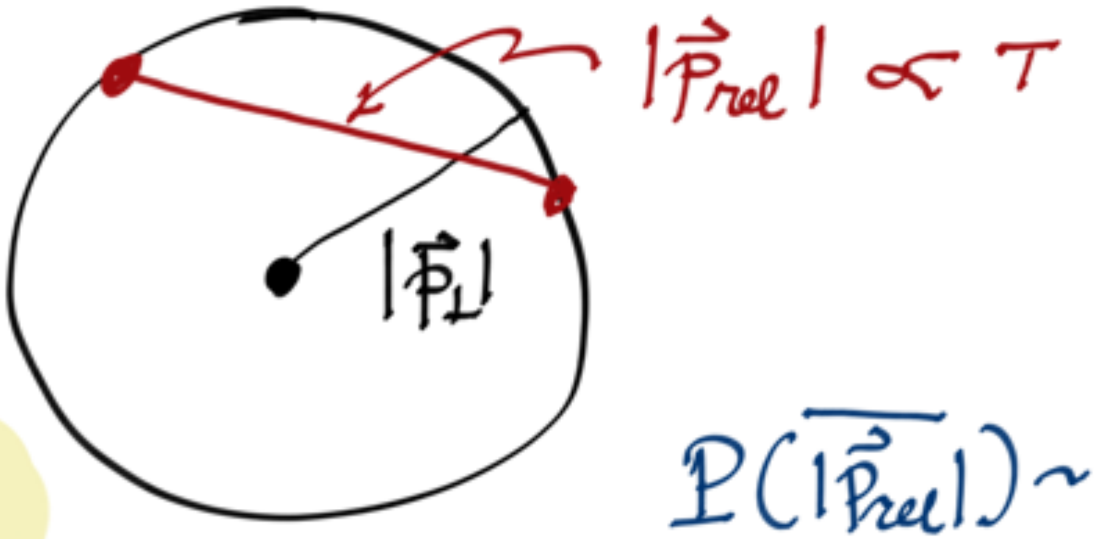


$(|\vec{p}_D| \simeq |\vec{p}_{D^*}|)$

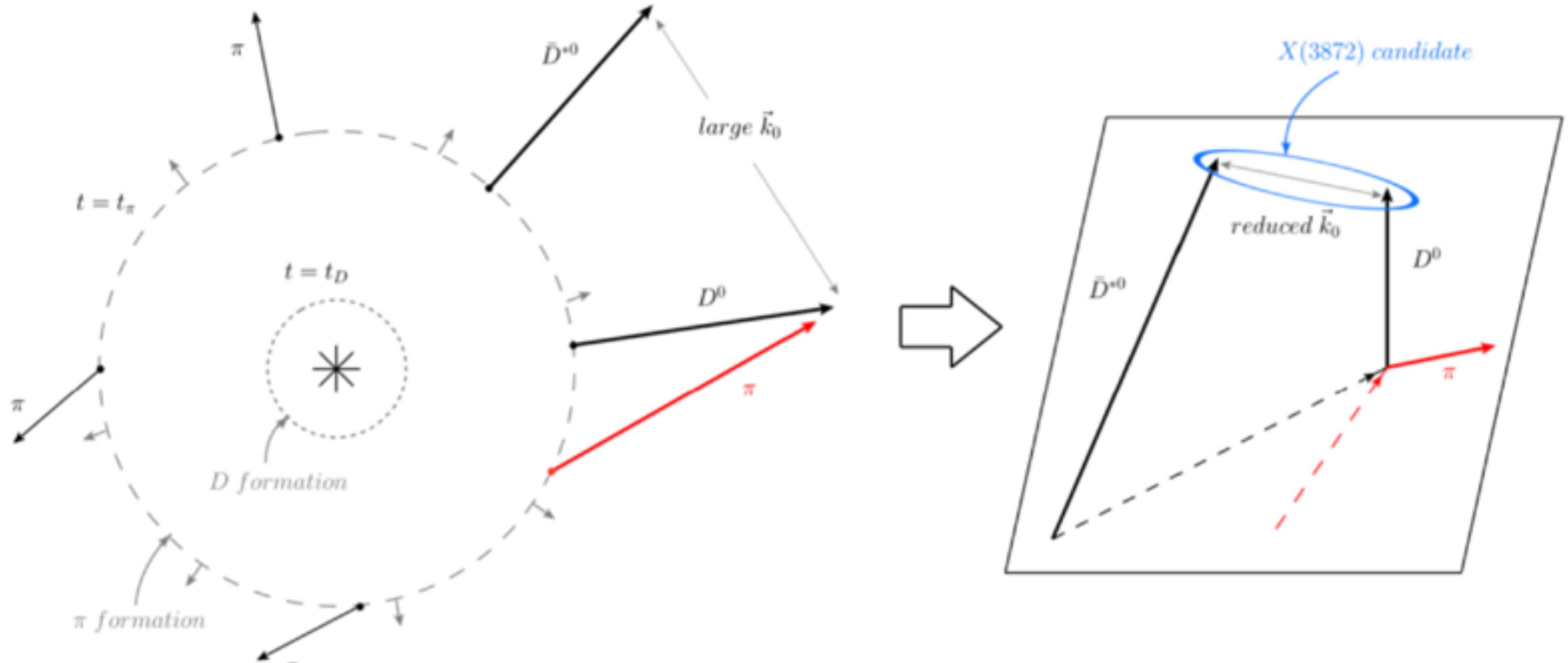
$$\overline{|\vec{p}_{rel}|} = 1.27\, |\vec{p}_\perp|$$



$$P(|\vec{p}_{rel}|) = \frac{1/\pi}{\sqrt{|\vec{p}_\perp|^2 - (|\vec{p}_{rel}|/2)^2}}$$

$$P(\overline{|\vec{p}_{rel}|}) \sim 40\%$$

RESCATTERINGS ?



Expanding hadronization sphere

(a)

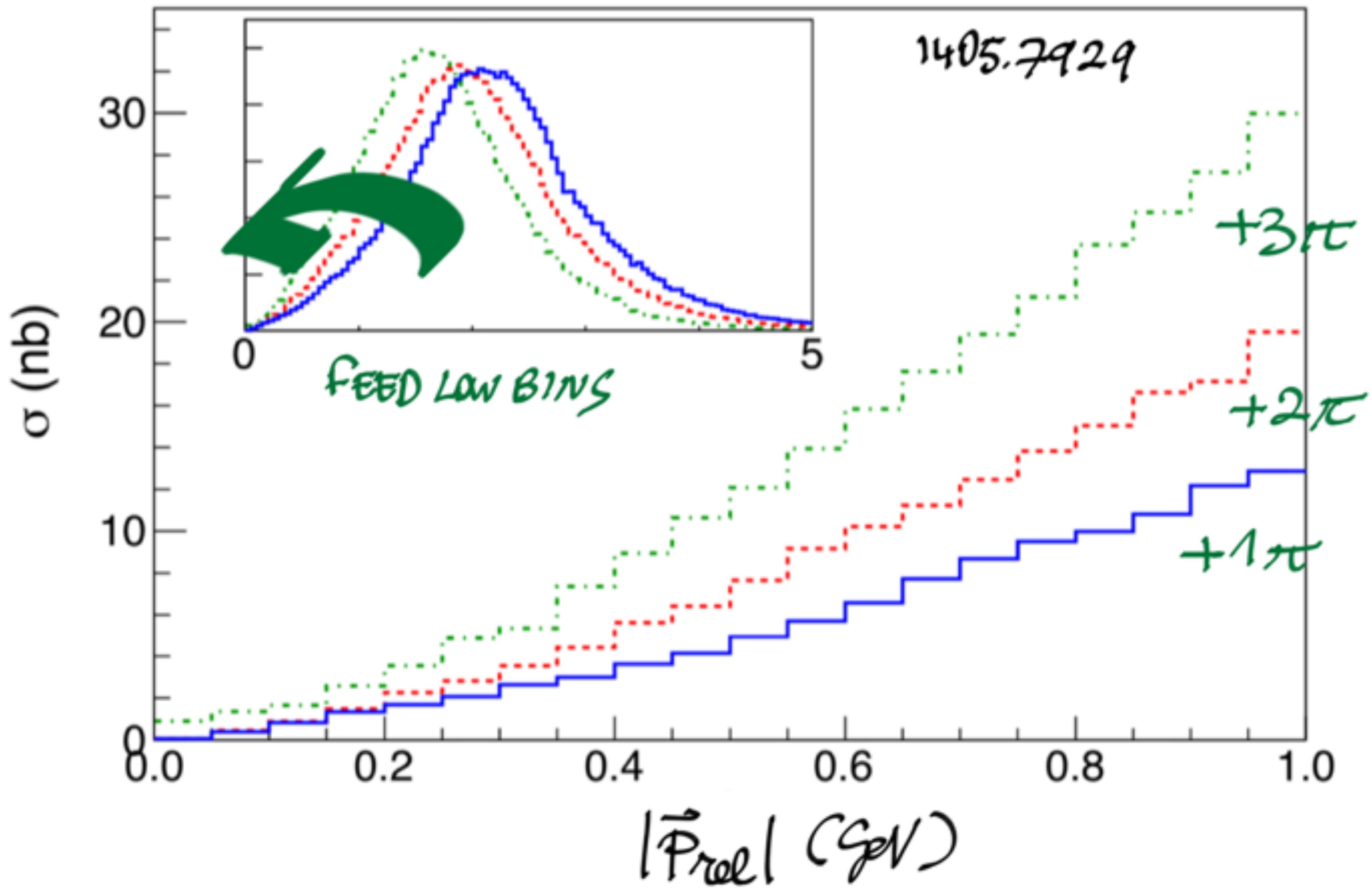
Plane π − D rescattering

(b)

RESCATTERINGS WITH HADRONS (π) MIGHT HELP TO DECREASE $|\vec{p}_{rel}|$ IN THE DD^* PAIR

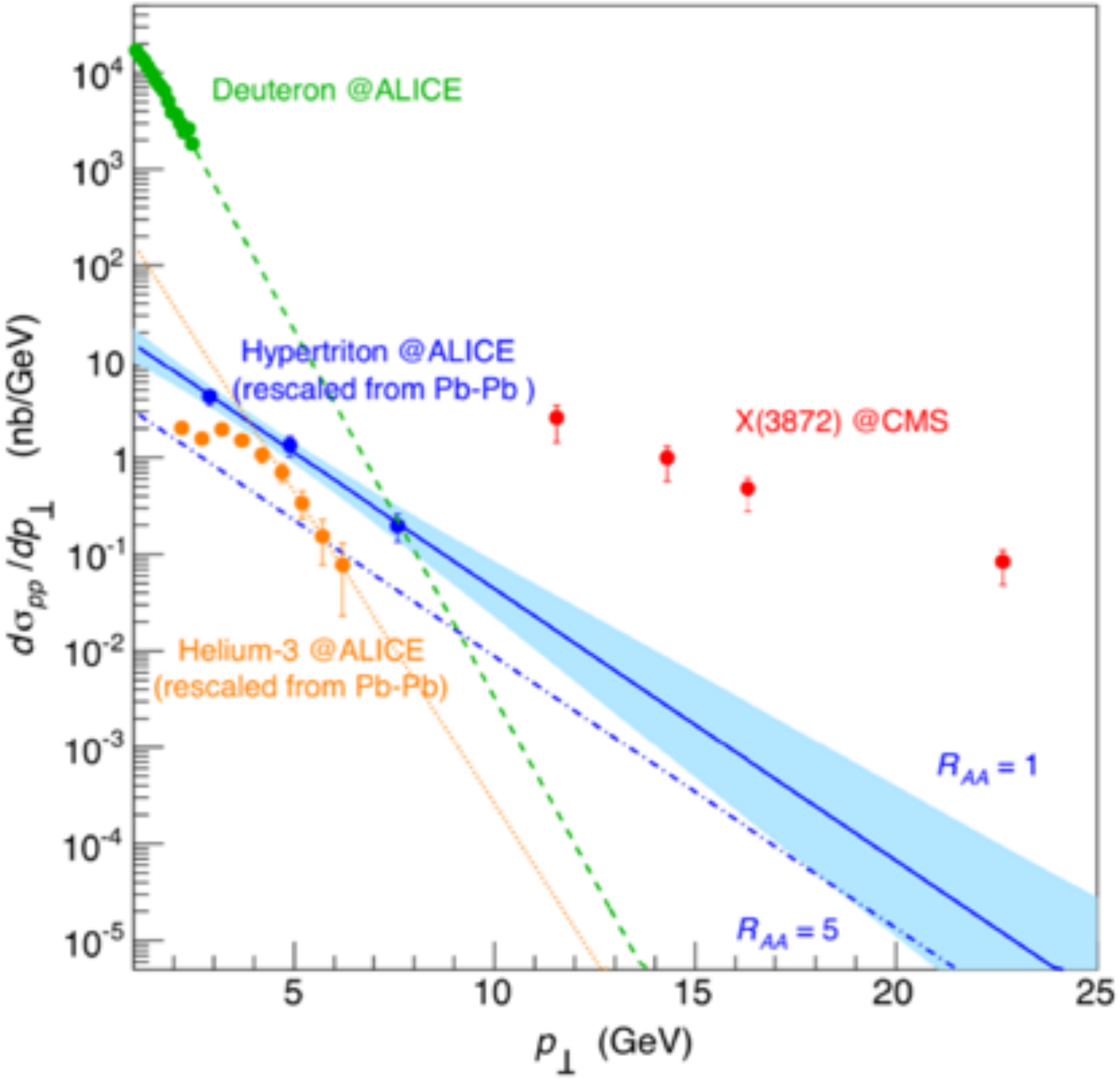
A Esposito et al. J.Mod.Phys. 4 (2013) 1569
A Guerrieri et al. PRD 90 (2014) 034003
C Bignamini et al PRL 103 (2009) 162001

RESCATTERINGS ?

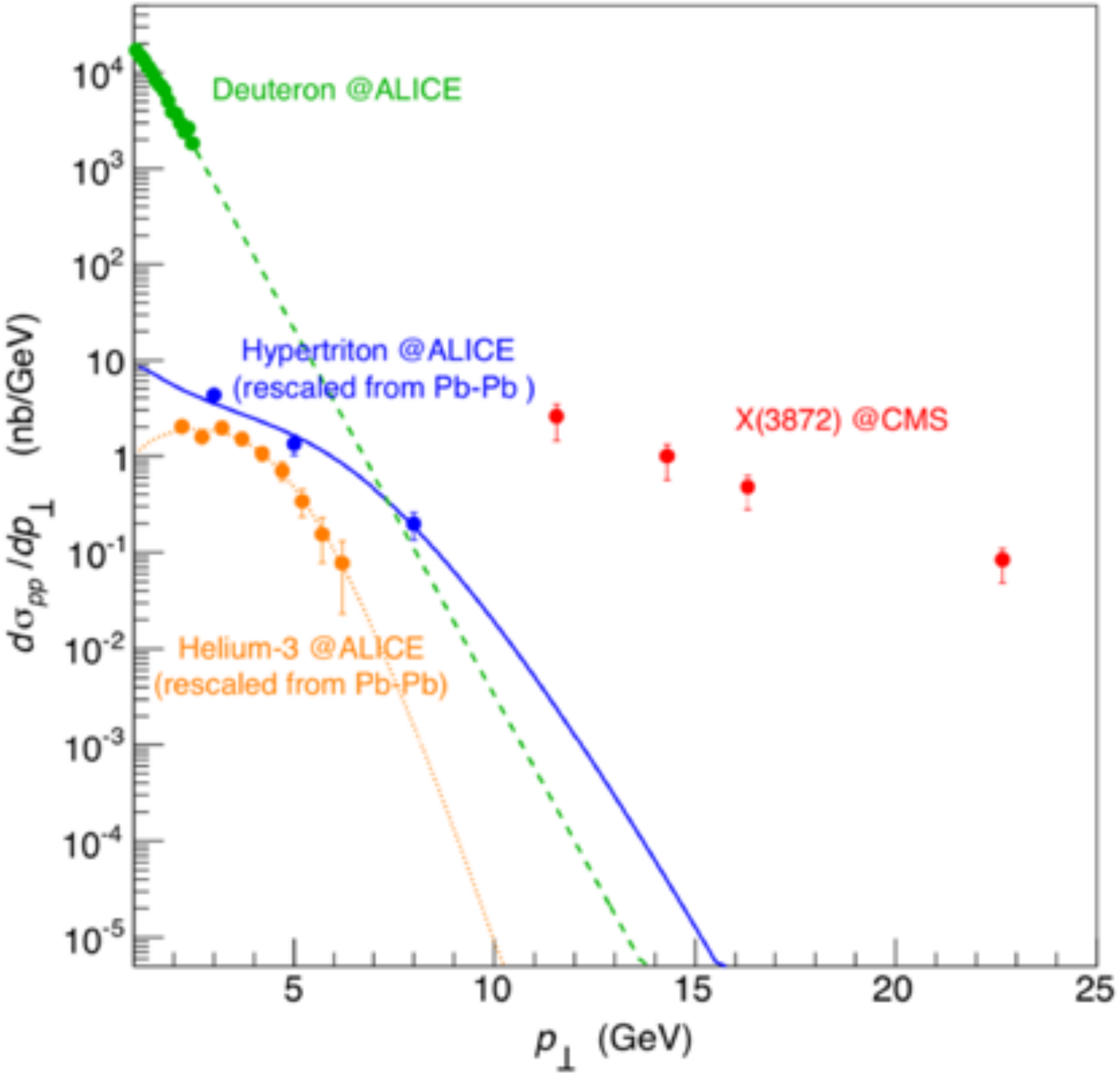


- THE MOST PROBABLE DD^* CONFIGURATIONS HAVE HIGH $|\vec{P}_{rel}|$
- THIS IS MORE AND MORE VISIBLE INCREASING THE CUT IN $|\vec{P}_{\perp}|$
- THE FEED-DOWN OBTAINED BY RESCATTERING ON 1,2,3π IS NEGLIGIBLE.

DATA FROM ALICE



Exponential fit -



'Blastwave' fit -

A Esposito et al. PRD 92 (2015) 034028

CHARGED RESONANCES

beauty

$\Upsilon(5S) \to \pi^\pm Z_b^\mp(10610)$

↳ $\pi^\mp \Upsilon(nS)$

$\to \pi^\pm Z_b^\mp(10650)$

↳ $\pi^\mp h_b(kP)$

BELLE 2012

	THR. (MeV)
BB^*	10604
B^*B^*	10650

charm

$Y(4260) \to \pi^\pm Z_c^\mp(3900)$

↳ $\pi^\mp J/\psi$

$\to \pi^\pm Z_c'^\mp(4025)$

↳ $\pi^\mp h_c$

BESIII 2013

	THR. (MeV)	
DD^*	3875	+24
D^*D^*	4017	+8

CHARGED RESONANCES

LHCb 2014 confirms BELLE 2007 (& disproves Babar 2007)

$$B \longrightarrow K^+ Z^-(4430)$$

$$\hookrightarrow \psi(2S)\pi^-$$

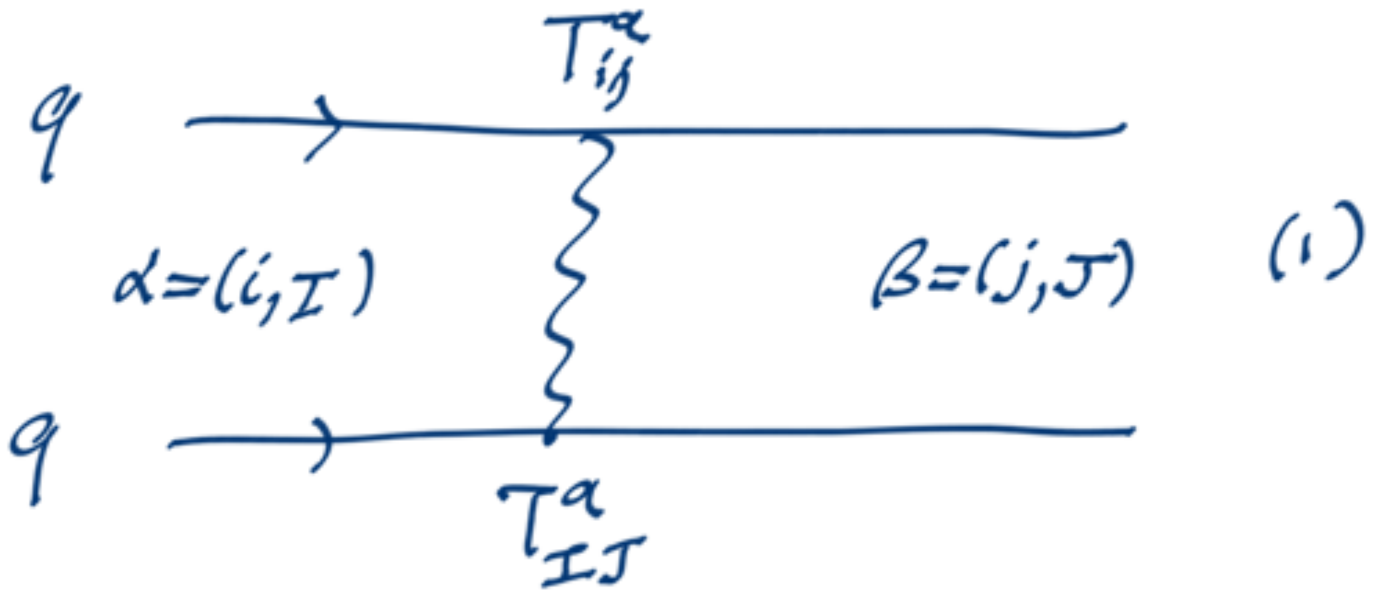
0708.3997 "A CRUCIAL CONSEQUENCE OF Z^- IS A CHARGED STATE IN $J/\psi\, \pi^\pm$ AT 3880 MeV" (Z^- is its radial excitation)

$$M(\psi(2S)) - M(\psi) \simeq M(Z(4430)) - M(Z(3880))$$

BES III FOUND $Z_c(3900)$ IN 2013.

CHARGED RESONANCES HAVE NOT (YET?) BEEN SEARCHED/OBSERVED IN pp PROMPT COLLISIONS.

DIQUARKS



$T^a_{ij}\,T^a_{IJ} \mapsto A_{\alpha\beta}$ (9×9)

eigenvectors v of A identify:

3 antisymmetric color config.

6 symmetric " "

$v^T A v = \sum$(diagrams like (1))

= color amplitude w/ same color config in α & β.

DIQUARKS

The eigenvalues λ (~product of charges in a QED amplitude) associated to r's are negative on antisymmetric reps.

Take $SU(N)$ and

$$N \otimes N = \underset{(A)}{\frac{N(N-1)}{2}} \oplus \underset{(S)}{\frac{N(N+1)}{2}}$$

	λ
$N(N-1)/2$	$-(N+1)/2N < 0$
$N(N+1)/2$	$(N-1)/2N > 0$

In the singlet channel of $N \otimes \bar{N}$ we have

$$\lambda = -(N^2-1)/2N$$

THE SINGLET CHANNEL IS $(N-1)$ TIMES MORE ATTRACTIVE THAN THE ANTISYMMETRIC CHANNEL IN $N \otimes N$.

DIQUARKS

$$d^{S,A} = q^{\alpha}\Gamma q'^{\beta} \pm q^{\beta}\Gamma q'^{\alpha}$$

BUILD NEW HADRONS WITH

$$S\begin{cases} q \mapsto \bar d^A \\ \bar q \mapsto d^A \end{cases}$$

$$\bar q\bar q\bar q \xmapsto{S} d^A\bar q\bar q \longrightarrow \underbrace{d^A\bar d^A}_{\text{TETRAQUARK (charged \& neutral!)}}$$

$$\longrightarrow \underbrace{d^A d^A \bar q}_{\text{PENTAQUARK}}$$

$$\longrightarrow \underbrace{d^A d^A d^A}_{\text{DIBARYON } (B=2)}$$

HEAVY-LIGHT DIQUARKS

$$H = \sum m_i + \sum_{i<j} 2k_{ij}\, \vec S_i \cdot \vec S_j$$

type I : $H \simeq 2k_{q\bar q}(\vec S_q \cdot \vec S_{\bar q})$ PRD71 (2005)

type II : $H \simeq 2k_{q\bar c}(\vec S_q \cdot \vec S_c + \vec S_{\bar q} \cdot \vec S_{\bar c})$ PRD89 (2014)

1. BECAUSE OF THE PRESENCE OF THE HEAVY QUARK, THE SPIN OF THE DIQUARK CAN EQUALLY BE 1 or 0 (not true for light ones)
2. We assume that $\vec S_{c\bar c}$ is CONSERVED in STRONG INTERACTIONS.

L Maiani et al., PRD 71 (2005) 014028; PRD89 (2014) 114010

THE SPIN OF THE HEAVY QUARK PAIR

Recall

$$Z_c(3900) \to J/\psi(S_{c\bar{c}}=1)\,\pi^-$$

$$h_c\,(S_{c\bar{c}}=0)\,\pi^-$$

$$\Rightarrow \begin{cases} Z = \frac{1}{\sqrt{2}}\left(|1,0\rangle - |0,1\rangle\right) \\ Z' = \frac{1}{\sqrt{2}}\left(|1,0\rangle + |0,1\rangle\right) \end{cases} \qquad |S_{c\bar{c}}, S_{q\bar{q}}\rangle$$

$C = (-1)^{L+S_{q\bar{q}}+S_{c\bar{c}}}$

'FIERZABLE' INTO

$$1^{+-} \quad \begin{cases} Z = \frac{1}{\sqrt{2}}\left(|1,0\rangle - |0,1\rangle\right) \\ Z' = |1,1\rangle, \end{cases} \qquad |S_{cq}, S_{\bar{c}\bar{q}}\rangle$$

$C = (-1)^J$

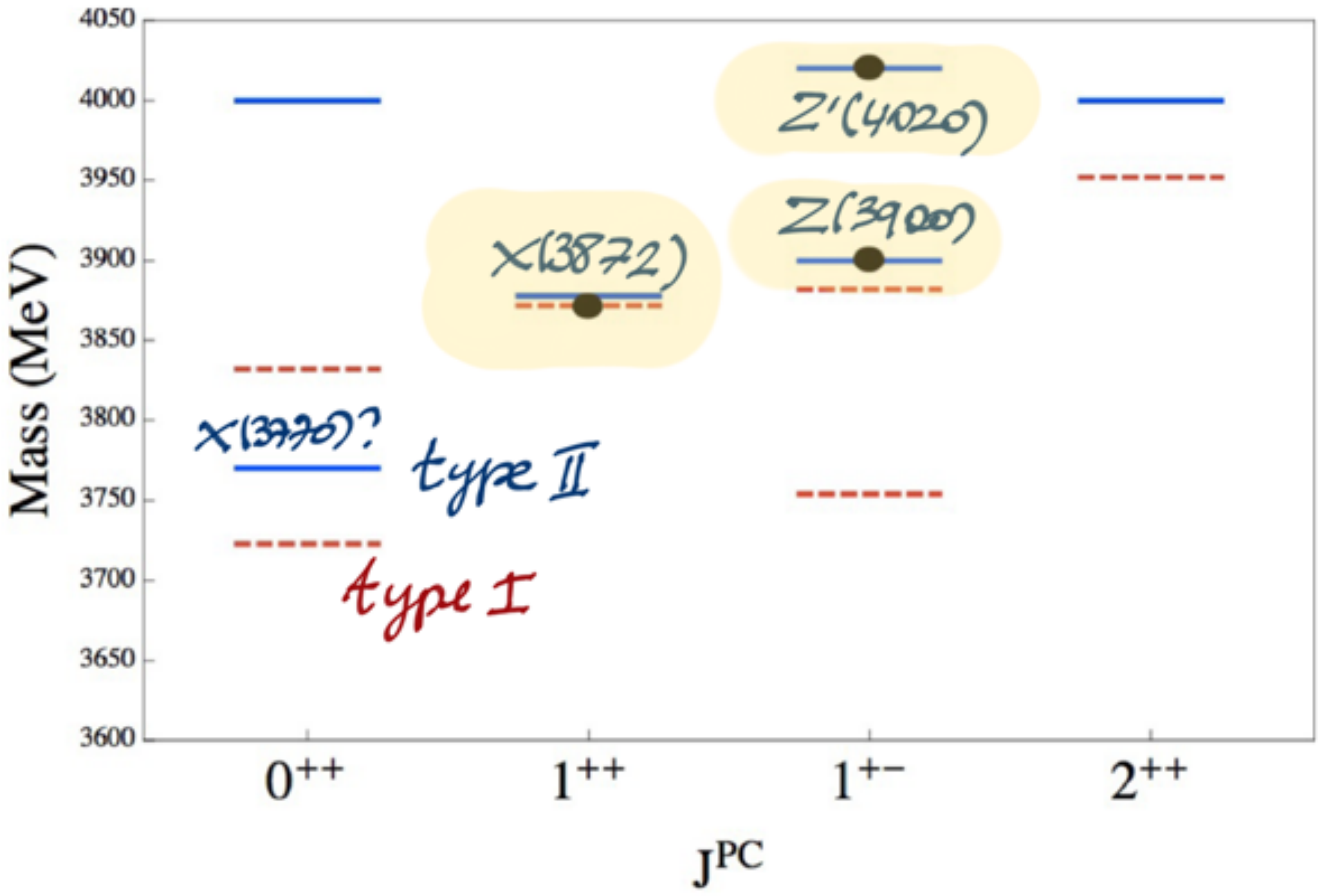
the spin 1 diquark is expected to be heavier than the spin 0. WHAT ABOUT THE ORTHOGONAL COMBI TO Z IN THIS LATTER BASIS ? (should be ~degenerate)

THE SPECTRUM

$$X = \frac{1}{\sqrt{2}}\left(|1,0\rangle + |0,1\rangle\right) \qquad 1^{++}$$

$$(H)_{1^{+-}} = \begin{pmatrix} -k & 0 \\ 0 & k \end{pmatrix} \qquad (H)_{1^{++}} = -k \qquad (H)_{0^{++}} = -3k$$

$$(H)_{2^{++}} = k \qquad (H)_{0^{++\prime}} = k$$



L Maiani et al., PRD 71 (2005) 014028; PRD89 (2014) 114010

NEGATIVE PARITY

The most famous 1^{--} state is $Y(4260)$

$$Y(4260) \longrightarrow \gamma X(3872)$$

$$\left(\frac{|1,0\rangle + |0,1\rangle}{\sqrt{2}}\right)_{L=1} \qquad \left(\frac{|1,0\rangle + |0,1\rangle}{\sqrt{2}}\right)_{L=0}$$

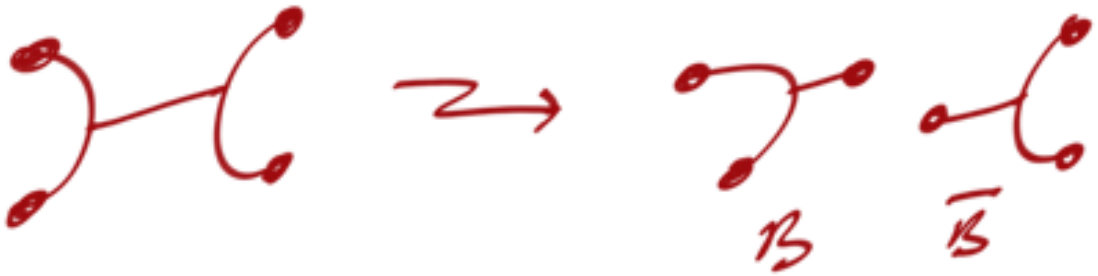
Two more states named $Y(4630)$ & $Y(4660)$ are 1^{--}

They could actually correspond to one state only: Y_B.

In that case

$$\frac{B(Y_B \to \Lambda_c \bar{\Lambda}_c)}{B(Y_B \to \psi(2S)\pi^+\pi^-)} = 24.6 \pm 6.6$$

The string breaking might be possible above $B\bar{B}$ thresh.



L Maiani et al., PRD 71 (2005) 014028; PRD89 (2014) 114010

G Cotugno et al., PRL 104 (2010) 132005

WEAK POINTS

LOOSELY BOUND MOLECULES :

- Prompt production
- Proliferation of states !!
- Binding energies (sometimes > 0 ...)
- Theoretical motivation (and appeal)

COMPACT TETRAQUARKS :

- Proliferation of states: where is $X^{\pm}$? (THIS IS A PROBLEM FOR MOLECULES TOO)
- What is the role of meson thresholds? Can't be an accident !

OTHER APPROACHES : The "physics of effects"... All or most of these resonances do not exists, they are "cusps", kinem. artifacts, results of wrong analyses... [GOOD LUCK]

THE PENTAQUARK

Highly undesirable option for molecules (before discovery)
Perfect molecule (after discovery)

LHCb 2015

$$\Lambda_b(bud) \to K^- \mathbb{P}^+$$

$$\hookrightarrow J/\psi\, p$$

$$\mathbb{P}^+ = \bar{c}\, c\, u\, u\, d \Rightarrow \text{negative parity}$$

TWO STATES OBSERVED

$$J^P = 3/2^- \ @ \ 4380 \text{ MeV}$$

$$J^P = 5/2^+ \ @ \ 4550 \text{ MeV}$$

$L=0$ & $L=1$ Pentaquarks?

Note: Lower baryons have $P=+$ / pentaq. have $P=-$!
Lower mesons have $P=-$ / tetraq. have $P=+$

MASS DIFFERENCE

ISN'T $\Delta M = 170$ MeV too SMALL for one unit of L ?

($\Delta M = 300$ MeV for $\Lambda(1405) - \Lambda(1116)$)

On the other hand, from $\Sigma_c - \Lambda_c$ we find

$$M_{[qq']_{S=1}} - M_{[qq']_{S=0}} \simeq 200\,\text{MeV}$$

So

$$\mathbb{P}(3/2^-) = \bar{c}\,[cq]_{S=1}\,[q'q'']_{S=1} \quad @\, L=0$$

$$\mathbb{P}(5/2^+) = \bar{c}\,[cq]_{S=1}\,[q'q'']_{S=0} \quad @\, L=1$$

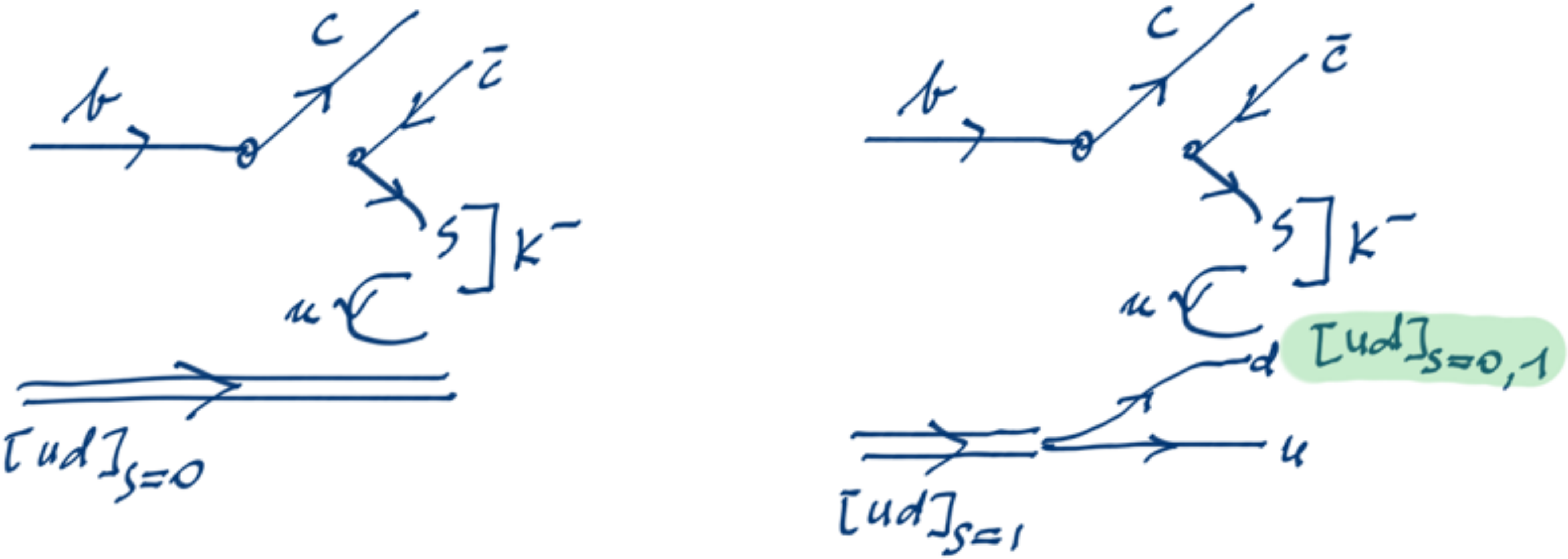
... combine diquark spin & orbital angular momentum -

Other states?

L Maiani, ADP, V Riquer, PRD 749 (2015) 289; PLB 750 (2015) 37

$\Lambda \to K^- \mathbb{P}^+$

Λ_b baryon might contain a $[ud]_{S=0}$, "good" diquark. But $\mathbb{P}(3/2^-)$ should contain $[ud]_{S=1}$, whereas $\mathbb{P}(5/2^+)$ has $[ud]_{S=0}$.



One can show that both pentaquarks have $S_{c\bar c} = 1$ so that HQ spin cons. allows decay into J/ψ.

L Maiani, ADP, V Riquer, PRD 749 (2015) 289; PLB 750 (2015) 37

Flavor

$$\langle \mathbb{P}, M \,|\, H_w(\Delta I=0, \Delta S=-1) \,|\, \Lambda_b \rangle$$

8_f $\qquad$ 3_f (from s,d,u) $\qquad$ $\bar{3}_f$ (from $[ud]$)

therefore $\mathbb{P}$ is either 8 or $\underline{10}$

We might expect

$$\Lambda_b \to \pi\, \mathbb{P}_{10}^{S=-1} \to \pi\, J/\psi\, \Sigma(1385)$$

$$\Lambda_b \to K\, \mathbb{P}_{10}^{S=-2} \to K\, J/\psi\, \Xi(1530)$$

or even

$$\Omega_b \to \phi\, \mathbb{P}_{10}^{S=-3} \to \phi\, J/\psi\, \Omega^-(1672)$$

L Maiani, ADP, V Riquer, PRD 749 (2015) 289; PLB 750 (2015) 37

Large N & Tetraquarks

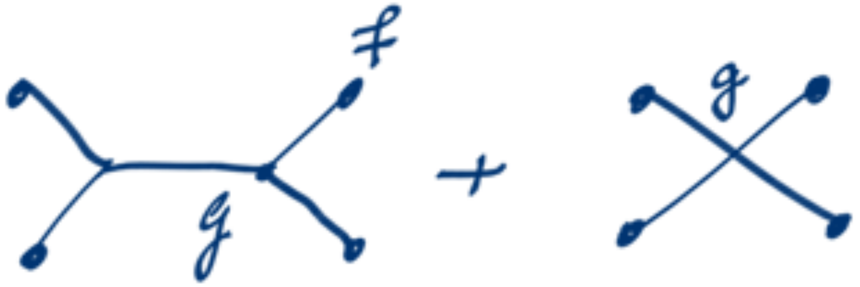
S. Coleman / E. Witten '79

Consider the 2-point function in SU(N)

$f_M = \langle 0|J|M\rangle$

$f_M^2 \sim N \Rightarrow f_M \sim \sqrt{N}$

and the 4-point function $MM \to MM$



$g^2 f^4 \sim N \Rightarrow g^2(\sqrt{N})^4 \sim N$

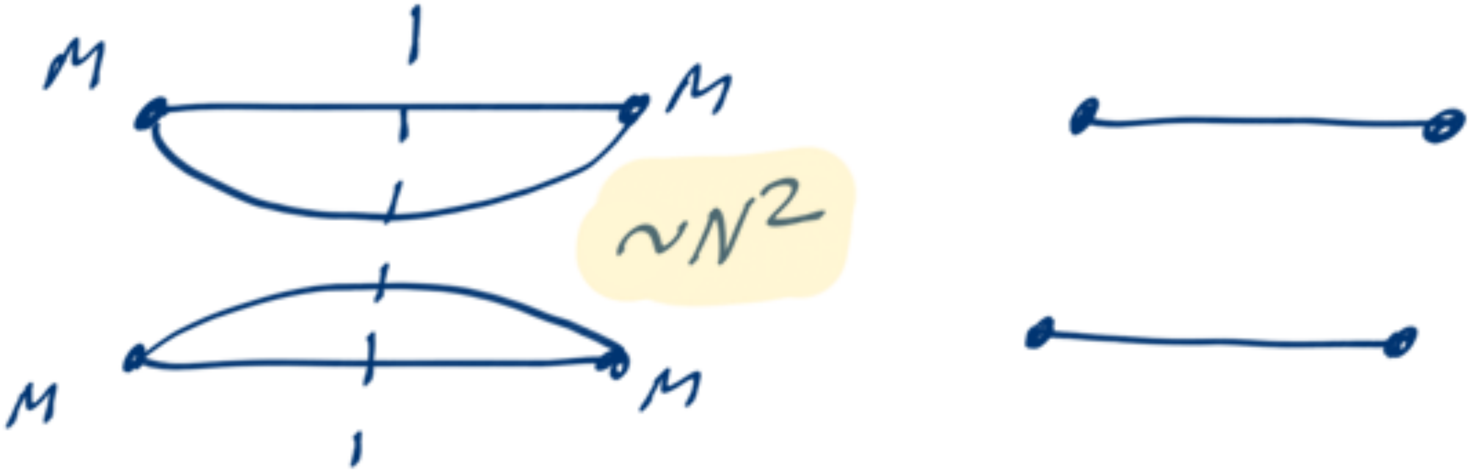
$g \sim \frac{1}{\sqrt{N}}$

S Coleman in Aspects of Symmetry. E Witten, in Baryons in the 1/N expansion, Nucl. Phys. B 160 (1979)

Large N & Tetraquarks

S. Coleman / E. Witten '79

Any tetraquarks at leading order in $1/N$ expansion?



This is the "fall apart decay". The 2-point function of a 4-quark operator cannot be distinguished, in meson theory, from two standard meson propagators.

Tetraquarks, if any, should be very **BROAD** resonances, therefore difficult/impossible to be detected.

Large N & Tetraquarks

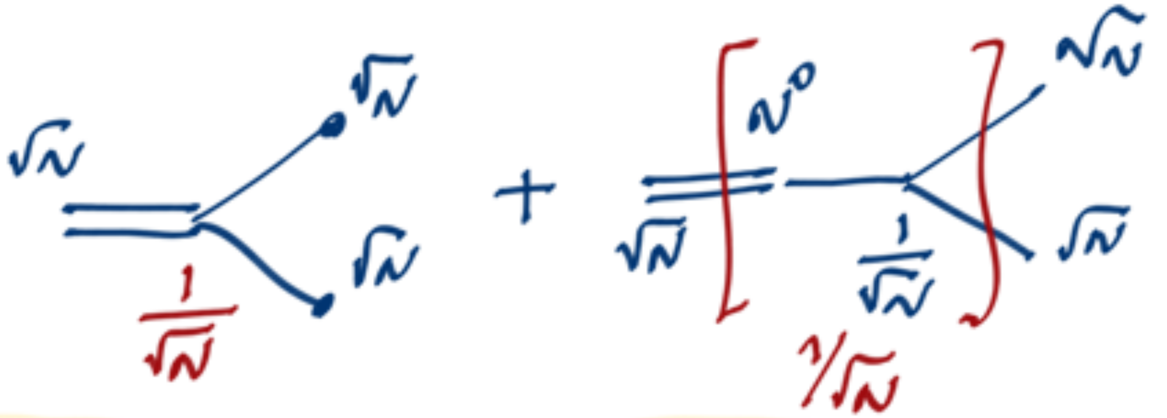
S. Weinberg / M. Knecht & S. Peris / R. Lebed ... 2013

Forget about the N^2 leading order. The tetraquark pole might appear at the N^1 or less subleading orders.

$f_{4q}^2 \sim N \Rightarrow f_{4q} \sim \sqrt{N}$

$f_{4q-M} \sim N^0$

Therefore



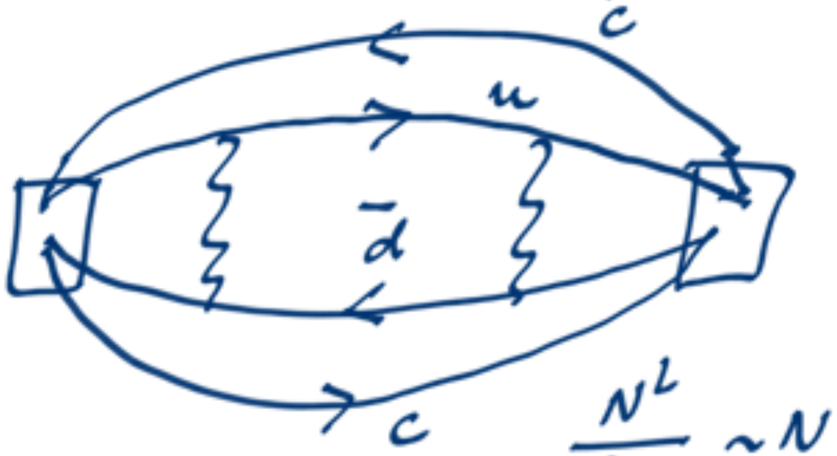
4q ↦ MM DECAY AMPL. ~ $1/\sqrt{N}$

S Weinberg, PRL 110 (2013) 261601

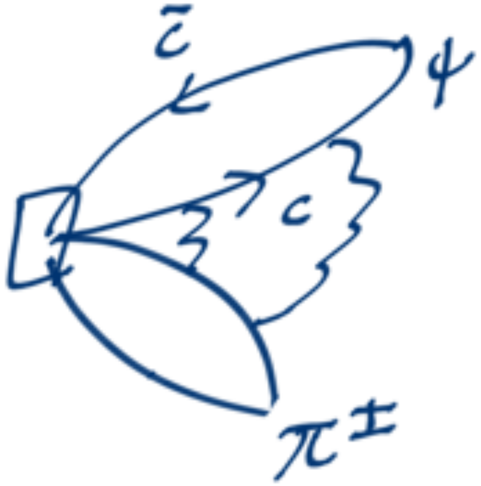
Large N & Tetraquarks

S. Weinberg / M. Knecht & S. Peris / R. Lebed ... 2013

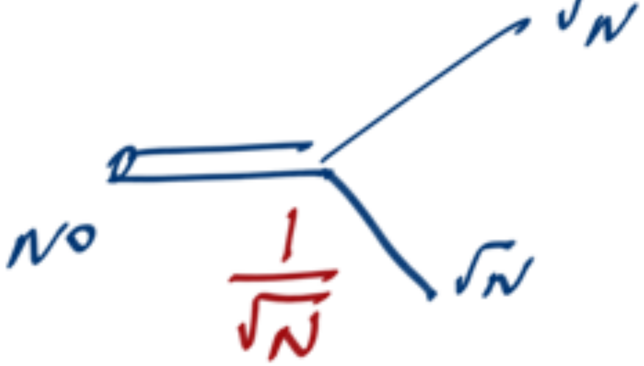
For charged states



$\frac{N^2}{(\sqrt{N})^4} \sim N^0$



$\sim N^0$



even narrower than in the 'neutral case'

(different decay constants for $f_{4q^\pm}$ & f_{4q^0} ?)

M Knecht and S Peris, PRD88 (2013) 036016; R Lebed PRD 88 (2013) 057901

Large N & Tetraquarks

S. Weinberg / M. Knecht & S. Peris / R. Lebed ... 2013

Consider the 2-point meson function

$$\frac{N^2}{(\sqrt{N})^4} \sim N^0$$

the $f_{qq\text{-}M}$ would be different from what found before
$- f_{qq} \sim N^0$ >< !

Maybe handels are required : go non planar !

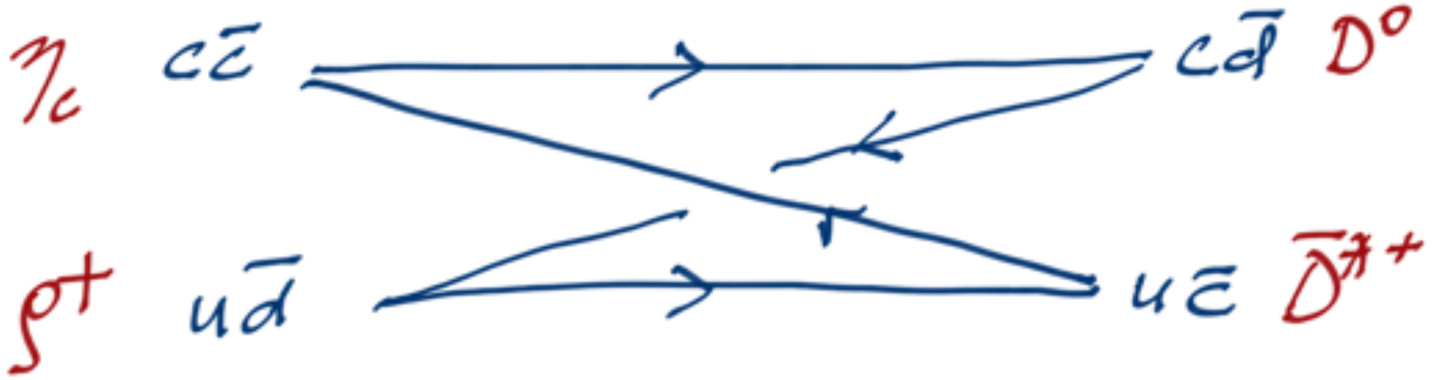
At any rate, the myth that large-N QCD conflicts w/ tetraquarks is over.

What about pentaquarks? 1/N w/ baryons is notoriously a different problem.

Large N & Tetraquarks

Consider the meson amplitudes $M_1 M_2 \to M_3 M_4$;

$$\eta_c \rho^+ \longrightarrow \bar{D}^0 D^{*+}$$



follow arrows $A^{ab}_{\alpha\beta} \propto \langle \sigma^2 \cdot \sigma^2 \cdot \sigma^2 \sigma^a \cdot (\sigma^2 \sigma^b)^\dagger \rangle$

$$\alpha = \eta_c \rho^+, \ \beta = D^0 \bar{D}^{*+}$$

The space is $\alpha = \eta_c \rho^+, \psi \pi^+, \psi \rho^+$

$\beta = \bar{D}^0 D^{*+}, D^+ \bar{D}^{*0}, \bar{D}^{*0} D^{*+}$

$\Rightarrow$ $A_{\alpha\beta}$ is a 3×3 matrix (found diagonal in spinor space : $\propto \delta^{ab}$)

Large N & Tetraquarks

Suppose that the quark loop has a pole in one of the EIGENCHANNELS (a particular combination of meson pairs).

Determine eigenchannels — the meson pairs coupled to the resonance.

They look like

$$i\,\frac{\psi\wedge\rho^+}{2\sqrt{2}} \pm \frac{\bar{D}^0 D^{*+} - D^+\bar{D}^{*0}}{\sqrt{2}}$$

$$\frac{\eta_c\rho^+ - \psi\pi^+}{\sqrt{2}} \pm i\,\frac{\bar{D}^{*0}\wedge D^{*+}}{2\sqrt{2}}$$

$$\frac{\eta_c\rho^+ + \psi\pi^+}{\sqrt{2}} \pm \frac{\bar{D}^0 D^{*+} + D^+\bar{D}^{*0}}{\sqrt{2}}$$

$$(\psi\wedge\rho^+)^c = (c\sigma^2\sigma^a\bar{c})(u\sigma^2\sigma^b\bar{d})^b\epsilon^{abc}$$

Large N & Tetraquarks

Suppose that the quark loop has a pole in one of the EIGENCHANNELS (a particular combination of meson pairs).

Determine eigenchannels — the meson pairs coupled to the resonance.

They look like

COLOR FIERZ-REARR.
4QUARK STATES!

$$i\,\frac{\psi\wedge\rho^+}{2\sqrt{2}} \pm \frac{\bar{D}^0 D^{*+} - D^+\bar{D}^{*0}}{\sqrt{2}} \leftarrow X^+$$

$$\frac{\eta_c\rho^+ - \psi\pi^+}{\sqrt{2}} \pm i\,\frac{\bar{D}^{*0}\wedge D^{*+}}{2\sqrt{2}} \leftarrow Z^+$$

$$\frac{\eta_c\rho^+ + \psi\pi^+}{\sqrt{2}} \pm \frac{\bar{D}^0 D^{*+} + D^+\bar{D}^{*0}}{\sqrt{2}} \leftarrow Z'^+$$

$$(\psi\wedge\rho^+)^c = (c\sigma^2\sigma^a\bar{c})(u\sigma^2\sigma^b\bar{d})^b\epsilon^{abc}$$

Large N & Tetraquarks

Suppose that the quark loop has a pole in one of the EIGENCHANNELS (a particular combination of meson pairs).

Determine eigenchannels — the meson pairs coupled to the resonance.

They look like

$$\left.\begin{array}{l} i\,\dfrac{\psi\wedge\rho^+}{2\sqrt{2}} \pm \dfrac{\bar{D}^0 D^{*+} - D^+ \bar{D}^{*0}}{\sqrt{2}} \\[2ex] \dfrac{\eta_c\rho^+ - \psi\pi^+}{\sqrt{2}} \pm i\,\dfrac{\bar{D}^{*0}\wedge D^{*+}}{2\sqrt{2}} \\[2ex] \dfrac{\eta_c\rho^+ + \psi\pi^+}{\sqrt{2}} \pm \dfrac{\bar{D}^0 D^{*+} + D^+ \bar{D}^{*0}}{\sqrt{2}} \end{array}\right\}$$

3 vs. 6 !

1/2 the # of states if there were one resonance for each meson-meson threshold.

$(\psi\wedge\rho^+)^c = (c\sigma^2\sigma^a\bar{c})(u\sigma^2\sigma^b\bar{d})^b\epsilon^{abc}$

Backup

courtesy of A Pilloni

Charged $Z_c(3900)$

$$G = G_\pi C_{J/\psi} =$$
$$= -1(-1) = +1$$
$$P = +1 \ (S - \text{wave})$$
$$\Rightarrow Z_c^0 \text{ has } J^{PC} = 1^{+-}$$

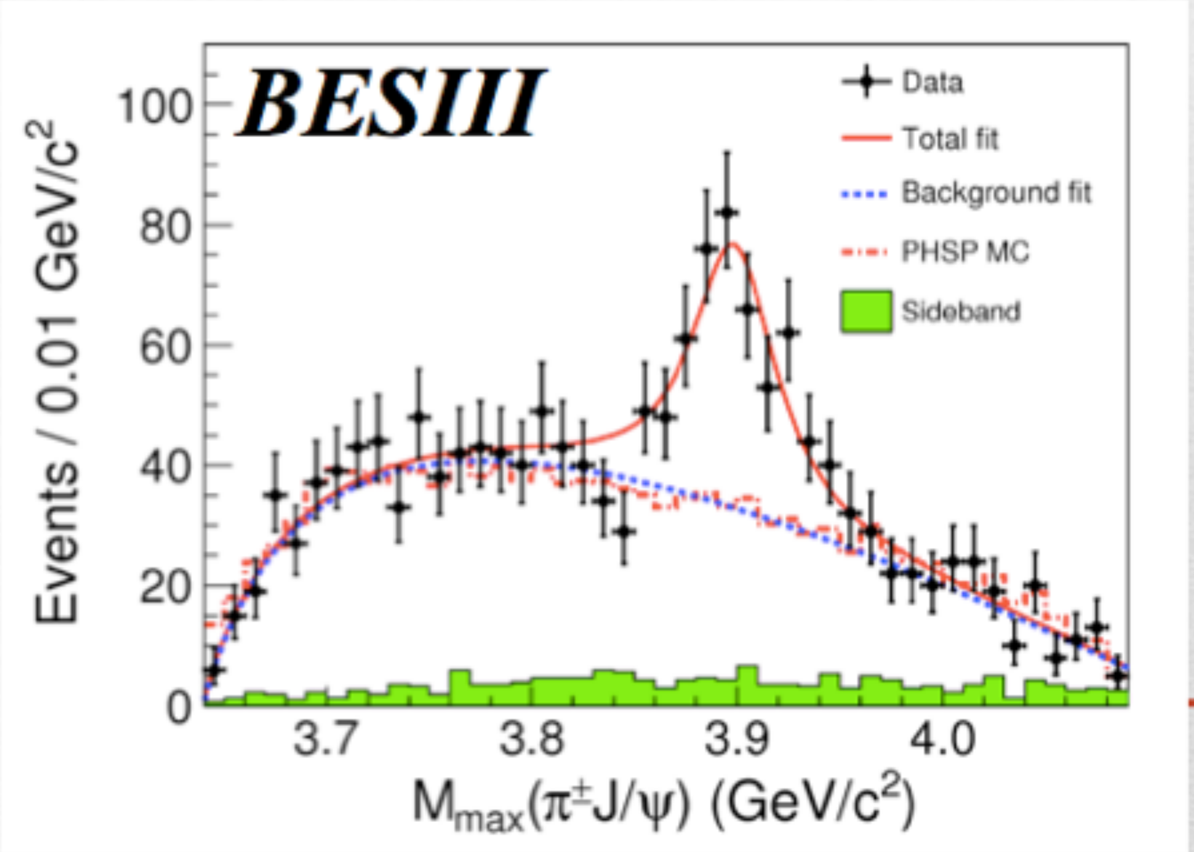
$$I^G J^{PC} = 1^+ 1^{+-}$$

Found in $Y(4260) \to Z_c^\pm(3900)\,\pi^\mp \to J/\psi\,\pi^\pm\,\pi^\mp$

Exotic charged charmonium-like state!

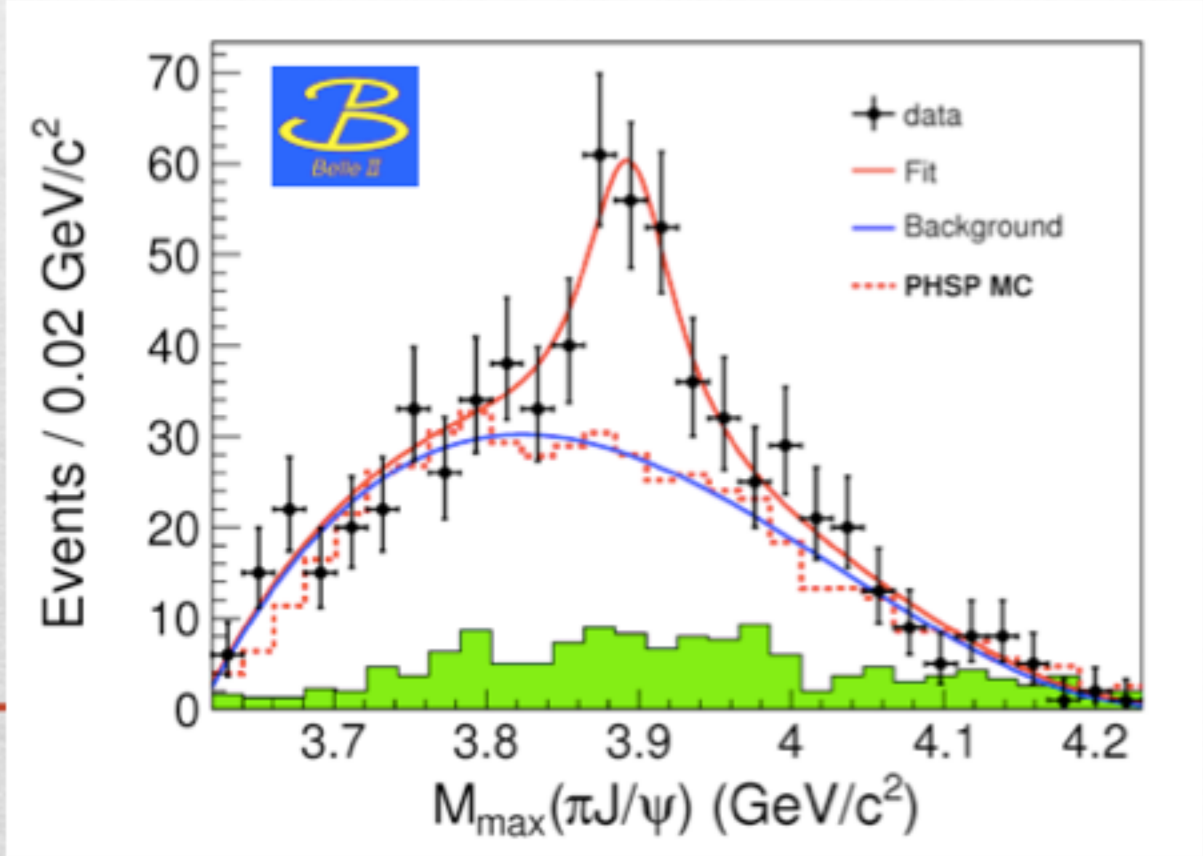
BESIII, arXiv:1303.5949

$$M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}$$
$$\Gamma = 46 \pm 10 \pm 20 \text{ MeV}$$

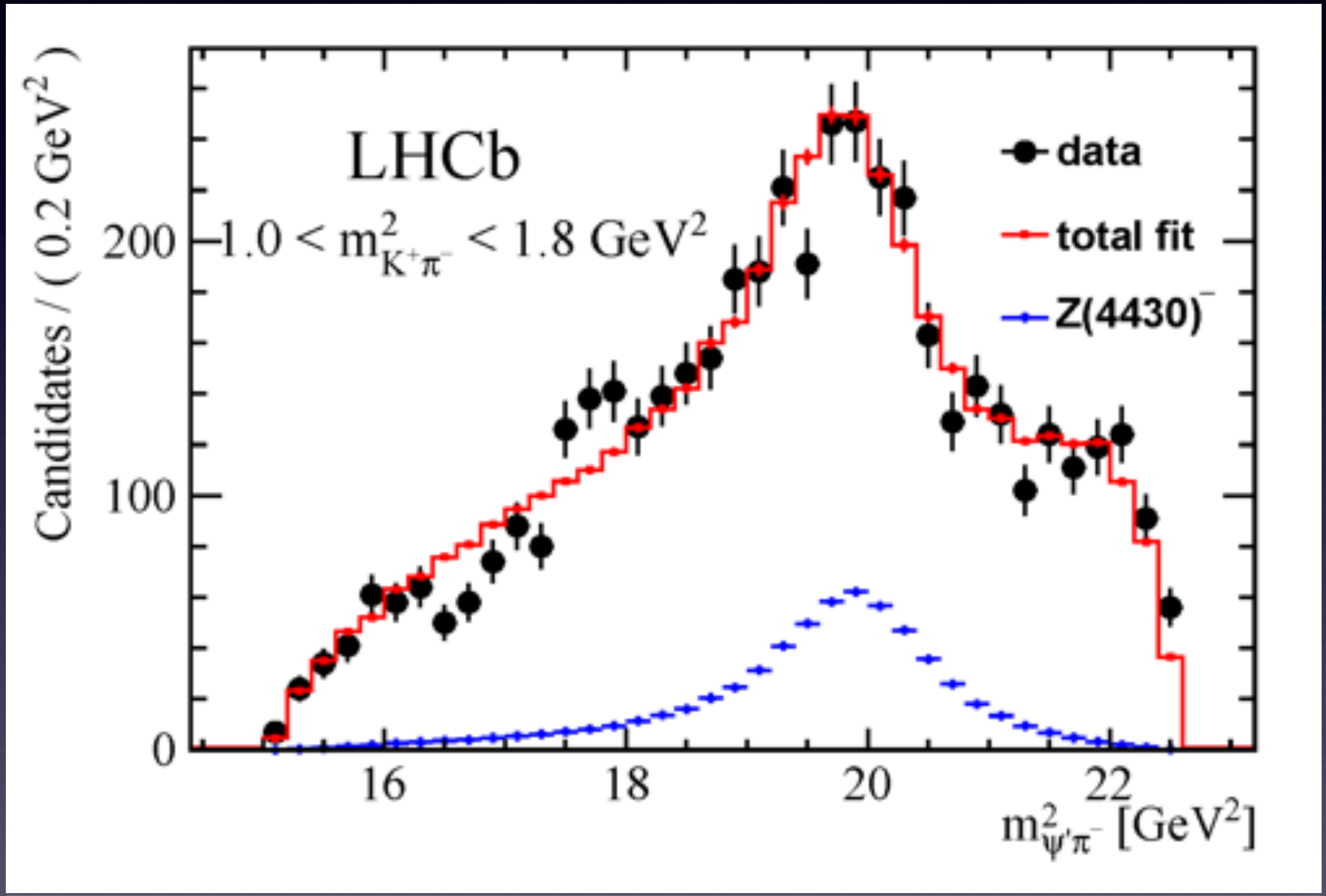


Belle, arXiv:1304.0121

$$M = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV}$$
$$\Gamma = 63 \pm 24 \pm 26 \text{ MeV}$$



Z(4430)$^-$ at LHCb | April 2014



$$B \to K^+(\psi(2S)\pi^-)_{J^{PG}=1^{++}}$$

Signal: 13.9 σ
Other assignments ruled out at 9.7σ

First observed by BELLE in 2007 and not confirmed by BaBar at that time

Tetraquarks Made of Diquarks

In our schemes tetraquarks could be described in terms of **heavy-light diquarks**

$$[cq]_i[\bar{c}\bar{q}]^i$$

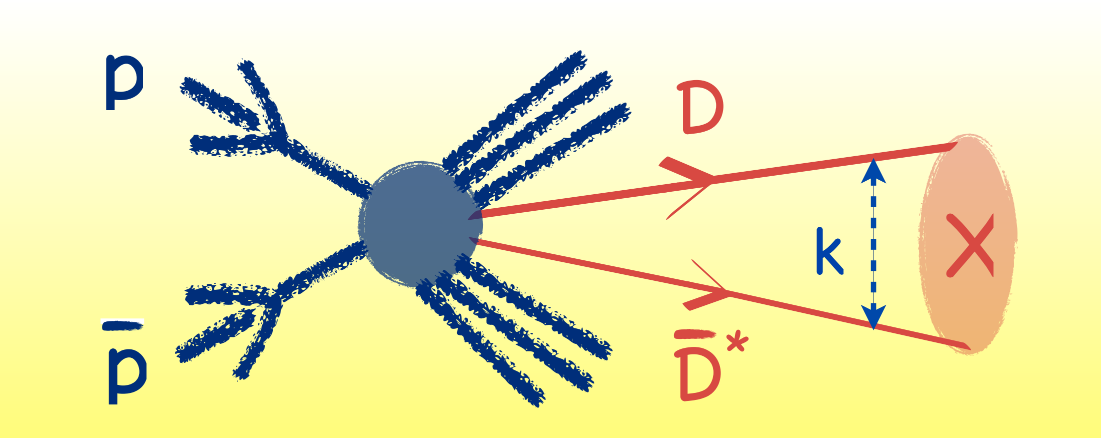
Diquark-antidiquark states might be formed in different spin combinations

	$cq\ \bar{c}\bar{q}$	$c\bar{c}\ q\bar{q}$	Resonance Assig.	Decays
0^{++}	$\lvert 0,0\rangle$	$1/2\lvert 0,0\rangle + \sqrt{3}/2\lvert 1,1\rangle_0$	$X_0(\sim 3770\ \mathrm{MeV})$	$\eta_c, J/\psi$ + light mesons
0^{++}	$\lvert 1,1\rangle_0$	$\sqrt{3}/2\lvert 0,0\rangle - 1/2\lvert 1,1\rangle_0$	$X_0'(\sim 4000\ \mathrm{MeV})$	$\eta_c, J/\psi$ + light mesons
1^{++}	$1/\sqrt{2}(\lvert 1,0\rangle + \lvert 0,1\rangle)$	$\lvert 1,1\rangle_1$	$X_1 = X(3872)$	$J/\psi + \rho/\omega,\ DD^*$
1^{+-}	$1/\sqrt{2}(\lvert 1,0\rangle - \lvert 0,1\rangle)$	$1/\sqrt{2}(\lvert 1,0\rangle - \lvert 0,1\rangle)$	$Z = Z(3900)$	$J/\psi + \pi,\ h_c/\eta_c + \pi/\rho$
1^{+-}	$\lvert 1,1\rangle_1$	$1/\sqrt{2}(\lvert 1,0\rangle + \lvert 0,1\rangle)$	$Z' = Z(4020)$	$J/\psi + \pi,\ h_c/\eta_c + \pi/\rho$
2^{++}	$\lvert 1,1\rangle_2$	$\lvert 1,1\rangle_2$	$X_2(\sim 4000\ \mathrm{MeV})$	J/ψ + light mesons

One should build a **diquark** Hamiltonian with **degenerate eigenvalues** for X(3872) and Z_c(3900) - look at exp. mass values

A. Esposito, A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1411.5997, IJMP**A**

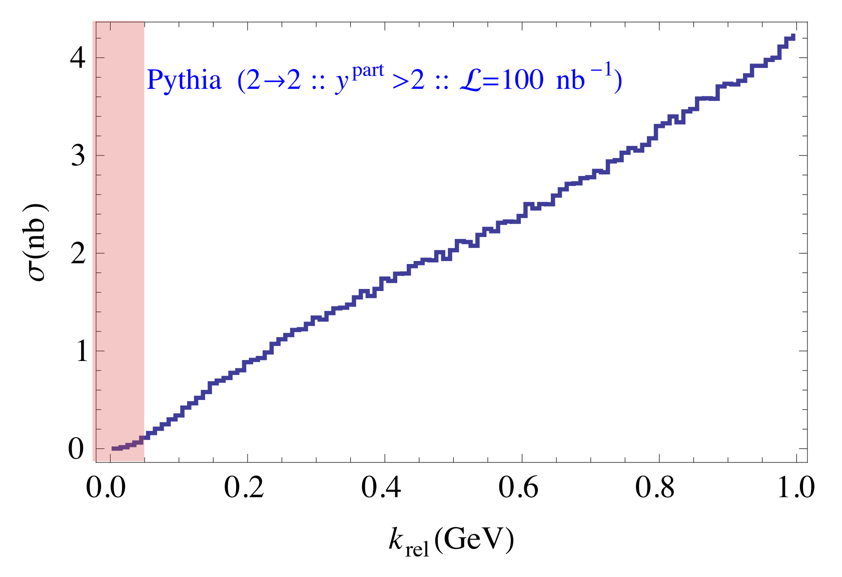
Barely Bound States in TeV Hadron Collisions?



$p_\perp^{\rm mol} > 5.5$ GeV

$|y^{\rm mol}| < 1$

k bounded by 50 MeV



Production xsect 300 times smaller than the observed one

C. Bignamini, B. Grinstein, F. Piccinini, ADP, C. Sabelli, *Phys Rev Lett*, ***103***, *162001 (2009)*

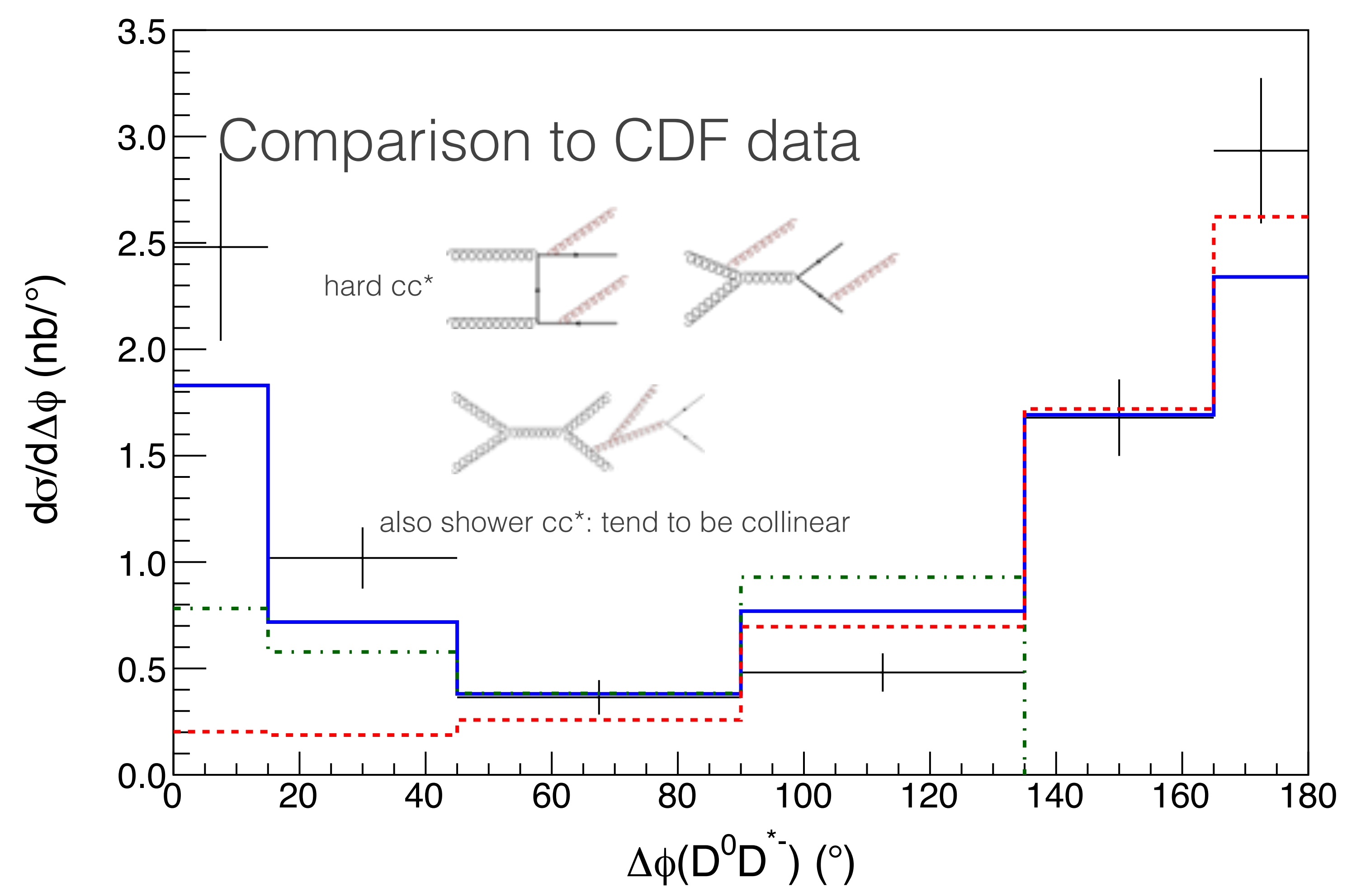
P. Artoisenet and E. Braaten, *Phys Rev* ***D81***, *114018 (2010)*

C. Bignamini, B. Grinstein, F. Piccinini, ADP, C. Sabelli, *Phys Lett*, ***B684***, *228 (2010)*

A. Esposito, F. Piccinini, A. Pilloni, A.D. Polosa, *J. Mod. Phys. 4, 1569, (2013)*

F-K. Guo, U. Meissner and Wang, arXiv: 1308.0193, 1402.6236 [. . .]

Production: MC Tuning



Comparison to CDF data

hard cc*

also shower cc*: tend to be collinear

red: cc* HERWIG/PYTHIA
green: cc*g(recoiling) ALPGEN + HERWIG/PYTHIA
blue: full qcd HERWIG/PYTHIA

A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1405.7929; PRD

Hadronization Must Proceed through 4q

A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1405.7929, PRD

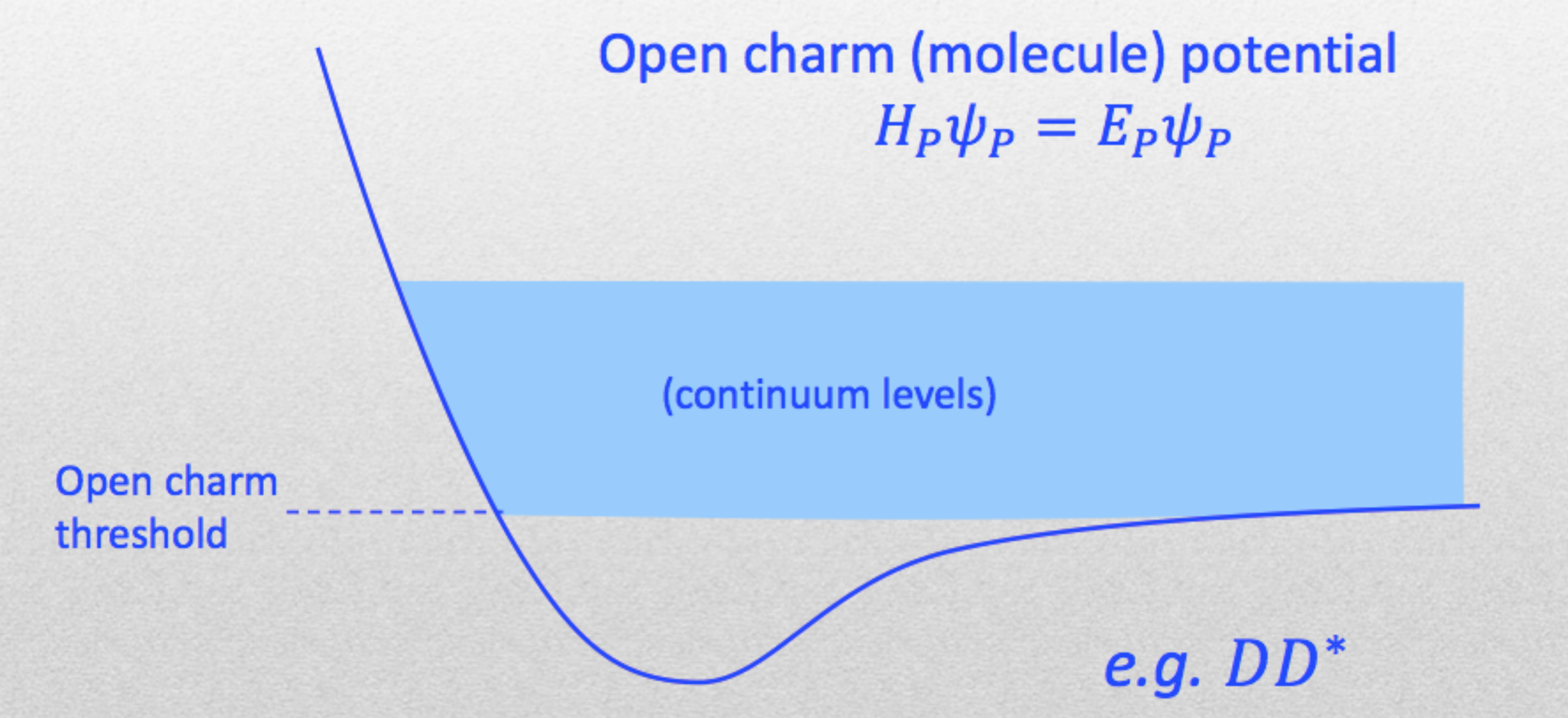
$$|\psi\rangle = \alpha|[Qq]_{\bar{\mathbf{3}}_c}[\bar{Q}\bar{q}]_{\mathbf{3}_c}\rangle_{\mathcal{C}} + \beta|(Q\bar{Q})_{\mathbf{1}_c}(q\bar{q})_{\mathbf{1}_c}\rangle_{\mathcal{O}} + \gamma|(Q\bar{q})_{\mathbf{1}_c}(\bar{Q}q)_{\mathbf{1}_c}\rangle_{\mathcal{O}}$$

— All ‘woud-be' loosely bound molecules do not form any bound state.
— Sometimes a compact 4quark state is formed, but it could be that $|\alpha| < |\beta|,|\gamma|$
— An amplification mechanism might be at work when the closed channel level matches the onset of the continuum spectrum of the two mesons with the same quantum numbers.

Do we know ‘amplification’ mechanisms between open/closed channels?

Another Mechanism

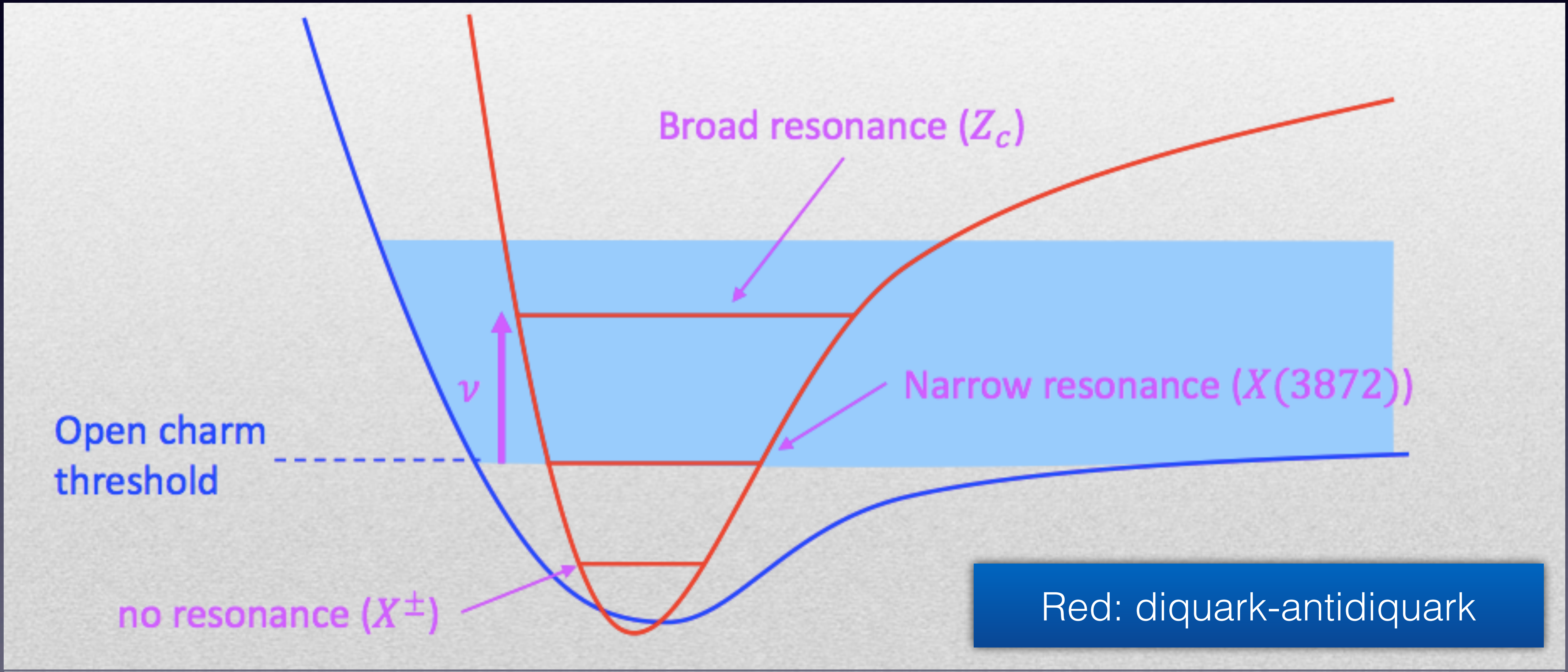
Borrow some ideas from cold atom physics. The Fano-Feshbach mechanism.



So shallow that does not bind

Another Mechanism

Borrow some ideas from cold atom physics. The Fano-Feshbach mechanism.



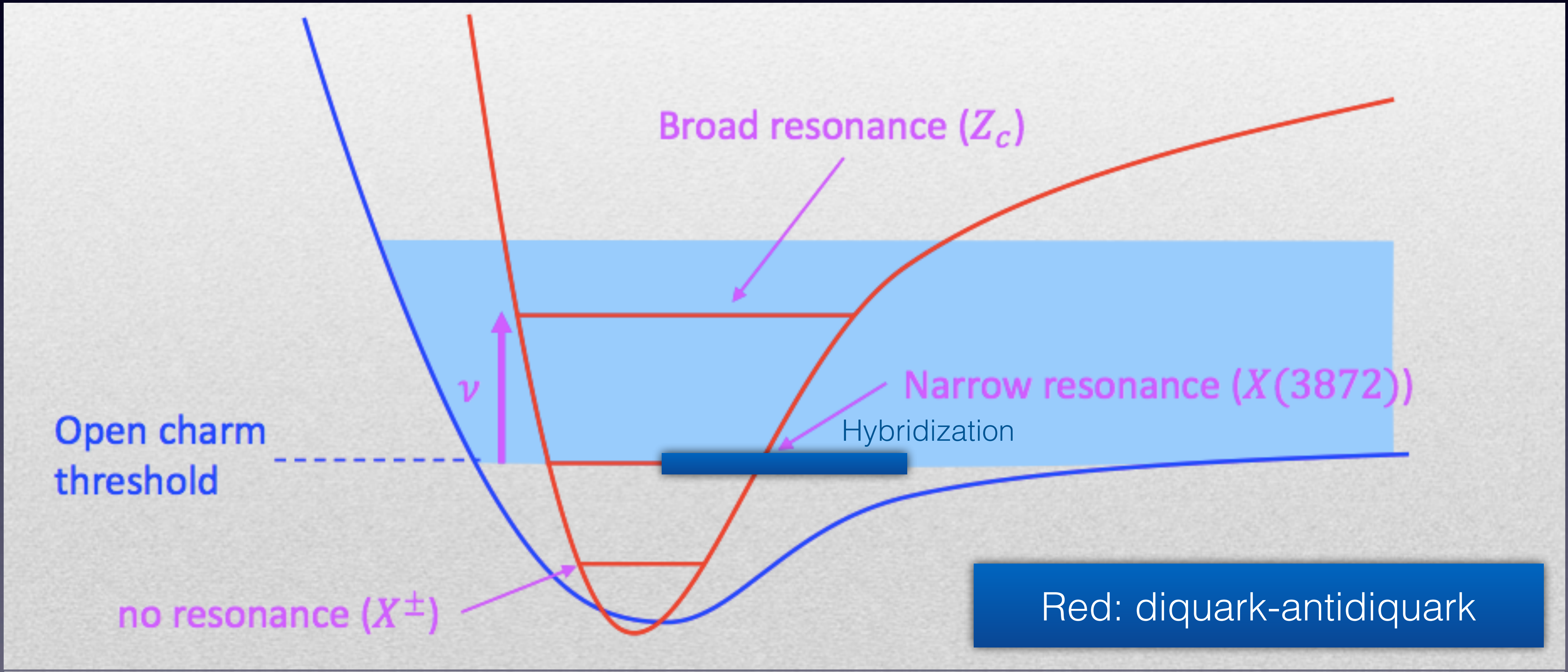
Red: diquark-antidiquark

Blue: loose molecule

$$a \sim |C| \sum_n \frac{c\langle [Qq]_{\bar{\mathbf{3}}_c} [\bar{Q}\bar{q}]_{\mathbf{3}_c}, n | H_{C\mathcal{O}} | (Q\bar{q})_{\mathbf{1}_c} (\bar{Q}q)_{\mathbf{1}_c} \rangle_{\mathcal{O}}}{E_{\mathcal{O}} - E_n}$$

Another Mechanism

Consider also that the J/ψ ρ⁺ is sensibly lower than the related open charm charged molecule. This could be why there is no charged X and *I*-violat.



Red: diquark-antidiquark

Blue: loose molecule

$$a \sim |C| \sum_n \frac{c\langle [Qq]_{\bar{\mathbf{3}}_c} [\bar{Q}\bar{q}]_{\mathbf{3}_c}, n | H_{C\mathcal{O}} | (Q\bar{q})_{\mathbf{1}_c} (\bar{Q}q)_{\mathbf{1}_c} \rangle_{\mathcal{O}}}{E_{\mathcal{O}} - E_n}$$

A. Guerrieri, F. Piccinini, A. Pilloni, ADP arXiv:1405.7929

Negative Parity: L=1

Spin (dq basis)

$$Y_1 = |0,0\rangle$$

$$Y_2 = \frac{|1,0\rangle + |0,1\rangle}{\sqrt{2}}$$

Like the X; Mass difference due to L

$$Y_3 = |1,1\rangle_{S=0}$$

$$Y_4 = |1,1\rangle_{S=2}$$

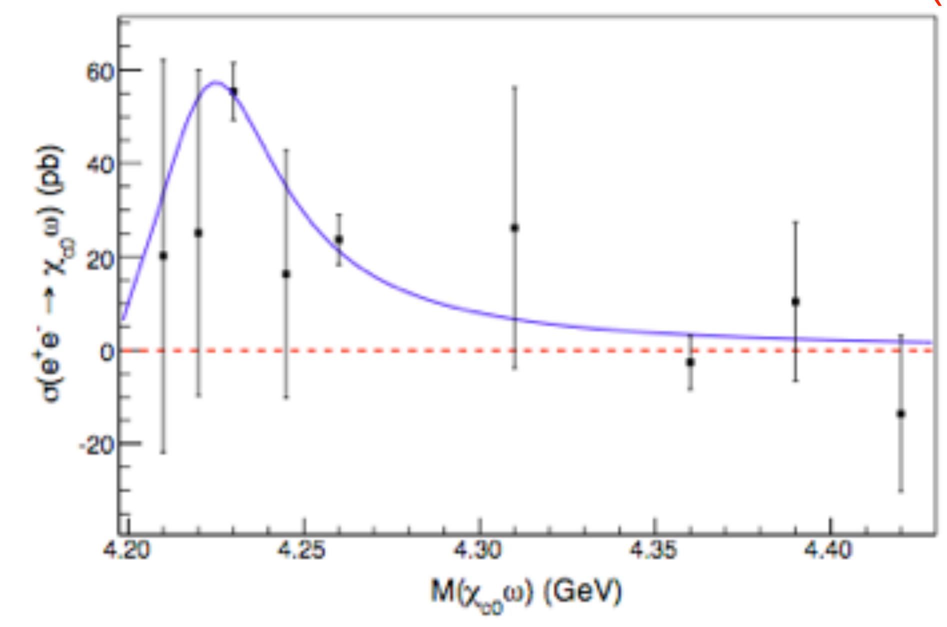
We identify Y(4360) and Y(4660), decaying into ψ(2S)π, as radial excitations of Y(4008) and Y(4260).

State	$P(S_{c\bar{c}}=1) : P(S_{c\bar{c}}=0)$	Assignment	Radiative Decay
Y_1	3:1	$Y(4008)$	$\gamma + X_0$
Y_2	1:0	$Y(4260)$	$\gamma + X$
Y_3	1:3	$Y(4290)/Y(4220)$	$\gamma + X_0'$
Y_4	1:0	$Y(4630)$	$\gamma + X_2$

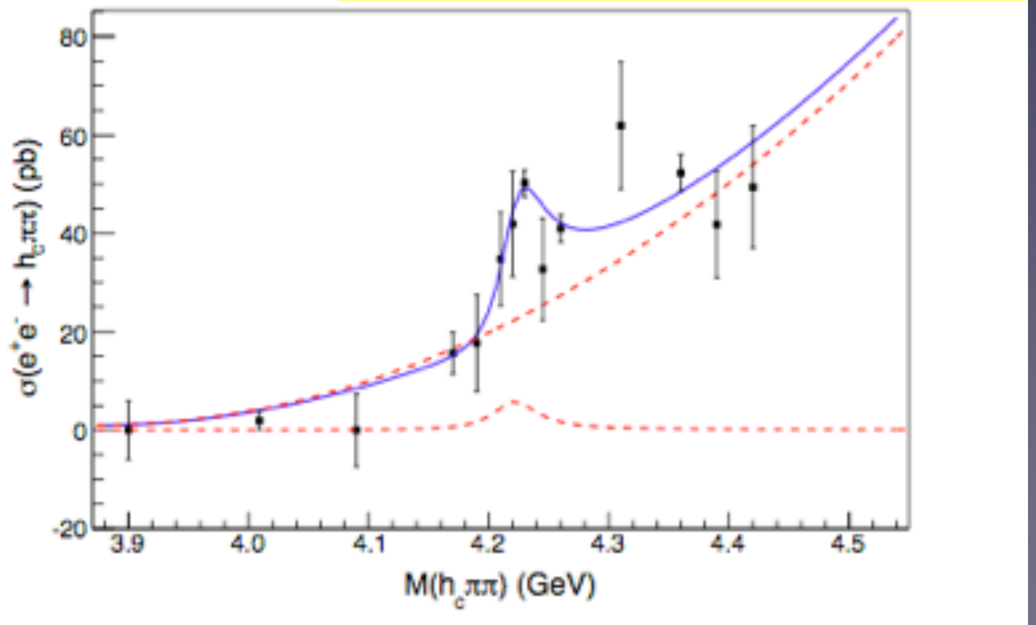
R. Faccini, G. Filaci, A. Guerrieri, A. Pilloni, ADP arXiv:1412.7196, PRD (Y(4230)=Y(4220))

M. Ablikim *et al.* [BESIII Collaboration], arXiv:1410.6538 [hep-ex].

Y(4230)



C. Z. Yuan, Chin. Phys. C **38** (2014) 043001
data from BES III Collab.



A Brief Tour in the Beauty Sector

A. Ali, L. Maiani, ADP, V. Riquer arXiv:1412.2049, PRD

1)

$$M(Z'_b) - M(Z_b) = 2\kappa_b$$

$$M(Z'_c) - M(Z_c) = 2\kappa_c = 120 \text{ MeV}$$

$$\kappa_b : k_c = M_c : M_b \approx 0.30$$

$$\Rightarrow 2\kappa_b \simeq 36 \text{ MeV vs. } 45 \text{ MeV (exp.)}$$

2)

$$\Upsilon(10890)(\Upsilon(5S)?) \to Z_b^{(\prime)}\pi \to h_b(nP)\pi\pi$$

$$Y(4260) \to Z_c(3900) + \pi$$

$S_{cc^*}=0$

heavy spin violation?

$S_{cc^*}=1$

but

$$Z_b = \frac{\alpha|1_{q\bar{q}}, 0_{b\bar{b}}\rangle - \beta|0_{q\bar{q}}, 1_{b\bar{b}}\rangle}{\sqrt{2}}$$

$$Z'_b = \frac{\beta|1_{q\bar{q}}, 0_{b\bar{b}}\rangle + \alpha|0_{q\bar{q}}, 1_{b\bar{b}}\rangle}{\sqrt{2}}$$

and comparing to data on 1—>0 and 1—>1 transitions strongly favor

$$\boxed{\alpha = \beta}$$