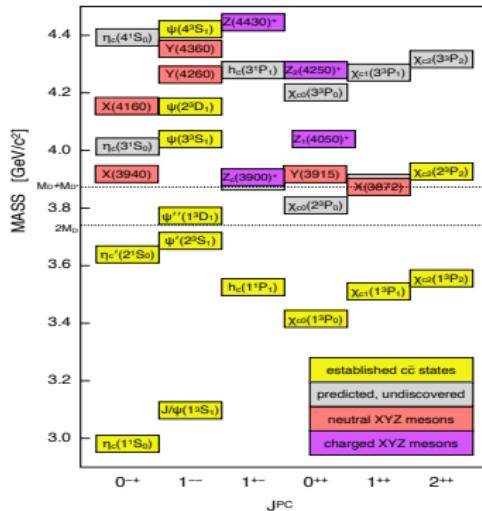


Theory progresses in understanding exotic quarkonium-like states

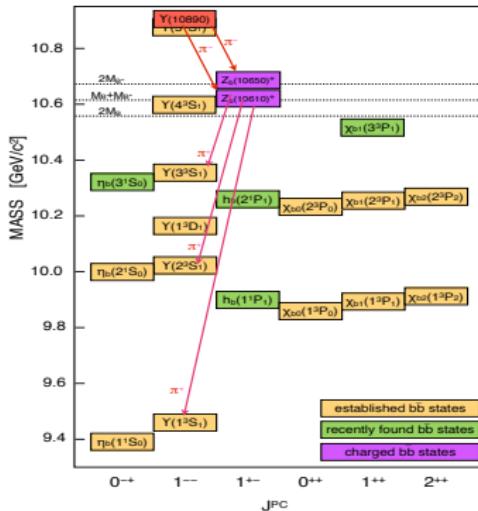
Fulvio Piccinini

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Charmonium and bottomonium spectrum



not shown $Y(4140)$ and $Y(4274)$



S. Olsen, arXiv:1403.1254[hep-ex]

- all $c\bar{c}/b\bar{b}$ states below open c/b threshold identified
- all $J^{PC} = 1^{--}$ $c\bar{c}/b\bar{b}$ states filled
- new neutral and charged particles above threshold

Summary of the available information on XYZ (I)

from T. Bodwin et al, arXiv:1307.7435[hep-ph] plus recent updates

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (# σ)	1 st observation
$X(3823)$	3823.1 ± 1.9	< 24	?? $-$	$B \rightarrow K + (\chi_{c1}\gamma)$	Belle (3.8)	Belle 2013
$X(3872)$	3871.68 ± 0.17	< 1.2	1 $++$	$B \rightarrow K + (J/\psi\pi^+\pi^-)$ $p\bar{p} \rightarrow (J/\psi\pi^+\pi^-) + \dots$ $B \rightarrow K + (J/\psi\pi^+\pi^-\pi^0)$ $B \rightarrow K + (D^0\bar{D}^0\pi^0)$ $B \rightarrow K + (J/\psi\gamma)$ $B \rightarrow K + (\psi(2S)\gamma)$ $pp \rightarrow (J/\psi\pi^+\pi^-) + \dots$	Belle (12.8), BaBar (8.6) CDF (np), D0 (5.2) Belle (4.3), BaBar (4.0) Belle (6.4), BaBar (4.9) Belle (4.0), BaBar (3.6) BaBar (3.5), Belle (0.4) LHCb (np), CMS	<u>Belle 2003</u>
$X(3915)$	3917.5 ± 1.9	20 ± 5	0 $++$	$B \rightarrow K + (J/\psi\omega)$ $e^+e^- \rightarrow e^+e^- + (J/\psi\omega)$	Belle (8.1), BaBar (19) Belle (7.7), BaBar (7.6)	Belle 2004
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2 $++$	$e^+e^- \rightarrow e^+e^- + (D\bar{D})$	Belle (5.3), BaBar (5.8)	Belle 2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	?? $+$	$e^+e^- \rightarrow J/\psi + (D^*\bar{D})$ $e^+e^- \rightarrow J/\psi + (\dots)$	Belle (6.0) Belle (5.0)	Belle 2007
$G(3900)$	3943 ± 21	52 ± 11	1 $--$	$e^+e^- \rightarrow \gamma + (D\bar{D})$	BaBar (np), Belle (np)	BaBar 2007
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1 $--$	$e^+e^- \rightarrow \gamma + (J/\psi\pi^+\pi^-)$	Belle (7.4)	Belle 2007
$Y(4140)$	4144.5 ± 2.6	15^{+11}_{-7}	?? $+$	$B \rightarrow K + (J/\psi\phi)$	CDF (5.0), D0 (3.1) CMS (>5)	<u>CDF 2009</u>
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	?? $+$	$e^+e^- \rightarrow J/\psi + (D^*\bar{D}^*)$	Belle (5.5)	Belle 2007

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (# σ)	1 st observer
$Y(4260)$	4263 $^{+8}_{-9}$	95 \pm 14	1 $^{--}$	$e^+e^- \rightarrow \gamma + (J/\psi \pi^+\pi^-)$	BaBar (8.0), CLEO (5.4)	BaBar 2008
				$e^+e^- \rightarrow (J/\psi \pi^+\pi^-)$	Belle (15)	
				$e^+e^- \rightarrow (J/\psi \pi^0\pi^0)$	CLEO (11)	
$Y(4274)$	4274.4 $^{+8.4}_{-6.7}$	32 $^{+22}_{-15}$? $?^{++}$	$B \rightarrow K + (J/\psi \phi)$	CDF (3.1) CMS	CDF 2010 CMS 2010
$X(4350)$	4350.6 $^{+4.6}_{-5.1}$	13.3 $^{+18.4}_{-10.0}$	0/2 $^{++}$	$e^+e^- \rightarrow e^+e^- (J/\psi \phi)$	Belle (3.2)	Belle 2009
$Y(4360)$	4361 \pm 13	74 \pm 18	1 $^{--}$	$e^+e^- \rightarrow \gamma + (\psi(2S) \pi^+\pi^-)$	BaBar (np), Belle (8.0)	BaBar 2008
$X(4630)$	4634 $^{+9}_{-11}$	92 $^{+41}_{-32}$	1 $^{--}$	$e^+e^- \rightarrow \gamma (\Lambda_c^+\Lambda_c^-)$	Belle (8.2)	Belle 2007
$Y(4660)$	4664 \pm 12	48 \pm 15	1 $^{--}$	$e^+e^- \rightarrow \gamma + (\psi(2S) \pi^+\pi^-)$	Belle (5.8)	Belle 2007
$Z_c^+(3900)$	3898 \pm 5	51 \pm 19	1? $^{--}$	$Y(4260) \rightarrow \pi^- + (J/\psi \pi^+)$	BESIII (np), Belle (5.2)	BESIII 2010
				$e^+e^- \rightarrow \pi^- + (J/\psi \pi^+)$	Xiao <i>et al.</i> (6.1)	
$Z'_c(3900)$	3883.9 \pm 6.3	24.8 \pm 11.5	1 $^{+-}$	$Y(4260) \rightarrow Z'_c \pi^+ \rightarrow D \bar{D}^* \pi^+$	BESIII (np)	BESIII 2010
$Z'_c(4020)$	4022.9 \pm 2.8	7.9 \pm 3.8	?	$Y(4260) \rightarrow Z'_c \pi^+ \rightarrow h_c \pi^- \pi^+$	BESIII (np)	BESIII 2010
$Z'_c(4025)$	4026.3 \pm 4.5	24.8 \pm 9.5	?	$Y(4260) \rightarrow Z'_c \pi^+ \rightarrow D^* \bar{D}^* \pi^+$	BESIII (np)	BESIII 2010
$Z_1^+(4050)$	4051 $^{+24}_{-43}$	82 $^{+51}_{-55}$?	$B \rightarrow K + (\chi_{c1}(1P) \pi^+)$	Belle (5.0), BaBar (1.1)	Belle 2008
$Z_2^+(4250)$	4248 $^{+185}_{-45}$	177 $^{+321}_{-72}$?	$B \rightarrow K + (\chi_{c1}(1P) \pi^+)$	Belle (5.0), BaBar (1.1)	Belle 2008
$Z^+(4430)$	4443 $^{+24}_{-18}$	107 $^{+113}_{-71}$?	$B \rightarrow K + (\psi(2S) \pi^+)$	Belle (6.4), BaBar (2.4)	Belle 2007
$Y_b(10888)$	10888.4 \pm 3.0	30.7 $^{+8.9}_{-7.7}$	1 $^{--}$	$e^+e^- \rightarrow (\Upsilon(nS) \pi^+\pi^-)$	Belle (2.0)	Belle 2010
$Z_b^+(10610)$	10607.2 \pm 2.0	18.4 \pm 2.4	1 $^{+-}$	$\Upsilon(5S) \rightarrow \pi^- + (\Upsilon(nS) \pi^+)$	Belle (16)	Belle 2011
				$\Upsilon(5S) \rightarrow \pi^- + (h_b(nP) \pi^+)$	Belle (16)	
$Z_b^+(10650)$	10652.2 \pm 1.5	11.5 \pm 2.2	1 $^{+-}$	$\Upsilon(5S) \rightarrow \pi^- + (\Upsilon(nS) \pi^+)$	Belle (16)	Belle 2011
				$\Upsilon(5S) \rightarrow \pi^- + (h_b(nP) \pi^+)$	Belle (16)	

Some striking features to be remarked

- charged states prove the internal composition of 4 valence quarks
- several states very close to open charm/bottom thresholds
- narrow (extreme case: $X(3872)$)
- $X(3872)$ has a large prompt production cross section at hadron colliders
- some states prefer to decay to $\psi(2S)$ w.r.t. J/ψ , despite more constrained phase space

challenge: can we give a theoretically unified description?

Features of most popular th-models of exotic mesons

• hadronic molecules

- $Q\bar{q}$ tightly bound in heavy mesons which move at distances longer than typical size of mesons
$$(R \sim \frac{\hbar c}{2M_{red}E_{bind}}) (\sim 10 \text{ fm for } X(3872))$$
- masses close to thresholds
- typically loosely bound systems which can decay easily through the independent decay of their constituents
- isospin breaking easily accommodated
- difficult to make predictions (in principle any pair of mesons at threshold can rescatter and form a molecule)

• hybrids ($c\bar{c}$ + excited gluons)

- different quantum numbers from charmonium
- natural preference to decay to $J/\psi +$ pions
- lowest lying state predicted around 4200 MeV by LQCD $\implies Y(4260)$
- this model can not be applied to charged states

• diquark-antidiquarks (tetraquarks)

- Qq tightly bound in diquarks, which interact by QCD colour force
- masses not necessarily close to threshold
- prediction of bound states with higher L and/or radially excited
- many new states (charged and neutral) foreseen (a nonet for each spin-parity)
- neutral states expected to appear in doublets
- decays include both open and hidden charm channels and (if kinematically allowed) baryonium

• hadro-quarkonium

- $Q\bar{Q}$ tightly bound as in quarkonium
- $Q\bar{Q}$ embedded in a spatially large excited state of light mesonic matter
- interactions through QCD analog of Van der Waals force
- natural suppression of decay to open charmed/beauty

$X(3872)$, the oldest and still debated one

- $M(X3872) = 3871.68 \pm 0.17 \text{ MeV}$ $\Gamma_X \lesssim 1.2 \text{ MeV}$ $J^{PC} = 1^{++}$
- $\Delta M \equiv M(X3872) - (M_{D^0} + M_{D^{*0}}) = -0.09 \pm 0.28 \text{ MeV}$ (LHCb)
- production
 - production through B decays at e^+e^- and $p\bar{p}/pp$ colliders
 - dominant prompt production at Tevatron/LHC ($p\bar{p} \rightarrow X + \text{all}$)
- decay
 - $J/\psi\rho \rightarrow J/\psi\pi^+\pi^-$
 - $J/\psi\omega \rightarrow J/\psi\pi^+\pi^-\pi^0$ (large isospin violation)
 - $D^0\bar{D}^{0*} \rightarrow D^0\bar{D}^0\pi^0$
 - $D^0\bar{D}^{0*} \rightarrow \bar{D}^0\gamma$
 - $J/\psi\gamma, \psi(2S)\gamma$
- $\Delta M \lesssim 0 \implies \text{molecular interpretation natural}$
- isospin violation explained with the distance of D^+D^{*-} and $D^0\bar{D}^{0*}$ thresholds of $\sim 8 \text{ MeV}$
- large cross sections (several nb) at hadron colliders compatible with this hypothesis? (\implies see later)

Threshold distance for charged states \Rightarrow molecules?

- $Z_b^+(10610) \rightarrow \Upsilon(nS)\pi^+$ ($n = 1, 2, 3$)
 - $M_Z = 10607.2 \pm 2.0 \text{ MeV}$, $\Gamma_Z = 18.4 \pm 2.4 \text{ MeV}$
 - $M_B + M_{B^*} = 10604.46 \pm 0.43 \text{ MeV}$ $\Delta M \sim 3 \pm 2 \text{ MeV}$
- $Z_b^+(10650) \rightarrow h_B(nP)\pi^+$ ($n = 1, 2$)
 - $M_Z = 10652.2 \pm 1.5 \text{ MeV}$, $\Gamma_Z = 11.5 \pm 2.2 \text{ MeV}$
 - $M_{B^*} + M_{B^{*+}} = 10650.4 \pm 0.6 \text{ MeV}$ $\Delta M \sim 2 \pm 2 \text{ MeV}$
- $Z_c(3900) \rightarrow J\psi\pi^+$
 - $M_Z = 3899.0 \pm 6.1 \text{ (MeV)}$, $\Gamma_Z = 46 \pm 22 \text{ MeV}$ (in $J\psi\pi^\pm$);
 $M_Z = 3883.9 \pm 4.5 \text{ (MeV)}$, $\Gamma_Z = 24.8 \pm 12 \text{ MeV}$ (in $D\bar{D}^*$)
 - $M_{D^0} + M_{D^{*+}} = 3875.15 \pm 0.18 \text{ MeV}$;
 $M_{D^\pm} + M_{D^{*0}} = 3876.61 \pm 0.21 \text{ MeV}$ $\Delta M \sim 24/8 \pm 5 \text{ MeV}$
- $Z'_c(4020) \rightarrow h_c(1P)\pi^+$
 - $M_Z(h_c\pi) = 4022.9 \pm 1.8 \text{ MeV}$, $\Gamma_Z = 7.9 \pm 3.8 \text{ MeV}$;
 $M_{D^{*+}} + M_{D^{*0}} = 4017.28 \pm 0.20 \text{ MeV}$ $\Delta M \sim 6 \pm 2 \text{ MeV}$
- $Z'_c(4025) \rightarrow D^*\bar{D}^*$
 - $M_Z(D^*\bar{D}^*) = 4026.3 \pm 4.5 \text{ MeV}$, $\Gamma_Z = 24.5 \pm 9.5 \text{ MeV}$

$\Delta M_Z > 0$ (even if higher experimental precision needed)

Prompt $X(3872)$ production: upper theoretical bounds

Bignamini, Grinstein, F.P., Polosa, Sabelli: Phys. Rev. Lett. 103, 162001, 2009

hypothesis: of $X(3872)$ as an S -wave bound state of two D mesons

$$\begin{aligned}\sigma(p\bar{p} \rightarrow X(3872)) &\sim \left| \int d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2 \\ &\leq \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2 \sim \sigma(p\bar{p} \rightarrow X(3872))_{\text{prompt}}^{\max}\end{aligned}$$

- \mathbf{k} is the rest-frame relative 3-momentum between the D and D^*
- $|\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2$ can be computed with MC simulations
- result: measured prompt cross section \ll upper estimate by more than 2 orders of magnitude unless integration over $|\mathbf{k}|$ extended up to ~ 400 MeV
- this could be made possible by FSI Artoisenet and Braaten, PRD81 (2010) 114018
- the same method recently adopted to estimate other Z state production cross sections @LHC

F.-K. Guo et al., arXiv:1308.0193[hep-ph], arXiv:1402.6236[hep-ph], arXiv:1403.4032[hep-ph]

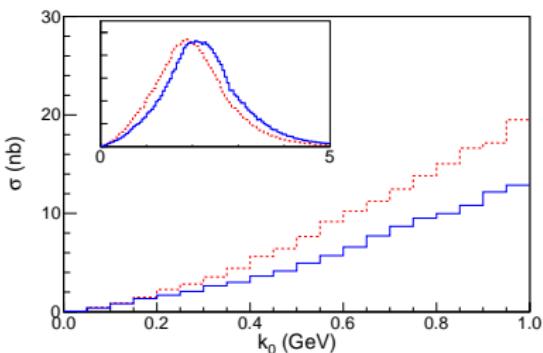
- actually the large hadronic activity (mainly π) close to D and D^* could prevent the effectiveness of FSI (Bignamini et al., PLB684 (2010) 228)
- but the same π could give an alternative contribution

Possible mechanism alternative to FSI

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

A.L. Guerrieri, F.P., A. Pilloni and A.D. Polosa, arXiv:1405.7929[hep-ph]

- additional pions close to $D^{0(*)}$ in momentum space can interact elastically and change the rel. momentum between D^0 and D^{0*}
- given the initial asymmetric distribution in k_{rel} there could be a feed-down process from larger relative momenta to lower ones and bring D pairs from positive to negative energies (bound state)

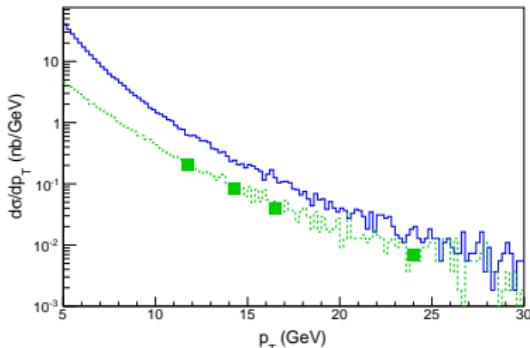
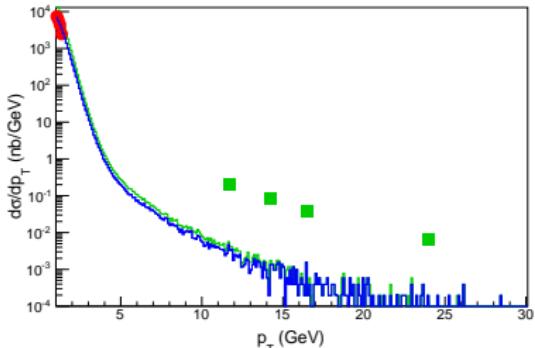


- there is a contribution but not enough
- additional ways to check the molecular hypothesis?

Antideuterium - $X(3872)$

A.L. Guerrieri, F.P., A. Pilloni, A.D. Polosa, arXiv:1405.7929[hep-ph]

- deuterium is the known hadronic molecule, would be analog of $X(3872)$
- antideuterium production is measured at ALICE
- we could study the relation indicated by data between antideuterium and $X(3872)$ production
- unfortunately, up to now, they are measured in two completely different p_T regimes. We can only have a qualitative idea through MC



Diquark-antidiquark / tetraquark model

L. Maiani, F.P., A.D. Polosa, V. Riquer, PRD 71 (2005) 014028

- in the original version a “democratic” hypothesis was made on spin-spin interactions

$$H = \sum_i m_i + \sum_{i < j} 2\kappa_{ij} \mathbf{s}_i \cdot \mathbf{s}_j$$

From conventional S -wave mesons and baryons

$$H \approx 2\kappa_{q\bar{q}} \mathbf{s}_q \cdot \mathbf{s}_{\bar{q}}$$

- tetraquark production cross sections of the same order of $Q\bar{Q}$
- drawback of the model: too many foreseen states, in particular charged ones w.r.t. what observed
- after the Belle announcement of $Z(4430)$ in 2007, a new state predicted, $Z^\pm \rightarrow J/\psi \pi^\pm$ or $\rightarrow \eta_c \rho^\pm$, with mass ~ 3880 MeV

Maiani, Polosa, Riquer, arXiv:0708.3997

- now several charged states have been found and there is renewed recent interest in the tetraquark model
- e.g.: S. Brodsky, R. Lebed, D.S. Hwang, M. Papinutto, S. Prelovsek, N. Tantalo, Z. -G. Wang, S. Weinberg and others

From type-I to type-II diquark-antidiquark model

L. Maiani, F.P., A.D. Polosa, V. Riquer, PRD 89 (2014) 114010

- new ansatz: only spin-spin coupling inside the diquark is leading

$$H \approx 2\kappa_{qc} (\mathbf{s}_q \cdot \mathbf{s}_c + \mathbf{s}_{\bar{q}} \cdot \mathbf{s}_{\bar{c}})$$

In the $|s, \bar{s}\rangle_J$ basis

$$J^P = 0^+ \quad C = + \quad X_0 = |0, 0\rangle_0, \quad X'_0 = |1, 1\rangle_0 \quad \textcolor{red}{X(3915), X(3940)?}$$

$$J^P = 1^+ \quad C = + \quad X_1 = \frac{1}{\sqrt{2}} (|1, 0\rangle_1 + |0, 1\rangle_1) \quad \textcolor{red}{X(3872)}$$

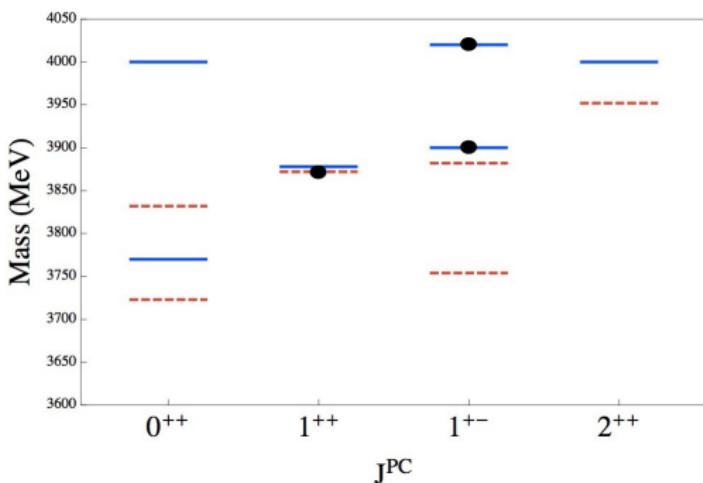
$$J^P = 1^+ \quad G = + \quad Z = \frac{1}{\sqrt{2}} (|1, 0\rangle_1 - |0, 1\rangle_1), \quad Z' = |1, 1\rangle_1 \quad \textcolor{red}{Z_c(3900), Z'_c(4020) \text{ lin. comb of } Z \text{ and } Z'}$$

$$J^P = 2^+ \quad C = + \quad X_2 = |1, 1\rangle_2$$

with a value of the coupling $\kappa_{qc} = 67 \text{ MeV}$ (cfr. 22 MeV of type I)

- $M(X_1) \sim M(Z)$
- $M(Z') - M(Z) \sim 2\kappa_{qc} = 134 \text{ MeV}$
- $M(X_2) \sim M(X'_0) \sim 4000 \text{ MeV}$
- $M(X_0) \sim 3770 \text{ MeV}$

Type-II diquark-antidiquark model (cnt'd)



- in this scheme $Z(4430)$ is the first radial excitation of $Z(3900)$
 - note that $M(Z(4430)) - M(Z(3900)) = 593 \text{ MeV} \sim M(\psi(2S)) - M(J/\psi) = 589 \text{ MeV}$
- both $Z(3900)$ and $Z(4020)$ have $s_{c\bar{c}} = 1, 0$
 - $\Rightarrow Z(4020) \rightarrow \pi h_c(^1P_1)$

What about Y states in the tetraquark model?

- tetraquark with $J^{PC} = 1^{--}$ can be obtained with odd L
- using the notation $|s, \bar{s}; S, L\rangle_{J=1}$

$$\begin{array}{lll} Y_1 = |0, 0; 0, 1\rangle_1 & \text{(Y(4008))} & P(s_{c\bar{c}} = 1) : P(s_{c\bar{c}} = 0) = 3 : 1 \\ Y_2 = \frac{1}{\sqrt{2}}(|1, 0; 1, 1\rangle_1 + |0, 1; 1, 1\rangle_1) & \text{(Y(4260))} & P(s_{c\bar{c}} = 1) = 1 \\ Y_3 = |1, 1; 0, 1\rangle_1 & \text{(Y(4290)/Y(4220))} & P(s_{c\bar{c}} = 1) : P(s_{c\bar{c}} = 0) = 1 : 3 \\ Y_4 = |1, 1; 2, 1\rangle_1 & \text{(Y(4630) } \rightarrow \Lambda_c \bar{\Lambda}_c \text{)} & P(s_{c\bar{c}} = 1) = 1 \end{array}$$

- $Y(4360)$: radial excitation of $Y(4008)$; $Y(4660)$: radial excitation of $Y(4260)$, since both decay to $\psi(2S)$
- $Y(4260)$ and $X(3872)$ have the same spin structure \implies the observed radiative decay $Y(4260) \rightarrow \gamma X(3872)$ is an $E1$ transition ($\Delta L = 1$ and $\Delta S = 0$) as in radiative decays of χ states

some predictions on radiative decays

- type-II tetraquark model seems to capture several features making also additional predictions

$$Y_4 = Y(4630) \rightarrow \gamma + X_2 \quad (J^{PC} = 2^{++}) = \gamma + X(3940), ??$$

$$Y_3 = Y(4290/4220) \rightarrow \gamma + X'_0 \quad (J^{PC} = 0^{++}) = \gamma + X(3916), ??$$

$$Y_2 = Y(4260) \rightarrow \gamma + X_1 \quad (J^{PC} = 1^{++}) = \gamma + X(3872), \text{ seen}$$

$$Y_1 = Y(4008) \rightarrow \gamma + X_0 \quad (J^{PC} = 0^{++}) = \gamma + X(3770 ??), ??$$

- however charged partners of X and Y states are still missing (or too large?)
- together with the hyperfine splitting among neutral states due to isospin breaking (maybe this could require additional experimental sensitivity)
- we conclude with a possible scenario which could be able to put effectively selection rules on the states

Four-quark states as Fano-Feshbach resonances?

A.L. Guerrieri, F.P., A. Pilloni, A.D. Polosa, arXiv:1405.7929[hep-ph]

- multiquark hadrons at LHC should be produced through the formation of compact clusters, with colour neutralized in all possible ways

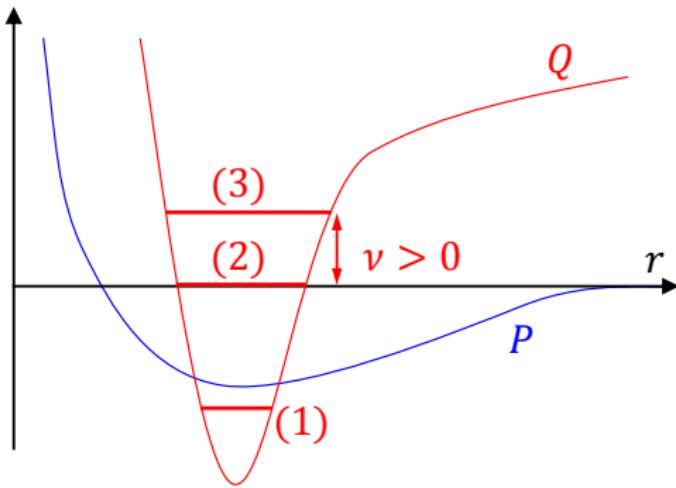
$$|Q\bar{Q}q\bar{q}\rangle = \alpha |[Qq]_{\bar{\mathbf{3}}_c} [\bar{Q}\bar{q}]_{\mathbf{3}_c}\rangle_c + \beta |(Q\bar{Q})_{\mathbf{1}_c} (q\bar{q})_{\mathbf{1}_c}\rangle_{\mathcal{O}} + \gamma |(Q\bar{q})_{\mathbf{1}_c} (\bar{Q}q)_{\mathbf{1}_c}\rangle_{\mathcal{O}}$$

- hypothesis: $|\beta|^2, |\gamma|^2 \gg |\alpha|^2$
- in this case we do not see directly the diquark-antidiquark spectrum; it could instead produce an effective attraction in the open channel which could produce a resonance (known as Feshbach resonance in atomic physics) decaying into two particles in one of the open channels
- contribution to the scattering length

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

- the “detuning” $\nu \equiv E_n - E_{\mathcal{O}}$ is the smallest denominator, which is supposed to dominate the sum
- Γ of the resonance $\sim \sqrt{\nu}$

Feshbach resonance in a picture



- for quantitative conclusions it would be necessary more information on the diquark-antidiquark spectrum
- to this aim LQCD studies of tetraquark would be very helpful

S. Prelovsek, Lang, Leskovek, Mohler; A.L. Guerrieri, M. Papinutto, A.D. Polosa, A. Pilloni, N. Tantalo