Spectroscopy: open problems

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based on work with
A. Esposito, A. Guerrieri, L. Maiani,
A. Pilloni, A.D. Polosa and V. Riquer

complementary to the talk of P. Colangelo

Charged states → hidden and open charm/beauty

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1$^{\rm st}$ obs.
$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to (J/\psi\,\pi^+)\,\pi^-$	BESIII, Belle	BESIII 2013
				$Y(4260) \to (D\bar{D}^*)^+\,\pi^-$	BESIII	
$Z'_c(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to (h_c\pi^+)\,\pi^-$	BESIII (np)	BESIII 2013
				$Y(4260) \to (D^*\bar{D}^*)^+\,\pi^-$	BESIII	
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle (5.0), BaBar (1.1)	Belle 2008
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle	Belle 2014
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$?^{?+}$	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle (5.0), BaBar (1.1)	Belle 2008
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi(2S)\,\pi^+)$	Belle, LHCb	Belle 2007
				$B \to K + (J/\psi\,\pi^+)$		LHCb 2014
$Z_b^+(10610)$	10607.2±2.0	18.4±2.4	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$	Belle	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$	Belle	
				$\Upsilon(5S) \to \pi^- + (B\bar{B}^*)^+$	Belle	
$Z_b^+(10650)$	10652.2±1.5	11.5±2.2	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$	Belle	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$	Belle	
				$\Upsilon(5S) \to \pi^- + (B^*\bar{B}^*)^+$	Belle	

Signature of 4q bound structures: $Q\bar{Q}q_i\bar{q}_j \qquad (q_i = u; q_j = d)$

Not impossible from first principle

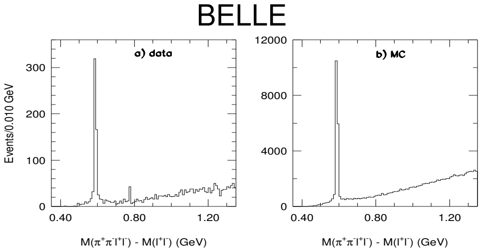
- Are qqq and $q\bar{q}$ the only binding configurations according to QCD?
- "Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**."

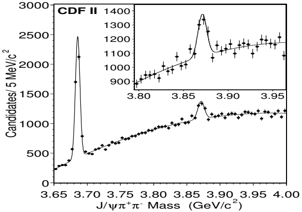
M. Gell-Mann, Phys. Lett. **8**(1964) 214

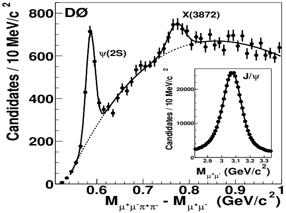
- 1977 first attempt to interpret scalar mesons as tetraquark $(qq\bar{q}\bar{q})$ bound states

R.L. Jaffe, Phys. Rev. **D15** (1977)

Actually the revolution dates back to 2003: $X(3872)$







- Phys.Rev.Lett. 91 (2003) 262001, most cited paper of Belle Collaboration $X(3872)$
- Phys.Rev.Lett. 95 (2005) 142001, 3rd most cited paper of BaBar Collaboration $Y(4260)$

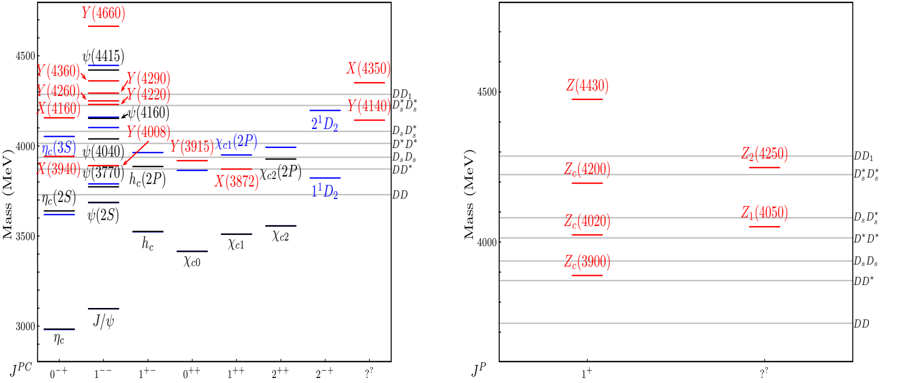
XYZ: naming scheme convention

- X: neutral states which decay in S-wave, with $P = +$
- Y: neutral states seen in e^+e^- annihilations, with $J^{PC} = 1^{--}$
- Z: charged states, with $P = +$ for S-wave decay to $J/\psi\pi^{\pm}$

Actually... in the PDG... every state is dubbed X

Charmonium spectrum

A. Esposito, A. Guerrieri, F.P., A. Pilloni, A. Polosa, arXiv:1411.5997[hep-ph]



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

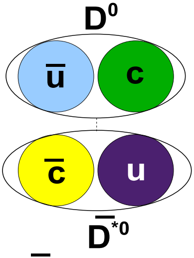
Summary of the available information on XYZ (I)

from T. Bodwin et al, arXiv:1307.7435[hep-ph] and A. Esposito et al., arXiv:1411.5997[hep-ph]

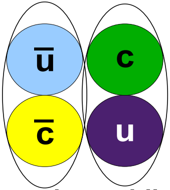
State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1$^{\text{st}}$ observation
$X(3823)$	3823.1±1.9	< 24	$?^{?-}$	$B \to K + (\chi_{c1}\gamma)$	Belle (3.8)	Belle 2013
$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle (12.8), BaBar (8.6)	Belle 2003
				$p\bar{p}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

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 (8.0), CLEO (5.4) Belle (15)	BaBar 2005
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO (11)	
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO (5.1)	
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF (3.1) CMS	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 (3.2)	Belle 2009
$Y(4360)$	4361 ± 13	74±18	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	BaBar (np), Belle (8.0)	BaBar 2007
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle (8.2)	Belle 2007
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	Belle (5.8)	Belle 2007
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle (2.0)	Belle 2010
$Z_b^0(10610)$	10607.2±2.0	18.4±2.4	1^{+-}	$\Upsilon(5S) \to \pi^0 + (\Upsilon(nS)\,\pi^0)$ $(n = 2, 3)$	Belle (6.5)	Belle 2013

Theoretical phenomenological models



D^0-$\bar{D}^{*0}$ **“molecule”**



diquark - antidiquark

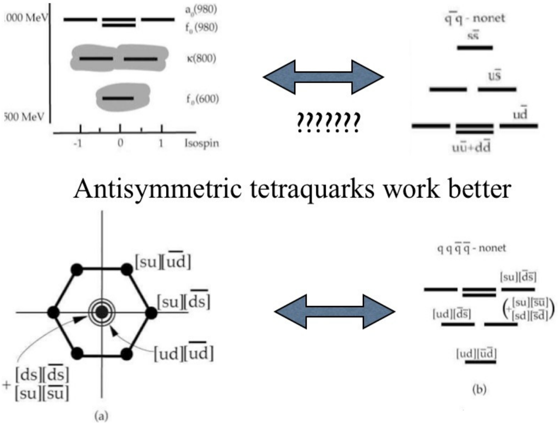
but also other models such as e.g.

- hadrocharmonium
- hybrids
- models including rescattering effects, like cusps, or $c\bar{c}$ dynamically coupled to open charm channels

E. Santopinto and collaborators; F. de Fazio

overall picture is still confused

diquarks from the light scalar meson sector



from L. Maiani lectures in Erice 2014

- a diquark based model for light scalar mesons developed in

L. Maiani, F.P., A.D. Polosa, V. Riquer, PRL93 (2004) 212002
G. 't Hooft, G. Isidori, L. Maiani, A.D. Polosa, V. Riquer, PLB662 (2008) 424

diquarks

From “colorspin” interaction

$$\mathcal{H}_{\text{eff}} \propto -\sum_{i\neq j} \tilde{\lambda}_i \cdot \tilde{\lambda}_j \vec{\sigma}_i \cdot \vec{\sigma}_j = 4P_{12}^F + \frac{4}{3}P_{12}^S + 2P_{12}^C - \frac{2}{3}$$

P_{12}^X are C, F, S exchange operator with eigenvalue $(-)+1$ for states (anti)symmetric under exchange

Flavor	Spin	Color	ΔE
$\bar{3}(A)$	$1(A)$	$\bar{3}(A)$	-8
$\bar{3}(A)$	$3(S)$	$6(S)$	$-4/3$
$6(S)$	$3(S)$	$\bar{3}(A)$	$8/3$
$6(S)$	$1(A)$	$6(S)$	4

R.L. Jaffe, hep-ph/0001123

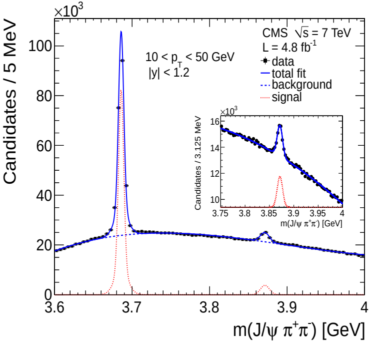
$X(3872)$, the oldest and still debated one

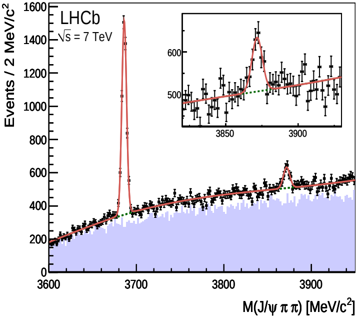
- $M(X3872) = 3871.68 \pm 0.17$ MeV $\Gamma_X \lesssim 1.2$ MeV $J^{PC} = 1^{++}$

  LHCb 2014
- $\Delta M \equiv M(X3872) - (M_{D^0} + M_{D^{*0}}) = -3 \pm 192$ keV

  Tomaradze et al. 2015
- production
  - production through B decays at e^+e^- and $p\bar{p}/pp$ colliders
- decay
  - $J/\psi\rho \to J/\psi\pi^+\pi^-$
  - $J/\psi\omega \to J/\psi\pi^+\pi^-\pi^0$ (large isospin violation)
  - $D^0\bar{D}^{0*} \to D^0\bar{D}^0\pi^0$
  - $D^0\bar{D}^{0*} \to \bar{D}^0\gamma$
  - $J/\psi\gamma$, $\psi'\gamma$ $\frac{\mathcal{BR}(\psi'\gamma)}{\mathcal{BR}(J/\psi\gamma))} = 2.46 \pm 0.64 \pm 0.29$ (LHCb)
- $\Delta M \lesssim 0 \Longrightarrow$ molecular interpretation natural
- isospin violation explained with the distance of D^+D^{*-} and $D^0\bar{D}^{0*}$ thresholds of ~ 8 MeV
- $R = \frac{1}{\sqrt{2\mu(-\Delta M)}} \Longrightarrow R \geq 10$ fm

$X(3872)$ at LHC





- large production cross section
- detected at large p_T
- prompt production dominant over B decay ($\sim 84\%$ @Tevatron)
- features at odds with a loosely bound molecule

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

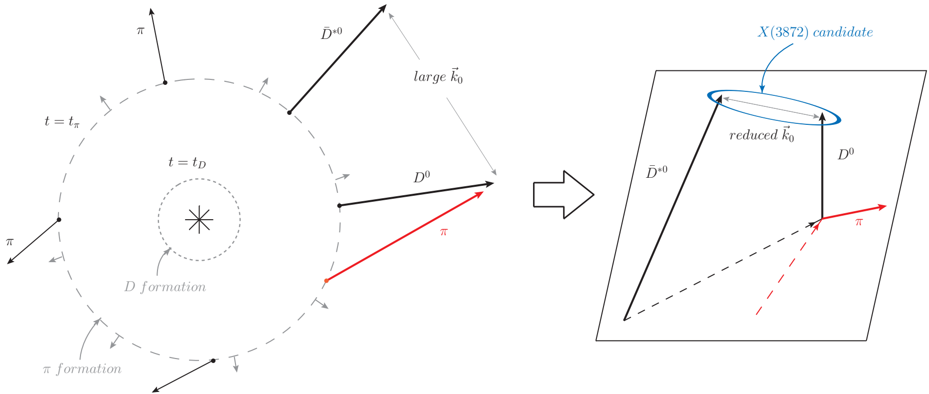
$$\begin{aligned} \sigma(p\bar{p} \to X(3872)) &\sim \left| \int d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2 \\ &\leq \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2 \sim \sigma(p\bar{p} \to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

- $\mathbf{k}$ 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
- 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]



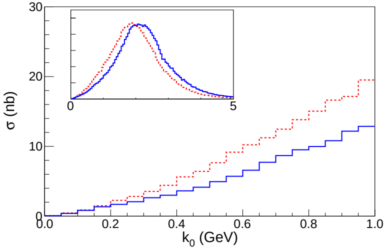
Expanding hadronization sphere

(a)

Plane $\pi - D$ rescattering

(b)

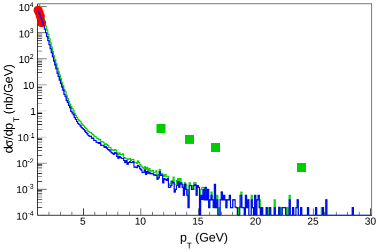
- additional pions close to $D^{0(*)}$ in momentum space can interact elastically and change the rel. momentum between D^0 and D^{0*}
- given the initial asymmetric distribution in $k_{\rm rel}$ there could be a feed-down process from larger relative momenta to lower ones and bring D pairs from positive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

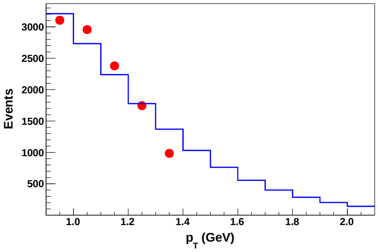


- there is a contribution but not enough
- additional ways to check the molecular hypothesis?

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 $p_\perp$ regimes. We can only have a qualitative idea through MC, referring to the coalescence model





A check with future precision measurements

A. Esposito, A. Guerrieri, F.P., A. Pilloni, A. Polosa, arXiv:1411.5997[hep-ph]

- by considering the scattering amplitude $f(DD^* \to DD^*)$ in the soft limit

$$\frac{1}{(p_D + p_{D^*})^2 - M_X^2} \to \frac{1}{(M_D + M_{D^*} + \mathcal{E})^2 - M_X^2}$$

the following relation holds

$$\epsilon = \frac{g^4}{512\pi^2} \frac{\mu^5}{M_D^4 M_{D^*}^4}$$

with $-\epsilon$ the discrete energy level and g the coupling XDD^*

- future measurements of ΔM, $\mathcal{BR}(X \to DD^*)$ crucial to test the molecular hypothesis

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

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

From conventional S-wave mesons and baryons

$$H \approx 2\kappa_{q\bar{q}}\ \boldsymbol{S}_q \cdot \boldsymbol{S}_{\bar{q}}$$

- 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, $Z^{\pm} \to J/\psi\pi^{\pm}$ or $\to \eta_c\rho^{\pm}$, 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, 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

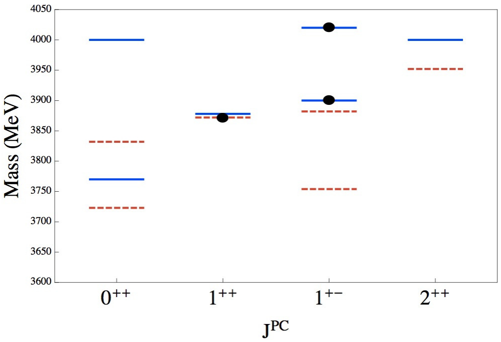
$$H \approx 2\kappa_{qc} \ (\boldsymbol{S}_q \cdot \boldsymbol{S}_c + \boldsymbol{S}_{\bar{q}} \cdot \boldsymbol{S}_{\bar{c}})$$

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

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

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

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



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

Y states: tetraquarks with $L = 1$

- $$H \approx 2\kappa'(\boldsymbol{S}_q \cdot \boldsymbol{S}_c + \boldsymbol{S}_{\bar{q}} \cdot \boldsymbol{S}_{\bar{c}}) - 2A\, \boldsymbol{S} \cdot \boldsymbol{L} + \frac{1}{2} B\, \boldsymbol{L}^2$$

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	$Y(4630)$	$\gamma + X_2$

- $Y(4360)$: 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 $\Longrightarrow$ the observed radiative decay $Y(4260) \to \gamma X(3872)$ 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

$$
\begin{aligned}
Y_4 &= Y(4630) \to \gamma + X_2 \ \ (J^{PC} = 2^{++}) = \gamma + X(3940), \ ?? \\
Y_3 &= Y(4290/4220) \to \gamma + X_0' \ \ (J^{PC} = 0^{++}) = \gamma + X(3916), \ ?? \\
Y_2 &= Y(4260) \to \gamma + X_1 \ \ (J^{PC} = 1^{++}) = \gamma + X(3872), \ \text{seen} \\
Y_1 &= Y(4008) \to \gamma + X_0 \ \ (J^{PC} = 0^{++}) = \gamma + X(3770\, ??), \ ??
\end{aligned}
$$

- 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)
- 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

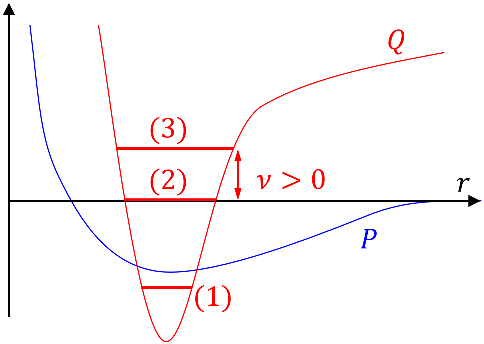
$$|Q\bar{Q}q\bar{q}\rangle = \alpha|[Qq]_{\bar{\mathbf{3}}_c}[\bar{Q}\bar{q}]_{\mathbf{3}_c}\rangle_{\mathcal{C}} + \beta|(Q\bar{Q})_{\mathbf{1}_c}(q\bar{q})_{\mathbf{1}_c}\rangle_{\mathcal{O}} + \gamma|(Q\bar{q})_{\mathbf{1}_c}(\bar{Q}q)_{\mathbf{1}_c}\rangle_{\mathcal{O}}$$

- 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 pysics) decaying into two particles in one of the open channels
- contribution to the scattering length

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

- 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 tetraquarks would be very helpful

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

Last sentence to LQCD

- recently first attempts to investigate tetraquarks with heavy quarks on the lattice
- not yet firm conclusions because of several difficulties, e.g.
  - very difficult the separation of the diquark-antidiquark contribution from the meson-meson one
  - lattices with dimensions of few fm's not suited for the simulation of extended objects such as the $X(3872)$
  - extrapolation from few hundreds MeV to the physical point can be critical

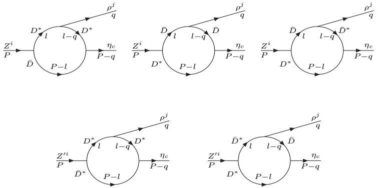
$Z_c^{(\prime)} \to \eta_c \rho$: a channel able to discriminate between molecule and tetraquark

A. Esposito, A. Guerrieri and A. Pilloni, arXiv:1409.3551[hep-ph]

- according to tetraquark models

	Kinematics only		Dynamics included	
	type I	type II	type I	type II
$\frac{\mathcal{BR}(Z_c \to \eta_c \rho)}{\mathcal{BR}(Z_c \to J/\psi \pi)}$	554	1/1.48	387	1/2.12
$\frac{\mathcal{BR}\left(Z_c' \to \eta_c \rho\right)}{\mathcal{BR}(Z_c' \to h_c \pi)}$	199	199	4.05	4.05

- according to molecular model



$$\frac{\mathcal{BR}(Z_c \to \eta_c \rho)}{\mathcal{BR}(Z_c \to J/\psi \pi)} \simeq 0.053$$

$$\frac{\mathcal{BR}(Z_c' \to \eta_c \rho)}{\mathcal{BR}(Z_c' \to h_c \pi)} \simeq 0.012.$$

To be improved: threshold distances for charged Z

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

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