Exotic spectroscopy in a diquark model with a little help from AdS/QCD

Floriana Giannuzzi
INFN Bari, Italy

HADRON2023
Genova, 8 June 2023

Outline

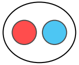
- Tetraquark and pentaquark masses in a potential model updated to recent observations
  - relativistic kinematics
  - $Q\bar{Q}$ potential from AdS/QCD
- Use Salpeter equation for tetraquarks and pentaquarks: reduce the problem of studying interactions among more quarks by considering a series of two-body interactions

Potential model

Masses of mesons containing at least one heavy quark, with $\ell = 0$

$$\left(\sqrt{m_1^2 - \nabla^2} + \sqrt{m_2^2 - \nabla^2} + V(r)\right)\psi(\mathbf{r}) \;=\; M\,\psi(\mathbf{r})$$

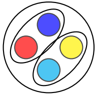
- relativistic dynamics
- two-body interaction



$\Rightarrow$ tetraquark and pentaquark as a result of a series of two-body interactions:

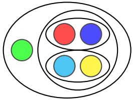
Tetraquark

bound state of diquark and antidiquark



Pentaquark

bound state of antiquark and 2-diquark state



Two-body interaction in mesons:

$$V(r) = V_{QCD}(r) + V_{spin}(r) + V_0$$

- $V_{QCD}(r)$ from AdS/QCD

- $V_{spin}(r)$ for spin-spin interaction [PRD 72, 054026 (2005)], in one-gluon exchange approximation:

  $$V_{spin}(r) = A\frac{\tilde{\delta}(r)}{m_1 m_2}\mathbf{S_1}\cdot\mathbf{S_2} \qquad \text{with} \qquad \tilde{\delta}(r) = \left(\frac{\sigma}{\sqrt{\pi}}\right)^3 e^{-\sigma^2 r^2}$$

  Different values of A for mesons containing a charm or a bottom quark $(A_c\ ,\ A_b)$ to account for the different values of α_s at the two scales

- V_0 a constant (parameter)

- cutoff at short distance to cure the singularity of the wavefunction. Such a divergence is an artifact of the approximations involved to get the Salpeter equation

  $V(r) = V(r_M)$ for $r \leqslant r_M$, with $r_M = \dfrac{k}{M}$

AdS/CFT correspondence [Maldacena, '97]

Equivalence between certain bulk string theories and boundary field theories

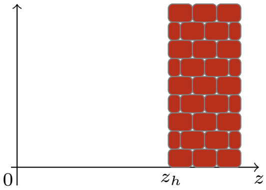
Type IIB string theory on $AdS_5 \times S^5$	$\Longleftrightarrow$ $g_s = g^2_{\mathsf{YM}}$ $R^4 = 4\pi g_s N \alpha'$	$\mathcal{N}$=4 SYM theory on 4d Minkowski
SUGRA limit $g_s \to 0$ $R \to \infty$	$\Longleftrightarrow$	large N + NP limit $N \to \infty$ $\lambda = g^2_{\mathsf{YM}} N \to \infty$

Holographic correspondence: the boundary of AdS space is a Minkowski space, so the gauge theory can be obtained from a projection of the gravity theory on the boundary

Application to QCD: make the gauge theory of the duality similar to QCD

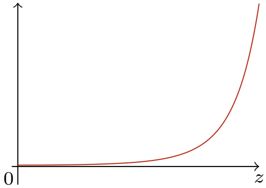
- Bottom-up approach: build a $5d$ effective field theory in AdS space and fit it to QCD
- Metric of $5d$ AdS space: $ds^2 = \frac{R^2}{z^2}(dt^2 - d\bar{x}^2 - dz^2)$
  Boundary $=$ $4d$ Minkowski space at $z = 0$
- Confining background: introduce a "wall" in the radial direction

Hard wall



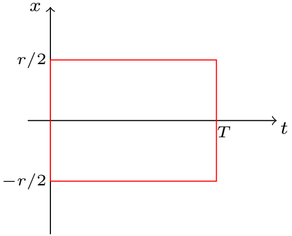
$$ds^2 = \frac{R^2}{z^2}(dt^2 - d\bar{x}^2 - dz^2) \quad z \leqslant z_h$$

Soft wall



$$ds^2 = \frac{R^2\, e^{\varphi}}{z^2}(dt^2 - d\bar{x}^2 - dz^2)$$

$Q\bar{Q}$ potential in soft-wall model



Compute the expectation value of the Wilson loop for $T \to \infty$ in static approximation:

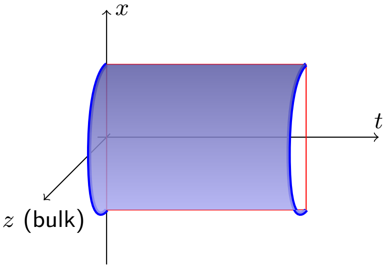
$$\langle W_{\mathcal{C}} \rangle = \mathrm{e}^{-T\,V(r)}$$

AdS/CFT correspondence: $\langle W_{\mathcal{C}} \rangle = e^{-\mathcal{S}_{NG}}$ [Maldacena, PRL 80, 4859 (1998)]

$\mathcal{S}_{NG}$ = Nambu Goto action = area of ws spanned by the string attached to $\mathcal{C}$ on the boundary

$$V(r) = \lim_{T\to\infty} \frac{1}{T} S_{NG}$$

$Q\bar{Q}$ potential in soft-wall model



Compute the expectation value of the Wilson loop for $T \to \infty$ in static approximation:

$$\langle W_{\mathcal{C}} \rangle = \mathrm{e}^{-T\,V(r)}$$

AdS/CFT correspondence: $\langle W_{\mathcal{C}} \rangle = e^{-\mathcal{S}_{NG}}$ [Maldacena, PRL 80, 4859 (1998)]

$\mathcal{S}_{NG}$ = Nambu Goto action = area of ws spanned by the string attached to $\mathcal{C}$ on the boundary

$$V(r) = \lim_{T\to\infty} \frac{1}{T} S_{NG}$$

[Andreev *et al.*, PRD 74, 025023 (2006)]

$$\mathcal{S}_{NG} = \frac{g}{2\pi} \int d^2\xi \, \sqrt{\text{det}\,[g_{MN}\,\partial_\alpha x^M\,\partial_\beta x^N]}$$

$$ds^2 = \frac{e^{cz^2/2}}{z^2}\left(dx^i dx^i + dz^2\right)$$

Choosing $\xi^1 = t$ and $\xi^2 = x$

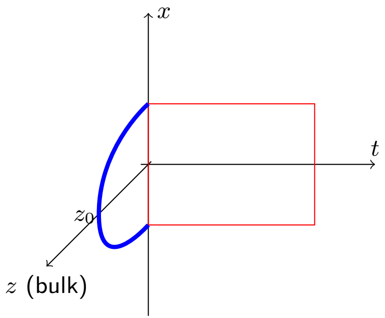
$$\mathcal{S}_{NG} = \frac{g}{2\pi} T \int_{-\frac{r}{2}}^{+\frac{r}{2}} dx \, \frac{e^{cz^2/2}}{z^2} \sqrt{1 + \left(\frac{dz}{dx}\right)^2}$$

Eom for string $z(x)$:

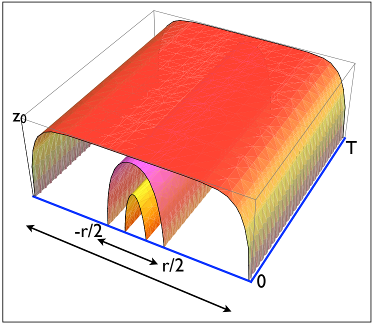
$$z\,z'' + (2 - c\,z^2)(1 + (z')^2) = 0$$

with boundary conditions:

$$z(r/2) = z(-r/2) = 0 \qquad z'(0) = 0$$



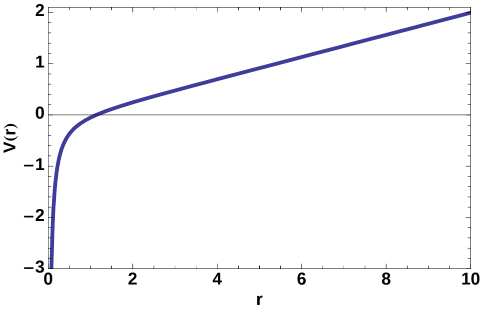
- In conformal background no limits for z_0, sting goes deeper into the bulk as distance between quarks increases
- In confined background $z_0 < \sqrt{2/c}$: when z_0 approaches the maximum value, the string becomes flat



Potential in parametric form:

$$r(z_0) \;=\; 2\,z_0 \int_0^1 dv\, v^2 e^{c z_0^2 (1-v^2)/2} \left(1 - v^4 e^{c z_0^2 (1-v^2)}\right)^{-1/2}$$

$$V_{QCD}(z_0) \;=\; \frac{g}{\pi}\frac{1}{z_0}\left(-1 + \int_0^1 dv\, v^{-2}\left[e^{c z_0^2 v^2/2}\left(1 - v^4 e^{c z_0^2 (1-v^2)}\right)^{-1/2} - 1\right]\right)$$



$$V(r) \xrightarrow[r\to 0]{} -\frac{g(2\pi)^2}{\Gamma(1/4)^2 r}$$

$$V(r) \xrightarrow[r\to\infty]{} \frac{g\,e\,c}{4\pi} r$$

Fit parameters from meson spectra, at least one heavy quark

Mean error $\sim 0.63\%$

Parameters:

$$c = 0.300 \text{ GeV}^2 \qquad g = 2.750 \qquad V_0 = -0.488 \text{ GeV} \qquad k = 1.48$$

$$A_c = 7.920 \qquad A_b = 3.087 \qquad \sigma = 1.209 \text{ GeV}$$

$$m_q = 0.302 \text{ GeV} \qquad m_s = 0.454 \text{ GeV} \qquad m_c = 1.733 \text{ GeV} \qquad m_b = 5.139 \text{ GeV}$$

Charm sector:

		$J=0$		$J=1$	
Flavor	Level	Th. mass	Exp. mass	Th. mass	Exp. mass
$c\bar{q}$	$1S$	1.862	1.867*	2.027	2.009*
	$2S$	2.486	2.549	2.597	2.627
	$3S$	2.923		2.987	
$c\bar{s}$	$1S$	1.973	1.968*	2.111	2.112*
	$2S$	2.585	2.591	2.675	2.714
	$3S$	3.018		3.069	
$c\bar{c}$	$1S$	2.990	2.984*	3.125	3.097*
	$2S$	3.600	3.637*	3.659	3.686*
	$3S$	4.006		4.054	
	$4S$	4.291		4.308	
	$5S$	4.659		4.735	

$\leftarrow$ $D_0(2550)$ and $D_1^*(2600)$ ok

$\leftarrow$ $D_1^*(2760)$ lighter

$\leftarrow$ $D_{s0}(2590)$ and $D_{s1}^*(2700)$ ok

$\leftarrow$ $D_{s1}^*(2860)$ lighter

$\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4230)$, $\psi(4360)$, $\psi(4415)$, $\psi(4660)$

Bottom sector:

		$J=0$		$J=1$	
Flavor	Level	Th. mass	Exp. mass	Th. mass	Exp. mass
$b\bar{q}$	$1S$	5.198	5.279*	5.288	5.325*
	$2S$	5.762		5.822	
	$3S$	6.183		6.224	
$s\bar{b}$	$1S$	5.301	5.367*	5.364	5.415*
	$2S$	5.860		5.899	
	$3S$	6.272		6.301	
$b\bar{c}$	$1S$	6.310	6.274*	6.338	
	$2S$	6.872	6.871	6.882	
	$3S$	7.225		7.232	
$b\bar{b}$	$1S$	9.387	9.399	9.405	9.460*
	$2S$	10.037	9.999	10.041	10.023*
	$3S$	10.370		10.373	10.355*
	$4S$	10.620		10.621	10.579*
	$5S$	10.898		10.901	
	$6S$	11.029		11.029	

$\Upsilon(10753)\,?^?(1^{--})$
$\Upsilon(10860)$, $\Upsilon(11020)$

$b\bar{q}/\bar{s}$ states with unknown SP: $B_J(5840)\,1/2(?^?)$, $B_J(5970)\,1/2(?^?)$, $B^*_{sJ}(5850)\,?(?^?)$, $B_{sJ}(6063)\,0(?^?)$, $B_{sJ}(6114)\,0(?^?)$

Diquarks in $\bar{3}_c$

$$\left(\sqrt{m_1^2 - \nabla^2} + \sqrt{m_2^2 - \nabla^2} + V(r)\right)\psi(\mathbf{r}) \;=\; M\,\psi(\mathbf{r})$$

- factor $1/2$ in the potential (one-gluon exchange approximation)

Diquark masses (GeV):

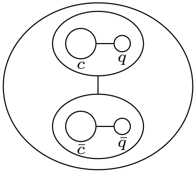
$[cq]$	$\{cq\}$	$[bq]$	$\{bq\}$	$[cs]$	$\{cs\}$	$[bs]$	$\{bs\}$	$\{cc\}$	$[cb]$	$\{cb\}$	$\{bb\}$
2.118	2.168	5.513	5.526	2.237	2.276	5.619	5.630	3.414	6.735	6.741	10.018

$[qq']$ = diquark with $S = 0$

$\{qq'\}$ = diquark with $S = 1$

Tetraquarks: diquark + antidiquark

$$\left(\sqrt{m_1^2 - \nabla^2} + \sqrt{m_2^2 - \nabla^2} + V(r)\right)\psi(\mathbf{r}) \;=\; M\,\psi(\mathbf{r})$$



- smeared potential (interaction between extended objects)

$$\tilde{V}(R) = \frac{1}{N}\int d\mathbf{r_1}\int d\mathbf{r_2}|\psi_d(\mathbf{r_1})|^2|\psi_d(\mathbf{r_2})|^2 V\left(\left|\mathbf{R} + \mathbf{r_1} - \mathbf{r_2}\right|\right)$$

$Qq\bar{Q}\bar{q}$ tetraquarks

		$Q=c$			$Q=b$	
J^{PC}	Flavor content	$1S$	$2S$	$3S$	$1S$	$2S$
0^{++}	$[Qq][\bar{Q}\bar{q}]$	3.857	4.377	4.745	10.260	10.807
1^{++}	$([Qq]\{\bar{Q}\bar{q}\}+[\bar{Q}\bar{q}]\{Qq\})/\sqrt{2}$	3.899	4.421	4.788	10.284	10.821
1^{+-}	$([Qq]\{\bar{Q}\bar{q}\}-[\bar{Q}\bar{q}]\{Qq\})/\sqrt{2}$	3.899	4.421	4.788	10.284	10.821
0^{++}	$\{Qq\}\{\bar{Q}\bar{q}\}$	3.729	4.389	4.773	10.264	10.828
1^{+-}	$\{Qq\}\{\bar{Q}\bar{q}\}$	3.833	4.418	4.796	10.275	10.831
2^{++}	$\{Qq\}\{\bar{Q}\bar{q}\}$	3.988	4.485	4.846	10.296	10.837

Experimental candidates:

- $\chi_{c1}(3872)$ (1^{++}): masses and decay properties challenge quark models for mesons
- $Z_c(3900)^{\pm}$ (1^{+-}), $X(4020)^{\pm}$ $(?^{?-})$, $X(4055)\,1^{+}(?^{?-})$, $Z_c(4200)^{\pm}$ (1^{+-}), $Z_c(4433)^{\pm}$ (1^{+-}): incompatible with a $Q\bar{Q}$ structure
- $Z_b(10610)^{\pm}$ (1^{+-}), $Z_b(10650)^{\pm}$ (1^{+-}): incompatible with a $Q\bar{Q}$ structure

Masses of $Z_c(4200)^{\pm}$, $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$ not found in table.

Try comparison with states in which one diquark is excited

J^{PC}	Mass ($Q = c$)	Mass ($Q = b$)
1^{+-}	4.19-4.23	10.57

The two 1^{+-} states in bottom sector almost degenerate.

$Qs\bar{Q}\bar{q}$ tetraquarks

		$Q = c$		$Q = b$	
J^P	Flavor content	$1S$	$2S$	$1S$	$2S$
0^+	$[Qs][\bar{Q}\bar{q}]$	3.961	4.483	10.283	10.868
1^+	$[Qs]\{\bar{Q}\bar{q}\}$	4.008	4.528	10.321	10.906
1^+	$\{Qs\}[\bar{Q}\bar{q}]$	3.999	4.519	10.311	10.896
0^+	$\{Qs\}\{\bar{Q}\bar{q}\}$	3.840	4.491	10.280	10.918
1^+	$\{Qs\}\{\bar{Q}\bar{q}\}$	3.952	4.527	10.312	10.925
2^+	$\{Qs\}\{\bar{Q}\bar{q}\}$	4.113	4.599	10.384	10.944

Experimental observations:

- $Z_{cs}(4000)\,(1^+)$, with mass $3980 - 4010$ MeV
- $Z_{cs}(4220)^+\,(1^+)$ with mass 4216^{+50}_{-40} MeV

Tetraquarks with open charm and strangeness ($c\bar{s}$)

J^P	Flavor content	Mass (GeV)
0^+	$[cq][\bar{q}\bar{s}]$	2.840
0^+	$\{cq\}\{\bar{q}\bar{s}\}$	2.503
1^+	$\{cq\}[\bar{q}\bar{s}]$	2.880
1^+	$\{cq\}\{\bar{q}\bar{s}\}$	2.748
1^+	$[cq]\{\bar{q}\bar{s}\}$	2.841
2^+	$\{cq\}\{\bar{q}\bar{s}\}$	2.983

- $D^*_{s0}(2317)$ (0^+), $D_{s1}(2460)$ (1^+) lighter
- $X_0(2900)$ different quark content (cs), not in this model

$QQ\bar{Q}\bar{Q}$ tetraquarks $= \{QQ\} + \{\bar{Q}\bar{Q}\}$

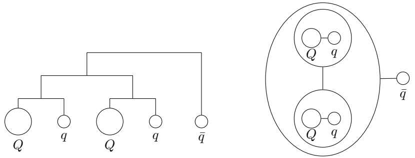
	$Q = c$			$Q = b$		
J^{PC}	$1S$	$2S$	$3S$	$1S$	$2S$	$3S$
0^{++}	6.158	6.761	7.105	18.798	19.573	19.893
1^{+-}	6.189	6.766	7.108	18.804	19.574	19.894
2^{++}	6.314	6.811	7.138	18.817	19.577	19.895

Experimental candidates in charm sector:

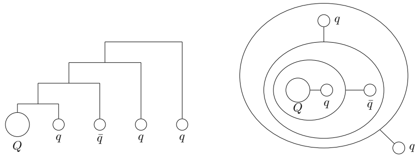
- observed narrow structure $X(6900)$ could be a $2S$ state, even though masses in table are lower

Pentaquark configurations: three ways of combining five objects two by two, each is a 3_c or $\bar{3}_c$

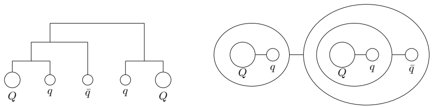
- Model $\mathcal{A}$ for $QQ'qq\bar{q}$



- Model $\mathcal{B}$ for $Qqqq\bar{q}$



- Model $\mathcal{C}$ for $QQqq\bar{q}$



Masses (GeV) in model $\mathcal{A}$ for $QQ'qq\bar{q}$

Content	J^P	$Q, Q' = c$		$Q, Q' = b$		$Q = b, Q' = c$	
		$q' = u, d$	$q' = s$	$q' = u, d$	$q' = s$	$q' = u, d$	$q' = s$
$\bar{q}[Qq][Q'q']$	$1/2^-$	4.54	4.66	11.15	11.25	7.85	7.96
$\bar{q}\{Qq\}[Q'q']$	$1/2^-$	4.57	4.68	11.16	11.26	7.86	7.97
$\bar{q}[Qq]\{Q'q'\}$	$1/2^-$	4.57	4.66	11.16	11.25	7.92	8.01
$\bar{q}(\{Qq\}\{Q'q'\})_1$	$1/2^-$	4.64	4.73	11.19	11.28	7.94	8.04
$\bar{q}(\{Qq\}\{Q'q'\})_0$	$1/2^-$	4.69	4.78	11.20	11.29	7.96	8.05
$\bar{q}(\{Qq\}\{Q'q'\})_2$	$3/2^-$	4.62	4.72	11.18	11.27	7.94	8.03
$\bar{q}\{Qq\}[Q'q']$	$3/2^-$	4.65	4.77	11.18	11.28	7.89	8.00
$\bar{q}[Qq]\{Q'q'\}$	$3/2^-$	4.65	4.75	11.18	11.28	7.95	8.04
$\bar{q}(\{Qq\}\{Q'q'\})_1$	$3/2^-$	4.72	4.82	11.21	11.30	7.97	8.06
$\bar{q}\{Qq\}\{Q'q'\}$	$5/2^-$	4.75	4.85	11.22	11.31	7.98	8.07

Masses (GeV) in model $\mathcal{B}$ for $QQqq\bar{q}$

Content	J^P	Mass (GeV)	Content	J^P	Mass (GeV)
$[[[[cq]\bar{q}]q]c]$	$1/2^-$	4.57	$[[[[bq]\bar{q}]q]b]$	$1/2^-$	11.18
$[[[\{cq\}\bar{q}]q]c]$	$1/2^-$	4.60	$[[[\{bq\}\bar{q}]q]b]$	$1/2^-$	11.19
$[\{[[cq]\bar{q}]q\}c]$	$1/2^-$	4.61	$[\{[[bq]\bar{q}]q\}b]$	$1/2^-$	11.19
$[[\{\{cq\}\bar{q}\}q]c]$	$1/2^-$	4.63	$[[\{\{bq\}\bar{q}\}q]b]$	$1/2^-$	11.20
$[\{[\{cq\}\bar{q}]q\}c]$	$1/2^-$	4.64	$[\{[\{bq\}\bar{q}]q\}b]$	$1/2^-$	11.20
$\{\{[[cq]\bar{q}]q\}c\}$	$3/2^-$	4.63	$\{\{[[bq]\bar{q}]q\}b\}$	$3/2^-$	11.19
$\{\{[\{cq\}\bar{q}]q\}c\}$	$3/2^-$	4.66	$\{\{[\{bq\}\bar{q}]q\}b\}$	$3/2^-$	11.20
$\{[\{\{cq\}\bar{q}\}q]c\}$	$3/2^-$	4.66	$\{[\{\{bq\}\bar{q}\}q]b\}$	$3/2^-$	11.20
$[\{\{\{cq\}\bar{q}\}q\}c]$	$3/2^-$	4.72	$[\{\{\{bq\}\bar{q}\}q\}b]$	$3/2^-$	11.22
$\{\{\{\{cq\}\bar{q}\}q\}c\}$	$5/2^-$	4.74	$\{\{\{\{bq\}\bar{q}\}q\}b\}$	$5/2^-$	11.23

Results in model $\mathcal{C}$ for $QQqq\bar{q}$

Content	J^P	Mass (GeV)	Content	J^P	Mass (GeV)
$[cq][[cq]\bar{q}]$	$1/2^-$	4.59	$[bq][[bq]\bar{q}]$	$1/2^-$	11.20
$[cq][\{cq\}\bar{q}]$	$1/2^-$	4.62	$[bq][\{bq\}\bar{q}]$	$1/2^-$	11.21
$\{cq\}[[cq]\bar{q}]$	$1/2^-$	4.68	$\{bq\}[[bq]\bar{q}]$	$1/2^-$	11.23
$\{cq\}[\{cq\}\bar{q}]$	$1/2^-$	4.71	$\{bq\}[\{bq\}\bar{q}]$	$1/2^-$	11.25
$\{cq\}\{\{cq\}\bar{q}\}$	$1/2^-$	4.77	$\{bq\}\{\{bq\}\bar{q}\}$	$1/2^-$	11.26
$\{cq\}[[cq]\bar{q}]$	$3/2^-$	4.69	$\{bq\}[[bq]\bar{q}]$	$3/2^-$	11.23
$[cq]\{\{cq\}\bar{q}\}$	$3/2^-$	4.70	$[bq]\{\{bq\}\bar{q}\}$	$3/2^-$	11.23
$\{cq\}[\{cq\}\bar{q}]$	$3/2^-$	4.72	$\{bq\}[\{bq\}\bar{q}]$	$3/2^-$	11.25
$\{cq\}\{\{cq\}\bar{q}\}$	$3/2^-$	4.78	$\{bq\}\{\{bq\}\bar{q}\}$	$3/2^-$	11.26
$\{cq\}\{\{cq\}\bar{q}\}$	$5/2^-$	4.80	$\{bq\}\{\{bq\}\bar{q}\}$	$5/2^-$	11.27

Results in model $\mathcal{B}$ for $Qqqq\bar{Q}$

Content	J^P	Mass (GeV)	Content	J^P	Mass (GeV)
$[[[[cq]\bar{c}]q]q]$	$1/2^-$	4.57	$[[[[bq]\bar{b}]q]q]$	$1/2^-$	11.19
$[\{[[cq]\bar{c}]q\}q]$	$1/2^-$	4.57	$[\{[[bq]\bar{b}]q\}q]$	$1/2^-$	11.19
$[[\{\{cq\}\bar{c}\}q]q]$	$1/2^-$	4.58	$[[\{\{bq\}\bar{b}\}q]q]$	$1/2^-$	11.21
$[\{[\{cq\}\bar{c}]q\}q]$	$1/2^-$	4.64	$[\{[\{bq\}\bar{b}]q\}q]$	$1/2^-$	11.22
$[[[\{cq\}\bar{c}]q]q]$	$1/2^-$	4.65	$[[[\{bq\}\bar{b}]q]q]$	$1/2^-$	11.22
$\{\{[[cq]\bar{c}]q\}q\}$	$3/2^-$	4.64	$\{\{[[bq]\bar{b}]q\}q\}$	$3/2^-$	11.20
$[\{\{\{cq\}\bar{c}\}q\}q]$	$3/2^-$	4.66	$[\{\{\{bq\}\bar{b}\}q\}q]$	$3/2^-$	11.22
$\{[\{\{cq\}\bar{c}\}q]q\}$	$3/2^-$	4.67	$\{[\{\{bq\}\bar{b}\}q]q\}$	$3/2^-$	11.22
$\{\{[\{cq\}\bar{c}]q\}q\}$	$3/2^-$	4.71	$\{\{[\{bq\}\bar{b}]q\}q\}$	$3/2^-$	11.23
$\{\{\{\{cq\}\bar{c}\}q\}q\}$	$5/2^-$	4.76	$\{\{\{\{bq\}\bar{b}\}q\}q\}$	$5/2^-$	11.24

Comparison among models for pentaquarks with $QQq q\bar{q}$

- overall agreement, small differences
- the masses in model $\mathcal{B}$ are slightly higher than in model $\mathcal{A}$ (mean difference $\sim 0.08\%$ for $Q = c$), and those in model $\mathcal{C}$ are slightly higher than in model $\mathcal{B}$ (mean difference $\sim 1.4\%$ for $Q = c$)

Comparison with the resonances observed by LHCb

State	Mass [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$

In this model:

- states with spin 1/2 have masses in the range 4.57-4.65 GeV
- states with spin 3/2 have masses in the range 4.64-4.71 GeV
- state with spin 5/2 has mass 4.76 GeV

Hypothesis: constituent quark masses in potential models can get different values in baryon and meson spectroscopy [Maiani *et al.*, PRD 71, 014028 (2005)]

A possible implementation: different V_0 for baryons and pentaquarks.

Assuming the mass of the lightest spin-$1/2$ pentaquark with hidden charm is 4312 MeV, we find

- $V_0 = -0.594$ GeV (value from meson spectra was $V_0 = -0.488$ GeV)
- mass of the heaviest spin-$1/2$ pentaquark is 4.39 GeV
- mass of the heaviest spin-$3/2$ pentaquark is 4.45 GeV

getting a better agreement with experimental observations.

Spin splittings are not modified by a change in V_0, while a different value of quark masses could, in principle, also affect the spin-spin interaction, so a proper investigation of this aspect would deserve a dedicated study based on baryon spectroscopy.

Conclusions

- AdS/QCD for $Q\bar{Q}$ potential in a potential model
- Adapt the two-body problem to states different from a meson, considering tetraquarks and pentaquarks as emerging from two and three subsequent interactions
  - Comparison of tetraquark spectra with some experimental data
  - Pentaquark masses are higher than those measured by LHCb, with a better agreement for $P_c(4440)^+$ and $P_c(4457)^+$
- Ongoing and future analyses:
  - study of baryon and pentaquark spectroscopy to establish if different parameters (V_0 or constituent quark masses) are needed
  - add $\ell \neq 0$
  - try multi-quark potential describing baryons, tetraquarks, pentaquarks with two heavy quarks in BO approximation recently developed in AdS/QCD