$QQ\bar{Q}\bar{Q}$ tetraquark states

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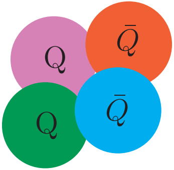
Based on: Wei Chen, Hua-Xing Chen, Xiang Liu, T. G. Steele, and Shi-Lin Zhu, Phys.Lett. B773, 247-251 (2017)

低质量多轻子末态研讨会 **2020/06/20**

Doubly hidden-flavor tetraquarks: $QQ\bar{Q}\bar{Q}$

$QQ\bar{Q}\bar{Q}$ Tetraquarks:

- They are far away from the mass range of the observed conventional $q\bar{q}$ hadrons.
- Can be clearly distinguished experimentally from the normal states.
- The light mesons $(\pi, \rho, \omega, \sigma ...)$ can not be exchanged between two charmonia/bottomonia.
- The binding force comes from the short-range gluon exchange.
- A molecule configuration is not favored and thus the $QQ\bar{Q}\bar{Q}$ is a good candidate for compact tetraquark.



Theoretical works:

- Quark-Gluon models: Prog. Theor. Phys. 54, 492 (1975); Zeit. Phys. C7, 317 (1981).
- Potential model: Phys.Rev. D25, 2370 (1982); Phys. Lett. B123, 449 (1983).
- MIT bag model: Phys. Rev. D32, 755 (1985).
- Hyperspherical harmonic formalism: Phys. Rev. D73, 054004 (2006).
- BS or Schroedinger Eqs: Phys.Rev.D86, 034004 (2012); Phys.Lett.B718, 545 (2012).
- Recent studies: arXiv:1605.01134; 1605.01647; 1612.00012; PRD95, 034011 (2017); EPJC77, 432 (2017); arXiv:1706.07553.

Experiments:

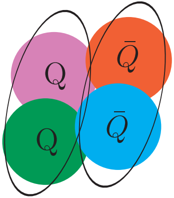
- $J/\psi J/\psi$ pairs: Phys. Lett. B707, 52 (2012) (LHCb); JHEP 1409, 094(2014) (CMS); Phys. Rev. D90, 111101 (2014) (D0).
- $J/\psi \Upsilon(1S)$ events: Phys. Rev. Lett. 116, 082002 (2016) (D0); K. Dilsiz's talk at APS April Meeting 2016 on behalf of CMS, see https://absuploads.aps.org/presentation.cfm?pid=11931.
- $\Upsilon(1S)\Upsilon(1S)$ pairs: JHEP 05, 013 (2017) (CMS).

Tetraquark Sum Rules

- Study two-point correlation function of current $J(x)$ with the same quantum numbers with hadron state:

$$\Pi(q^2) = i\int d^4x e^{iq\cdot x}\langle\Omega|T[J(x)J^\dagger(0)]|\Omega\rangle$$

- Classify states $|X\rangle$ by coupling to current $\langle\Omega|J(x)|X\rangle \neq 0$
- Currents are probes of spectrum and might not overlap with state



Interpolating currents with $J^{PC}=0^{++}$:

$$J_1 = Q_a^T C\gamma_5 Q_b \bar{Q}_a \gamma_5 C \bar{Q}_b^T ,$$
$$J_2 = Q_a^T C\gamma_\mu\gamma_5 Q_b \bar{Q}_a \gamma^\mu\gamma_5 C \bar{Q}_b^T ,$$
$$J_3 = Q_a^T C\sigma_{\mu\nu} Q_b \bar{Q}_a \sigma^{\mu\nu} C \bar{Q}_b^T ,$$
$$J_4 = Q_a^T C\gamma_\mu Q_b \bar{Q}_a \gamma^\mu C \bar{Q}_b^T ,$$
$$J_5 = Q_a^T C Q_b \bar{Q}_a C \bar{Q}_b^T ,$$

- Hadron level: described by the dispersion relation

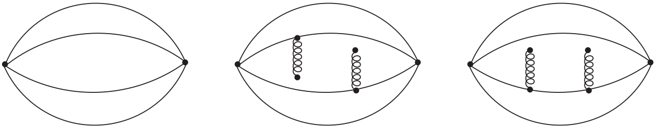
$$\Pi(q^2) = \frac{(q^2)^N}{\pi}\int \frac{\mathrm{Im}\Pi(s)}{s^N(s-q^2-i\epsilon)}ds + \sum_{n=0}^{N-1} b_n(q^2)^n,$$

$$\rho(s) = \frac{1}{\pi}\mathrm{Im}\Pi(s) = \sum_n \delta(s-m_n^2)\langle 0|J|n\rangle\langle n|J^\dagger|0\rangle$$

$$= f_X^2\delta(s-m_X^2) + \mathrm{continuum},$$

- Quark-gluon level: evaluated via operator product expansion(OPE)

$$\Pi(s) = \Pi^{pert}(s) + \Pi^{\langle GG\rangle}(s) + \ldots,$$



- Define moments in Euclidean region $Q^2 = -q^2 > 0$:

$$M_n(Q_0^2) = \frac{1}{n!}\left(-\frac{d}{dQ^2}\right)^n \Pi(Q^2)|_{Q^2=Q_0^2}$$
$$= \int_{m_H^2}^{\infty} \frac{\rho(s)}{(s+Q_0^2)^{n+1}} ds = \frac{f_X^2}{(m_X^2+Q_0^2)^{n+1}}\left[1+\delta_n(Q_0^2)\right],$$

where $\delta_n(Q_0^2)$ contains the higher states and continuum.

- Ratio of the moments

$$r(n, Q_0^2) \equiv \frac{M_n(Q_0^2)}{M_{n+1}(Q_0^2)} = \left(m_X^2 + Q_0^2\right)\frac{1+\delta_n(Q_0^2)}{1+\delta_{n+1}(Q_0^2)}.$$

- Predict hadron mass

$$m_X = \sqrt{r(n, Q_0^2) - Q_0^2}$$

for sufficiently large n when $\delta_n(Q_0^2) \cong \delta_{n+1}(Q_0^2)$ for convergence.

Limitations for (n, ξ) parameter space:

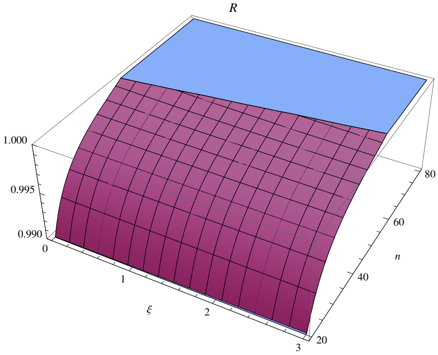
$$\xi = Q_0^2/16m_c^2, \text{ for } cc\bar{c}\bar{c} \text{ system;}$$
$$\xi = Q_0^2/m_b^2, \text{ for } bb\bar{b}\bar{b} \text{ system.}$$

- Small ξ: higher dimensional condensates give large contributions to $M_n(Q_0^2)$, leading to bad OPE convergence.
- Large ξ: slower convergence of $\delta_n(Q_0^2)$. This can be compensated by taking higher derivative n for the lowest lying resonance to dominate.
- Large n: moving further away from the asymptotically free region. The OPE convergence would also become bad.
- Requiring $\Pi^{\langle GG\rangle}(s) \leq \Pi^{pert}(s)$ to obtain an upper limit n_{max}, which will increase with respect to ξ.
- Good (n, ξ) region: the lowest lying resonance dominates the moments while the OPE series has good convergence.

$$n_{max} = 75, 76, 77, 78 \text{ for } \xi = 0.2, 0.4, 0.6, 0.8$$

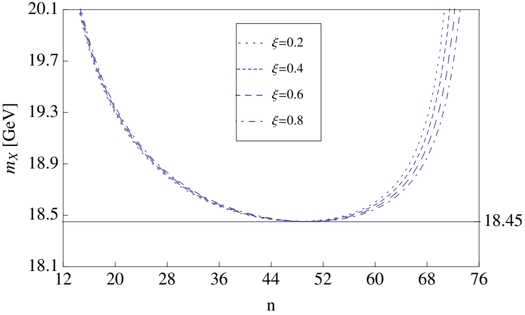
Hölder's inequality:

$$R = \frac{M_n(Q_0^2)^2}{M_r(Q_0^2)M_{2n-r}(Q_0^2)} \leq 1\,,$$



The boundary gives $(n, \xi) = (48, 0.2), (49, 0.4), (49, 0.6), (50, 0.8)$.

Mass for scalar $bb\bar{b}\bar{b}$ tetraquark: mass curves have plateaus at $(n, \xi) = (48, 0.2), (49, 0.4), (49, 0.6), (50, 0.8)$



$$m_{X_b} = (18.45 \pm 0.15)\,\text{GeV}.$$

Mass spectra for the $cc\bar{c}\bar{c}$ and $bb\bar{b}\bar{b}$ tetraquarks:

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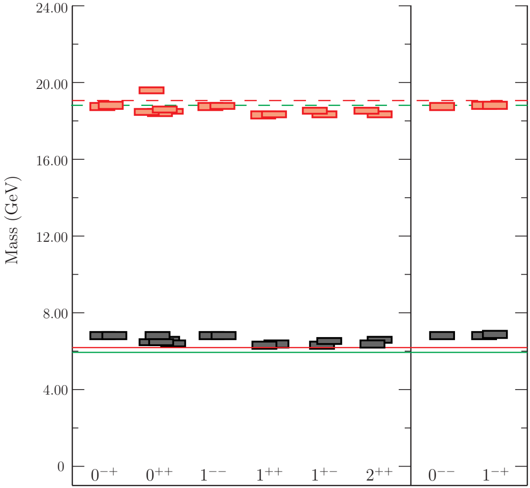
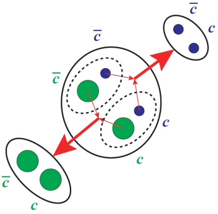
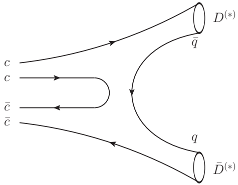
J^{PC}	Currents	m_{X_c}(GeV)	m_{X_b}(GeV)
0^{++}	J_1	6.44 ± 0.15	18.45 ± 0.15
	J_2	6.59 ± 0.17	18.59 ± 0.17
	J_3	6.47 ± 0.16	18.49 ± 0.16
	J_4	6.46 ± 0.16	18.46 ± 0.14
	J_5	6.82 ± 0.18	19.64 ± 0.14
1^{++}	$J_{1\mu}^{+}$	6.40 ± 0.19	18.33 ± 0.17
	$J_{2\mu}^{+}$	6.34 ± 0.19	18.32 ± 0.18
1^{+-}	$J_{1\mu}^{-}$	6.37 ± 0.18	18.32 ± 0.17
	$J_{2\mu}^{+}$	6.51 ± 0.15	18.54 ± 0.15
2^{++}	$J_{1\mu\nu}$	6.51 ± 0.15	18.53 ± 0.15
	$J_{2\mu\nu}$	6.37 ± 0.19	18.32 ± 0.17
0^{-+}	J_1^{+}	6.84 ± 0.18	18.77 ± 0.18
	J_2^{+}	6.85 ± 0.18	18.79 ± 0.18
0^{--}	J_1^{-}	6.84 ± 0.18	18.77 ± 0.18
1^{-+}	$J_{1\mu}^{+}$	6.84 ± 0.18	18.80 ± 0.18
	$J_{2\mu}^{+}$	6.88 ± 0.18	18.83 ± 0.18
1^{--}	$J_{1\mu}^{-}$	6.84 ± 0.18	18.77 ± 0.18
	$J_{2\mu}^{-}$	6.83 ± 0.18	18.77 ± 0.16

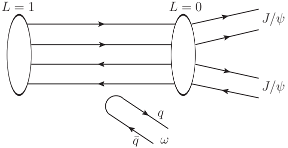

Mass (GeV)
24.00
20.00
16.00
12.00
8.00
4.00
0
0^{-+}
0^{++}
1^{--}
1^{++}
1^{+-}
2^{++}
0^{--}
1^{-+}

Decay behavior: $cc\bar{c}\bar{c}$ tetraquarks

- $cc\bar{c}\bar{c} \to (c\bar{c}) + (c\bar{c})$: charm quark pair rearrangement or annihilation.
- $cc\bar{c}\bar{c} \to (q\bar{c}) + (c\bar{q})$: possible via a heavy quark pair annihilation and a light quark pair creation.
- $cc\bar{c}\bar{c} \to (cqq) + (\bar{c}\bar{q}\bar{q})$: suppressed by two light quark pair creation.
- $cc\bar{c}\bar{c}(L=1) \to cc\bar{c}\bar{c}(L=0) + (q\bar{q})_{I=0}$: OZI forbidden.
- These $cc\bar{c}\bar{c}$ states may not be very narrow.







$bb\bar{b}\bar{b}$ tetraquarks

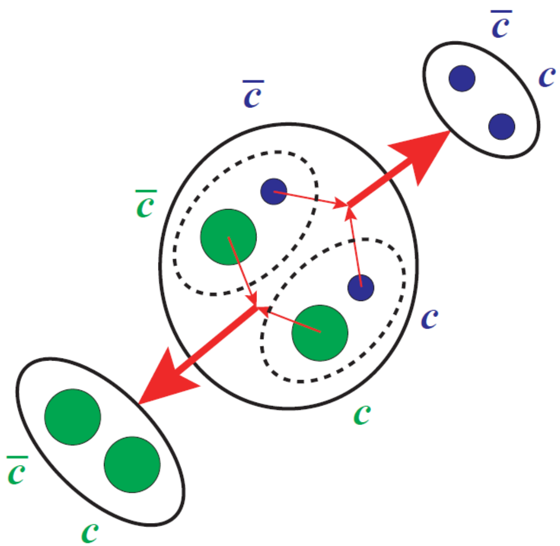
The $bb\bar{b}\bar{b}$ tetraquarks lie below two bottomonium thresholds:

- $bb\bar{b}\bar{b} \to (b\bar{b}) + (b\bar{b})$: kinematically forbidden.
- $bb\bar{b}\bar{b} \to (q\bar{b}) + (b\bar{q})$: possible via a heavy quark pair annihilation and a light quark pair creation.
- $bb\bar{b}\bar{b} \to (b\bar{b}) + \gamma$: electromagnetic decay via $b\gamma_\mu\bar{b} \to \gamma$ photon production process.
- These $bb\bar{b}\bar{b}$ states are expected to be very narrow.

Preliminary

The interpolating currents with $J^{PC} = 0^{-+}$ are

$$J_1 = Q_a^T C Q_b \bar{Q}_a \gamma_5 C \bar{Q}_b^T + Q_a^T C \gamma_5 Q_b \bar{Q}_a C \bar{Q}_b^T ,$$
$$J_2 = Q_a^T C \sigma_{\mu\nu} Q_b \bar{Q}_a \sigma^{\mu\nu} \gamma_5 C \bar{Q}_b^T ,$$

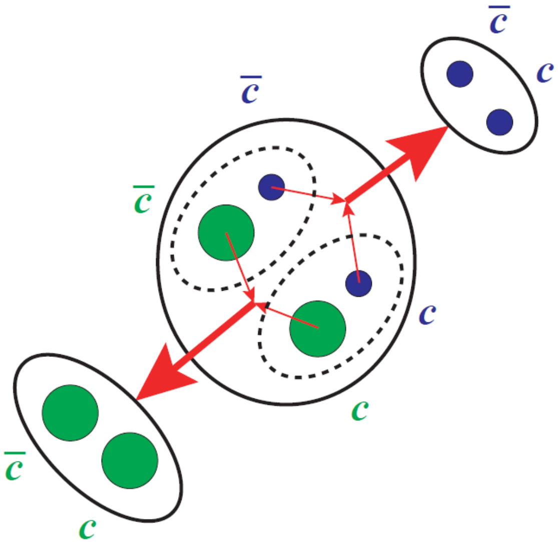


Preliminary

The interpolating currents with $J^{PC} = 0^{-+}$ are

$$J_1 = \quad 0^- \qquad 0^+ \qquad + Q_a^T C \gamma_5 Q_b \bar{Q}_a C \bar{Q}_b^T \,,$$

$$J_2 = \quad 1^\pm \qquad 1^\mp \qquad ,$$



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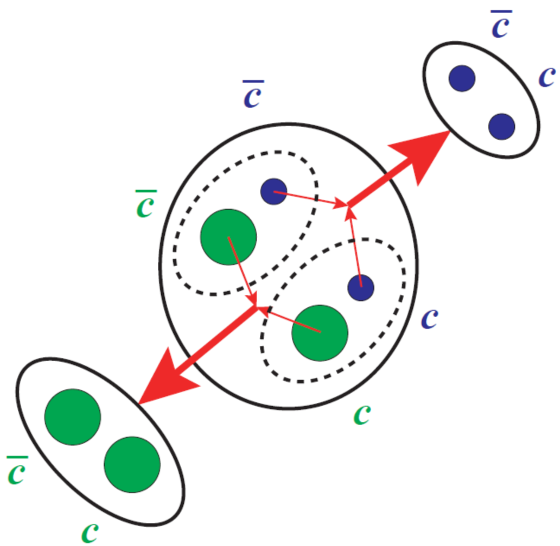

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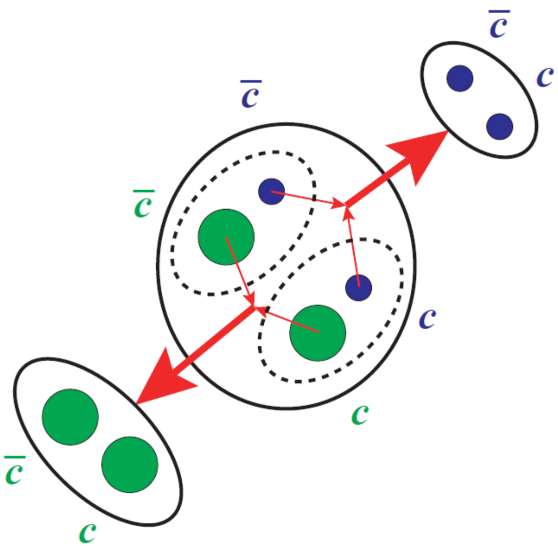
$$J_2 = Q_a^T C \sigma_{\mu\nu} Q_b \bar{Q}_a \sigma^{\mu\nu} \gamma_5 C \bar{Q}_b^T \,,$$

After applying the Fierz transformation, we obtain

$$J_1 \;\rightarrow\; -\,\bar{Q}_a Q_a \;\bar{Q}_b \gamma_5 Q_b + \frac{1}{4}\;\bar{Q}_a \sigma_{\mu\nu} Q_a \;\bar{Q}_b \sigma^{\mu\nu} \gamma_5 Q_b$$
$$J_2 \;\rightarrow\; 6\;\bar{Q}_a Q_a \;\bar{Q}_b \gamma_5 Q_b - \frac{1}{2}\;\bar{Q}_a \sigma_{\mu\nu} Q_a \;\bar{Q}_b \sigma^{\mu\nu} \gamma_5 Q_b$$

Preliminary



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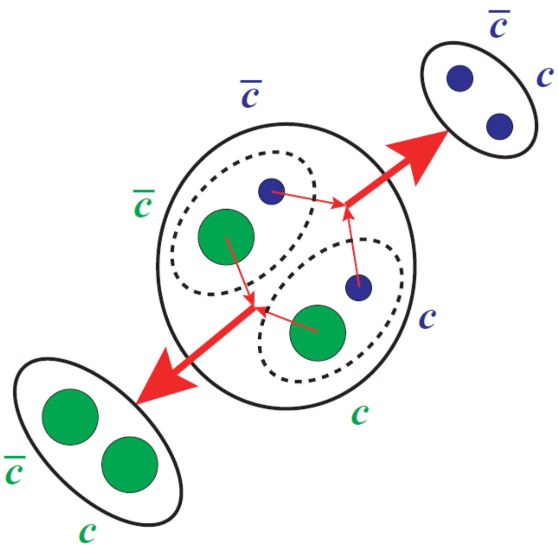
$$J_2 = Q_a^T C \sigma_{\mu\nu} Q_b \bar{Q}_a \sigma^{\mu\nu} \gamma_5 C \bar{Q}_b^T \,,$$

After applying the Fierz transformation, we obtain

$$J_1 \;\rightarrow\; - \quad 0^+ \qquad 0^- \quad \frac{1}{4} \quad 1^{\pm} \qquad\qquad 1^{\mp}$$
$$J_2 \;\rightarrow\; 6\; \bar{Q}_a Q_a \;\bar{Q}_b \gamma_5 Q_b - \frac{1}{2}\; \bar{Q}_a \sigma_{\mu\nu} Q_a \;\bar{Q}_b \sigma^{\mu\nu} \gamma_5 Q_b$$

Preliminary



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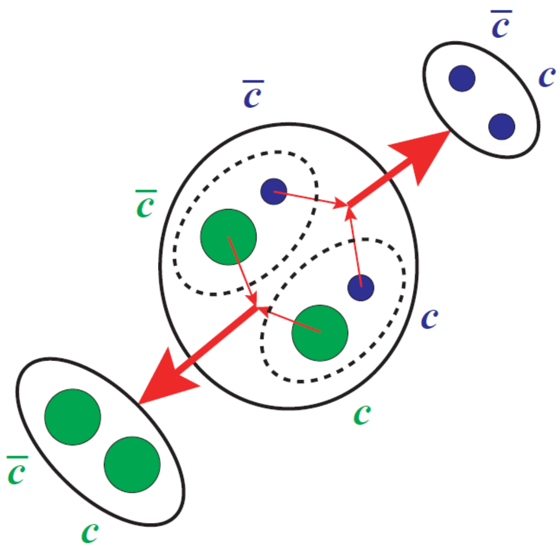
$$J_2 \rightarrow 6 \ \bar{Q}_a Q_a \ \bar{Q}_b \gamma_5 Q_b - \frac{1}{2} \bar{Q}_a \sigma_{\mu\nu} Q_a \ \bar{Q}_b \sigma^{\mu\nu} \gamma_5 Q_b$$

$\chi_{c0} \, \eta_c$ $\quad$ $J/\psi J/\psi, J/\psi h_c, h_c h_c$

Preliminary



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After applying the Fierz transformation, we obtain

$$J_1 \rightarrow -\bar{Q}_a Q_a \; \bar{Q}_b \gamma_5 Q_b + \frac{1}{4} \bar{Q}_a \sigma_{\mu\nu} Q_a \; \bar{Q}_b \sigma^{\mu\nu} \gamma_5 Q_b$$
$$J_2 \rightarrow 6 \; \bar{Q}_a Q_a \; \bar{Q}_b \gamma_5 Q_b - \frac{1}{2} \bar{Q}_a \sigma_{\mu\nu} Q_a \; \bar{Q}_b \sigma^{\mu\nu} \gamma_5 Q_b$$

$\chi_{c0}\,\eta_c$ $\quad$ $J/\psi J/\psi, J/\psi h_c, h_c h_c$

$$Br(|0^-0^+ > \rightarrow J/\psi J/\psi : J/\psi h_c : \chi_{c0}\,\eta_c) = 6.3 : 1.3 : 4.3$$

$$Br(|1^{\pm}1^{\mp} > \rightarrow J/\psi J/\psi : J/\psi h_c : \chi_{c0}\,\eta_c) = 6.3 : 1.3 : 39$$

Summary

- Many new charmonium-like states were observed experimentally. They are good candidates for $cq\bar{c}\bar{q}$ states.
- Hidden-charm pentaquark states were observed by LHCb.
- Doubly hidden-charm/bottom $QQ\bar{Q}\bar{Q}$ states favor the compact tetraquark configuration than the hadron molecule.
- We have calculated the mass spectra for the $cc\bar{c}\bar{c}$ and $bb\bar{b}\bar{b}$ tetraquark states. Our results show that the $cc\bar{c}\bar{c}$ states lie above two charmonium thresholds and thus mainly decay via spontaneous dissociations. The $bb\bar{b}\bar{b}$ states are expected to be very narrow.
- The recent observations of the J/ψ pair, $J/\psi\Upsilon(1S)$ and $\Upsilon(1S)\Upsilon(1S)$ events shed some light for the production of these doubly hidden-charm/bottom tetraquarks.

Thank you for your attention!