Charmonium and Bottomonium Hybrid States

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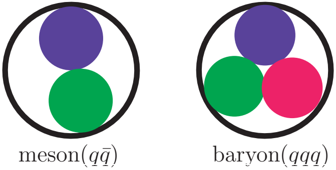
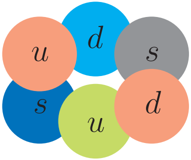
Contents

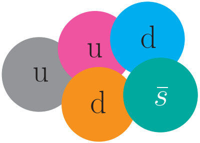


- **Quark model** is quite successful in the classification of hadrons: J^{PC} quantum numbers and flavour quantum numbers;
- However, the hadron structures are more complicated in **QCD**. It may allow for hadrons which lie outside the naive quark model;
- Mesons with exotic J^{PC} quantum numbers: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, ...$
- Baryons with exotic flavour quantum numbers: dibaryon, pentaquark,...

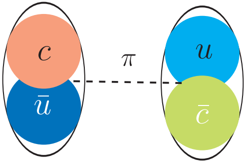
Many possible candidates of exotic hadrons in QCD:



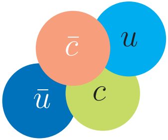
dibaryon



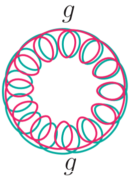
pentaquark



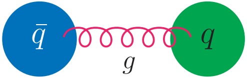
molecule



tetraquark

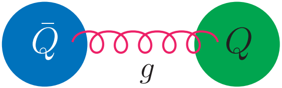


glueball



hybrid

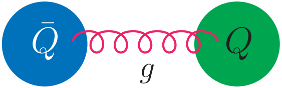
Hybrid Mesons:



- The existence of hybrids was suggested by Jaffe and Johnson in 1976;
- Hybrid mesons were studied in MIT bag model, flux tube model, LQCD, QCD sum rule and so on;
- Heavy quarkonium hybrids were originally studied in QCD sum rule:
  - J. Govaerts et al., Nucl. Phys. B258, 215 (1985);
  - J. Govaerts et al., Nucl. Phys. B262, 575 (1985);
  - J. Govaerts et al., Nucl. Phys. B284, 674 (1987).

  Only dimension-4 condensate contributions were studied to the correlation functions. Many channels are unstable!

Heavy Quarkonium Hybrids:



- The $1^{--}, 1^{++}, 0^{-+}$ channels have been re-analyzed by including the tri-gluon condensate:
  - C. F. Qiao et al., J. Phys. G39, 015005 (2012);
  - D. Harnett et al., J. Phys. G39, 125003 (2012);
  - R. Berg et al., Phys. Rev. D86, 034002 (2012).
- We study the effects of the dimension six condensates on remaining channels: $J^{PC} = 0^{++}$, $0^{--}, 0^{+-}, 1^{-+}$, $1^{+-}, 2^{-+}$ and 2^{++};
- We confirm the hybrid supermultiplet structures.

Hybrid Sum Rules

Two-point Correlation Function:

$$\Pi_{\mu\nu}(q^2) = i\int d^4x e^{iq\cdot x}\langle 0|T[J_\mu(x)J_\nu^\dagger(0)]|0\rangle,$$

where $J_\mu(x)$ is the hybrid interpolating currents

$$\begin{aligned} J_\mu &= g_s\bar{Q}\frac{\lambda^a}{2}\gamma^\nu G_{\mu\nu}^a Q, \quad && J^{PC} = 1^{-+}, 0^{++}, \\ J_\mu &= g_s\bar{Q}\frac{\lambda^a}{2}\gamma^\nu\gamma_5 G_{\mu\nu}^a Q, \quad && J^{PC} = 1^{+-}, 0^{--}, \\ J_{\mu\nu} &= g_s\bar{Q}\frac{\lambda^a}{2}\sigma_\mu^\alpha\gamma_5 G_{\alpha\nu}^a Q, \quad && J^{PC} = 2^{-+}, 1^{++}, 1^{-+}, 0^{-+}, \end{aligned}$$

By replacing $G_{\mu\nu}^a$ with $\tilde{G}_{\mu\nu}^a = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}G^{\alpha\beta,a}$, we obtain the corresponding currents with opposite parities.

- Hadron level: Dispersion relation

$$\Pi(q^2) = (q^2)^N \int_{4m^2}^{\infty} \frac{\rho(s)}{s^N(s - q^2 - i\epsilon)} ds + \sum_{n=0}^{N-1} b_n (q^2)^n,$$

- Quark-gluon level: $\Pi(q^2)$ can be calculated via the OPE method;
- Hybrid sum rules: Quark-hadron duality and Borel transform

$$f_X^2 m_X^{8+2k} e^{-m_X^2/M_B^2} = \int_{4m^2}^{s_0} ds\, s^k\, \rho(s)\, e^{-s/M_B^2} = \mathcal{L}_k \left(s_0, M_B^2\right),$$

where s_0 and M_B are threshold parameter and Borel mass respectively.

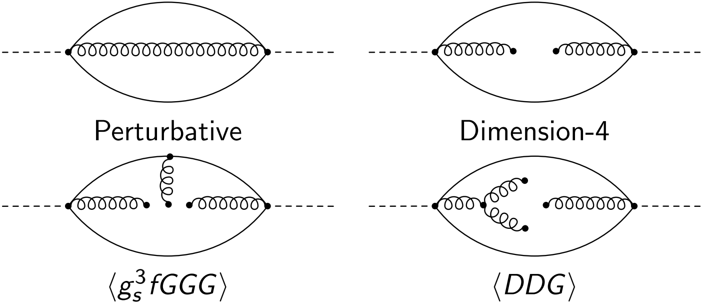
- Hybrid mass:

$$m_X^2 = \frac{\mathcal{L}_1 \left(s_0\,, M_B^2\right)}{\mathcal{L}_0 \left(s_0\,, M_B^2\right)}\,.$$

Correlation Function and Spectral Density

- Quark-gluon level: $\Pi(q^2)$ and $\rho(s)$ are calculated up to dimension six:

$$\rho(s) = \rho^{pert}(s) + \rho^{\langle GG \rangle}(s) + \rho^{\langle GGG \rangle} + \rho^{\langle jj \rangle},$$



Working Regions of M_B and s_0:

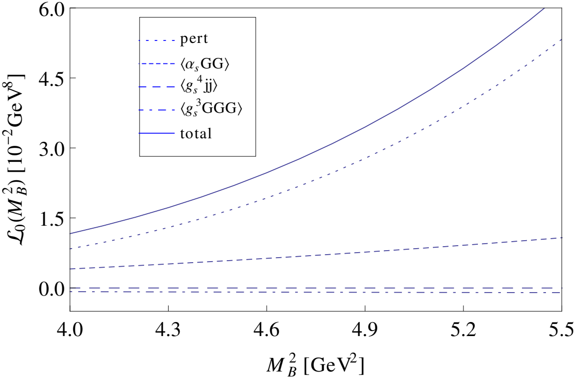
Limitations of the parameters:

- OPE convergence: gluon condensate is less than one third of the perturbative term while tri-gluon condensate is less than one third of the gluon condensate;
- Upper bound on M_B^2 is obtained by requiring PC be larger than 10%;
- We fix on the value of s_0 around which the variation of m_X with M_B^2 is minimum;
- The Borel curves should be stable.

Pole Contribution(PC):

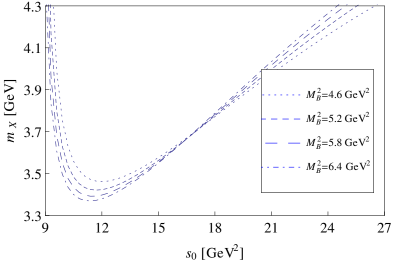
$$\mathrm{PC}(s_0, M_B^2) = \frac{\int_{4m_c^2}^{s_0} ds e^{-s/M_B^2} \rho(s)}{\int_{4m_c^2}^{\infty} ds e^{-s/M_B^2} \rho(s)}.$$

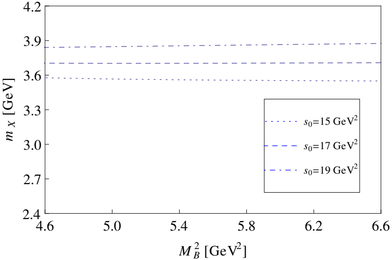
The OPE convergence for 1^{-+} $\bar{c}Gc$ hybrid:



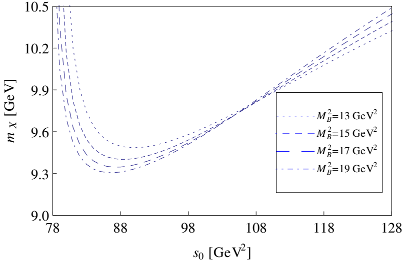
$$M_B^2 \geq 4.6\ \text{GeV}^2$$

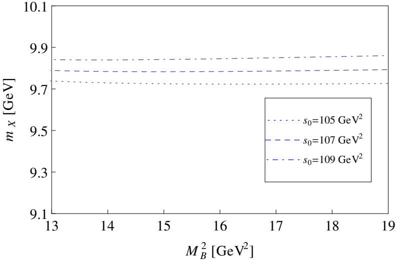
The Borel curves for 1^{-+} $\bar{c}Gc$ hybrid:





The Borel curves for 1^{-+} $\bar{b}Gb$ hybrid:





Numerical results for $\bar{c}Gc$ charmonium hybrids

J^{PC}	$s_0(\text{GeV}^2)$	$[M^2_{min}, M^2_{max}](\text{GeV}^2)$	$m_X(\text{GeV})$	PC(%)
1^{--}	15	$2.5 \sim 4.8$	3.36 ± 0.15	18.3
0^{-+}	16	$5.6 \sim 7.0$	3.61 ± 0.21	15.4
1^{-+}	17	$4.6 \sim 6.5$	3.70 ± 0.21	18.8
2^{-+}	18	$3.9 \sim 7.2$	4.04 ± 0.23	26.0
0^{+-}	20	$6.0 \sim 7.4$	4.09 ± 0.23	15.5
2^{++}	23	$3.9 \sim 7.5$	4.45 ± 0.27	21.5
1^{+-}	24	$2.5 \sim 8.4$	4.53 ± 0.23	33.2
1^{++}	30	$4.6 \sim 11.4$	5.06 ± 0.44	30.4
0^{++}	34	$5.6 \sim 14.6$	5.34 ± 0.45	36.3
0^{--}	35	$6.0 \sim 12.3$	5.51 ± 0.50	31.0

- Unstable channels are stabilized and the mass predictions are reliable!
- 1^{++} charmonium hybrid is much heavier than $X(3872)$, which seems to preclude a pure charmonium hybrid interpretation for this state;

Numerical results for $\bar{b}Gb$ bottomonium hybrids

J^{PC}	$s_0(\text{GeV}^2)$	$[M^2_{\text{min}}, M^2_{\text{max}}](\text{GeV}^2)$	$m_X(\text{GeV})$	PC(%)
1^{--}	105	$11 \sim 17$	9.70 ± 0.12	17.2
0^{-+}	104	$14 \sim 16$	9.68 ± 0.29	17.3
1^{-+}	107	$13 \sim 19$	9.79 ± 0.22	20.4
2^{-+}	105	$12 \sim 19$	9.93 ± 0.21	21.7
0^{+-}	114	$14 \sim 19$	10.17 ± 0.22	17.6
2^{++}	120	$12 \sim 20$	10.64 ± 0.33	19.7
1^{+-}	123	$10 \sim 21$	10.70 ± 0.53	28.5
1^{++}	134	$13 \sim 27$	11.09 ± 0.60	27.7
0^{++}	137	$13 \sim 31$	11.20 ± 0.48	30.0
0^{--}	142	$14 \sim 25$	11.48 ± 0.75	24.1

We have confirmed the hybrid supermultiplet structure:

- Lightest hybrid supermultiplet: negative-parity states with $J^{PC} = 1^{--}, (0,1,2)^{-+}$;
- Heavier hybrid supermultiplet: positive-parity states with $J^{PC} = (0,1)^{+-}, (0,1,2)^{++}$;
- Heaviest 0^{--} hybrid may suggest a highly excited gluonic structure.

Possible Decay Patterns: $\bar{c}Gc$ charmonium hybrids

$I^G J^{PC}$	S-wave	P-wave
0^-1^{--}	–	–
0^+0^{-+}	$\eta_c(1S)f_0(600)$	–
0^+1^{-+}	–	$\eta_c(1S)\eta, J/\psi\omega(782)$
0^+2^{-+}	–	$D\bar{D}^*, J/\psi\omega(782)$
0^-0^{+-}	–	$J/\psi f_0(600)$
0^+2^{++}	$J/\psi\omega(782), J/\psi\phi(1020), \chi_{c2}(1P)f_0(600)$	$D\bar{D}_1, D\bar{D}_2^*, D^*\bar{D}_0^*, D^*\bar{D}_1, D^*\bar{D}_0^*, J/\psi h_1(1170), \eta_c(1S)f_1(1285), \eta_c(1S)f_2(1270), \chi_{c(1,2)}(1P)\eta$
0^-1^{+-}	$D\bar{D}^*, J/\psi\eta, \psi(2S)\eta, \chi_{c0}(1P)h_1(1170)$	$D\bar{D}_0^*, D\bar{D}_1, D\bar{D}_2^*, D^*\bar{D}_0^*, D^*\bar{D}_2^*, D^*\bar{D}_1, \eta_c(1S,2S)h_1(1170)$
0^+1^{++}	$D\bar{D}^*, D_0^*\bar{D}_1, D_1\bar{D}_2^*, J/\psi\omega(782), J/\psi\phi(1020), \chi_{c0}(1P)f_1(1285), \chi_{c1}(1P)f_0(600), \chi_{c2}(1P)f_1(1285)$	$D\bar{D}_0^*, D\bar{D}_1, D\bar{D}_2^*, D^*\bar{D}_0^*, D^*\bar{D}_2^*, D^*\bar{D}_1, \eta_c(1S,2S)f_0(600), \eta_c(1S,2S)f_0(980), J/\psi h_1(1170), \eta_c(1S)f_1(1285), \eta_c(1S)f_2(1270), \chi_{c(0,1,2)}(1P)\eta$
0^+0^{++}	$J/\psi\omega, J/\psi\phi, \eta_c(1S,2S)\eta, \chi_{c0}(1P)f_0(600), \chi_{c0}(1P)f_0(980), \chi_{c1}(1P)f_1(1285)$	$D\bar{D}_1, D^*\bar{D}_0^*, D^*\bar{D}_1, D^*\bar{D}_2^*, \eta_c(1S,2S)f_1(1285), J/\psi h_1(1170), \psi(2S)h_1(1170), \chi_{c1}(1P)\eta$
0^-0^{--}	$D\bar{D}_0^*, D^*\bar{D}_1, J/\psi f_1(1285), \psi(2S)f_1(1285), \chi_{c1}(1P)\omega(782)$	$D\bar{D}^*, D_0^*\bar{D}_1, D_1\bar{D}_2^*, J/\psi\eta, \psi(2S)\eta, \eta_c(1S)\omega(782), \eta_c(2S)\omega(782), \chi_{c(0,1,2)}(1P)h_1(1170)$

$S+P$-wave selection rule: $D^{(*)}\bar{D}_0^*$ and $D^{(*)}\bar{D}_1$ are dominant decay modes!

Could be a strong signature at future experiments, especially BESIII, PANDA and LHCb!

Summary

Correlation function and spectral density:

- We calculate the correlation functions and spectral densities by including dimension six condensates.

Mass predictions of the $\bar{c}Gc$ and $\bar{b}Gb$ hybrids:

- Unstable channels are stabilized by the dimension six condensates;
- Predict the masses of the exotic hybrid channels: $1^{-+}, 0^{+-}, 0^{--}$;
- Pure hybrid interpretation of $X(3872)$ seems to be precluded;
- We confirm the supermultiplet structure of the hybrid spectrum.

Possible decay patterns:

- $D^{(*)}\bar{D}_0^*$, $D^{(*)}\bar{D}_1$ and $D_s^{(*)}\bar{D}_{s0}^*$, $D_s^{(*)}\bar{D}_{s1}$ are dominant decay modes;
- A strong signature at BESIII, PANDA and LHCb in the future.

Thank You Very Much!