Baryonium、Hybrid and Glueball in Charmonium Energy Region

---hadronic spectroscopy

Cong-Feng Qiao
Graduate University
Chinese Academy of Sciences

Contents

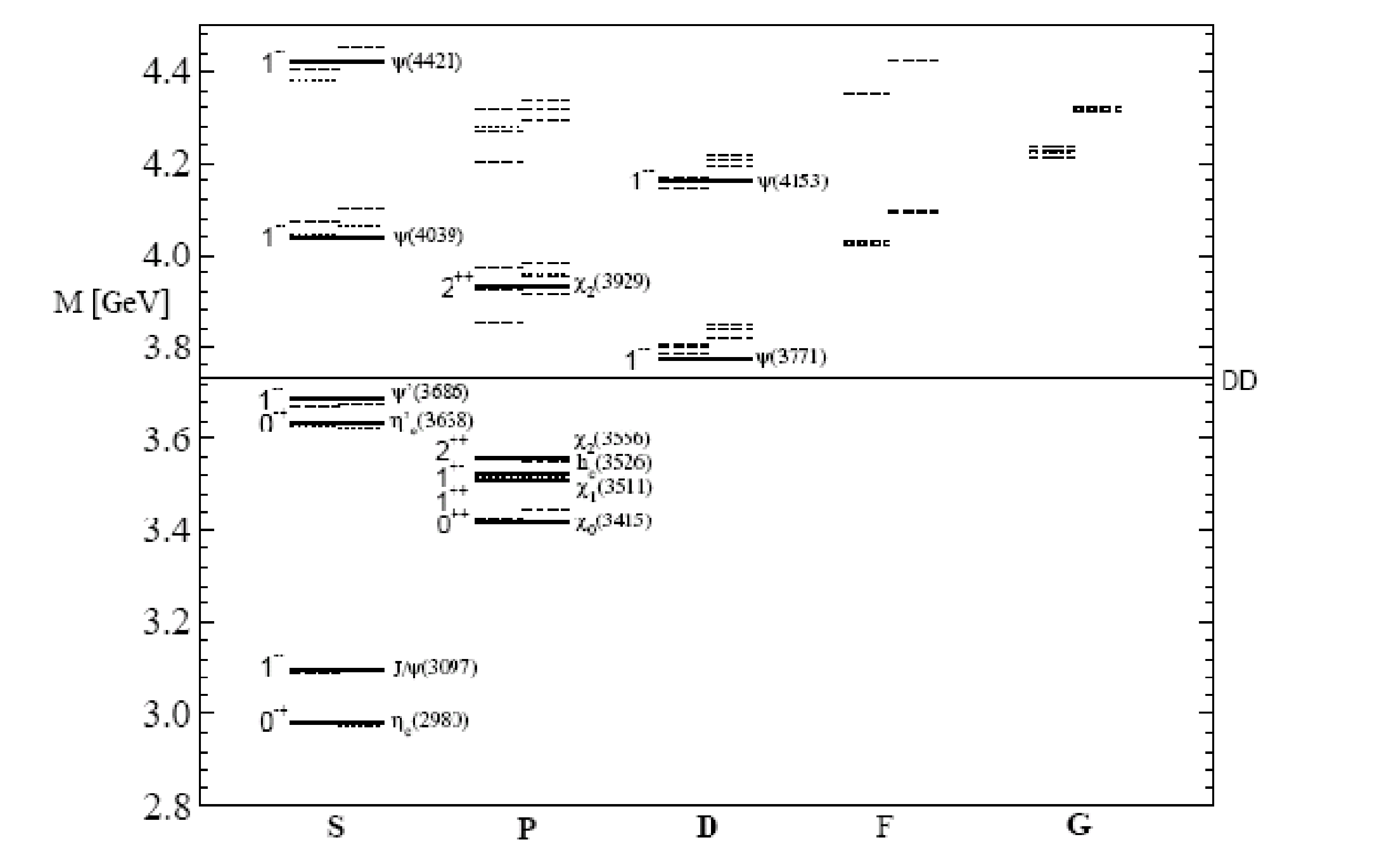
- Introduction
- Charmonium-like states--the experimental realities
- Charmed Baryonium、Hybrid and Glueball
- Summary

I. Introduction

- After the discovery of J/ψ in 1974, the potential model was proposed, which can describe charmonium very well, like the Cornell potential

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br$$

- The success of potential model makes people believe its legitimacy in describing meson mass spectrum, especially in heavy sector



Charmonium spectroscopy: experimental measurements vs theoretical predictions.

- Many resonant states predicted by potential model were confirmed by experiments in the past decades

- Nevertheless, the QCD does not rule out the existence of so-called “exotic” states, that is hadronic states other than regular meson and baryon, like glueball, hybrid, multiquark state, etc.

- B- and Charm-factories provide large dataset for studying the charm and beauty hadrons, which enables even the study of exotic states feasible

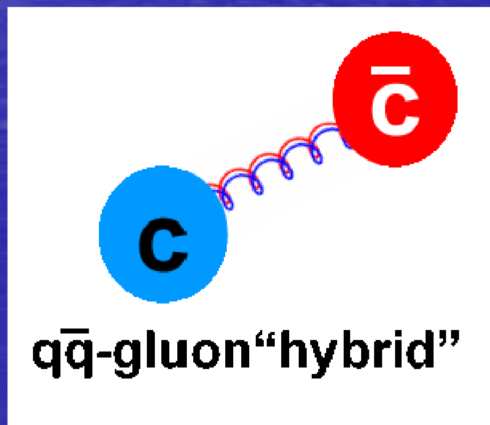
- Exotic states study may shed light on the nature of non-perturbative interaction and enrich our knowledge of hadron physics

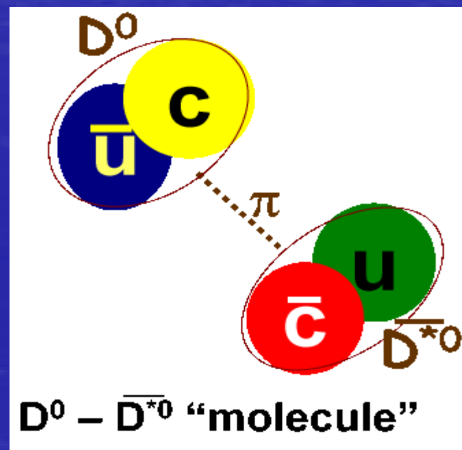
II. Experiment Realities

Puzzles: we bump into the exotic state era

- **The discovery of X(3872) in 2003 exhibit unusual properties which can't be explained as conventional charmonium state**

- **There were many models being proposed for the interpretation of X, the most popular ones include**



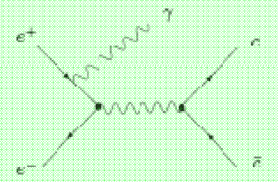
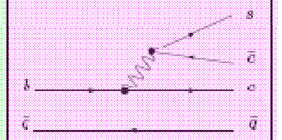
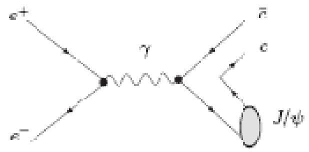
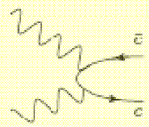


Soon after X(3872), a series of new hadronic structures, like Ys, were observed by different experiment groups

Table II: Measured parameters of the Y states

State	M, MeV/c^2	Γ_{tot}, MeV	J^{PC}	Decay Modes	Production	Collaboration
$Y(4008)$	$4008 \pm 40^{+114}_{-28}$	$226 \pm 44 \pm 87$	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)	Belle 07 [12]
$Y(4260)$	$4259 \pm 8^{+2}_{-6}$	$88 \pm 23^{+6}_{-4}$	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)	BaBar 05 [9]
$Y(4260)$	$4252 \pm 6^{+2}_{-3}$	$105 \pm 18^{+4}_{-6}$	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)	BaBar 08 [45]
$Y(4260)$	$4247 \pm 12^{+17}_{-32}$	$108 \pm 19 \pm 10$	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)	Belle 07 [10]
$Y(4325)$	4324 ± 24	172 ± 33	1^{--}	$\pi^+\pi^- \psi(2S)$	e^+e^-(ISR)	BaBar 06 [11]
$Y(4325)$	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$	1^{--}	$\pi^+\pi^- \psi(2S)$	e^+e^-(ISR)	Belle 07 [12]
$Y(4660)$	$4664 \pm 11 \pm 54$	$48 \pm 15 \pm 3$	1^{--}	$\pi^+\pi^- \psi(2S)$	e^+e^-(ISR)	Belle 07 [12]
$X(4630)$	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^-(ISR)	Belle 08 [13]

According to the production mechanism, the newly found charmonium-like states X, Y, Z can be categorized in four groups:

$(e^+ + e^-)_{\rm ISR} \to (c\bar{c})$	$b \to s(c\bar{c})$	$e^+ + e^- \to J/\psi + (c\bar{c})$	$\gamma\gamma$ fusion
			
$Y(4260)$ $Y(4008)$ $Y(4320)$ $Y(4664)$ $X(3773)$¶	$X(3872)$ $Y(3940)$ $Z^+(4430)$ $Z^+(4051)$ $Z^+(4248)$ $Y(4140)$ $Y(4274)$	$X(3940)$ $X(4160)$	$Z(3930)$ $Y(3915)$ $Y(4350)$

These are unexpected states

- These states' quantum number, mass, and decay patterns make them unlike the conventional charmonium states

- Via ISR method, many 1^{--} states were discovered, by this method the final state has the same quantum number with photon

- Y(4260), Y(4360), Y(4660), their mass are much higher than open charm threshold, while decay patterns are not as same as usual states

- Z(4433) has electric charge, which is obviously exotic states with hidden charm

- How to understand these unusual structures becomes a hot topic currently

III.Charmed Baryonium、Hybrid and Glueball

Baryonium

- In baryonium scheme $\Lambda_c - \Sigma_c$ can be taken as basis vector, one can make up four baryon-antibaryon configuration

- Due to the spin structure of Fermions, many fine structures exist naturally, then it may explain why there exist so many 1^{--} states

- Y(4260) is treated as loosely bound state of Lamda_c and anti Lamda_c

- Imitate the isospin for proton and neutron, introducing C-spin

$$B_1^+ \equiv | \Lambda_c^+ \bar{\Sigma}_c^0 >$$
$$B_1^0 \equiv \frac{1}{\sqrt{2}}(| \Lambda_c^+ \bar{\Lambda}_c > - | \Sigma_c^0 \bar{\Sigma}_c^0 >)$$
$$B_1^- \equiv | \Lambda_c^- \Sigma_c^0 >$$

$$B_0^0 \equiv \frac{1}{\sqrt{2}}(| \Lambda_c^+ \bar{\Lambda}_c > + | \Sigma_c^0 \bar{\Sigma}_c^0 >)$$

QCF，PLB2006，JPG2008

Heavy hadrons properties:

- **Heavy flavor hadron contains both heavy and light quark, so it has heavy quark symmetry and chiral symmetry**

- **In order to deal with baryon anti-baryon bound state, we employ the Heavy flavor chiral perturbation theory**

Yan, Cheng, Cheung, Lin, Lin and Yu, PRD, 1992, 1993

- Heavy flavor chiral perturbative theory collecting both heavy and light properties of quarks in the hadrons, which extend chiral perturbation theory to heavy sector

- In terms of Heavy flavor chiral perturbation theory, we make use of the method of treating NN potential to extract potential

Lagrangian

- **In dealing with the light meson system**

$$U(x) = \exp\left(i\frac{\phi(x)}{F_0}\right),$$

$$\phi(x) = \sum_{a=1}^{8} \lambda_a \phi_a(x) \equiv \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix}$$

$$\mathcal{L}_{\rm eff} = \frac{F_0^2}{4}\mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right)$$

Lagrangian containing heavy quarks

$$\mathcal{L}_B=\frac{1}{2}\mathrm{tr}[\bar{B}_{\bar{3}}(i\not{D}-M_{\bar{3}})B_{\bar{3}}]+\mathrm{tr}[\bar{B}_6(i\not{D}-M_6)B_6]$$
$$+\mathrm{tr}\{\bar{B}_6^{*\mu}[-g_{\mu\nu}(i\not{D}-M_6^*)+i(\gamma_\mu D_\nu+\gamma_\nu D_\mu)-\gamma_\mu(i\not{D}+M_6^*)\gamma_\nu]B_6^{*\nu}\}$$
$$+g_1\mathrm{tr}(\bar{B}_6\gamma_\mu\gamma_5 A^\mu B_6)+g_2\mathrm{tr}(\bar{B}_6\gamma_\mu\gamma_5 A^\mu B_{\bar{3}})+\mathrm{H.c.}$$
$$+g_3\mathrm{tr}(\bar{B}_{6\mu}^{*}A^\mu B_6)+\mathrm{H.c.}+g_4\mathrm{tr}(\bar{B}_6^{*\mu}A_\mu B_{\bar{3}})+\mathrm{H.c.}+g_5\mathrm{tr}(\bar{B}_6^{*\nu}\gamma_\mu\gamma_5 A^\mu B_{6\nu}^{*})+g_6\mathrm{tr}(\bar{B}_{\bar{3}}\gamma_\mu\gamma_5 A^\mu B_{\bar{3}})$$

$$B_6=\begin{pmatrix}\Sigma_Q^{+1} & \frac{1}{\sqrt{2}}\Sigma_Q^0 & \frac{1}{\sqrt{2}}\Xi_Q'^{+1/2}\\ \frac{1}{\sqrt{2}}\Sigma_Q^0 & \Sigma_Q^{-1} & \frac{1}{\sqrt{2}}\Xi_Q'^{-1/2}\\ \frac{1}{\sqrt{2}}\Xi_Q'^{+1/2} & \frac{1}{\sqrt{2}}\Xi_Q'^{-1/2} & \Omega_Q\end{pmatrix}\qquad B_{\bar{3}}=\begin{pmatrix}0 & \Lambda_Q & \Xi_Q^{+1/2}\\ -\Lambda_Q & 0 & \Xi_Q^{-1/2}\\ -\Xi_Q^{+1/2} & -\Xi_Q^{-1/2} & 0\end{pmatrix}$$

Yan, Cheng, Cheung, Lin, Lin and Yu, PRD, 1992, 1993

- Expand the above Lagrangian we obtain what is relevant to our problem:

$$\mathcal{L}_2 = -\frac{g_3}{2f_\pi}\bar{\Sigma}_\mu^{+*}\partial^\mu\pi^+\Sigma^0 + H.c$$

$$L_4 = \frac{-g_4}{\sqrt{2}f_\pi}\bar{\Sigma}^{++}\partial_\mu\pi^+\Lambda^+ + H.c$$

- We may get the two body scattering amplitude, and then doing the non-relativistic expansion and spinor reduction

In terms of heavy quark chrial perturbative theory, following steps are necessary

1) Compute the scattering amplitude, defined in terms of the S matrix element

2) Perform the non-relativistic limit and including form factor

3) Obtain the potential V(r) via the Fourier transform

4) Solving Schrodinger Equation

Contribution to potential

- Due to isospin conservation in strong interaction, the potential is generated at loop level
- In principle all terms at the fourth order should be included
- The basic diagrams are:

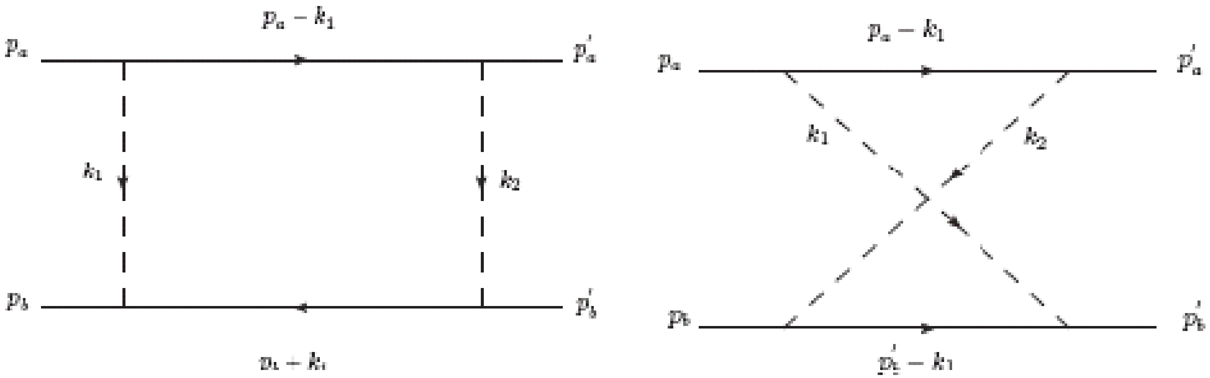


Figure 1: Schematic Diagrams which contribute to the baryonium potential.

After a lengthy calculation, one finally obtain the Λ_c-$\bar{\Lambda}_c$ potential

$$\begin{aligned}
V_C(r_1,\ r_2) = & - \left(\frac{g_4^4}{f_\pi^4}\right)\int\int\frac{d^3\mathbf{k}_1 d^3\mathbf{k}_2}{(2\pi)^6}\frac{O_1(\mathbf{k}_1,\mathbf{k}_2)e^{i\mathbf{k}_1\mathbf{r}_1}e^{i\mathbf{k}_2\mathbf{r}_2}F(\mathbf{k}_1^2)F(\mathbf{k}_2^2)}{2E_{\mathbf{k}_1}E_{\mathbf{k}_2}(E_{\mathbf{k}_1}+\Delta_1)(E_{\mathbf{k}_2}+\Delta_1)(E_{\mathbf{k}_1}+E_{\mathbf{k}_2})} \\
= & - \left(\frac{g_4^4}{f_\pi^4}\right)[\frac{1}{\pi}\int_0^\infty\frac{d\lambda}{\Delta_1^2+\lambda^2}O_1(\mathbf{k}_1,\mathbf{k}_2)F(\lambda,r_1)F(\lambda,r_2) \\
& - \frac{2\Delta_1}{\pi^2}O_1(\mathbf{k}_1,\mathbf{k}_2)\int_0^\infty\frac{d\lambda}{\Delta_1^2+\lambda^2}F(\lambda,r_1)\int_0^\infty\frac{d\lambda}{\Delta_1^2+\lambda^2}F(\lambda,r_2)] \\
= & - \frac{g_4^4\Lambda^5 m}{128\sqrt{2}f_\pi^4\Delta_1^2\pi^{7/2}}\frac{1}{r}e^{-\frac{\Lambda^2 r^2}{2}}+\cdots .
\end{aligned}$$

Chen and QCF, Arxiv: 1102.3487

The Λ_c-$\bar{\Lambda}_c$ potential beheaves like

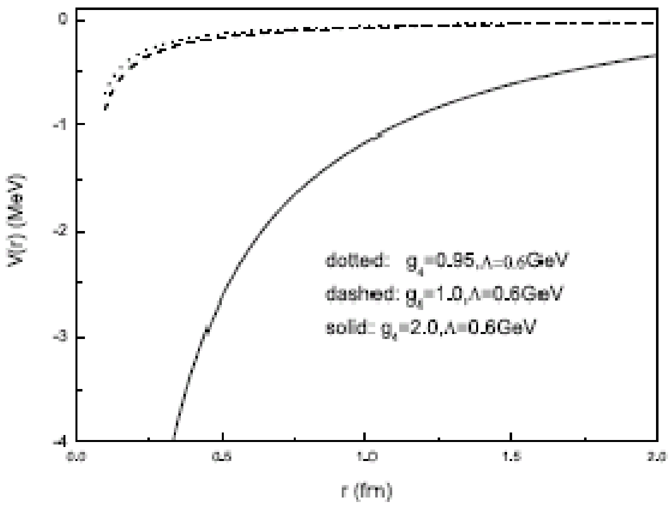


Figure 2: The Λ_c-$\bar{\Lambda}_c$ central potential behavior versus different parameter choices.

With the obtained potential, by solving Schrodinger equation one can readily get Λ_c-$\bar{\Lambda}_c$ baryonium eigenvalue of

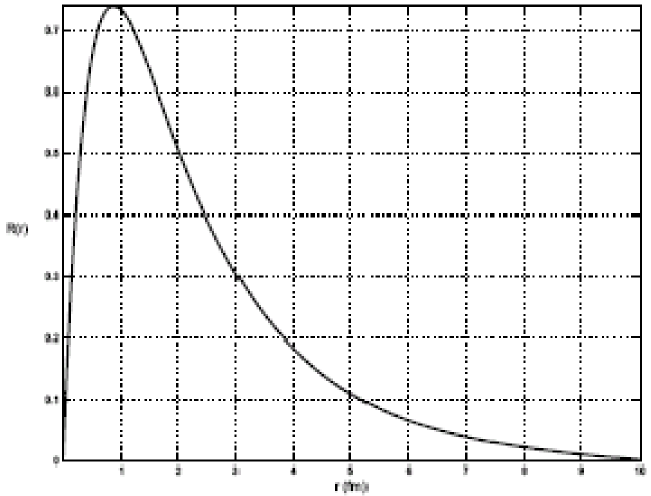


Figure 3: Radial wave function of Λ_c-$\bar{\Lambda}_c$ ground state under the condition of $g_2 = 0.63$ and $\Lambda = 0.75$. The Σ_c-$\bar{\Sigma}_c$ system wave function having a similar shape under certain choice of parameters is hence not shown here.

The binding energies for Λ_c-$\bar{\Lambda}_c$ and Σ_c-$\bar{\Sigma}_c$ systems go like

Table 2: Binding energies with the change of parameters. The left one is for the Λ_c-$\bar{\Lambda}_c$ system, and the right one for Σ_c-$\bar{\Sigma}_c$ system.

g_2	g_4	Λ(GeV)	Binding Energy	g_1	g_3	Λ(GeV)	Binding Energy
<0.6	<1.06	<0.7	Nope	< 0.8	<0.7	< 0.6	Nope
-0.61	1.06	0.7	-0.6MeV	0.85	-0.74	0.6	Nope
-0.61	1.06	0.75	-58MeV	0.85	-0.74	0.7	-14MeV
-0.61	1.06	0.8	-252MeV	0.85	-0.74	0.8	-307MeV
-0.60	1.04	0.75	-30MeV	0.8	-0.7	0.75	-24MeV
-0.63	1.09	0.75	-113MeV	0.85	-0.74	0.75	-121MeV
-0.65	1.23	0.75	-206MeV	0.9	-0.78	0.75	-317MeV

In all: the heavy baryonium may really exist!

Charmonium Hybrid

- **In the framework of QCD Sum Rules, the two-point correlation function reads**

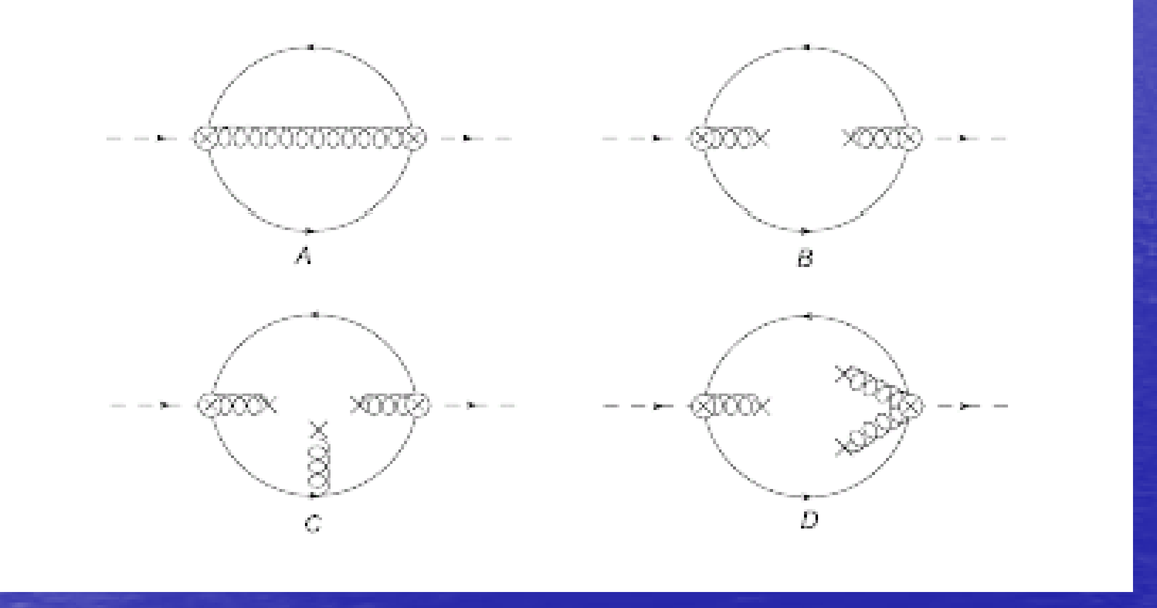
$$\Pi_{\mu\nu}(q) = i\int d^4x e^{iqx}\langle 0|T\{J_\mu(x)J_\nu^\dagger(0)\}|0\rangle$$

Here, the interpolating current J goes like

$$J_\mu(x) = g_s\bar{\psi}^a(x)\gamma^\nu\gamma_5\frac{\lambda^n_{ab}}{2}\tilde{G}^n_{\mu\nu}(x)\psi^b(x)$$

QCF, Tang, Hao and Li, arXiv:1012.2614

The typical diagrams concerned about are



By the operator product expansion (OPE) technique, the correlation function $\Pi_V(q^2)$ can be written as

$$\Pi_V(q^2) = \Pi^{\rm pert}(q^2) + \Pi_i^{\rm cond}(q^2) , \tag{4}$$

First, we calculate the imaginary part, the absorptive part, of the Feynman diagrams which represents the perturbative contribution to the correlator as, and result reads

$$\begin{aligned}\rho^{\rm pert}(t) &= -\frac{\alpha_s m_Q^6}{720\pi^2\sqrt{1-t}\ t^3}\Big[-15t^5 + 185t^4 - 778t^3 - 496t^2 + 1296t - 192 \\ &\quad +15t^2\sqrt{1-t}(t^3 - 12t^2 + 48t - 128)\log\frac{\sqrt{1-t}+1}{\sqrt{t}}\Big] ,\end{aligned} \tag{5}$$

where, $t = 4m_Q^2/s$, and m_Q is the mass of the heavy quark, and $\rho^{\rm pert}(t) \equiv {\rm Im}\,\Pi(t)$.

The contributions coming from the diagrams of Figure 1 involving condensates are listed as follows:

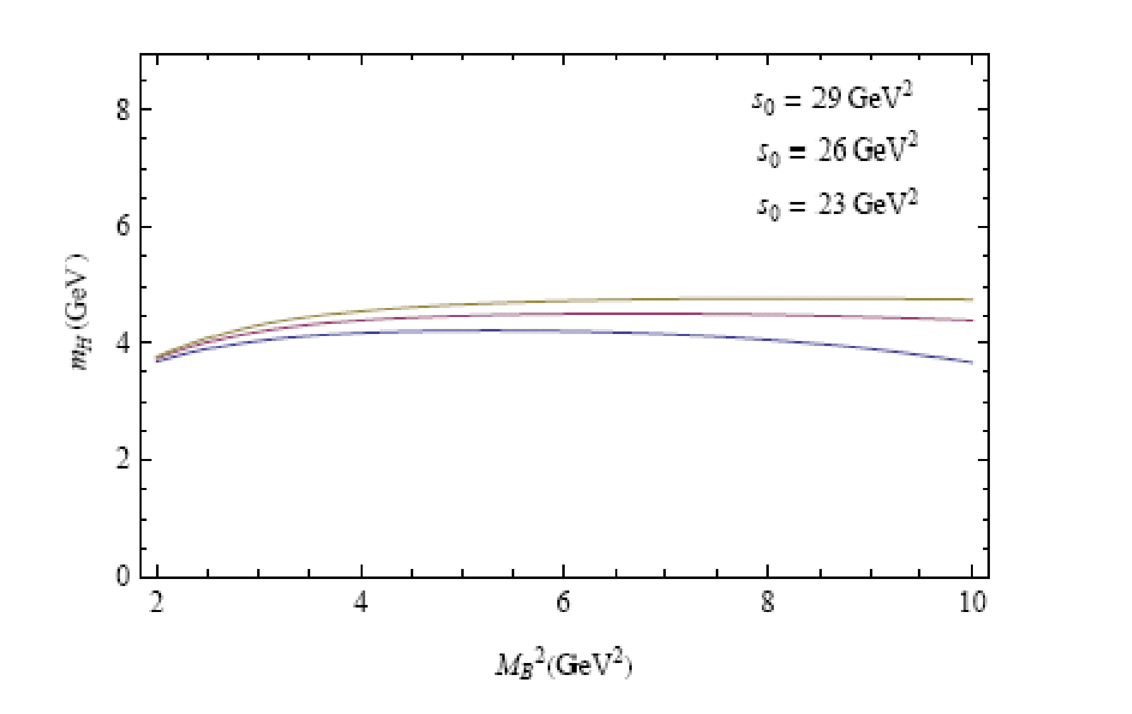
$$\Pi_4^{\rm cond,B}(q^2) = \int_0^1 dx \frac{\langle g_s^2 G^2\rangle}{48\pi^2}\{[8(1-x)xq^2 - 11m_Q^2] + \ln(\Delta)[2(1-x)xq^2 - 3m_Q^2]\} , \quad (6a)$$

$$\Pi_6^{\rm cond,C}(q^2) = \int_0^1 dx \frac{\langle g_s^3 G^3\rangle}{192\pi^2}[3x\ln(\Delta) + \frac{2xm_Q^2}{\Delta} + 17x] , \quad (6b)$$

$$\Pi_6^{\rm cond,D}(q^2) = \int_0^1 dx \frac{\langle g_s^3 G^3\rangle}{384\pi^2}\{2x(2-3x)\ln(\Delta) - \frac{[2(3-4x)m_Q^2 + x(14x^2 - 27x + 13)q^2]x}{\Delta} + \frac{(x-1)q^2[3xq^2(x-1)^2 + (2-3x)m_Q^2]x^2}{\Delta^2} + \frac{2(5-24x)x}{3}\} . \quad (6c)$$

Here, $\Delta = -(1-x)xq^2 + m_Q^2$ and B, C, D correspond to the B, C and D diagrams, respectively.

- **After taking the standard QCD Sum Rule procedures, we obtain:**



In the end we obtain the masses of 1-- charmonium hybrid and bottomium hybrid, as:

$$m_{H_c} = 4.52^{+0.27}_{-0.38}\ \mathrm{GeV}\ .$$

$$m_{H_b} = 10.81^{+0.23}_{-0.24}\ \mathrm{GeV}\ .$$

- **The above theoretical predictions may confront to the experimental data now or later**

Glueball

- In recent years, BESII and III observe hadronic structures around proton-proton threshold, like X(1835), X(1859), X(2120) and X(2370)

- Possibly, the X(1859) is a proton-proton bound state, or a glueball, or a mixture of exotic state with other regular states

Hao, QCF and Zhang, Phys.Lett.B642:53,2006

- We calculate the mass of 0^-+ triple-gluon state in the framework of Sum Rules
- The mass lying between 1.9 to 2.7 GeV, which is in the energy region of BES newly found structures
- Our calculation favors the baryonium-glueball mixing picture for BES observation

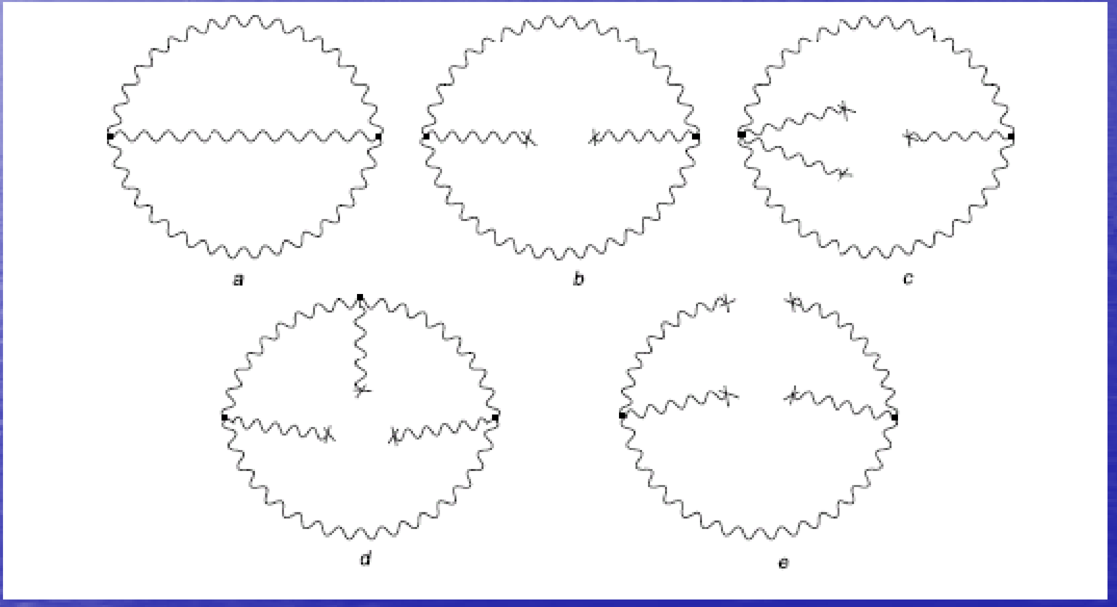
- **In the framework of QCD Sum Rules, the two-point correlation function reads**

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

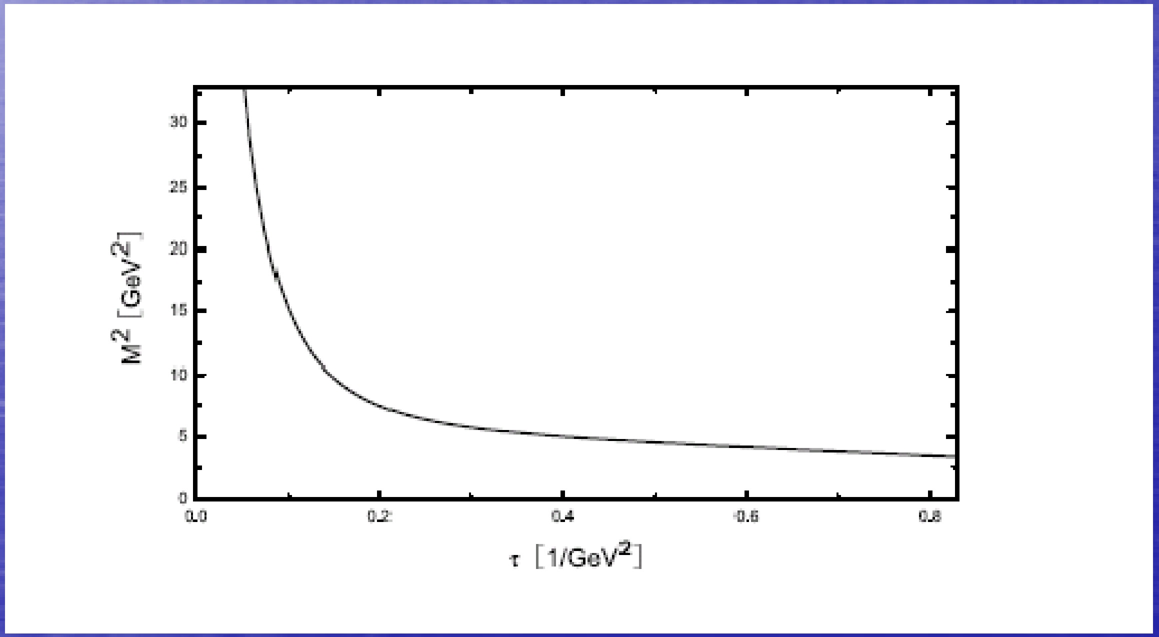
Here, the interpolating current J goes like

$$j(x) = g_s^3 f^{abc}\tilde{G}^a_{\mu\nu}(x)\tilde{G}^b_{\nu\rho}(x)\tilde{G}^c_{\rho\mu}(x)$$

The typical diagrams concerned about are



- After taking the standard QCD Sum Rule procedures, we obtain the mass of triple gluon glueball is about 2 GeV



IV. Summary

- Our calculation in heavy baryon chiral theory favors the existence of heavy baryonium
- The potential sensitivity on coupling constants and energy cutoff in our calculation looks unnatural and asks for further investigations
- One should also investigate the potential while two baryon-like triquark clusters carrry colors
- The tough and confusing annihilation channel effect on the heavy baryonium potential should be clarified

- We recalculate the 1^-- charmonium hybrid in the framework of QCD Sum Rules

- The trigluon condensate contribution is taken into account, and we find it is necessary to attain a stable hybrid mass

- The correct interpolate current is employed in our calculation

- The predicted hybrid mass lying in 4.52GeV, hence neither of the Y(4260), Y(4360) and Y(4660) states could be a pure hybrid sate

- We calculated the triple gluon glueball mass, and found it lies in the region of BES recently observed structures

- The relation between glueball, hybrid and baryonium with the exotic structures observed in experiment deserves more investigations

Thank for your attention!