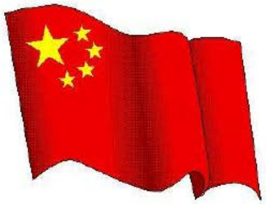
Status report of B2 project
—— Hadron Spectroscopy



CRC 110 general meeting of 2017, Aug.29-31,2017,PKU

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Akira Watanabe (IHEP)

Hadron Spectroscopy:

- Singly heavy baryons
- Doubly heavy baryons
- Charmonium & Bottomonium
- Tetraquarks
- Pentaquarks
- Deuteron-like molecules
- Glueballs
- Other interesting stuff

Methods:

Quark model

QCD sum rules

Holographic QCD model

Hadron spectroscopy from QCD sum rules

---- by Shilin Zhu’s group

- **Singly heavy baryons**
- **Doubly heavy baryons**
- **Tetraquarks**
- **Pentaquarks**
- **Deuteron-like molecules**
- **Other interesting stuff**

Two long reviews:

- **A review of the open charm and open bottom systems.**
  H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu.
  Rept. Prog. Phys. 80 (2017) 076201.

- **The hidden-charm pentaquark and tetraquark states.**
  H.-X. Chen, W. Chen, X. Liu, S.-L. Zhu.
  Phys. Rept. 639 (2016) 1-121. (cited 183 times)

Singly heavy baryons

- Ideal platform to test heavy quark symmetry

- **D-wave heavy baryons of the $SU(3)$ flavor $\mathbf{6}_F$**
  By Qiang Mao, Hua-Xing Chen, Atsushi Hosaka, Xiang Liu, Shi-Lin Zhu.
  arXiv:1707.03712 [hep-ph].
- **Decay properties of P-wave charmed baryons from light-cone QCD sum rules.**
  By H-X Chen, Qiang Mao, Wei Chen, A. Hosaka, Xiang Liu, Shi-Lin Zhu.
  arXiv:1703.07703 [hep-ph]. Phys.Rev. D95 (2017) no.9, 094008
- **D-wave charmed and bottomed baryons from QCD sum rules**
  By Hua-Xing Chen, Qiang Mao, Atsushi Hosaka, Xiang Liu, Shi-Lin Zhu.
  arXiv:1611.02677 [hep-ph]. Phys.Rev. D94 (2016) no.11, 114016.

Doubly heavy baryons

- Very good system to study both heavy quark symmetry and chiral symmetry simultaneously.
- They firstly studied the masses and axial currents of the doubly charmed baryons in chiral perturbation theory in 2015.
  (Sun, Liu, Liu, Zhu. Phys.Rev. D91 (2015no.9, 094030.)

- Two heavy quarks act as nearly static color source and "share" the light quark, which is very similar to the ion of the hydrogen molecule H_2^+
- "QCD-like" valence bond *vs* QED valence bond?

- There also exists deep connection/implication between QQq and exotic (QQ q_bar q_bar) systems

Doubly heavy baryons

- Radiative decays of the doubly charmed baryons in chiral perturbation theory
  By Hao-Song Li, Lu Meng, Zhan-Wei Liu, Shi-Lin Zhu.
  arXiv:1708.03620 [hep-ph].
- Strong and radiative decays of the doubly charmed baryons
  By Li-Ye Xiao, Kai-Lei Wang, Qi-fang Lv, Xian-Hui Zhong, Shi-Lin Zhu
  arXiv:1708.04384 [hep-ph].
- Magnetic moments of the doubly charmed and bottomed baryons
  By Hao-Song Li, Lu Meng, Zhan-Wei Liu, Shi-Lin Zhu.
  arXiv:1707.02765 [hep-ph].
- Establishing low-lying doubly charmed baryons
  By Hua-Xing Chen, Qiang Mao, Wei Chen, Xiang Liu, Shi-Lin Zhu.
  arXiv:1707.01779 [hep-ph]. Phys. Rev. D (2017) Rapid communications

Tetraquarks

- They studied some tetraquark systems with QCD sum rules formalism and chromomagnetic interactions:

a) Singly heavy tetraquark: Q q q_bar q_bar
b) Doubly heavy tetraquark: Q1 Q2_bar q q_bar
c) Triply heavy tetraquark: Q1 Q2 Q3_bar q_bar
d) Doubly hidden-heavy flavor tetraquark: Q1 Q1_bar Q2 Q2_bar

- Q1 Q2 q_bar q_bar has connection with doubly heavy baryons
- Chromomagnetic interaction provides a uniform framework to investigate the mass splittings between the partner states within the same multiplet for both tetraquarks and pentaquarks

Tetraquarks

- Triply heavy $QQ\bar Q\bar q$ tetraquark states
  By Jin-Feng Jiang, Wei Chen, Shi-Lin Zhu.
  arXiv:1708.00142 [hep-ph].
- Exotic tetraquark states with the $qq\bar{Q}\bar{Q}$ configuration
  By Si-Qiang Luo, Kan Chen, Xiang Liu, Yan-Rui Liu, Shi-Lin Zhu.
  arXiv:1707.01180 [hep-ph].
- Mass spectra for $qc\bar q\bar c$, $sc\bar s\bar c$, $qb\bar q\bar b$, $sb\bar s\bar b$ tetraquark states with $J^{PC}=0^{++}$ and 2^{++}
  By Wei Chen, Hua-Xing Chen, Xiang Liu, T.G. Steele, Shi-Lin Zhu.
  arXiv:1706.09731 [hep-ph].
- Triply heavy tetraquark states with the $QQ\bar{Q}\bar{q}$ configuration
  By Kan Chen, Xiang Liu, Jing Wu, Yan-Rui Liu, Shi-Lin Zhu.
  arXiv:1609.06117 [hep-ph]. Eur.Phys.J. A53 (2017) no.1, 5.

Tetraquarks

- X(4140), X(4270), X(4500) and X(4700) and their cs\bar{c}\bar{s} tetraquark partners
  By Jing Wu, Yan-Rui Liu, Kan Chen, Xiang Liu, Shi-Lin Zhu.
  arXiv:1608.07900 [hep-ph]. Phys.Rev. D94 (2016) 094031.
- Open-flavor charm and bottom sq\bar q\bar Q and qq\bar q\bar Q tetraquark states
  By Wei Chen, Hua-Xing Chen, Xiang Liu, T.G. Steele, Shi-Lin Zhu.
  arXiv:1705.10088 [hep-ph]. Phys.Rev. D95 (2017) no.11, 114005.
- Understanding the internal structures of the X(4140), X(4274), X(4500) and X(4700)
  By Hua-Xing Chen, Er-Liang Cui, Wei Chen, Xiang Liu, Shi-Lin Zhu.
  arXiv:1606.03179 [hep-ph]. Eur.Phys.J. C77 (2017) no.3, 160.
- Hunting for exotic doubly hidden-charm/bottom tetraquark states
  By Wei Chen, Hua-Xing Chen, Xiang Liu, T.G. Steele, Shi-Lin Zhu.
  arXiv:1605.01647 [hep-ph].

Tetraquarks

- **Heavy-flavored tetraquark states with the QQ\bar{Q}\bar{Q} configuration**
  By Jing Wu, Yan-Rui Liu, Kan Chen, Xiang Liu, Shi-Lin Zhu.
  arXiv:1605.01134 [hep-ph].
- **$X(5568)$ and its partner states**
  By Yan-Rui Liu, Xiang Liu, Shi-Lin Zhu.
  ArXiv:1603.01131 [hep-ph]. Phys.Rev. D93 (2016) no.7, 074023.
- **Decoding the X(5568) as a fully open-flavor su\bar b\bar d tetraquark state**
  By Wei Chen, Hua-Xing Chen, Xiang Liu, T.G. Steele, Shi-Lin Zhu.
  arXiv:1602.08916 [hep-ph]. Phys.Rev.Lett. 117 (2016) 022002.

Pentaquarks

- Axial charges and magnetic moments encode the crucial information of the underlying structure
- Different color, orbital, spin and flavor configurations lead to very different predictions of the axial charge and magnetic moment of Pc states
- They studied the axial charges and magnetic moments of two Pc states

- They discussed the partner states of Pc within the molecular scheme

- They also discussed the mass splittings between the partner states within the compact pentaquark scheme with the chromomagnetic interaction

Pentaquarks

- Hidden-charm pentaquarks and their hidden-bottom and B_c-like partner states
  By Jing Wu, Yan-Rui Liu, Kan Chen, Xiang Liu, Shi-Lin Zhu.
  arXiv:1701.03873 [hep-ph]. Phys.Rev. D95 (2017) no.3, 034002.
- Axial charges of the hidden-charm pentaquark states
  By Guang-Juan Wang, Zhan-Wei Liu, Shi-Lin Zhu.
  arXiv:1608.07824 [hep-ph]. Phys.Rev. C94 (2016) no.6, 065202.
- Magnetic moments of the hidden-charm pentaquark states
  By Guang-Juan Wang, Rui Chen, Li Ma, Xiang Liu, Shi-Lin Zhu.
  arXiv:1605.01337 [hep-ph]. Phys.Rev. D94 (2016) no.9, 094018.
- QCD sum rule study of hidden-charm pentaquarks
  By Hua-Xing Chen, Er-Liang Cui, Wei Chen, Xiang Liu, T.G. Steele, Shi-Lin Zhu.
  arXiv:1602.02433 [hep-ph]. Eur.Phys.J. C76 (2016) no.10, 572.
- Hidden-charm molecular pentaquarks and their charm-strange partners
  By Rui Chen, Xiang Liu, Shi-Lin Zhu.
  arXiv:1601.03233 [hep-ph]. Nucl.Phys. A954 (2016) 406-421.

Deuteron-like molecules

- Deuteron is the well-established hadronic molecule
- The formation of the hadronic molecule depends on the competition between the potential and kinetic energy (plus various channel coupling …)
- The presence of the heavy quarks helps lower the kinetic energy

➢ Possible hadronic molecules composed of the doubly charmed baryon and nucleon, By Lu Meng, Ning Li, Shi-lin Zhu. arXiv:1707.03598 [hep-ph].

➢ Deuteron-like states composed of two doubly charmed baryons By Lu Meng, Ning Li, Shi-Lin Zhu. arXiv:1704.01009 [hep-ph]. Phys.Rev. D95 (2017) no.11, 114019.

➢ Searching for hidden-charm baryonium signals in QCD sum rules By Hua-Xing Chen, Dan Zhou, Wei Chen, Xiang Liu, Shi-Lin Zhu. arXiv:1605.07453 [hep-ph]. Eur.Phys.J. C76 (2016) no.11, 602.

Other interesting stuff

- Two collaborations are measuring various deculplet → octet transitions

➢ Decuplet to octet baryon transitions in chiral perturbation theory
By Hao-Song Li, Zhan-Wei Liu, Xiao-Lin Chen, Wei-Zhen Deng, Shi-Lin Zhu.
arXiv:1706.06458 [hep-ph].

➢ Magnetic moments and electromagnetic form factors of the decuplet baryons in chiral perturbation theory
By Hao-Song Li, Zhan-Wei Liu, Xiao-Lin Chen, Wei-Zhen Deng, Shi-Lin Zhu.
arXiv:1608.04617 [hep-ph]. Phys.Rev. D95 (2017) no.7, 076001.

Hadron spectroscopy from Quark model

---- by Bingsong Zou's group

See Yu Lu's talk on Aug.31st

Motivation

- Quenched quark model (QQM) is successful, but cannot be the whole story.
  - Effective degree of freedom is frozen, sea quarks' contributions are ignored.
  - The threshold effect is missing etc.
- Quenched quark model should be upgraded to unquenched quark model, which can
  - explicitly contain sea quarks' contributions
  - recover the threshold effects, more generally, Coupled-Channel Effects (CCE)
- The simplest ingredient to add is to introduce a quark pair creation mechanism, $^3P_0$ model, which assumes quark-antiquark pairs are created from the vacuum.
- Despite the success of $^3P_0$ model, some issues still await to be solved:
  - Inaccurate wave functions are widely used.
  - A thorough calculation of the CCE is missing.
  - The excited meson/baryon loops' contributions are unknown.

Achievements

Coupled-Channel Effects for the Bottomonium with Realistic Wave Functions
Yu Lu, M.N Anwar, Bing-Song Zou, PhysRevD.94.034021

- **Make a thorough and precise calculation of CCE for the bottomonium,**
  - **spectrum, decay width, $S - D$ mixing angle θ_{SD}, renormalization of wave functions**
- **Point out the possible misconceptions:**
  - **Simple harmonic wave functions are impropriate for states near open bottom threshold.**
  - **Only focusing on the spectrum or decay width is misleading**
- **Reproduce the leptonic decay width Γ_{ee} up to $\Upsilon(5S)$, and suggest**
  - **$\Upsilon(4S)$'s small Γ_{ee} is due to the B meson pairs components other than large θ_{SD}**
  - **experimentalist to measure radiative decay width of $\Upsilon(4S)$ to distinguish the two mechanisms**

Achievements

How Large is the Contribution of Excited Mesons in Coupled-Channel Effects?
Yu Lu, M.N Anwar, Bing-Song Zou, PhysRevD.95.034018

- **Push the calculation to include excited B mesons' contributions, and find that**
  - **Contrary to what has been widely considered, the excited B mesons' contributions are large in traditional $^3P_0$ model**
  - **The form factor reflecting the size of constituent quarks successfully suppresses the excited B mesons' contributions for relatively low lying states, but fails for highly excited states.**
  - **A suppression mechanism from the dynamics may be more effective to make the excited B mesons' contributions smaller.**

Achievements

X(4260) Revisited --- A Coupled Channel's Perspective
Yu Lu, M.N Anwar, Bing-Song Zou, arXiv:1705.00449

They specifically analyze the CCE for the vector charmonium around the mass region of $X(4260)$, the calculation reveals that

- **Although heavy quark spin symmetry (HQSS) forbids S wave coupling of D_1D to $^3S_1$chamonium $\psi(nS)$, the D wave coupling is allowed and not small.**
- **D_1D couples stronger to $^3D_1$charmonium $\psi(nD)$.**
- **Besides D_1D, $\psi(nS)$ also has strong couplings to other D meson molecules.**
- **Under the assumption that $X(4260)$ is composed of $\psi(nD)$ and D_1D, the D_1D molecule scenario agree with experimentally measured R ratio.**
- **Other D meson molecular components' contribution may be not negligible.**

Hadron spectroscopy from Holographic QCD

---- by Mei Huang's group

A systematic framework: Graviton-dilaton system

$$S_G = \frac{1}{16\pi G_5}\int d^5x\sqrt{g_s}e^{-2\Phi}\left(R_s + 4\partial_M\Phi\partial^M\Phi - V_G^s(\Phi)\right)$$

N=4 Super YM

conformal

AdS$_5$

$$ds^2 = \frac{L^2}{z^2}\left(dt^2 + d\vec{x}^2 + dz^2\right)$$

$$V_E(\phi) = -\frac{12}{L^2}$$

QCD

nonconformal

deformed AdS$_5$

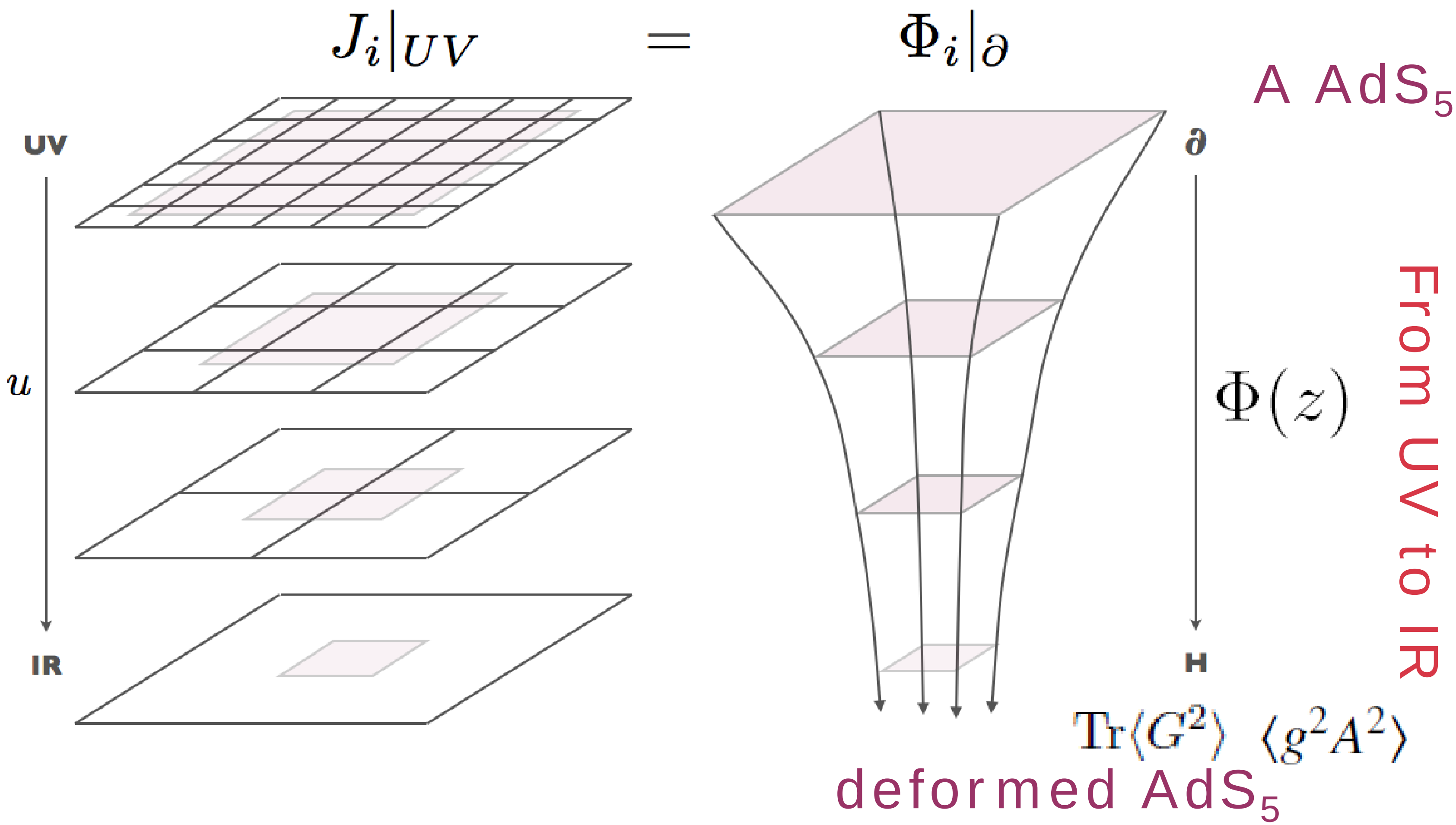
$$ds^2 = \frac{h(z)L^2}{z^2}\left(dt^2 + d\vec{x}^2 + dz^2\right)$$

Dilaton field breaks conformal symmetry

Input: QCD dynamics at IR

Solve: Metric structure, dilaton potential

Graviton-dilaton system



$$g^s_{MN} = b_s^2(z)(dz^2 + \eta_{\mu\nu}dx^\mu dx^\nu), \quad b_s(z) \equiv e^{A_s(z)}$$

Pure gluon system:

D.N. Li, M.H., JHEP2013, arXiv:1303.6929

$$\mathscr{L}_G = -\frac{1}{4} G^a_{\mu\nu}(x) G^{\mu\nu,a}(x),$$

IR: Gluon condensate $\mathrm{Tr}\langle G^2 \rangle$

Effective gluon mass $\langle g^2 A^2 \rangle$

5D action: graviton-dilaton **Gluonic background**

$$S_G = \frac{1}{16\pi G_5} \int d^5x \sqrt{g_s} e^{-2\Phi} \left(R_s + 4\partial_M \Phi \partial^M \Phi - V^s_G(\Phi)\right)$$

$\mathrm{Tr}\langle G^2 \rangle$ $\langle g^2 A^2 \rangle$ dual to $\Phi(z)$

$$\Phi(z) = \mu_G^2 z^2 \tanh(\mu_{G^2}^4 z^2 / \mu_G^2)$$

$$\Phi(z) \overset{z \to 0}{\rightarrow} \mu_{G^2}^4 z^4, \qquad \Phi(z) \overset{z \to \infty}{\rightarrow} \mu_G^2 z^2.$$

Two-gluon and tri-gluon Glueball spectra:

Yidian Chen, M.H., **Chin.Phys. C40 (2016) no.12, 123101**

$$M_5^2 = (\Delta - f)(\Delta + f - 4)$$

J^{PC}	$4D : \mathcal{O}(x)$	Δ	f	M_5^2	
0^{++}	$Tr(G^2)$	4	0	0	
0^{--}	$Tr(\tilde{G}\{D_{\mu_1}D_{\mu_2}G, G\})$	8	0	32	**tri-gluon**
0^{-+}	$Tr(G\tilde{G})$	4	0	0	
$1^{\pm -}$	$Tr(G\{G, G\})$	6	1	15	**tri-gluon**
2^{++}	$Tr(G_{\mu\alpha}G_{\alpha\nu} - \frac{1}{4}\delta_{\mu\nu}G^2)$	4	2	4	
2^{++}	$E_i^a E_j^a - B_i^a B_j^a - trace$	4	2	4	
2^{-+}	$E_i^a B_j^a + B_i^a E_j^a - trace$	4	2	4	
$2^{\pm -}$	$Tr(G\{G, G\})$	6	2	16	**tri-gluon**

Glueball

$$S_{\mathscr{G}} = -\frac{1}{2}\int d^5x\sqrt{g_s}e^{-p\Phi}\left(\partial_M \mathscr{G}\partial^M \mathscr{G} + M^2_{\mathscr{G},5}(z)\mathscr{G}^2\right),$$

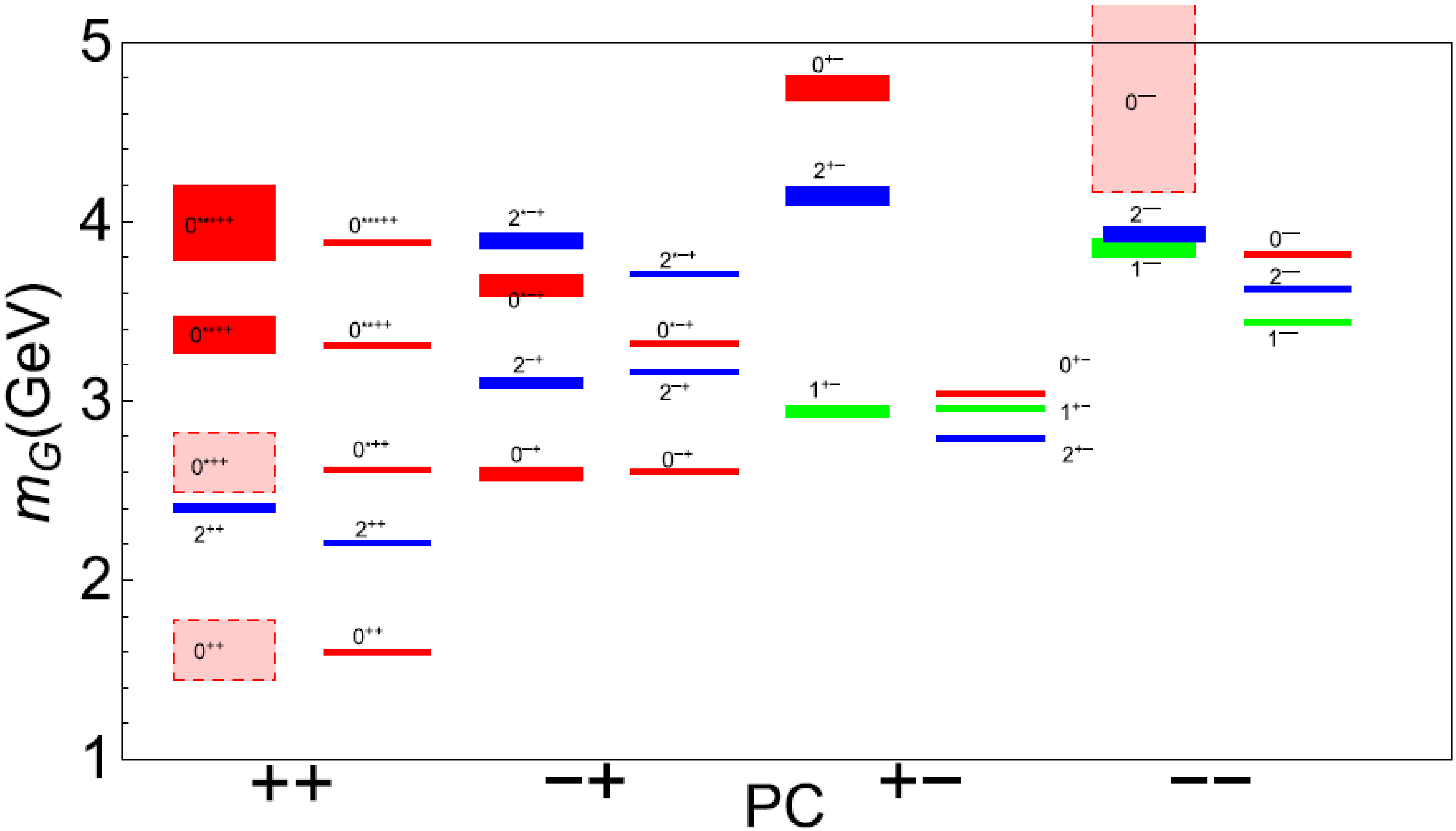
$$S_V = -\frac{1}{2}\int d^5x\sqrt{g_s}e^{-p\Phi}\left(\frac{1}{2}F^{MN}F_{MN} + M^2_{\mathscr{V},5}(z)\mathscr{V}^2\right),$$

$$S_T = -\frac{1}{2}\int d^5x\sqrt{g_s}e^{-p\Phi}\left(\nabla_L h_{MN}\nabla^L h^{MN} - 2\nabla_L h^{LM}\nabla^N h_{NM} + 2\nabla_M h^{MN}\nabla_N h\right.$$
$$\left. -\nabla_M h\nabla^M h + M^2_{h,5}(z)(h^{MN}h_{MN} - h^2)\right)$$

$M^2_5(z) = M^2_5 e^{-2\Phi/3}$, $p = 1$ for even parity and $p = -1$ for odd parity.

Glueball spectra:

Yidian Chen, M.H., **Chin.Phys. C40 (2016) no.12, 123101**



Agree well with lattice result except three trigluon glueball0^{--} , 0^{+-} and 2^{+-}

Glueball spectra: Yidian Chen, M.H., **Chin.Phys. C40 (2016) no.12, 123101**

J^{PC}	LQCD	Flux tube model	QCDSR	MDSM
0^{++}	1.475-1.73	1.52	1.5	1.593
0^{*++}	2.67-2.83	2.75	–	2.618
0^{**++}	3.37	–	–	3.311
0^{***++}	3.99	–	–	3.877
0^{-+}	2.59	2.79	2.05	2.606
0^{*-+}	3.64	–	–	3.317
0^{--}	5.166	2.79	3.81	3.817
0^{+-}	4.74	2.79	4.57	3.04
$0^{++\S}$	–	–	3.1	2.667
1^{+-}	2.94	2.25	–	2.954
1^{--}	3.85	–	–	3.44
2^{++}	2.4	2.84	2	2.203
2^{-+}	3.1	2.84	–	3.161
2^{*-+}	3.89	–	–	3.703
2^{+-}	4.14	2.84	6.06	2.786
2^{--}	3.93	2.84	–	3.619

In the DhQCD model, we have achieved:

1. QCD vacuum properties

   glueball spectra, light-flavor meson spectra,

   chiral symmetry breaking and linear confinement

2. QCD phase transitions

   deconfinement phase transition

   chiral phase transition

3. Equation of state for QCD matter

4. Transport properties for QCD matter

Work in progress:

Heavy flavor Hadron spectra?
Exotic states?
PDF?

Thanks for your attention!