Unraveling $K(1690)$ as a pseudoscalar $ud\bar{d}\bar{s}$ tetraquark state

报告人：张锦鹏
SUN YAT-SEN UNIVERSITY

Based on arxiv: 2507.05726
张锦鹏，陈绪梁，欧阳梓熙，俞祥，陈伟，吴佳俊

第八届强子谱与强子结构研讨会 7.13

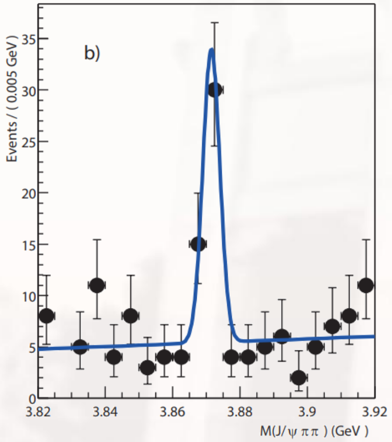
QCD and exotic hadron states

- Hadron can be classified as mesons and baryons.
- QCD allows existence of exotic structures. Glueball, hybrid, tetraquark…

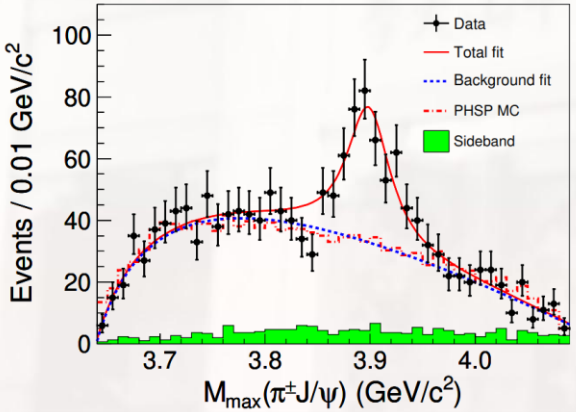
PLB, 205(2-3): 397-400. PLB, 313(1-2): 276-282. PRL, 129(19), 192002.

- Exotic quantum number ----- J^{PC}: $\pi_1(1400), \pi_1(1600), \eta_1(1855)$ ...

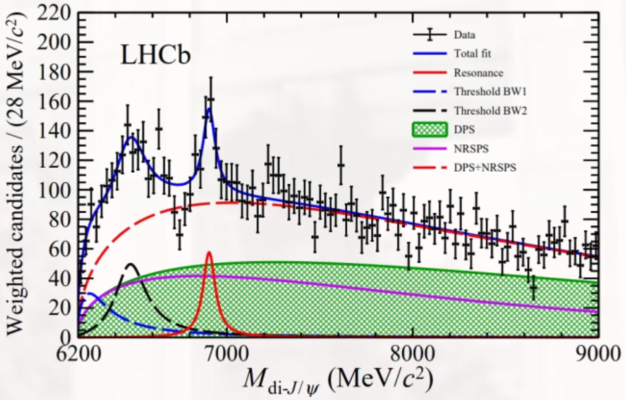
PRL, 91, 262001



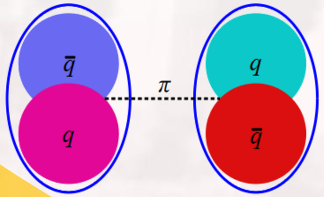
PRL, 110(25), 252001

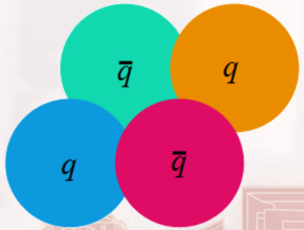


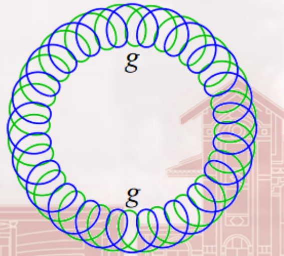
Sci. Bull. 65 (2020) 23

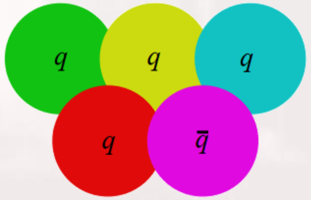


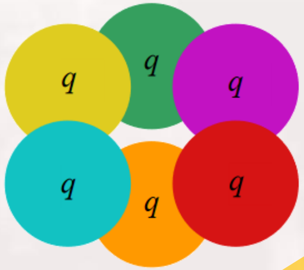
L	$S=0$	$S=1$
0	0^{-+}	1^{--}
1	1^{+-}	$0^{++}, 1^{++}, 2^{++}$
2	2^{-+}	$1^{--}, 2^{--}, 3^{--}$











A crypto-exotic $J^P = 0^-$ state

- Three resonance structures in P-wave ρK channel around (1.4,1.7,1.9)GeV.

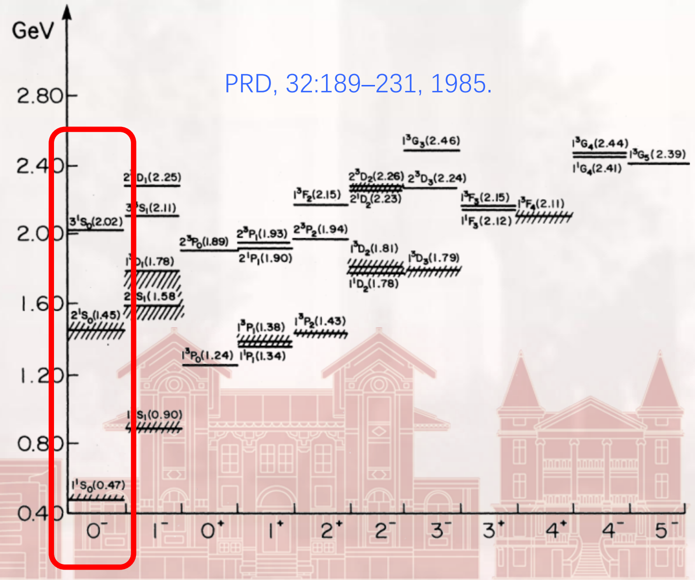
PRD, 79:114029, 2009 PRD, 32:189–231, 1985. PRD, 108(1):014034, 2023. EPJC, 77(12):861, 2017. EPJA, 59(3):40, 2023.

- QM predicts only two excited K meson below 2.5GeV
- Lightest--$K(1430)$ Heaviest--$K(1830)$
- Middle one -- $K(1690)$??? A candidate for exotic strange meson

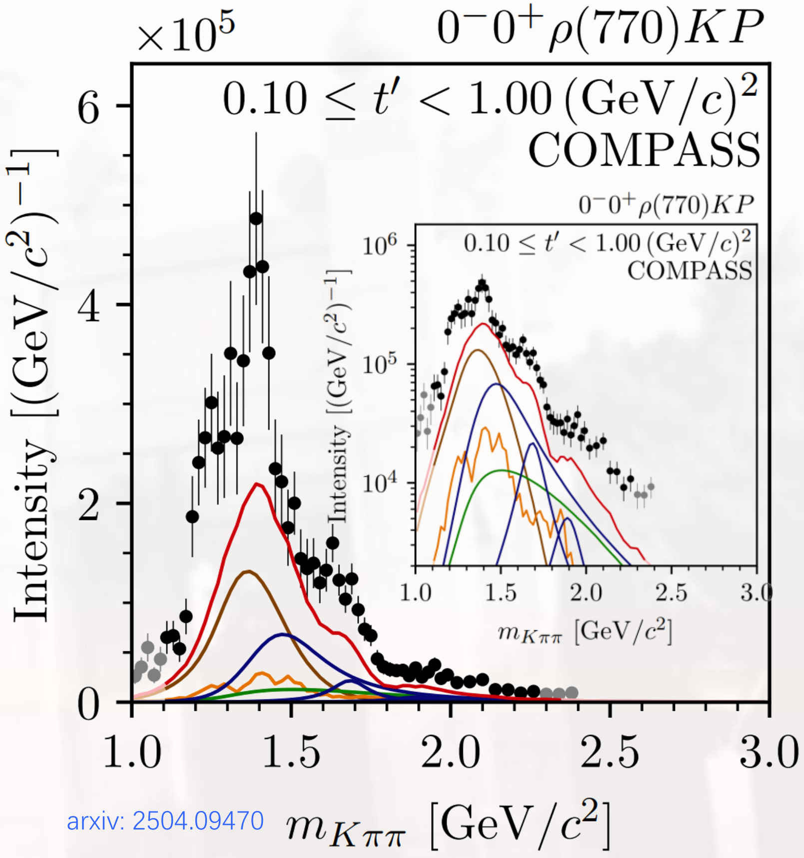
Tetraquark or hybrid meson ?

arxiv: 2504.09470		$K(1690)/K(1630)$	$K(1830)$
COMPASS	m_0 [MeV/c^2]	$1687 \pm 10^{+2}_{-67}$	$1893 \pm 17^{+13}_{-39}$
	Γ_0 [MeV/c^2]	$140 \pm 20^{+50}_{-50}$	$160 \pm 40^{+60}_{-80}$
PDG	m_0 [MeV/c^2]	1629 ± 7	$1874 \pm 43^{+59}_{-115}$
	Γ_0 [MeV/c^2]	16^{+19}_{-16}	$168 \pm 90^{+208}_{-104}$

$J^P = ?^?$ of $K(1630)$



PRD, 32:189–231, 1985.



arxiv: 2504.09470

Bule-resonance components

QCD Sum Rules

Quark-gluon level: Operator product expansion (OPE)

$$\Pi(q^2) = \sum C_n(q^2)\langle \mathcal{O}_n \rangle$$

Start from two-point correlation function

$$\Pi(q^2) = i\int d^4x\, e^{iqx}\langle 0|T[J(x)J^+(0)]|0\rangle$$

Hadron level:
Dispersion relation and

$$\rho(q^2) = f_X^2\delta(q^2 - m^2) + \cdots$$

Quark-hadron duality, Boral transform

$$f_X^2 e^{-m^2/M_B^2} = \int_0^{s_0} \rho(s) e^{-s/M_B^2} ds$$

Mass m and decay constant f_X

$K(1690)$ – pseudoscalar Tetraquark $uq\bar{q}\bar{s}$?

- There exist 10 $J^P = 0^-$ tetraquark currents
- Up to dimension-8: $\langle\bar{q}q\rangle, \langle g^2G^2\rangle, \langle\bar{q}q\rangle^2, \langle\bar{q}Gq\rangle, \langle g^3fG^3\rangle$
  $\langle\bar{q}GDq\rangle, \langle\bar{q}(DG)q\rangle, \langle\bar{q}q\rangle\langle g^2G^2\rangle, \langle\bar{q}q\rangle\langle\bar{q}Gq\rangle$

$$6_F\otimes\bar{6}_F(S)\begin{cases} S_6 = u_a^T C d_b(\bar{d}_a\gamma_5 C\bar{s}_b^T + \bar{d}_b\gamma_5 C\bar{s}_a^T) \\ V_6 = u_a^T C\gamma_5 d_b(\bar{d}_a C\bar{s}_b^T + \bar{d}_b C\bar{s}_a^T) \\ T_3 = u_a^T C\sigma_{\mu\nu} d_b(\bar{d}_a\sigma_{\mu\nu}\gamma_5 C\bar{s}_b^T - \bar{d}_b\sigma_{\mu\nu}\gamma_5 C\bar{s}_a^T) \end{cases}$$

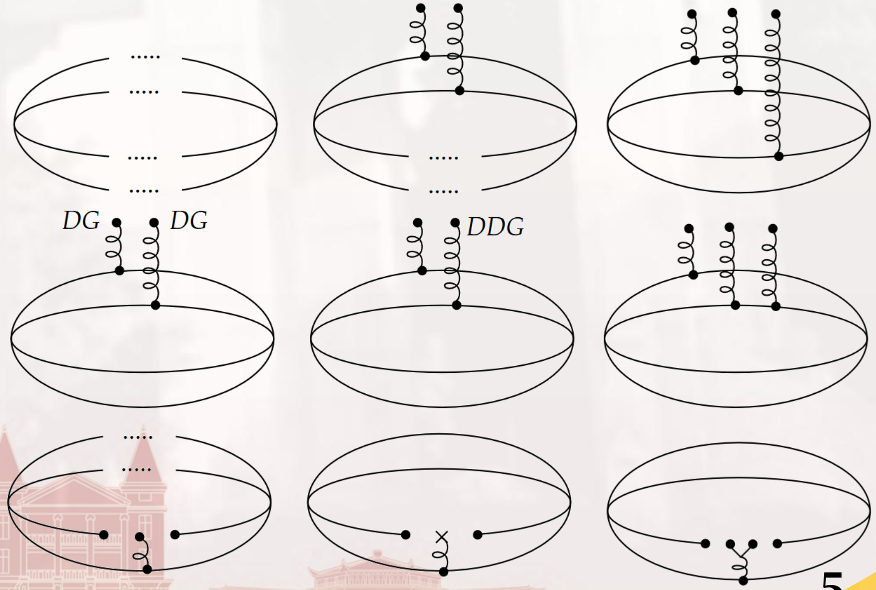
$$\bar{3}_F\otimes 3_F(A)\begin{cases} S_3 = u_a^T C d_b(\bar{d}_a\gamma_5 C\bar{s}_b^T - \bar{d}_b\gamma_5 C\bar{s}_a^T) \\ V_3 = u_a^T C\gamma_5 d_b(\bar{d}_a C\bar{s}_b^T - \bar{d}_b C\bar{s}_a^T) \\ T_6 = u_a^T C\sigma_{\mu\nu} d_b(\bar{d}_a\sigma_{\mu\nu}\gamma_5 C\bar{s}_b^T + \bar{d}_b\sigma_{\mu\nu}\gamma_5 C\bar{s}_a^T) \end{cases}$$

$$\bar{3}_F\otimes\bar{6}_F(M)\begin{cases} A_6 = u_a^T C\gamma_\mu d_b(\bar{d}_a\gamma_\mu\gamma_5 C\bar{s}_b^T + \bar{d}_b\gamma_\mu\gamma_5 C\bar{s}_a^T) \\ P_3 = u_a^T C\gamma_\mu\gamma_5 d_b(\bar{d}_a\gamma_\mu C\bar{s}_b^T - \bar{d}_b\gamma_\mu C\bar{s}_a^T) \end{cases}$$

$$6_F\otimes 3_F(M)\begin{cases} P_6 = u_a^T C\gamma_\mu\gamma_5 d_b(\bar{d}_a\gamma_\mu C\bar{s}_b^T + \bar{d}_b\gamma_\mu C\bar{s}_a^T) \\ A_3 = u_a^T C\gamma_\mu d_b(\bar{d}_a\gamma_\mu\gamma_5 C\bar{s}_b^T - \bar{d}_b\gamma_\mu\gamma_5 C\bar{s}_a^T) \end{cases}$$

Convergence $$\left|\frac{\Pi_{D=6}(M_B^2)}{\Pi_{\rm pert}(M_B^2)}\right| \leqslant 25\%, \left|\frac{\Pi_{D=8}(M_B^2)}{\Pi_{\rm pert}(M_B^2)}\right| \leqslant 10\%.$$

Pole Contribution $$\frac{L_0(s_0, M_B^2)}{L_0(\infty, M_B^2)} \geqslant 10\%$$



$\langle g^3 fG^3\rangle$ in QCD Sum Rules

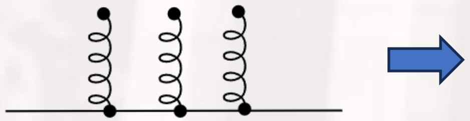
- Vacuum condensates are important in QCDSR. $\langle\bar{q}q\rangle, \langle g^2G^2\rangle, \langle\bar{q}q\rangle^2, \langle\bar{q}Gq\rangle, \langle g^3fG^3\rangle$ ...
- Tri-gluon condensate $\langle g^3fG^3\rangle$ is usually neglected.

PLB 110 (1982) 476 NPB 213 (1983) 285–304 CPC 45 (9) (2021) 093103.

- Its contribution is unimportant in systems with heavy quarks.
- Complexity: too many diagrams. There exist 7 diagrams in LO of $\langle g^3fG^3\rangle$

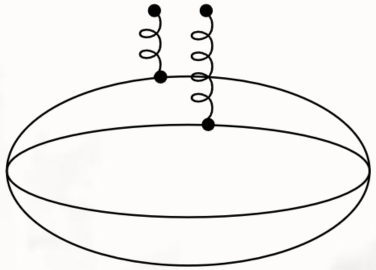
$$\text{diagrams } of\ \langle g^3fG^3\rangle > \langle\bar{q}q\rangle + \langle g^2G^2\rangle + \langle\bar{q}q\rangle^2 + \langle\bar{q}Gq\rangle$$

- Unavoidable IR divergence:

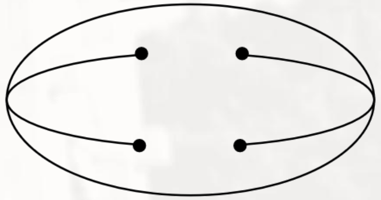


$$S^{ij}_{\langle GGG\rangle}(x) = \frac{-i\delta_{ij}\langle g^3 fG^3\rangle\Gamma\left(\frac{d}{2}-2\right)\not{x}}{9216 d\pi^{d/2}(-x^2)^{d/2-3}},$$

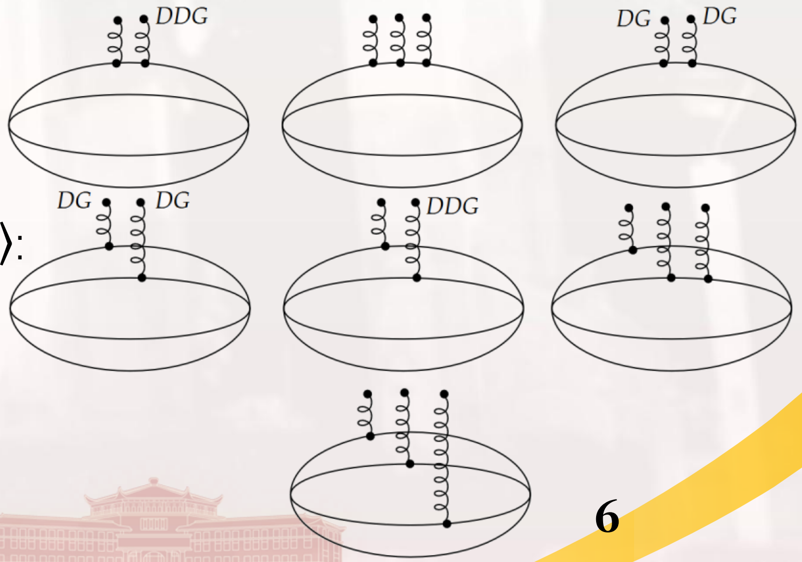
$\langle g^2G^2\rangle$:



$\langle\bar{q}q\rangle^2$:

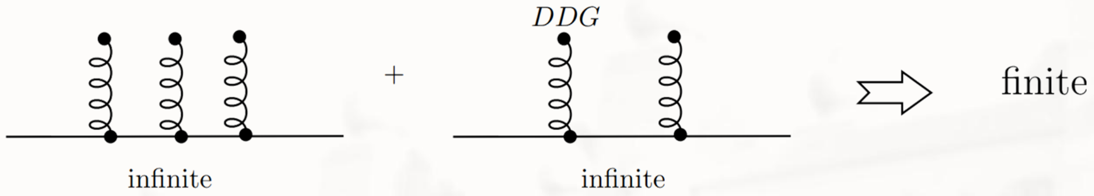


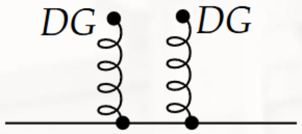
$\langle g^3fG^3\rangle$:



IR safety of $\langle g^3 fG^3\rangle$ in QCD Sum Rules

- IR safety for the single quark propagator. (ignore $g^4\langle\bar{q}q\rangle^2$)

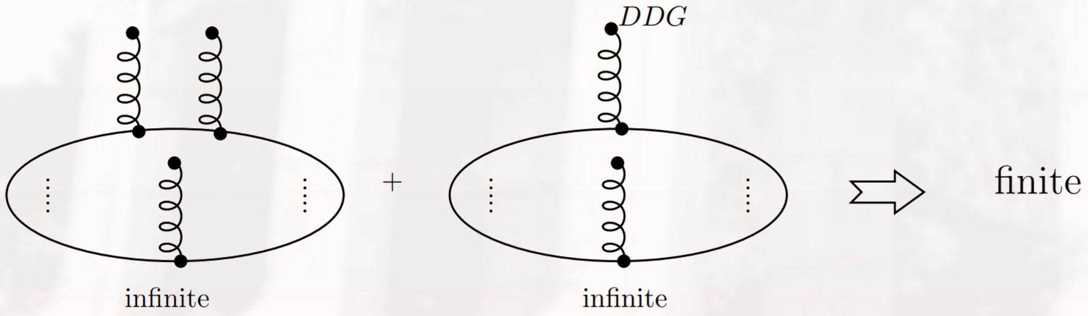


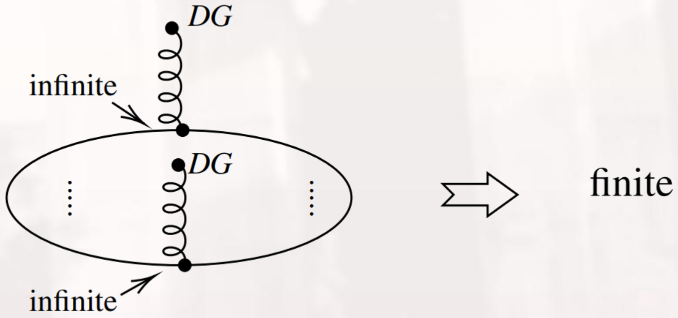


$$= \frac{-i\delta_{ij}\langle g^3 fG^3\rangle\Gamma\left(\frac{d}{2}-1\right)\not{x}}{1728d(d+2)\pi^{d/2}(-x^2)^{d/2-3}}$$

Must be calculated in d-dimensional !
Propagator and condensate.

- IR safety for the two different quark propagators.



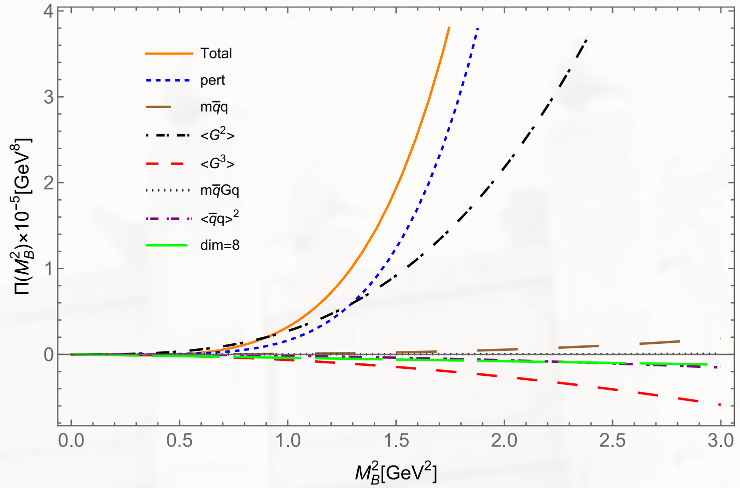


The LO of $\langle g^3 fG^3\rangle$ can be fully calculated.

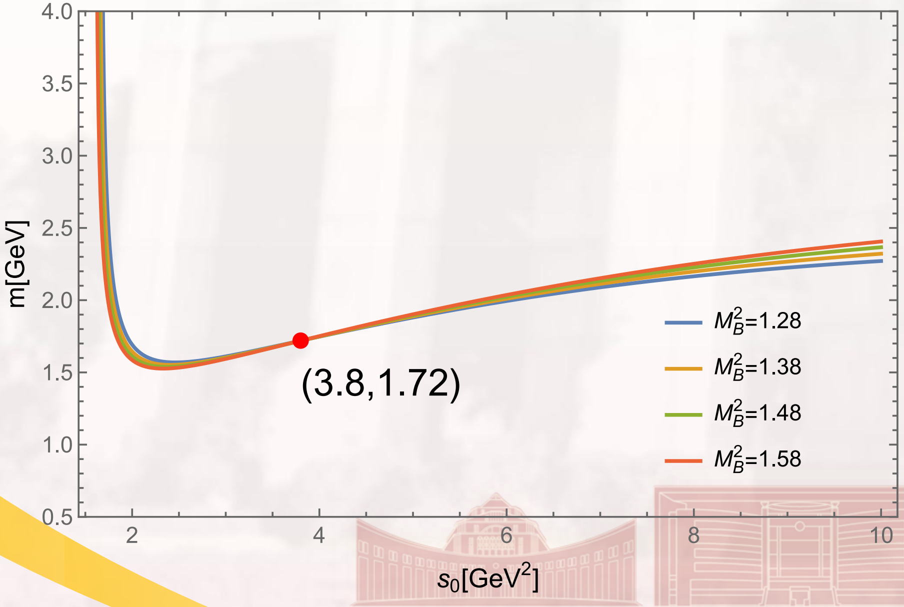
The impact of $\langle g^3 f G^3 \rangle$

- Take current P_3 as an example. Contribution

$$\Pi^{\text{pert}} > \Pi^{\langle G^2 \rangle} > \Pi^{\langle G^3 \rangle} > \Pi^{\langle \bar{q} q \rangle^2} > \cdots$$

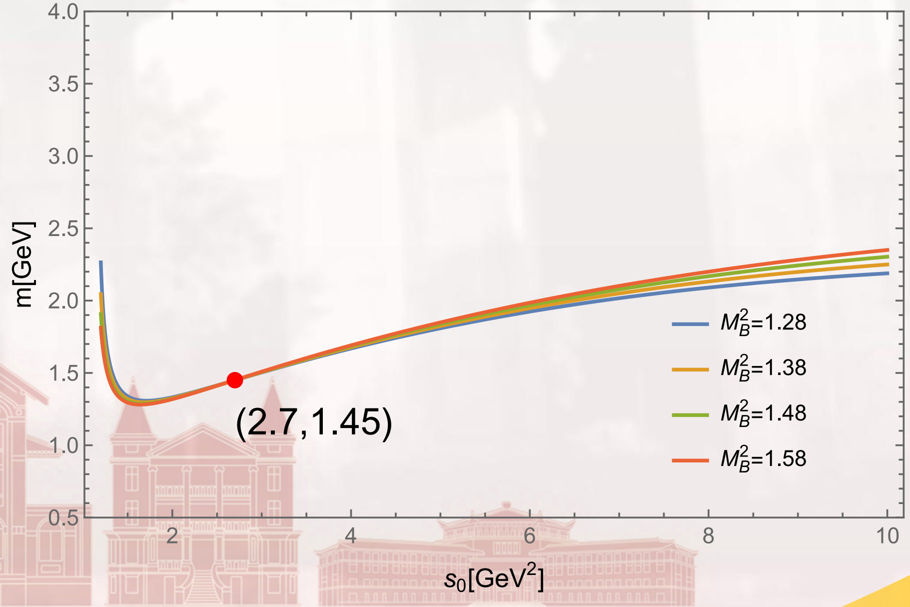


With $\langle g^3 f G^3 \rangle$



Differ by 20%!

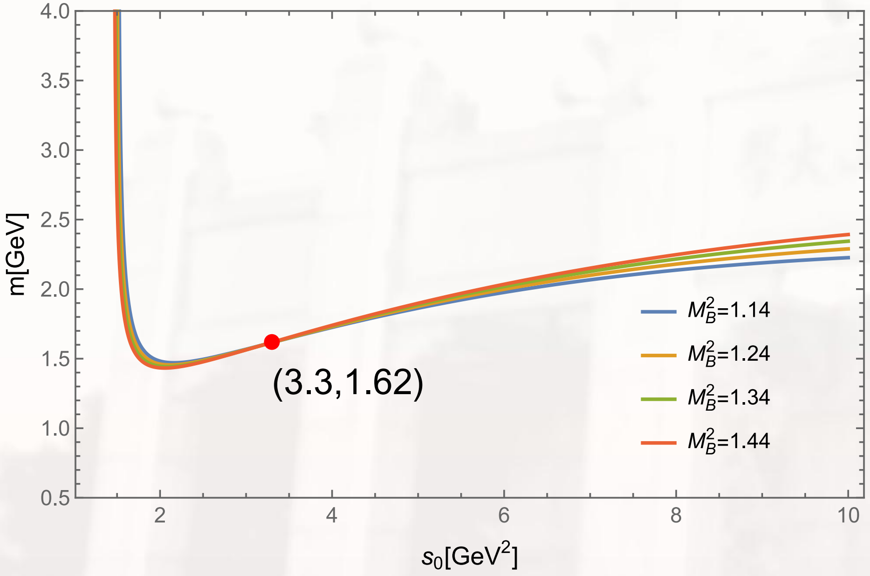
Without $\langle g^3 f G^3 \rangle$



The impact of $\langle g^3 f G^3 \rangle$

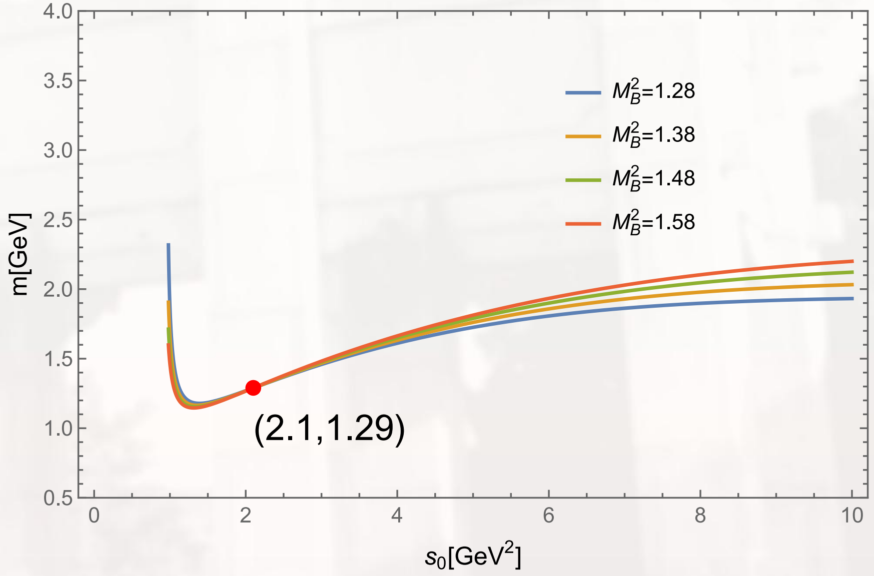
- Take current P_6 as another example.

With $\langle g^3 f G^3 \rangle$



Differ by 25%!

Without $\langle g^3 f G^3 \rangle$



$\langle g^3 f G^3 \rangle$ provides significant contribution in light tetraquark systems!

Results for $ud\bar{d}\bar{s}$

- Uncertainty is from s_0, condensates and m_s.

Currents	$s_0(\pm 0.2\,\mathrm{GeV}^2)$	$M_B^2\ (\mathrm{GeV}^2)$	m (GeV)	PC(%)
P_6	3.3	$1.14 \sim 1.35$	1.62 ± 0.10	> 15
P_3	3.8	$1.28 \sim 1.50$	1.72 ± 0.10	> 20
V_3	3.3	$1.42 \sim 1.62$	1.60 ± 0.16	> 10
A_3	2.8	$0.95 \sim 1.20$	1.48 ± 0.20	> 10
T_6	2.4	$0.75 \sim 1.10$	1.36 ± 0.05	> 15
T_3	4.7	$0.90 \sim 1.35$	1.92 ± 0.04	> 25

1.Masses of currents (P_6, P_3, V_3) are consistent with $K(1690)$

3.(A_3, T_6) and T_3 are close to $K(1460)$ and $K(1830)$

Summary

- Complete $\langle g^3 f G^3 \rangle$ provides significant contribution in light tetraquark systems.
- 10 currents for 0^- $ud\bar{d}\bar{s}$ have been calculated by QCDSR.
- The masses of currents (P_6, P_3, V_3) are consistent with $K(1690)$

Thank you!

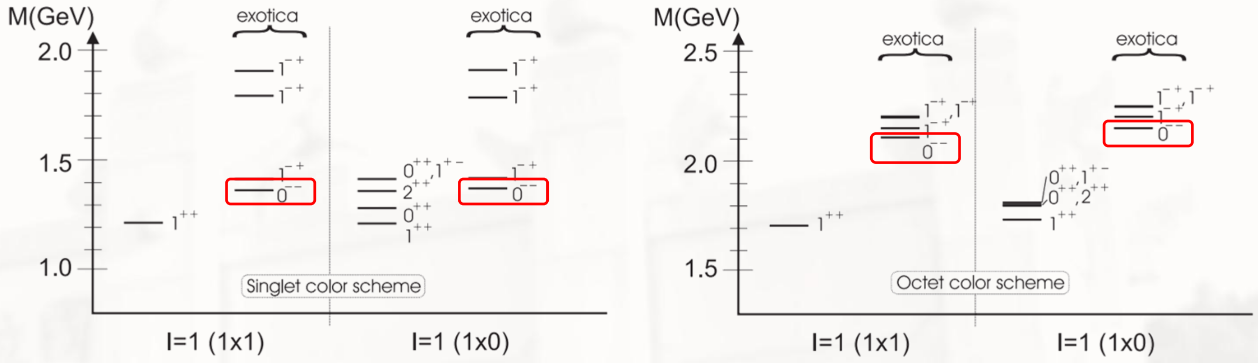
Related research

- QCD Coulomb gauge approach

EPJA 31 (2007) 656–661 PLB 653 (2007) 216–223.

$qq\bar{q}\bar{q}$ 0^{--}: ~1.36GeV(singlet color)

~2.1GeV(octet color)



- Cornell potential-based phenomenology

arXiv:2505.01195.

Table 1: S Wave SSSQ All units are in MeV.

State	J^P	T_{sssq} $\bar{3}\otimes 3$ M_{SR}	T_{sssq} $\bar{3}\otimes 3$ M_{NR}	T_{sssq} $6\otimes\bar{6}$ M_{SR}	T_{sssq} $6\otimes\bar{6}$ M_{NR}	T_{sqqq} $\bar{3}\otimes 3$ M_{SR}	T_{sqqq} $\bar{3}\otimes 3$ M_{NR}	T_{sqqq} $6\otimes\bar{6}$ M_{SR}	T_{sqqq} $6\otimes\bar{6}$ M_{NR}
1^1S_0		1688.83	1845.90	1161.27	899.72	1439.99	1239.35	1631.54	739.30
2^1S_0	0^+	2705.68	2797.19	2932.67	3104.81	2470.83	2790.35	2595.88	2973.53
3^1S_0		3181.37	3280.76	3879.06	4055.92	2962.87	3091.70	3749.25	3932.74
1^3S_1		1871.25	1998.89	-	-	1653.02	1804.26	-	-
2^3S_1	1^+	2754.48	2840.05	-	-	2535.26	2647.59	-	-
3^3S_1		3214.45	3306.98	-	-	3003.36	3122.71	-	-
1^5S_2		2338.73	2300.37	-	-	2070.76	2140.97	-	-
2^5S_2	2^+	2852.10	2918.98	-	-	2658.23	2742.72	-	-
3^5S_2		3277.07	3359.33	-	-	3083.88	3187.37	-	-
1^1P_1		2635.17	2710.62	2706.09	2868.47	2415.16	2513.20	2561.05	2732.62
2^1P_1	1^-	3091.39	3175.25	3692.30	3850.09	2876.64	2985.56	3552.21	3721.48
3^1P_1		3455.38	3554.63	4403.68	4580.34	3248.90	3374.29	4278.30	4463.72
1^3P_0		2314.79	2390.20	1010.72	1151.97	2082.28	2180.37	841.42	988.89
2^3P_0	0^-	2821.00	2905.99	2353.68	2501.65	2590.99	2701.27	2173.36	2327.59
3^3P_0		3206.10	3304.82	3204.07	3376.79	2982.91	3109.17	3034.28	3212.69

QCDSR

PRD 79 (2009) 114034 0^{--} currents for $qq\bar{q}\bar{q}$

All currents give results over 2GeV

PRD 95 (2017) 7, 076017 1^{+-} currents $qq\bar{q}\bar{q}$

~1.66GeV for 0^{--}