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

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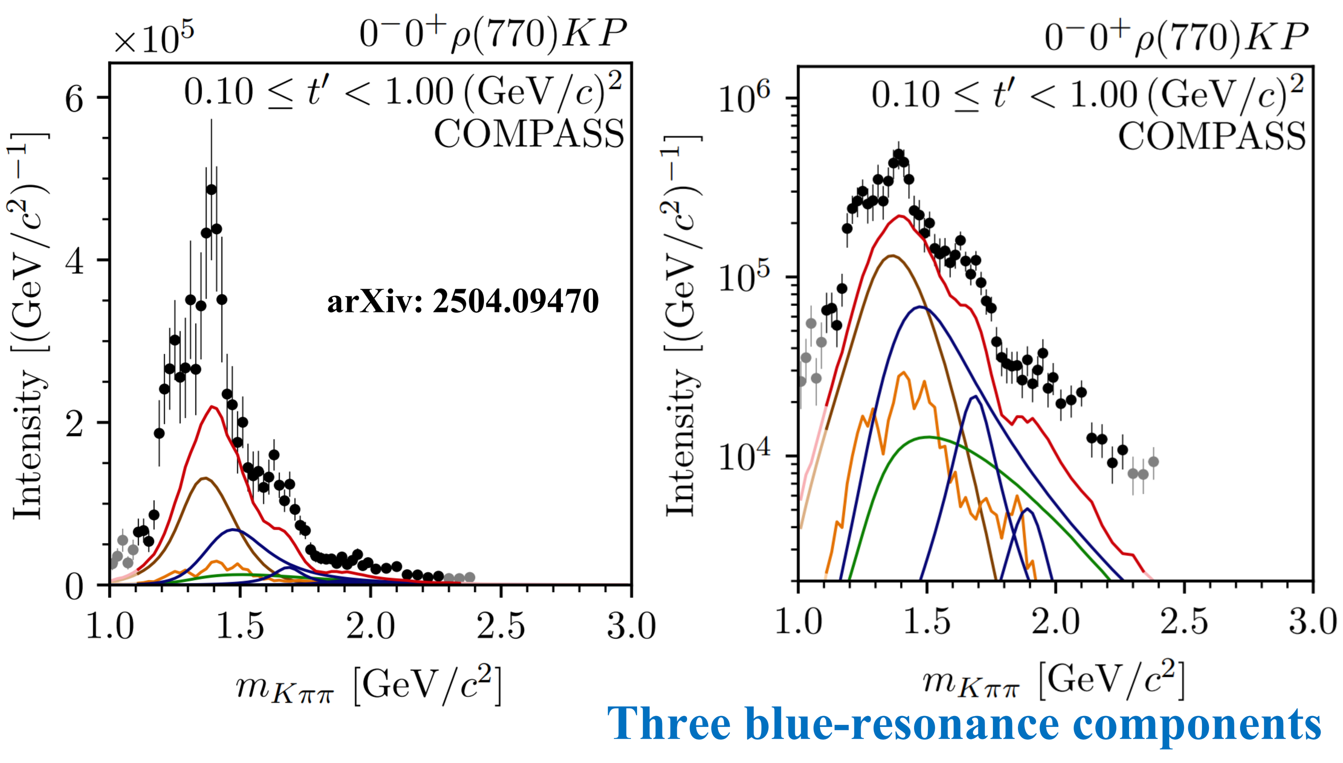
## Abstract

The recent observed $K(1690)$ has been identified as a supernumerary pseudoscalar resonance signal in the strange-meson spectrum predicted by quark model calculations. It is the best candidate of a strange crypto-exotic state. In this work, we systematically study the hadron masses of $ud\bar{d}\bar{s}$ tetraquark states with $J^P = 0^-$ in the method of QCD sum rules. We calculate the correlation functions up to dimension-8 nonperturbative condensates. To calculate the tri-gluon condensate, we comprehensively consider the contributions from different operators with and without covariant derivatives. The IR safety can be guaranteed for the completely calculated tri-gluon condensate by properly addressing the IR divergences in Feynman diagrams. It is demonstrated that the tri-gluon condensate provides significant contributions to the sum-rule analyses in these light tetraquark systems. Our results support the interpretation of $K(1690)$ resonance to be a pseudoscalar $ud\bar{d}\bar{s}$ tetraquark state.

## Background

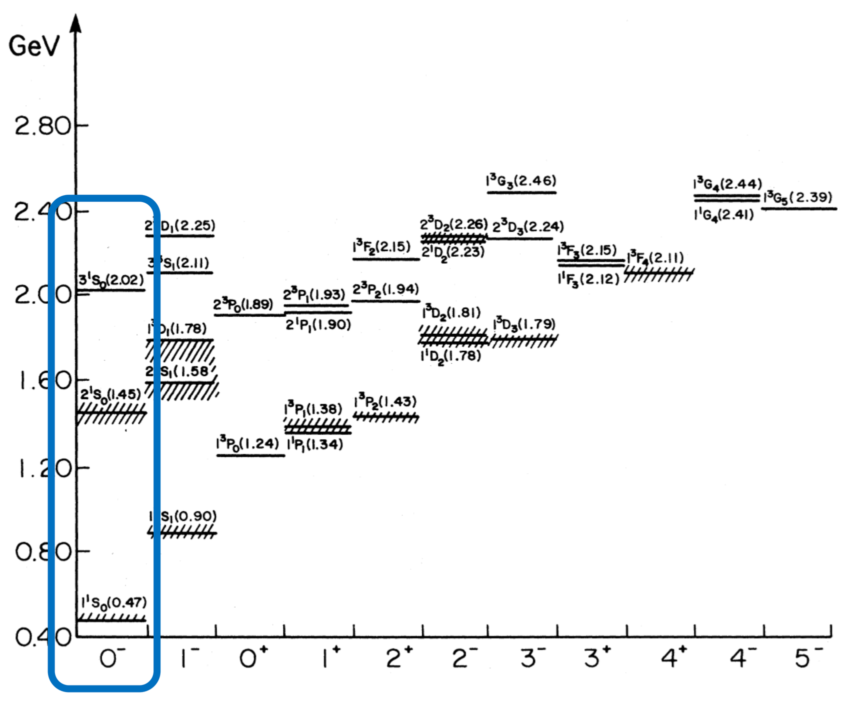
Recently, COMPASS Collaboration observed three resonance structures in the $\rho K$ channel with $J^P = 0^-$. The lightest and heaviest structures roughly match predictions by the quark model. The middle one $K(1690)$ can be considered as the clear candidate for a crypto-exotic state.




Three blue-resonance components

Spectroscopy of strange mesons predicted by the relativized quark model.

Phys. Rev. D 32 (1985) 189-231



$K(1690)$: $M = 1687 \pm 10^{+2}_{-67}$MeV
$\Gamma = 140 \pm 20^{+50}_{-50}$MeV

**$K(1690) \notin$ Quark Model**

## Formalism

QCD sum rules starts from the correlation functions:

$$\Pi(q^2) = \mathrm{i}\int \mathrm{d}^d x\, \mathrm{e}^{\mathrm{i}qx}\langle 0|T[J(x)J^\dagger(0)|0\rangle$$

The pseudoscalar tetraquarks currents with $J^P = 0^-$ ⟺

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

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

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

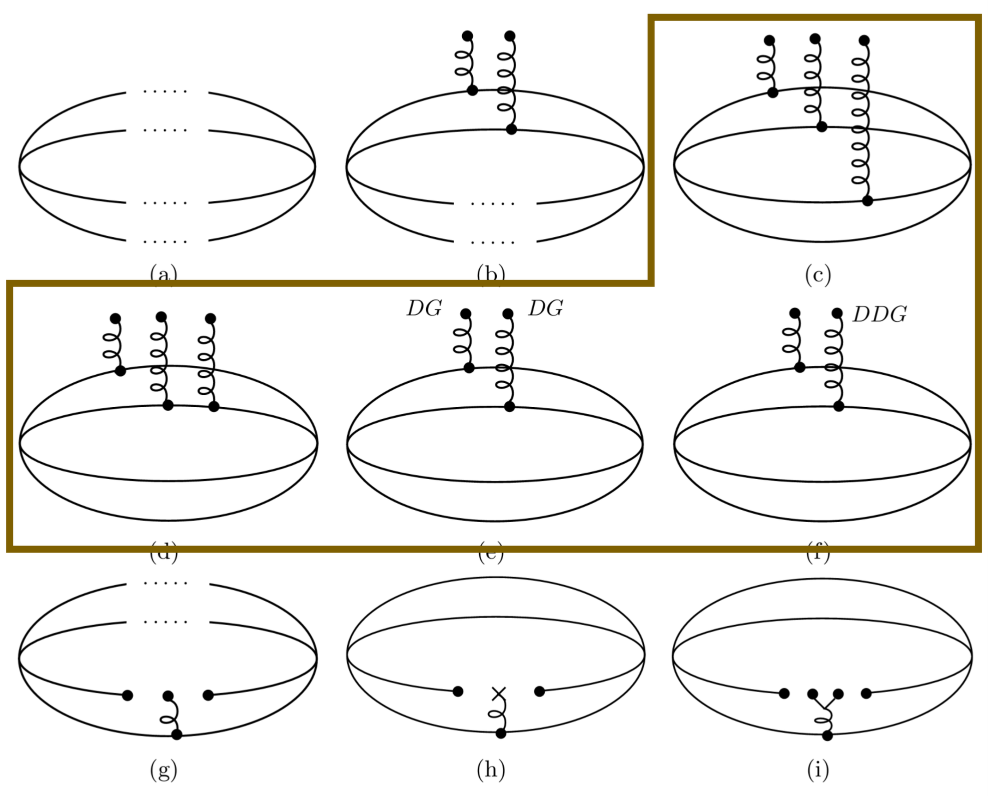
$$6_F \otimes 3_F(M)\begin{cases} P_6 = u_a^T C\gamma_\mu\gamma_5 d_b[\bar{d}_a\gamma_\mu C\bar{s}_b^T + (a\leftrightarrow b)] \\ A_3 = u_a^T C\gamma_\mu d_b[\bar{d}_a\gamma_\mu\gamma_5 C\bar{s}_b^T - (a\leftrightarrow b)]\end{cases}$$

The lowest lowing resonance

$$M_X = \sqrt{\frac{L_1(s_0,M_B^2)}{L_0(s_0,M_B^2)}} \quad L_k(s_0,M_B^2) = \int_0^{s_0}\rho(s)s^k \mathrm{e}^{-s/M_B^2}\mathrm{d}s$$

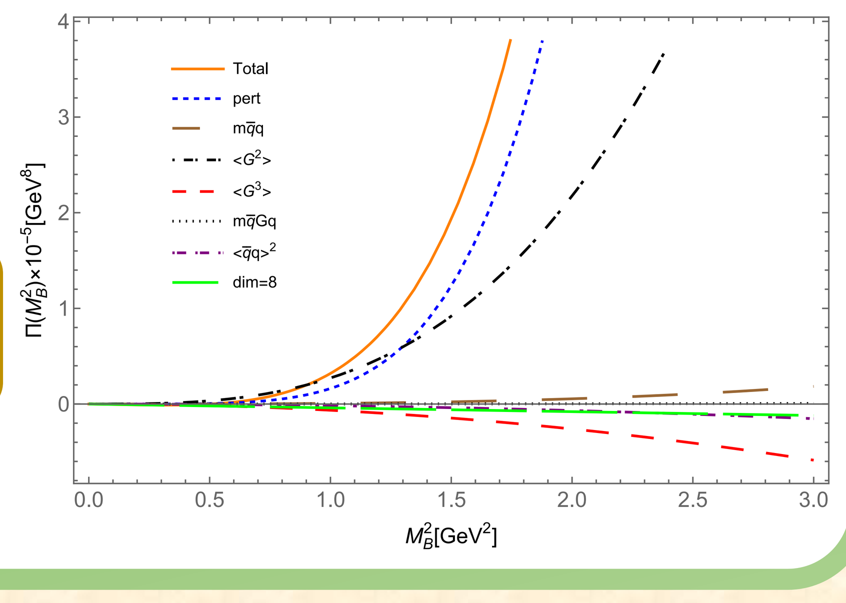
The Feynman diagrams involved in our calculations

Containing IR divergence



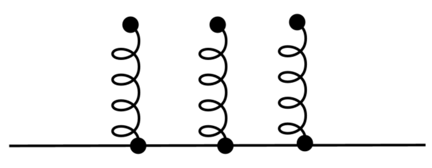

OPE convergence

Contribution: $\Pi^{\mathrm{pert}} > \Pi^{\langle G^2\rangle} > \Pi^{\langle G^3\rangle} > \dots$



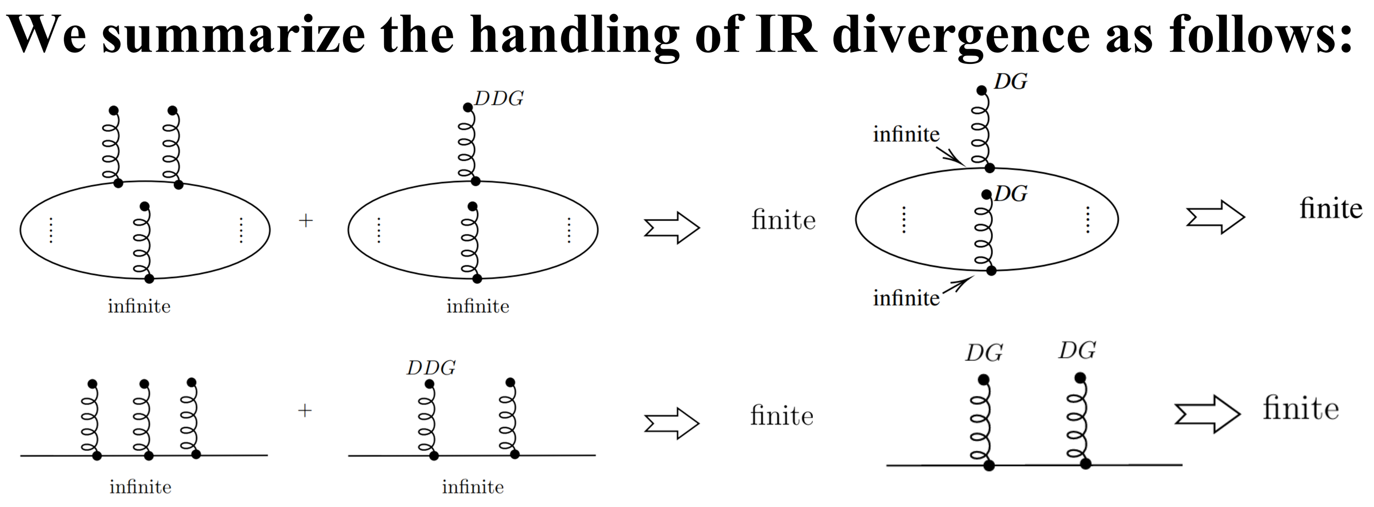

## IR safety for $\langle g^3 fG^3\rangle$

The LO of $\langle g^3 fG^3\rangle$ contains IR divergence:

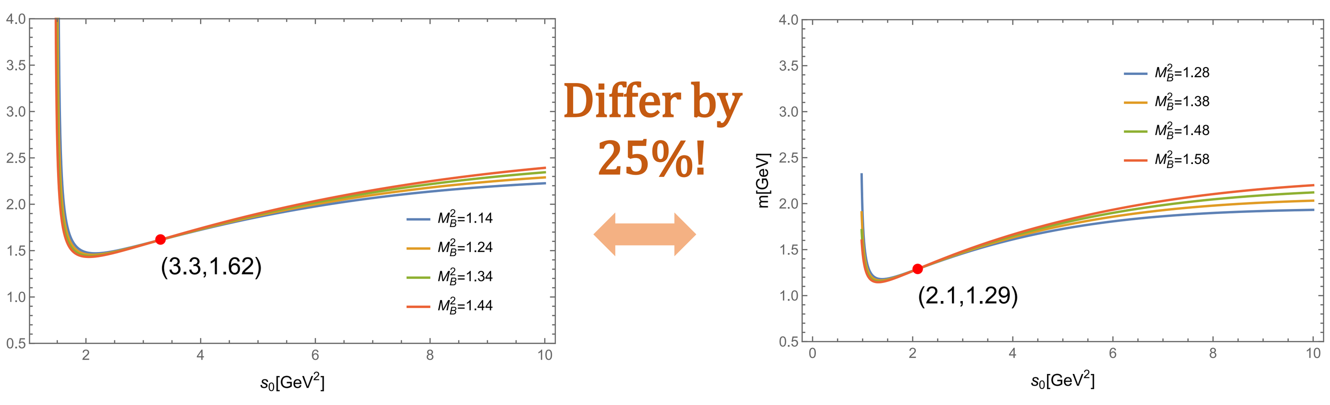


$$= S^{ij}_{\langle GGG\rangle}(x) = \frac{-\mathrm{i}\delta^{ij}\langle g^3 fG^3\rangle \boxed{\Gamma\left(\frac{d}{2}-2\right)} \not{x}}{9216 d\pi^{d/2}(-x^2)^{d/2-3}}$$

We summarize the handling of IR divergence as follows:

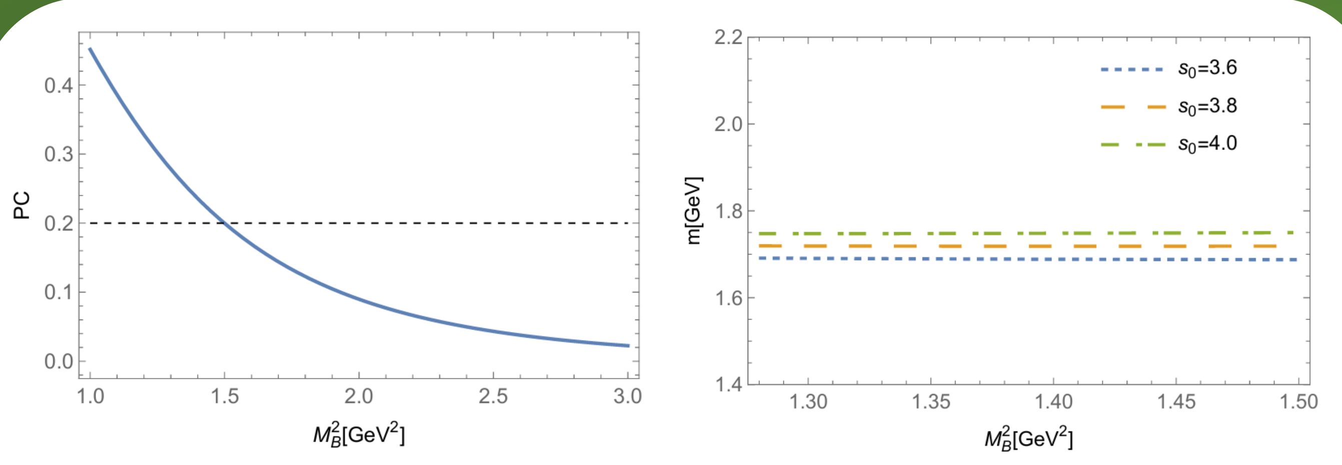



Then $\langle g^3 fG^3\rangle$ can be completely calculated at the LO of $\alpha_s$. Our results indicate well-calculated $\langle g^3 fG^3\rangle$ is important and cannot be neglected.




Current $P_6$ with $\langle g^3 fG^3\rangle$ Current $P_6$ without $\langle g^3 fG^3\rangle$

## Tetraquark interpretation




Pole contribution and mass for current $P_3$

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

Masses of $(P_6, P_3, V_3)$ are consistent with $K(1690)$, supporting the interpretation of it as a tetraquark state. $(A_3, T_6)$ and $T_3$ are close to $K(1460)$ and $K(1830)$.

## References

[1] arXiv: 2507.05726 [2] Phys. Rev. D 32 (1985) 189-231
[3] arXiv: 2504.09470 [4] Phys. Rev. D 79 (2009) 114029

## Summary

- The $K(1690)$ observed by COMPASS can be considered as a candidate for a crypto-exotic state with $J^P = 0^-$.
- We summarize the cancellation laws of IR divergence in the leading-order of $\langle g^3 fG^3\rangle$.
- Well-calculated $\langle g^3 fG^3\rangle$ is important to the fully-light tetraquark sum rule analyses.
- Our results support the interpretation of $K(1690)$ as a compact tetraquark state.

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