The Z_{cs} states and the mixture of hadronic molecule and diquark-anti-diquark components within effective field theory

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arXiv:2205.11150

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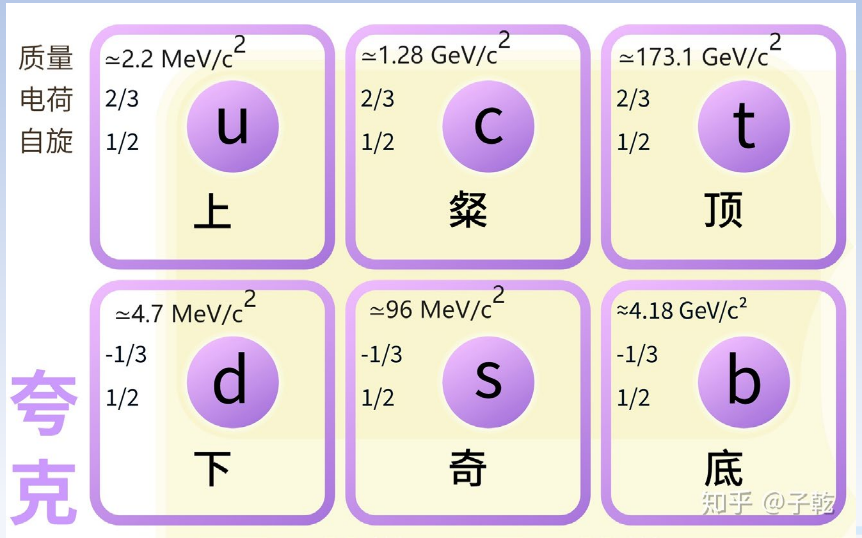
Introduction



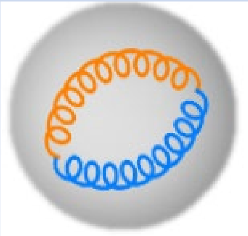
Murray Gell-Mann
1929-2019

Meson: A pair of quark and anti-quark

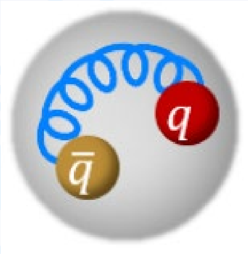
Baryon: three quarks

Exotic hadron

- Glueball： $N_q = 0, N_g \geq 2$

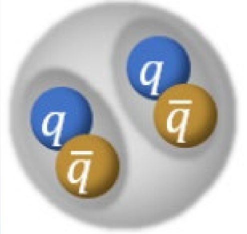


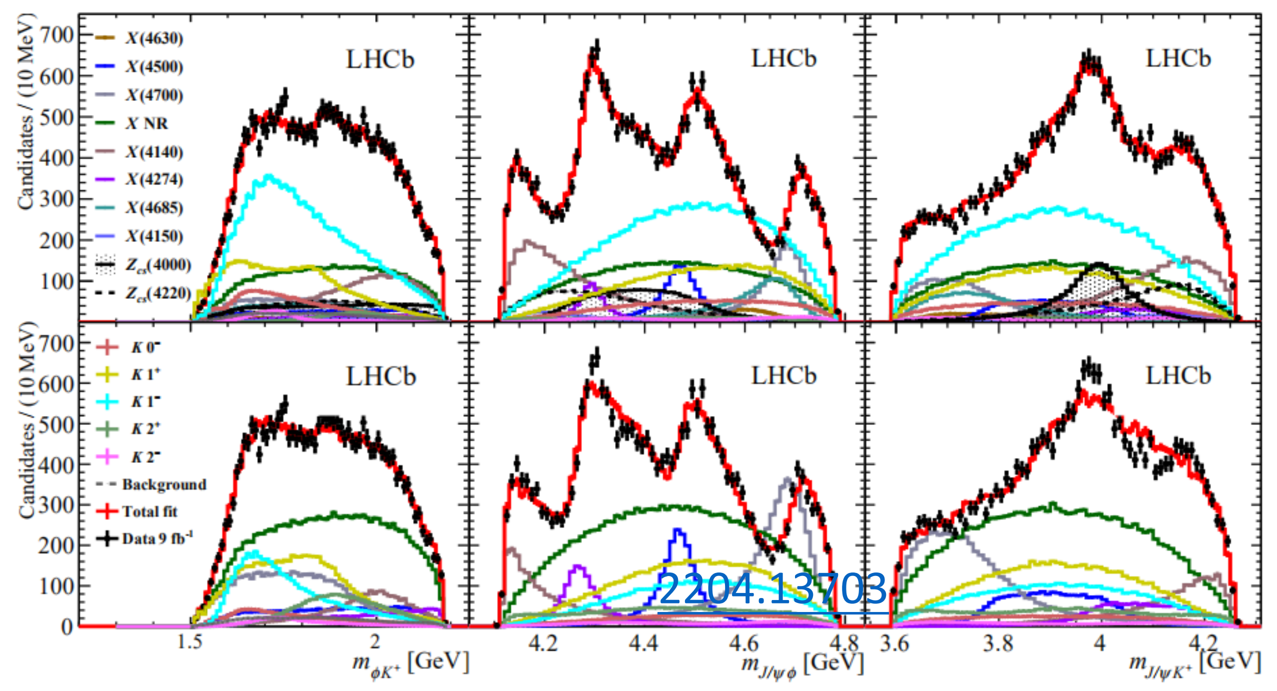
- Hybrid： $N_q \geq 2, N_g \geq 1$

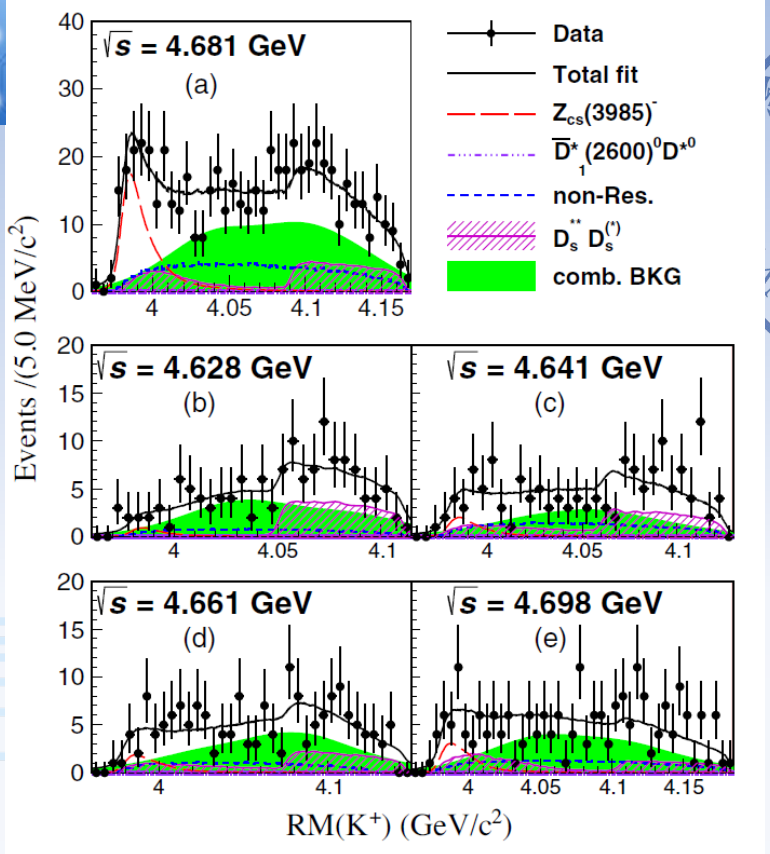


- Multiquark state: $N_q \ > 3$

- Molecule: $N_Q \ \geq 2$







$Z_{cs}(4000)^+$： M=4003 ± 6^{+4}_{-14} MeV， Γ =131 ± 15 ± 26 MeV

$Z_{cs}(4220)^+$： M=4216 ± 24^{+43}_{-30} MeV， Γ =233 ± 52^{+97}_{-73} MeV

The first observation of exotic states with a new quark content $c\bar{c}u\bar{s}$ decaying to the $J/\psi K^+$ final state is reported with high significance from an amplitude analysis of the $B^+ \to J/\psi\phi K^+$ decay.

Spin-Parity： $J^P = 1^+$

Isospin： I=$\frac{1}{2}$

Phys. Rev. Lett. 127, 082001

Respectively, the BESIII Collaboration reported a new resonance through the processes of $e^+e^- \longrightarrow K^+ D_s^- D^{*0}$ and $K^+ D_s^{*-} D^0$ based on e^+e^- annihilation samples collected

$Z_{cs}(3985)^-$: M= $3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV， Γ =$12.8^{+5.3}_{-4.4} \pm 3.0$ MeV

Phys.Rev.Lett.126.102001

The neutral isospin partner $Z_{cs}(3985)^0$ arXiv:2204.13703

Theoretical research

D.-Y. Chen, X. Liu, and T. Matsuki, *Predictions of charged charmoniumlike structures with hidden-charm and open-strange channels*, Phys. Rev. Lett. 110 (2013) 232001, arXiv:1303.6842.

J. M. Dias, X. Liu, and M. Nielsen, *Prediction for the decay width of a charged state near the $D_s\bar{D}^*/D_s^*\bar{D}$ threshold*, Phys. Rev. D88 (2013) 096014, arXiv:1307.7100.

The prediction of the decay width of a charged state near the $D_s\bar{D}^*/D_s^*\bar{D}$ threshold

Table: Coupling constants and decay widths in different channels

Vertex	coupling constant (GeV)	decay width (MeV)
$Z_{cs}^+ J/\psi K^+$	2.58 ± 0.30	11.2 ± 3.5
$Z_{cs}^+ \eta_c K^{*+}$	3.4 ± 0.3	10.8 ± 6.2
$Z_{cs}^+ D_s^+ \bar{D}^{*0}$	1.4 ± 0.3	1.5 ± 1.5
$Z_{cs}^+ \bar{D}^0 D_s^{*+}$	1.4 ± 0.4	1.4 ± 1.4

M. B. Voloshin, Phys. Lett. B **798**, 135022 (2019) doi:10.1016/j.physletb.2019.135022 [arXiv:1901.01936 [hep-ph]].

It has been recently suggested that the charged charmoniumlike resonances $Z_c(4100)$ and $Z_c(4200)$ are two states of hadrocharmonium, related by the charm quark spin symmetry in the same way as the lowest charmonium states η_c and J/ψ. It is pointed out here that in this picture one might expect existence of their somewhat heavier strange counterparts, Z_{cs}, decaying to $\eta_c K$ and $J/\psi K$. Some expected properties of such charmoniumlike strange resonances are discussed that set benchmarks for their search in the decays of the strange B_s mesons.

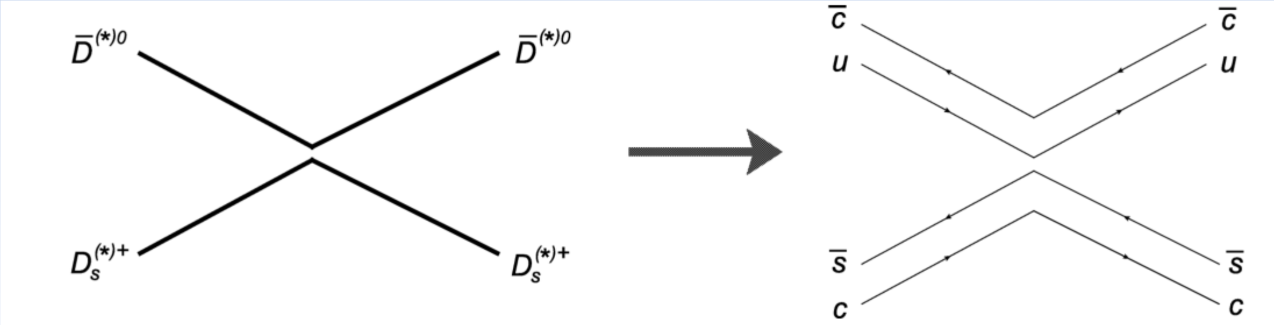
molecular, compact tetraquark or the mixture of them:

L. Meng, B. Wang and S. L. Zhu, Phys. Rev. D 102, no.11, 111502 (2020) doi:10.1103/PhysRevD.102.111502
Z. H. Guo and J. A. Oller, Phys. Rev. D 103, no.5, 054021 (2021) doi:10.1103/PhysRevD.103.054021
……

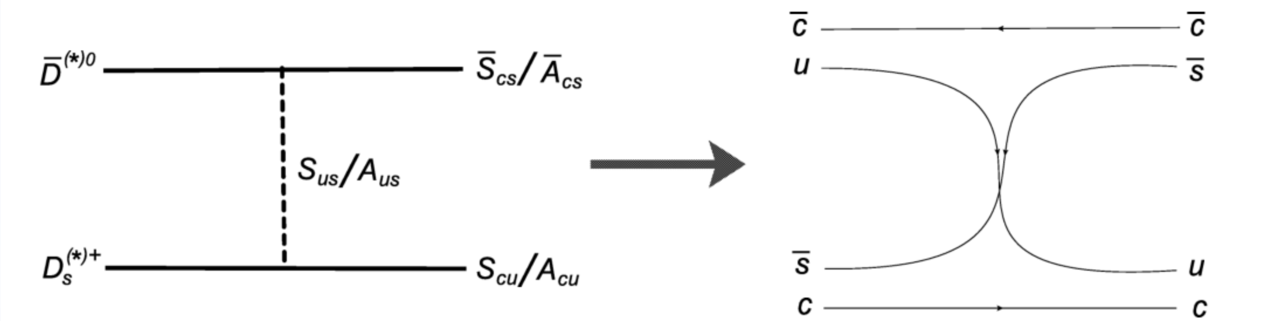
other theoretical works:

J. Z. Wang, Q. S. Zhou, X. Liu and T. Matsuki, Eur. Phys. J. C 81, no.1, 51 (2021) doi:10.1140/epjc/s10052-021-08877-4
……

Research motivation



- the heavy quarks can be seen as spectators in hadrons.
- the light-meson exchange is dominant in the charmed and anti-charmed mesons interactions.
- the effective potentials are suppressed by the Okubo-Zweig-Iizuka (OZI)rule.



So , we have to consider the Lagrangian containing meson-diquark interaction……

The Lagrangian containing meson-diquark interaction

In this work, we extend the hidden local symmetry to the meson-diquark interaction sector, considering as well the chiral symmetry, parity, and charge conjugation. The constructed Lagrangian is shown below

$$
\begin{aligned}
\mathcal{L} = {} & e_1(iPD_\mu S A_c^{\mu\dagger} - iA_c^\mu D_\mu S^\dagger P^\dagger) \\
& + e_2(iPA_\mu D^\mu S_c^\dagger - iD^\mu S_c A_\mu^\dagger P^\dagger) \\
& + e_3(\epsilon^{\mu\nu\alpha\beta} P A_{\mu\nu} A_{c\alpha\beta}^\dagger + \epsilon^{\mu\nu\alpha\beta} A_{c\alpha\beta} A_{\mu\nu}^\dagger P^\dagger) \\
& + e_4(iP_\mu^* D^\mu S S_c^\dagger - iS_c D^\mu S^\dagger P_\mu^{*\dagger}) \\
& + e_5(\epsilon^{\mu\nu\alpha\beta} P_\mu^* D_\nu S A_{c\alpha\beta}^\dagger + \epsilon^{\mu\nu\alpha\beta} A_{c\alpha\beta} D_\nu S^\dagger P_\mu^{*\dagger}) \\
& + e_6(\epsilon^{\mu\nu\alpha\beta} P_\mu^* A_{\nu\alpha} D_\beta S_c^\dagger + \epsilon^{\mu\nu\alpha\beta} D_\beta S_c A_{\nu\alpha}^\dagger P_\mu^{*\dagger}) \\
& + e_7(iP_\mu^* A^{\mu\nu} A_{c\nu}^\dagger - iA_{c\nu} A^{\mu\nu\dagger} P_\mu^*) \\
& + e_8(iP_\mu^* A_\nu A_c^{\mu\nu\dagger} - iA_c^{\mu\nu} A_\nu^\dagger P_\mu^{*\dagger}) \\
& + e_9(iP_{\mu\nu}^* A^\mu A_c^{\nu\dagger} - iA_c^\nu A^{\mu\dagger} P_{\mu\nu}^{*\dagger}),
\end{aligned}
$$

$$
\Phi = \begin{pmatrix} \frac{\sqrt{3}\pi^0+\eta_8+\sqrt{2}\eta_0}{\sqrt{3}} & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & \frac{-\sqrt{3}\pi^0+\eta_8+\sqrt{2}\eta_0}{\sqrt{3}} & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & \frac{-2\eta_8+\sqrt{2}\eta_0}{\sqrt{3}} \end{pmatrix}
$$

$$
V_\mu = \frac{g_V}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(\rho^0+\omega) & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}(\rho^0-\omega) & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu .
$$

$$
\begin{aligned}
S^a &= \begin{pmatrix} 0 & S_{ud} & S_{us} \\ -S_{ud} & 0 & S_{ds} \\ -S_{us} & -S_{ds} & 0 \end{pmatrix}^a, \\
A_\mu^a &= \begin{pmatrix} A_{uu} & \frac{1}{\sqrt{2}}A_{ud} & \frac{1}{\sqrt{2}}A_{us} \\ \frac{1}{\sqrt{2}}A_{ud} & A_{dd} & \frac{1}{\sqrt{2}}A_{ds} \\ \frac{1}{\sqrt{2}}A_{us} & \frac{1}{\sqrt{2}}A_{ds} & A_{ss} \end{pmatrix}_\mu^a \\
S_c^a &= \begin{pmatrix} S_{cu} & S_{cd} & S_{cs} \end{pmatrix}^a, \\
A_{c\mu}^a &= \begin{pmatrix} A_{cu} & A_{cd} & A_{cs} \end{pmatrix}_\mu^a,
\end{aligned}
$$

$$
\begin{aligned}
P &= (D^0, D^+, D_s^+),\ P_\tau^* = (D^{*0}, D^{*+}, D_s^{*+})_\tau, \\
D_\mu P &= \partial_\mu P + iP\alpha_{\|\mu}^\dagger = \partial_\mu P + iP\alpha_{\|\mu}, \\
D_\mu P_\tau^* &= \partial_\mu P_\tau^* + iP_\tau^*\alpha_{\|\mu}^\dagger = \partial_\mu P_\tau^* + iP_\tau^*\alpha_{\|\mu}, \\
\alpha_{\perp\mu} &= (\partial_\mu\xi_R\xi_R^\dagger - \partial_\mu\xi_L\xi_L^\dagger)/(2i), \\
\alpha_{\|\mu} &= (\partial_\mu\xi_R\xi_R^\dagger + \partial_\mu\xi_L\xi_L^\dagger)/(2i), \\
\hat{\alpha}_{\perp\mu} &= (D_\mu\xi_R\xi_R^\dagger - D_\mu\xi_L\xi_L^\dagger)/(2i), \\
\hat{\alpha}_{\|\mu} &= (D_\mu\xi_R\xi_R^\dagger + D_\mu\xi_L\xi_L^\dagger)/(2i), \\
\xi_L &= e^{i\sigma/F_\sigma}e^{-im/(2F_\pi)},\ \xi_R = e^{i\sigma/F_\sigma}e^{im/(2F_\pi)}, \\
A_{\mu\nu}^a &= D_\mu A_\nu^a - D_\nu A_\mu^a,\ A_{c\mu\nu}^a = D_\mu A_{c\nu}^a - D_\nu A_{c\mu}^a, \\
D_\mu A_\nu^a &= \partial_\mu A_\nu^a - iV_\mu A_\nu^a - iA_\nu^a V_\mu^T, \\
D_\mu S^a &= \partial_\mu S^a - iV_\mu S^a - iS^a V_\mu^T, \\
D_\mu A_{c\nu}^a &= \partial_\mu A_{c\nu}^a - iA_{c\nu}^a \alpha_{\|\mu}^T,\ D_\mu S_c^a = \partial_\mu S_c^a - iS_c^a \alpha_{\|\mu}^T
\end{aligned}
$$

The pion decay constant F_π = 93 MeV.
In the unitary gauge, i.e., σ = 0.

To determine the constants e_i in $^3P_0$ Model

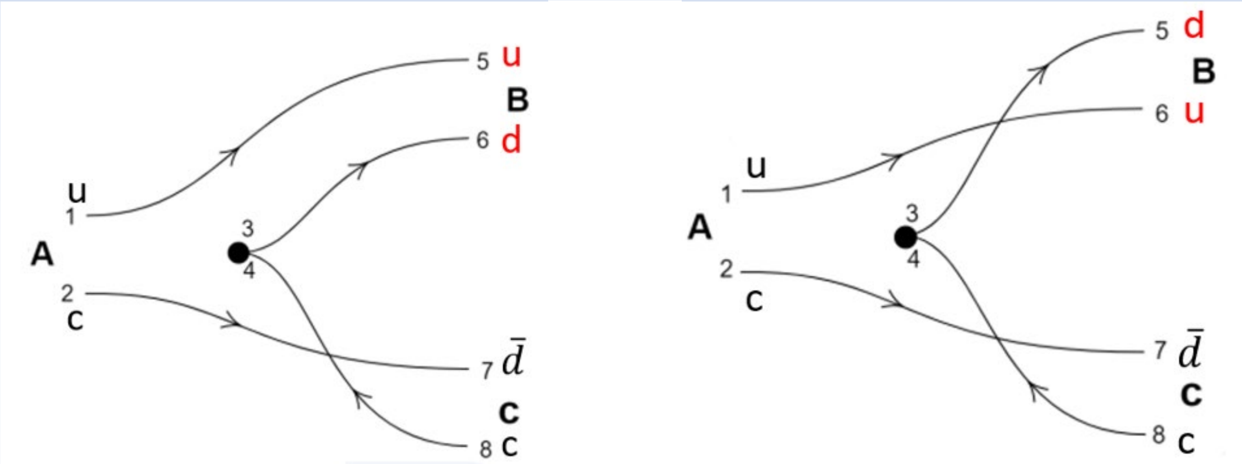


Table: The values of the low energy constants in the Lagrangian

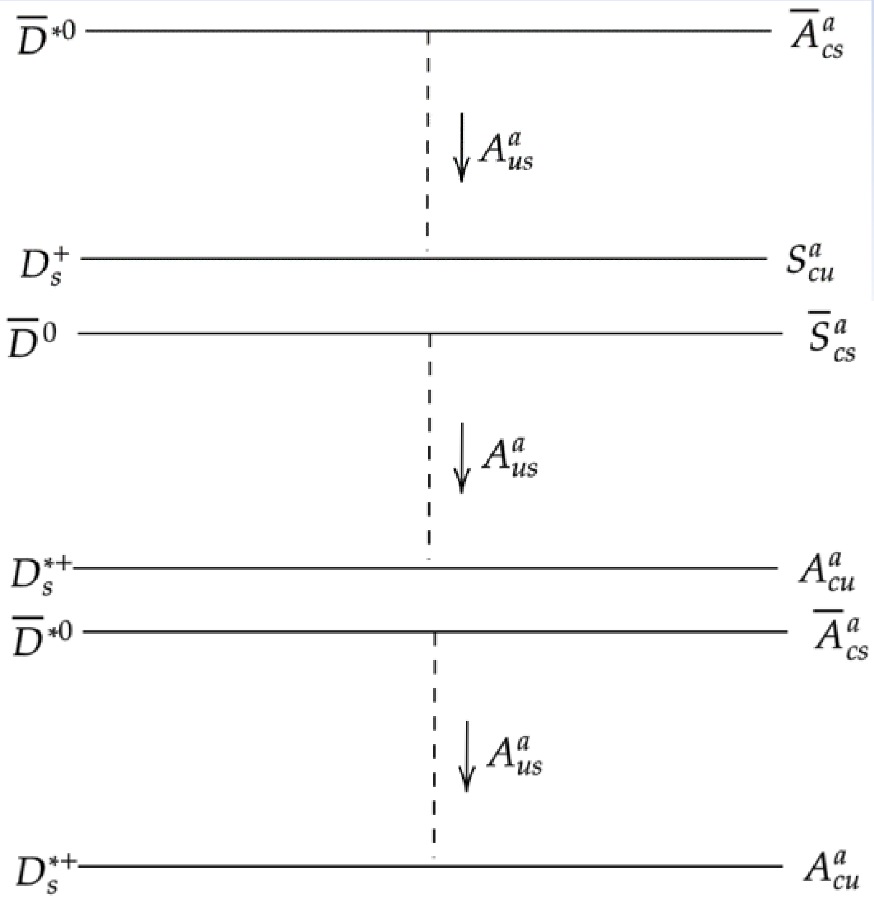
e_1 (GeV^{-1})	e_2 (GeV^{-1})	e_3 (GeV^{-2})	e_4 (GeV^{-1})	e_5 (GeV^{-2})
-6.939	4.161	±1.520	4.039	±1.588
e_6 (GeV^{-2})	e_7 (GeV^{-1})	e_8 (GeV^{-1})	e_9 (GeV^{-1})	
±2.595	-2.840	-16.778	11.098	

The another possibly choice of (e_7, e_8, e_9):

e_7(GeV^{-1})	e_8(GeV^{-1})	e_9(GeV^{-1})
2.840	-11.098	16.778
-16.778	-2.840	-2.840

Here, other amplitudes are negligible due to the OZI suppressed processes and the very small momentum of the initial and final particles.

In the case of $\bar{D}^{*0} D_s^{*+} / \bar{A}_{cs} A_{cu}$, the spin of the states can be 0, 1 and 2. We got exactly the same result for different spins.



$$V^{\bar{D}^{*0} D_s^+ \to \bar{A}^a_{cs} S^a_{cu}} = -\frac{e_2 \sqrt{m_{S_{cu}} m_{D_s^+} m_{\bar{A}_{cs}} m_{\bar{D}^{*0}}}}{2m^2_{A_{us}}} \left(e_8 \frac{s - m^2_{\bar{A}_{cs}} - m^2_{S_{cu}}}{2} + e_9 \frac{m^2_{\bar{D}^{*0}} + m^2_{S_{cu}} - u}{2} \right) \vec{\epsilon}_1 \cdot \vec{\epsilon}_3^{\dagger},$$

$$V^{\bar{D}^{0} D_s^{*+} \to \bar{S}^a_{cs} A^a_{cu}} = -\frac{e_2 \sqrt{m_{\bar{D}^0} m_{\bar{S}_{cs}} m_{A_{cu}} m_{D_s^{*+}}}}{2m^2_{A_{us}}} \left(e_8 \frac{s - m^2_{\bar{S}_{cs}} - m^2_{A_{cu}}}{2} + e_9 \frac{m^2_{D_s^{*+}} + m^2_{\bar{S}_{cs}} - u}{2} \right) \vec{\epsilon}_2 \cdot \vec{\epsilon}_4^{\dagger},$$

$$V^{\bar{D}^{*0} D_s^{*+} \to \bar{A}^a_{cs} A^a_{cu}} = -\frac{1}{2} \sqrt{m_{\bar{D}^{*0}} m_{\bar{A}_{cs}} m_{A_{cu}} m_{D_s^{*+}}} \Bigg(e_8^2 \frac{s - m^2_{\bar{A}_{cs}} - m^2_{A_{cu}}}{2} + e_8 e_9 \frac{m^2_{D_s^{*+}} + m^2_{\bar{A}_{cs}} + m^2_{\bar{D}^{*0}} + m^2_{A_{cu}} - 2u}{2} + e_9^2 \frac{s - m^2_{\bar{D}^{*0}} - m^2_{D_s^{*+}}}{2} \Bigg) \frac{1}{m^2_{A_{us}}} \vec{\epsilon}_1 \cdot \vec{\epsilon}_3^{\dagger} \vec{\epsilon}_2 \cdot \vec{\epsilon}_4^{\dagger}$$

$$\mathcal{P}(1) = \vec{\epsilon}_1 \cdot \vec{\epsilon}_3^{\dagger} = \vec{\epsilon}_2 \cdot \vec{\epsilon}_4^{\dagger},$$

$$\mathcal{P}'(0) = \frac{1}{3} \vec{\epsilon}_1 \cdot \vec{\epsilon}_2 \vec{\epsilon}_3^{\dagger} \cdot \vec{\epsilon}_4^{\dagger},$$

$$\mathcal{P}'(1) = \frac{1}{2} (\vec{\epsilon}_1 \cdot \vec{\epsilon}_3^{\dagger} \vec{\epsilon}_2 \cdot \vec{\epsilon}_4^{\dagger} - \vec{\epsilon}_1 \cdot \vec{\epsilon}_4^{\dagger} \vec{\epsilon}_2 \cdot \vec{\epsilon}_3^{\dagger}),$$

$$\mathcal{P}'(2) = \frac{1}{2} (\vec{\epsilon}_1 \cdot \vec{\epsilon}_3^{\dagger} \vec{\epsilon}_2 \cdot \vec{\epsilon}_4^{\dagger} + \vec{\epsilon}_1 \cdot \vec{\epsilon}_4^{\dagger} \vec{\epsilon}_2 \cdot \vec{\epsilon}_3^{\dagger}) - \frac{1}{3} \vec{\epsilon}_1 \cdot \vec{\epsilon}_2 \vec{\epsilon}_3^{\dagger} \cdot \vec{\epsilon}_4^{\dagger}.$$

we utilize the Bethe-Salpeter equation of the on-shell factorized form to calculate the T-matrix considering the coupled-channel effect

$$T = (I - VG)^{-1} V.$$

G is the one of the two-meson loop function whose non-zero element has the form of

$$G_{ii} = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^2 - m_{i1}^2 + i\epsilon} \frac{1}{(P-q)^2 - m_{i2}^2 + i\epsilon}$$

$$G_{ii} = \frac{1}{32\pi^2} \left\{ \frac{\nu}{s} \left[\log \frac{s - \Delta + \nu\sqrt{1 + \frac{m_{i1}^2}{q_{max}^2}}}{-s + \Delta + \nu\sqrt{1 + \frac{m_{i1}^2}{q_{max}^2}}} + \log \frac{s + \Delta + \nu\sqrt{1 + \frac{m_{i2}^2}{q_{max}^2}}}{-s - \Delta + \nu\sqrt{1 + \frac{m_{i2}^2}{q_{max}^2}}} \right] - \frac{\Delta}{s} \log \frac{m_{i1}^2}{m_{i2}^2} + \frac{2\Delta}{s} \log \frac{1 + \sqrt{1 + \frac{m_{i1}^2}{q_{max}^2}}}{1 + \sqrt{1 + \frac{m_{i2}^2}{q_{max}^2}}} + \log \frac{m_{i1}^2 m_{i2}^2}{q_{max}^4} \right.$$
$$\left. -2 \log \left[\left(1 + \sqrt{1 + \frac{m_{i1}^2}{q_{max}^2}} \right) \left(1 + \sqrt{1 + \frac{m_{i2}^2}{q_{max}^2}} \right) \right] \right\}$$

J. A. Oller, E. Oset, and J. R. Peláez. Meson-meson interactions in a nonperturbative chiral approach. Phys. Rev. D,59:074001, Feb 1999.

the effective couplings to each channel from the residue of the amplitudes：

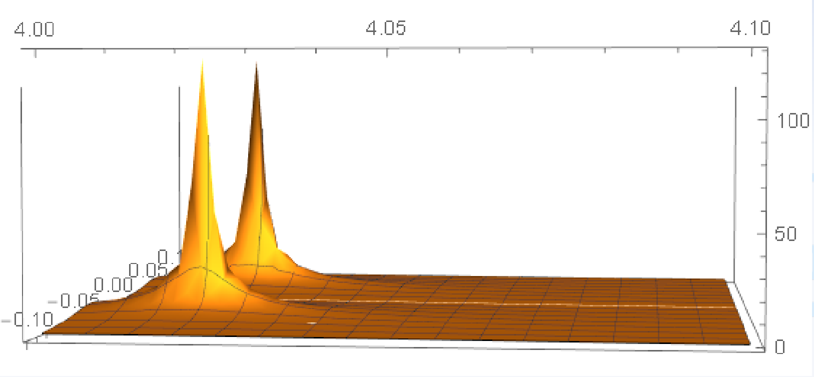
$$T_{ij} = \frac{g_i g_j}{s - s_R}$$

Numerical results

$\bar{D}^{*0}D_s^+/\bar{A}_{cs}S_{cu}$ RS-II

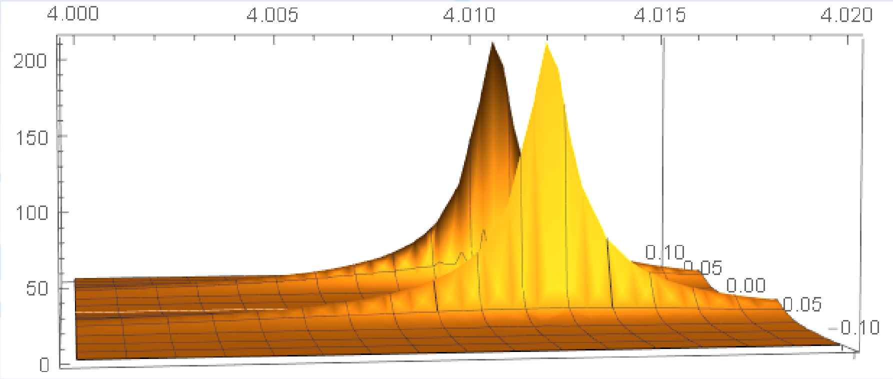
qmax=1.36GeV

Pole=4018±i46



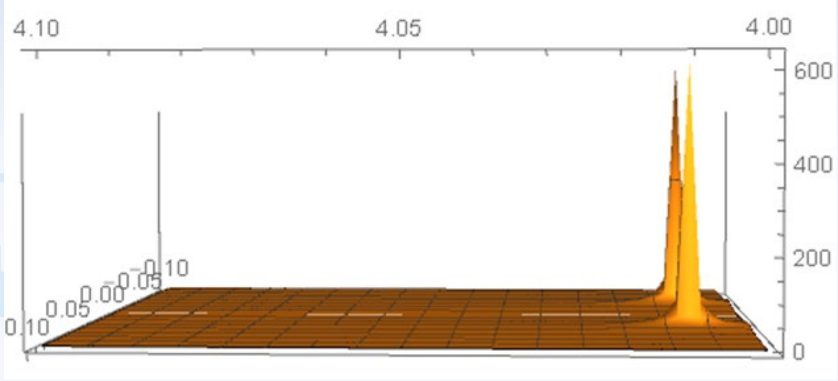
qmax=1.385GeV

Pole=4013±i42



qmax=1.41GeV

Pole=4009±i39



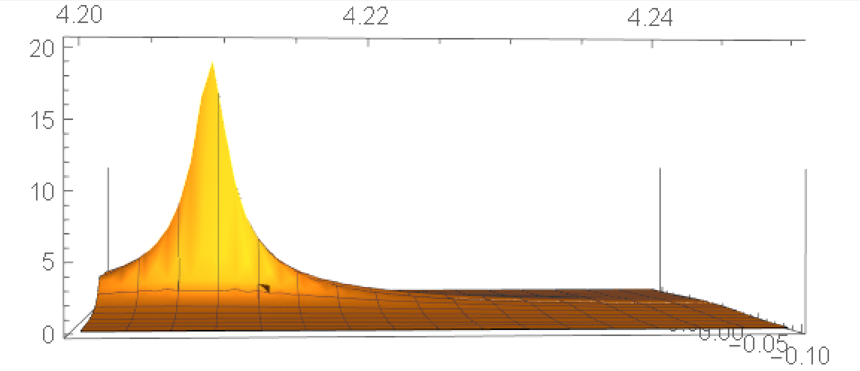
$g_{\bar{D}^{*0}D_s^+}(g_{\bar{A}_{cs}S_{cu}})$=9.8GeV(18.6GeV)

$Z_{cs}(4000)^+$: M=4003 ± 6^{+4}_{-14} MeV， Γ =131 ± 15 ± 26 MeV

$\bar{D}^{*0}D_s^{*+}/\bar{A}_{cs}A_{cu}$ RS-II

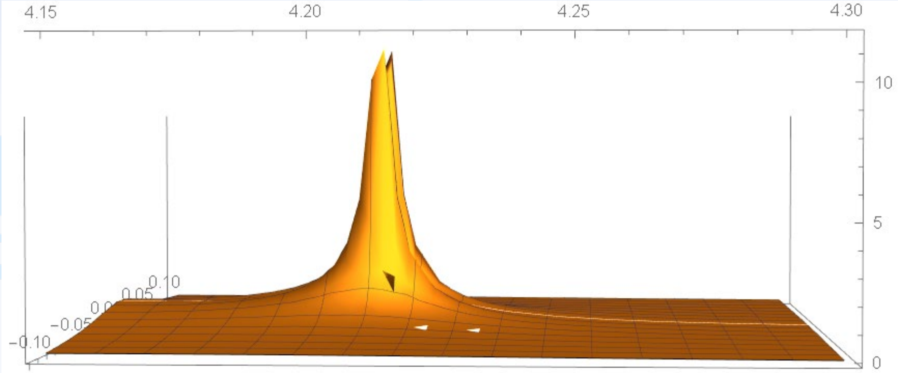
qmax=1.36GeV

Pole=4209±i13



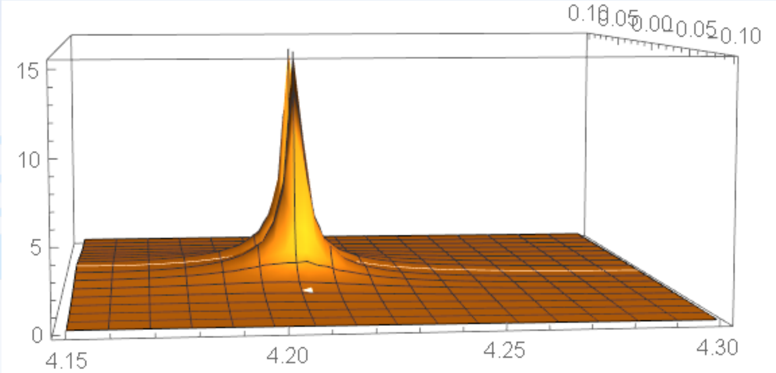
qmax=1.385GeV

Pole=4208±i13



qmax=1.41GeV

Pole=4207±i12



$g_{\bar{D}^{*0}D_s^{*+}}(g_{\bar{A}_{cs}A_{cu}})$=4.88GeV(7.62GeV)

$Z_{cs}(4220)^+$: M=$4216\pm24^{+43}_{-30}$ MeV, Γ =$233\pm52^{+97}_{-73}$ MeV

Table: The results

q_{max}		1360	1385	1410
$\bar{D}^{*0}D_s^+/\bar{A}_{cs}S_{cu}$	RS-II	$4018 \pm i46$	$4013 \pm i42$	$4009 \pm i39$
	RS-II	$4209 \pm i13$	$4208 \pm i13$	$4207 \pm i12$
$\bar{D}^{*0}D_s^{*+}/\bar{A}_{cs}A_{cu}$	RS-II	4105	4106	4107
	RS-I	4088	4091	4093
$\bar{D}^0D_s^{*+}/\bar{S}_{cs}A_{cu}$	RS-II	$4115 \pm i69$	$4112 \pm i66$	$4108 \pm i64$

q_{max}		1385MeV
$g_{\bar{D}^{*0}D_s^+}(g_{\bar{A}_{cs}S_{cu}})$	RS-II	9.8GeV(18.6GeV)
	RS-II	4.88GeV(7.62GeV)
$g_{\bar{D}^{*0}D_s^{*+}}(g_{\bar{A}_{cs}A_{cu}})$	RS-II	4.39 GeV (8.02 GeV)
	RS-I	7.79 GeV (11.27 GeV)
$g_{\bar{D}^0D_s^{*+}}(g_{\bar{S}_{cs}A_{cu}})$	RS-II	9.12GeV(16.27GeV)

Summary

- In this work, we apply the HLS approach to the meson-diquark sector.
- We find three resonances of spin 1 with the pole positions on the second Riemann sheet of (4013 ± 42i) MeV, (4208 ± 13i) MeV, (4112 ± 66i) MeV for $\bar{D}^{*0}D_s^{+}/\ \bar{A}_{cs}S_{cu}$, $\bar{D}^{*0}D_s^{*+}/\ \bar{A}_{cs}A_{cu}$, $\bar{D}^{0}D_s^{*+}/\ \bar{S}_{cs}A_{cu}$ systems, respectively.
- The first resonance is identified as the $Z_{cs}(4000)^{+}$ since the calculated mass agrees with the value by LHCb.
- The mass of the second resonance is agree with that of $Z_{cs}(4220)^{+}$.
- There are as well a bound state and a virtual state for $\bar{D}^{*0}D_s^{*+}/\ \bar{A}_{cs}A_{cu}$ system.

Thanks