Reveal short range interactions between *u*/*d* quarks in the *NN*, D_{03}, and D_{30} systems

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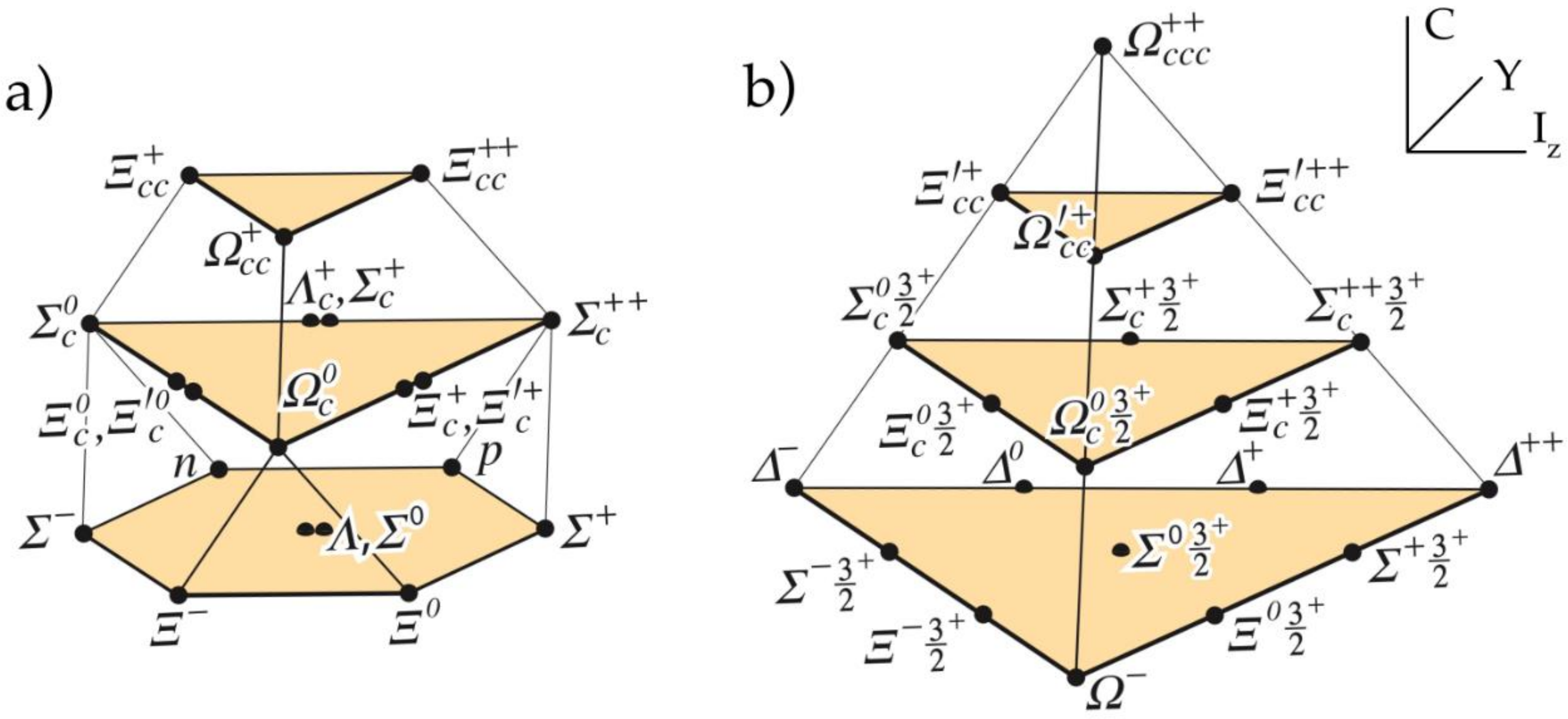
长沙 **2025.04.12**

Outline

- Background
- Model and method
- Results and discussions
- Summary

Conventional baryons

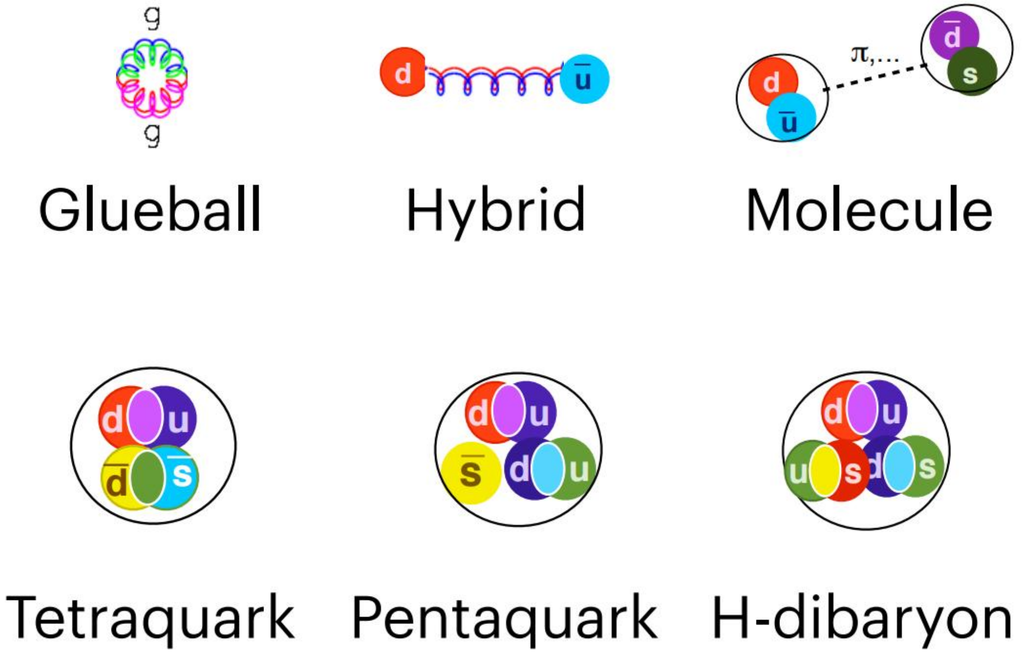


Conventional baryons

S. Navas *et al*. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

Exotic states

In addition to the conventional states, QCD also permits the existence of other types of hadrons, known as exotic states.

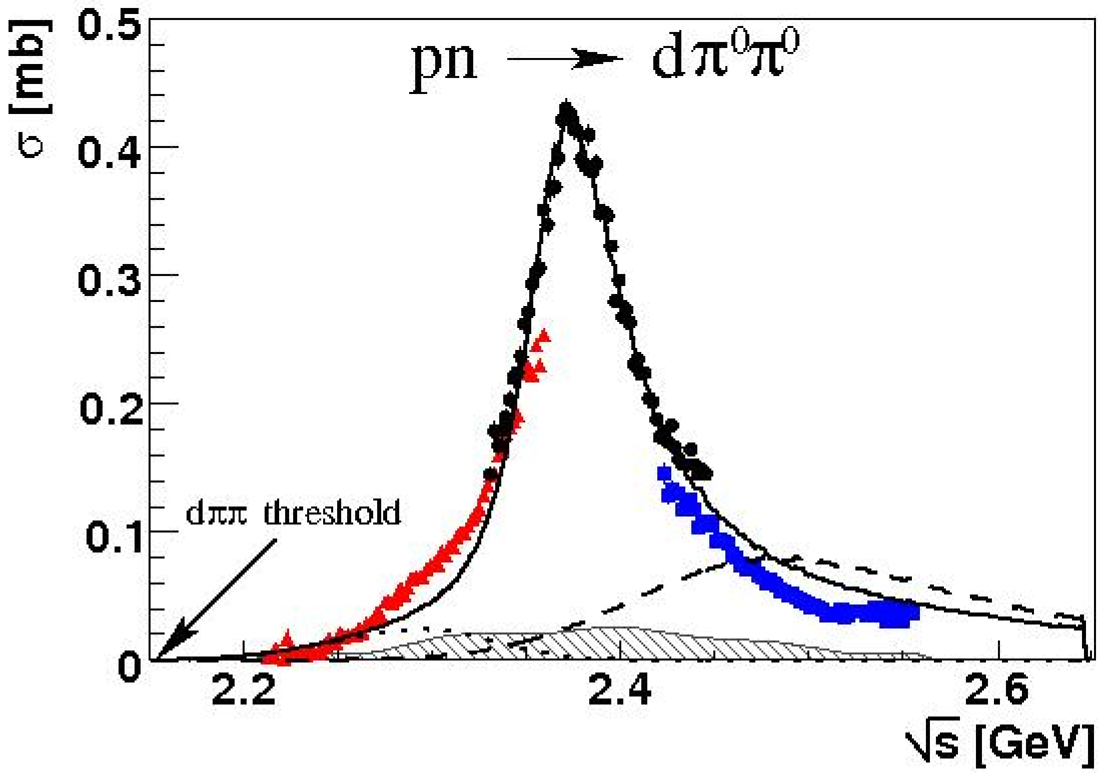


Some tetraquark candidates observed recently：X(6900), X(2900), $Z_{cs}(3985)$, $Z_{cs}(4000)$, $T_{cc}(3875)$ ...

Nonstrange dibaryon sextet

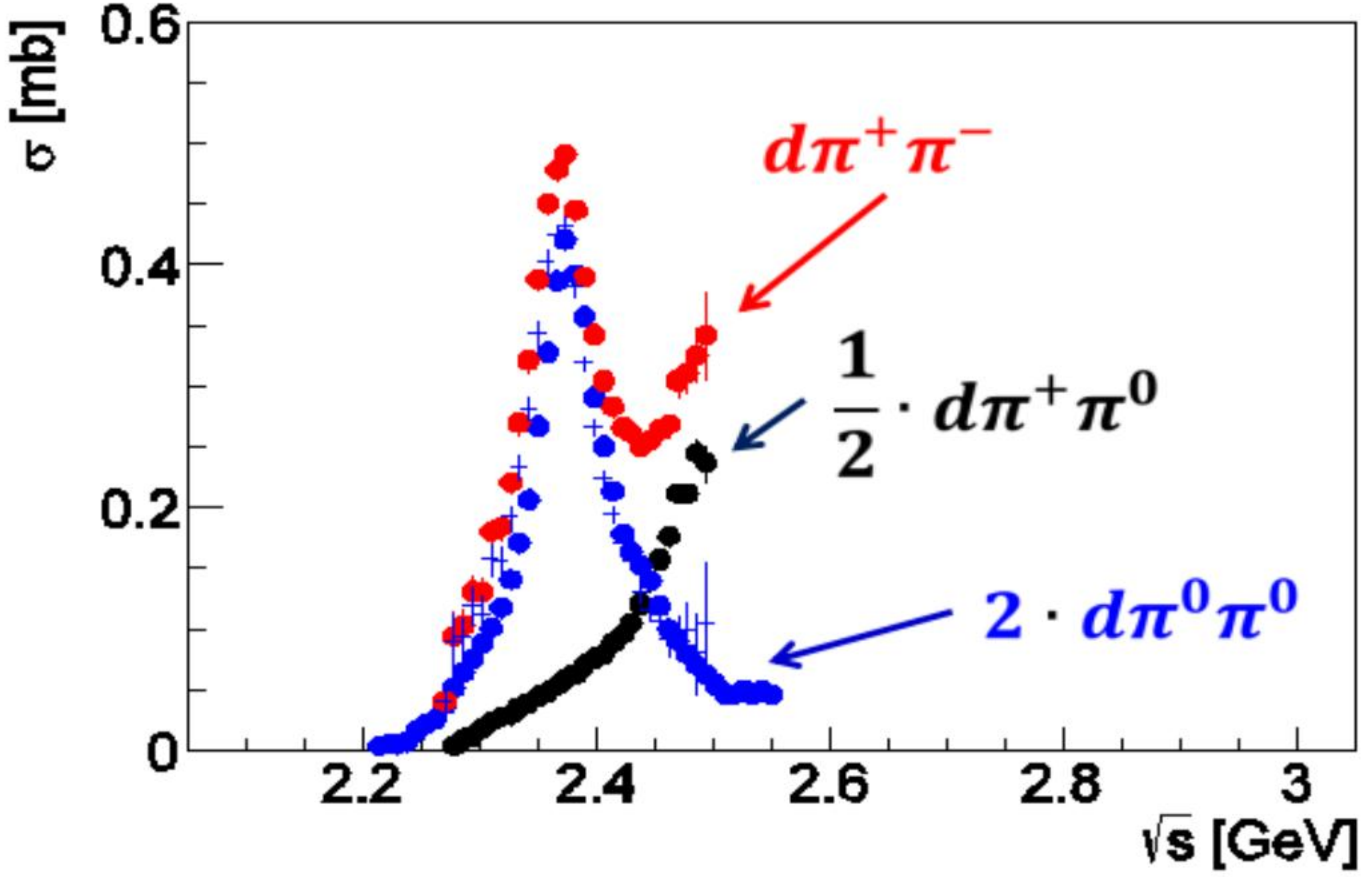
Nonstrange dibaryons	BB	Threshold (MeV)	Particle/Candidate	Binding energy
D_{01}	NN	1878	Deuteron	2.2 MeV
D_{10}	NN	1878	A virtual state	67 keV
D_{12}	$N\Delta$	2171	Evidence	UN
D_{21}	$N\Delta$	2171	Evidence	UN
D_{03}	$\Delta\Delta$	2464	d^*(2380)	~80 MeV
D_{30}	$\Delta\Delta$	2464	No signal	UN

Experimental observation of *d**(2380)



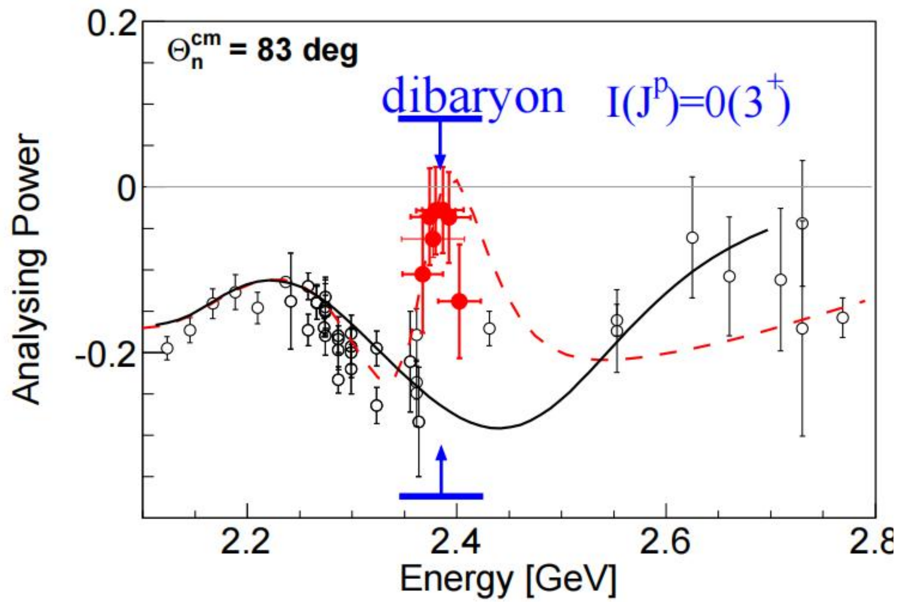
P. Adlarson, et al. [WASA-at-COSY Collaboration], Phys. Rev. Lett. 106, 242302 (2011).

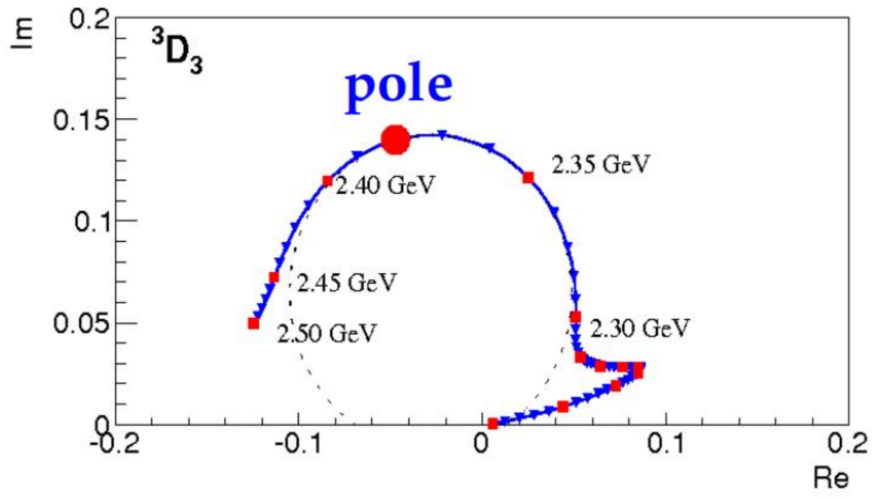
Experimental observation of $d^*(2380)$



P. Adlarson, et al. [WASA-at-COSY Collaboration], Phys. Lett. B 721, 229 (2013).

Experimental observation of *d**(2380)





Analysing power data and Argand diagram

P. Adlarson et al., Phys. Rev. Lett. 112, 202301 (2014).
R. L. Workman, W. J. Briscoe and I. I. Strakovsky, Phys. Rev. C 93, 045201 (2016); Phys. Rev. C 94, 065203 (2016).
P. Adlarson et al., Phys. Rev. C 90, 035204 (2014).

Experimental observation of $d^*(2380)$

- Channels: $pn \rightarrow d\pi\pi$, $pd \rightarrow {}^3He\pi\pi$, $dd \rightarrow {}^4He\pi\pi$, $pn \rightarrow pn\pi\pi$ ...
- Binding energy : 80 MeV below the ΔΔ threshold.
- A large binding energy suggests that it has a small size, which may be compact.
- Total width: 70 MeV.
- A small width compared with Δ baryon.

Notations and references

- We use symbol D to represent the dibaryon.
- D_{IJ} is used to denote the isospin I and spin J.
- The $d^*(2380)$ is a good candidate of the D_{03} state.

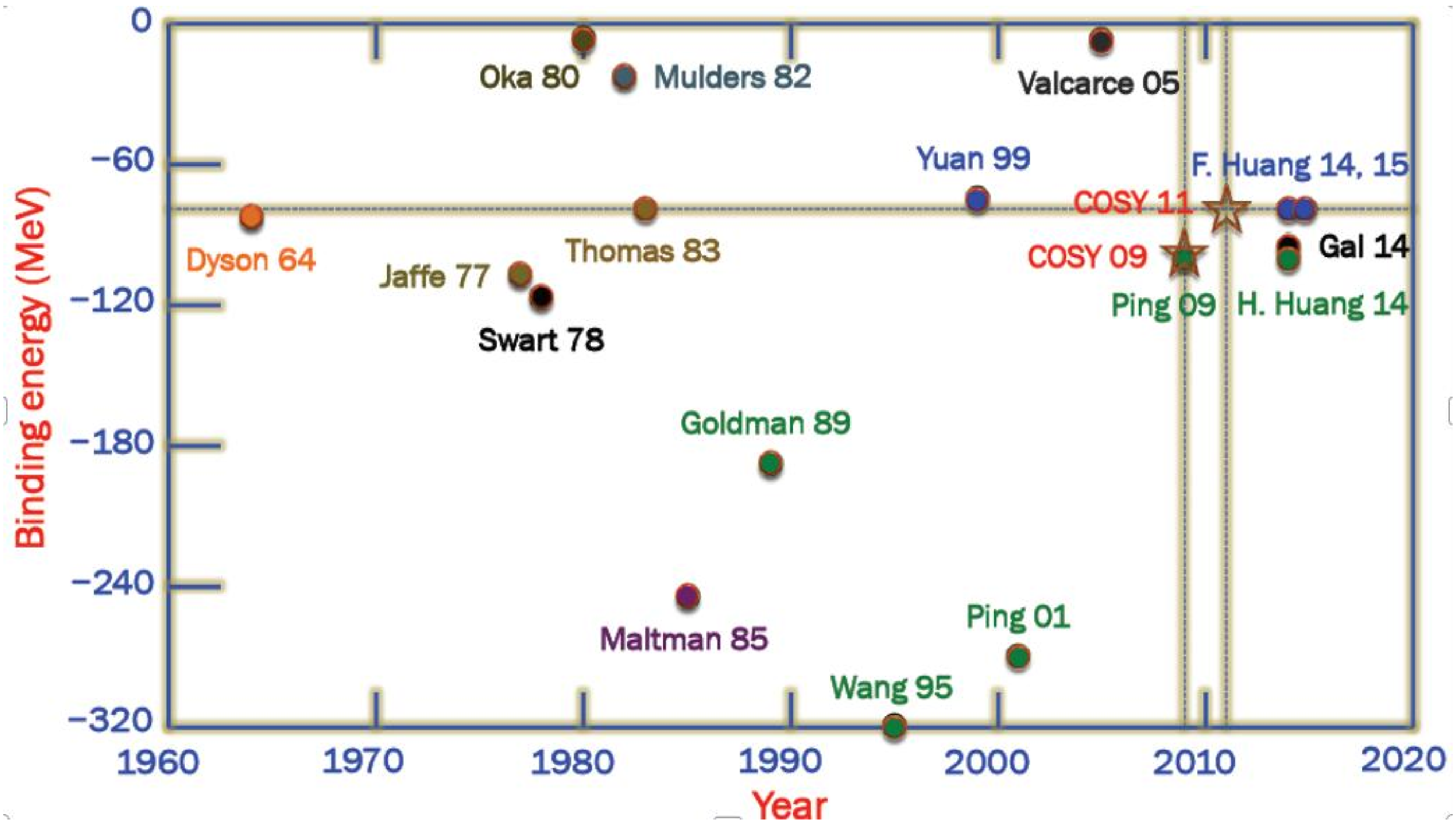
Many theoretical and experimental works exist. Some recent reviews：

Y. Dong, P. Shen and Z. Zhang, Prog. Part. Nucl. Phys. 131, 104045 (2023).

L. Dai, Y. Wang, L. Chen and T. Zhang, Symmetry 15, 446 (2023).

M Bashkanov et al, J. Phys. G: Nucl. Part. Phys. 51, 045106 (2024).

Some theoretical calculations of D_{03}



A long-standing problem in the quark models

- One gluon exchange or vector meson exchange, which one dominates the short range interactions between light quarks?
- Which systems are suitable for investigating this problem?

Our proposal: investigating the NN, D_{03}, and D_{30} systems jointly in the extended chiral SU(3) quark models

The extended chiral quark models

Chiral quark model: OGE, confinement, pseudoscalar and scalar mesons

$$H = \sum_{i=1}^{6} T_i - T_G + \sum_{j>i=1}^{6} \left(V_{ij}^{OGE} + V_{ij}^{conf} + V_{ij}^{ch} \right),$$

$$V_{ij}^{\mathrm{ch}} = \sum_{a=0}^{8} V_{ij}^{\sigma_a} + \sum_{a=0}^{8} V_{ij}^{\pi_a},$$

Extended chiral quark model: extra vector meson exchanges

$$V_{ij}^{\mathrm{ch}} = \sum_{a=0}^{8} V_{ij}^{\sigma_a} + \sum_{a=0}^{8} V_{ij}^{\pi_a} + \sum_{a=0}^{8} V_{ij}^{\rho_a}$$

L. R. Dai, Z. Y. Zhang, Y. W. Yu and P. Wang, Nucl. Phys. A 727, 321-332 (2003).
F. Huang, P. N. Shen, Y. B. Dong and Z. Y. Zhang, Sci. China Phys. Mech. Astron. 59, 622002 (2016).

The extended chiral quark models

$$V_{ij}^{\sigma_a} = -C(g_{\rm ch}, m_{\sigma_a}, \Lambda)\left(\lambda_a^i \lambda_a^j\right) Y_1(m_{\sigma_a}, \Lambda, r_{ij}),$$

$$V_{ij}^{\pi_a} = C(g_{\rm ch}, m_{\pi_a}, \Lambda)\left(\lambda_a^i \lambda_a^j\right)\Big[Y_3(m_{\pi_a}, \Lambda, r_{ij}) \times (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) + H_3(m_{\pi_a}, \Lambda, r_{ij}) S_{ij}\Big]\frac{m_{\pi_a}^2}{12 m_q^2},$$

$$V_{ij}^{\rho_a} = C(g_{\rm chv}, m_{\rho_a}, \Lambda)\left(\lambda_a^i \lambda_a^j\right)\Bigg\{Y_1(m_{\rho_a}, \Lambda, r_{ij}) + \frac{m_{\rho_a}^2}{6 m_q^2}\Bigg[\left(1 + \frac{f_{\rm chv}}{g_{\rm chv}}\frac{2m_q}{M_N} + \frac{f_{\rm chv}^2}{g_{\rm chv}^2}\frac{m_q^2}{M_N^2}\right) \times \left(Y_3(m_{\rho_a}, \Lambda, r_{ij})\left(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j\right) - \frac{1}{2} S_{ij} \times H_3(m_{\rho_a}, \Lambda, r_{ij})\right)\Bigg]\Bigg\},$$

$$V_{ij}^{\rm OGE} = \frac{1}{4} g_i g_j \left(\lambda_i^c \cdot \lambda_j^c\right)\Bigg\{\Bigg[\frac{1}{r_{ij}} - \frac{\pi}{m_q^2}\delta(\boldsymbol{r}_{ij}) \times \left(1 + \frac{2}{3}\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j\right) - \frac{1}{4 m_q^2}\frac{1}{r_{ij}^3} S_{ij}\Bigg]\Bigg\},$$

$$V_{ij}^{\rm conf} = -\left(\lambda_i^c \cdot \lambda_j^c\right)\left(a_{ij}^c r_{ij}^2 - a_{ij}^{c0}\right),$$

Wave functions for D_{03}

$$\Psi_{6q} = \mathcal{A}\left[\phi_\Delta(\boldsymbol{\xi}_1,\boldsymbol{\xi}_2)\,\phi_\Delta(\boldsymbol{\xi}_4,\boldsymbol{\xi}_5)\,\eta_{\Delta\Delta}(\boldsymbol{r}) + \phi_C(\boldsymbol{\xi}_1,\boldsymbol{\xi}_2)\,\phi_C(\boldsymbol{\xi}_4,\boldsymbol{\xi}_5)\,\eta_{CC}(\boldsymbol{r})\right]_{S=3,I=0,C=(00)}.$$

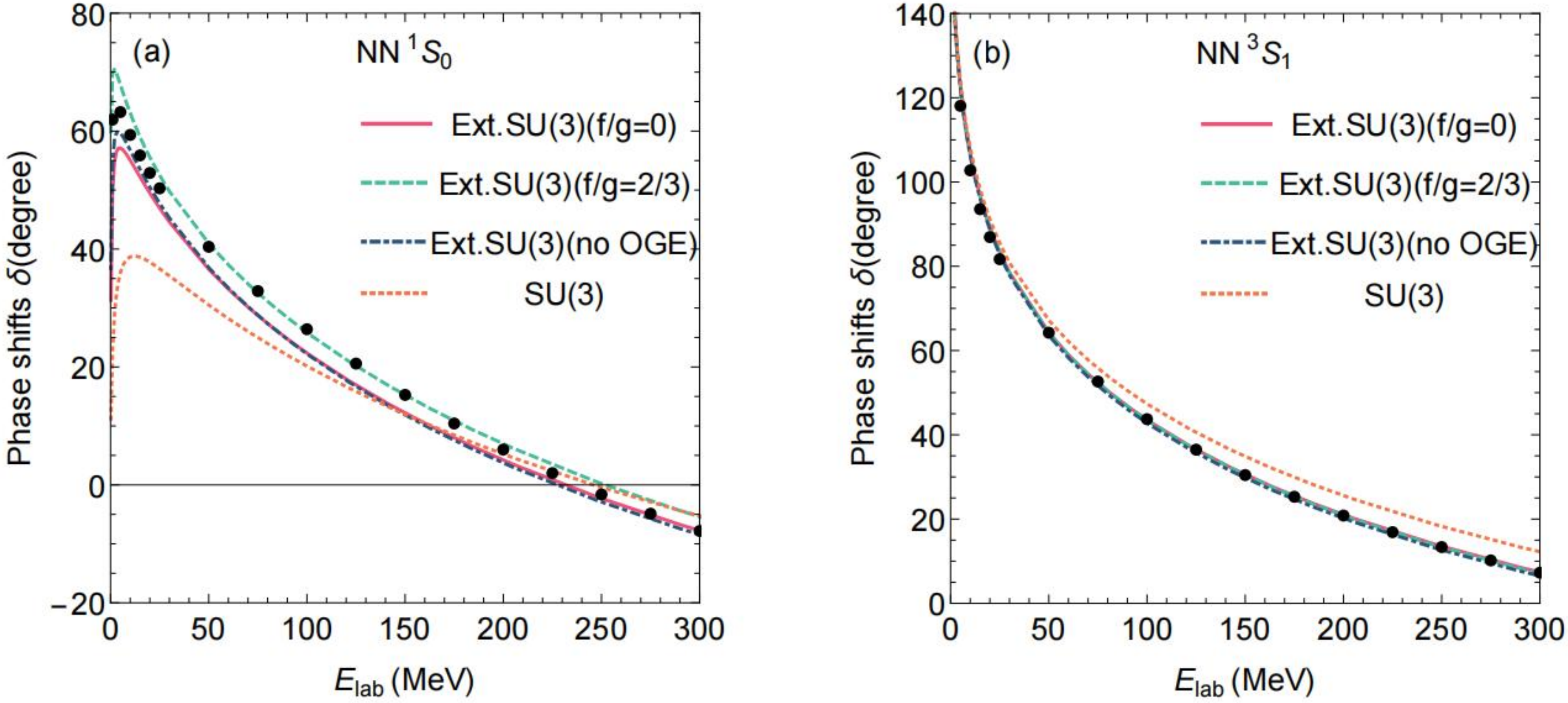
$$\Delta: \quad (0s)^3\,[3]_{\rm orb}, S = 3/2, I = 3/2, C = (00),$$

$$C: \quad (0s)^3\,[3]_{\rm orb}, S = 3/2, I = 1/2, C = (11),$$

Solving the RGM equation to obtain the mass of a dibaryon.

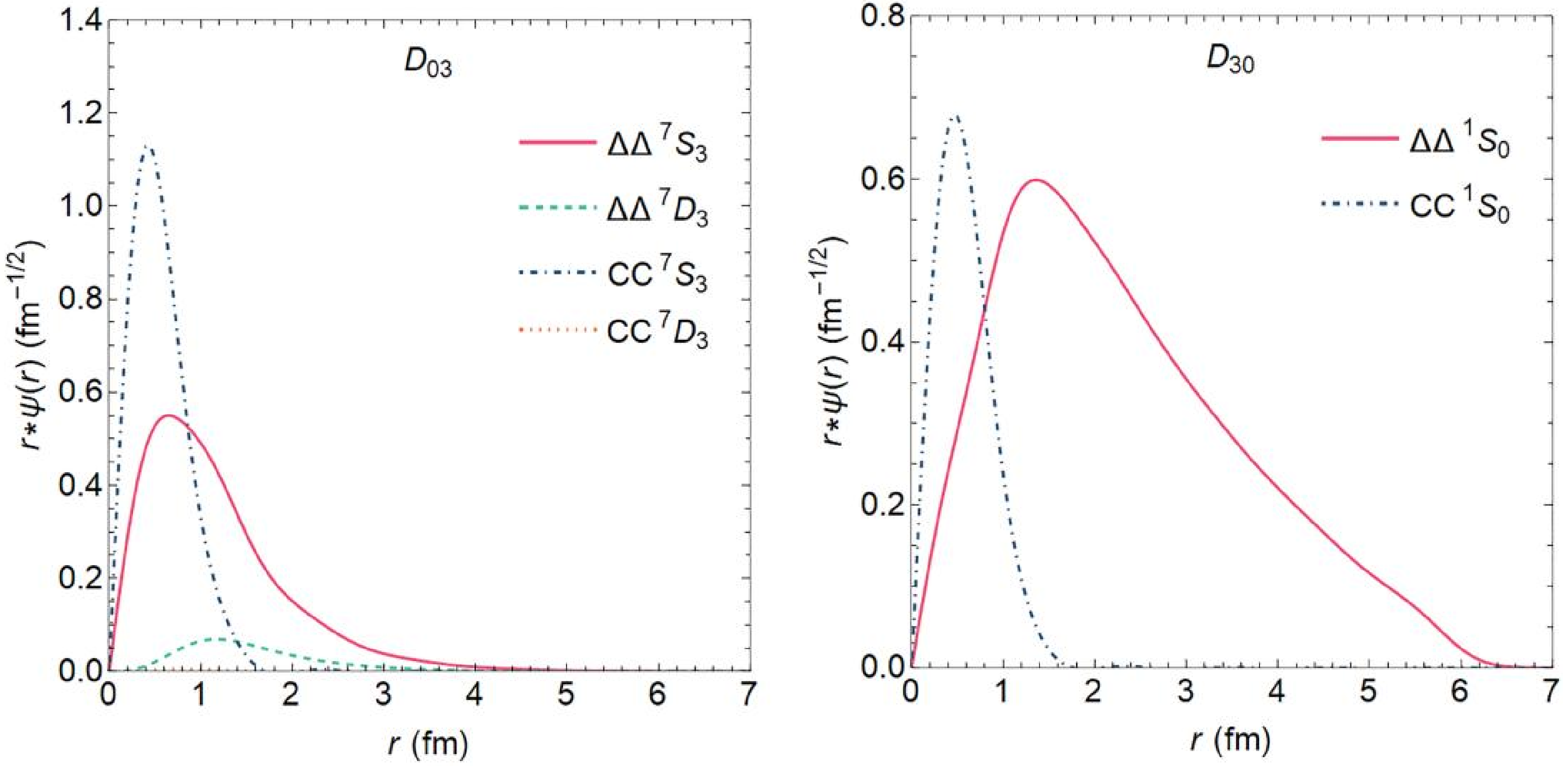
$$\langle \delta\Psi_{6q}|H - E|\Psi_{6q}\rangle = 0,$$

Results for *NN* scattering phase shifts



NN scattering phase shifts. Other higher partial waves can be also described well. Insensitive to the short range interactions.

Results for D_{03} [d^*(2380)] and D_{30}



Wave functions of D_{03} [d^*(2380)] and D_{30}

Not only the colorless ΔΔ, but also hidden color components.

Results for D_{03} [d^*(2380)] and D_{30}

Set II	D_{03}				D_{30}			
	SU(3)	Ext. SU(3) ($f/g = 0$)	Ext. SU(3) ($f/g = 2/3$)	Ext. SU(3) (no OGE)	SU(3)	Ext. SU(3) ($f/g = 0$)	Ext. SU(3) ($f/g = 2/3$)	Ext. SU(3) (no OGE)
Binding energy	25.09	80.08	66.40	91.21	12.30	6.00	11.65	5.28
$\mathcal{R}_{\Delta\Delta/CC}$	1.04	0.73	0.77	0.71	1.50	1.94	1.67	2.01
$\mathcal{R}_{6q}$	0.94	0.77	0.79	0.76	1.10	1.25	1.14	1.27
Fraction of $(\Delta\Delta)_{L=0}$	42.07	31.91	33.41	30.90	61.29	74.30	68.31	76.19
Fraction of $(\Delta\Delta)_{L=2}$	1.59	0.49	0.57	0.41	–	–	–	–
Fraction of $(CC)_{L=0}$	56.34	67.60	66.02	68.68	38.71	25.70	31.69	23.81
Fraction of $(CC)_{L=2}$	0.00	0.00	0.00	0.00	–	–	–	–

- Vector meson exchange is essential for the correct binding energies
- Compact nature of the D_{03} state
- The D_{30} state is a weekly bound state (about 5~12 MeV)

Short range interactions between light quarks

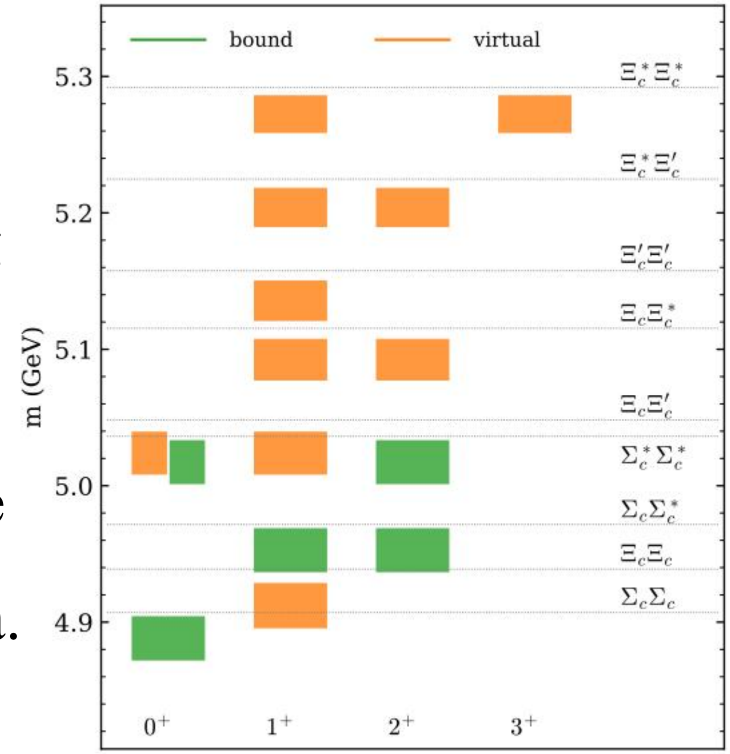
- The deuteron cannot help us to distinguish the short range interaction, since it is a loosely bound state.
- The results of D_{03} and D_{30} states indicate that the vector meson exchange interactions dominate the short range interactions.
- The small residual one gluon exchange coupling strength is also allowed.

Our work: Q. F. Lü, Y. B. Dong, P. N. Shen and Z. Y. Zhang, Sci. China Phys. Mech. Astron. 68, 232011 (2025).

Research Highlight: B. S. Zong, Sci. China Phys. Mech. Astron. 68, 232031 (2025).

More evidence from other works

- The empiric vector dominance for the interactions between hadrons containing light quarks at the hadron level.
- Vector meson exchange can improve the description of meson and baryon spectra.



X. K. Dong, F. K. Guo, B. S. Zou, Commun. Theor. Phys. 73, 125201 (2021).

B. R. He, M. Harada and B. S. Zou, Phys. Rev. D 108, 054025 (2023).

Other problems

Why is the binding energy of $d^*(2380)$ so large?

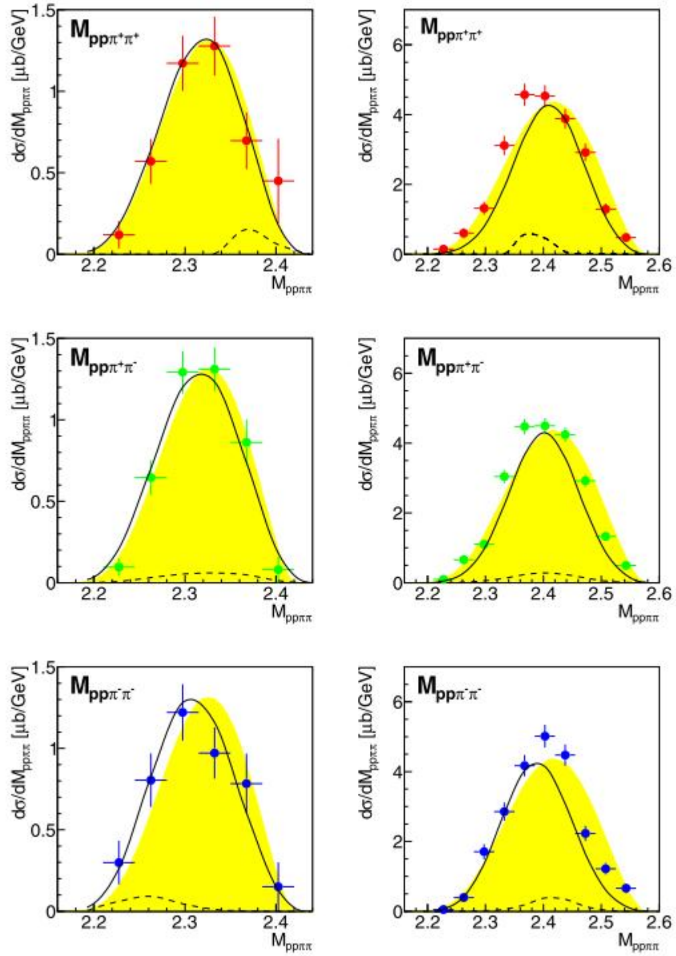
- Large hidden color components exist in the $d^*(2380)$.
- It has a sizable compact core.
- Quark exchange effects are significant.

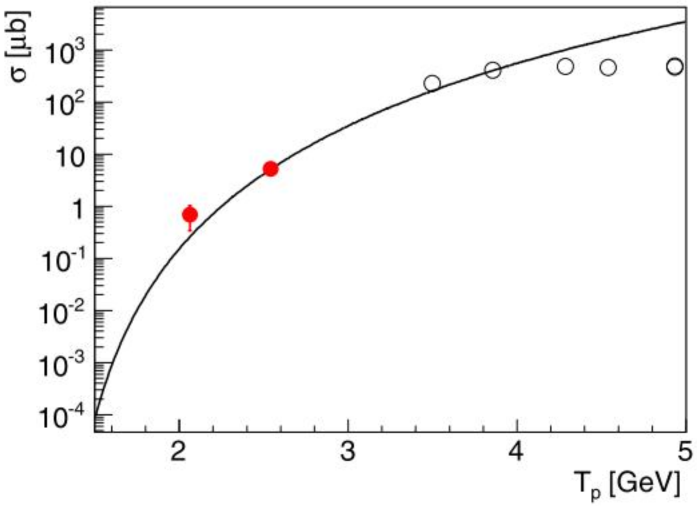
Other problems

What about the mirror state D_{30}?

- The mirror state D_{30} is a weakly bound state.
- It also has a significant hidden color component.
- Only S-wave channels exist in this system.
- No signal of D_{30} is observed until now. (Near threshold?)

Searching for the D_{30} state





Invariant masses for *ppππ* and the total cross section. Limited data.

P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Lett. B 762, 455-461 (2016).

Further investigations

- Other possible channels for $d^*(2380)$:

$$\gamma d \to d\pi\pi,\ \gamma d \to d\pi\pi\pi,\ e^+e^- \text{ collisions},\ \Upsilon \text{ decay}$$

- The D_{30} state can be searched for in the $pp \to pp\pi^+\pi^+\pi^-\pi^-$ reaction
- Possible nonstrange D_{12} and D_{21} states which are composed of ΔN and hidden color components
- Systems like $NN^*(1535)$, ηd, and so on
- Systems with strange, charm, and bottom quarks

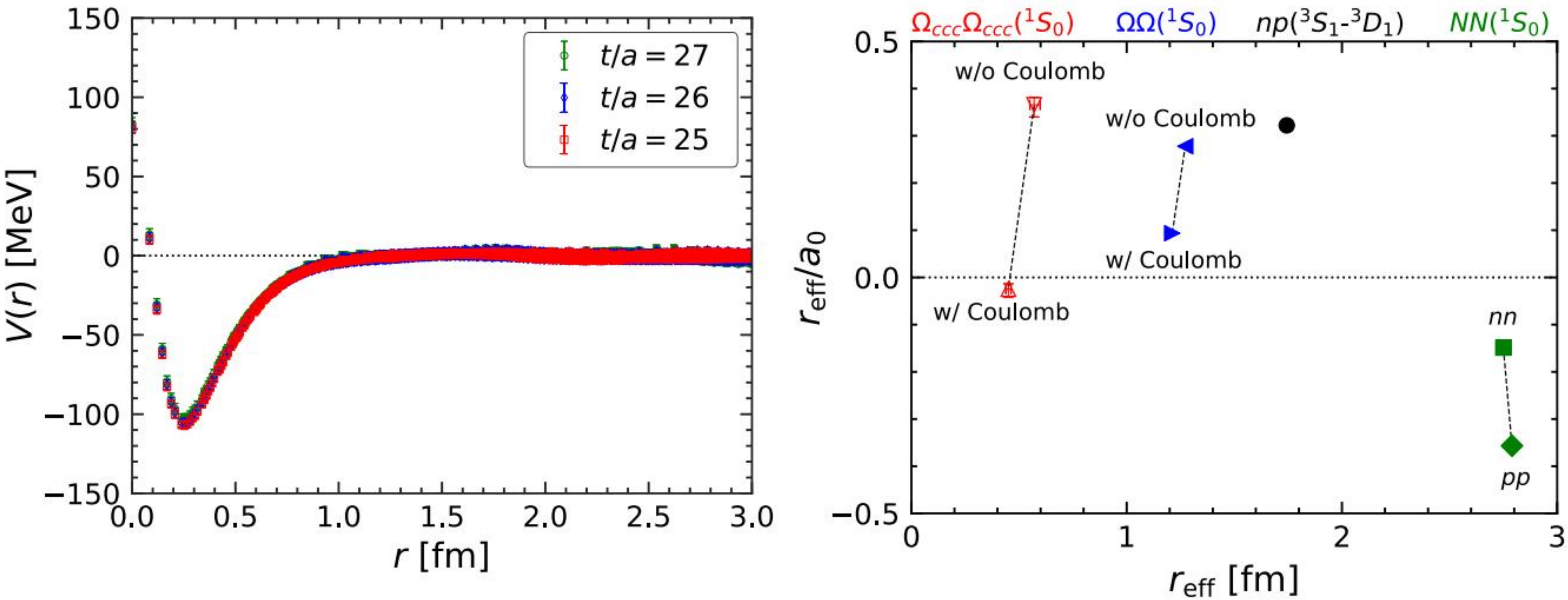
T. Ishikawa, et al., Phys. Rev. C 104, L052201 (2021); Phys. Rev. C 105, 045201 (2022).

Symmetry analysis

	$\langle P_{36}^{sfc} \rangle$	$\langle \mathcal{A}^{sfc} \rangle$
deuteron	$-\frac{1}{81}$	$\frac{10}{9}$
$(\Delta\Delta)_{ST=03}$	$-\frac{1}{9}$	2
$(\Delta\Delta)_{ST=30}$	$-\frac{1}{9}$	2
$(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$	$-\frac{1}{9}$	2
$(\Sigma^*\Delta)_{ST=3\frac{1}{2}}$	$-\frac{1}{9}$	2
$(\Xi^*\Omega)_{ST=0\frac{1}{2}}$	$-\frac{1}{9}$	2
$(\Omega\Omega)_{ST=00}$	$-\frac{1}{9}$	2

When antisymmetrizer A^{sfc} is large enough, the system is very possible to become a bound state. More systems like ΔΔ?

Example of lattice calculations on $\Omega_{ccc}\Omega_{ccc}$ system



Y. Lyu, H. Tong, T. Sugiura, S. Aoki, T. Doi, T. Hatsuda, J. Meng and T. Miyamoto, Phys. Rev. Lett. 127, 072003 (2021).

Summary

- The vector meson exchange interactions dominate the short range interactions between light quarks.
- The $d^*(2380)$ is a $\Delta\Delta$ system with large hidden color component.
- Predicting the mirror state D_{30}, which is a weakly bound state.
- Needing more investigations on other systems.

More works about spectroscopy for mesons, baryons, tetraquarks, pentaquarks, and hexaquarks can be found in

My homepage **https://inspirehep.net/authors/1383269**

Thanks for your attentions！