Study on $\Omega\Omega$ and $N\Omega$ dibaryons

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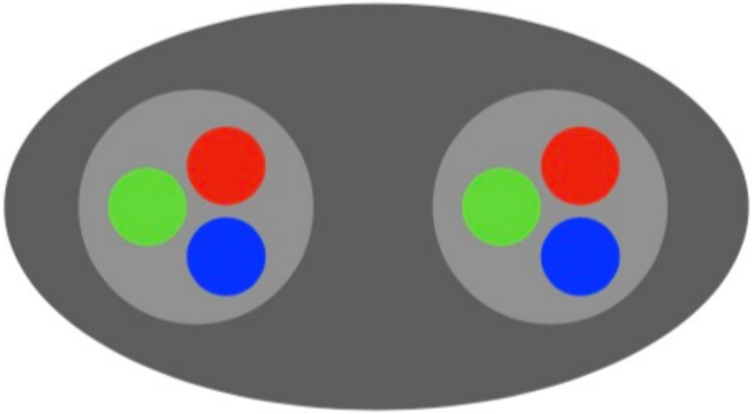
Outline

- Background of dibaryon states
- Method of the QCD sum rules
- Mass predictions for the $\Omega\Omega$ and $N\Omega$ dibaryons
- Decay properties
- Summary

Dibaryons

Dibaryons are **bound states** or **resonances** of two baryons!

Baryon (B=1)	Dibaryon (B=2)
	
Baryon Octet, Decuplet…	Deuteron, $d^*(2380)$

Dyson and Xuong's prediction for **non-strange dibaryons:**

PRL13 (1964),815; PPNP93(2017),195

notation	I	J	asymptotic baryon-baryon configuration	mass (formula)	mass (value) (MeV)
D_{01}	0	1	deuteron	A	1876
D_{10}	1	0	$^1S_0$ NN virtual state	A	1876
D_{12}	1	2	ΔN	A + 6B	2160
D_{21}	2	1	ΔN	A + 6B	2160
D_{03}	0	3	$\Delta\Delta$	A + 10B	2350
D_{30}	3	0	$\Delta\Delta$	A + 10B	2350

- D_{01} is the **deuteron ground state** (Phys.Rev.40(1932),1);
- D_{10} is the **virtual $^1S_0$ isovector state**: final state interaction from low-energy N-N scattering;
- D_{03} is the **bound state of ΔΔ** system: $d^*(2380)$ candidate

PRL102,052301;106,242302;112,202301

H dibaryons: $\Lambda\Lambda, \Sigma\Sigma, \Xi N$ with strangeness $S = -2$

Theoretical predictlons for the H-dibaryon:

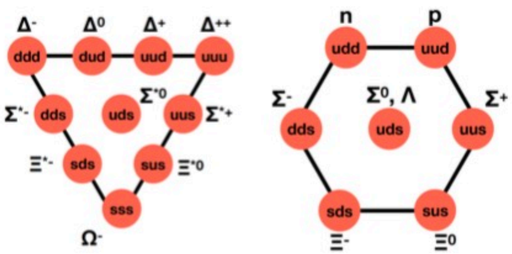
- Jaffe's prediction for **H dibaryon: $\Lambda\Lambda$ deep bound state** with $IJ^P = 00^+$ and $S = -2$ (PRL38(1977),195);
- Many theoretical predictions in various models for the $\Lambda\Lambda, \Sigma\Sigma, \Xi N$ **structures**: masses ranges from very deeply bound to unbound;
- **LQCD predictions**: **weakly bound state** with binding energies about 17 MeV (PRL106(2011),162001), 30-40 MeV (PRL106(2011),162002);

Experimental search for the H dibaryon:

- None of the numerous experiments have found any evidence of the existence of the H dibaryon;
- However, as of yet none of them could completely rule out its existence;
- Double-Λ hypernuclei: **a deeply bound H dibaryon can be excluded**.

NPA835(2010),207

SU(3) classification for Dibaryon candidates (B=2)



Jaffe (1977)
H-dibaryon(J=0)

1) octet-octet system

$$8 \otimes 8 = 27 \oplus 8_s \oplus \boxed{1} \oplus \boxed{\overline{10}} \oplus 10 \oplus 8_a$$

Deuteron(J=1)

2) decuplet-octet system

NΩ system and NΔ system (J=2)

$$10 \otimes 8 = 35 \oplus \boxed{8} \oplus 10 \oplus 27$$

Goldman et al (1987)
Dyson, Xuong (1964)

3) decuplet-decuplet system

$$10 \otimes 10 = \boxed{28} \oplus 27 \oplus 35 \oplus \boxed{\overline{10}}$$

$d^*(2380)$ resonance

ΩΩ system (J=0) **ΔΔ system (J=3)**

Zhang et al(1997)

Dyson, Xuong (1964)
Kamae, Fujita(1977)
Oka, Yazaki(1980)

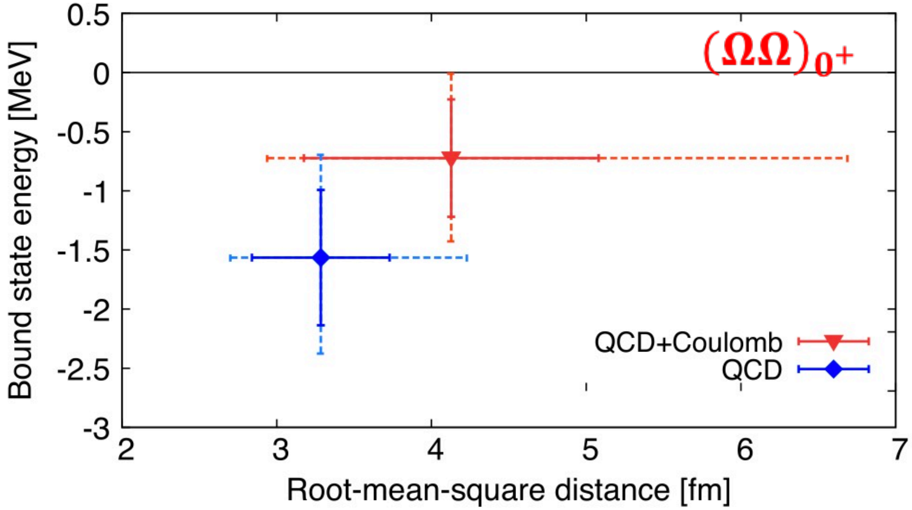
From S. Aoki's slide

$\Omega\Omega$ and $N\Omega$ dibaryons

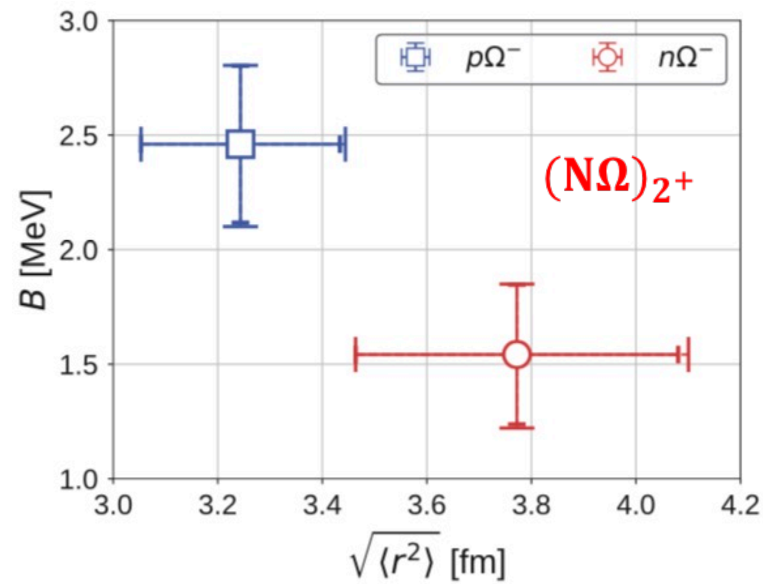
- The **$\Omega\Omega\ (S=-6)$ and $N\Omega\ (S=-3)$ dibaryons are expected to be sable:** the nucleon and Ω are the most stable states in the octet and decuplet baryons respectively.
- **$\Omega\Omega$ system** (Pauli exclusion principle): $J^P = 0^+({}^1S_0),\ 2^+({}^5S_2)$. A deep attraction in the Chiral quark model (PR51(1995), 3411); a weekly repulsive interaction (PRC61(2000),065204);
- **NΩ system**: $J^P = 1^+({}^3S_1),\ 2^+({}^5S_2)$; a deeply bound state (PRL59(1987),627; PRC69(2004),065207);shallow bound state(EPJA8(2000),417; PRC98(2018), 015205);
- **LQCD simulations** supported the existence of the **weakly bound state** of $(\Omega\Omega)_{0^+}$(B~1.6 MeV) (PRL120(2018),212001) and $(N\Omega)_{2^+}$ (B~1.5 MeV) dibaryons (PLB792(2019),284);
- The **pΩ** correlation function was measured by STAR(PLB790(2019),490).

LQCD predictions

PRL120(2018),212001



PLB792(2019),284



The scattering length, effective range, and the binding energy obtained by HAL QCD method strongly indicate that **the $(\Omega\Omega)_{0^+}$ and $(N\Omega)_{2^+}$ has an overall attraction**.

QCD sum rules

- Study two-point correlation function of current $J_\mu(x)$ with the same quantum numbers with hadron state:

$$\Pi_{\mu\nu}(q^2) = i \int d^4x e^{iq\cdot x} \langle \Omega | T[J_\mu(x) J_\nu^\dagger(0)] | \Omega \rangle$$

- Classify states $|X\rangle$ by coupling to current $\langle \Omega | J_\mu(x) | X \rangle \neq 0$
- Currents are probes of spectrum and might not overlap with state
- Hadron level: described by the dispersion relation

$$\Pi(q^2) \;=\; \frac{(q^2)^N}{\pi} \int \frac{\mathrm{Im}\Pi(s)}{s^N(s - q^2 - i\epsilon)} ds + \sum_{n=0}^{N-1} b_n (q^2)^n,$$

QCD sum rules

- Quark-gluon level: evaluated via operator product expansion(OPE)

$$\rho(s) = \rho^{pert}(s) + \rho^{\langle\bar{q}q\rangle}(s) + \rho^{\langle GG\rangle}(s) + \rho^{\langle\bar{q}q\rangle^2}(s) + \rho^{\langle\bar{q}g_s\sigma\cdot Gq\rangle}(s) + \ldots,$$

- Apply Borel transform to correlation functions
- Quark-hadron duality: Laplace Sum Rules with QCD spectral function

$$\mathcal{L}_k\left(s_0, M_B^2\right) = \int_{4m_Q^2}^{s_0} ds e^{-s/M_B^2}\rho(s)s^k = f_X^2 m_X^{2k} e^{-m_X^2/M_B^2},$$

- Predict Hadron mass via:

$$m_X\left(s_0, M_B^2\right) = \sqrt{\frac{\mathcal{L}_1\left(s_0, M_B^2\right)}{\mathcal{L}_0\left(s_0, M_B^2\right)}}.$$

The Ioffe currents for the Ω and N baryons:

$$J_\mu^\Omega(x) = \epsilon^{abc}\left[s_a^T(x)C\gamma_\mu s_b(x)\right]s_c(x)\,,$$
$$J_1^N(x) = \epsilon^{abc}\left[u_a^T(x)C\gamma_\mu u_b(x)\right]\gamma^\mu\gamma^5 d_c(x)\,,$$
$$J_2^N(x) = \epsilon^{abc}\left[u_a^T(x)C\gamma_5 d_b(x)\right]u_c(x)\,.$$

The dibaryon currents for the $\Omega\Omega$ and $N\Omega$ systems:

$$J_{\mu\nu}^{\Omega\Omega}(x) = \epsilon^{abc}\epsilon^{def}\left[s_a^T(x)C\gamma_\mu s_b(x)\right]s_c^T(x)\cdot C\gamma_5\cdot s_f(x)\left[s_d^T(x)C\gamma_\nu s_e(x)\right]\,,$$
$$J_{\mu\nu,1}^{N\Omega}(x) = \epsilon^{abc}\epsilon^{def}\left[u_a^T(x)C\gamma_\lambda u_b(x)\right]\left(\gamma^\lambda\gamma^5 d_c(x)\right)^T\cdot C\gamma_\mu\cdot s_f(x)\left[s_d^T(x)C\gamma_\nu s_e(x)\right]\,,$$
$$J_{\mu\nu,2}^{N\Omega}(x) = \epsilon^{abc}\epsilon^{def}\left[u_a^T(x)C\gamma_5 d_b(x)\right]u_c^T(x)\cdot C\gamma_\mu\cdot s_f(x)\left[s_d^T(x)C\gamma_\nu s_e(x)\right]\,.$$

$$\langle 0|J_{\mu\nu}^{\Omega\Omega}|X_0\rangle = f_0 g_{\mu\nu} + f_q q_\mu q_\nu\,,$$
$$\langle 0|J_{\mu\nu}^{\Omega\Omega}|X_T\rangle = f_T\epsilon_{\mu\nu}\,,$$

$$\langle 0|J_{\mu\nu}^{N\Omega}|X_A\rangle = f_A\varepsilon_{\mu\nu\alpha\beta}\epsilon^\alpha q^\beta,$$
$$\langle 0|J_{\mu\nu}^{N\Omega}|X_T\rangle = f_T\epsilon_{\mu\nu},$$

Projectors to pick out the invariant functions：

$$P_{0T} = \frac{1}{16} g_{\mu\nu} g_{\rho\sigma} , \qquad \text{for } J^P = 0^+, \text{ T}$$

trace part

$$P_{0S} = T_{\mu\nu} T_{\rho\sigma} , \qquad \text{for } J^P = 0^+, \text{ S}$$

traceless symmetric part

$$P_{0TS} = \frac{1}{4}(T_{\mu\nu} g_{\rho\sigma} + T_{\rho\sigma} g_{\mu\nu}) , \ \text{for } J^P = 0^+, \text{ TS}$$

cross term

$$P_{1A} = \left[\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho}\right] , \ \text{for } J^P = 1^+,$$

$$P^P_{2S} = \frac{1}{2}\left(\eta_{\mu\rho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho} - \frac{2}{3}\eta_{\mu\nu}\eta_{\rho\sigma}\right) , \ \text{for } J^P = 2^+, \text{ S}$$

where

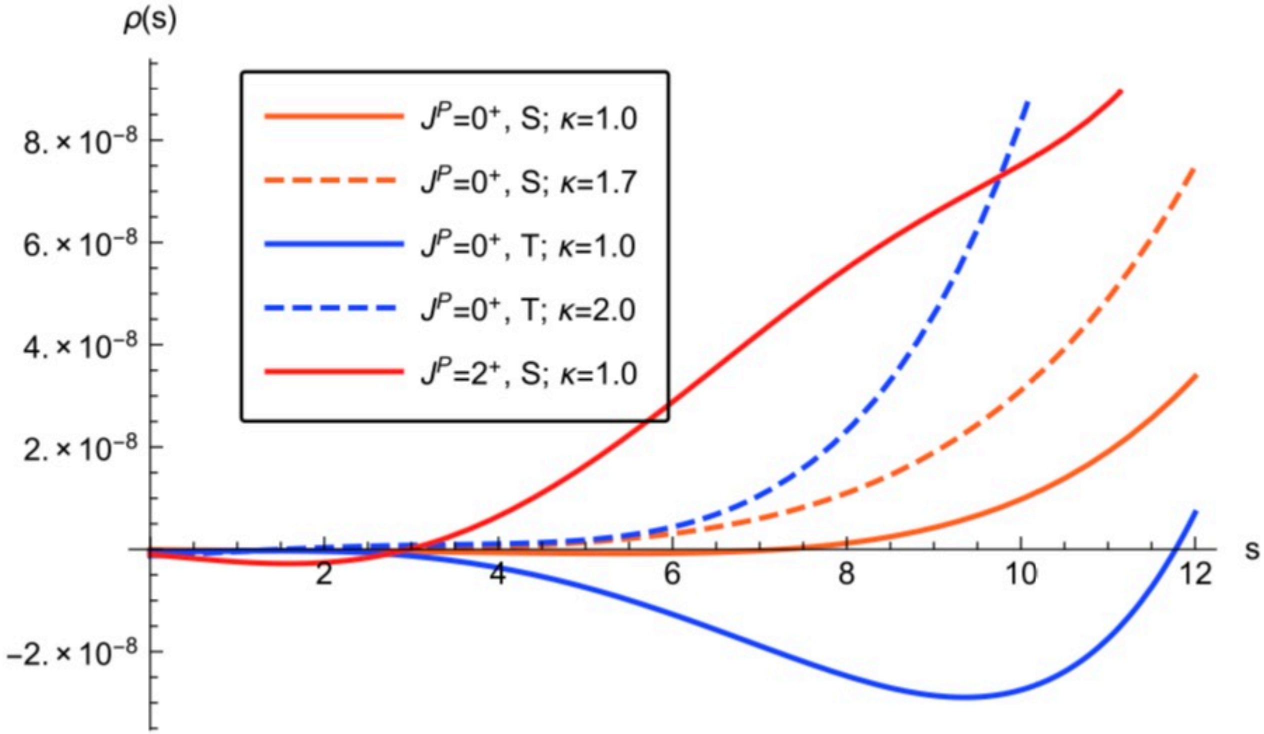
$$\eta_{\mu\nu} = \frac{q_\mu q_\nu}{q^2} - g_{\mu\nu} ,$$

$$T_{\mu\nu} = \frac{q_\mu q_\nu}{q^2} - \frac{1}{4} g_{\mu\nu} ,$$

$$T^{\pm}_{\mu\nu,\rho\sigma} = \left[\frac{q_\mu q_\rho}{q^2}\eta_{\nu\sigma} \pm (\mu \leftrightarrow \nu)\right] \pm (\rho \leftrightarrow \sigma) .$$

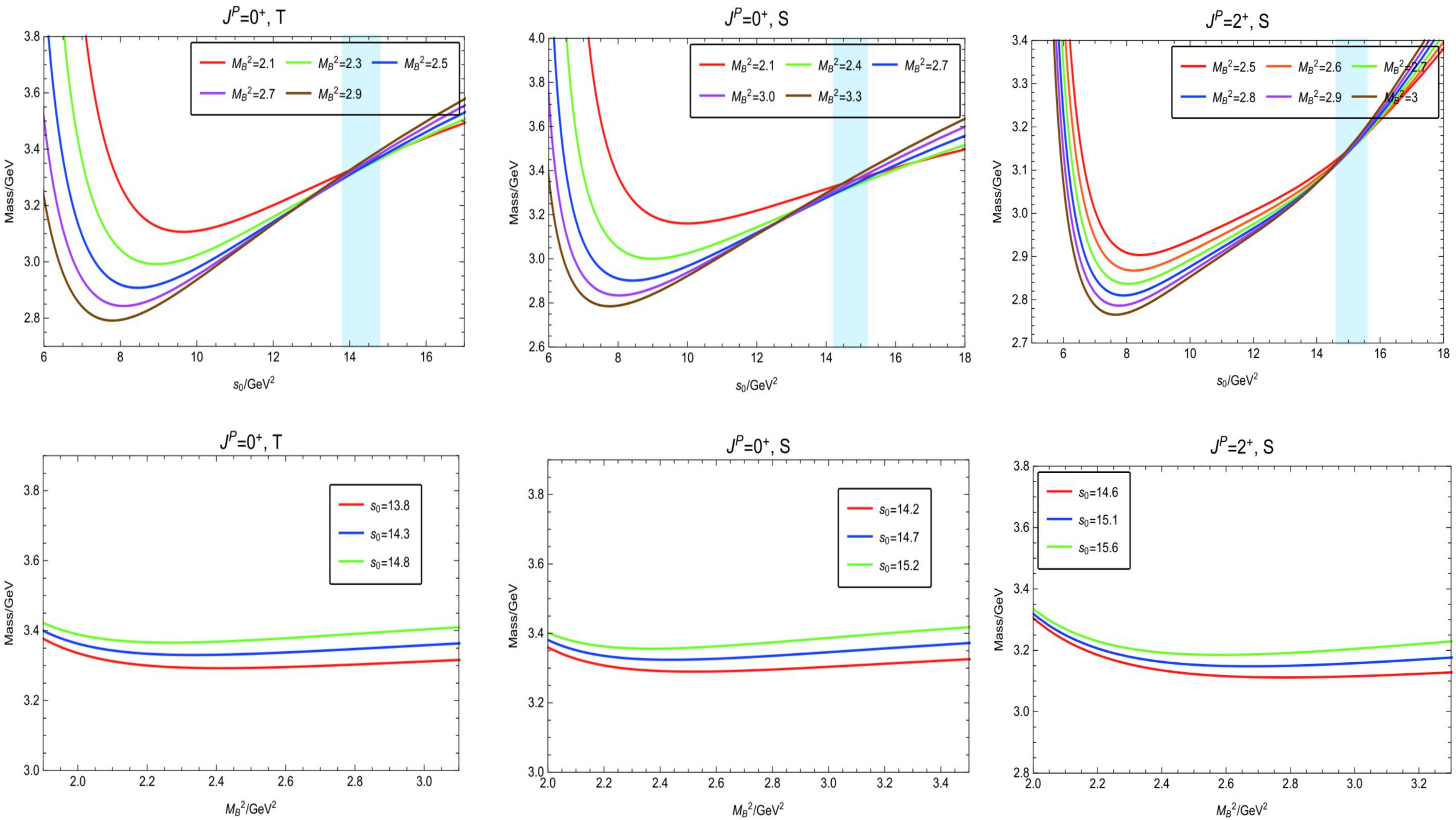
ΩΩ dibaryon systems

$\rho(s)$ was calculated up to dim-16



The violation of factorization assumption is considered to eliminate the negative behavior of the spectral functions

Mass sum rules



X.H.Chen,Q.N.Wang,W.Chen*,H.X.Chen, CPC45, 041002 (2021)

Mass predictions:

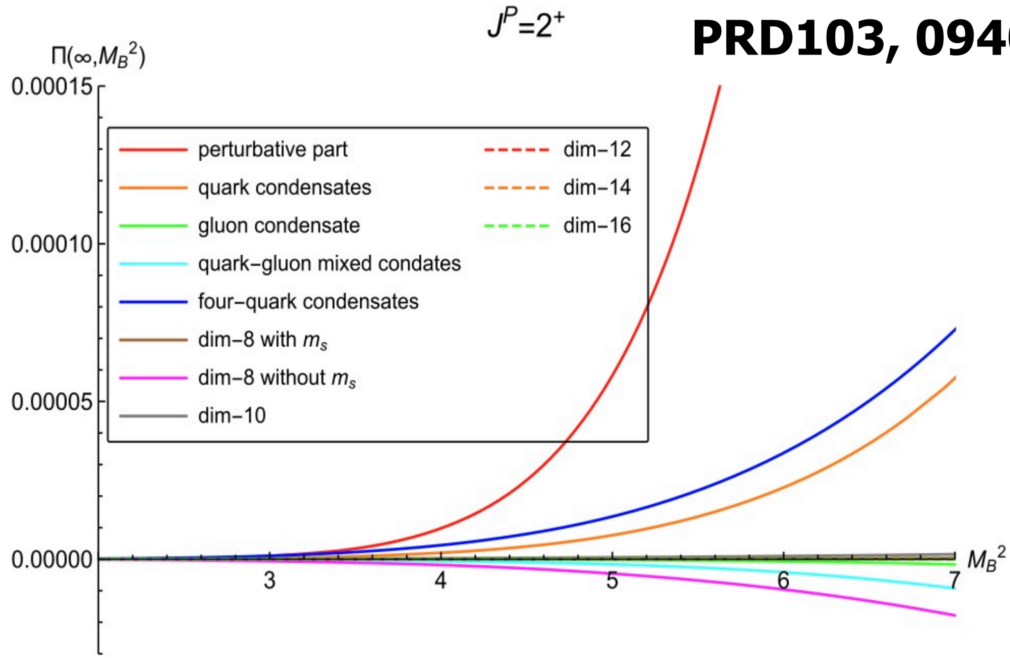
Chin. Phys. C45, 041002 (2021)

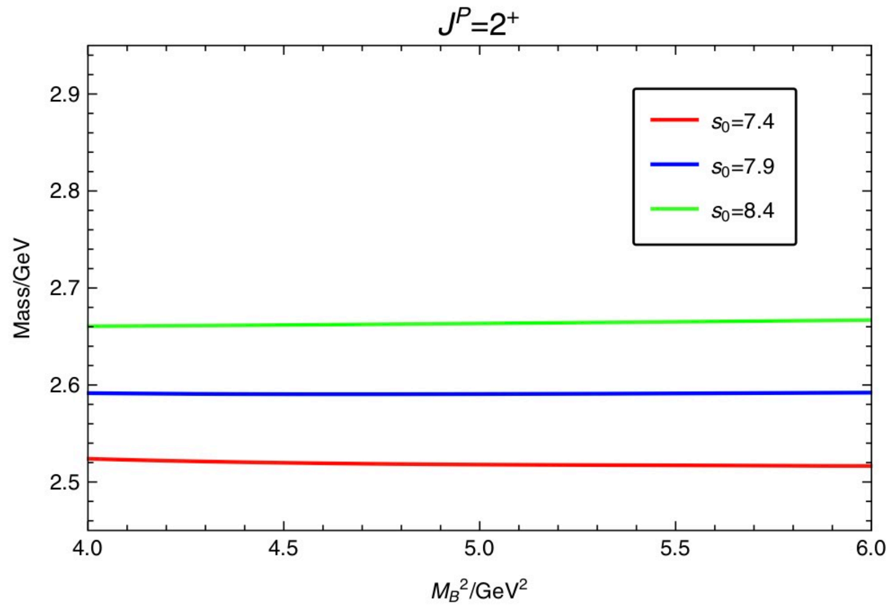
Channel	mass/GeV	coupling/10^{-4} GeV^8	PC	κ	s_0/GeV^2	M_B^2/GeV^2
$(0^+, T)$	3.33 ± 0.31	10.10 ± 5.44	39%	2.0	[13.8, 14.8]	[2.1, 2.9]
$(0^+, S)$	3.33 ± 0.37	6.25 ± 1.60	43%	1.7	[14.2, 15.2]	[2.1, 3.3]
$(2^+, S)$	3.15 ± 0.20	9.01 ± 6.60	20%	1.0	[14.6, 15.6]	[2.5, 3.0]

- The $(\Omega\Omega)_{0^+}$ system lie very close to the $2m_\Omega$ threshold; may form a shallow bound state;
- The $(\Omega\Omega)_{2^+}$ may form a deeper bound state in the $^5S_2$ channel;
- **They may very narrow via the weak decays:** $(\Omega\Omega)_{0^+} \to \Omega + \Lambda + K$, $(\Omega\Omega)_{0^+} \to \Omega + \Xi + \pi$, $(\Omega\Omega)_{0^+} \to \Xi + \Xi + K$, $(\Omega\Omega)_{2^+} \to \Xi + \Xi + K$

Mass sum rules

PRD103, 094001 (2021)

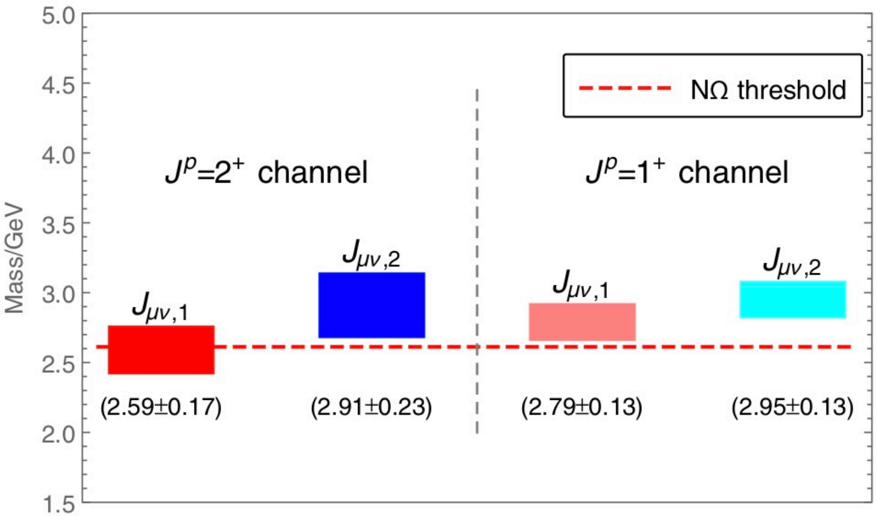




Mass predictions:

PRD103, 094001 (2021)

Current	J^P	Mass/GeV	Coupling/ 10^{-4} GeV^8	s_0/GeV^2	M_B^2/GeV^2
$J^{N\Omega}_{\mu\nu,1}$	2^+	2.59 ± 0.17	6.68 ± 0.46	[7.4, 8.4]	[4.0, 6.0]
	1^+	2.79 ± 0.13	5.19 ± 1.20	[8.8, 9.8]	[3.0, 5.0]
$J^{N\Omega}_{\mu\nu,2}$	2^+	2.91 ± 0.23	5.58 ± 1.16	[9.2, 10.2]	[5.0, 7.0]
	1^+	2.95 ± 0.13	2.84 ± 0.17	[9.5, 10.5]	[4.0.6.0]



- $(N\Omega)_{2^+}$ **may be weakly bound!**
- D-wave decay processes: $(N\Omega)_{2^+} \to \Lambda + \Xi$, $(N\Omega)_{2^+} \to \Sigma + \Xi$;
- $(N\Omega)_{1^+}$ lies above the $N\Omega$, $\Lambda\Xi$, $\Sigma\Xi$ thresholds: $(N\Omega)_{1^+} \to \Lambda\Xi$, $\Sigma\Xi$, $N\Omega$

Summary

- Masses for the $(\Omega\Omega)_{0^+}, (\Omega\Omega)_{2^+}$ and $(N\Omega)_{1^+}, (N\Omega)_{2^+}$ dibaryons are predicted;
- The $(\Omega\Omega)_{0^+}$ **may form a shallow bound state**, while the $(\Omega\Omega)_{2^+}$ **can be much deeper**;
- The $(N\Omega)_{2^+}$ **may be weakly bound**, while $(N\Omega)_{1^+}$ **lies above the $N\Omega$, $\Lambda\Xi$, $\Sigma\Xi$ thresholds.**
- These dibaryons may be identified in the relativistic heavy-ion collision experiments.

Thank you!