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第五届粒子物理天问论坛

The $\Xi_c^{('*)}N$ interactions and the corresponding bound states

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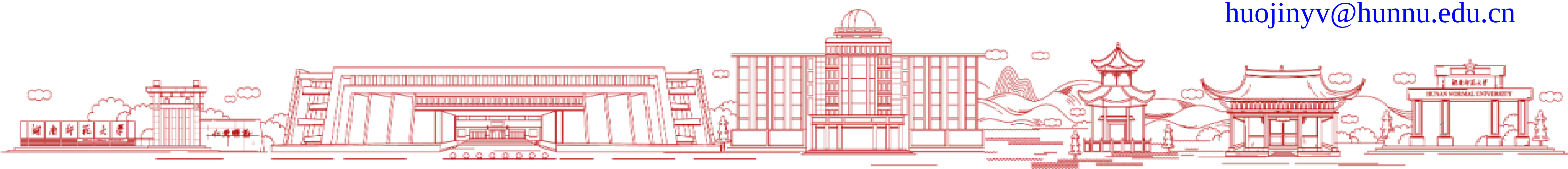
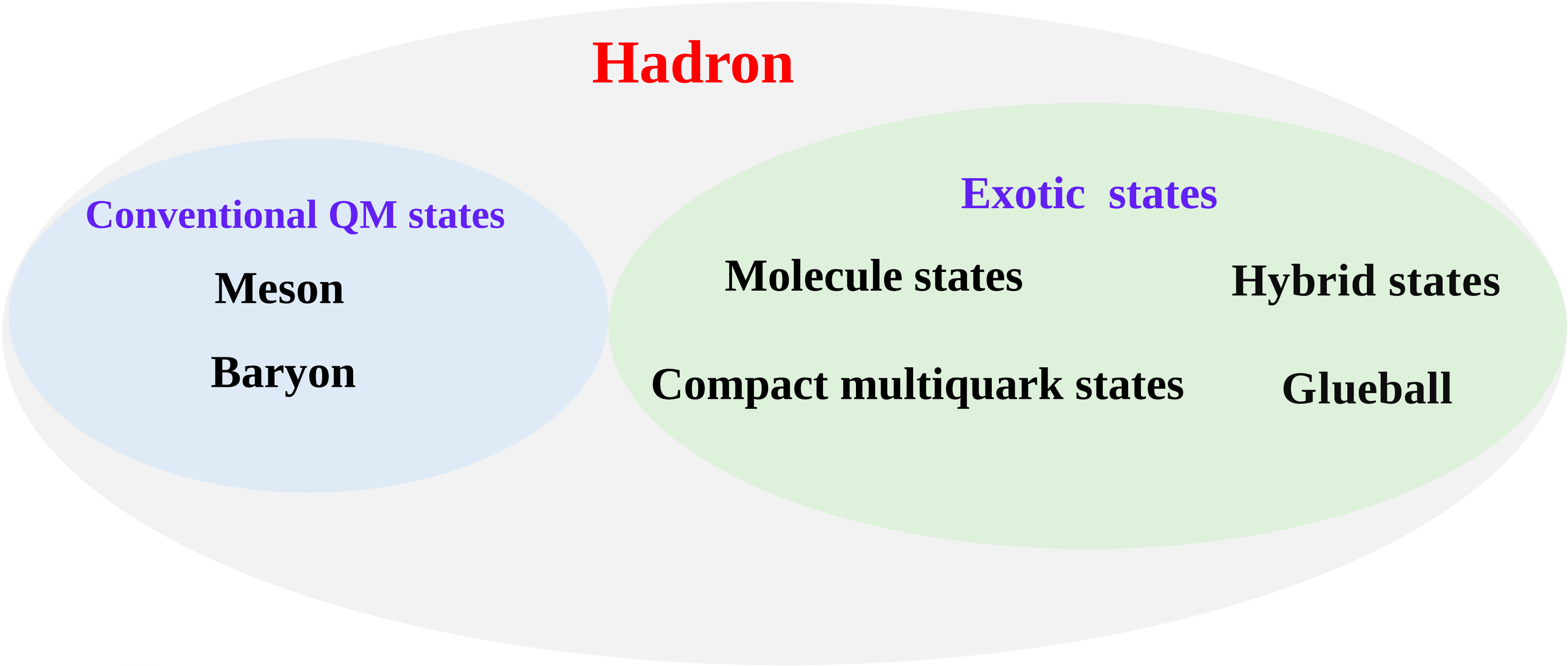
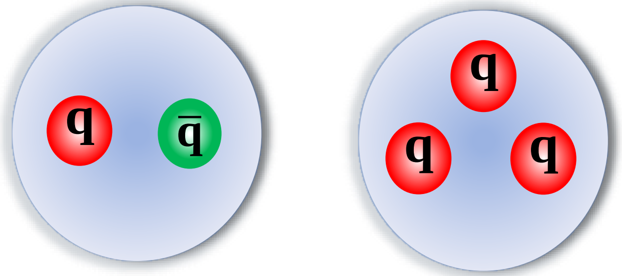


Outline

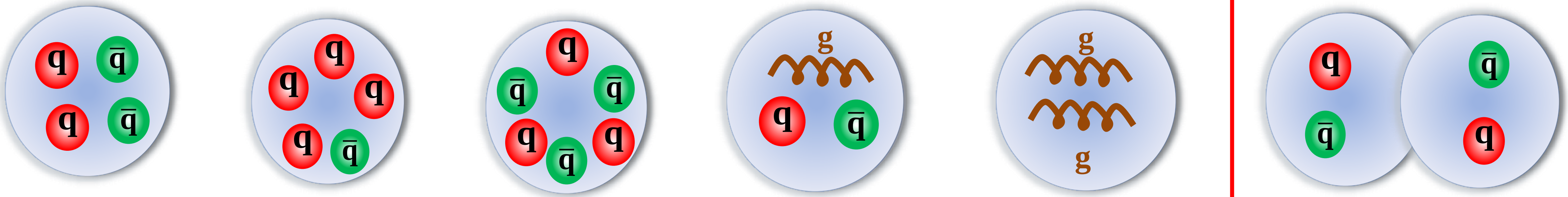
1. **Why do we study $\Xi_c N$ system?**
2. **One-boson-exchange (OBE) model**
3. **Numerical results**
4. **Summary**

1.1 QCD color singlet



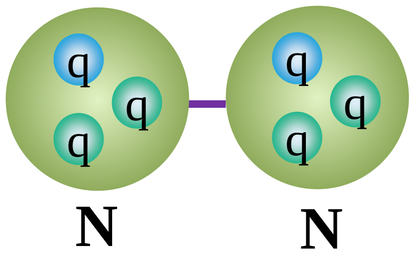


Meson Baryon



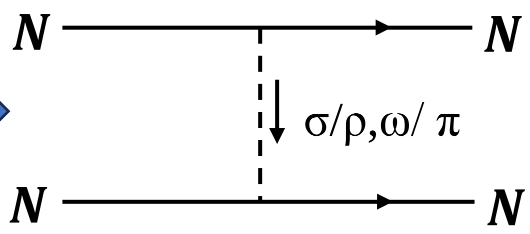
Tetraquark Pentaquark Hexaquark Hybrid Glueball Molecule

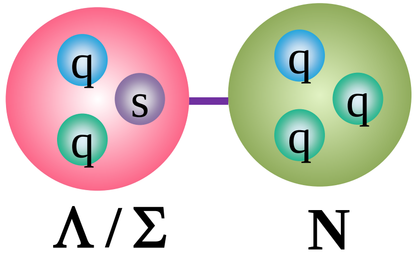
1.2 From deuteron to hyperon-nucleon



Deuteron

OBE model applied in
$N-N$ interactions

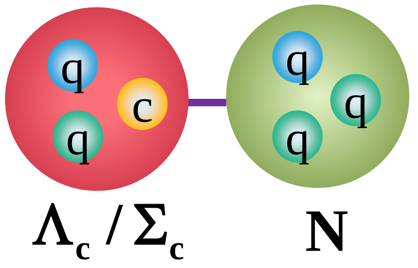




Hyperon-nucleon

Prog. Part. Nucl. Phys. 96, 88-153 (2017)
Prog. Part. Nucl. Phys. 100, 161-210 (2018)

- To predict the existence of YN hypernuclei
- To investigate the properties of strange baryons within nuclear matter



The hypernuclei in the charmed sector

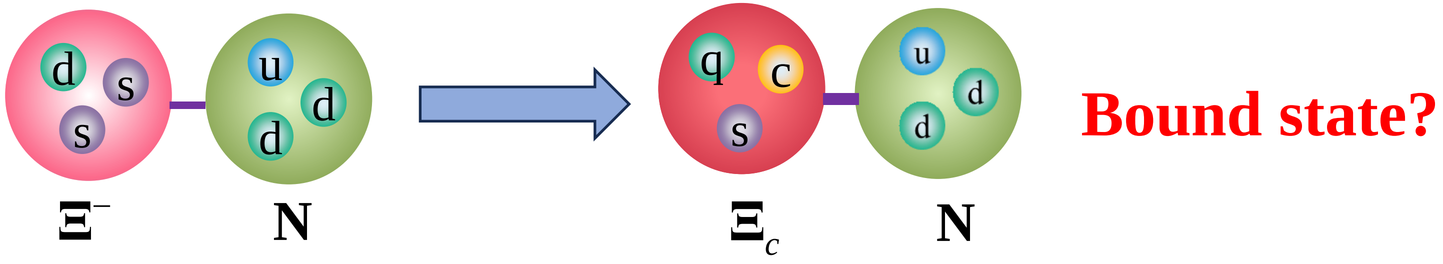
Phys. Rev. Lett. 39, 1506-1509 (1977)

- The meson-exchange model
- Exist both two-body and many-body bound states.

1.3 ΞN and $\Xi_c N$

Phys. Rev. Lett. **126**, 062501

For the binding energy of the Ξ^- hyperon in the $\Xi^- - {}^{14}N$ system a value of 1.27±0.21MeV was deduced.



1. The Ξ_cN attraction interaction may be **slightly weaker** due to the presence of fewer light quarks.

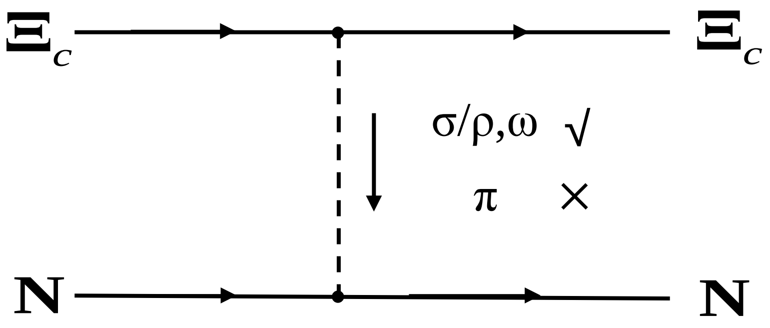
2. The Ξ_cN system is substantially **heavier** than the ΞN system because of charm quark. It is favorable to form a bound state for ΞN system.

$$\left(\frac{\hat{p}^2}{2\mu}+\hat{V}\right)|\Psi\rangle = E|\Psi\rangle \qquad m_{\Xi_c} > m_{\Xi^-} \qquad \frac{\hat{p}^2}{2\mu_{\Xi_c N}} < \frac{\hat{p}^2}{2\mu_{\Xi^- N}}$$

It is essential to perform a calculation to explore the existence of a $\Xi_c N$ bound state!

1.4 NN and $\Xi_c N$

1. The π/η exchange interactions are suppressed due to the conservation of light quark spin-parity.



Ξ_c: $J^P = \frac{1}{2}^+$

$s_l^P = 0^+$

N: $J^P = \frac{1}{2}^+$

2. The coupled channel effects

$$|\psi\rangle = |R_1(r)\rangle|\Xi_c N\rangle|{}^{2S+1}L_J\rangle + |R_2(r)\rangle|\Xi_c' N\rangle|{}^{2S'+1}L'_J\rangle + |R_3(r)\rangle|\Xi_c^* N\rangle|{}^{2S''+1}L''_J\rangle$$

$$M_{\Xi_c'} - M_{\Xi_c} \simeq 100 \text{ MeV}$$

$$M_{\Xi_c^*} - M_{\Xi_c} \simeq 170 \text{ MeV}$$

Phys. Rev. D 85, 014015 (2012) ,Y. R. Liu and M. Oka,

The coupled channel effects from the Σ_c N and $\Sigma_c^* N$ channels are essential to generate the Λ_c N bound state.

2.1 One-boson-exchange (OBE) model

Scattering amplitude

↓

Effective potential in momentum space

↓

Effective potential in coordinate

↓

Coupled channel Schrödinger equation

$$\langle f|S|i\rangle = \delta_{fi} + i\langle f|T|i\rangle = \delta_{fi} + i(2\pi)^4\delta^4(p_f - p_i)\mathcal{M}_{fi},$$

$$\langle f|S|i\rangle = \delta_{fi} - i(2\pi)\delta(E_f - E_i)V_{fi}(p),$$

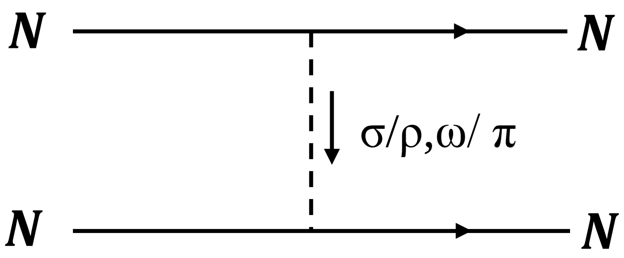
$$V_{fi}(p) = -\frac{\mathcal{M}_{fi}}{\sqrt{\prod_f 2p_f^0 \prod_i 2p_i^0}} \approx -\frac{\mathcal{M}_{fi}}{\sqrt{\prod_f 2m_f^0 \prod_i 2m_i^0}}$$

$$V(r) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \mathcal{V}_{fi}(\boldsymbol{q}) \mathcal{F}^2(q^2, m_E^2)$$

Form factor

$$\mathcal{F}(q^2, m_E^2) = (\Lambda^2 - m_E^2)/(\Lambda^2 - q^2).$$

→ Λ , One free parameter



Cut off Λ ~ 1GeV

2.2 Effective potentials

- **The effective Lagrangians**

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}} = l_B\langle\bar{\mathcal{B}}_{\bar{3}}\sigma\mathcal{B}_{\bar{3}}\rangle + i\beta_B\langle\bar{\mathcal{B}}_{\bar{3}}v^{\mu}(\mathcal{V}_{\mu}-\rho_{\mu})\mathcal{B}_{\bar{3}}\rangle$$

$$\mathcal{L}_{\mathcal{B}_6} = l_S\langle\bar{\mathcal{S}}_{\mu}\sigma\mathcal{S}^{\mu}\rangle - \frac{3}{2}g_1\varepsilon^{\mu\nu\lambda\kappa}v_{\kappa}\langle\bar{\mathcal{S}}_{\mu}\mathcal{A}_{\nu}\mathcal{S}_{\lambda}\rangle + i\beta_S\langle\bar{\mathcal{S}}_{\mu}v_{\alpha}(\mathcal{V}^{\alpha}-\rho^{\alpha})\mathcal{S}^{\mu}\rangle + \lambda_S\langle\bar{\mathcal{S}}_{\mu}F^{\mu\nu}(\rho)\mathcal{S}_{\nu}\rangle$$

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}\mathcal{B}_6} = ig_4\langle\bar{\mathcal{S}}^{\mu}\mathcal{A}_{\mu}\mathcal{B}_{\bar{3}}\rangle + i\lambda_I\varepsilon^{\mu\nu\lambda\kappa}v_{\mu}\langle\bar{\mathcal{S}}_{\nu}F_{\lambda\kappa}\mathcal{B}_{\bar{3}}\rangle + h.c..$$

$$\mathcal{L}_N = g_{\sigma NN}\bar{N}\sigma N + \sqrt{2}g_{\pi NN}\bar{N}i\gamma_5 PN + \sqrt{2}g_{\rho NN}\bar{N}\gamma_{\mu}V^{\mu}N + \frac{f_{\rho NN}}{\sqrt{2}m_N}\bar{N}\sigma_{\mu\nu}\partial^{\mu}V^{\nu}N.$$

Y. R. Liu and M. Oka, Phys. Rev. D 85, 014015 (2012)

Constructed based on the heavy quark symmetry, chiral symmetry and hidden local symmetry

$$g_{\sigma NN} = 8.46,\ g_{\pi NN} = 13.07,\quad g_{\rho NN} = 3.25,\ f_{\rho NN} = 19.82.$$

Phys. Rept.149, 1 (1987).
Phys.Rev.C63, 024001(2001).
Phys. Rev. C 81, 065201 (2010).

$$l_s = -2l_B = -\frac{2}{3}g_{\sigma NN},\ g_1 = \frac{2\sqrt{2}}{3}g_4 = \frac{2\sqrt{2}f_{\pi}g_{\pi NN}}{5M_N},\ \beta_s g_V = -2\beta_B g_V = -4g_{\rho NN},$$

$$\lambda_s g_V = -\sqrt{8}\lambda_I g_V = -\frac{6(g_{\rho NN}+f_{\rho NN})}{5M_N}$$

Estimated from the quark model

- **The spin-orbit wave functions**

$$\Xi_c^* N:\ \begin{aligned} &J^P = 1^+\ \ |{}^3S_1\rangle,\ |{}^3D_1\rangle,\\ &J^P = 0^+\ \ |{}^5D_0\rangle,\\ &J^P = 1^+\ \ |{}^3S_1\rangle,\ |{}^3D_1\rangle,\ |{}^5D_1\rangle,\\ &J^P = 2^+\ \ |{}^5S_2\rangle,\ |{}^3D_2\rangle,\ |{}^5D_2\rangle.\end{aligned}$$

$$\Xi_c^{(\prime)}N:\ J^P = 0^+\ \ |{}^1S_0\rangle$$

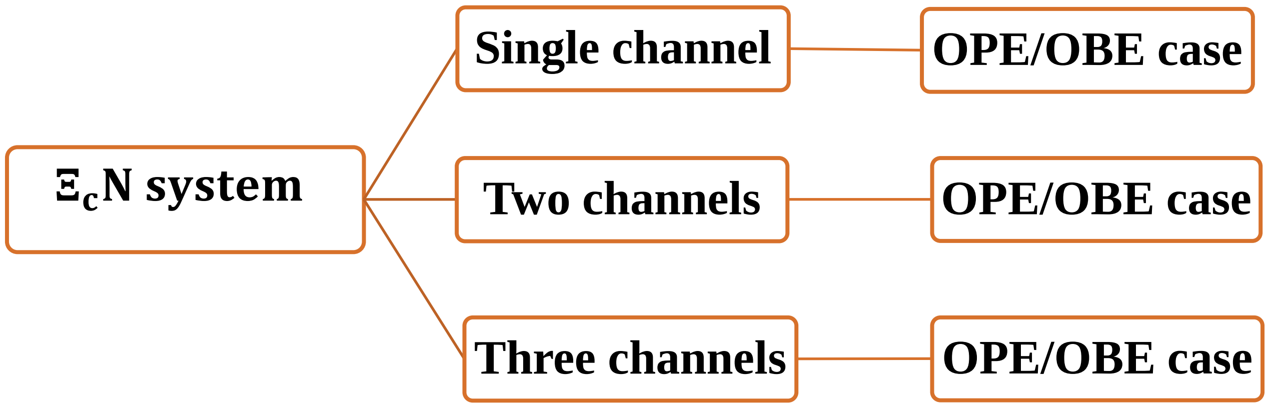
$$V^{C}_{\Xi_c N} = \begin{pmatrix} V_{\Xi_c N\to\Xi_c N} & V_{\Xi_c' N\to\Xi_c N} & V_{\Xi_c^* N\to\Xi_c N} \\ V_{\Xi_c N\to\Xi_c' N} & V_{\Xi_c' N\to\Xi_c' N} & V_{\Xi_c^* N\to\Xi_c' N} \\ V_{\Xi_c N\to\Xi_c^* N} & V_{\Xi_c' N\to\Xi_c^* N} & V_{\Xi_c^* N\to\Xi_c^* N} \end{pmatrix}$$

3.1 Numerical results

- Two essential features
  ① Binding energy: several MeV to several tens of MeV.
  ② The root-mean-square(RMS)~1.00 fm or greater.

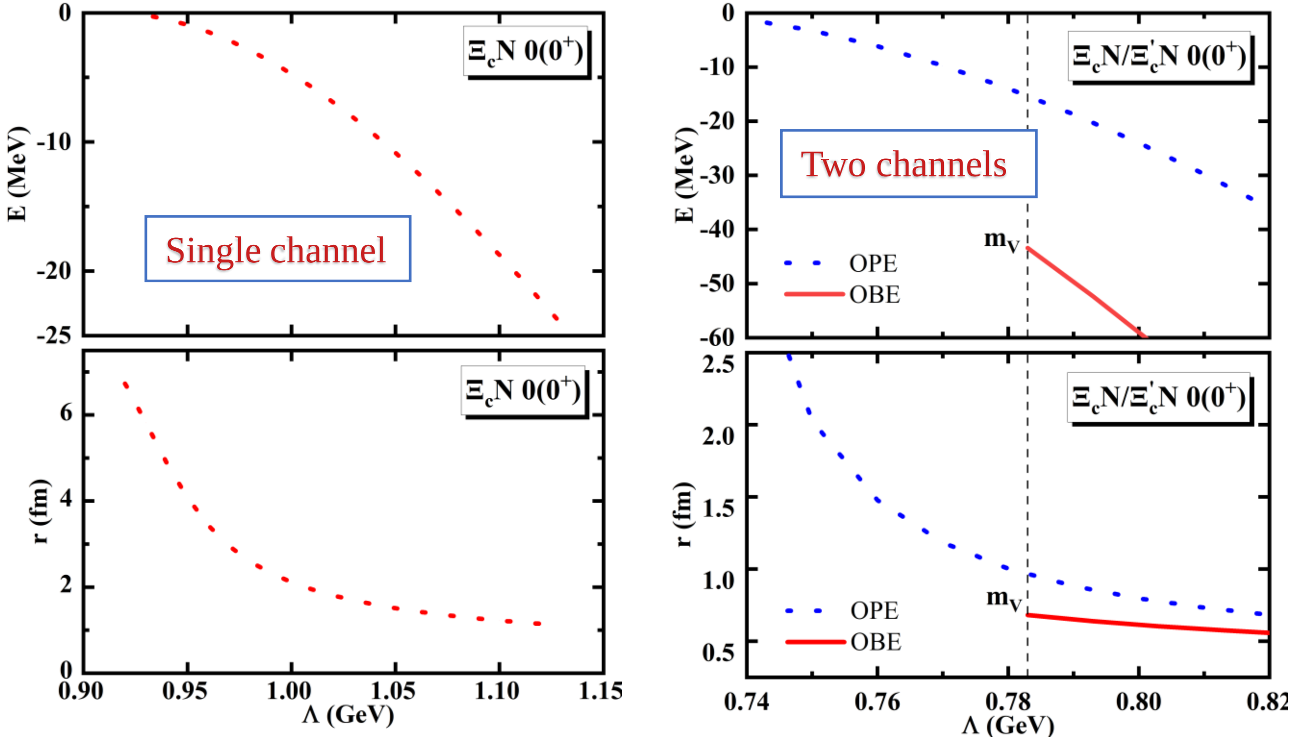
$I(J^P)$	Λ	E	r_{RMS}	$\Xi_c' N(^3S_1)$	$\Xi_c' N(^3D_1)$	$\Xi_c^* N(^3S_1)$	$\Xi_c^* N(^3D_1)$	$\Xi_c^* N(^5D_1)$
$0(1^+)$	0.89	−0.29	5.23	86.81	1.83	11.31	~ 0.00	0.04
	0.92	−5.63	1.47	50.13	2.43	47.37	0.01	0.07
	0.95	−16.32	0.86	32.53	1.76	65.55	0.02	0.15

- Investigate strategy



Λ, E, r_{RMS} , *Probability*

3.2 $\Xi_c N$ $0(0^+)$ system



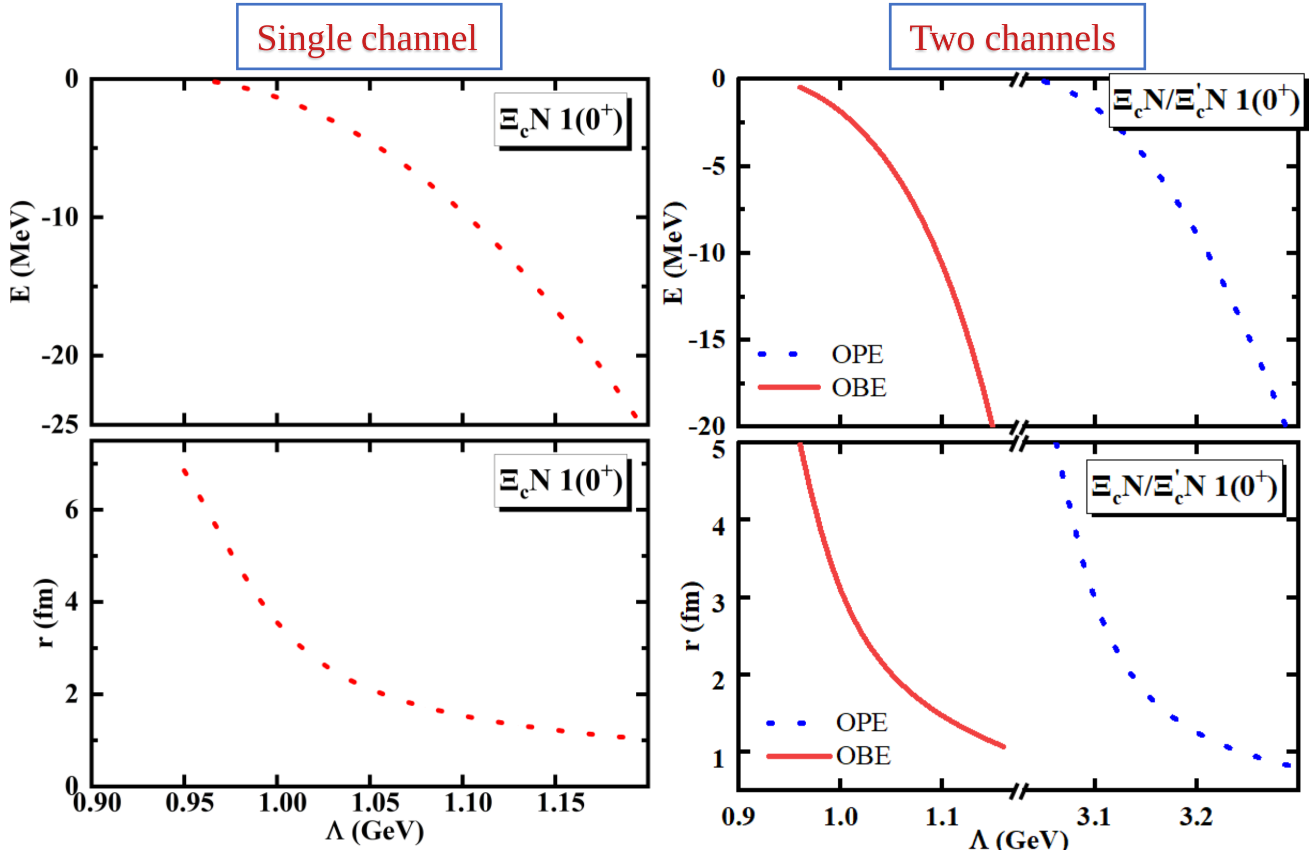
OPE $\Xi_c N/\Xi_c' N$ $0(0^+)$

$I(J^P)$	Λ	E	r_{RMS}	$\Xi_c N(^1S_0)$	$\Xi_c' N(^1S_0)$
$0(0^+)$	0.73	−0.05	5.96	93.25	6.75
	0.76	−6.14	1.48	69.50	30.50
	0.79	−18.72	0.88	55.83	44.17

The cutoff Λ,the binding energy E,and the root-mean-square r_{RMS} are in the units of GeV, MeV, and fm, respectively.

1. $\Xi_c N$ $0(0^+)$:Can be regarded as a molecular candidate because of the cut value around 1 GeV
2. The OPE interactions are sufficiently strong to bind $\Xi_c N/\Xi_c' N$ $0(0^+)$ system.
3. The scalar σ, ρ,and ω exchanges have the positive contribution to form the bound state.
4. Compared to $\Xi_c N$ $0(0^+)$ single channel, $\Xi_c N/\Xi_c' N$ $0(0^+)$ channel binds much deeper due to the coupled channel effects.
5. The results for the coupled $\Xi_c N/\Xi_c' N$ $/\Xi_c^* N$ $0(0^+)$ system don’t change too much

3.2 $\Xi_c N$ 1(0$^+$) system



OPE $\Xi_c N/\Xi_c' N$ 1(0$^+$)

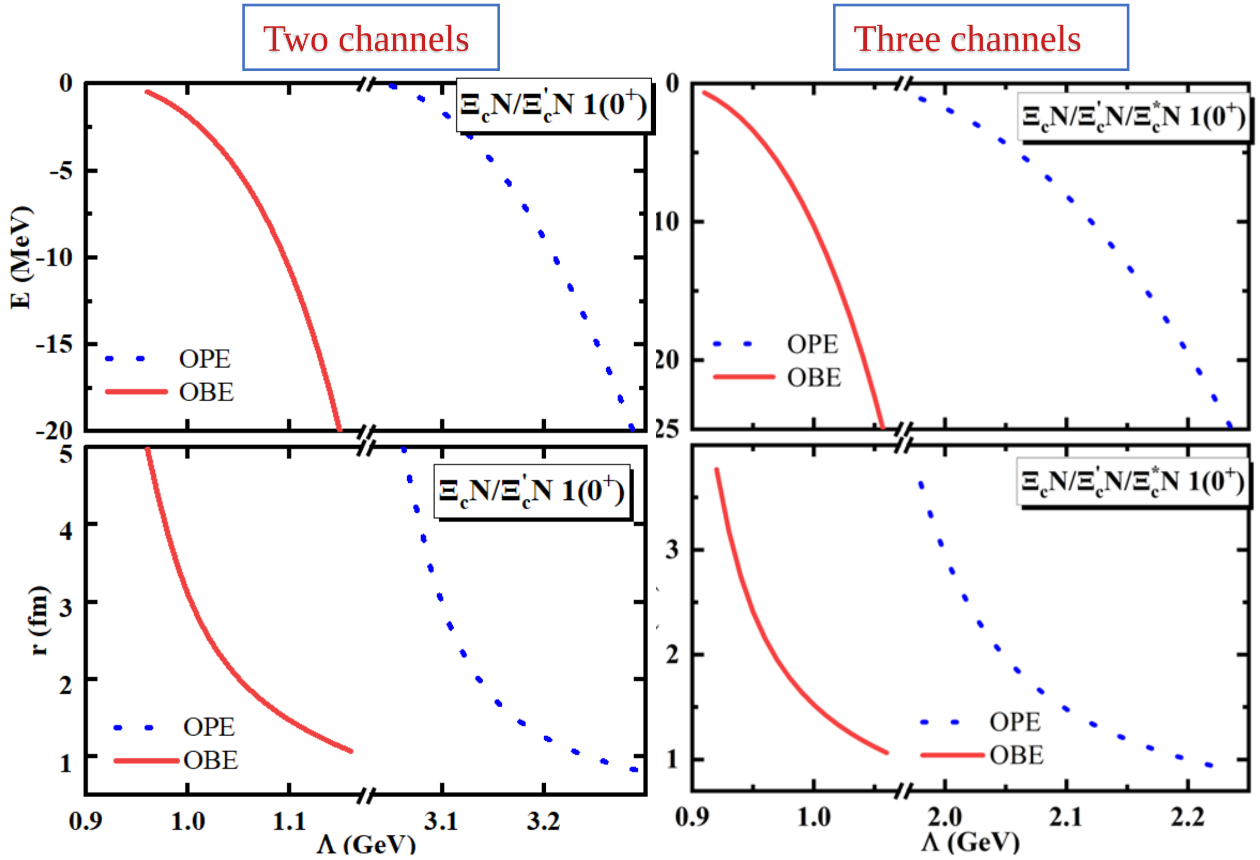
$I(J^P)$	Λ	E	r_{RMS}	$\Xi_c N(^1S_0)$	$\Xi_c' N(^1S_0)$
$1(0^+)$	3.05	−0.10	5.78	98.26	1.74
	3.15	−4.52	1.76	93.01	6.99
	3.25	−14.70	0.97	88.68	11.32

2. The OPE interactions are not strong enough attractive to bind $\Xi_c N/\Xi_c' N$ $1(0^+)$ system.

3. For the OBE case, $\Xi_c N$ $1(0^+)$ channel is dominant.

1. Compared to $\Xi_c N$ $0(0^+)$,the result of $\Xi_c N$ $1(0^+)$ don't change too much. So, the scalar σ interaction is dominant.

3.2 $\Xi_c N$ $1(0^+)$ system



OPE $\Xi_c N/\Xi_c' N/\Xi_c^* N 1(0^+)$

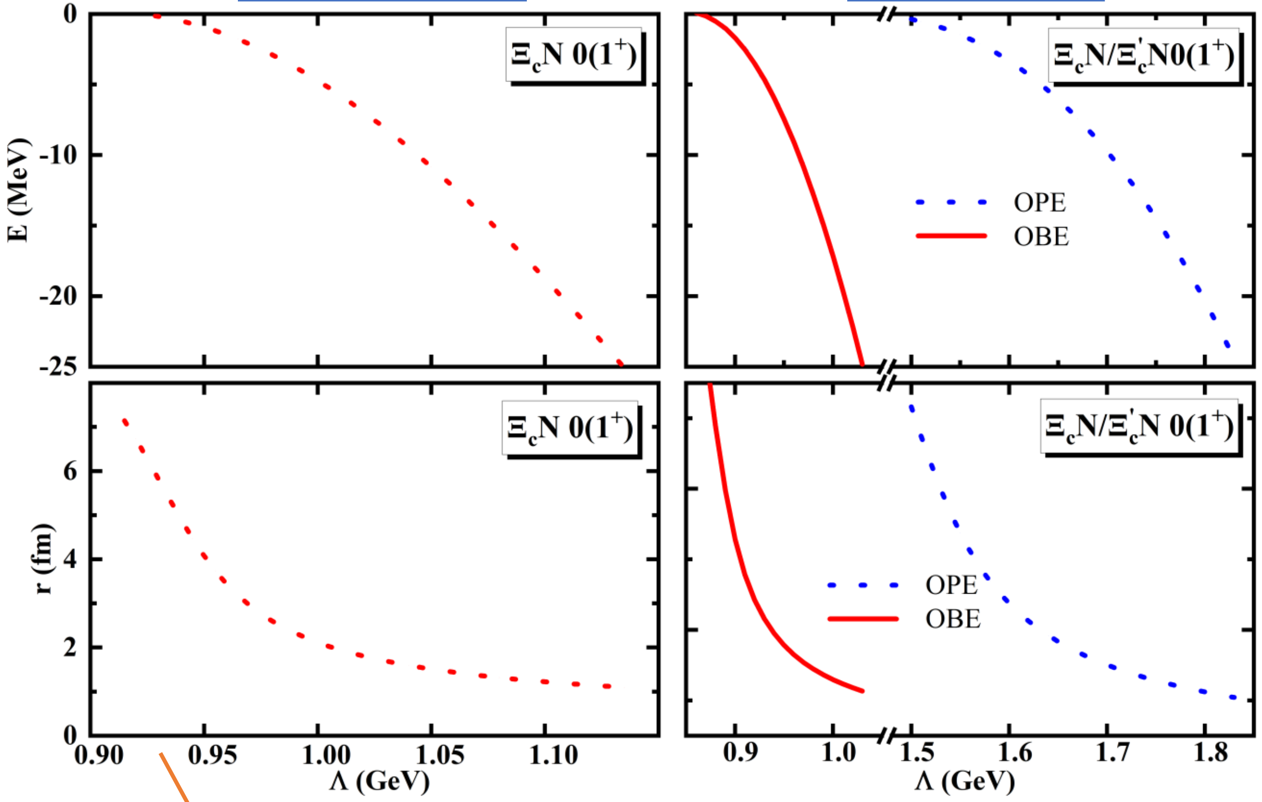
$I(J^P)$	Λ	E	r_{RMS}	$\Xi_c N(^1S_0)$	$\Xi_c' N(^1S_0)$	$\Xi_c^* N(^5D_0)$
$1(0^+)$	1.94	−0.19	5.59	98.53	0.59	0.87
	2.04	−3.74	2.11	94.99	2.13	2.88
	2.14	−12.01	1.24	91.45	3.74	4.81

1. Although the OPE interactions are stronger than before, for this bound state, it is not strong enough attractive to bind $\Xi_c N/\Xi_c' N$ $/\Xi_c^* N$ $1(0^+)$ system yet.
2. For the OBE case, $\Xi_c N$ $1(0^+)$ channel is dominant.
3. The $\Xi_c N$ $1(0^+)$ system can be regarded as a good molecular candidate

3.1 $\Xi_c N$ $0(1^+)$ system

Single channel

Two channels



same with $\Xi_c N$ $0(0^+)$ single system

OPE $\Xi_c N/\Xi_c' N$ $0(1^+)$

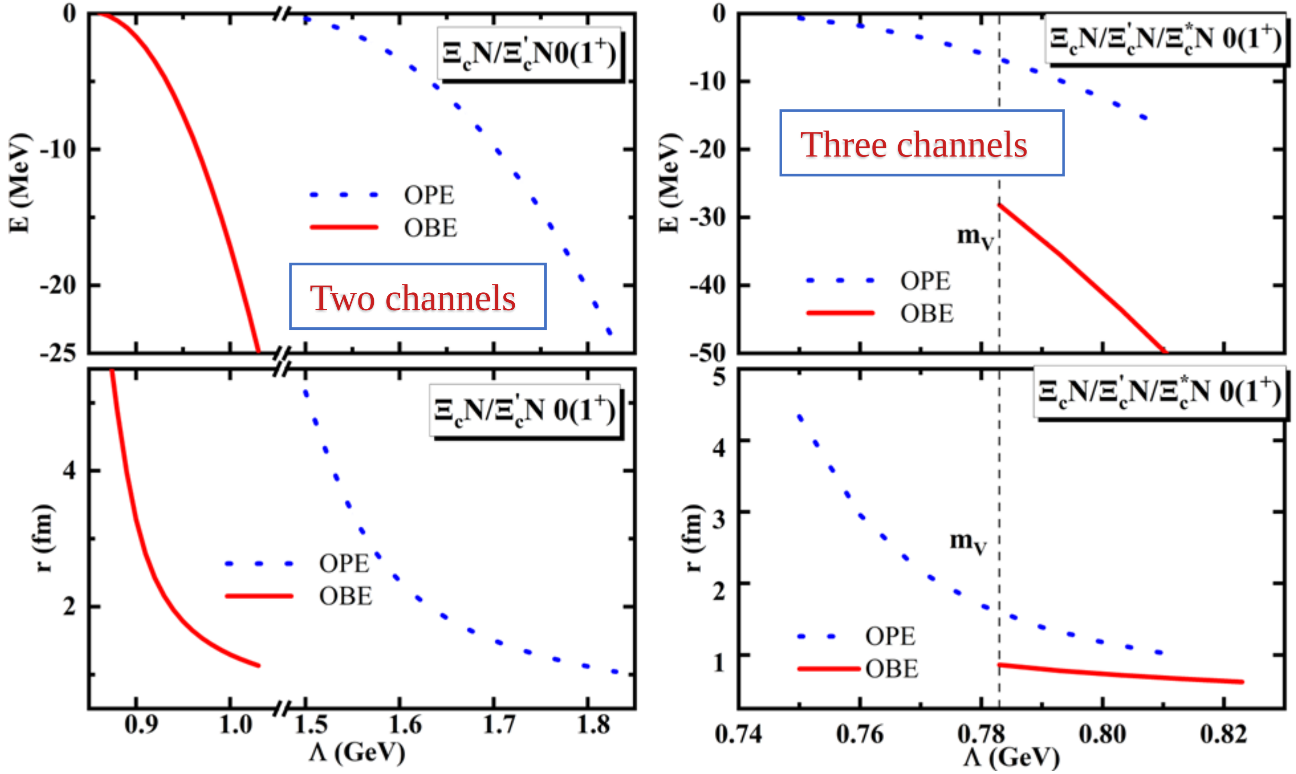
$I(J^P)$	Λ	E	r_{RMS}	$\Xi_c N(^3S_1)$	$\Xi_c N(^3D_1)$	$\Xi_c' N(^3S_1)$	$\Xi_c' N(^3D_1)$
$0(1^+)$	1.50	−0.38	5.16	98.37	0.06	0.19	1.38
	1.62	−4.32	2.12	94.82	0.12	0.92	4.13
	1.74	−13.42	1.32	90.47	0.12	2.45	6.96

1. The loosely $\Xi_c N$ $0(1^+)$ bound states emerge as the cutoffs is 0.92 GeV.
2. For the $\Xi_c N/\Xi_c' N$ $0(1^+)$ system ,$\Xi_c N(^3S_1)$ channel is dominant.
3. The scalar σ and vector mesons exchanges ρ, ω still have the positive contribution to form the bound state.
4. The $\Xi_c N$ $0(1^+)$ channel is dominant in the OBE interactions.

3.2 $\Xi_c N$ $0(1^+)$ system

OPE $\Xi_c N/\Xi'_c N/\Xi^*_c N$ $0(1^+)$

$I(J^P)$	Λ	E	r_{RMS}	$\Xi_c N(^3S_1)$	$\Xi_c N(^3D_1)$	$\Xi'_c N(^3S_1)$	$\Xi'_c N(^3D_1)$	$\Xi^*_c N(^3S_1)$	$\Xi^*_c N(^3D_1)$	$\Xi^*_c N(^3D_1)$
$0(1^+)$	0.75	−0.68	4.33	94.01	~0.00	0.85	0.21	4.71	0.02	0.20
	0.78	−5.83	1.69	81.66	~0.00	2.68	0.31	14.98	0.04	0.33
	0.81	−16.63	1.02	69.59	~0.00	4.46	0.26	25.36	0.03	0.30

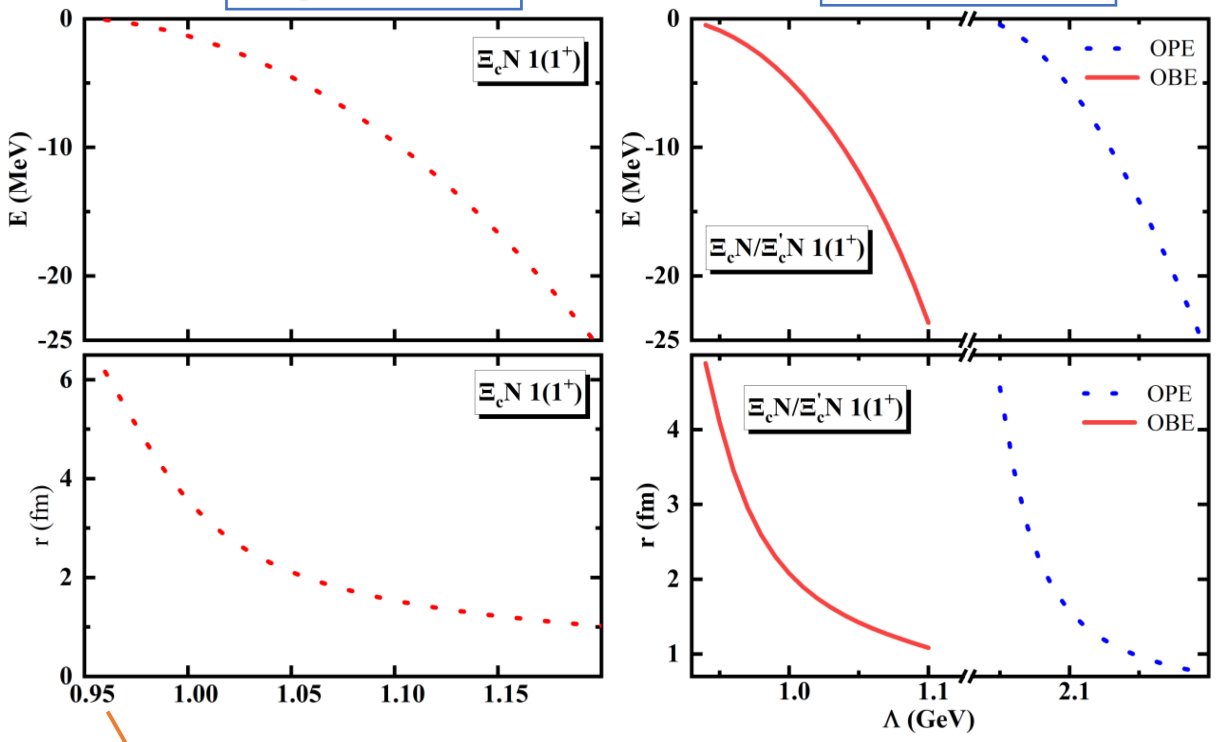


1. In the OPE case, $\Xi^*_c N$ channel deepens the binding and gain significance.
2. The σ, ρ, and ω still have the positive contribution to form the bound state.
3. The $\Xi^*_c N(\,^3S_1)$ channel gains significance and play a positive role in forming the bound state.
4. The $\Xi_c N$ $1(0^+)$ system can be regarded as a good molecular candidate

3.2 $\Xi_c N$ 1(1$^+$) system

Single channel

Two channels



same with $\Xi_c N$ $1(0^+)$ single system

OPE $\Xi_c N/\Xi_c' N 1(1^+)$

$I(J^P)$	Λ	E	r_{RMS}	$\Xi_c N(^3S_1)$	$\Xi_c N(^3D_1)$	$\Xi_c' N(^3S_1)$
$1(1^+)$	2.05	−0.47	4.56	89.51	0.58	7.83
	2.10	−5.28	1.57	70.12	1.67	22.79
	2.15	−14.19	0.97	56.98	2.41	33.21

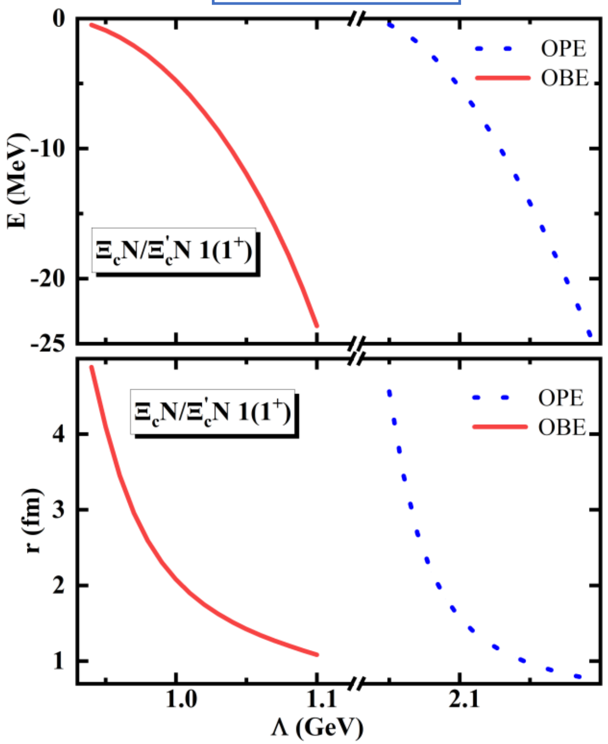
1. For $\Xi_c N$ $1(1^+)$ single channel, we can get the bound state solutions at the cutoff around 1.00 GeV .
2. The OPE interactions are sufficiently strong to bind $\Xi_c N/\Xi_c' N$ $1(1^+)$ system.
3. The σ, ρ,and ω still have the positive contribution to form the bound state.
4. For the OBE case, $\Xi_c N$ $1(1^+)$ channel is dominant.

3.2 $\Xi_c N$ $1(1^+)$ system

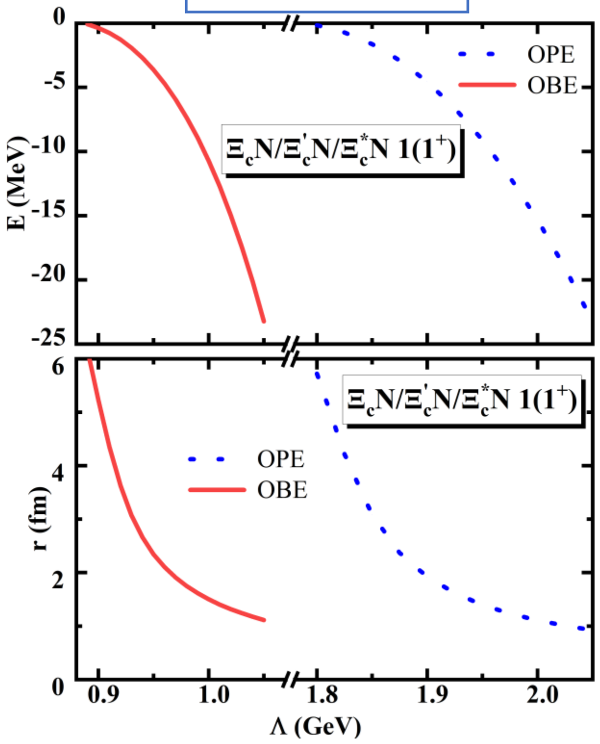
OPE $\Xi_c N/\Xi_c' N/\Xi_c^* N$ $1(1^+)$

$I(J^P)$	Λ	E	r_{RMS}	$\Xi_c N(^3S_1)$	$\Xi_c N(^3D_1)$	$\Xi_c' N(^3S_1)$	$\Xi_c' N(^3D_1)$	$\Xi_c^* N(^3S_1)$	$\Xi_c^* N(^3D_1)$	$\Xi_c^* N(^3D_1)$
$1(1^+)$	1.80	−0.16	5.72	98.16	~0.00	0.20	0.53	0.64	0.05	0.42
	1.90	−4.57	1.92	92.59	0.01	0.95	2.01	2.70	0.17	1.57
	2.00	−15.31	1.11	86.97	0.02	1.87	3.41	4.84	0.29	2.60

Two channels



Three channels



1. The OPE interactions are not strong enough attractive to bind $\Xi_c N/\Xi_c' N$ $/\Xi_c^* N$ $1(1^+)$ system yet.
2. The σ , ρ,and ω still have the positive contribution to form the bound state.
3. For the OBE case, $\Xi_c N$ $1(1^+)$ channel is dominant yet.
4. The $\Xi_c N$ $1(1^+)$ system can be regarded as a good molecular candidate

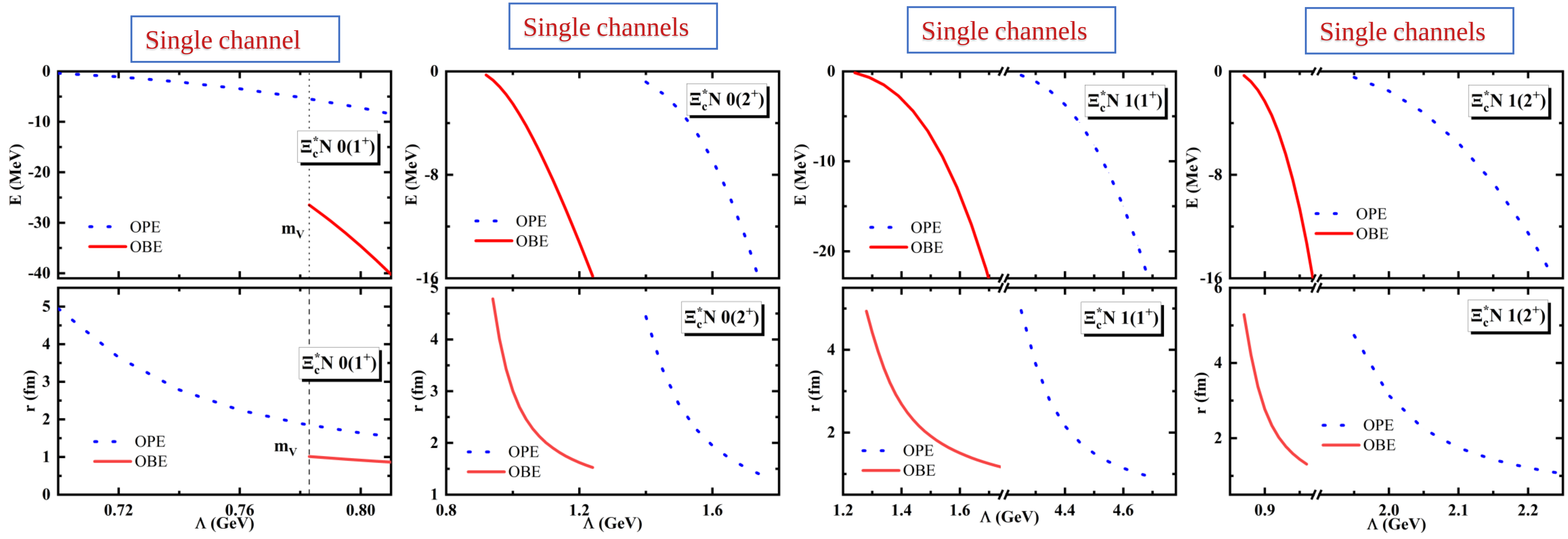
3.2 A short summary for $\Xi_c N$ system

1. For $\Xi_c N$ single system, we always gain the bound state solutions at the cutoff 1.00 GeV.
2. The σ, ρ ,and ω exchanges interactions have the positive contribution to form the bound state.
3. The coupled channel effects always deepen the binding.
4. We can predict the $\Xi_c N$ states with $0(0^+)$, $1(0^+)$, $0(1^+)$, $1(1^+)$ as good hadronic molecular candidates.

3.3 $\Xi_c^{'} N$ system

1. We can predict the $\Xi_c' N$ states with $0(0^+)$, $1(0^+)$, $0(1^+)$ and $1(0^+)$ as good hadronic molecular candidates.
2. The OPE interactions are pivotal in the formation of $\Xi_c' N$ states with $0(0^+)$, $1(0^+)$ and $0(1^+)$, while the OBE interactions also contribute positively.
3. However, the coupled channel effects do not significantly impact these four bound states.

3.4 $\Xi_c^* N$ system



OPE: 0(1⁺) and 0(2⁺) can be regard as the good hadronic molecular candidate.

OBE: Gained deeper binging energy.
The states with $I(J^P) = 0,1(1^+,2^+)$ can be regard as good hadronic molecular candidates.

4 Summary

1. Explore the interactions between charm-strange baryons and nucleons, employing the OBE model.
2. Take into account both the S −D wave mixing effects and the coupled channel effects.
3. Our results indicate the molecular candidates as follows.

   $\Xi_c N$ states with $0(0^+)$, $1(0^+)$, $0(1^+)$ and $1(1^+)$

   $\Xi_c' N$ states with $0(0^+)$, $1(0^+)$, $0(1^+)$ and $1(0^+)$

   $\Xi_c^* N$ states with $0(1^+)$, $1(1^+)$, $0(2^+)$ and $1(2^+)$

Thanks for your attention