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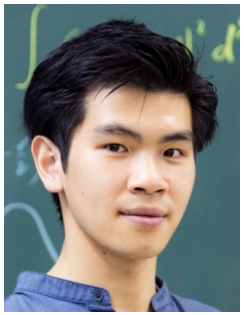
RIKEN Interdisciplinary Theoretical and Mathematical Sciences Program

SINAP 中国科学院上海应用物理研究所

FUDAN UNIVERSITY 復旦大學

BARYONS 2025

Probing Nucleon-Ωccc Interaction via Lattice QCD at Physical Quark Masses



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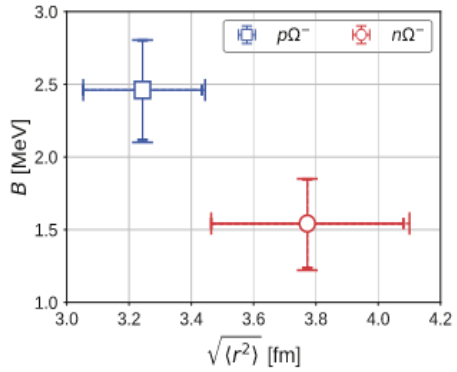
arxiv:2508.10388
Phys. Lett. B in press.

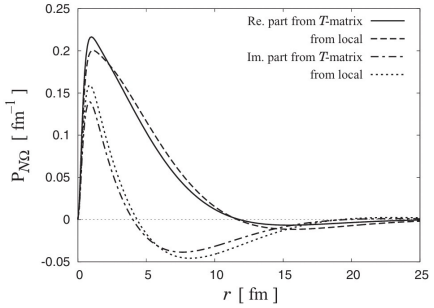
Introduction ($N\Omega_{3s}$)

Theoretical Efforts

Lattice QCD (HALQCD:2018qyu)



Meson exchange (Sekihara:2018tsb)
quasi-bound state for ${}^5S_2$ $N\Omega_{3s}$



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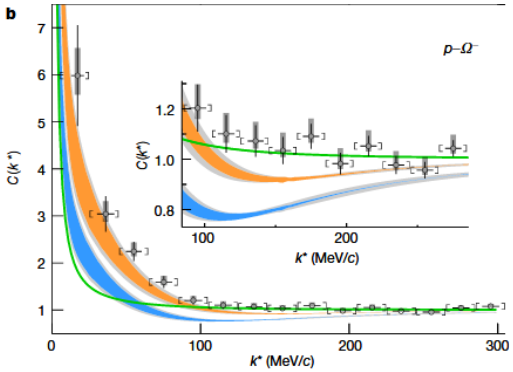
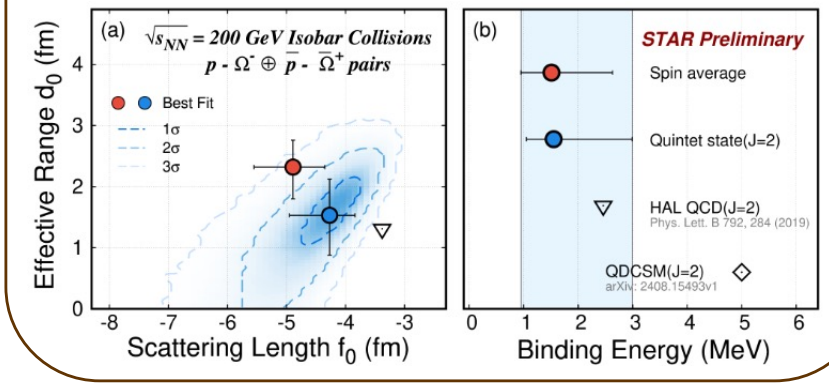
Experimental Efforts

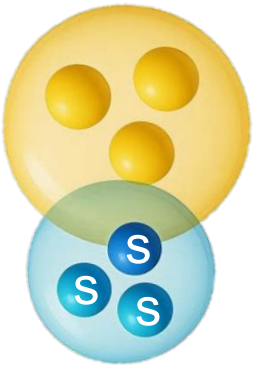


Femtoscopy in pp collisions at LHC (ALICE:2020mfd)

Femtoscopy in heavy-ion at RHIC (STAR:QM2025-763)



A Possible Bound Dibaryon



$N\Omega_{3s}$

Further researches:

- Bound $NN\Omega_{3s}$ and $N\Omega_{3s}\Omega_{3s}$ hypernuclei (Garcilazo:2019igo)
- Investigating the production of $N\Omega_{3s}$, $NN\Omega_{3s}$ and $N\Omega_{3s}\Omega_{3s}$ in Heavy Ion collisions (Zhang: 2020dma, Zhang:2021vsf)
- ……

Introduction ($N\Omega_{3c}$)

Theoretical Effort before

Quark model :

	a_0 (fm)	r_0 (fm)	B' (MeV)
ChQM	1.4989	0.40810	−15.5
QDCSM	1.3347	0.43343	−21.6

Huang:2019esu

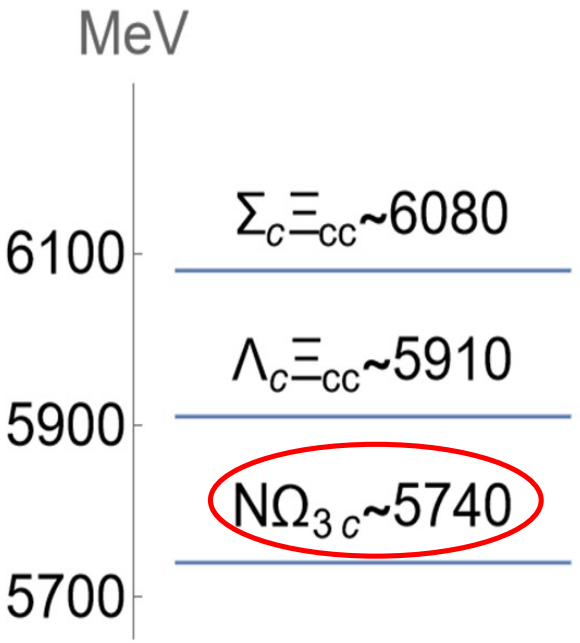
Lattice QCD

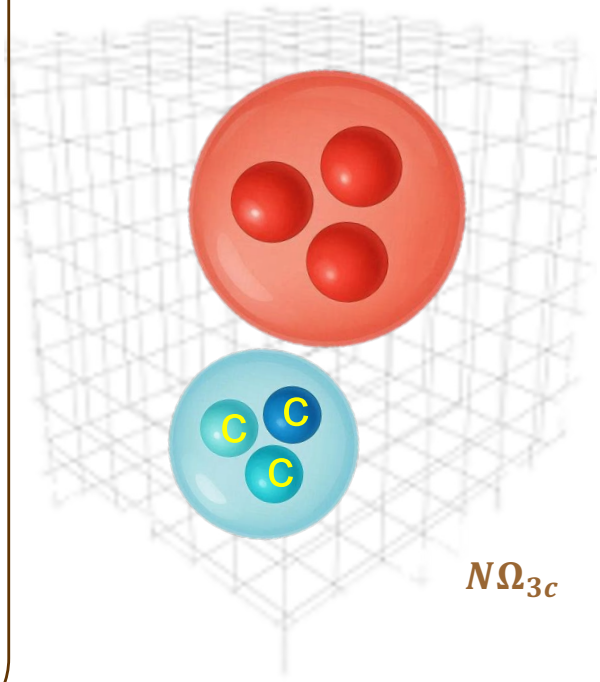
- The lowest threshold among $C = 3$ dibaryons (~ 5740 MeV)

→ No open channels
→ Clean lattice set up to study low-energy int.
→ spin-dependent $N\Omega_{3c}$ int. can be studied

→ Implications for possible charmed rnuclei

$C = 3$ dibaryon threshold





HAL QCD method

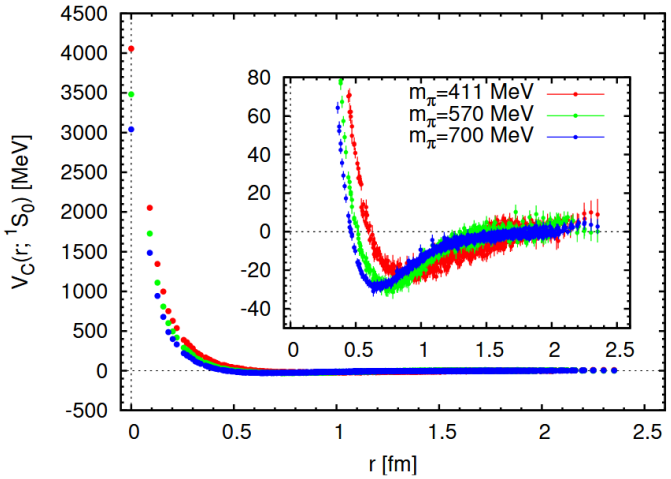
Related talk: 11st 10:15 Doi
11st 15:05 Murakami
13rd 09:00 Hatsuda

Time-dependent HAL method [1,2,3] used in this work

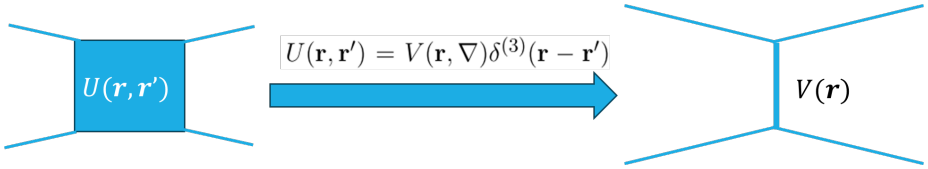
$$R^J(\boldsymbol{r},t) = \frac{F^J(\boldsymbol{r},t)}{G_{B_1}(t)G_{B_2}(t)} = \sum_n B_n^J \phi_{\boldsymbol{kn}}(\boldsymbol{r}) e^{-\Delta W_{\boldsymbol{kn}} t}$$

$$E_n \equiv \frac{k_n^2}{2\mu} = \Delta W_n + \frac{1+3\delta^2}{8\mu}(\Delta W_n)^2 + \mathcal{O}\left((\Delta W_n)^3\right)$$

$$\left(\frac{1+3\delta^2}{8\mu}\partial_t^2 - \partial_t - H_0\right) R^J(\boldsymbol{r},t) = \int d^3\boldsymbol{r}' U(\boldsymbol{r},\boldsymbol{r}') R^J(\boldsymbol{r}',t)$$



Ishii:2013ira.



$$V^{\mathrm{LO}}(\mathbf{r},\nabla) = \frac{(E_k - H_0)\phi_k(r)}{\phi_k(r)}$$

PHYSICAL POINT CALCULATION IS AVAILABLE NOW! [4]

[1] Ishii:2006ec [2] Ishii:2012ssm
[3] Aoki:2020bew [4] Aoyama:2024cko

Gauge Configurations (at $m_\pi \simeq 137$MeV)

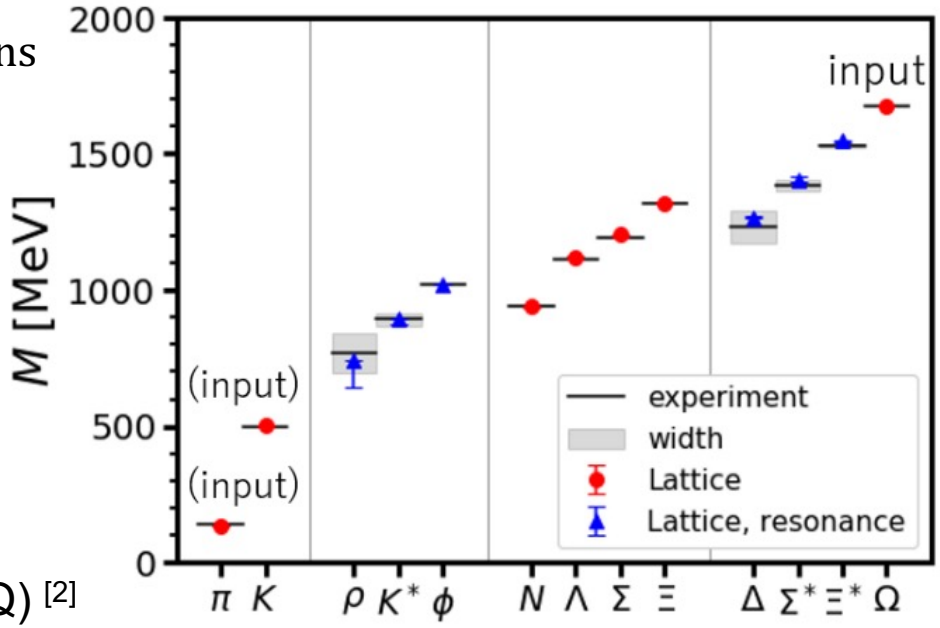
Here we using HAL-conf-2023[1] configuration which enable lattice simulations at the physical point on a large lattice volume and with a large number of ensembles.

- ✓ $(2+1)$-flavor nonperturbatively improved Wilson fermions with stout smearing
- ✓ the Iwasaki gauge action
- ✓ 8,000 trajectories

- ✓ lattice size 96^4, corresponding to $(8.1\text{fm})^4$

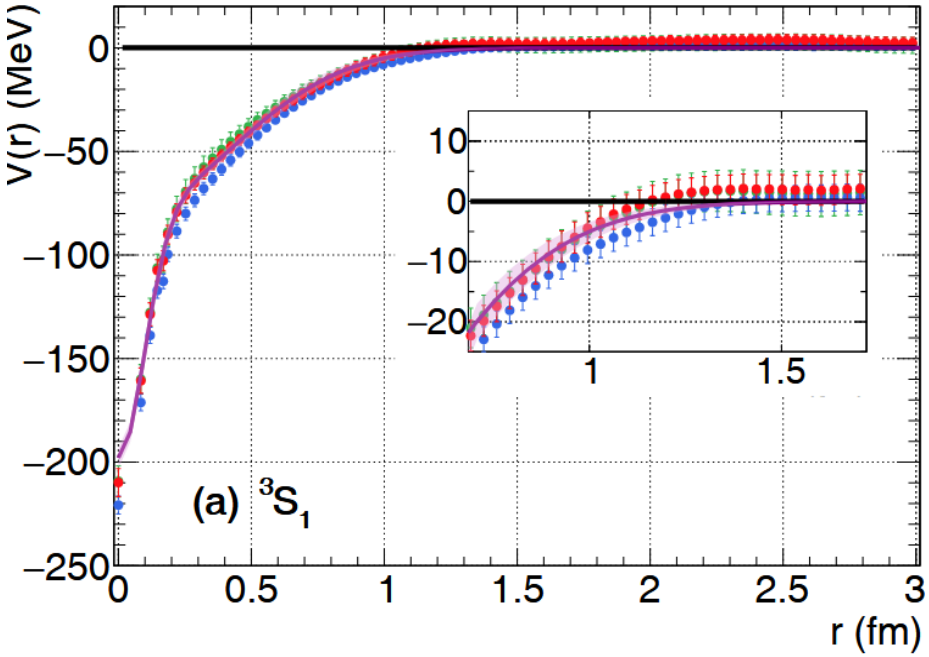
$$a^{-1} = 2338.8(1.5)(^{+0.2}_{-3.0})\ \text{MeV}$$

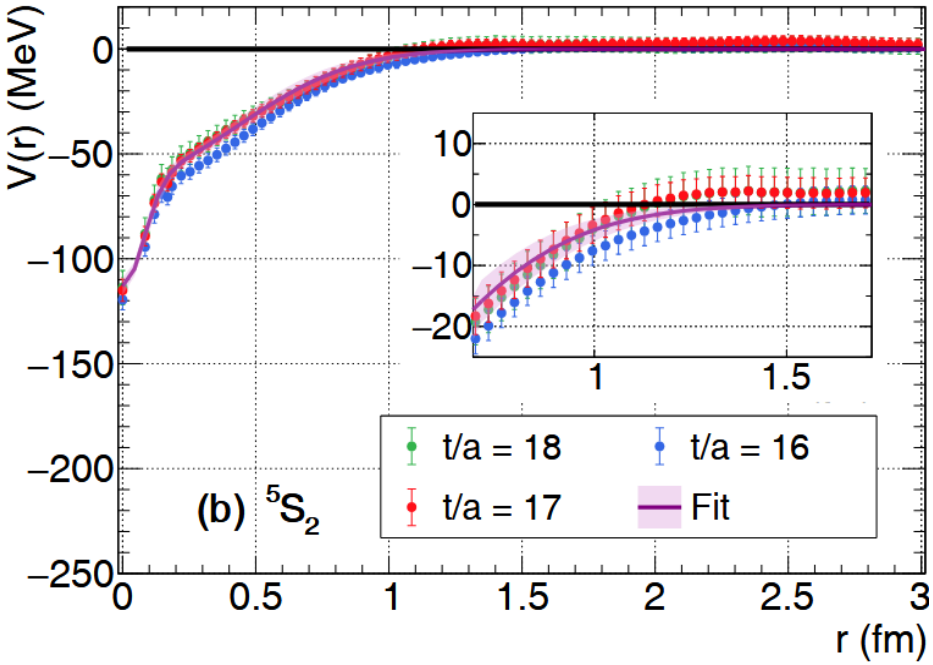
- ✓ $m_\pi \simeq 137\ MeV$, $m_K \simeq 502\ MeV$ (at the physical point)
- ✓ Physical charm mass with relativistic quark action (RHQ) [2]



[1] Aoyama:2024cko [2] Aoki:2001ra

$N\Omega_{3c}$ potentials (channel dependence)





$^3S_1$ channel

t/a	A_1 [MeV]	A_2 [MeV]	B_1 [fm]	B_2 [fm]
16	−118.9(1.6)	−85.7(2.6)	0.142(7)	0.633(33)
17	−118.0(3.0)	−80.0(3.7)	0.135(8)	0.601(37)
18	−119.7(4.6)	−75.0(8.5)	0.141(12)	0.608(56)

$^5S_2$ channel

t/a	A_1 [MeV]	A_2 [MeV]	B_1 [fm]	B_2 [fm]
16	−50.5(3.6)	−66.5(3.0)	0.110(15)	0.665(46)
17	−52.6(2.5)	−60.4(2.5)	0.110(12)	0.612(50)
18	−53.0(5.2)	−57.8(5.2)	0.113(21)	0.636(67)

$N\Omega_{3c}$ potentials (spin decomposition)

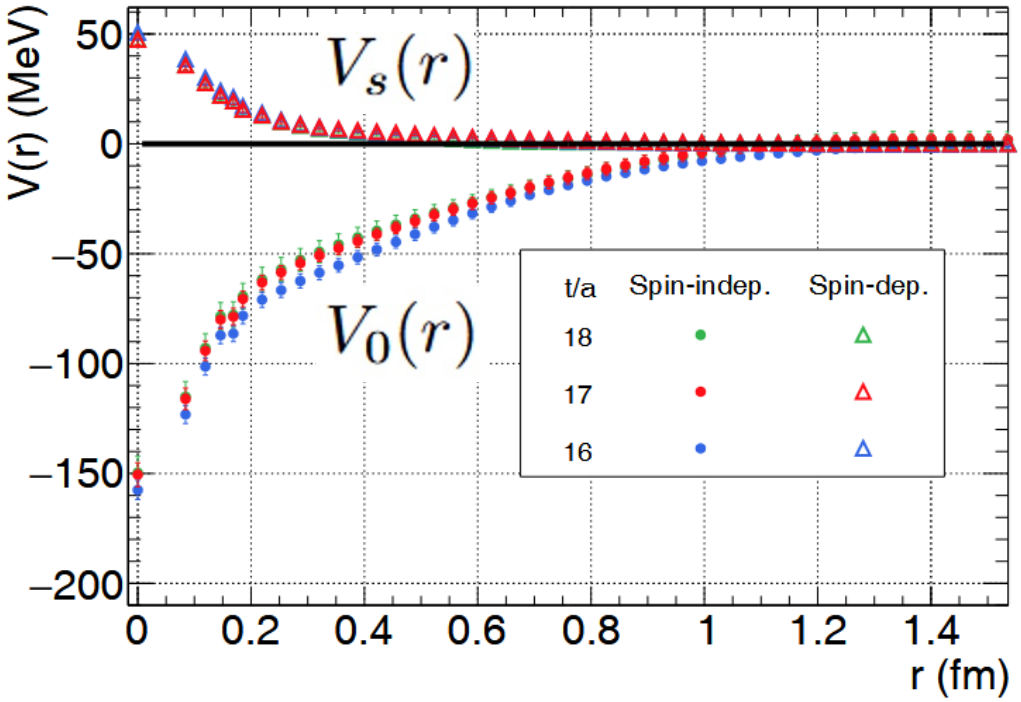
$$V_{\mathrm{LO}}^{J}(r) = V_0(r) + \vec{s}_N \cdot \vec{s}_{\Omega_{3c}} V_s(r)$$

$$\vec{s}_N \cdot \vec{s}_{\Omega_{3c}} = \frac{1}{2}\left(J(J+1) - \frac{3}{4} - \frac{15}{4}\right),$$

$$V_0 = \frac{1}{8}\left(5V_{\mathrm{LO}}^{J=2} + 3V_{\mathrm{LO}}^{J=1}\right),$$

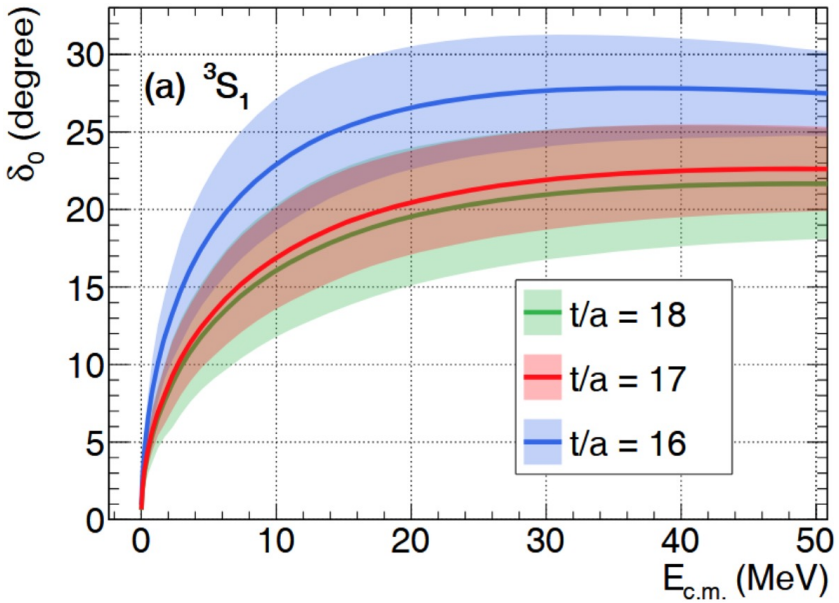
$$V_s = \frac{1}{2}\left(V_{\mathrm{LO}}^{J=2} - V_{\mathrm{LO}}^{J=1}\right).$$

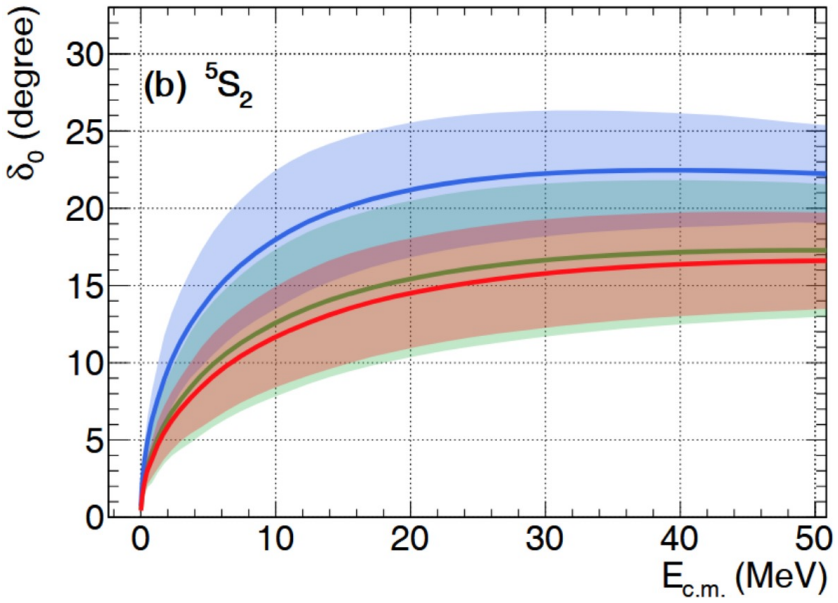
- The spin-dependent potential makes a significant contribution at short distances.
- The spin-independent potential gives a dominating contribution for whole distance.



$N\Omega_{3c}$ phase shift

Attractive but No Bound State

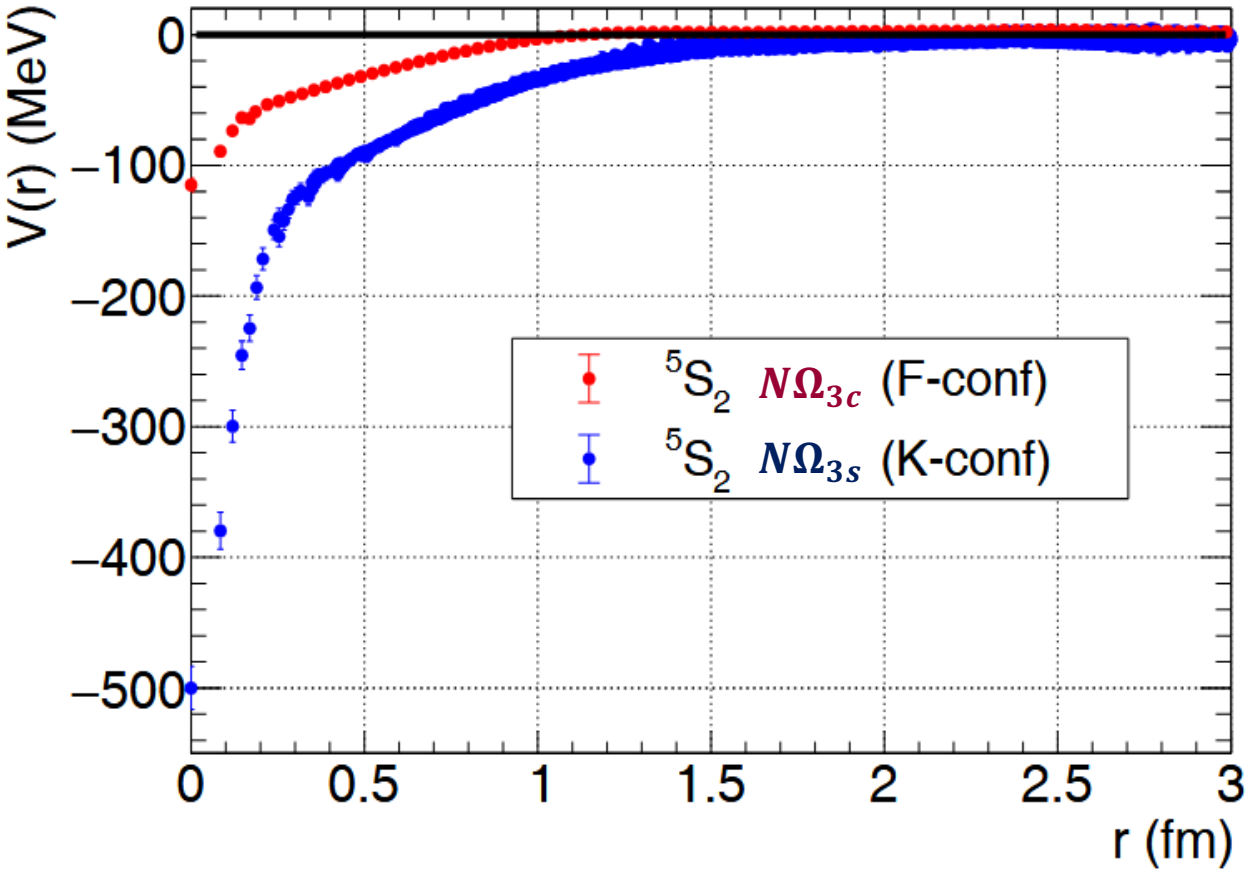




channel	a_0 [fm]	$r_{\rm eff}$ [fm]
$^3S_1$	$0.56(0.13)\binom{+0.26}{-0.03}$	$1.60(0.05)\binom{+0.04}{-0.12}$
$^5S_2$	$0.38(0.12)\binom{+0.25}{-0.00}$	$2.04(0.10)\binom{+0.03}{-0.22}$

mean values and statical errors from $t/a = 17$; systematic errors from $t/a = 16$ & 18.

Comparison between $N\Omega_{3c}$ and $N\Omega_{3s}$



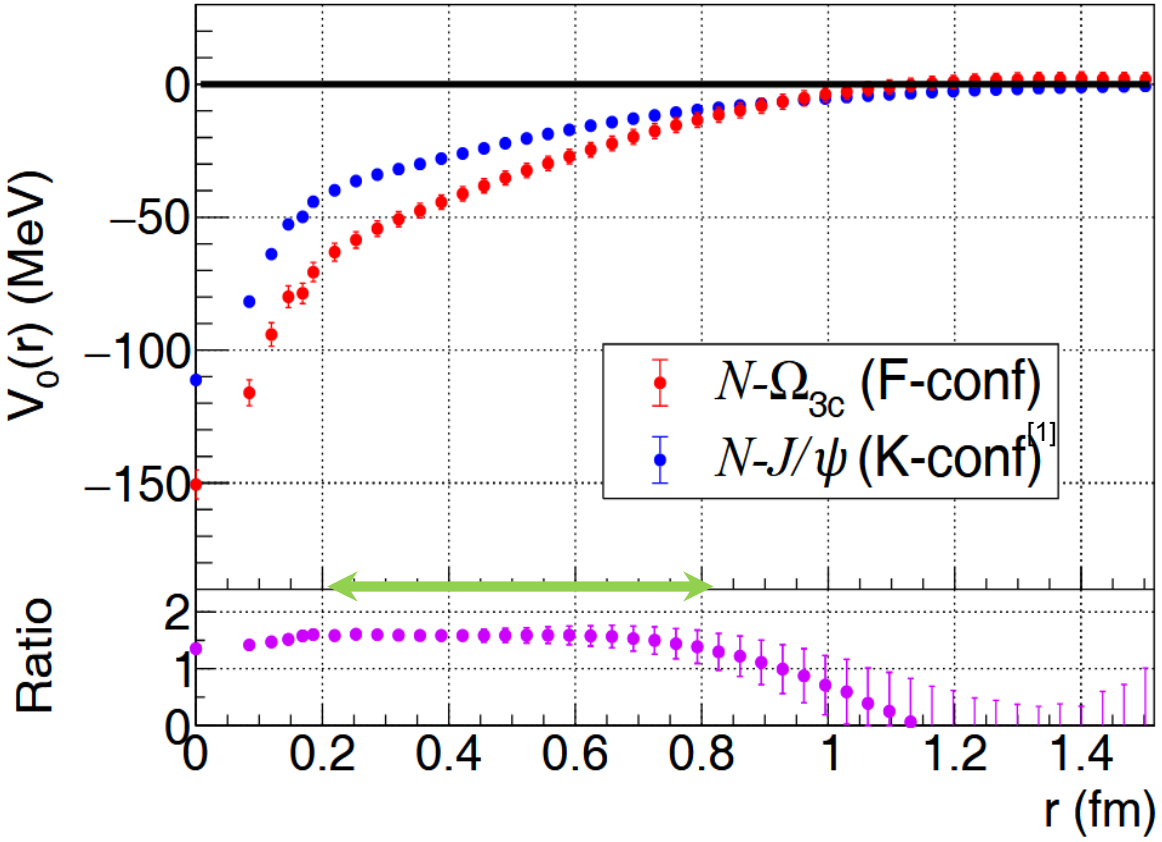
$^5S_2$ $N\Omega_{3c}$ (Fconf) potential exhibits a similar shape but is 2–5 times less attractive compared to the $^5S_2$ $N\Omega_{3s}$ (Kconf)[1]

There are two possible reasons:

- Long range: two-K exchange vs. two-D exchange.
- Short distances: chromo-magnetic interaction inversely proportional to the constituent quark mass[2]

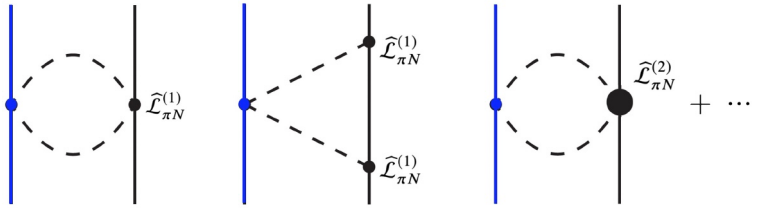
[1] HALQCD:2018qyu [2] Oka:1986fr

Comparison between $N-\Omega_{3c}$ and $N-J/\psi$

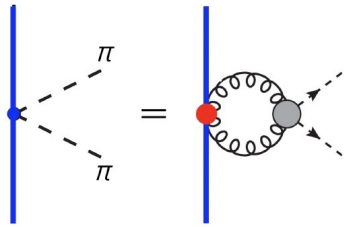


- Observed similarity between the $N\Omega_{3c}$ and $N-J/\psi$ potentials.

  →common 2-pion mechanism[2] ?



- The plateau indicates the ratio of the coupling strength to the gluons[3,4] between Ω_{3c} and J/ψ ?



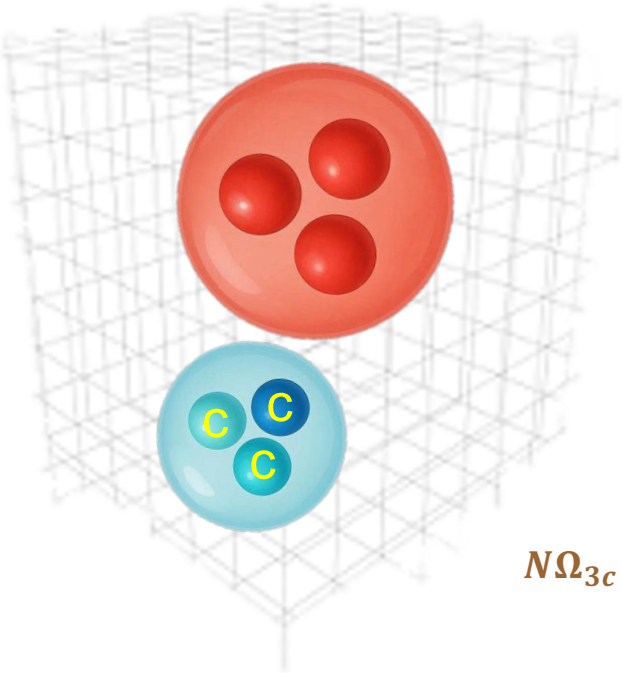
[1] Lyu:2024ttm [2] Hatsuda:2025djd [3] Brambilla:2015rqa [4] Dong:2022rwr

Summary

- Physical-point lattice QCD simulation to analyze the $N\Omega_{3c}$ interaction with HAL QCD method.

- $N\Omega_{3c}$ $^3S_1$ and $^5S_2$ effective potentials and phase shifts.
  - Overall attraction in both channels
  - Dominated by spin-independent potential V_0, with a short-range spin-dependent potential V_s
  - No bound state found in $N\Omega_{3c}$ system
  - $N\Omega_{3c}$ potential is weaker than $N\Omega_{3s}$
  - V_0 for $N\Omega_{3c}$ is similar to NJ/ψ

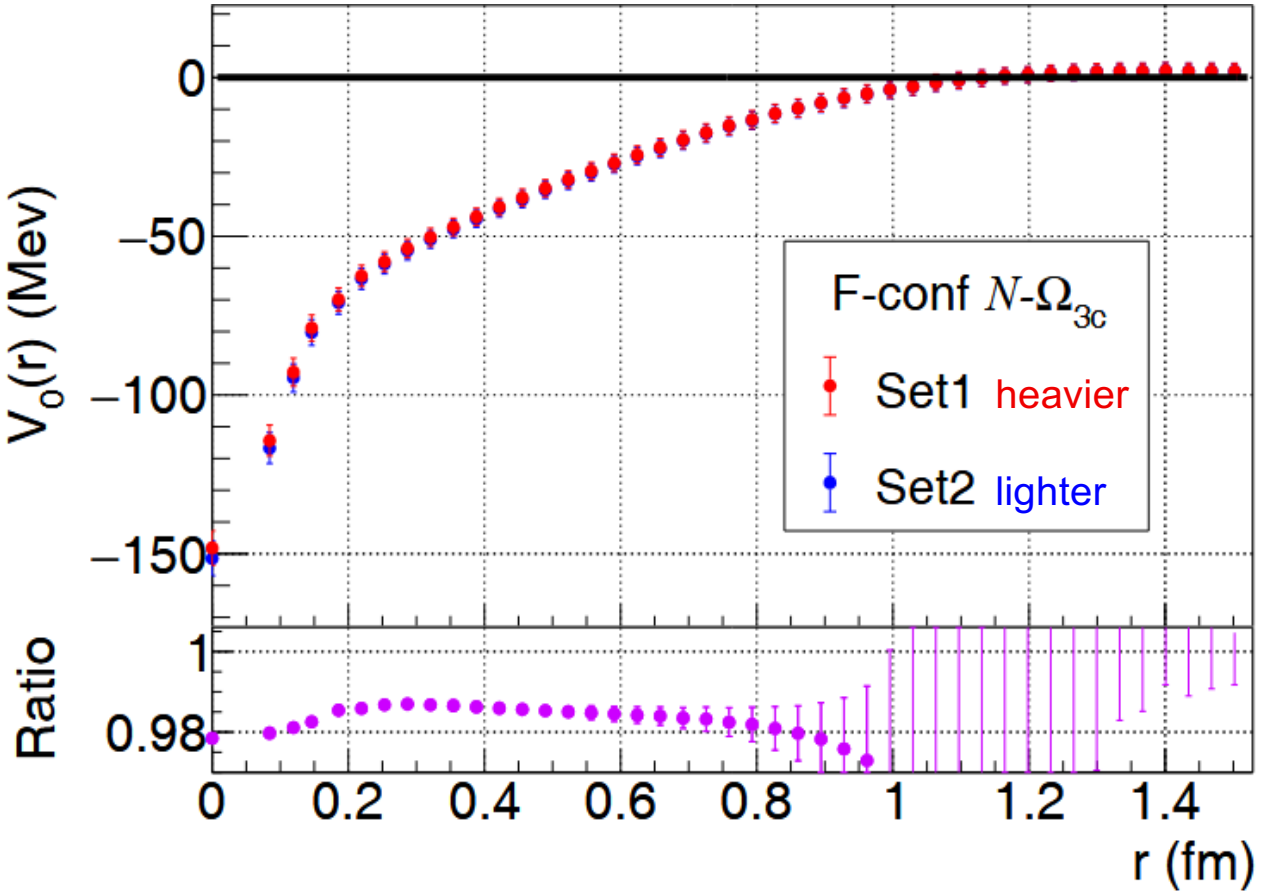
    ⇒ possibly governed by the same soft-gluon/two-pion mechanism?
  - charm mass dependence of V_0 of $N\Omega_{3c}$ is also observed
  - Possibility of Ω_{3c} charmed nuclei with an intermediate mass nuclei, e.g. ^{12}C ?



$N\Omega_{3c}$

Back up

Comparison of V_0 between different charm mass for $N\Omega_{ccc}$ system

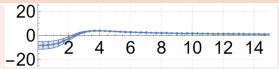
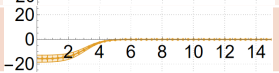
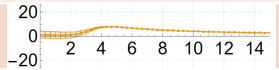
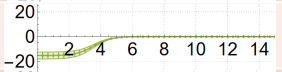
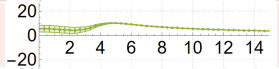
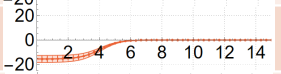
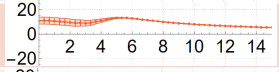
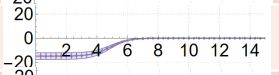
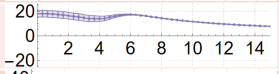
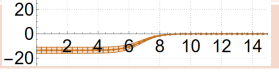
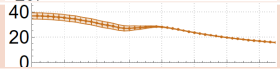


- Charm quark mass dependence is found in the spin-independent $N\Omega_{3c}$ potential
- The obtained ratio between these two sets of potential may imply that the charm quark mass dependence is described by an approximate $\frac{1}{m_{\Omega_{3c}}}$ scaling.

Ω_{ccc} charmed nuclei

For $A = 3$ case: No bound state is found in $\Omega_{3c}NN$, but serval resonances are found via the Faddeev equations[1,2]

For higher A case: we apply folding model to estimate the existence of Ω_{3c} charmed nuclei

Core nuclei	Ω_{3c} separation energy / MeV			
	w/o coulomb		w/ coulomb	
^{12}C	8.31(2.26)		0.127(-)	
^{28}Si	10.7(2.45)		-	
^{40}Ca	11.5(2.51)		-	
^{58}Ni	12.4(2.61)		-	
^{90}Zr	12.8(2.61)		-	
^{208}Pb	12.5(2.44)		-	

ρ_A is token form El-AzabFarid:2000mgb

$$V_F(\vec{r}) = \int d^3r' \rho_A(\vec{r}') V_{0,N\Omega_{3c}}(\vec{r} - \vec{r}'),$$

$V_{0,N\Omega_{3c}}$ is the spin-independent potential of $N\Omega_{3c}$ system obtained from the mean value of $t/a = 17$

$\boldsymbol{\Omega_{3c}^{++}}$**-** $\boldsymbol{^{12}C}$ could be a Ω_{3c} charmed nuclei candidate

Due to the strong coulomb repulsion, heavier Ω_{3c} charmed nuclei may not exist

[1] Filikhin:2025ige
[2] Etminan:2025emv