iTHEMS RIKEN Interdisciplinary Theoretical and Mathematical Sciences Program

SINAP 中国科学院上海应用物理研究所

复旦大学 FUDAN UNIVERSITY

QPT 2025 Guilin, China

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

arxiv:2508.10388

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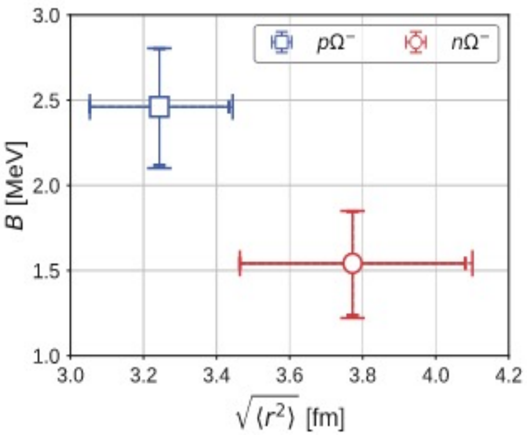
FOR HAL QCD COLLABORATION

Introduction

Theoretical Efforts



HALQCD:2018qyu

A quasibound state for $^5S_2$ $\mathrm{N}\Omega_{3s}$

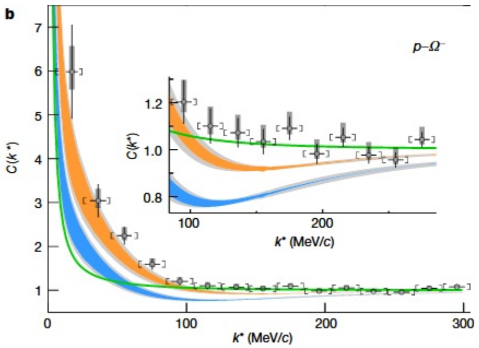
$E_h = -0.1 - 0.7i$ MeV w/o Coulomb

$E_h = -1.0 - 1.0i$ MeV w/ Coulomb

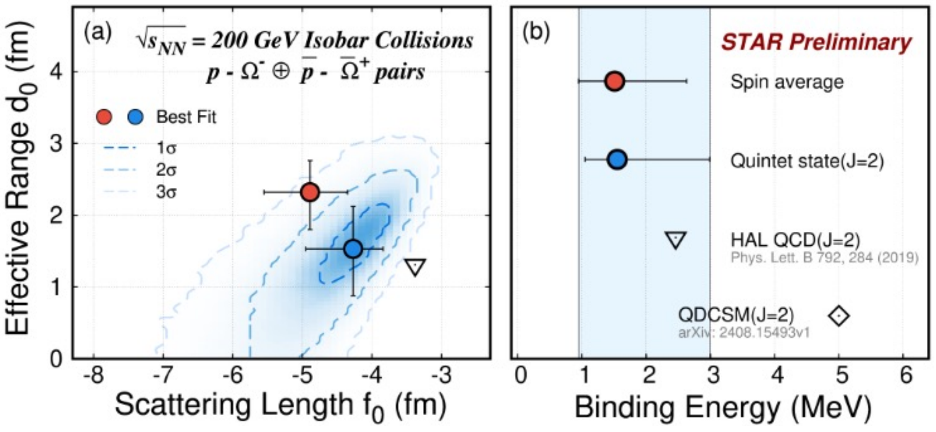
Calculated by Sekihara:2018tsb

+

Experimental Efforts



ALICE:2020mfd



STAR:QM2025-763

Belle's effort: Uchida, 30p1C 14:35

A Possible Bound Dibaryon

$\boldsymbol{N\Omega_{3s}}$

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

Theoretical Efforts

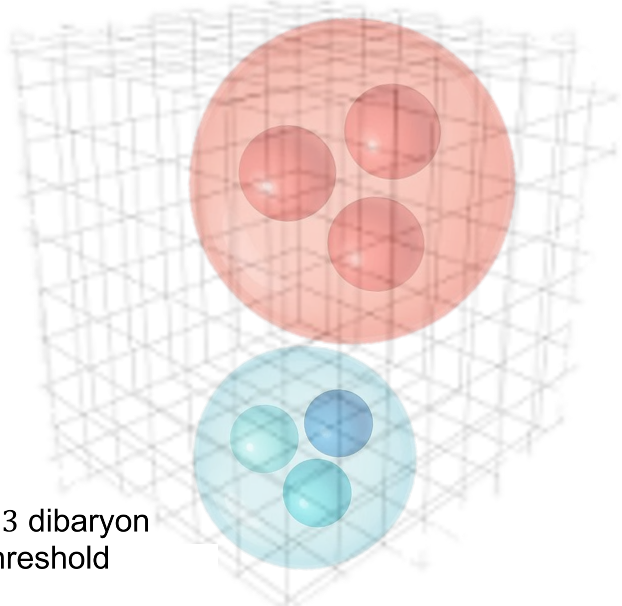
Quark model prediction:

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

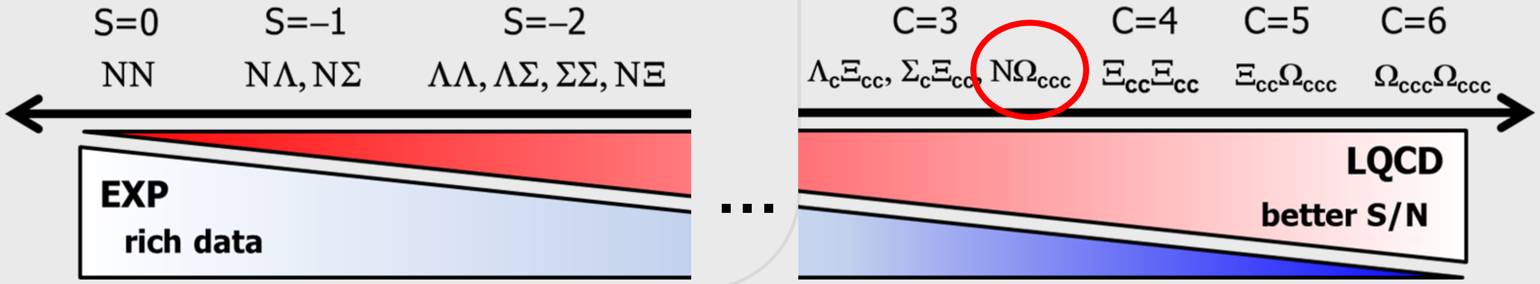
Huang:2019esu

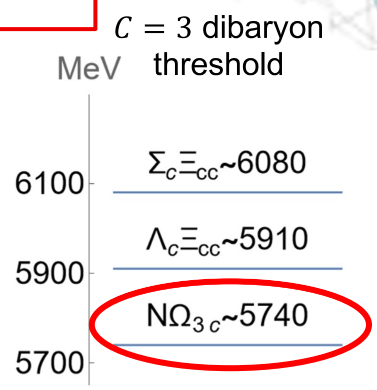
- Unlike $N\Omega_{3s}$ system[1] limited by open channels
- The lowest threshold among $C=3$ dibaryons (~ 5740 MeV)
- Clean setting to study low-energy $N\Omega_{3c}$ interactions.
  - Enables phenomenological study of scattering mechanism
  - Implications for possible charm hypernuclei

How about Nucleon-Ω_{3c}



First-principles calculations from lattice QCD can provide a valuable theoretical prediction for such triply charmed states.





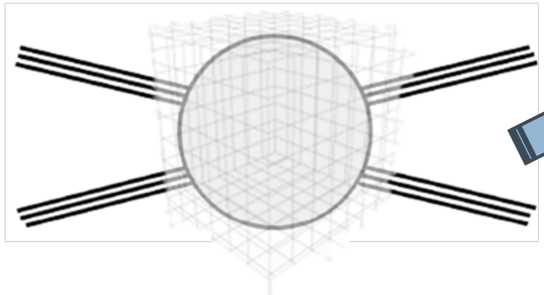
[1] HALQCD:2018qyu

HAL QCD method

HAL QCD method provide a First-Principles calculation method on hadron interaction.

$$\langle 0|B_1(\boldsymbol{x}+\boldsymbol{r})B_2(\boldsymbol{x})|B_1B_2,W_{\boldsymbol{k}}\rangle$$

$$\boxed{\phi_{\mathbf{k}}(\mathbf{r})}e^{-W_{\mathbf{k}}t} \equiv$$



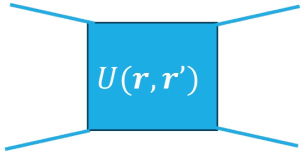
Nambu-Bethe-Salpeter (NBS) wave function

Lattice calculation

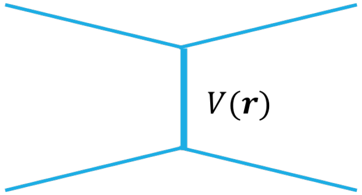
$$\xleftarrow{(W_{\boldsymbol{k}1}-W_{\boldsymbol{k}0})t\gg 1} F^J(\boldsymbol{r},t-t_0) = \langle 0|B_1(\boldsymbol{x}+\boldsymbol{r},t)B_2(\boldsymbol{x},t)\bar{J}_{B_1B_2}(t_0)|0\rangle$$
$$= \sum_n \langle 0|B_1(\boldsymbol{x}+\boldsymbol{r},t)B_2(\boldsymbol{x},t)|W_{\boldsymbol{k}n}\rangle\langle W_{\boldsymbol{k}n}|\bar{J}_{B_1B_2}(t_0)|0\rangle$$
$$= \sum_n A_n^J \phi_{\boldsymbol{k}n}(\boldsymbol{r})e^{-W_{\boldsymbol{k}n}(t-t_0)}$$

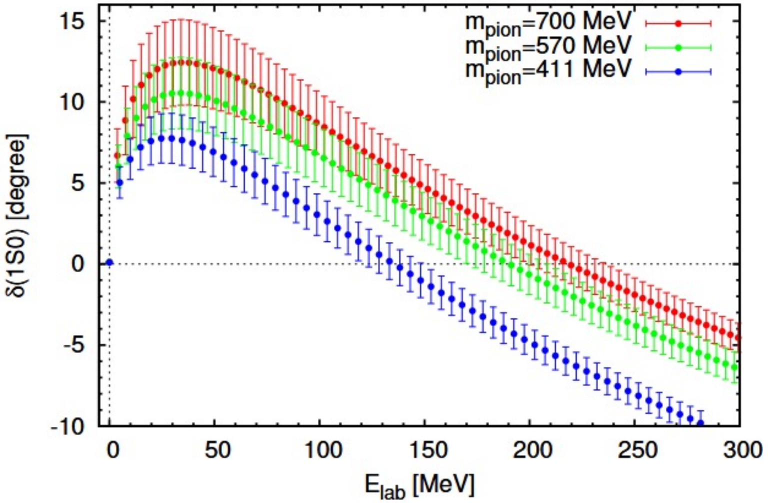
$$(E_k - H_0)\phi_{\mathbf{k}}(\mathbf{r}) = \int d^3r' U(\mathbf{r},\mathbf{r}')\phi_{\mathbf{k}}(\mathbf{r}')$$

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



$$U(\mathbf{r},\mathbf{r}') = V(\mathbf{r},\nabla)\delta^{(3)}(\mathbf{r}-\mathbf{r}')$$





N. Ishii, S. Aoki, and T. Hatsuda, Phys. Rev. Lett. **99**, 5 (2007).
S. Aoki and T. Doi, Front. Phys. **8**, 1 (2020).

From N. Ishii, *Pos(Cd12)*, p. 25.

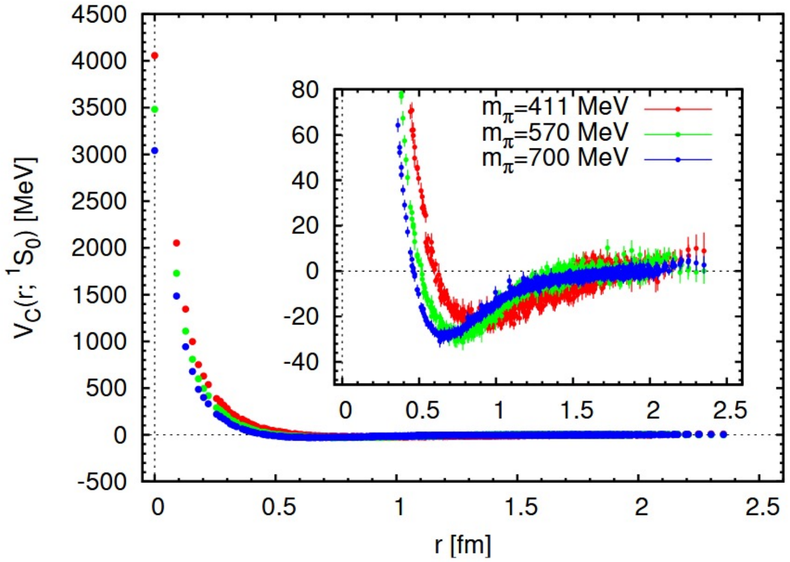
HAL QCD method

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

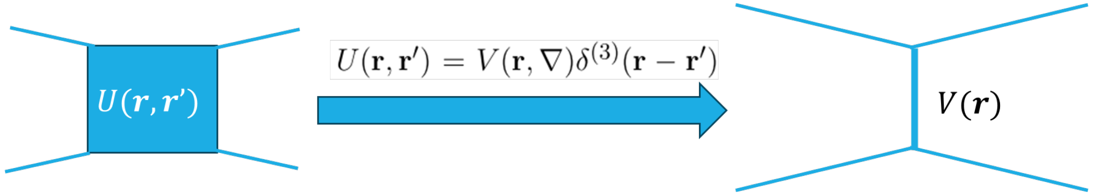
$$R^J(\boldsymbol{r},t) = \frac{F^J(\boldsymbol{r},t)}{G_{B_1}(t)G_{B_2}(t)} = \sum_n B_n^J \phi_{\boldsymbol{k}n}(\boldsymbol{r}) e^{-\Delta W_{\boldsymbol{k}n} t}$$

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

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



Ishii:2013ira.



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

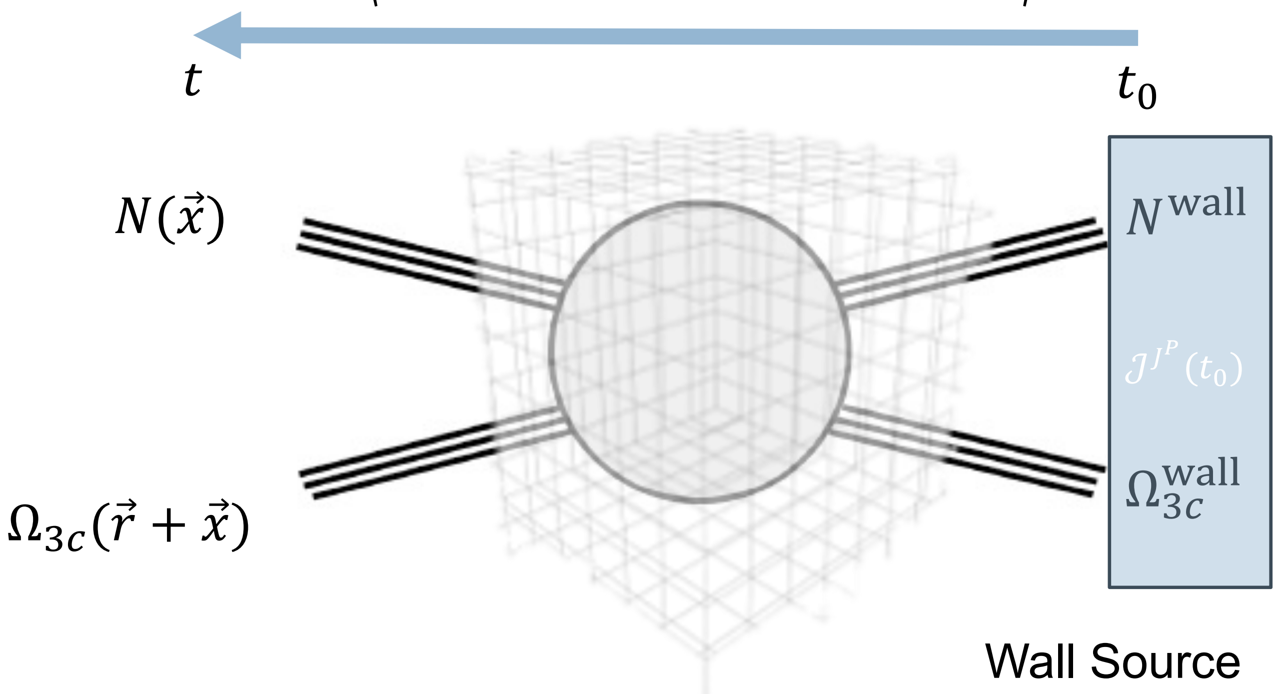
PHYSICAL POINT CALCULATION IS AVAILABLE NOW![4]

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

$N\Omega_{ccc}$ system

$$\left\langle 0 \middle| N(\boldsymbol{r}+\boldsymbol{x},t)\Omega_{3c}(\boldsymbol{x},t)\mathcal{J}^{J^P}(t_0) \middle| 0 \right\rangle$$

$$F^{J^P}(\boldsymbol{r}, t-t_0) = \sum_{\vec{x}}$$



$$N_\alpha(\boldsymbol{x}) = \varepsilon_{i,j,k}\left(u^{i^T}(\boldsymbol{x})C\gamma_5 d^j(\boldsymbol{x})\right)q_\alpha^k(\boldsymbol{x}) \qquad q = \begin{pmatrix} u \\ d \end{pmatrix}$$

$$q^{\text{wall}}(t_0) \equiv \sum_{\vec{x}} q(\vec{x}, t_0)$$

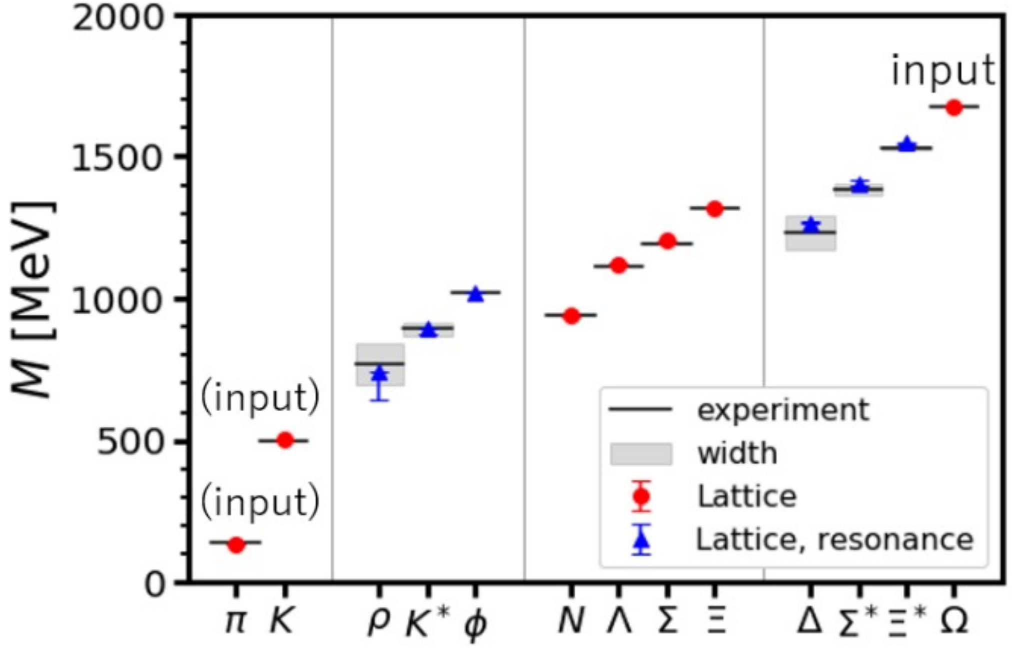
$$\Omega_{ccc\beta,l}(\boldsymbol{x}) = \varepsilon_{i,j,k}c_\beta^i(\boldsymbol{x})\left(c^{j^T}(\boldsymbol{x})C\gamma_l c^k(\boldsymbol{x})\right)$$

1. Using wall source
2. Calculating 4-point correlation $F^{J^P}(\boldsymbol{r}, t-t_0)$ with source projected to J^P state
3. Calculate $R^{J^P}(\boldsymbol{r}, t-t_0)$ for time-dependent HAL method
4. Solve effective potential
5. Calculate observables

Configurations

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

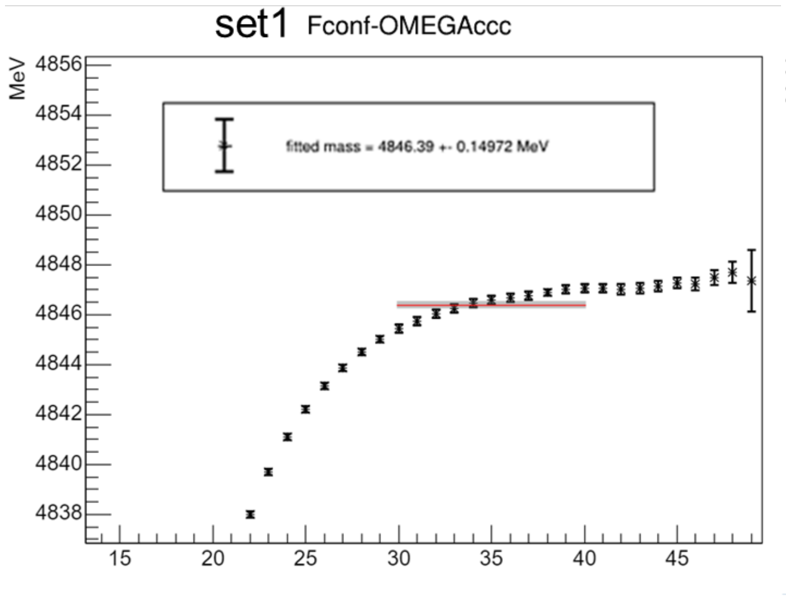
- ✓ $(2+1)$-flavor nonperturbatively improved Wilson fermions with stout smearing
- ✓ the Iwasaki gauge action
- ✓ Size of the lattice is 96^4, corresponding to $(8.1\mathrm{fm})^4$ in physical units
- ✓ $a^{-1} = 2338.8(1.5)(^{+0.2}_{-3.0})$ MeV
- ✓ $m_\pi \simeq 137\ MeV,\ m_K \simeq\ 502\ MeV$ (at the physical point)
- ✓ 8,000 trajectories

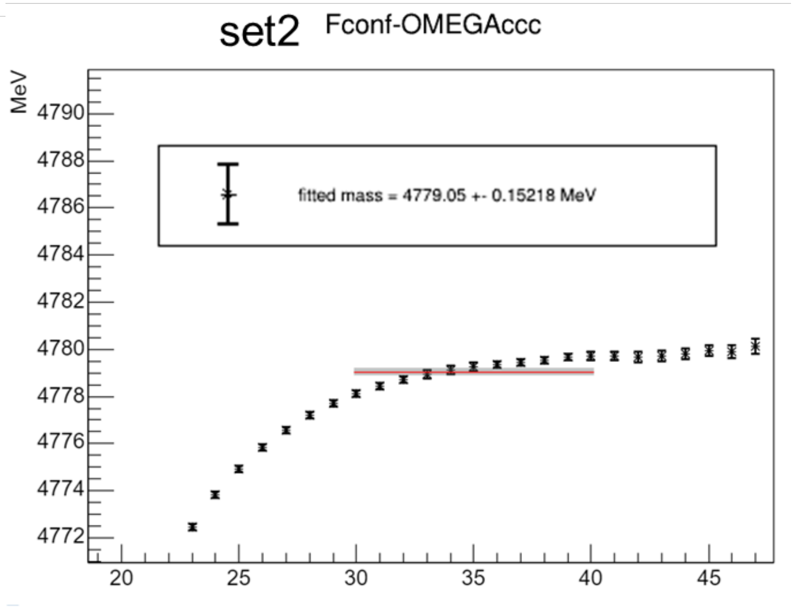


Charm quark is simulated by relativistic heavy quark (RHQ) action[2], we adopt two sets of RHQ parameters, one heavier charm mass and one lighter, to do interpolation towards physical charm mass.

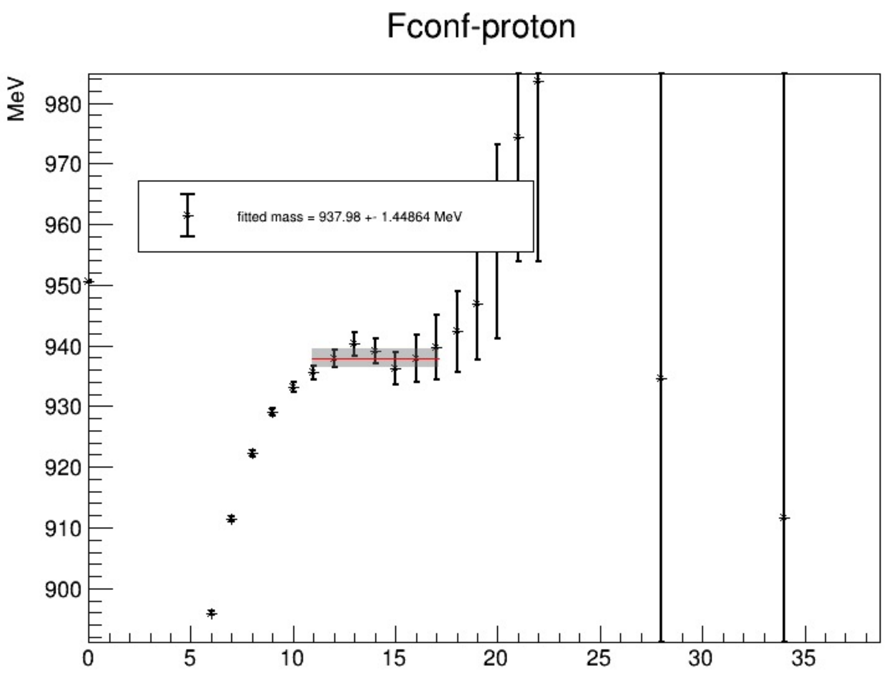
[1] Aoyama:2024cko
[2] Aoki:2001ra

Mass measurement



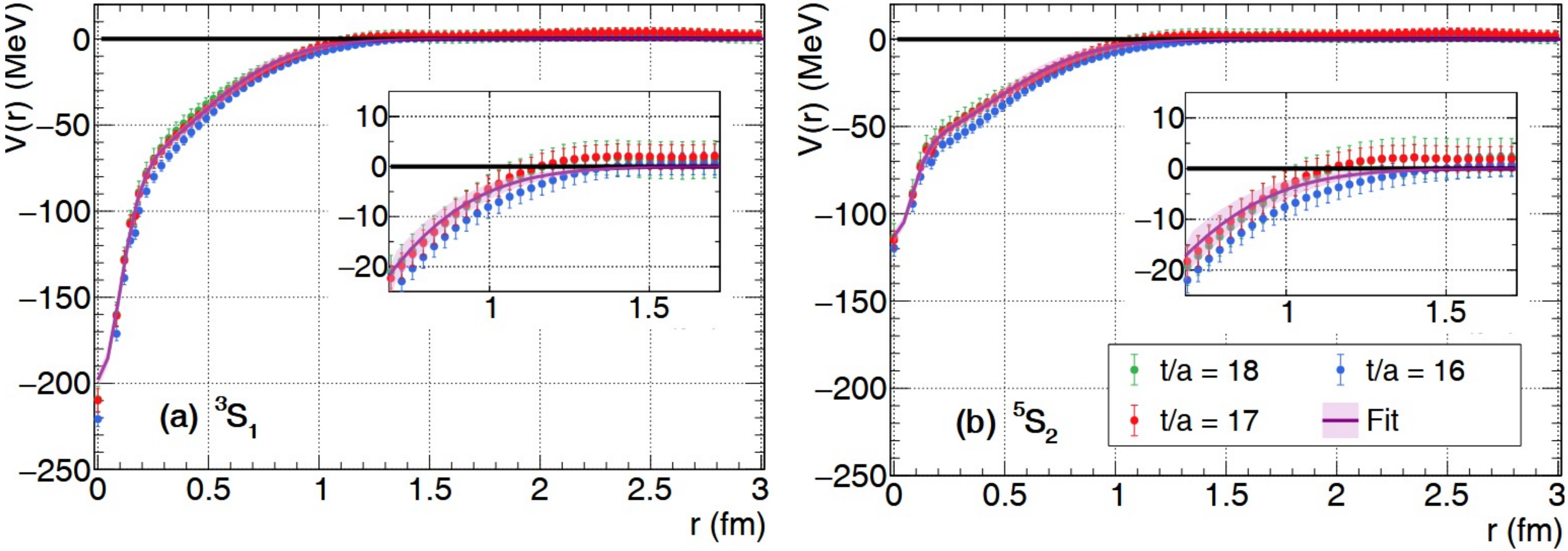


	$\left(m_{\eta_c}+3m_{J/\Psi}\right)/4$ [MeV]	$m_{\Omega_{ccc}}$ [MeV]
Set1	3101.9(0.1)	4846.4(0.1)
Set2	3056.6(0.1)	4779.0(0.1)
Interpolation	3068.5(0.1)	4796.8(0.1)
Experiment	3068.5(0.1)	*



$N\Omega_{ccc}$ potentials

Fitted with $\sum_{i=1}^{2} A_i \exp\left(-\left(\frac{r}{B_i}\right)^2\right)$ with $r \in [0.08, 3.00]\mathrm{fm}$



$^3S_1$ 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)

Decomposed $N\Omega_{ccc}$ potentials

We further decompose the potential V_{LO}^{J} into the spin-independent central potential V_0 and the spin-dependent one V_s with the ${}^3S_1$ and ${}^5S_2$ channels, extracted as,

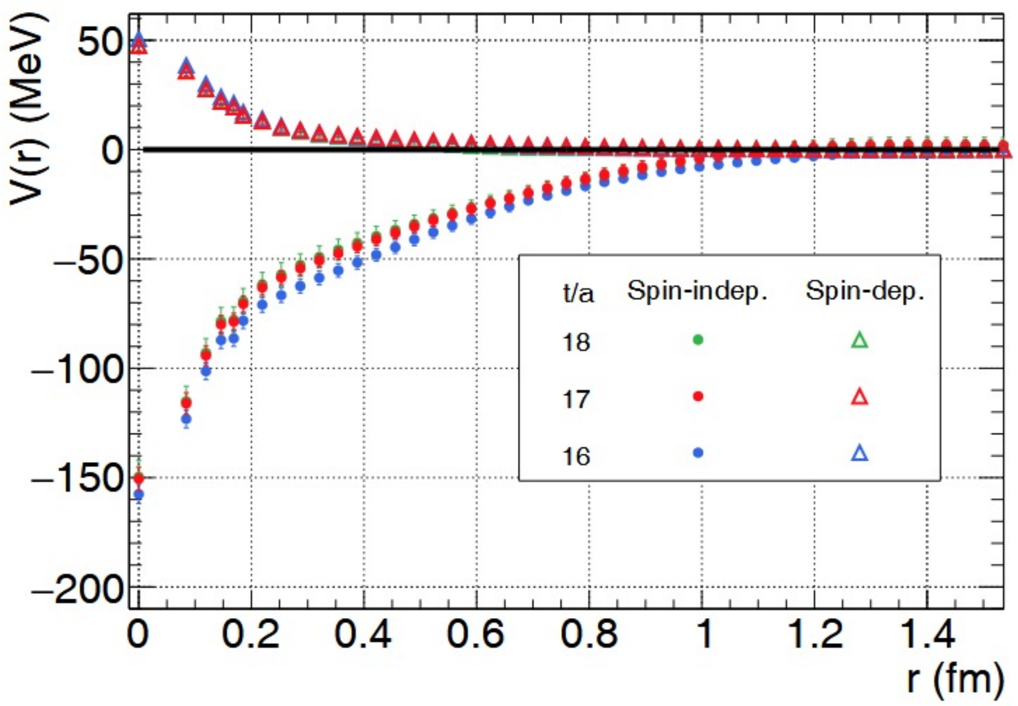
$$V_{\mathrm{LO}}^{J}(r) = V_0(r) + \vec{s}_N \cdot \vec{s}_{\Omega_{3c}} V_s(r)$$

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

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

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

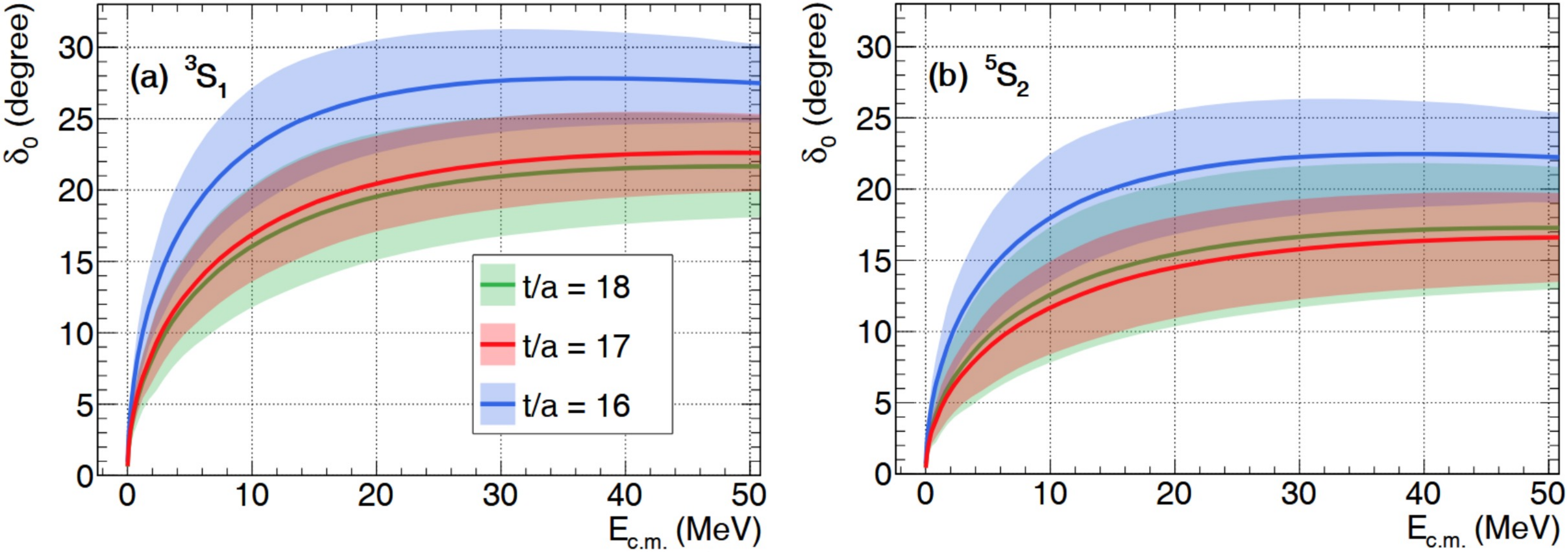
- The spin-dependent potential makes a significant contribution at short distances.
- The spin-independent potential gives a dominating contribution for whole $N\Omega_{3c}$ potentials



What can we learn from the lattice calculated potentials?

$N\Omega_{ccc}$ phase shift

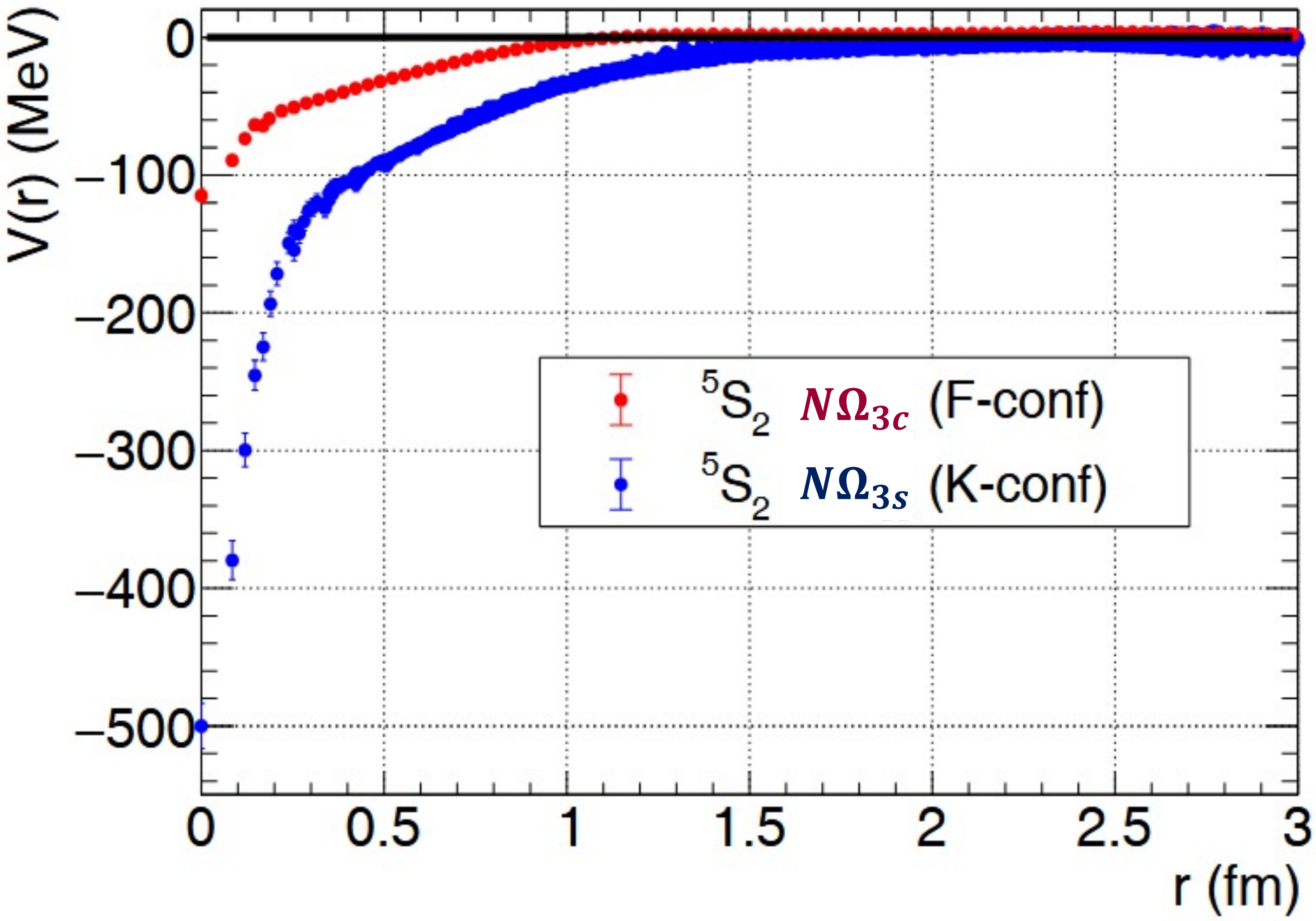
No Bound State Found according to Levinson's theorem



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

Where the mean values and statical errors are calculated from $t/a = 17$
And the systematic errors are derived from $t/a\ =\ 16$ and 18.

Comparison of $V^{J=5/2}$ between $N\Omega_{ccc}$ and $N\Omega_{sss}$



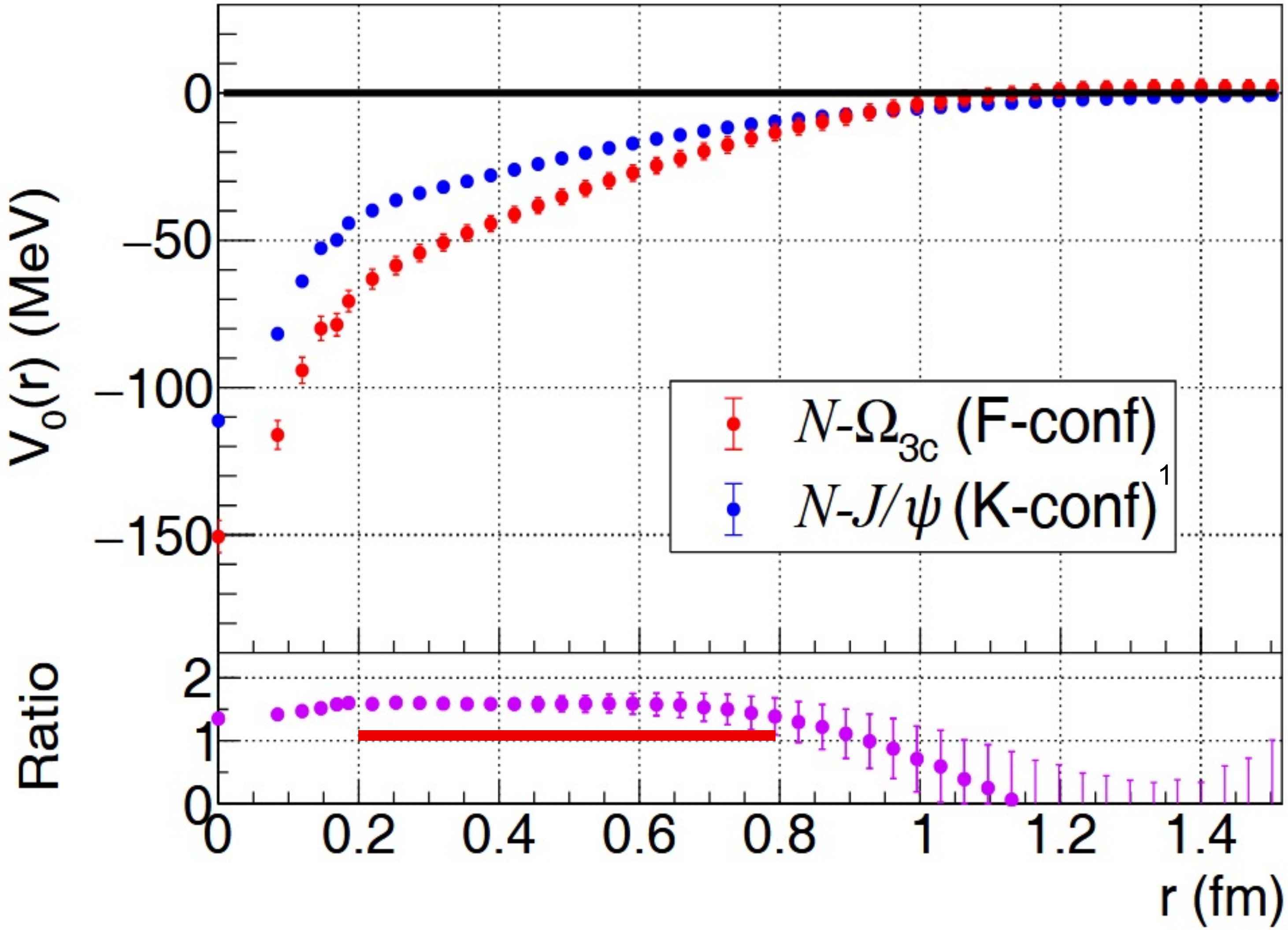
$^5S_2$ $\boldsymbol{N\Omega_{3c}}$ (Fconf) potential exhibits a similar shape but is 2–5 times less attractive compared to the $^5S_2$ $\boldsymbol{N\Omega_{3s}}$ (Kconf)[1]

There are two possible reasons:

- The exchange of two kaons (K) is deeper and longer-ranged than two D mesons.
- At short distances, the chromo-magnetic interaction may also contribute, which is inversely proportional to the constituent quark mass[2]

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

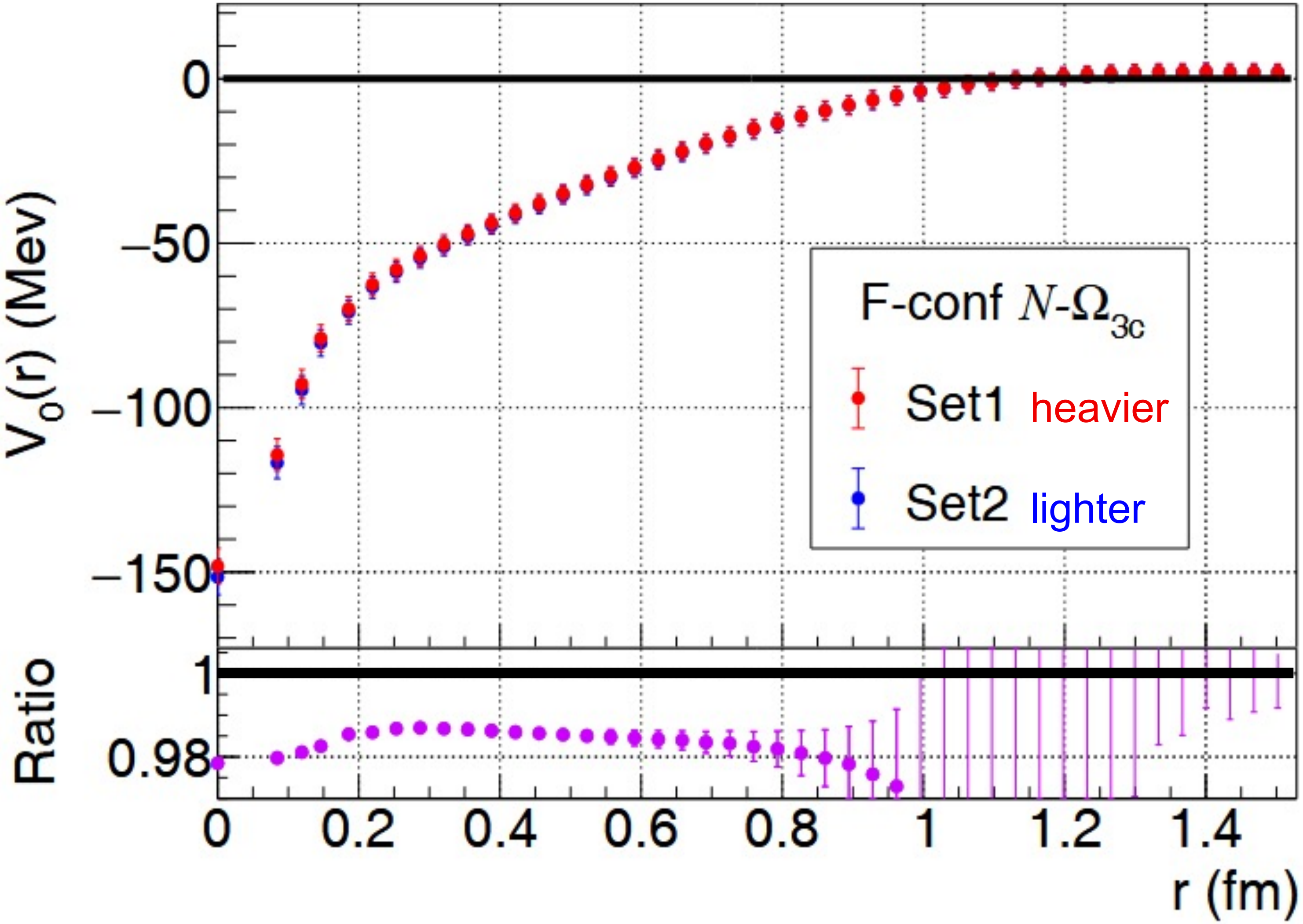
Comparison of spin-independent potentials V_0 between $N\Omega_{ccc}$ and NJ/ψ



- The soft-gluon exchange governs the scattering for NJ/ψ[2], which related to V_0 (gWEFT[3]).
- Given the observed similarity between the $N\Omega_{3c}$ and $N\,J/\psi$ potentials. Extend similar mechanism to $N\Omega_{3c}$
- The plateau shown indicates the ratio between the coupling strength of the Ω_{3c} to the gluon field and that of the J/ψ to the gluon field.

[1] Lyu:2024ttm
[2] Wu:2024xwy
[3] Dong:2022rwr

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.

Summary

- Performed physical-point lattice QCD simulation to analyze the $\boldsymbol{N\Omega_{3c}}$ interaction with HAL QCD method.
- Reported $\boldsymbol{N\Omega_{3c}}$ $^3S_1$ and $^5S_2$ effective potentials and phase shifts from lattice calculation
  - Overall attractive for both channels
  - Dominated by spin-independent potential V_0, with a short-range spin-dependent potential V_s
  - There is no bound state found in $\boldsymbol{N\Omega_{3c}}$ system
  - $^5S_2$ $\boldsymbol{N\Omega_{3c}}$ (Fconf) potential is qualitatively weaker than $^5S_2$ $\boldsymbol{N\Omega_{3s}}$ (Kconf)
  - V_0 of $\boldsymbol{N\Omega_{3c}}$ is similar with $NJ/\psi \Rightarrow$ possibly governed by the same soft-gluon exchange mechanism
  - charm mass dependence of V_0 of $\boldsymbol{N\Omega_{3c}}$ is also observed

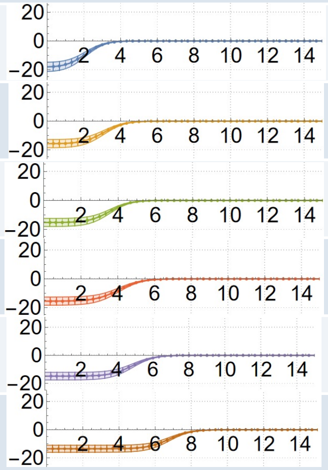
Back up

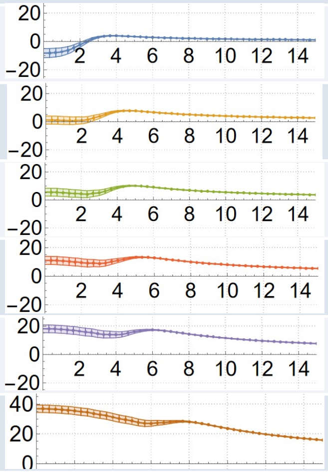
Ω_{ccc} hypernuclei

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} hypernuclei

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)	\





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

$V_{0,N\Omega_{3c}}$ 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} hypernuclei candidate

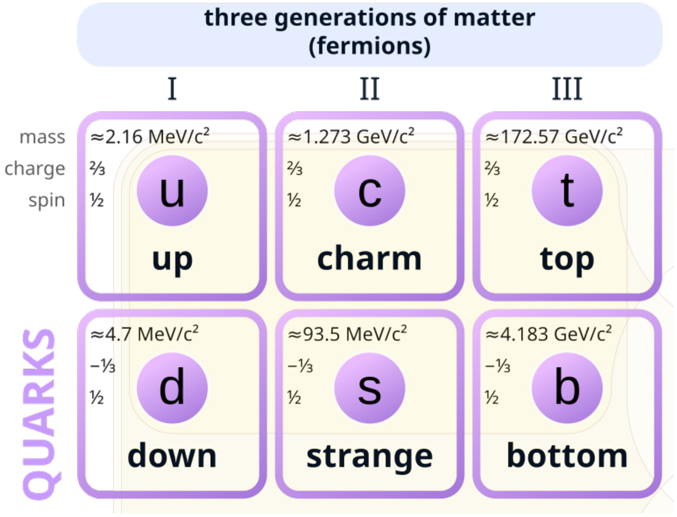
Due to the strong coulomb repulsion, heavier Ω_{3c} hypernuclei may not exist

ρ_A is token form El-AzabFarid:2000mgb

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

Introduction

From quark model, it's nature that we will have all these baryons defined as this formula shows



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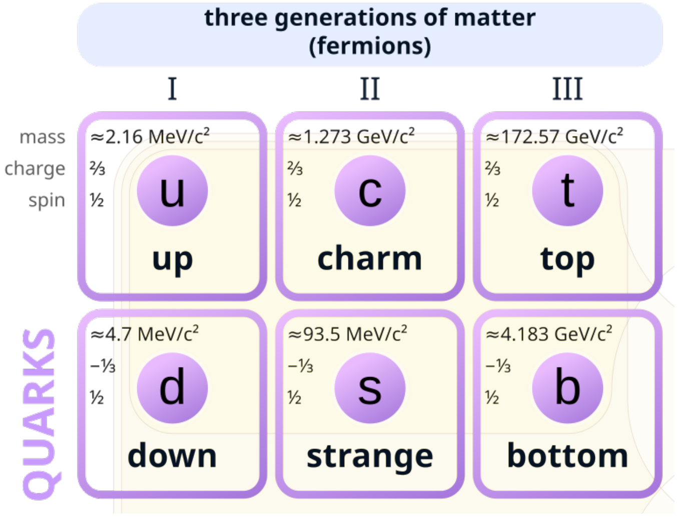

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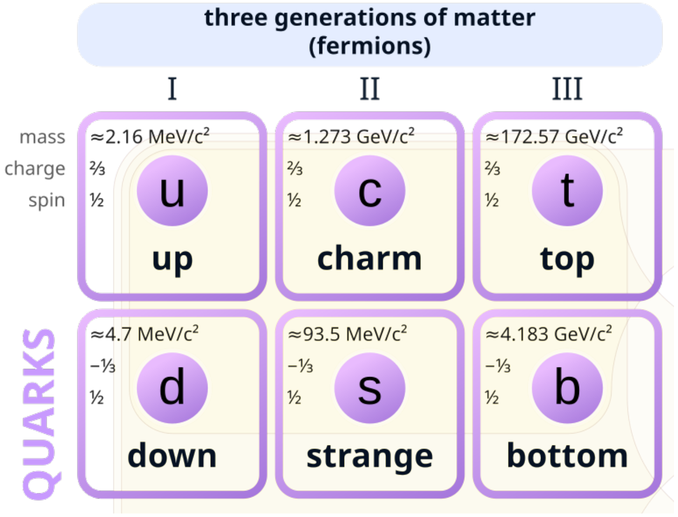


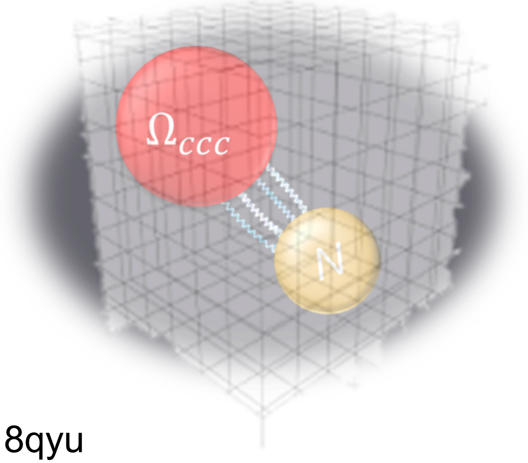
The baryon with highest charm number predicted by quark model is Ω_{ccc}, which is predicted with mass around 4.8~4.9 GeV from different model[1-5]
Although it's not found in experiment, theoretical research has long been carried out.
Except its mass, the production in HIC[4], di-Ω_{ccc} interaction[5] and other properties have been studied

[1] P. Hasenfratz *et al.*, Phys. Lett. B **94**, 401 (1980). [2] J. D. Bjorken, AIP Conf. Proc. **132**, 390 (1985). [3] PACS-CS Collaboration *et al.*, Phys. Rev. D **87**, 94512 (2013).
[4] H. He, Y. Liu, and P. Zhuang, Physics Letters B **746**, 59 (2015). [5] Y. Lyu *et al.*, Physical Review Letters **127**, 72003 (2021).

Introduction

- The HAL QCD Collaboration has revealed a strongly attractive interaction in the $N\Omega$ system, suggesting the formation of a quasi-bound state[1].

- At the low-energy, NJ/ψ scattering is dominated by the soft gluon exchange mechanism[2]



[1] HALQCD:2018qyu
[2] Wu:2024xwy

- Ω_{3c} hypernuclei
  - Similar with $\boldsymbol{N\Omega_{3s}}$ system, interaction between $\boldsymbol{N\Omega_{3c}}$ may be attractive due to there is no Puail blocking between valance quarks.
  - Existence of heavier $\boldsymbol{\Omega_{3c}}$ hypernuclei.

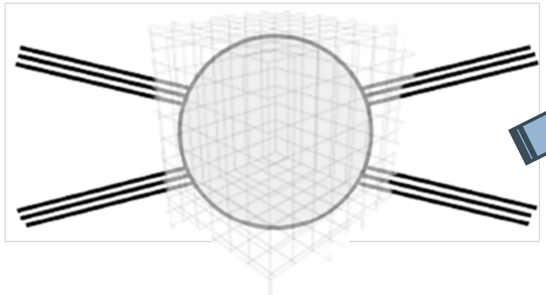
- What kind of mechanism behind $N\Omega_{3c}$ system?
  - Suppressed light-meson exchange due to Okubo-Zweig-Iizuka (OZI) rule violation in both $\boldsymbol{N\Omega_{3c}}$ and NJ/ψ
  - Comparison between $\boldsymbol{N\Omega_{3c}}$ and NJ/ψ potentials provides a valuable reference framework for understanding heavy-quark nuclear interactions

HAL QCD method

Related talk: Doi, 29a1 10:00
Murakami, 29p1B 14:45
Sasaki, 30p1B 15:25
Murase, 1p1B 15:25

HAL QCD method provide a First-Principles calculation method on hadron interaction.

$$\boxed{\phi_{\mathbf{k}}(\mathbf{r})} e^{-W_{\mathbf{k}} t} \equiv \langle 0 | B_1(\boldsymbol{x}+\boldsymbol{r}) B_2(\boldsymbol{x}) | B_1 B_2, W_{\boldsymbol{k}} \rangle$$



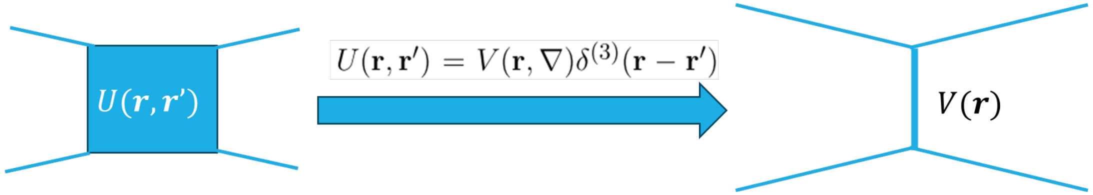
Nambu-Bethe-Salpeter (NBS) wave function

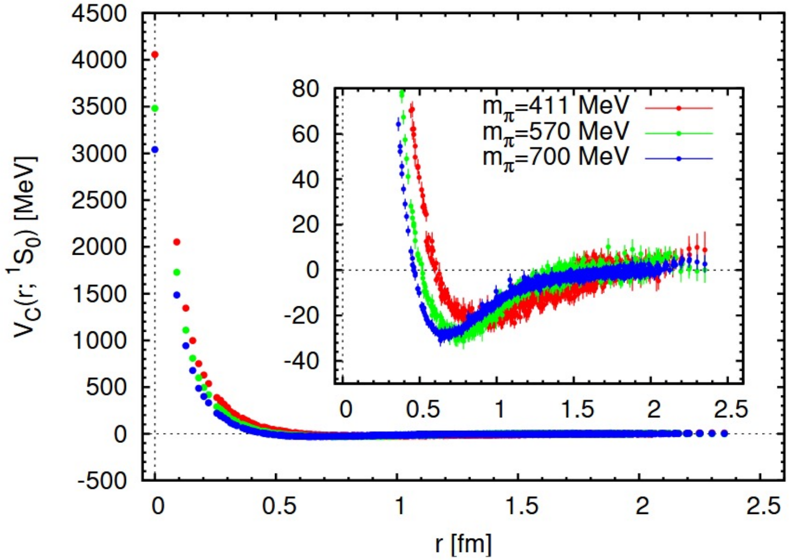
Lattice calculation

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

$$(E_k - H_0)\phi_{\mathbf{k}}(\mathbf{r}) = \int d^3 r' U(\mathbf{r},\mathbf{r}')\phi_{\mathbf{k}}(\mathbf{r}')$$

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





Ishii:2013ira.

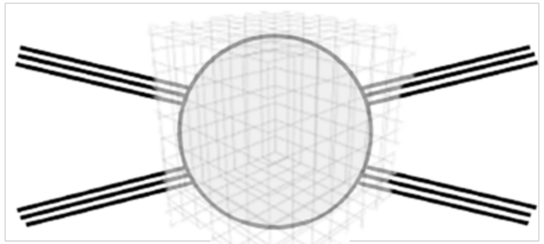
[1] Ishii:2006ec
[2] Aoki:2020bew

HAL QCD method

HAL QCD method provide a First-Principles calculation method on hadron interaction.

$$\langle 0|B_1(\boldsymbol{x}+\boldsymbol{r})B_2(\boldsymbol{x})|B_1B_2,W_{\boldsymbol{k}}\rangle$$

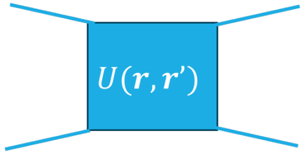
$$\boxed{\phi_{\mathbf{k}}(\mathbf{r})}e^{-W_{\mathbf{k}}t} \equiv$$



Nambu-Bethe-Salpeter (NBS) wave function

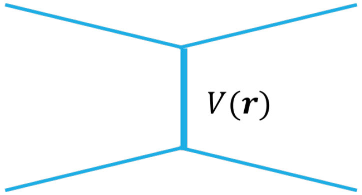
Lattice calculation

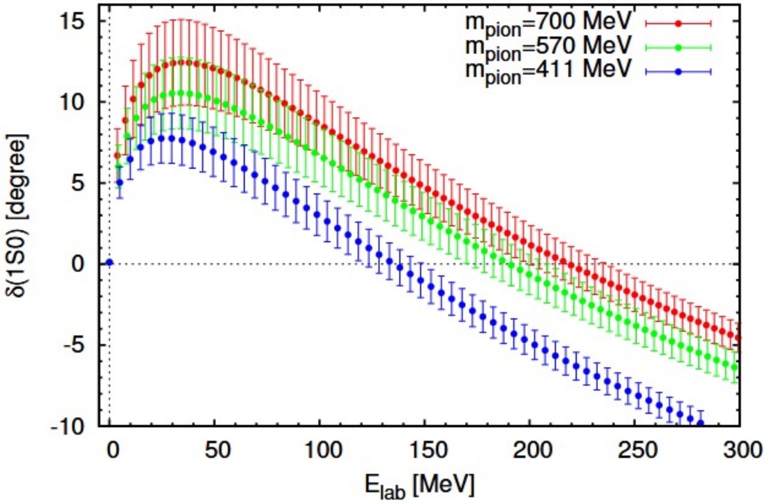
$$(E_k - H_0)\phi_{\mathbf{k}}(\mathbf{r}) = \int d^3 r' U(\mathbf{r},\mathbf{r}')\phi_{\mathbf{k}}(\mathbf{r}')$$



$$U(\mathbf{r},\mathbf{r}') = V(\mathbf{r},\nabla)\delta^{(3)}(\mathbf{r}-\mathbf{r}')$$

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

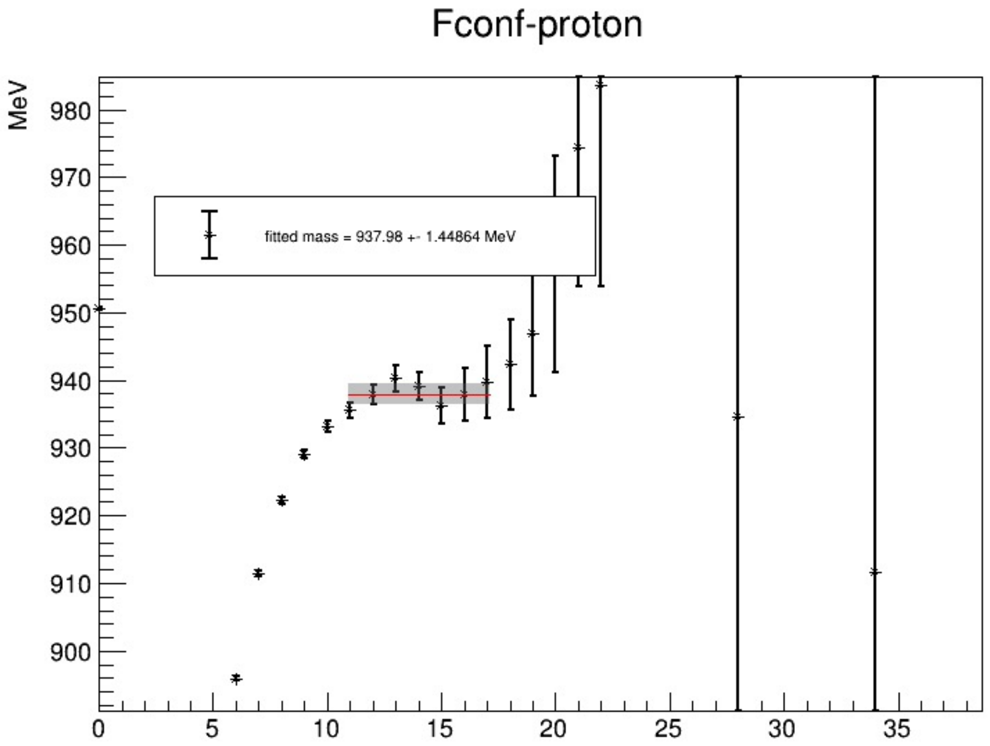


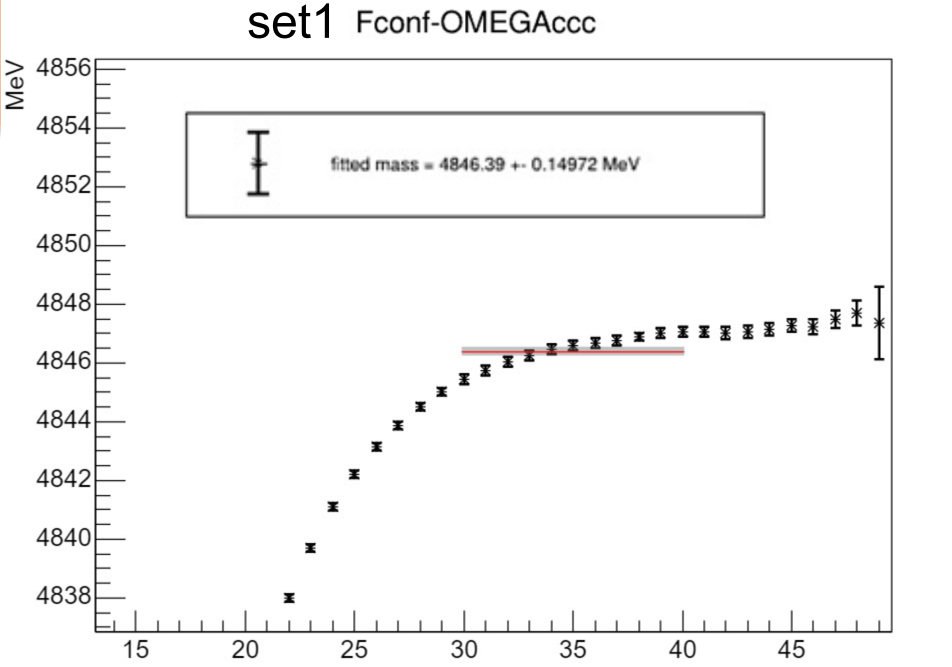


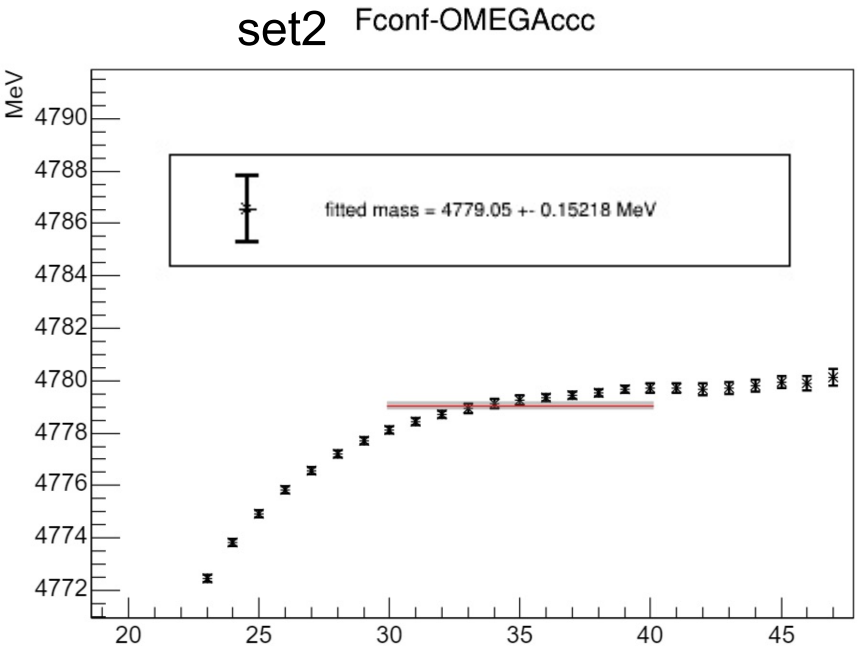
From N. Ishii, *Pos(Cd12)*, p. 25.

N. Ishii, S. Aoki, and T. Hatsuda, Phys. Rev. Lett. **99**, 5 (2007).
S. Aoki and T. Doi, Front. Phys. **8**, 1 (2020).

Mass measurement







	$\left(m_{\eta_c}+3m_{J/\Psi}\right)/4$ [MeV]	$m_{\Omega_{ccc}}$ [MeV]
Set1	3101.9(0.1)	4846.4(0.1)
Set2	3056.6(0.1)	4779.0(0.1)
Interpolation	3068.5(0.1)	4796.8(0.1)
Experiment	3068.5(0.1)	*

Summary

We perform the physical point simulation by employing “HAL-conf-2023” generated by the HAL Collaboration

Using HAL QCD method to analysis $\Omega_{ccc} - N$ interaction

- Reported $\Omega_{ccc}N\ \ ^3S_1$ and $^5S_2$ effective potential
- As well as these channels’ phase shift
- Both potentials are overall attractive
- But we don’t find a bound state for $\Omega_{ccc}N$ system

What’s more can we learn from $\Omega_{ccc} - N$ interaction

Folding potentials