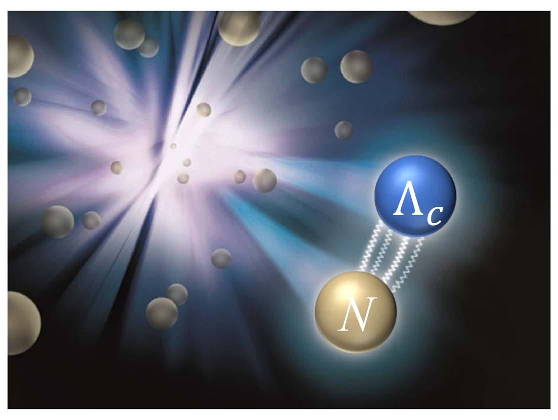
Lattice Simulation on $\Lambda_c N$ and $\Omega_{ccc} N$ interaction at physical point

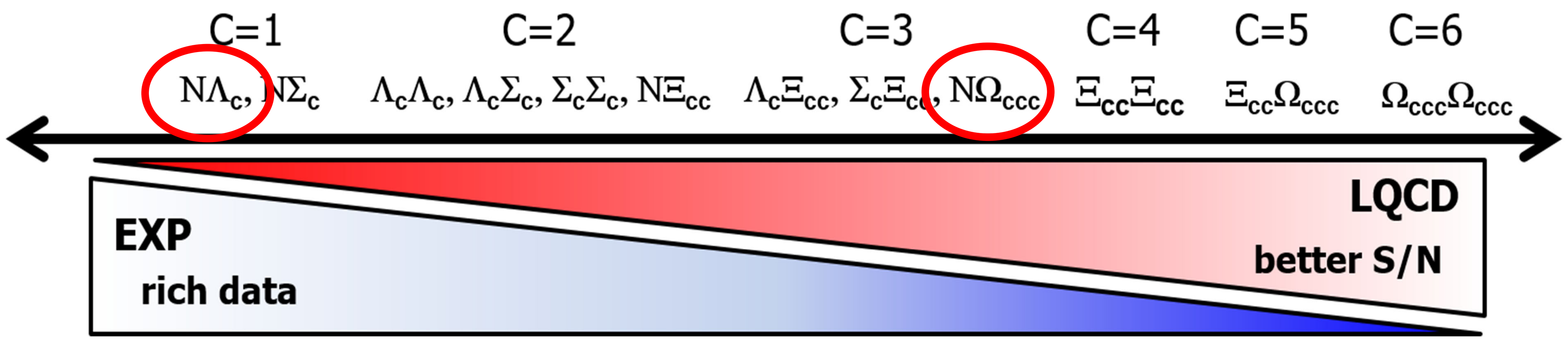
Liang Zhang[1,2], Tetsuo Hatsuda[1], Takumi Doi[1]

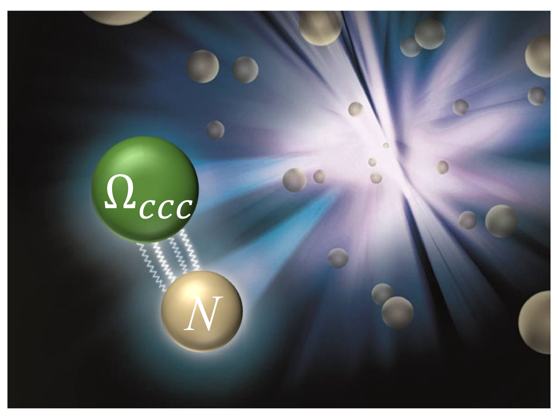
1. *Interdisciplinary Theoretical & Mathematical Science Program (iTHEMS), RIKEN, Hirosawa, Saitama 351-0198, Japan*
2. *Shanghai Institute of Applied Physics, Chinese Academy of Science, Shanghai 201800, China*

Introduction

- The interactions between baryons, which are the key to understand the properties of hadronic matter, are important to particle physics and nuclear physics. A short-range and spin-orbit-dependent nucleon–nucleon (NN) interaction is proposed to describe low-energy nucleon–nucleon (NN) scattering data and the properties of finite nuclei[1]. Hyperon–nucleon (YN) and hyperon–hyperon (YY) interactions can be used to reproduce hyperon–nucleon femotoscopy[2] and predict masses of hypernucleus[3].







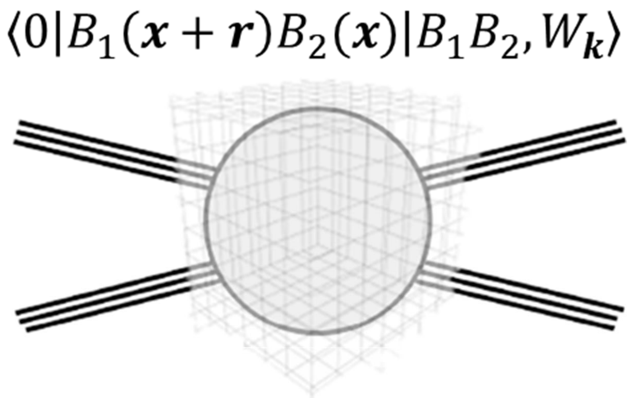
- The study of integrations between baryons still needs more lattice QCD calculations which depend on the strong interaction coupling constant and simulate the baryon-baryon interactions from first principles with HAL QCD method.
- The HAL QCD collaboration has calculated the $\Lambda_c N$ interaction for $m_\pi = 410-700$ MeV[4], while EFT theory has made some extrapolations of the system to the physical point. However, different EFT extrapolations present conflicting results[5], particularly in the $^3S_1 - {}^3D_1$ coupled channel calculations. Therefore, it is crucial to compute the $\Lambda_c N$ interaction at the physical point using LQCD.
- In 2020, the HAL QCD collaboration reported a bound state of $N\Omega$ based on LQCD calculations[6]. Later, the STAR[7] and ALICE[8] collaborations measured the $N\Omega$ femtoscopy correlation, which aligned with the HAL QCD calculations. This raises the natural question of whether $N\Omega_{ccc}$ could also form a bound state, potentially revealing $s-c$ quark symmetry in future studies.

[1] XT Lu, *Nuclear Physics*, 2000 [2] S. Acharya *et al.*, Nature **588**, 232 (2020). [3] L. Zhang, S. Zhang, and Y.-G. Ma, Eur. Phys. J. C **82**, 416 (2022). [4]T. Miyamoto, *et al*(2018). Nucl. Phys. A, **971**, 113 (2018).
[5] J. Haidenbauer & G. Krein arXiv:2101.07160v1 (2021). [6] T. Iritani *et al*, *Phy. Let. B*, **792**, 284 (2019) [7] STAR Collaboration, *Phys. Lett. B*, **790**, 490(2019) [8] S. Acharya *et al*, *Nature*, **588**(7837), 232 (2020).

HAL QCD and Configurations

HAL QCD method provide a First-Principles calculation method on hadron interaction[1,2].

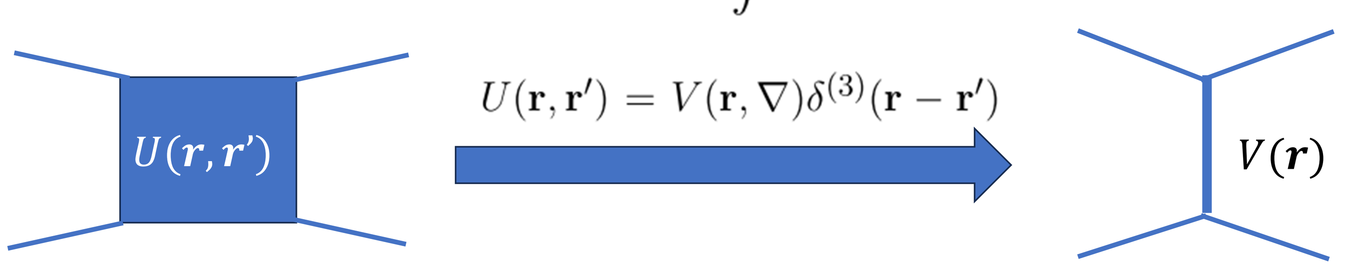
$\langle 0|B_1(\boldsymbol{x}+\boldsymbol{r})B_2(\boldsymbol{x})|B_1B_2,W_{\boldsymbol{k}}\rangle$



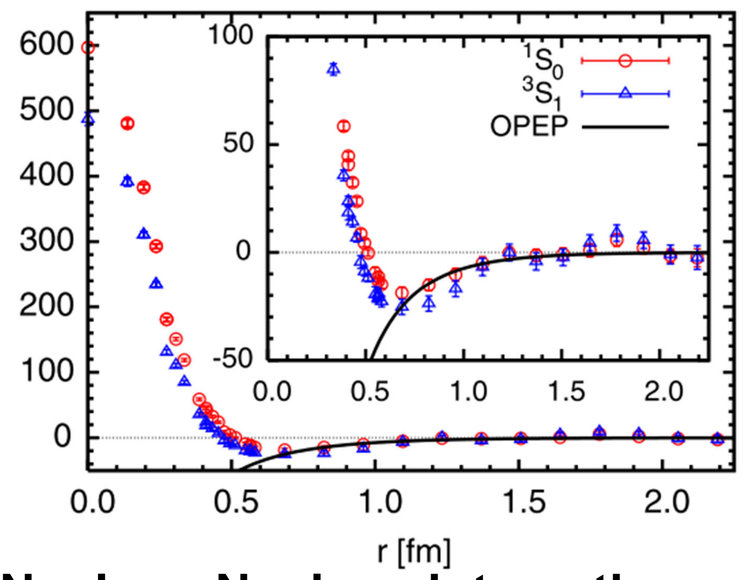
$\equiv \phi_{\mathbf{k}}(\mathbf{r})e^{-W_{\mathbf{k}}t}$

Nambu-Bethe-Salpeter (NBS) wave function

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



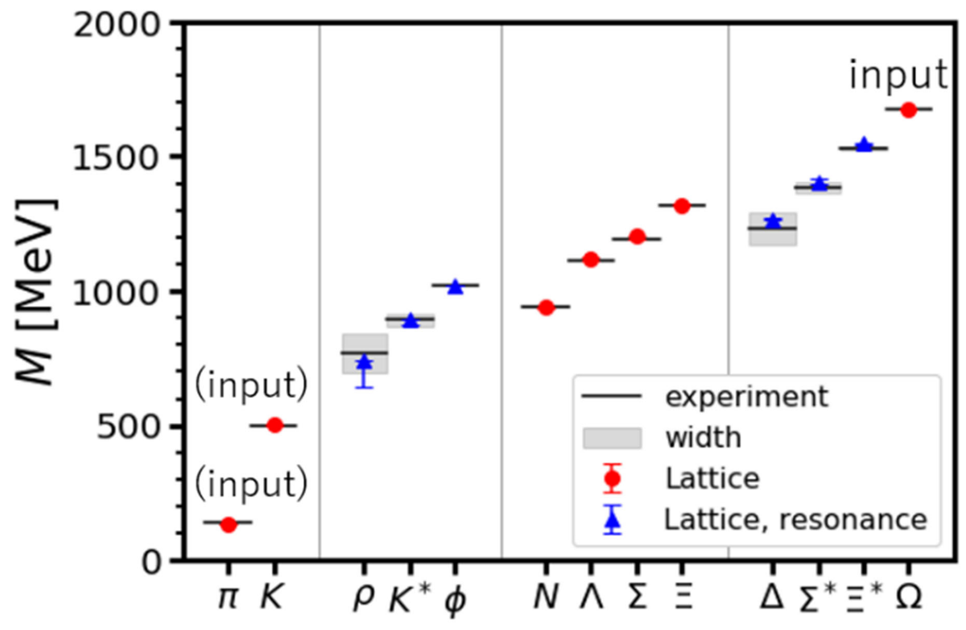
$$V(\mathbf{r},\nabla) = \underbrace{V_0(r) + V_\sigma(r)(\sigma_1\cdot\sigma_2) + V_T(r)S_{12}}_{\text{LO}} + \underbrace{V_{\text{LS}}(r)\mathbf{L}\cdot\mathbf{S}}_{\text{NLO}} + O(\nabla^2),$$



Nucleon-Nucleon interaction form HAL QCD method[2]

Here we using HAL-conf-2023[6,7] to do the calculation

- ✓ $m_\pi \simeq 137$ MeV, $m_K \simeq 502$ MeV
- ✓ Size of the lattice is 96^4, corresponding to $(8.1\text{fm})^4$ in physical units
- ✓ 8,000 trajectories
- ✓ $a^{-1} = 2338.8(1.5)(^{+0.2}_{-3.0})$ MeV



Fugaku（2021-）·440PF

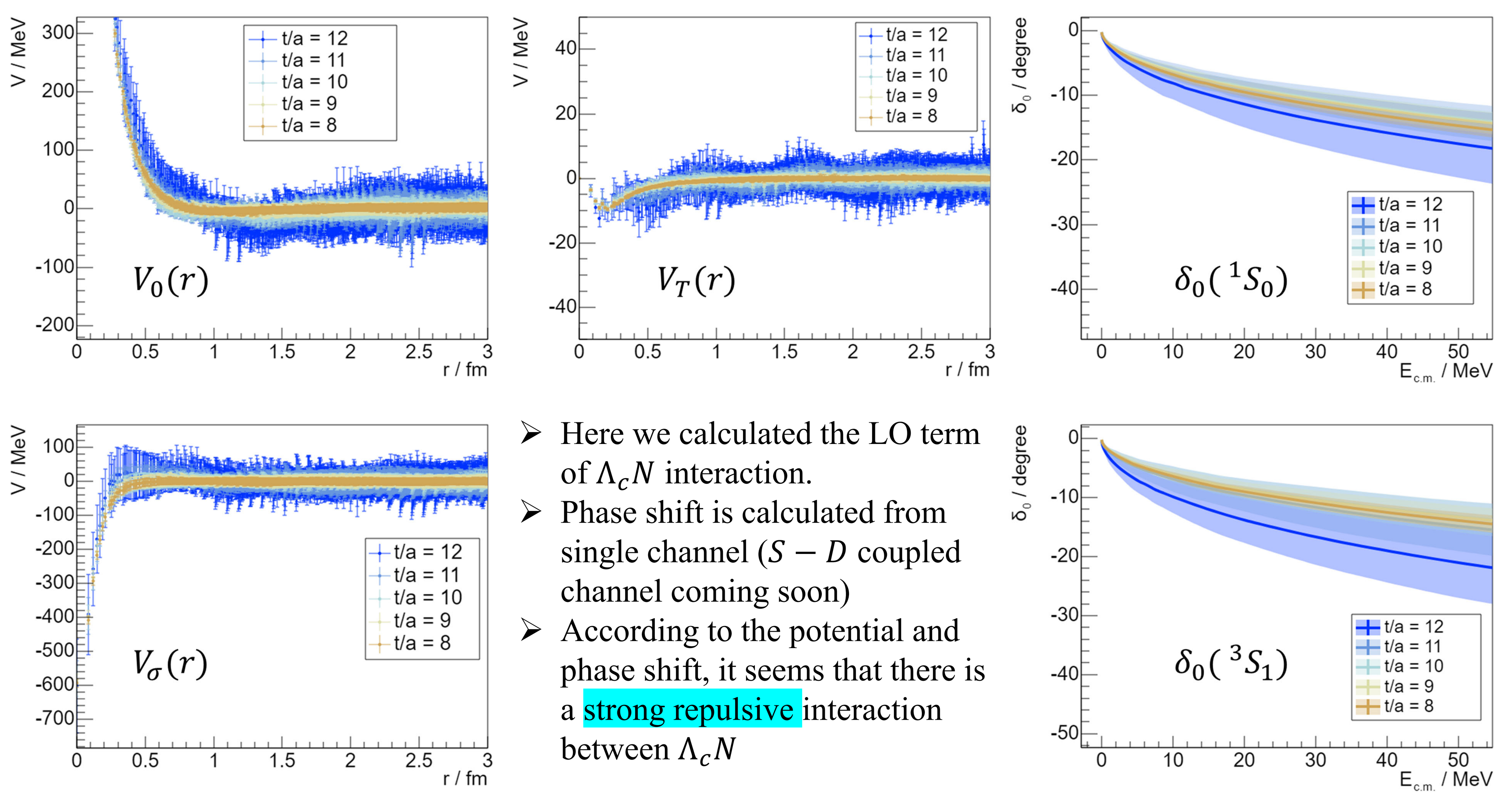
Hadron spectra on the Physical Point[3,4] Compared with Experiment Mass

[1] N. Ishii, S. Aoki, and T. Hatsuda, Phys. Rev. Lett. **99**, 5 (2007). [2] S. Aoki and T. Doi, Front. Phys. **8**, 1 (2020). [3] T. Aoyama *et al.*, arXiv:2406.16665. [4] E. Itou, *PoS(LATTICE2023)* p. 140.

Λ_c N interaction

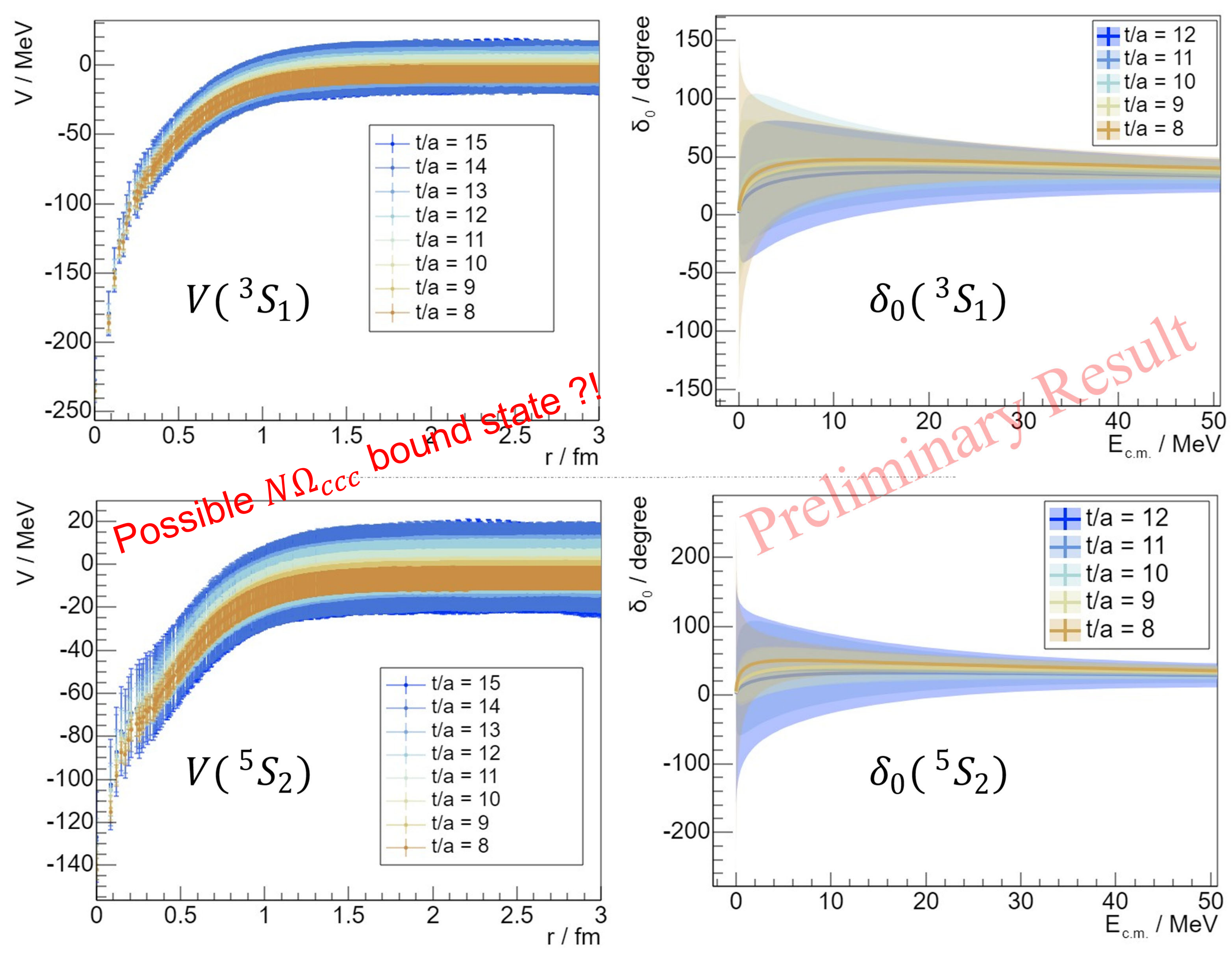
$$V(\boldsymbol{r},\boldsymbol{\nabla}) = V_0(r) + V_\sigma(r)(\sigma_1\cdot\sigma_2) + V_T S_{12} + O(\nabla)$$

(Both $\Lambda_c N$ and $\Omega_{ccc} N$ interactions are fitted with 3-Gaussian type potential)



- Here we calculated the LO term of $\Lambda_c N$ interaction.
- Phase shift is calculated from single channel ($S-D$ coupled channel coming soon)
- According to the potential and phase shift, it seems that there is a strong repulsive interaction between $\Lambda_c N$

Ω_{ccc} N interaction



Conclusion & Future

◆ $\Lambda_c N$ interaction

- There is a strong repulsive interaction between Λ_c and N, making the existence of Λ_c hypernuclei challenging
- Both tensor force V_T and spin-dependent central force V_σ are relatively weak.

◆ $\Omega_{ccc} N$ interaction

- In the $\Omega_{ccc} N$ system, there is no Pauli exclusion principle at the quark level, which is one reason the interaction is entirely attractive.
- The combination of a deep attractive potential and the heavy Ω_{ccc} suggests the possibility of a deeply bound dibaryon

◆ Outlook

- $S-D$ coupled channel calculation of $\Lambda_c N$
- Calculate the binding energy of $\Omega_{ccc} N$ dibaryon
- Inspire researches on charmed baryon – nucleon