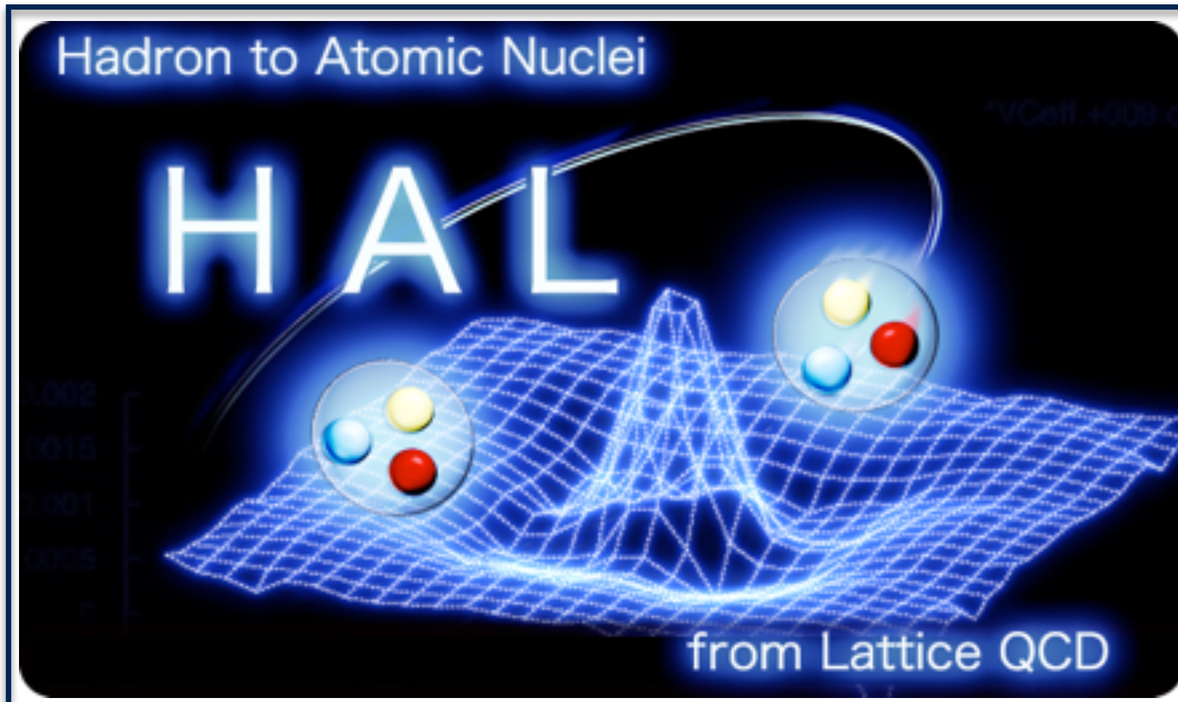
ΛcN interaction from lattice QCD and Λc nuclei

Takaya Miyamoto

(Yukawa Institute for Theoretical Physics, Kyoto University)

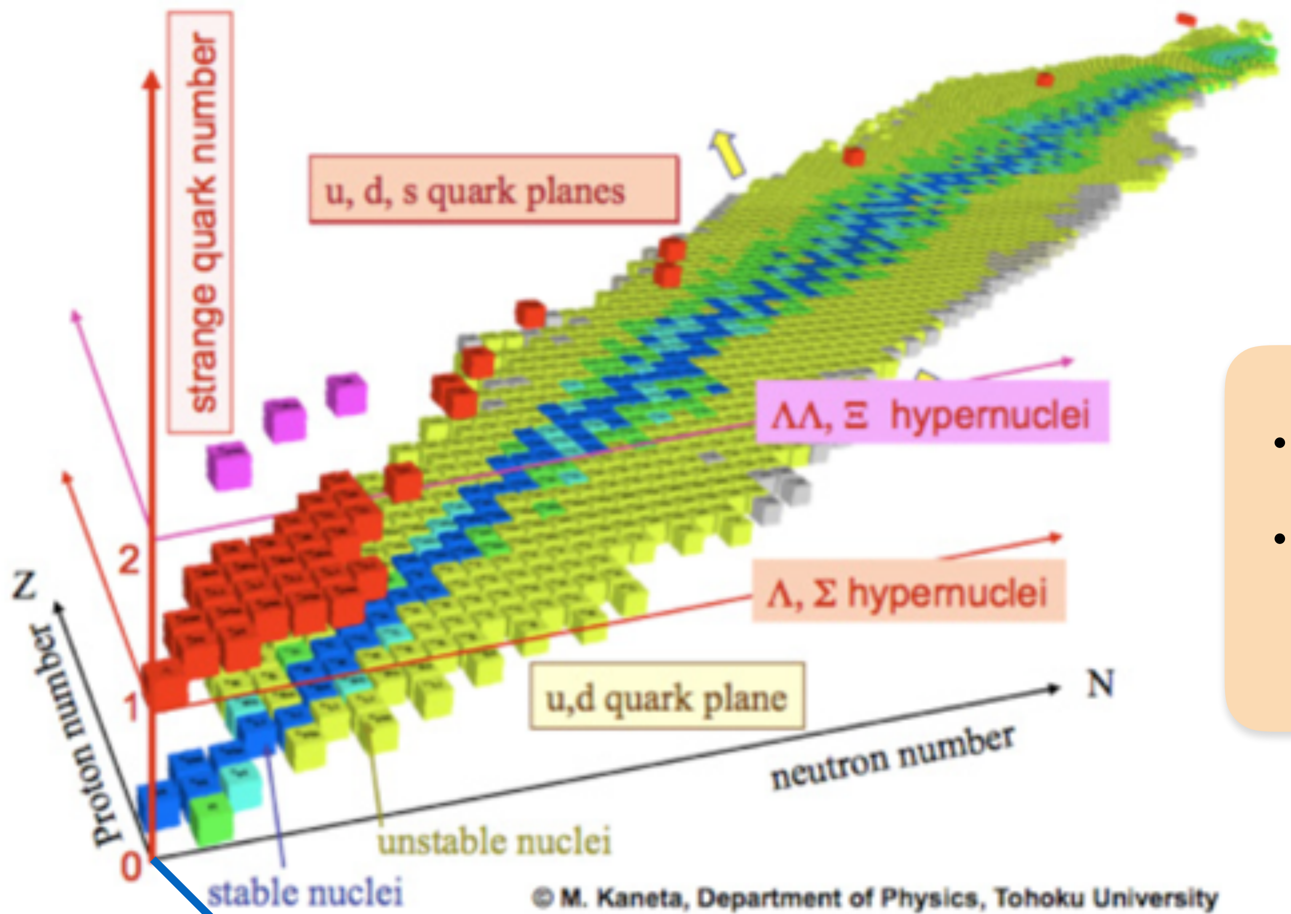
for **HAL QCD Collaboration**



S. Aoki, T. Aoyama, K. Sasaki,	(YITP Kyoto Univ.)
D. Kawai	
T. Doi, T.M. Doi, T. Hatsuda,	(RIKEN Nishina)
T. Iritani	
T. Inoue	(Nihon Univ.)
N. Ishii, Y. Ikeda, K. Murano	(RCNP Osaka Univ.)
H. Nemura	
S. Gongyo	(Univ. of Tours)
F. Etminan	(Univ. of Birjand)

Introduction

Various (hyper-) nuclei are found in experiments



charm quark number

- Are there any **charmed hyper-nuclei** ?
- What is the difference between hyper-nuclei and charmed hyper-nuclei ?

To discuss possibility of **charmed hyper-nuclei**, the interaction between a charmed baryon and a nucleon is a key

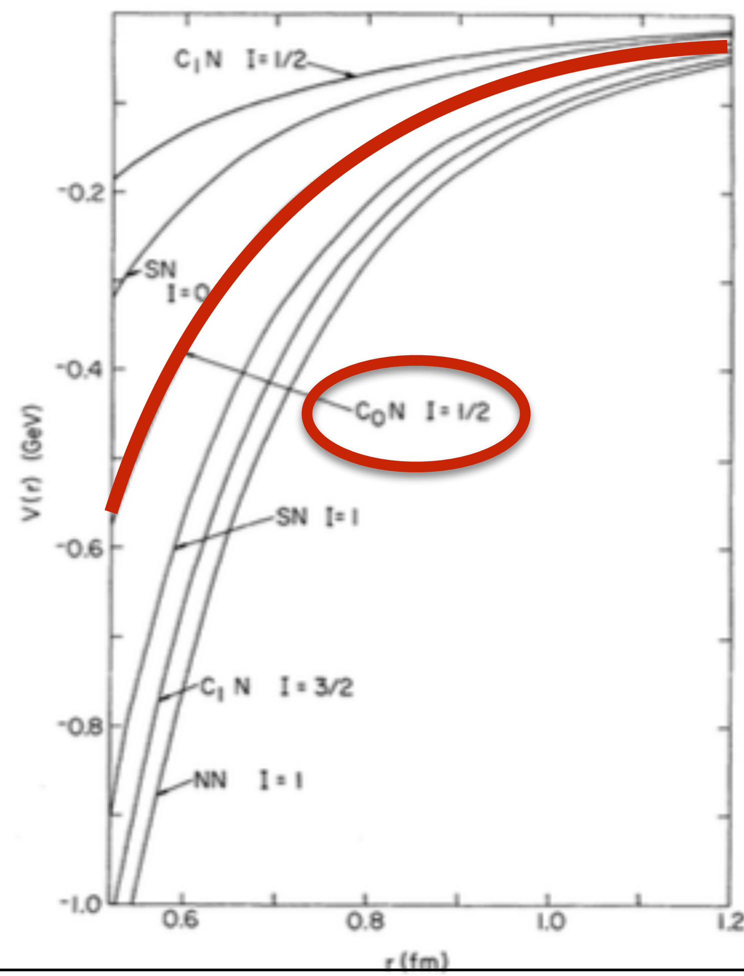
What about the interaction?

YcN interactions → **Yc-nuclei**

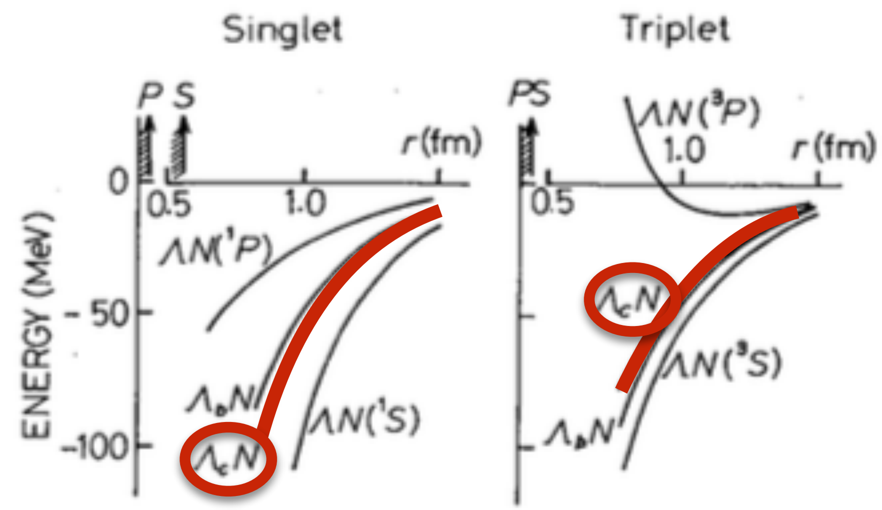
Introduction

There are several theoretical studies for charmed baryon interactions

- One-Boson-Exchange (OBE) potential model extended to flavor SU(4)
  + Infinite hard core at short range (~ 0.5 fm)



C. B. Dover and S. H. Kahana, Phys. Rev. Lett. 39, 1506 (1977).



H. Bandō and S. Nagata, Prog. Theor. Phys. (1983) 69.

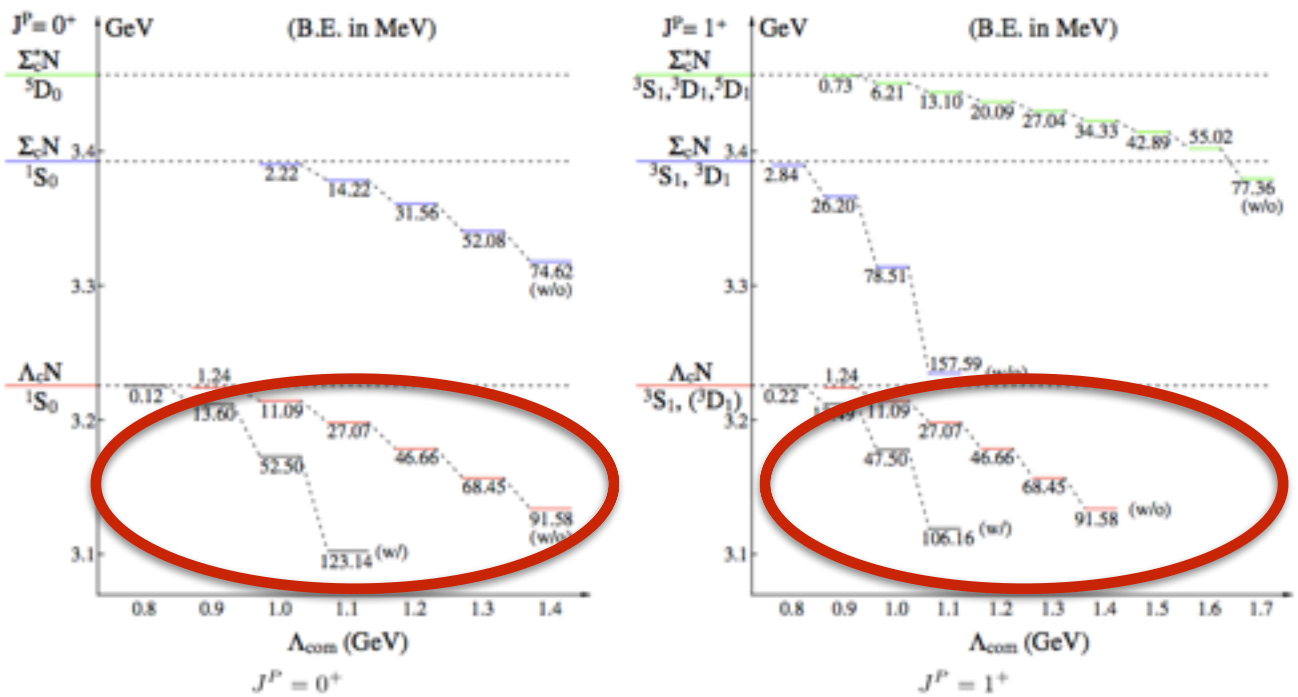
These studies show that
ΛcN interactions are attractive.

⇨ Various Λc-nuclei were predicted

Introduction

[There are several theoretical studies for charmed baryon interactions]

- OBEP model based on the heavy quark effective theory
  - Coupled-channel ($\Lambda_c N$-$\Sigma_c N$-$\Sigma_c^* N$) effects are take into account



Y. R. Liu, M. Oka, Phys. Rev. D85, 014015 (2012).

Channel coupling has important effects for the $\Lambda_c N$ bound states

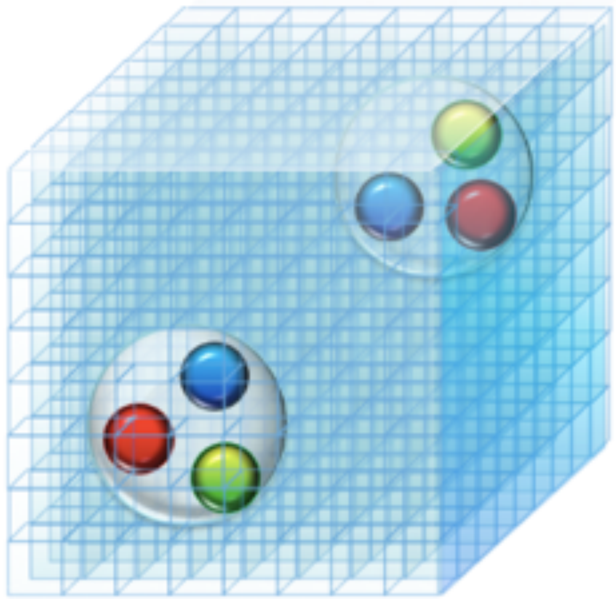
The possibility of **bound $\Lambda_c N$** was claimed

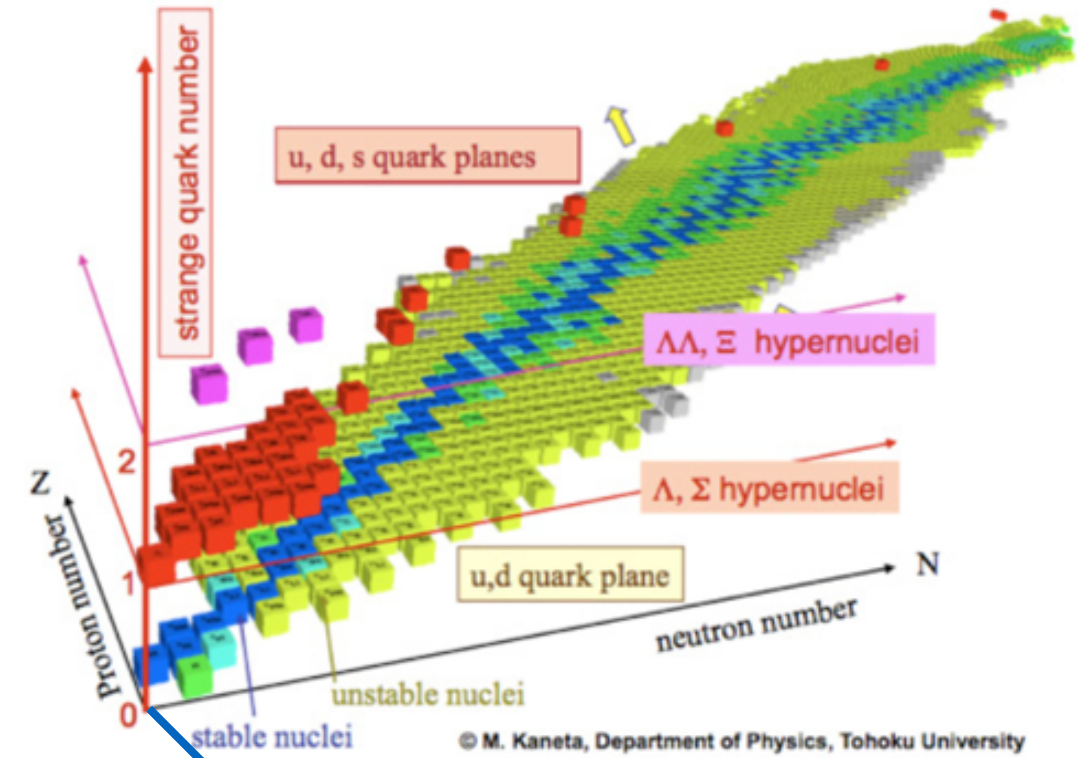
The results are sensitive to the phenomenological cutoff parameter, which encodes the information of the short-range interaction. This feature indicates that **the binding energy is sensitive to the short-range interaction**.

The determination of interactions from QCD is desirable

Introduction

Lattice QCD





charm quark number

Our strategy

HAL QCD method

Input

hadron-hadron potential

- Faithful to QCD S-matrix
- No experimental data are needed
- Extending to charmed baryon is easy

Outline

(1) Motivation

(2) HAL QCD method

(3) Simulation setup

(4) Numerical results of $\Lambda_c N$ and ΛN interactions

(5) Folding potential analysis for Λ_c-nuclei

(6) Summary and conclusion

HAL QCD method

S. Aoki, T. Hatsuda, N. Ishii, Prog. Theor. Phys., 123 (2010).
S. Aoki *et al*, [HAL QCD Collaboration], PTEP., 01A105 (2012).

- **Nambu-Bethe-Salpeter (NBS) wave functions**

$$\psi_{\Lambda_c N}^{(W_n)}(\vec{r})\, e^{-W_n t} = \sum_{\vec{x}} \langle 0|\Lambda_c(\vec{r}+\vec{x},t)N(\vec{x},t)|\Lambda_c N, W_n\rangle$$

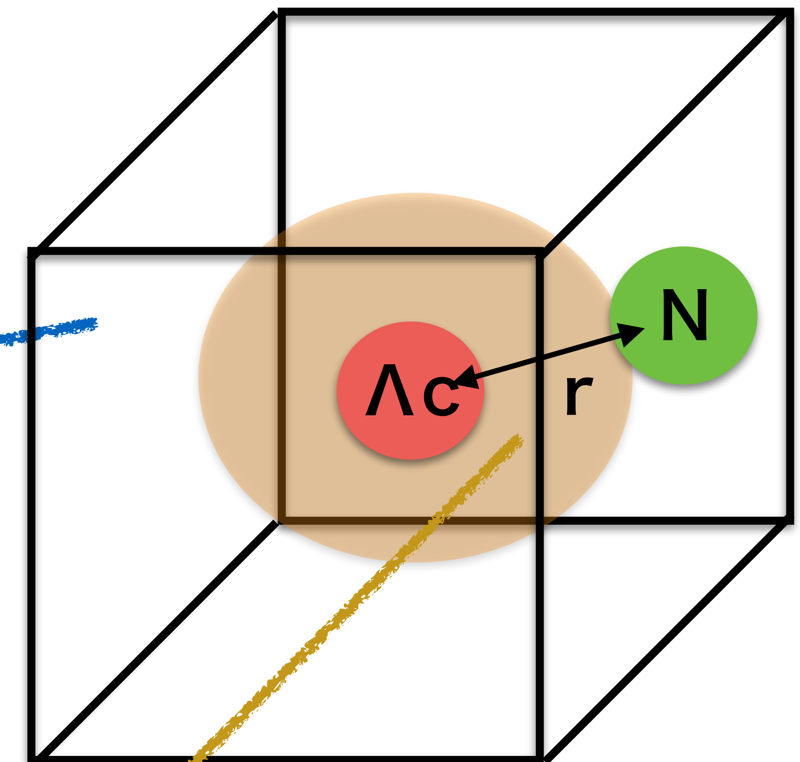
$$W_n \equiv \sqrt{k_n^2 + m_{\Lambda_c}^2} + \sqrt{k_n^2 + m_N^2}$$

At large r

$$(k_n^2 + \nabla^2)\psi^{(W_n)}(\vec{r}) = 0$$

$$\psi^{(W_n)}(|\vec{r}|) \propto \frac{\sin(k_n r - l\pi/2 + \delta_l(k_n))}{k_n r}$$

outside interactions



interacting region

Define the energy-independent non-local potentials through the **Schrödinger-type equation**

$$(E_n - H_0)\,\psi_{\Lambda_c N}^{(W_n)}(\vec{r}) = \int d^3 r'\, U_{\Lambda_c N}(\vec{r},\vec{r}')\psi_{\Lambda_c N}^{(W_n)}(\vec{r}')$$

- Potentials faithful to S-matrix by construction
- All 2PI contributions are included in potentials
- Potentials are energy-independent until a new channel opens

HAL QCD method

S. Aoki, T. Hatsuda, N. Ishii, Prog. Theor. Phys., 123 (2010).
S. Aoki *et al*, [HAL QCD Collaboration], PTEP., 01A105 (2012).

- **To extract "energy-independent" potentials, we employ time-dependent HAL QCD method**

N. Ishii et al [HAL QCD Coll.], PLB712 (2012) 437.

$$R_{\Lambda_c N}(\vec{r},t) \equiv \frac{G_{\Lambda_c N}(\vec{r},t)}{e^{-m_{\Lambda_c}t} e^{-m_N t}}$$

Normalized 4pt-correlation function (**R-correlator**)

$$(E_0 - H_0)\,\psi_0(\vec{r}) = \int d^3r' U(\vec{r},\vec{r}\,')\psi_0(\vec{r}\,')$$

$$(E_1 - H_0)\,\psi_1(\vec{r}) = \int d^3r' U(\vec{r},\vec{r}\,')\psi_1(\vec{r}\,')$$

$$(E_2 - H_0)\,\psi_2(\vec{r}) = \int d^3r' U(\vec{r},\vec{r}\,')\psi_2(\vec{r}\,')$$

All equations are combined into one t-dep. eq.

$$\left(-\frac{\partial}{\partial t} + \left[\frac{1+\delta^2}{8\mu}\right]\frac{\partial^2}{\partial t^2} - H_0\right) R_{\Lambda_c N}(\vec{r},t) = \int d^3r' U_{\Lambda_c N}(\vec{r},\vec{r}\,') R_{\Lambda_c N}(\vec{r}\,',t)$$

$$\mu \equiv \frac{m_{\Lambda_c} m_N}{m_{\Lambda_c} + m_N} \qquad \delta \equiv \frac{m_{\Lambda_c} - m_N}{m_{\Lambda_c} + m_N}$$

Within the approximation up to $O(k^2)$

- **Non-local potentials —> local potentials**

Derivative (velocity) expansion

In the low energy state, **LO term of the potentials** is significant.

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

LO term

$$V(\vec{r},\vec{\nabla}) = V_0(\vec{r}) + V_\sigma(\vec{r})\,(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + V_T(\vec{r}) S_{12} + \mathcal{O}(\vec{\nabla})$$

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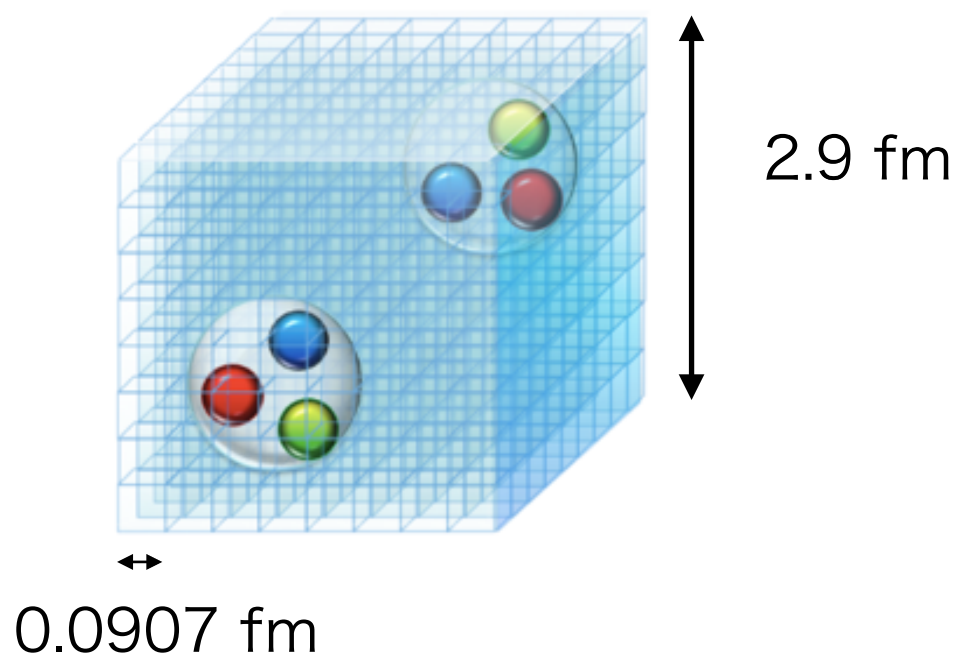
Lattice QCD setup

Nf=2+1 full QCD configurations generated by PACS-CS Coll



PACS-CS Collaboration:

S. Aoki, et al., Phys. Rev. D79 (2009) 034503

- Iwasaki gauge action
- O(a) improved Wilson-clover quark action
- a ~ 0.09 fm, L ~ 3 fm (32^3 x 64)

m_π ~ 700, 570, 410 MeV

For charm quark, we use

Relativistic Heavy Quark (RHQ) action

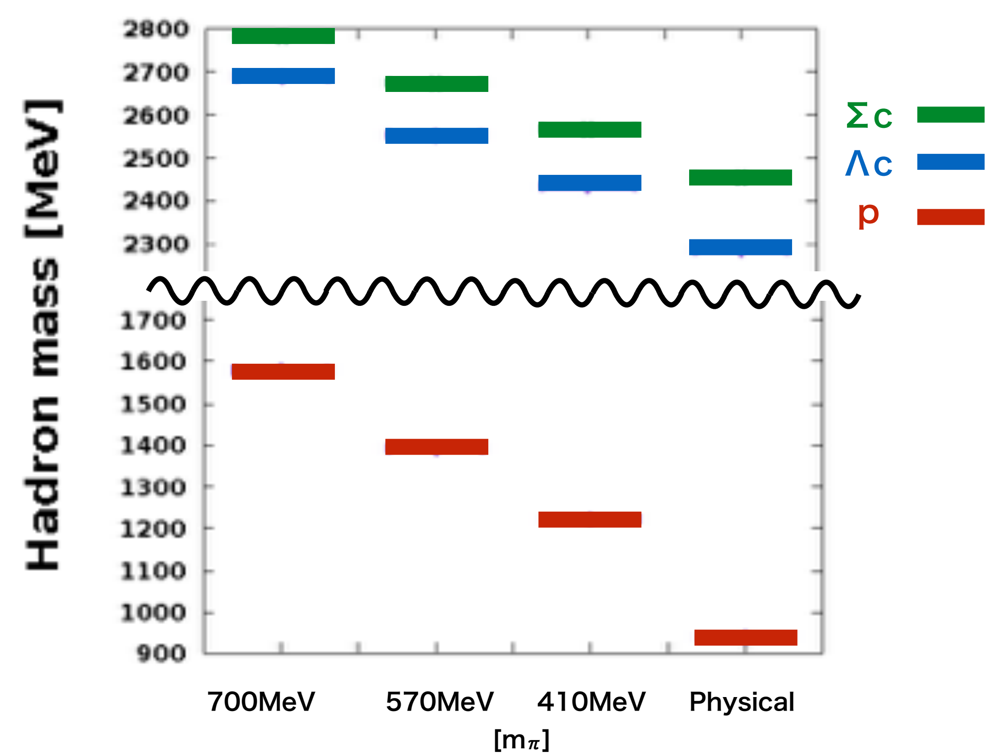
to remove the leading $O((ma)^n)$ discretization error

For more details, see,

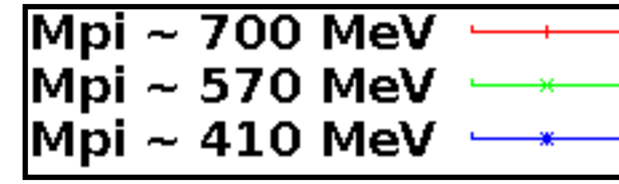
Namekawa, et al.,

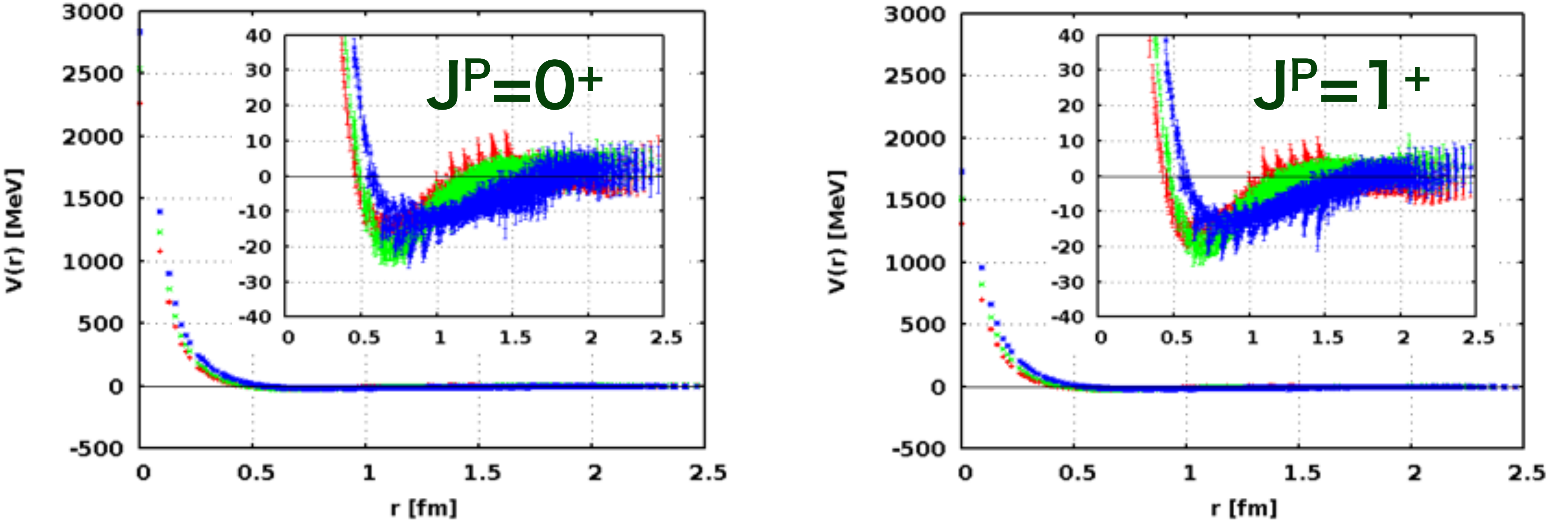
Phys. Rev. D84 (2011) 074505

BG/Q @ KEK



S-wave Λc-N
effective central potentials



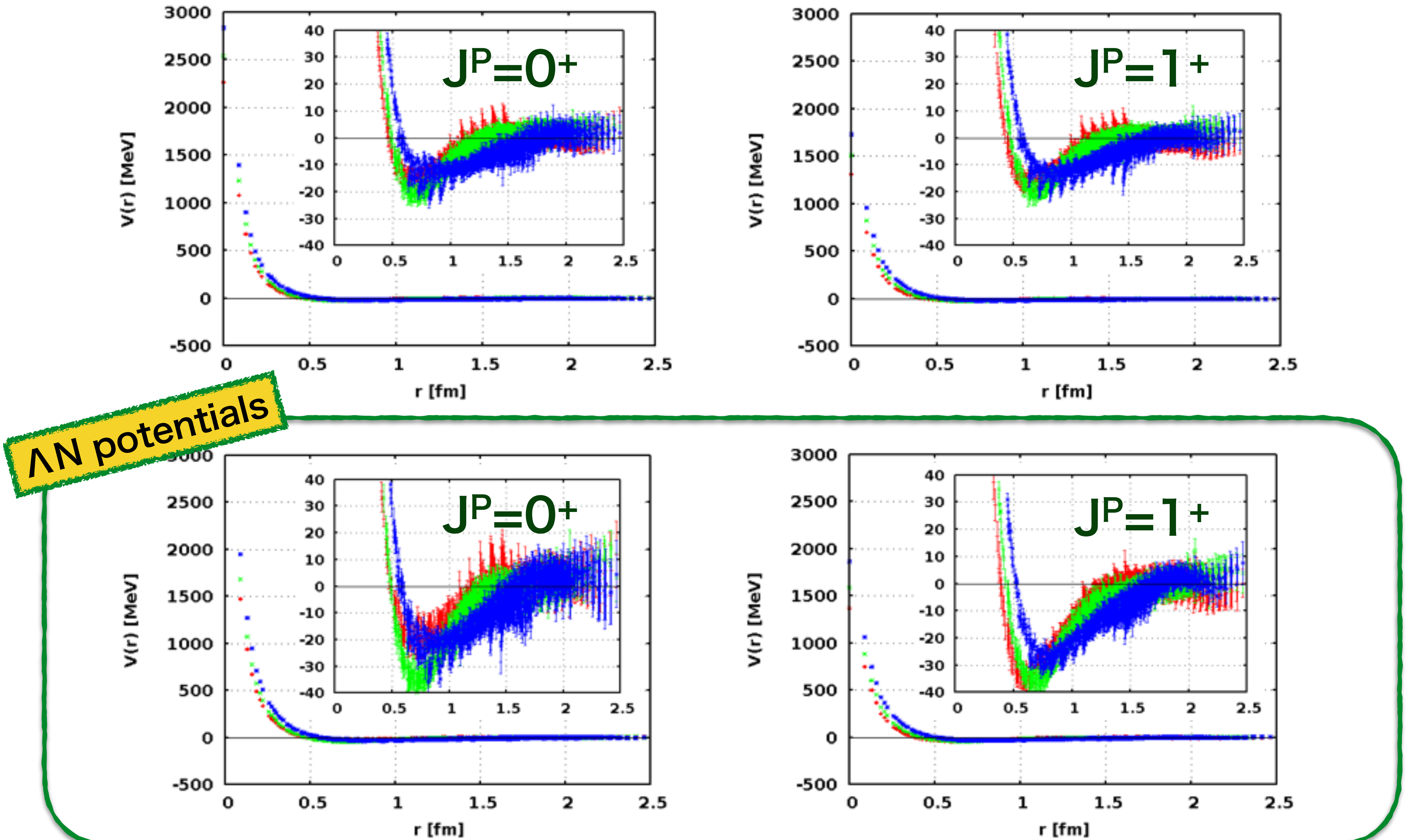


Λc-N potential = repulsive core + attractive pocket

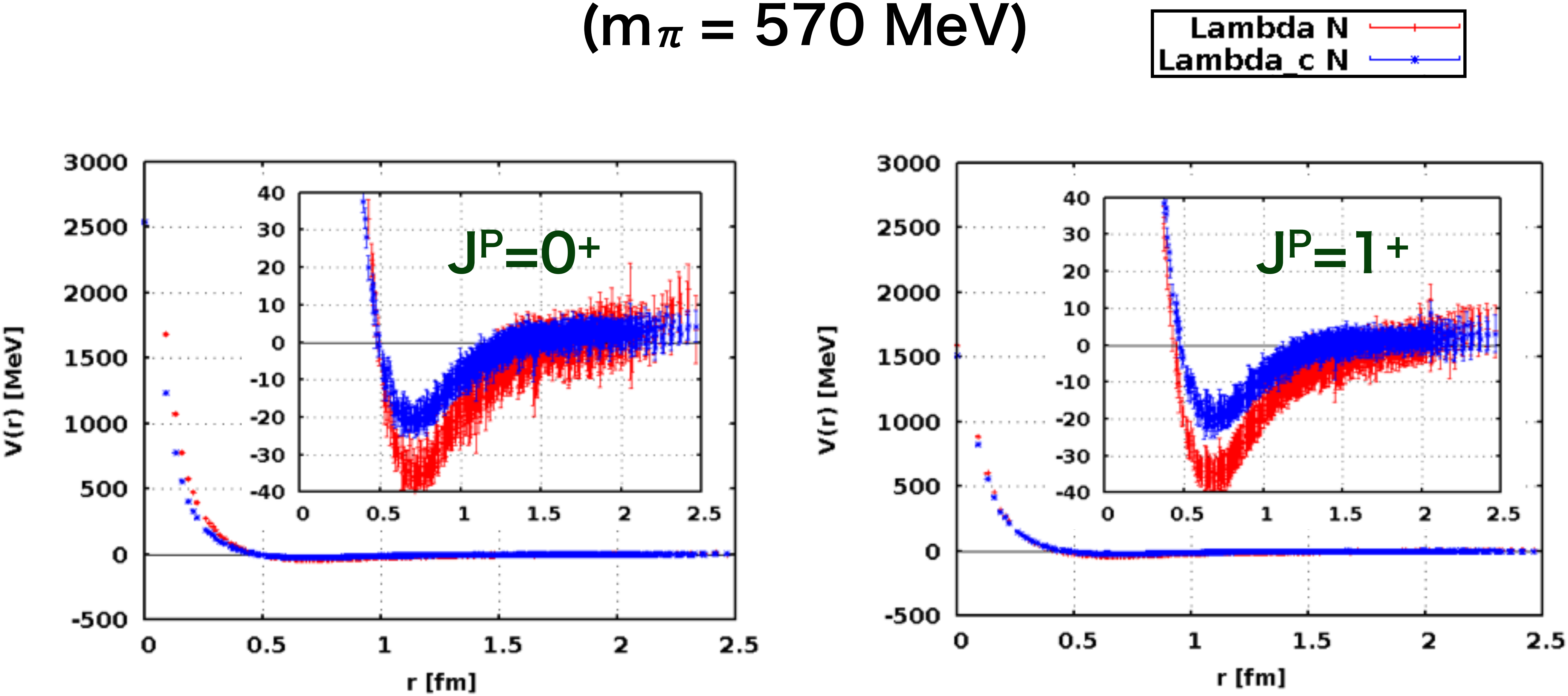
As m_q decreasing,

- repulsive core becomes larger
- attractive pocket shifts outward

S-wave Λ(c)-N effective central potentials



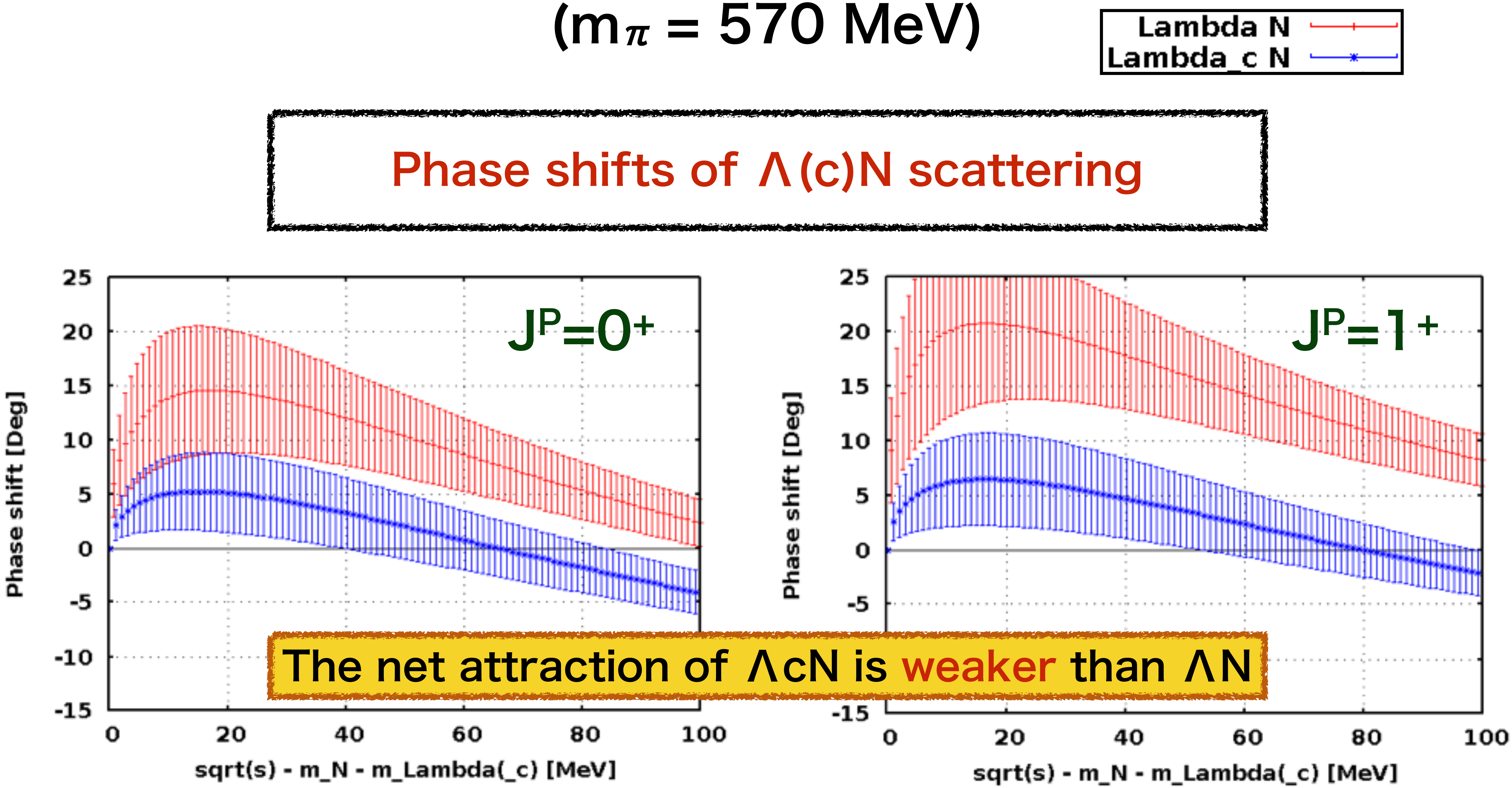
Comparison of ΛN and ΛcN potential
(m_π = 570 MeV)



Both attractive pocket and
repulsive core of ΛcN potentials
are **smaller** than those of ΛN potentials

Comparison of ΛN and Λ_cN potential
(m_π = 570 MeV)

Phase shifts of Λ(c)N scattering



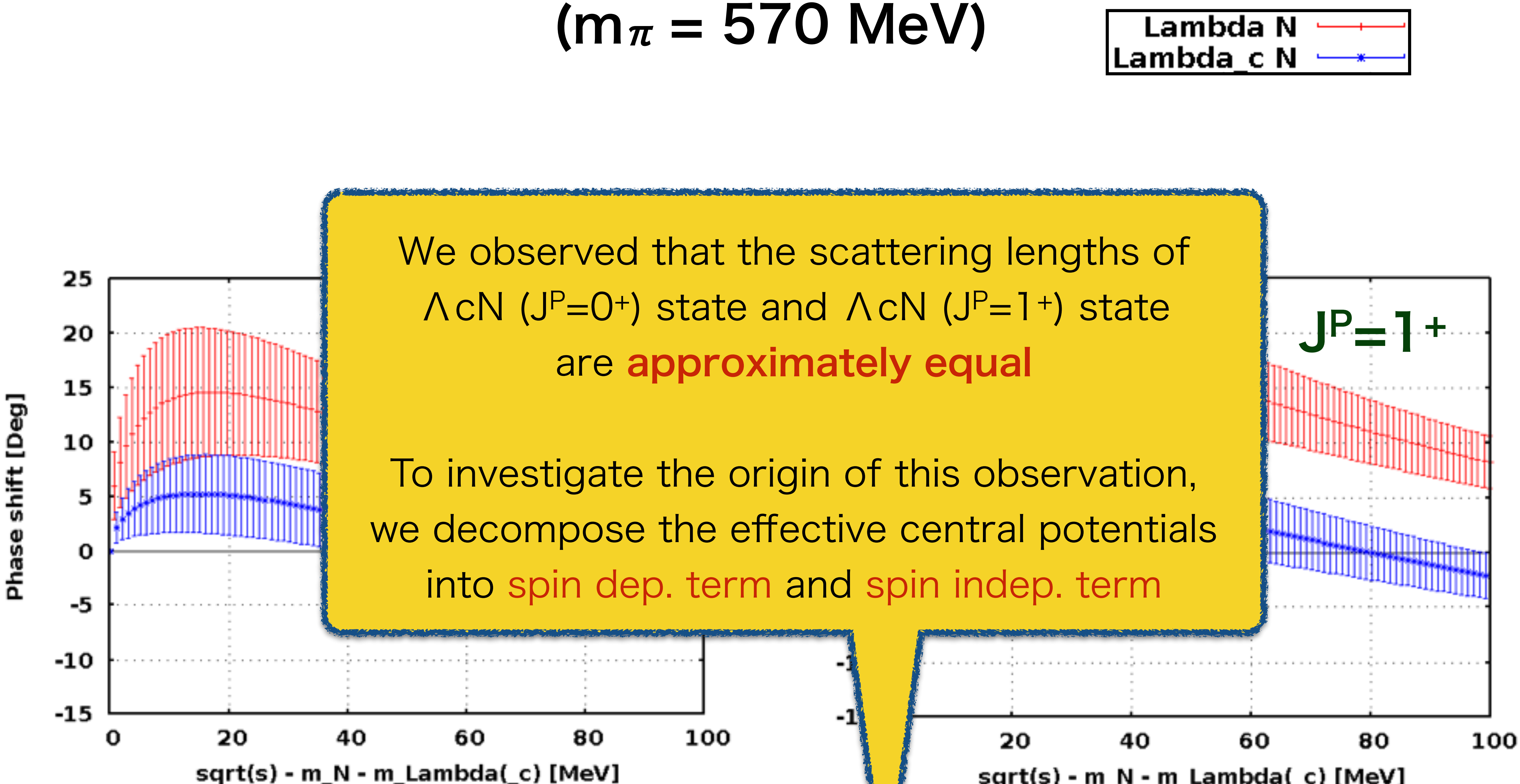
The net attraction of Λ_cN is weaker than ΛN

Scattering length:

$$a = \lim_{k\to 0} \frac{\tan\delta(k)}{k}$$

$J^P=0^+$	$J^P=1^+$
$a_{\Lambda N}$ = 0.56(30) fm	$a_{\Lambda N}$ = 0.87(45) fm
$a_{\Lambda_c N}$ = 0.18(12) fm	$a_{\Lambda_c N}$ = 0.21(15) fm

Comparison of ΛN and ΛcN potential
(m_π = 570 MeV)



We observed that the scattering lengths of ΛcN ($J^P=0^+$) state and ΛcN ($J^P=1^+$) state are **approximately equal**

To investigate the origin of this observation, we decompose the effective central potentials into spin dep. term and spin indep. term

Scattering length:

$$a = \lim_{k \to 0} \frac{\tan \delta(k)}{k}$$

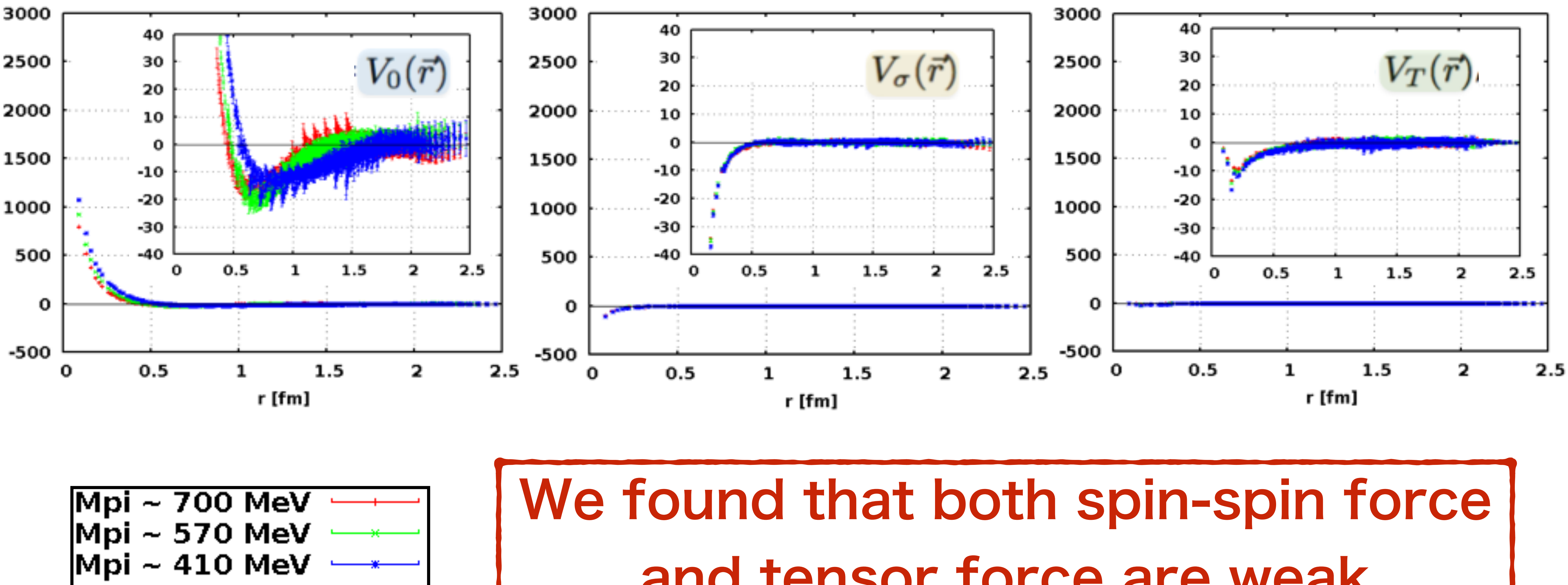
$a_{\Lambda N}$ = 0.56(30) fm
$a_{\Lambda cN}$ = 0.18(12) fm

$a_{\Lambda N}$ = 0.87(45) fm
$a_{\Lambda cN}$ = 0.21(15) fm

Leading order of ΛcN potential in velocity expansion

$$V_{\Lambda_c N}(\vec{r}) = V_0(\vec{r}) + V_\sigma(\vec{r})\,(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + V_T(\vec{r}) S_{12}$$

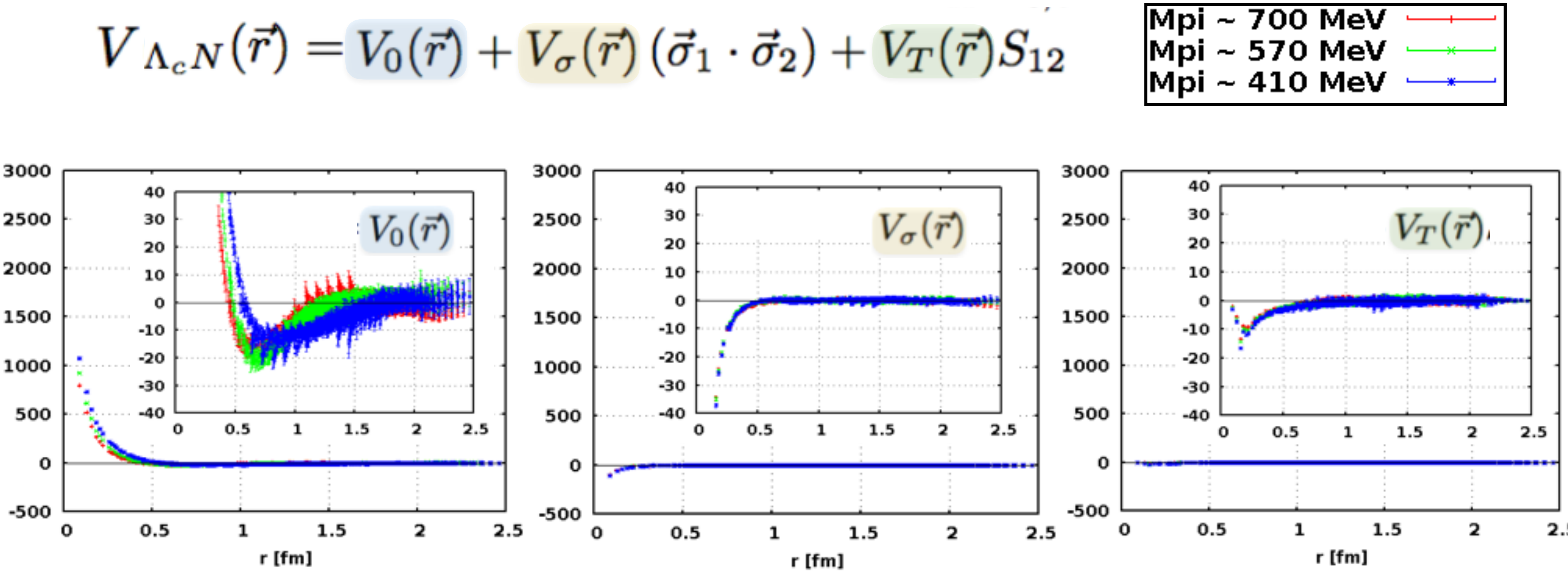
These three potentials can be obtained from NBS wave functions in $J^P=0^+$ and 1^+

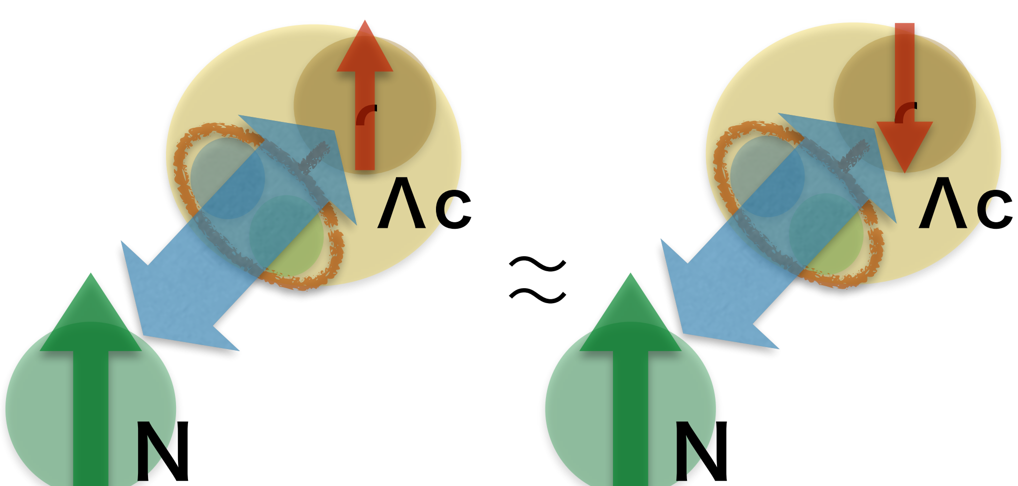


We found that both spin-spin force and tensor force are weak

Leading order of ΛcN potential in velocity expansion

$$V_{\Lambda_c N}(\vec{r}) = V_0(\vec{r}) + V_\sigma(\vec{r})\,(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + V_T(\vec{r}) S_{12}$$

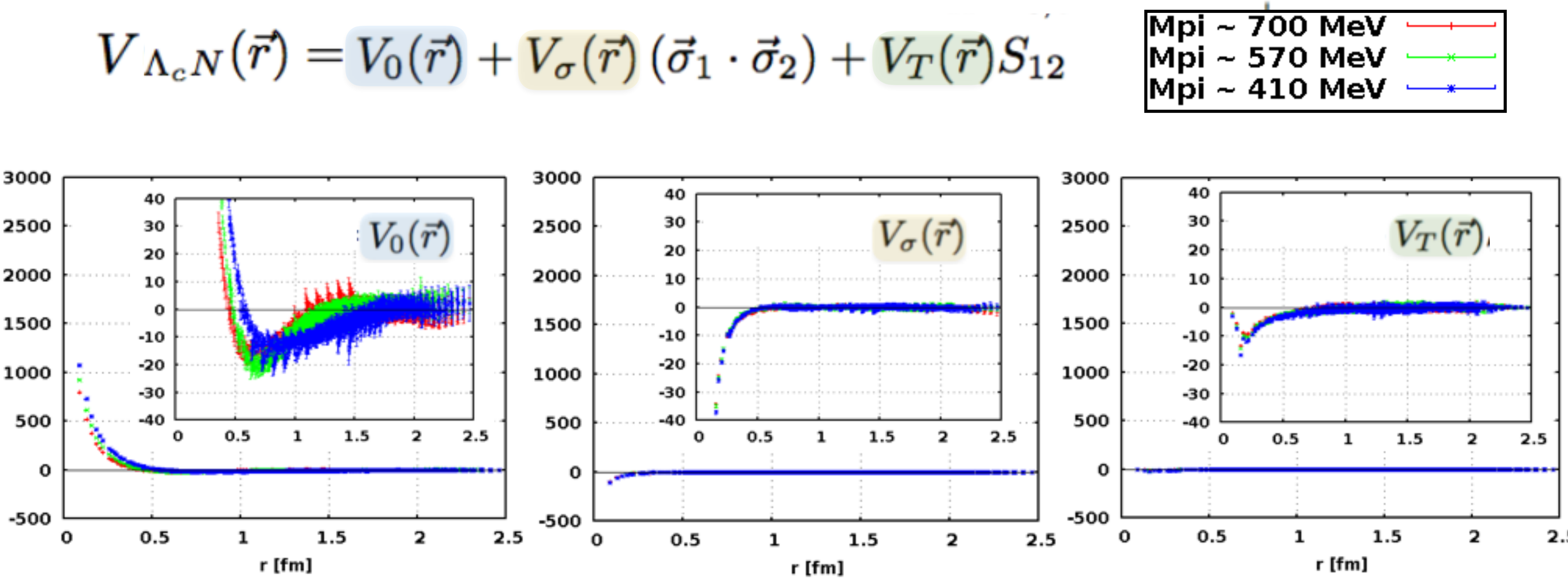


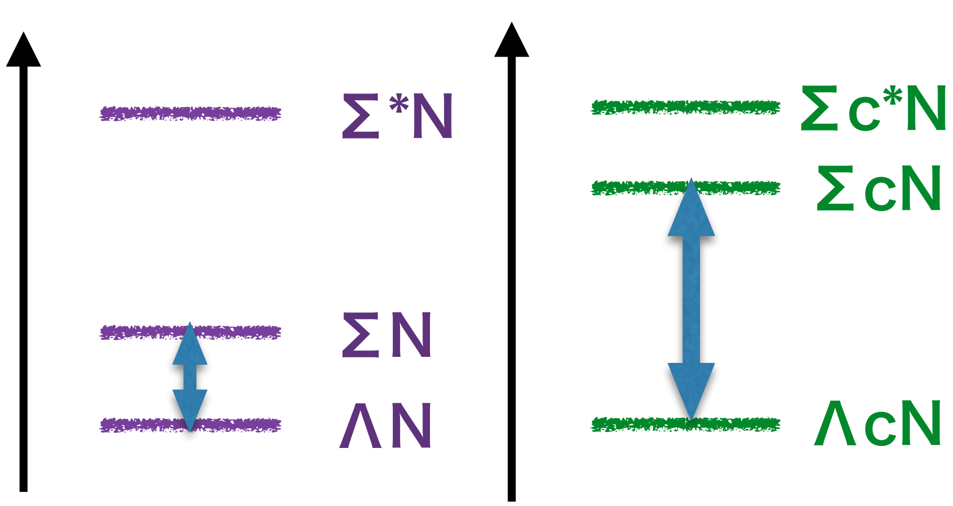


Weak spin-spin force of ΛcN
—> It could be explained from
the HQ spin symmetry

Leading order of ΛcN potential in velocity expansion

$$V_{\Lambda_c N}(\vec{r}) = V_0(\vec{r}) + V_\sigma(\vec{r})(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + V_T(\vec{r}) S_{12}$$

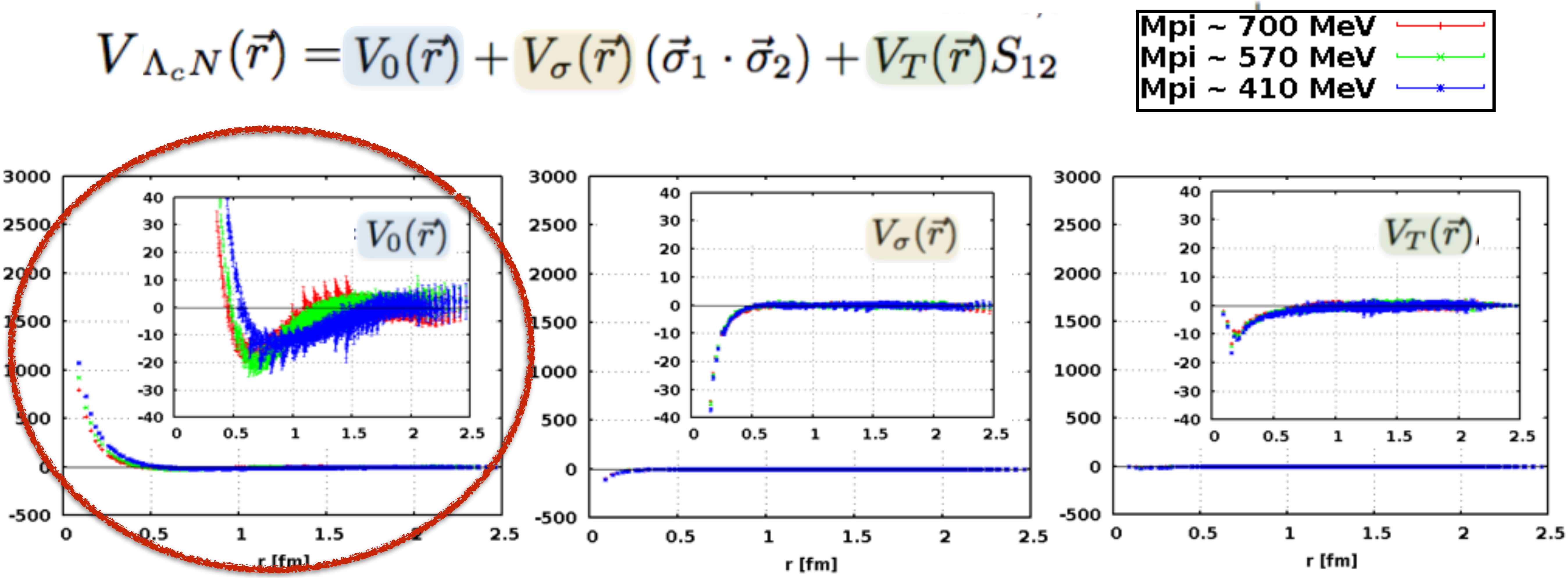




Weak tensor force of ΛcN
—> It could be explained from
large difference of ΛcN-ΣcN threshold

Comparison of ΛN potential and ΛcN potential

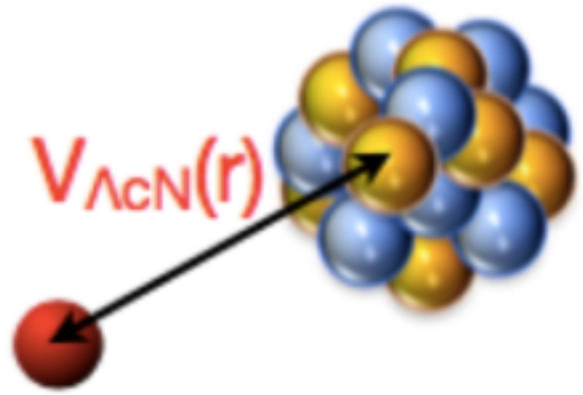
$$V_{\Lambda_c N}(\vec{r}) = V_0(\vec{r}) + V_\sigma(\vec{r})(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + V_T(\vec{r}) S_{12}$$



Spin independent central potential is significant in ΛcN interaction

We use this potential for the investigation of Λc-nuclei

Λc-nuclei



(Single-) folding potential

$$V_F(\boldsymbol{r}) = \int d^3r' \rho_A(\boldsymbol{r}') V_{\Lambda_c N}(\boldsymbol{r} - \boldsymbol{r}')$$

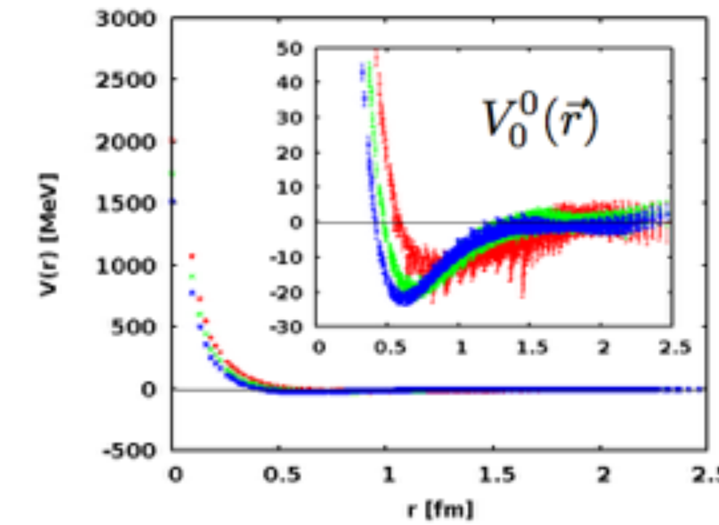
density distributions for nuclear matter

$$\rho_A(r) = \rho_0 \left[1 + \exp\left(\frac{r - c}{a} \right) \right]^{-1}$$

two-parameter Fermi (FM) form

$$\left(\int d^3r \, \rho_A(r) = A \right)$$

HAL QCD potential



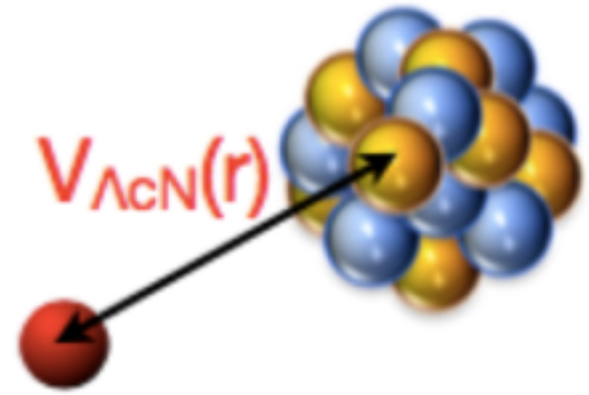
Since the spin dep. force is weak, we use only the spin indep. force for the folding potentials.

・Parameters for several stable nuclei

Nucleus	^{12}C	^{28}Si	^{40}Ca	^{58}Ni	^{90}Zr	^{208}Pb
ρ_0 (fm^{-3})	0.207	0.175	0.169	0.172	0.165	0.150
c (fm)	2.1545	3.15	3.60	4.094	4.90	6.80
α (fm)	0.425	0.475	0.523	0.54	0.515	0.515

Ref: M. El-Azab Farid a, M.A. Hassanain, Nuclear Physics A 678 (2000) 39–75

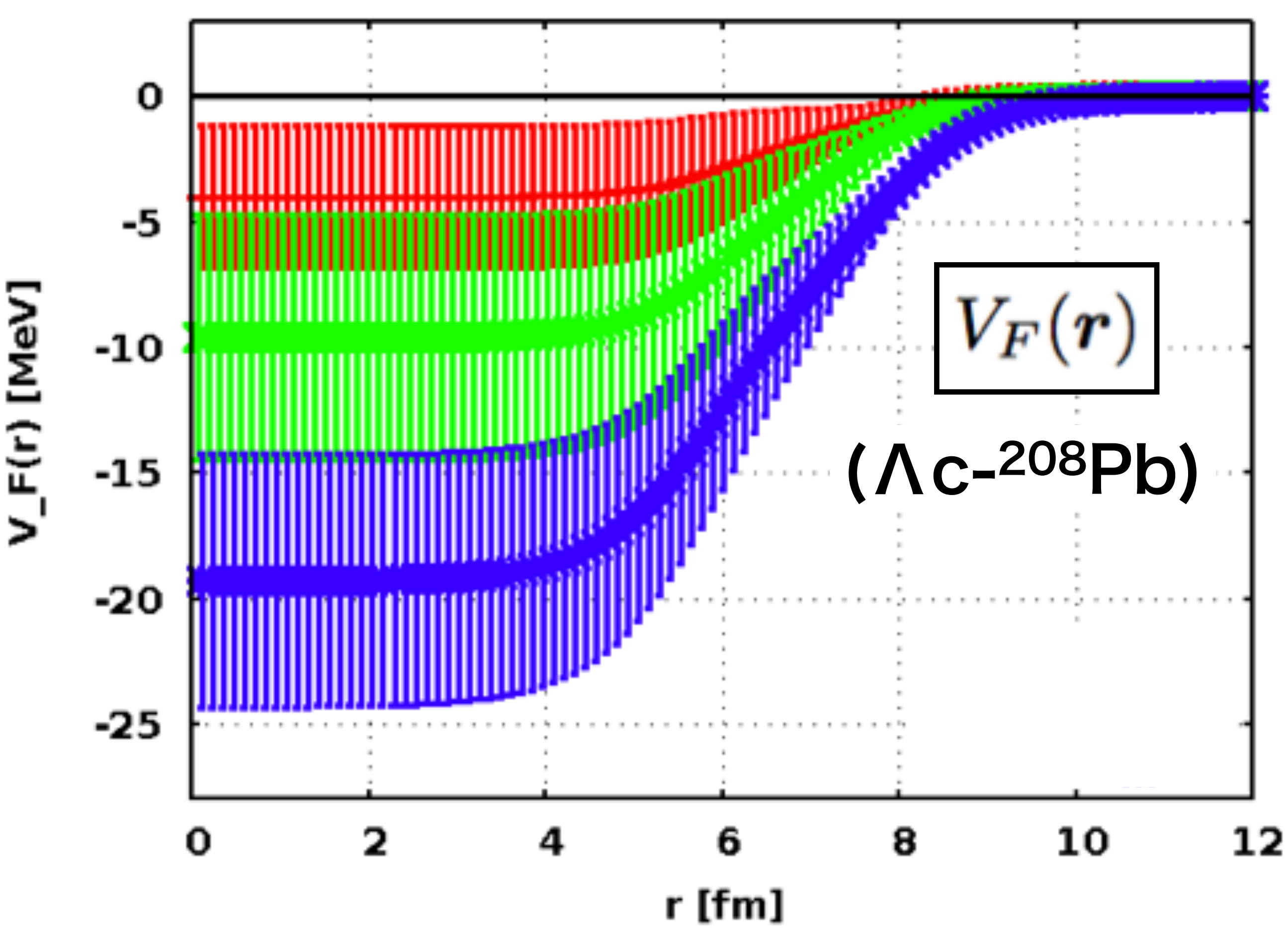
Λc-nuclei

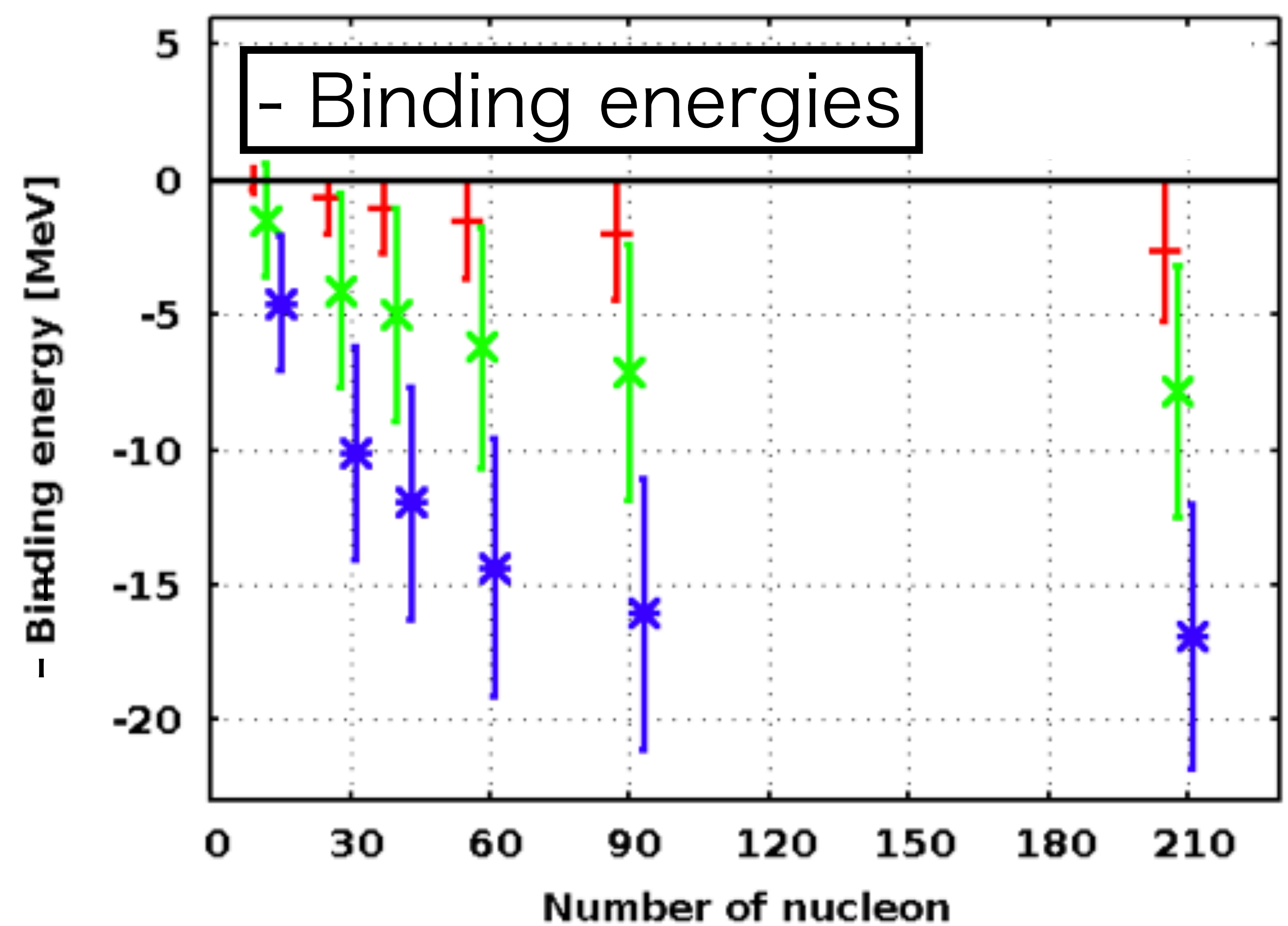


(Single-) folding potential

$$V_F(\boldsymbol{r}) = \int d^3r' \rho_A(\boldsymbol{r}') V_{\Lambda_c N}(\boldsymbol{r} - \boldsymbol{r}')$$

HAL QCD potential (spin-indep. force)

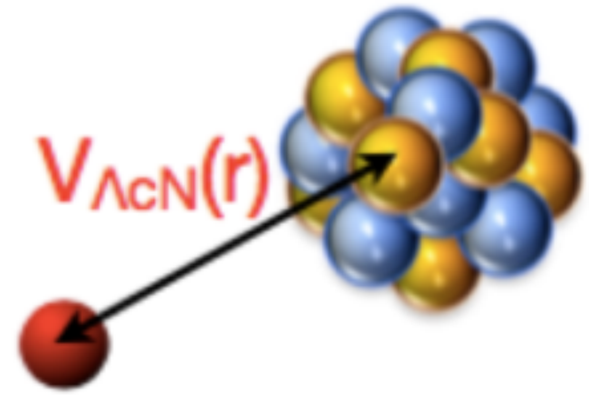




Mpi ~ 700 MeV
Mpi ~ 570 MeV
Mpi ~ 410 MeV

w/o Coulomb force

Λc-nuclei

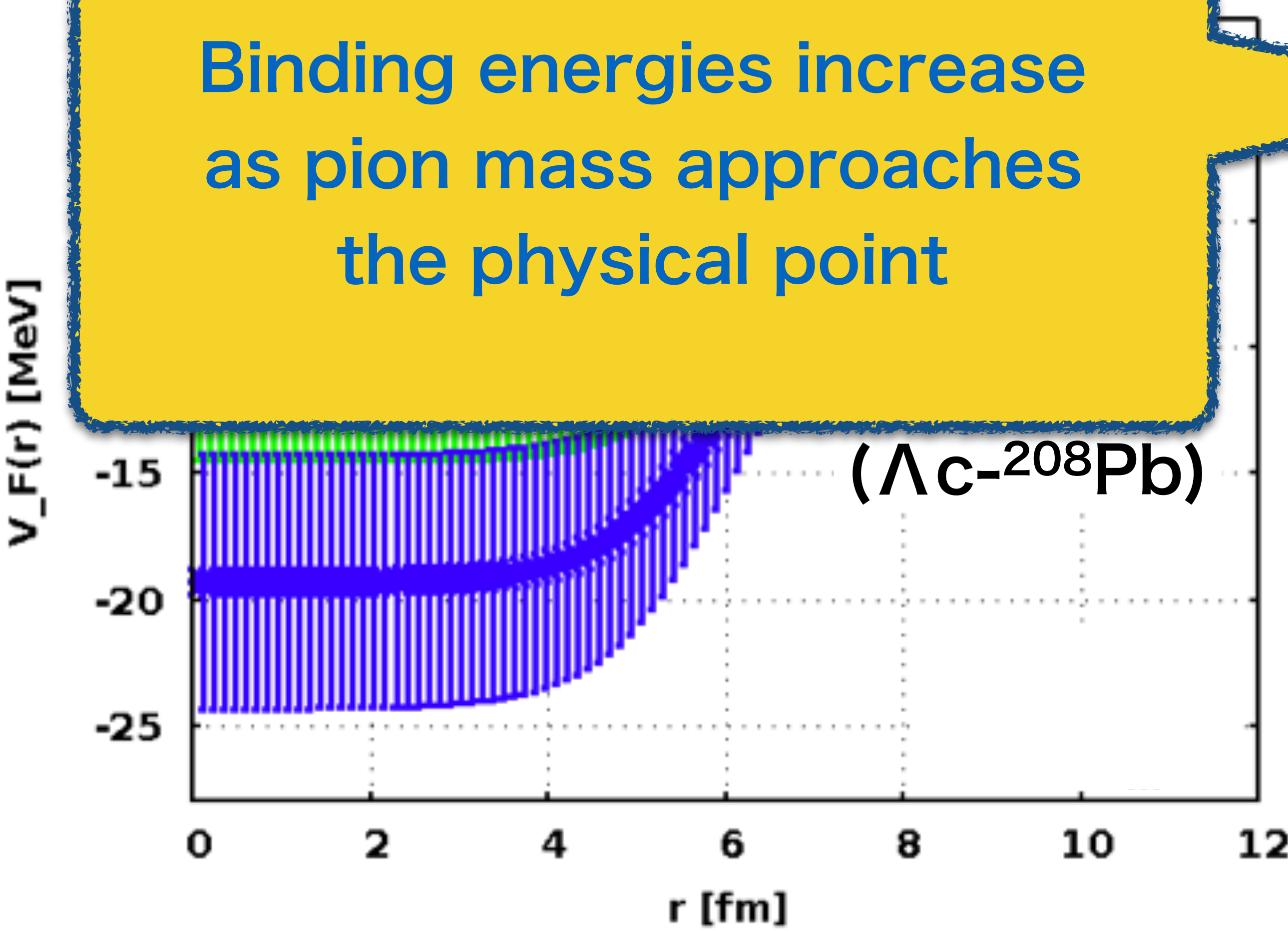


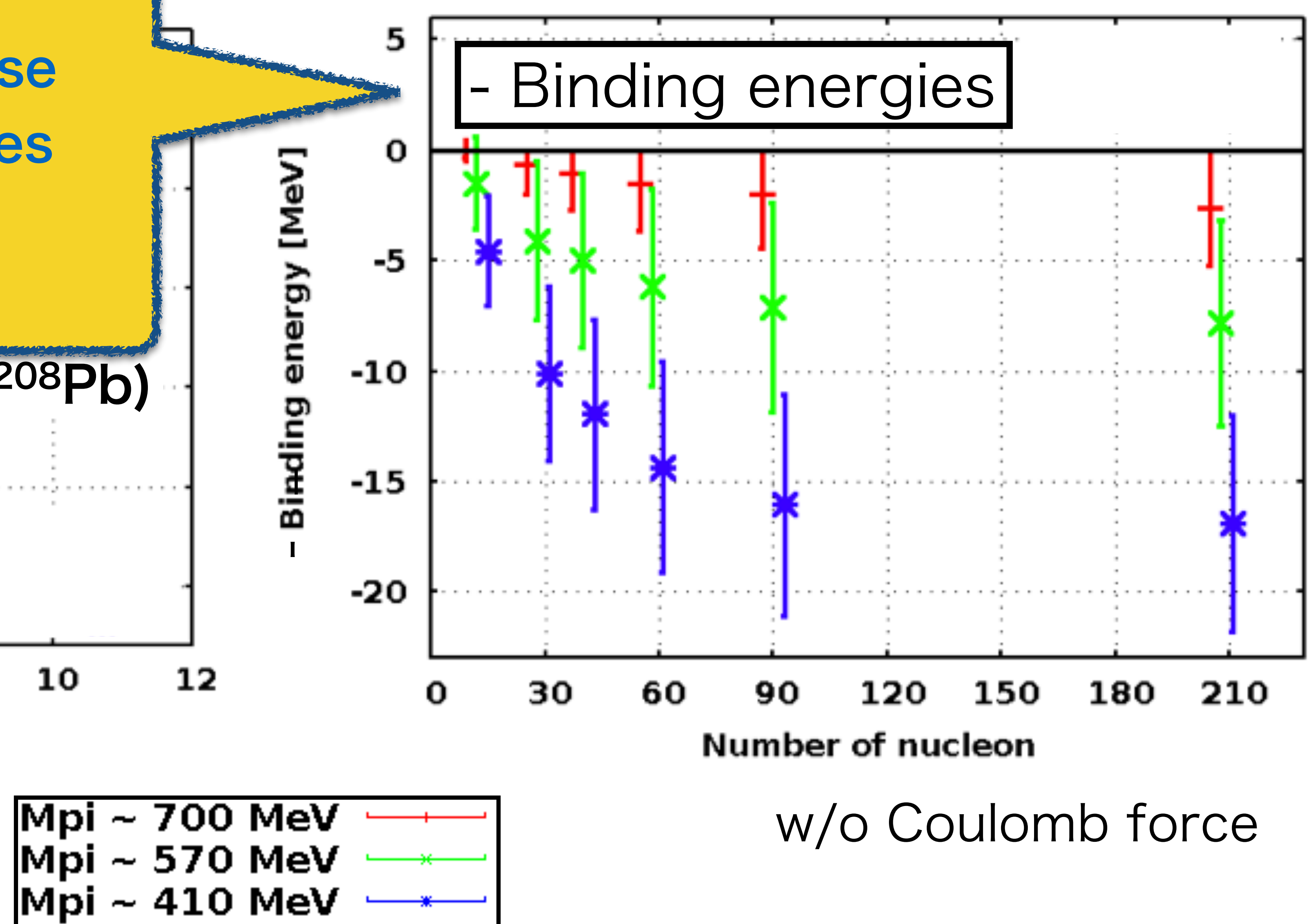
(Single-) folding potential

$$V_F(\boldsymbol{r}) = \int d^3r'\rho_A(\boldsymbol{r}')V_{\Lambda_c N}(\boldsymbol{r} - \boldsymbol{r}')$$

HAL QCD potential
(spin-indep. force)

Binding energies increase
as pion mass approaches
the physical point





w/o Coulomb force

Conclusions

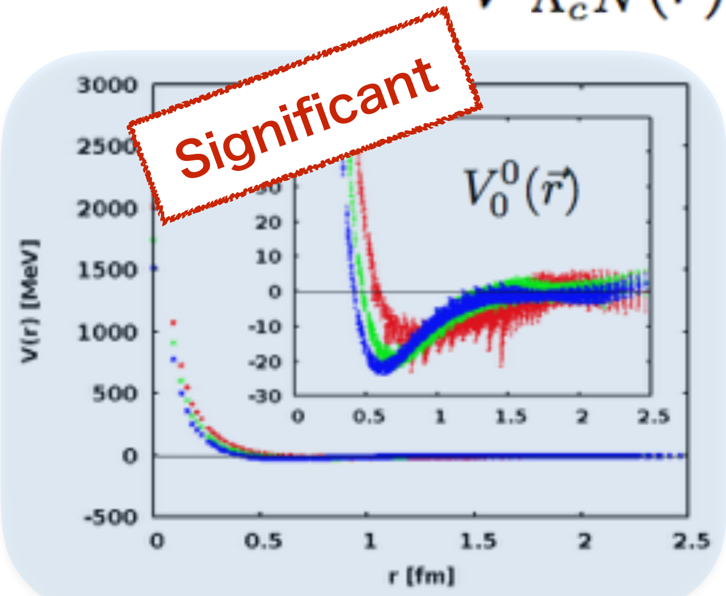
- We investigate ΛcN interactions by the HAL QCD method

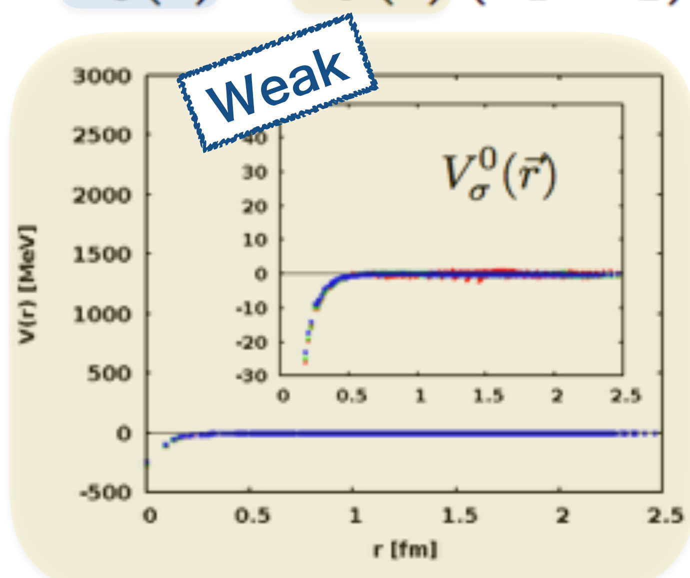
Our results show that ΛcN interactions are **attractive**

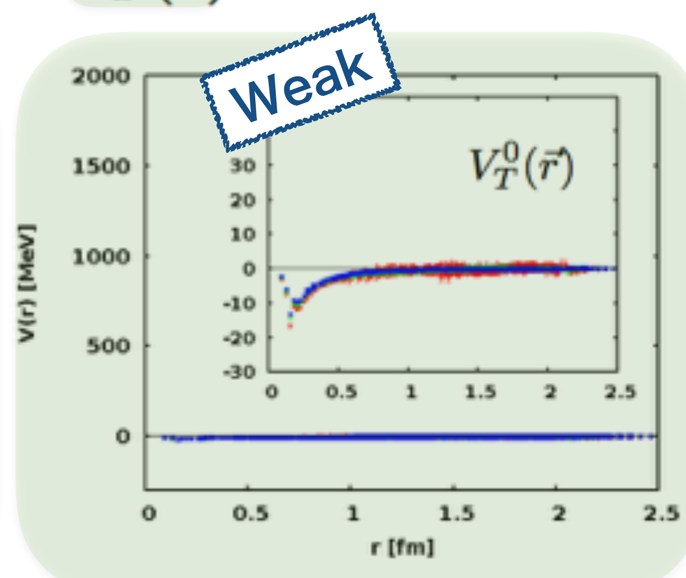
The feature of ΛcN potentials is **spin-independent**

→ The spin-spin force and the tensor force are almost negligible

$$V_{\Lambda_c N}(\vec{r}) = V_0(\vec{r}) + V_\sigma(\vec{r})\,(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + V_T(\vec{r}) + \cdots$$







The analysis of the folding potentials with LQCD potentials shows that Λc could be bound with heavy nuclei.

Prospects:

— We will investigate Λc - light nuclei by using few/many-body calculation (GEM, AMD, ···)

— We will also investigate Σc-nuclei

— Physical point calculation is the next step