Λ_c-N interaction from lattice QCD

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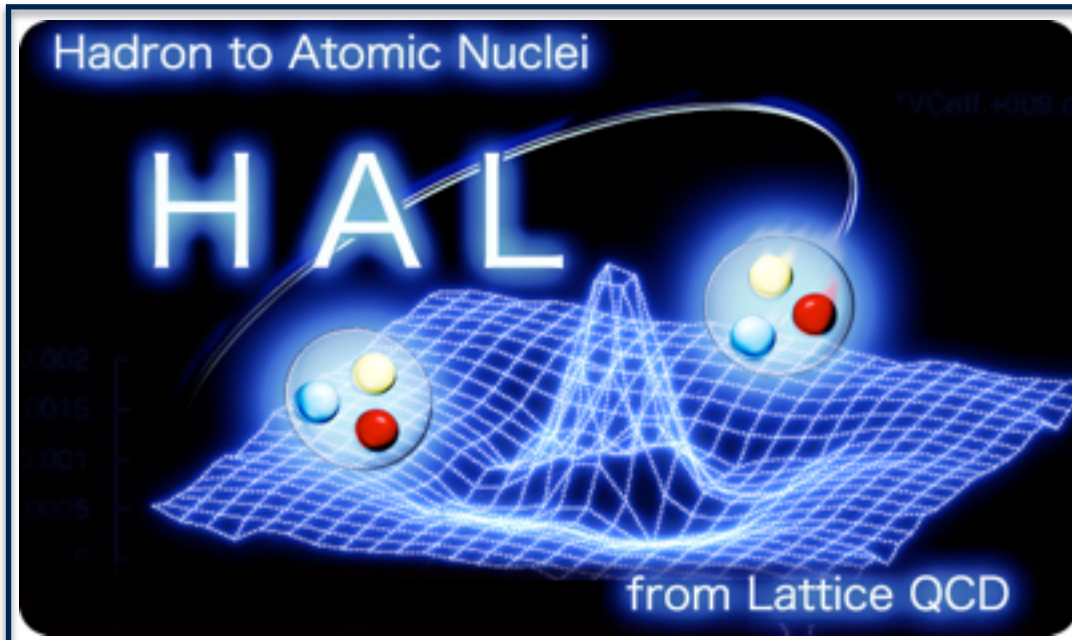
for **HAL QCD Collaboration**



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T. Inoue	(Nihon Univ.)
N. Ishii, K. Murano	(RCNP Osaka Univ.)
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F. Etminan	(Univ. Birjand)

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Motivation

Whether the 2-body bound state between Charmed-baryon and Nucleon exists?

- The formation of the Λc, Σc charmed-nuclei was predicted more than 30 years ago.

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

- However, it is inconclusive whether the 2-body bound states in the Λc-N channel exist or not.

Motivation

Whether the 2-body bound state between Charmed-baryon and Nucleon exists?

- The possibility of Λc-N bound state was claimed by one-boson exchange potential model.

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

⇨ We investigate the Λc-N bound state by the Lattice QCD calculation.

HAL QCD method

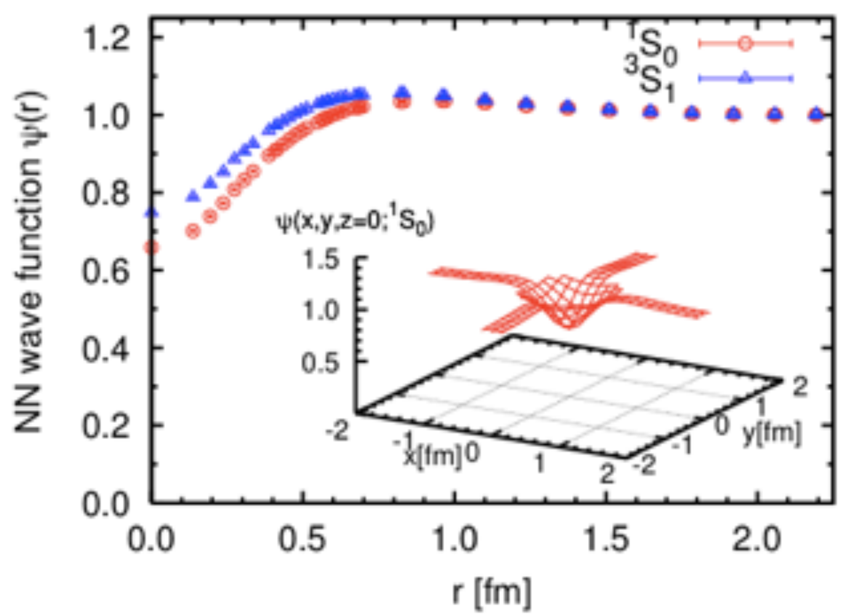
Outline

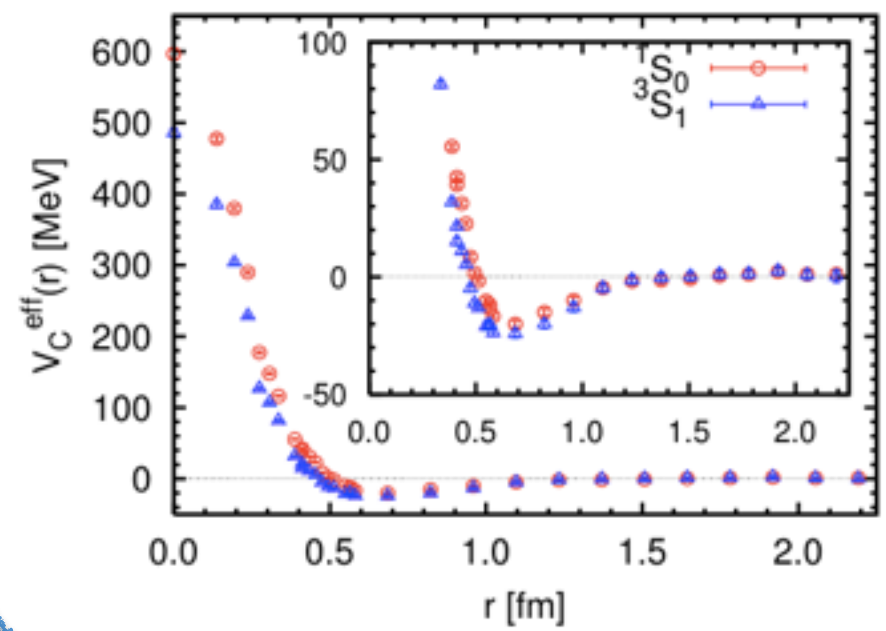
- Motivation
- HAL QCD method
- Lattice simulation setup
- Numerical results
- Summary & Conclusion
- Future work

HAL QCD method

S. Aoki, T. Hatsuda, N. Ishii,
Prog. Theor. Phys., 123 (2010).

Define the **potential** from **NBS wave function**





Schrödinger-type equation

HAL QCD method

S. Aoki, T. Hatsuda, N. Ishii, Prog. Theor. Phys., 123 (2010).

Define the **potential** from **NBS wave function**

In this work

Calculate the NBS wave function of **Λc-N** state on the lattice

→ Extract the **potential** of **Λc-N** state

Schrödinger-type equation

Lattice simulation setup

- Nf=2+1 full QCD configurations generated by the 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)

	Kud	Ks	M_π	#. confs
Ensemble 1	0.13700	0.13640	701(1) MeV	399
Ensemble 2	0.13740	0.13640	568(1) MeV	400

For charm quark, we choose Ks = 0.12240. (partial quench)

- $M_{J/\psi}$: Ens1 = 3163.7(7) MeV

Ens2 = 3143.7(8) MeV [PDG: 3097 MeV]

Lattice simulation setup

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

PACS-CS Collaboration: S. Aoki, et al., Phys. Rev. D79 (2009) 034503

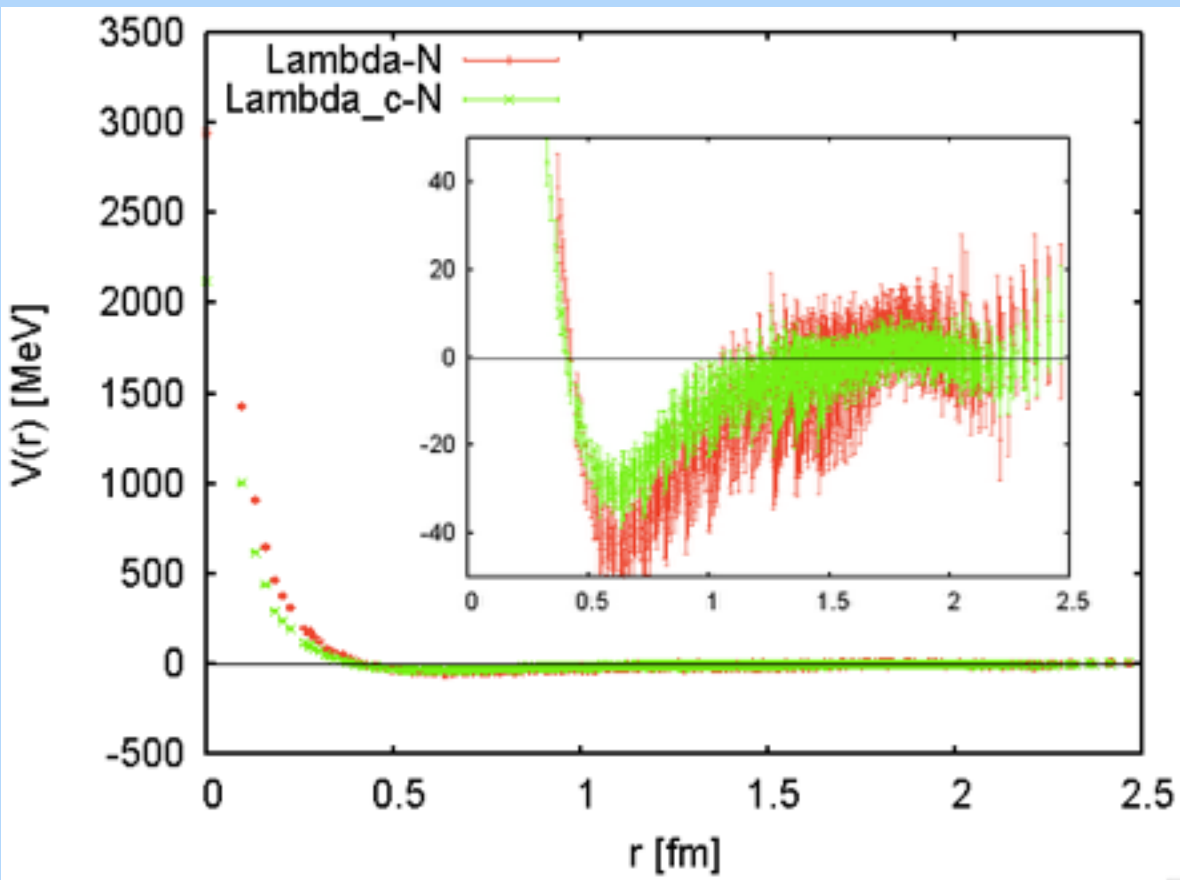
	Kud	Ks	M_π	#. confs
Ensemble 1	0.13700	0.13640	701(1) MeV	399
Ensemble 2	0.13740	0.13640	568(1) MeV	400

	Ensemble 1	Ensemble 2	PDG
ϕ	1211(3) MeV	1166(12) MeV	1019 MeV
J/ψ	3163.7(7) MeV	3143.7(8)MeV	3097 MeV
proton	1571(10) MeV	1392(7) MeV	938 MeV
Lambda	1637(10) MeV	1489(8) MeV	1115 MeV
Lambda_c	2712(8) MeV	2573(7) MeV	2286 MeV

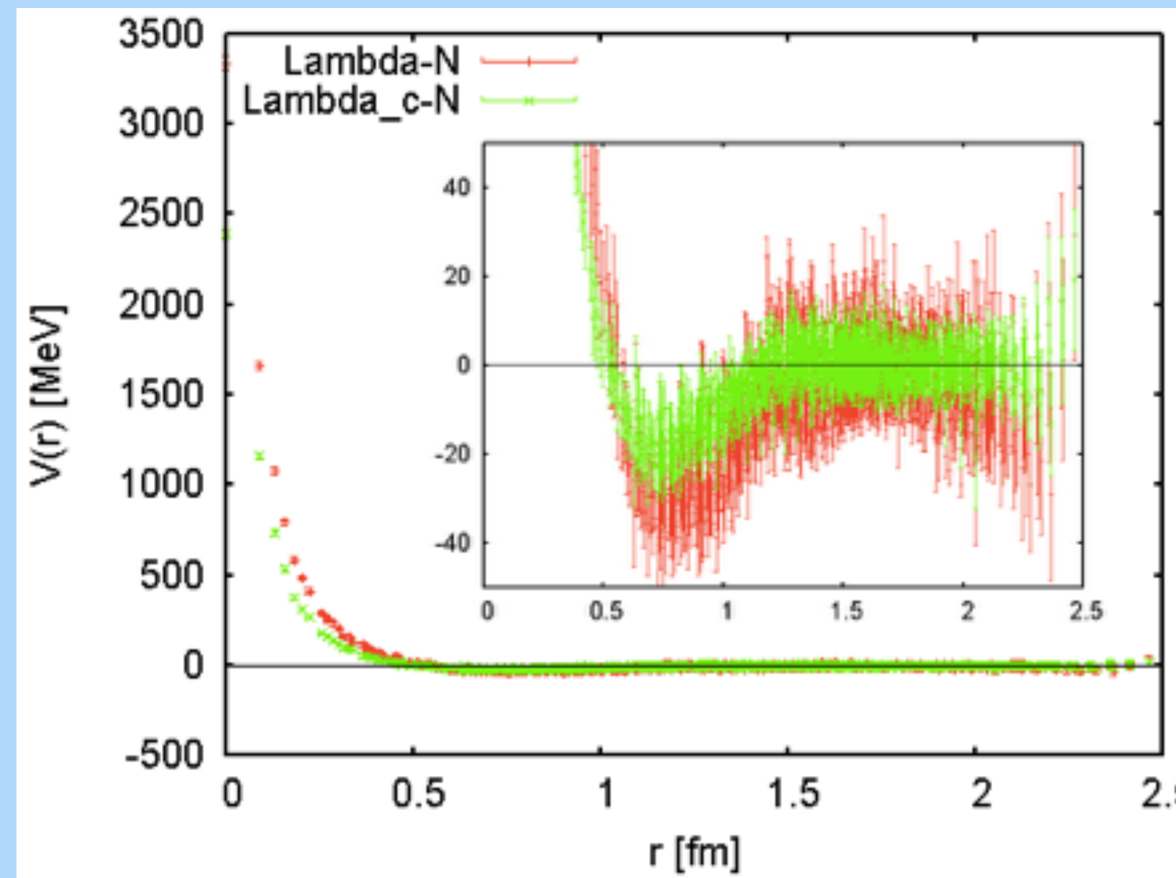
Numerical results

1S0 state

M_π=700MeV



M_π=570MeV

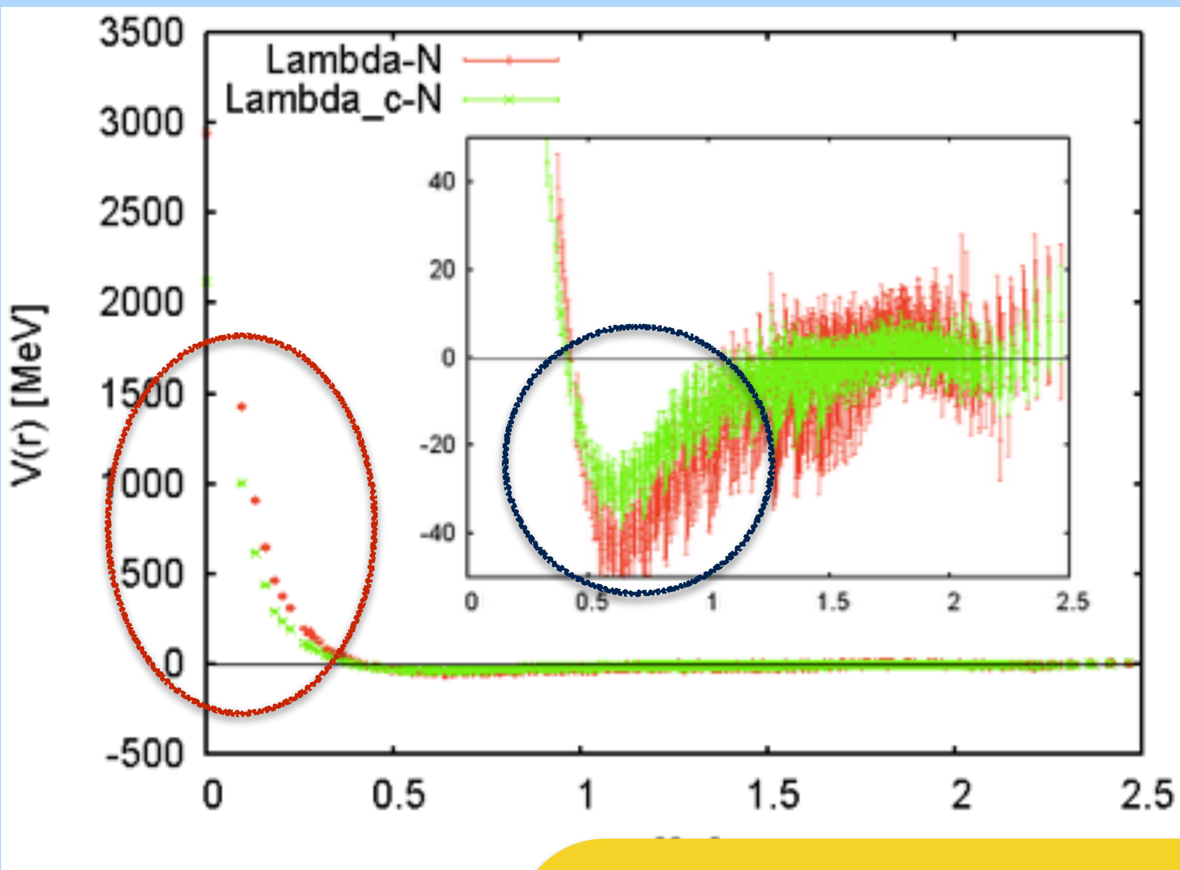


Each figure shows potential of Λ-N channel and Λc-N channel simultaniously, to compare the qualitative behavior

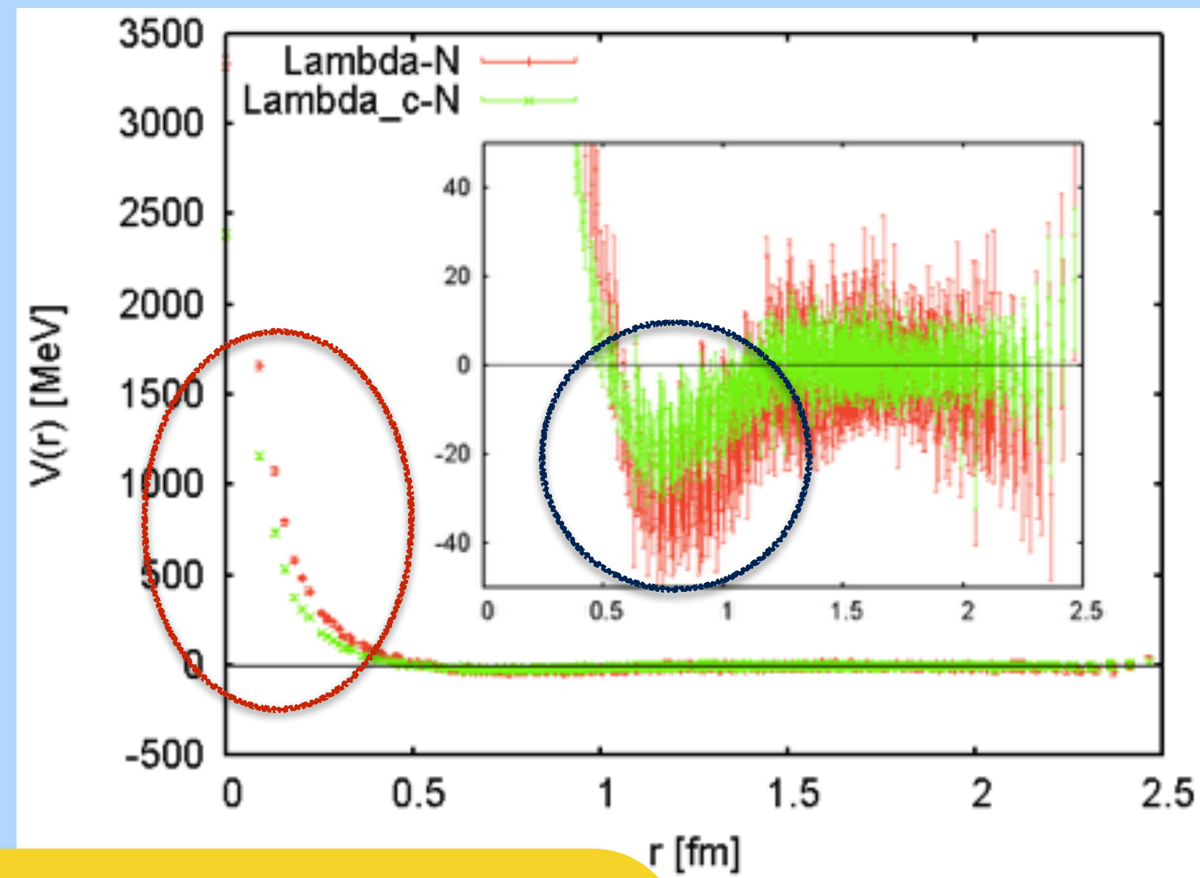
Numerical results

1S0 state

M_π=700MeV



M_π=570MeV



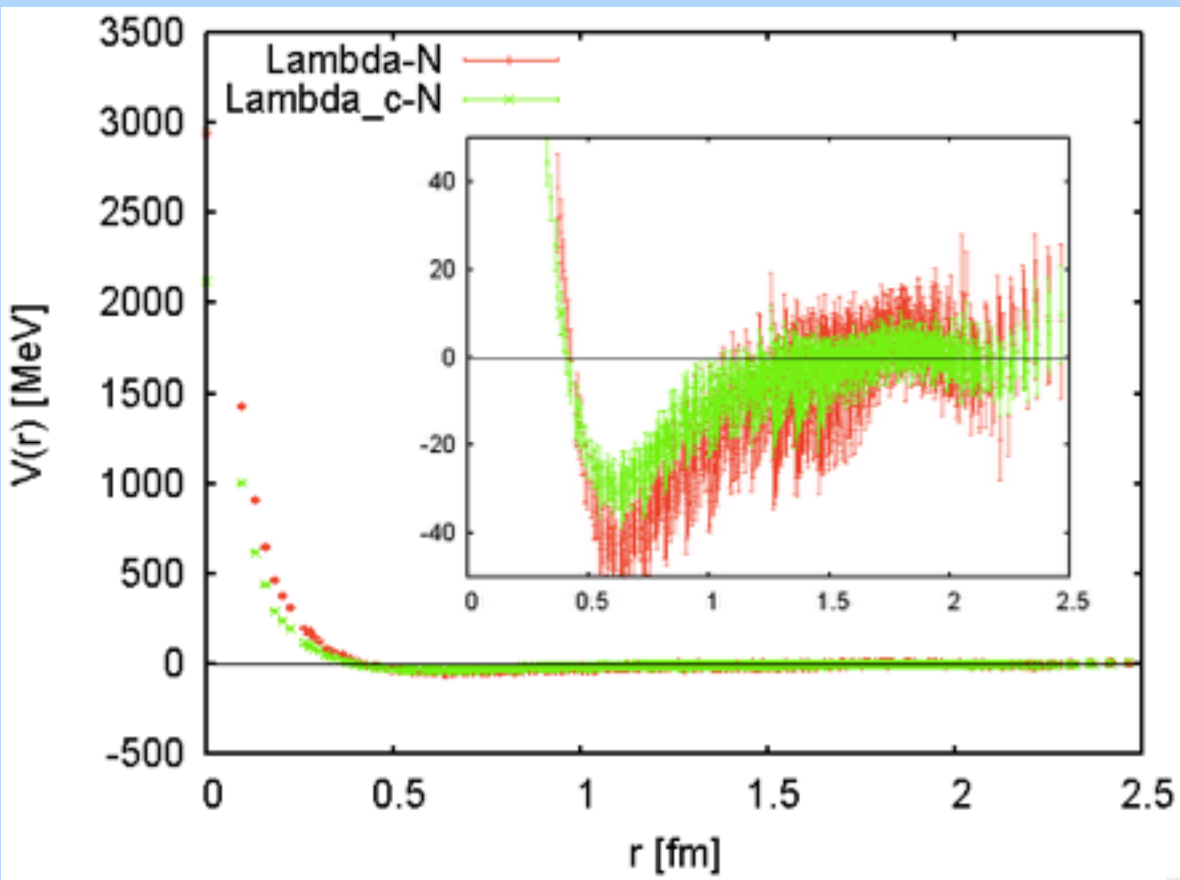
Repulsive core and **attractive pocket** of Λc-N channel potential are **weaker** than Λ-N channel potential !

Each figure show ... el simultaniously,
to compare the q...

Numerical results

1S0 state

M_π=700MeV



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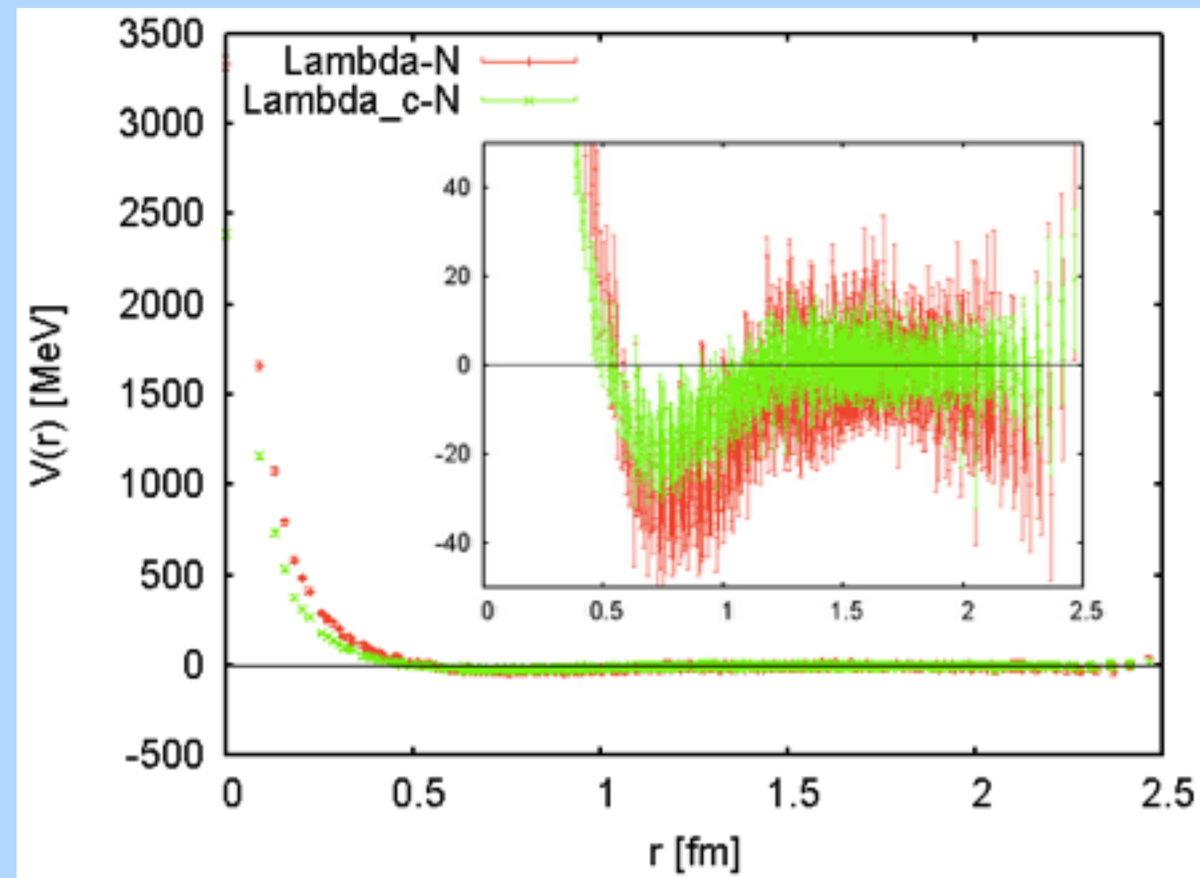
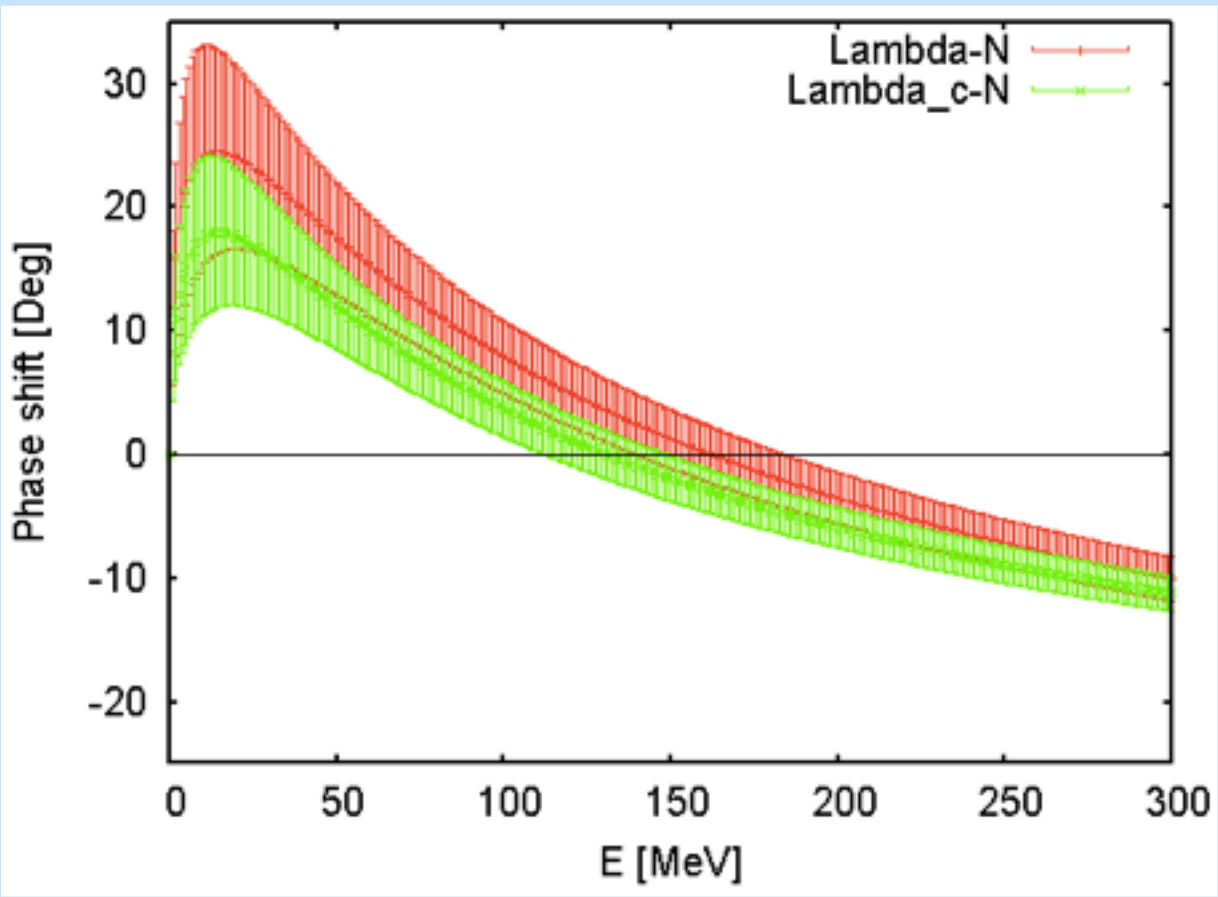


We fitted these potentials to extrapolate to infinite volume

Fitting function: $V(r) = A_1 \exp\left[-\left(\frac{r}{B_1}\right)^2\right] + A_2 \exp\left[-\left(\frac{r}{B_2}\right)^2\right] + A_3 \exp\left[-\left(\frac{r}{B_3}\right)^2\right]$

Phase shift

M_π=700MeV

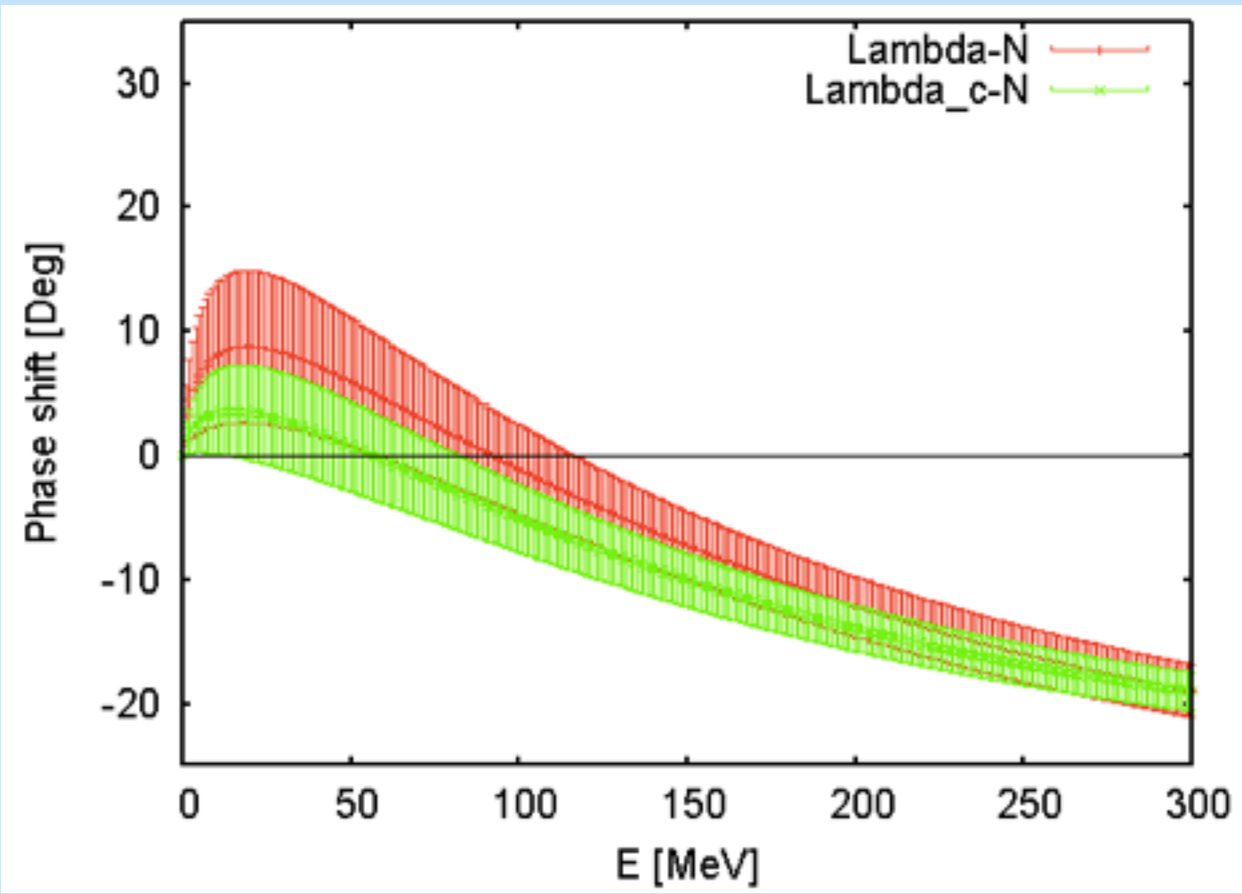


Scattering length:

-1.18 fm (Λ-N channel)

-0.68 fm (Λc-N channel)

M_π=570MeV



Scattering length:

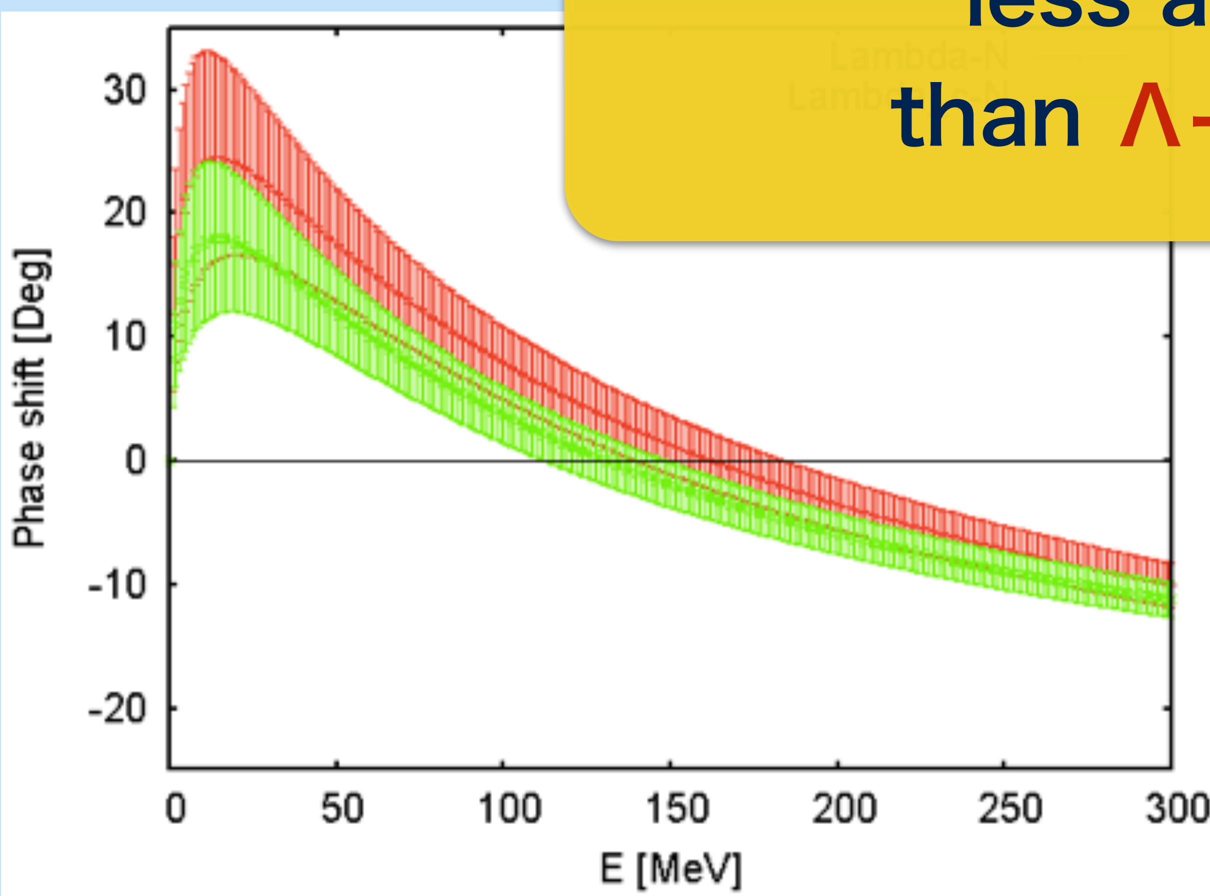
-0.41 fm (Λ-N channel)

-0.15 fm (Λc-N channel)

Phase shift

Λc-N channel is less attractive than Λ-N channel

M_π=700MeV

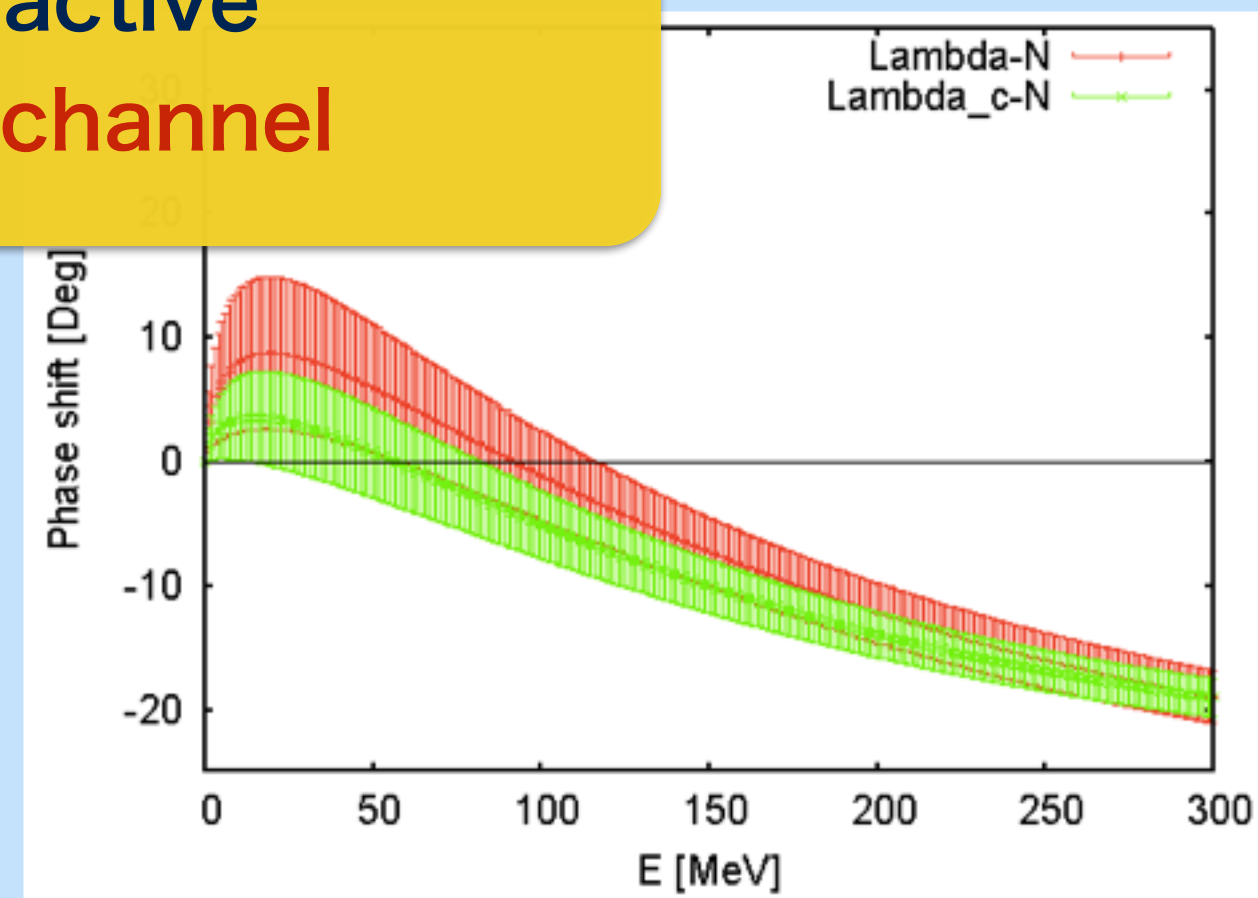


Scattering length:

-1.18 fm (Λ-N channel)

-0.68 fm (Λc-N channel)

M_π=570MeV



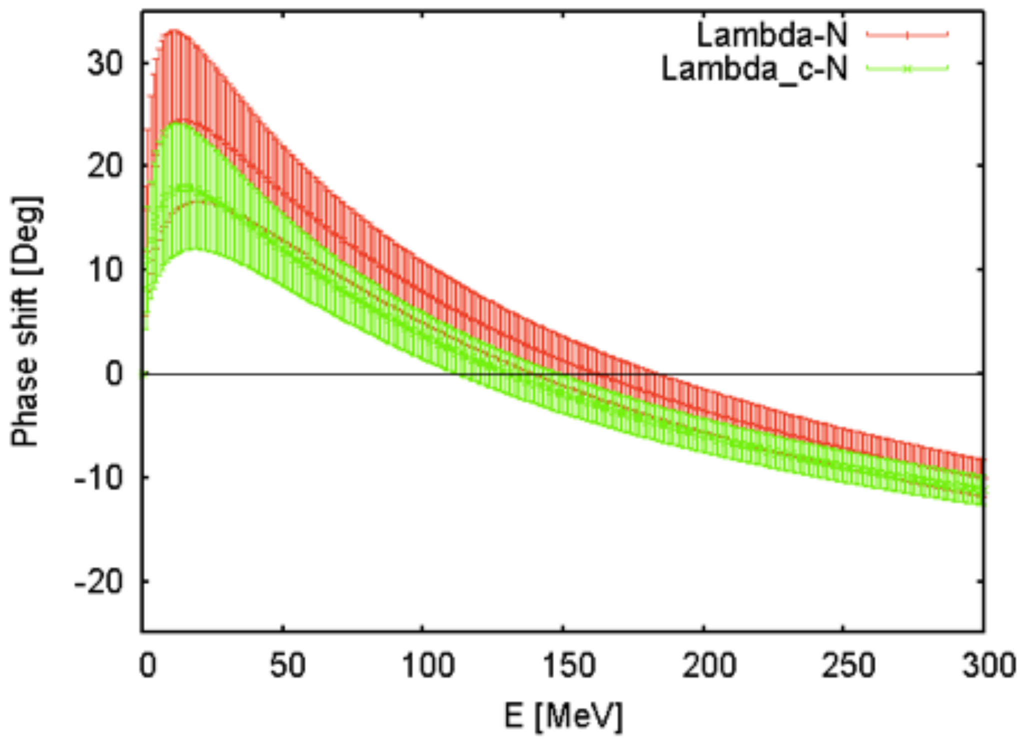
Scattering length:

-0.41 fm (Λ-N channel)

-0.15 fm (Λc-N channel)

According to the some experiments,
Λ-N 1S0 state doesn't form bound state

Our results suggest
Λc-N 1S0 state is
more difficult to bound
than Λ-N 1S0 state



It suggest Λc-N 1S0 state is also unbound

Summary & conclusion

・We investigate Λc-N interaction in 1S0 channel and quark mass dependence by the HAL QCD method.

・Numerical results of the potentials suggest that attraction in Λc-N channel is weak compared to Λ-N channel. Also, the bound Λc-N is unlikely.

・We will study Λc-N 3S1-3D1 to investigate the effect of tensor force.

Future work

- According to phenomenology,
  the $\Lambda_c N$-$\Sigma_c N$-$\Sigma_c^* N$ channel coupling effects
  are important for the Λ_c-N bound state
  due to the nearby Σ_c-N and Σ_c^*-N thresholds.

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

⇒ We will include channel coupling effects in our calculation.

Future work

Extraction of potential above inelastic threshold

Coupled channel Schrodinger equation

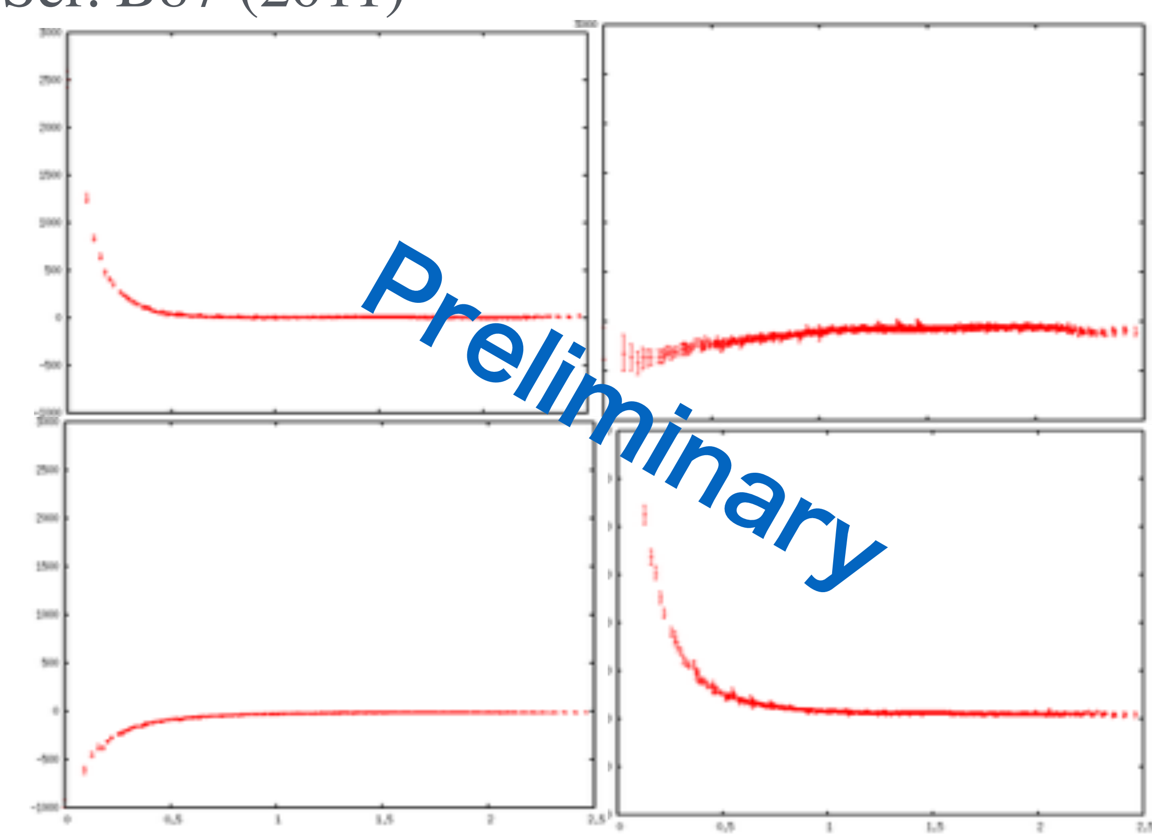
$$[E_p^X - H_0]\,\psi_X^{(W)}(\vec{x}) = \sum_Y \int d^3y\, U_{X,Y}(\vec{x},\vec{y})\,\psi_Y^{(W)}(\vec{y})$$

X, Y represents each channel

To solve the Schrödinger equation, coupled channel potential is extracted.

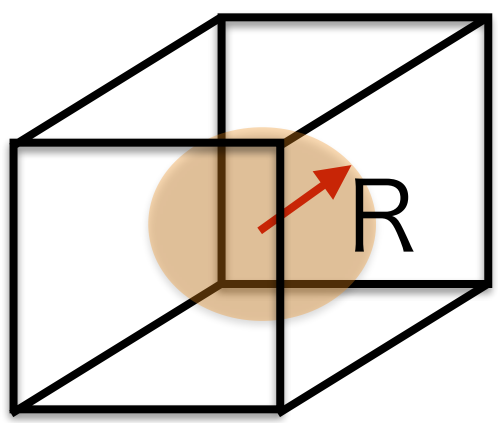
S. Aoki et al [HAL QCD Coll.], Proc. Jpn. Acad., Ser. B87 (2011)

$$\begin{pmatrix} V\_(\Lambda cN\ \Lambda cN) & V\_(\Lambda cN\ \Sigma cN) \\ V\_(\Sigma cN\ \Lambda cN) & V\_(\Sigma cN\ \Sigma cN) \end{pmatrix} =$$



Backup

HAL QCD method



Nambu-Bethe-Salpeter (NBS) wave function

$$\psi_{\alpha\beta}^{(W)}(\vec{r})e^{-Wt} = \sum_{\vec{x}} \langle 0|T\{B_\alpha^{(1)}(\vec{r}+\vec{x},t)B_\beta^{(2)}(\vec{x},t)\}|B^{(1)}B^{(2)},W,s_1s_2\rangle$$

$$(k^2+\vec{\nabla}^2)\,\psi_{\alpha\beta}^{(W)}(\vec{r}) = 0 \quad (\,|r| > \mathrm{R}\,)$$

$$\psi_{\alpha\beta}^{(W)}(\vec{r}) \propto \frac{\sin\left(kr - \frac{L\pi}{2} + \delta_{LS}(k)\right)}{kr}$$

same behavior with **QM wave function** at large r.

Hadron 4pt function on the Lattice

$$G_{\alpha\beta}(\vec{r},t-t_0) = \sum_{\vec{x}} \langle 0|B_\alpha^{(1)}(\vec{r}+\vec{x},t)B_\beta^{(2)}(\vec{x},t)\overline{\mathcal{J}^{(1,2)}}(t_0)|0\rangle$$
$$= \sum_{ns_1s_2} A_{ns_1s_2}\psi_{\alpha\beta}^{(W_n)}(\vec{r})e^{-W_n(t-t_0)} + \cdots$$

Extract NBS wave function from **Hadron 4pt function.**

Using NBS wave function, define
Energy-independent non-local "potential"

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

S. Aoki, T. Hatsuda, N. Ishii,
Prog. Theor. Phys., 123 (2010).

HAL QCD method

Using NBS wave function, define

Energy-independent non-local "potential"

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

Velocity expansion

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

$$V(\vec{r},\vec{v}) = V_0(r) + V_\sigma(r)\vec{\sigma_1}\cdot\vec{\sigma_2} + V_T(r)S_{12} + V_{LS}(r)\vec{L}\cdot\vec{S} + \mathcal{O}(v^2)$$

LO NLO

Time-dependent HAL QCD method

$$R_{\alpha\beta}(\vec{r},t) = \frac{G_{\alpha\beta}(\vec{r},t)}{\mathrm{e}^{-(m_{B(1)}+m_{B(2)})t}} \qquad (\ m_1 = m_2 \equiv m\ )$$

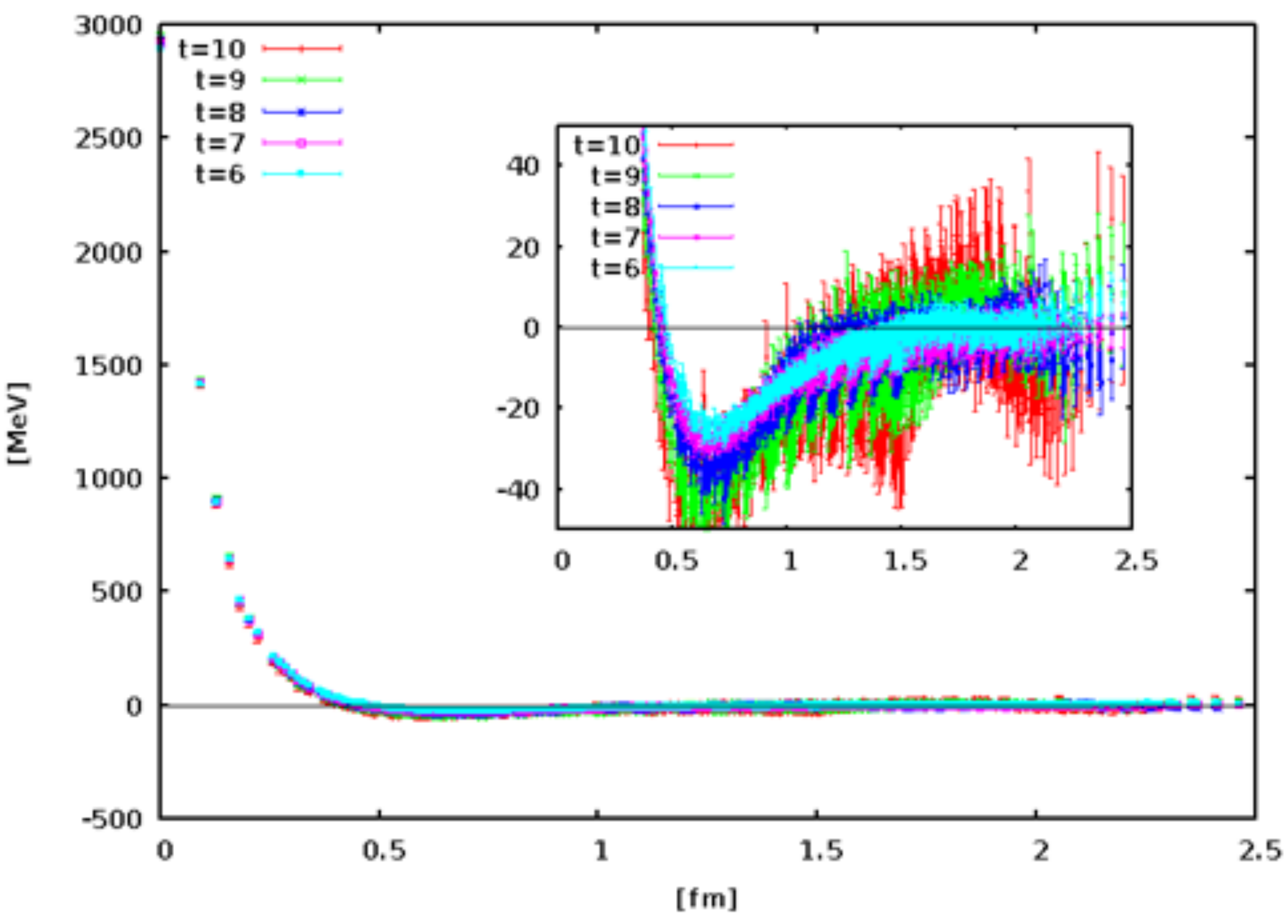
$$V(\vec{r},\vec{v}) = -\frac{H_0 R_{\alpha\beta}(\vec{r},t)}{R_{\alpha\beta}(\vec{r},t)} - \frac{\frac{\partial}{\partial t}R_{\alpha\beta}(\vec{r},t)}{R_{\alpha\beta}(\vec{r},t)} + \frac{1}{4m}\frac{\frac{\partial^2}{\partial t^2}R_{\alpha\beta}(\vec{r},t)}{R_{\alpha\beta}(\vec{r},t)}$$

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

Numerical results for Λc-N potential

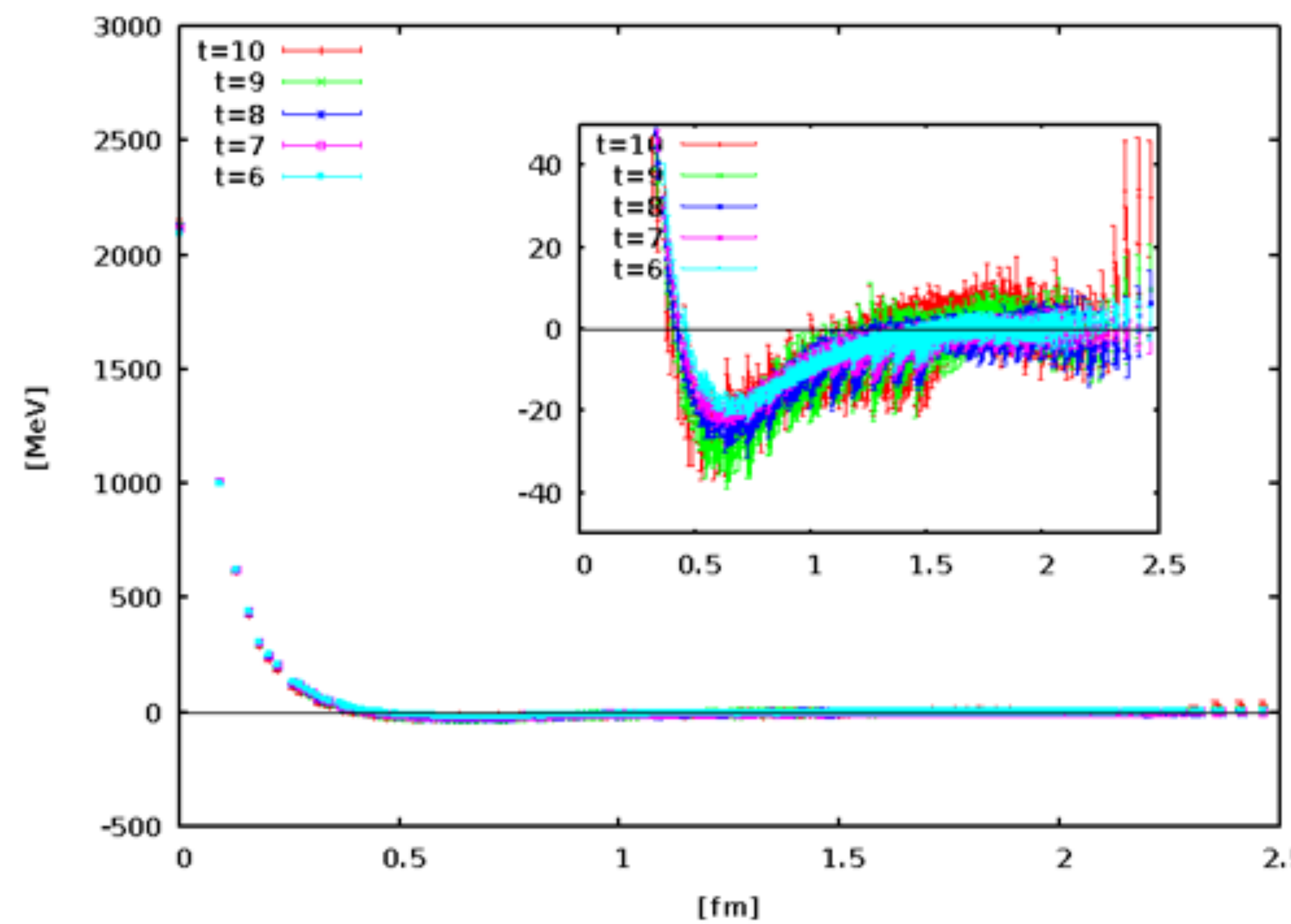
1S0 state

M_π=700MeV



Ks=0.13640

(Λ-N channel)



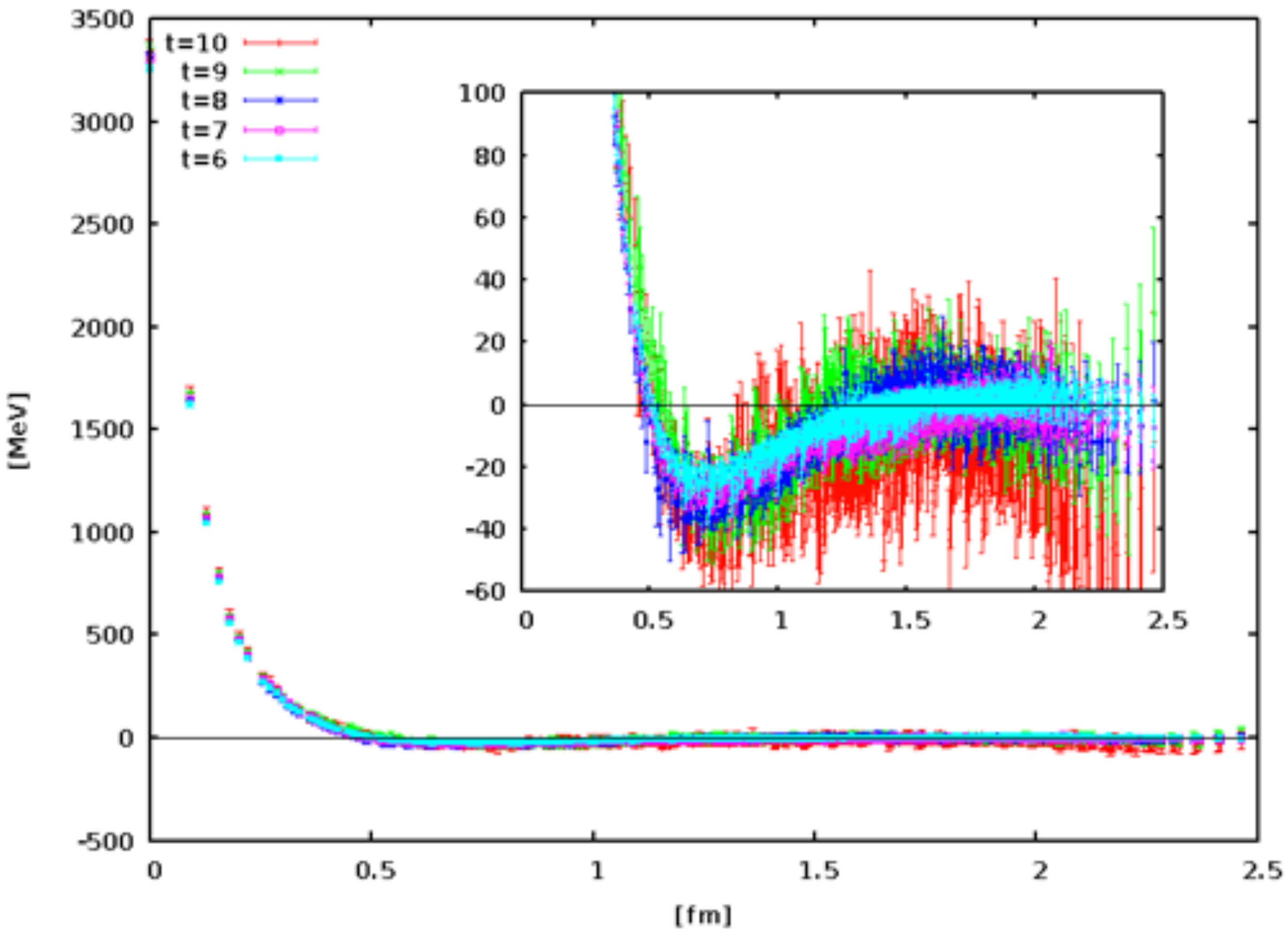
Ks=0.12240

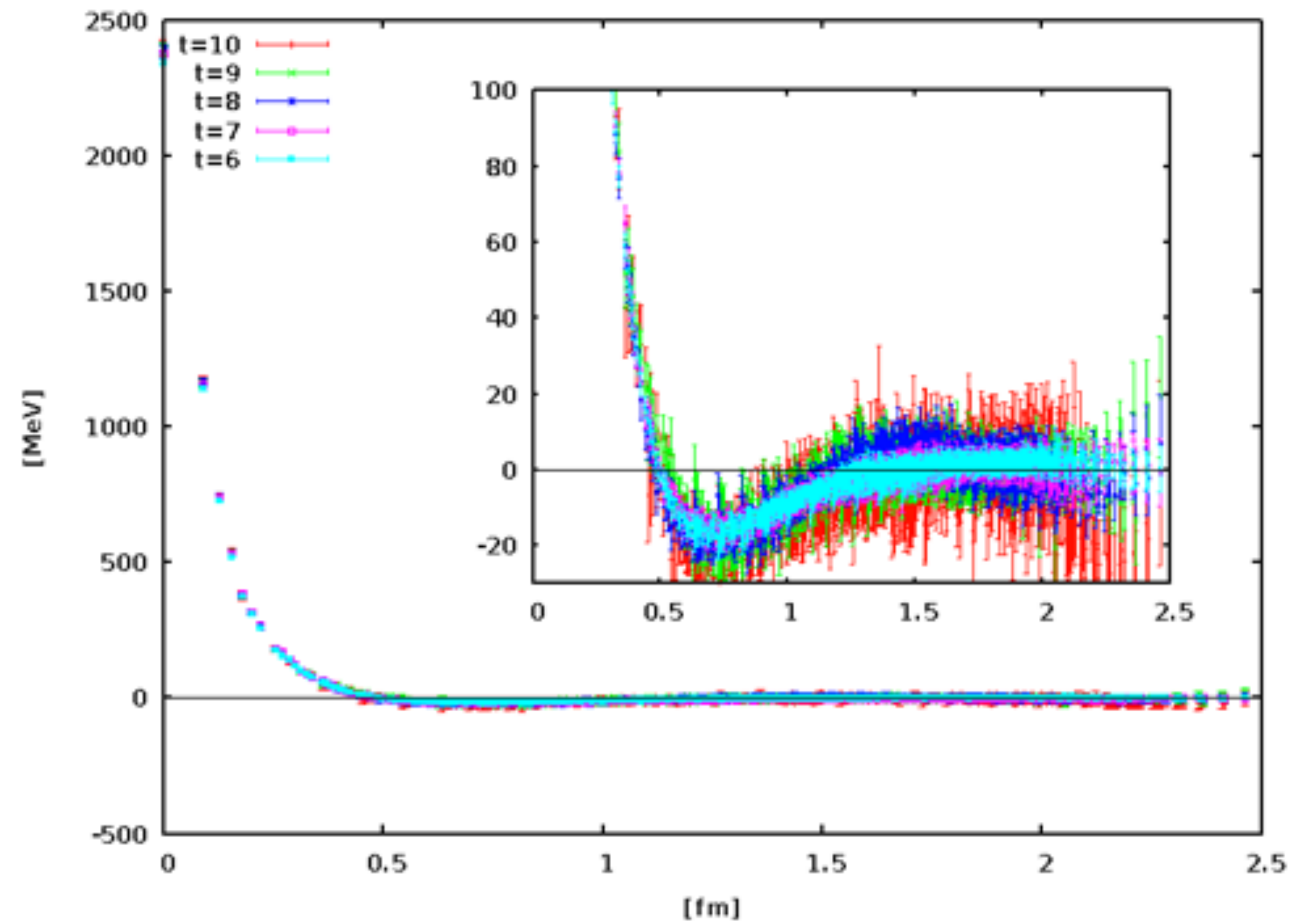
(Λc-N channel)

Numerical results for Λc-N potential

1S0 state

M_π=570MeV





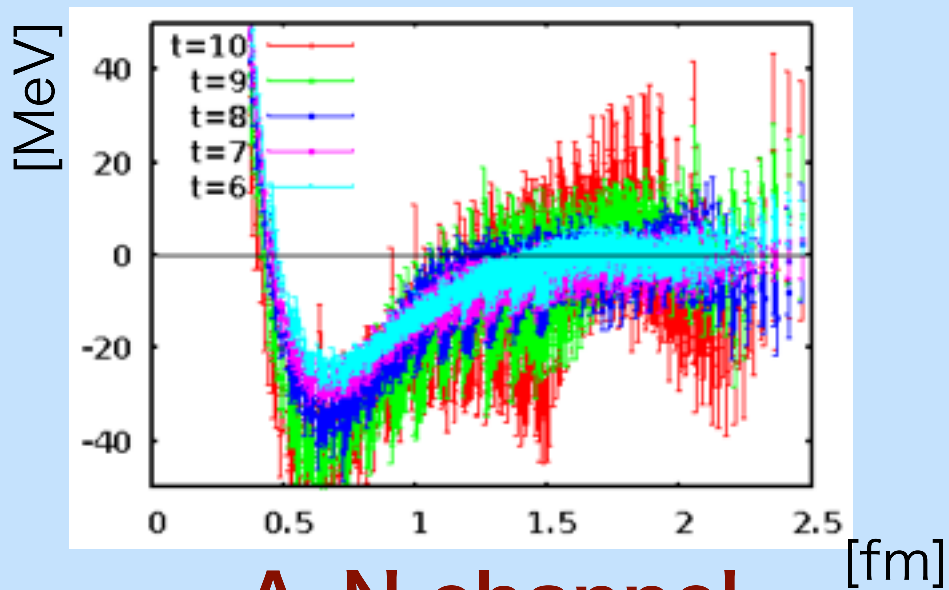
Ks=0.13640
(Λ-N channel)

Ks=0.12240
(Λc-N channel)

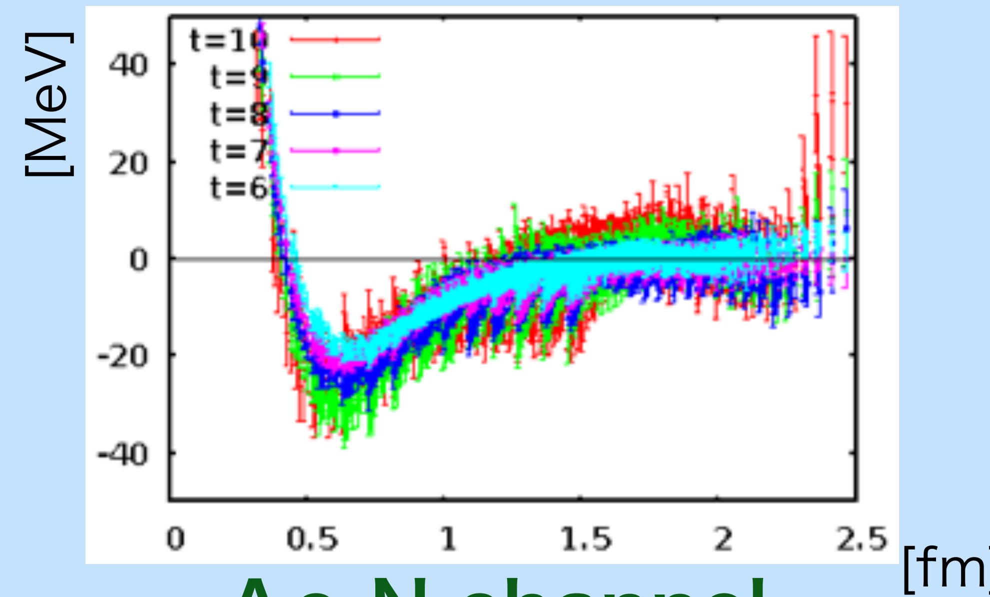
Numerical results

1S0 state

M_π=700MeV

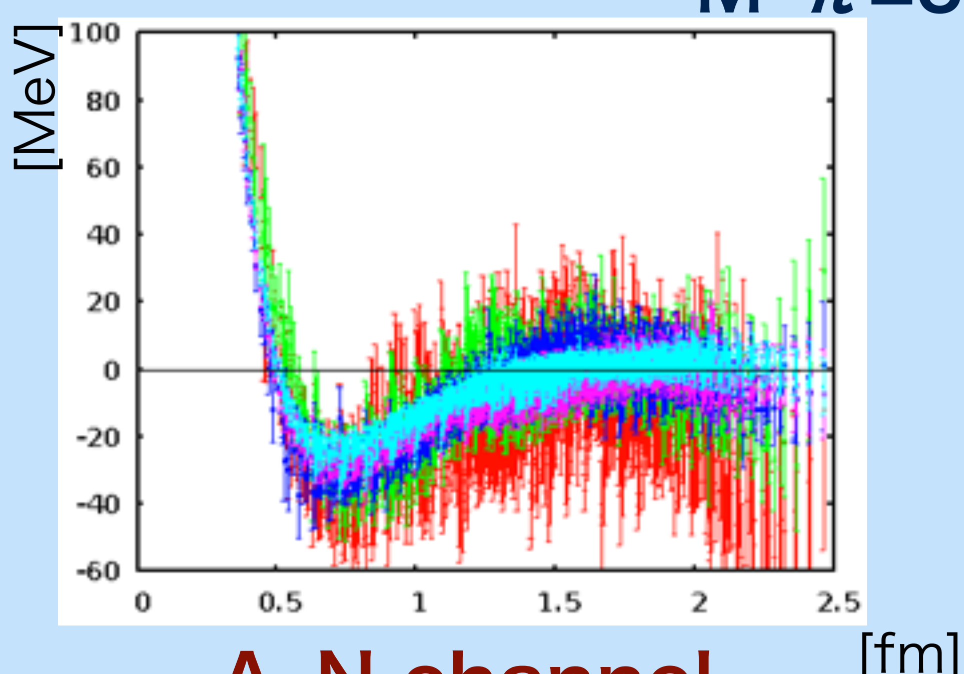


Λ-N channel

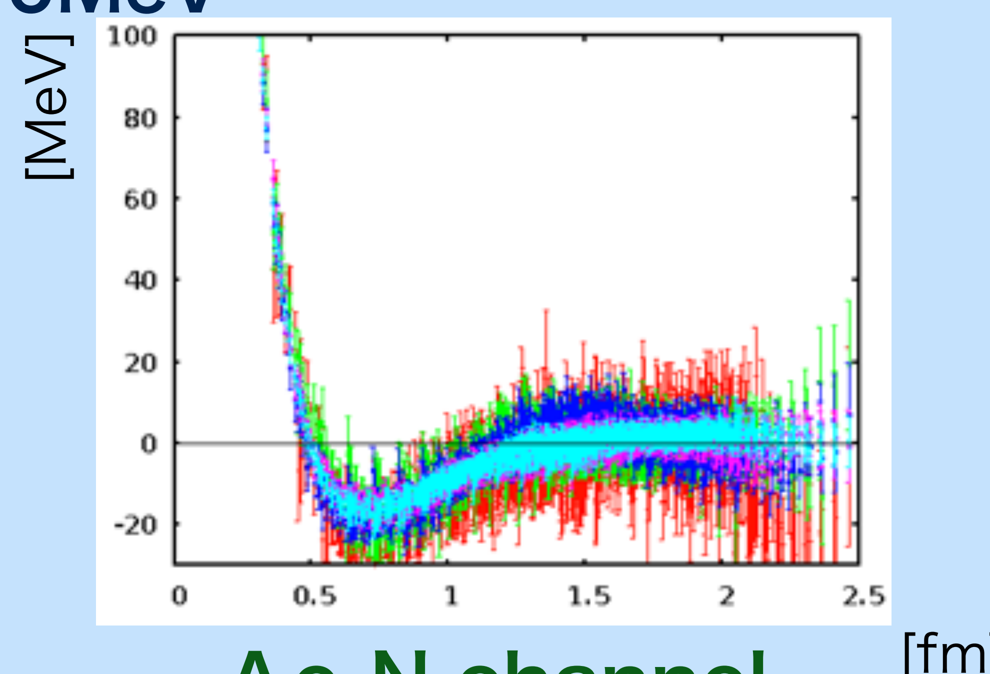


Λc-N channel

M_π=570MeV



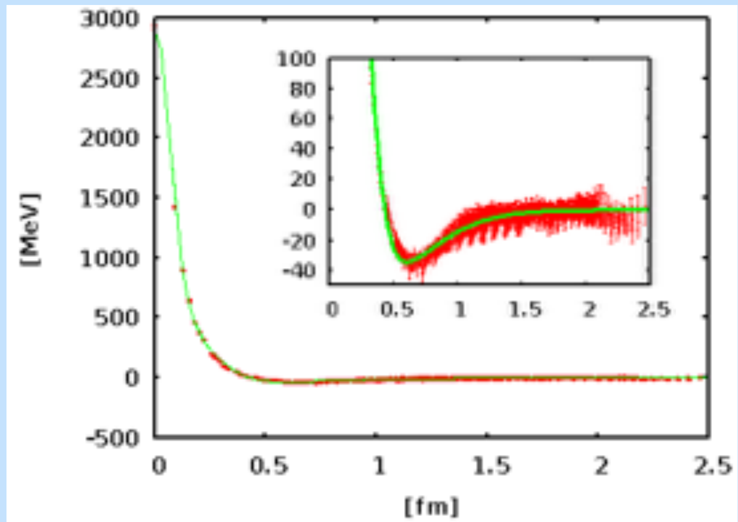
Λ-N channel



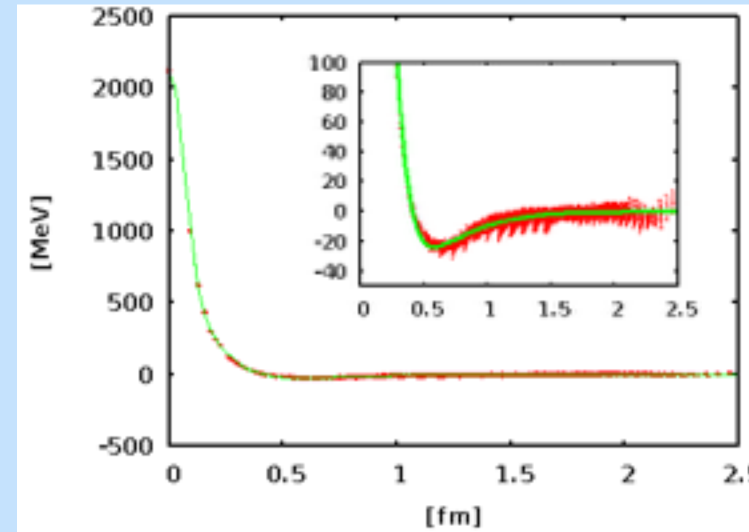
Λc-N channel

Fitting: $V(r) = A_1 \exp\left[-\left(\frac{r}{B_1}\right)^2\right] + A_2 \exp\left[-\left(\frac{r}{B_2}\right)^2\right] + A_3 \exp\left[-\left(\frac{r}{B_3}\right)^2\right]$

M_π=700MeV

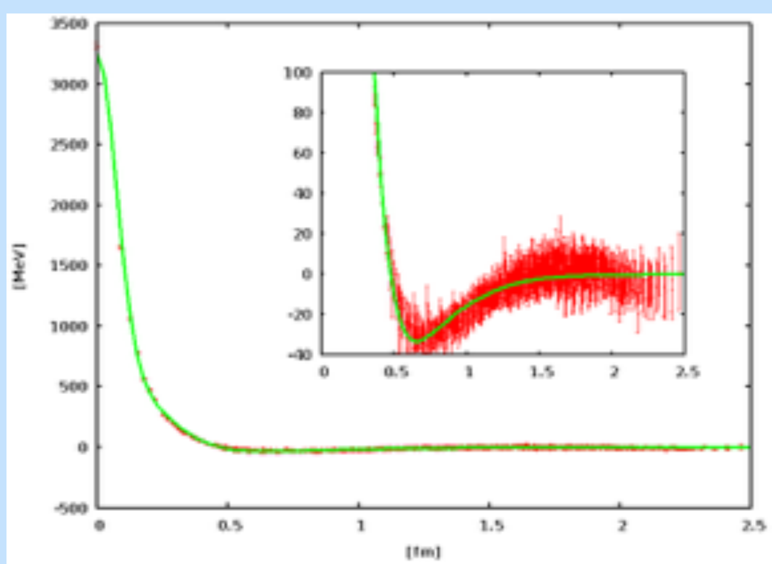


Λ-N channel

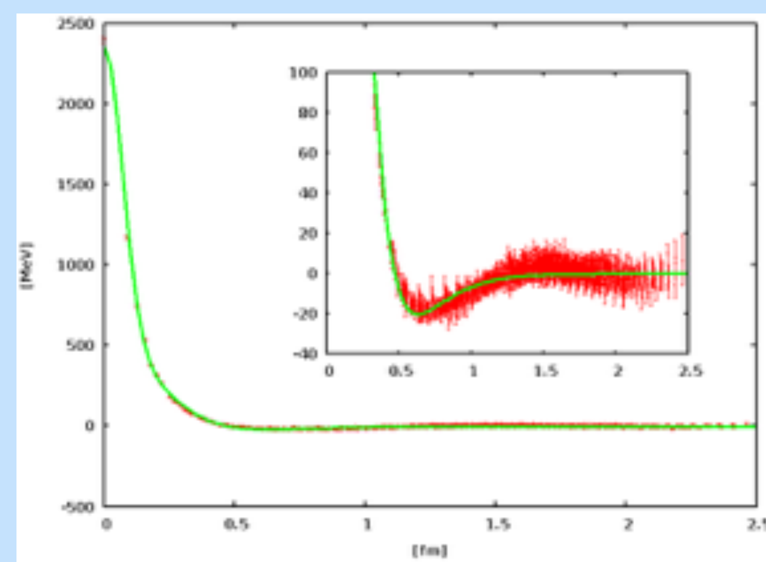


Λc-N channel

M_π=570MeV



Λ-N channel

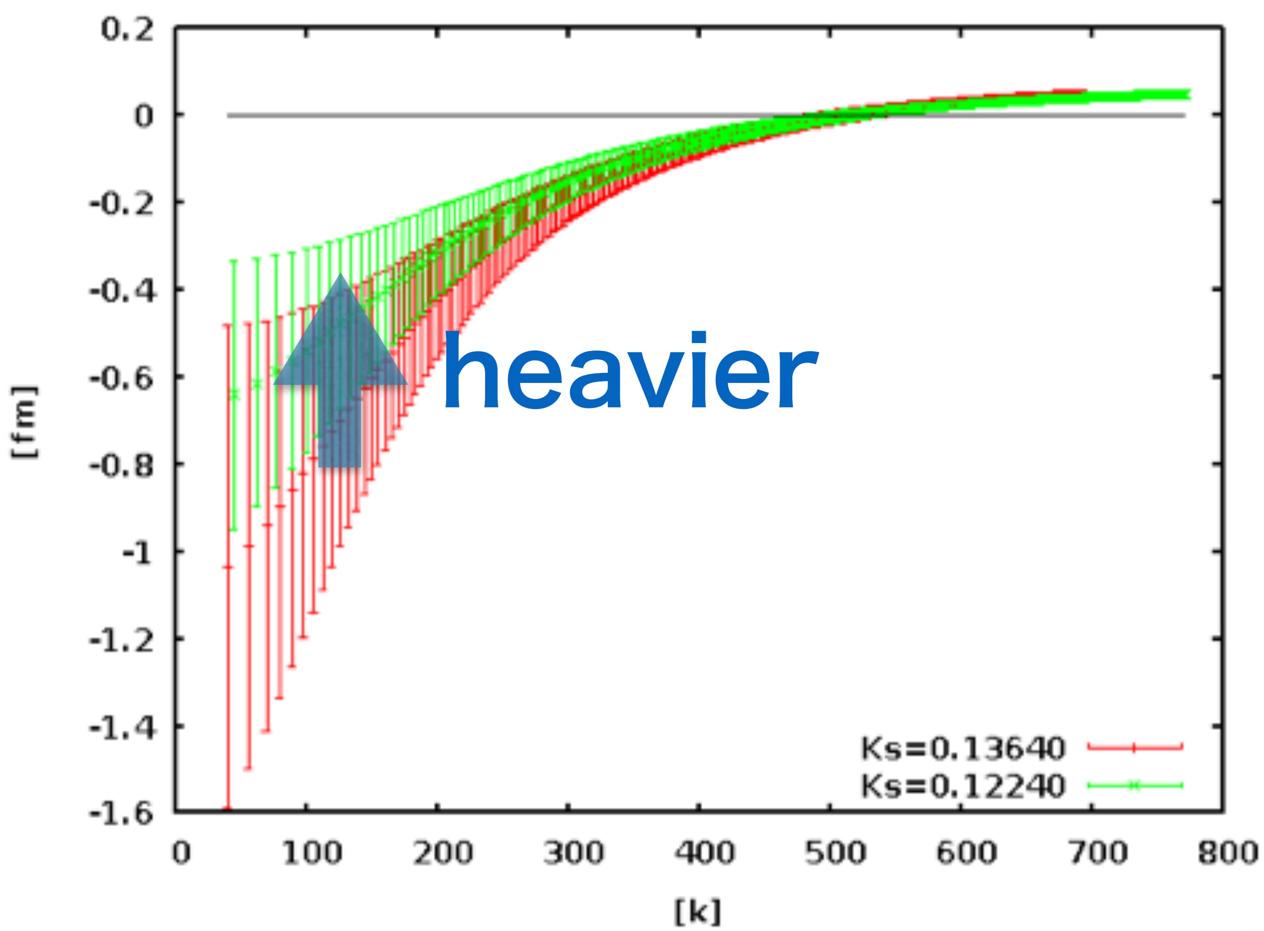


Λc-N channel

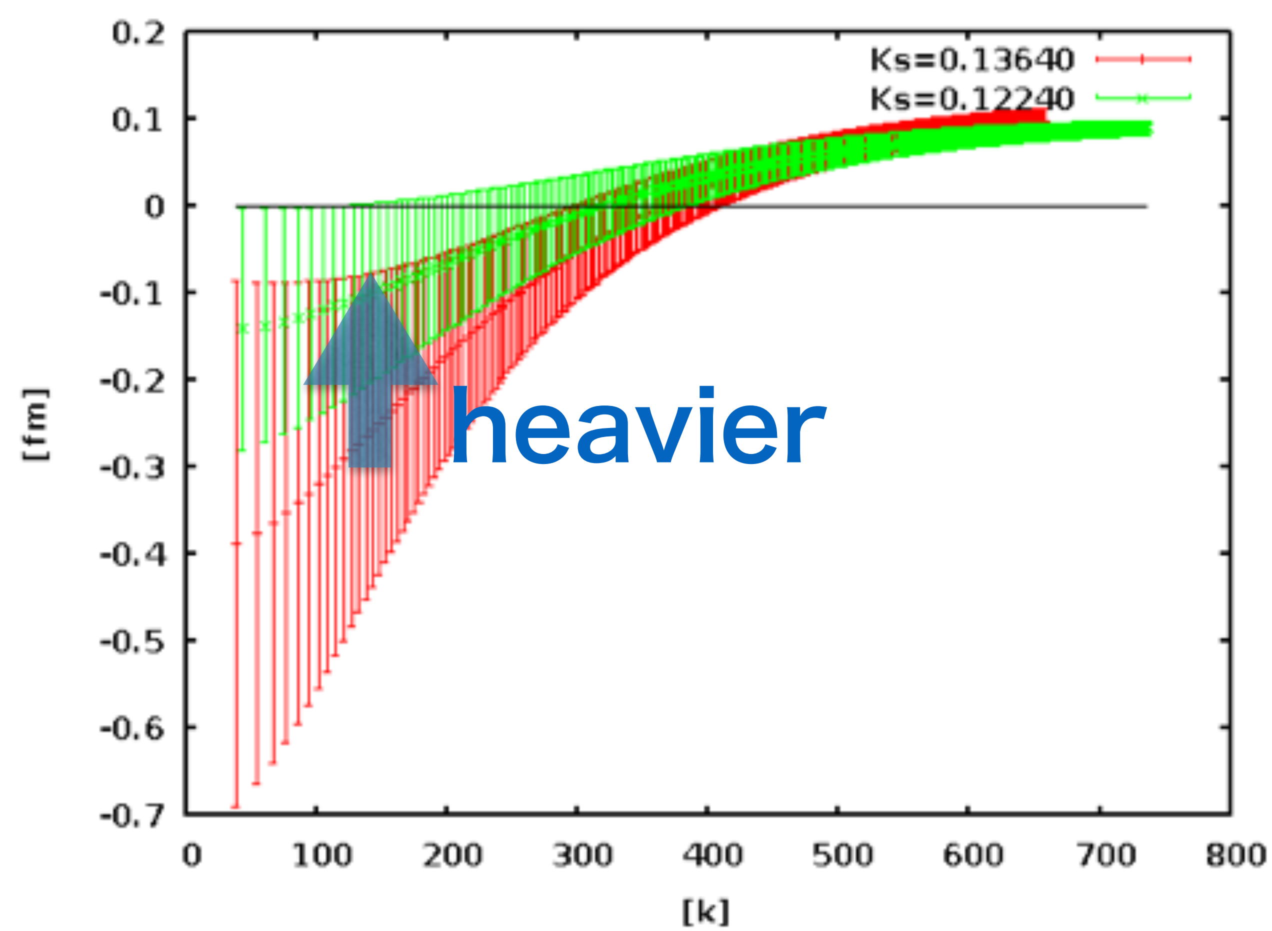
Numerical results for Scattering length: (t - t0) = 9

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

Ks=0.13640 (Λ-N channel)   Ks=0.12240 (Λc-N channel)



M_π=700MeV



M_π=570MeV