Application of the Misner's method to the coupled-channel NΛ-NΣ potential in lattice QCD

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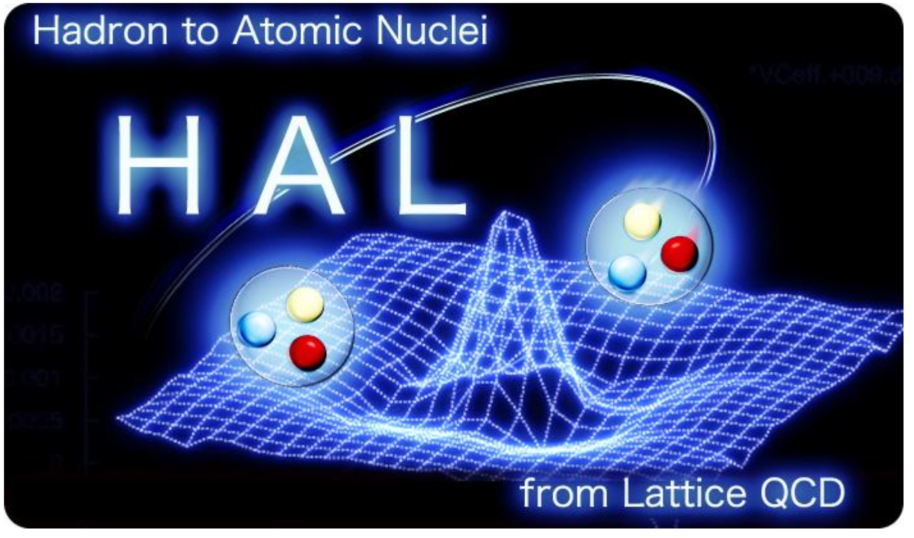
And HAL QCD collaboration.



Target in this study:

Baryon-Baryon interactions in S=-1 channel

= NΛ and NΣ (coupled) channel potentials

- Σ(1193) I=1
- Λ(1116) I=0
- N(939) I=1/2

- N-Λ & N-Σ I=1/2
  - 1S0 central potential
  - 3S1-3D1 central & tensor potential
- N-Σ I=3/2
  - 1S0 central potential
  - 3S1-3D1 central & tensor potential

Ishii, Aoki & Hatsuda, Phys. Rev. Lett. 99 (2007) 022001
Ishii+ [HAL QCD Coll.], Phys. Lett. B712 (2012) 437

HAL QCD method

An efficient method to calculate hadron-hadron potential in the lattice QCD

In the case of NN potential

- Nonlocal NN potential U is defined from NN correlator

$$\left(\frac{1}{8\mu}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu}\right) R(\boldsymbol{r}, t) = \int d\boldsymbol{r}' U(\boldsymbol{r}, \boldsymbol{r}') R(\boldsymbol{r}', t)$$

NN correlator obtained by lattice calc.

Nonlocal NN potential

- Local NN potential is defined by derivative expansion of nonlocal potential

$$U(r) = V_{\mathrm{C}}(r) + V_{\mathrm{T}}(r) S_{12} + V_{\mathrm{LS}}(r) \boldsymbol{L} \cdot \boldsymbol{S} + \cdots$$

NΛ-NΣ(I=1/2) coupled channel central & tensor potentials in 3S1-3D1

S. Aoki et al. (HAL Coll.) Proc.Jpn.Acad.B87(2011)509.
H. Nemura for HAL Coll., AIP Conference Proceedings 2130, 040005 (2019).

$$V_{^3\mathrm{S}_1} = \Psi^{-1} K$$

$$V_{^3\mathrm{S}_1} = \begin{pmatrix} V^{\mathrm{NL-NL}}_{^3\mathrm{S}_1,\mathrm{C}} & V^{\mathrm{NL-NL}}_{^3\mathrm{S}_1,\mathrm{T}} & V^{\mathrm{NL-NS}}_{^3\mathrm{S}_1,\mathrm{C}}\Delta^{\mathrm{NL}}_{\mathrm{NS}} & V^{\mathrm{NL-NS}}_{^3\mathrm{S}_1,\mathrm{T}}\Delta^{\mathrm{NL}}_{\mathrm{NS}} \\ V^{\mathrm{NS-NL}}_{^3\mathrm{S}_1,\mathrm{C}}\Delta^{\mathrm{NS}}_{\mathrm{NL}} & V^{\mathrm{NS-NL}}_{^3\mathrm{S}_1,\mathrm{T}}\Delta^{\mathrm{NS}}_{\mathrm{NL}} & V^{\mathrm{NS-NS}}_{^3\mathrm{S}_1,\mathrm{C}} & V^{\mathrm{NS-NS}}_{^3\mathrm{S}_1,\mathrm{T}} \end{pmatrix}$$

$$\Psi = \begin{pmatrix} R^{\mathrm{NL-NL}}_{\mathrm{S}} & R^{\mathrm{NL-NL}}_{\mathrm{D}} & R^{\mathrm{NL-NS}}_{\mathrm{S}} & R^{\mathrm{NL-NS}}_{\mathrm{D}} \\ 2\sqrt{2}R^{\mathrm{NL-NL}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NL-NL}}_{\mathrm{S}} - 2R^{\mathrm{NL-NL}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NL-NS}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NL-NS}}_{\mathrm{S}} - 2R^{\mathrm{NL-NS}}_{\mathrm{D}} \\ R^{\mathrm{NS-NL}}_{\mathrm{S}} & R^{\mathrm{NS-NL}}_{\mathrm{D}} & R^{\mathrm{NS-NS}}_{\mathrm{S}} & R^{\mathrm{NS-NS}}_{\mathrm{D}} \\ 2\sqrt{2}R^{\mathrm{NS-NL}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NS-NL}}_{\mathrm{S}} - 2R^{\mathrm{NS-NL}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NS-NS}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NS-NS}}_{\mathrm{S}} - 2R^{\mathrm{NS-NS}}_{\mathrm{D}} \end{pmatrix}$$

$$K = \begin{pmatrix} (\frac{1+3\delta^2_{\mathrm{NL}}}{8\mu_{\mathrm{NL}}}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu_{\mathrm{NL}}}) & 0 & 0 & 0 \\ 0 & (\frac{1+3\delta^2_{\mathrm{NL}}}{8\mu_{\mathrm{NL}}}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu_{\mathrm{NL}}}) & 0 & 0 \\ 0 & 0 & (\frac{1+3\delta^2_{\mathrm{NS}}}{8\mu_{\mathrm{NS}}}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu_{\mathrm{NS}}}) & 0 \\ 0 & 0 & 0 & (\frac{1+3\delta^2_{\mathrm{NS}}}{8\mu_{\mathrm{NS}}}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu_{\mathrm{NS}}}) \end{pmatrix} \Psi$$

NΛ-NΣ(I=1/2) coupled channel central & tensor potentials in 3S1-3D1

S. Aoki et al. (HAL Coll.) Proc.Jpn.Acad.B87(2011)509.
H. Nemura for HAL Coll., AIP Conference Proceedings 2130, 040005 (2019).

$R_{\mathrm{S}}, R_{\mathrm{D}}$ **: S-wave(L=0), D-wave(L=2) BB correlator obtained by partial wave decomposition**

$$V_{^3\mathrm{S}_1} = \Psi^{-1} K$$

$$V_{^3\mathrm{S}_1} = \begin{pmatrix} V^{\mathrm{NL-NL}}_{^3\mathrm{S}_1,\mathrm{C}} & V^{\mathrm{NL-NL}}_{^3\mathrm{S}_1,\mathrm{T}} & V^{\mathrm{NL-NS}}_{^3\mathrm{S}_1,\mathrm{C}} \Delta^{\mathrm{NL}}_{\mathrm{NS}} & V^{\mathrm{NL-NS}}_{^3\mathrm{S}_1,\mathrm{T}} \Delta^{\mathrm{NL}}_{\mathrm{NS}} \\ V^{\mathrm{NS-NL}}_{^3\mathrm{S}_1,\mathrm{C}} \Delta^{\mathrm{NS}}_{\mathrm{NL}} & V^{\mathrm{NS-NL}}_{^3\mathrm{S}_1,\mathrm{T}} \Delta^{\mathrm{NS}}_{\mathrm{NL}} & V^{\mathrm{NS-NS}}_{^3\mathrm{S}_1,\mathrm{C}} & V^{\mathrm{NS-NS}}_{^3\mathrm{S}_1,\mathrm{T}} \end{pmatrix}$$

$$\Psi = \begin{pmatrix} R^{\mathrm{NL-NL}}_{\mathrm{S}} & R^{\mathrm{NL-NL}}_{\mathrm{D}} & R^{\mathrm{NL-NS}}_{\mathrm{S}} & R^{\mathrm{NL-NS}}_{\mathrm{D}} \\ 2\sqrt{2}R^{\mathrm{NL-NL}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NL-NL}}_{\mathrm{S}} - 2R^{\mathrm{NL-NL}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NL-NS}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NL-NS}}_{\mathrm{S}} - 2R^{\mathrm{NL-NS}}_{\mathrm{D}} \\ R^{\mathrm{NS-NL}}_{\mathrm{S}} & R^{\mathrm{NS-NL}}_{\mathrm{D}} & R^{\mathrm{NS-NS}}_{\mathrm{S}} & R^{\mathrm{NS-NS}}_{\mathrm{D}} \\ 2\sqrt{2}R^{\mathrm{NS-NL}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NS-NL}}_{\mathrm{S}} - 2R^{\mathrm{NS-NL}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NS-NS}}_{\mathrm{D}} & 2\sqrt{2}R^{\mathrm{NS-NS}}_{\mathrm{S}} - 2R^{\mathrm{NS-NS}}_{\mathrm{D}} \end{pmatrix}$$

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Partial wave(L=0,2) decomposition on the lattice

Method 1. A_1^+ projection of cubic group

M. Luscher, Nucl. Phys. B 354 (1991), 531.
Aoki, Hatsuda, Ishii, PTEP 123 (2010).

$$R^{A_1^+}(\boldsymbol{r}) \equiv \frac{1}{48} \sum_{g \in O_h} R(g^{-1}\boldsymbol{r})$$

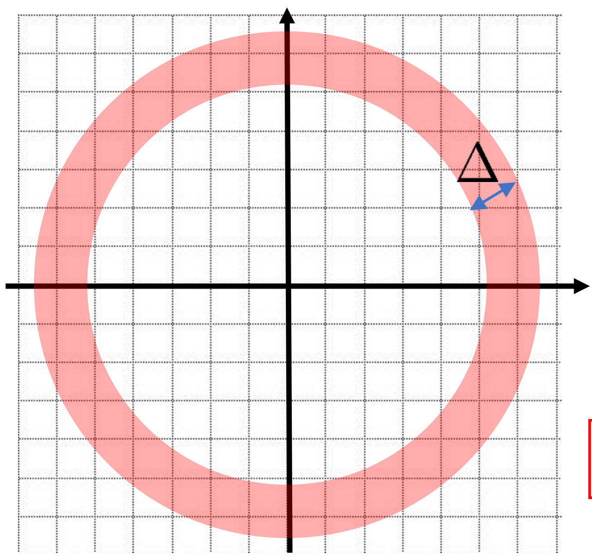
: This has dominant contribution from L=0 and small contribution from L=4,6,….

S-wave $R_{\mathrm{S}}(\boldsymbol{r}) = R^{A_1^+}(\boldsymbol{r})$

D-wave $R_{\mathrm{D}}(\boldsymbol{r}) = R(\boldsymbol{r}) - R^{A_1^+}(\boldsymbol{r})$

Method 2. Misner's method

C. W. Misner, Class. Quant. Grav. 21 (2004) S243.
T. Miyamoto et al., Phys. Rev. D 101 (2020) 074514.



Use $R(\boldsymbol{r}) = \sum_{n,l,m} c_{nlm}^{\Delta} G_n^{\Delta}(r) Y_{lm}(\theta,\phi)$

new basis function in r

instead of $R(\boldsymbol{r}) = \sum_{l,m} g_{lm}(r) Y_{lm}(\theta,\phi)$

sophisticated partial wave decomposition on the lattice

Setup

Configuration: Nearly physical point $(m_\pi \simeq 146[\mathrm{MeV}])$

Lattice: $L = 96^4$

$a = 0.0846(7)\ \mathrm{fm}\ (2333\ \mathrm{MeV})$

$La = 8.12\ \mathrm{fm}$

414 configurations($\times 2 \times 4 \times 96$)

- forward / backward propagation for correlator
- x,y,z,t rotation for gauge conf
- 96 wall-source point

Baryon mass:

N：0.4093 (955 MeV)

Λ：0.4884 (1139 MeV)

Σ：0.5233 (1221 MeV)

NΛ and NΣ potentials

- I=1/2 (NΛ-NΣ) — threshold
  - NΛ-NΣ coupled potential
    - **1S0 central potential** — $E_{\Lambda N\pi}$
    - 3S1-3D1 central & tensor potential — $E_{\Lambda N\pi}$

- I=3/2 (NΣ)
    - 1S0 central potential — $E_{\Sigma N\pi}$
    - 3S1-3D1 central & tensor potential — $E_{\Sigma N\pi}$

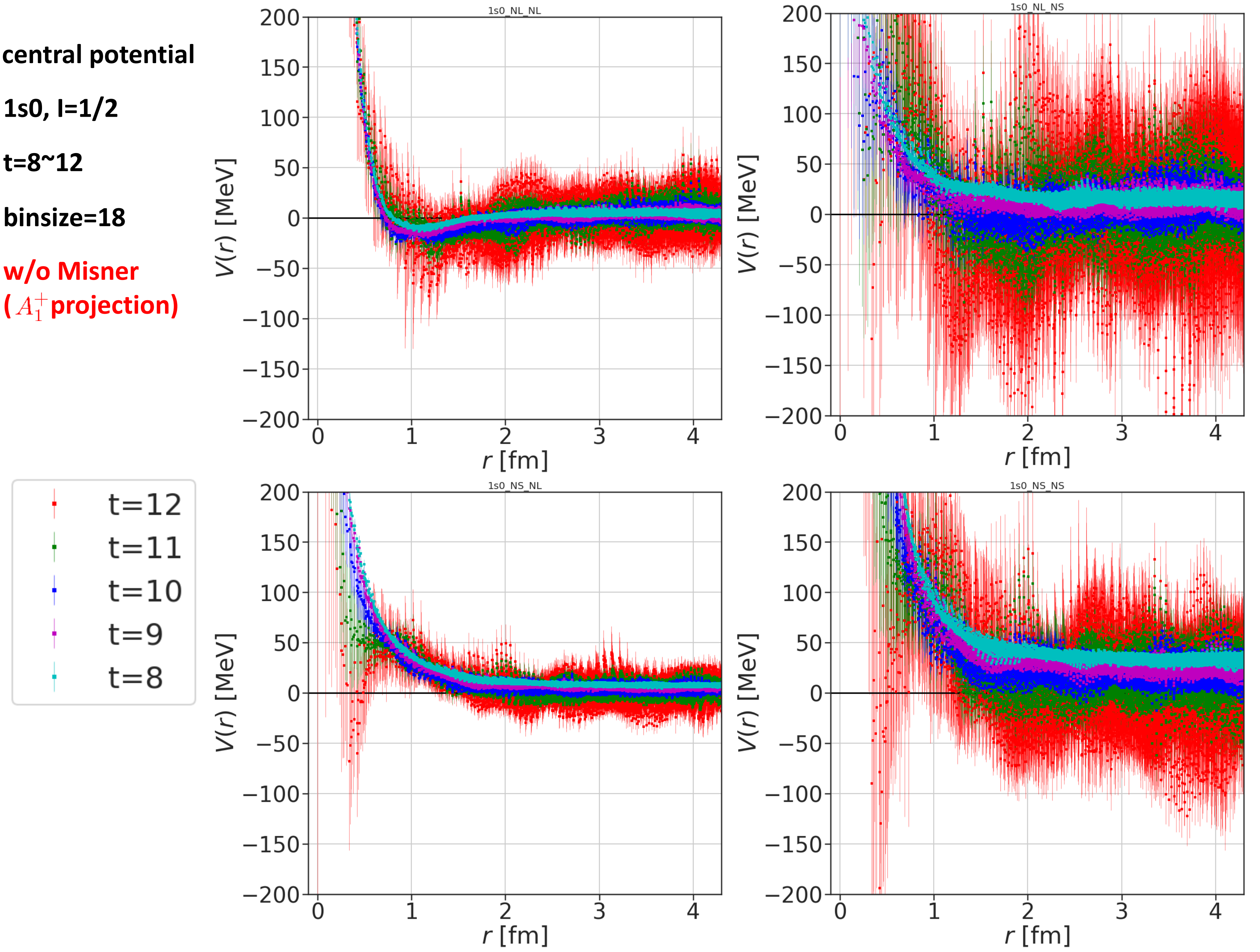
central potential

1s0, I=1/2

t=8~12

binsize=18

w/o Misner
(A_1^+ projection)



central potential

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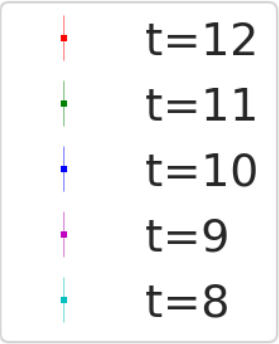
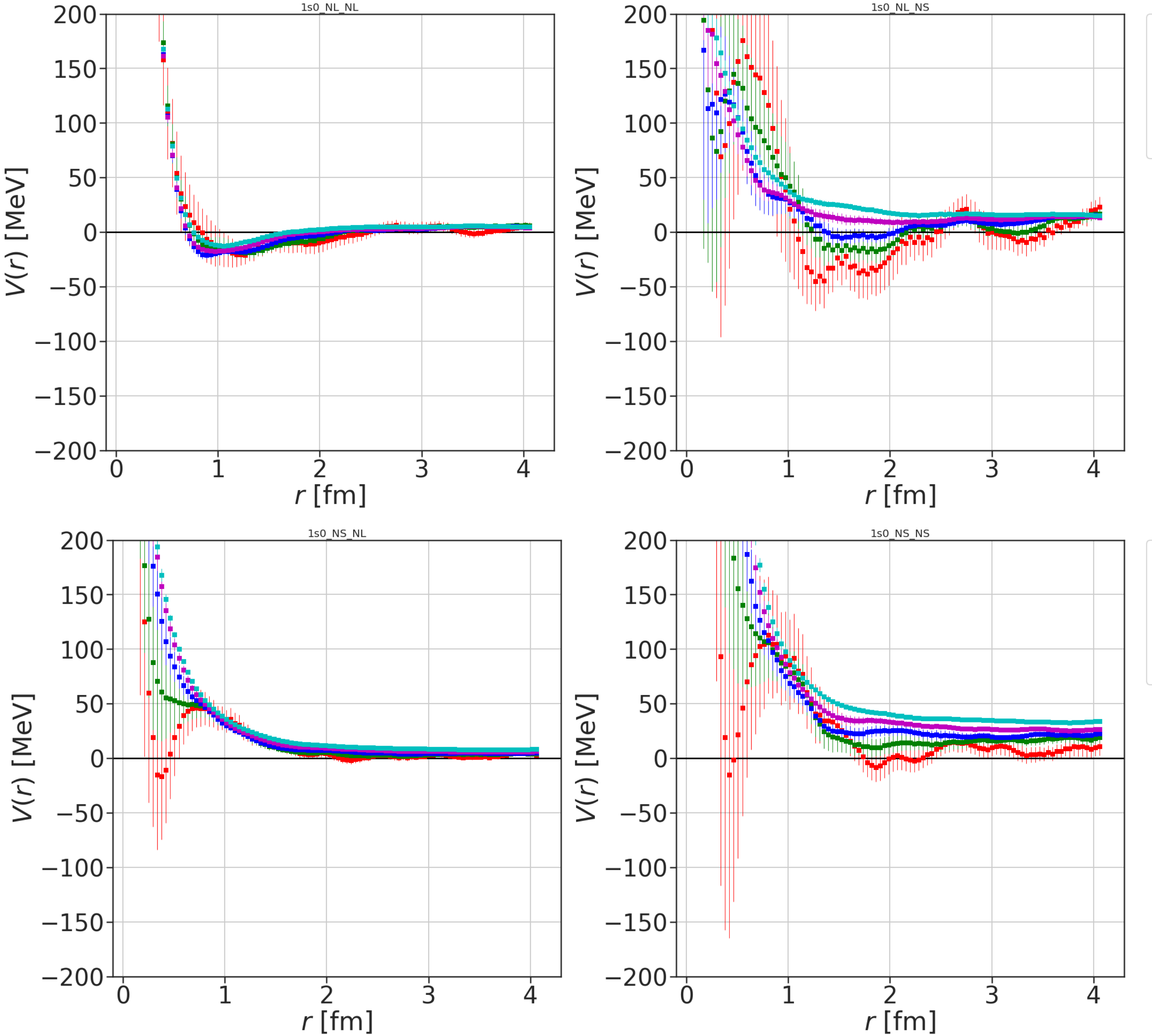
w/ Misner





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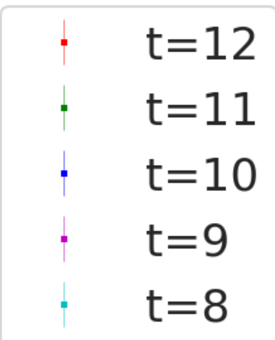
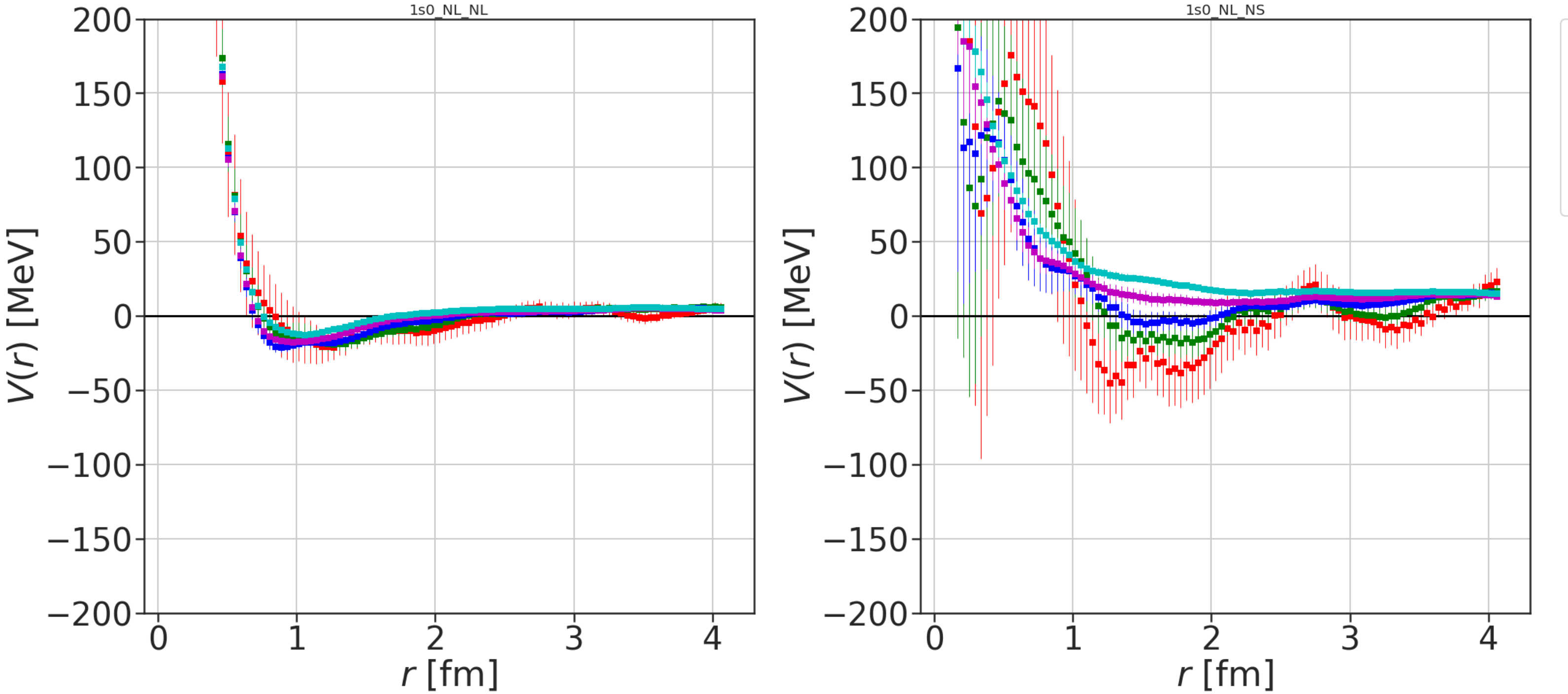
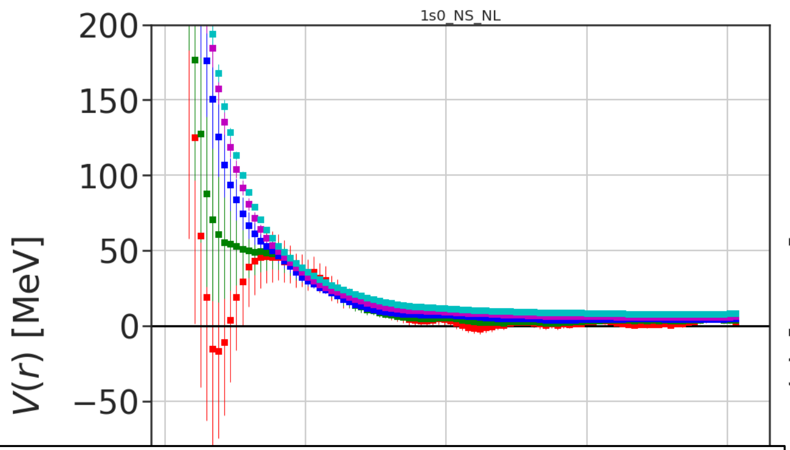
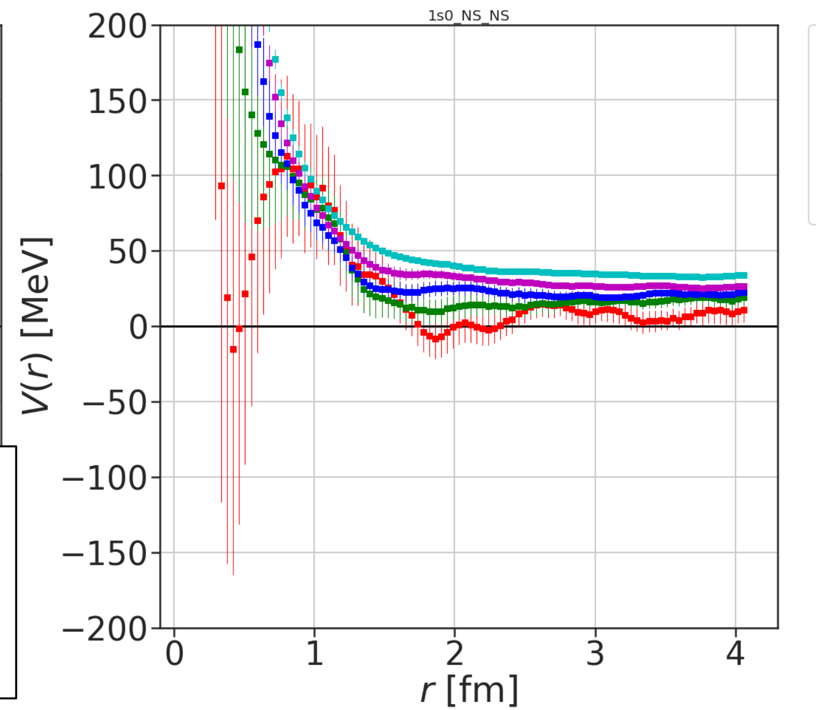








- Misner method makes error bar small.
- Change of the central values is small.
- Potentials at long range do not reach to 0 for any t.
- Wavy behavior is seen at large t.

NΛ and NΣ potentials

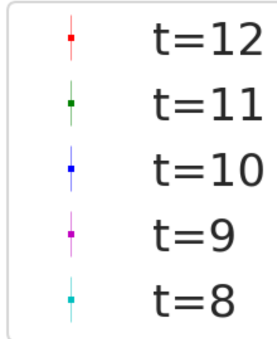
- I=1/2 (NΛ-NΣ) — threshold
  - NΛ-NΣ coupled potential
    - 1S0 central potential — $E_{\Lambda N \pi}$
    - 3S1-3D1 central & tensor potential — $E_{\Lambda N \pi}$
  - effective NΛ potential
    - **1S0 central potential** — $E_{\Lambda N}$
    - 3S1-3D1 central & tensor potential — $E_{\Lambda N}$
- I=3/2 (NΣ)
  - 1S0 central potential — $E_{\Sigma N \pi}$
  - 3S1-3D1 central & tensor potential — $E_{\Sigma N \pi}$

effective NΛ central potential

1s0, I=1/2

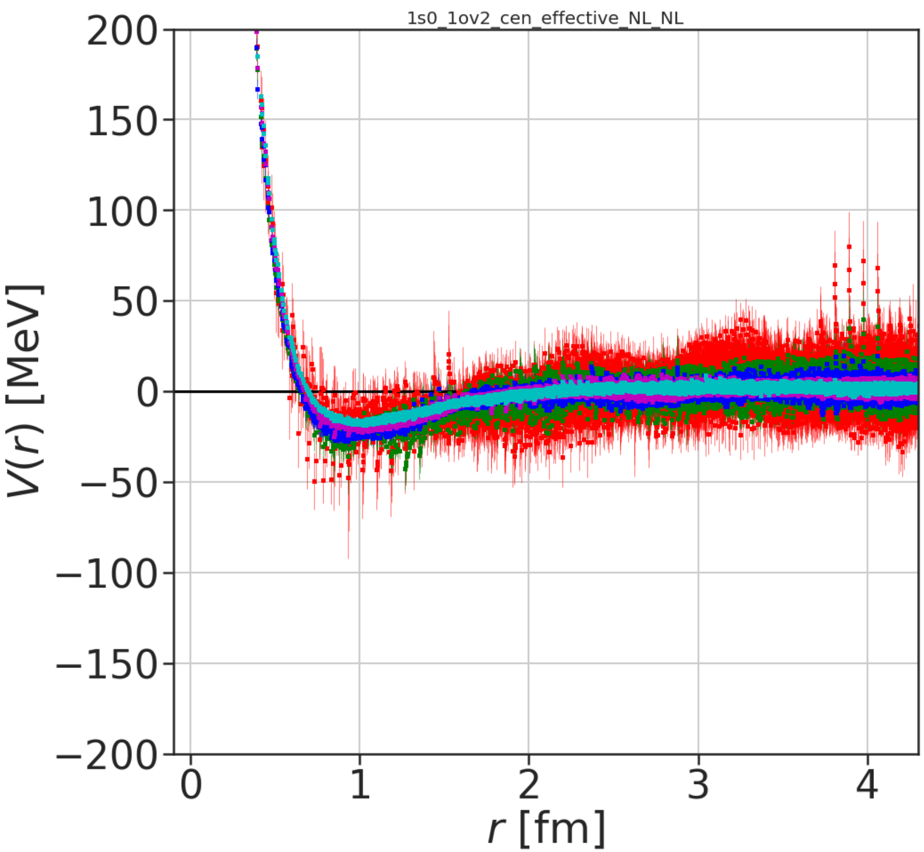
t=8~12

binsize=18

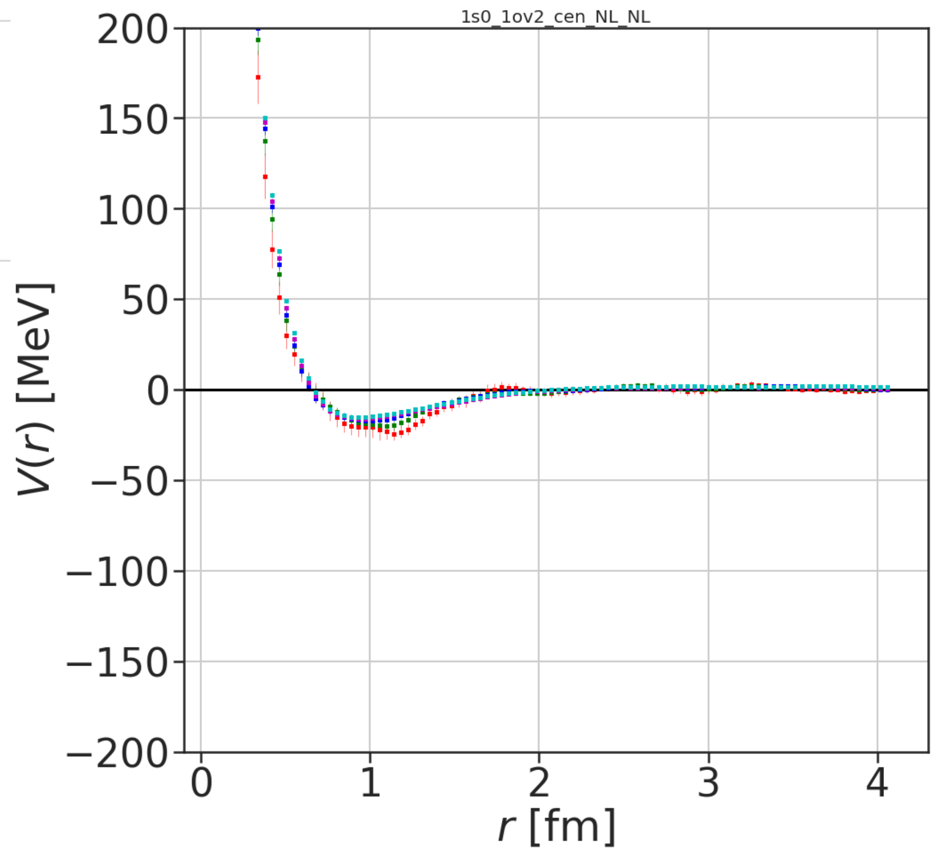


- Potentials at long range reach to 0 for any t.
- Wavy behavior is suppressed.
- At low energy, this effective NΛ potential is useful in application of HALQCD potential.

w/o Misner
(A_1^+ projection)



w/ Misner



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    - 3S1-3D1 central & tensor potential — $E_{\Sigma N\pi}$

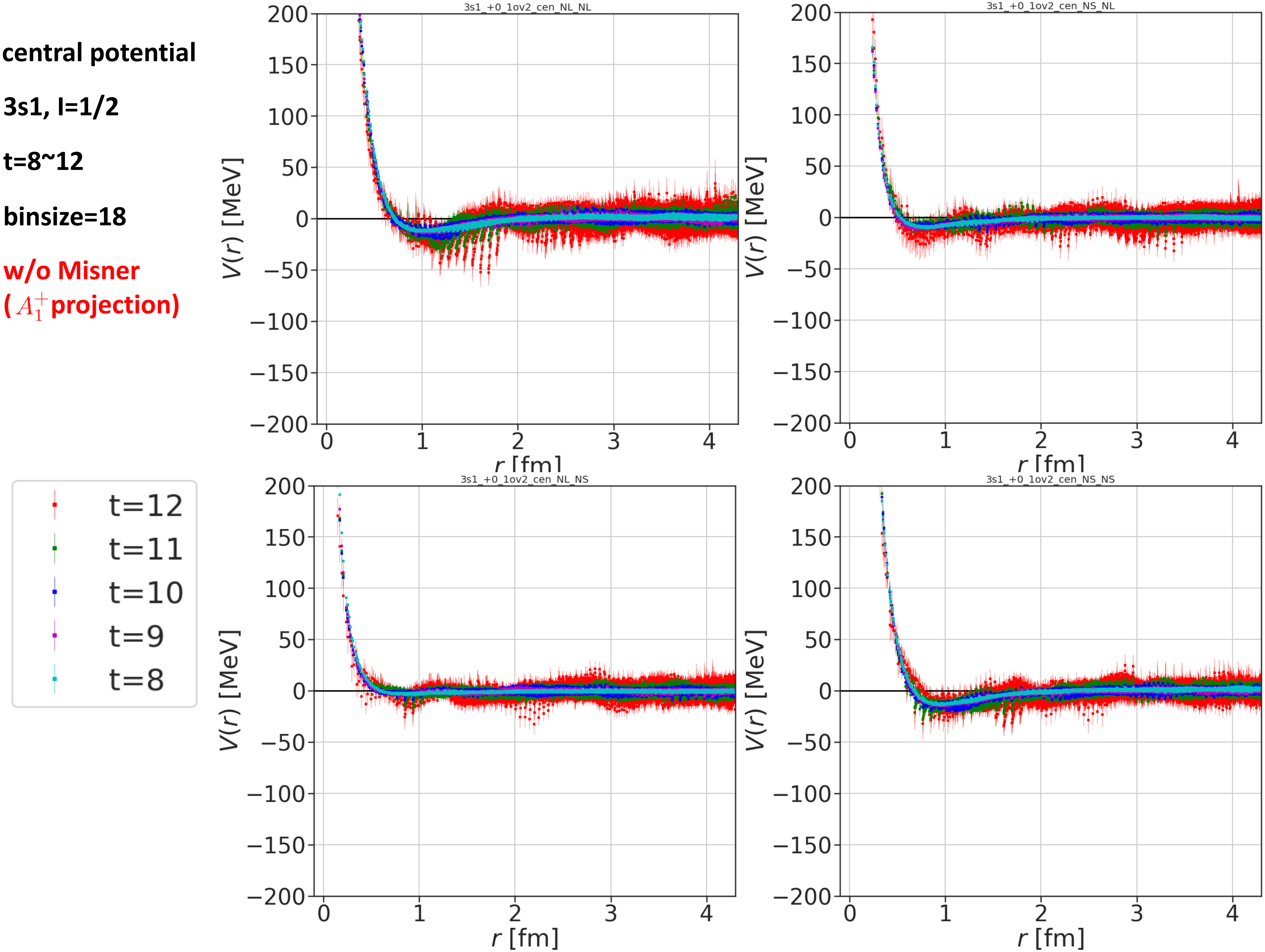
central potential

3s1, I=1/2

t=8~12

binsize=18

w/o Misner (A_1^+ projection)



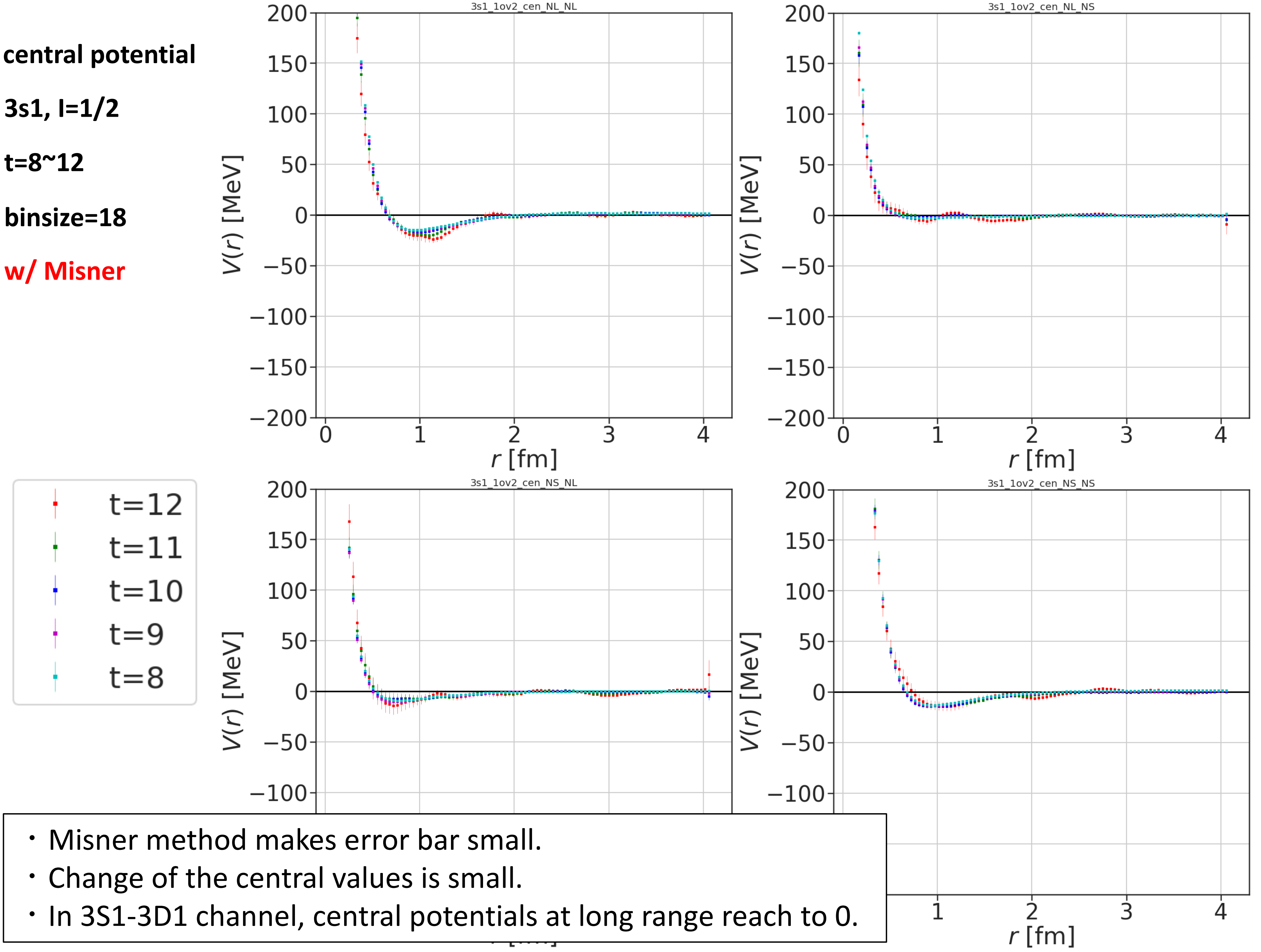
central potential

3s1, I=1/2

t=8~12

binsize=18

w/ Misner



- Misner method makes error bar small.
- Change of the central values is small.
- In 3S1-3D1 channel, central potentials at long range reach to 0.

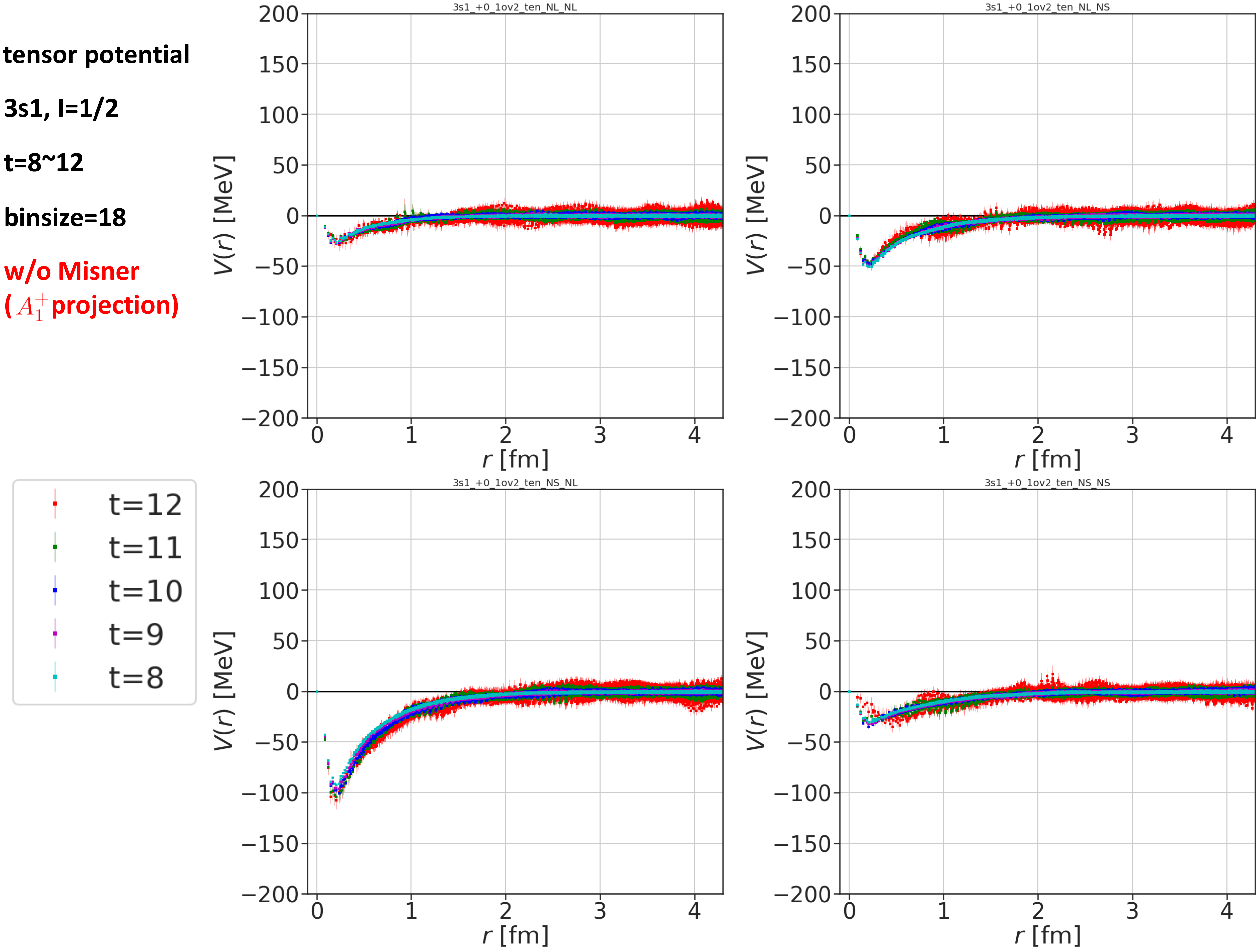
tensor potential

3s1, I=1/2

t=8~12

binsize=18

w/o Misner (A_1^+ projection)



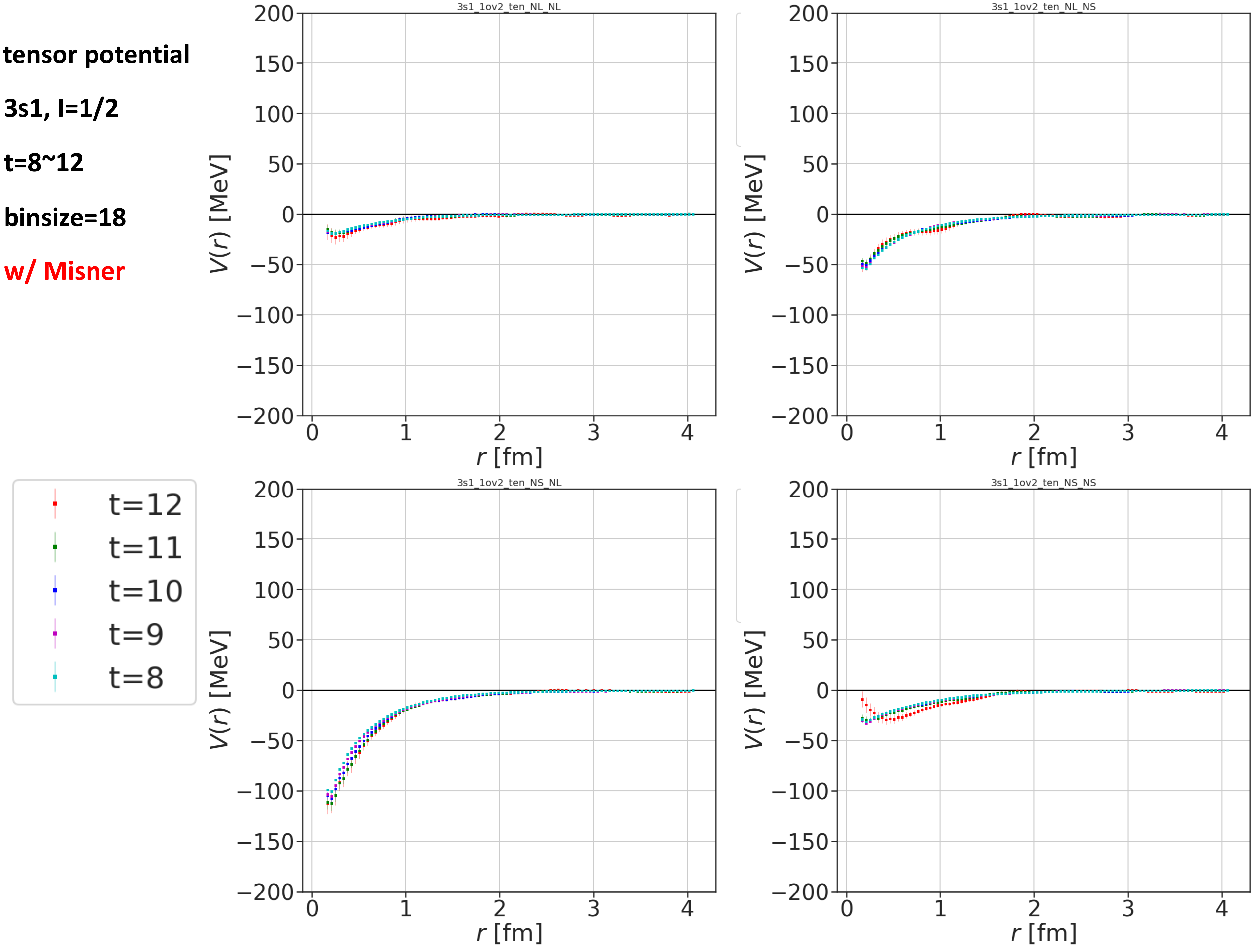
tensor potential

3s1, I=1/2

t=8~12

binsize=18

w/ Misner



NΛ and NΣ potentials

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    - 1S0 central potential — $E_{\Lambda N\pi}$
    - 3S1-3D1 central & tensor potential — $E_{\Lambda N\pi}$

- I=3/2 (NΣ)
    - **1S0 central potential** — $E_{\Sigma N\pi}$
    - 3S1-3D1 central & tensor potential — $E_{\Sigma N\pi}$

NΣ central potential

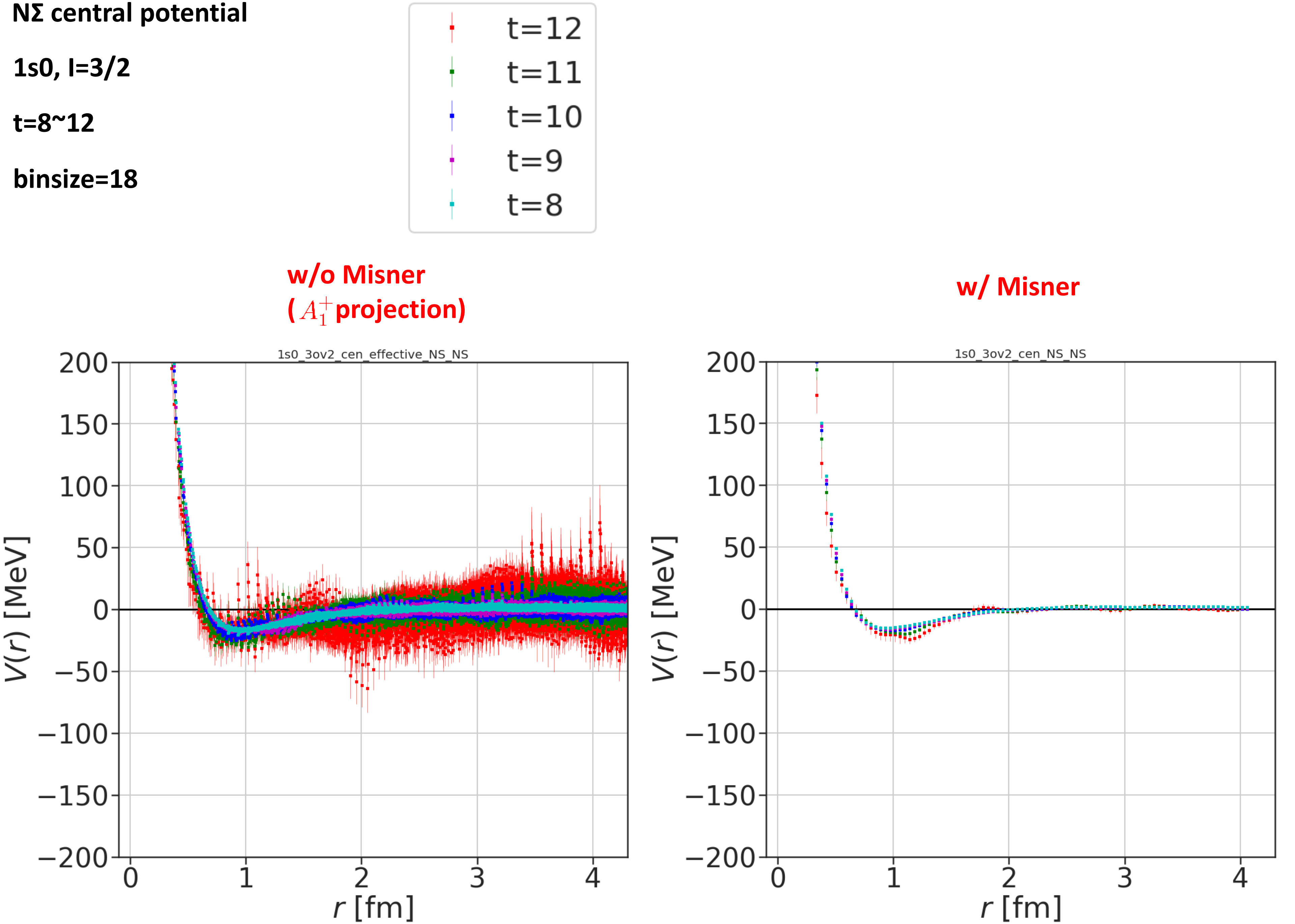
1s0, I=3/2

t=8~12

binsize=18

w/o Misner
(A_1^+ projection)

w/ Misner



NΛ and NΣ potentials

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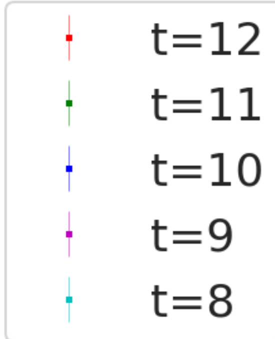
    - 1S0 central potential — $E_{\Sigma N\pi}$
    - **3S1-3D1 central & tensor potential** — $E_{\Sigma N\pi}$

NΣ central potential

3s1, I=3/2

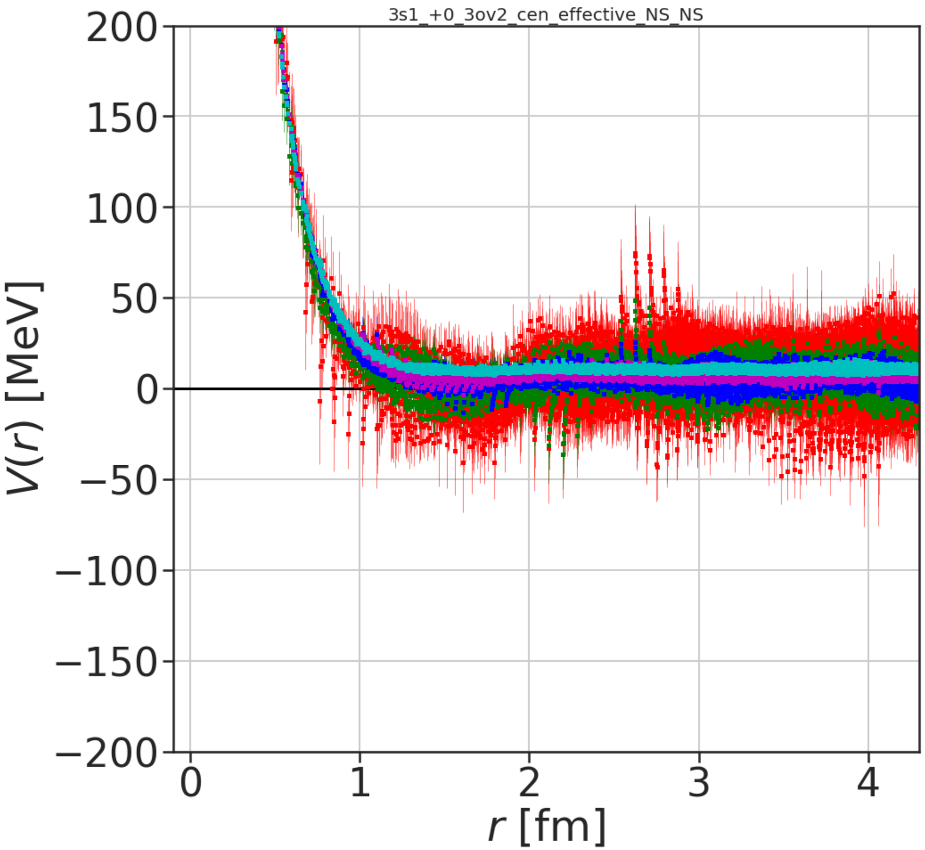
t=8~12

binsize=18

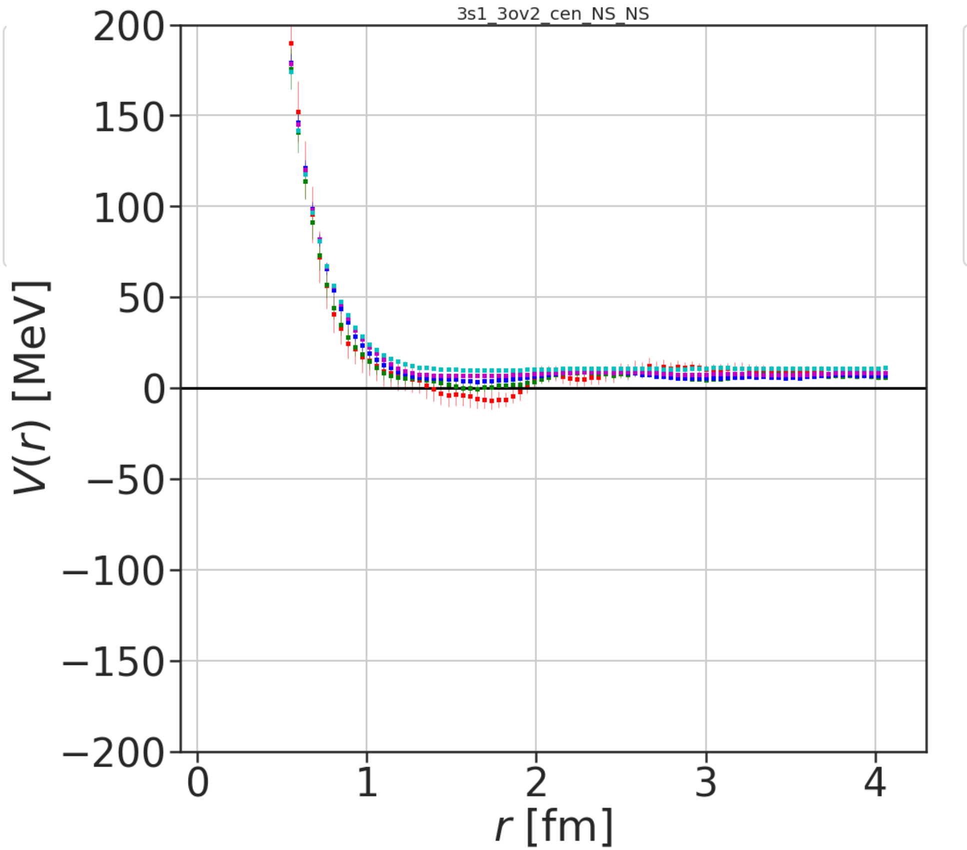


- Central potentials at long range does not reach to 0.

w/o Misner
(A_1^+ projection)



w/ Misner



NΣ tensor potential

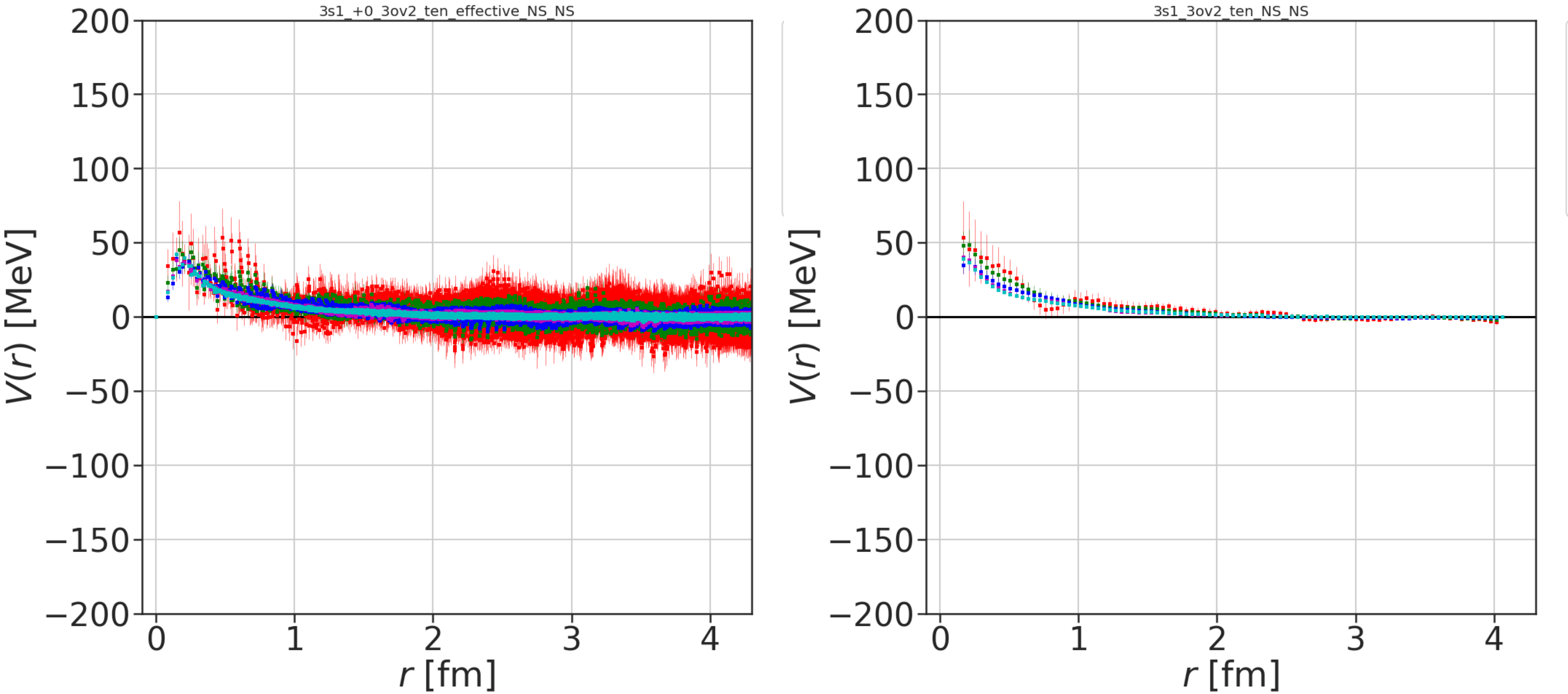
3s1, I=3/2

t=8~12

binsize=18

w/o Misner
(A_1^+ projection)

w/ Misner



Summary

- NΛ & NΣ potentials are calculated by HAL QCD method at almost physical point.
  - I=1/2, 1S0 NΛ-NΣ coupled channel central potential
  - I=1/2, 3S1-3D1 NΛ-NΣ coupled channel central & tensor potential
  - I=3/2, 1S0 NΣ single channel central potential
  - I=3/2, 3S1-3D1 NΣ single channel central & tensor potential

- As for partial wave decomposition on the lattice,
  Misner method works, and Misner method is better than
  the method by the projection of cubic group.

Future

- Calculate observables(phase shifts).
  - Fit potentials
  - Investigate the wavy behavior at large t
- Potentials are applied to many body calculations of NY system.

Appendix

Ishii, Aoki & Hatsuda, Phys. Rev. Lett. 99 (2007) 022001
Ishii+ [HAL QCD Coll.], Phys. Lett. B712 (2012) 437

HAL QCD method

An efficient method to calculate hadron-hadron potential in the lattice QCD

Properties of HAL-QCD potential

- Potential itself is not observable.
- Observables (phase shift, binding energy, …) are correctly reproduced by HAL-QCD potential.
- Ground state saturation is NOT required.
- Elastic excited states $E \leq E_{NN\pi}$ are signals in HAL QCD method.
- HAL QCD potentials can be applied to many-body calculations of hadrons.

NΛ-NΣ(I=1/2) coupled channel central & tensor potentials in 3S1-3D1

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$$V_{^3\mathrm{S}_1} = \Psi^{-1} K$$

generalization of NN case $V_\mathrm{C} = \frac{1}{R^\mathrm{NN}} \left(\frac{1}{8\mu} \frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu} \right) R^\mathrm{NN}$

$$V_{^3\mathrm{S}_1} = \begin{pmatrix} V^{\mathrm{NL-NL}}_{^3\mathrm{S}_1,\mathrm{C}} & V^{\mathrm{NL-NL}}_{^3\mathrm{S}_1,\mathrm{T}} & V^{\mathrm{NL-NS}}_{^3\mathrm{S}_1,\mathrm{C}} \Delta^{\mathrm{NL}}_{\mathrm{NS}} & V^{\mathrm{NL-NS}}_{^3\mathrm{S}_1,\mathrm{T}} \Delta^{\mathrm{NL}}_{\mathrm{NS}} \\ V^{\mathrm{NS-NL}}_{^3\mathrm{S}_1,\mathrm{C}} \Delta^{\mathrm{NS}}_{\mathrm{NL}} & V^{\mathrm{NS-NL}}_{^3\mathrm{S}_1,\mathrm{T}} \Delta^{\mathrm{NS}}_{\mathrm{NL}} & V^{\mathrm{NS-NS}}_{^3\mathrm{S}_1,\mathrm{C}} & V^{\mathrm{NS-NS}}_{^3\mathrm{S}_1,\mathrm{T}} \end{pmatrix}$$

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$$K = \begin{pmatrix} (\frac{1+3\delta^2_\mathrm{NL}}{8\mu_\mathrm{NL}} \frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu_\mathrm{NL}}) & 0 & 0 & 0 \\ 0 & (\frac{1+3\delta^2_\mathrm{NL}}{8\mu_\mathrm{NL}} \frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu_\mathrm{NL}}) & 0 & 0 \\ 0 & 0 & (\frac{1+3\delta^2_\mathrm{NS}}{8\mu_\mathrm{NS}} \frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu_\mathrm{NS}}) & 0 \\ 0 & 0 & 0 & (\frac{1+3\delta^2_\mathrm{NS}}{8\mu_\mathrm{NS}} \frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu_\mathrm{NS}}) \end{pmatrix} \Psi$$

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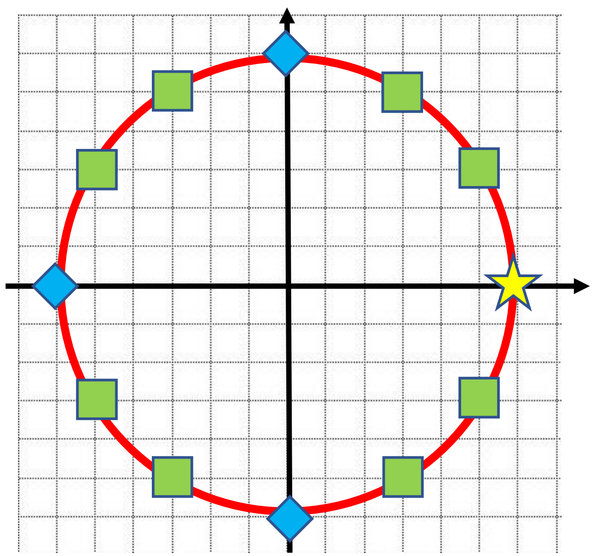
C. W. Misner, Class. Quant. Grav. 21 (2004) S243.
T. Miyamoto et al., Phys. Rev. D 101 (2020) 074514.



◆ : cubic transformation of ☆

■ : Other transformation of ☆

◆ and ■ have same r

→ **Exact partial wave decomposition on the lattice**

NΛ and NΣ potentials

	threshold
● I=1/2 (NΛ-NΣ)	
➢ NΛ-NΣ coupled potential	
• 1S0 central potential	$E_{\Lambda N\pi}$
• 3S1-3D1 central & tensor potential	$E_{\Lambda N\pi}$
➢ effective NΛ potential	
• 1S0 central potential	$E_{\Lambda N}$
• **3S1-3D1 central & tensor potential**	$E_{\Lambda N}$
● I=3/2 (NΣ)	
• 1S0 central potential	$E_{\Sigma N\pi}$
• 3S1-3D1 central & tensor potential	$E_{\Sigma N\pi}$

example:

$$E_{\Lambda N\pi} = m_\Lambda + m_N + m_\pi \simeq 2210[\mathrm{MeV}]$$

effective NΛ central&tensor potential

3s1, I=1/2

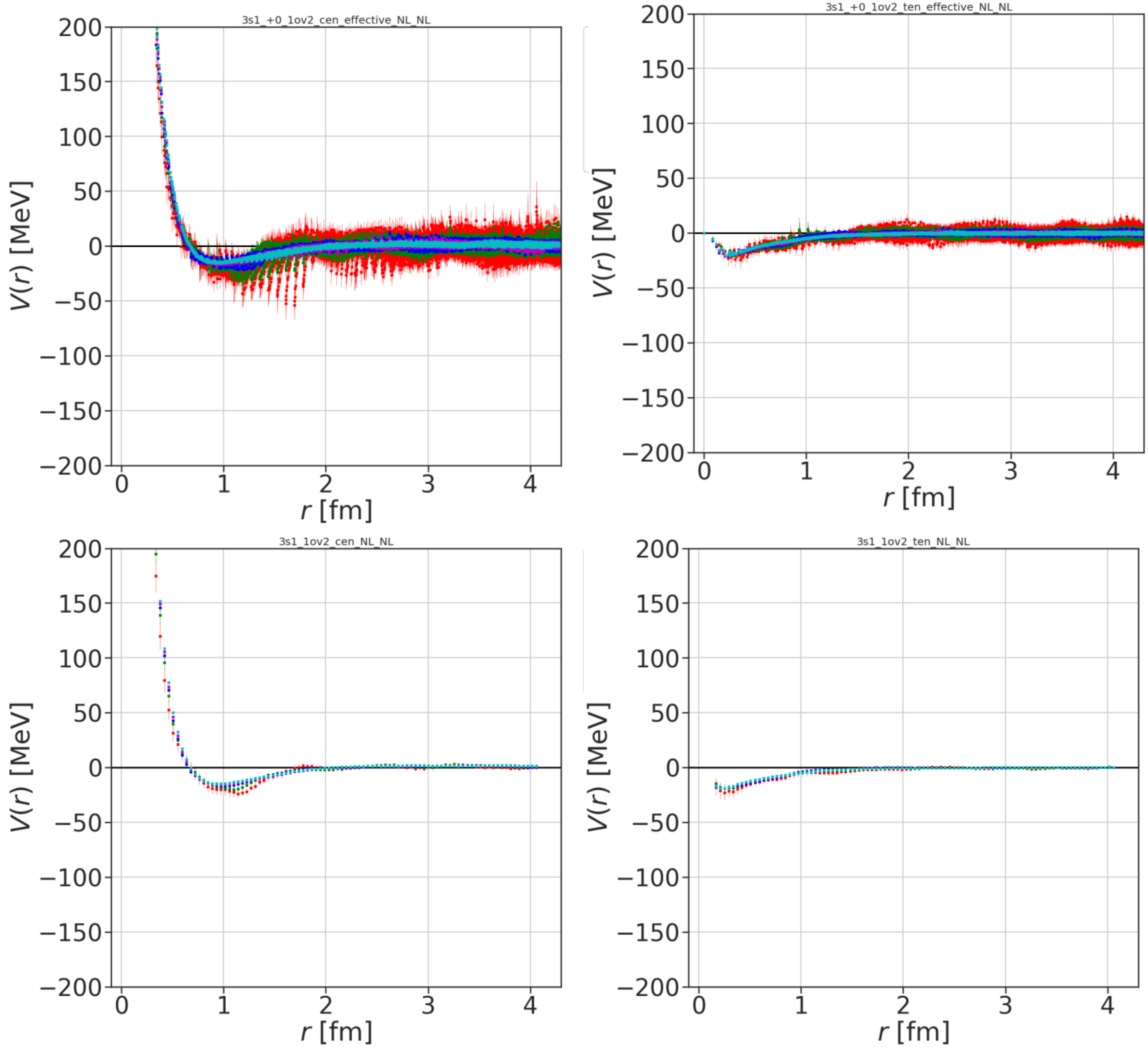
t=8~12

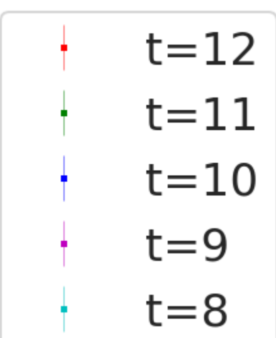
binsize=18

central **tensor**

w/o Misner (A_1^+ projection)

w/ Misner





3s1, I=1/2

t=8~12

binsize=18

w/ Misner

NΛ-NΣ coupled channel
central&tensor potential

effective NΛ
central&tensor potential