Baryon interactions from lattice QCD at m_π = 0.27 GeV

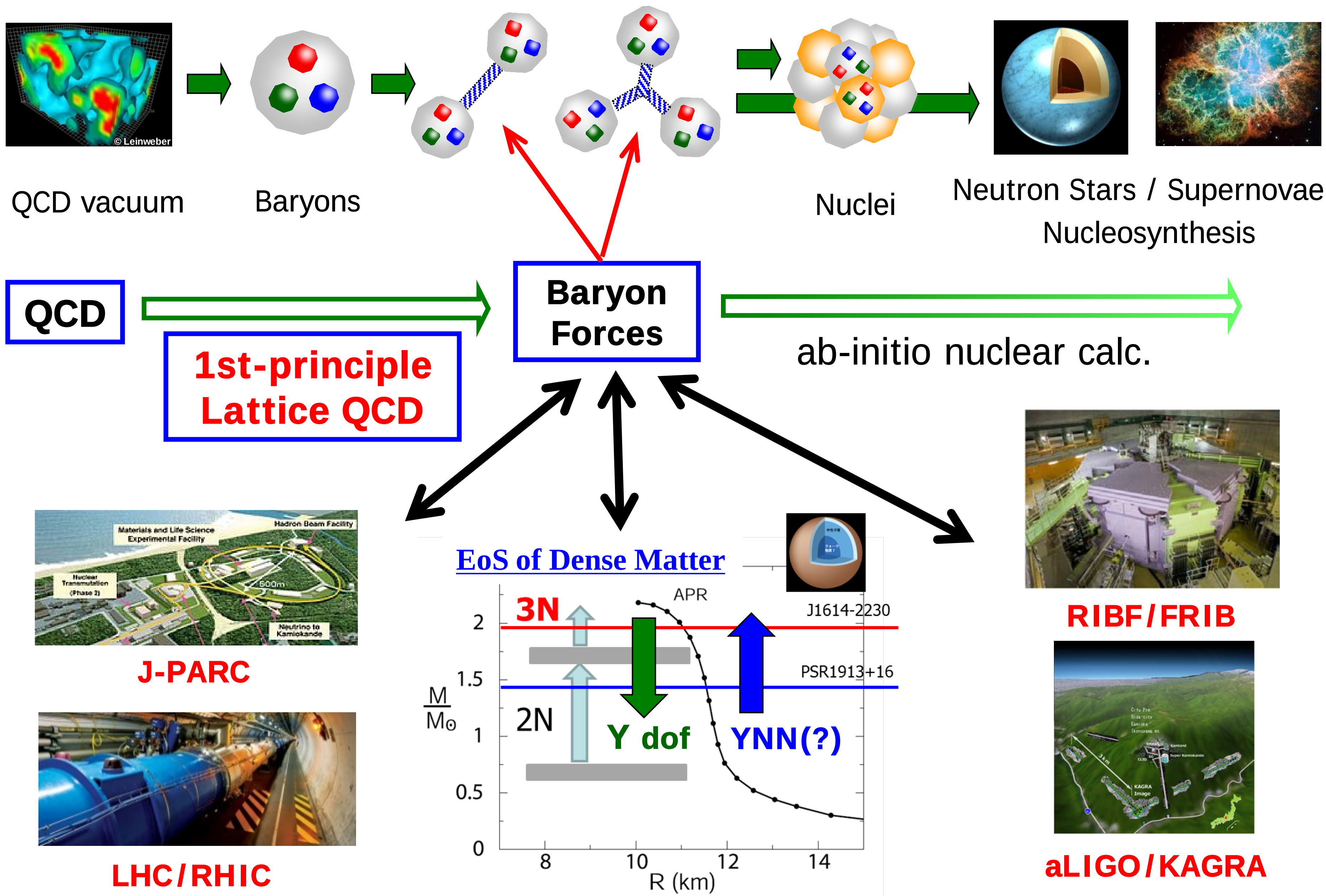
Takumi Doi

(RIKEN Nishina Center / iTHEMS)

for HAL QCD Collaboration

Y. Akahoshi, S. Aoki, T. Miyamato, K. Sasaki (YITP)
T. Aoyama (KEK)
T. Doi, T. M. Doi, S. Gongyo, T. Hatsuda,
T. Iritani, T. Sugiura (RIKEN)
F. Etminan (Univ. of Birjand)
Y. Ikeda, N. Ishii, K. Murano, H. Nemura (RCNP)
T. Inoue (Nihon Univ.)

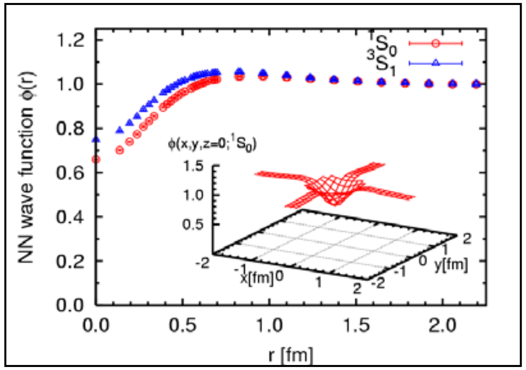
The Odyssey from Quarks to Universe



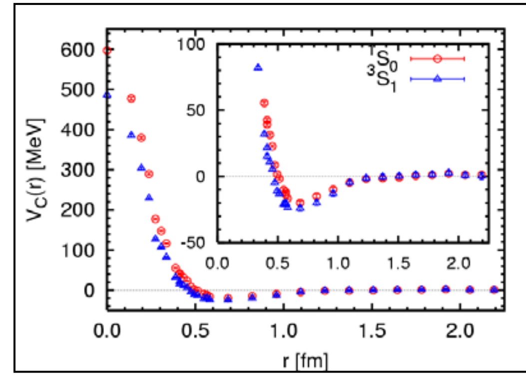
HAL QCD method

Lattice QCD

NBS wave func.



Lat Baryon Force



$$\psi_{NBS}(\vec{r}) = \langle 0|N(\vec{r})N(\vec{0})|N(\vec{k})N(-\vec{k}), in\rangle \simeq A_k \sin(kr - l\pi/2 + \delta_l(k))/(kr)$$

$$\left(k^2/m_N - H_0\right)\psi(\vec{r}) = \int d\vec{r}\,' U(\vec{r},\vec{r}\,')\psi(\vec{r}\,')$$

- **E-indep potentail from NBS w.f.** — Aoki-Hatsuda-Ishii PTP123(2010)89
  - **Faithful to Phase Shifts by construction** — (non-locality: derivative expansion)
- **Time-dependent HAL method** — N.Ishii et al. (HAL Coll.) PLB712(2012)437
  - **G.S. saturation NOT required** — “Signal” from (elastic) excited states
- **Coupled Channel formalism** — S. Aoki et al. (HAL Coll.) Proc.Jpn.Acad.B87(2011)509
  - **Above inelastic threshold** ➔ Essential for **YN/YY-forces**

Luscher method vs. HAL method: Issue resolved !

T. Iritani et al. (HAL) JHEP10(2016)101, PRD96(2017)034521, PRD99(2019)014514, JHE03(2019)007

NN @ heavy quark masses

The results are "scattering" (Doi@Lat12)

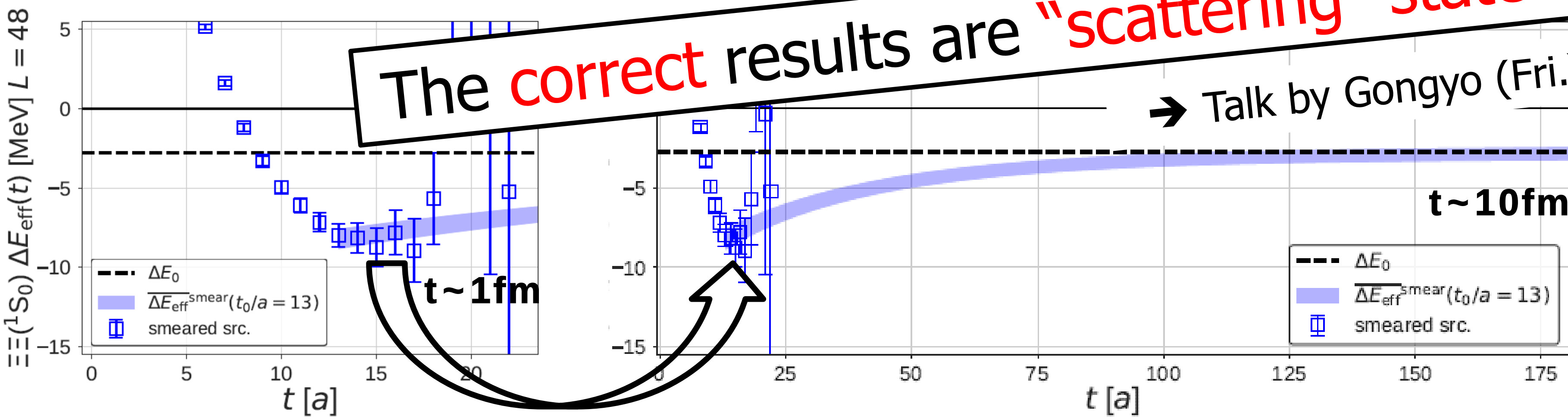
HAL method (HAL) : **unbound**

Direct method (PACS-CS (Yamazaki et al.)/NPL/CalLat): **bound**

New (improved) calc w/ Direct method (Mainz) : **unbound**

The correct results are "scattering" states

➔ Talk by Gongyo (Fri.)



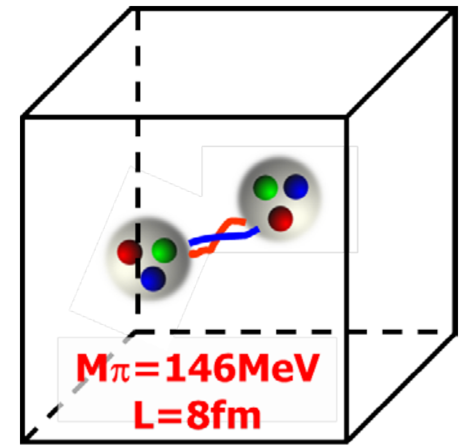
"Pseudo-Plateau" by excited states

HAL QCD pot = Luscher's method w/ Eigenstate projection

≠ Direct method w/ naïve plateau fitting

Lattice QCD @ near physical point

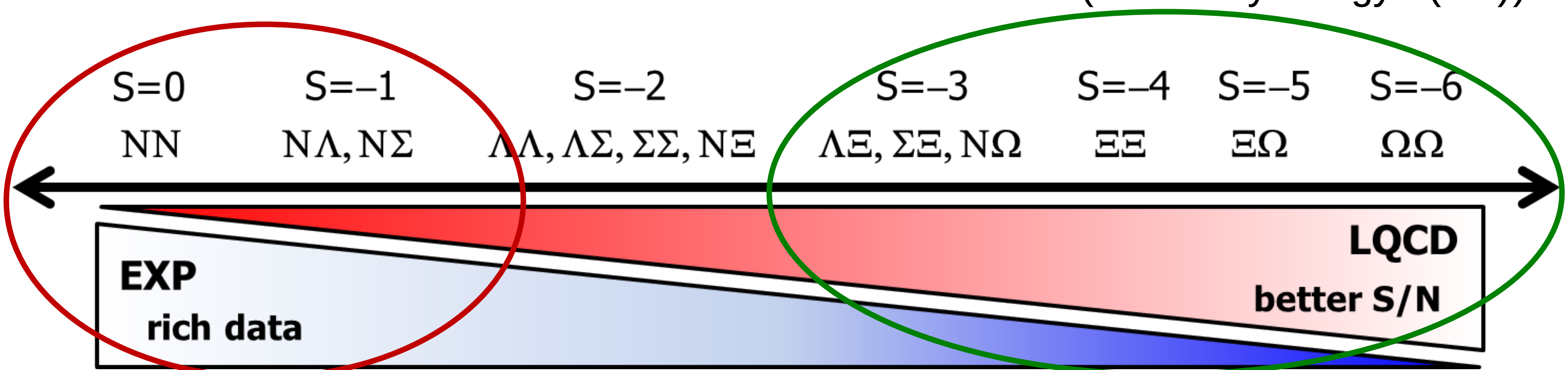
- **Nf = 2 + 1 gauge configs**
  - clover fermion + Iwasaki gauge w/ stout smearing
  - V=(8.1fm)^4, a=0.085fm (1/a = 2.3 GeV)
  - m(pi) ~= 146 MeV, m(K) ~= 525 MeV
  - #traj ~= 2000 generated



PACS Coll., PoS LAT2015, 075

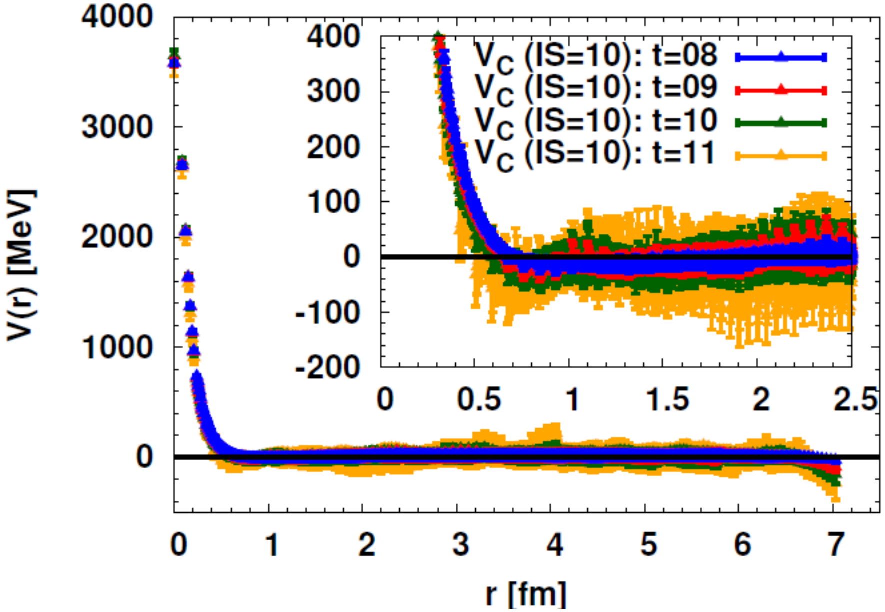
- **Measurement**
  - All of NN/YN/YY for central/tensor forces in P=(+) (S, D-waves)

ΩΩ, NΩ: (quasi) Bound states
(➔ talk by Gongyo (Fri.))



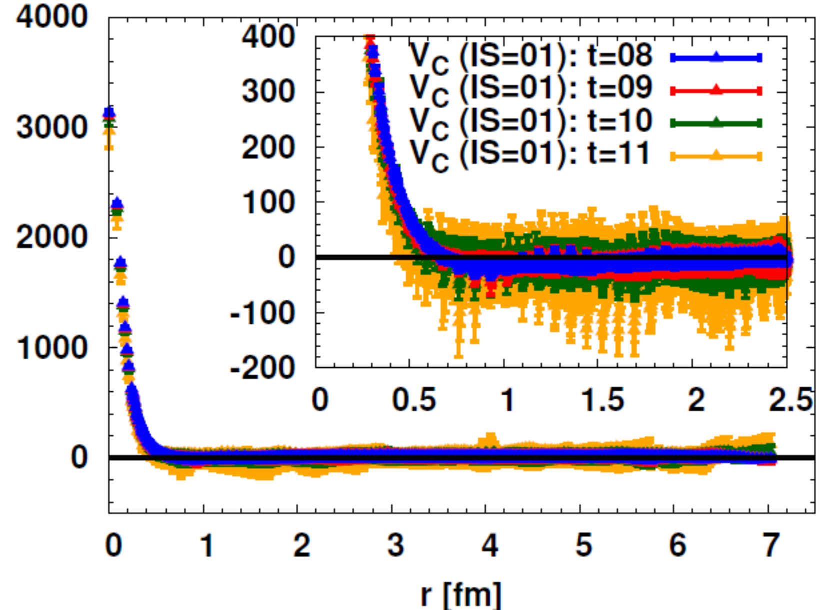
NN-Potentials

$^1S_0$

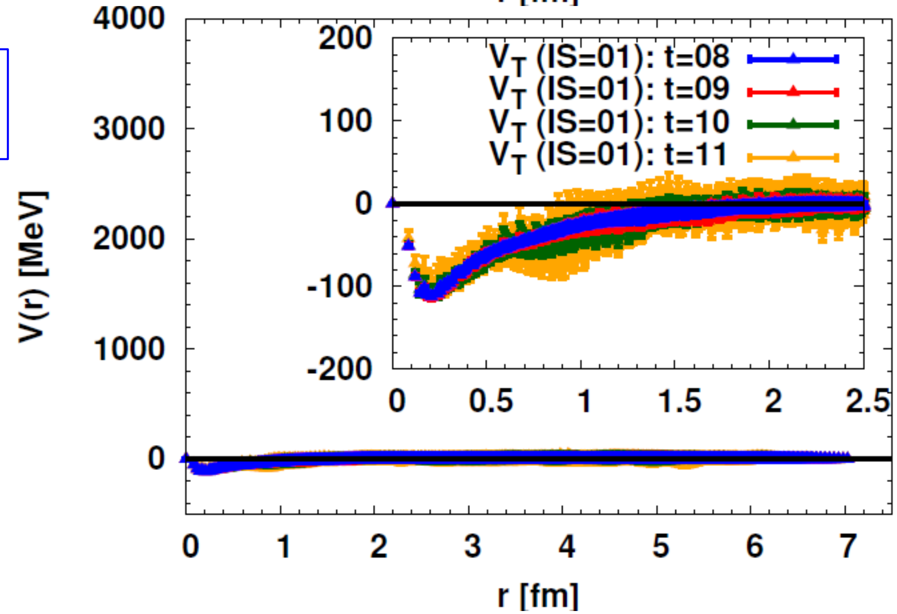


$^3S_1$-$^3D_1$

Central



Tensor



Preliminary

- **Vc: repulsive core + long-range attraction**
- **Vt: strong tensor force !**

(400conf x 4rot x 96src)

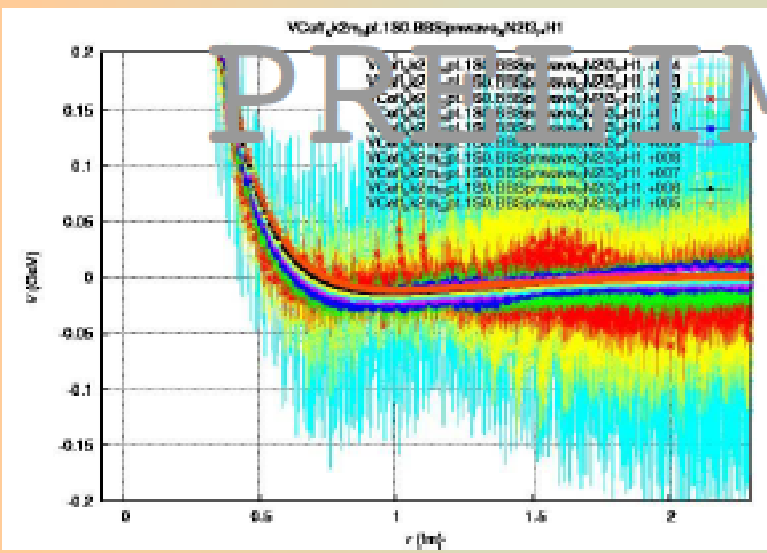
ΣN (I=3/2) potential in $^1S_0$, $^3S_1$–$^3D_1$

H. Nemura
(FLQCD2019)

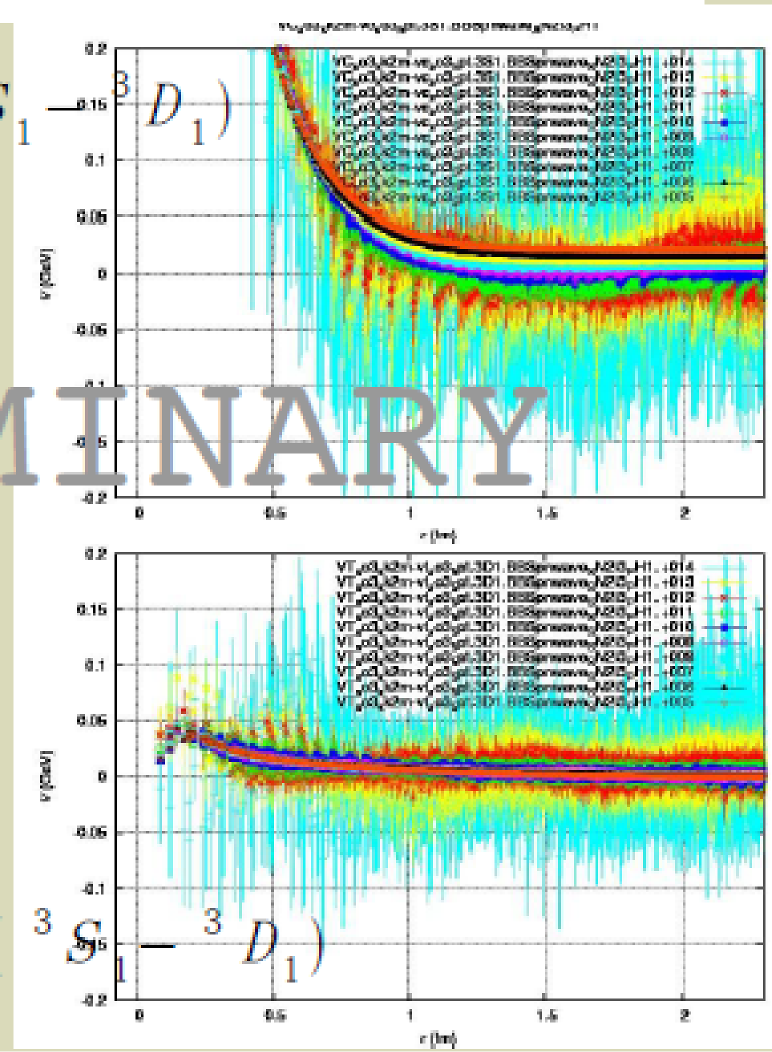
Very preliminary result of LN potential at the physical point

$$\left(\frac{\nabla^2}{2\mu} - \frac{\partial}{\partial t}\right) R(\vec{r},t) = \int d^3r' \, U(\vec{r},\vec{r}') R(\vec{r}',t) + O(k^4) = V_{\rm LO}(\vec{r}) R(\vec{r},t) + \cdots (8)$$

$\Sigma N \, (I=3/2)$



$V_C(^1S_0)$



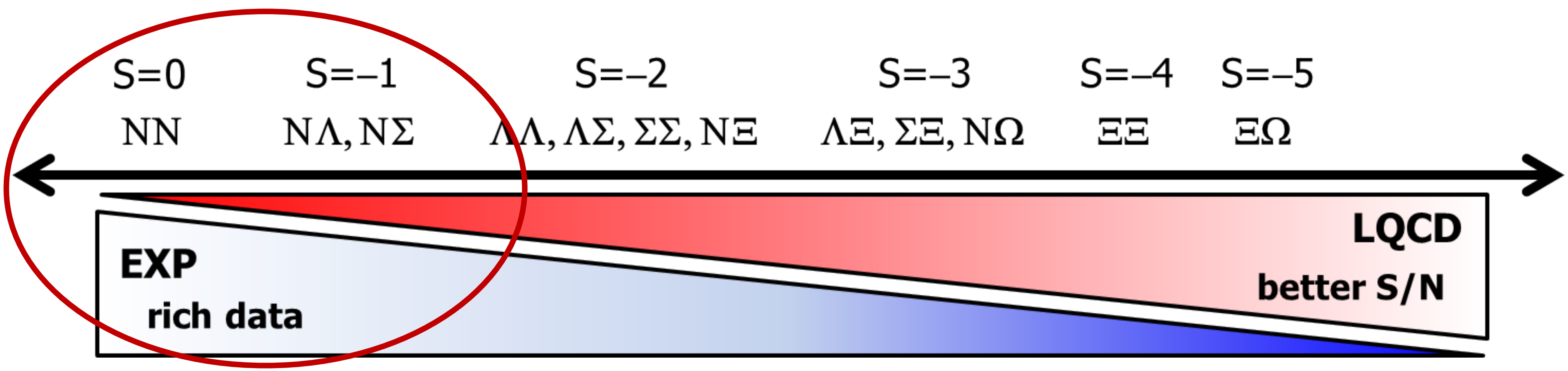
$V_C(^3S_1 - ^3D_1)$

$V_T(^3S_1 - ^3D_1)$

Lattice QCD @ heavier masses

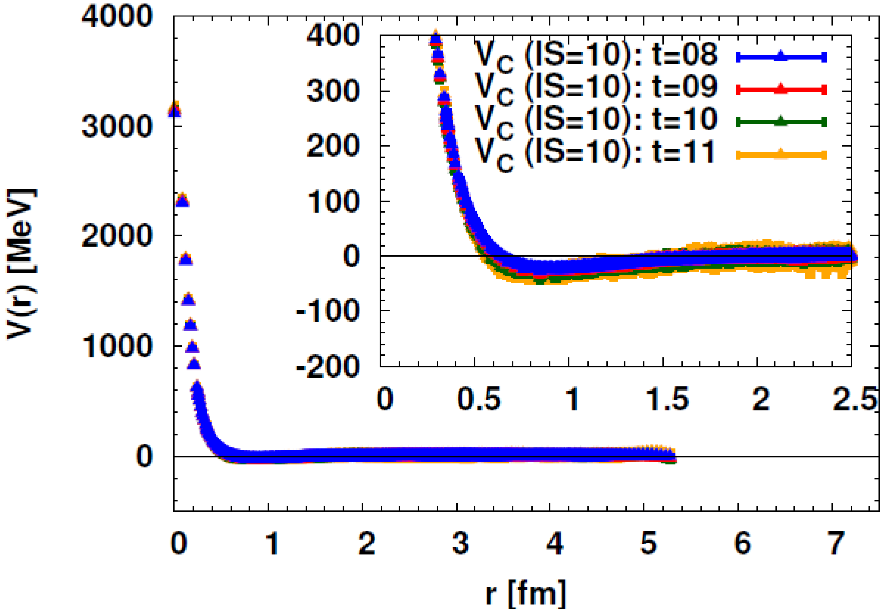
- **Nf = 2 + 1 gauge configs**
  - clover fermion + Iwasaki gauge w/ stout smearing ←→ same action
  - a=0.085fm (1/a = 2.3 GeV)
  - $V=(8.1\text{fm})^4$ w/ 96^4 → $V=(6.1\text{fm})^4$ w/ 72^4
  - (m(pi), m(K)) ~= (146, 525) MeV → (m(pi), m(K)) ~= (269, 532) MeV
    - Strange quark is retuned so that it is almost at physical mass (~parameter from PACS Coll.)
  - #traj ~= 2,000 generated → #traj ~= 14,000 generated

Coll. w/ I. Kanamori, K.-I. Ishikawa

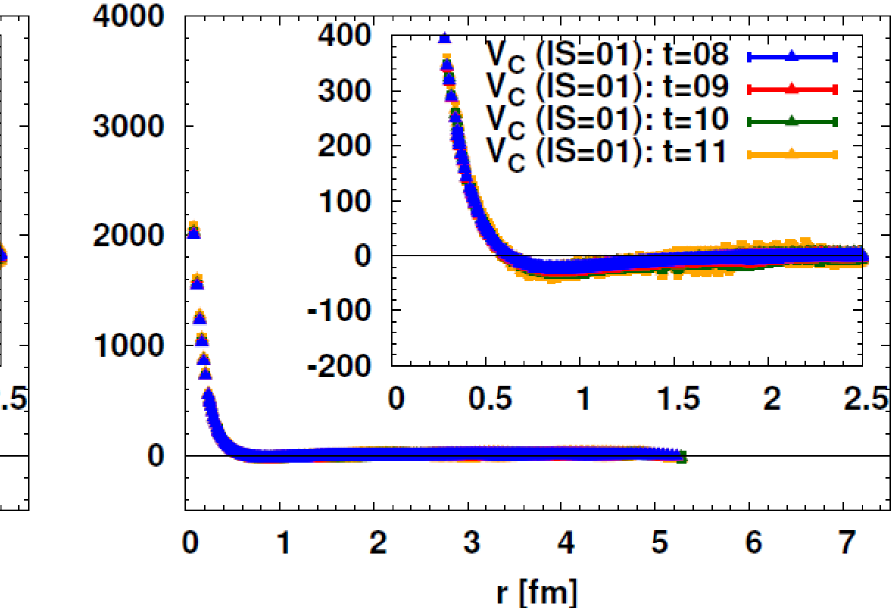


NN-Potentials

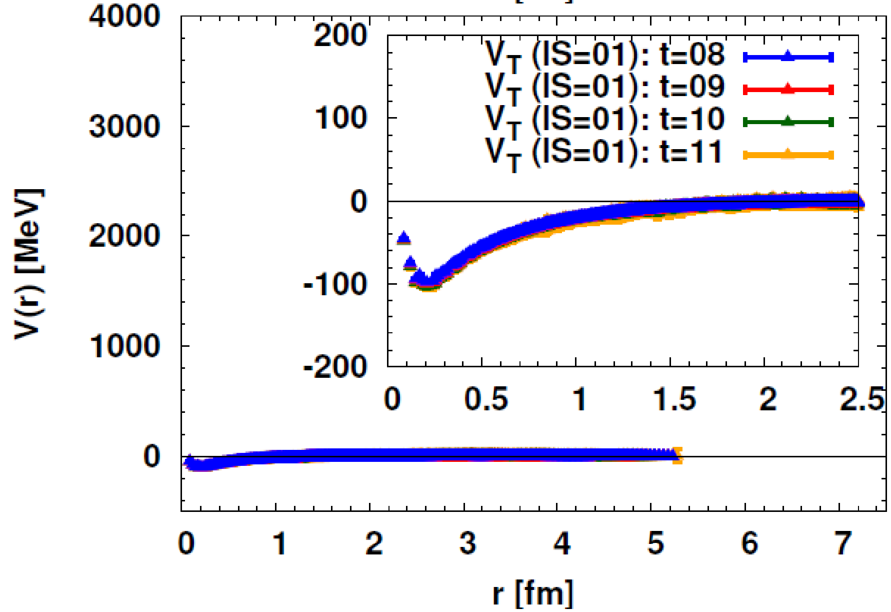
$^1S_0$



$^3S_1$-$^3D_1$



Central



Tensor

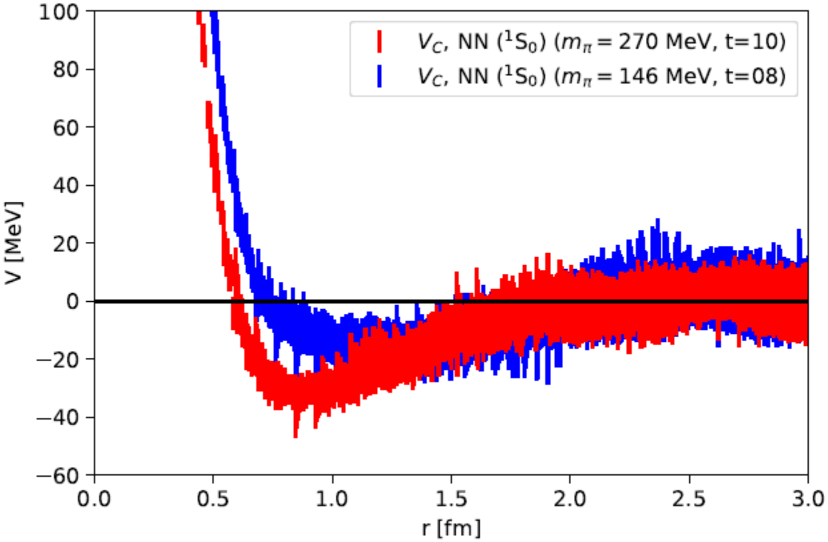
Much better S/N

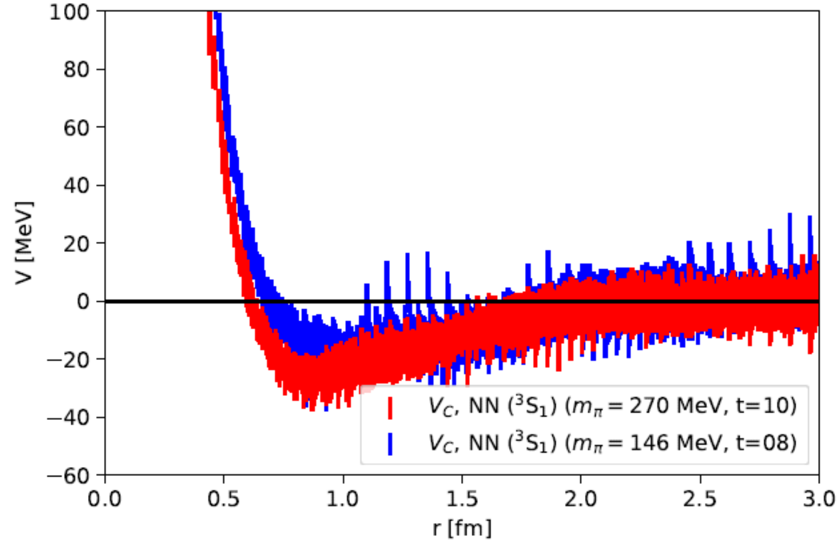
(Preliminary)

[T. Miyamoto]

NN

$^1S_0$ | $^3S_1$-$^3D_1$





Central

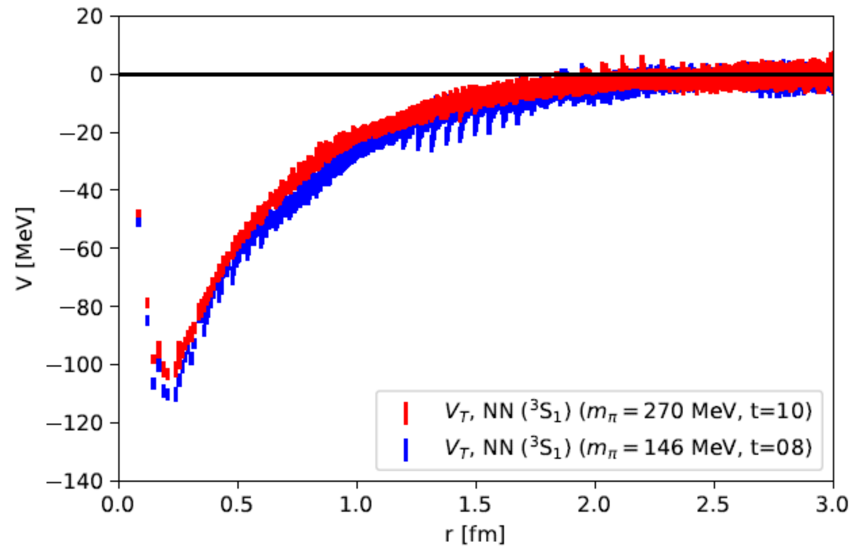
Blue: m(pi) = 146 MeV
Red: m(pi) = 270 MeV

heavier quark masses
←→ weaker tensor forces

(Preliminary)

[T. Miyamoto]

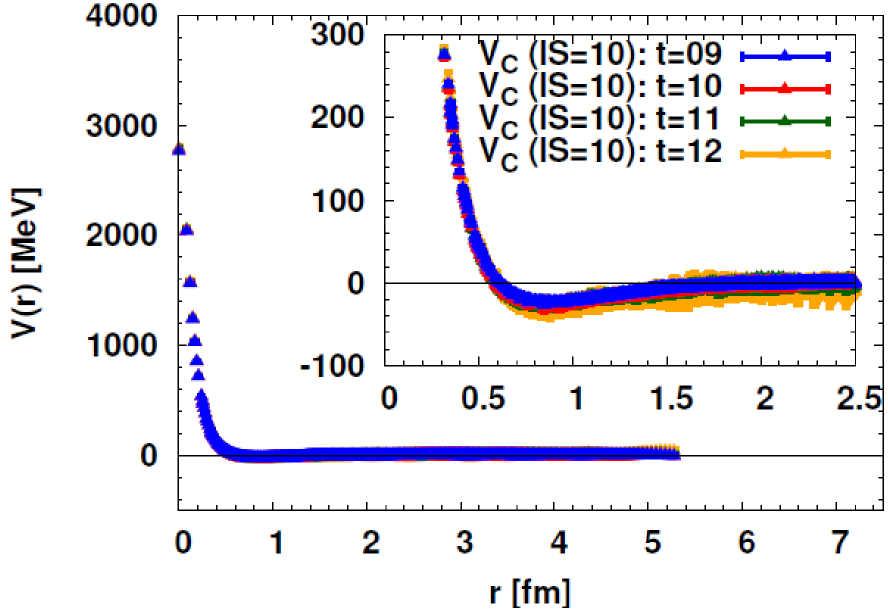
(N.B. sys err by t-dep could be larger)



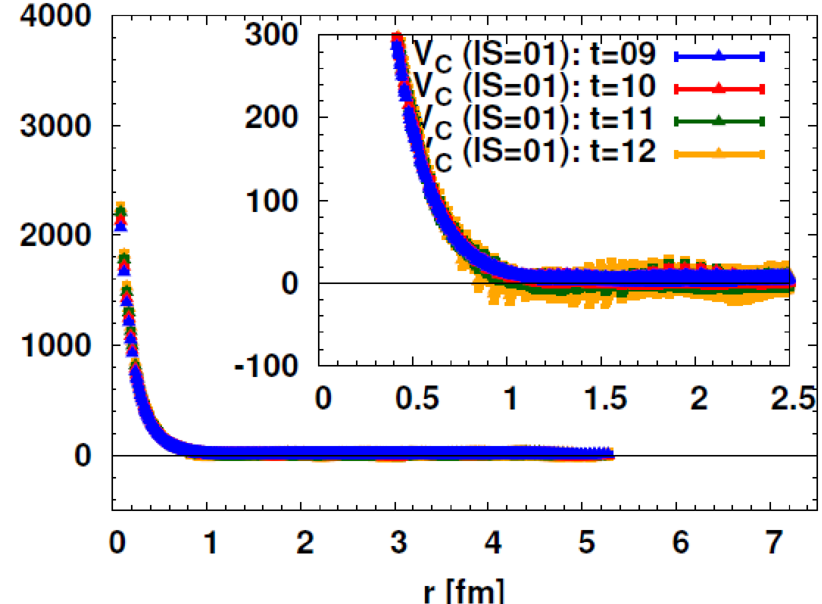
Tensor

ΣN (I=3/2)

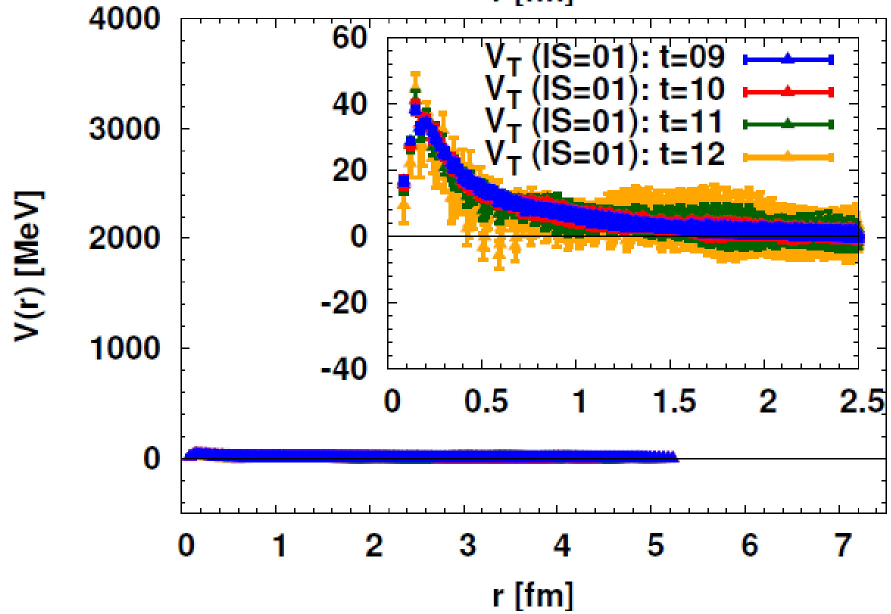
$^1S_0$ (27-plet)



$^3S_1$-$^3D_1$ (10-plet)



Central



Tensor

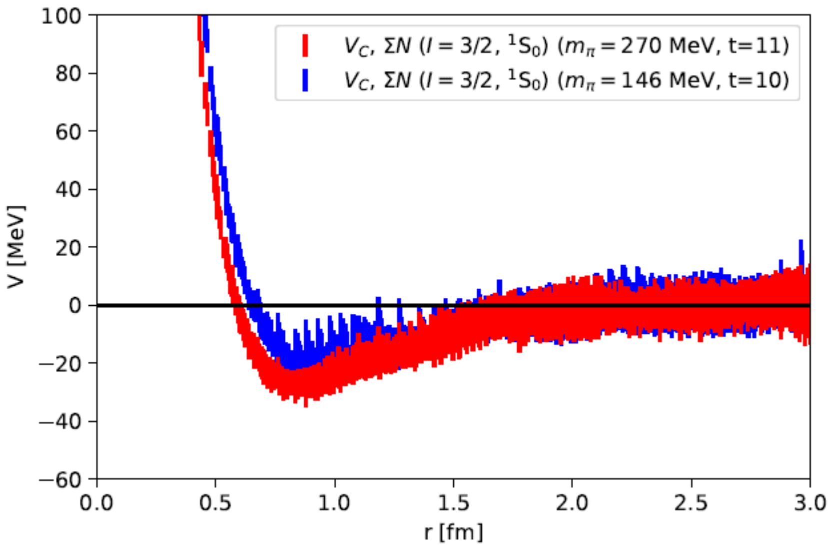
Much better S/N

(Preliminary)

[T. Miyamoto]

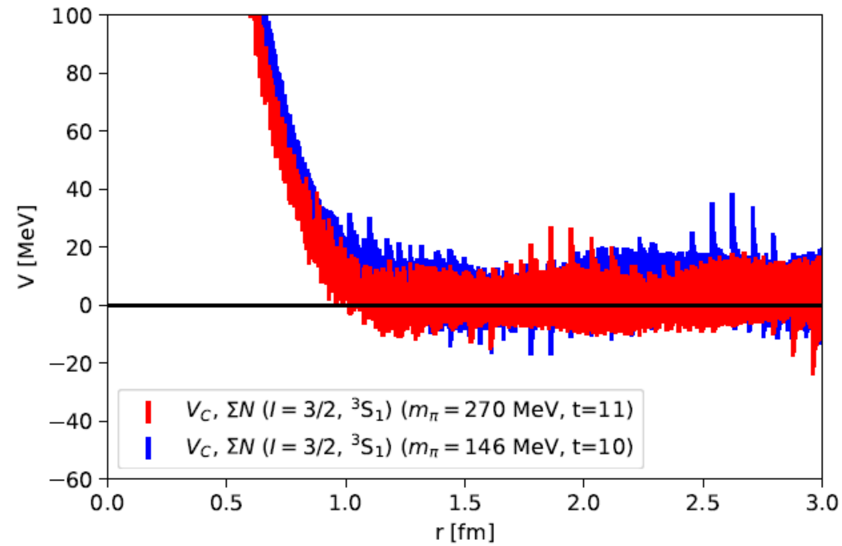
ΣN (I=3/2)

$^1S_0$ (27-plet)

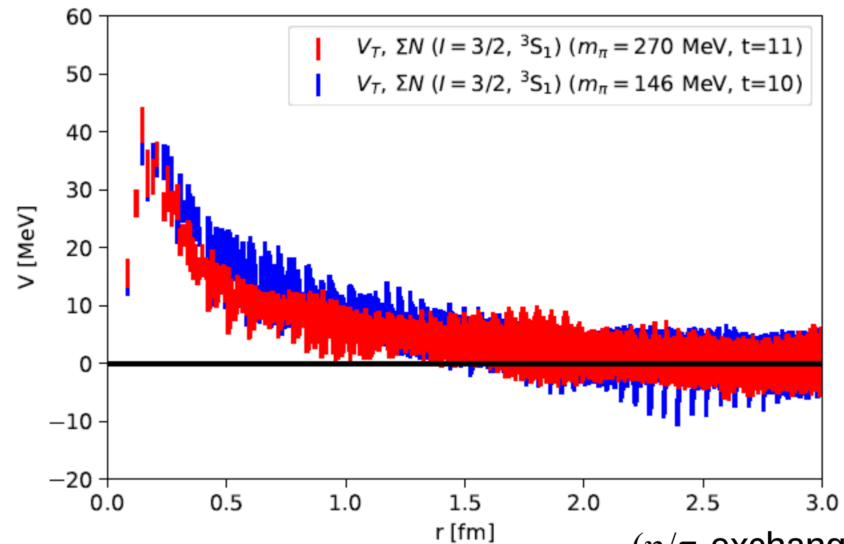


$^3S_1$-$^3D_1$ (10-plet)

Central



Tensor



(η/π-exchange ?)

Blue: m(pi) = 146 MeV
Red: m(pi) = 270 MeV

heavier quark masses
←→ weaker tensor forces

(Preliminary)

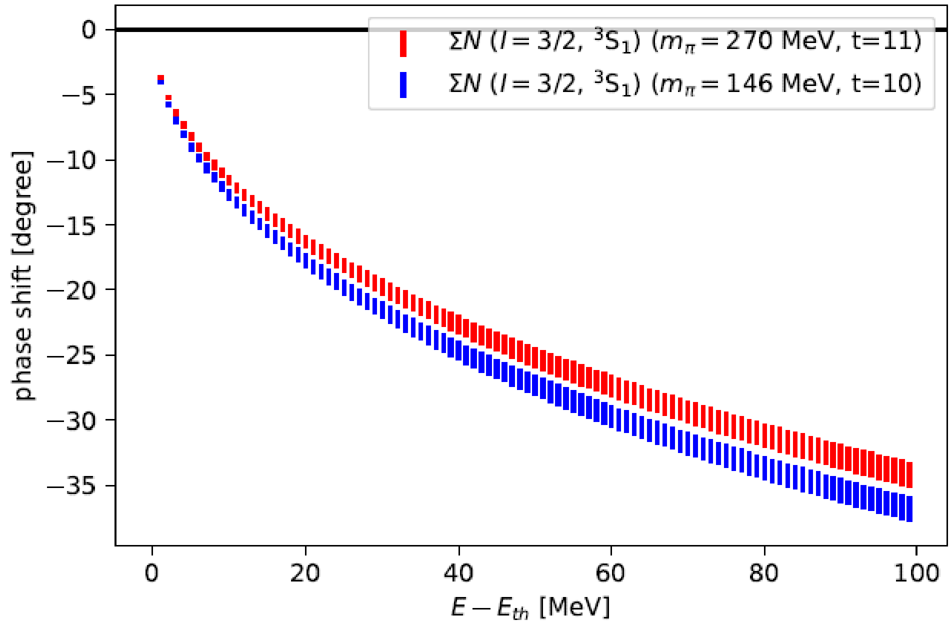
[T. Miyamoto]

(N.B. sys err by t-dep could be larger)

ΣN (I=3/2)

Very preliminary analysis for phase shifts

Effective $^3S_1$ channel



Dependence on fit-function of potential will be studied in future

Blue: m(pi) = 146 MeV
Red: m(pi) = 270 MeV

Strong repulsive core by quark-Pauli blocking effect
←→ J-PARC E40 exp

(Preliminary)

[T. Miyamoto]

(N.B. sys err by t-dep could be larger)

Σ^- in neutron star ?

Summary

- Baryon Interactions at m(pi) = 0.27 GeV
  - L ~= 6fm, 1/a ~= 2.3GeV
  - Central/Tensor forces for NN/YN/YY in P=(+) channel
  - Good signal even for small strangeness |S| sectors, e.g., S=0 (NN), S=-1 (ΛN, ΣN)

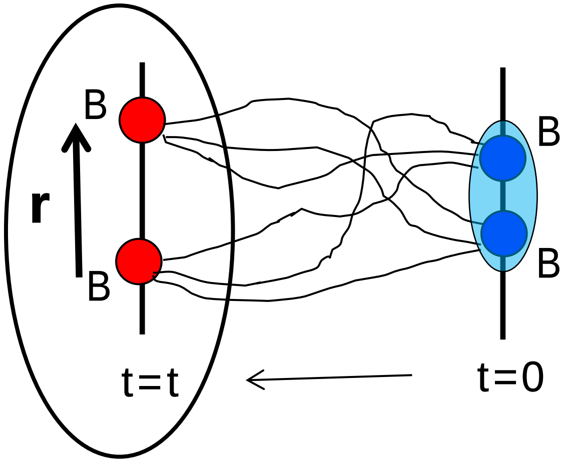
- Quark mass dependence of baryon interactions
  - Compared with results @ near physical point (m(pi) = 146 MeV)
  - Lighter/Heavier quark masses ←→ Stronger/Weaker tensor forces
  - Dependence in central forces could be more non-trivial

- TODO
  - Analysis w/ Misner's method (←→ talk by S. Aoki)
  - More statistics, More on Phase shift analysis
  - (better control of inelastic state contaminations)

Backup Slides

Operator dependence in the direct method

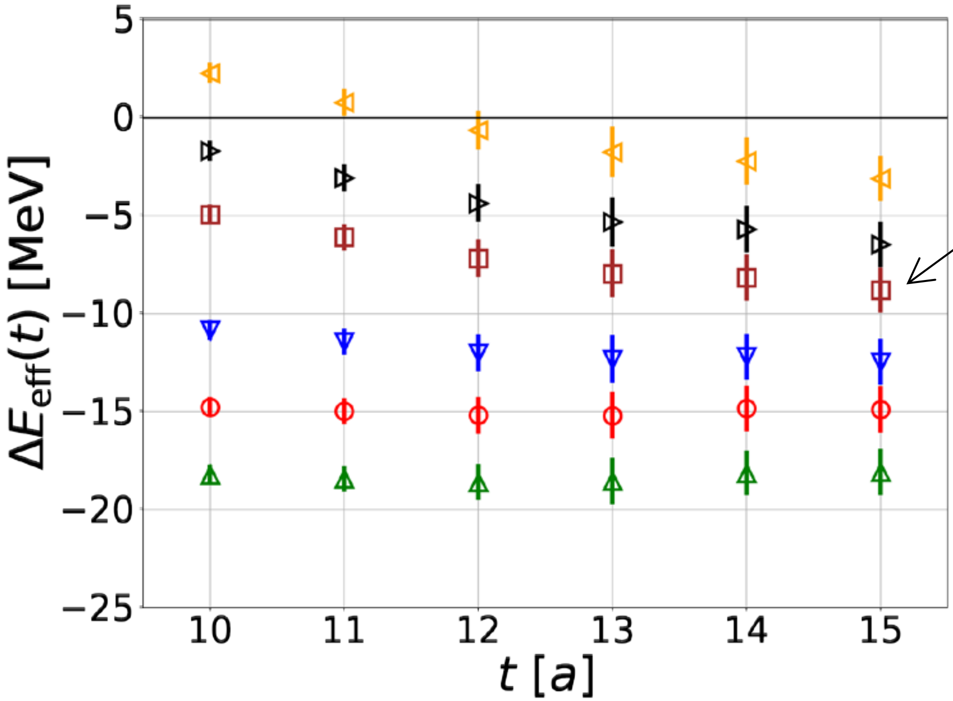
$$C_{2B}(t) = \langle 0|\mathrm{T}[\mathcal{J}^{2B}_{\rm sink}(t)\overline{\mathcal{J}}^{2B}_{\rm src}(0)]|0\rangle$$



Study sink op dep
w/ smeared src tuned in single-baryon

$$\mathcal{J}^{2B}_{\rm sink} = \sum_{\vec{r}} g(r) \sum_{\vec{x}} B(\vec{r}+\vec{x})B(\vec{x})$$

Usual direct method: g(r)=1 only

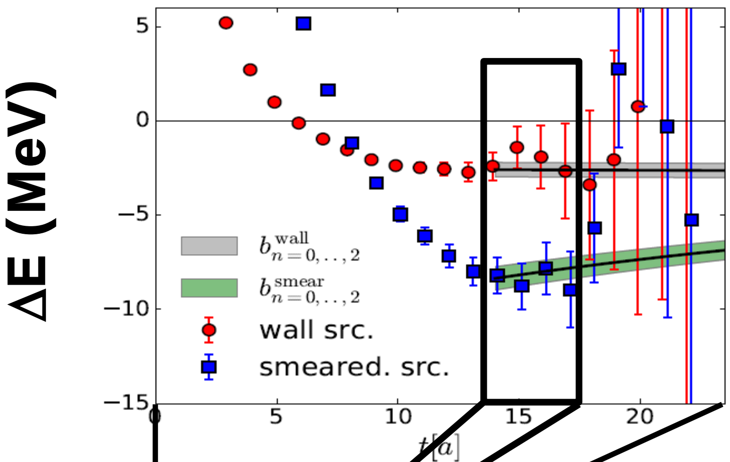


No predictive power in direct method w/ naïve plateau fitting !

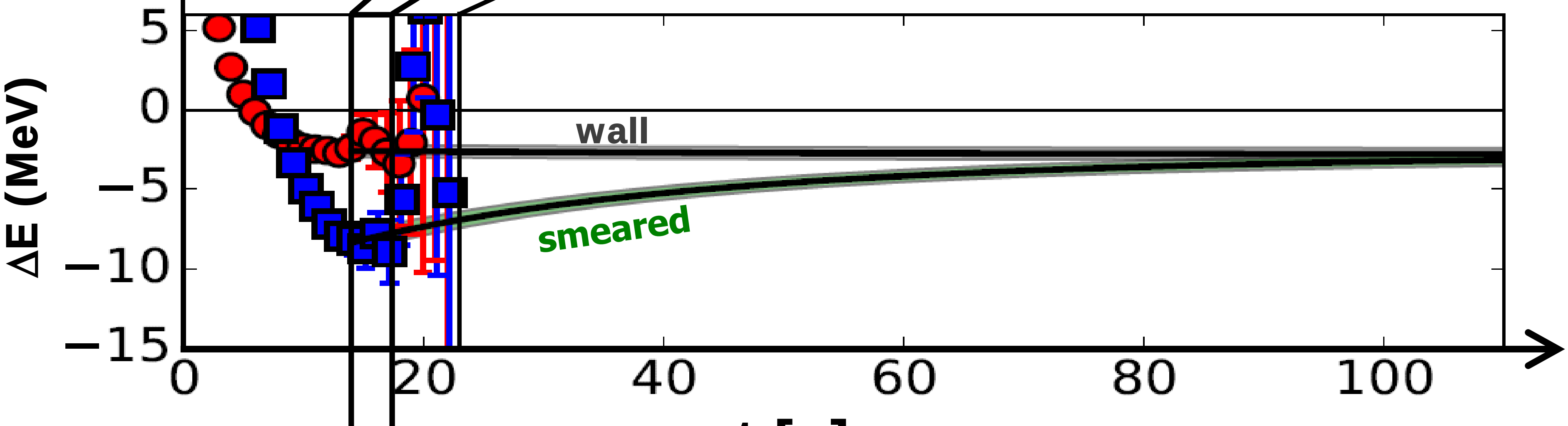
T. Iritani et al. JHEP10(2016)101 + update

Understand the origin of "pseudo-plateaux"

We are now ready to "predict" the behavior of m(eff) of ΔE at any "t"



"prediction" reproduce the real data well



"pseudo-plateaux" at t ~ 1fm

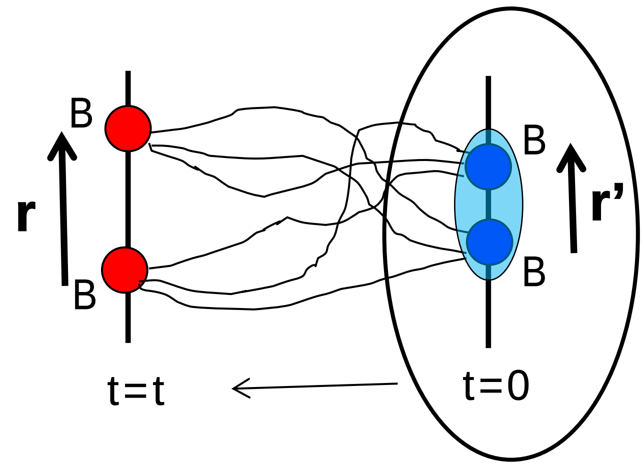
"real plateau" at t ~ 10fm

(E_1-E_0=50MeV)

Ideal and real of “optimized” smeared src

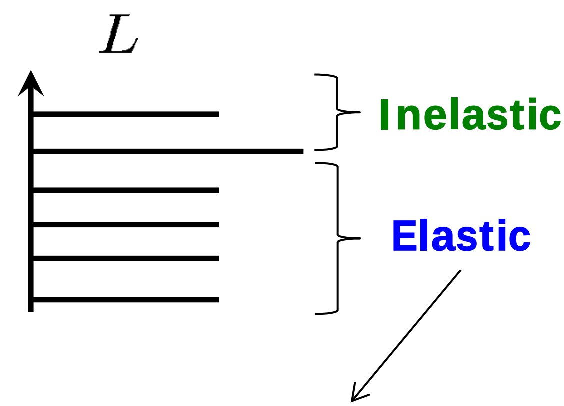
Smeared src:

Optimized to suppress **1-body inelastic states**



Recall the real challenge for two-baryon systems:

➔ Noises from **2-body elastic excited states**

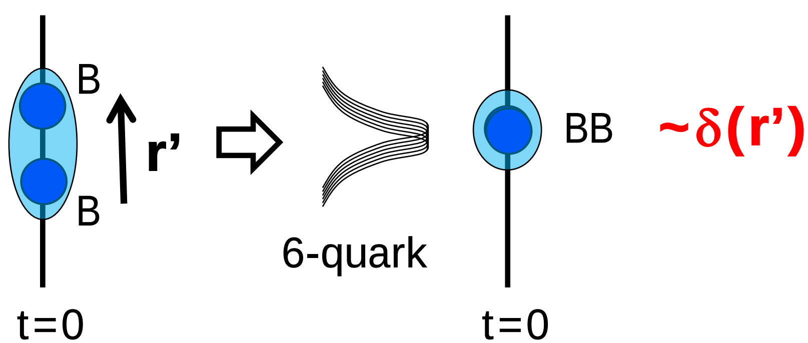


➔ Traditional smeared src is NOT optimized for two-body systems !

$$\sim B(\vec{p'})B(-\vec{p'}),\ \vec{p'} = (2\pi/L)\vec{n}$$

Detailed implementation of smeared src

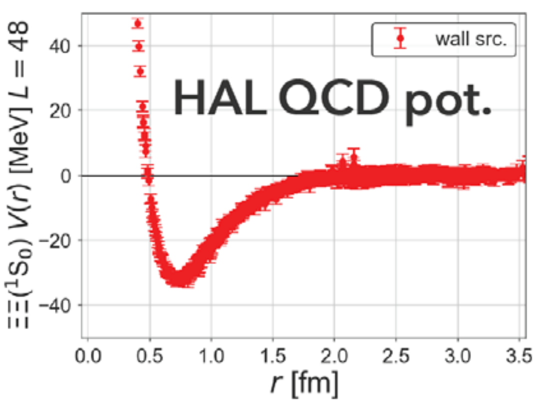
all 6-quarks are smeared at the same spacial point



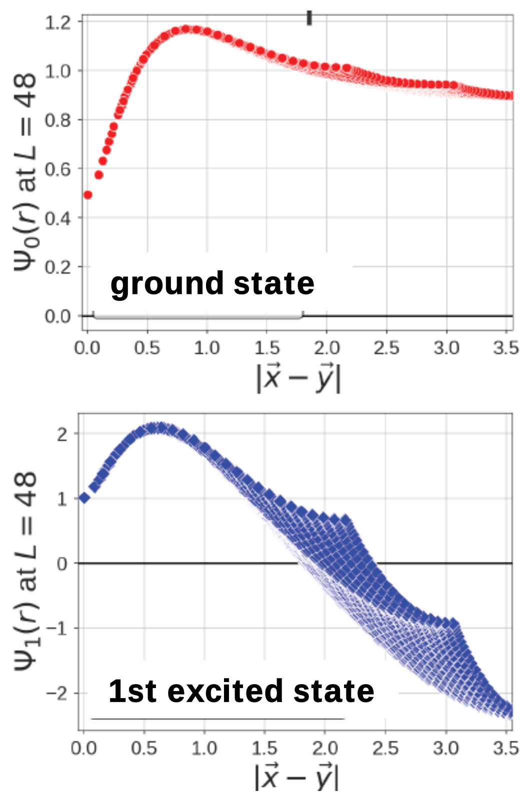
➔ Large contaminations from 2-body elastic excited states are “rather natural”

Operator optimized for 2-body system by HAL

- HAL method ➔ HAL pot ➔ 2-body wave func. @ finite V
- 2-body wave func. ➔ optimized operator
  - Applicable for sink and/or src op : Here we apply for sink op
- While utilizing info by HAL, formulation is Luscher's method

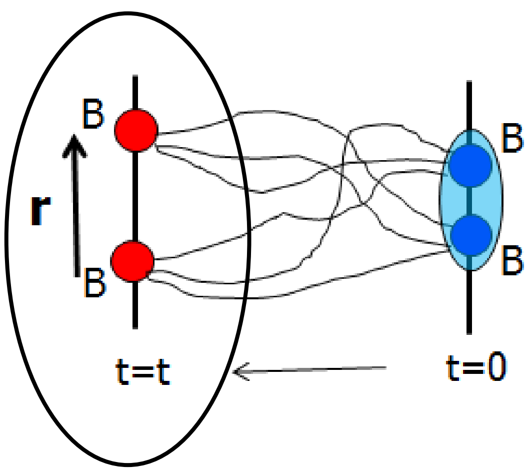


wave func. ψ(r)



HAL-optimized sink op

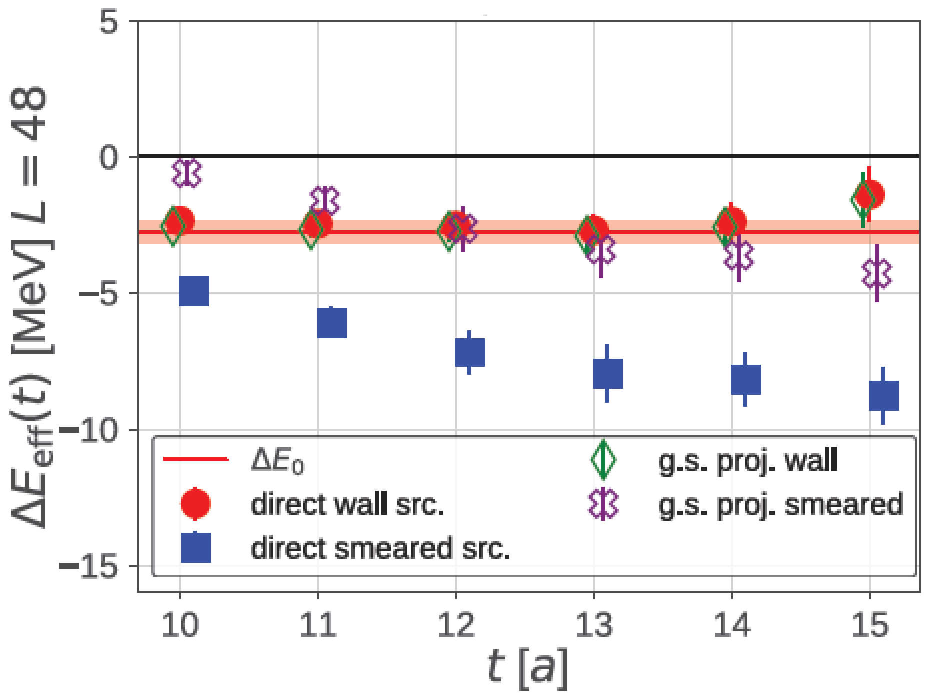
$$\mathcal{J}^{2B}_{\rm sink} = \sum_{\vec{r}} \psi^\dagger(r) \sum_{\vec{x}} B(\vec{r}+\vec{x}) B(\vec{x})$$



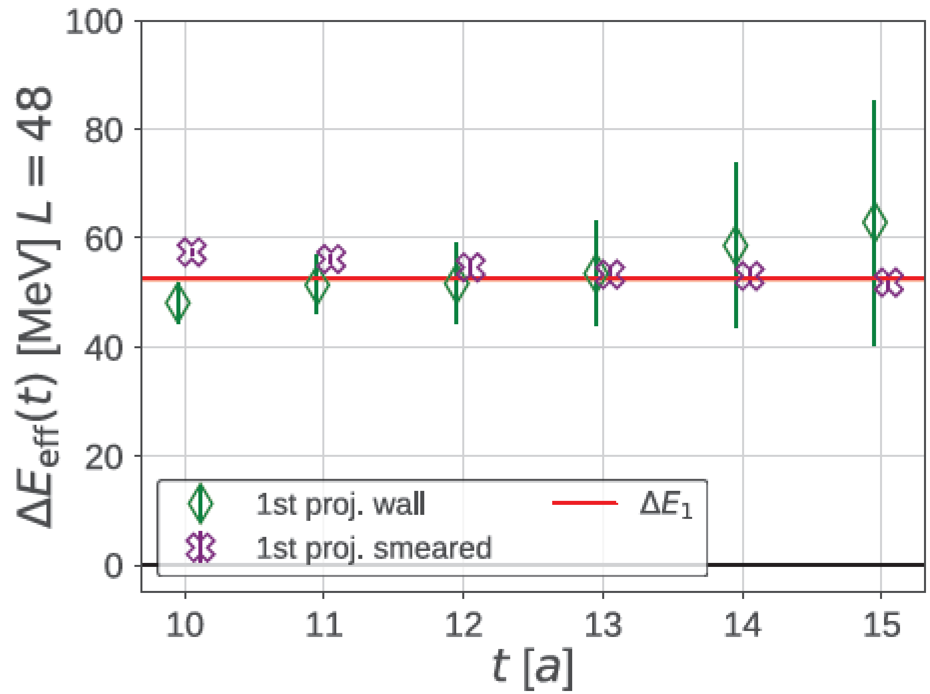
Effective energy shift ΔE from “HAL-optimized op”

HAL-optimized sink op ➔ projected to each state ➔ “True” plateaux

Ground State



1st excited state



HAL QCD pot = Lushcer’s method w/ proper projection

≠ Direct method w/ naïve plateau fitting