Recent developments on LQCD studies of nuclear force

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Plan of research

QCD

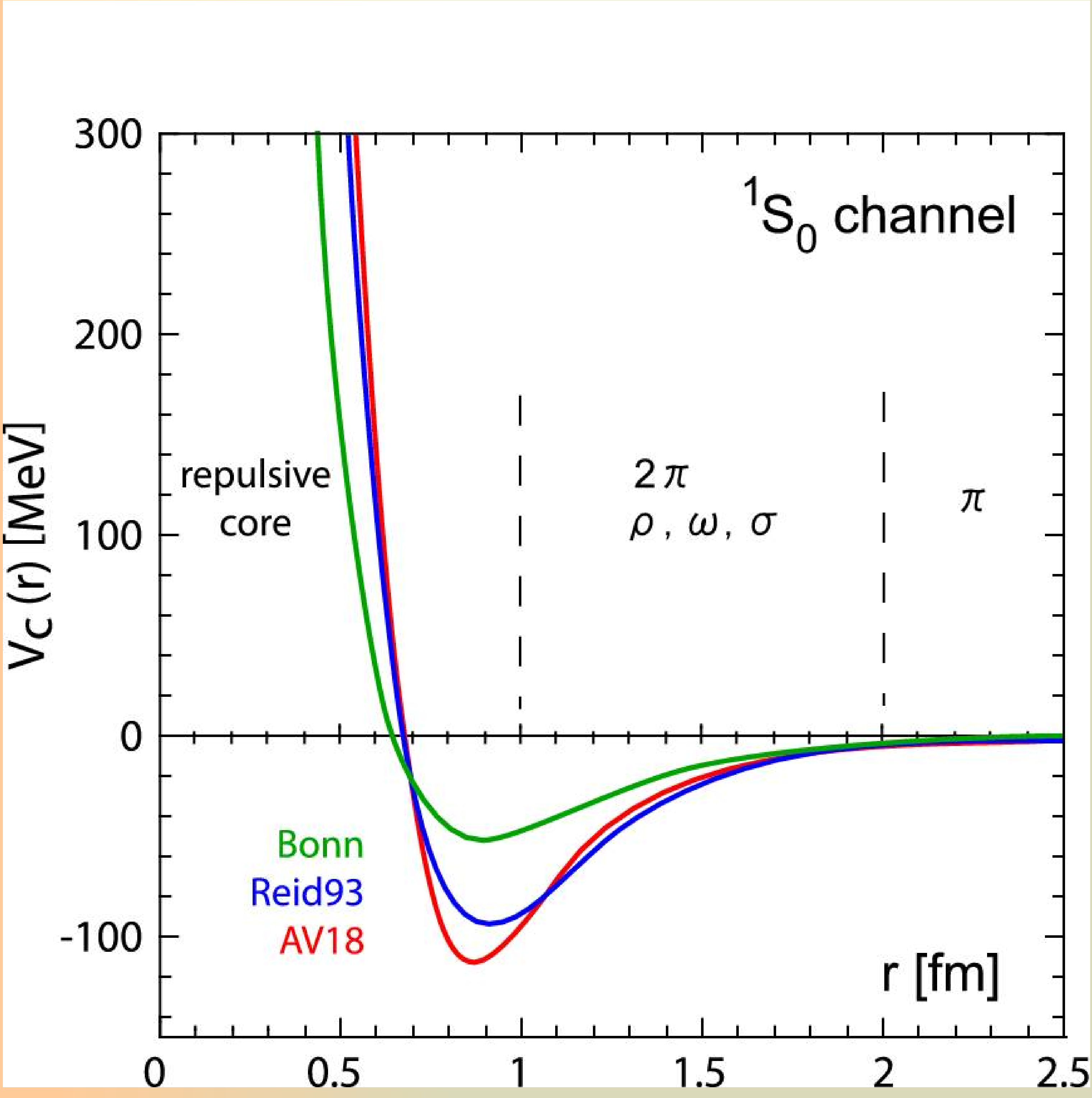
Baryon interaction

J-PARC
hyperon-nucleon (YN) scattering

Structure and reaction of (hyper)nuclei

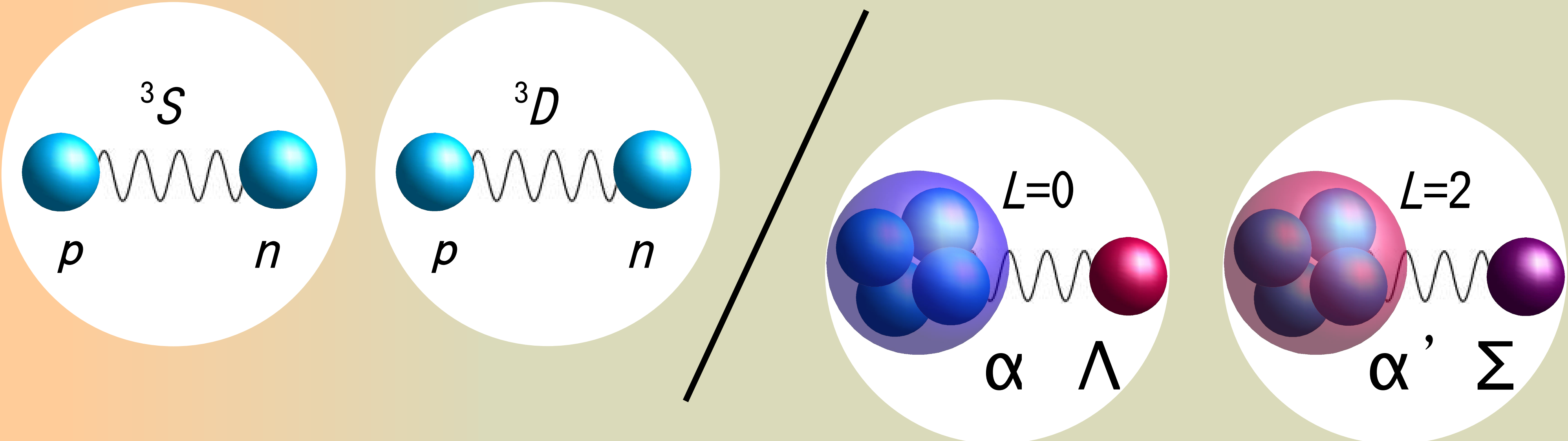
Equation of State (EoS) of nuclear matter

Neutron star and supernova



$^1S_0$ channel
repulsive core
2π
ρ, ω, σ
π
Bonn
Reid93
AV18
V_C (r) [MeV]
r [fm]
300
200
100
0
-100
0
0.5
1
1.5
2
2.5

Comparison between d=p+n and core+Y



	$\langle T_S \rangle$ (MeV)	$\langle T_D \rangle$ (MeV)	$\langle V_{NN}(\mathrm{central}) \rangle$ (MeV)	$\langle V_{NN}(\mathrm{tensor}) \rangle$ (MeV)	$\langle V_{NN}(\mathrm{LS}) \rangle$ (MeV)
AV8	8.57	11.31	−4.46	−16.64	−1.02
G3RS	10.84	5.64	−7.29	−11.46	0.00

	$\langle T_{Y\text{-}c} \rangle_\Lambda$	$\langle T_{Y\text{-}c} \rangle_\Sigma + \Delta \langle H_C \rangle$	$\langle V_{YN}$(のこり)$\rangle$	$2\langle V_{\Lambda N-\Sigma N}(\mathrm{tensor}) \rangle$
${}^{5}_{\Lambda}\mathrm{He}$	9.11	3.88+4.68	−0.86	−19.51
${}^{4}_{\Lambda}\mathrm{H}^*$	5.30	2.43+2.02	0.01	−10.67
${}^{4}_{\Lambda}\mathrm{H}$	7.12	2.94+2.16	−5.05	−9.22

Outline

- Introduction
- Formulation --- potential (central + tensor)
- Numerical results:
  - $N\Lambda$ force (V_C + V_T)
  - $N\Sigma$ (I=3/2) force (V_C + V_T)
- Recent improvement for Vc and VT
- Stochastic variational calculation of 4He with using a lattice potential
- Summary and outlook

Introduction:

- Study of hyperon-nucleon (*YN*) and hyperon-hyperon (*YY*) interactions is one of the important subjects in the nuclear physics.
  - Structure of the neutron-star core,
    - Hyperon mixing, softning of EOS, inevitable strong repulsive force,
  - H-dibaryon problem,
    - To be, or not to be,
- The project at J-PARC:
  - Explore the multistrange world,
- However, the phenomenological description of *YN* and *YY* interactions has large uncertainties, which is in sharp contrast to the nice description of phenomenological *NN* potential.

The purposes of this work

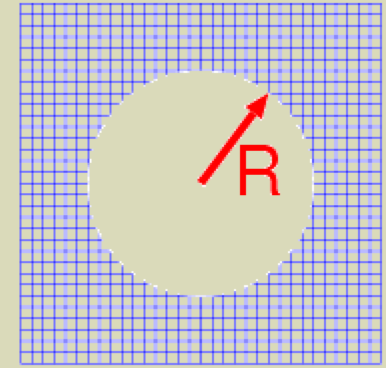
- NY forces from lattice QCD

- Spin dependence
- Potential (central + tensor)

- Numerical calculation:
  - Full lattice QCD by using N_F=2+1 PACS-CS full QCD gauge configurations with the spatial lattice volume $(2.86\ \mathrm{fm})^3$

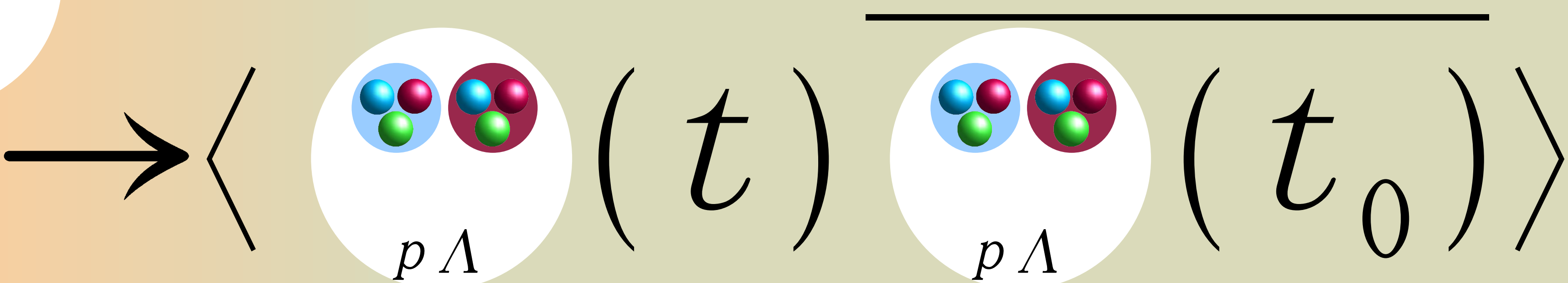
Formulation

Lattice QCD simulation



$$L = -\frac{1}{4} G^{a}_{\mu\nu} G^{a\mu\nu} + \bar{q}\gamma^{\mu}(i\partial_{\mu} - g t^{a} A^{a}_{\mu})q - m\bar{q}q$$

$$\begin{aligned}\langle O(\bar{q}, q, U)\rangle &= \int dU\, d\bar{q}\, dq\, e^{-S(\bar{q}, q, U)} O(\bar{q}, q, U) \\ &= \int dU \det D(U) e^{-S_U(U)} O(D^{-1}(U)) \\ &= \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} O(D^{-1}(U_i))\end{aligned}$$

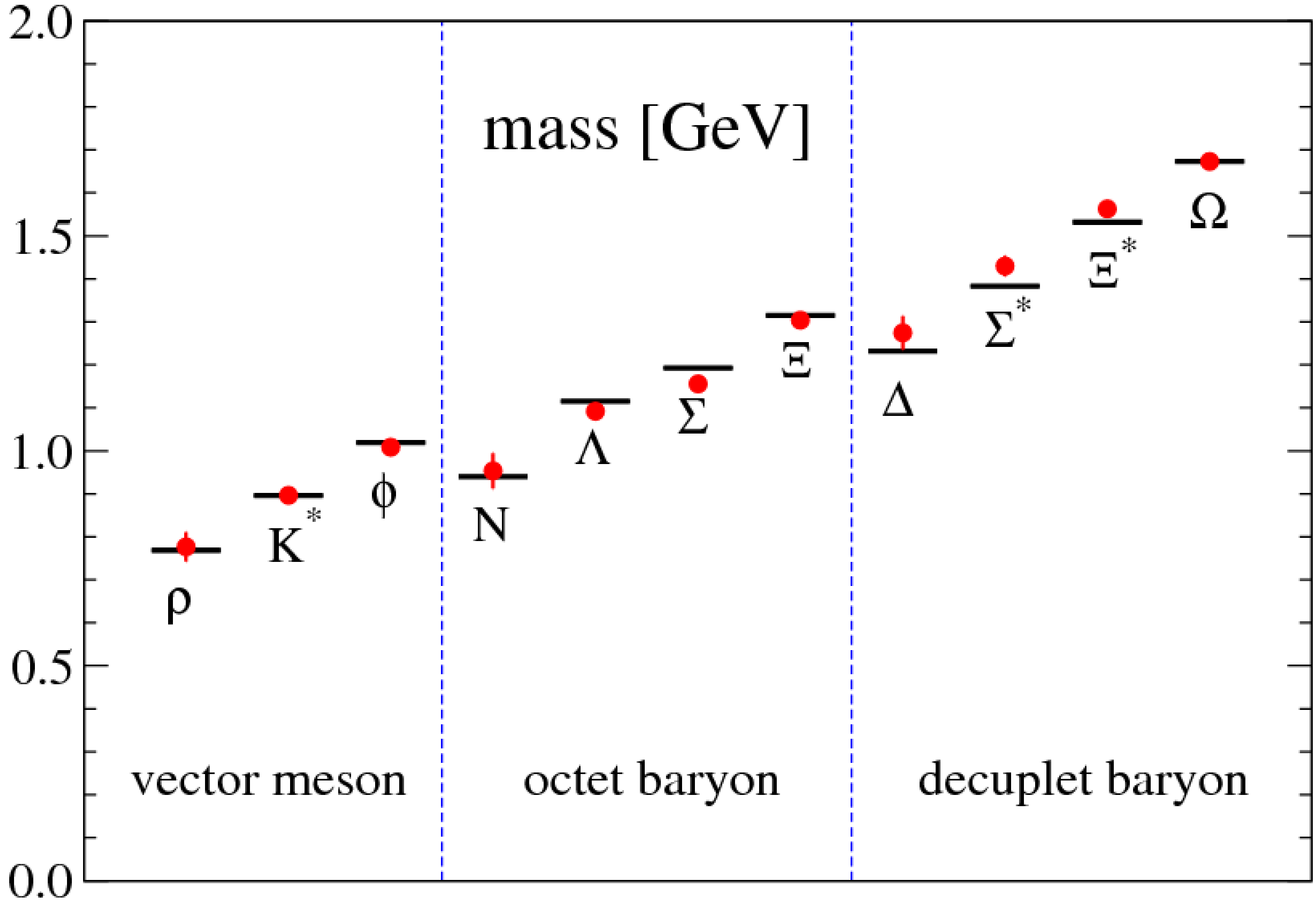


PHYSICAL REVIEW D **79**, 034503 (2009)

2 + 1 flavor lattice QCD toward the physical point

S. Aoki,[1,2] K.-I. Ishikawa,[4] N. Ishizuka,[1,3] T. Izubuchi,[2,5] D. Kadoh,[3] K. Kanaya,[1] Y. Kuramashi,[1,3] Y. Namekawa,[3] M. Okawa,[4] Y. Taniguchi,[1,3] A. Ukawa,[1,3] N. Ukita,[3] and T. Yoshié[1,3]

(PACS-CS Collaboration)



PHYSICAL REVIEW D **81,** 111504(R) (2010)

Helium nuclei in quenched lattice QCD

T. Yamazaki,[1] Y. Kuramashi,[1,2] and A. Ukawa[1]

(PACS-CS Collaboration)

[1]*Center for Computational Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan*
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(Received 7 December 2009; published 24 June 2010)

We present results for the binding energies for ^{4}He and ^{3}He nuclei calculated in quenched lattice QCD at the lattice spacing of $a = 0.128$ fm with a heavy quark mass corresponding to $m_\pi = 0.8$ GeV. Enormous computational cost for the nucleus correlation functions is reduced by avoiding redundancy of equivalent contractions stemming from permutation symmetry of protons or neutrons in the nucleus and various other symmetries. To distinguish a bound state from an attractive scattering state, we investigate the volume dependence of the energy difference between the nucleus and the free multinucleon states by changing the spatial extent of the lattice from 3.1 to 12.3 fm. A finite energy difference left in the infinite spatial volume limit leads to the conclusion that the measured ground states are bounded. It is also encouraging that the measured binding energies and the experimental ones show the same order of magnitude.

DOI: 10.1103/PhysRevD.81.111504 PACS numbers: 12.38.Gc, 21.45.−v, 27.10.+h

The atomic nuclei have been historically treated as collections of protons and neutrons. The great success of the nuclear shell model since 1949 [1,2], explaining the nuclear magic numbers and detailed spectroscopy, has established that protons and neutrons are very good effective degrees of freedom at the nuclear energy scale of a few MeV. Nonetheless, 60 years later, we know for certain that protons and neutrons are made of quarks and gluons whose laws are governed by QCD. It is a great challenge to quantitatively understand the structure and property of in quenched lattice QCD using a heavy quark mass at a single lattice spacing.

The binding energy ΔE of the nucleus, consisting of N_N nucleons with the mass m_N, is very tiny compared with the mass M of the nucleus: $\Delta E/M \sim O(10^{-3})$ with $\Delta E = N_N m_N - M$. This causes a complicated situation in that it is difficult to distinguish the physical binding energy from the energy shift due to the finite volume effect in the attractive scattering system [10]. One way to solve the problem is to investigate the volume dependence of the

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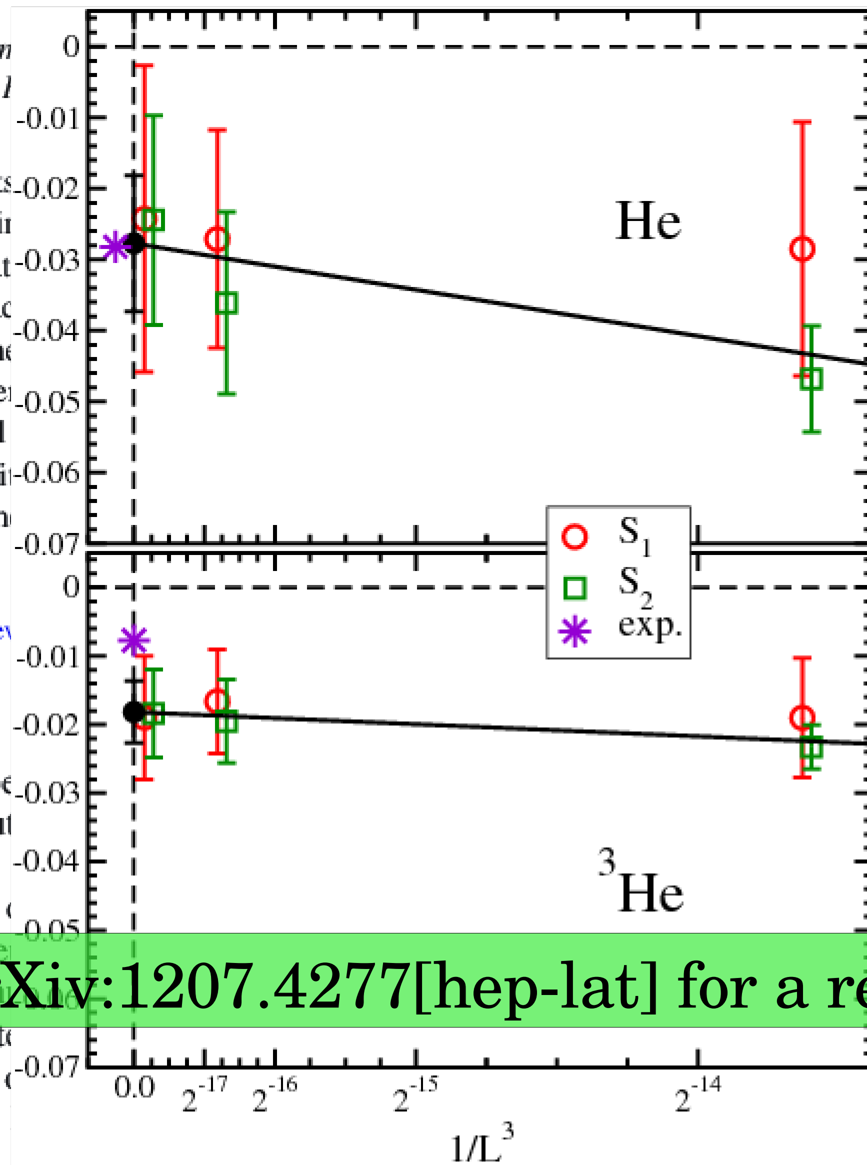

We present results … enched lattice QCD
at the lattice spaci … to $m_\pi = 0.8$ GeV.
Enormous computat … voiding redundancy
of equivalent contrac … ns in the nucleus and
various other symme … state, we investigate
the volume depende … ultinucleon states by
changing the spatial … ce left in the infinite
spatial volume limi … bounded. It is also
encouraging that th … the same order of
magnitude.

DOI: 10.1103/PhysRev … c, 21.45.−v, 27.10.+h

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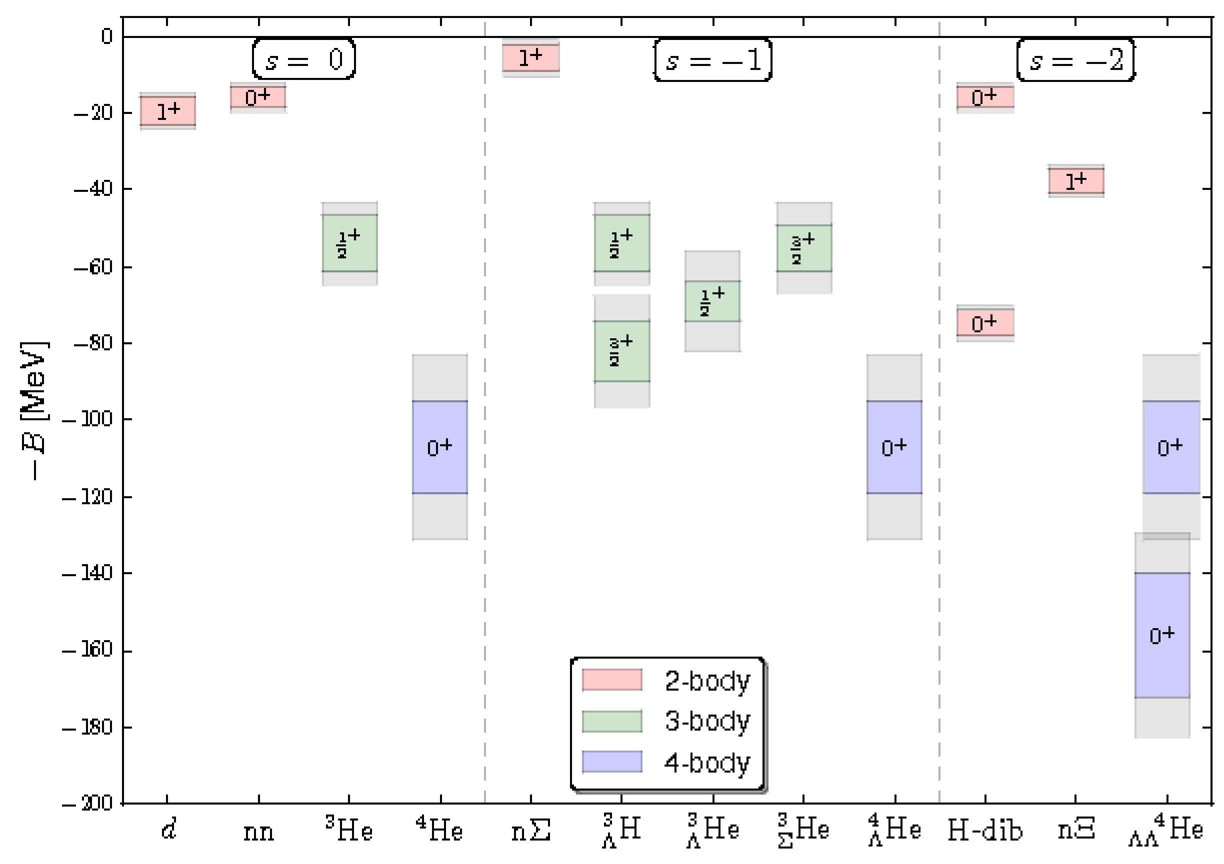
collections of protons and neut …
the nuclear shell model since … of the nucleus, consisting of N_N
nuclear magic numbers and … is very tiny compared with the
establi … $\Delta E/M \sim O(10^{-3})$ with ΔE =
tive de … that
MeV. Nonetheless, 60 years lat … n the physical binding energy
protons and neutrons are made … the finite volume effect in the
laws are governed by QCD. … n [10]. One way to solve the
quantitatively understand the … he volume dependence of the

See, e.g., arXiv:1207.4277[hep-lat] for a recent progress.

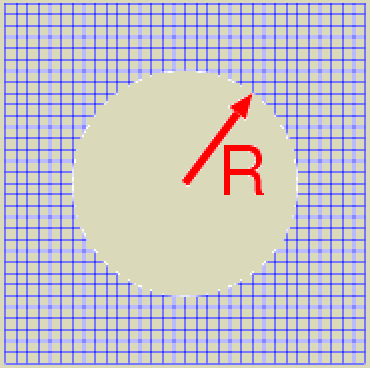


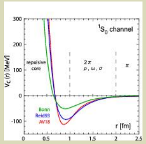
Light nuclei and hypernuclei from quantum chromodynamics in the limit of SU(3) flavor symmetry, PRD87, 034506 (2013)

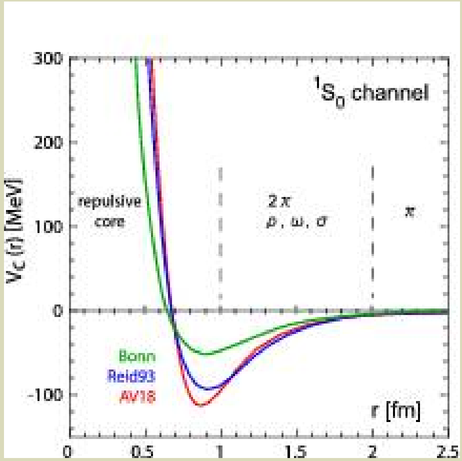
Formulation

i) basic procedure:
asymptotic region
--> phase shift

ii) advanced (HAL's) procedure: interacting region
--> potential







Formulation

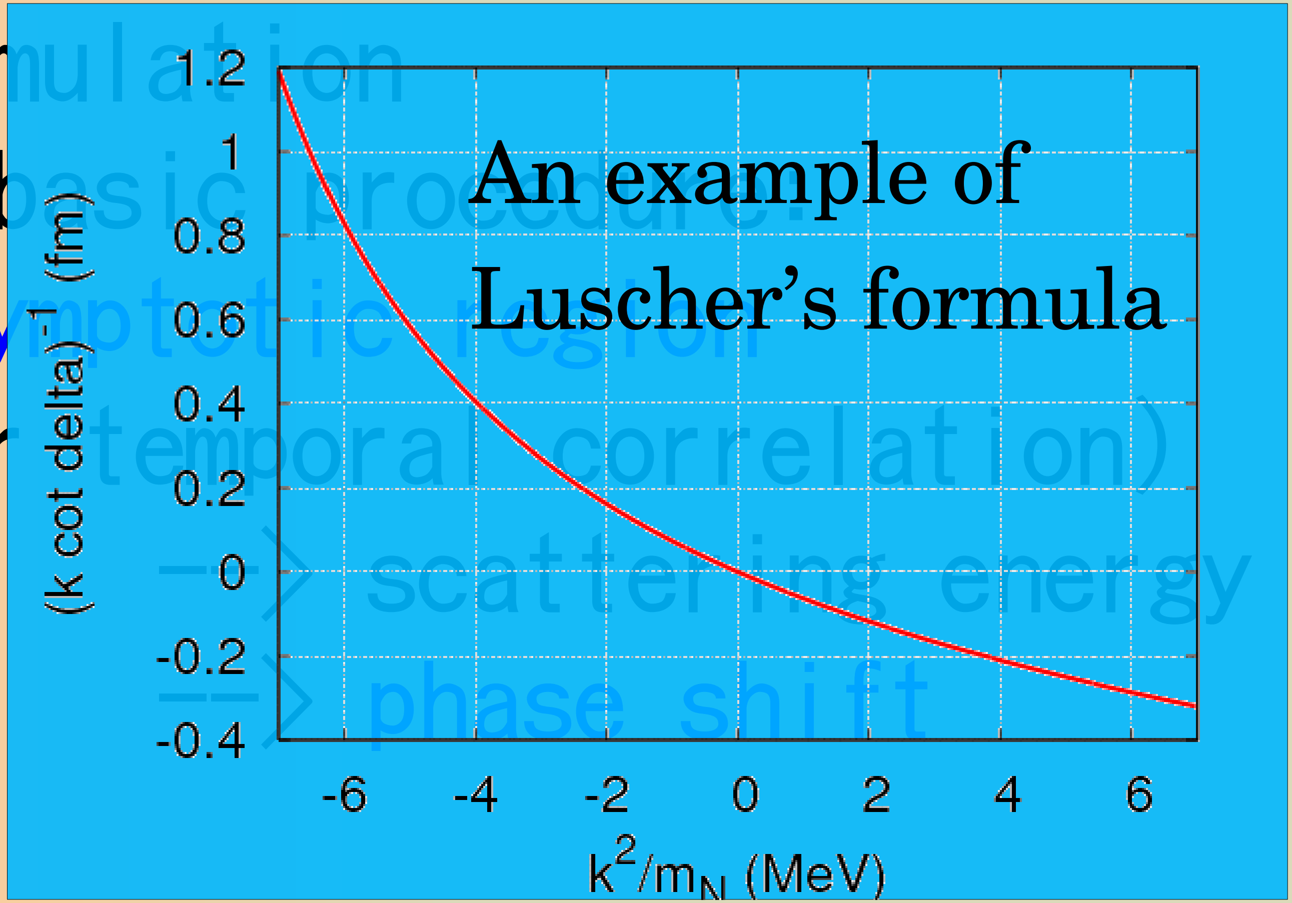
i) basic procedure:

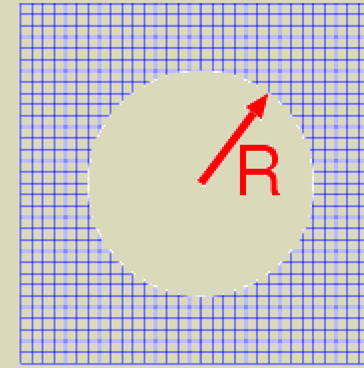
asymptotic region

(or temporal correlation)

--> scattering energy

--> phase shift





$$E=\frac{k^2}{2\mu}$$

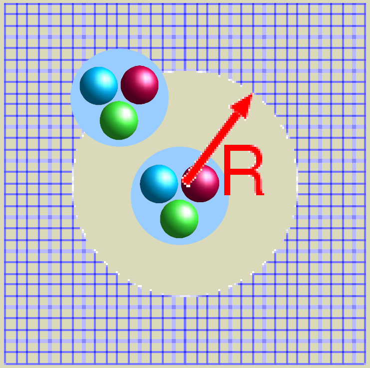
$$k\cot\delta_0(k)=\frac{2}{\sqrt{\pi}L}Z_{00}(1;(kL/(2\pi))^2)=\frac{1}{a_0}+O(k^2)$$

$$Z_{00}(1;q^2)=\frac{1}{\sqrt{4\pi}}\sum_{\vec{n}\in Z^3}\frac{1}{(n^2-q^2)^s} \qquad \Re\, s>\frac{3}{2}$$

Luscher, NPB354, 531 (1991).

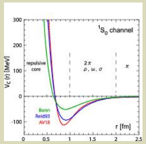
Aoki, et al., PRD71, 094504 (2005).

Formulation

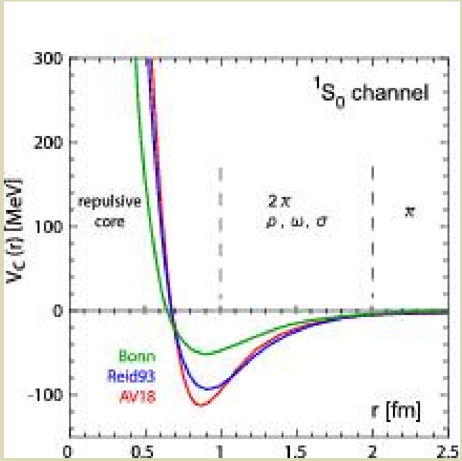


Lattice QCD simulation

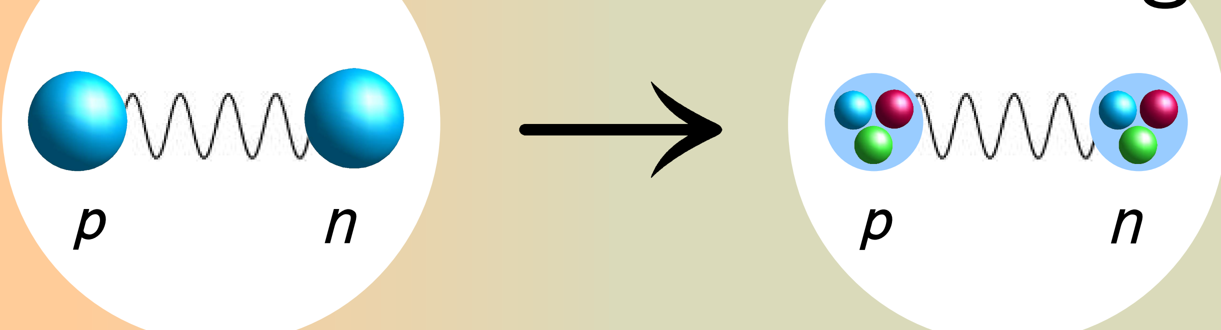
$$L = -\frac{1}{4} G^{a}_{\mu\nu} G^{a\mu\nu} + \bar{q}\gamma^{\mu}(i\partial_{\mu} - g t^{a} A^{a}_{\mu})q - m\bar{q}q$$



$$\langle O(\bar{q}, q, U)\rangle = \int dU\, d\bar{q}\, dq\, e^{-S(\bar{q}, q, U)} O(\bar{q}, q, U)$$
$$= \int dU \det D(U) e^{-S_U(U)} O(D^{-1}(U))$$
$$= \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} O(D^{-1}(U_i))$$



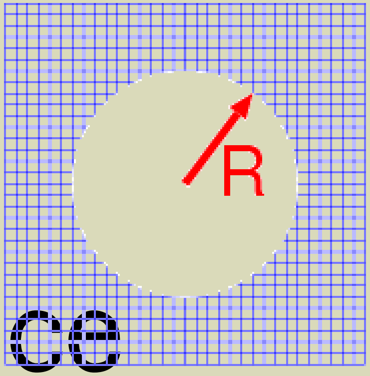
Calculate the scattering state



HAL formulation

ii) advanced procedure:

make better use of the lattice output ! (wave function)



interacting region

--> potential

Ishii, Aoki, Hatsuda,
PRL99, 022001 (2007);
ibid., arXiv:0805.2462[hep-ph].

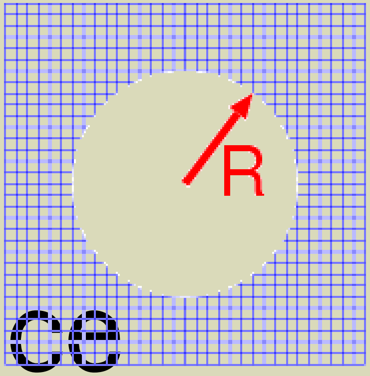
NOTE:

> Potential is not a direct experimental observable.

> Potential is a useful tool to give (and to reproduce) the physical quantities. (e.g., phase shift)

....

HAL formulation



ii) advanced procedure:

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Ishii, Aoki, Hatsuda,
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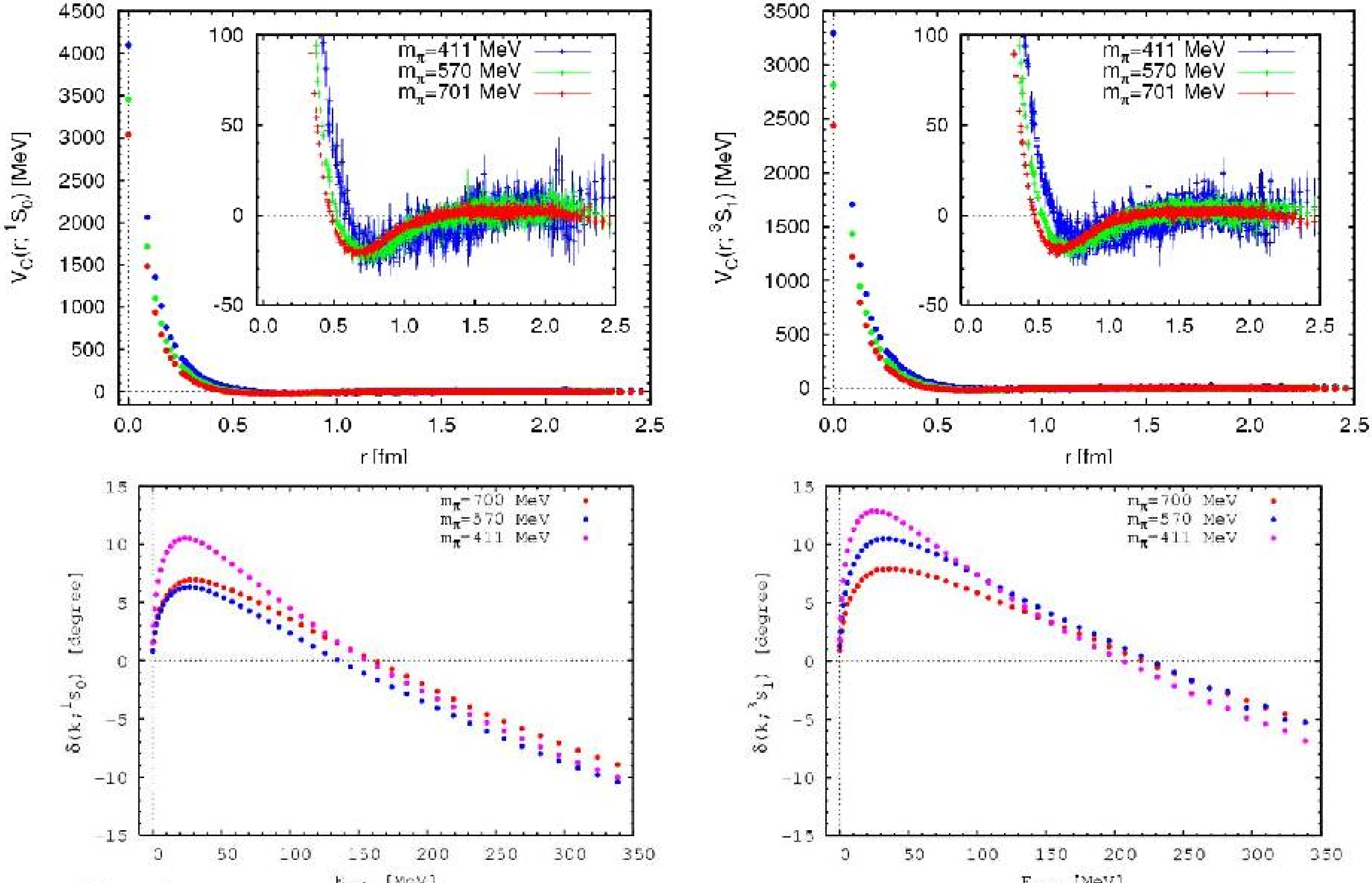
> Phase shift
> Nuclear many-body problems

> pn

NN (phase shift from potentials)



They have reasonable shapes.

Ishii (HAL QCD, 2010).

A recipe for NΛ potential:

.

- The equal time BS wave function with angular momentum (J,M) on the lattice,

$$\phi^{(JM)}_{\alpha\beta}(\vec{r}) = \sum_{\vec{x}} \left\langle 0 \left| p_\alpha(\vec{r}+\vec{x})\,\Lambda_\beta(\vec{x}) \right| p\Lambda\,; k\,, JM \right\rangle$$

$$p_\alpha(x) = \varepsilon_{abc}(u_a(x)\,C\gamma_5\,d_b(x))\,u_{c\alpha}(x)\,,$$

$$\Lambda_\alpha(x) = \varepsilon_{abc}\left\{(d_a C\gamma_5 s_b)\,u_{c\alpha} + (s_a C\gamma_5 u_b)\,d_{c\alpha} - 2(u_a C\gamma_5 d_b)\,s_{c\alpha}\right\}$$

- The 4-point $N\Lambda$ correlator on the lattice,

$$F^{(JM)}_{\alpha\beta}(\vec{x},\vec{y},t-t_0) = \left\langle 0 \left| p_\alpha(\vec{x},t)\,\Lambda_\beta(\vec{y},t)\,\overline{\Theta^{(JM)}_{p\Lambda}}(t_0) \right| 0 \right\rangle$$

$$= \sum_n A^{(JM)}_n \left\langle 0 \left| p_\alpha(\vec{x})\,\Lambda_\beta(\vec{y}) \right| E_n \right\rangle e^{-E_n(t-t_0)}$$

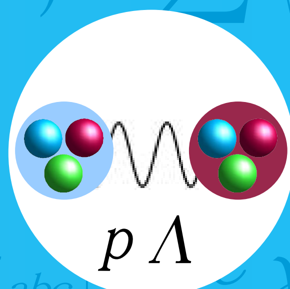
wall source at $t = t_0$

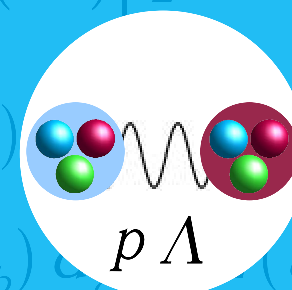
$$\overline{\Theta^{(JM)}_{p\Lambda}}(t_0)$$

A recipe for NΛ potential:

The (equal) time BS wave function with angular momentum (J,M) on the lattice,

$$F^{(JM)}_{\alpha\beta}(\vec{r}, t-t_0),$$

$\rightarrow \langle$ 

$(\vec{r}, t)$ 

$(t_0)\rangle$

- The 4-point NΛ correlator on the lattice,

$$F^{(JM)}_{\alpha\beta}(\vec{x},\vec{y},t-t_0) = \langle 0 | p_\alpha(\vec{x},t)\Lambda_\beta(\vec{y},t)\overline{\Theta^{(JM)}_{p\Lambda}}(t_0)|0\rangle$$

$$= \sum_n A^{(JM)}_n \langle 0 | p_\alpha(\vec{x})\Lambda_\beta(\vec{y})|E_n\rangle e^{-E_n(t-t_0)}$$

$\overline{\Theta^{(JM)}_{p\Lambda}}(t_0)$ wall source at $t = t_0$

An improved recipe for lattice potential:

- cf. Ishii (HAL QCD), PLB712 (2012) 437.

- Take account of the temporal correlation as well as the spatial correlation of the NBS amplitude in terms of the R-correlator:

$$R(t,\vec{r}) = \frac{C_{YN}(t,\vec{r})}{C_Y(t)C_N(t)}$$

$$R(t+\Delta t,\vec{r}) = \mathrm{e}^{-\Delta t H} R(t,\vec{r})$$

$$= (1-\Delta t H) R(t,\vec{r})$$

- Time-dependent effective Schroedinger eq.:

$$-\frac{\partial}{\partial t} R(t,\vec{r}) = H R(t,\vec{r})$$

An improved recipe for NY potential:

- cf. Ishii (HAL QCD), PLB712 (2012) 437.

- Take account of not only the spatial correlation but also the temporal correlation in terms of the R-correlator:

$$-\frac{1}{2\mu}\nabla^2 R(t,\vec{r})+\int d^3r' \, U(\vec{r},\vec{r}\,')R(t,\vec{r}\,')=-\frac{\partial}{\partial t}R(t,\vec{r})$$

$$\rightarrow \frac{k^2}{2\mu}R(t,\vec{r})$$

$$U(\vec{r},\vec{r}\,')=V_{NY}(\vec{r},\nabla)\delta(\vec{r}-\vec{r}\,')$$

- A general expression of the potential:

$$V_{NY}=V_0(r)+V_\sigma(r)(\vec{\sigma}_N\cdot\vec{\sigma}_Y)$$
$$+V_T(r)S_{12}+V_{LS}(r)(\vec{L}\cdot\vec{S}_+)$$
$$+V_{ALS}(r)(\vec{L}\cdot\vec{S}_-)+O(\nabla^2)$$

A recipe for NΛ potential:

- cf. Ishii (HAL QCD), PLB712 (2012) 437.

- Effective central potential is obtained from the effective Schroedinger equation.

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + V(r)\right) R(t,\vec{r}) = -\frac{\partial}{\partial t} R(t,\vec{r})$$

$$\rightarrow \quad V(r) = \frac{-\frac{\partial}{\partial t} R(t,\vec{r})}{R(t,\vec{r})} + \frac{\hbar^2}{2\mu} \frac{\nabla^2 R(t,\vec{r})}{R(t,\vec{r})}$$

A recipe for NY potential: (contd.)

- For $J = 1$, ϕ comprises *S*-wave and *D*-wave,

$$| \phi \rangle = | \phi_S \rangle + | \phi_D \rangle$$

where,

$$| \phi_S \rangle = \mathcal{P} | \phi \rangle = (1/24) \sum_{\mathcal{R} \in O} \mathcal{R} | \phi \rangle$$

$$| \phi_D \rangle = Q | \phi \rangle = (1 - \mathcal{P}) | \phi \rangle$$

- Therefore, we have 2-component Schrödinger eq.

S-wave:

$$\mathcal{P} (T + V_C + V_T S_{12}) |\phi\rangle = -\partial/\partial t \, \mathcal{P} |\phi\rangle$$

D-wave:

$$Q (T + V_C + V_T S_{12}) |\phi\rangle = -\partial/\partial t \, Q |\phi\rangle$$

- Obtain the $V_C(r)$ and the $V_T(r)$ simultaneously.

Numerical results

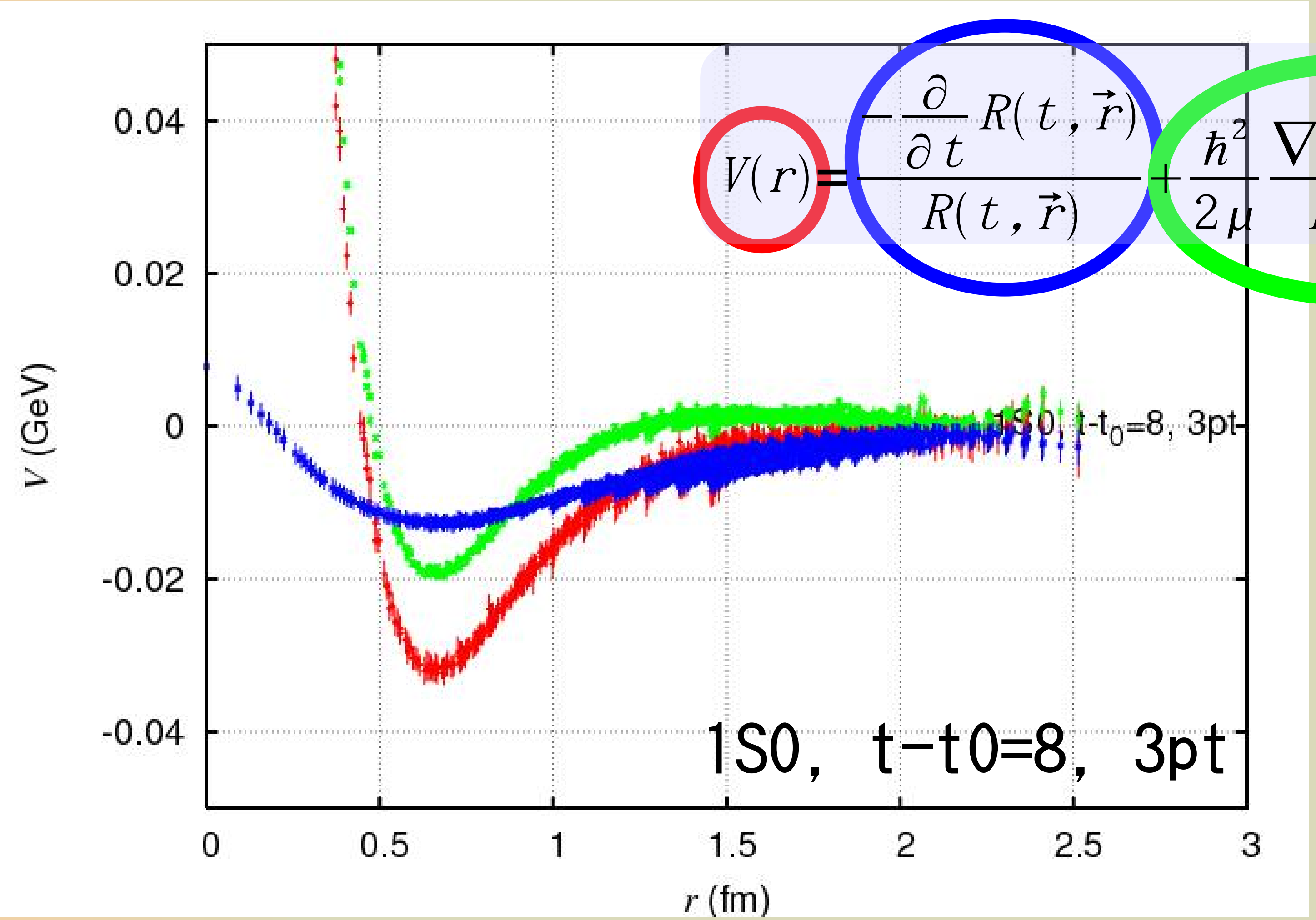
Full QCD calculations by using N_F=2+1 PACS-CS gauge configurations:

- S. Aoki, et al., (PACS-CS Collaboration), PRD**79**, 034503 (2009), arXiv:0807.1661 [hep-lat].
- Iwasaki gauge action at β=1.90 on $32^3 \times 64$ lattice
- O(a) improved Wilson quark action
- $1/a$ = 2.17 GeV (a = 0.0907 fm)

$(\kappa_{ud})_{N_{conf}}$	m_π	m_ρ	m_K	m_{K^*}	m_N	m_Λ	m_Σ	m_Ξ
2+1 flavor QCD by PACS-CS with κ_s = 0.13640 @present calc (Dirichlet BC along T)								
$(0.13700)_{609}$	700.0(4)	1108(3)	785.8(3)	1159(2)	1573(4)	1632(4)	1650(5)	1700(4)
Exp.	135	770	494	892	940	1116	1190	1320

ΛN potential

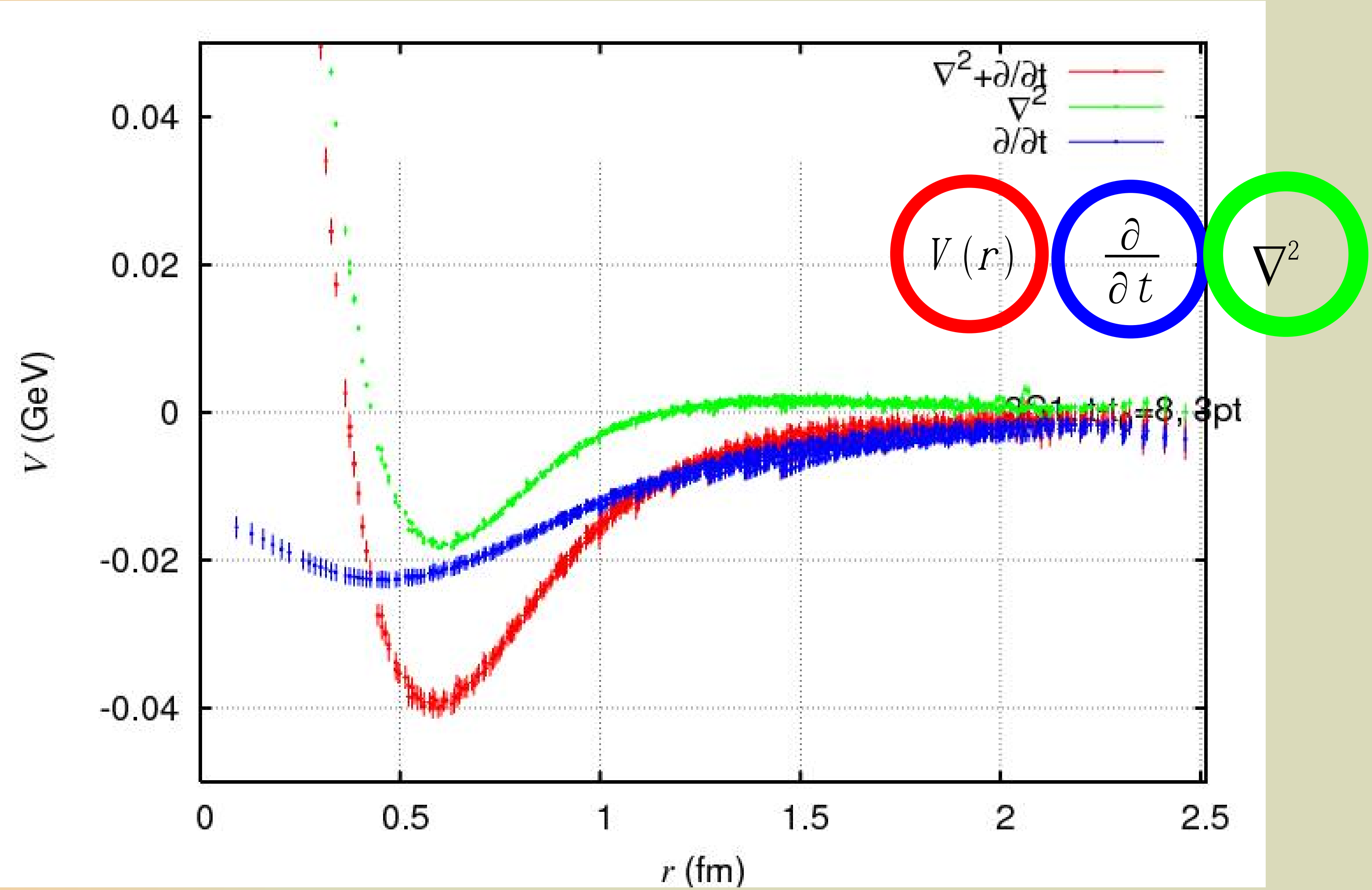
$V_C(\Lambda N;\ 1S0)$



$$V(r) = \frac{-\frac{\partial}{\partial t}R(t,\vec{r})}{R(t,\vec{r})} + \frac{\hbar^2}{2\mu}\frac{\nabla^2 R(t,\vec{r})}{R(t,\vec{r})}$$

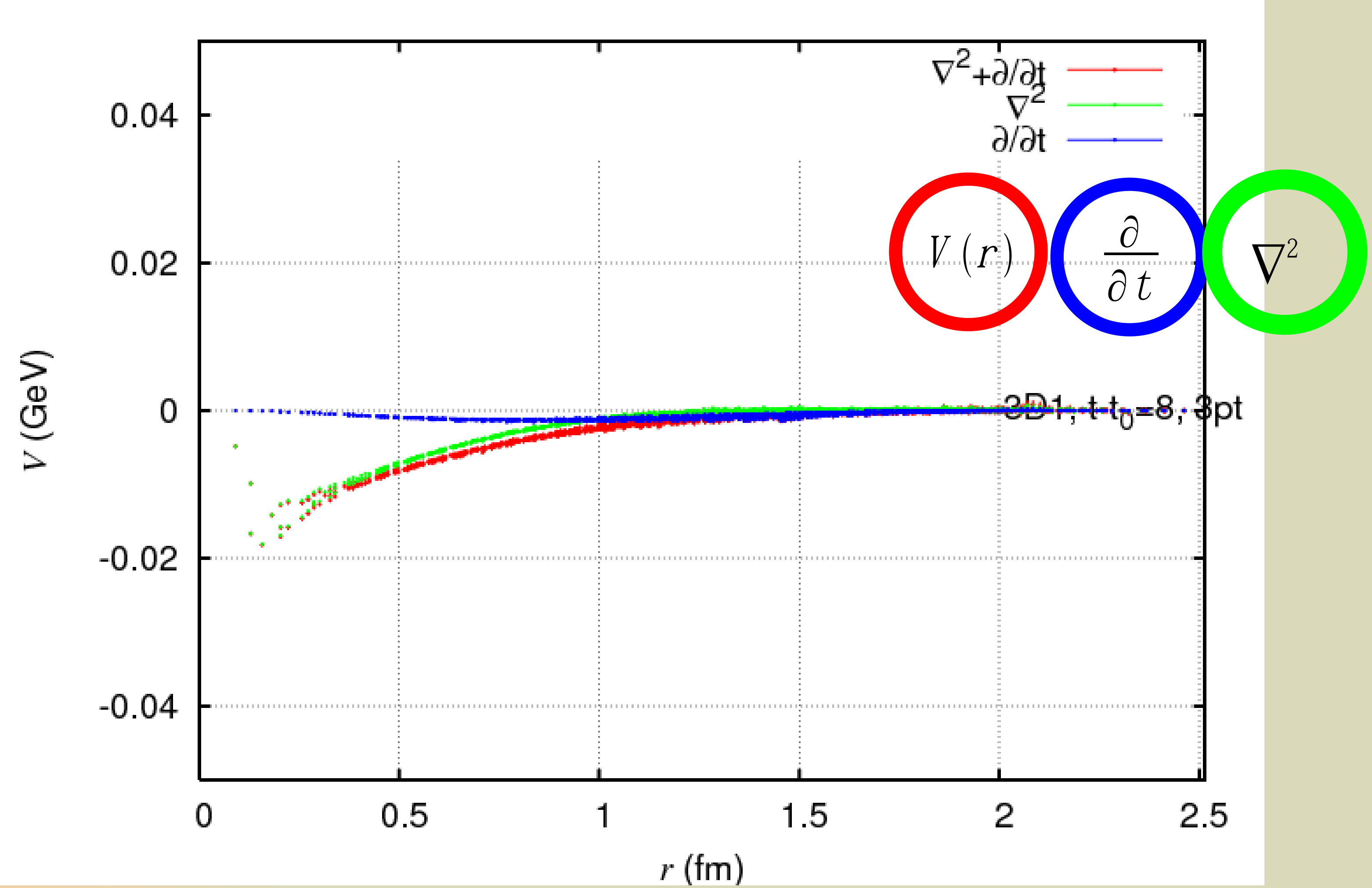
- {27}+{8s}
- Similar to NN (1S0)
- Sizable contribution from time-derivative part

$V_C(\Lambda N;\ 3S1-3D1)$



- {10*}+{8a}
- Sizable attractive contribution from time-derivative part

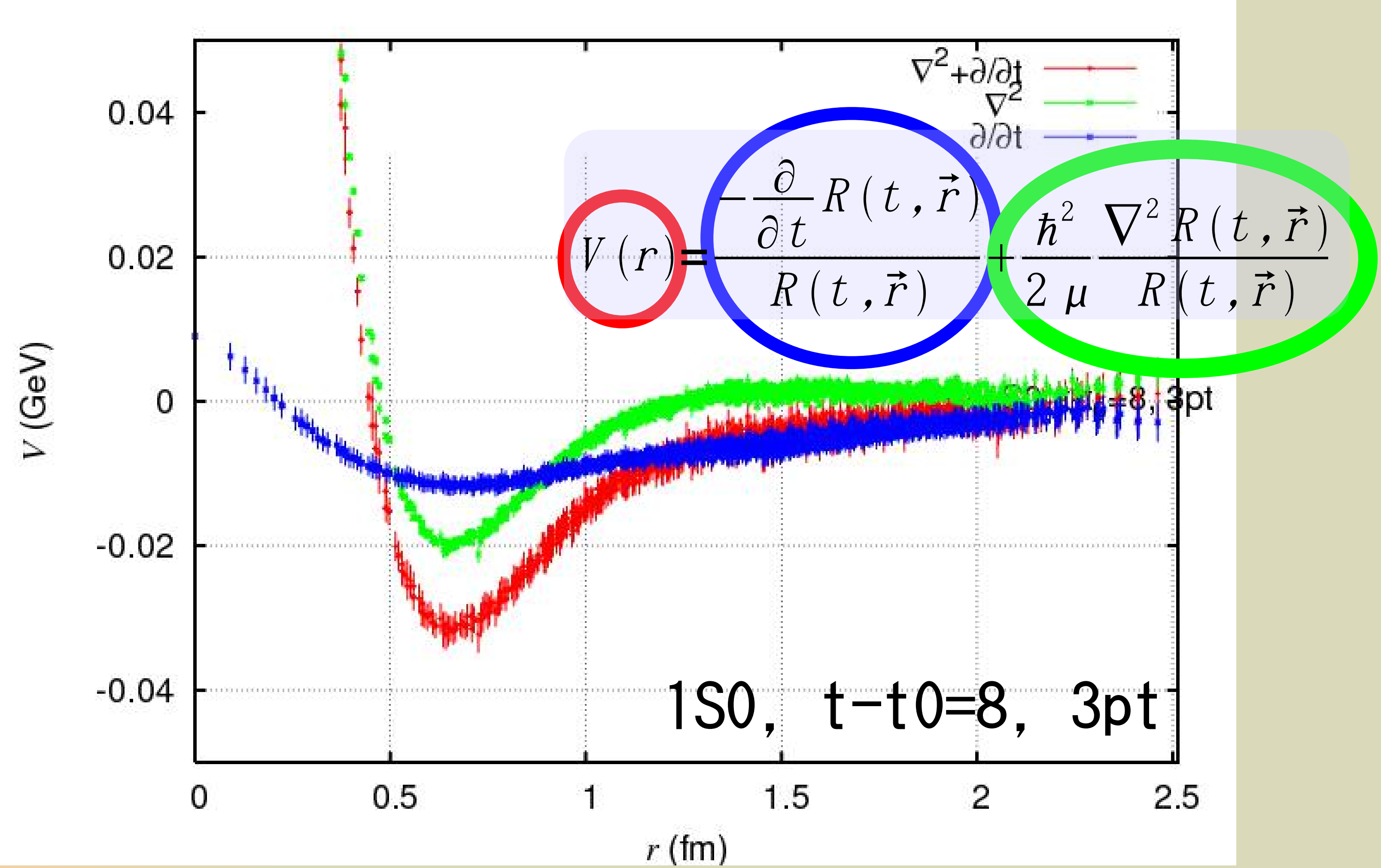
V_T(ΛN; 3S1-3D1)



- Weaker tensor force than NN
- Small contribution from time-derivative part

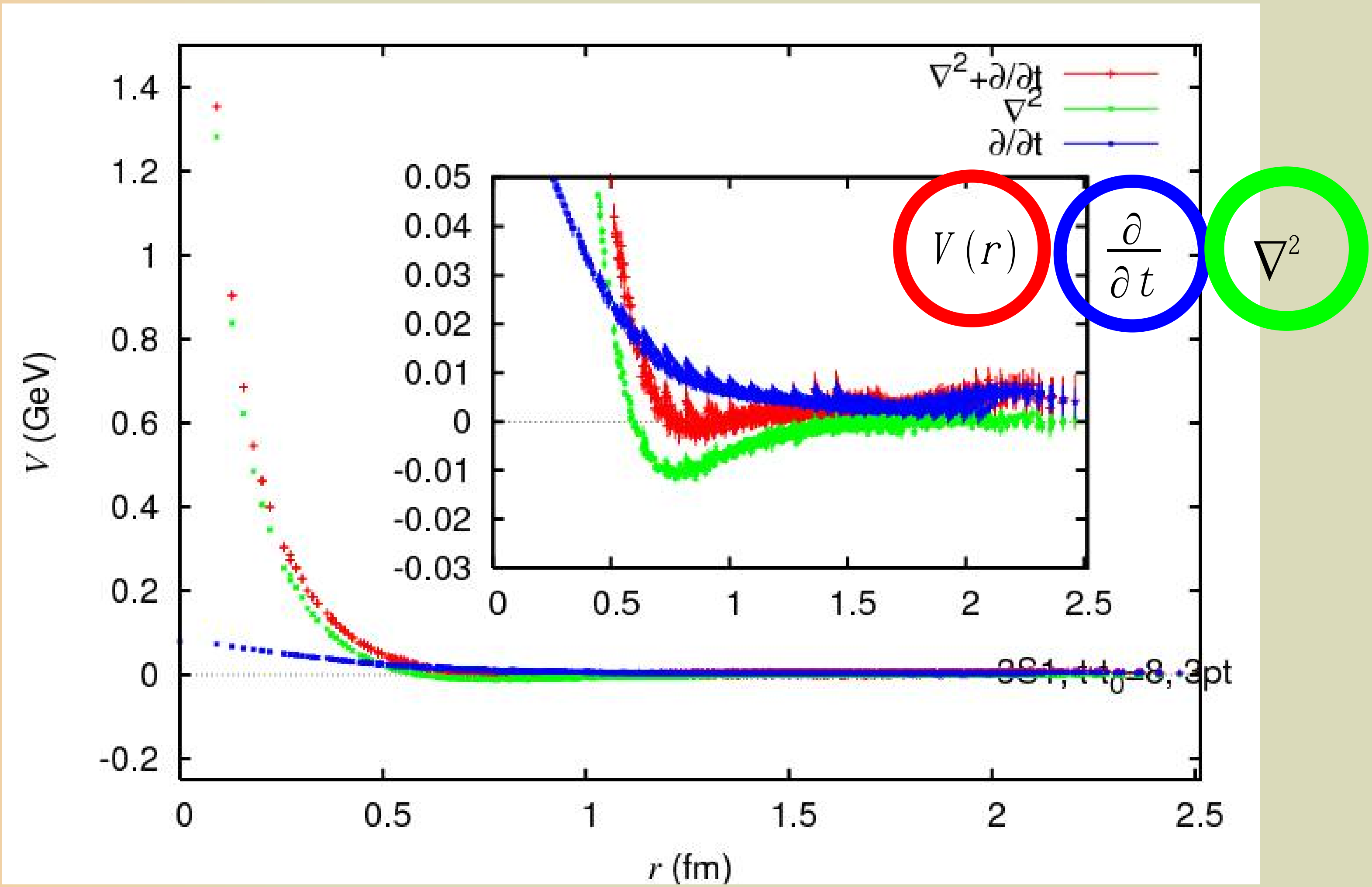
$\Sigma N(I=3/2)$ potential

V_c(ΣN(I=3/2); 1S0)



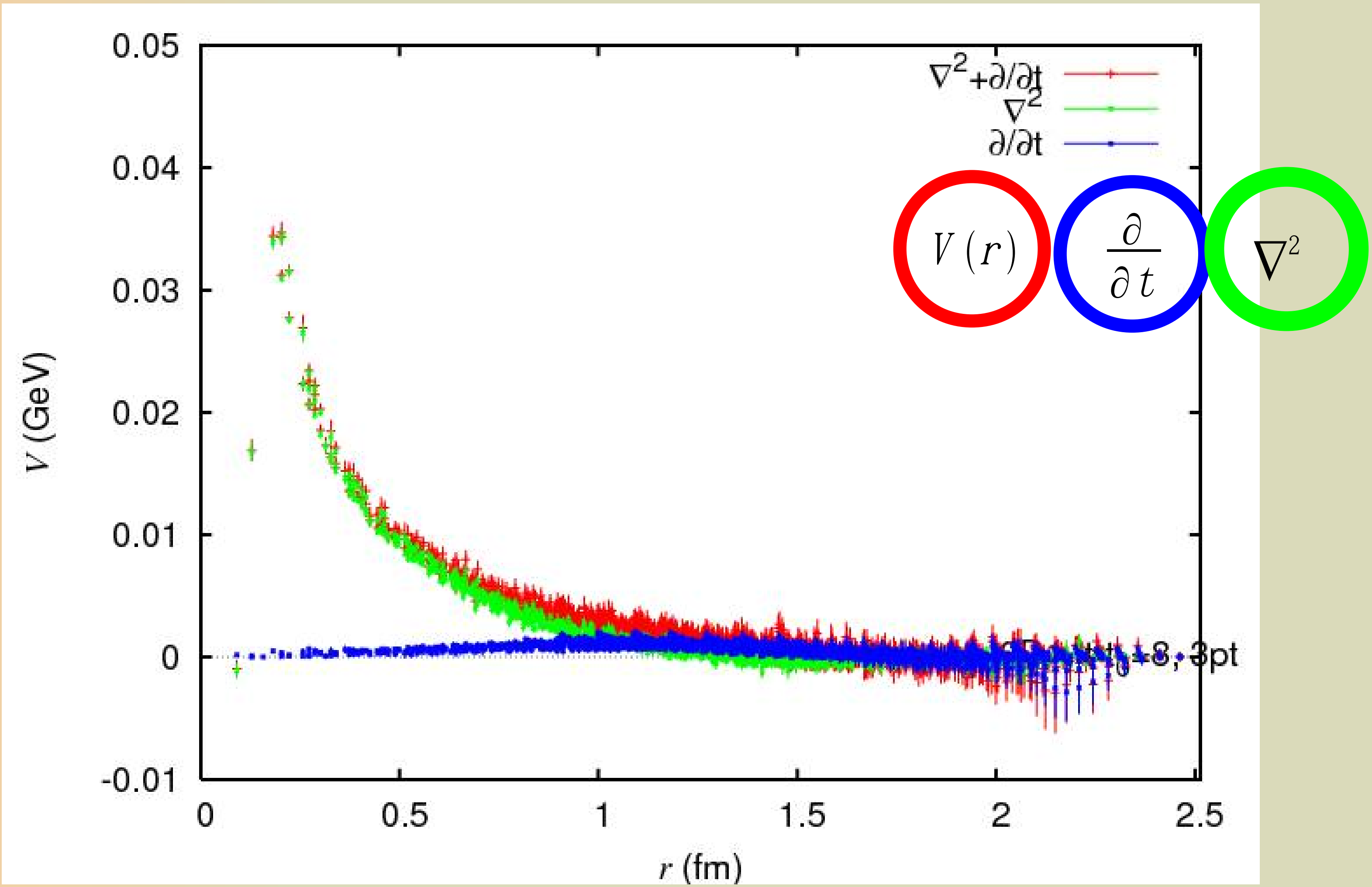
- {27}
- Similar to NN (1S0) (as well as Lambda-N (1S0))
- Sizable contribution from time-derivative part

$V_C(\Sigma N(I=3/2);\ 3S1-3D1)$



- {10}
- Repulsive potential (consistent with quark model)
- sizable repulsive contribution from time-derivative part

V_T(ΣN(I=3/2); 3S1-3D1)



- Weak tensor force
- Small contribution from time-derivative part

Scattering phase shifts

Proton-Lambda scattering (preliminary)

Parametrized potential → Phase shift

Summary:

- The lattice QCD study for Lambda-Nucleon and Sigma-nucleon(I=3/2) interactions.
- $p\Lambda$:
    - Central, tensor. For full QCD
    - Time-derivative terms enhance the attractive force.
    - Qualitatively similar to well-known nuclear forces.
        - Repulsive at short distance.
        - Attractive well at medium to long distance.
- $N\Sigma(I=3/2)$:
    - Central, tensor. For full QCD
    - The 1S0 potential is similar to Lambda-N potential
    - The 3S1 potential is repulsive

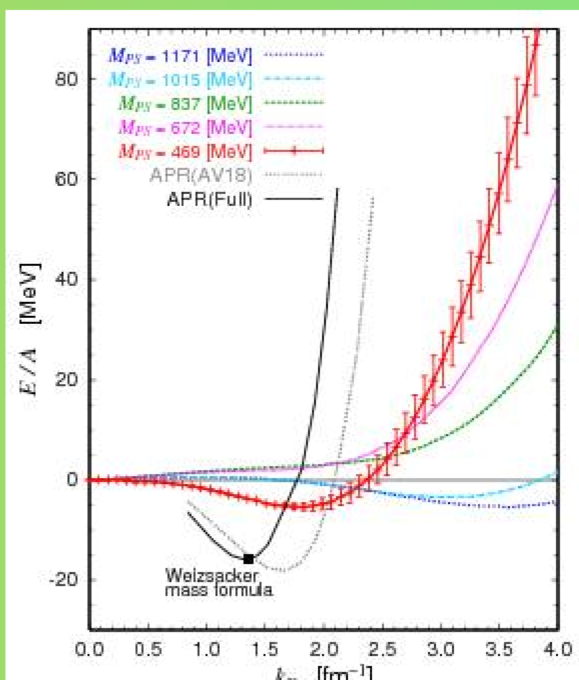
Outlook:

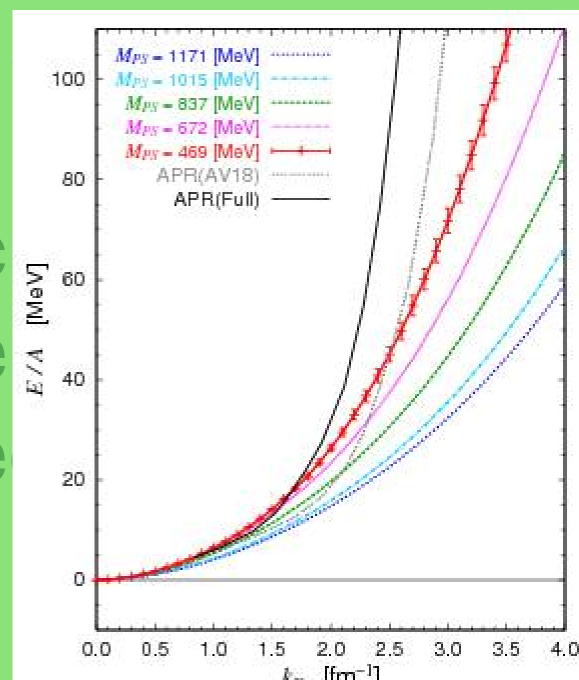
- Quark mass dependence.
- Scattering lengths.
  - spin-dependence.
  - Comparison with the hypernuclear data.
- Coupled-channel potential.
- Application to nuclear physics (few-body systems)

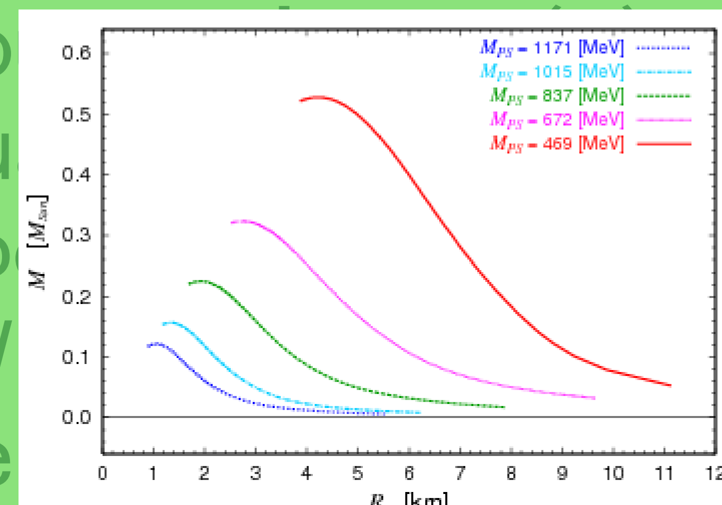
Stochastic variational calculation of 4He with using a lattice potential

- For NN potential, we use Inoue-san’s SU(3) potential at the lightest quark mass(m_ps = 469 MeV), which has been reported to have a 4N bound state (about 5.1MeV) within a tensor-included effective central potential; NPA881, 28-43 (2011).

Stochastic variational calculation of 4He with using a lattice potential







See also, PRL111, 112503 (2013) for a recent work.

Stochastic variational calculation of 4He with using a lattice potential

The wave function of A-body system is described by a linear combination of basis functions as

$$\Psi = \sum_{k=1}^{K} c_k \varphi_k, \qquad \text{with} \qquad \varphi_k = \mathcal{A}\{G(\mathbf{x}; A_k)[\theta_{(LL')_k}(\mathbf{x}; (uu')_k), \chi_{S_k}]_{JM}\eta_{kIM_I}\}, \tag{11}$$

where c_k is the linear variational parameter determined by the variational principle, $\mathcal{A}$ is antisymmetrizer for identical particles. χ_{S_k} (η_{kIM_I}) is the spin (isospin) function of the system. $G(\mathbf{x}; A_k)$ is the correlated Gaussian function which is given by

$$G(\mathbf{x}; A_k) = \exp\left\{-\frac{1}{2}\sum_{i<j}^{A} \alpha_{kij}(\mathbf{r}_i - \mathbf{r}_j)^2\right\} = \exp\left\{-\frac{1}{2}\sum_{i,j=1}^{A-1} A_{kij}\mathbf{x}_i \cdot \mathbf{x}_j\right\}. \tag{12}$$

Stochastic variational calculation of 4He with using a lattice potential

A set of relative coordinates $\{\mathbf{x}_1, \cdots, \mathbf{x}_{A-1}\}$ and the center-of-mass coordinate $\mathbf{x}_A$ are given by a linear transformation of single particle coordinates $\{\mathbf{r}_1, \cdots, \mathbf{r}_A\}$ such as

$$\mathbf{x}_i = \sum_{j=1}^{A} U_{ij}\mathbf{r}_j, \qquad (i = 1, \cdots, A). \tag{13}$$

In order to obtain the accurate solution of the four-nucleon bound state with explicitly utilizing the the tensor potential, we consider nonzero orbital angular momentum states $(L, S)J^\pi = (1, 1)0^+$ and $(2, 2)0^+$ in addition to the $(0, 0)0^+$ configuration. We employ the global vector representation[11] for these nonzero orbital angular momentum states. Therefore, the angular part of the basis function is given by

$$\theta_{(LL')_k}(\mathbf{x}; (uu')_k) = v_k^{L_k} {v'_k}^{L'_k} [Y_{L_k}(\hat{\mathbf{v}}_k) \times Y_{L'_k}(\hat{\mathbf{v}}'_k)]_{L_k}, \qquad \begin{pmatrix} \mathbf{v} \\ \mathbf{v}' \end{pmatrix}_k = \sum_{i=1}^{A-1} \mathbf{x}_i \begin{pmatrix} u \\ u' \end{pmatrix}_{ki}. \tag{14}$$

The validity of the present choice of basis function is examined for several realistic NN potentials[11]. The A_{kij} and $(u, u')_{ki}$ are the nonlinear variational parameters which are determined by the stochastic variational method[12].

Inoue san's SU(3) potential

- Central potentials
  - Two Vc's for spin singlet and triplet

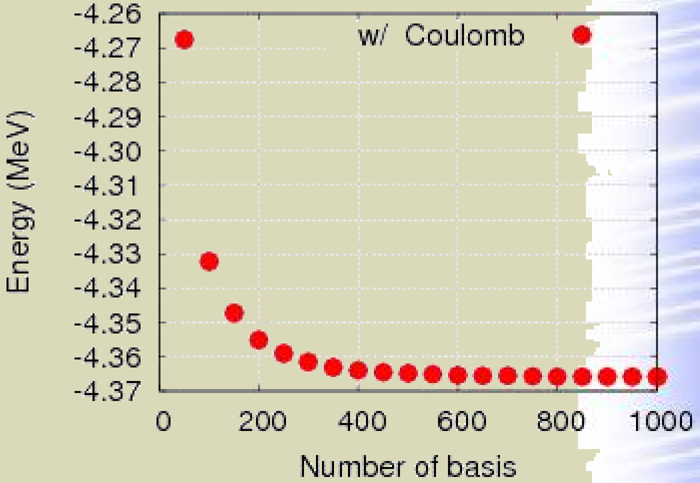
$$V_C(r) = V_1 \exp(\alpha_1 r^2) + V_2 \exp(\alpha_2 r^2) - V_3 (1 - \exp(\alpha_3 r^2))^2 (\exp(-\alpha_4 r)/r)^2$$

- Tensor potential

$$V_T(r) = V_1 (1 - \exp(\alpha_1 r^2))^2 \left(1 + \frac{3}{\alpha_2 r} + \frac{3}{\alpha_2 r^2}\right) \frac{\exp(-\alpha_2 r)}{r} + V_2 (1 - \exp(\alpha_3 r^2))^2 \left(1 + \frac{3}{\alpha_4 r} + \frac{3}{\alpha_4 r^2}\right) \frac{\exp(-\alpha_4 r)}{r}$$

Results of few-body calculation

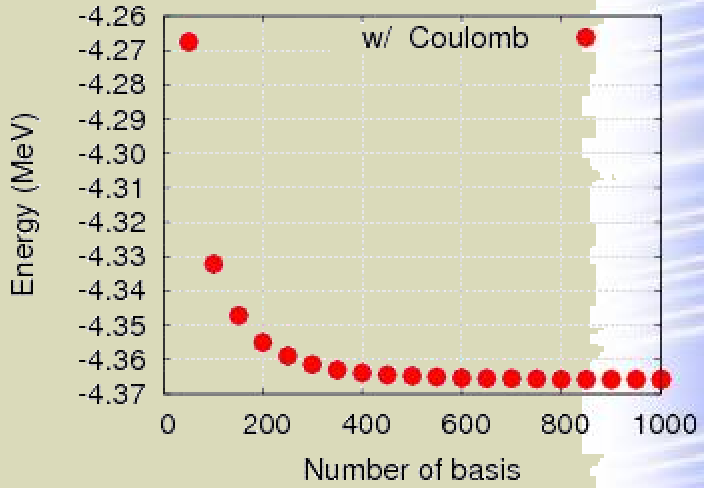
- Inputs:
  - m=1161.0 MeV,
  - hbar c = 197.3269602 MeV fm
  - hbar c/e^2 = 137.03599976
  - V_NN is treated as a Serber-type potential.



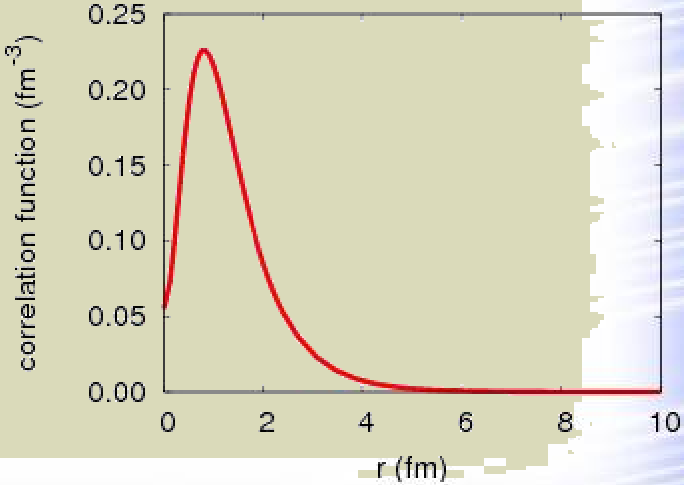
- Results:
  - B(4He)=4.37 MeV (w/ Coulomb)
    - Probabilities of (S, P, D) waves = (98.6%, 0.003%, 1.3%)
    - cf. roughly speaking (S,P,D)~(<90%, <0.1%, >10%) for a realistic NN force
  - B(4He)=5.09 MeV (w/o Coulomb)
    - Probabilities of (S, P, D) waves = (98.6%, 0.003%, 1.4%)

Results of few-body calculation

- Inputs:
  - m=1161.0 MeV,
  - hbar c = 197.3269602 MeV fm
  - hbar c/e^2 = 137.03599976
  - V_NN is treated as a Serber-type potential.



- Results:
  - B(4He)=4.37 MeV (w/ Coulomb)
    - Probabilities of (S, P, D) waves = (98.6%, 0.003%, 1.3%)
    - I also calculate the correlation function.



Results when we cut off the tensor potntial

- **Inputs:**
  - m=1161.0 MeV,
  - hbar c = 197.3269602 MeV fm
  - hbar c/e^2 = 137.03599976
  - V_NN is treated as a Serber-type potential with just cutting off the tensor part.
- **Results:**
  - B(4He)=1.61 MeV (w/ Coulomb)
    - Probabilities of (S, P, D) waves = (100%, 0%, 0%)
    - cf. roughly speaking (S,P,D)~(<90%, <0.1%, >10%) for a realistic NN force
  - B(4He)=2.25 MeV (w/o Coulomb)
    - (Probabirity of each component is almost same as the case including Coulomb)

Few-body calculations of *s*-shell Λ hypernuclei

	A=3	A=4	A=5	Tensor	Σ	
Dalitz, *et al.*	☑	☑	☑	☐	☑ (blue)	NP**B47**, 109 (1972).
Shinmura, *et al.*,	☑	☑	☑	☑	☐	PTP**71**, 546 (1984).
Gibson, *et al.*,	☐	☑	☐	☐	☑	PRC**37**, 679 (1988).
Carlson,	☐	☑	☑	☑	☑	AIP Conf. Proc. No. 224 (1991).
Miyagawa, *et al*,	☑	☐	☐	☑	☑	PRC**51**, 2905 (1995).
Hiyama, *et al.*,	☑	☑	☐	☑	☑	PRC**65**, 011301 (2002).
Sinha, *et al*,	☐	☑	☑	☑	☑ (blue)	PRC**66**, 024006 (2002).
Nogga, *et al.*,	☑	☑	☐	☑	☑	PRL**88**, 172501 (2002).
HN, *et al.*,	☑	☑	☑	☑	☑	PRL**89**, 142504 (2002).

☑ (blue): Λ*NN* 3BF

Plan of research

QCD

Baryon interaction

J-PARC
hyperon-nucleon (YN)
scattering

Structure and reaction of
(hyper)nuclei

Equation of State (EoS)
of nuclear matter

Neutron star and
supernova