物理点格子QCDによる ストレンジネスS=-1セクタのバリオン间力

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arXiv:1810.04046 [hep-lat]

Baryon force in strangeness S=−1 sector from physical point lattice QCD

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arXiv:1810.04046 [hep-lat]

Outline

- Introduction
  - Importance of LN-SN tensor force for hypernuclei
  - Brief introduction of HAL QCD method
    - Effective block algorithm for various baryon-baryon channels, CPC**207**,91(2016)[1510.00903]
- Preliminary results of LN-SN potentials at nearly physical point; update from [1702.00734]
  - LN-SN(I=1/2), central and tensor potentials
  - SN(I=3/2), central and tensor potentials
    - Phase shifts of SN(I=3/2) scattering
- Summary

Plan of research

QCD

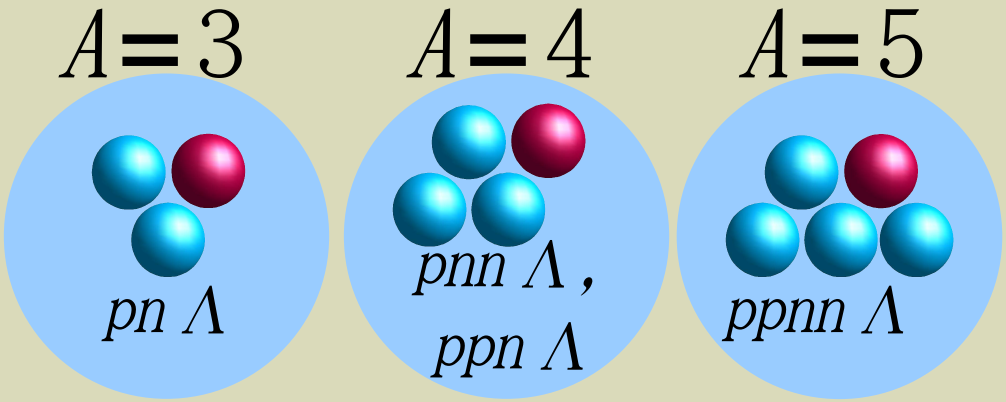
Baryon interaction

J-PARC,
JLab, GSI, MAMI, ...
YN scattering,
hypernuclei

Structure and reaction of (hyper)nuclei

Equation of State (EoS) of nuclear matter

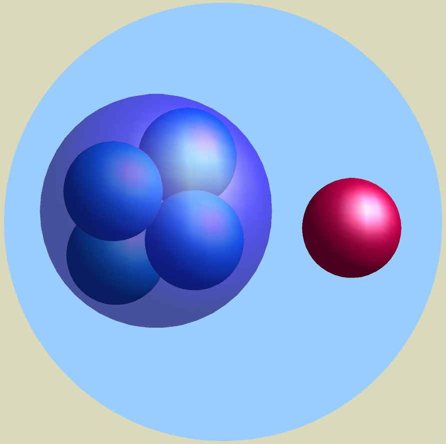
Neutron star and supernova



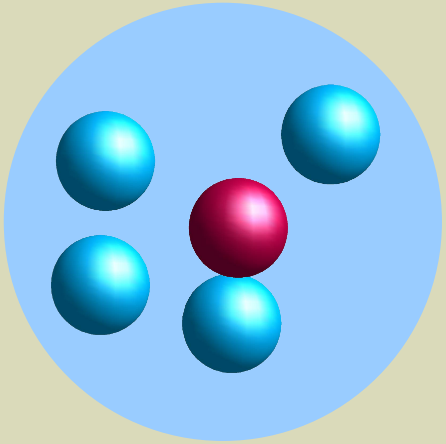
What is realistic picture of hypernuclei?

- $B(\text{total}) = B(^4\text{He}) + B_\Lambda(^5_\Lambda\text{He})$

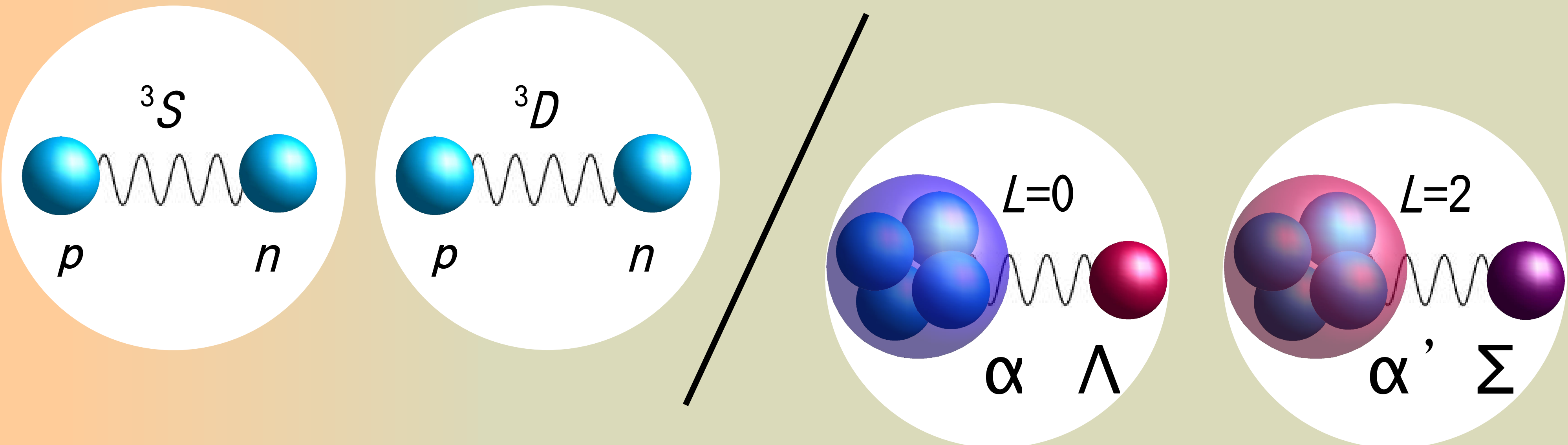
- A conventional picture:
  $B(\text{total})$
  $= B(^4\text{He}) + B_\Lambda(^5_\Lambda\text{He})$
  $= 28+3$ MeV.



- A (probably realistic) picture:
  $B(\text{total})$
  $= (B(^4\text{He}) - \Delta E_c) + (B_\Lambda(^5_\Lambda\text{He}) + \Delta E_c)$
  $= ??+??$ MeV.



Comparison between d=p+n and core+Y



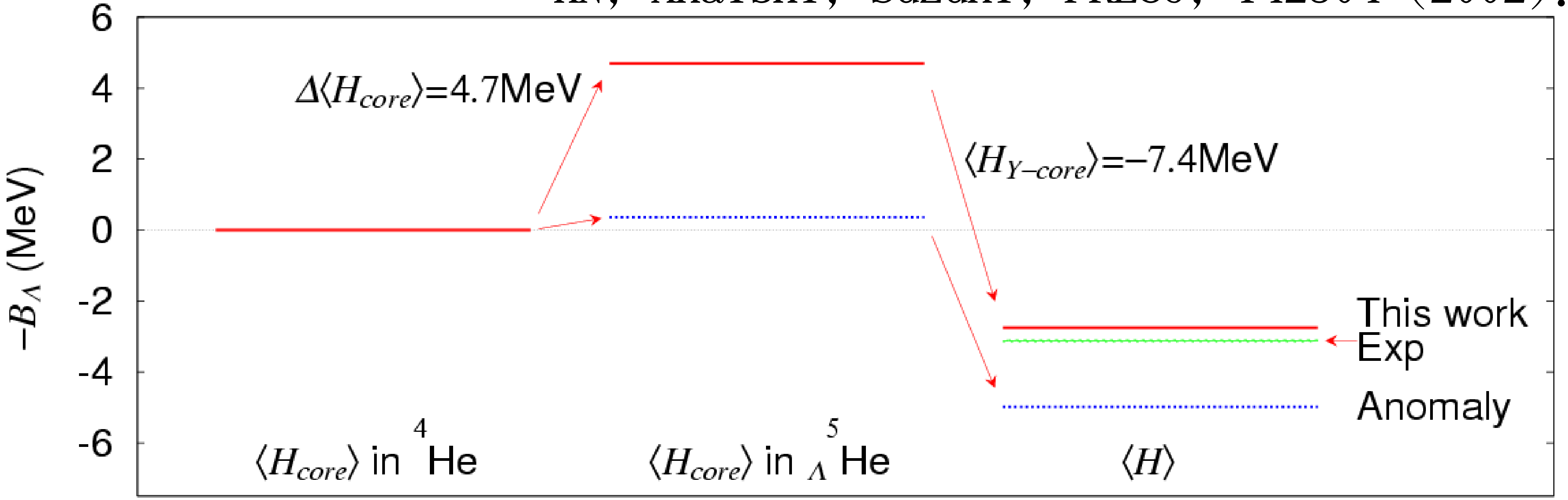
	$\langle T_S \rangle$ (MeV)	$\langle T_D \rangle$ (MeV)	$\langle V_{NN}(\mathrm{central}) \rangle$ (MeV)	$\langle V_{NN}(\mathrm{tensor}) \rangle$ (MeV)	$\langle V_{NN}(\mathrm{LS}) \rangle$ (MeV)
AV8	8.57	11.31	−4.46	−16.64	−1.02
G3RS	10.84	5.64	−7.29	−11.46	0.00

	$\langle T_{Y\text{-}c} \rangle_\Lambda$	$\langle T_{Y\text{-}c} \rangle_\Sigma + \Delta \langle H_C \rangle$	$\langle V_{YN}($ 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

HN, Akaishi, Suzuki, PRL89, 142504 (2002).

Rearrangement effect of ${}^{5}_{\Lambda}$He

HN, Akaishi, Suzuki, PRL89, 142504 (2002).



$$H = \sum_{i=1}^{A}\left(m_i c^2 + \frac{\boldsymbol{p}_i^2}{2\,\mathrm{m}_i}\right) - T_{CM} + \sum_{i<j}^{A-1} v_{ij}^{(NN)} + \sum_{i=1}^{A-1} v_{iY}^{(NY)} = H_{core} + H_{Y-core} \;,$$

$$H_{core} = \sum_{i=1}^{A-1}\frac{\boldsymbol{p}_i^2}{2\,\mathrm{m}_N} - \frac{\left(\sum_{i=1}^{A-1}\boldsymbol{p}_i\right)^2}{2(A-1)\,m_N} + \sum_{i<j}^{A-1} v_{ij}^{(NN)} = T_{core} + V_{NN} \;.$$

What is realistic picture of hypernuclei?

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  $B(\text{total})$
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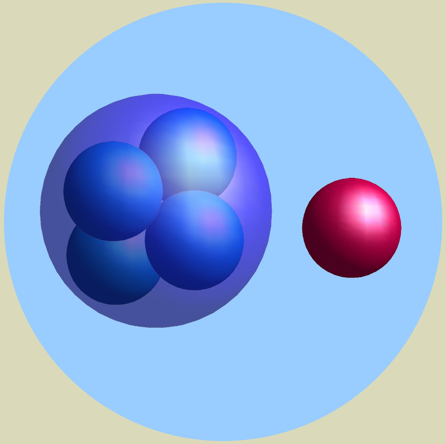
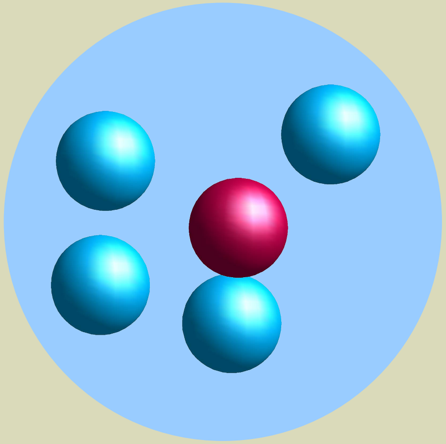


- A (probably realistic) picture:
  $B(\text{total})$
  $= (B(^4\text{He}) - \Delta E_c) + (B_\Lambda(^5_\Lambda\text{He}) + \Delta E_c)$
  $= 24+7$ MeV.



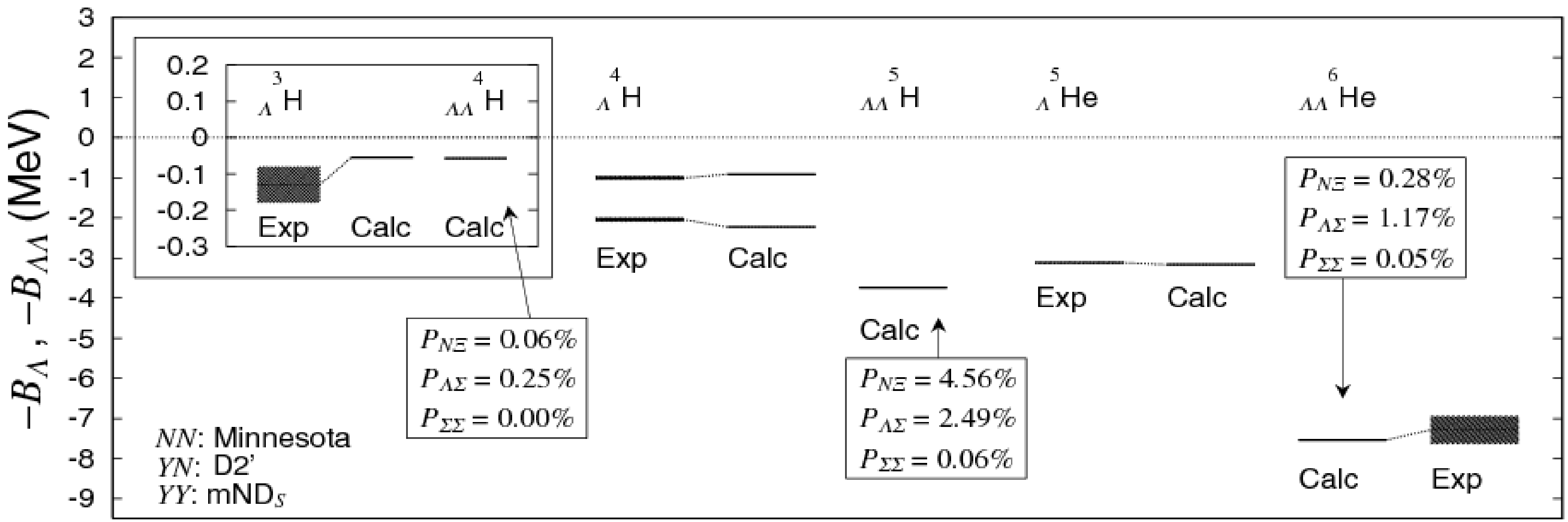
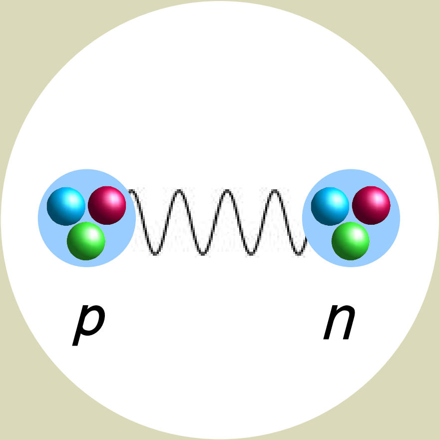
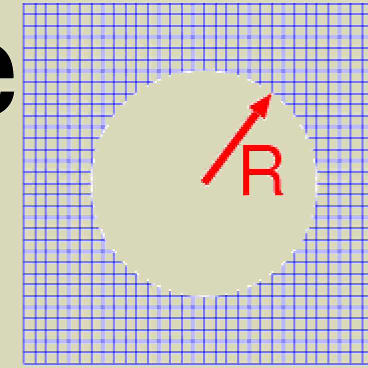


FIG. 1. Λ and $\Lambda\Lambda$ separation energies of $A = 3 - 6$, $S = -1$ and -2 s-shell hypernuclei. The Minnesota NN, D2$'$ YN, and mND$_S$ YY potentials are used. The width of the line for the experimental B_Λ or $B_{\Lambda\Lambda}$ value indicates the experimental error bar. The probabilities of the $N\Xi$, $\Lambda\Sigma$, and $\Sigma\Sigma$ components are also shown for the $\Lambda\Lambda$ hypernuclei.

Lattice QCD calculation



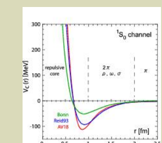
Multi-hadron on lattice



i) basic procedure:

asymptotic region

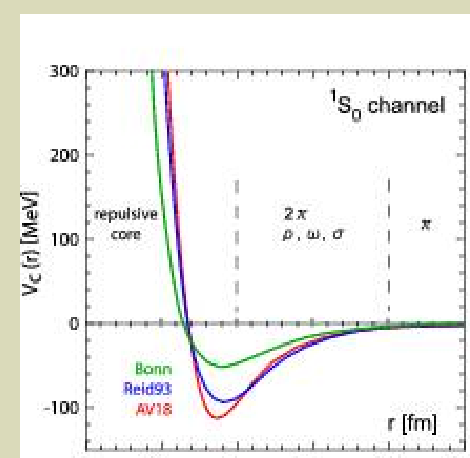
--> phase shift



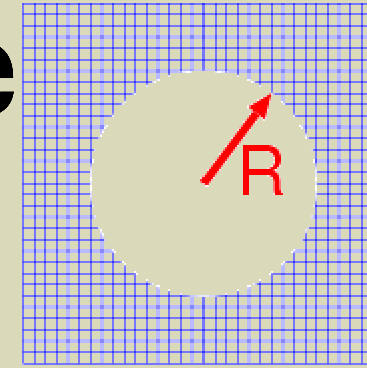
ii) HAL's procedure:

interacting region

--> potential



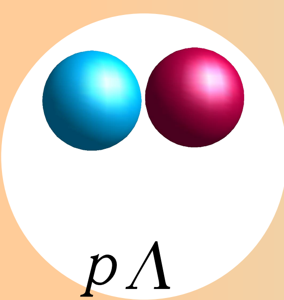
Multi-hadron on lattice

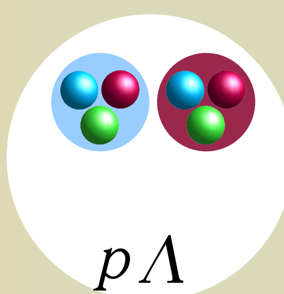
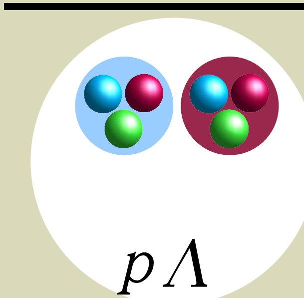


Lattice QCD simulation

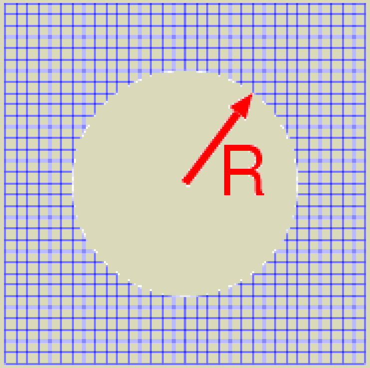
$$L = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q} q$$

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



$\rightarrow \langle$  (t) $\overline{}$  $(t_0) \rangle$

Multi-hadron on lattice



i) basic procedure:

asymptotic region

(or temporal correlation)

--> scattering energy

--> phase shift

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

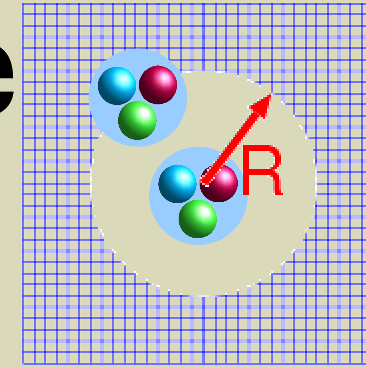
$$k\cot\delta_0(k) = \frac{2}{\sqrt{\pi}L} Z_{00}(1; (kL/(2\pi))^2) = \frac{1}{a_0} + O(k^2)$$

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

Luscher, NPB354, 531 (1991).

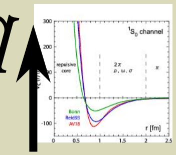
Aoki, et al., PRD71, 094504 (2005).

Multi-hadron on lattice

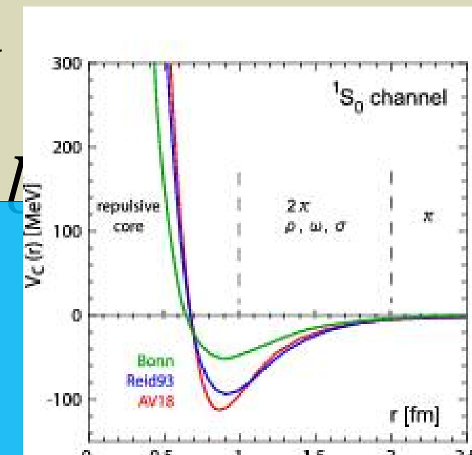


Lattice QCD simulation

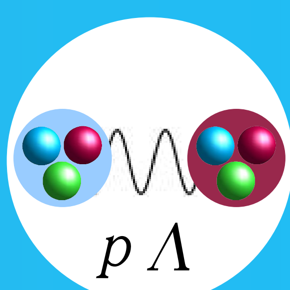
$$L = -\frac{1}{4} G^{a}_{\mu\nu} G^{a\mu\nu} + \bar{q}\gamma^{\mu}(i\partial_{\mu} - g t^{a} A^{a}_{\mu})q - m\bar{q}q$$

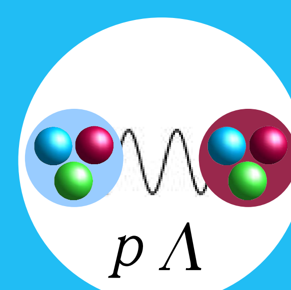


$$\langle O(\bar{q}, q, U)\rangle = \int dU\, d\bar{q}\, dq\, \mathrm{e}^{-S(\bar{q}, q, U)} O(\bar{q}, q \ldots$$
$$= \int dU \det D(U)\, \mathrm{e}^{-S_U(U)} O(D^{-1}(U \ldots$$
$$= \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} O(D^{-1}(U_i))$$



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

$\rightarrow \langle$ 

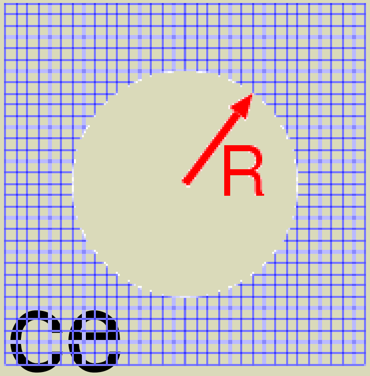
$(\vec{r}, t)$ $\overline{}$ 

$(t_0)\rangle$

Calculate the scattering state

Multi-hadron on lattice

ii) HAL's procedure:
make better use of the lattice output ! (wave function)



interacting region
--> potential

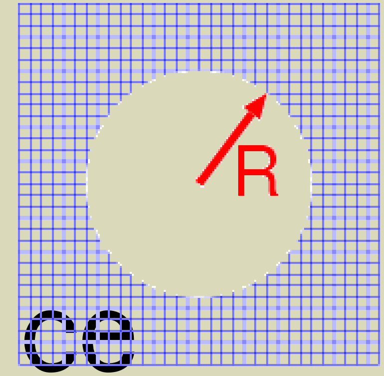
Ishii, Aoki, Hatsuda,
PRL99, 022001 (2007);
ibid., PTP123, 89 (2010).

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)

....

Multi-hadron on lattice

ii) HAL's procedure:
make better use of the lattice
output ! (wave function)



interacting region
--> potential

Ishii, Aoki, Hatsuda,
PRL99, 022001 (2007);
ibid., PTP123, 89 (2010).

=>
> Phase shift
> Nuclear many-body problems

The potential is obtained at moderately large imaginary time; no single state saturation is required.

[1]The potential is obtained from the NBS wave function at moderately large imaginary time; it would be $t-t_0 \gg 1/m_\pi \sim 1.4$ fm. In addition, no single state saturation between the ground state and the excited states with respect to the relative motion, e.g., $t-t_0 \gg (\Delta E)^{-1} = \left((2\pi)^2/(2\mu(La)^2)\right)^{-1} \simeq 8.0$ fm, is required for the HAL QCD method[13].

RECIPE:

Compute the 4pt correlator

$$F^{\langle B_1B_2\overline{B_3B_4}\rangle}_{\alpha\beta,JM}(\vec{r},t-t_0) = \sum_{\vec{X}} \left\langle 0 \left| B_{1,\alpha}(\vec{X}+\vec{r},t) B_{2,\beta}(\vec{X},t) \overline{\mathscr{J}^{(J,M)}_{B_3B_4}(t_0)} \right| 0 \right\rangle, \qquad (2.3)$$

Take into account the threshold energy differences for coupled-channel system

$$R^{\langle B_1B_2\overline{B_3B_4}\rangle}_{\alpha\beta,JM}(\vec{r},t-t_0) = \mathrm{e}^{(m_{B_1}+m_{B_2})(t-t_0)} F^{\langle B_1B_2\overline{B_3B_4}\rangle}_{\alpha\beta,JM}(\vec{r},t-t_0)$$

$$= \sum_n A_n \sum_{\vec{X}} \left\langle 0 \left| B_{1,\alpha}(\vec{X}+\vec{r},0) B_{2,\beta}(\vec{X},0) \right| E_n \right\rangle \mathrm{e}^{-(E_n-m_{B_1}-m_{B_2})(t-t_0)} + O(\mathrm{e}^{-(E_{\mathrm{th}}-m_{B_1}-m_{B_2})(t-t_0)}) \qquad (2.4)$$

elastic inelastic

Obtain the potential by using the appropriate equation(s); For spin-singlet,

$$\left(\frac{\nabla^2}{2\mu_\lambda} - \frac{\partial}{\partial t}\right) R_{\lambda\varepsilon}(\vec{r},t) \simeq V^{(\mathrm{LO})}_{\lambda\lambda'}(\vec{r}) \theta_{\lambda\lambda'} R_{\lambda'\varepsilon}(\vec{r},t), \text{ with } \theta_{\lambda\lambda'} = \mathrm{e}^{(m_{B_1}+m_{B_2}-m_{B'_1}-m_{B'_2})(t-t_0)}.$$

For spin-triplet, the “tensor force” becomes active

$$\left\{\begin{matrix}\mathscr{P}\\ \mathscr{Q}\end{matrix}\right\} \times \left\{V^{(0)}_{\lambda\lambda'}(r) + V^{(\sigma)}_{\lambda\lambda'}(r) + V^{(T)}_{\lambda\lambda'}(r) S_{12}\right\} \theta_{\lambda\lambda'} R_{\lambda'\varepsilon}(\vec{r},t-t_0) = \left\{\begin{matrix}\mathscr{P}\\ \mathscr{Q}\end{matrix}\right\} \times \left\{\frac{\nabla^2}{2\mu_\lambda} - \frac{\partial}{\partial t}\right\} R_{\lambda\varepsilon}(\vec{r},t-t_0) \qquad (2.7)$$

Where

$$\begin{cases} R(\vec{r};\,^3S_1) = \mathscr{P}R(\vec{r};J=1) \equiv \frac{1}{24}\sum_{\mathscr{R}\in O} \mathscr{R}R(\vec{r};J=1), \\ R(\vec{r};\,^3D_1) = \mathscr{Q}R(\vec{r};J=1) \equiv (1-\mathscr{P})R(\vec{r};J=1). \end{cases} \qquad (2.6)$$

In the lowest few orders, we have

$$V(\vec{r},\vec{\nabla}_r) = V^{(0)}(r) + V^{(\sigma)}(r)\vec{\sigma}_1\cdot\vec{\sigma}_2 + V^{(T)}(r)S_{12} + V^{(\substack{LS\\ ALS})}(r)\vec{L}\cdot(\vec{\sigma}_1 \pm \vec{\sigma}_2) + O(\nabla^2), \qquad (2.5)$$

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:

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

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

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

- A general expression of the potential:

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

Determination of baryon-baryon potentials at nearly physical point

Effective block algorithm for various baryon-baryon correlators

HN, CPC207,91(2016), arXiv:1510.00903(hep-lat)

Numerical cost (# of iterative operations) in this algorithm

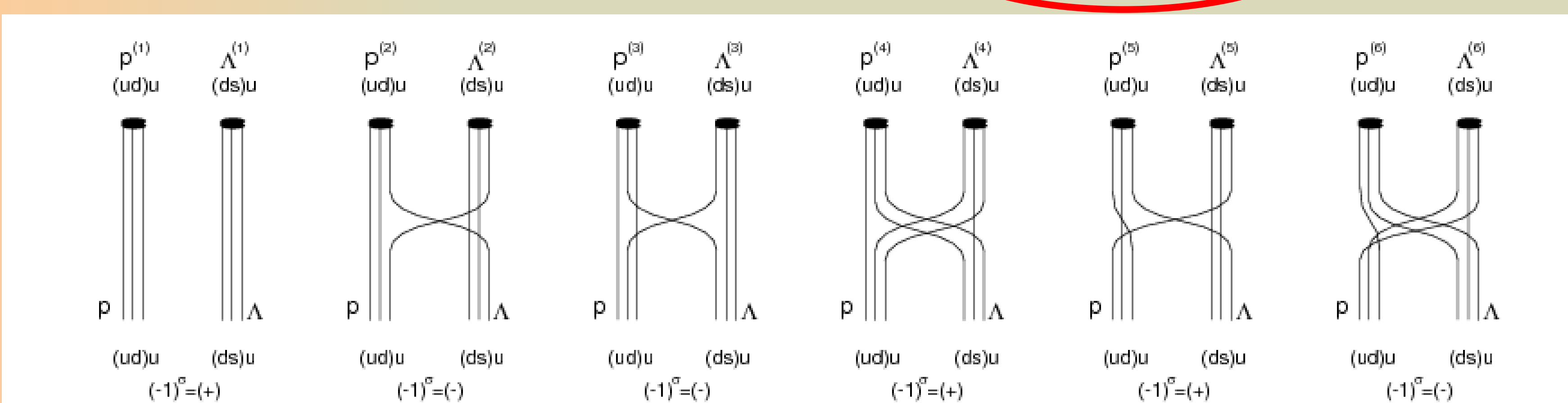
$$1+N_c^{\,2}+N_c^{\,2}N_\alpha^{\,2}+N_c^{\,2}N_\alpha^{\,2}+N_c^{\,2}N_\alpha+N_c^{\,2}N_\alpha = 370$$

In an intermediate step:

$$(N_c!\,N_\alpha)^B\times N_u!\,N_d!\,N_s!\times 2^{N_\Lambda+N_{\Sigma^0}-B} = 3456$$

In a naïve approach:

$$(N_c!\,N_\alpha)^{2B}\times N_u!\,N_d!\,N_s! = 3,981,312$$



Generalization to the various baryon-baryon channels strangeness S=0 to -4 systems

$$\langle pn\overline{pn}\rangle, \tag{4.1}$$

$$\begin{aligned}
&\langle p\Lambda\overline{p\Lambda}\rangle,\ \langle p\Lambda\overline{\Sigma^+ n}\rangle,\ \langle p\Lambda\overline{\Sigma^0 p}\rangle,\\
&\langle \Sigma^+ n\overline{p\Lambda}\rangle,\ \langle \Sigma^+ n\overline{\Sigma^+ n}\rangle,\ \langle \Sigma^+ n\overline{\Sigma^0 p}\rangle,\\
&\langle \Sigma^0 p\overline{p\Lambda}\rangle,\ \langle \Sigma^0 p\overline{\Sigma^+ n}\rangle,\ \langle \Sigma^0 p\overline{\Sigma^0 p}\rangle,
\end{aligned} \tag{4.2}$$

$$\begin{aligned}
&\langle \Lambda\Lambda\overline{\Lambda\Lambda}\rangle,\ \langle \Lambda\Lambda\overline{p\Xi^-}\rangle,\ \langle \Lambda\Lambda\overline{n\Xi^0}\rangle,\ \langle \Lambda\Lambda\overline{\Sigma^+\Sigma^-}\rangle,\ \langle \Lambda\Lambda\overline{\Sigma^0\Sigma^0}\rangle,\\
&\langle p\Xi^-\overline{\Lambda\Lambda}\rangle,\ \langle p\Xi^-\overline{p\Xi^-}\rangle,\ \langle p\Xi^-\overline{n\Xi^0}\rangle,\ \langle p\Xi^-\overline{\Sigma^+\Sigma^-}\rangle,\ \langle p\Xi^-\overline{\Sigma^0\Sigma^0}\rangle,\ \langle p\Xi^-\overline{\Sigma^0\Lambda}\rangle,\\
&\langle n\Xi^0\overline{\Lambda\Lambda}\rangle,\ \langle n\Xi^0\overline{p\Xi^-}\rangle,\ \langle n\Xi^0\overline{n\Xi^0}\rangle,\ \langle n\Xi^0\overline{\Sigma^+\Sigma^-}\rangle,\ \langle n\Xi^0\overline{\Sigma^0\Sigma^0}\rangle,\ \langle n\Xi^0\overline{\Sigma^0\Lambda}\rangle,\\
&\langle \Sigma^+\Sigma^-\overline{\Lambda\Lambda}\rangle,\ \langle \Sigma^+\Sigma^-\overline{p\Xi^-}\rangle,\ \langle \Sigma^+\Sigma^-\overline{n\Xi^0}\rangle,\ \langle \Sigma^+\Sigma^-\overline{\Sigma^+\Sigma^-}\rangle,\ \langle \Sigma^+\Sigma^-\overline{\Sigma^0\Sigma^0}\rangle,\ \langle \Sigma^+\Sigma^-\overline{\Sigma^0\Lambda}\rangle,\\
&\langle \Sigma^0\Sigma^0\overline{\Lambda\Lambda}\rangle,\ \langle \Sigma^0\Sigma^0\overline{p\Xi^-}\rangle,\ \langle \Sigma^0\Sigma^0\overline{n\Xi^0}\rangle,\ \langle \Sigma^0\Sigma^0\overline{\Sigma^+\Sigma^-}\rangle,\ \langle \Sigma^0\Sigma^0\overline{\Sigma^0\Sigma^0}\rangle,\\
&\langle \Sigma^0\Lambda\overline{p\Xi^-}\rangle,\ \langle \Sigma^0\Lambda\overline{n\Xi^0}\rangle,\ \langle \Sigma^0\Lambda\overline{\Sigma^+\Sigma^-}\rangle,\ \langle \Sigma^0\Lambda\overline{\Sigma^0\Lambda}\rangle,
\end{aligned} \tag{4.3}$$

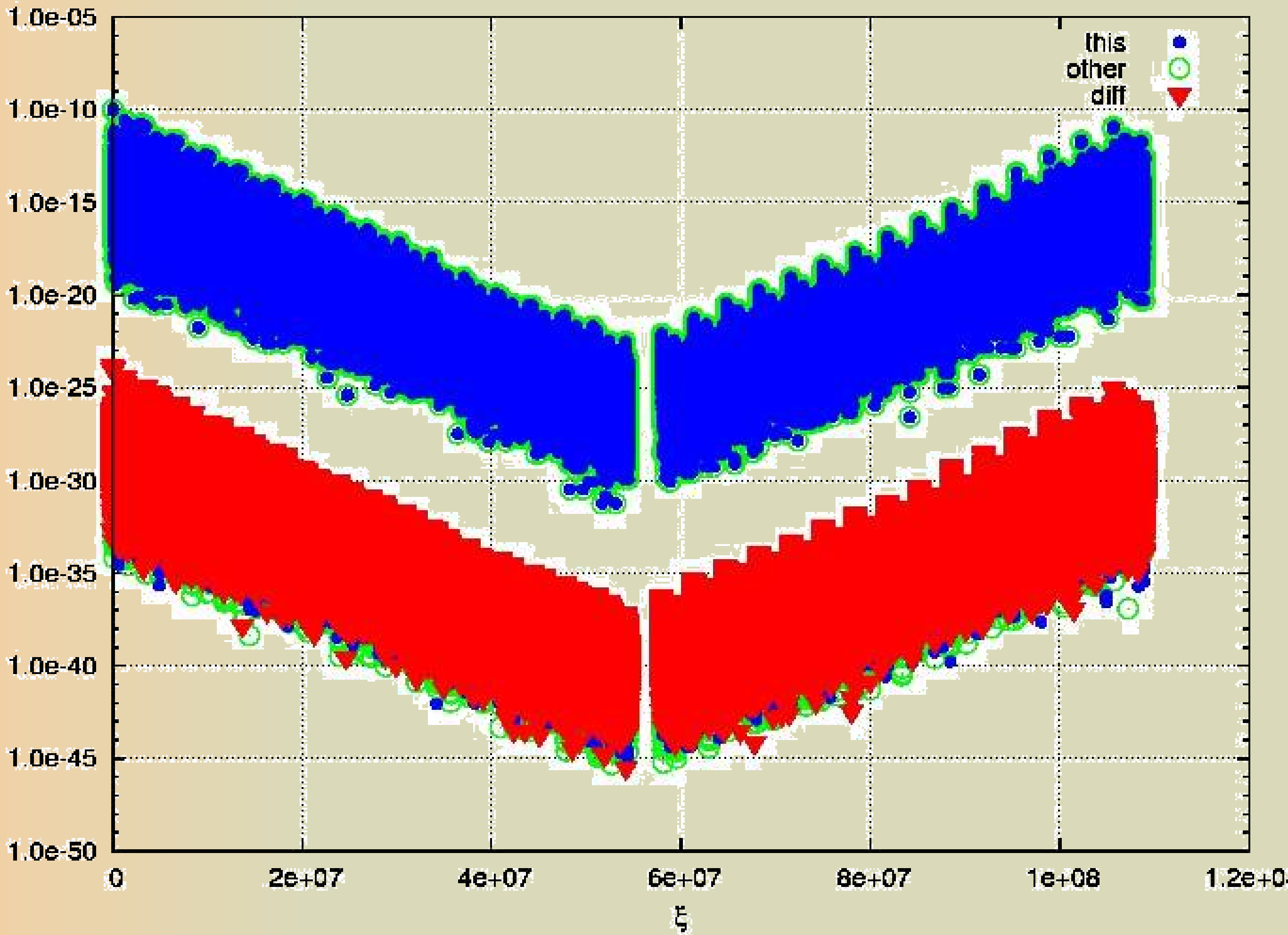
$$\begin{aligned}
&\langle \Xi^-\Lambda\overline{\Xi^-\Lambda}\rangle,\ \langle \Xi^-\Lambda\overline{\Sigma^-\Xi^0}\rangle,\ \langle \Xi^-\Lambda\overline{\Sigma^0\Xi^-}\rangle,\\
&\langle \Sigma^-\Xi^0\overline{\Xi^-\Lambda}\rangle,\ \langle \Sigma^-\Xi^0\overline{\Sigma^-\Xi^0}\rangle,\ \langle \Sigma^-\Xi^0\overline{\Sigma^0\Xi^-}\rangle,\\
&\langle \Sigma^0\Xi^-\overline{\Xi^-\Lambda}\rangle,\ \langle \Sigma^0\Xi^-\overline{\Sigma^-\Xi^0}\rangle,\ \langle \Sigma^0\Xi^-\overline{\Sigma^0\Xi^-}\rangle,
\end{aligned} \tag{4.4}$$

$$\langle \Xi^-\Xi^0\overline{\Xi^-\Xi^0}\rangle. \tag{4.5}$$

Make better use of the computing resources!

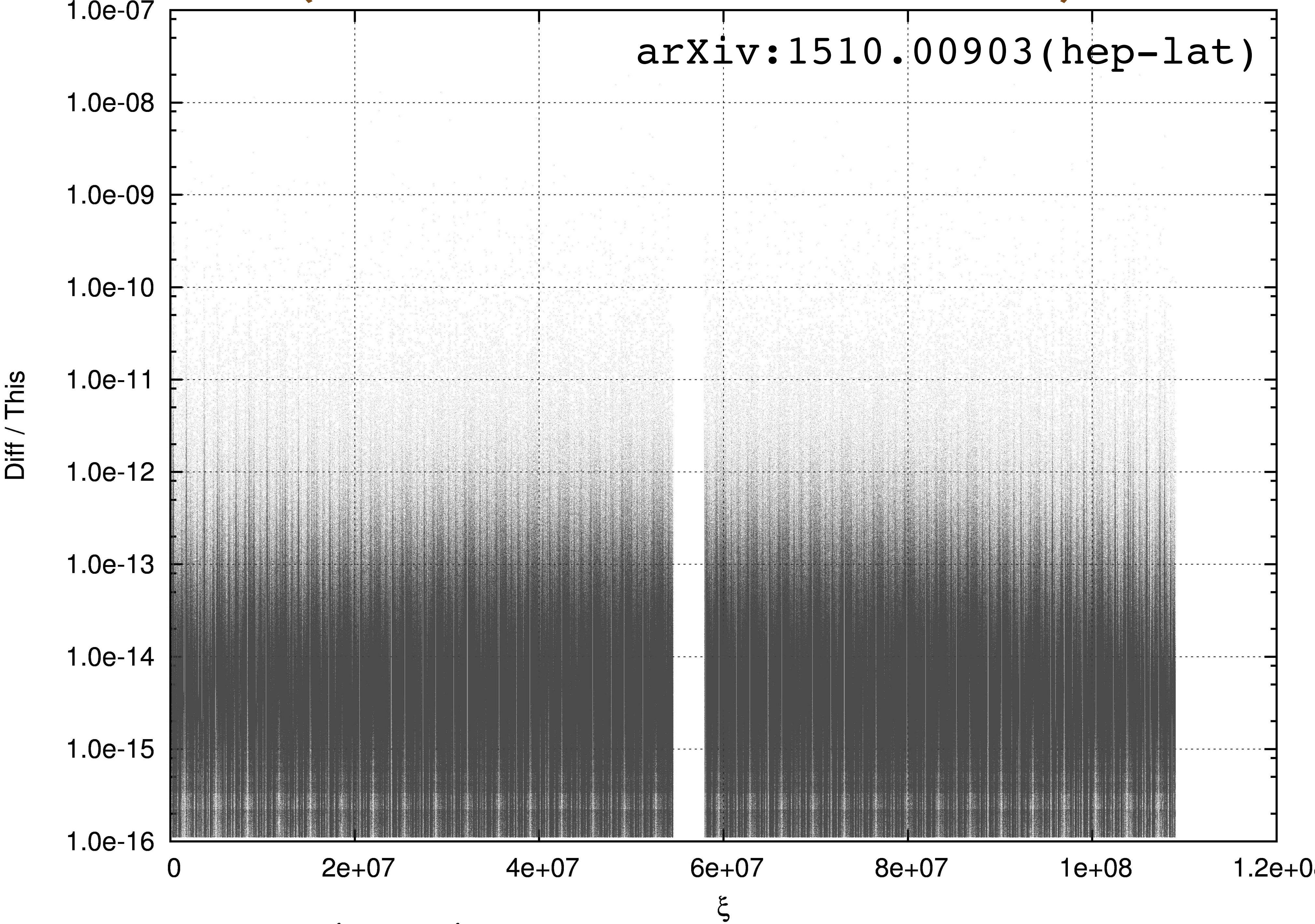
HN, CPC **207**, 91(2016) [arXiv:1510.00903[hep-lat]],
(See also arXiv:1604.08346)

Benchmark (from NN to XiXi channels)



numerical results of the correlators of entire 52 channels from NN to $\Xi\Xi$ systems given in Eqs. (32)–(36), over 31 time-slices, 16^3 points for spatial, and 2^4 points for the spin degrees of freedom, obtained by using this effective block algorithm (dot) and by using the unified contraction algorithm (open circle) as a function of one-dimensionally aligned data point $\xi = \tilde{\alpha} + 2(\tilde{\beta} + 2(\tilde{\alpha}' + 2(\tilde{\beta}' + 2(x + 16(y + 16(z + 16(c + 52((t - t_0 + T) \bmod T)))))))$, where $c = 0, \cdots, 51$ selects one of the 52 channels. The absolute value of their difference is also shown (triangle).

Benchmark (from NN to XiXi channels)



$$\xi = \alpha + 2(\beta + 2(\alpha' + 2(\beta' + 2(x + 16(y + 16(z + 16(c + 52(t - t_0))))))))$$

Almost physical point lattice QCD calculation using N_F=2+1 clover fermion + Iwasaki gauge action

- APE-Stout smearing (ρ=0.1, n_{stout}=6)
- Non-perturbatively O(a) improved Wilson Clover action at β=1.82 on $96^3 \times 96$ lattice
- $1/a$ = 2.3 GeV (a = 0.085 fm)
- Volume: $96^4 \rightarrow (8\text{fm})^4$
- m_π=145MeV, m_K=525MeV
- DDHMC(ud) and UVPHMC(s) with preconditioning
- K.-I.Ishikawa, et al., PoS LAT2015, 075; arXiv:1511.09222 [hep-lat].

- NBS wf is measured using wall quark source with Coulomb gauge fixing, spatial PBD and temporal DBC; #stat=207configs x 4rotation x Nsrc
  (Nsrc=4 → 20 → 52 → 96 (2015FY+))

ΛN-ΣN potentials at nearly physical point

The methodology for coupled-channel V is based on:
Aoki, et al., Proc.Japan Acad. B87 (2011) 509.
Sasaki, et al., PTEP 2015 (2015) no.11, 113B01.
Ishii, et al., JPS meeting, March (2016).
Nemura, et al., [1702.00734].

#stat: (this/scheduled in FY2015+) 0.2 ⇨ 0.54 ➡ 1.00

$t-t_0=5-12$, $t-t_0=5-14$

$\Lambda N-\Sigma N\ (I=1/2)$

$V_C(^1S_0)$ $V_C(^3S_1-{}^3D_1)$ $V_T(^3S_1-{}^3D_1)$

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

$V_C(^1S_0)$ $V_C(^3S_1-{}^3D_1)$ $V_T(^3S_1-{}^3D_1)$

LN-SN potentials at nearly physical point

The methodology for coupled-channel V is based on:
Aoki, et al., Proc.Japan Acad. B87 (2011) 509.
Sasaki, et al., PTEP 2015 (2015) no.11, 113B01.
Ishii, et al., JPS meeting, March (2016).
Nemura, et al., [1702.00734].

#stat: (this/scheduled in FY2015+) 0.2 → 0.54 → 1.00 → **2.00**

$t-t_0=5-12$, $t-t_0=5-14$

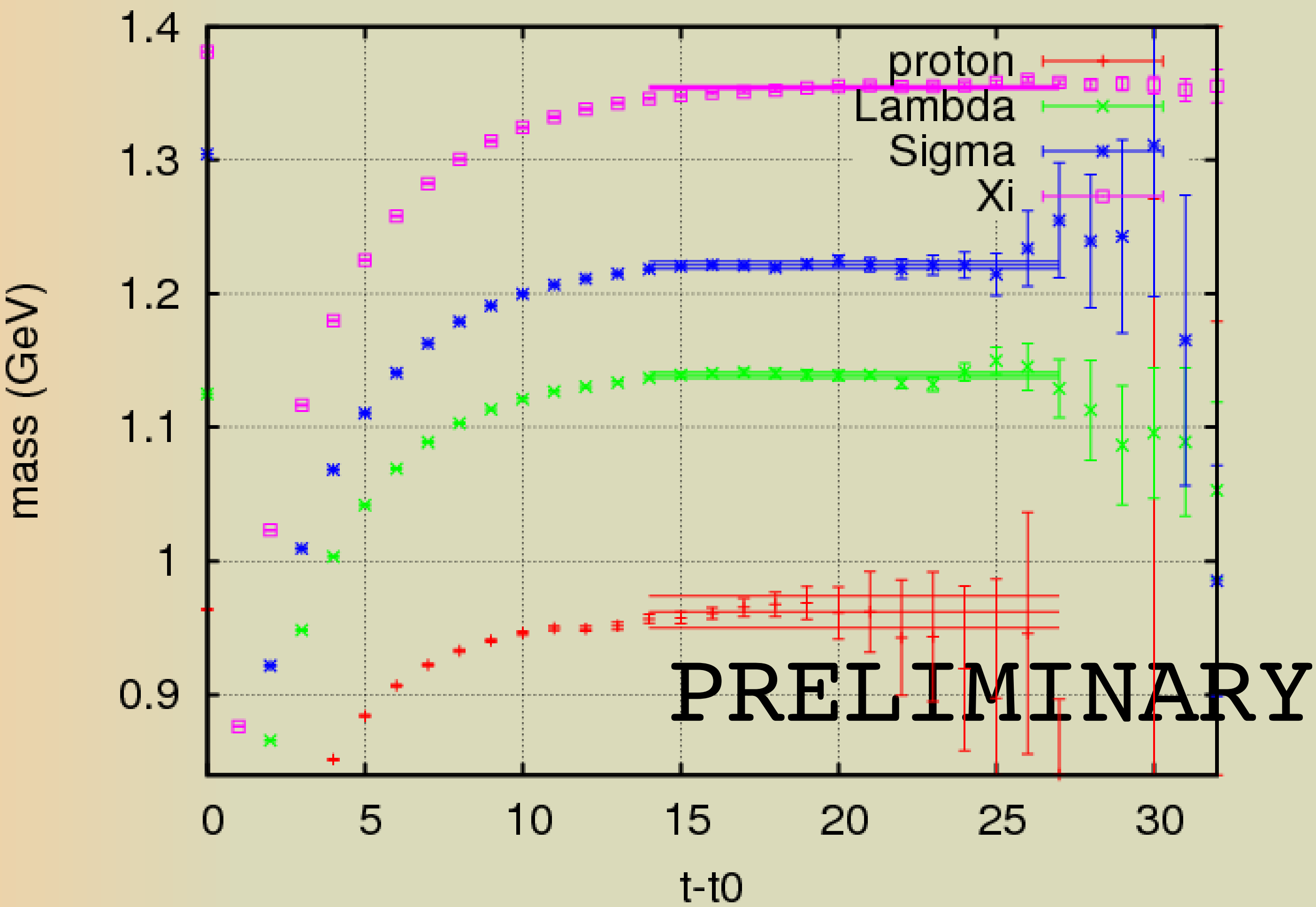
$\Lambda N-\Sigma N\ (I=1/2)$

$V_C(^1S_0)$ $V_C(^3S_1-{}^3D_1)$ $V_T(^3S_1-{}^3D_1)$

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

$V_C(^1S_0)$ $V_C(^3S_1-{}^3D_1)$ $V_T(^3S_1-{}^3D_1)$

Effective mass plot of the single baryon's correlation function



Potentials obtained at t-t0 = 5 to 12 are shown;
For the largest statistics, t-t0 = 13 and 14 will also be shown.

TABLE 4

The eigenvalues of the normalization kernel in eq. (3.3) for $S=-1$ two-baryon (BB) system

$S=-1$

I	J	BB	Eigenvalues (uncoupled)	Eigenvalues (coupled)
$\frac{1}{2}$	0	NΛ	1	0 $\frac{10}{9}$
		NΣ	$\frac{1}{9}$	
$\frac{1}{2}$	1	NΛ	1	$\frac{8}{9}$ $\frac{10}{9}$
		NΣ	1	
$\frac{3}{2}$	0	NΣ	$\frac{10}{9}$	
$\frac{3}{2}$	1	NΣ	$\frac{2}{9}$	

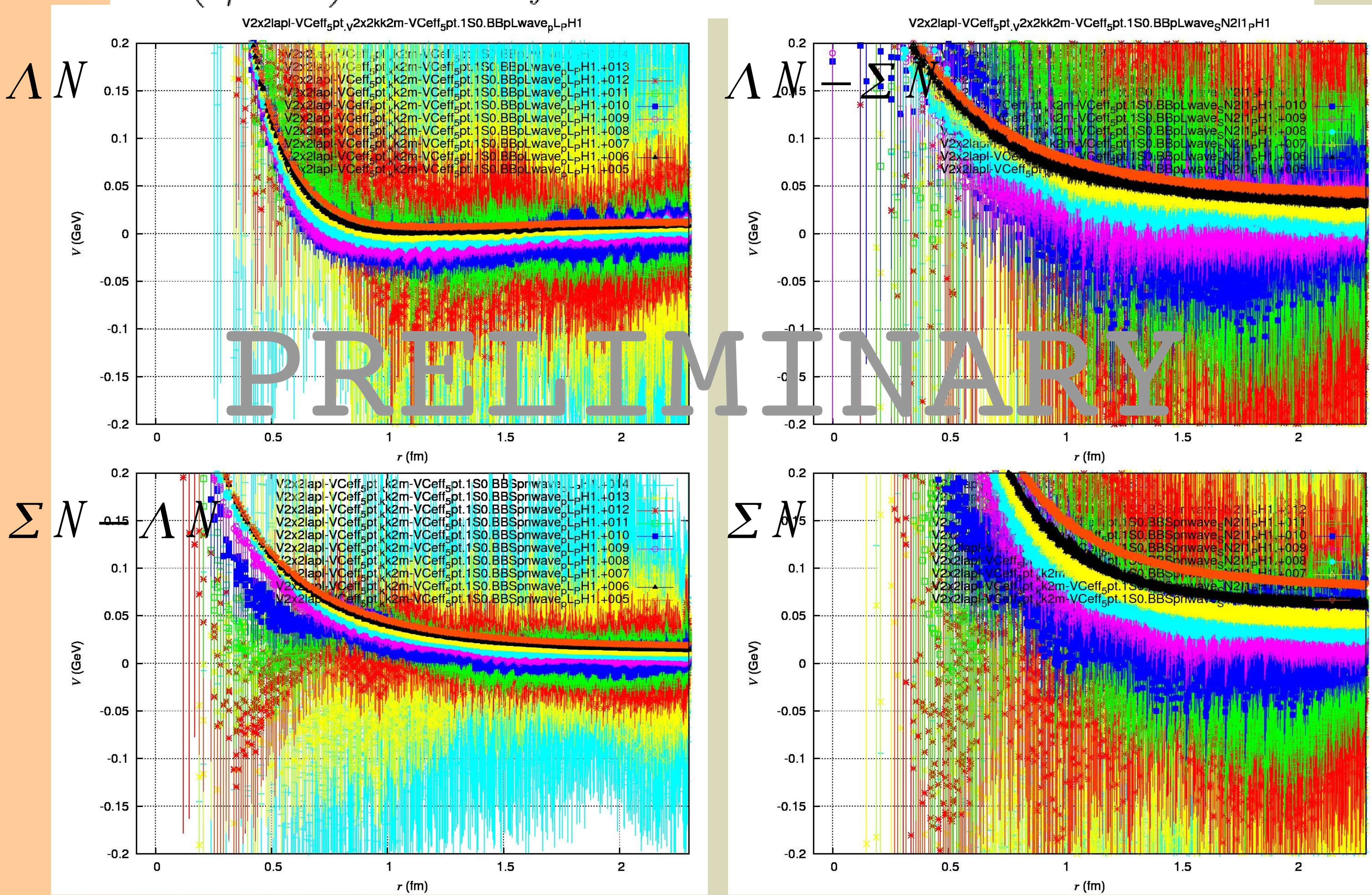
Eigenvalues of single and coupled channels are given.

Oka, Shimizu and Yazaki (1987)

Very preliminary result of LN potential at the physical point

$V_C(^1S_0)$

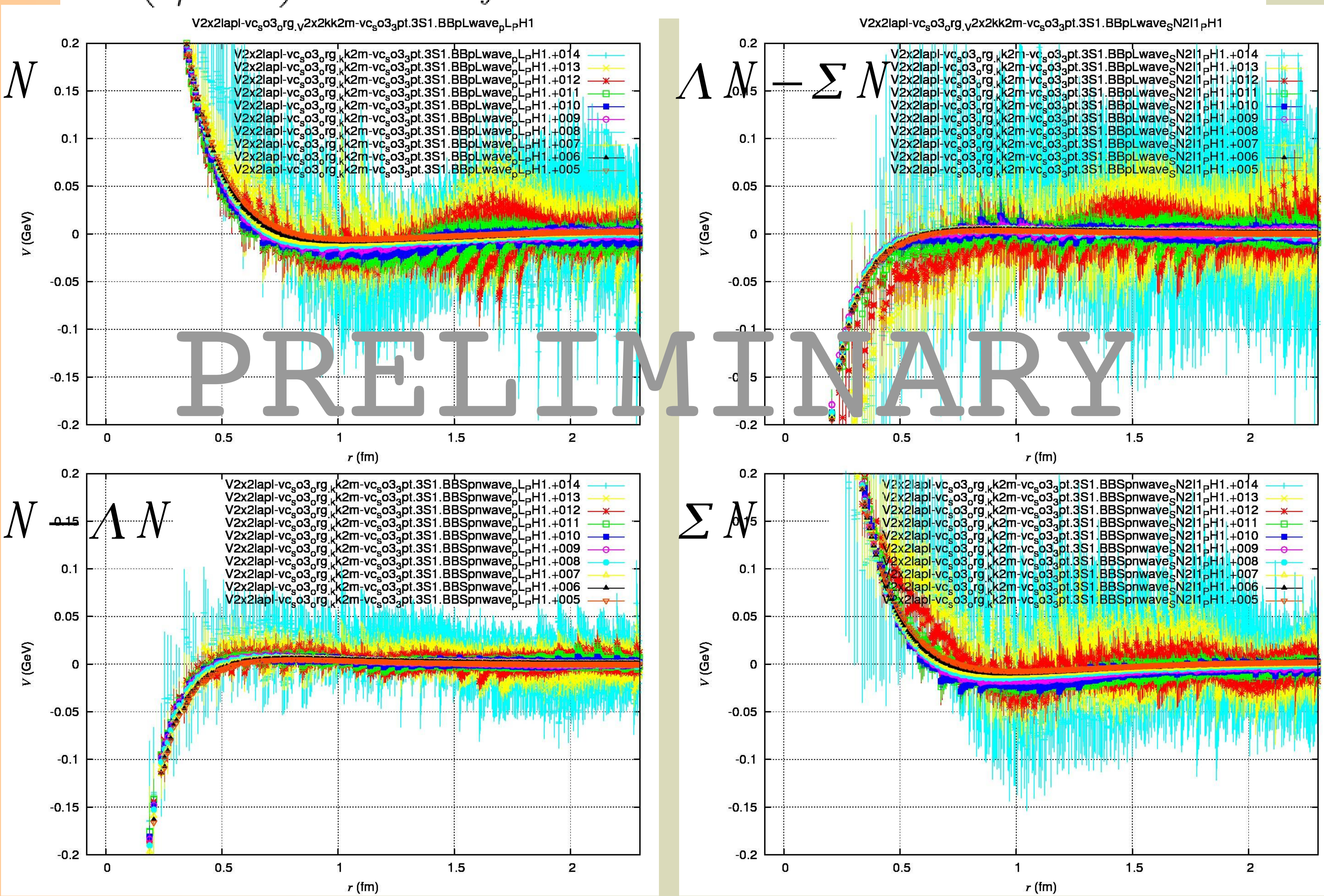
$$\left(\frac{\nabla^2}{2\mu} - \frac{\partial}{\partial t}\right) R(\vec{r},t) = \int d^3r'\, U(\vec{r},\vec{r}')R(\vec{r}',t) + O(k^4) = V_{\rm LO}(\vec{r})R(\vec{r},t) + \cdots (8)$$



Very preliminary result of LN potential at the physical point

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

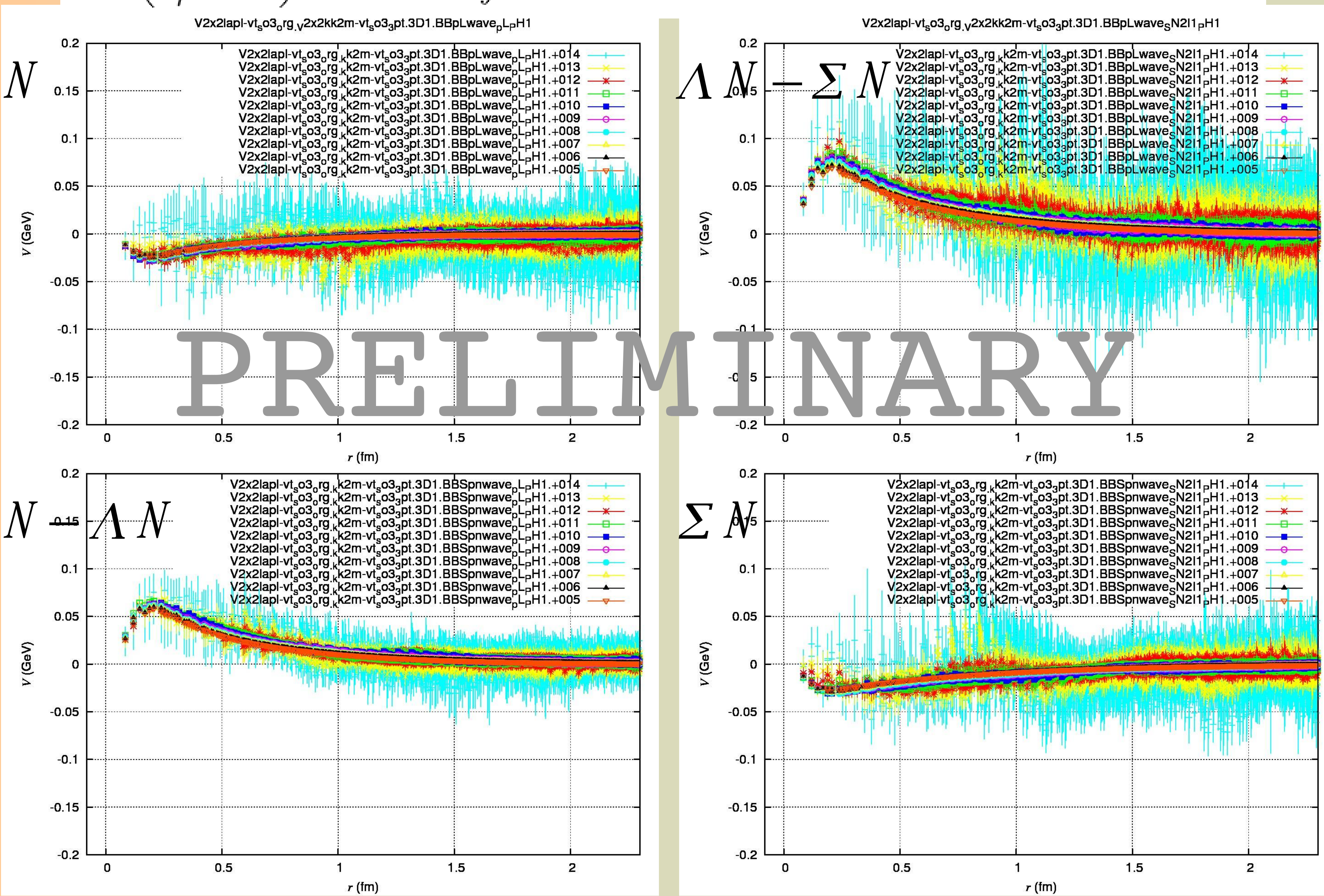
$$\left(\frac{\nabla^2}{2\mu} - \frac{\partial}{\partial t}\right) R(\vec{r},t) \;=\; \int d^3r'\, U(\vec{r},\vec{r}\,')R(\vec{r}\,',t) + O(k^4) = V_{\rm LO}(\vec{r})R(\vec{r},t) + \cdots \quad (8)$$



Very preliminary result of LN potential at the physical point

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

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

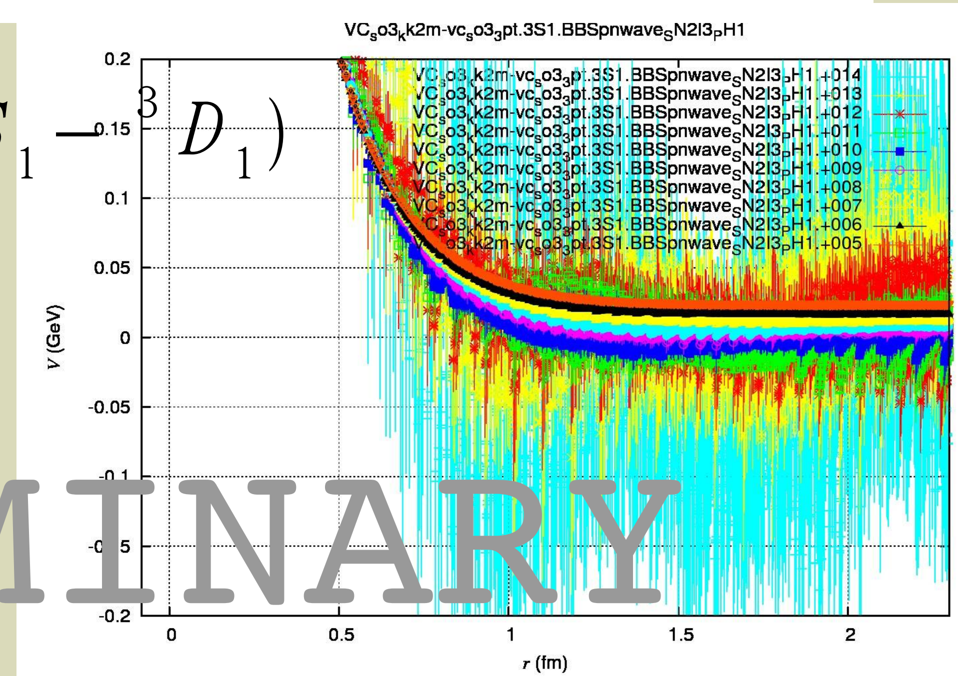


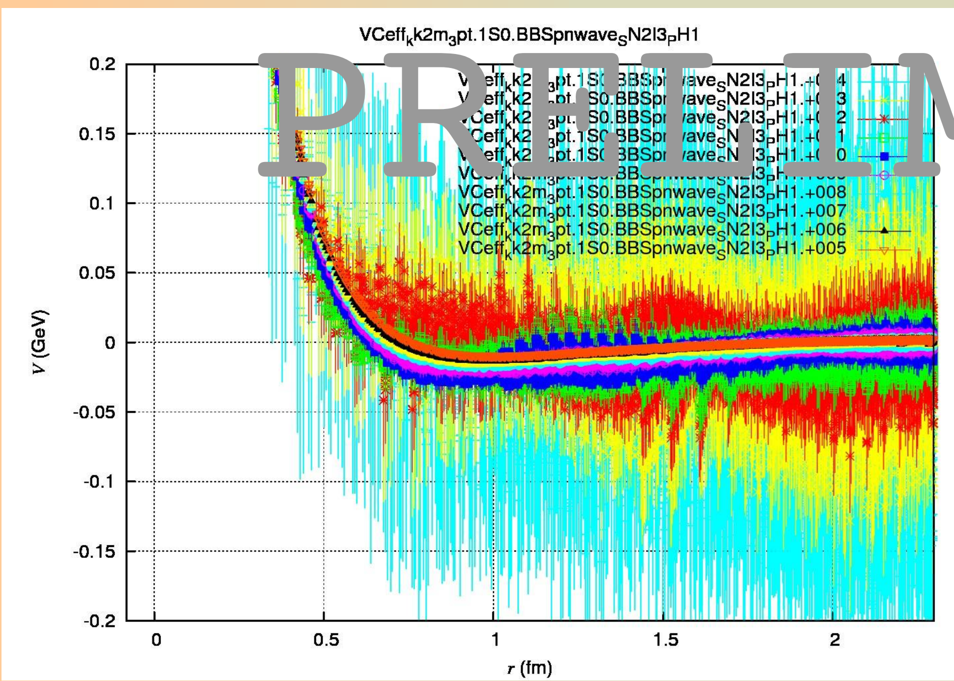
Very preliminary result of LN potential at the physical point

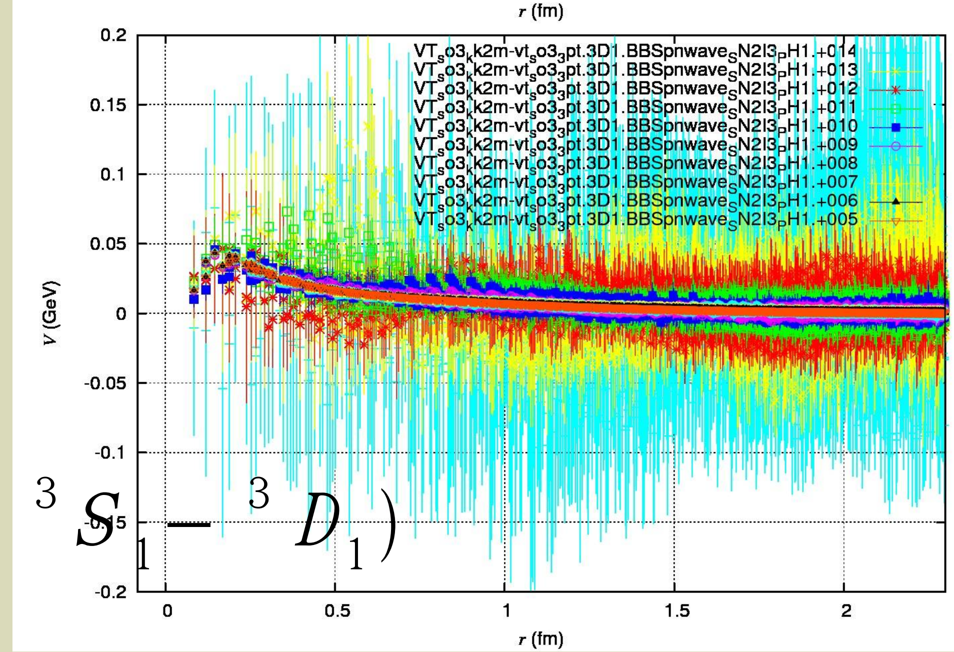
$$\left(\frac{\nabla^2}{2\mu} - \frac{\partial}{\partial t}\right) R(\vec{r},t) \;=\; \int d^3r'\, U(\vec{r},\vec{r}')R(\vec{r}',t) + O(k^4) = V_{\rm LO}(\vec{r})R(\vec{r},t) + \cdots (8)$$

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

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







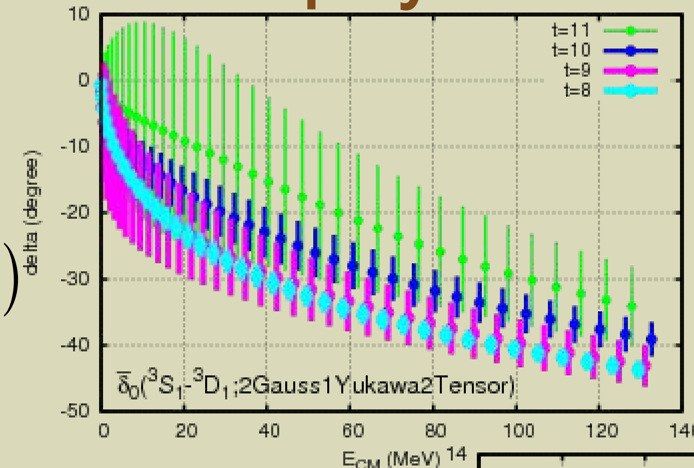
PRELIMINARY

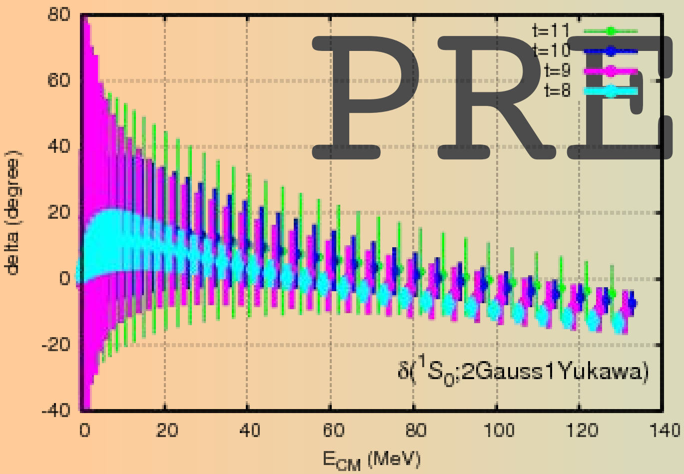
$V_C(\,^1S_0)$

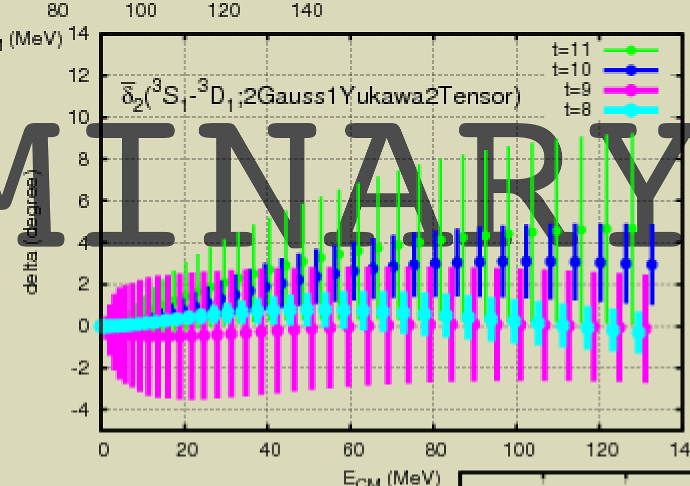
$V_T(\,^3S_1-\,^3D_1)$

Very preliminary results of the SN(I=3/2) phase shift at the physical point

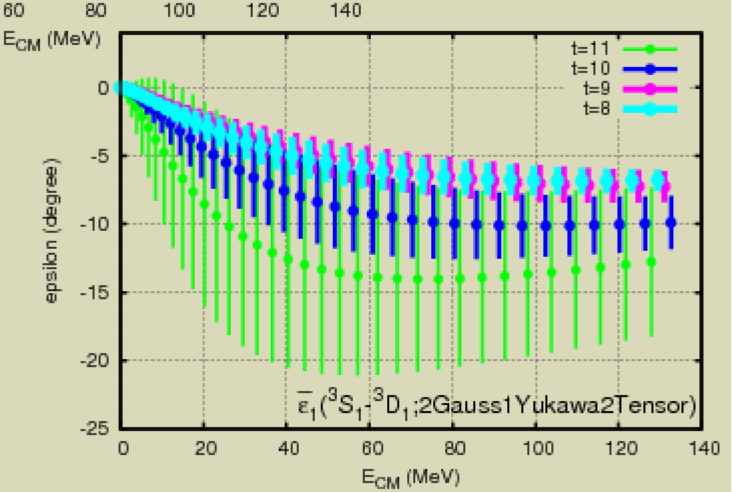
$$\Sigma N(I=3/2)$$







PRELIMINARY



More or less qualitatively similar to (recent) phenomenological approaches:
Fujiwara, et al., PRC54(1996)2180,
Arisaka, et al., PTP104(2000)995,
Haidenbauer et al., NPA915(2013)24.

Summary

(I-1) Latest results of LN-SN potentials at nearly physical point.
(Lambda-N, Sigma-N: central, tensor)
Statistics approaching to 1.96 => 2.0 (=present/scheduled in 2015)

Increasing statistics, the result at large t converges to the result at next-to-smaller t (with poor statistics).

Signals in spin-triplet are relatively going well smoothly.

The channels that the quark model predicts strongly repulsive have relatively poor signals; Simultaneous calcs (NN to XiXi) is the point we have to take into account for the comprehensive perspective as well as energy-computing-resource efficiency.

(I-2) Effective hadron block algorithm for the various baron-baryon interaction

Comput.Phys.Commun.**207**,91(2016) [arXiv:1510.00903(hep-lat)]

The algorithm will be applied to more wide range problems.

Future work:

(II-1) Physical quantities including the binding energies of few-body problem of light hypernuclei with the lattice YN (and NN) potentials