CHARMONIUM-NUCLEON INTERACTION FROM LATTICE QCD

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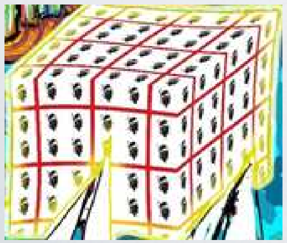


LATTICE 2010 THE XXVIII INTERNATIONAL SYMPOSIUM ON LATTICE FIELD THEORY
June 14th-19th Villasimius, Cagliari, Italy

Why cc^{bar}-nucleon interaction ?

✦Flavor singlet interaction

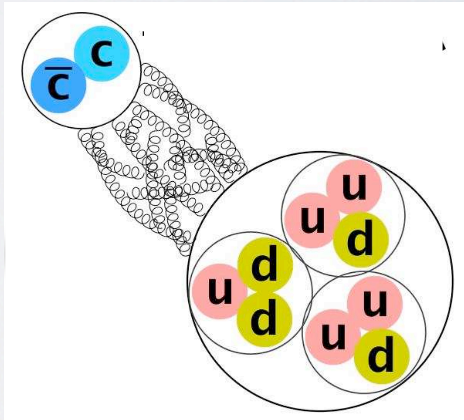
1) No quark interchange

2) Multiple gluon exchange plays essential role

→ Interaction is described by color van der Waals interaction, which is weakly attractive in principle. (e.g. $-1/r^7$ behavior given by color dipoles)

H. Fujii and D. Kharzeev PRD60, 114039 (1999)

✦If such an attraction is strong enough, charmonium may be bound to the nucleon or to the large nuclei.



Model study of nuclear-bound charmonium

✦ A semi-quantitative study of the charmonium-nucleus bound state was given by Brodsky et al. Brodsky, Schmidt, de Teramond, PRL 64 (1990) 1011

1. A simple Yukawa-type potential is assumed for the cc^{bar} -N system.

$$V(r) = -\gamma \frac{\exp(-\alpha r)}{r}$$

γ=0.6 α=600 MeV

2. The cc^{bar}-Nucleus potential

D. A. Wasson, PRL 67 (1991) 2237

$$V_{c\bar{c}\text{-}A}(r) = A \times V_{c\bar{c}\text{-}N}(r) \quad \text{or} \quad \int d^3\vec{r}'\rho(\vec{r}')V_{c\bar{c}\text{-}N}(\vec{r}')$$

They predicted a formation of nuclear-bound charmonium when A ≧ 3.

✦ Precise information of the cc^{bar}-N potential $V_{cc^{-}\text{-}N}(r)$ is indispensable for exploring nuclear-bound charmonium state.

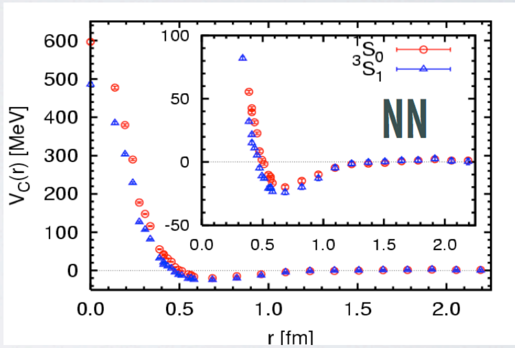
Our strategy

1. Tokyo-Tsukuba approach for hadron-hadron potential

To define the potential through the Bethe-Salpeter wave function measured on the lattice.

N. Ishii, S. Aoki and T. Hatsuda, Phys. Rev. Lett. 90, 022001 (2007)

S. Aoki, T. Hatsuda and N. Ishii, Prog. Theor. Phys. 123 (2010) 89.



2. Fermilab approach for heavy quark

To remove large discretization errors for heavy quarks.

A. X. El-Khadra, A. S. Kronfeld and P. B. Mackenzie, (1997)

Hadron-hadron potential

✦Equal-time Bethe-Salpeter amplitude

M. Lüscher, Nucl. Phys. B 354, 531 (1991)

$$
\begin{aligned}
F_{\eta_c-N}(\vec{x},\vec{y},t;t_0) &= \langle 0|N(\vec{x},t)\eta_c(\vec{y},t)J_{\eta_c-N}|0\rangle \\
&= \sum_n A_n \langle 0|N(\vec{x},t)\eta_c(\vec{y},t)|n\rangle e^{-E_n(t-t_0)} \\
&\longrightarrow A_0\phi_0(\vec{r})e^{-E_0(t-t_0)} \quad t \gg t_0 \ , \ \vec{r}=\vec{x}-\vec{y}
\end{aligned}
$$

Interpolating operators

$$
\begin{aligned}
N(\vec{x}) &= \epsilon_{abc}(u_a^t C\gamma_5 d_b)d_c(\vec{x}) \\
\eta_c(\vec{y}) &= \bar{c}\gamma_5 c_a(\vec{y})
\end{aligned}
$$

✦Schrödinger type equation for general cases.

$$
E\phi(\vec{r}) + \frac{1}{2m_{red}}\nabla^2\phi(\vec{r}) = \int d^3r' U(\vec{r},\vec{r}')\phi(\vec{r}')
$$

For cc^{bar}-N scattering at low energy

$$
U(\vec{r},\vec{r}') = V_{\eta_c-N}(\vec{r})\delta(\vec{r}-\vec{r}')
$$

Reduced mass; $m_{red} = m_{\eta c}m_N/(m_{\eta c}+m_N)$

Relativistic heavy quark action

✦Heavy quark mass introduces discretization errors of **O((ma)^n)**

✓ At charm quark mass, it becomes severe: **m_c ~ 1.5 GeV** and **1/a ~ 2 GeV**, then **$m_c a$ ~O(1).**

✦The Fermilab group proposed relativistic heavy quark action (RHQ) approach where all O((ma)^n) errors are removed by the appropriate choice of **m_0, ξ, r_s, C_B, C_E** . **A. X. El-Khadra, A. S. Kronfeld and P. B. Mackenzie, (1997)**

$$S_{\rm lat} = \sum_{n,n'} \bar{\psi}_{n'} (\gamma^0 D^0 + \zeta \vec{\gamma} \cdot \vec{D} + m_0 a - \frac{r_t}{2} a (D^0)^2 - \frac{r_s}{2} a (\vec{D})^2 + \sum_{i,j} \frac{i}{4} c_B a \sigma_{ij} F_{ij} + \sum_i \frac{i}{2} c_E a \sigma_{0i} F_{0i})_{n',n} \psi_n$$

We take the Tsukuba procedure in our study.

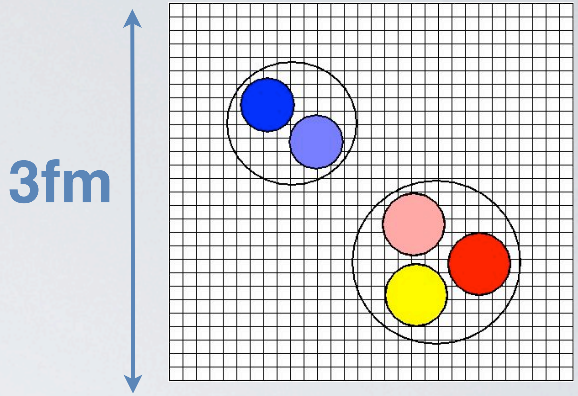
S. Aoki, Y. Kuramashi, and S.-i. Tominaga, Prog. Theor. Phys. 109, 383 (2003)

Y. Kayaba et al. [CP-PACS Collaboration], JHEP 0702, 019 (2007).

Lattice set up

✦ low energy η_c-N interaction

✦ Quenched QCD simulation

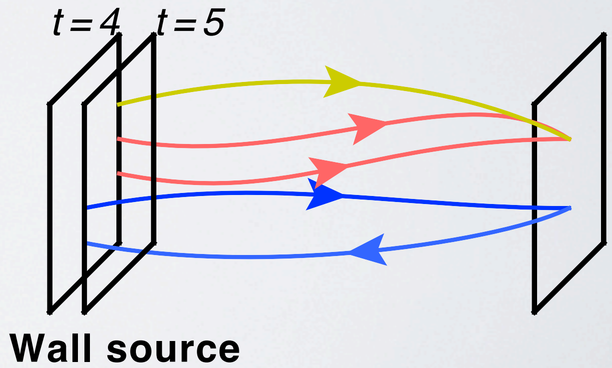


✦ Lattice size:
$L^3 \times T$ = **32^3 x 48**, 16^3 x 48 (La ≈ **3.0**, 1.5 fm)

✦ plaquette action (gauge) β=6.0 (a=0.093 fm or a^{-1}=2.1GeV)
+ non-perturbative O(a) improvement action (up & down)
+ **RHQ** action with one-loop PT coefficients (charm)

Y. Kayaba et al. [CP-PACS Collaboration], JHEP 0702, 019 (2007).

✦ Statistics : **O(600) configs**



✦ Quark mass
- charm κ_Q = 0.10190 $m_{\eta c}$= 2.92 GeV
- Light

κ	0.1342	0.1339	0.1333
m_π [GeV]	0.64	0.73	0.87
m_N [GeV]	1.43	1.52	1.70

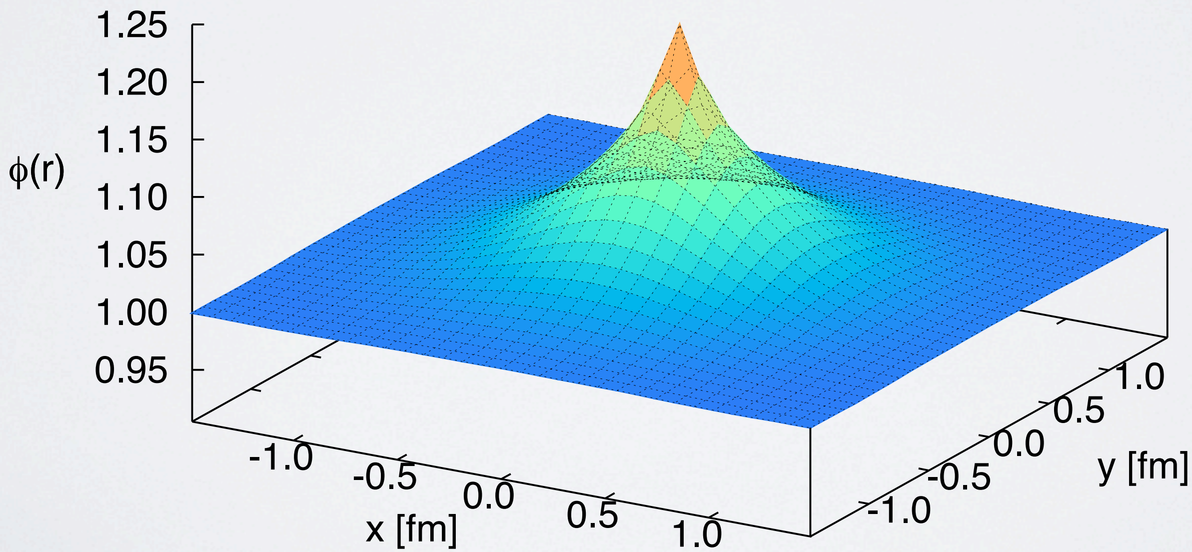
Result; η_c-N wave function

★"S-wave" BS wave fucntion can be projected out as

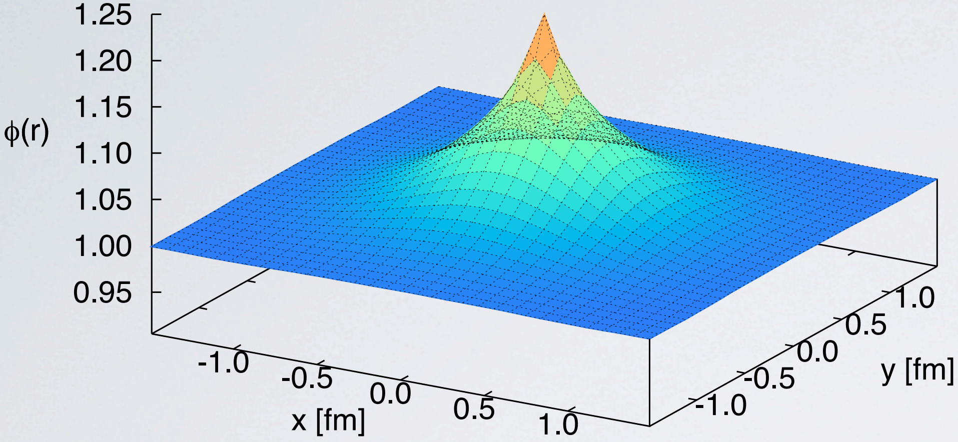
$$\phi(\vec{r}) = \frac{1}{24}\sum_{R\in O}\frac{1}{L^3}\sum_{\vec{x}}\langle 0|N(R[\vec{r}]+\vec{x})\eta_c(\vec{x})|N\eta_c\rangle$$

R represents an element of cubic group. The summation over R and x projects out the A_1^+ sector of cubic group and zero total momentum.

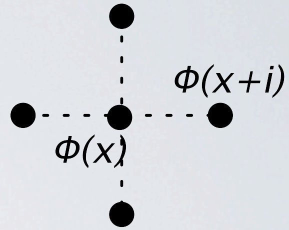
★The "S-wave" η_c-N wave function.



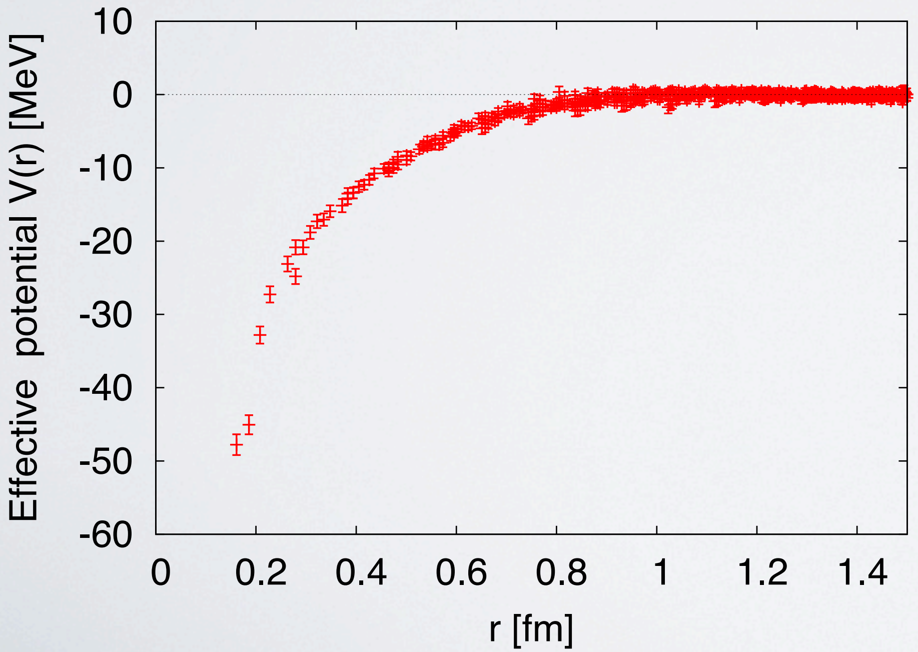
Result; η_c-N potential



- The reduced mass is estimated from 2pt correlation functions
- ∇^2 denotes the discrete Laplacian

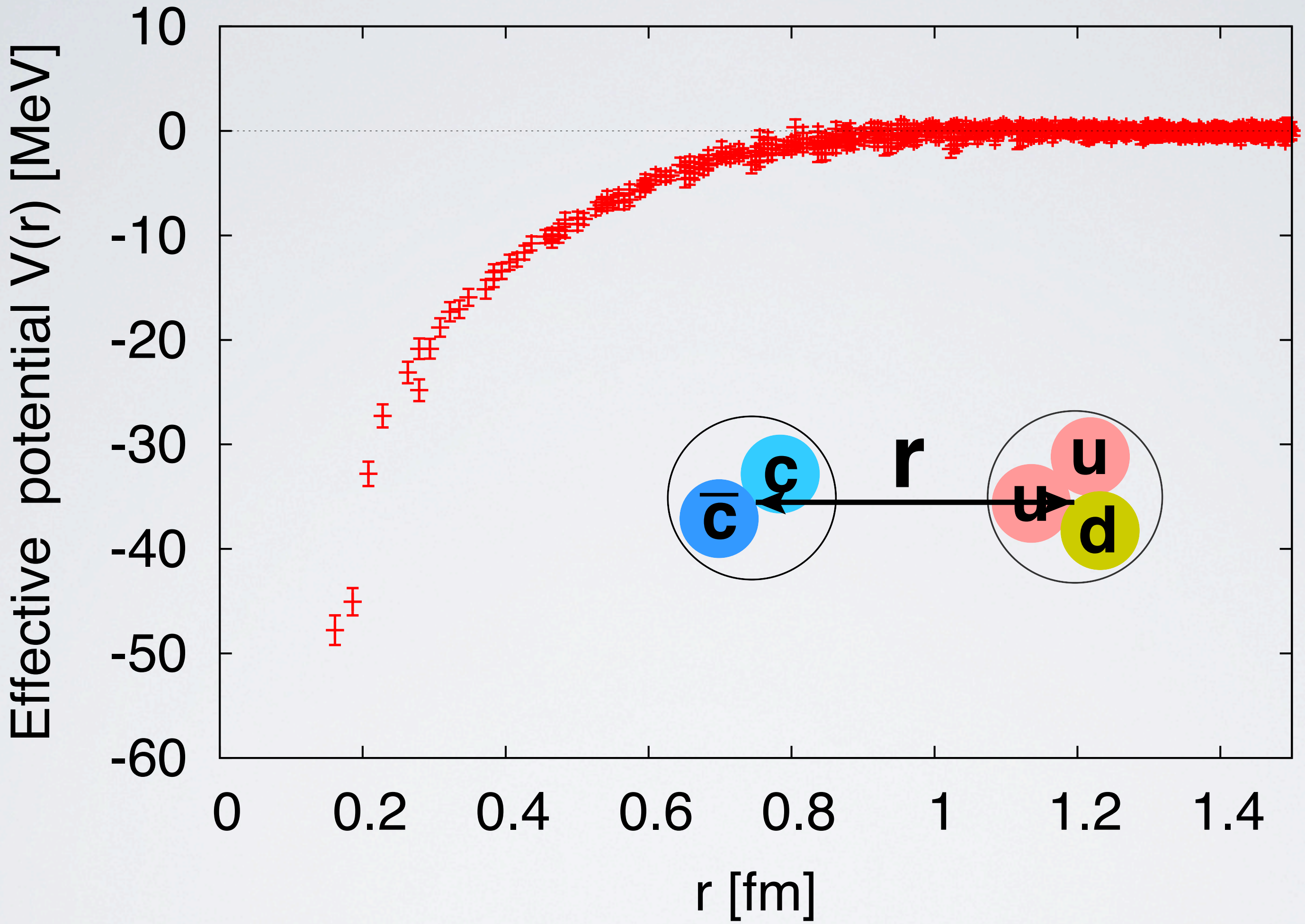


$$\frac{1}{2m_{\mathrm{red}}}\frac{\nabla^2\phi(r)}{\phi(r)} = V(r) - E$$



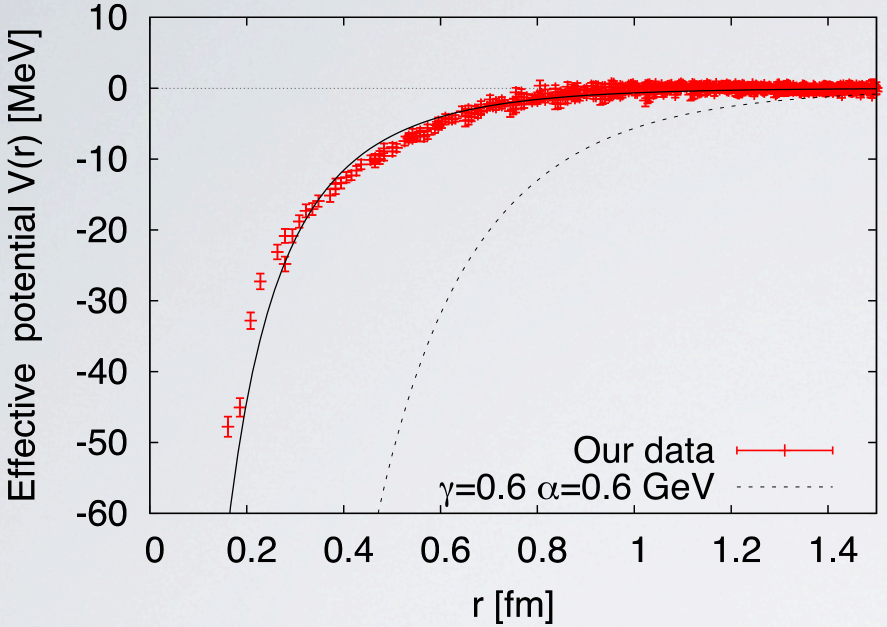
- V(r) is adjusted as V(r)=0 for r>1fm
  → Energy shift E

Result; η_c-N potential



- The η_c-N potential exhibits entire attraction without any repulsion.
- The interaction is exponentially screened in long distance region.

Result; η_c-N potential



Check of the long range screening.
-We have tried to fit data with two types of fitting function.

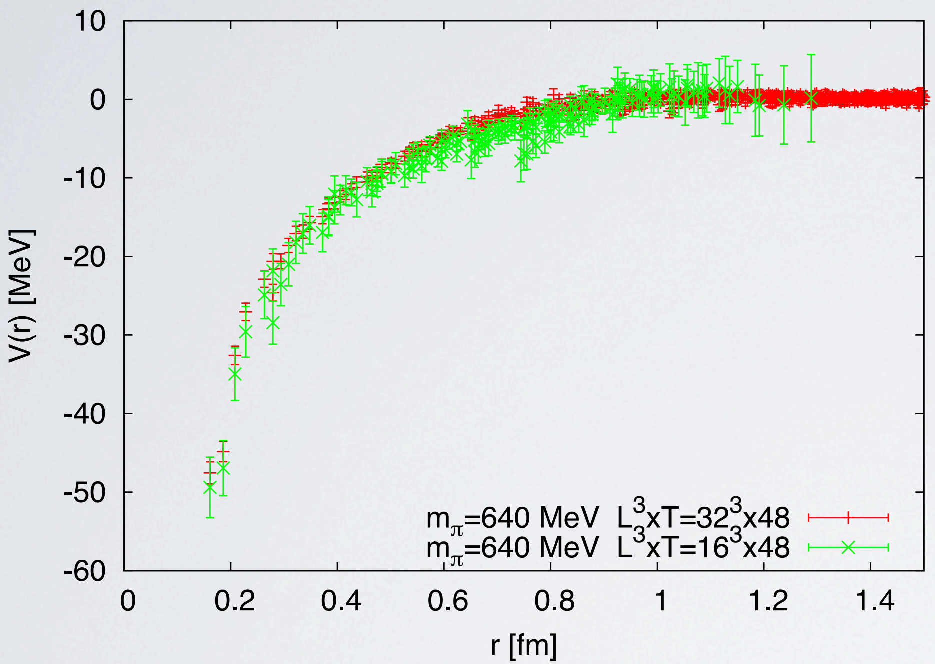
1) Exponential type function - $\exp(-r^n)/r^m$
→ gives a good fit with small χ^2/ndf

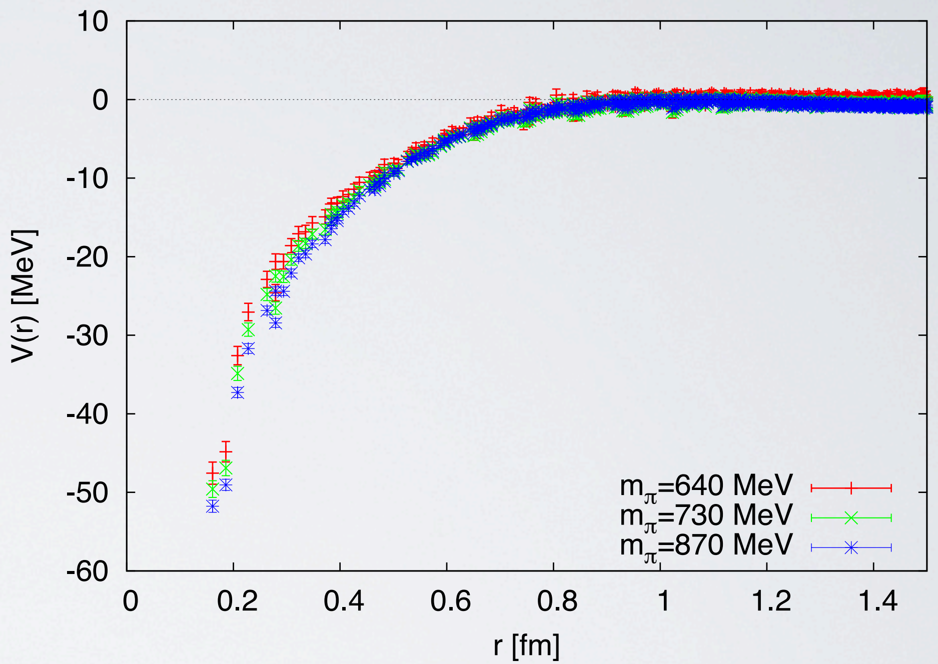
2) Inverse power low function $-1/r^n$
→ cannot gives a reasonable fit.

- If we adopt the Yukawa form $-\gamma \exp(-\alpha r)/r$ to fit our potential, we obtain γ~0.1 α~ 600 MeV .
- cf. Phenomenological model γ=0.6 α = 600 MeV

→The $c\bar{c}$-N potential observed from lattice QCD is rather weak.

Result; volume & quark mass dependence





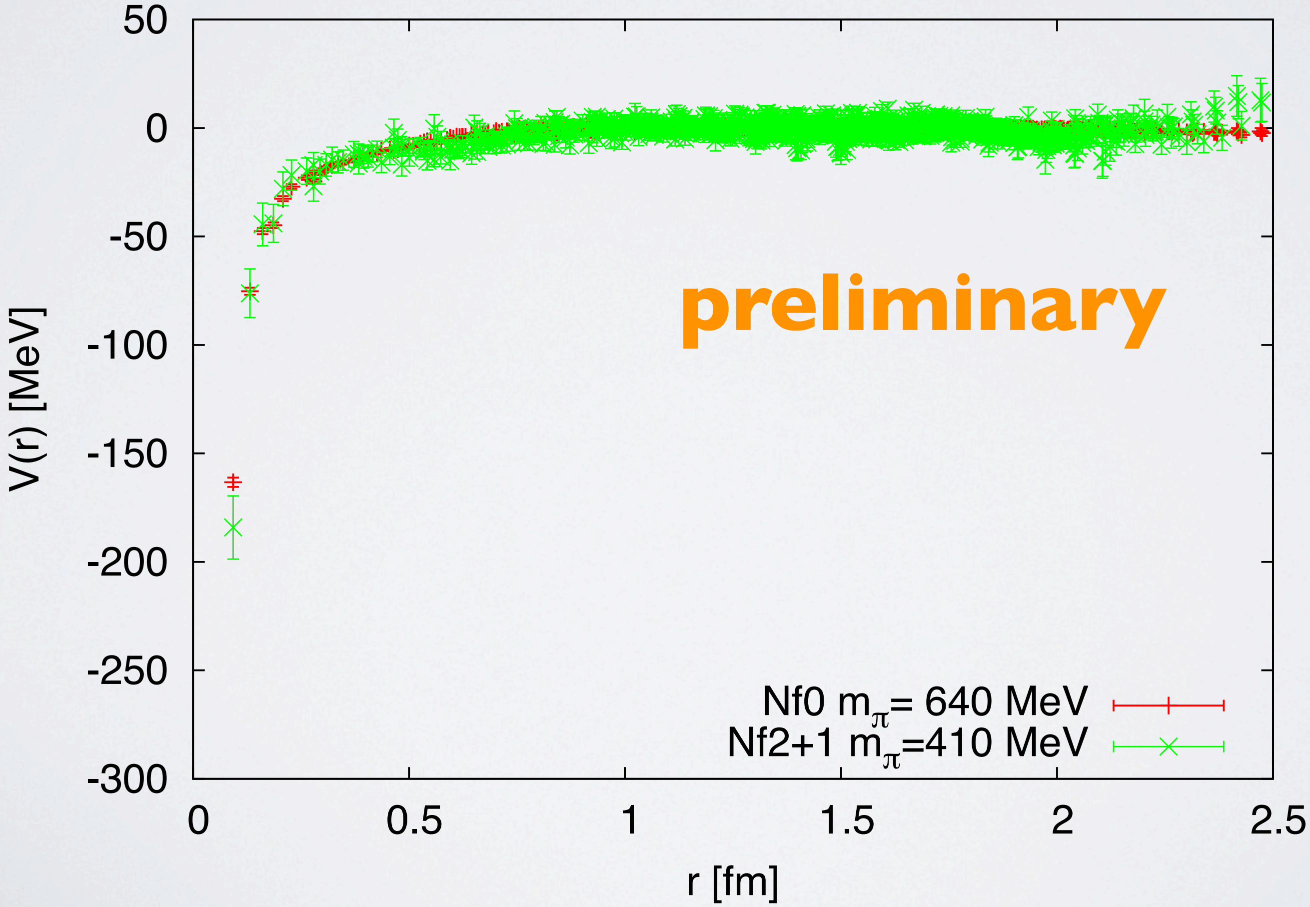
- No volume dependence
- No quark mass dependence

Result; η_c-N potential using PACS-CS 2+1 flavor dynamical configuration

S.Aoki et al., PRD 79, 034503 (2009)

- Quark mass; κ_{ud}=0.13754 ,κ_s=013640 (m_π=0.41GeV, m_N=1.2GeV)

  κ_c =0.106787 ($m_{\eta c}$ = 3GeV)
- Lattice size; $L^3 \times T = 32^3 \times 64$ (La ≈ 3.0 fm)
- Statistics ; 200 measurements



Summary

- ✦ We derived the $c\bar{c}$-nucleon potential with quenched QCD simulations (pilot study) and Nf2+1 full QCD simulations (preliminary)

  - ✓ The low energy $c\bar{c}$-N interaction is attractive in the whole range of r.

  - ✓ The Long-range part is likely suppressed exponentially.

    - No quark mass dependence up to $m_\pi \sim$ 400MeV.
    - No drastic difference between quenched QCD and Full QCD.

- ✦ Future perspective

  - ✓ We need to perform the simulation in lighter quark mass region.

  - ✓ Calculation of the spin dependent system; J/ψ-N state

  - ✓ Exploring nuclear-bound charmonium state with theoretical inputs.