Strange sector of baryon-baryon interactions from lattice QCD

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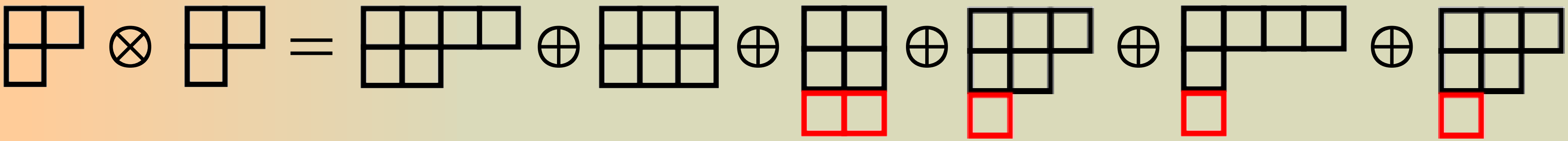
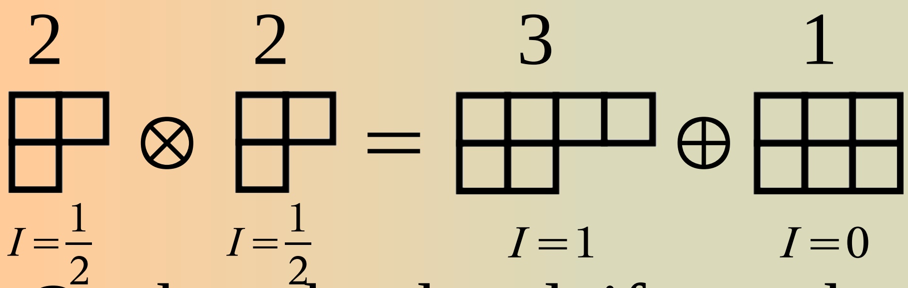


Introduction:

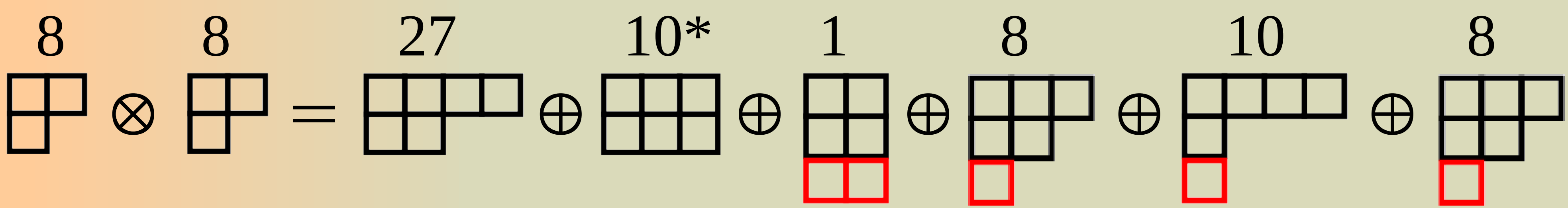
- Study of hyperon-nucleon (*YN*) and hyperon-hyperon (*YY*) interactions is one of the important subjects in the nuclear physics.
  - Structure of the neutron-star core,
    - Hyperon mixing, softning of EOS, inevitable strong repulsive force,
  - H-dibaryon problem,
    - To be, or not to be,
- The 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.

Extension from NN to YN and YY:

- If we take only non-strange sector,
  there are only 2 representations for isospin space.



- On the other hand, if we take account of strange degree of free-dom, other representations should be included.



- This means that the *YN* and *YY* interactions cannot be determined from the precise *NN* experimental data even if we assume the flavor SU(3) symmetry.
- Lattice QCD is desirable for the study of the *YN* and *YY* interac-tion, because this is *ab initio* numerical simulation.

Recent impressive works of lattice QCD:

- S. Aoki, *et al*., PRD**71**, 094504 (2005);

  π-π scattering length from the wave function.

- N. Ishii, *et al*., nucl-th/0611096, PRL in press;

  NN potential from the wave function.

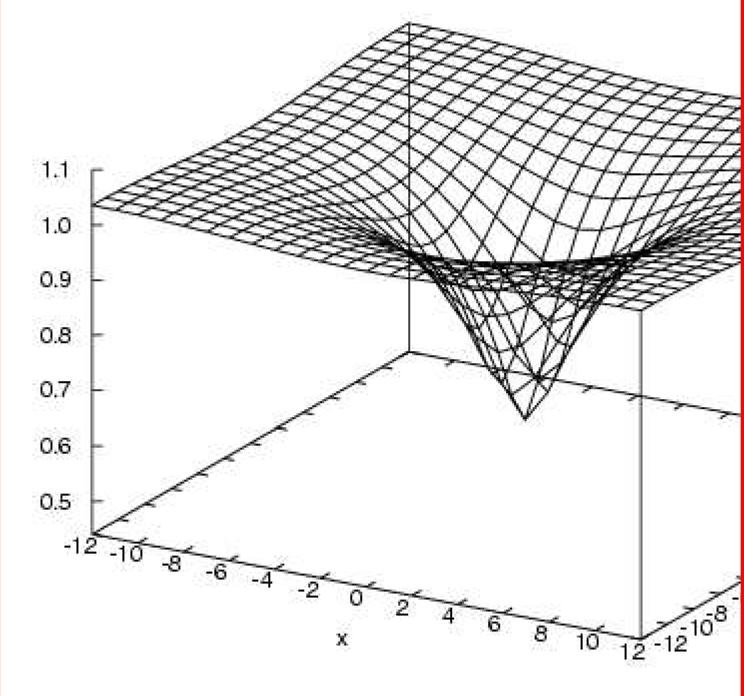
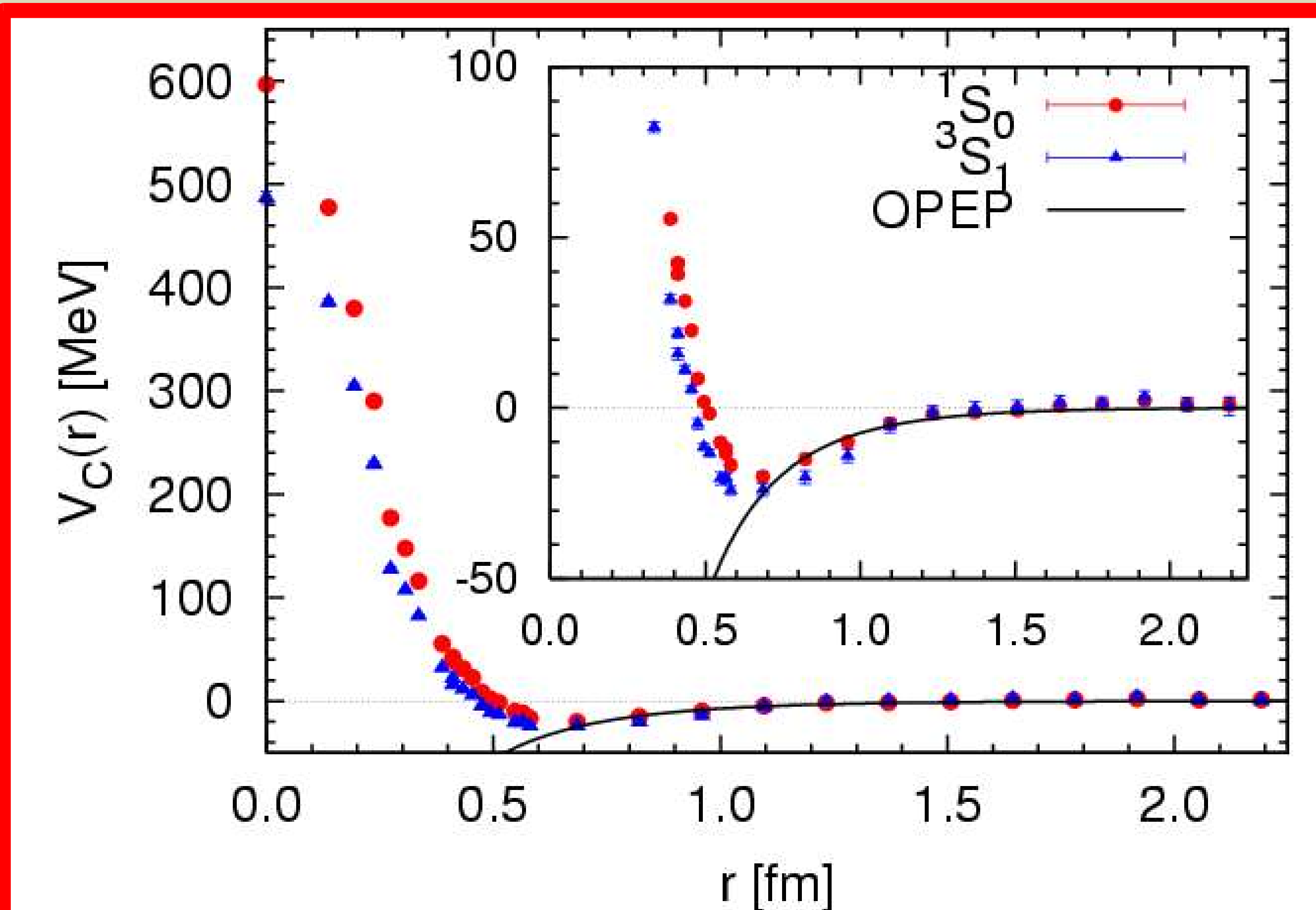


FIG. 1. Two-pion wave function $\phi(\vec{x};k)$ o
$(t,z)=(52,0)$ plane for $m_\pi^2 = 0.273$ GeV^2. T
tor is set at $\vec{x}_0 = (7,5,2)$ $(x_0 = |\vec{x}_0| = 8.832)$.



- This work;

  YN and *YY* potentials by applying these techniques.

The purpose of this work

- *YN* and *YY* potentials from lattice QCD
  - $N\Lambda$, $N\Sigma$, $\Lambda\Lambda$, $N\Xi$, ...
- $N\Xi$ potential as a first step
  - Main target of the J-PARC DAY-1 experiment
  - Few experimental information, so far
- Focus on the I=1 channel, $^1S_0$, $^3S_1$
  - I=1; $N\Xi$-$\Lambda\Sigma$-$\Sigma\Sigma$: $N\Xi$ is the lowest state.
  - I=0; $\Lambda\Lambda$-$N\Xi$-$\Sigma\Sigma$: $N\Xi$ is not the lowest state.
- I=0 channel will be studied in the future.

A recipe for NΞ potential:

- More accurate explanation, for *NN*, was given by Ishii-san.

- Calculate the 4-point *N*Ξ correlator on the lattice,

$$\phi_{N\Xi}(x-y)\mathrm{e}^{-E(t-t_0)} \simeq \langle p_\alpha(x,t)\Xi^0_\beta(y,t)\overline{\Xi^0_{\beta'}}(0,t_0)\overline{p_{\alpha'}}(0,t_0)\rangle$$

  - Which has the physical meanings of,
    - Create a *N*Ξ state and making imaginary time evolution, in order to have the lowest state of the *N*Ξ system.
    - Take the amplitude $\phi(\boldsymbol{x}-\boldsymbol{y})$, which can be understood as a wave function of the non-relativistic quantum mechanics.

- Obtain the effective central potential by assuming that the WF is a solution of effective Schroedinger equation.

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2+V(r)\right)\phi(r)=E\,\phi(r)$$

$$\rightarrow\quad V(r)=E+\frac{\hbar^2}{2\mu}\frac{\nabla^2\phi(r)}{\phi(r)}$$

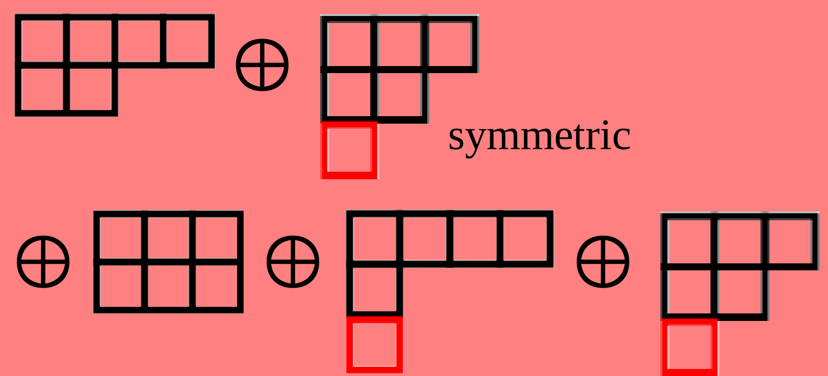
My turn in this work:

- Calculate the 4-point $N\Xi$ correlator on the lattice,

$$\phi_{N\Xi}(x-y)e^{-E(t-t_0)} \simeq \langle p_\alpha(x,t)\,\Xi^0_\beta(y,t)\,\overline{\Xi^0_{\beta'}}(0,t_0)\,\overline{p_{\alpha'}}(0,t_0)\rangle$$

  - This gives the different pattern of the Wick contraction from the NN,

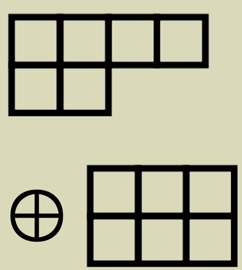
$(N\Xi) \in$



for ${}^1S_0$,

for ${}^3S_1$,

cf. , $(NN) \in$



for ${}^1S_0$,

for ${}^3S_1$,

- Calculate the 2-point correlators for N and Ξ,

$$\sum_y \langle \Xi^0_\beta(y,t)\,\overline{\Xi^0_{\beta'}}(0,t_0)\rangle \qquad \sum_x \langle p_\alpha(x,t)\,\overline{p_{\alpha'}}(0,t_0)\rangle$$

We need the reduced mass to construct the potential.

$$V(r) = E + \frac{\hbar^2}{2\mu}\frac{\nabla^2\phi(r)}{\phi(r)}$$

Interpolating fields and parameters:

- Interpolating fields:

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

$$\Xi^0_\beta(y) = \varepsilon_{abc}(u_a(y) C\gamma_5 s_b(y)) s_{c\beta}(y),$$

- The lattice calculations were performed by using KEK Blue Gene/L supercomputer.
  - The C++ code reached 1.3GFlops/processor, which is almost a half of the peak value.

1.3TFlops at 512node que

- Volume: $32^3 \times 32$ lattice ($L \sim 4.4$ fm).
- Lattice spacing: $a \sim 0.14$ fm.
- Standard Wilson action:
  - $\kappa_{ud} = 0.1678$ for u and d quarks, and
  - $\kappa_s = 0.1665$ for s quark.
    - For more details, see Ishii-san's talk.

Meson masses:

$m_\pi \sim 0.377(3)$ GeV

$m_\rho \sim 0.844(6)$ GeV

$m_K \sim 0.463(1)$ GeV

$m_{K^*} \sim 0.868(3)$ GeV

Results —— hadron masses

- Path integrals for the correlators are performed by using 491 gauge configurations, so far:

- Calculated baryon masses (in units of GeV):

m_p	m_Ξ	m_Λ	m_Σ
1.210(11)	1.291(5)	1.244(8)	1.271(7)

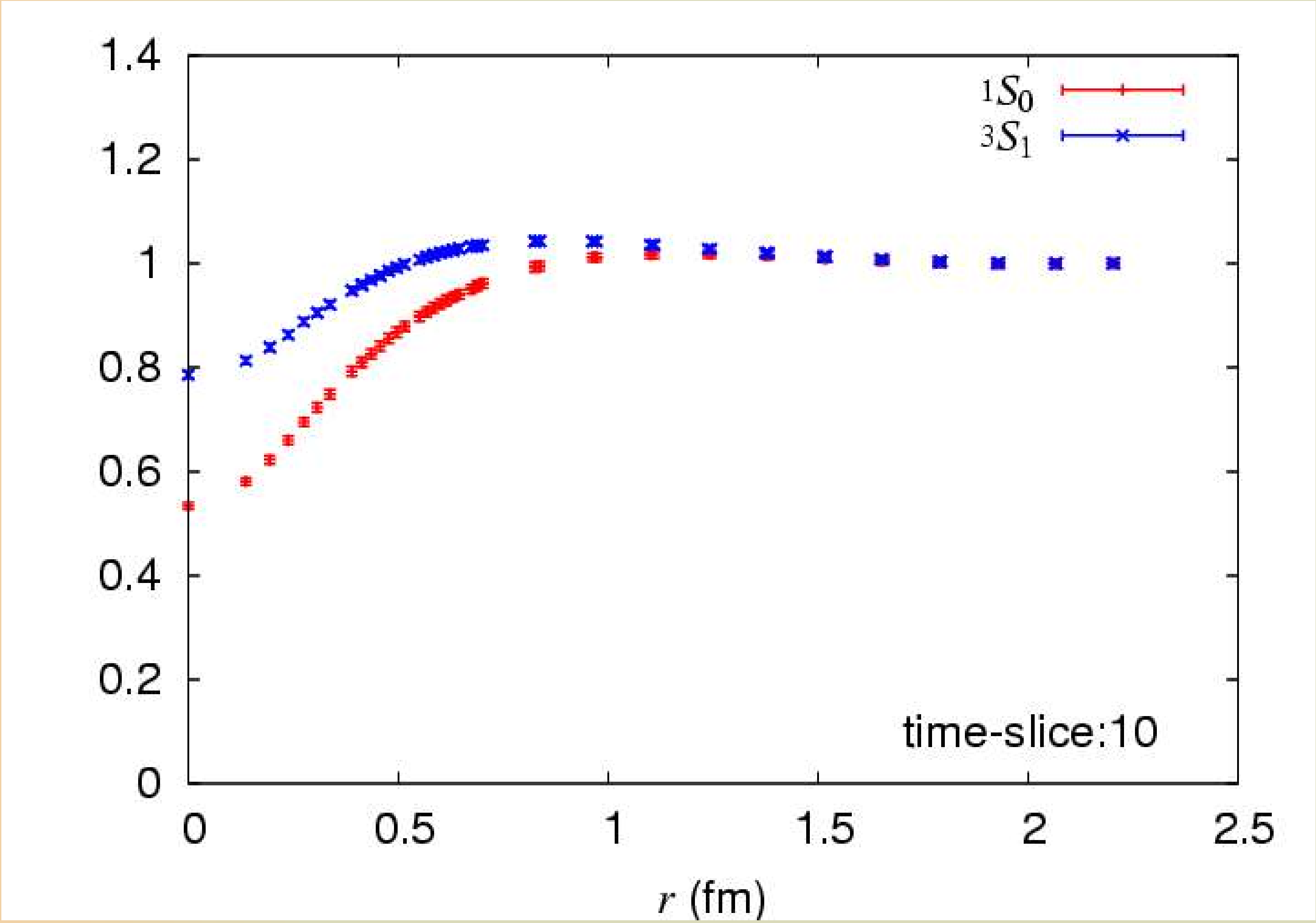
- Interpolating fields for Λ and Σ^+:

$$\Lambda_\alpha(x) = \frac{1}{\sqrt{3}} \varepsilon_{abc} \left\{ (d_a C \gamma_5 s_b) u_{c\alpha} + (s_a C \gamma_5 u_b) d_{c\alpha} - 2 (u_a C \gamma_5 d_b) s_{c\alpha} \right\}$$

$$\Sigma_\beta^+(y) = -\varepsilon_{abc} (u_a(y) C \gamma_5 s_b(y)) u_{c\beta}(y),$$

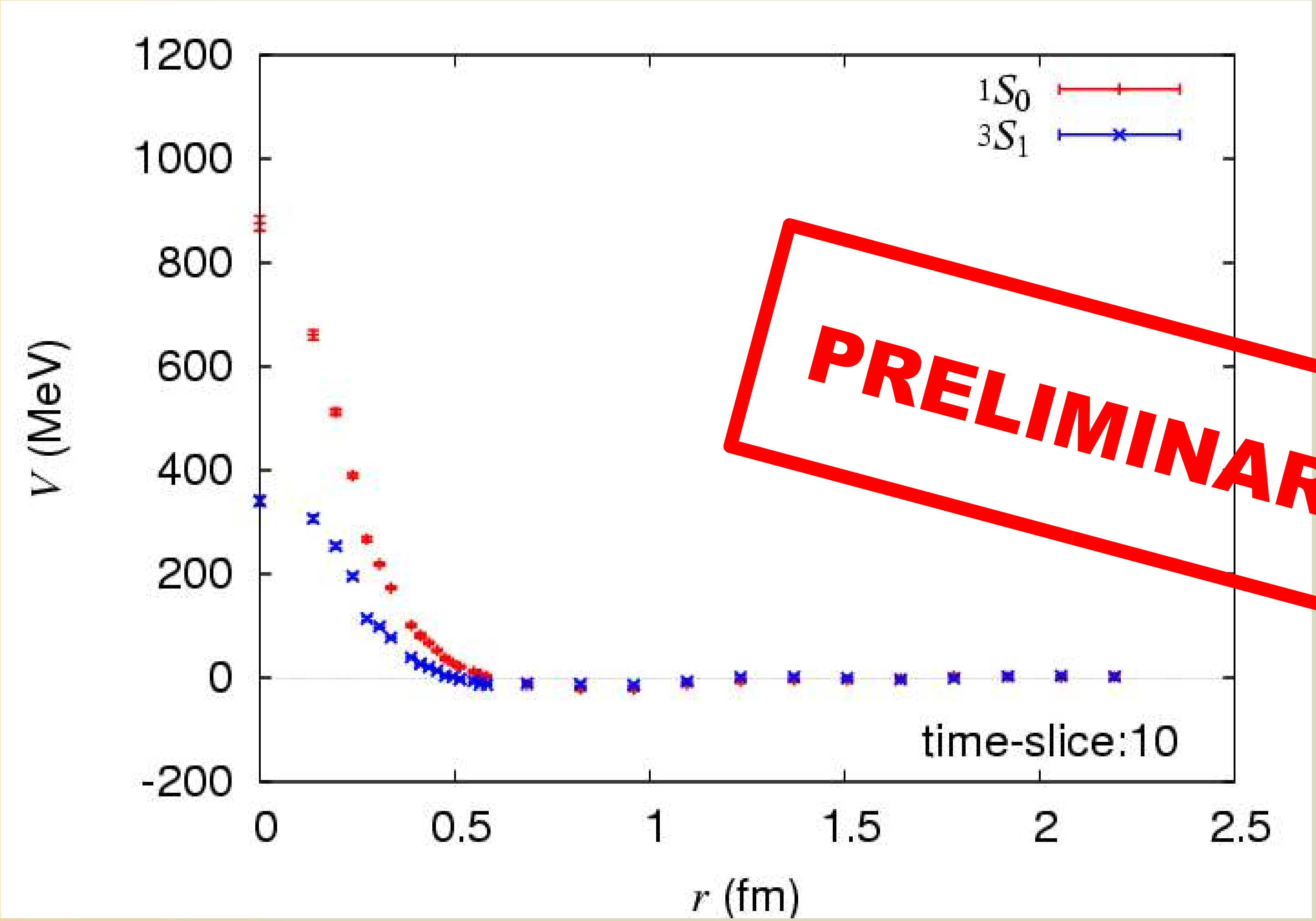
Results —— wave function

- Suggests the repulive core in short range and attractive force in medium range (0.5fm < r < 1fm) for both spin S=0 and 1.



Results —— potential

- NΞ potential (I=1), from lattice QCD for the first time.



- Strong repulsive core in spin S=0 channel.
- Strong spin dependence.

Results —— potential

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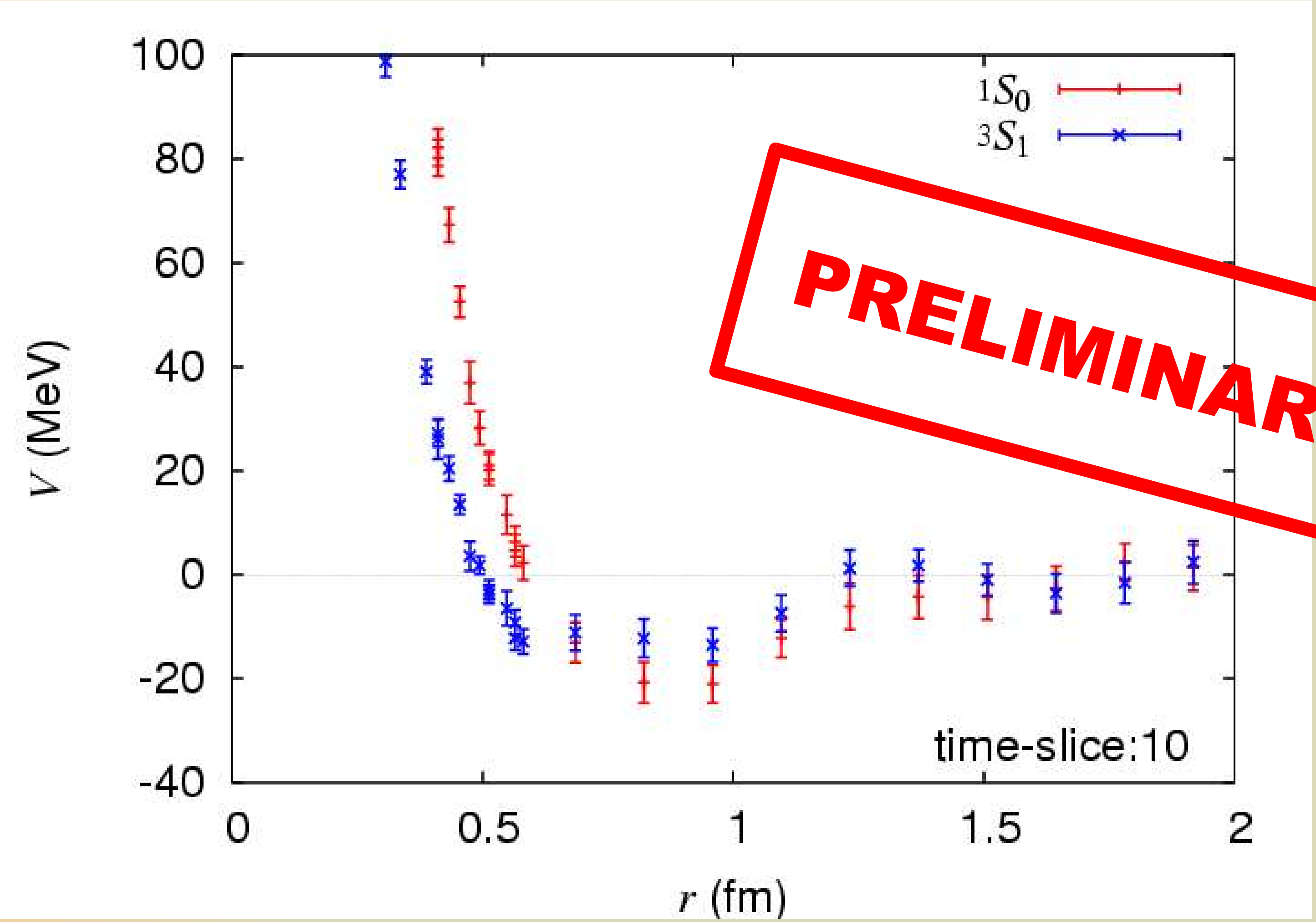

- Attractive force in medium and long-range region for both spin S=0 and 1.

Summary:

- The first lattice QCD results for hyperon-nucleon potentials.
- $N\Xi$ potential in isospin I=1 channel.
  - Which will be studied by DAY-1 experiment at J-PARC.
- Strong spin dependence:
  - Strong repulsive core in spin S=0 channel and
  - Relatively weak repulsive core in spin S=1 channel.
- The present preliminary results suggest that $N\Xi$ potential (I=1) is attractive for both spin S=0 and 1 channels.
- We will study further with
  - More statistics.
  - Physical quark mass for u, d and s quarks.
  - Beyond the quenched approximation.
  - Other baryon-baryon pairs.