Baryon-Baryon Interactions from Lattice QCD

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HAL QCD Collaboration

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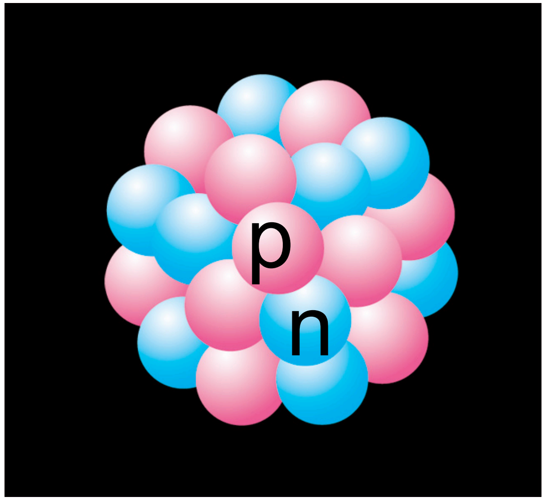
1. Introduction

What binds protons and neutrons inside a nuclei ?



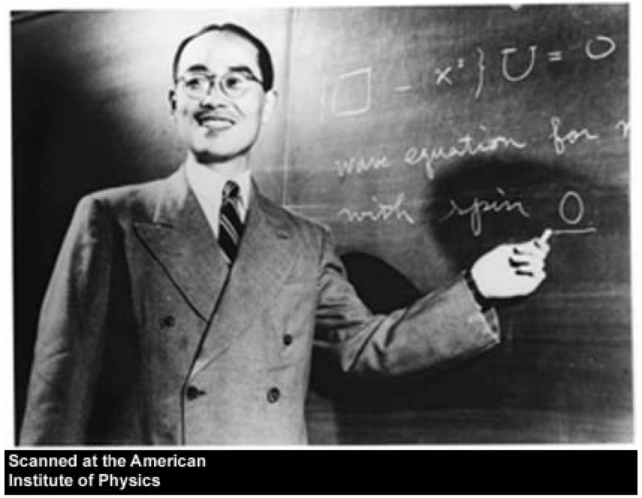
gravity: too weak

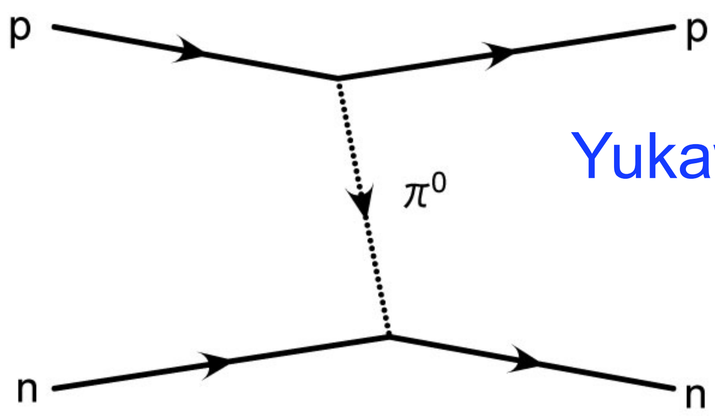
Coulomb: repulsive between pp
no force between nn, np

New force (nuclear force) ?

1935 H. Yukawa

introduced virtual particles (mesons) to explain the nuclear force



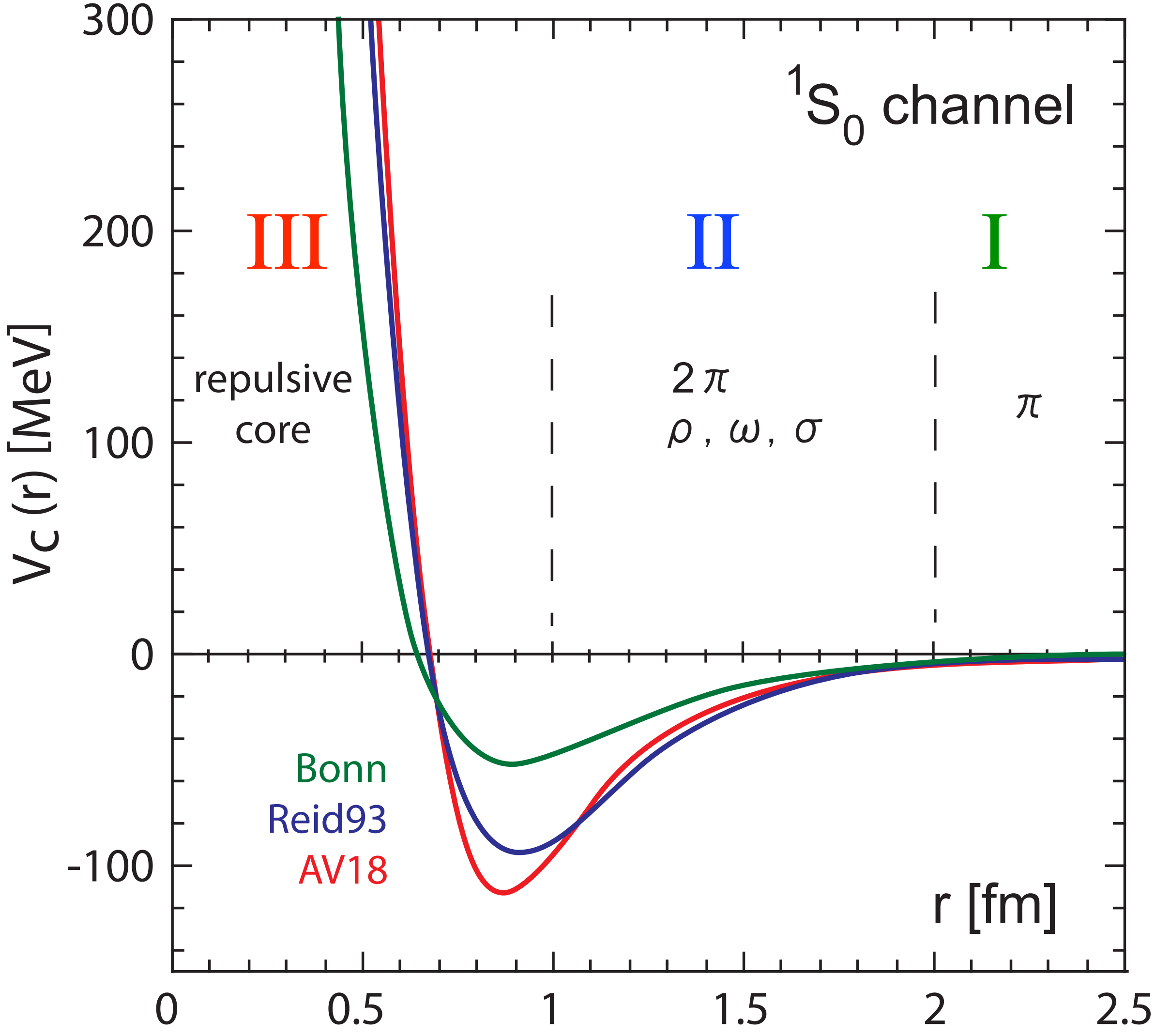


Yukawa potential

$$V(r) = \frac{g^2}{4\pi}\frac{e^{-m_\pi r}}{r}$$

1949 Nobel prize

Modern nucleon-nucleon potential



I Long range part

one pion exchange potential (OPEP) H. Yukawa(1935)

II Medium range part

$\sigma,\ \rho,\ \omega$ exchange

2π exchange

III Short range part

repulsive core (RC)

R. Jastrow(1951)

quark ?

Bonn: Machleidt, Phys.Rev. C63('01)024001

Reid93: Stoks et al., Phys. Rev. C49('94)2950.

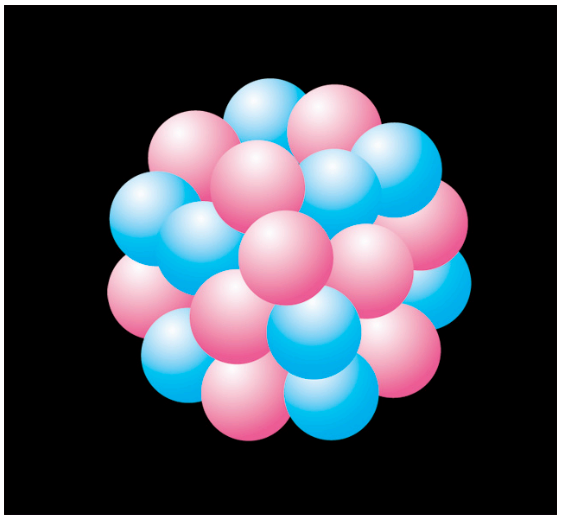
AV18: Wiringa et al., Phys.Rev. C51('95) 38.

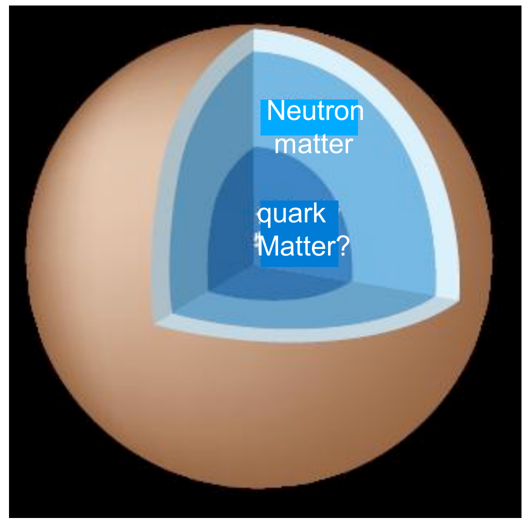
Repulsive core is important

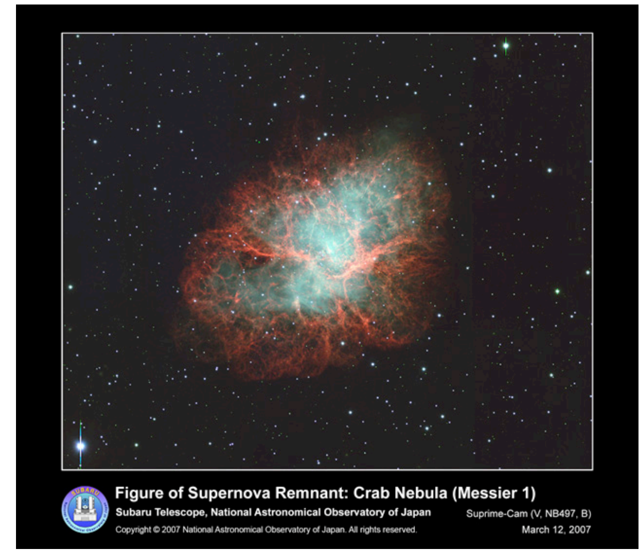
stability of nuclei

maximum mass of neutron star

explosion of type II supernova

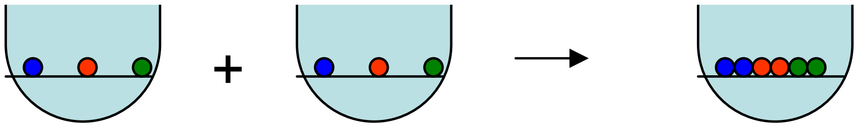


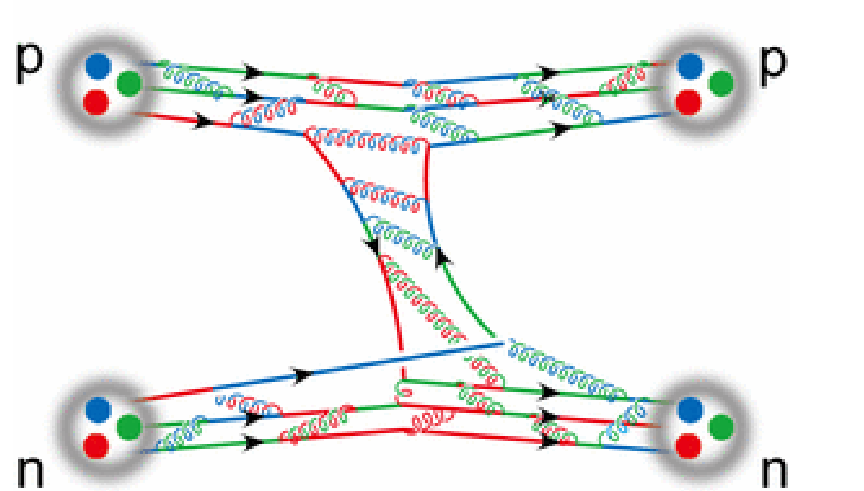




Origin of RC: "The most fundamental problem in Nuclear physics."

Note: Pauli principle is not essential for the "RC".





A challenge in (lattice) QCD !

Plan of my talk

1. Introduction
2. Strategy in (Lattice) QCD
    1) Previous attempt
    2) Strategy
    3) 1st (quenched) result
3. Recent Developments
    1) Velocity Dependence
    2) Quark mass dependence
    3) Tensor potential
    4) Full QCD
    5) Hyperon-Nucleon interaction
4. Conclusion

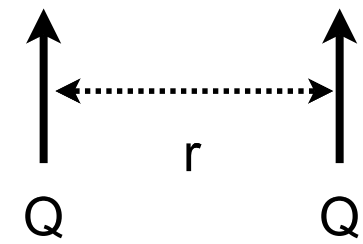
2. Strategy in (Lattice) QCD

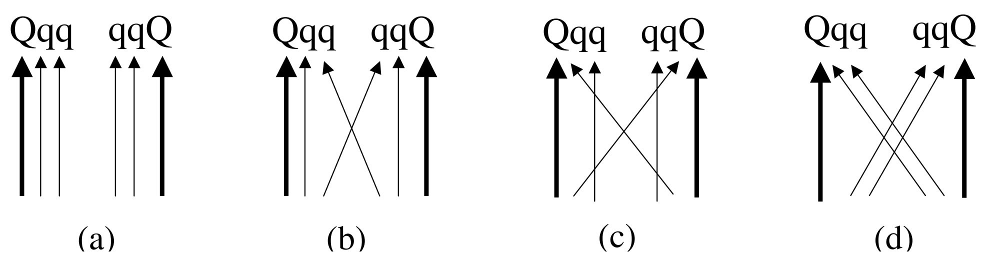
Definition of "Potential" in (lattice) QCD ?

Previous attempt

Takahashi-Doi-Suganuma, AIP Conf.Proc. 842,249(2006)

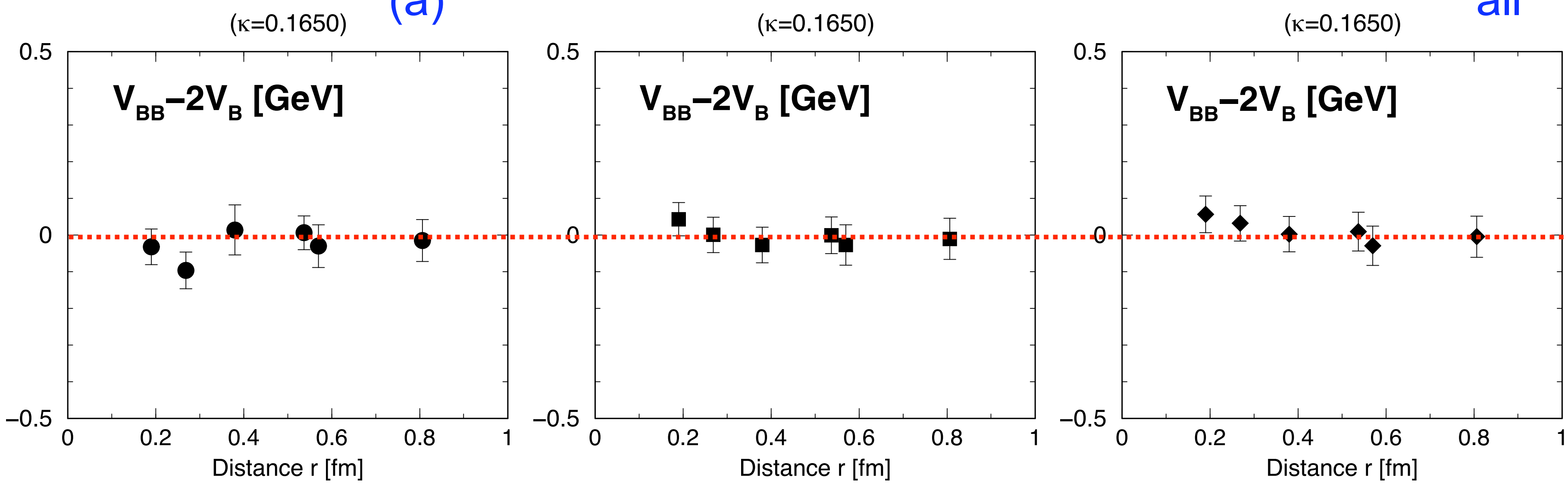
calculate energy of Qqq +Qqq as a function of r between 2Q.
Q:static quark, q: light quark





Quenched result

(a) +(b)+(c) all



Almost no dependence on r !

Quantum Field Theoretical consideration

- S-matrix below inelastic threshold

$$S = e^{2i\delta}$$

- Bethe-Salpeter (BS) Wave function

$$\varphi_E(\mathbf{r}) = \langle 0 | N(\mathbf{x}+\mathbf{r},0) N(\mathbf{x},0) | 6q, E \rangle$$

6 quark state with energy E

$$N(x) = \varepsilon_{abc} q^a(x) q^b(x) q^c(x): \text{ local operator}$$

Asymptotic behavior

$$r = |\mathbf{r}| \to \infty$$

$$\varphi_E^l(r) \longrightarrow A_l \frac{\sin(kr - l\pi/2 + \delta_l(k))}{kr} \qquad E = \frac{k^2}{2\mu_N} = \frac{k^2}{m_N}$$

partial wave

⇒ $\delta_l(k)$ is the scattering phase shift

Our Strategy

Ishii-Aoki-Hatsuda, 2007

1. Define a (non-local) potential from the BS wave function as

$$[E - H_0]\varphi_E(\mathbf{x}) = \int d^3y\, U(\mathbf{x}, \mathbf{y})\varphi_E(\mathbf{y}) \qquad H_0 = \frac{-\nabla^2}{2\mu_N}$$

2. Expand the potential as $U(\mathbf{x}, \mathbf{y}) = V(\mathbf{x}, \nabla)\delta^3(\mathbf{x} - \mathbf{y})$

$$V(\mathbf{x}, \nabla) = V_C(r) + V_T(r)S_{12} + V_{\mathrm{LS}}(r)\mathbf{L}\cdot\mathbf{S} + \{V_D(r), \nabla^2\} + \cdots$$

Okubo-Marshak (1958)

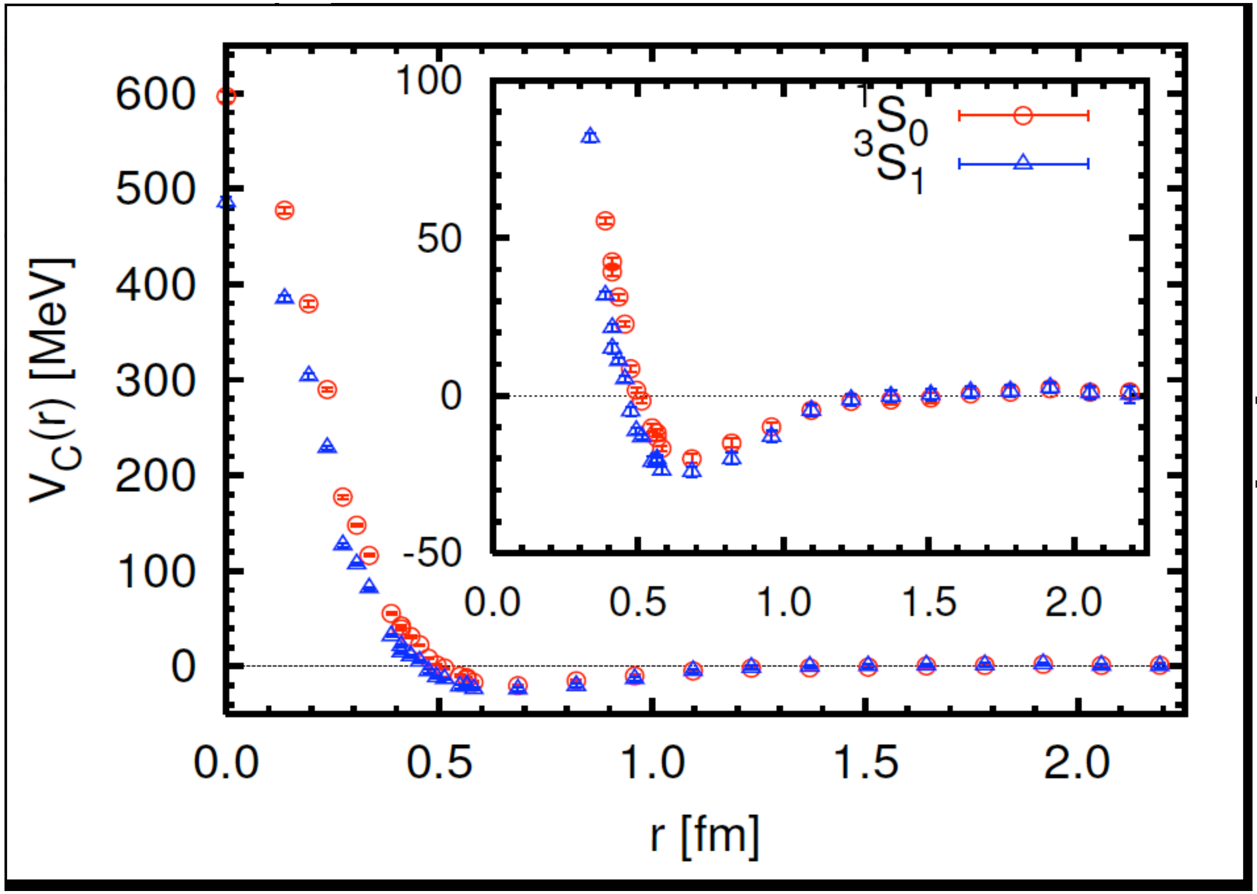
tensor operator $S_{12} = \frac{3}{r^2}(\boldsymbol{\sigma_1}\cdot\mathbf{x})(\boldsymbol{\sigma_2}\cdot\mathbf{x}) - (\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2})$ $\quad r = |\mathbf{x}|$

3. Successive determination using BS wave function at different E
   - similar to the expansion of EFT

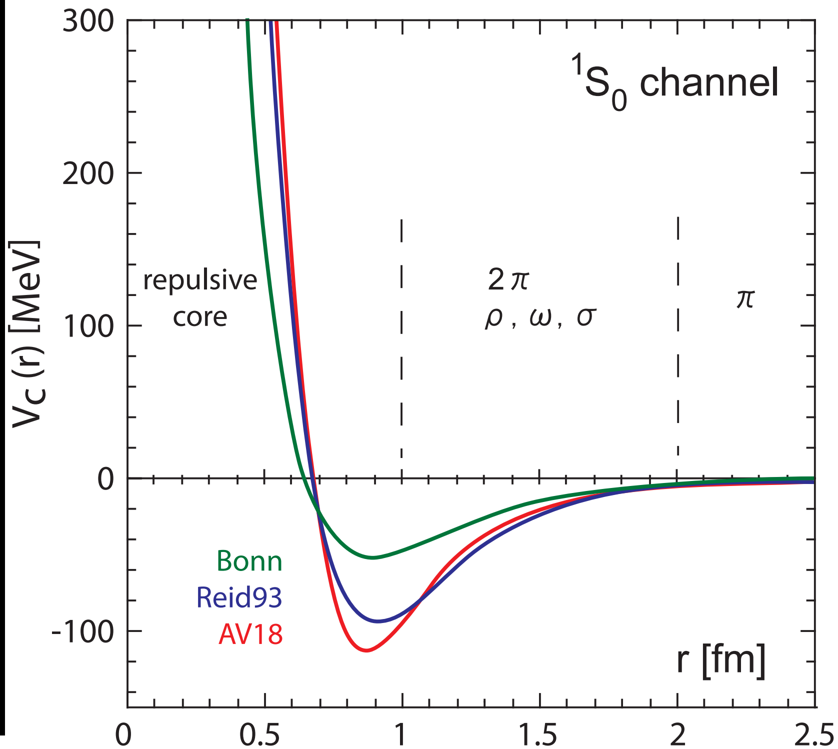
4. Calculate observables (phase shift, binding energy etc.)

First (quenched) results

Central Potential $^1S_0, \ ^3S_1$



$E \simeq 0 \qquad m_\pi \simeq 0.53 \text{ GeV}$



Qualitative features of NN potential are reproduced !

Ishii-Aoki-Hatsuda, PRL90(2007)0022001

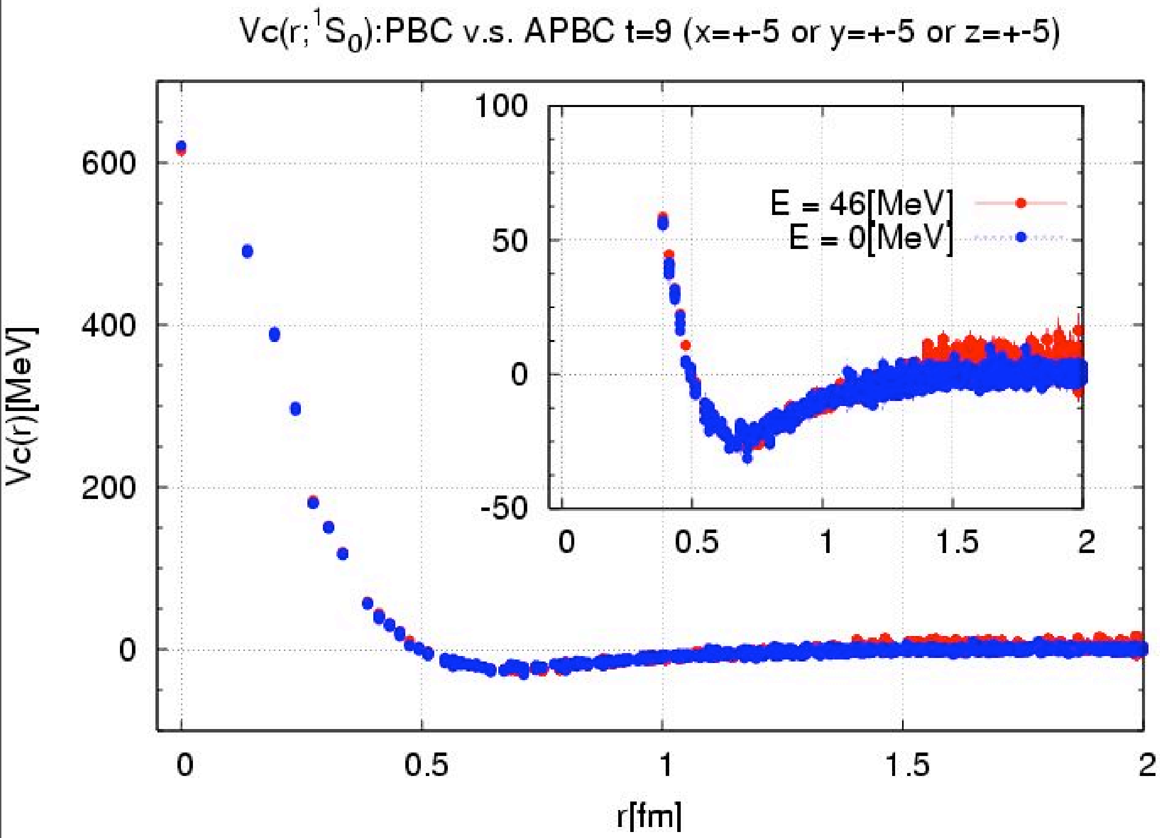
This paper has been selected as one of 21 papers in Nature Research Highlights 2007

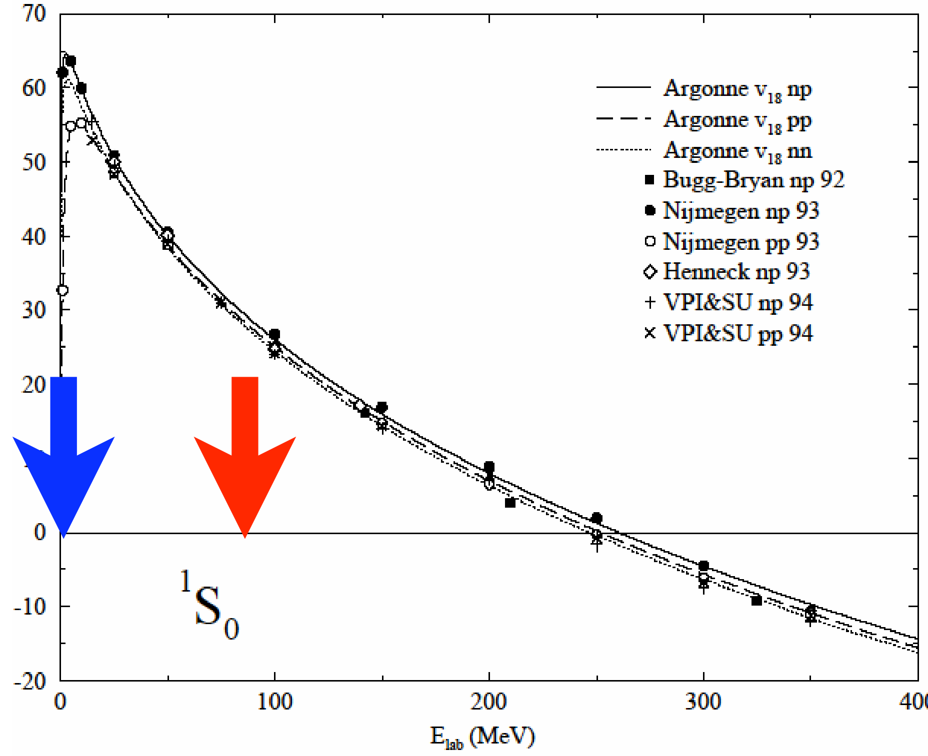
3. Recent developments

velocity dependence of V

$$V(\mathbf{x}, \nabla) = V_C(r) + V_T(r)S_{12} + V_{\text{LS}}(r)\mathbf{L}\cdot\mathbf{S} + \{V_D(r), \nabla^2\} + \cdots$$

K. Murano, S. Aoki, T. Hatsuda, N. Ishii, H. Nemura





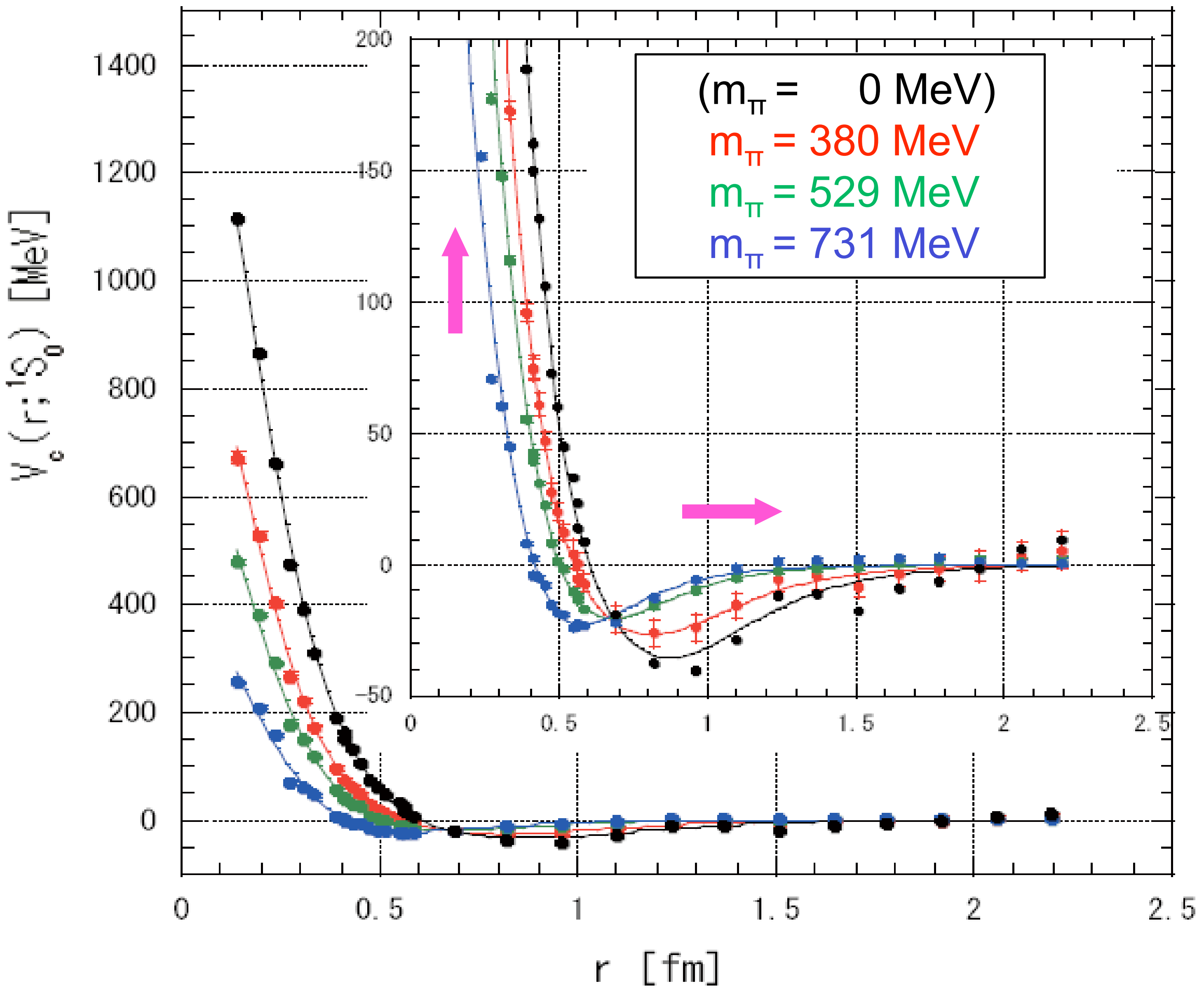
1. velocity-dep. terms can be determined form E-dependence of V.
2. E-dep. turns out to be small at low energy in our choice of N(x).

Quark mass dependence of V

$^1S_0$

Quenched

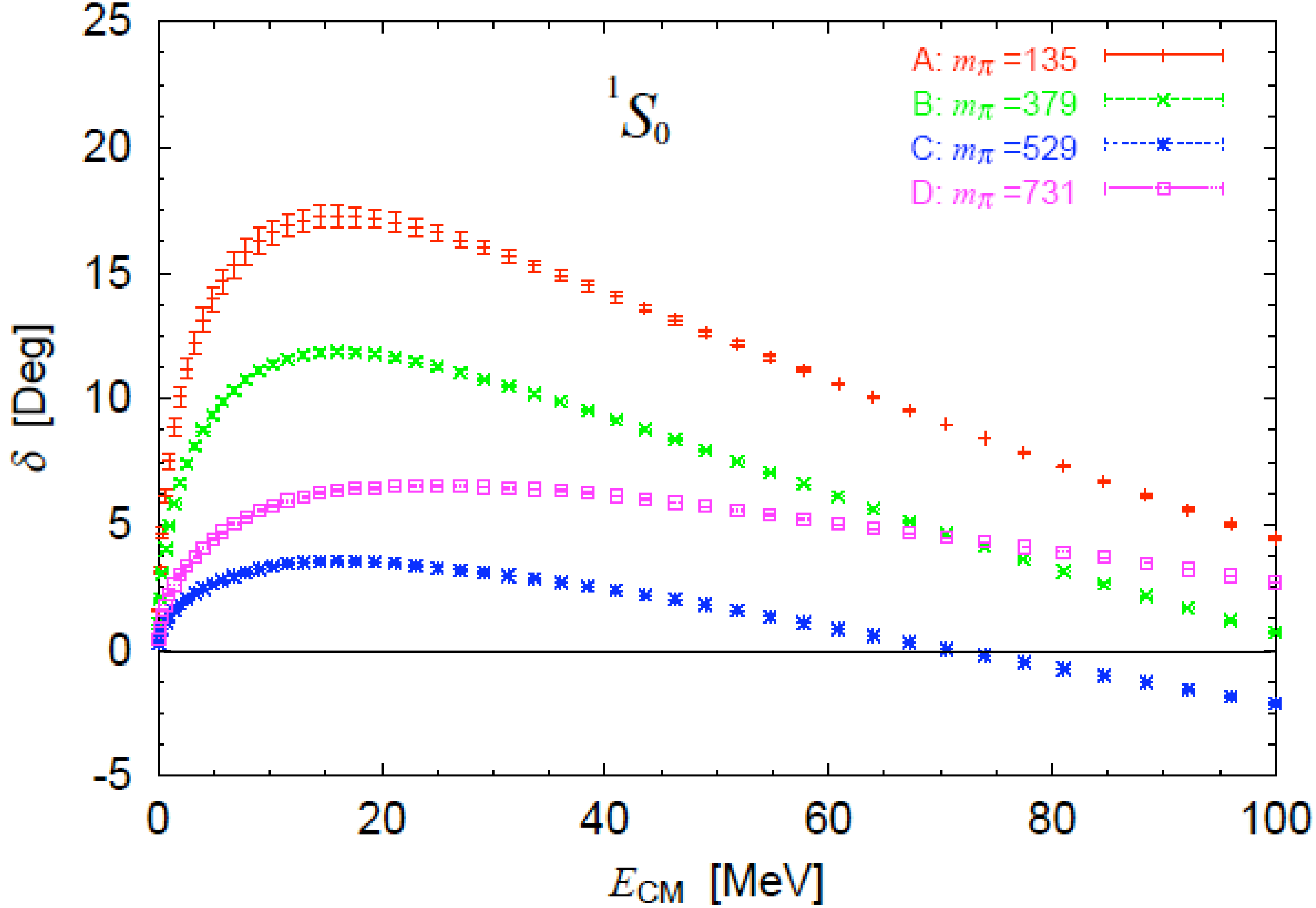
Preliminary



as quark mass decreases stronger repulsive core at short distance

stronger attraction at intermediate distance

$^1S_0$ phase shift from $V_c(r)$



Tensor potential

Ishii, Aoki, Hatsuda (in progress)

Triplet (S=1) $\quad {}^3S_1 \quad J=1, L=J\pm 1=2,0 \quad \text{mix with } {}^3D_1$

$$(E-H_0)\psi = [V_{\rm C} + V_T S_{12}]\psi$$

$$P\psi \equiv \frac{1}{24}\sum_R \psi(R\vec{r})$$

"projection" to L=0 $\quad {}^3S_1$

$$Q = 1 - P$$

"projection" to L=2 $\quad {}^3D_1$

$$\begin{pmatrix} P\psi & PS_{12}\psi \\ Q\psi & QS_{12}\psi \end{pmatrix} \times \begin{pmatrix} V_{\rm C} \\ V_T \end{pmatrix} = (E-H_0)\begin{pmatrix} P\psi \\ Q\psi \end{pmatrix}$$

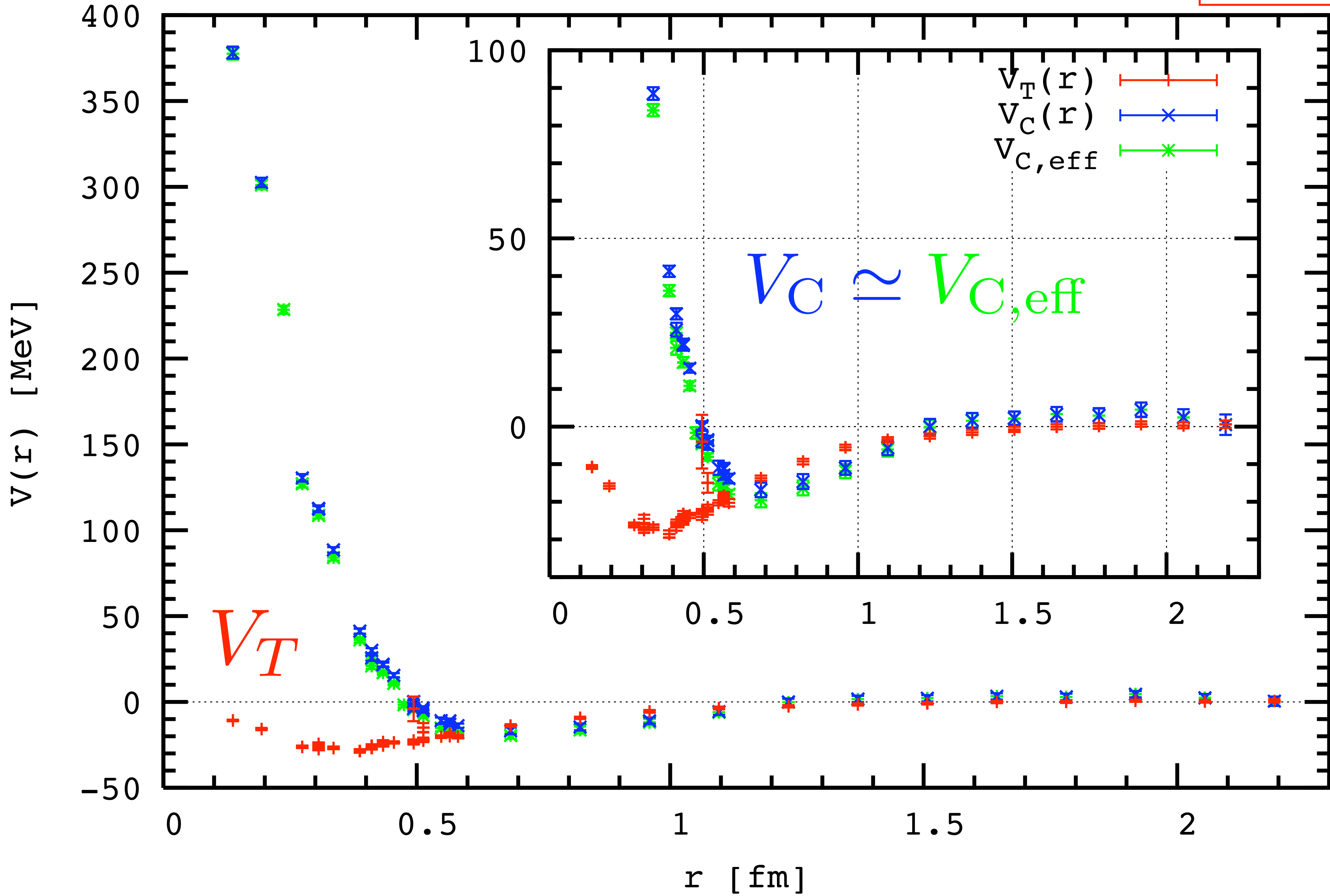
$$\Rightarrow \quad \begin{pmatrix} V_{\rm C} \\ V_T \end{pmatrix} = \begin{pmatrix} P\psi & PS_{12}\psi \\ Q\psi & QS_{12}\psi \end{pmatrix}^{-1} (E-H_0)\begin{pmatrix} P\psi \\ Q\psi \end{pmatrix}$$

Preliminary

$m_\pi \simeq 0.53$ GeV

Quenched

Tensor Force and Central Force ($t-t_0=5$)



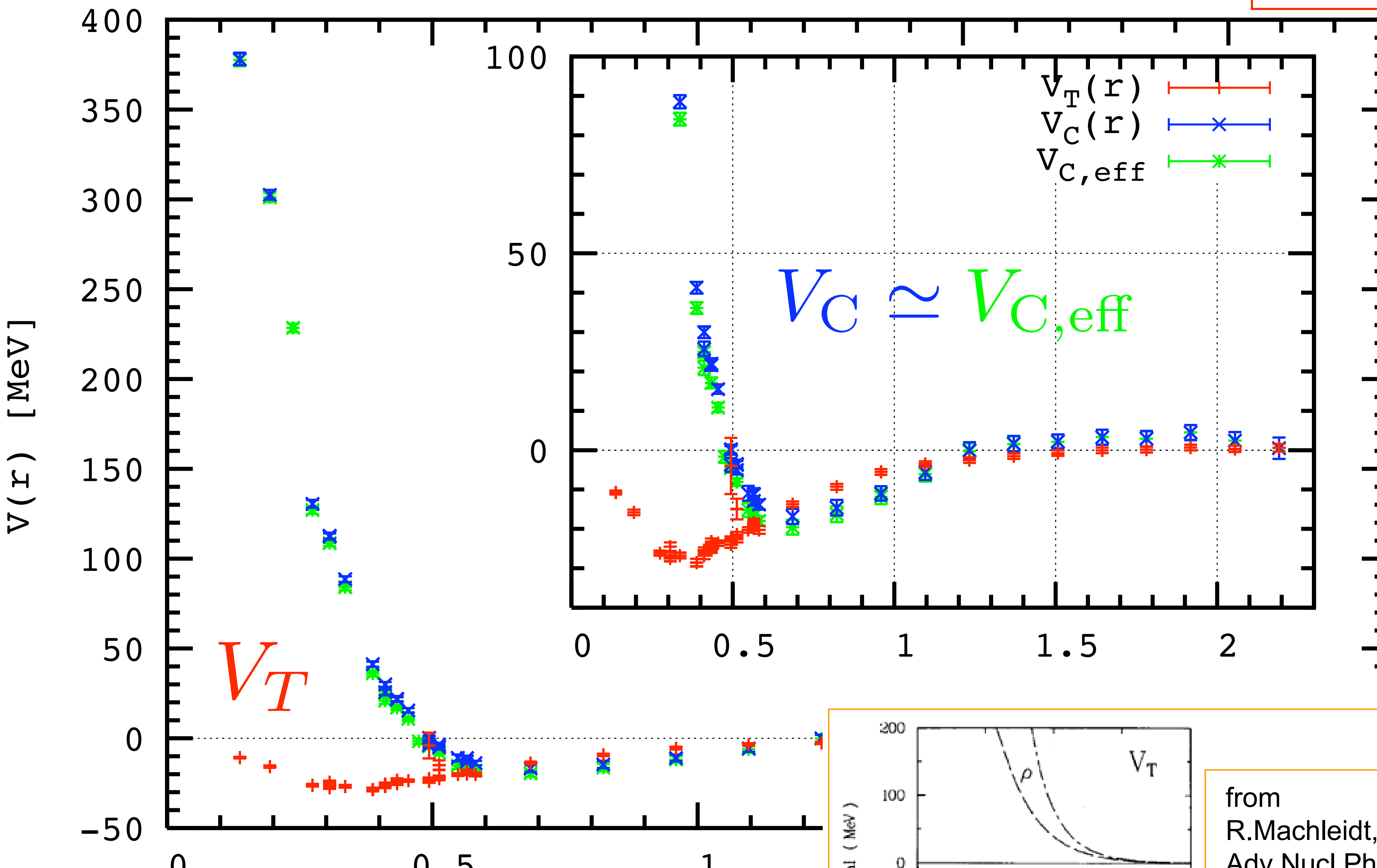
No repulsive core in tensor

Preliminary

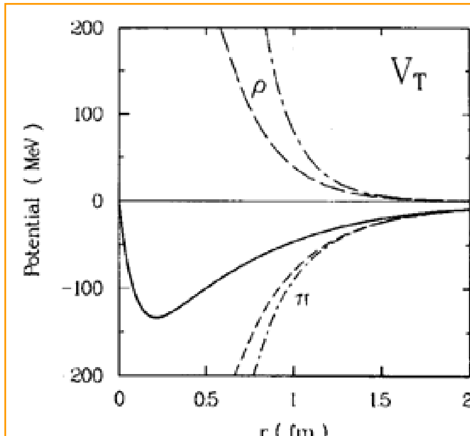
$m_\pi \simeq 0.53$ GeV

Quenched

Tensor Force and Central Force ($t-t_0=5$)



No repulsive core in tensor

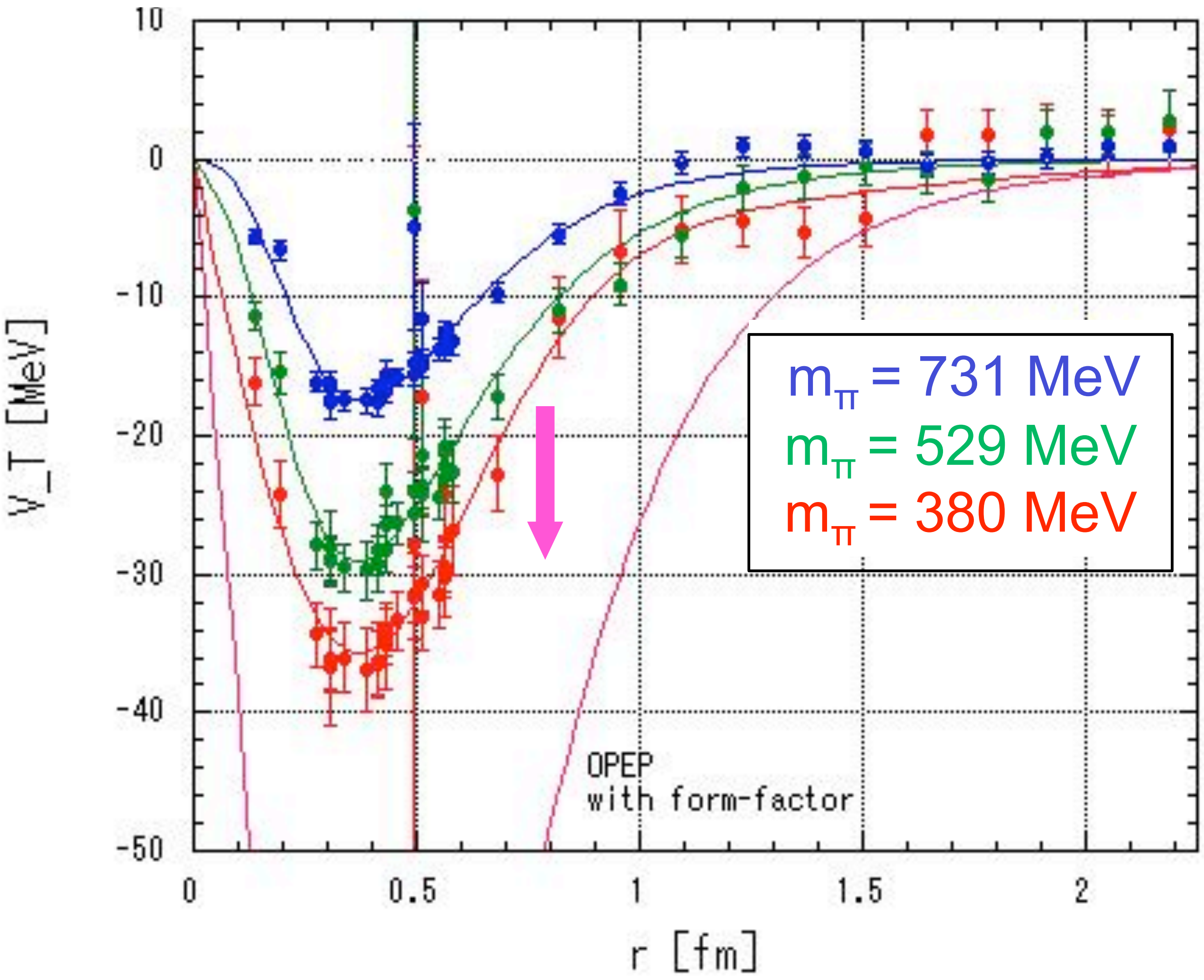


from
R.Machleidt,
Adv.Nucl.Phys.**19**

Fig. 3.7. The contributions from π and ρ (dashed) to the $T=0$ tensor potential. The solid line is the full potential. The dash-dot lines are obtained when the cutoff is omitted.

Quark mass dependence

Preliminary



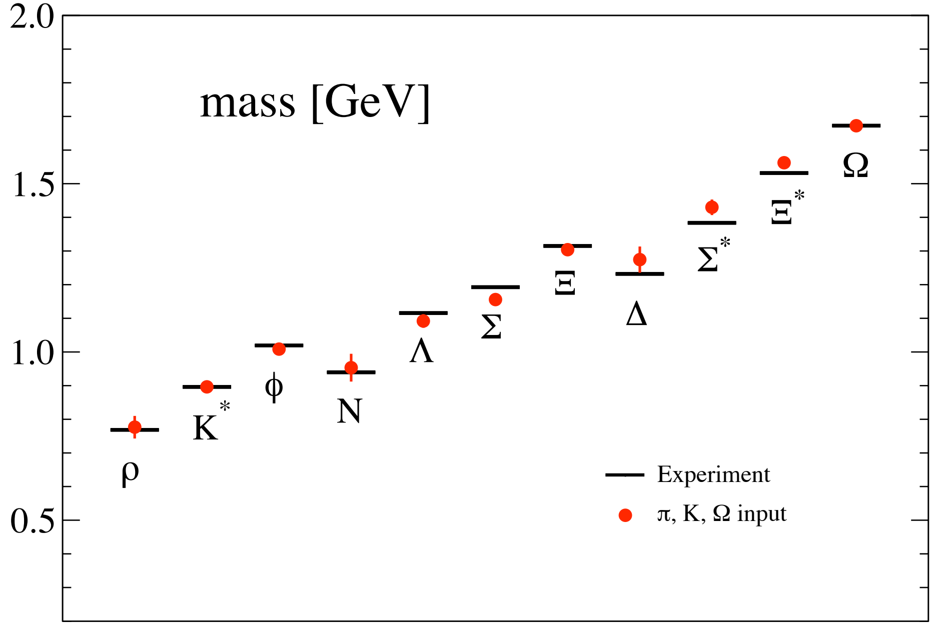
Fit: pi+rho with gaussian form-factors

Tensor forces becomes stronger as quark mass decreases.

Full QCD calculations

PACS-CS gauge configurations(2+1 flavors)

Phys. Rev. D79(2009)034503

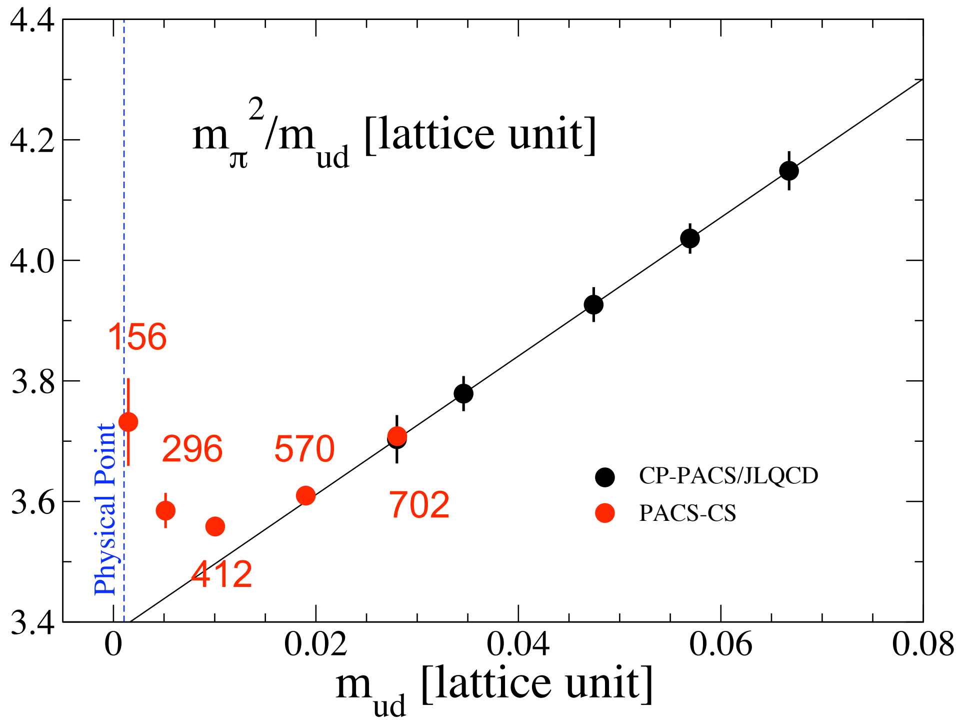


$$a = 0.09 \text{ fm}$$

$$L = 2.9 \text{ fm}$$

$$m_\pi^{\text{min.}} = 156 \text{ MeV} \qquad m_\pi L = 2.3$$

We are almost on the "physical point".



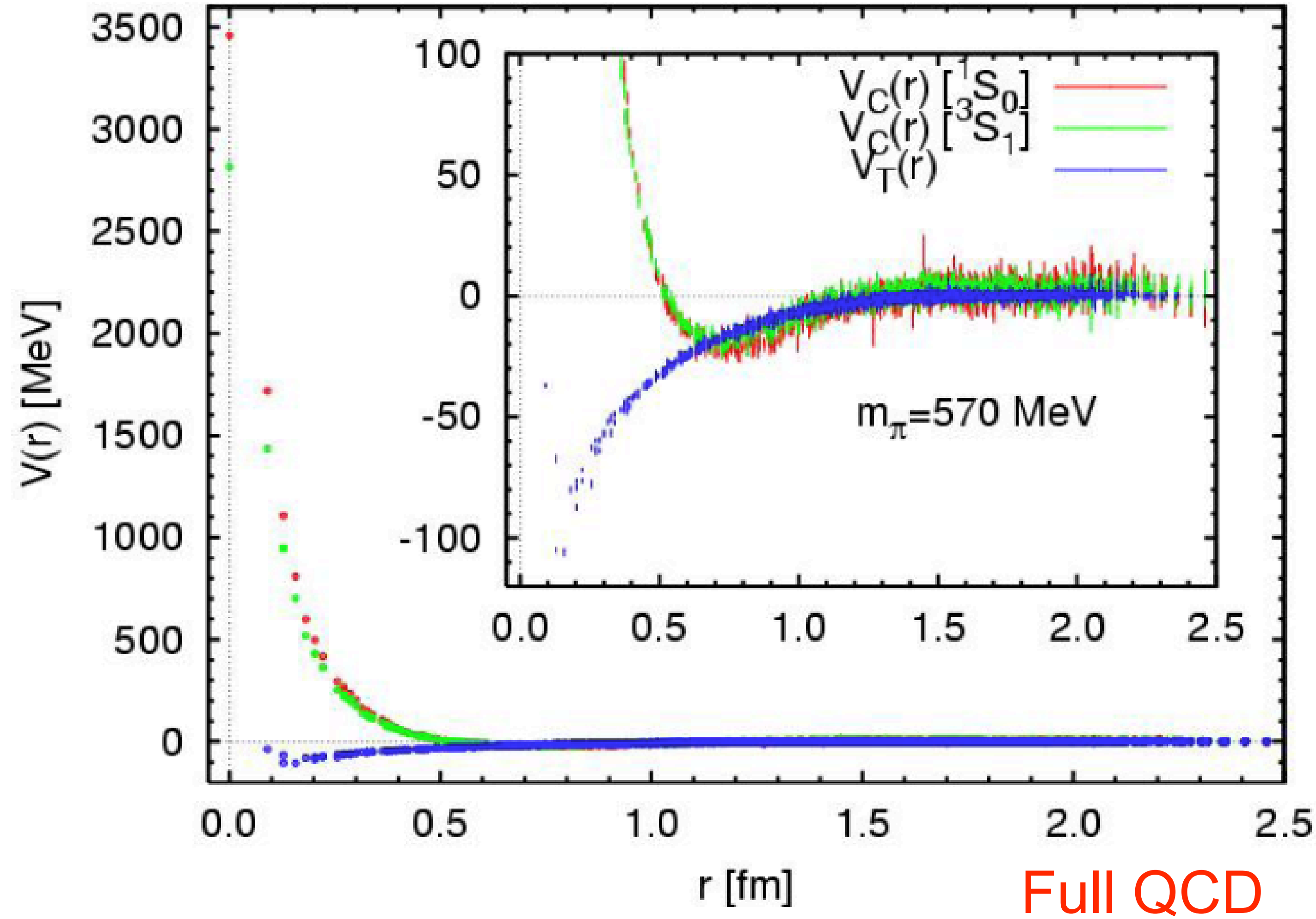
$$m_\pi L > 4$$

Calculations with L=5.8 fm and $m_\pi \simeq 140$ MeV are on-going.

"Real QCD"

$V_C(r)$ and $V_T(r)$ in full QCD (m_π = 570 MeV, L=2.9 fm)

Preliminary



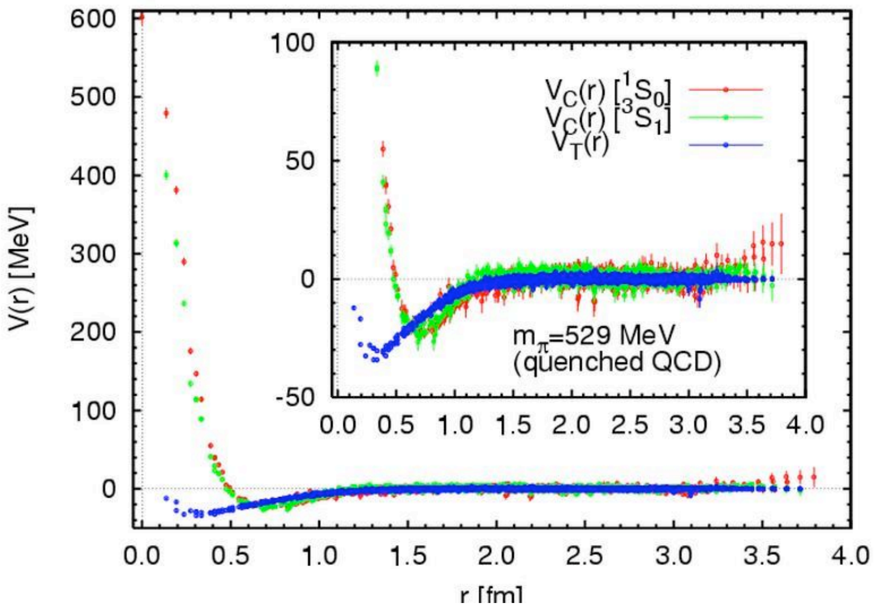
Full QCD

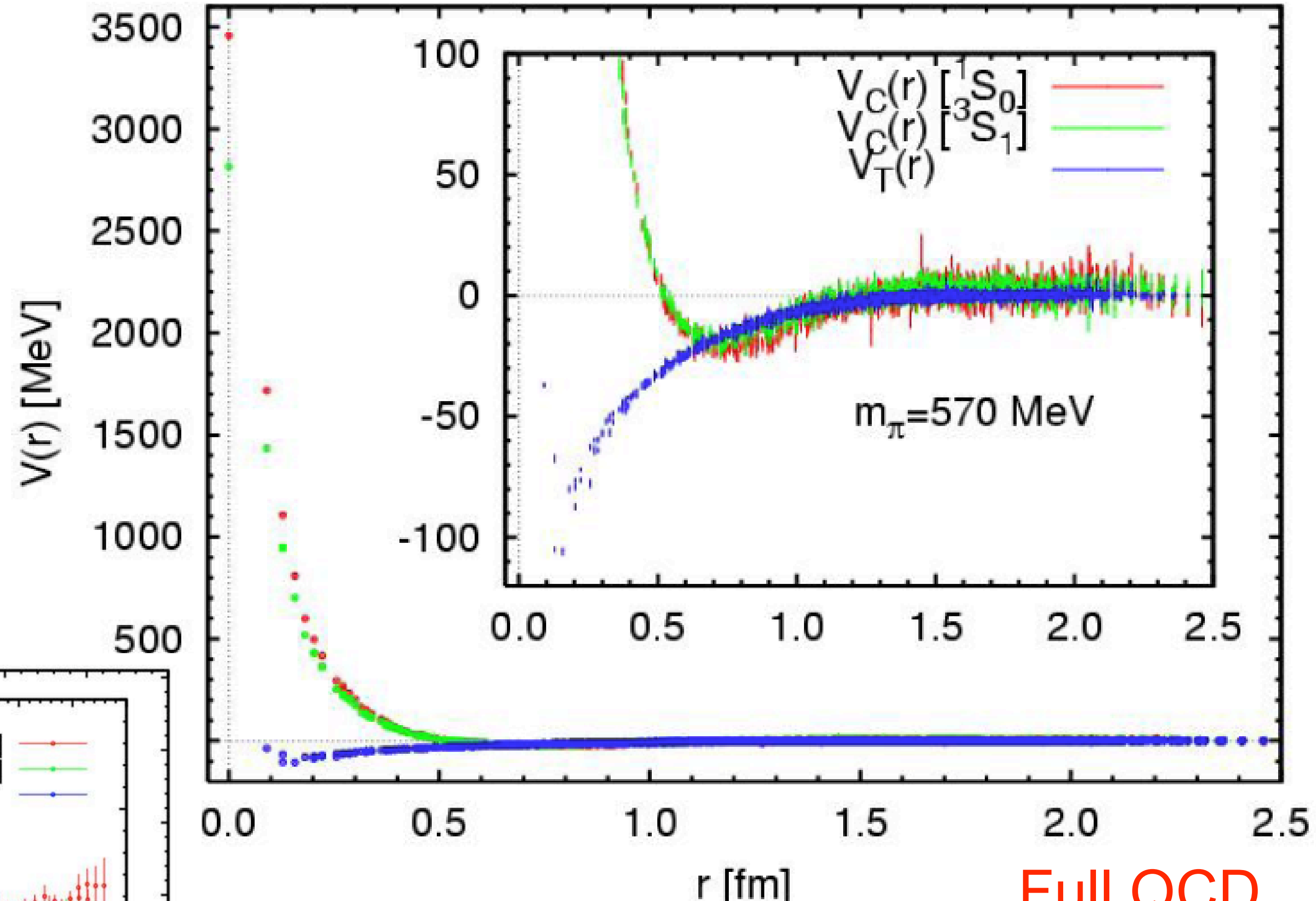
* Larger repulsive core than quenched
* Larger tensor force than quenched

$V_C(r)$ and $V_T(r)$ in full QCD (m_π = 570 MeV, L=2.9 fm)

Preliminary

Quenched QCD





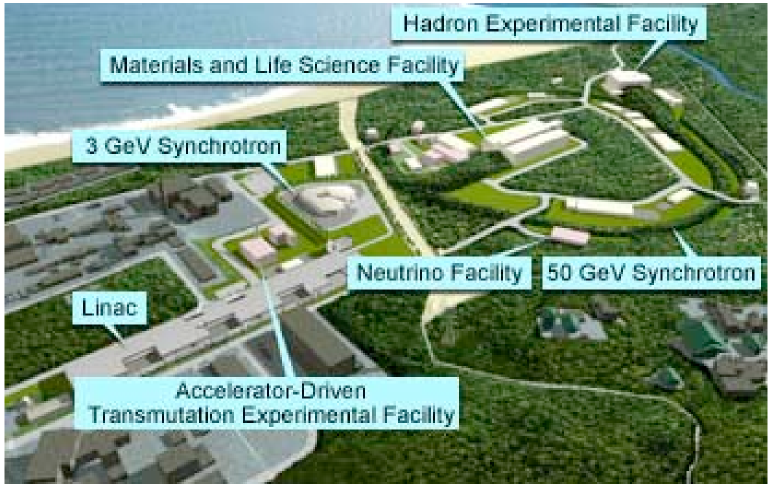
Full QCD

* Larger repulsive core than quenched
* Larger tensor force than quenched

Hyperon-Nucleon interactions

Almost no information from experiments → J-PARC

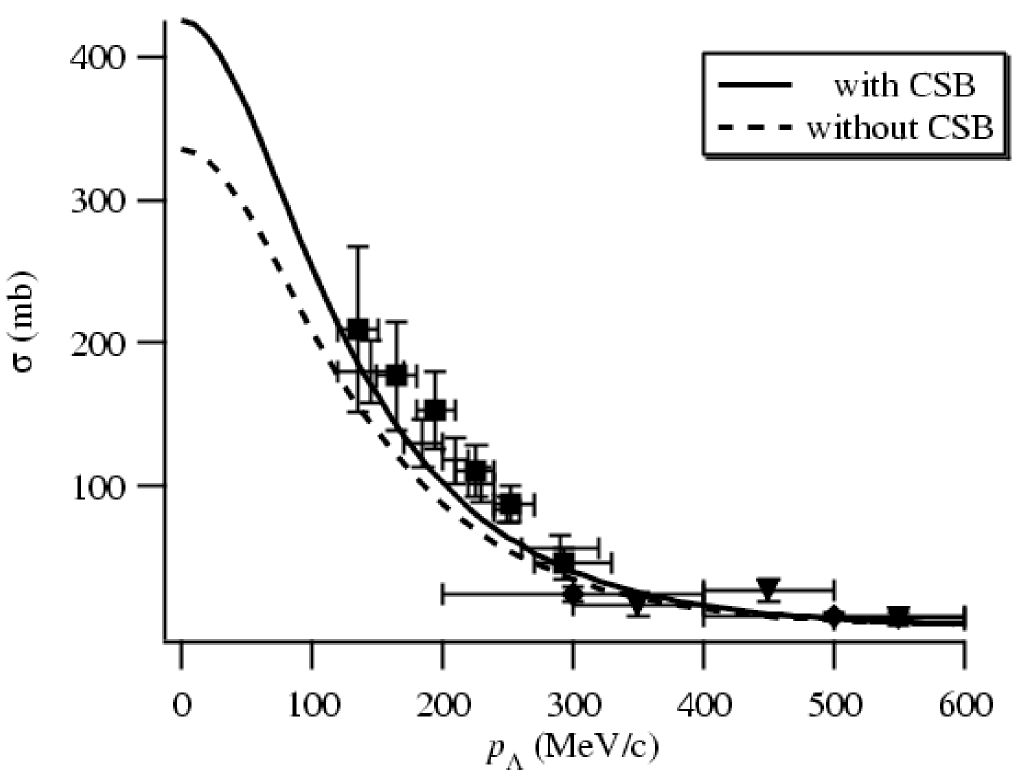
Explore the multistrange world.



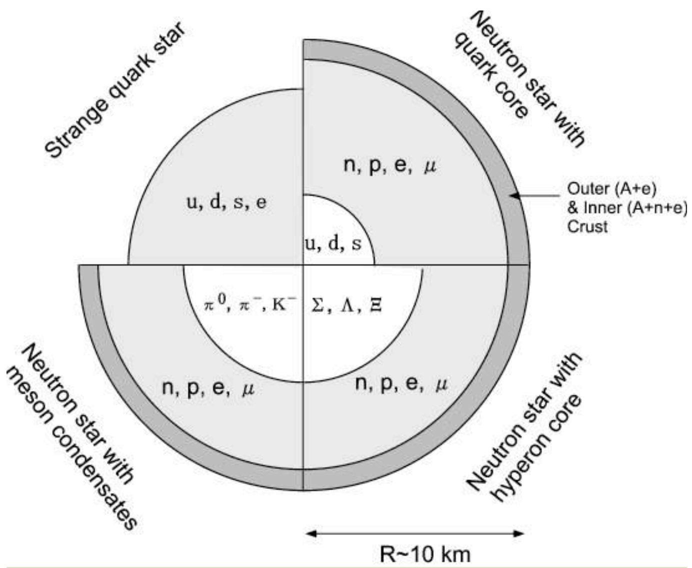
Experminetal data for ΛN

Only total cross section. No phase-shift analysis.

Spin-dependence is unclear.

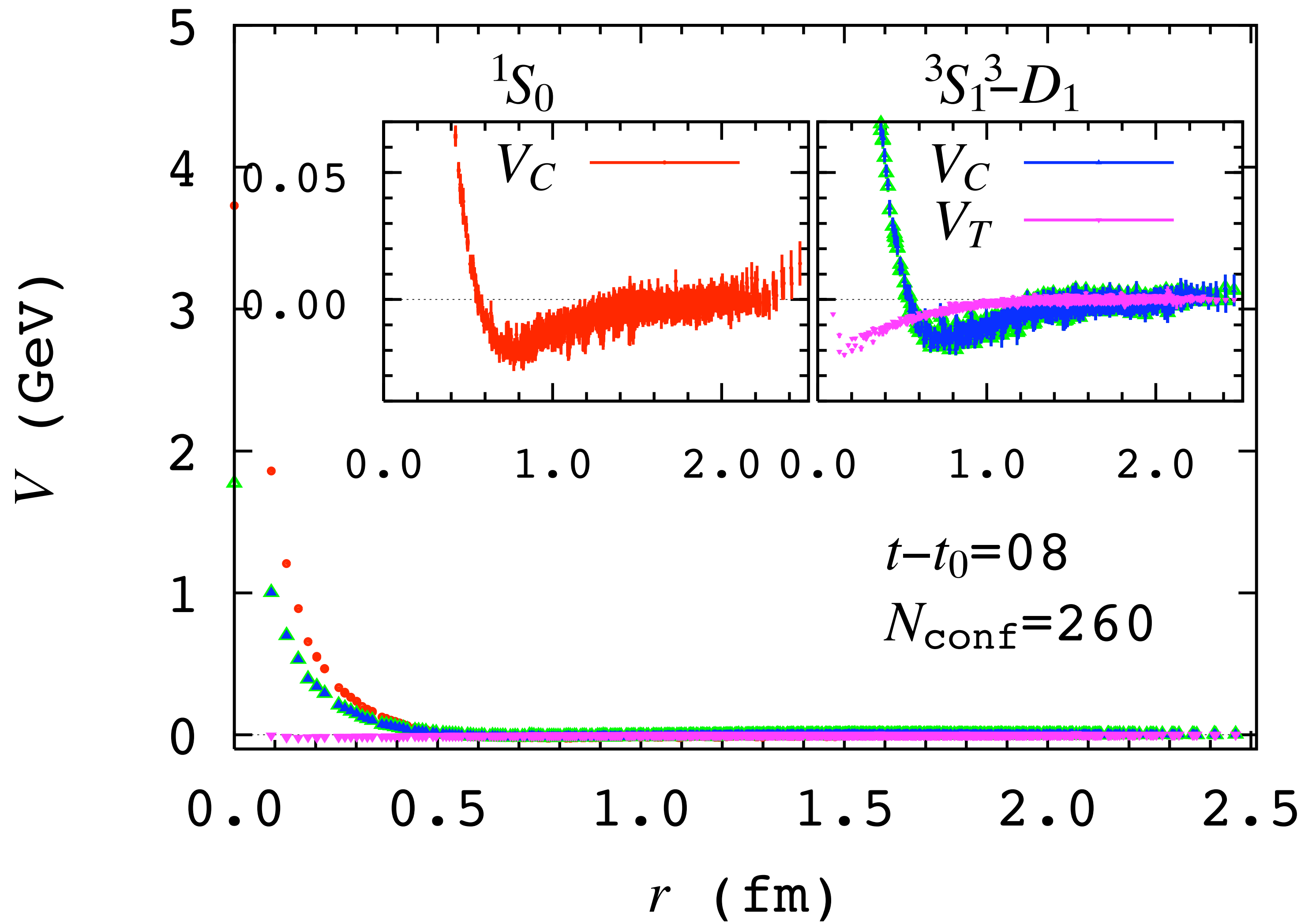


Structure of the neutron-star core



ΛN in full QCD ($m_\pi = 415$ MeV, L=2.9 fm)

Preliminary



* Weaker repulsive core than NN
* Stronger spin dependence than NN
* Weaker tensor force than NN

4. Conclusion

Summary

1. Nuclear force from lattice QCD

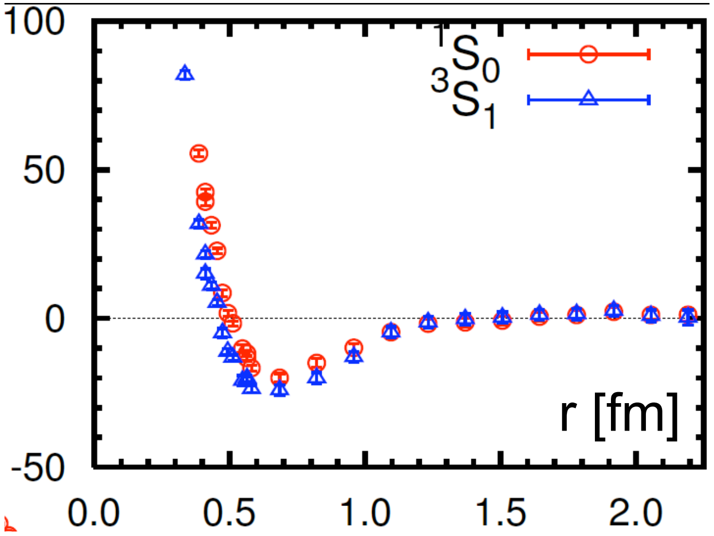
   - BS wave function -> NN, NY, YY potentials -> observables

2. NN potential in quenched QCD: good “shape”

   - repulsive core, intermediate attraction, tensor force

“The achievement is both a computational *tour de force* and a triumph for theory.”

Nature Research Highlights 2007



3. Hyperon force:

   - various channel -> input to hyper- nuclear physics

Current and Future

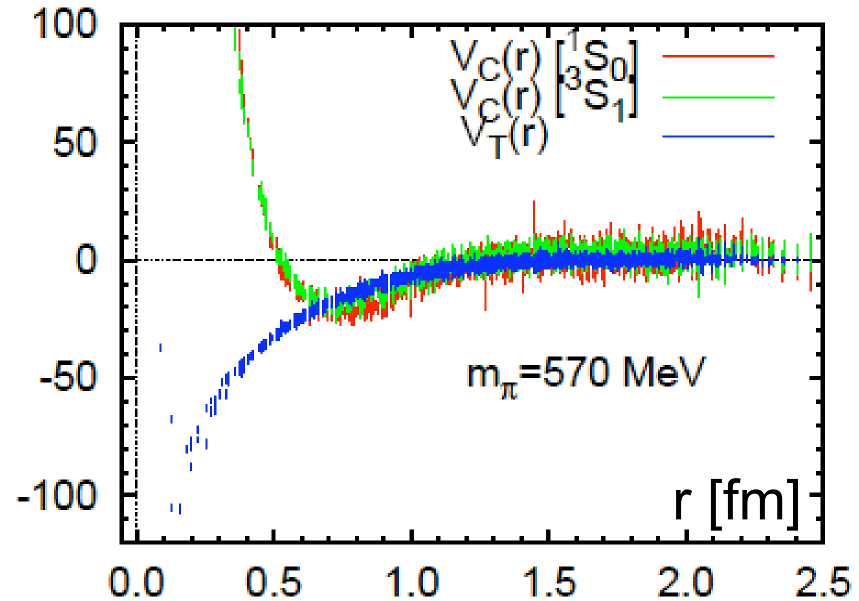
- Full QCD with 140 MeV pion is our ultimate goal.

  current: PACS-CS config. with L=2.9 fm & pion mass = 156 -701 MeV

  in 1-2 years: PACS-CS config. wiyj L=5.8 fm & pion mass = 140 MeV

  in 5 years: new config. on 20 PFlops machine (2011-)

- Current and Future target of HAL QCD
  - tensor force and deuteron binding
  - origin of the repulsive core
  - LS force
  - YN and YY forces
  - 3 body forces
  - light nuclei from lattice QCD
  - relation to EFT



温故知新

Some References

- NN force in quenched QCD:

  Ishii, Aoki & Hatsuda, Phys. Rev. Lett. 99 (2007) 022001 (nucl-th/0611.096).

- Introductory review:

  Aoki, Hatsuda & Ishii, Comput. Sci. Disc. 1 (2008) 015009 (arXiv:0805.2462[hep-lat]).

- YN force in quenched QCD:

  Nemura, Ishii, Aoki & Hatsuda, Phys. Lett. B673 (2009) 136 (arXiv:0806.1094[nucl-th]).

- NN force in full QCD:

  Ishii, Aoki & Hatsuda, arXiv: 0903.5497[hep-lat].

- YN force in full QCD:

  Nemura, Ishii, Aoki & Hatsuda, arXiv:0902.12251[hep-lat].