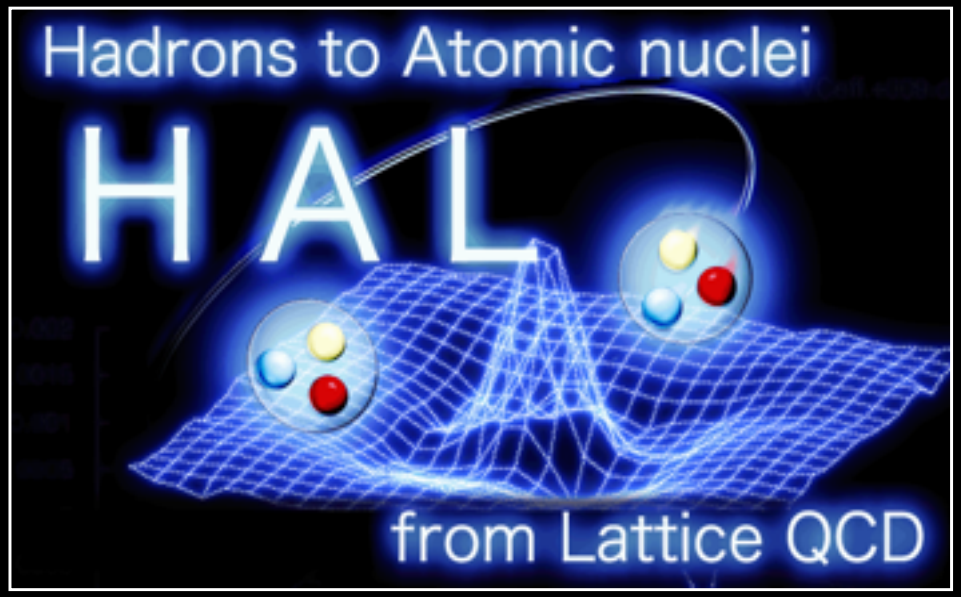
Two-Pion Exchange Universality in Hadron-Hadron Interactions from Lattice QCD

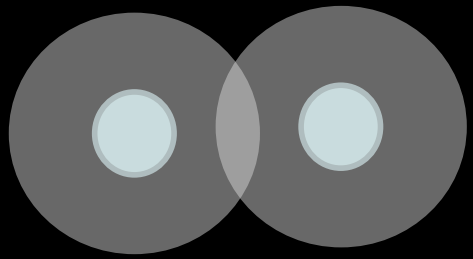
Tetsuo Hatsuda (RIKEN iTHEMS)



S. Aoki, T. Doi, T. Hatsuda, Y. Lyu, L. Wang,
W. A. Yamada, L. Zhang (RIKEN)
T. Aoyama (ISSP)
T. M. Doi, E. Itou (Kyoto U.)
F. Etminan (U. of Birjand)
Y. Ikeda, N. Ishii, P. Junnarkar, K. Murase,
H. Nemura (Osaka U.)
T. Inoue (Nihon U.)
K. Murakami (Science Tokyo)
K. Sasaki (U. of Niigata Pref.)
T. Sugiura (Rissho U.)
H. Tong (U. of Bonn)
L. Zhang (SINAP)

Question:

What is the force between
“neutral particles” at long range ?



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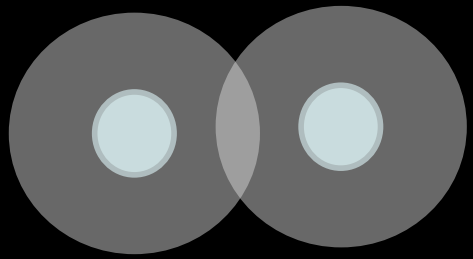
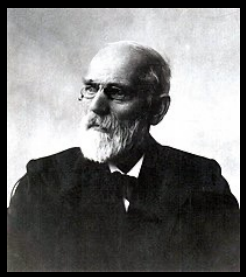


Answer:



QED

2-photon exchange force

= van der Waals (Casimir-Polder) force → $-1/r^7$

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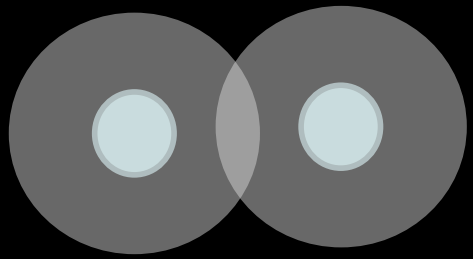

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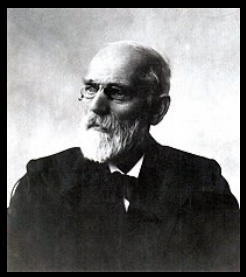

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QCD

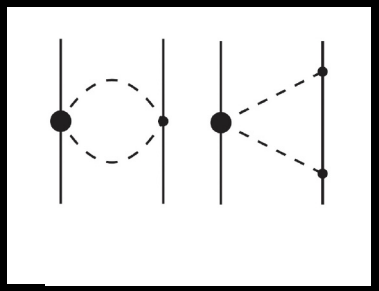
2-pion exchange force

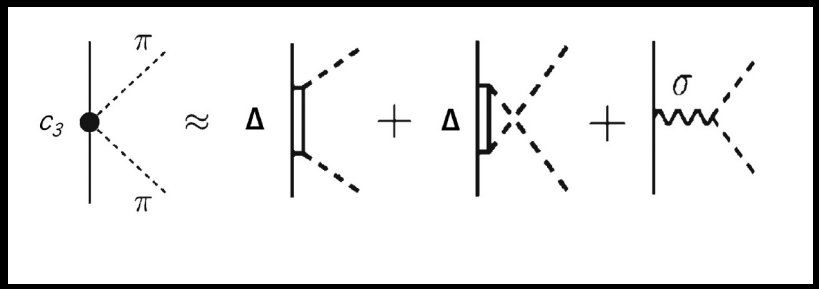
2

Bhanot and Peskin, Nucl. Phys. B156 (1979) 391
Fujii and Kharzeev, Phys. Rev. D60 (1999) 114039
Brambilla, Klein, Tarrus Castella and Vairo Phys. Rev. D93 (2016) 054002

Brief overview: T. Hatsuda; https://arxiv.org/abs/2507.08359

TPE between nucleons (NN):





$$V(\boldsymbol{r}) = \frac{3g_A^2 c_3 m_\pi^4}{32\pi^2 f_\pi^4} \cdot \frac{e^{-2m_\pi r}}{r^2},$$

Kaiser, Brockmann Weise, Nucl. Phys. A (1997)

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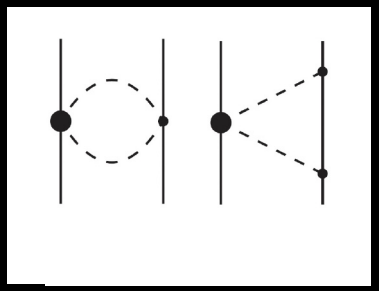

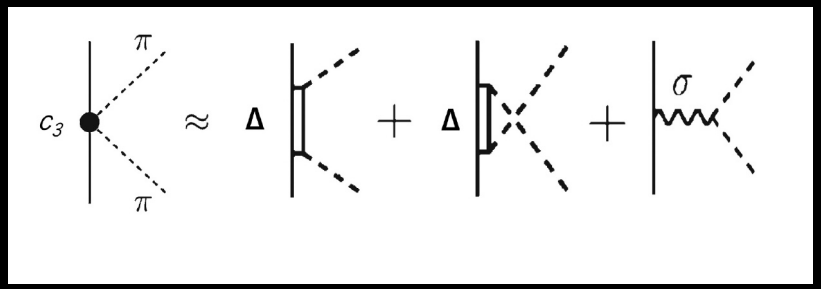

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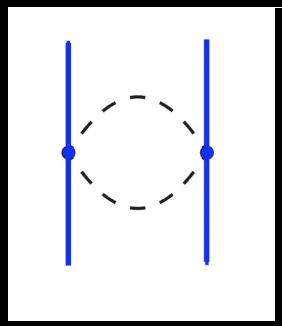
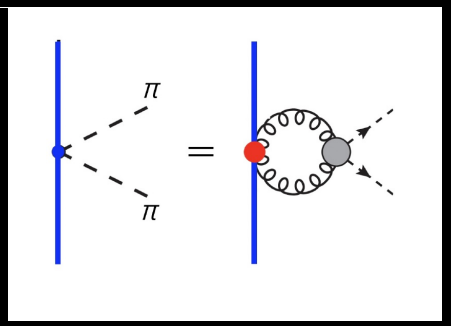
TPE between flavor-singlet hadrons (e.g. J/ψ-J/ψ)





$$V(\boldsymbol{r}) = -\frac{3(3+\kappa_2)^2 \pi^{3/2} \beta^2 m_\pi^{9/2}}{4b^2} \cdot \frac{e^{-2m_\pi r}}{r^{5/2}}.$$

Brambilla et al., Phys. Rev.D (2016)

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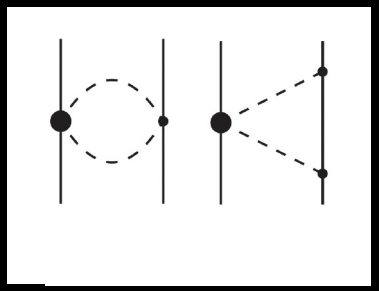

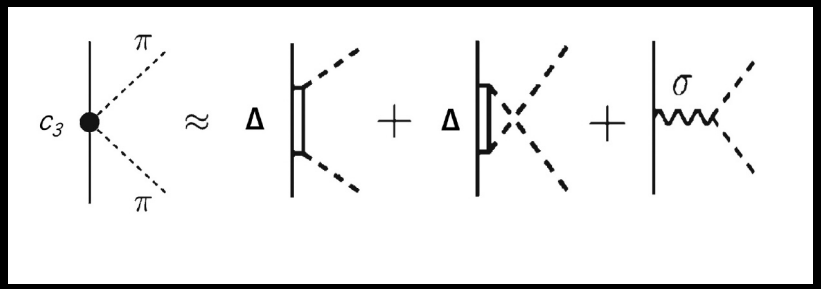

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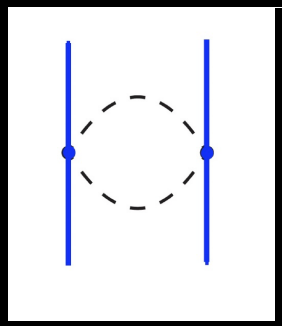

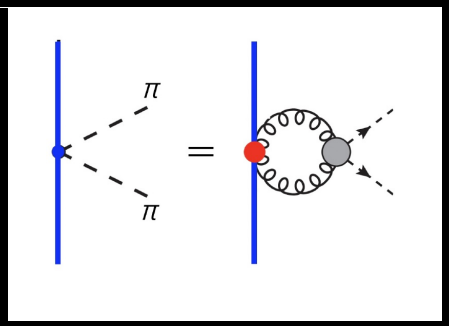

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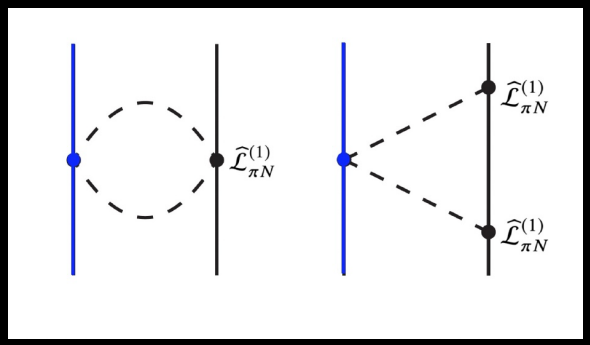
Brambilla et al., Phys. Rev.D (2016)

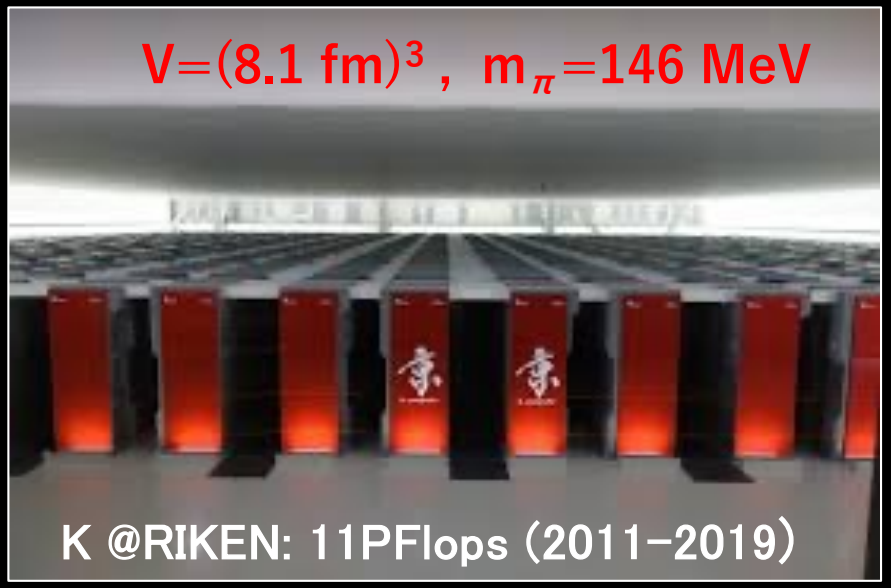
TPE between flavor-singlet hadron and N (e.g. ϕ-N, J/ψ-N)

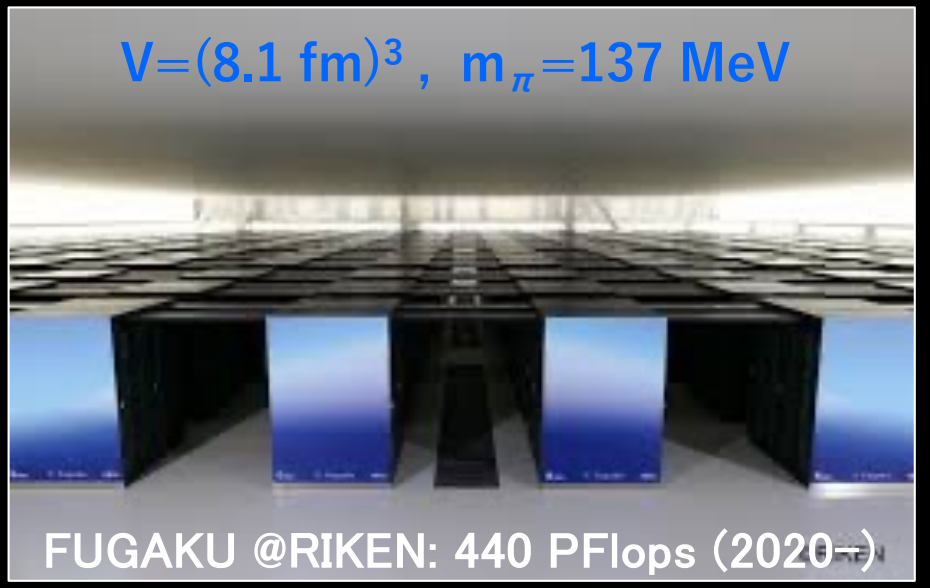


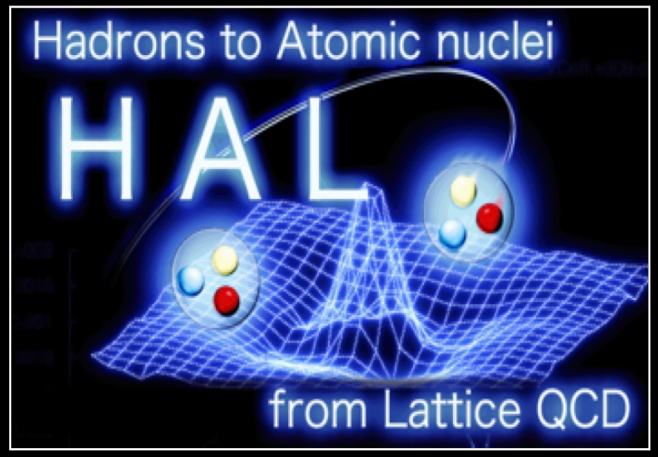
$$V(\boldsymbol{r}) = \frac{3g_A^2 m_\pi^4 (c_{di} + c_m)}{128\pi^2 F^2} \frac{e^{-2m_\pi r}}{r^2}.$$

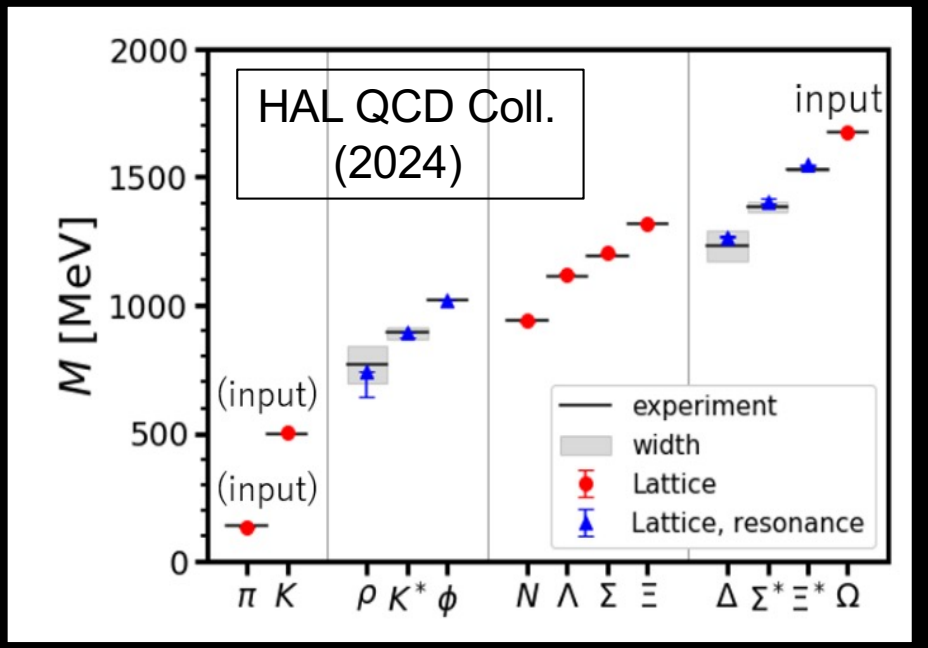
Krein, Casttela , Phys. Rev. D (2018)

Large-Scale LQCD Simulations of Hadron-Hadron Int.









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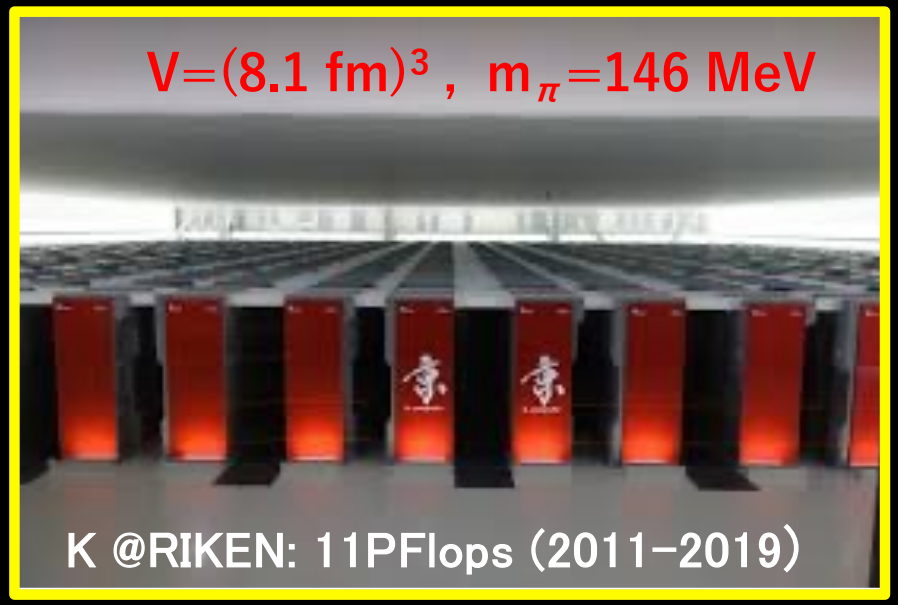
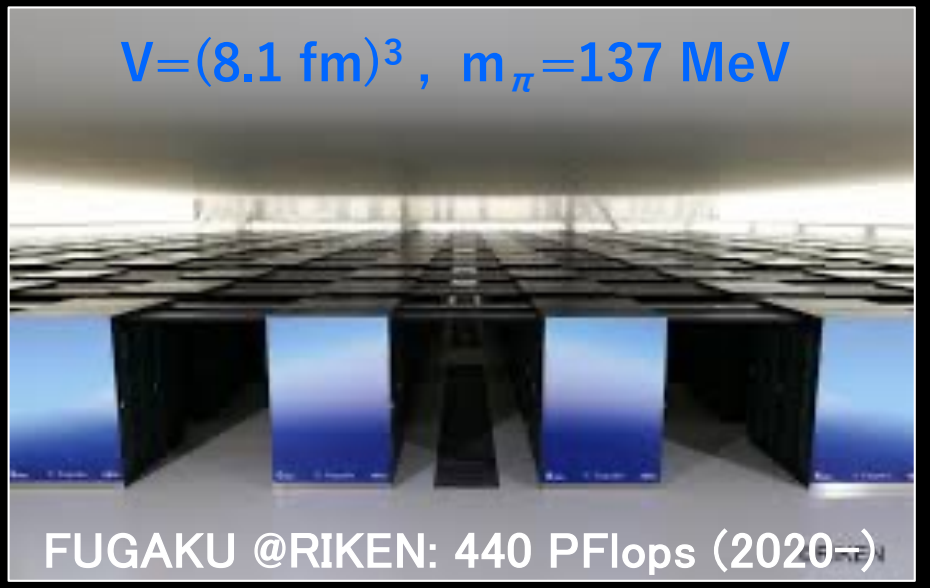
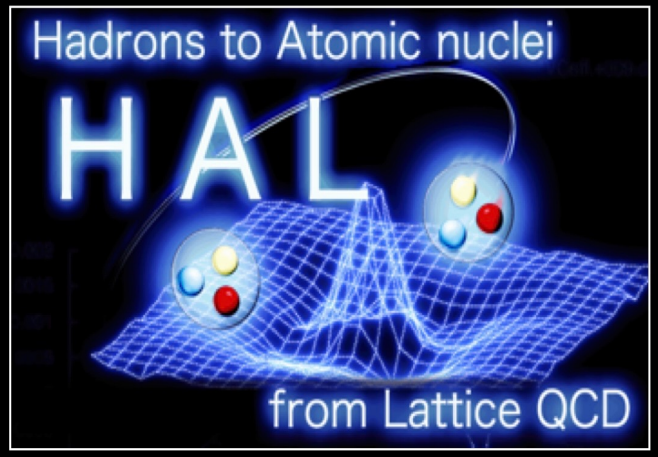
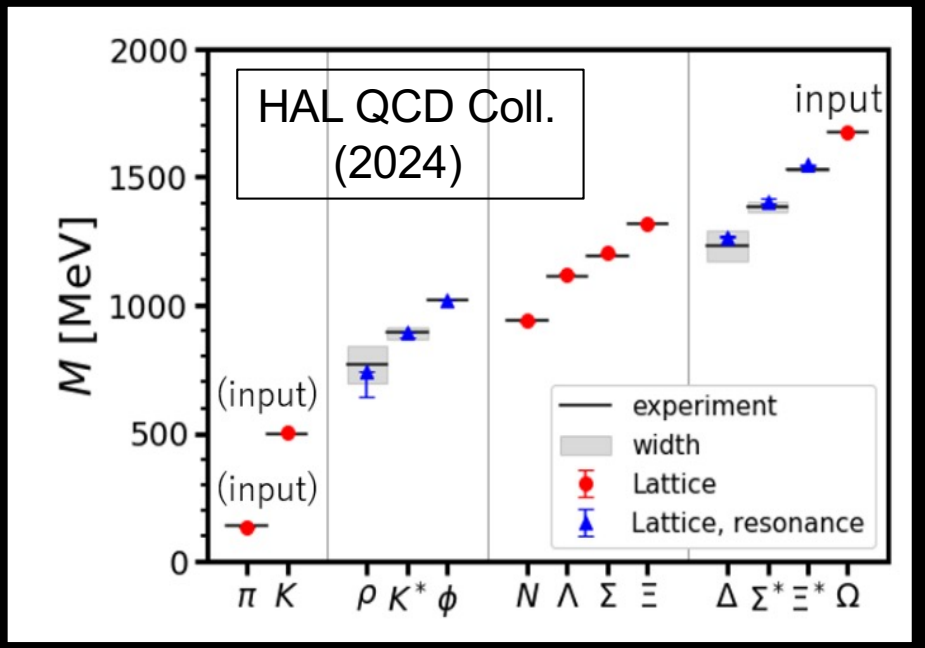








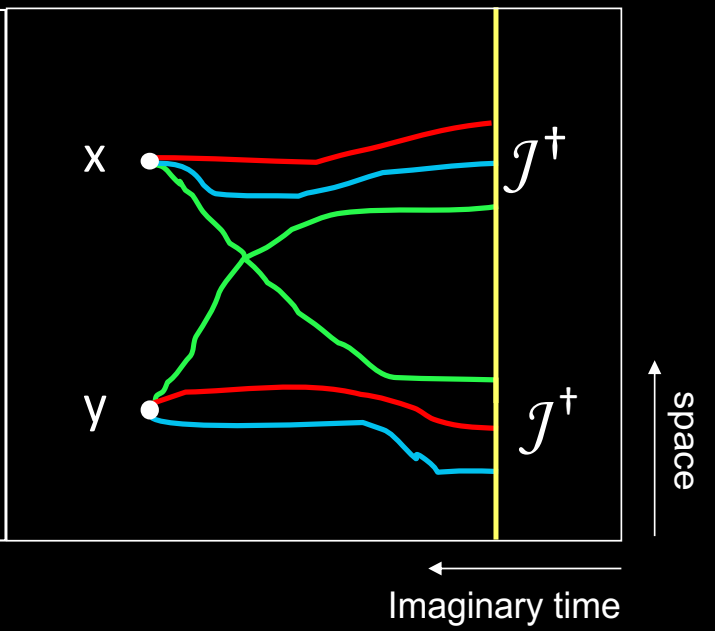
HAL QCD Method

11/11 (Tues) 10:15-
Takumi Doi

Spacetime correlation of composite particles

- Haag-Nishijima-Zimmermann formula (1958)
- Borchers Theorem (1960)

$$R(t, \mathbf{r}) = \sum_n \Psi_n(r) e^{-E_n \tau}$$



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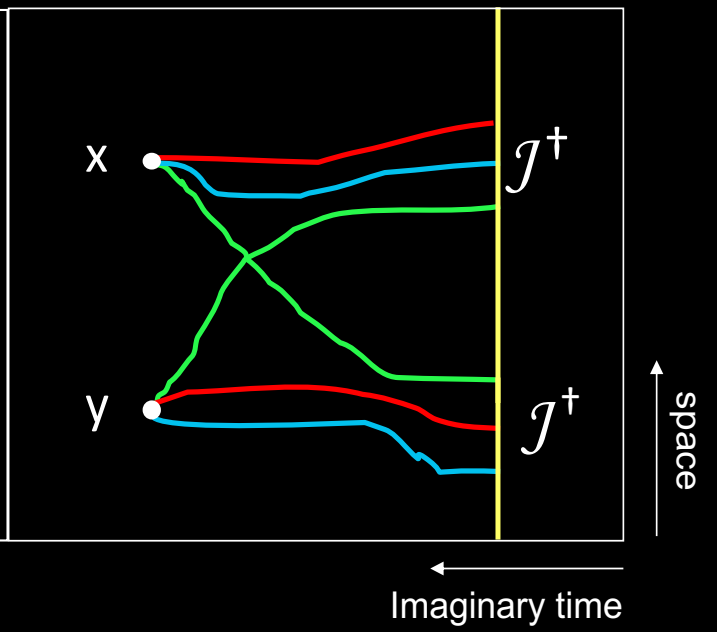


HAL QCD Method

$$\left\{ \frac{1}{4m_B}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} - H_0 \right\} R(t,\mathbf{r}) = \int d^3\mathbf{r}'\, U(\mathbf{r},\mathbf{r}') R(t,\mathbf{r}').$$

Ishii, Aoki & Hatsuda, PRL 99 (2007);
Ishii+ [HALQCD Coll.], PLB 712 (2012)

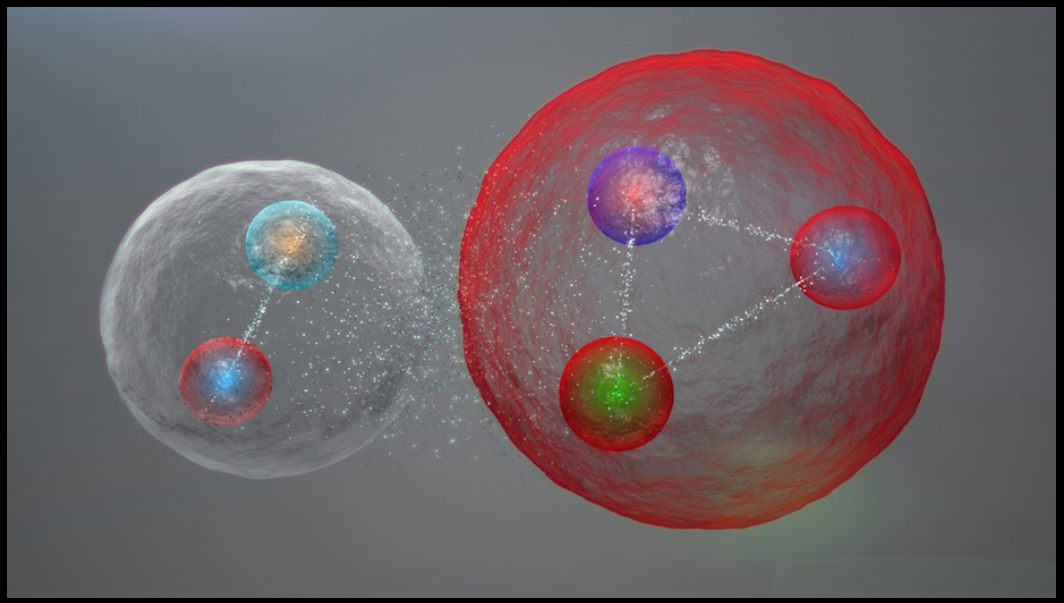
$R \rightarrow U$ (Inverse Problem)

- Derivative expansion: $U(r,r') = V_0(r) + V_2(r)\,\nabla^2\,\delta(r-r') + \ldots$
- Neural network : $U_\theta(r,r')$

L. Wang, T. Hastuda, Y. Lyu, arXiv:2410.03082

Meson-Baryon Interactions

- color-dipole and nucleon -

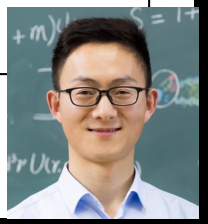


$s\bar{s}$ -N

$c\bar{c}$ -N

Attractive N-ϕ interaction and two-pion tail from lattice QCD near physical point

Yan Lyu, Takumi Doi, Tetsuo Hatsuda, Yoichi Ikeda, Jie Meng, Kenji Sasaki, and Takuya Sugiura
Phys. Rev. D **106**, 074507 – Published 21 October 2022



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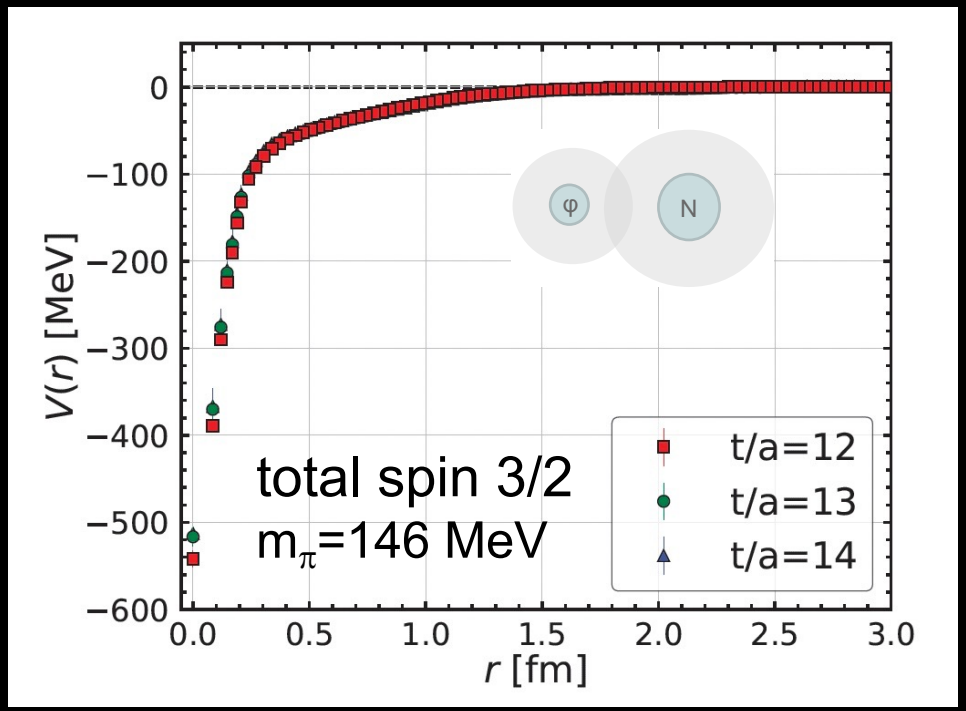

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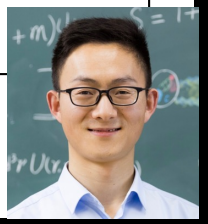

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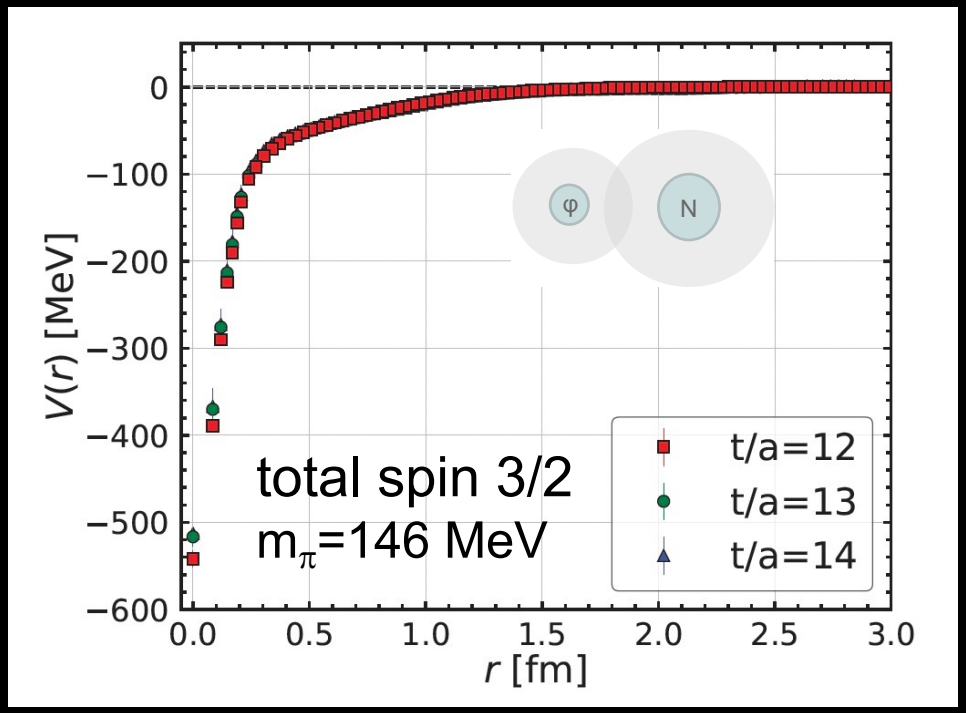

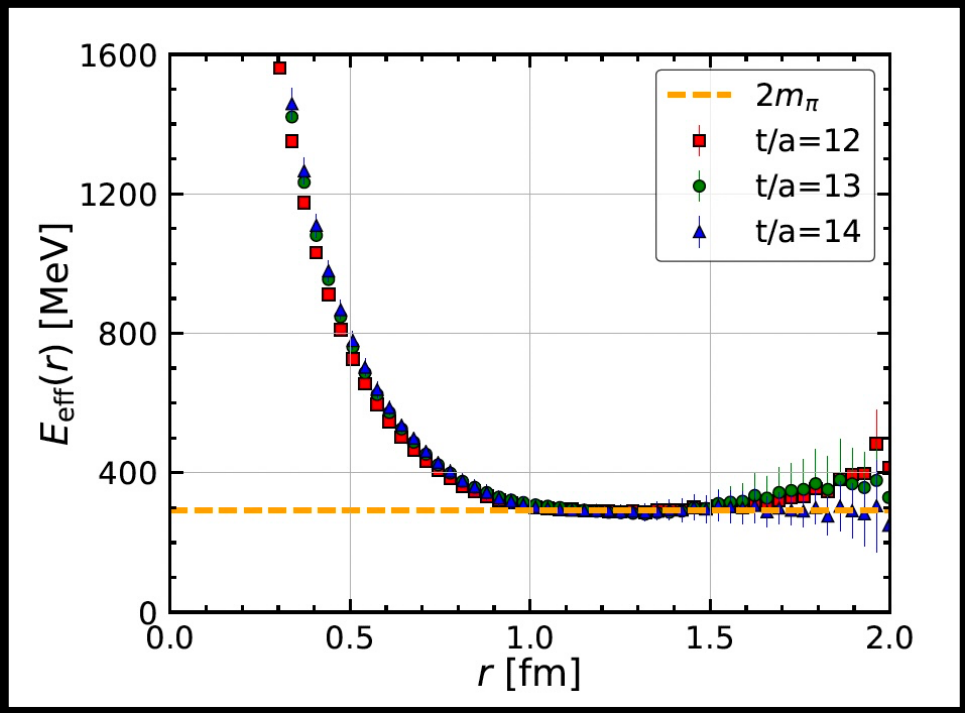

$$E_{\mathrm{eff}}(r) = -\frac{\ln[-V_{\mathrm{lat}}(r)r^{\nu}/\alpha]}{r}.$$

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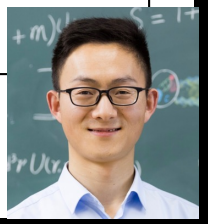

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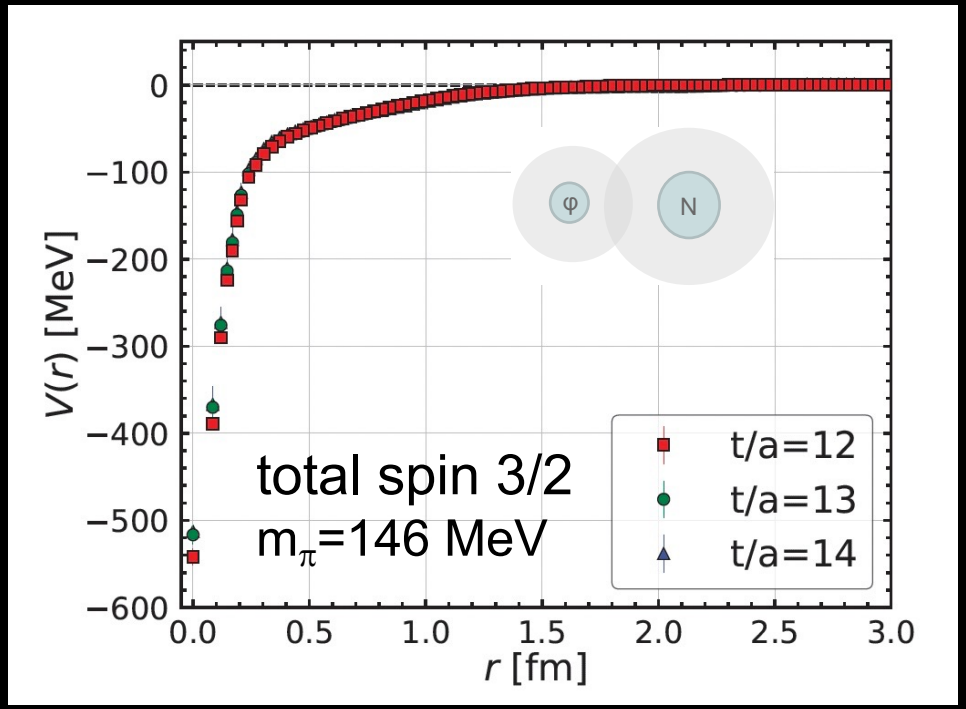
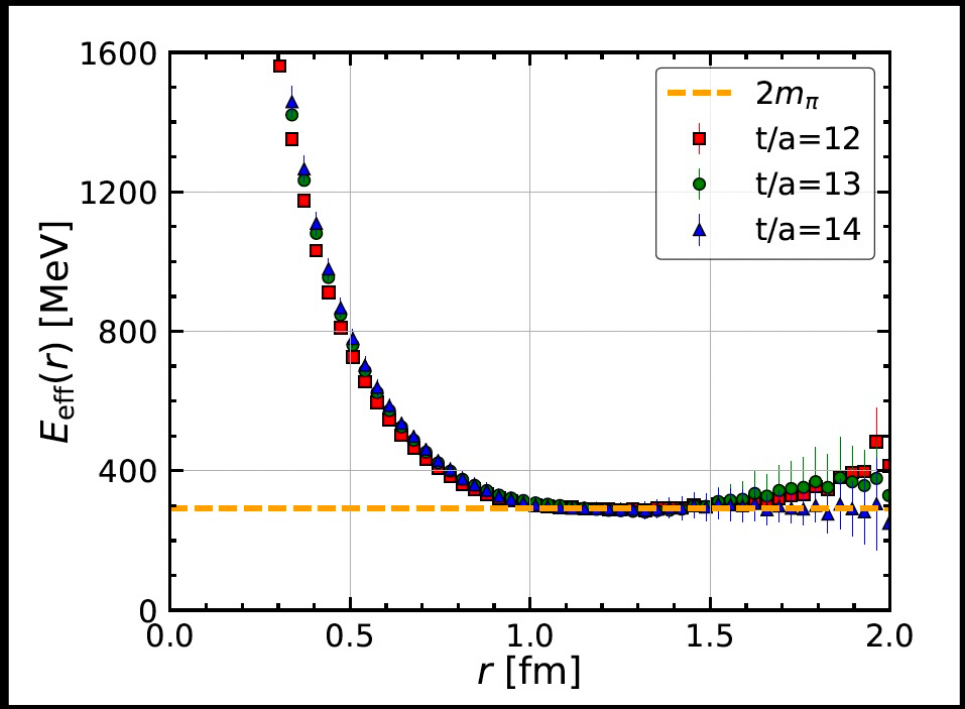
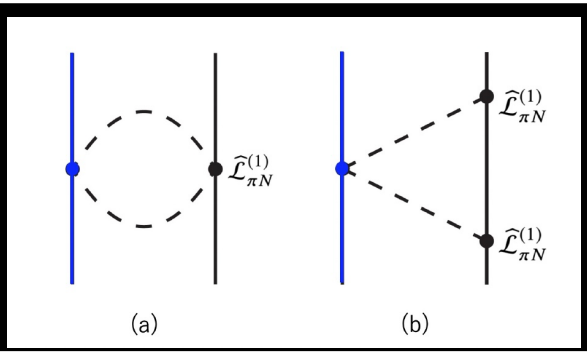




Two-pion Tail at $r > (2m_\pi)^{-1}$



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Krein and Casttela , Phys. Rev. D98 (2018) 0140289.

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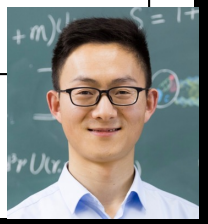

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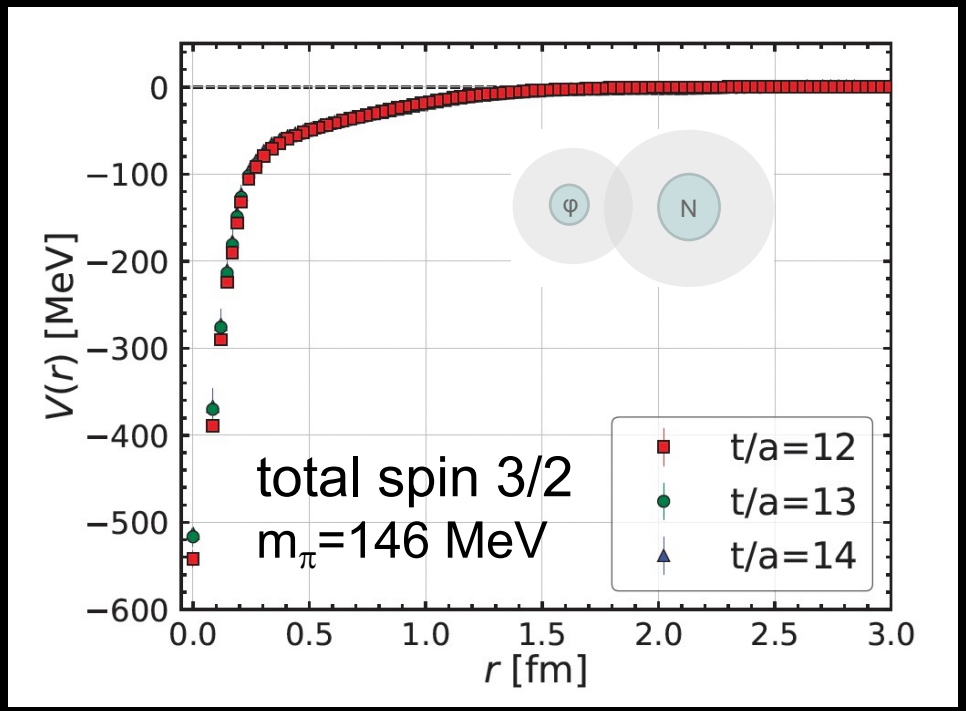
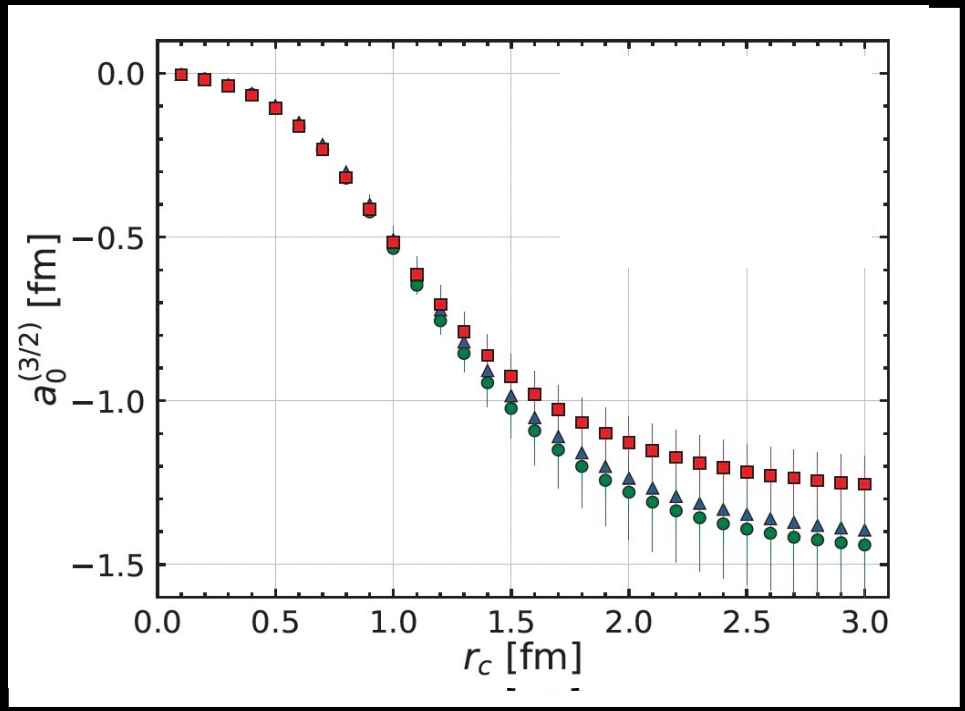
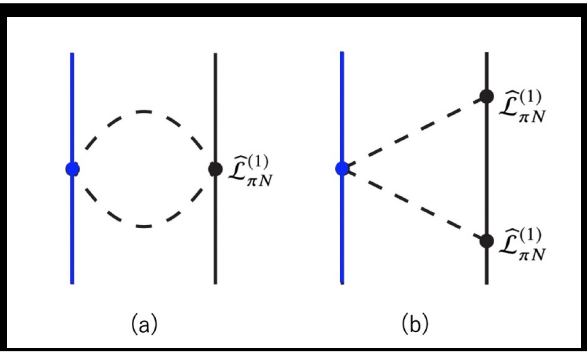
(RIKEN)





Two-pion Tail at $r > (2m_\pi)^{-1}$

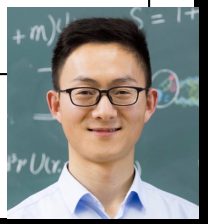


$$V(\boldsymbol{r}) = \frac{3g_A^2 m_\pi^4 (c_{di} + c_m)}{128\pi^2 F^2} \frac{e^{-2m_\pi r}}{r^2}.$$

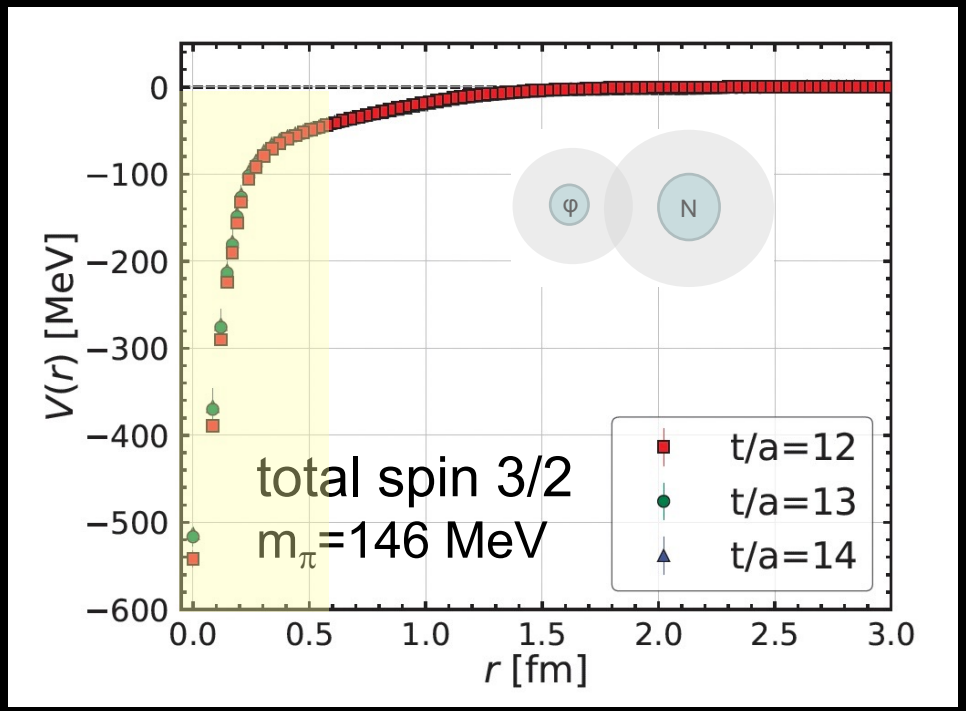
Krein and Casttela , Phys. Rev. D98 (2018) 0140289.

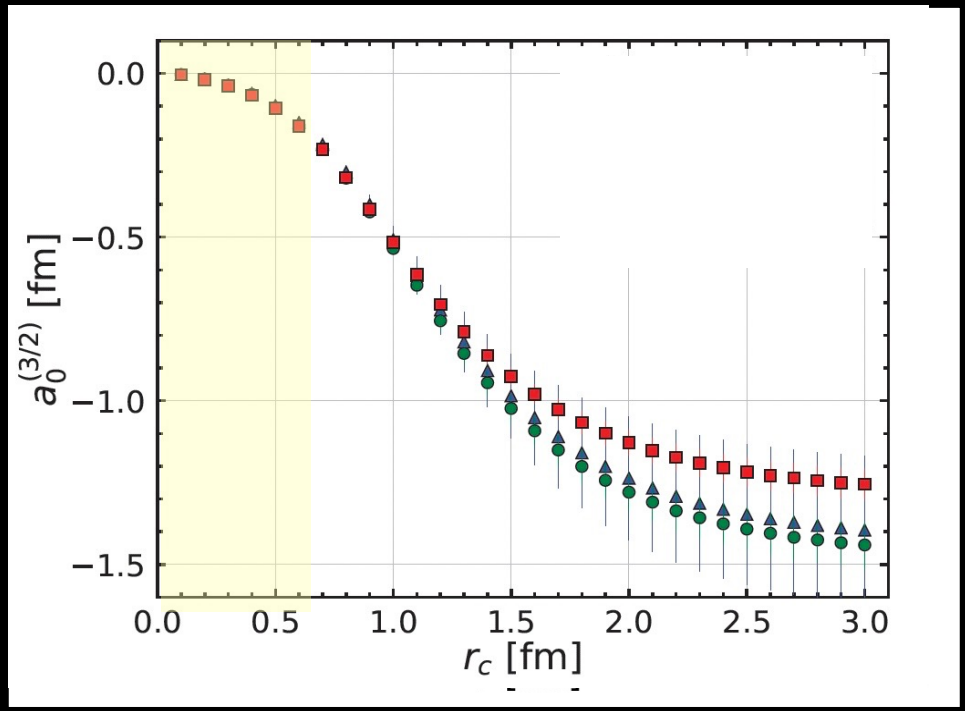
Attractive N-ϕ interaction and two-pion tail from lattice QCD near physical point

Yan Lyu, Takumi Doi, Tetsuo Hatsuda, Yoichi Ikeda, Jie Meng, Kenji Sasaki, and Takuya Sugiura
Phys. Rev. D **106**, 074507 – Published 21 October 2022



Yan Lyu
(RIKEN)





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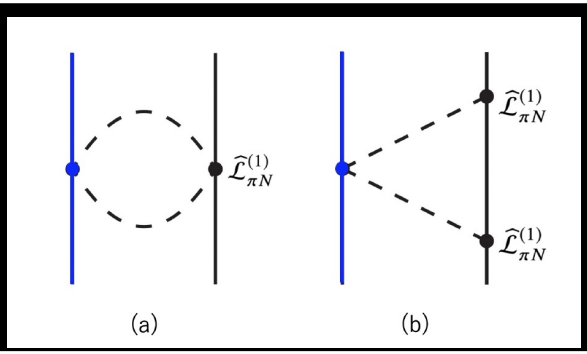

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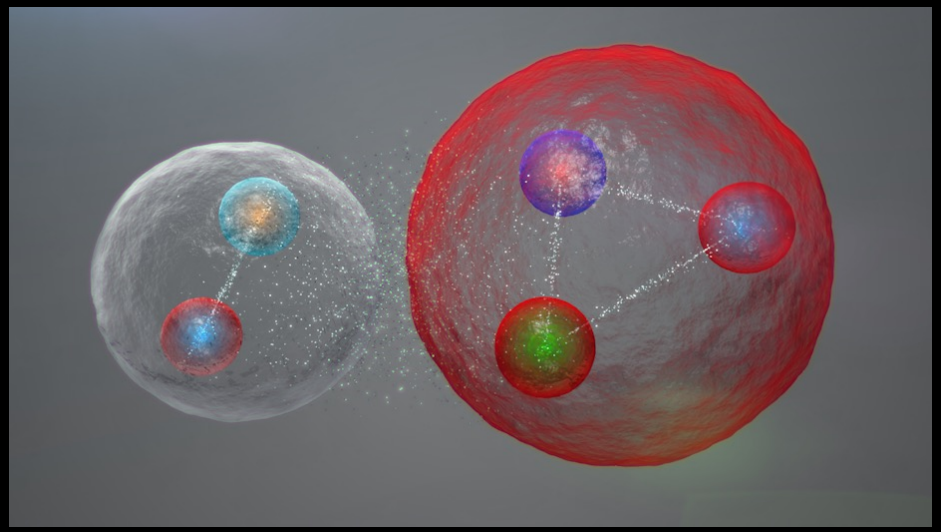
What about $c\bar{c}$ -N interaction ?



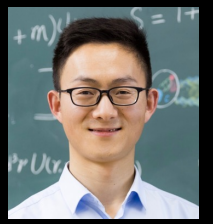
$c\bar{c}$ N

Nucleon-charmonium interactions from lattice QCD

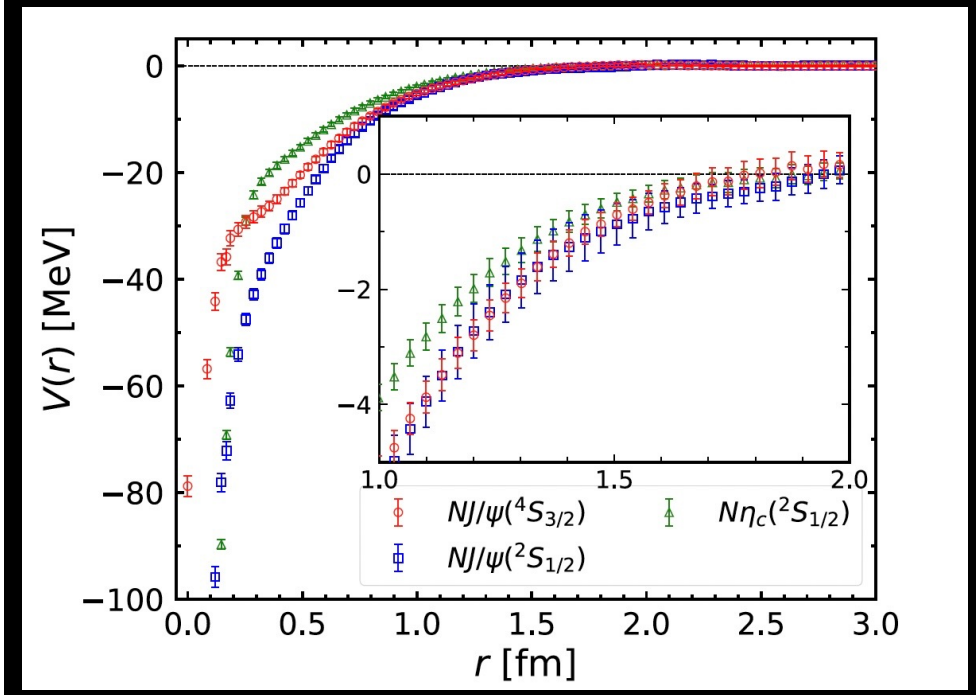
Yan Lyu [a,*], Takumi Doi [a,*], Tetsuo Hatsuda [a,*], Takuya Sugiura [b,a,*]

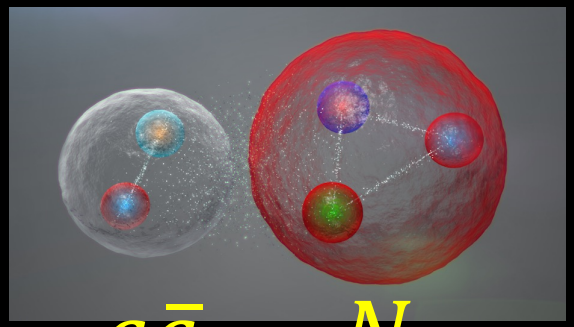
Phys. Lett. B 860 (2025) 139178

HAL QCD Collaboration



Yan Lyu
(RIKEN)





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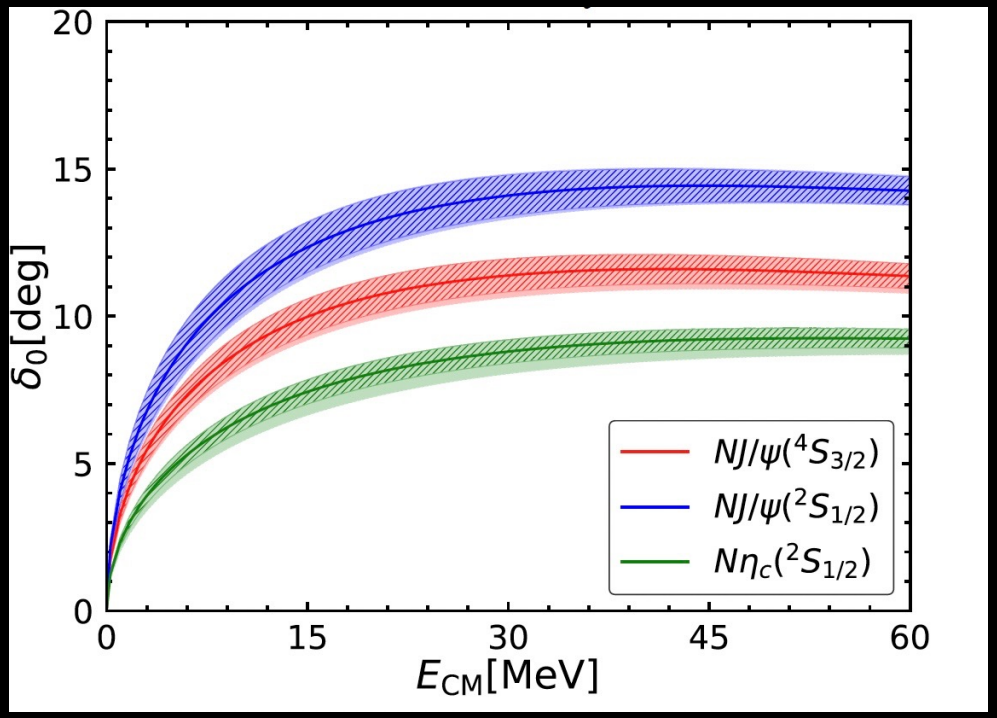

Scattering length and effective range

channel	a_0 [fm]	$r_{\rm eff}$ [fm]
$NJ/\psi(^4S_{3/2})$	$0.30(2)\binom{+0}{-2}$	$3.25(12)\binom{+6}{-9}$
$NJ/\psi(^2S_{1/2})$	$0.38(4)\binom{+0}{-3}$	$2.66(21)\binom{+0}{-10}$
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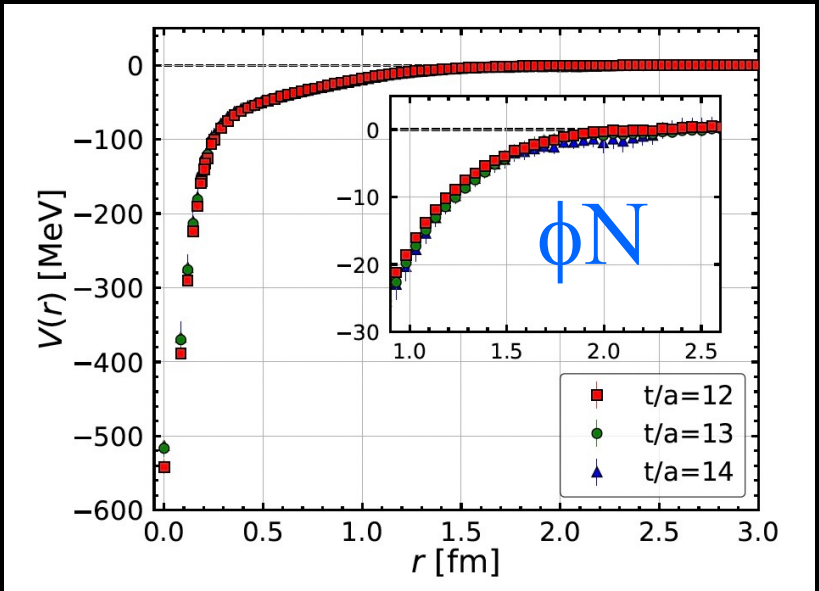
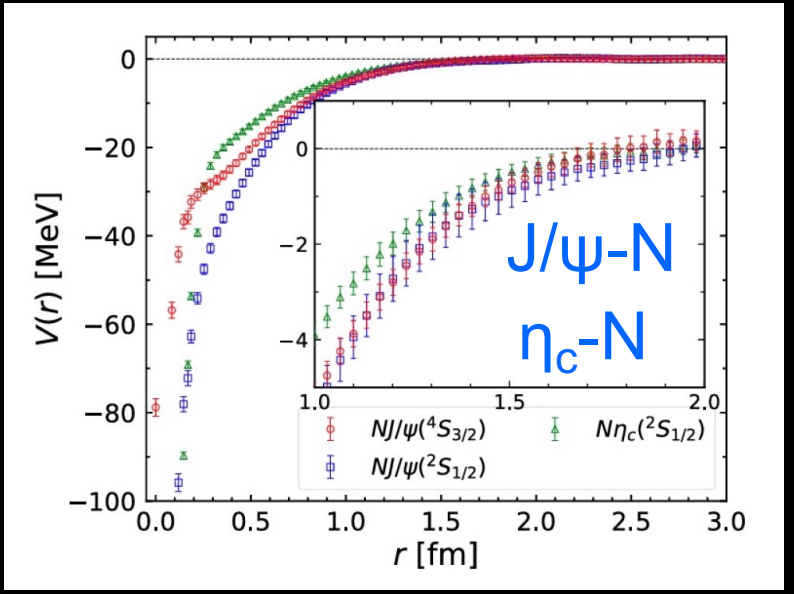
J/ψ optical potential in nuclear matter

$$\delta m_{J/\psi} \simeq \frac{2\pi(m_N + m_{J/\psi})}{m_N m_{J/\psi}} a_{J/\psi}^{\text{spin-av}} \rho_{\rm nm} = 19(3)\ \text{MeV},$$

⇔ Krein, Tsushima, Thomas,
Nuclear-bound quankonia and heavy-flavor hadrons
Prog. in Part. Nucl. Phys. 100 (2018) 161

“Evidence” of uncorrelated TPE at long distance





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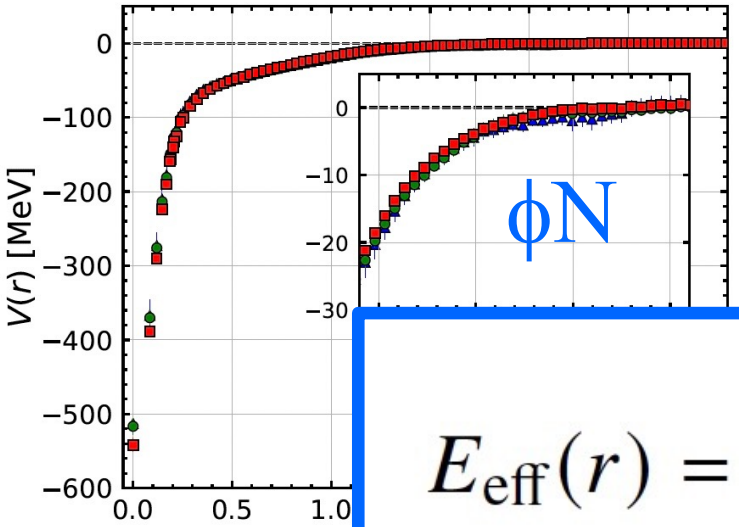
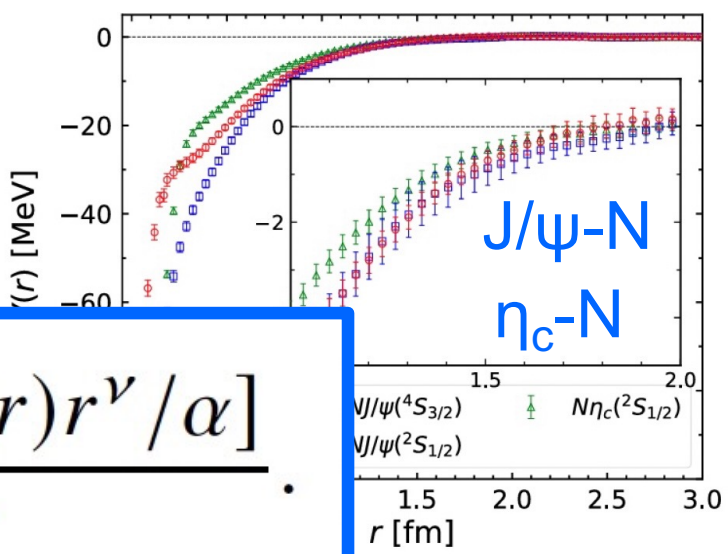
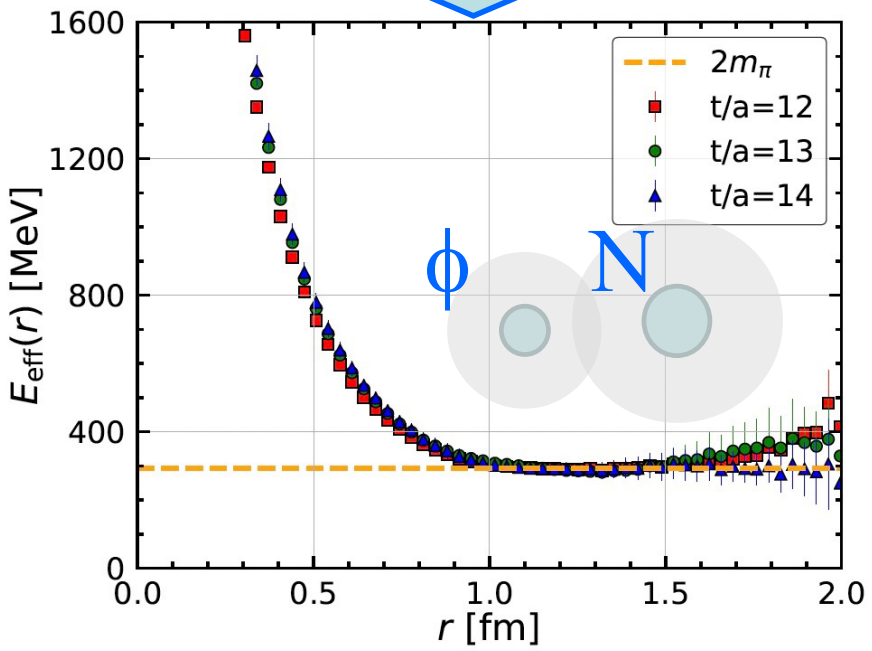
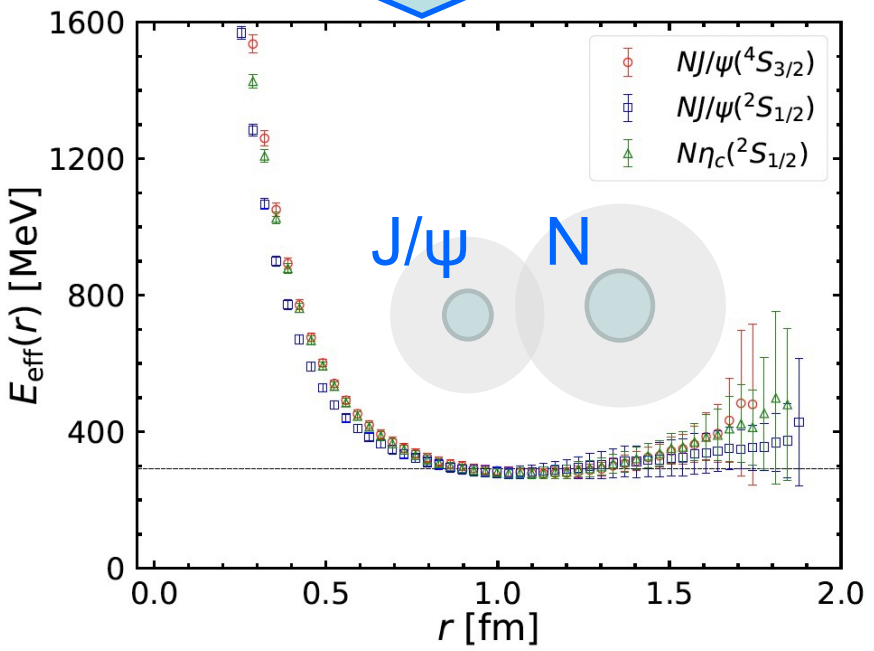




$$E_{\mathrm{eff}}(r) = -\frac{\ln[-V_{\mathrm{lat}}(r) r^{\nu}/\alpha]}{r}.$$





Summary

Hadron-hadron int. from LQCD at m_π = 146 MeV and 137 MeV
opens the door to the "coevolution" of LQCD and Experiments
(examples) BB: $\Lambda\Lambda$–$N\Xi$, $N\Omega$, $\Omega\Omega$, MM: T_{cc}^+ , MB: $s\bar{s}$ -N, $c\bar{c}$ -N

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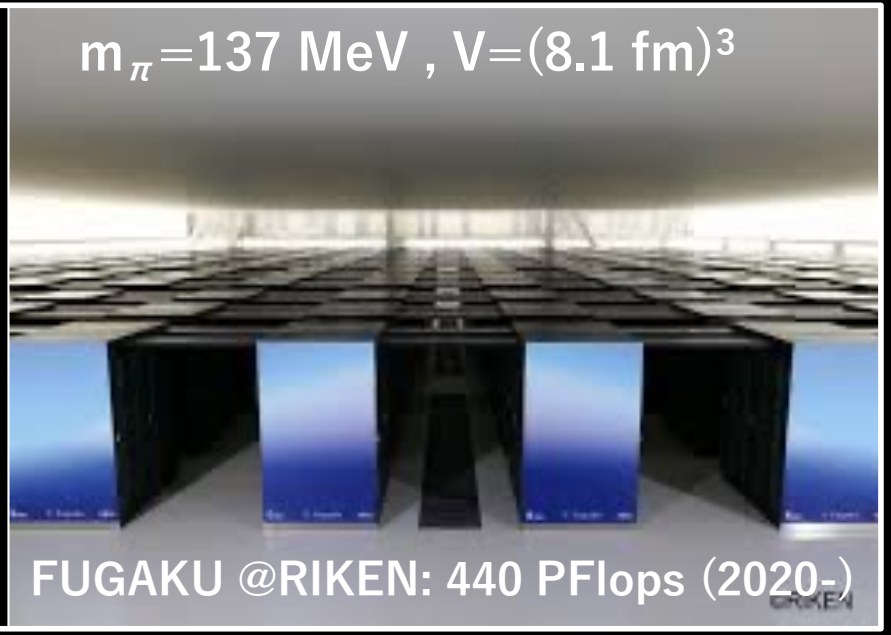
Open issues

- TPE universality in BB and MM ?
- Power ? $1/r^{2.5}$ vs. $1/r^2$
- Derivation of chromo-polarizability



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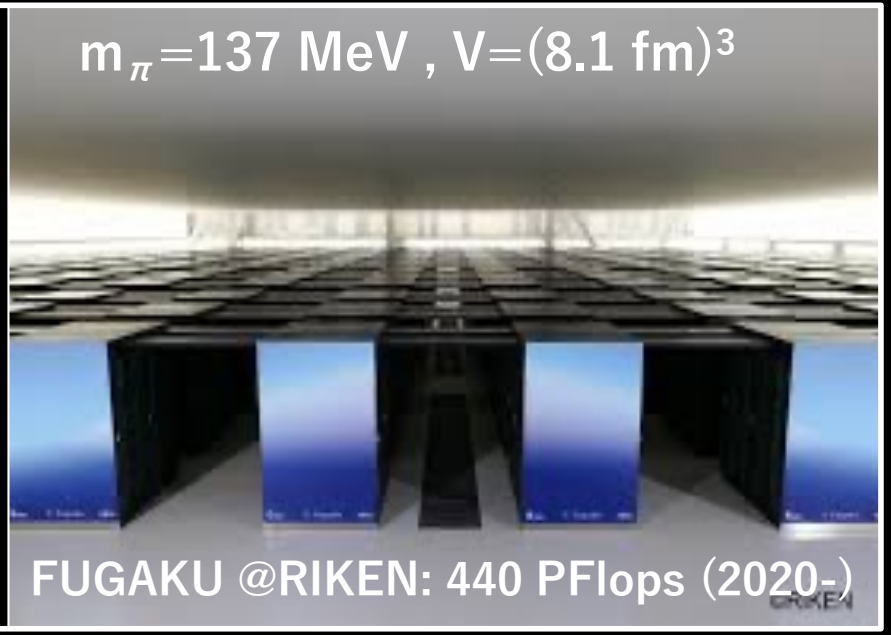
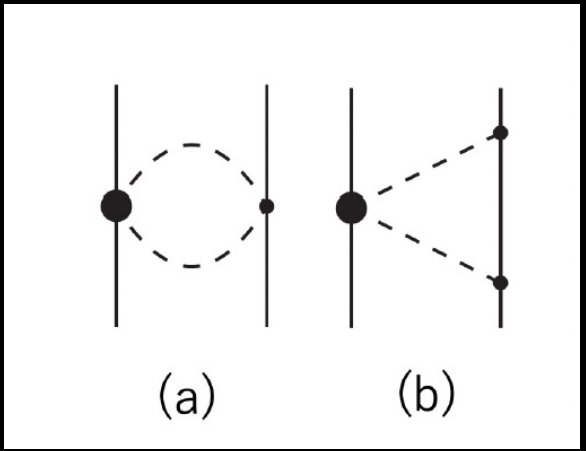
Stay tuned !



Backup

Two-pion exchange between nucleons (NN):

Kaiser, Brockmann Weise, Nucl. Phys. A (1997)



$$V^{2\pi}_{\mathrm{NN;C}}(r)\Big|^{(a)}_{\mathrm{N^2LO}} = 0,$$

$$V^{2\pi}_{\mathrm{NN;C}}(r)\Big|^{(b)}_{\mathrm{N^2LO}} = \frac{3g_A^2}{32\pi^2 f_\pi^4}\frac{e^{-2x}}{r^6}\left\{\left(2c_1+\frac{3g_A^2}{16M}\right)x^2(1+x)^2+\frac{g_A^2x^5}{32M}+\left(c_3+\frac{3g_A^2}{16M}\right)(6+12x+10x^2+4x^3+x^4)\right\},$$

$$\xrightarrow[M\to\infty,\ x\ll 1]{} \frac{9g_A^2c_3}{16\pi^2 f_\pi^4}\cdot\frac{1}{r^6},$$

$$\xrightarrow[M\to\infty,\ x\gg 1]{} \frac{3g_A^2c_3m_\pi^4}{32\pi^2 f_\pi^4}\cdot\frac{e^{-2m_\pi r}}{r^2},$$

$$x = m_\pi r$$