第十届手征有效场论研讨会,
10/17-10/21, 南京师范大学, 南京

Nucleon-vector meson interactions from lattice QCD

Yan Lyu (吕岩)

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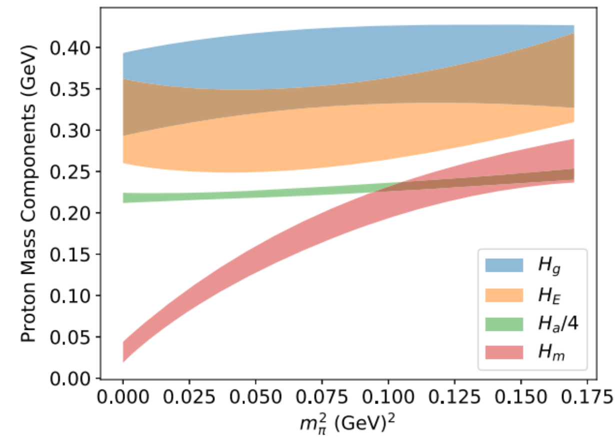
Oct. 20, 2025

N-J/ψ interaction

M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, Phys. Lett. B 78 (1978)
X.-D. Ji, Phys. Rev. Lett. 74 (1995)

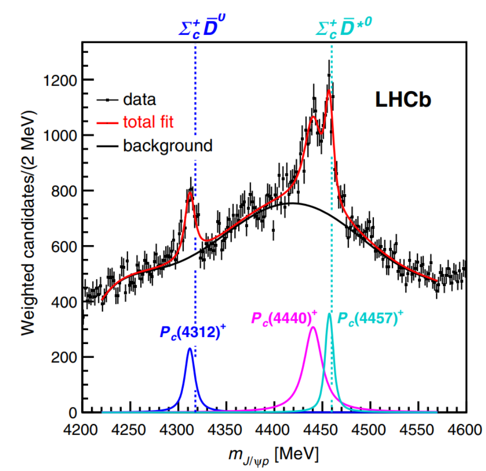
- How hadrons gain/loss masses ?
  - The trace anomaly contribution of proton mass, as N-J/ψ forward scattering amplitude ~ $\langle N|G_{\mu\nu}G^{\mu\nu}|N\rangle$
  - J/ψ mass modification in nuclear medium



Y.-B. Yang *et. al.*, Phys. Rev. Lett. 121 212001 (2018)

- What kind of multi hadrons can exist ?
  - Pentaquark P_c
    - found in the $p\,J/\psi$ spectrum
    - coupled-channel studies need N-$c\bar{c}$ interaction
  - Charmonium-nucleus bound states (A-$c\bar{c}$)

R. Aaij, *et al.* [LHCb Coll.], Phys. Rev. Lett. 115 072001 (2015)
Phys. Rev. Lett. 122 (22) 222001 (2019)



S. Brodsky, I. Schmidt, and G. Teramond, Phys. Rev. Lett. 64 (1990)
J.-J. Wu, T.-S. H. Lee, Phys. Rev. C 86 (2012)
A. Yokota, E. Hiyama, M. Oka, PTEP 2013 (11) (2013)
G. Krein, A. W. Thomas, and K. Tsushima, Prog. Part. Nucl. Phys. 100 (2018)

$N\phi$ interaction

- Fundamental input for studying R. S. Hayano and T. Hatsuda, Rev. Mod. Phys. **82**, 2949 (2010)
  - meson properties in nuclear matter
  - chiral symmetry and its restoration
  - renewed interest thanks to J-PARC experiments

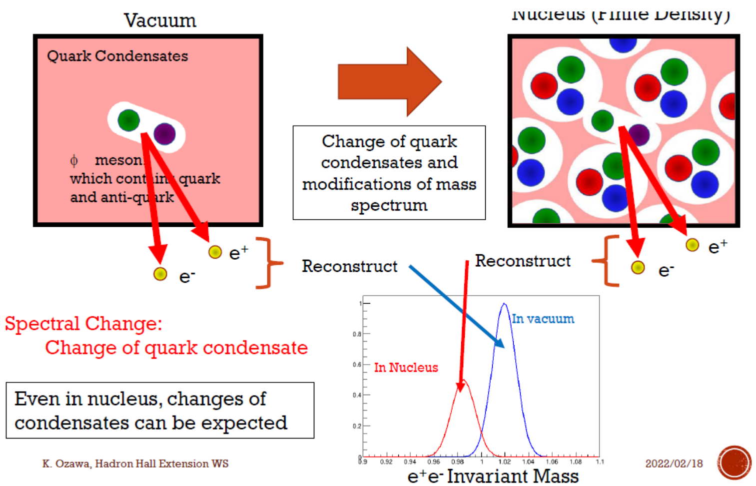
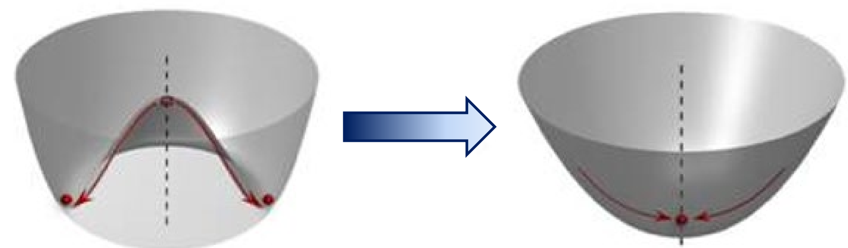


Fig. taken from K. Ozawa



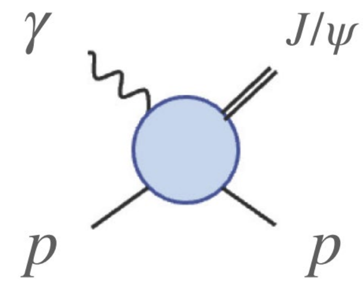
- Theoretical studies

P. Gubler and D. Satow, Prog. Part. Nucl. Phys. 106, 1 (2019); T. Hatsuda and S. H. Lee, Phys. Rev. C 46, R34 (1992)
J. Castella and G. Krein, Phys. Rev. D 98, 014029 (2018)

  - ϕ in-medium property $\leftrightarrow$ $\bar{s}s$ condensate
  - open questions on $N\phi$: microscopic origin, the role of dynamical π

Large uncertainties in experiments

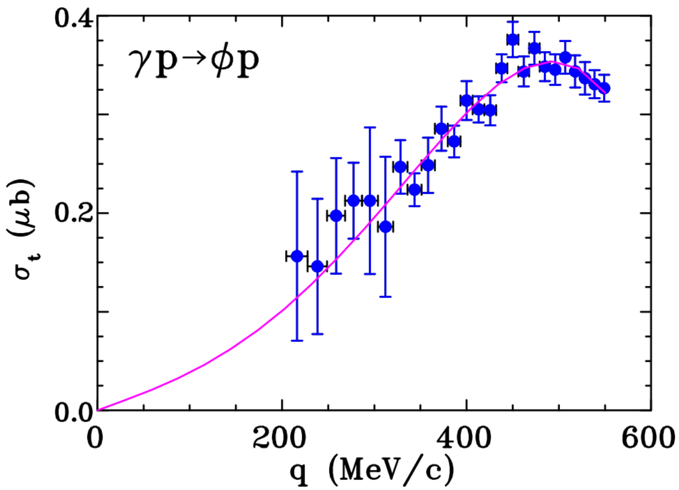
- The N-J/ψ scattering length (spin averaged)
  - Vector-meson dominance: $a_{NJ/\psi} \sim O(1-10) \times 10^{-3}$ fm
  - Low-energy unitary: $a_{NJ/\psi} \sim O(1)$ fm



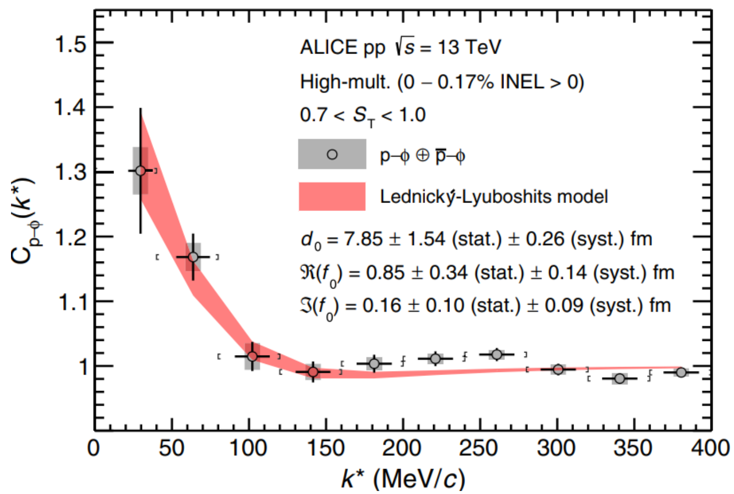
L. Pentchev, and I. I. Strakovsky, Eur. Phys. J. A 57 (2) 56 (2021)
D. Winney, *et al.* (Joint Physics Analysis Center), Phys. Rev. D 108 (5) 054018 (2023)

- The N-ϕ scattering length (spin averaged)

I. Strakovsky, L. Pentchev, and A. Titov, Phys. Rev. C 101, 045201 (2020)



ALICE Coll, Phys. Rev. Lett. 127, 172301 (2021)



Reference	Spin-averaged a_0 [fm]
Strakovsky *et al.* 2020	$\pm 0.063(10)$
ALICE 2021	$0.85(34)_{\text{stat.}}(14)_{\text{syst.}}$

Lattice QCD study of N-V meson interaction

➢ In this talk: First realistic LQCD results on N-V meson systems

- interaction potential from lattice QCD
- interaction mechanism and the role of dynamical pion
- scattering properties

PHYSICAL REVIEW D **106,** 074507 (2022)

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

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Letter

Nucleon-charmonium interactions from lattice QCD

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Letter

Indication of a p–ϕ bound state from a correlation function analysis

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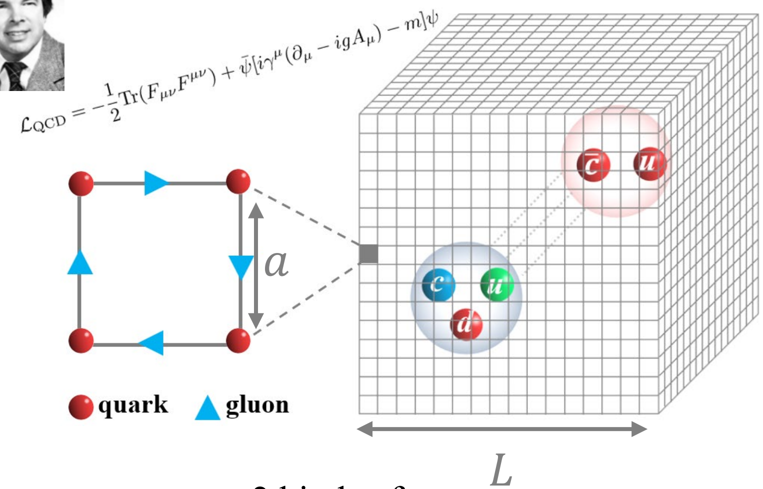
Lattice QCD

K.G. Wilson, Phys. Rev. D 10, 2445 (1974)



2 kinds of parameters: m_q, g

Lattice regularization

- UV cutoff $\sim \frac{1}{a}$; IR cutoff $\sim \frac{1}{L}$
- Quark field $q(x)$ on lattice sites
- Gauge field $U_\mu(x) = e^{iagA_\mu(x)}$ on links

Path integral

- dof: $\sim 100^4 \times 8 \times 4$

$$\boxed{\langle \hat{O} \rangle = \frac{1}{Z_E}\int [\mathcal{D}\bar{q}][\mathcal{D}q][\mathcal{D}U] O e^{-S_E}}$$

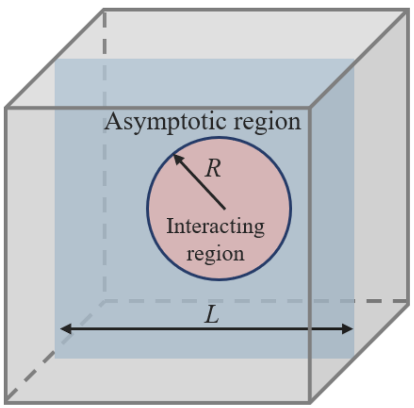
Monte Carlo Simulation

- Importance sampling: a series of QCD configurations with probability e^{-S_E}
- Multiple measurements $O_1, \cdots, O_N$

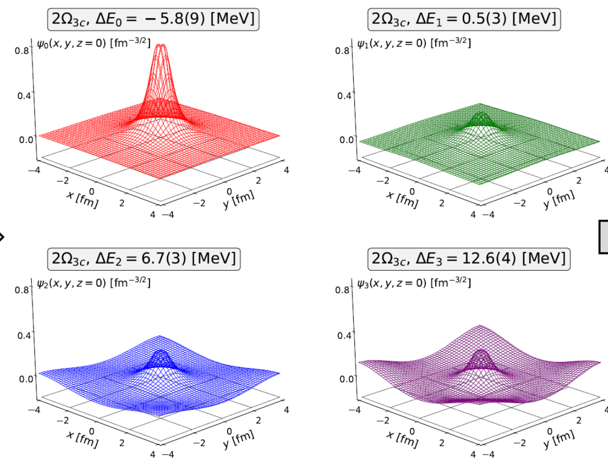
$$\boxed{\langle \hat{O} \rangle = \bar{O} \pm \frac{\sigma}{\sqrt{N}}}$$

HAL QCD method

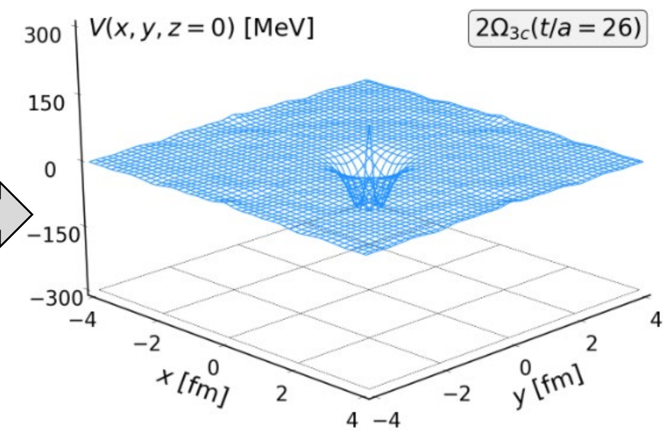
N. Ishii, S. Aoki and T. Hatsuda, Phys. Rev. Lett. 99, 022001 (2007)
N. Ishii, *et al.* [HAL QCD Coll.], Phys. Lett. B 712, 437 (2012)



Lattice simulation



NBS amplitude



Potential

$$V(r) = R(\boldsymbol{r}, t)^{-1}\left(\frac{1}{8\mu}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{2\mu}\right) R(\boldsymbol{r}, t)$$

Lattice setup

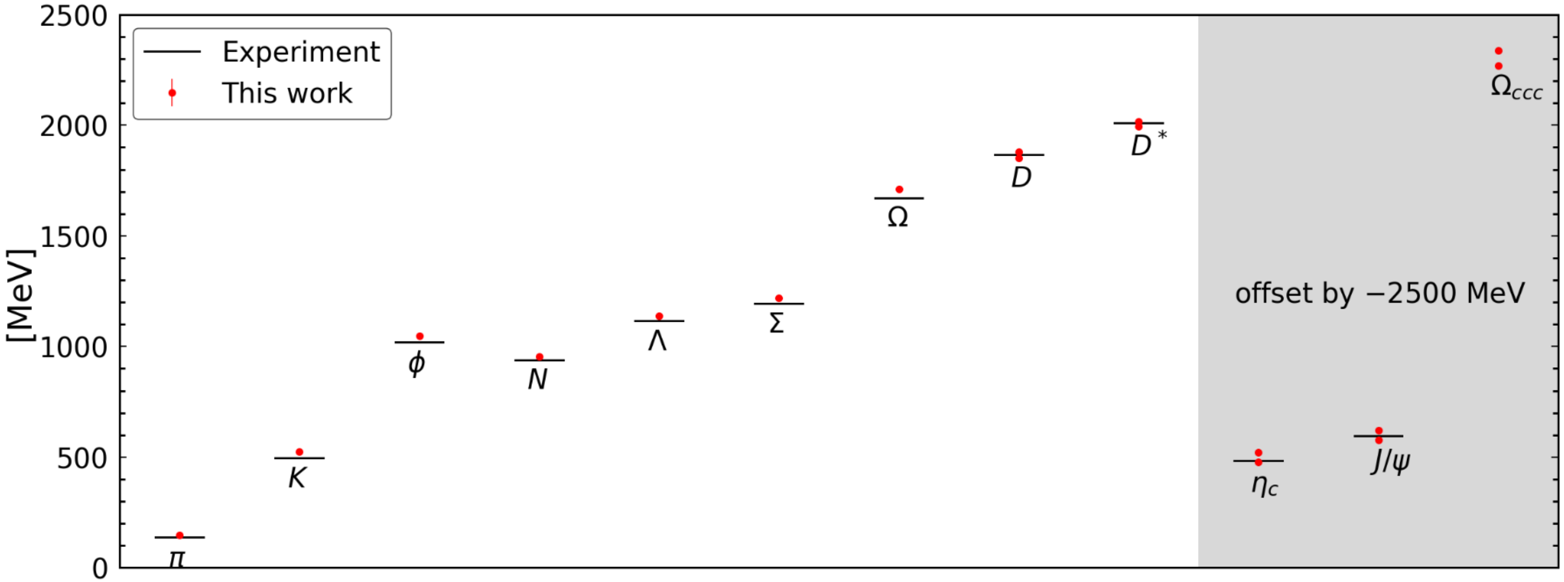
- (2+1)-flavor configurations
  - Iwasaki gauge action
  - $O(a)$-improved Wilson quark action for uds quark
  - Relativistic heavy quark action for c quark

Fugaku supercomputer (440 PFlops)

K.-I. Ishikawa, *et al.* (PACS Collaboration), *Proc. Sci.*, LATTICE2015 075 (2016)
Y. Namekawa et al. (PACS Collaboration), Proc. Sci., LATTICE2016 125 (2017)

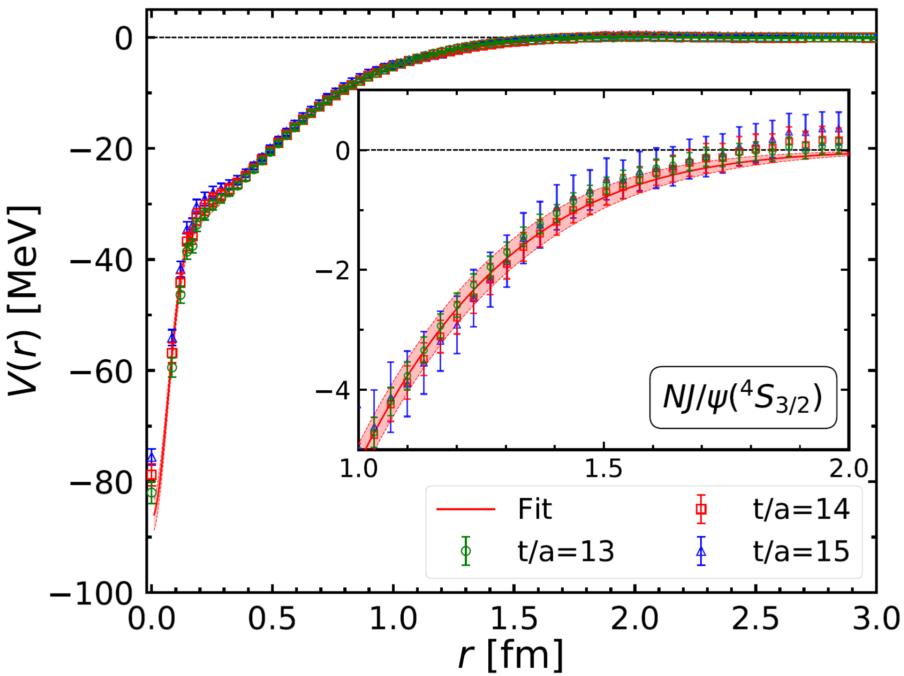
$L^3 \times T$	a [fm]	La [fm]	m_π [MeV]	m_K [MeV]
$96^3 \times 96$	0.0846	8.1	146	525

- Hadron mass

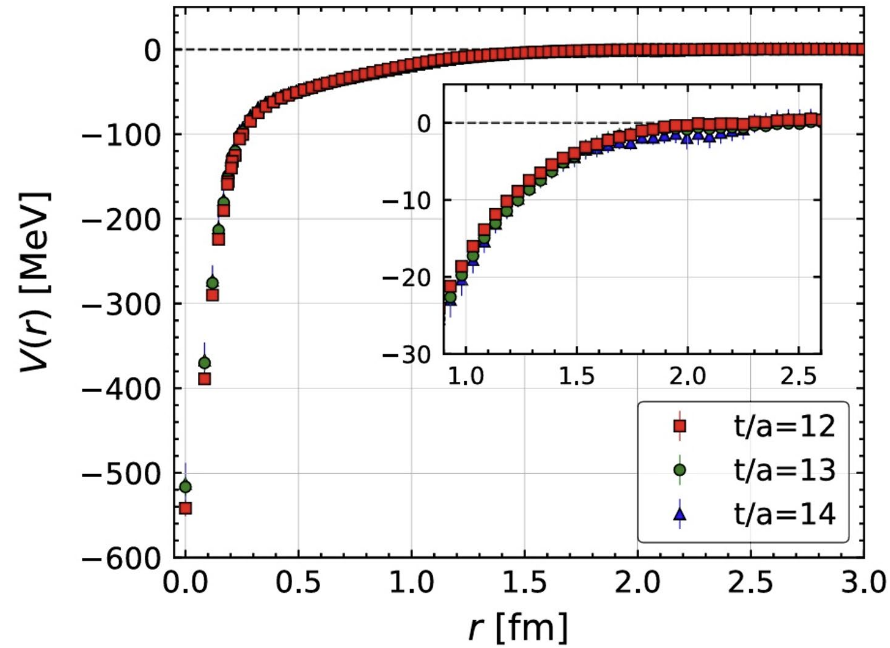


N-V meson potentials

➤ N-J/ψ (spin 3/2)



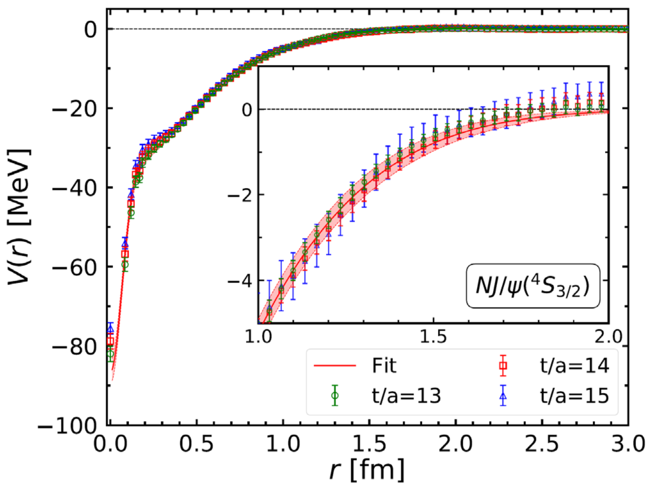
➤ N-ϕ (spin 3/2)

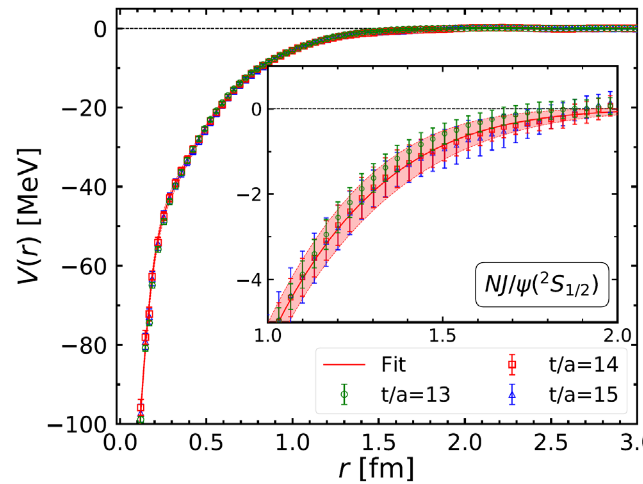


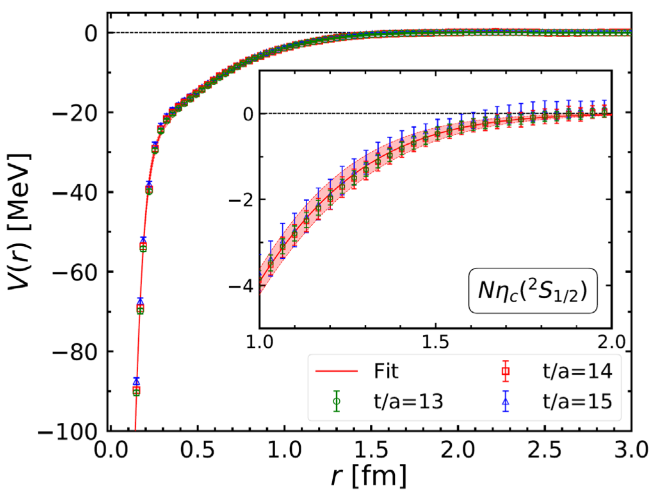
- The attractive potentials weakly depend on t→small systematic errors
- Attractive core, partially because of no Pauli exclusion, similar as $N\Omega$
- At short distance, N–J/ψ is less attractive than N-ϕ, possibly due to $m_c > m_s$

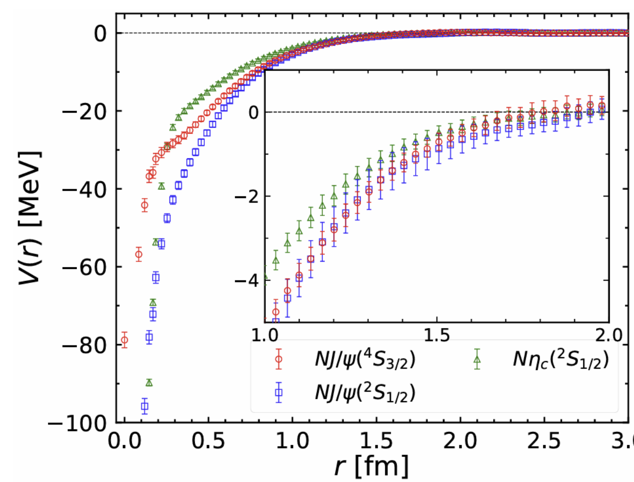
More N-$c\bar{c}$ potentials

➢ S-wave N-$c\bar{c}$ potential at $t/a = 14 \pm 1$ ($t \simeq 1.2$ fm)



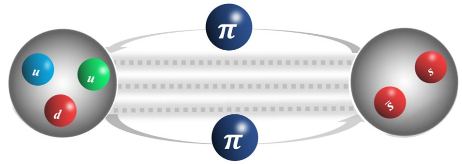






- The long-range potentials exhibit similar decreasing behavior→a common mechanism operates at long distances

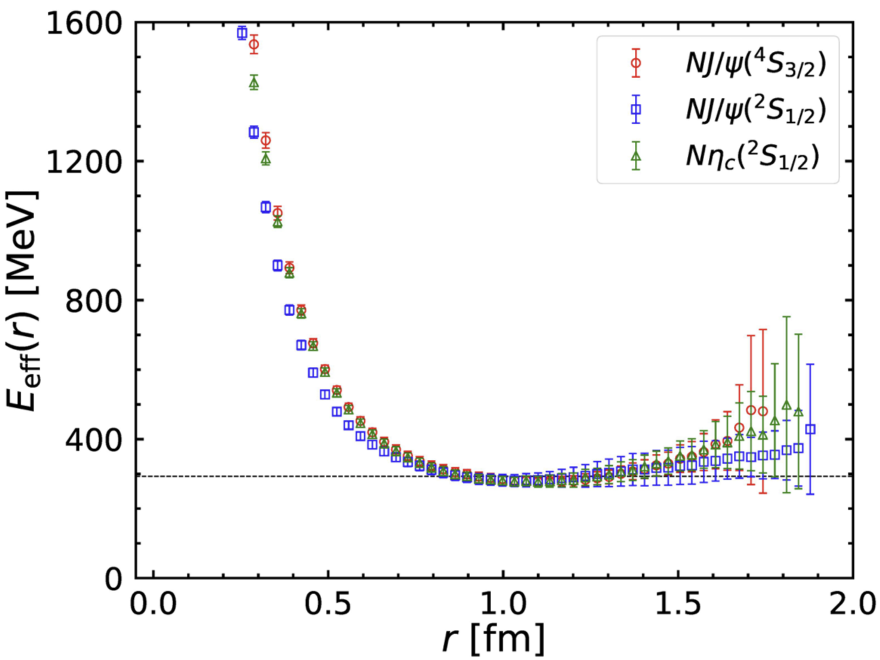
Two-pion-exchange tail



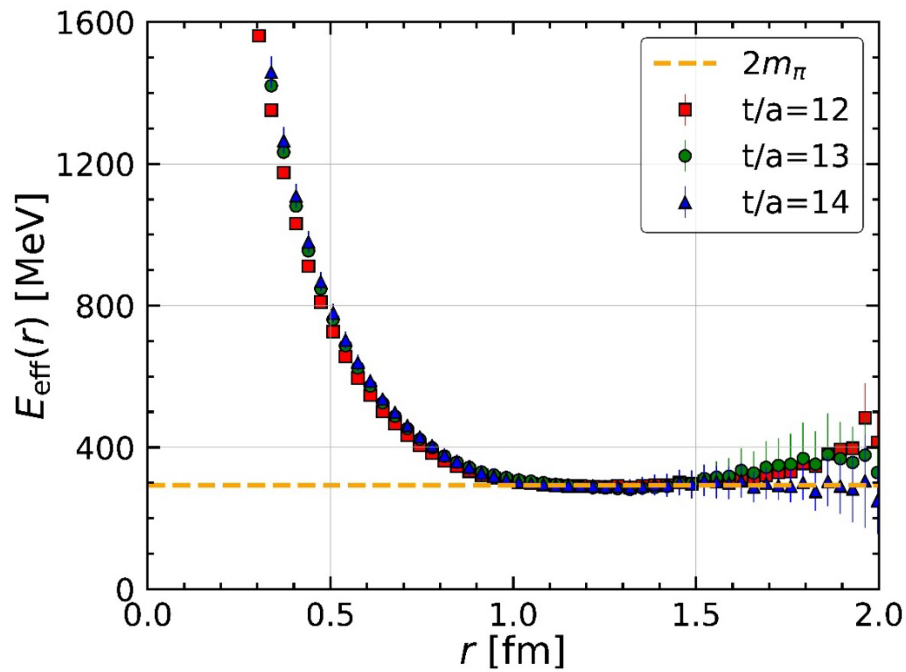
J. Castella and G. Krein, Phys. Rev. D **98**, 014029 (2018)
H. Fujii and D. Kharzeev, Phys. Rev. D **60**, 114039 (1999)
G. Bhanot and M. E. Peskin, Nucl. Phys. B **156**, 391(1979)

$$\boxed{V(r) = -\alpha \frac{e^{-2m_\pi r}}{r^2}} \Rightarrow \boxed{E_{\text{eff}}(r) = -\frac{\ln\left[-V(r)r^2/\alpha\right]}{r}}$$

- N-$c\bar{c}$



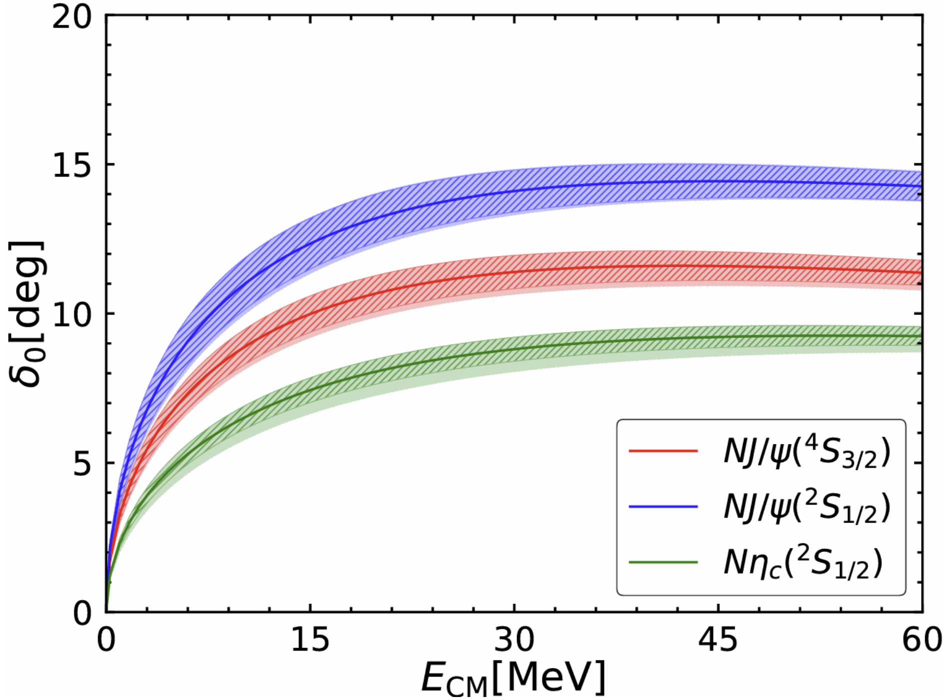
- N-ϕ



- long-range ($r > 1$ fm) potential is indeed dominated by the TPE
- nonperturbative gluon exchange manifests as TPE

Physical observables for N-$c\bar{c}$

- Scattering phase shifts



$$k \cot \delta_0 = \frac{1}{a_0} + \frac{1}{2} r_{\rm eff} k^2$$

channel	a_0 [fm]	$r_{\rm eff}$ [fm]
N-$J/\psi(^4S_{3/2})$	$0.30(2)\binom{+0}{-2}$	$3.25(12)\binom{+6}{-9}$
N-$J/\psi(^2S_{1/2})$	$0.38(4)\binom{+0}{-3}$	$2.66(21)\binom{+0}{-10}$
$N\eta_c(^2S_{1/2})$	$0.21(2)\binom{+0}{-1}$	$3.65(19)\binom{+0}{-6}$

- A direct phenomenological application
  - The J/ψ mass modification in nuclear medium is related to the spin-averaged scattering length of N-J/ψ scattering

A. Hayashigaki, Prog. Theor. Phys. 101 (1999)

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

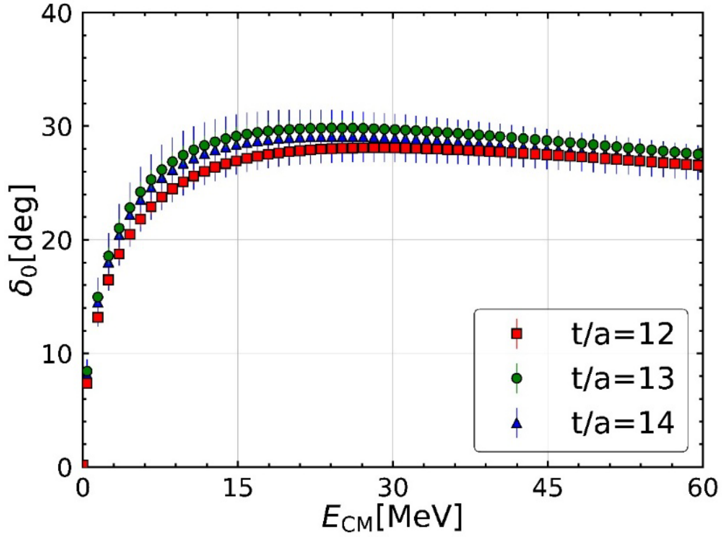
Comparison

- The spin averaged N-J/ψ scattering length

a [fm]	Year	Author	Method
0.046(5)	2016	Gryniuk-Gryniuk	Photoproduction (VMD)
$3\sim25\cdot10^{-3}$	2021	Pentchev-Strakovsky	Photoproduction (VMD)
$O(1)$	2023	JPAC	Photoproduction (unitarity)
0.05	1992	Kaidalov-Volkovitsky	QCD multipole expansion
0.24	1997	Brodsky-Miller	QCD multipole expansion
≥0.37	2005	Sibirtsev-Voloshin	QCD multipole expansion
0.10(2)	1999	Hayashigaki	QCD sum rule
$0.2\sim3\cdot10^{-3}$	2020	Du-Baru-Guo et. al.	Coupled channel
0.71(48)	2006	Yokokawa-Sasaki etal	LQCD (quenched)
0.1(7)	2008	Liu-Lin-Orginos	LQCD (full, extrapolate to phys. Pt.)
0.33(5)	2010	Kawanai-Sasaki	LQCD (quenched)
0.47(1)	2019	Sugiura-Ikeda-Ishii	LQCD ($m_\pi = 700$)
$\simeq 0$	2019	Skerbis-Prelovsek	LQCD ($m_\pi = 266$)
0.33(4)	**2024**	**The present work**	**LQCD ($m_\pi = 146$)**

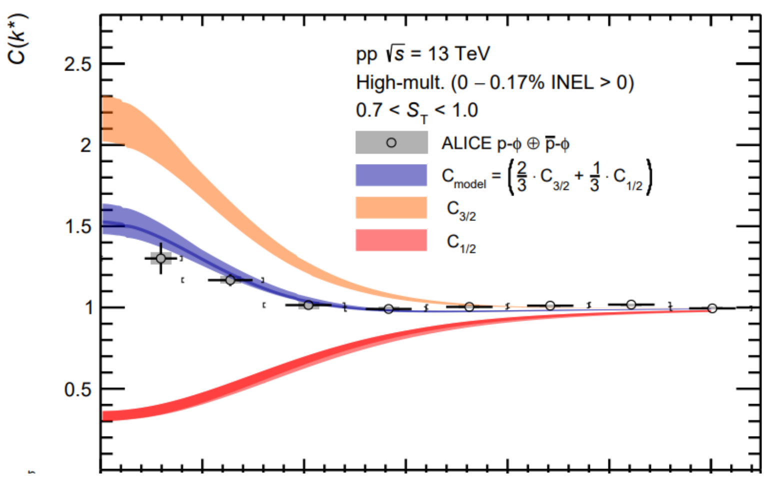
Physical observables for N-ϕ

- Scattering phase shifts in spin-3/2 channel



a_0 [fm]	r_{eff} [fm]
$1.43(23)(^{+06}_{-36})$	$2.36(10)(^{+02}_{-48})$

- "spin-1/2= spin-ave.(experiment) – spin-3/2 (lattice)"



$$\mathrm{Re}\ f_0^{(1/2)} = -1.47^{+0.44}_{-0.37}(\mathrm{stat.})^{+0.14}_{-0.17}(\mathrm{syst.})\ \mathrm{fm},$$

$$\mathrm{Im}\ f_0^{(1/2)} = \ \ 0.00^{+0.26}_{-0.00}(\mathrm{stat.})^{+0.15}_{-0.00}(\mathrm{syst.})\ \mathrm{fm},$$

$$\mathrm{Re}\ d_0^{(1/2)} = +0.37^{+0.07}_{-0.08}(\mathrm{stat.})^{+0.03}_{-0.03}(\mathrm{syst.})\ \mathrm{fm},$$

$$\mathrm{Im}\ d_0^{(1/2)} = \ \ 0.00^{+0.00}_{-0.02}(\mathrm{stat.})^{+0.00}_{-0.01}(\mathrm{syst.})\ \mathrm{fm}.$$

$$E_B = \frac{1}{2\mu d_0^2}\left(1 - 1\sqrt{1 + 2d_0/f_0}\right)^2 \simeq 13.6 - 92.0\ \mathrm{MeV}$$

Summary & Outlook

- **Summary:** we present a first realistic study of low-energy N-V meson (N-J/ψ and N-ϕ) interaction based on lattice QCD calculations near the physical point

  - The potential is found to be attractive at all distances
  - Long-range potential→consistent w/ TPE
  - Detailed analysis for near-threshold scattering properties

- **Outlook:**

  - The physical point simulations
  - The long-range potential for other hadron pairs