PEKING UNIVERSITY

The 38th International Symposium on Lattice Field Theory, July 26-30 2021, Zoom @ MIT

Most charming dibaryon near unitarity

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July 29(30), 2021

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Phys. Rev. Lett **xxx**, xxxxxx (2021) [arXiv:2102.00181]

Contents

QCD and baryon-baryon interaction

- QCD is a fundamental theory of strong interaction among quarks and gluons

  D. Gross and **F. Wilczek**, Phys. Rev. Lett. **30**, 1343 (1973)
  H. Politzer, Phys. Rev. Lett. **30**, 1346 (1973)

- Baryon-baryon interaction is the residual force of strong interaction

  E. Epelbaum, H.-W. Hammer and **Ulf-G. Meissner,** Rev. Mod. Phys. **81,** 1773 (2009)

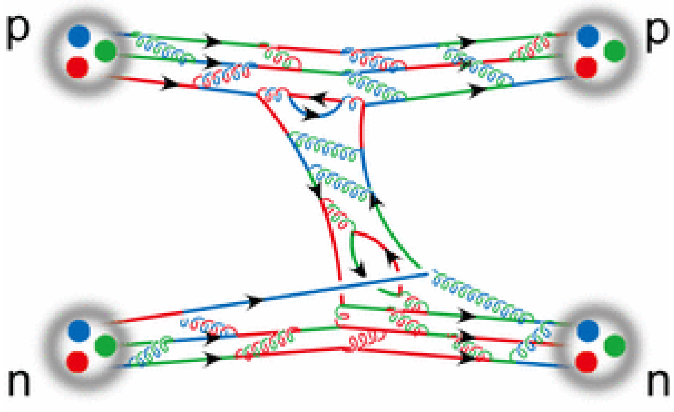
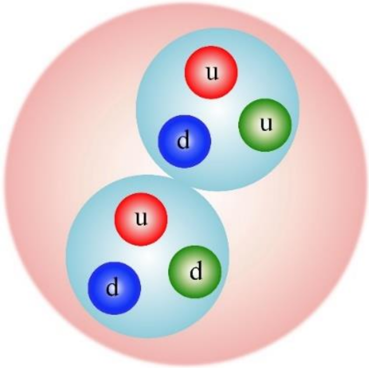


Figure from S. Aoki's lecture

- Baryon-baryon interaction is important in hadronic physics, nuclear physics and astrophysics
  - Exotic hadrons: dibaryon… **H. Clement**, Prog. Part. Nucl. Phys. **93**, 195 (2017)
  - Finite nuclei and neutron star **S. Shen *et al.***, Prog. Part. Nucl. Phys. **109,** 103713 (2019)

Dibaryon

- Dibaryon is defined as a baryon number $B = 2$ system
  - complex quark configuration than qqq and $q\bar{q}$
  - deuteron (bound state of proton and neutron)



H. Clement, Prog. Part. Nucl. Phys. **93**, 195 (2017)

- In the light quark (u, d, s) sector, other possible dibaryons were predicted by lattice QCD (LQCD) simulations near the physical point
  - $p\Omega$ $(uudsss)$ — **T. Iritani *et al.*** (HAL QCD Collaboration**),** Phys. Lett. B **792,** 284 (2019)
  - $\Omega\Omega$ $(ssssss)$ — **S. Gongyo *et al.*** (HAL QCD Collaboration**),** Phys. Rev. Lett. **120**, 212001 (2018)

- The study of dibaryon with heavy quark, e.g. charm quark, is at the forefront of hadronic physics

A. Ali *et al.*, Prog. Part. Nucl. Phys. **97**, 123 (2017)
H. Clement, Prog. Part. Nucl. Phys. **93**, 195 (2017)

Charmed baryonic system

- Experimental and theoretical studies
  - Ω_{ccc}: perturbative and nonperturbative QCD — **J. Bjorken**, AIP Conf. Proc. **132**, 390 (1985)
  - LHC: Ω_{c}, Ξ_{cc} — LHCb Collaboration, Phys. Rev. Lett. **119**, 112001 (2017); LHCb Collaboration, Phys. Rev. Lett. **118**, 182001 (2017)
  - LQCD : Ω_{ccc} — **K. Can *et. al.***, Phys. Rev. D **92**, 114515 (2015)
  - LQCD : $\Omega_{ccc}\Omega_{bbb}$ — **P. Junnarkar *et al.***, Phys. Rev. Lett. **123**, 162003 (2019)
  - Quark model: $\Omega_{ccc}\Omega_{ccc}$ — **H. X. Huang *et al.***, arXiv. 2011, 00513 (2020)

In this work

- Most charming dibaryon, $\Omega_{ccc}\Omega_{ccc}$ as the simplest possible heavy system, is investigated for the first time from a LQCD approach
  - Potential in the $^1S_0$ channel
  - Phase shift, scattering length and the effective range
  - Unitary limit

Apply HAL QCD method to $\Omega_{ccc}\Omega_{ccc}$

- The reduced 4-point function $R(\boldsymbol{r},t)$

$$R(\boldsymbol{r},t) = \langle 0|\Omega_{ccc}(\boldsymbol{r},t)\Omega_{ccc}(\boldsymbol{0},t)\overline{\mathcal{J}}(0)|0\rangle / e^{-2M_{\Omega_{ccc}}t}$$
$$\Omega_{ccc}(x) = \varepsilon^{c_1c_2c_3}[c^T_{c_1}(x)\mathcal{C}\gamma_k c_{c_2}(x)]c_{c_3}(x)$$

  - $\bar{\mathcal{J}}(0)$ is a source operator creating $(B,C)=(2,6)$ system , $M_{\Omega_{ccc}}$ is the mass

- $R(\boldsymbol{r},t)$ satisfies following equation

$$\left(\frac{\nabla^2}{M_{\Omega_{ccc}}} - \frac{\partial}{\partial t} + \frac{1}{4M_{\Omega_{ccc}}}\frac{\partial^2}{\partial t^2}\right)R(\boldsymbol{r},t) = \int d\boldsymbol{r}' U(\boldsymbol{r},\boldsymbol{r}')R(\boldsymbol{r}',t)$$

  - $t > \Lambda^{-1}_{\text{QCD}} \sim 0.7$ fm: elastic state saturation instead of ground state saturation

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

- At low energies, derivative expansion $U(\boldsymbol{r},\boldsymbol{r}') \cong V(r)\delta(\boldsymbol{r}-\boldsymbol{r}')$

$$V(r) = R^{-1}(\boldsymbol{r},t)\left(\frac{\nabla^2}{M_{\Omega_{ccc}}} - \frac{\partial}{\partial t} + \frac{1}{4M_{\Omega_{ccc}}}\frac{\partial^2}{\partial t^2}\right)R(\boldsymbol{r},t)$$

Lattice setup

- (2+1)-flavor configuration near the physical point
  - Iwasaki gauge action and $O(a)$-improved Wilson quark action

$L \times T$	a [fm]	La [fm]	m_π [MeV]	m_K [MeV]
$96^3 \times 96$	0.0846(7)	8.1	146	525

K.-I. Ishikawa, *et al.* (PACS Collaboration), *Proc. Sci.*, LATTICE2015 (2016) 075

- Relativistic heavy quark (RHQ) action for charm quark
  - Remove the leading order and the next-to-leading order cutoff errors

	$(m_{\eta_c} + 3m_{J/\Psi})/4$ [MeV]	$m_{\Omega_{ccc}}$ [MeV]
set 1	3096.6(0.3)	4837.3(0.7)
set 2	3051.4(0.3)	4770.2(0.7)
Interpolation	3068.5(0.3)	4795.6(0.7)
Exp.	3068.5(0.1)	-

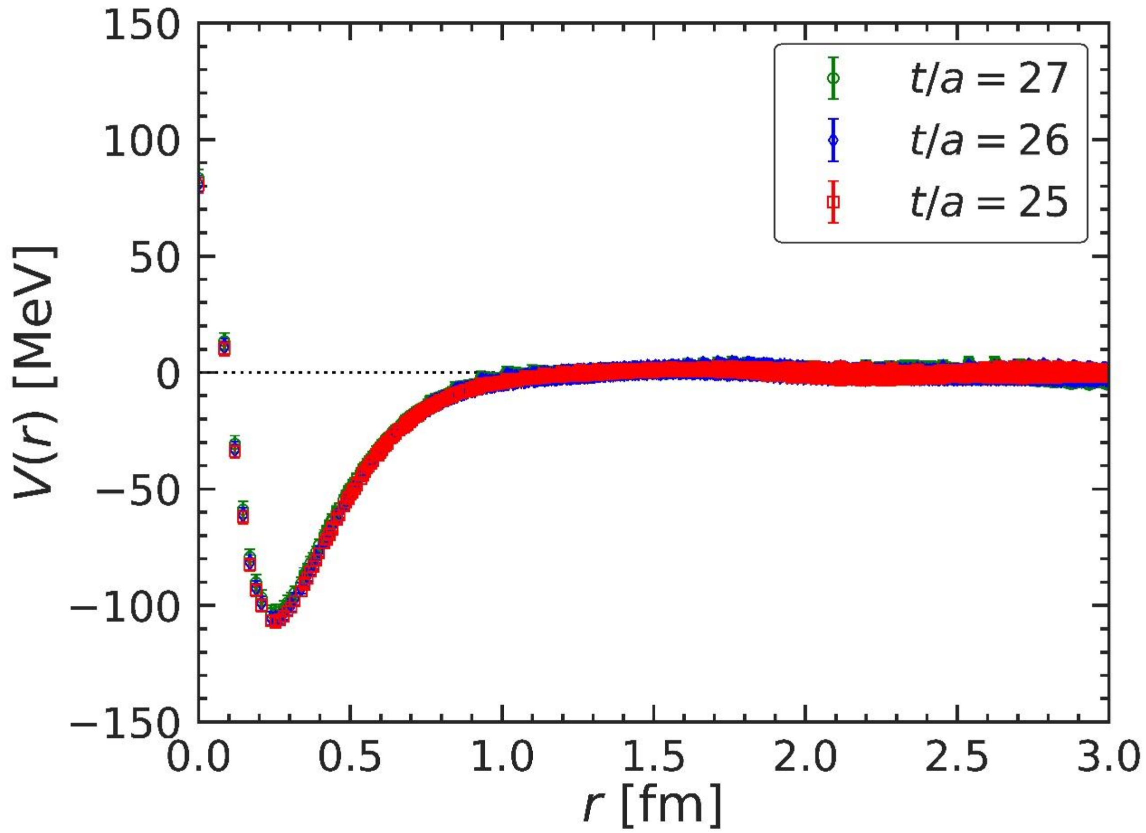
S. Aoki *et al.*, Prog. Theo. Phys. **109**, 383 (2003)
Y. Namekawa *et al.* (PACS Collaboration), *Proc. Sci.*, LATTICE2016 125 (2017)

- Statistics

$$112_{\text{conf.}} \times 4_{\text{src}} \times 2_{\text{b.f.}} = 896$$

Potential from LQCD

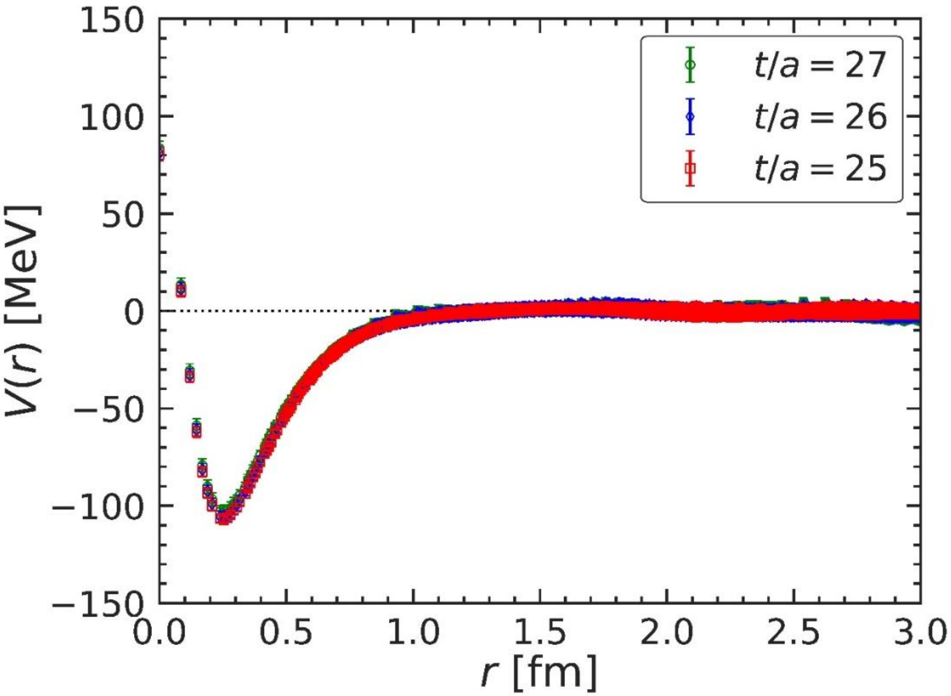
- $\Omega_{ccc}\Omega_{ccc}$ potential in $^1S_0$ channel at $t/a = 25,26,27$ ($t \simeq 2.2$ fm)

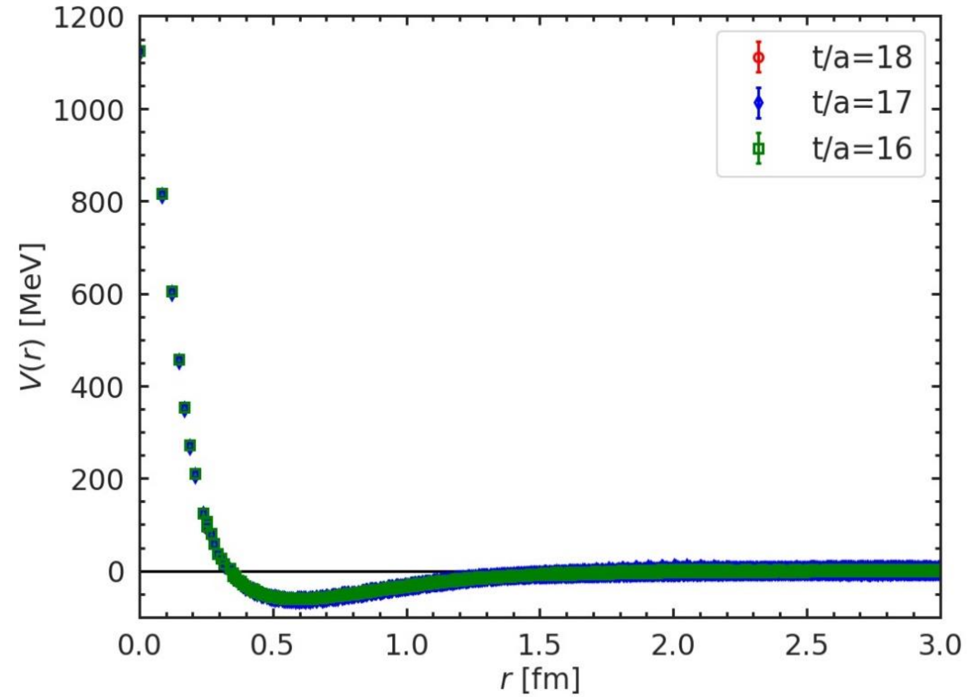


The short range repulsion is surrounded by an attractive well

$\Omega_{ccc}\Omega_{ccc}$ v.s. $\Omega_{sss}\Omega_{sss}$

- $\Omega_{ccc}\Omega_{ccc}$ potential in ${}^1S_0$ channel
- $\Omega_{sss}\Omega_{sss}$ potential in ${}^1S_0$ channel



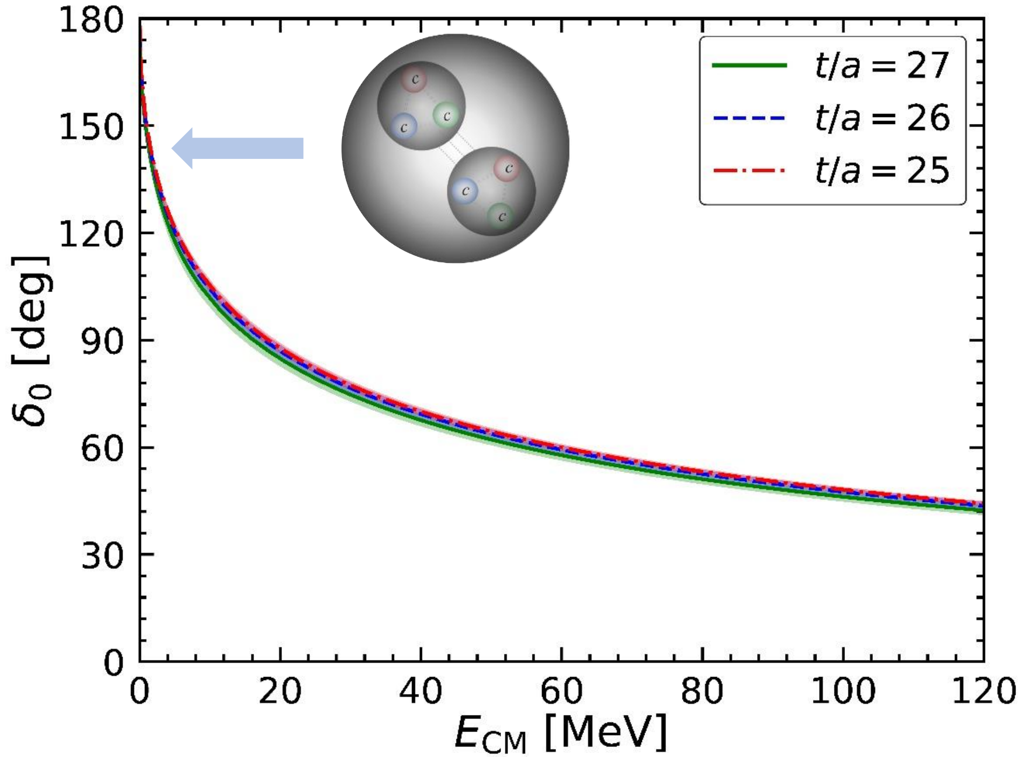


S. Gongyo *et al.* (HAL QCD Collaboration)**,** Phys. Rev. Lett. **120**, 212001 (2018)

- ☐ Magnitude of repulsion: $V^c_{\rm cm}/V^s_{\rm cm} = (m_s/m_c)^2 \sim (500/1500)^2 \sim 0.1$
- ☐ Range of attraction: absence of light-meson exchange

Physical observables

- The phase shift $\delta_0(k)$ in $^1S_0$ channel as function of kinetic energy



- Scattering parameters, binding energy and root-mean-square distance

$$a_0 = 1.57(8)_{\text{sta.}} \left(^{+12}_{-4}\right)_{\text{sys.}} \text{ fm}, \qquad r_{\text{eff}} = 0.57(2)_{\text{sta.}} \left(^{+1}_{-0}\right)_{\text{sys.}} \text{ fm}$$

$$B = 5.68(77)_{\text{sta.}} \left(^{+46}_{-102}\right)_{\text{sys.}} \text{ MeV}, \qquad \sqrt{\langle r^2 \rangle} = 1.13(6)_{\text{sta.}} \left(^{+8}_{-3}\right)_{\text{sys.}} \text{ fm}$$

Coulomb repulsion

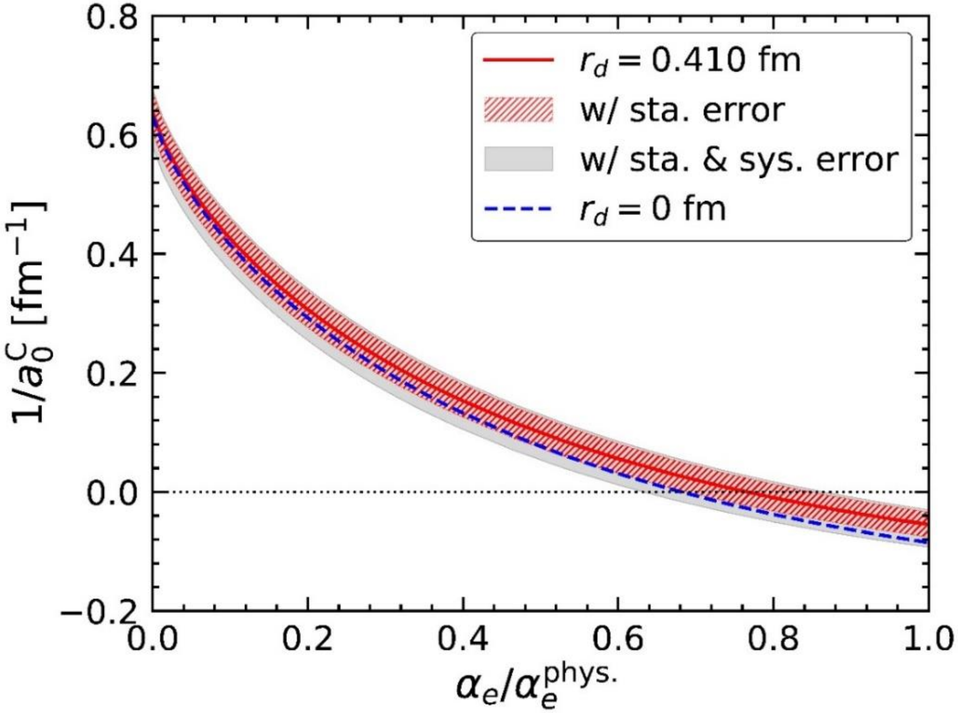
- QCD + Coulomb

$$V^{\mathrm{QCD}} \to V^{\mathrm{QCD}} + V^{\mathrm{Coulomb}}, \quad V^{\mathrm{Coulomb}} = \frac{4\alpha_e}{r} F(r)$$

  - $F(r)$ represents effects of charge distribution of Ω_{ccc}^{++}

K. Can *et. al.*, Phys. Rev. D **92**, 114515 (2015)

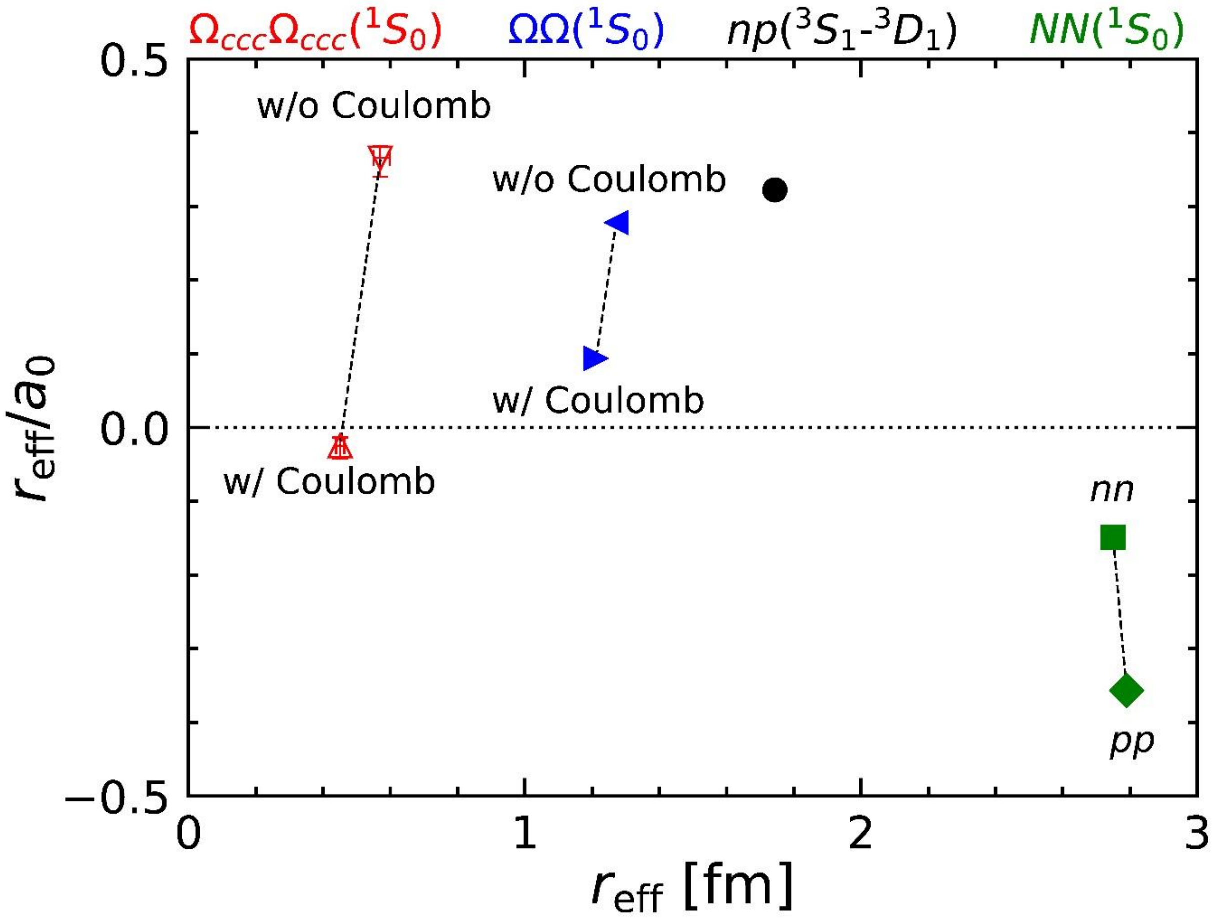
- The inverse of the scattering length $1/a_0^{\mathrm{C}}$ as a function of α_e



$$a_0^{\mathrm{C}} = -19(7)_{\mathrm{sta.}} \left(^{+7}_{-6}\right)_{\mathrm{sys.}} \mathrm{fm}, \quad r_{\mathrm{eff}}^{\mathrm{C}} = 0.45(1)_{\mathrm{sta.}} \left(^{+1}_{-0}\right)_{\mathrm{sys.}} \mathrm{fm}$$

Unitary limit ($r_{\rm eff}/a_0 = 0$)

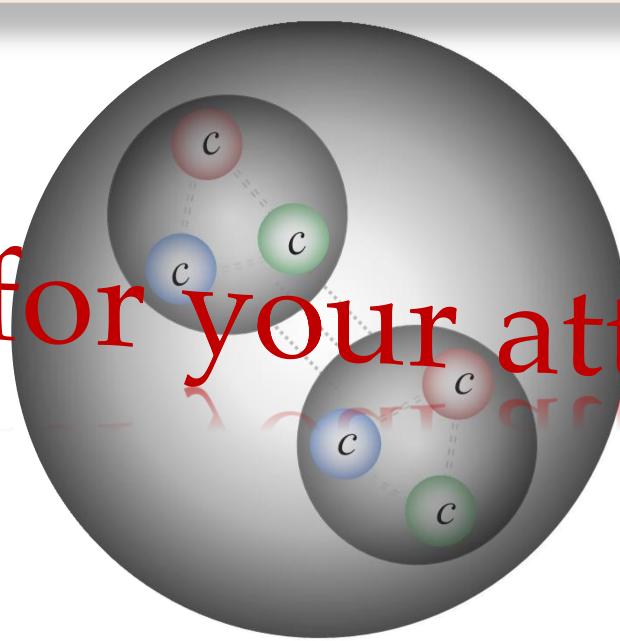
- The dimensionless ratio $r_{\rm eff}/a_0$ as a function of $r_{\rm eff}$.



$\Omega_{ccc}^{++}\Omega_{ccc}^{++}(\,^1S_0)$ with $\frac{r_{\rm eff}}{a_0} = -0.024(10)(^{+6}_{-14})$ is the closet to the unitary limit

Summary and outlook

- **Summary:** $\Omega_{ccc}\Omega_{ccc}$ is studied from LQCD for the first time
  - Potential: repulsion and attractive well
  - Attraction and repulsion: loosely bound state
  - QCD and Coulomb: unitary region
- **Outlook:**
  - $\Omega_{bbb}\Omega_{bbb}$ quark mass dependence of scattering parameters
  - Channels relevant to exotic states w/ charm: $J/\Psi\, p, J/\Psi\, J/\Psi$



Thanks for your attention !