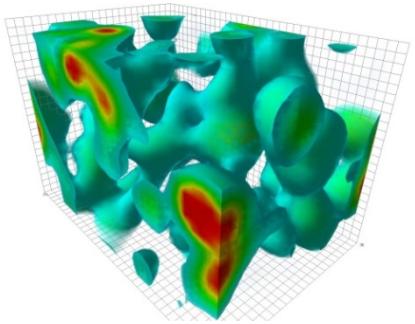
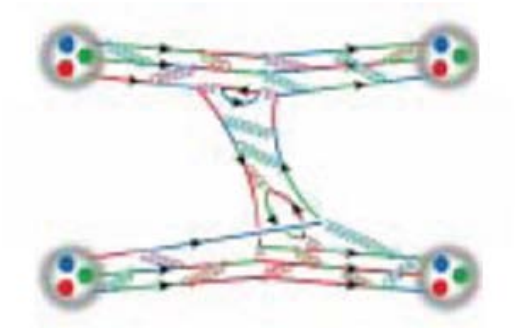
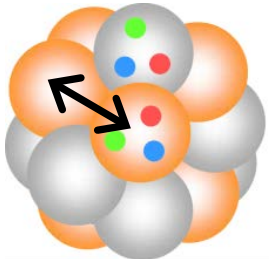
Recent Lattice QCD results of hadron interactions from the HAL QCD method

Takumi Doi

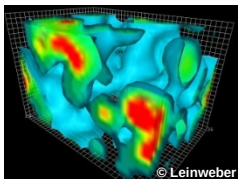
(RIKEN iTHEMS)

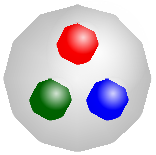


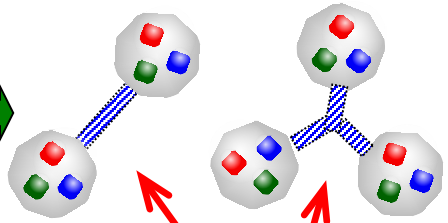


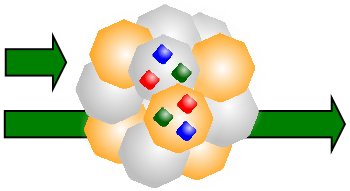


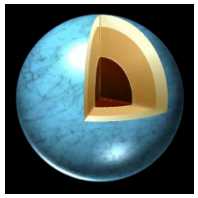
The Odyssey from Quarks to Universe

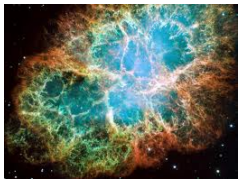












QCD vacuum Baryons Nuclei Neutron Stars / Supernovae Nucleosynthesis

QCD

1st-principle Lattice QCD

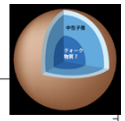
Hadron Forces

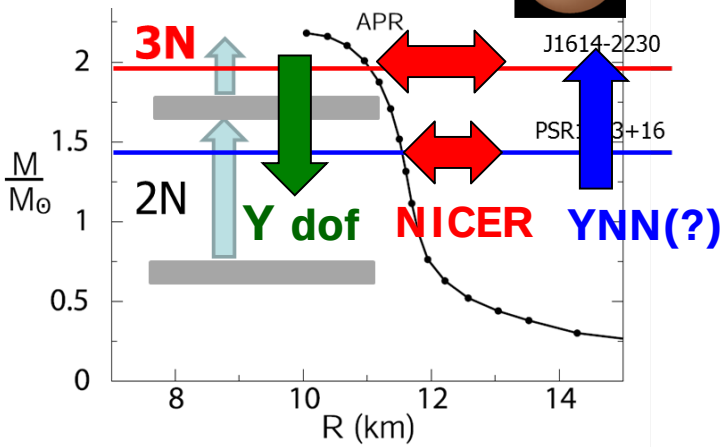
ab-initio nuclear calc.

J-PARC

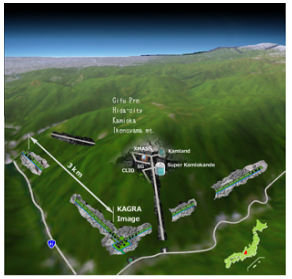
LHC/RHIC

EoS of Dense Matter

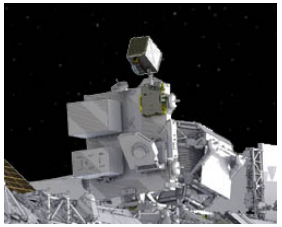




RIBF/FRIB



aLIGO/KAGRA



NICER

Nuclear/Hyperon Forces ➔ Charmed Forces

light ~ a few MeV ~100 MeV ~300 MeV ~1.3 GeV ~4.2 GeV **heavy**

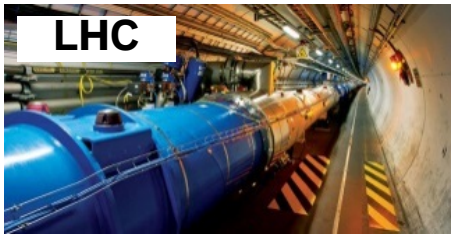
up,down quarks | strange quark | Λ_{QCD} | charm quark | bottom quark | top

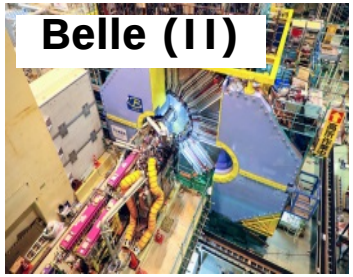
chiral symmetry

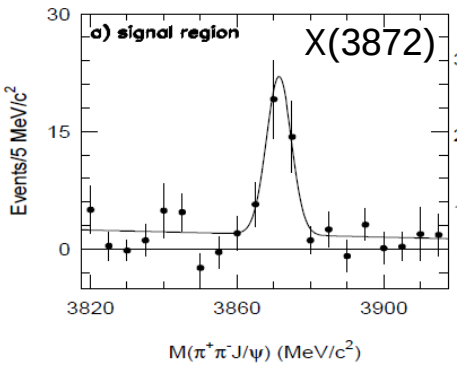
heavy quark symmetry

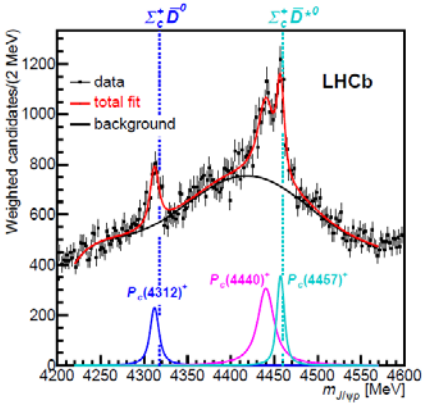
Heavy quarks: New doorway to the mysteries of QCD

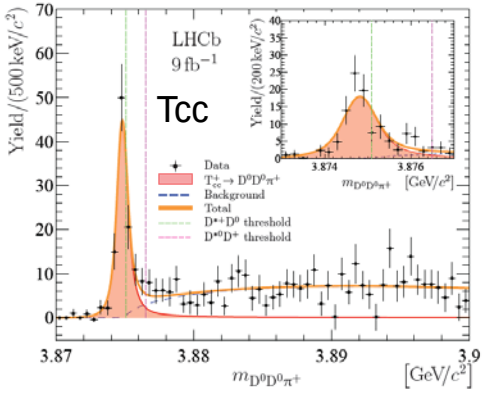
Many new exotic particles being reported!









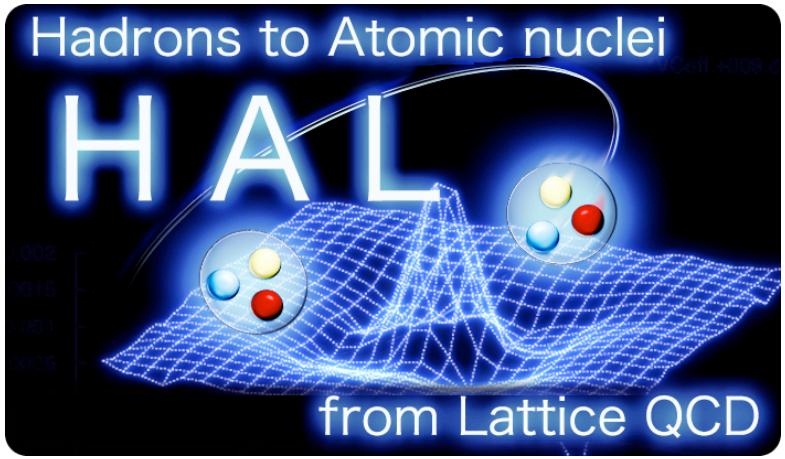


Hadron interactions crucial to understand these “signals” !

e.g., Zc(3900) from HAL LQCD → threshold cusp

Y. Ikeda et al. (HAL), PRL117(2016)242001

Hadrons to Atomic nuclei from Lattice QCD (HAL QCD Collaboration)



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

「20XX年宇宙の旅」

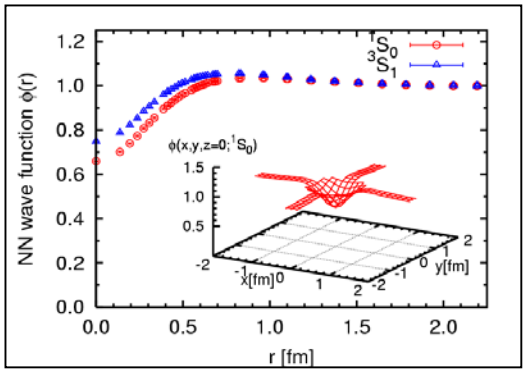
from Quarks to Universe

+
I. Kanamori (RIKEN)
K.-I. Ishikawa (Hiroshima U.)
M. Harada (Nagoya U.)
T. Hyodo (Tokyo Metropolitan U.)
and many more

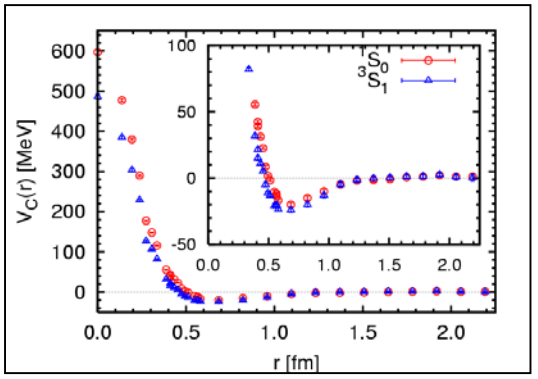
HAL QCD method

Lattice QCD

NBS wave func.



Lat Hadron Force



$$\psi_{NBS}(\vec{r}) = \langle 0|N(\vec{r})N(\vec{0})|N(\vec{k})N(-\vec{k}),in\rangle \simeq A_k \sin(kr - l\pi/2 + \delta_l(k))/(kr)$$

$$\left(k^2/m_N - H_0\right)\psi(\vec{r}) = \int d\vec{r}' U(\vec{r},\vec{r}')\psi(\vec{r}')$$

- **E-indep potentail from NBS w.f.** — Aoki-Hatsuda-Ishii PTP123(2010)89
  - **Faithful to Phase Shifts by construction** — (non-locality: derivative expansion)
- **Time-dependent HAL method** — N.Ishii et al. (HAL Coll.) PLB712(2012)437
  - **G.S. saturation NOT required** — "Signal" from (elastic) excited states
- **Coupled Channel formalism** — S. Aoki et al. (HAL Coll.) Proc.Jpn.Acad.B87(2011)509
  - **Above inelastic threshold** ➔ Essential for **YN/YY-forces, Exotics**

Challenge toward LQCD w/ physical mass

~2012

➔lighter u,d-quark masses
(=lighter pion mass Mπ)

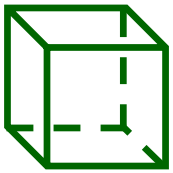
~2018

We were here

➔ more challenging

Phys. point

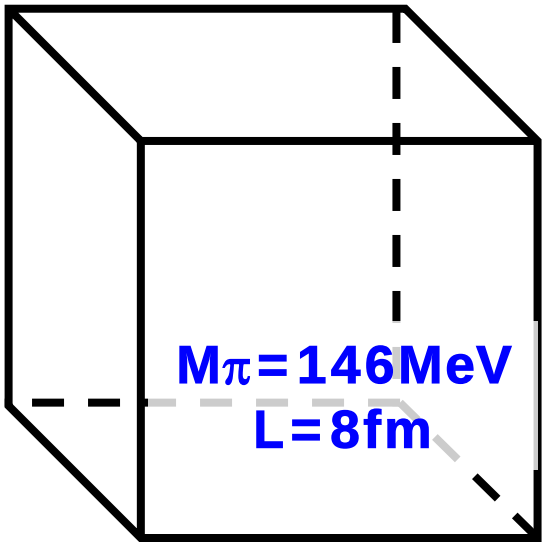
Mπ=400MeV
L=3fm



Simulation w/
Unrealistic mass

Theoretical development
+
New supercomputer

K-computer (11PFlops)



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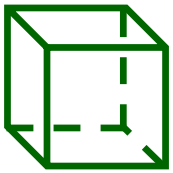
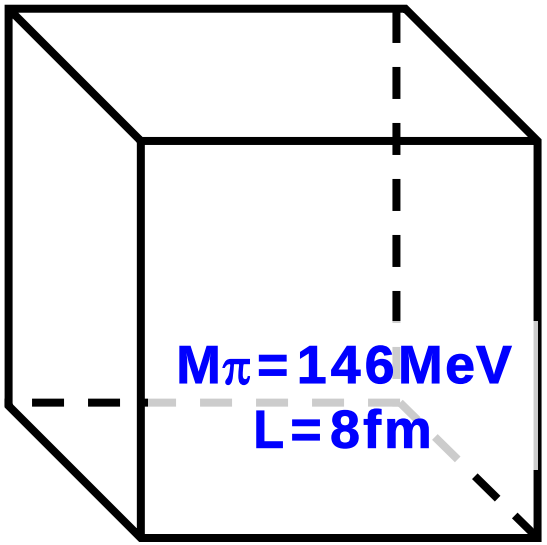


Simulation w/
Unrealistic mass

Theoretical development
+
New supercomputer

Fugaku (440PFlops)

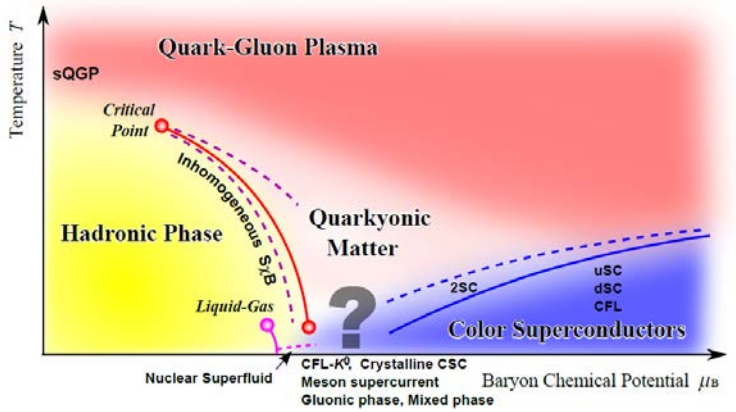


Simulation w/
~Near physical mass

Nϕ system

Medium effects on hadron properties

←→ partial restoration
of chiral symmetry

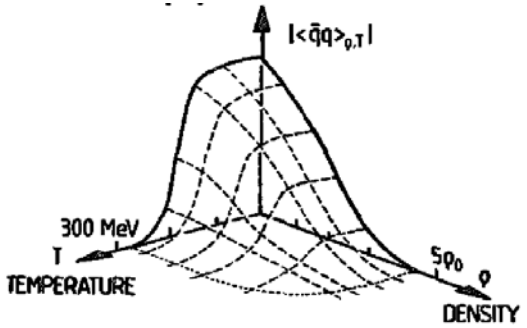


Hayano-Hatsuda, ReV. Mod. Phys. 82 (2010) 2949

Fukushima-Hatsuda, RPP74(2011)014001

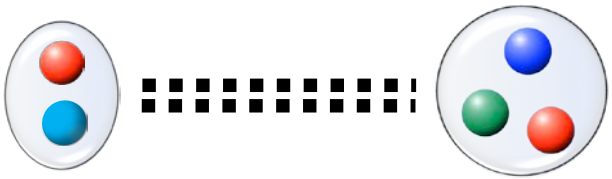
ϕ-meson is one of the ideal probes

Brown-Rho, RRL66(1991)2720
Hatsuda-Lee, PRC46(1992)R34
Gubler-Weise, NPA954(2016)125)



Weise, NPA553(1993)59

How color-dipole interacts w/ other hadrons?



2-pion-exchange?

Dipole-Dipole int: H. Fujii and D. Kharzeev, PRD60(1999)114039
Dipole-Nucleon int: J. Castella and G. Krein, PRD98(2018)014029

Nϕ system

Nϕ interaction (J=3/2,1/2)

$a_0^{\text{spin-ave}}$ [fm] (Re-part)

Theor.	Koike+	−0.15(02)
	Klingl+	+0.01
Expt.	CLAS	±0.063(010)
	ALICE	−0.85(34)(14) (r_{eff}=7.85(1.54)(0.26) fm)

Y. Koike+, PTP98(1997)631
F. Klingl+, NPA624(1997)527
I.I. Strakovsky+, PRC102(2020)045201
ALICE Coll., PRL127(2021)172301

Nϕ interaction from LQCD

ΛK, ΣK thresholds are open
Coupled channel calc expensive

Nϕ : 1958 MeV
ΛK : 1612 MeV
ΣK : 1689 MeV

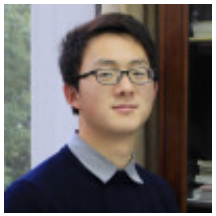
J=3/2 : ΛK, ΣK suppressed by D-wave

J=1/2 : ΛK, ΣK S-wave mixing, no suppression

(3-body decay modes,
ϕ–decay modes neglected)

→ We calculate Nϕ (J=3/2) w/ single-channel approximation

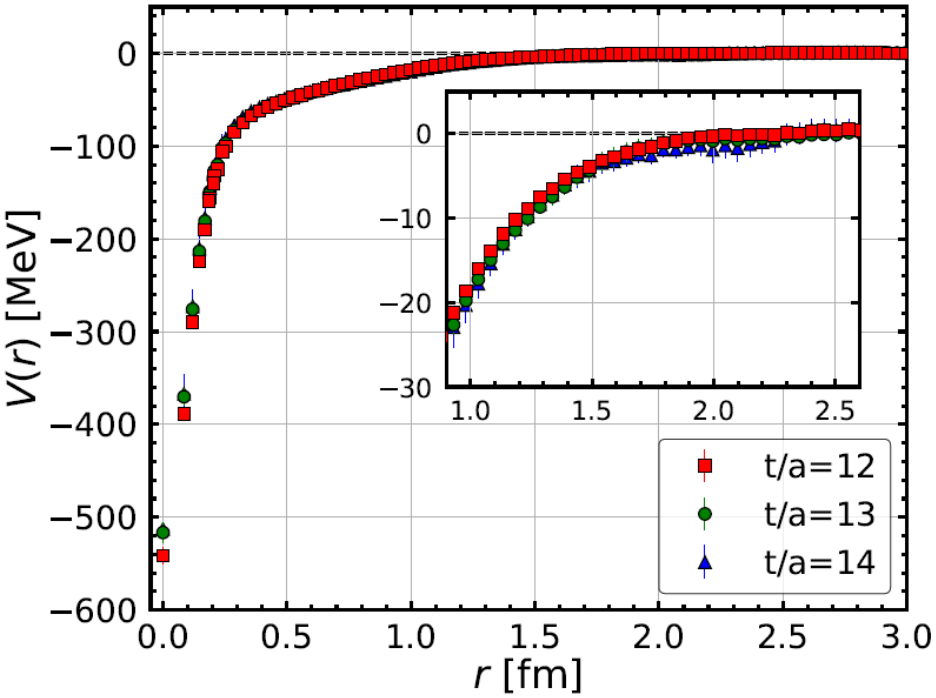
Y. Lyu et al., PRD106(2022)074507

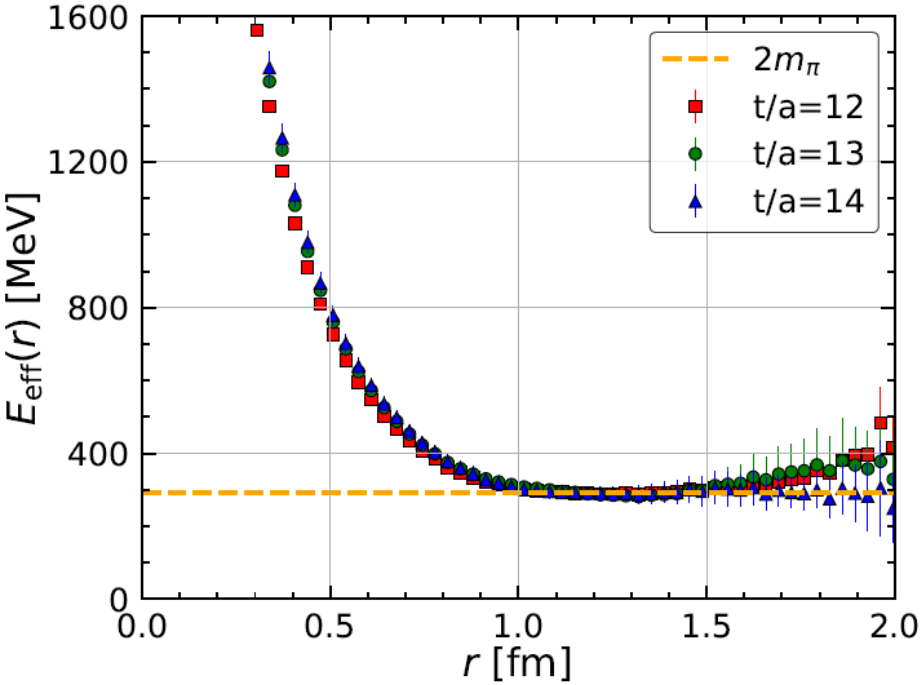


Y. Lyu

Nϕ system ($^4S_{3/2}$)

Potential ⇨ Tail structure of potential





$$V(r) \xrightarrow{r\to\infty} -\alpha\frac{e^{-2m_\pi r}}{r^2} \quad \Longrightarrow \quad E_{\rm eff}(r) = -\frac{\ln\left[-V(r)r^2/\alpha\right]}{r} \xrightarrow{r\to\infty} 2m_\pi$$

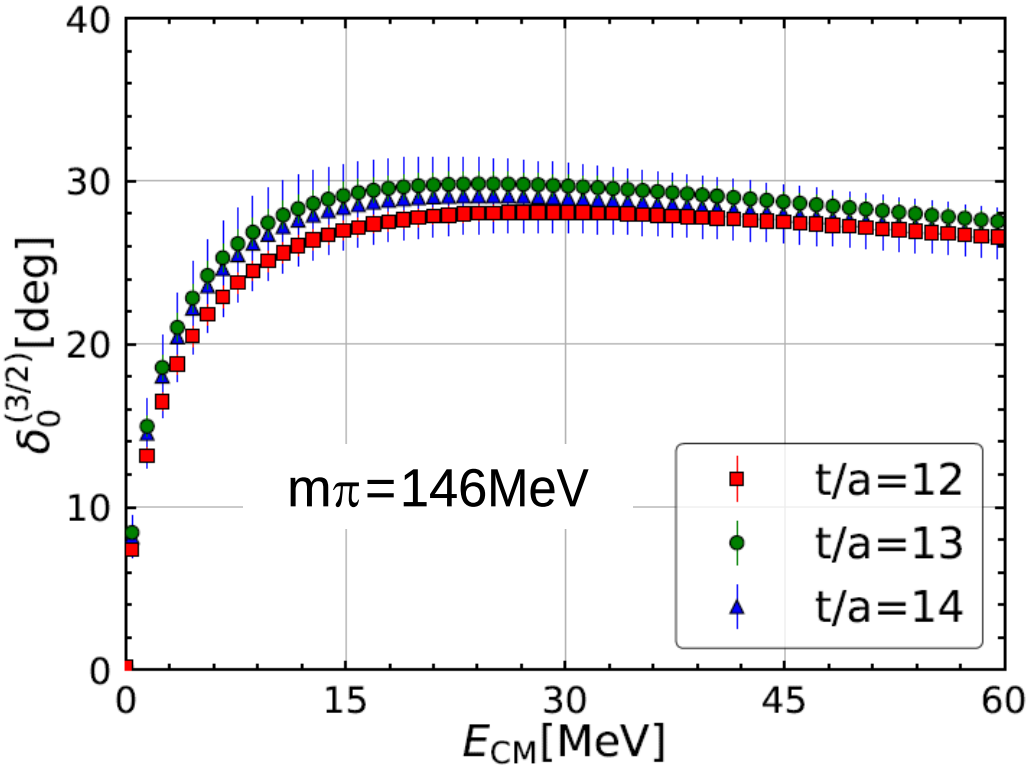
Potential is attractive at all distances

Tail is consistent w/ two-pion exchange (TPE) !

Y. Lyu et al., PRD106(2022)074507

c.f. H. Fujii and D. Kharzeev, Phys. Rev. D 60, 114039 (1999)
J. Castella and G. Krein, Phys. Rev. D 98, 014029 (2018)

Phase shifts of Nϕ ($^4S_{3/2}$)



Fit the potential and solve Schrodinger eq. in infinite V

$$V_{\rm fit}(r) = \sum_{i=1,2} a_i e^{-(r/b_i)^2} + a_3 m_\pi^4 f(r;b_3) \frac{e^{-2m_\pi r}}{r^2}$$

EFT by Castella-Krein

Fit w/ mπ = mπ(LQCD)

Semi-quantitative extrapolation by mπ → mπ(phys)

m_π [MeV]	$a_0^{(3/2)}$ [fm]	$r_{\rm eff}^{(3/2)}$ [fm]
146.4	$-1.43(23)_{\rm stat}(^{+36}_{-06})_{\rm syst}$	$2.36(10)_{\rm stat}(^{+02}_{-48})_{\rm syst}$
138.0	$\simeq -1.25$	$\simeq 2.49$

c.f. ALICE Coll. $a_0^{(\rm spin-ave)} = -0.85(34)(14)$ fm $r_{\rm eff}^{(\rm spin-ave)} = 7.85(1.54)(0.26)$ fm

New avenue for Hadron interactions by Combined analysis of LQCD & femtoscopy

Nϕ J=3/2 ← LQCD calc possible (ΛK, ΣK mixings suppressed by D-wave)

Nϕ J=1/2 ← LQCD challenging (ΛK, ΣK mixings are S-wave)

Nϕ spin average ← ALICE femtoscopy possible
(but spin projection difficult)

➔By combining LQCD and ALICE femtoscopy, we can extract Nϕ J=1/2

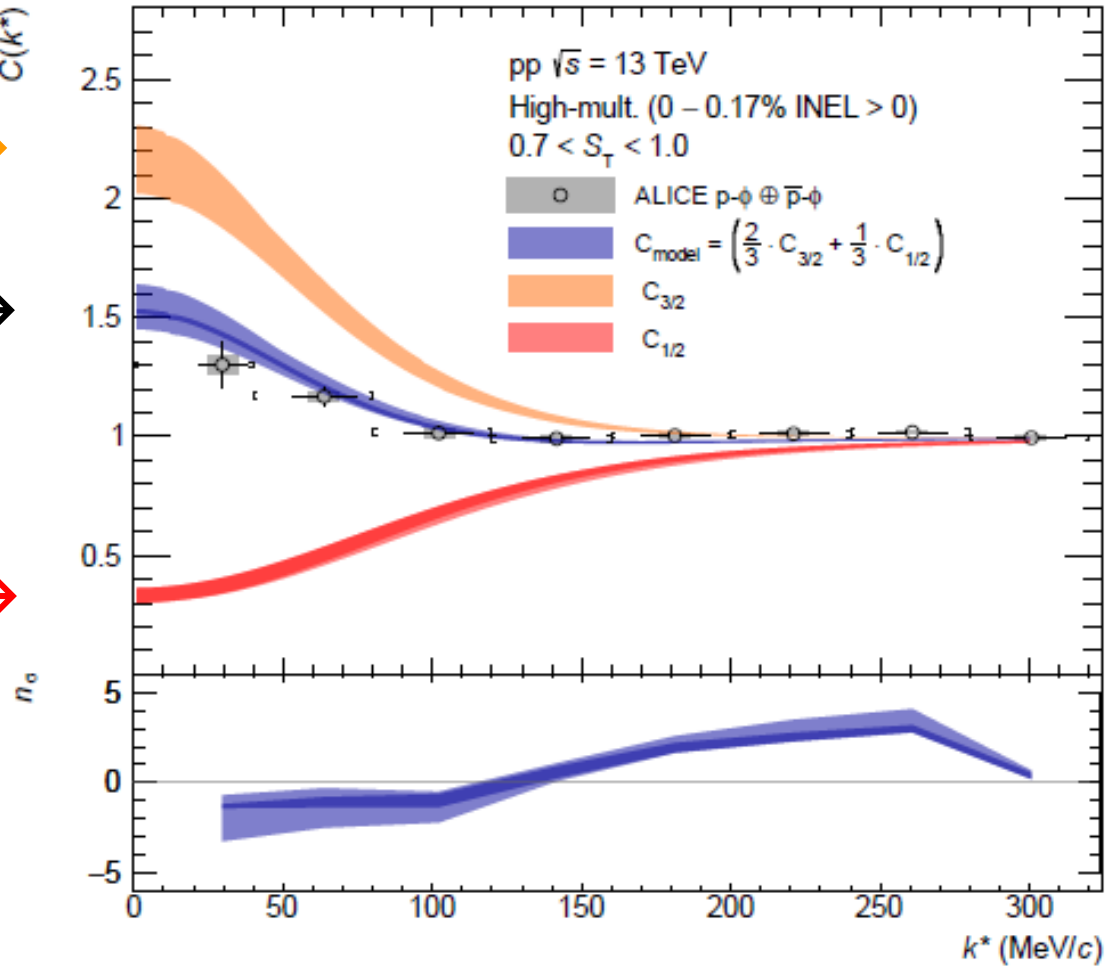
E. Chizzali+, PLB848(2024)138358

Nϕ system ($^2S_{1/2}$) from LQCD + Exp

J=3/2 → (LQCD)

J=ave → (Exp)

J=1/2 → (new!)

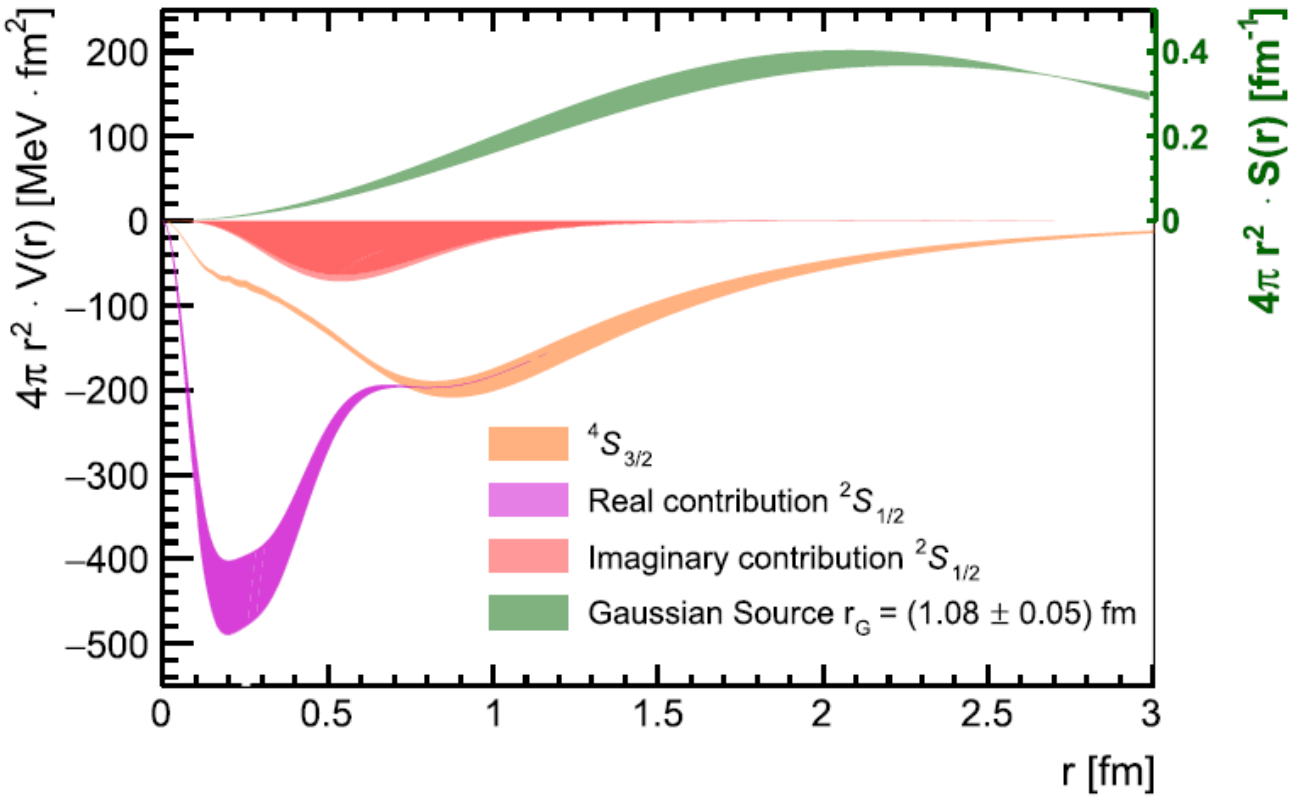


Correlation function measured by ALICE

Fit the femtoscopy data w/ parameters in potential in J=1/2

Nϕ system ($^2S_{1/2}$) from LQCD + Exp

Potential (w/ phase space factor of $4\pi r^2$)



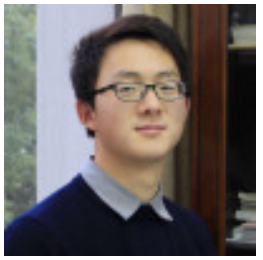
Indication of Nϕ bound state in J=1/2

B.E. = 12.8-56.1 MeV

$$\mathrm{Re}\ f_0^{(1/2)} = -1.54^{+0.53}_{-0.53}(\mathrm{stat.})^{+0.16}_{-0.09}(\mathrm{syst.})\ \mathrm{fm},$$
$$\mathrm{Im}\ f_0^{(1/2)} = \ 0.00^{+0.35}_{-0.00}(\mathrm{stat.})^{+0.16}_{-0.00}(\mathrm{syst.})\ \mathrm{fm},$$
$$\mathrm{Re}\ d_0^{(1/2)} = +0.39^{+0.09}_{-0.09}(\mathrm{stat.})^{+0.02}_{-0.03}(\mathrm{syst.})\ \mathrm{fm},$$
$$\mathrm{Im}\ d_0^{(1/2)} = \ 0.00^{+0.00}_{-0.04}(\mathrm{stat.})^{+0.00}_{-0.02}(\mathrm{syst.})\ \mathrm{fm}.$$

LQCD studies of Charming interactions

N J/Ψ system ($^2S_{1/2}$, $^4S_{3/2}$)

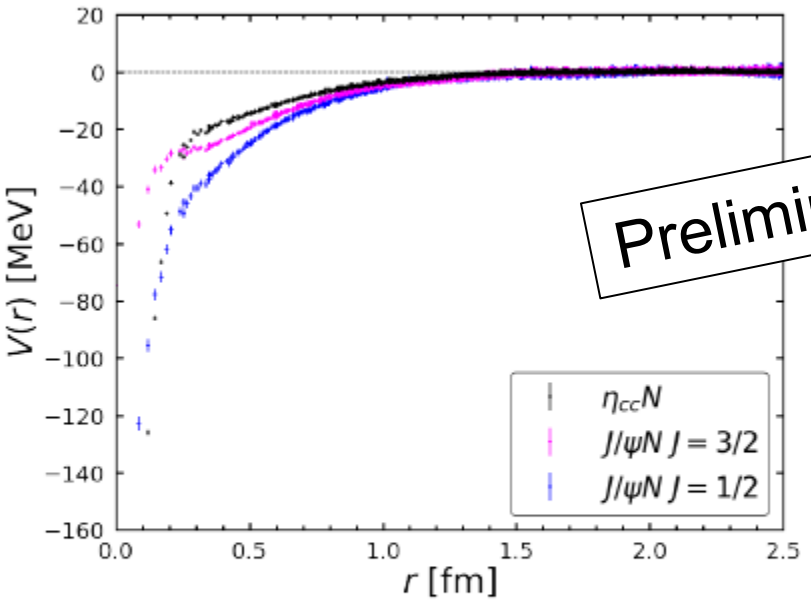


Y. Lyu

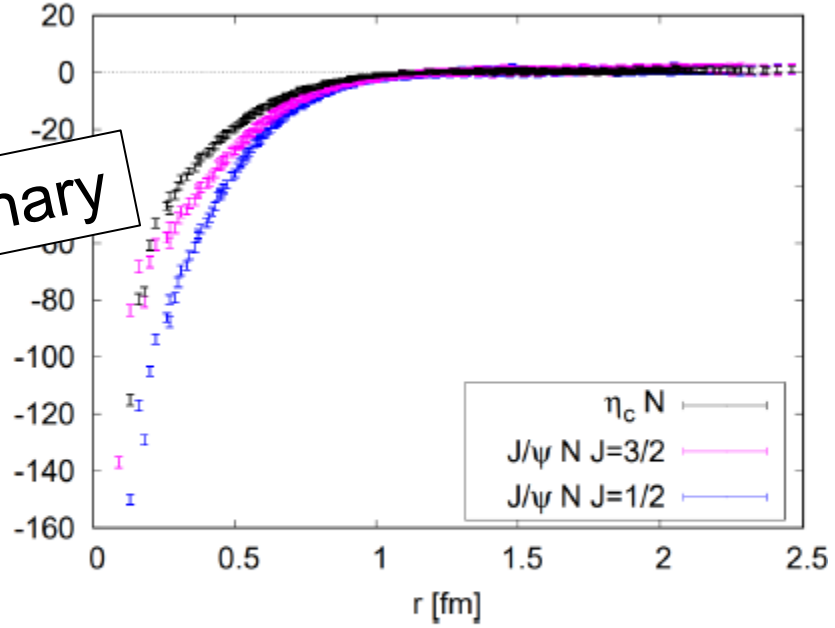
N-quarkonium systems and their light/heavy-quark mass dep

Relevant to Pc-pentaquark

- $m_\pi = 146$ MeV ($t = 15$ [a])



- $m_\pi = 700$ MeV ($t = 15$ [a])



Preliminary

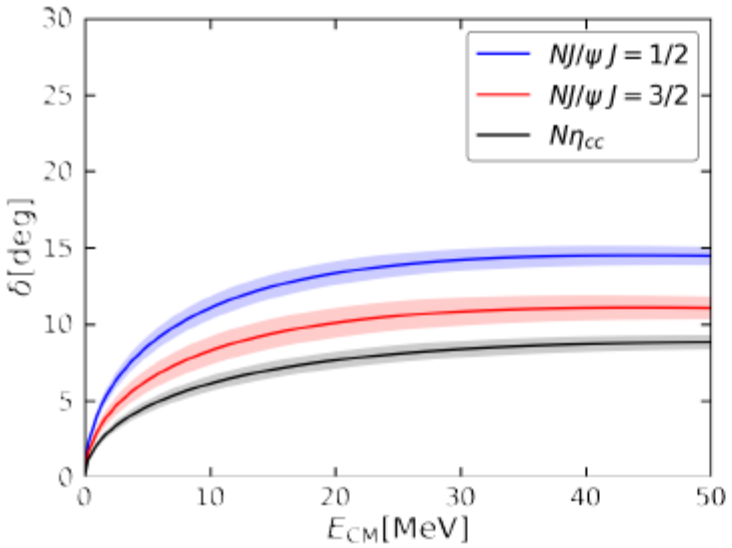
T. Sugiura, Y. Ikeda, and N. Ishii, *PoS* LATTICE2018 (2019) 093

- Similar, (slightly) less attraction at lighter m_π
- Caution: NJ/ψ with spin $1/2$ can couple with s-wave $N\eta_{cc}$

Light quark mass dependence

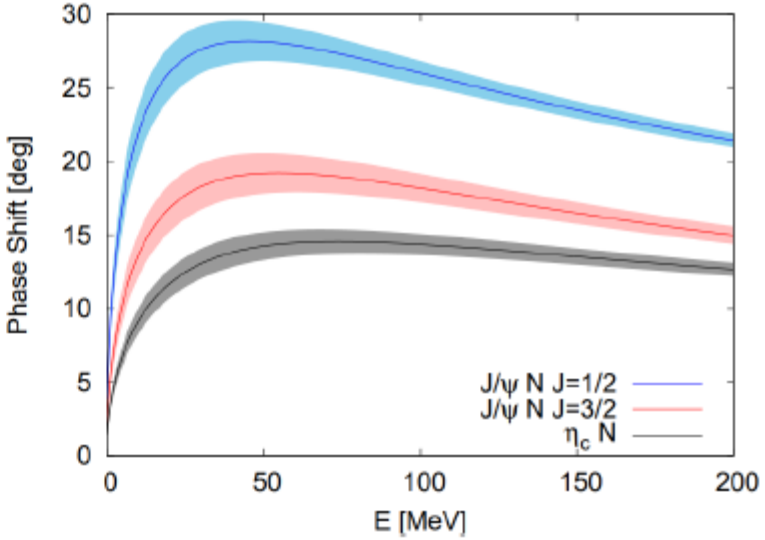
Preliminary

➢ $m_\pi = 146$ MeV ($t = 15$ [a])



channel	a_0 [fm]	r_{eff} [fm]
$NJ/\psi, J = 1/2$	0.38(3)	2.66(19)
$NJ/\psi, J = 3/2$	0.28(4)	3.25(12)
$N\eta_{cc}$	0.20(2)	3.72(17)

➢ $m_\pi = 700$ MeV ($t = 15$ [a])

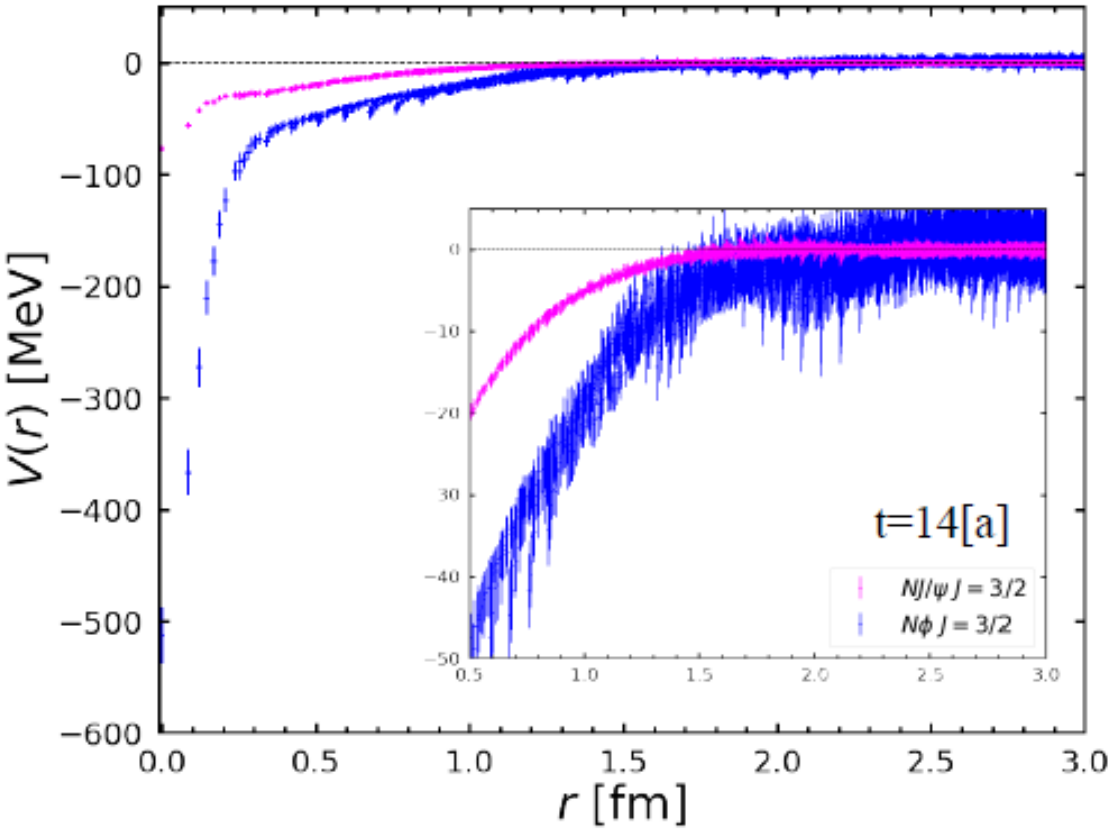


T. Sugiura, Y. Ikeda, and N. Ishii, *PoS* LATTICE2018 (2019) 093

channel	a[fm]	r[fm]
$J/\psi N, J = 1/2$	0.656 ± 0.071	1.105 ± 0.016
$J/\psi N, J = 3/2$	0.380 ± 0.048	1.476 ± 0.039
$\eta_c N$	0.246 ± 0.026	1.703 ± 0.045

- a_0 for NJ/ψ ($J = 1/2$) decreases at lighter m_π
- r_{eff} for all three channels increase a lot at lighter m_π

Heavy quark mass dependence (NJ/Ψ vs. Nϕ)



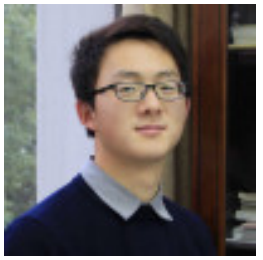
Preliminary

channel	a_0 [fm]	r_{eff} [fm]
$N\phi, J = 3/2$	1.43(23)	2.36(10)
$NJ/\psi, J = 3/2$	0.28(4)	3.25(12)

- NJ/ψ is less attractive than $N\phi$

Exotic tetraquark T_{cc}^{+} $(cc\bar{u}\bar{d})$ from Lattice QCD

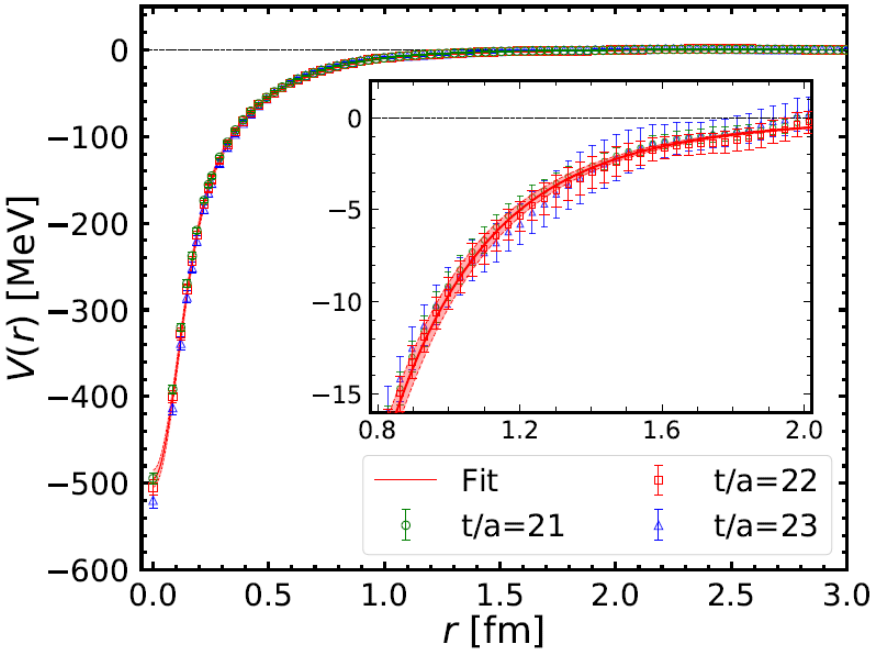
Y. Lyu, et al., PRL131(2023)161901 (Editor's suggestion)



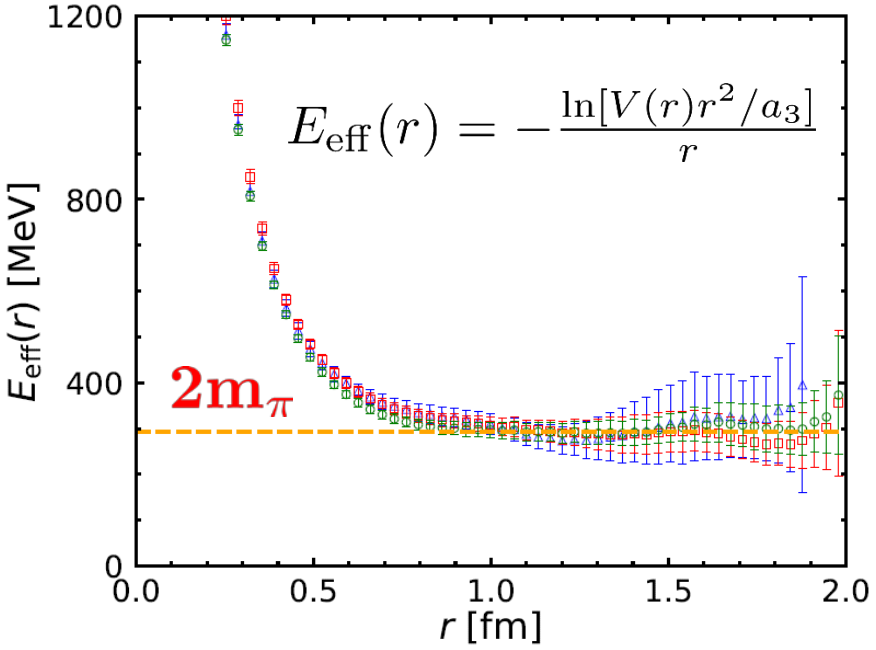
Y. Lyu

- LQCD calc of D-D* (I=0, $J^P=1^+$) interactions at $m\pi$=146MeV

Potential



Tail structure of Potential



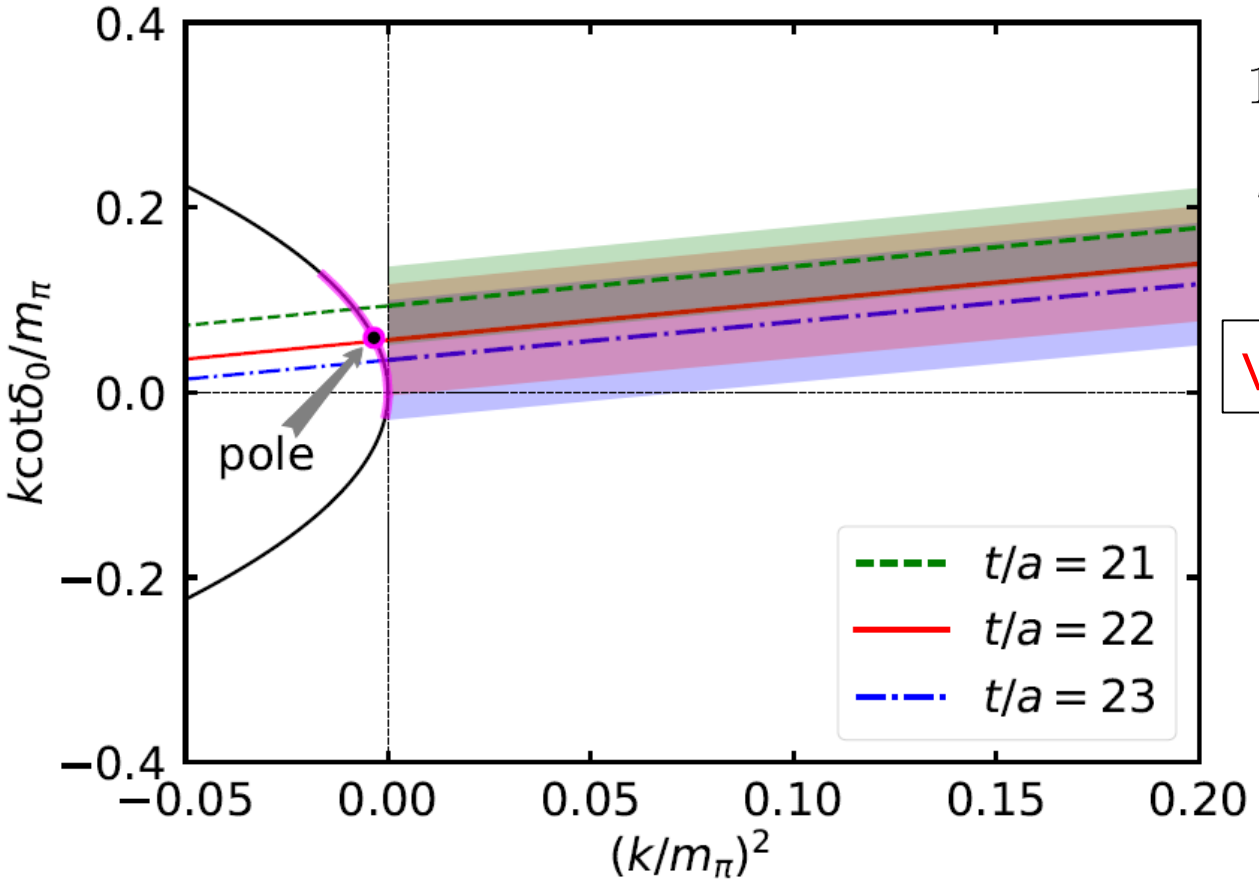
Attractive at all distance

Two-pion exchange!

$$V_{\rm fit}(r) = \sum_{i=1,2} a_i e^{-(r/b_i)^2} + a_3(1-e^{-(r/b_3)^2})^2 \left(\frac{e^{-m_\pi r}}{r}\right)^2$$

Phase shifts and pole in the scattering matrix

ERE (Effective Range Expansion) $k \cot \delta_0(k) = \frac{1}{a_0} + \frac{1}{2} r_{\rm eff} k^2 + \cdots$



$1/a_0 = 0.05(5)\,\left(^{+2}_{-2}\right)\ \mathrm{fm}^{-1}$

$r_{\rm eff} = 1.12(3)\,\left(^{+3}_{-8}\right)\ \mathrm{fm}$

Virtual state near unitarity

$\kappa_{\rm pole} = (-ik)_{\rm pole}$
$= \quad -8(8)\,\left(^{+3}_{-5}\right)\ \mathrm{MeV}$

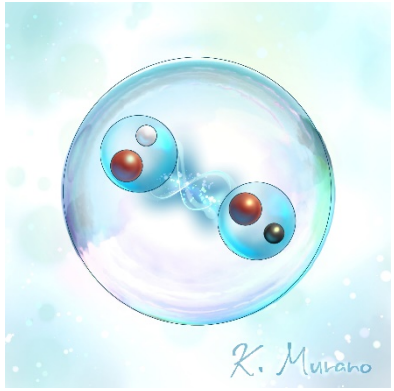
$E_{\rm pole} =$
$-59\,\left(^{+53}_{-99}\right)\,\left(^{+2}_{-67}\right)\ \mathrm{keV}$

Extrapolation towards physical quark mass

$$V_{\rm fit}(r) = \sum_{i=1,2} a_i e^{-(r/b_i)^2} + a_3(1 - e^{-(r/b_3)^2})^2 \left(\frac{e^{-m_\pi r}}{r}\right)^2$$

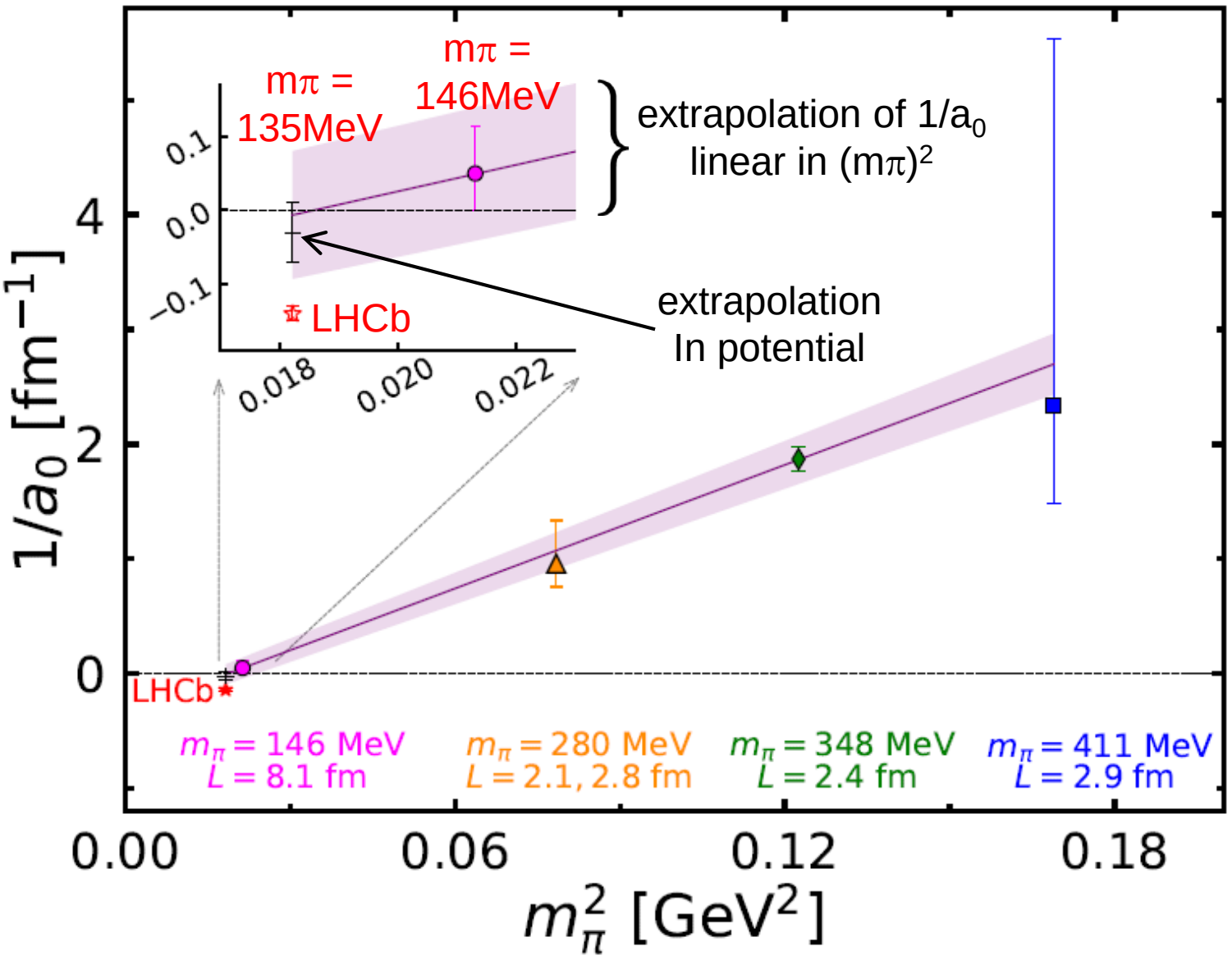
$$m_\pi = 146.4 \to 135.0 \text{ MeV}$$

m_π [MeV]	146.4	135.0
$1/a_0$ [fm^{-1}]	$0.05(5)\,(^{+2}_{-2})$	$-0.03(4)$
$r_{\rm eff}$ [fm]	$1.12(3)\,(^{+3}_{-8})$	$1.12(3)$
$\kappa_{\rm pole}$ [MeV]	$-8(8)\,(^{+3}_{-5})$	$+5(8)$
$E_{\rm pole}$ [keV]	$-59\,(^{+53}_{-99})\,(^{+2}_{-67})$	$-45\,(^{+41}_{-78})$

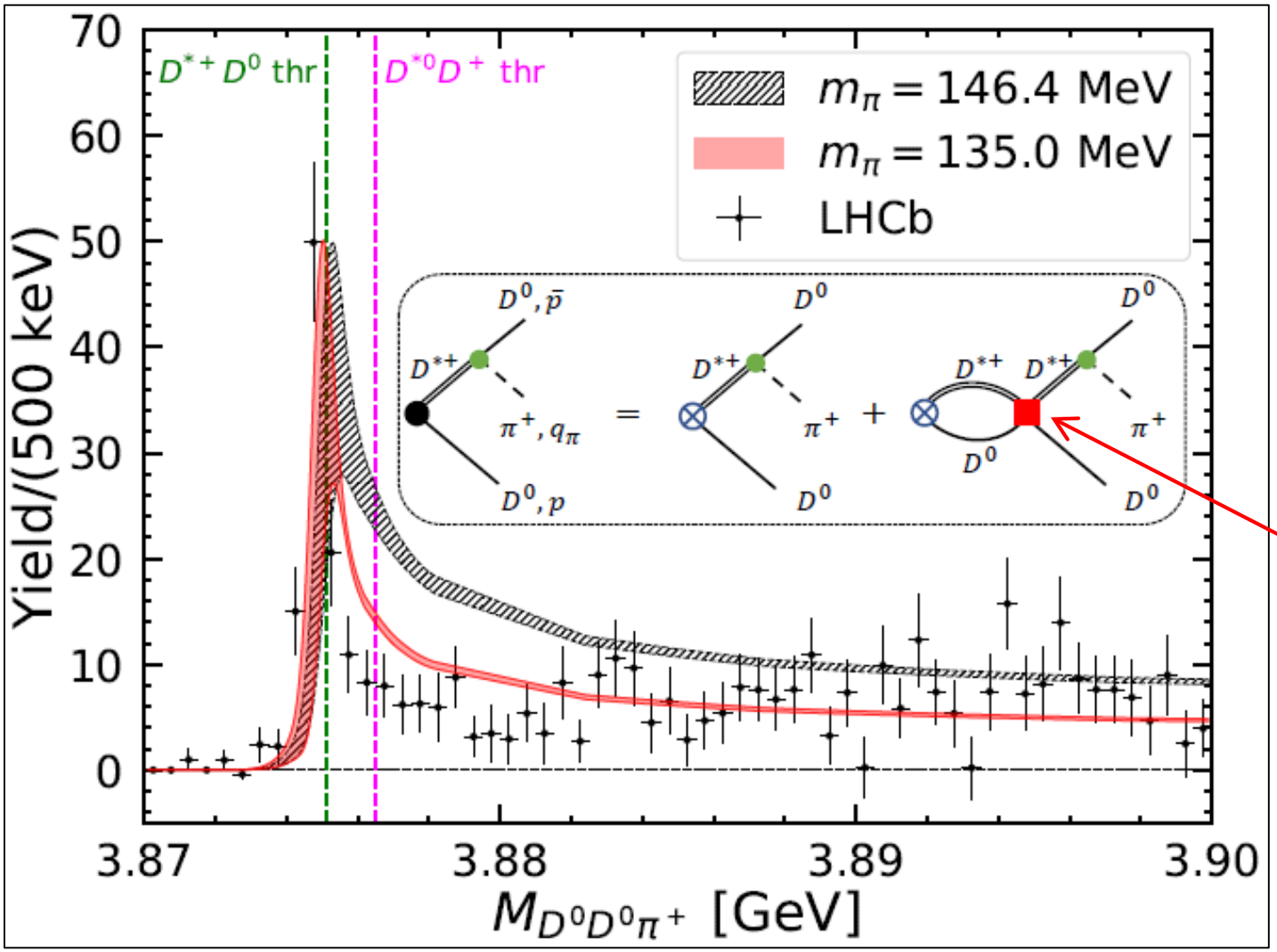


virtual state @ mπ = 146 MeV evolves to
a shallow bound state near unitarity @ mπ = 135 MeV

Quark mass dependence of $1/a_0$



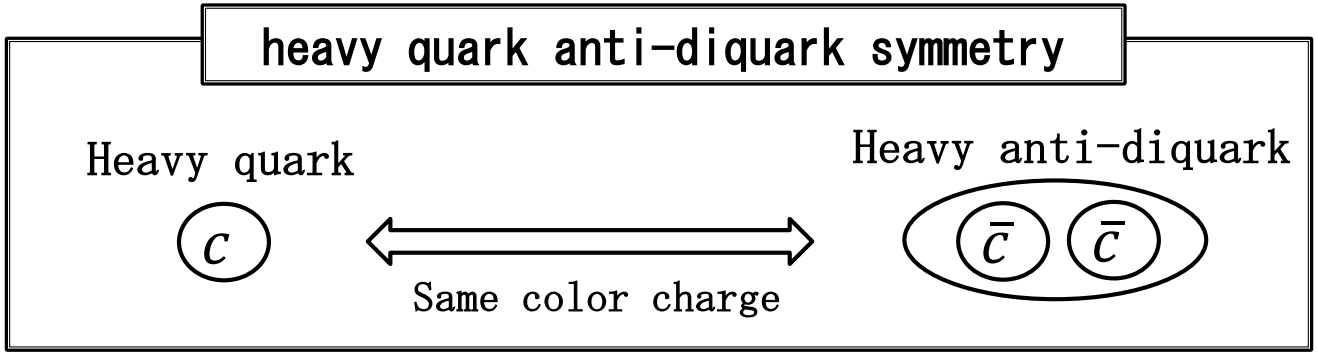
Mass spectrum of $D^0D^0\pi^+$



LQCD potential

Better agreement w/ “physical mass” potential

Superflavor partner of Tcc ?



Georgi-Wise, PLB243(1990)279

Tcc (D-D*) ⟺ Pentaquark state? (Dbar$^{(*)}$-$\Xi_{cc}^{(*)}$)

Asanuma-Yamaguchi-Harada, arXiv:2311.04695

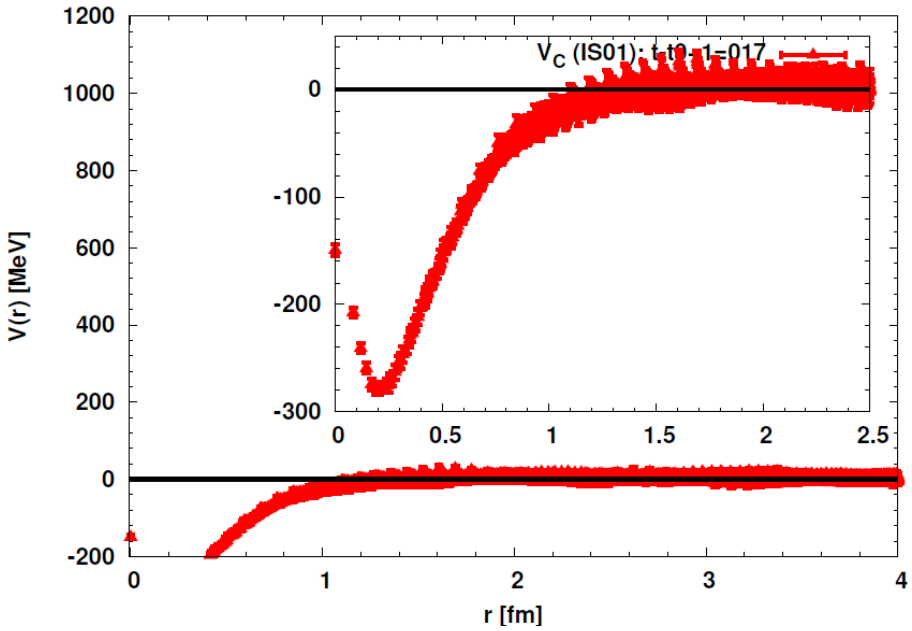
⟺ Hexaquark state? (Ξ_{cc}–Ξ_{cc})

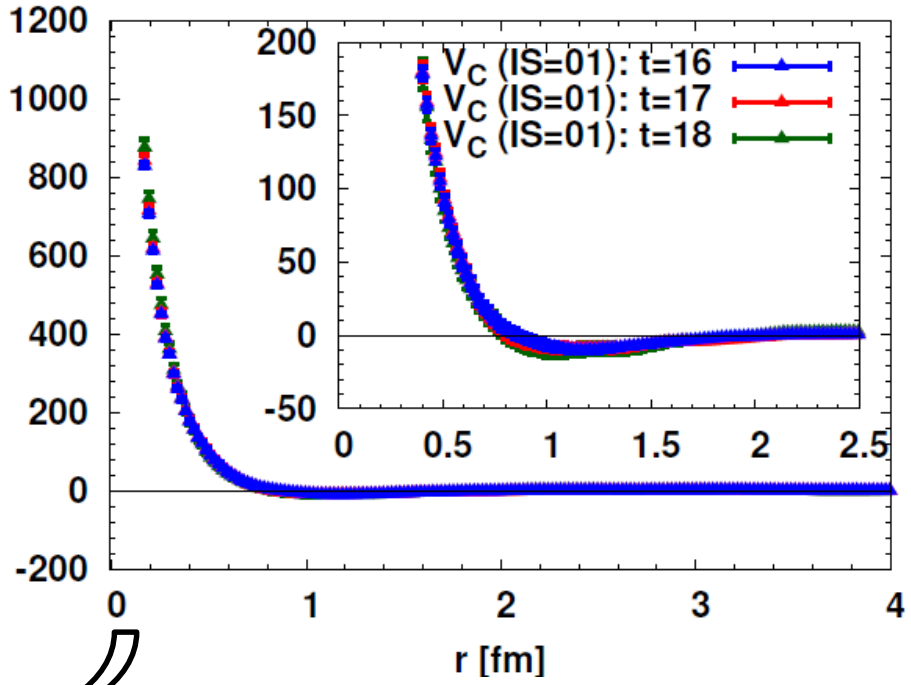
Ξ_{cc}—Ξ_{cc} : Central potential in 3S1-3D1 channel

$\Xi_{cc} - \Xi_{cc}$

Preliminary

$\Xi_{ss} - \Xi_{ss}$





(scale is different for inner plot)

Completely different!

N.B. This is single channel study while $\Xi_{cc}\Xi_{cc}$ (7243) can couple to $\Lambda_c\Omega_{ccc}$(~7082)

Λ_c–N interactions near the phys point

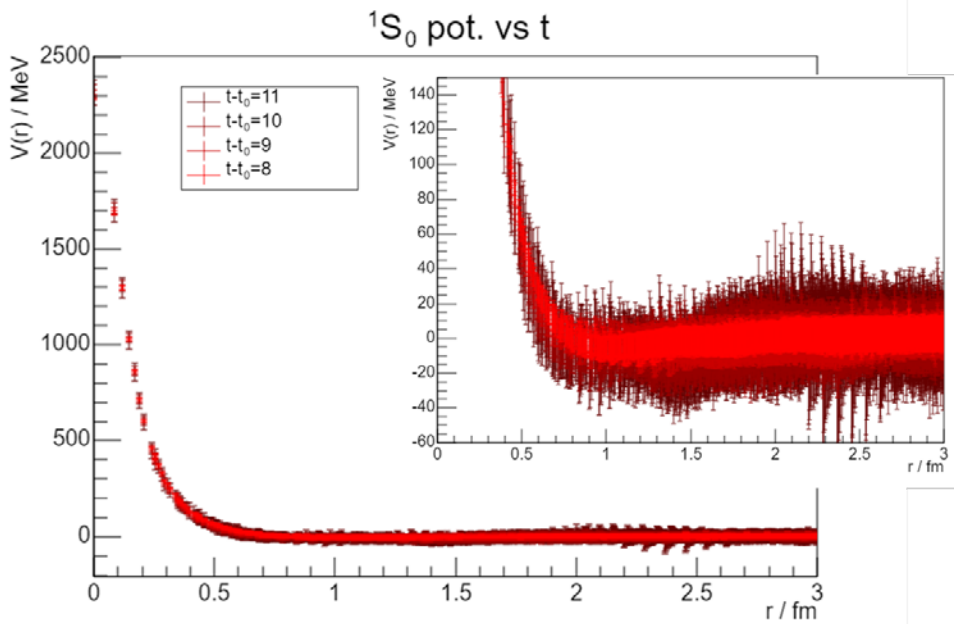
L. Zhang

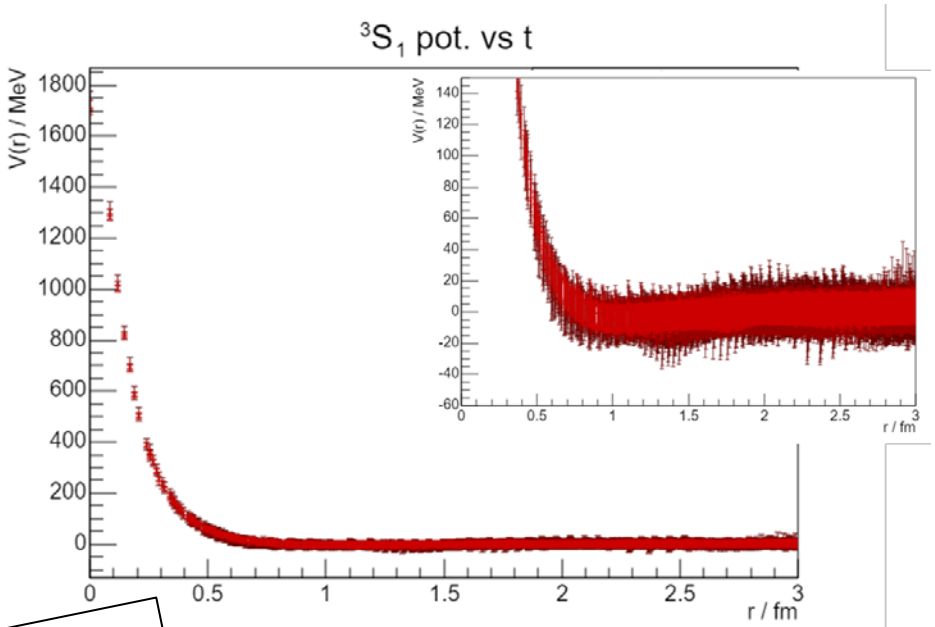
Possibility of Λ_c hypernuclei?

c.f. T. Miyamoto et al., (HAL Coll.) NPA971(2018)113
m(pi)=0.41-0.70 GeV

Impact on EFT

Haidenbauer-Krein (2018, 2021), J. Song et al. (2020)





Preliminary

Challenge toward LQCD w/ physical mass

~2012

➔lighter u,d-quark masses
(=lighter pion mass Mπ)

~2018

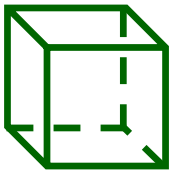
2023 !

We were here

➔ more challenging

Phys. point

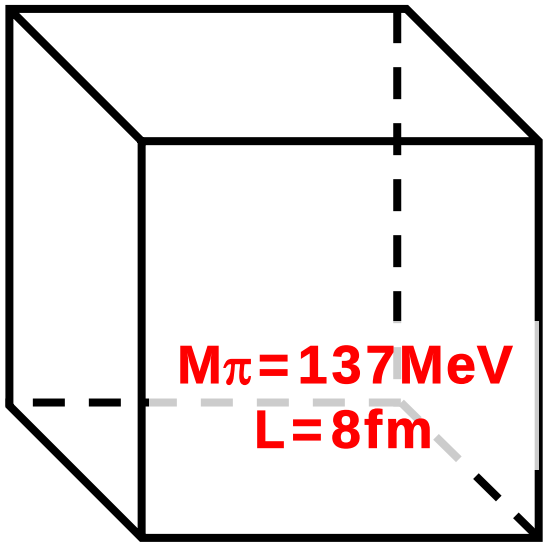
Mπ=400MeV
L=3fm



Simulation w/
Unrealistic mass

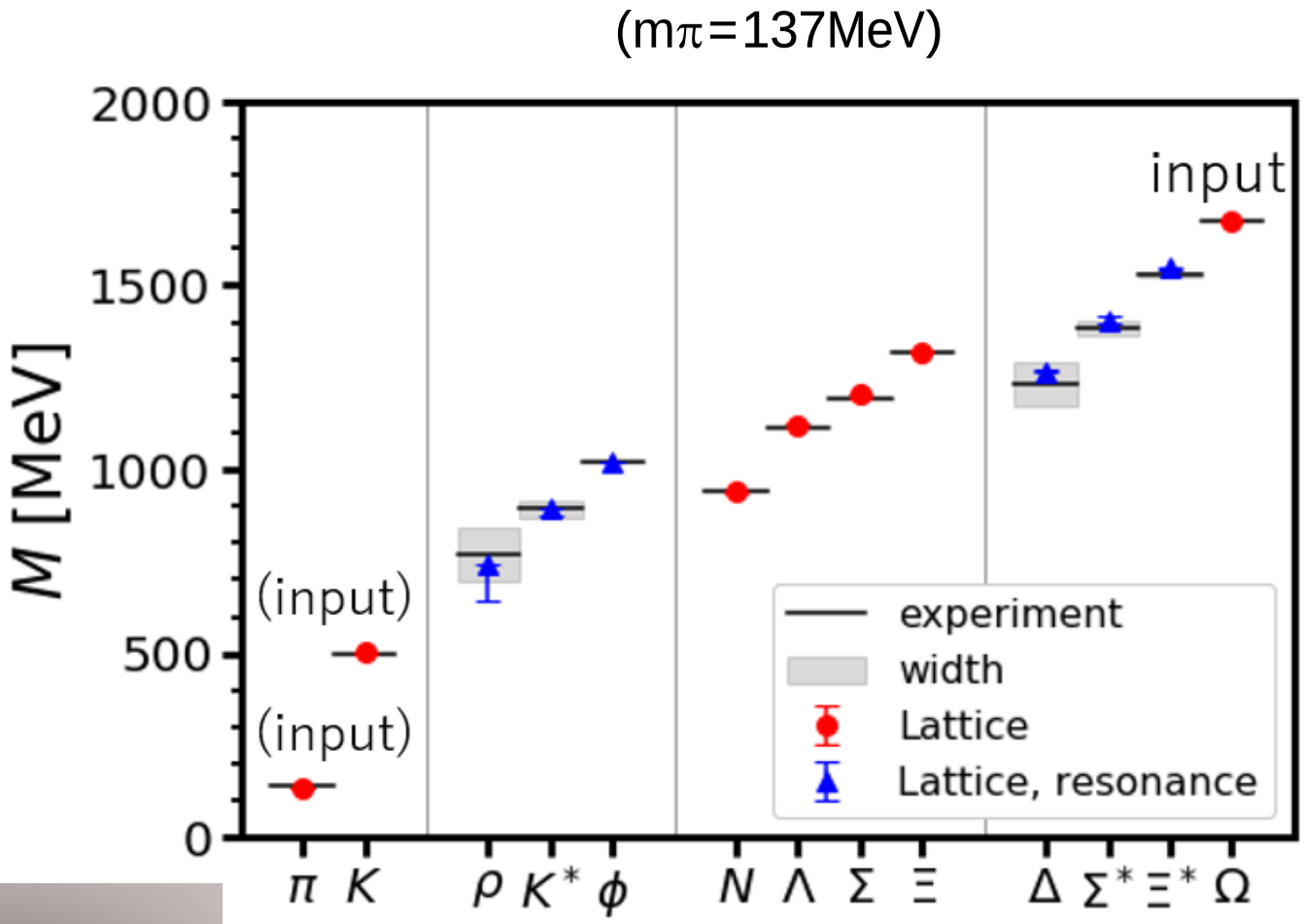
Theoretical development
+
New supercomputer

Fugaku (440PFlops)



Simulation w/
the physical mass

LQCD simulations at the physical quark masses

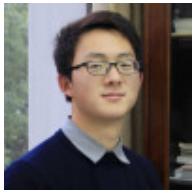
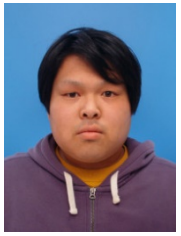


Fugaku (440PFlops)

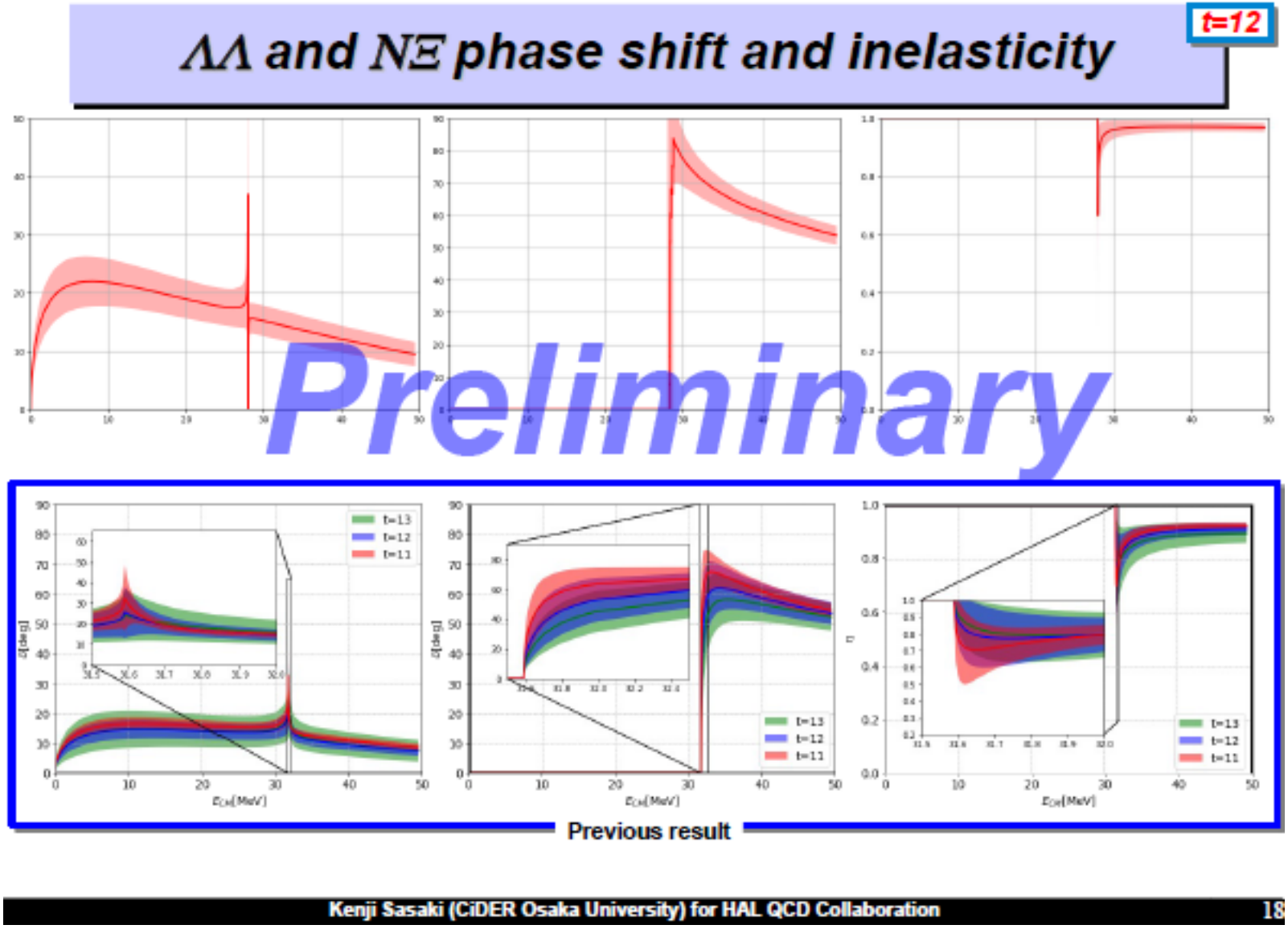
Single hadron spectrum well reproduced!

T. Aoyama et al. (HAL Coll.), arXiv:2406.16665




Analysis on the physical point on-going (Mπ=137MeV)



[K. Sasaki]

Summary

- Renaissance in particle/nuclear/astro-physics
  - **Experiments** of hadrons/nuclei
  - **Observations** of neutron stars
  - **Theory** by LQCD calc of hadron interactions

- The 1st LQCD for Hadron Interactions
  near and on the physical quark mass point by Fugaku
  - Various baryon interactions for NN/YN/YY as well as exotics
  - Predictions, Applications in progress
  - Future: Exotics, P-wave forces, LS-forces, 3-baryon forces & EoS