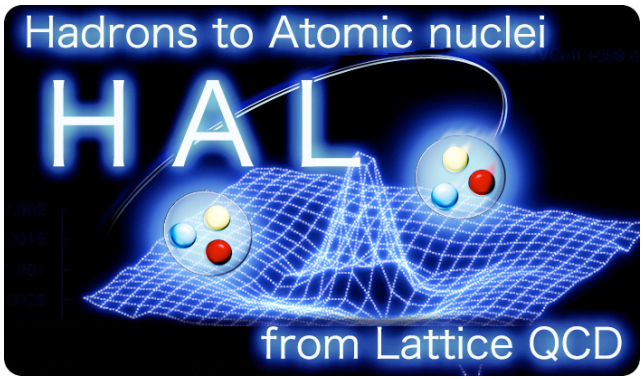
Lattice QCD study of Ξ_{cc}-Ξ_{cc} interactions on the physical point

Takumi Doi

(RIKEN iTHEMS)



With

Yan Lyu (RIKEN iTHEMS)

Kotaro Murakami (TITech)

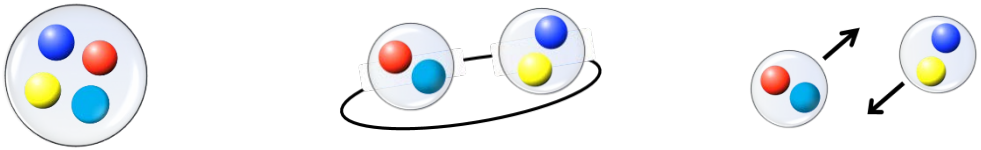
Liang Zhang (RIKEN iTHEMS / CAS SINAP)

for HAL QCD Collaboration

Mysteries of Exotic hadrons

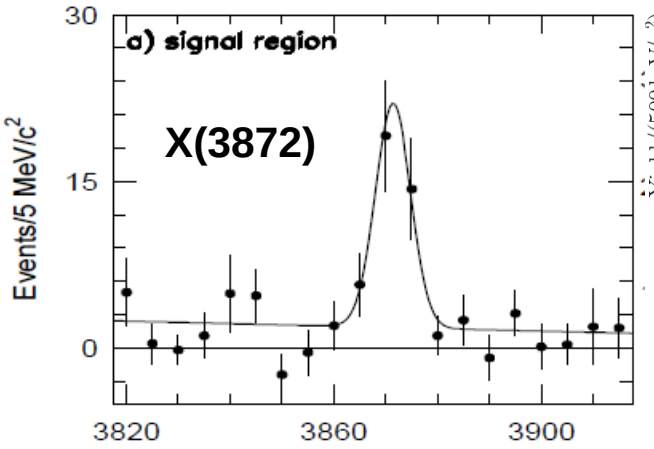
New theoretical paradigm is necessary!

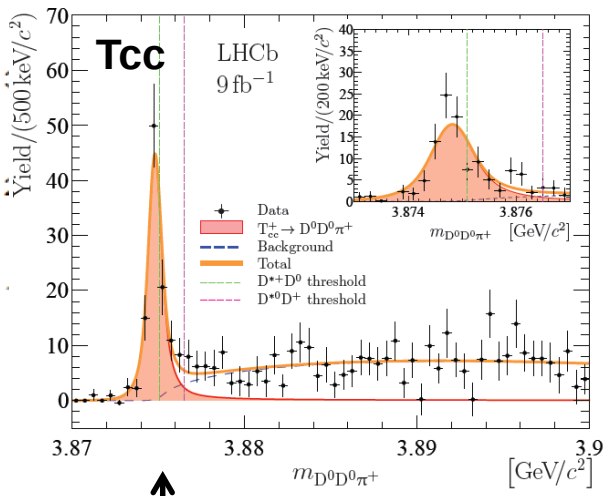
Various models proposed:

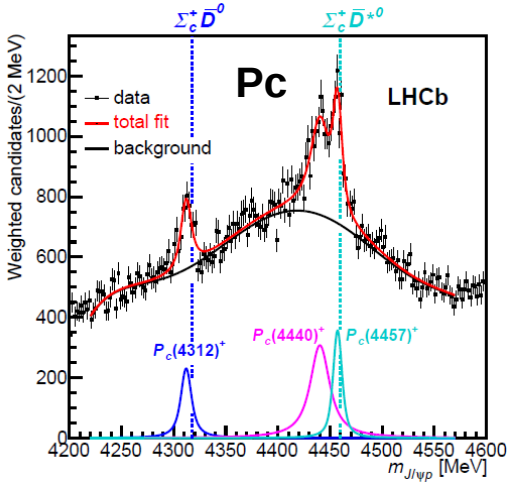


Compact state? Hadron molecule? Threshold cusp?

→ But reliability of a model is unclear





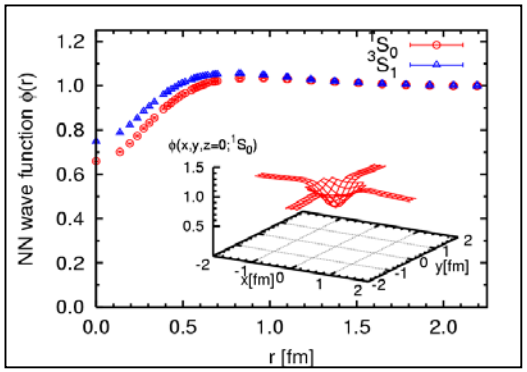


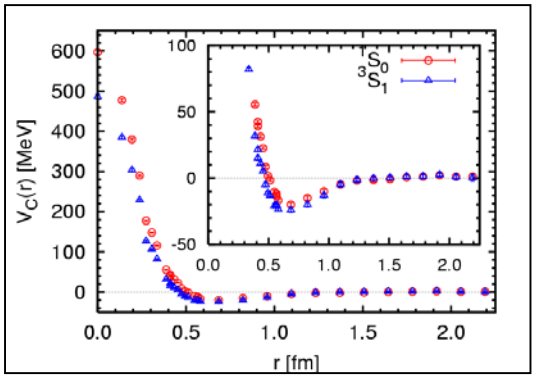
Exotics close to the thresholds : Determination of Hadron interactions is crucial

←→ Systematic investigation of families of exotics

HAL QCD method

Lattice QCD → **NBS wave func.** → **Lat Hadron Force**





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

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

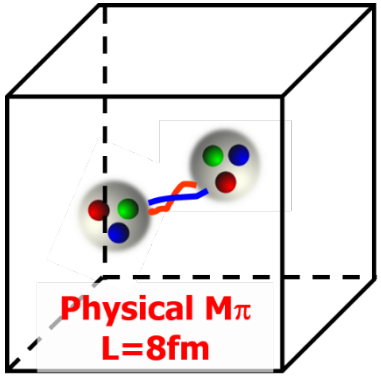
- **E-indep potentail from NBS w.f.** — Aoki-Hatsuda-Ishii PTP123(2010)89
  - **Faithful to Phase Shifts by construction** (non-locality: derivative expansion)

Non-local pot by Deep-Learning: talk by L. Wang (Aug 2)

- **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 **Exotics, YN/YY-forces**

LQCD @ near & on the physical point

- **Nf = 2 + 1 gauge configs**
  - clover fermion + Iwasaki gauge w/ stout smearing
  - $V = (96\ a)^4 = (8.1\text{fm})^4$
  - a = 0.084372(54)(+109/-6) fm
    1/a = 2338.8(1.5)(+0.2/-3.0) MeV

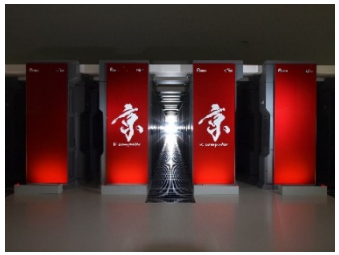


- **[K-conf]**

  $(m_\pi, m_K) = (146, 525)$ MeV, (#traj ~= 2000)

  PACS Coll., PoS LAT2015, 075

  K computer（2012-19）・10PF



- **[F-conf] (HAL-conf-2023)**

  $(m_\pi, m_K) = (137, 502)$ MeV, (#traj= 8000)

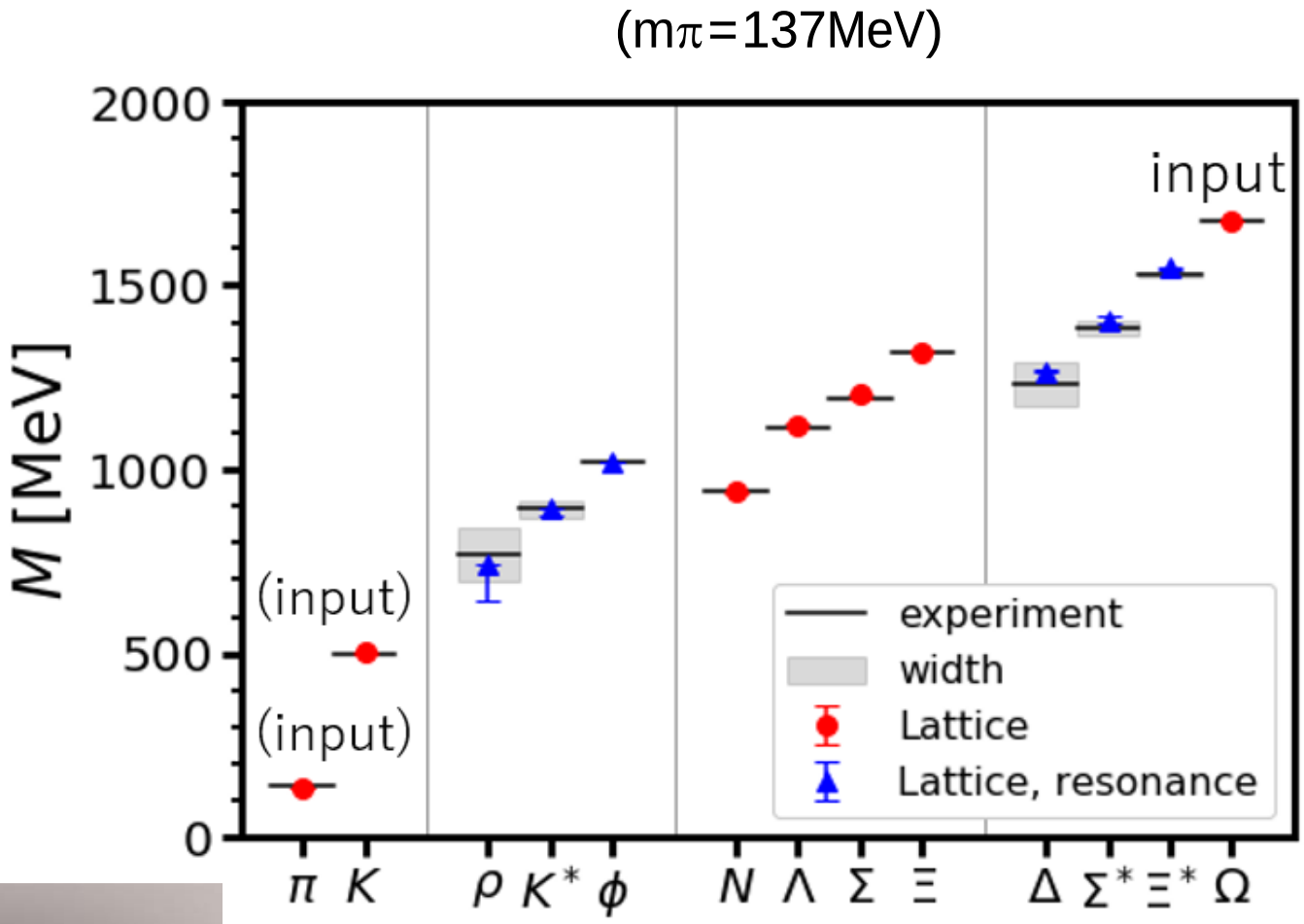
  HAL QCD Coll., arXiv:2406.16665

  Fugaku（2021-）・440PF

← Parameters from PACS10 conf (PACS Coll., PRD99, PRD100 ('19))

Talks: NJ/ψ, $N\eta_c$ by Y. Lyu (Jul 31), $\Lambda_c N$ by L. Zhang (Jul 31)

LQCD simulations at the physical quark masses

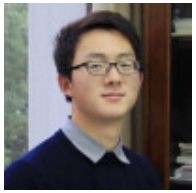
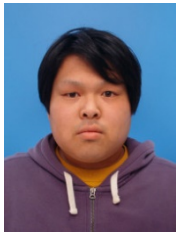


Fugaku (440PFlops)

Single hadron spectrum well reproduced!

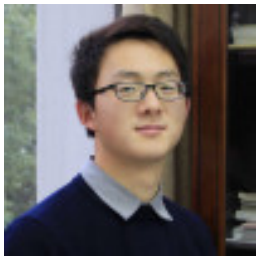
T. Aoyama et al. (HAL Coll.), arXiv:2406.16665




Exotic tetraquark T_{cc}^{+} $(cc\bar{u}\bar{d})$ near physical point

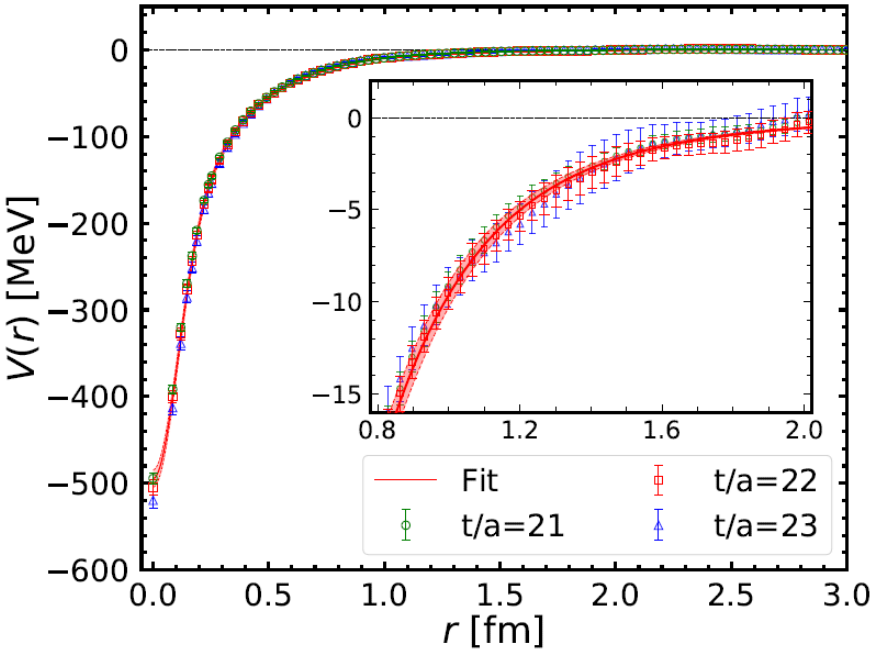
Y. Lyu, et al., PRL131(2023)161901 (Editor's suggestion)



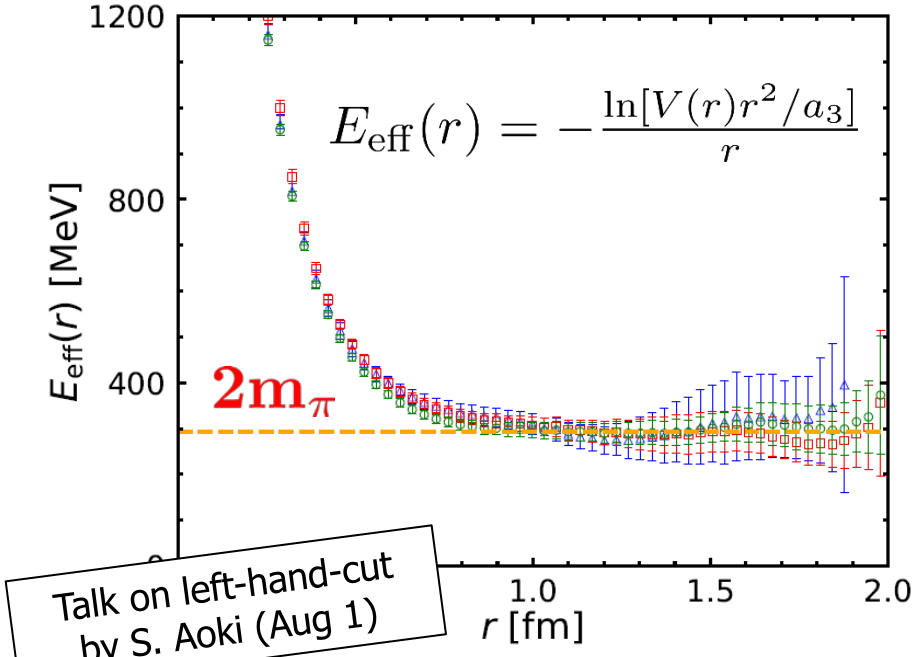
Y. Lyu

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

Potential



Tail structure of Potential



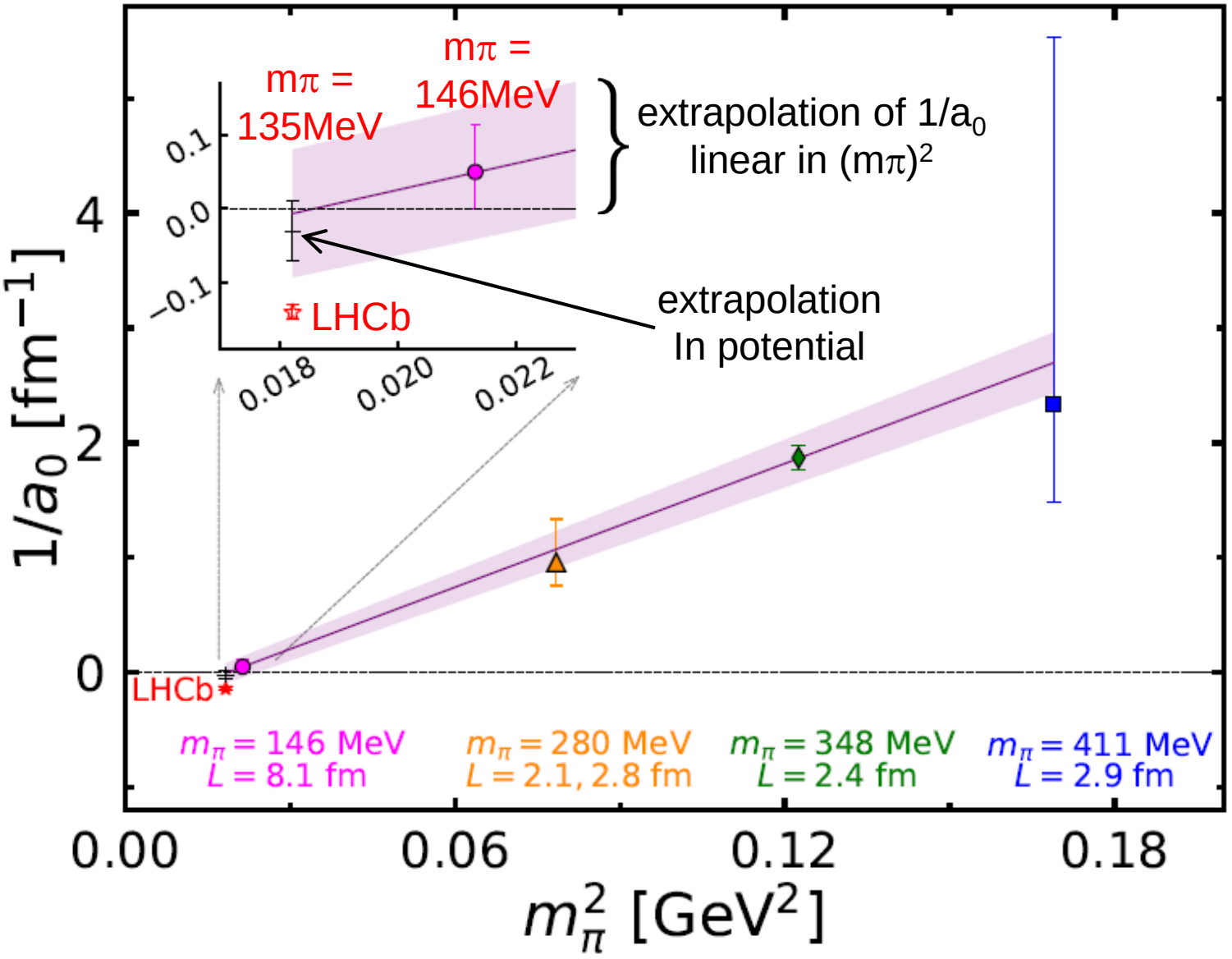
Talk on left-hand-cut by S. Aoki (Aug 1)

Attractive at all distance

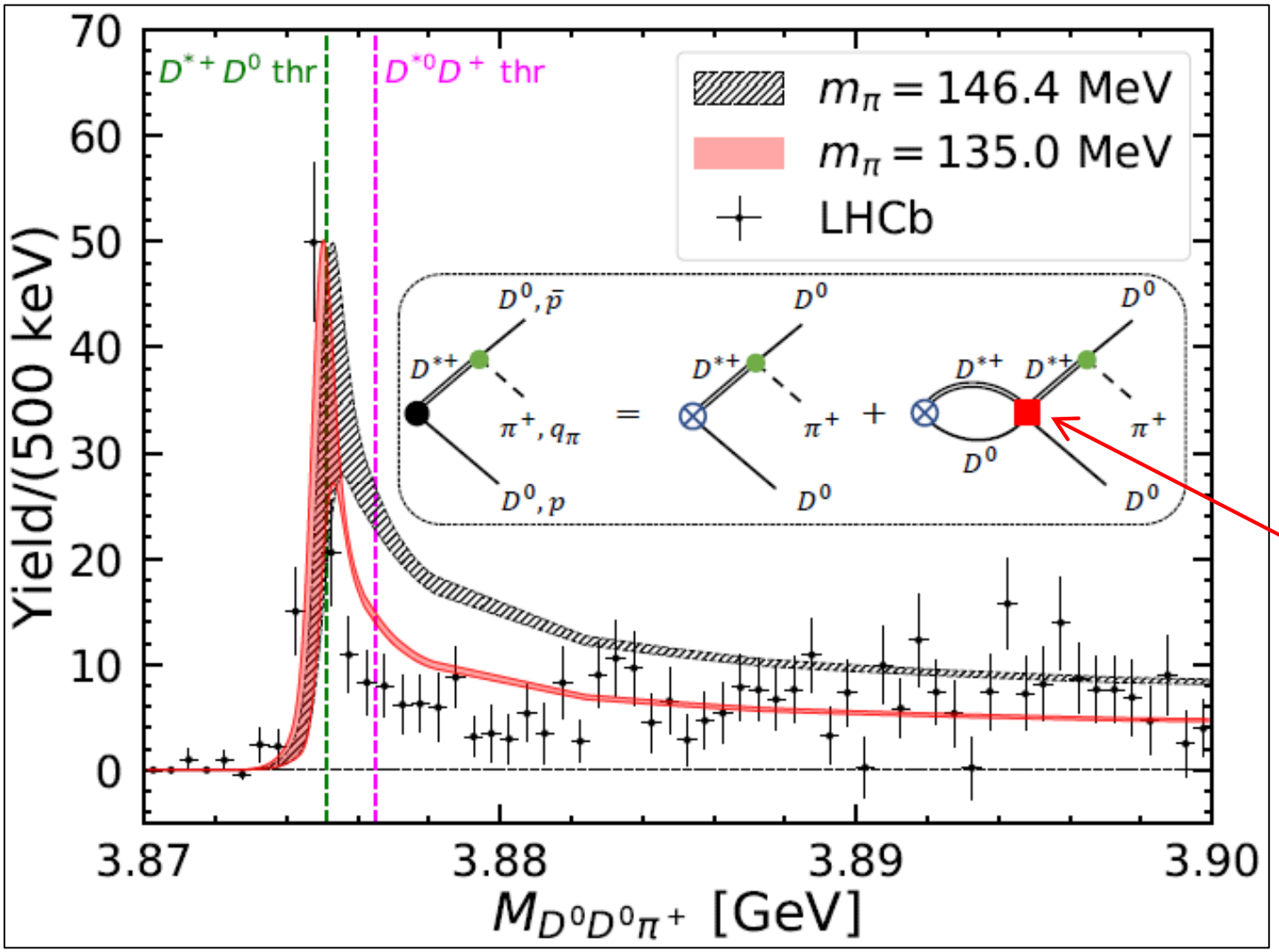
Two-pion exchange!

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

Quark mass dependence of $1/a_0$



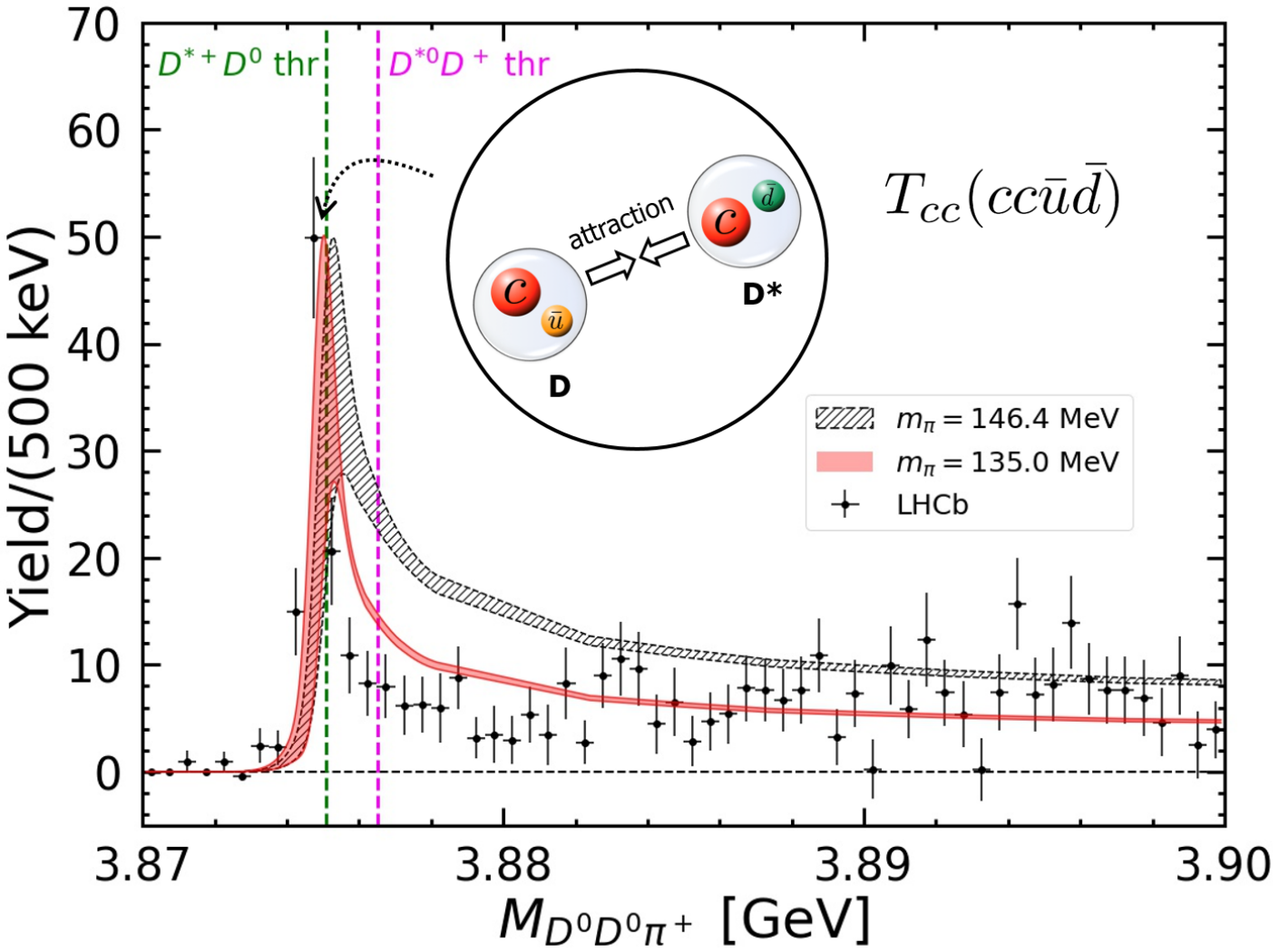
Mass spectrum of $D^0D^0\pi^+$



LQCD potential

Better agreement w/ “physical mass” potential

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



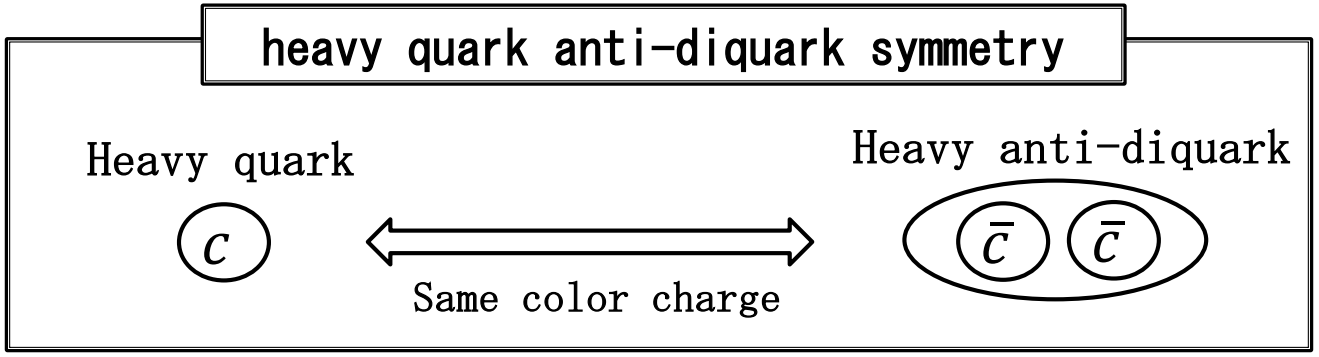
Tcc : ~ meson molecular like state of D-D*

Exotic Family of Tcc state?

- Family of Heavy quark DoF

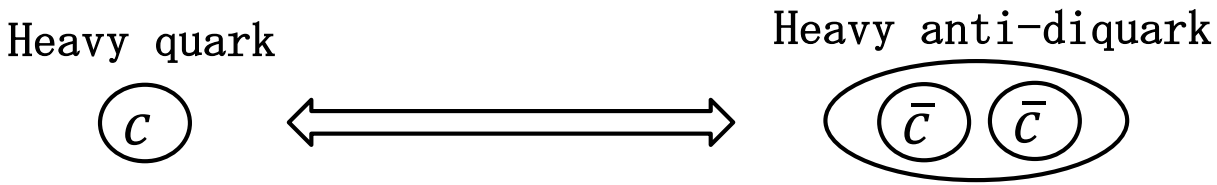
Tcs, Tbs, Tbc, Tbb, ...

- Here, we consider “superflavor symmetry” (heavy quark anti-diquark symmetry)



Georgi-Wise, PLB243(1990)279
Savage-Wise, PLB248(1990)177

Superflavor partner of Tcc ?



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

Tcc bar: (cbar u) – (cbar d)

$I(J^P) = 0(1^+)$

(cbar u) – (cc d)

$I(J^P) = 0(1/2^-)$

Asanuma-Yamaguchi-Harada, arXiv:2311.04695

OBEP + superflavor sym → Bound state could exist

⟺ Hexaquark state? (Ξ_{cc}–Ξ_{cc})

(cc u) – (cc d)

$I(J^P) = 0(1^+)$

Physical point simulation of Ξ_{cc}–Ξ_{cc} interactions

- F-conf is used for phys point calc on Fugaku
- Ξ_{cc}–Ξ_{cc} interactions

$I(J^P) = 0(1^+)$ $^3S_1$-$^3D_1$ channel ⇦ Candidate of Tcc partner

$I(J^P) = 1(0^+)$ $^1S_0$ channel

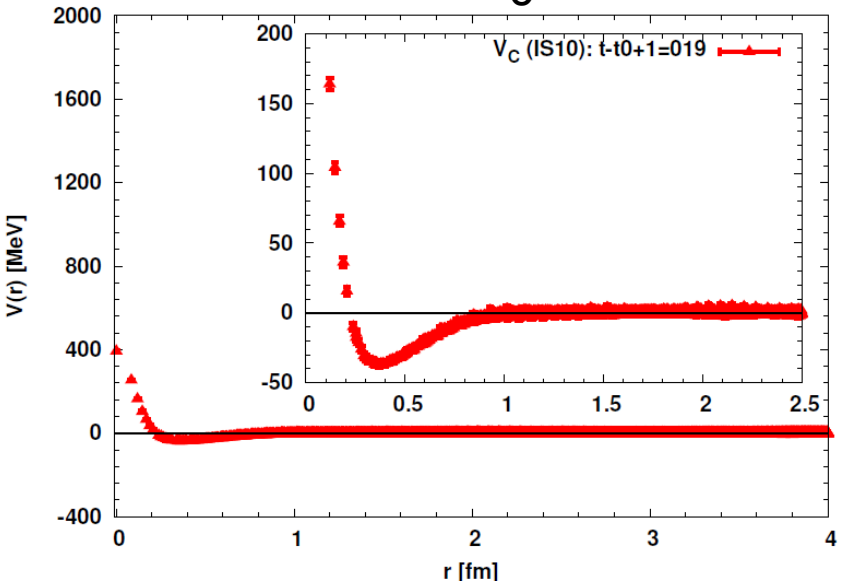
- Ξ_{ss}–Ξ_{ss} (= usual Ξ–Ξ) interactions
  - We can use this system as a “reference” to probe the role of heavy quark

$I(J^P) = 0(1^+)$ $^3S_1$-$^3D_1$ channel ← SU(3)f 10-plet

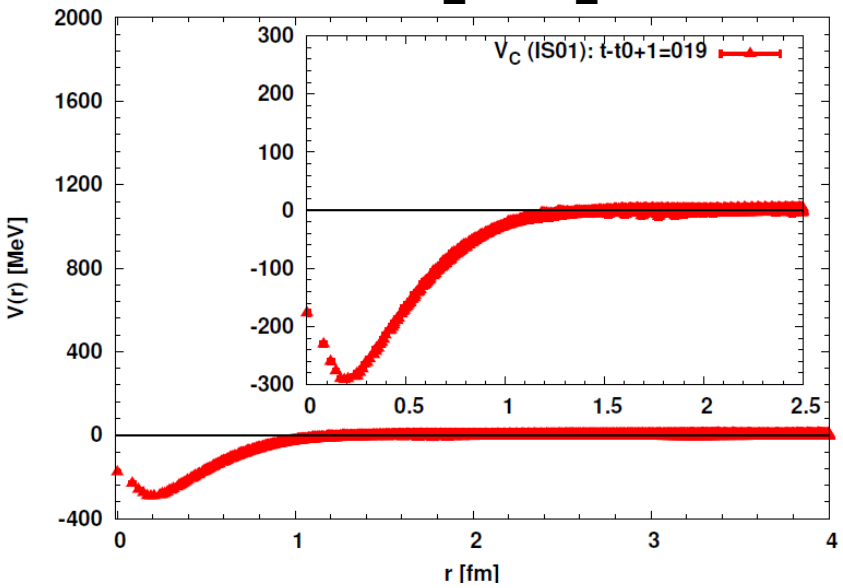
$I(J^P) = 1(0^+)$ $^1S_0$ channel ← SU(3)f 27-plet

Ξ_{cc}–Ξ_{cc} interactions

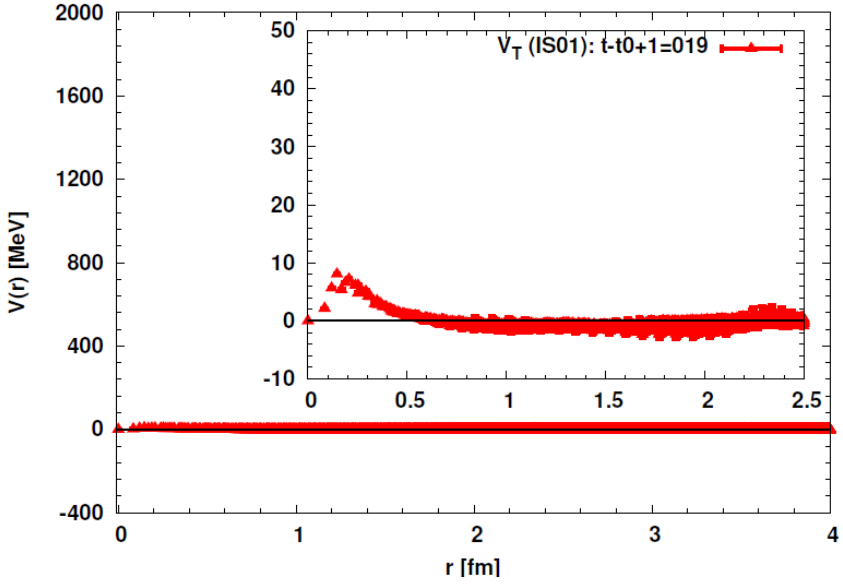
$^1S_0$



$^3S_1$-$^3D_1$



Central



Tensor

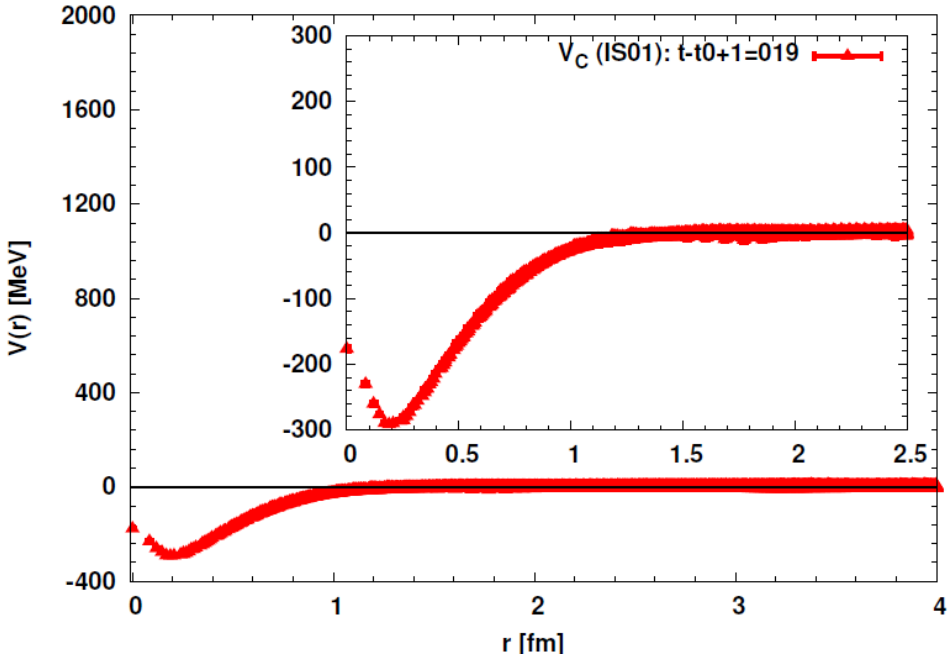
$^1S_0$: Repulsive core
+ attractive pocket

$^3SD_1$: Strong attraction
& weak tensor force

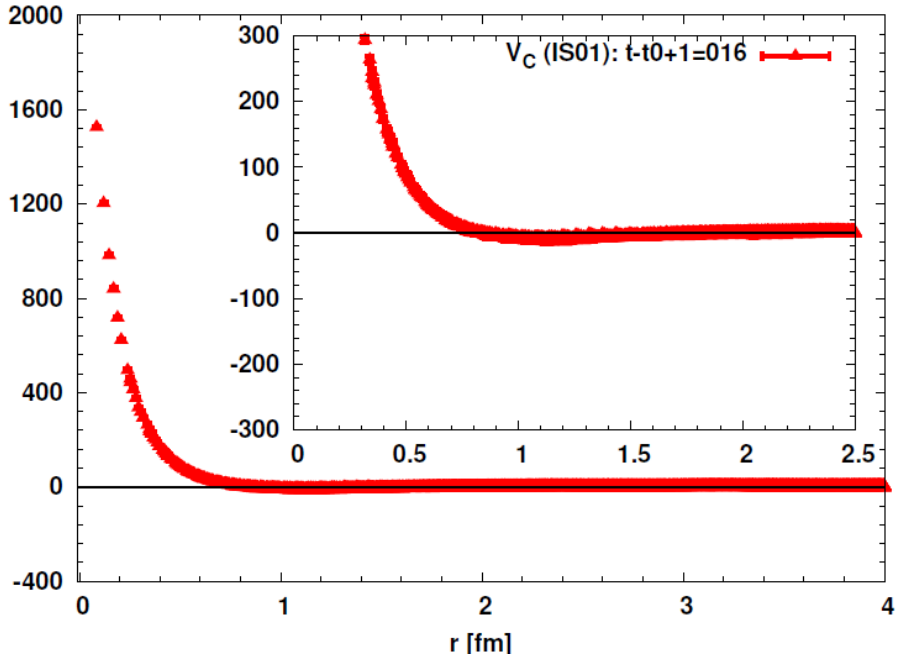
$M(\Xi_{cc})$= 3642.9(1.4) MeV

Comparison of central potential in $^3SD_1$ channel

Ξ_{cc}—Ξ_{cc}



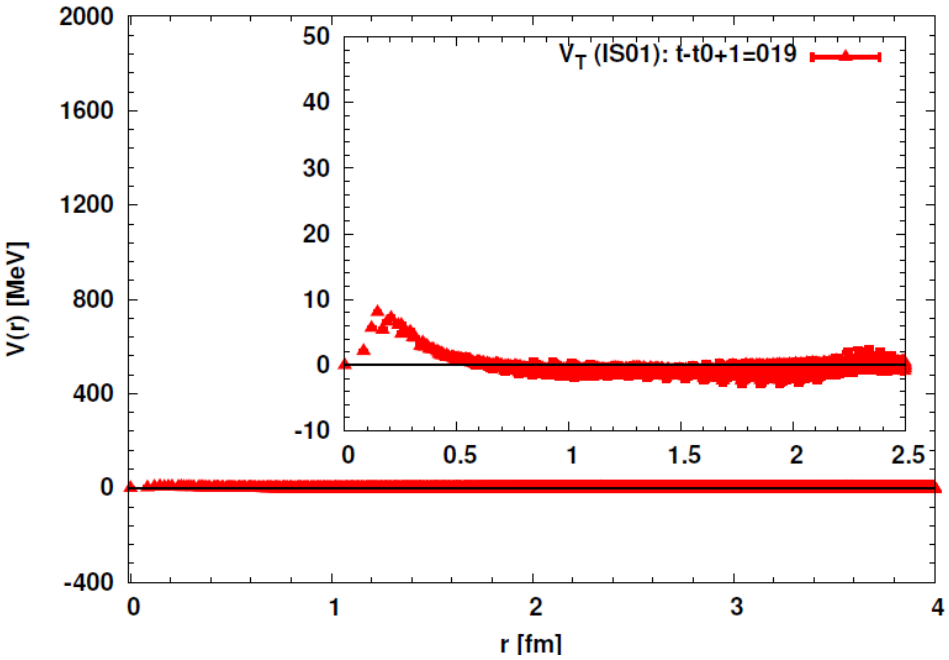
Ξ_{ss}—Ξ_{ss}



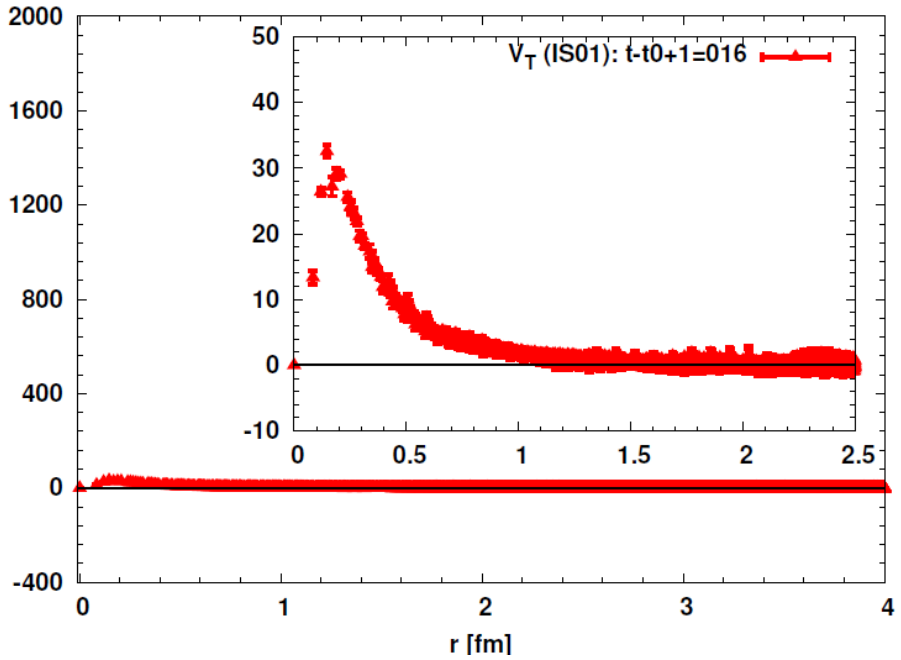
Completely different!

Comparison of tensor potential in $^3SD_1$ channel

Ξ_{cc}—Ξ_{cc}



Ξ_{ss}—Ξ_{ss}

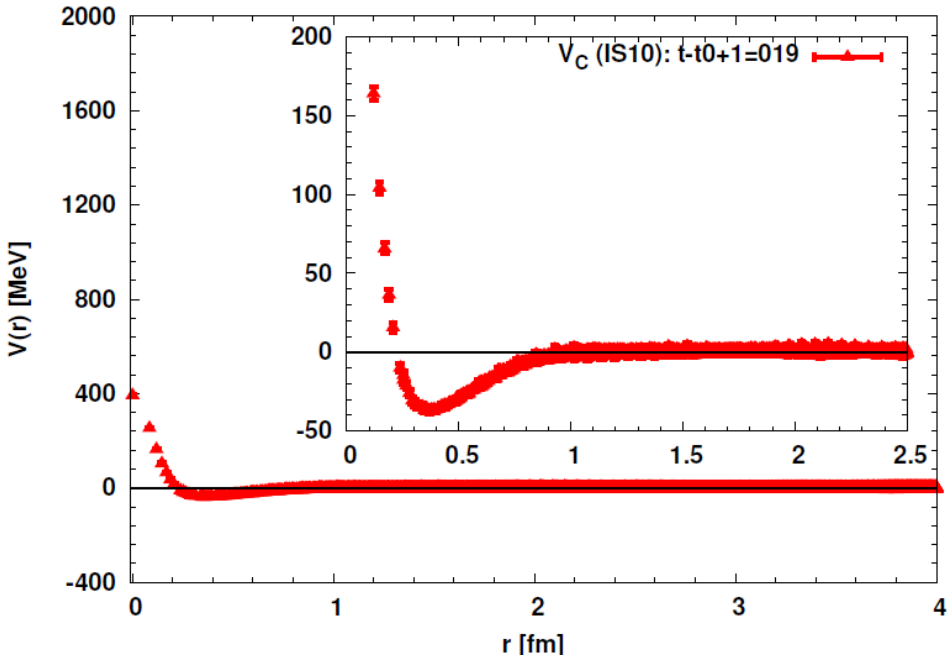


Qualitatively similar

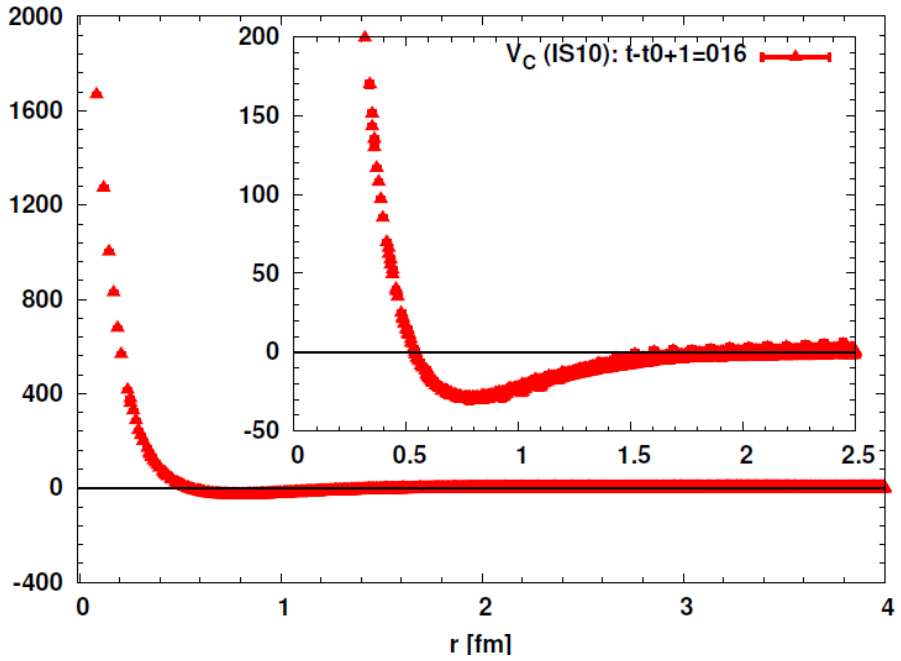
Tensor force is small for both systems

Comparison of central potential in $^1S_0$ channel

Ξ_{cc}—Ξ_{cc}



Ξ_{ss}—Ξ_{ss}



Qualitatively similar

Repulsive core is suppressed for $\Xi_{cc}\Xi_{cc}$

Coupled channel effect?

- Approximation in $\Xi_{cc}\Xi_{cc}$ (I=0, $J^P=1^+$ channel)
  - There exists open channel, $\Lambda_c\Omega_{ccc}$, below $\Xi_{cc}\Xi_{cc}$ channel

    $\Lambda_c\Omega_{ccc}$ (~7082) vs. $\Xi_{cc}\Xi_{cc}$(7243)
  - The issue is less significant in $\Xi_{cc}\Xi_{cc}$ (I=1, $J^P=0^+$ channel)

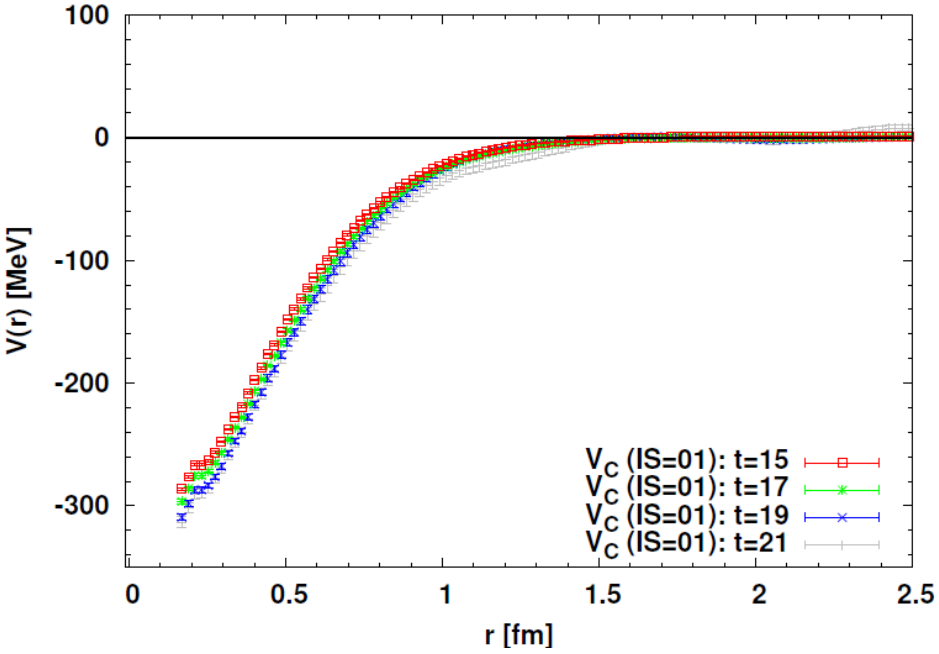
    $\Sigma_c\Omega_{ccc}$ (~7251) (D-wave) vs. $\Xi_{cc}\Xi_{cc}$(7243)
  - The issue does not exist in strangeness counter parts:

    $\Lambda_s\Omega_{sss}$ (2788) vs. $\Xi_{ss}\Xi_{ss}$(2637)

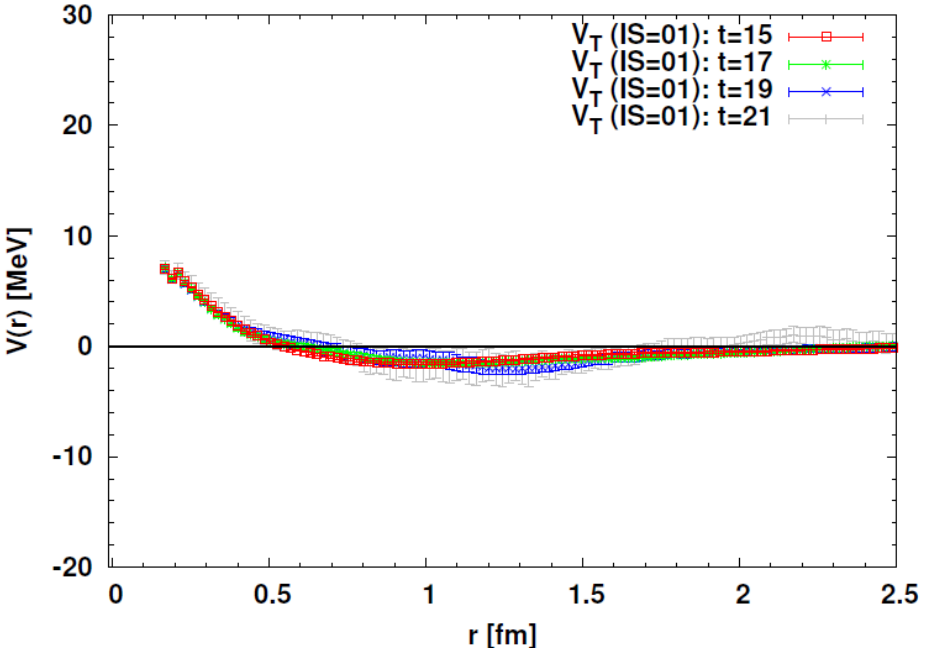
- At this moment, all analyses are performed in single-channel approximation (w.r.t. particle base)

$\Xi_{cc}\Xi_{cc}$ ($^3SD_1$) : Time-dependence of potential

Central



Tensor



Error reduction by Misner's method
(partial wave decomposition on lattice)

T. Miyamoto+, PRD101(2020)074514

Coupled channel effect seems to be suppressed

Summary

- Hadron interactions from Lattice QCD at physical point
  - New configuration set, “HAL-conf-2023” (F-conf), were generated
  - $(m_\pi, m_K) = (137, 502)$ MeV, L ~= 8fm, 1/a ~= 2.3GeV, #traj= 8000
  - Various interactions /exotic states, e.g., Tcc state
- $\Xi_{cc}\Xi_{cc}$ interactions in $I(J^P)=0(1^+)$, $I(J^P)=1(0^+)$ channels
  - $\Xi_{cc}\Xi_{cc}$ ($I(J^P)=0(1^+)$) could be superflavor partner of Tcc
  - Compared with counter-part systems w/ strangeness, $\Xi_{ss}\Xi_{ss}$
  - Possibly strong attraction in $\Xi_{cc}\Xi_{cc}$ ($I(J^P)=0(1^+)$)
  - Future:
    Systematic study of families of exotics
    Nuclear / Hadron physics from Lattice QCD