Doubly charmed tetraquark T_{cc}^{+} in (2+1)-flavor QCD near physical point

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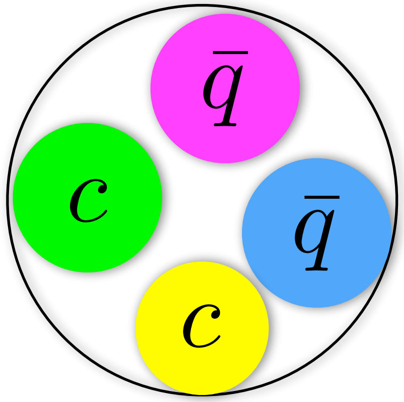
References

Yan Lyu, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Yoichi Ikeda and Jie Meng,
"Doubly Charmed Tetraquark T_{cc}^{+} from Lattice QCD near Physical Point", arXiv:2302.04505.

for
HAL QCD collaboration

Heavy tetra-quark states T_{cc}

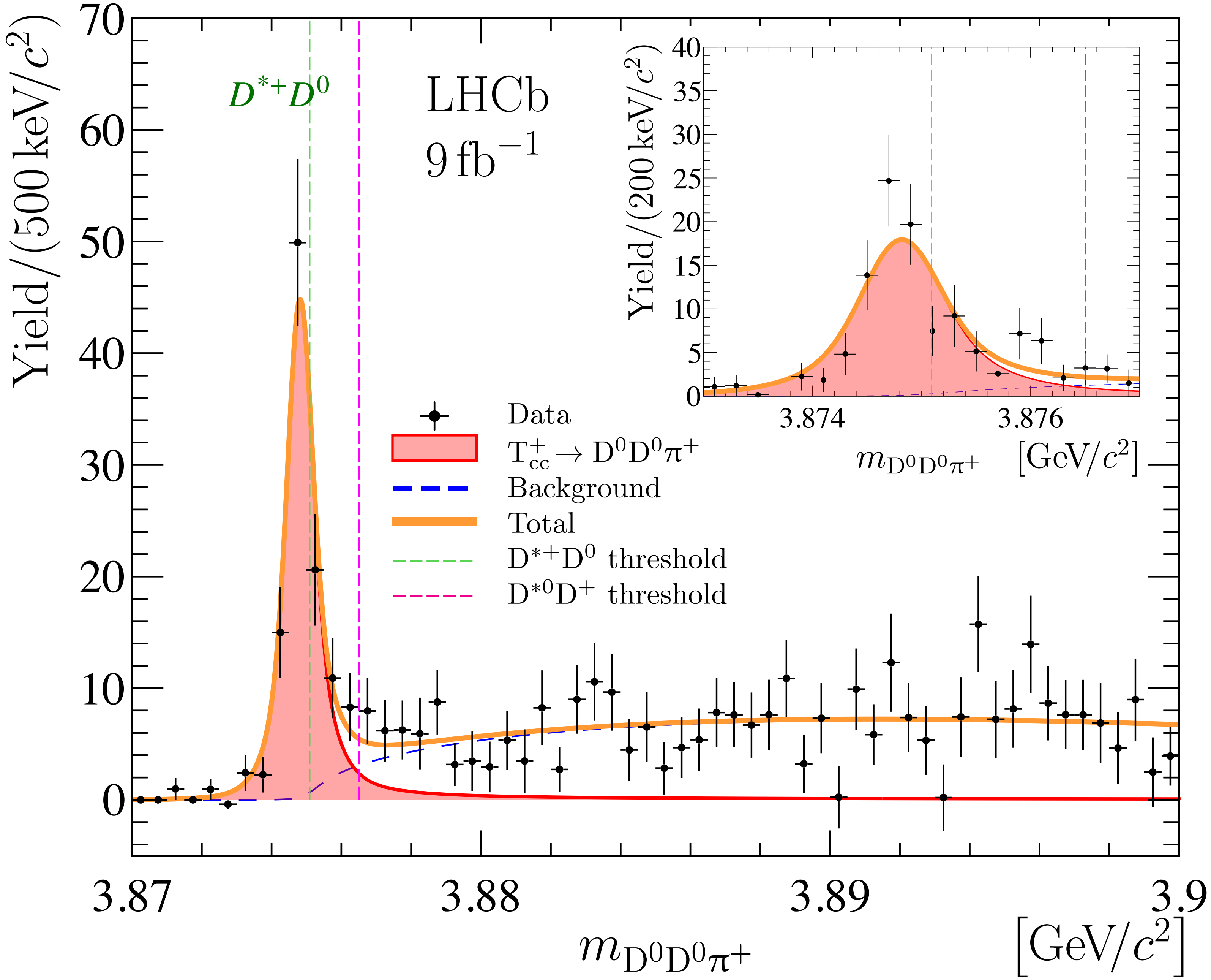


$\bar{q}$: light anti-quark

genuine tetra-quark states

$T_{cc}(cc\bar{u}\bar{d})$ observation by LHCb.

Aaij et al. (LHCb Collaboration), Nature Phys. (2022)



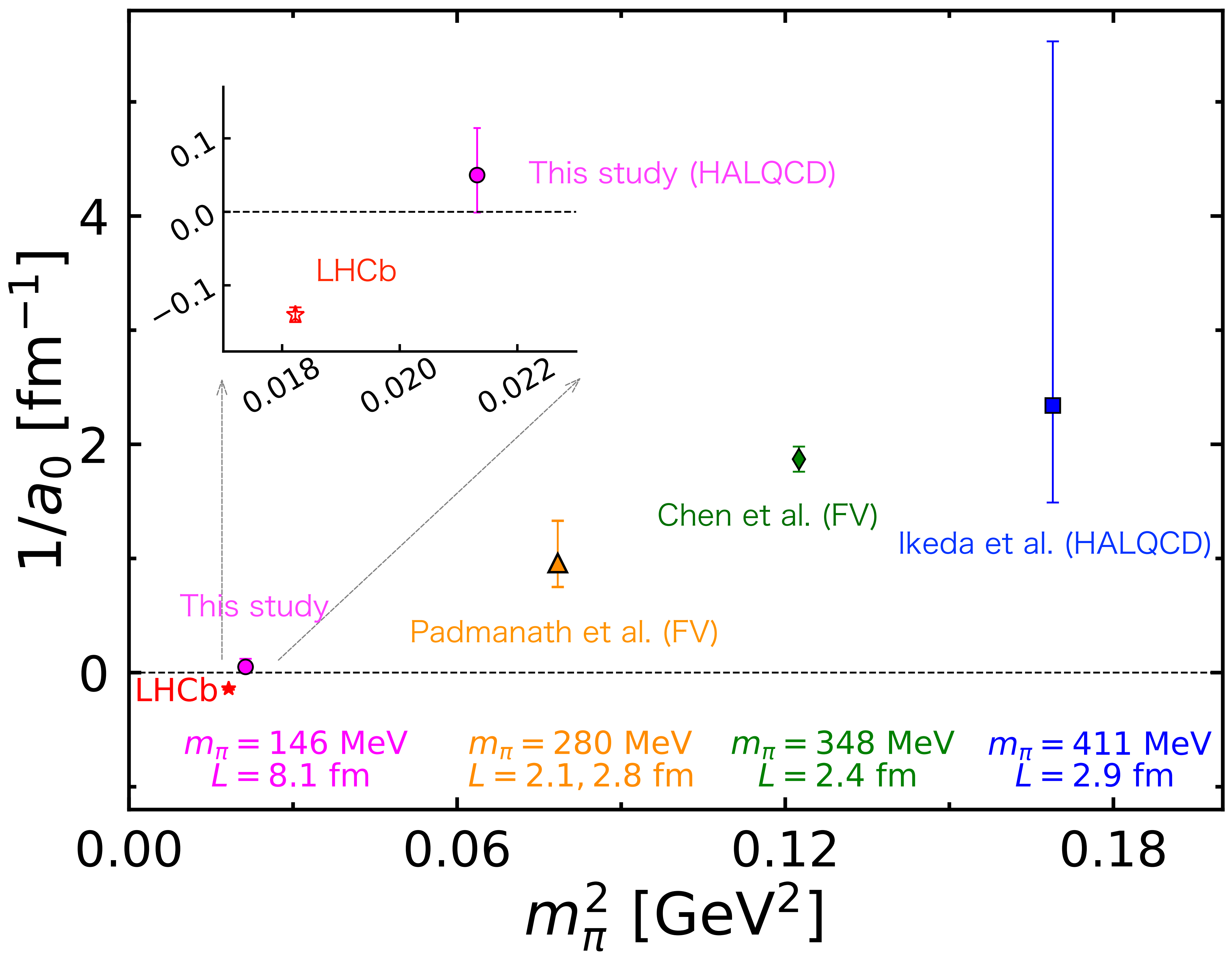
360 keV below $D^{*+}D^0$ threshold

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

(Latest) Lattice QCD results

inverse scattering length

significant pion mass dependence



HAL QCD method

N. Ishii, S. Aoki, T. Hatsuda, PRL99(2007) 022001.

Nambu-Bethe-Salpeter (NBS) wave function

$$\psi_W^{H_1+H_2}(\mathbf{r})e^{-Wt} := \frac{1}{\sqrt{Z_{H_1}}}\frac{1}{\sqrt{Z_{H_2}}}\sum_{\mathbf{x}}\langle 0|H_1(\mathbf{x}+\mathbf{r},t)H_2(\mathbf{x},t)|(H_1+H_2);W\rangle$$

Non-local potential

$$\left(\frac{\nabla^2}{2\mu}+\frac{p_W^2}{2\mu}\right)\psi_W(\mathbf{r}) = \int \mathrm{d}^3\mathbf{r}'\, U(\mathbf{r},\mathbf{r}')\psi_W(\mathbf{r}'),$$

derivative expansion

$$U(\mathbf{r},\mathbf{r}') = V(\mathbf{r},\nabla)\delta(\mathbf{r}-\mathbf{r}') = \sum_{k=0}^{\infty} V^{(k)}(\mathbf{r})\nabla^k\delta(\mathbf{r}-\mathbf{r}')$$

Leading order (LO) potential

$$V^{(0)}(\mathbf{r};W) = \frac{1}{\psi_W(\mathbf{r})}\left(\frac{\nabla^2}{2\mu}+\frac{p_W^2}{2\mu}\right)\psi_W(\mathbf{r})$$

+ Some improvements

time-dependent HAL QCD method — Ishii *et al.* (HAL QCD), PLB712(2012)437.

partial wave decomposition — Miyamoto *et al.* (HAL QCD), PRD101(2020)074514.

higher order terms in the derivative expansion — Iritani *et al.* (HAL QCD), PRD99(2019)014514.

Lattice setup

2+1 flavor gauge configuration on 96^4 lattice

with Iwasaki gauge + NP $O(a)$ improved clover quark

$a \simeq 0.0846$ fm, $m_\pi \simeq 146$ MeV, $m_K \simeq 525$ MeV (near physical point)

$La \simeq 8.1$ fm

Ishikawa *et al.* (PACS), PoS Lattice2015(2016) 075.

relativistic heavy quark action (Tsukuba-type) for quenched charm quark

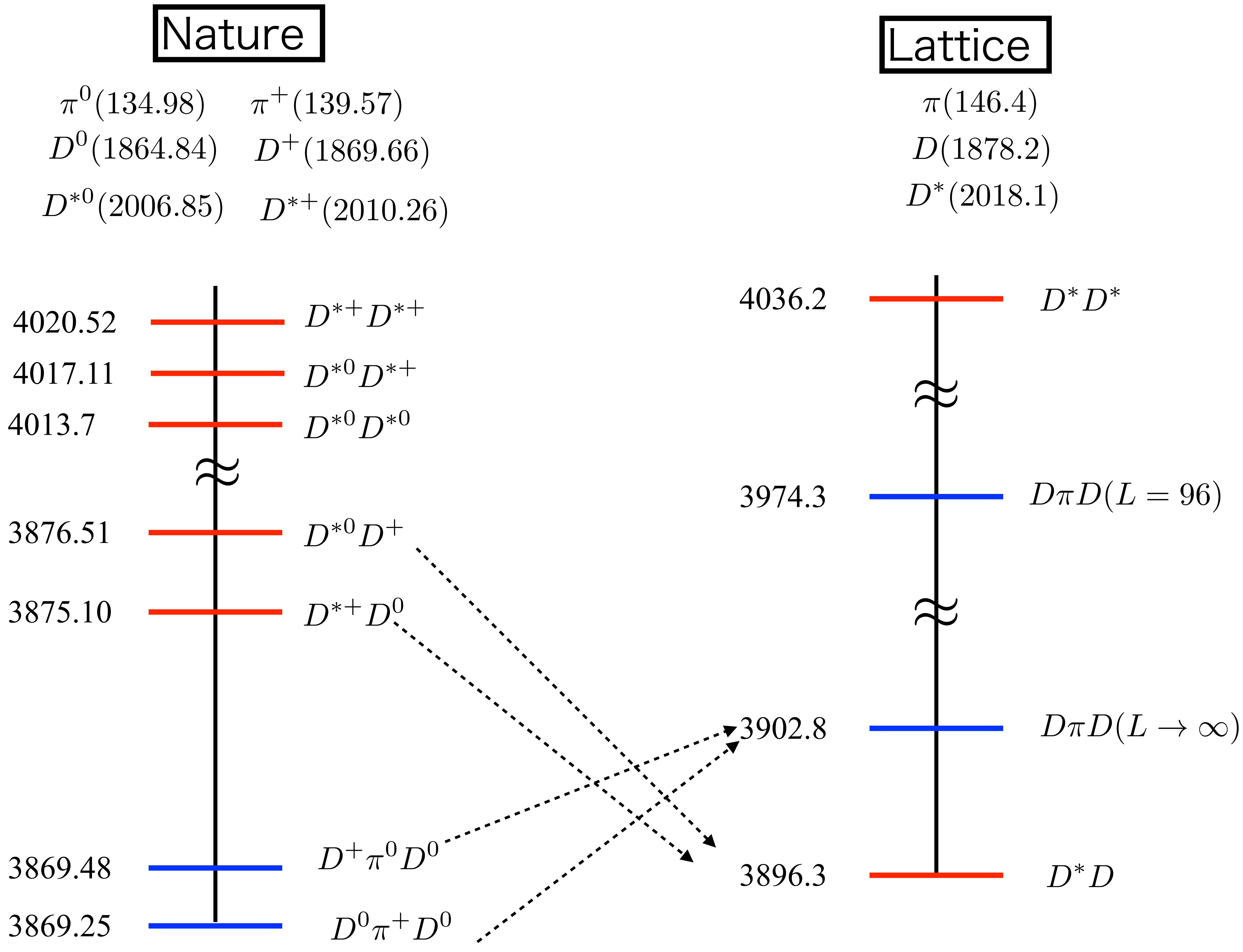
S. Aoki, Y. Kuramashi, S-i. Tominaga, PTEP 109(2003) 383.

charm quark mass from a spin-averaged mass of charmonium

	$(m_{\eta_c} + 3m_{J/\Psi})/4$ [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)	-

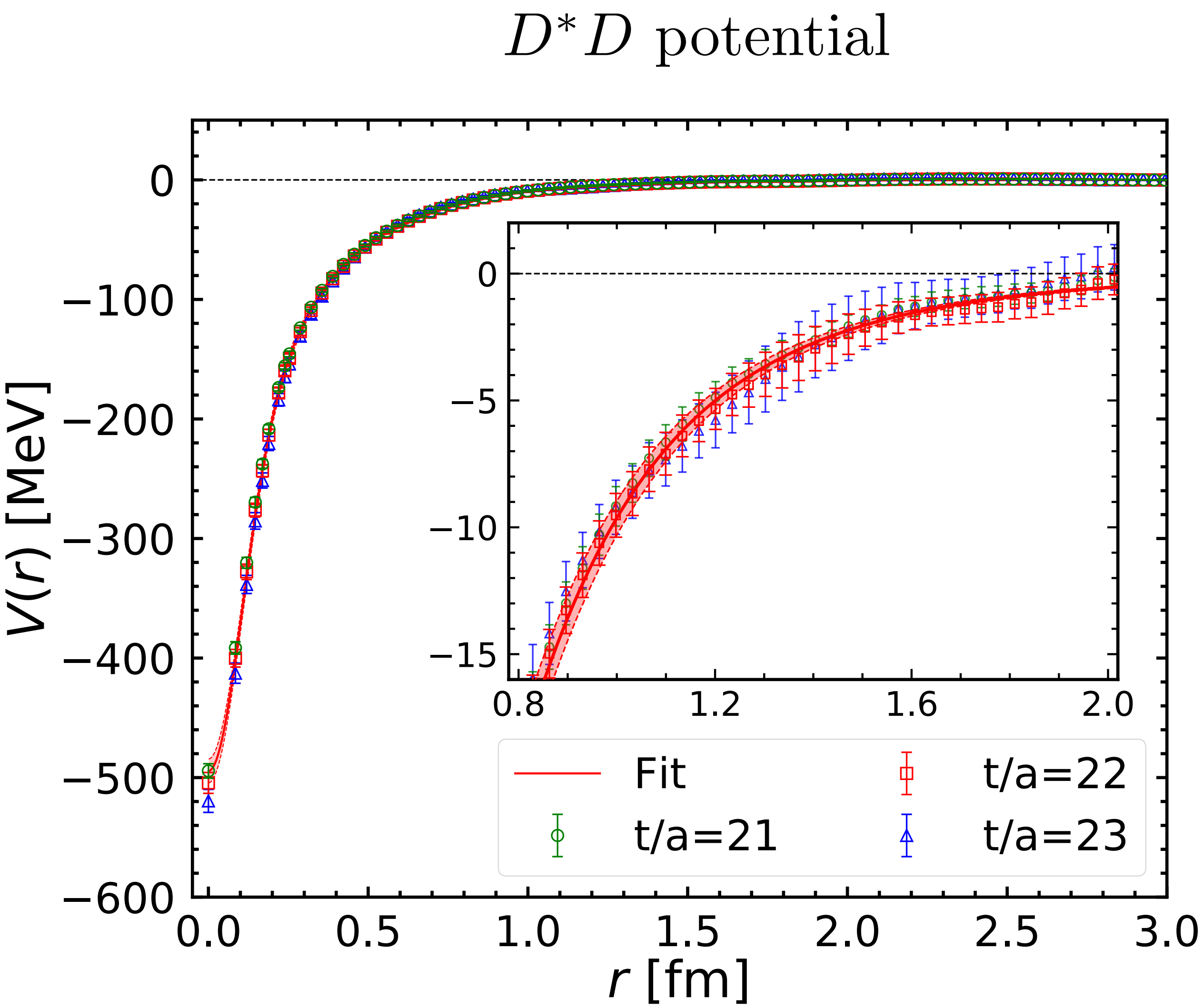
c.f. Y. Namekawa,(PACS), PoS Lattice2016(2017) 125.

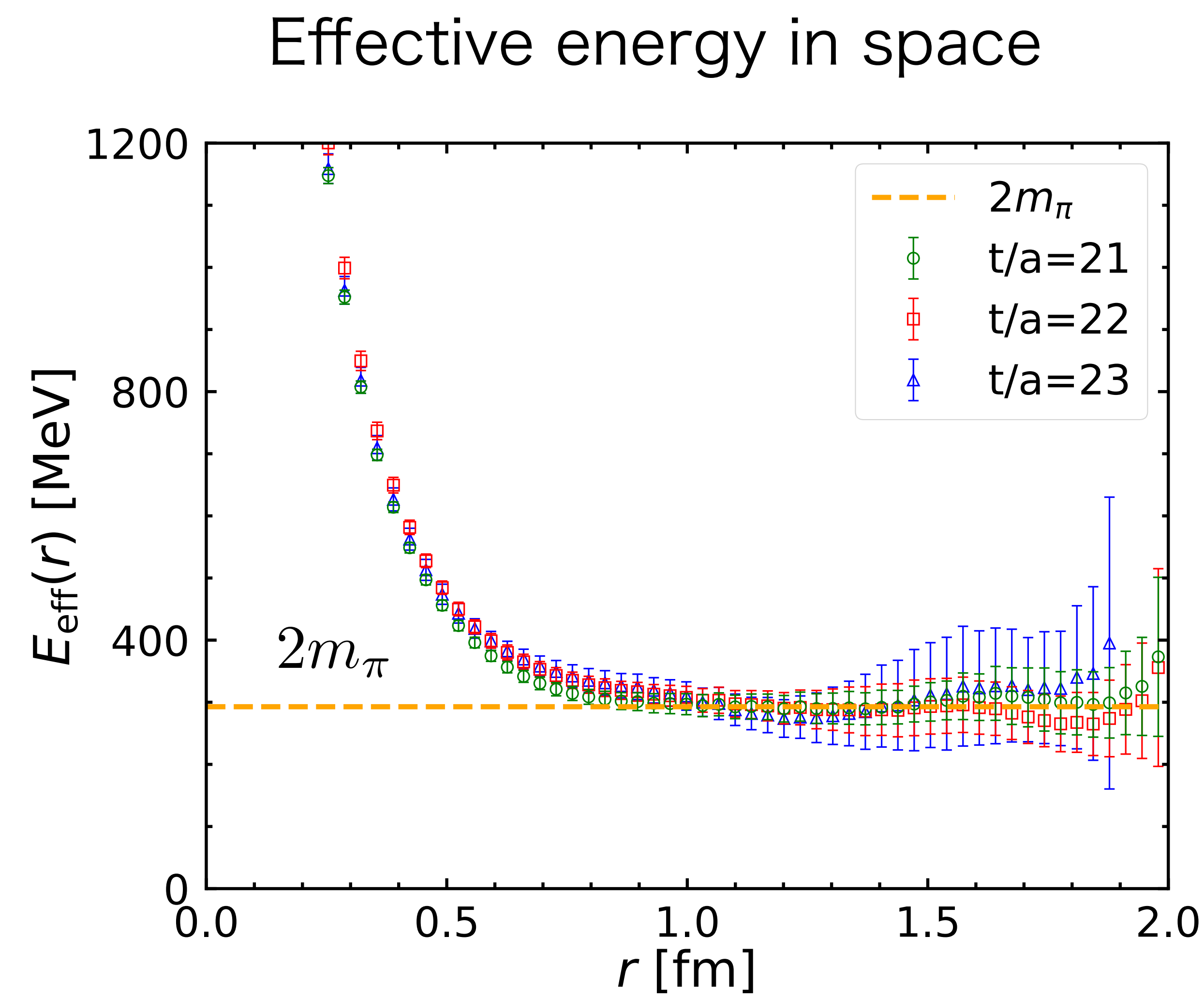
calculate D^*D potential   isospin-symmetric, single channel



Nature
$\pi^0(134.98)$ $\pi^+(139.57)$
$D^0(1864.84)$ $D^+(1869.66)$
$D^{*0}(2006.85)$ $D^{*+}(2010.26)$
4020.52 $D^{*+}D^{*+}$
4017.11 $D^{*0}D^{*+}$
4013.7 $D^{*0}D^{*0}$
3876.51 $D^{*0}D^+$
3875.10 $D^{*+}D^0$
3869.48 $D^+\pi^0D^0$
3869.25 $D^0\pi^+D^0$
Lattice
$\pi(146.4)$
$D(1878.2)$
$D^*(2018.1)$
4036.2 D^*D^*
3974.3 $D\pi D(L=96)$
3902.8 $D\pi D(L\to\infty)$
3896.3 D^*D

D^*D Potentials $m_\pi \simeq 146$ MeV





attractive at all distances

$$E_{\rm eff}(r) = -\frac{\ln[V(r)r^2/a_3]}{r}$$

consistent with Yukawa^2 at large r

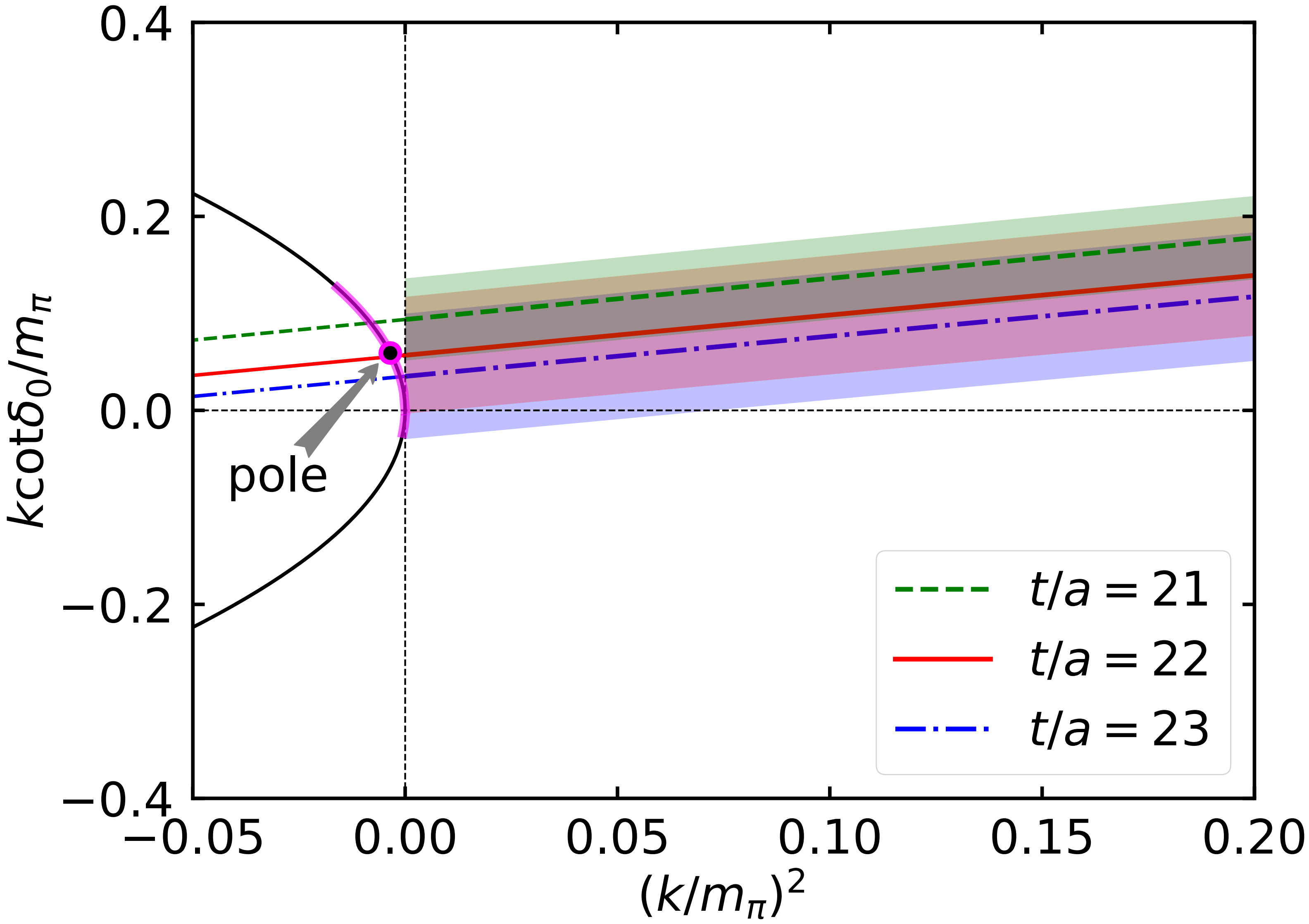
2-Gauss + Yukawa^2

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

Scattering phase shift

$m_\pi \simeq 146$ MeV

$k \cot \delta_0(k)$



ERE (effective Range Expansion)

$$k \cot \delta_0(k) = \frac{1}{a_0} + \frac{1}{2} r_{\mathrm{eff}} k^2 + O(k^4)$$

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

one shallow “virtual” state

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

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

“chiral” correction to the potential

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

$$m_\pi\ : 146.4\,\mathrm{MeV} \to 135\,\mathrm{MeV}$$

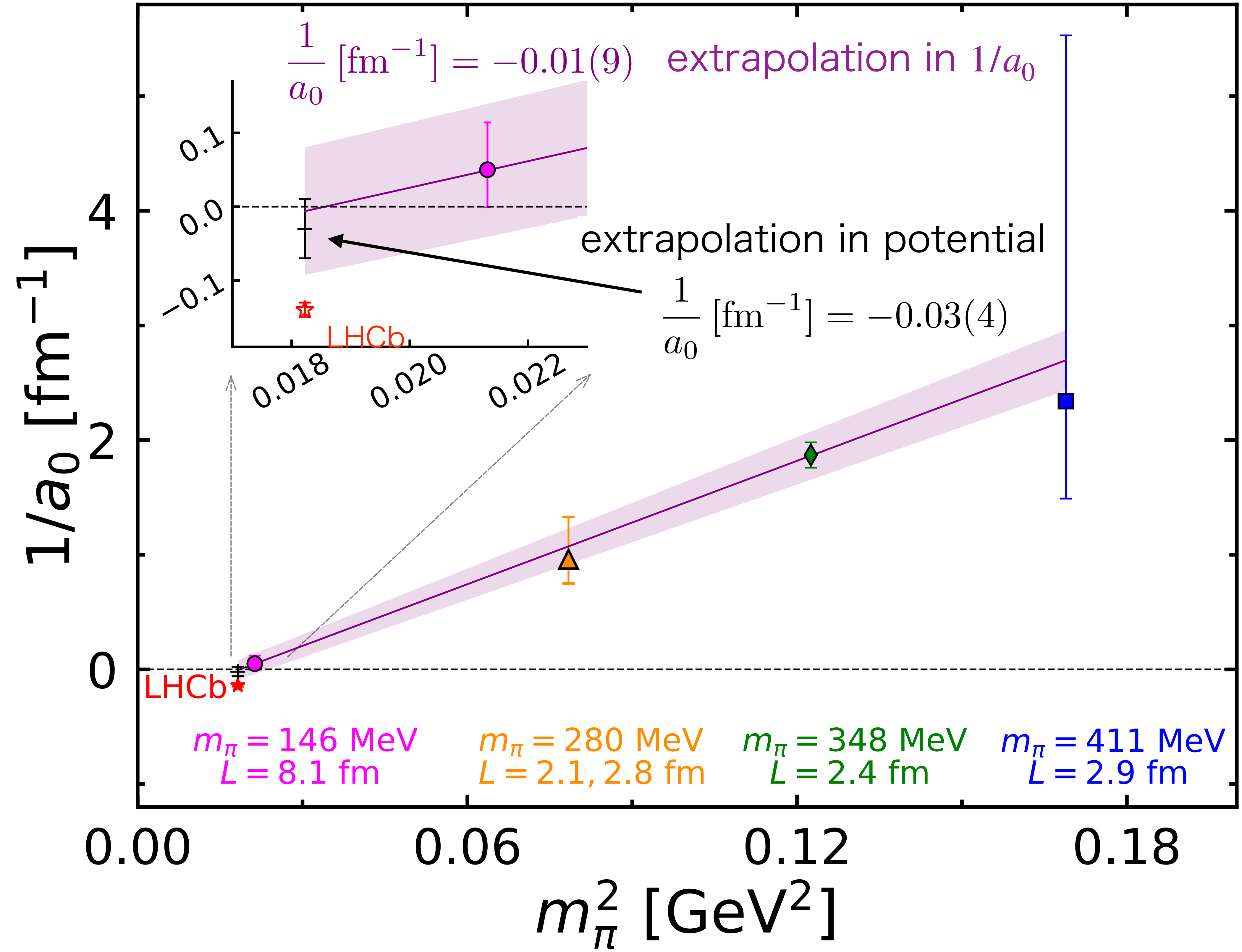
ERE $$k\cot\delta_0(k) = \frac{1}{a_0} + \frac{1}{2} r_{\rm eff} k^2 + O(k^4)$$

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

one shallow “bound” state appears at “physical” pion mass

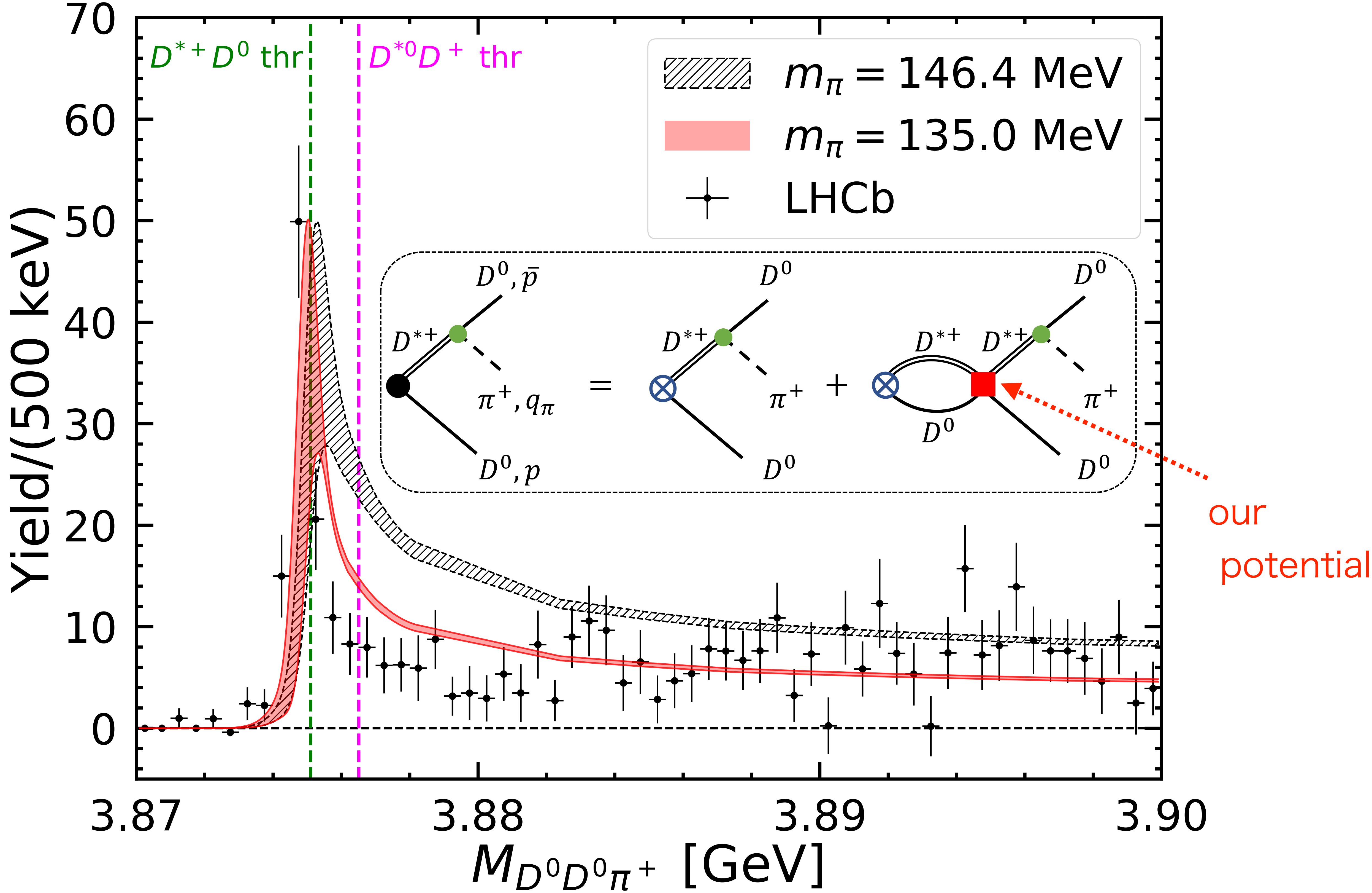
$$E_{\rm pole} = -45\ \left({}^{+41}_{-78}\right)\ \mathrm{keV}$$

chiral extrapolation of $1/a_0$ linear in m_π^2



Two chiral "extrapolations" are consistent.

$D^0D^0\pi^+$ mass spectrum



Our potential at “physical” pion mass explains LHCb data better.

Summary & Outlook

- We employ the HAL QCD method to investigate a doubly charmed tetra-quark T_{cc}^{+} at almost physical pion $m_\pi = 146$ MeV .
  - D^*D potential is attractive at all distances.
  - The system appears very close to unitarity, so that a small change in pion mass from 146 MeV to 135 MeV leads to significant changes in physical observables.
    - from a virtual state to a bound state
    - better agreement in the mass spectrum with LHCb
- A more reliable chiral extrapolation is required.
  - This may be a challenge for the finite volume method, since energy shift is very small.
  - configurations at a “physical” pion mass ($m_\pi \simeq 135$ MeV) are generated on Fugaku. Stay tuned.

    E. Itou (HALQCD), poster. T.M. Doi (HALQCD), Thu 03/08 17:00@Hadron and Nucelar Spectrum and interactions
  - (Challenge) Inclusion of iso-spin breaking effect (quark mass and QED) might be required. Then a coupled channel analysis is mandatory.

Thank you !