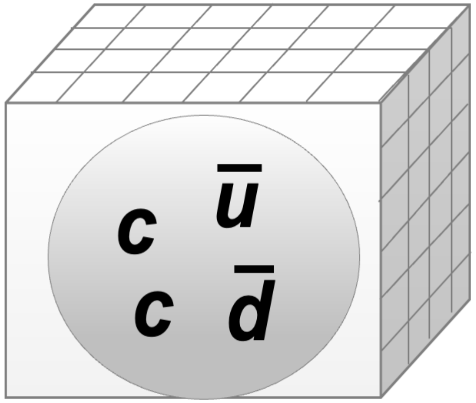
Towards quark mass dependence of T_{cc}



Sasa Prelovsek

University of Ljubljana & Jozef Stefan Institute, Slovenia

sasa.prelovsek@ijs.si

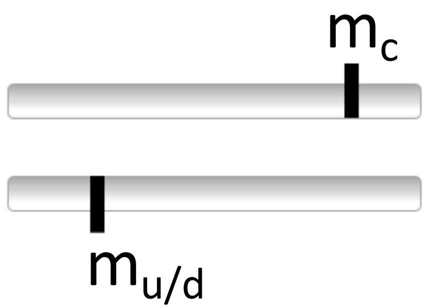
Lattice 2024, July 2024, Liverpool

Sara Collins, Alexey Nefediev, M. Padmanath , SP [2402.14715, PRD]

Regensburg

Ljubljana

Chennai



follow-up of M. Padmanath, SP [2202.10110, PRL]

T_{cc} from LHCb experiment

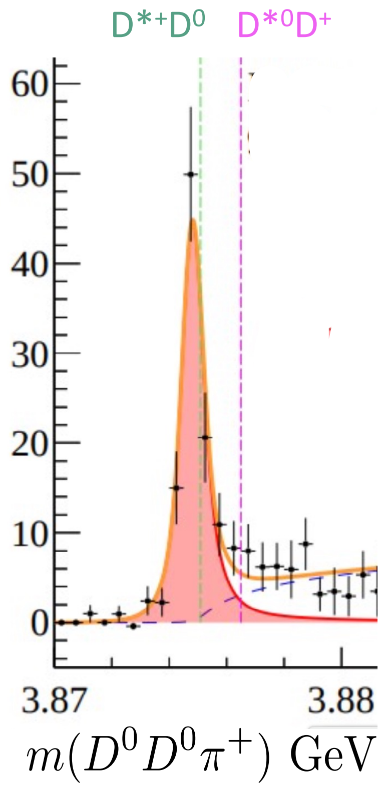
$D^* \to D\pi$

$m_{\pi^0} \simeq 135$ MeV

$m_{D^{*+}} - m_{D^+} \simeq 140$ MeV

$cc\bar{d}\bar{u}$ I=0, $J^P=1^+$ (most likely)

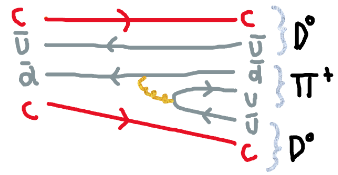
The longest lived exotic hadron ever discovered



$$\delta m = m - (m_{D^{*+}} + m_{D^0})$$

$$\delta m_{pole} = -0.36 \pm 0.04 \text{ MeV}$$

LHCb 2109.01038, 2109.01056, Nature Physics



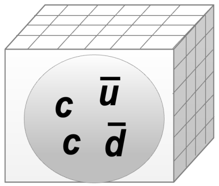
Omitting $D^* \to D\pi,\ T_{cc} \to DD\pi$

T_{cc} would be a bound state

T_{cc} from lattice

all analyzed in 2402.14715, PRD

Collins, Nefediev, Padmanath , SP



all simulations :

$$m_u = m_d > m_{u,d}^{ph} \qquad m_\pi > m_{D^*} - m_D$$

$$D^* \not\to D\pi$$

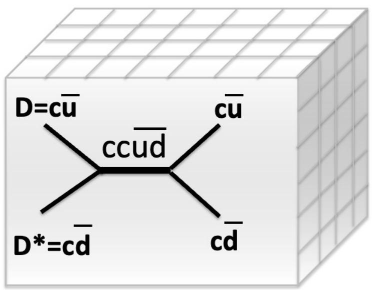
single lattice spacing

(J. Green et al are exploring

several lattice spacings, lat 2023, unpublished)

mc	mpi	L	ensmbles	ref.
five values m_D=1.7–2.4 GeV	280 MeV	~ 2.1, 2.8 fm	CLS Nf=2+1	our, 2402.14715, PRD eigenenergies

mc	mpi	L	ensembles	ref.
~ physical	146 MeV	~ 8 fm	Nf=2+1	HALQCD, 2302.04505, PRL HALQCD potentials
~ physical	280 MeV	~ 2.1, 2.8 fm	Nf=2+1, CLS	our, 2402.14715, PRD eigenenergies
~ physical	348 MeV	~ 2.4 fm	Nf=2	CLQCD, 2206.06186, PLB eigenenergies



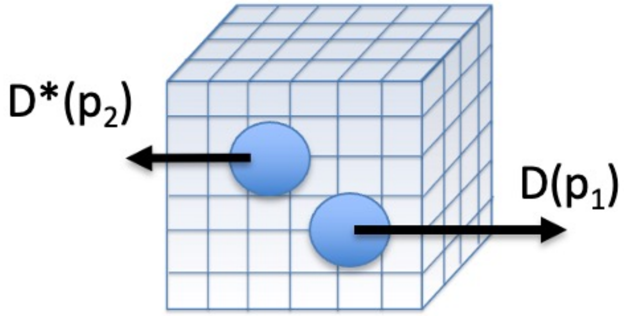
Interpolators and E_n [our simulation, CLQCD]

$I=0,\ J^P=1^+$

$cc\bar{u}\bar{d}$

$\vec{P}=\vec{p}_1+\vec{p}_2$

$|\vec{P}|=0,1$



D(p1) D*(p2)

$$\mathcal{O}=(\bar{u}\gamma_5 c)_{\vec{p}_1}\ (\bar{d}\gamma_i c)_{\vec{p}_2}-(\vec{p}_1\leftrightarrow\vec{p}_2)\qquad \vec{p}_{1,2}=\vec{n}_{1,2}\,\frac{2\pi}{L}$$

$$(\bar{u}\gamma_5\gamma_t c)_{\vec{p}_1}\ (\bar{d}\gamma_i\gamma_t c)_{\vec{p}_2}$$

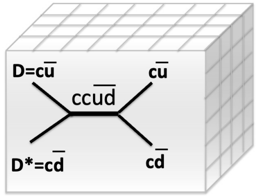
[cc][ud] interloators not employed

[their effect discussed in the next talk by Ivan Vujmilovic]

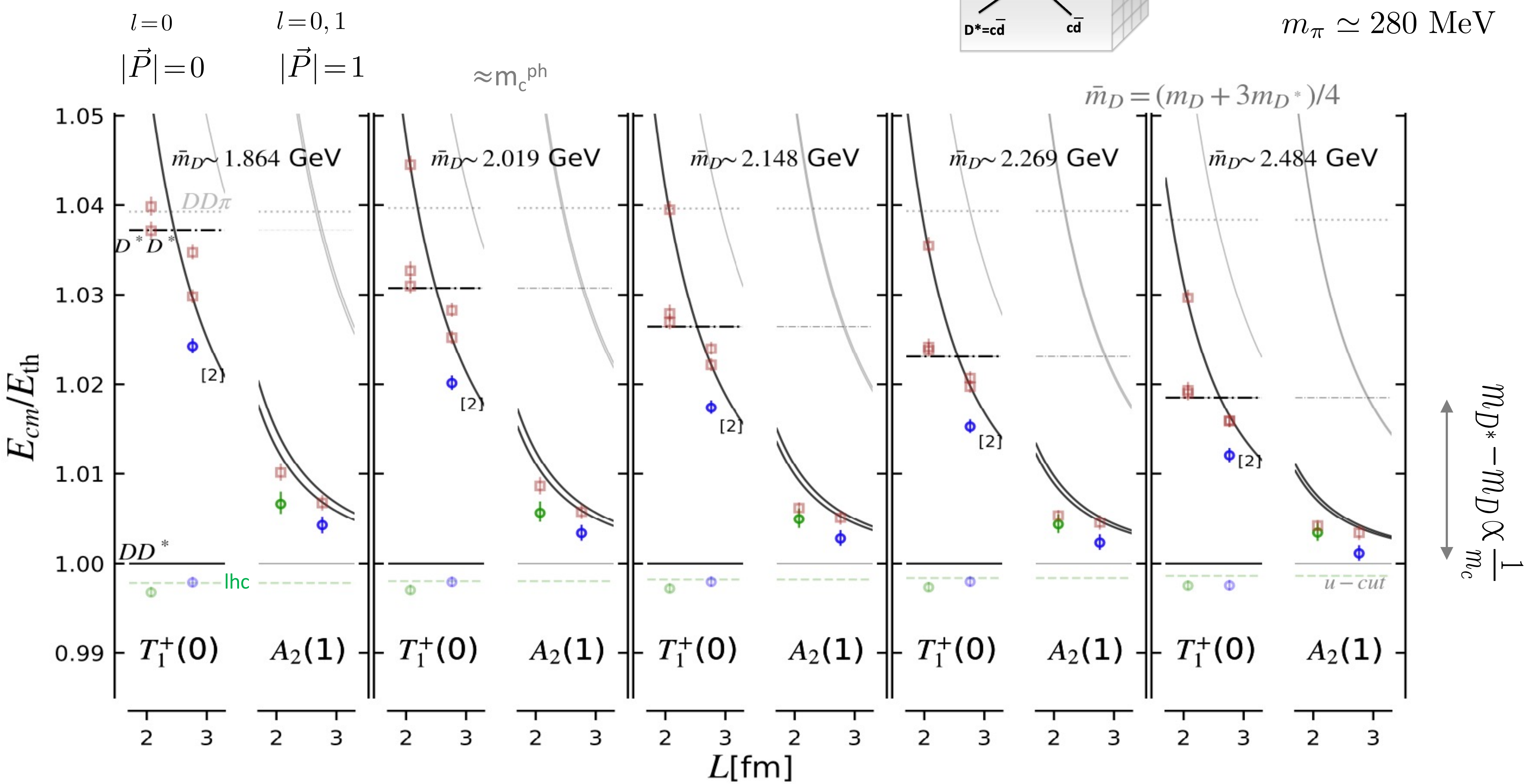
$$C^{2pt}_{ij}(t)=\langle 0|\mathcal{O}_i(t)\ \mathcal{O}_j^{+}(0)|0\rangle=\sum_n \langle 0|\mathcal{O}_i|n\rangle\ e^{-E_n t_E}\langle n|\mathcal{O}_j^{+}|0\rangle$$

- our simulation: distillation
- GeVP

T_{cc} : finite-volume eigen-energies



$m_\pi \simeq 280$ MeV



lines

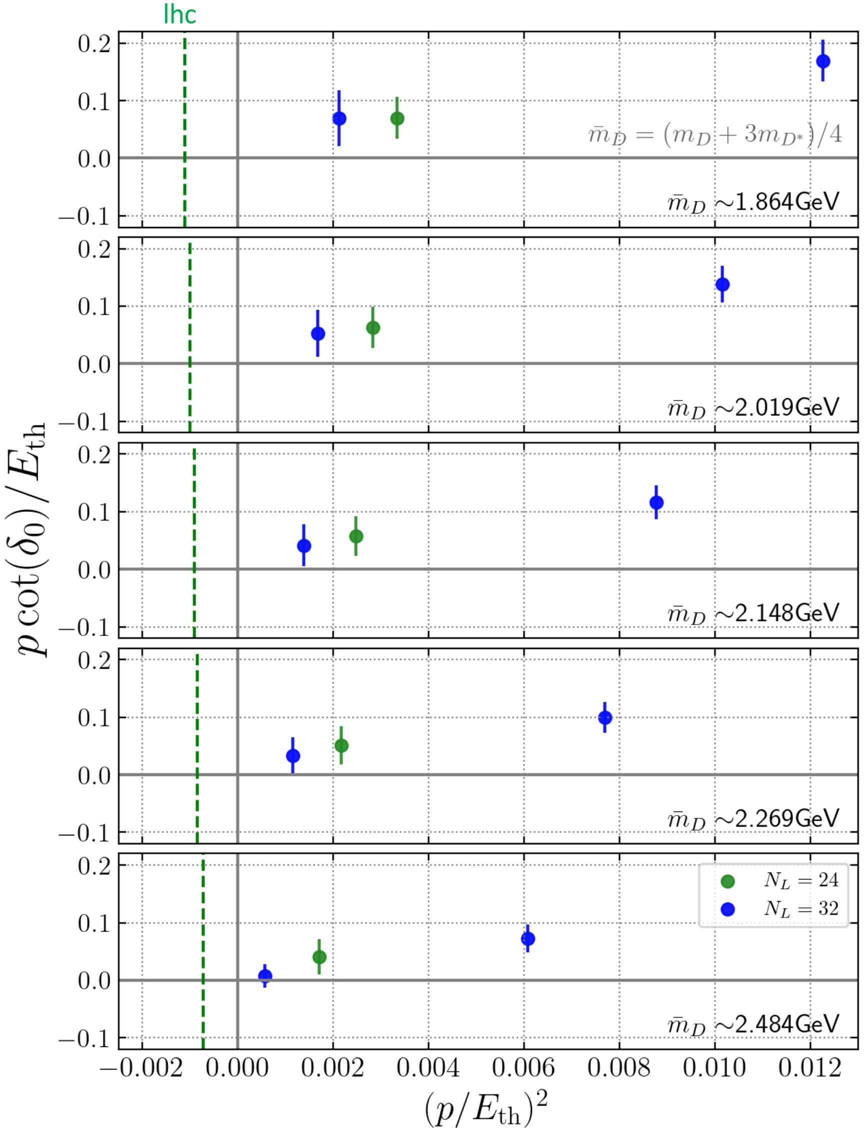
$$E^{n.i.} = \sqrt{m_D^2 + \vec{p}_1^{\,2}} + \sqrt{m_{D^*}^2 + \vec{p}_2^{\,2}}$$

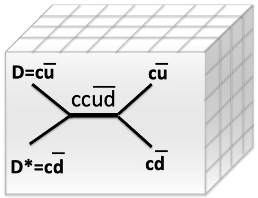
$$\vec{p}_i = \vec{n}_i \frac{2\pi}{L}$$

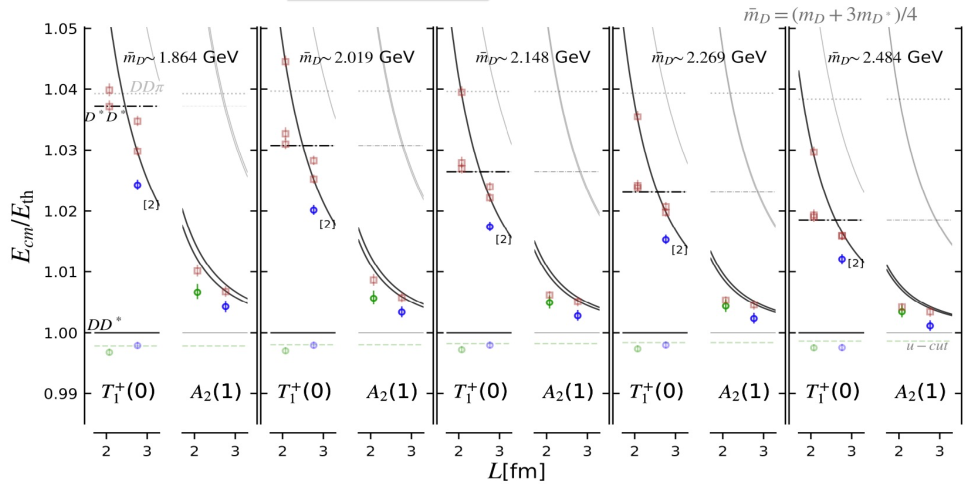
- all levels below threshold are omitted from the scattering analysis (throught this talk)

T_{cc} : scattering amplitude

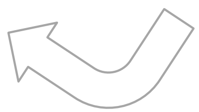
- all levels below threshold are omitted from the scattering analysis
- result on s-wave are consistent if p-wave included in analysis of A_2(P=1) or not
- p-wave constrained also from A_1^- (P=0) which is not shown

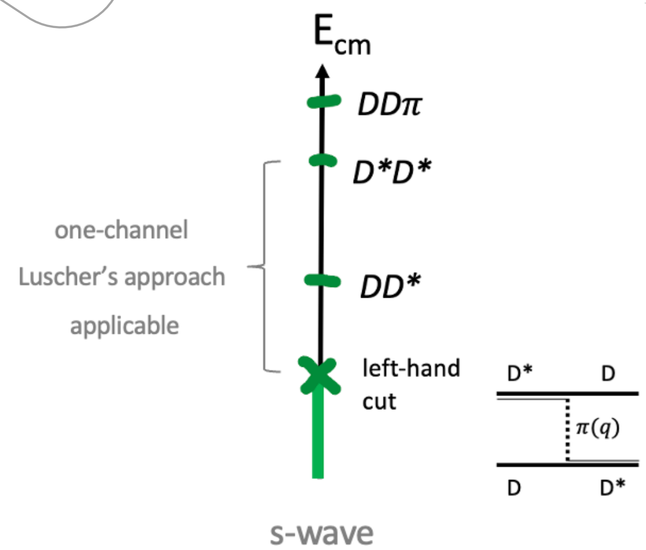




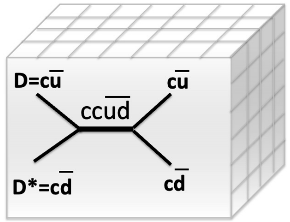


δ(E) E



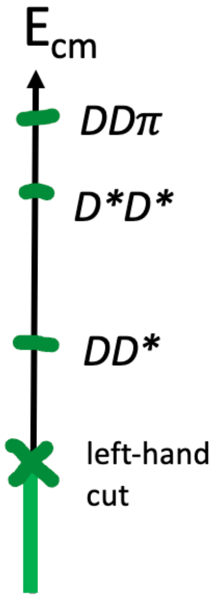


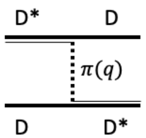
Plan: intepolating/extrapolating energy dependence of DD* scattering amplitude



Part 1 (main result)

EFT approach
incorporating
left-hand cut



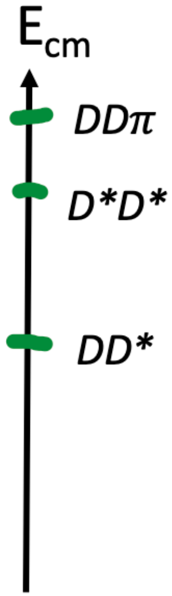


Part 2 (briefly)

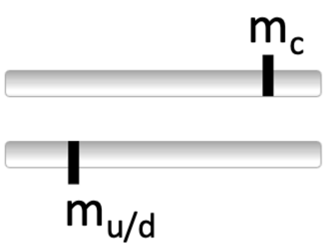
assuming eff. range

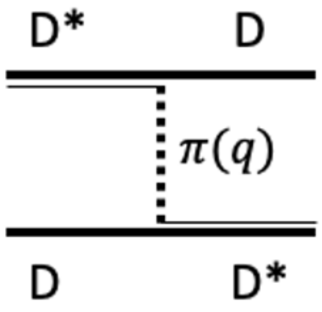
$$p\cot\delta_0 = \frac{1}{a_0} + \frac{1}{2}\, r_0\, p^2$$

ignoring left-hand cut



In both cases:





Analysis of T_{cc} lattice results based on Effective Field Theory

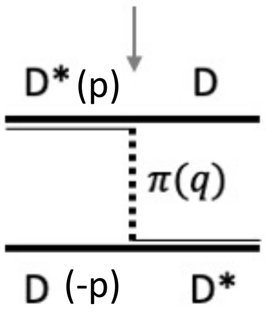
taking into account effect from left-hand cut

Pion exchange, left-hand cut etc

Heavy meson ChPT

$g_c(m_\pi),\ f_\pi(m_\pi)$

$$\frac{g_c}{2f_\pi}\vec{q}$$



$$q^2 = q_0^2 - \vec{q}^{\,2} \simeq (m_{D^*} - m_D)^2 - \vec{q}^{\,2}$$

$$V_\pi^{cent}(\vec{q}) = \frac{g_c^2}{4f_\pi^2}\,\frac{\vec{q}^{\,2}}{q^2 - m_\pi^2} = \frac{g_c^2}{4f_\pi^2}\left(-1 + \frac{\mu_\pi^2}{\vec{q}^{\,2} + \mu_\pi^2}\right)$$

$$\mu_\pi^2 = m_\pi^2 - (m_{D^*} - m_D)^2$$

$\mathrm{lat}:\ \mu_\pi^2 > 0$

$\mathrm{ph}:\ \mu_\pi^2 < 0$

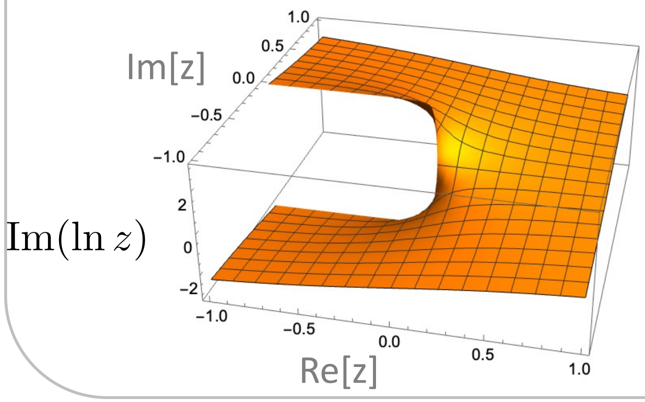
attraction at short distance	slight repulsion at long distance
$-\delta^{(3)}(\vec{r})$	$\frac{\mu_\pi^2}{r} e^{-\mu_\pi r}$

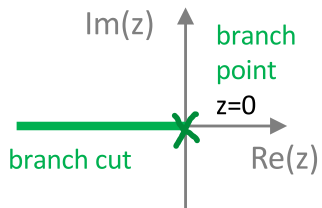
s-wave projection

$$V_\pi^S(p,p) \propto \int V_\pi(\vec{q})\ d\cos\theta, \quad \vec{q}^{\,2} = 2p^2(1-\cos\theta)$$

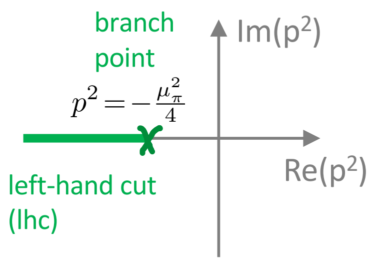
$$V_\pi^S(p,p) \propto \ln\left(1 + \frac{4p^2}{\mu_\pi^2}\right)$$

complex p cot δ (Luscher's eq would render it real)





$\ln(z)$



$V_\pi(p^2),\ T_\pi(p^2)$

lhc slightly below DD*, BB*, NN ... th.

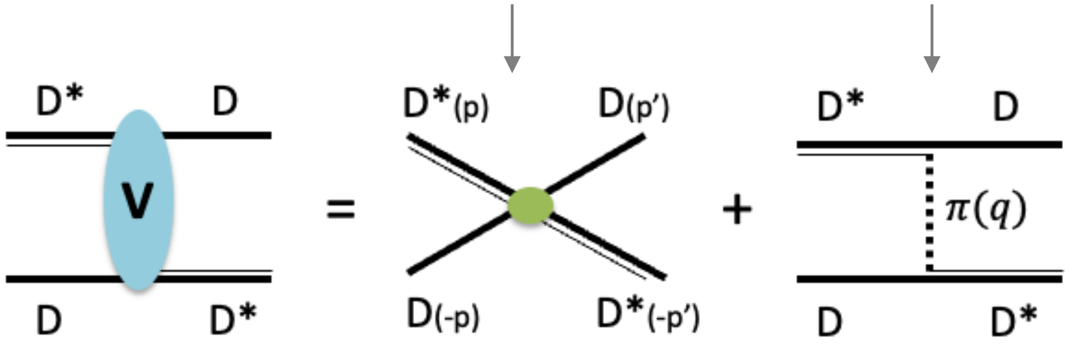
T_{cc} analysis based on EFT

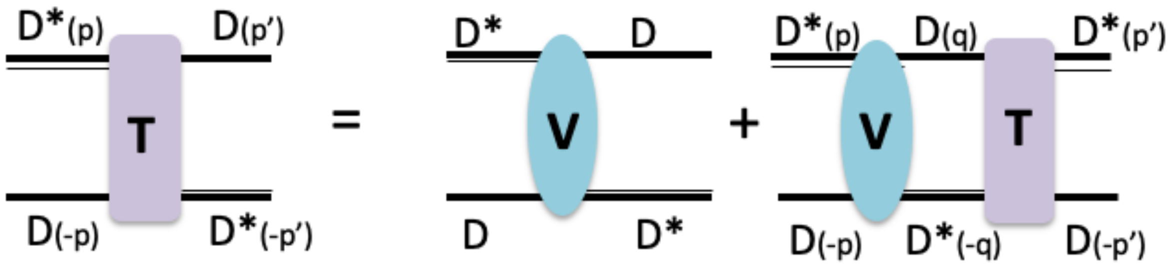
$c_{0,2}$ fitted from lat. data

significant short-distance attraction

$$V_{CT} = 2c_0 + 2c_2(p^2 + p'^2)$$

$$\frac{g_c}{2 f_\pi} \vec{q}$$





$$T = V - VGT$$

$$T = \frac{1}{V^{-1} + G}$$

$$T(\boldsymbol{p}, \boldsymbol{p}'; E) = V(\boldsymbol{p}, \boldsymbol{p}') - \int \frac{d^3 q}{(2\pi)^3} V(\boldsymbol{p}, \boldsymbol{q}) G(\boldsymbol{q}; E) T(\boldsymbol{q}, \boldsymbol{p}'; E)$$

Lipmann-Schwinger eq.

$$|\vec{q}| < \Lambda = 0.5 \text{ GeV}$$

cut-off on q:

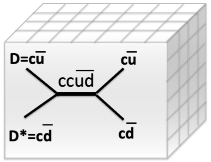
$c_{0,2}$ depend on Λ,

poles dont

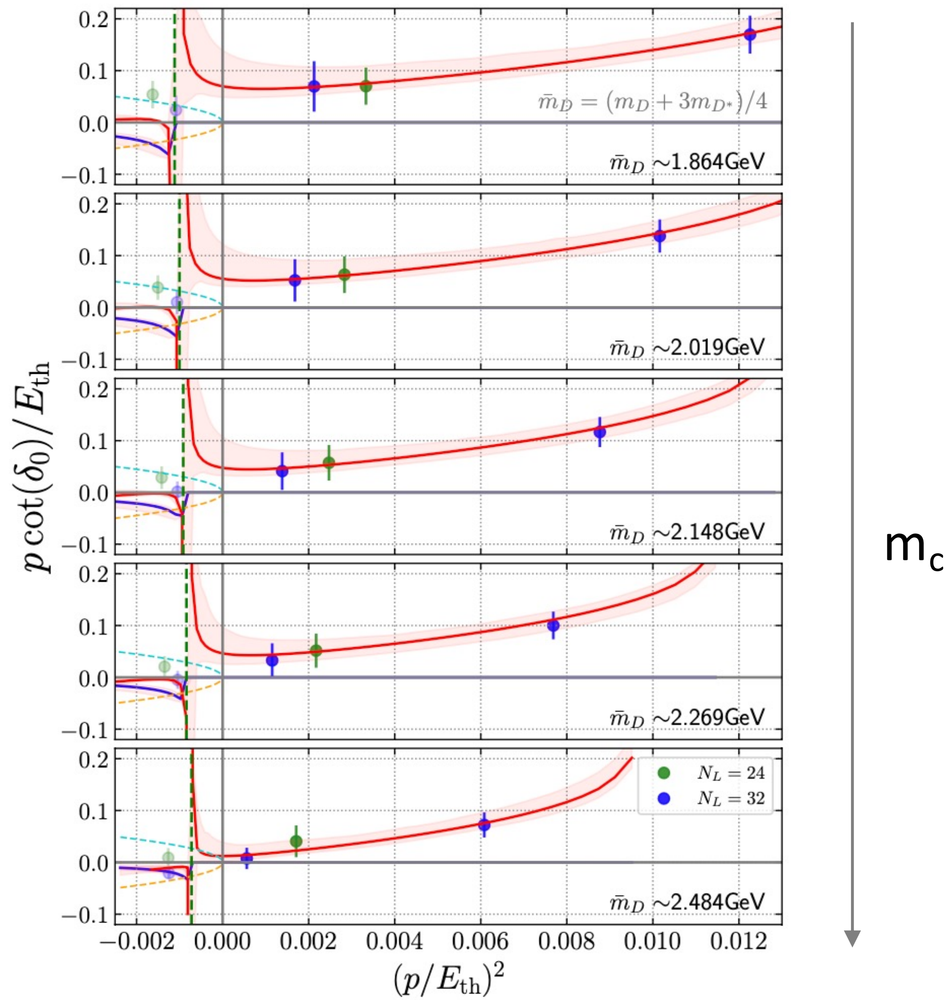
inspired by

Du, Hanhart, Guo, Nefediev, Filin, et al, PRL 2023, 2303.09441

T_{cc} : pole trajectory



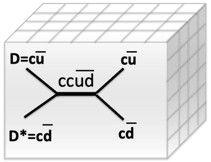
$m_\pi \simeq 280$ MeV

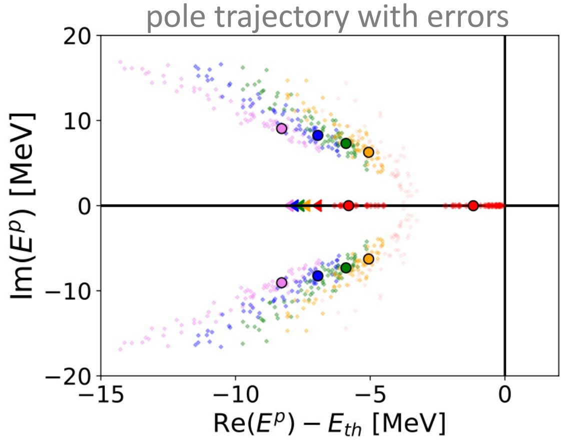


levels below lhc omitted from the fit

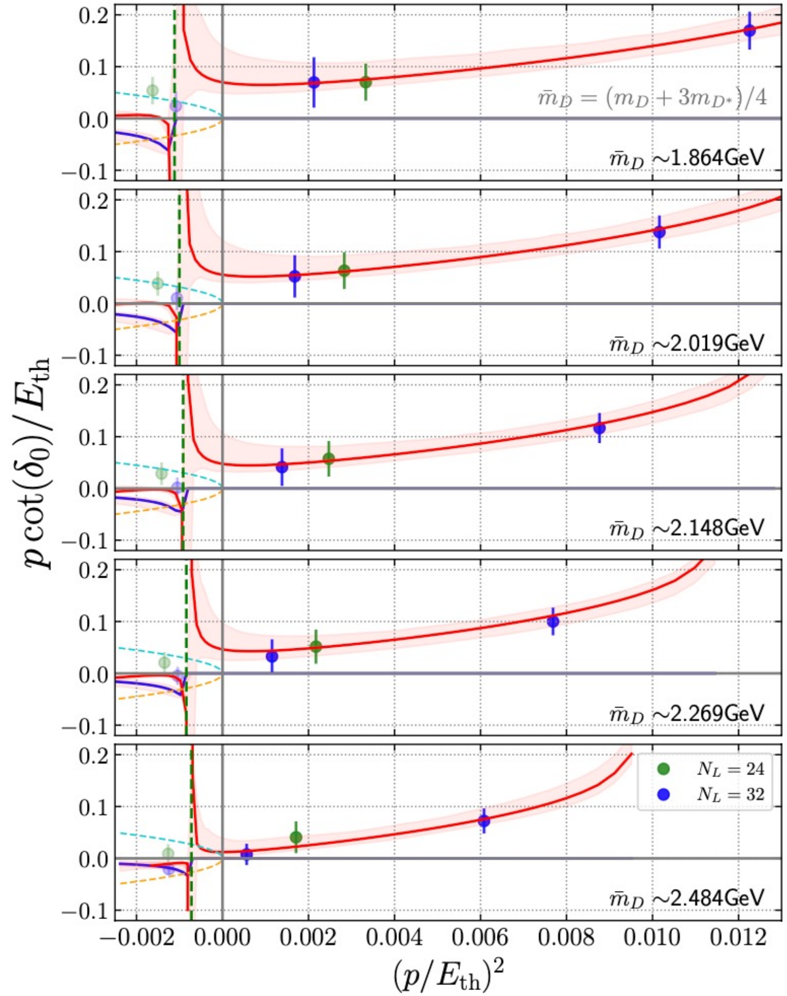
it is reassuring that consistent results are obtained via plane-wave method, which can incorporate also levels on lhc, Meng, Baru, Epelbaum et al., 2312.01930, PRD; Vujmilovic (next talk)

T_{cc} : pole trajectory

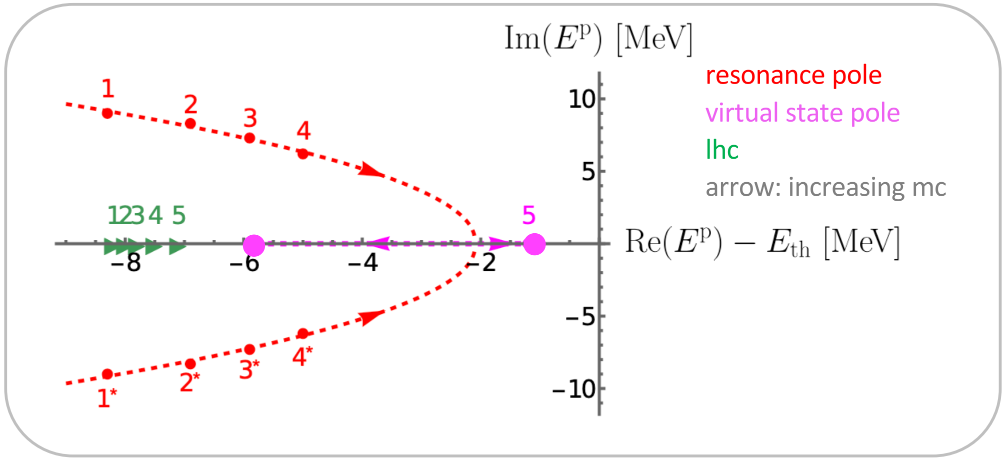


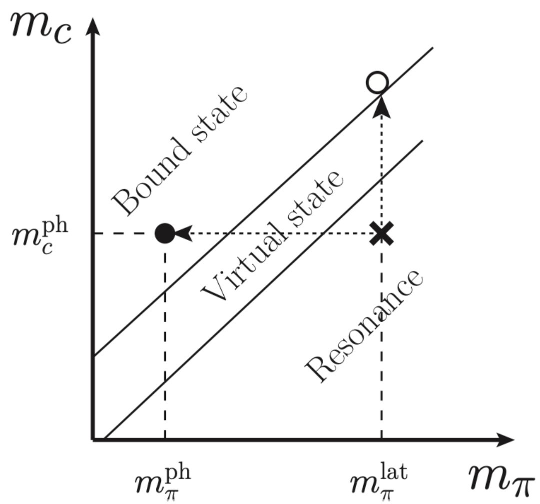


$m_\pi \simeq 280$ MeV



pole trajectory: central values





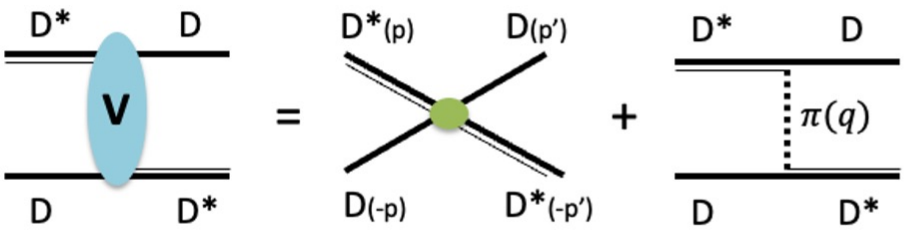
levels below lhc omitted from the fit

it is reassuring that consistent results are obtained via plane-wave method, which can incorporate also levels on lhc, Meng, Baru, Epelbaum et al., 2312.01930, PRD; Vujmilovic (next talk)

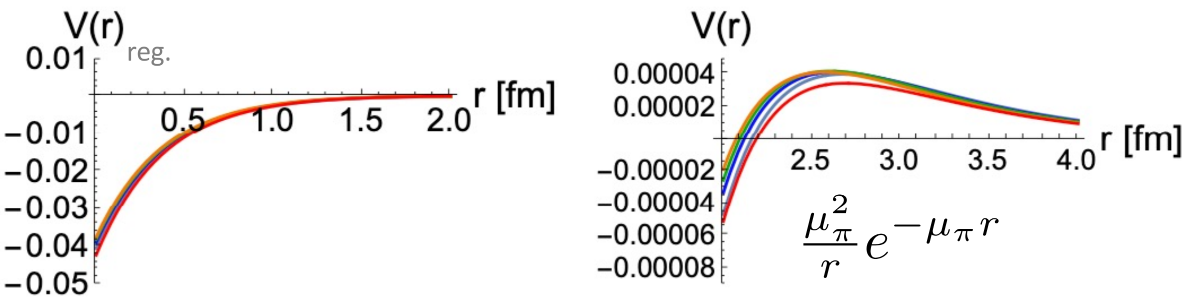
T_{cc} : interpretation

$m_\pi \simeq 280$ MeV

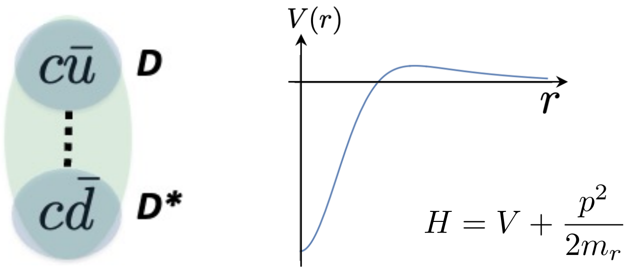
V(q)



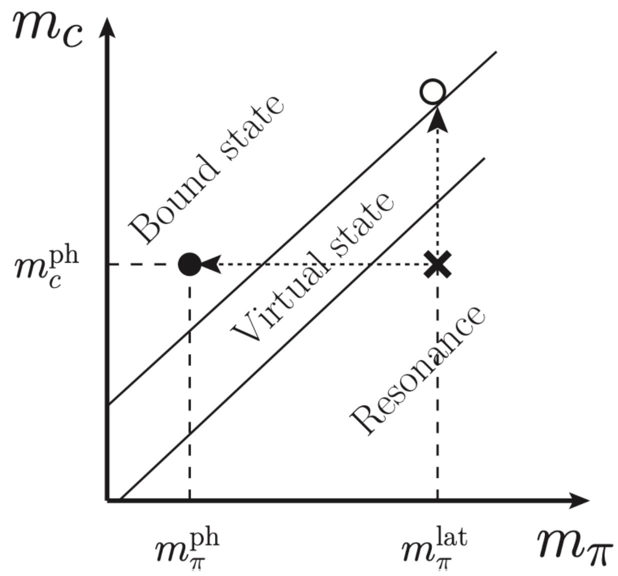
FT



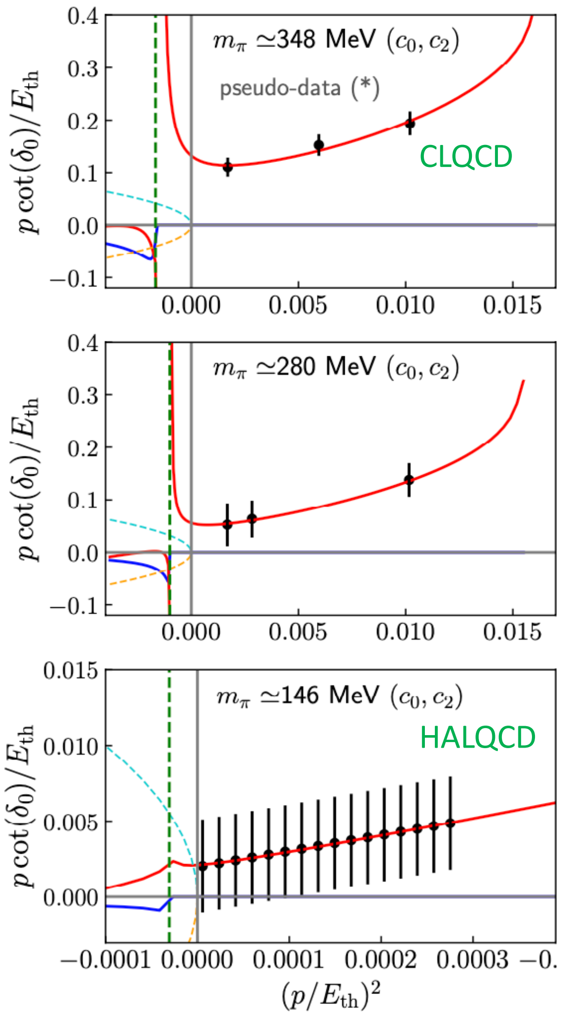
$\mu_\pi^2 = m_\pi^2 - (m_{D^*} - m_D)^2 > 0$

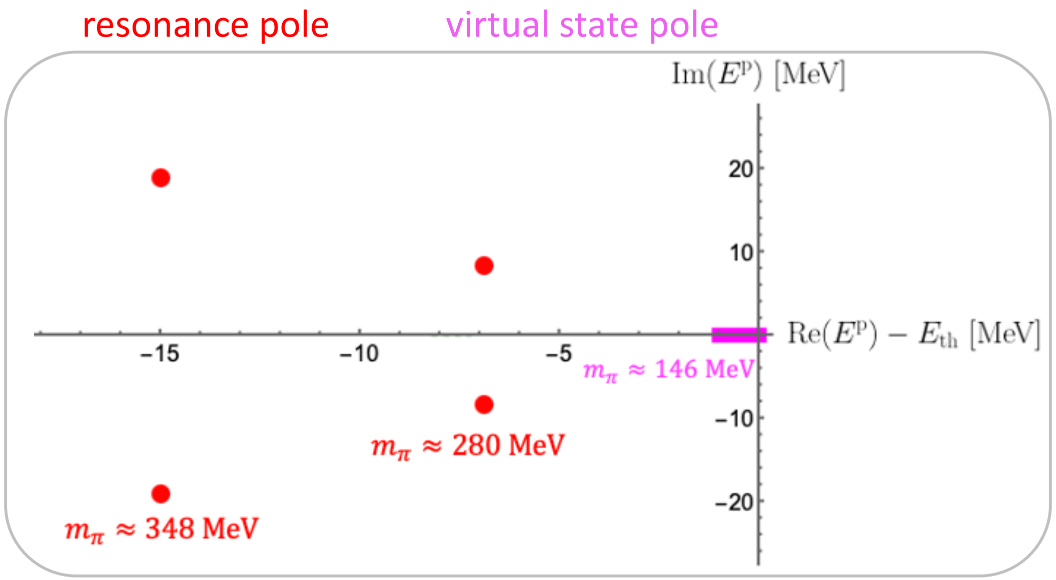


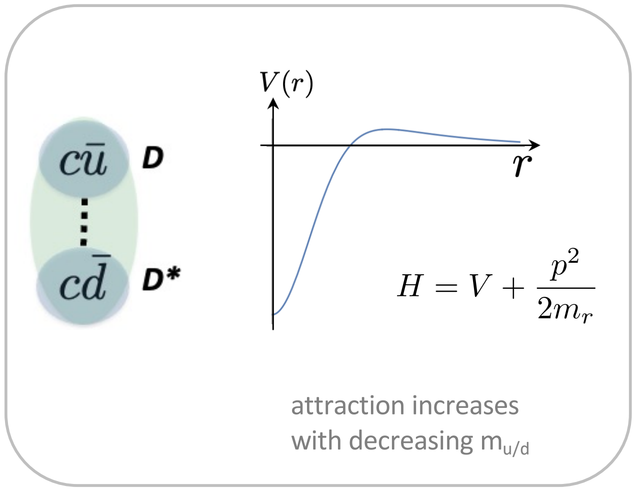
V almost independent on m_c

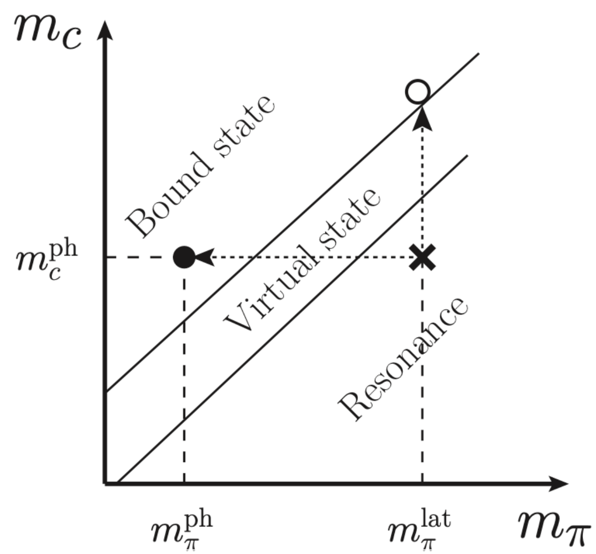


T_{cc} analysis based on EFT









errors on $m_{u/d}$ dependence not reliably determined

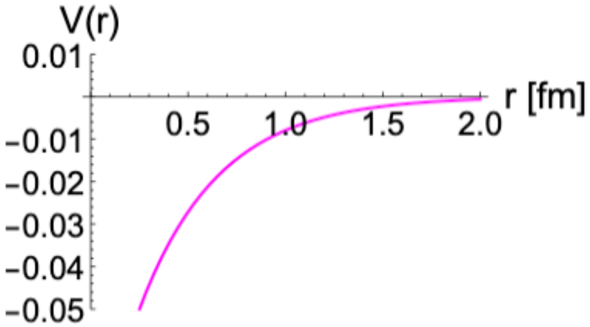
(see disclaimers in our paper)

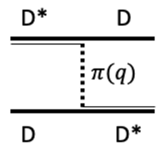
see also: 2407.04649,

Abolnikov, Baru, Epelbaum, Filin, Hanhart, Meng

Signature of one-pion exchange in HALQCD potential ?

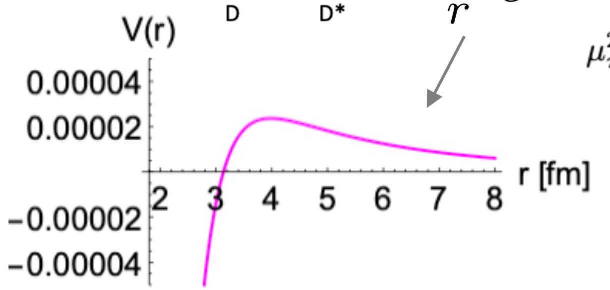
$m_\pi \simeq 146\ \mathrm{MeV}$



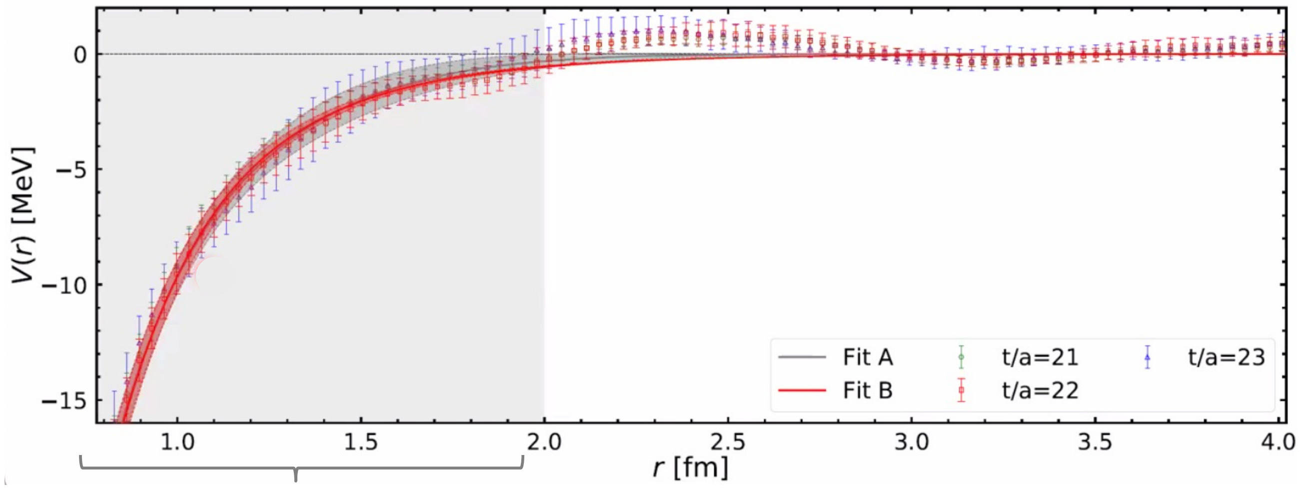


$$\frac{\mu_\pi^2}{r} e^{-\mu_\pi r}$$

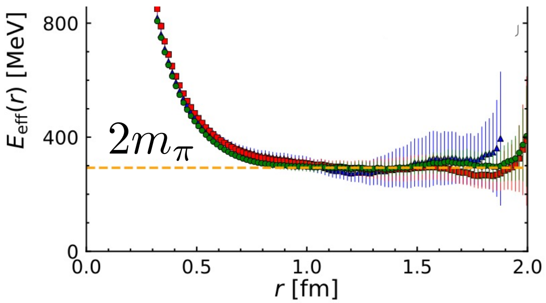
$$\mu_\pi^2 = m_\pi^2 - (m_{D^*} - m_D)^2$$



HALQCD, 2302.04505, PRL, talk by Yan Lyu



used in fit by HALQCD



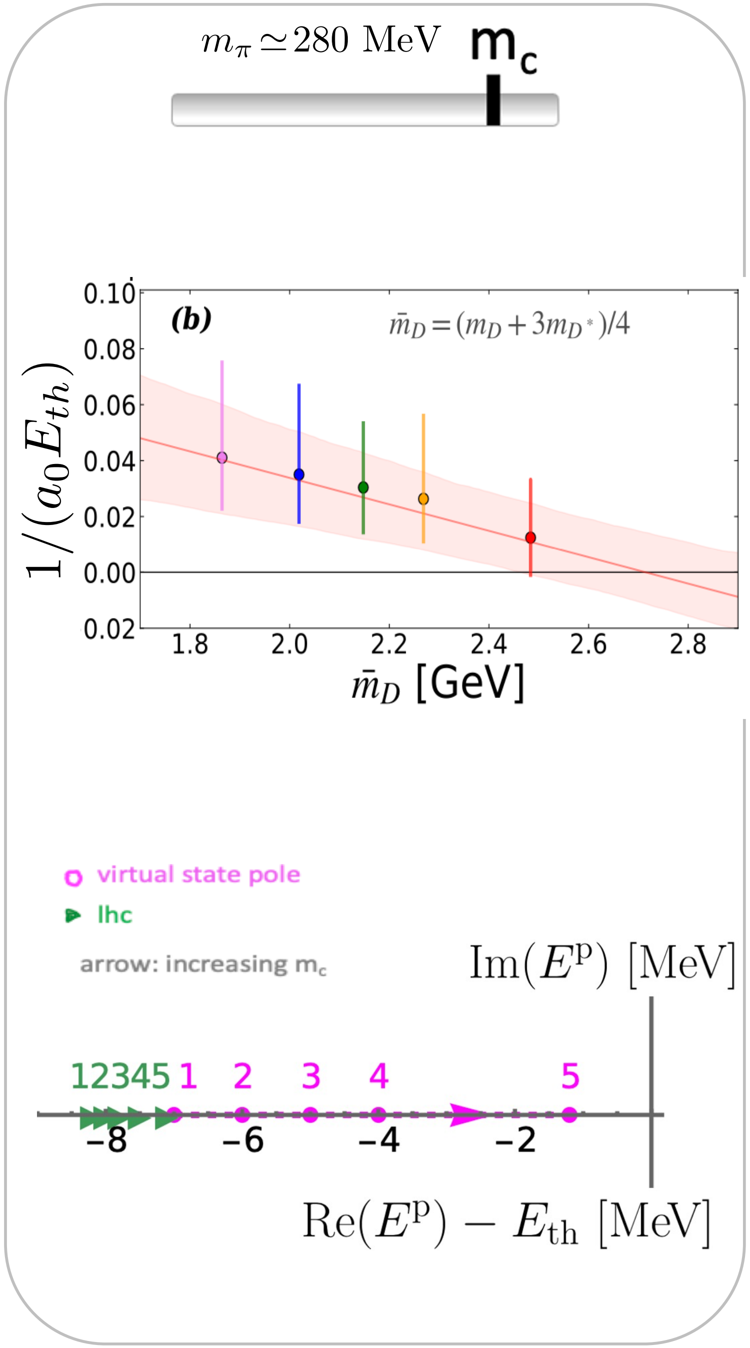
Analysis of T_{cc} lattice results assuming effective range expansion

omitting effects from left-hand cut

$$p \cot \delta_0 = \frac{1}{a_0} + \frac{1}{2}\, r_0\, p^2 + \ldots$$

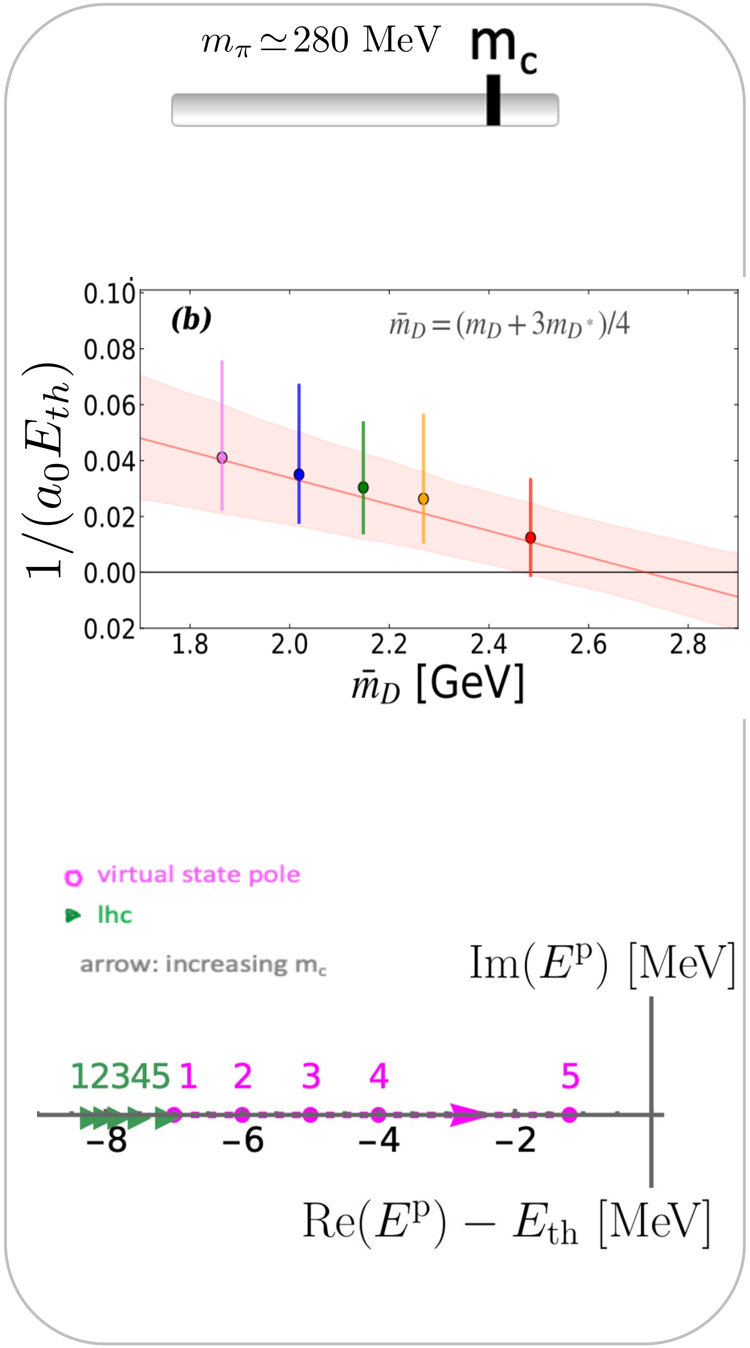
T_{cc} assuming eff. range expansion

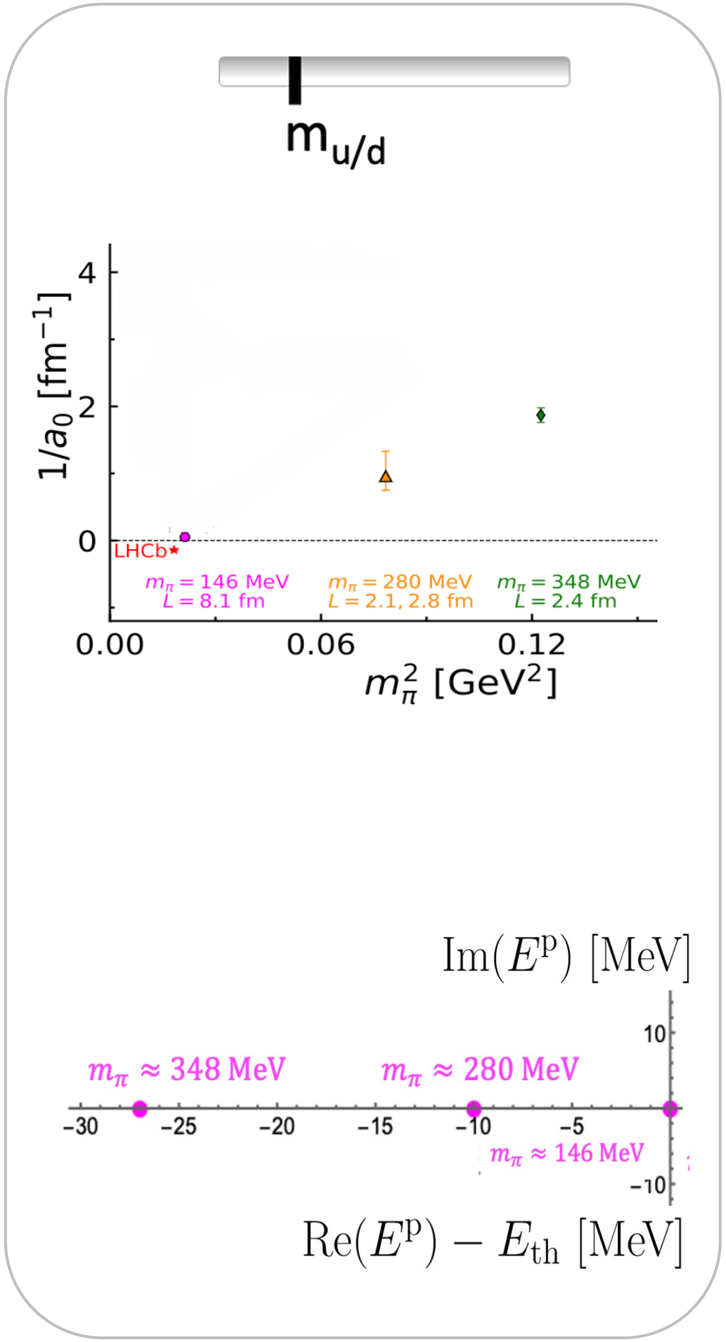
$$p \cot \delta_0 = \frac{1}{a_0} + \frac{1}{2}\ r_0\ p^2$$



T_{cc} assuming eff. range expansion

$$p \cot \delta_0 = \frac{1}{a_0} + \frac{1}{2}\, r_0\, p^2$$



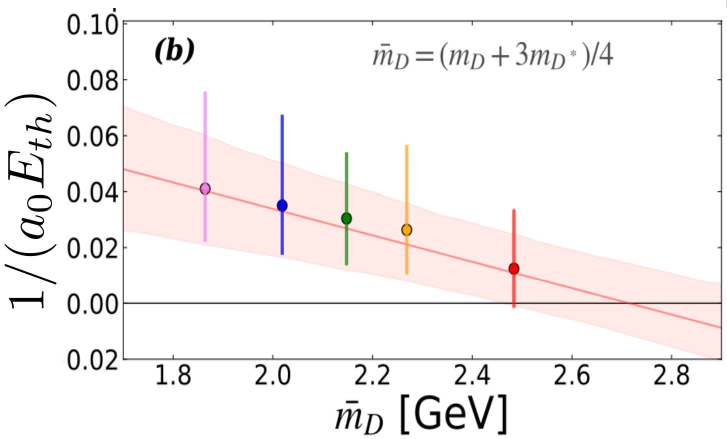


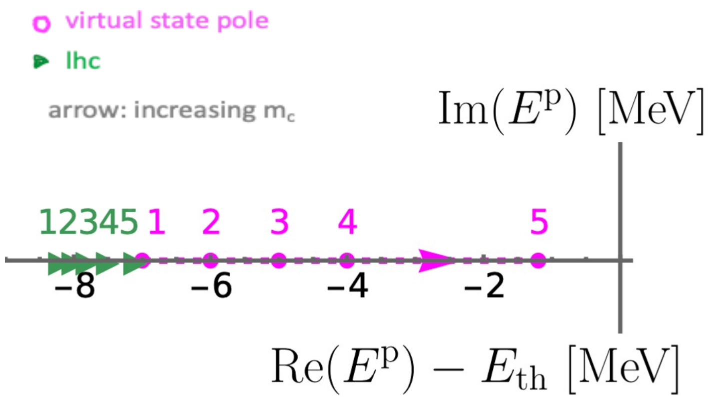
T_{cc} assuming eff. range expansion

$$p \cot \delta_0 = \frac{1}{a_0} + \frac{1}{2}\, r_0\, p^2$$

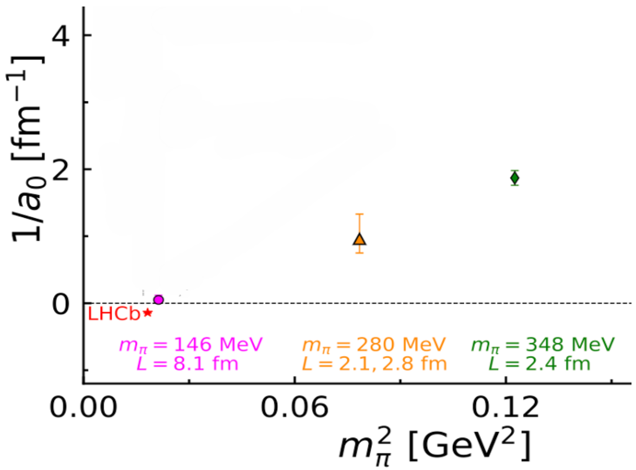
$m_\pi \simeq 280$ MeV

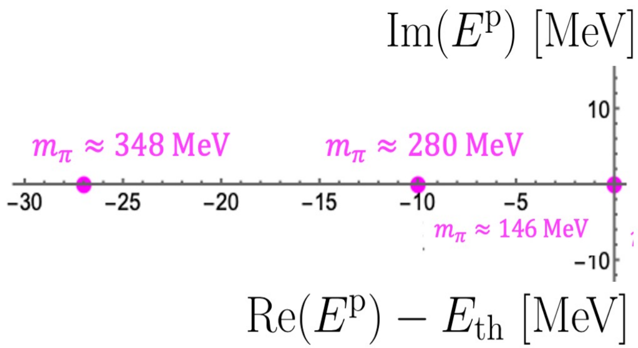
m_c



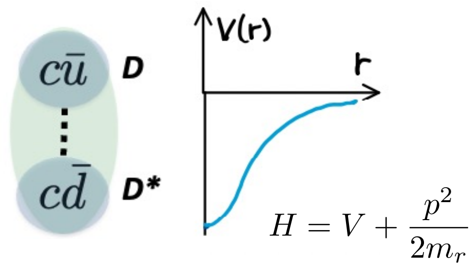


$m_{u/d}$



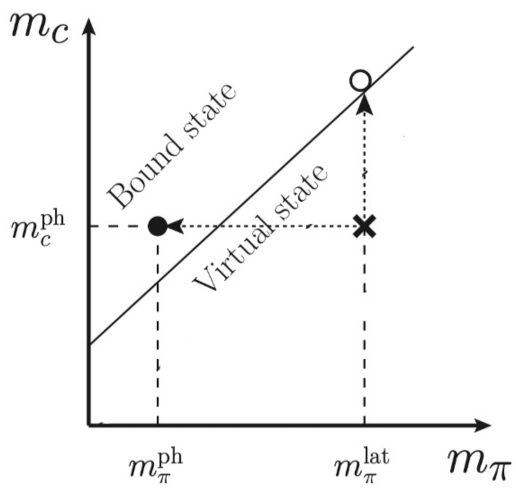


interpretation



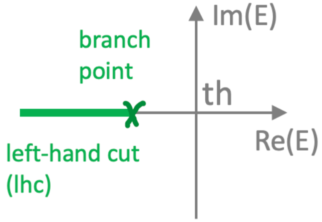
V almost independent on m_c

attraction increases with decreasing $m_{u/d}$



Scattering on the lattice and the left-hand cut

$$E_n \leftrightarrow T(E_n)$$



- **two-body formalism**

- EFT approach here inspired by: Du, Hanhart, Guo, Nefediev, Filin, et al, PRL 2023, 2303.09441

- plane-wave approach : Meng, Epelbaum, 2108.02709; Meng, Baru, Epelbaum et al., 2312.01930, PRD
  Vujmilovic: next talk

- generalization of Luscher's equation on left-hand cut [Raposo, Hansen, 2311.18793]

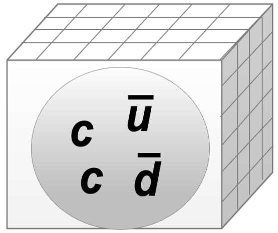
- Luscher eq. with long-range forces [Bubna, Hammer, Muller, Pand, Rusetsky, Wu, 2402.12985], comparison with existing approaches

- **three-body formalism**

- T_{cc} channel, D* as Dπ bound state, Romero-Lopez, Sharpe, Hansen, Draper [2401.06609

- Islam, Dawid, Briceno, Lattice 2023, 2303.04394 (signal for break-down of two-body Luscher's equation)

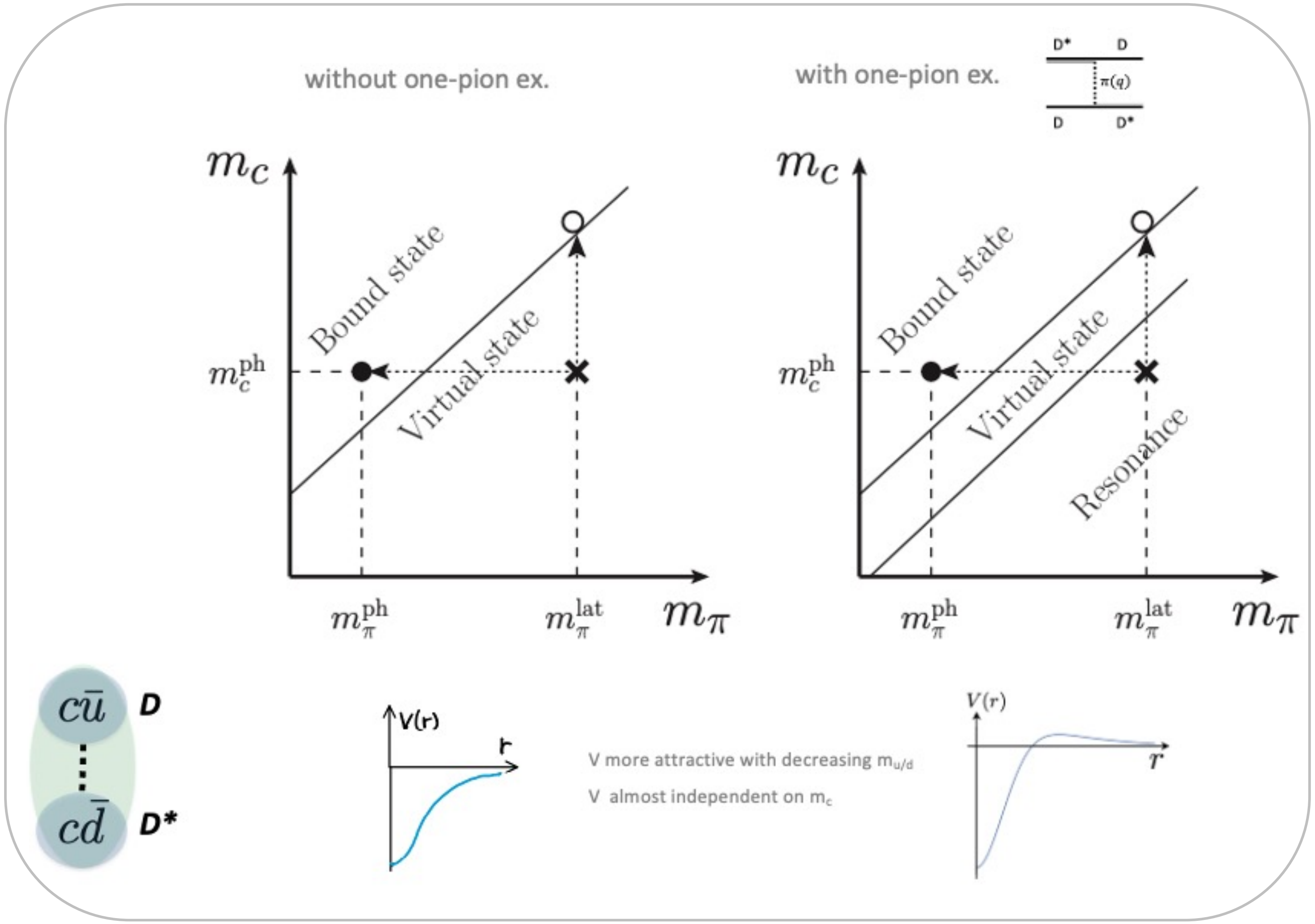
Conclusions



T_{cc}

- T_{cc} is the longest-lived exotic hadron discovered in experiment
- lies near threshold -> has to be extracted from DD* scattering amplitude
- lattice studies find attraction

quark mass dependence of T_{cc}. for stable D* , $m_\pi > m_{D^*} - m_D$



consistent with

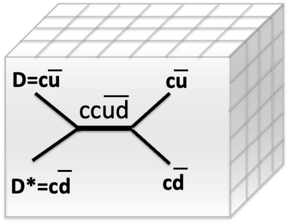
(does not uniqely imply)

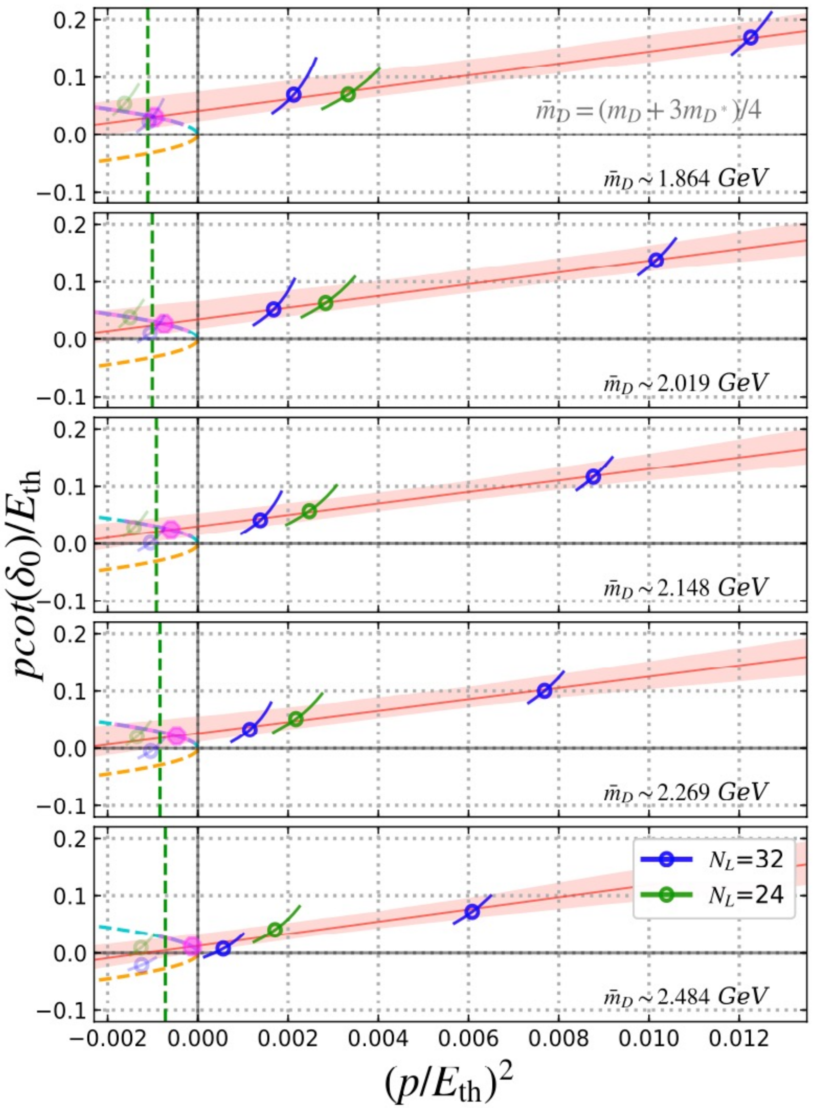
Backup

T_{cc} assuming eff. range expansion

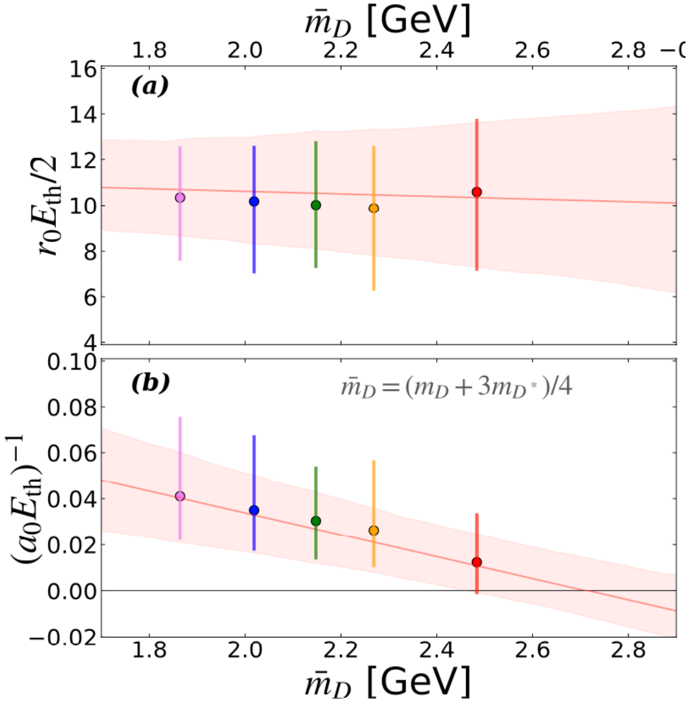
$$T \propto \frac{1}{p\cot\delta - ip}$$ s-wave

$$p\cot\delta_0 = \frac{1}{a_0} + \frac{1}{2}\, r_0\, p^2$$



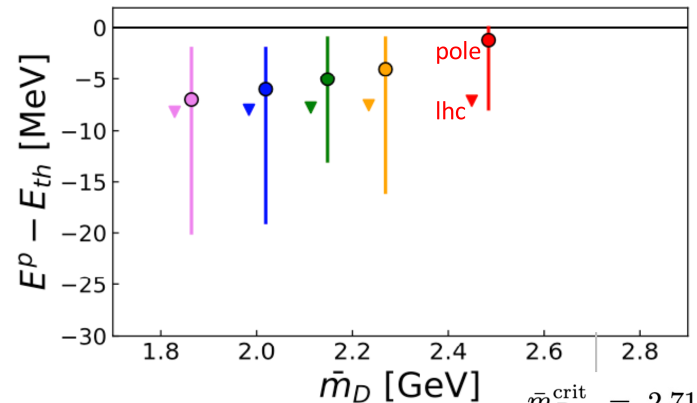


$m_\pi \simeq 280$ MeV



virtual state

bound state

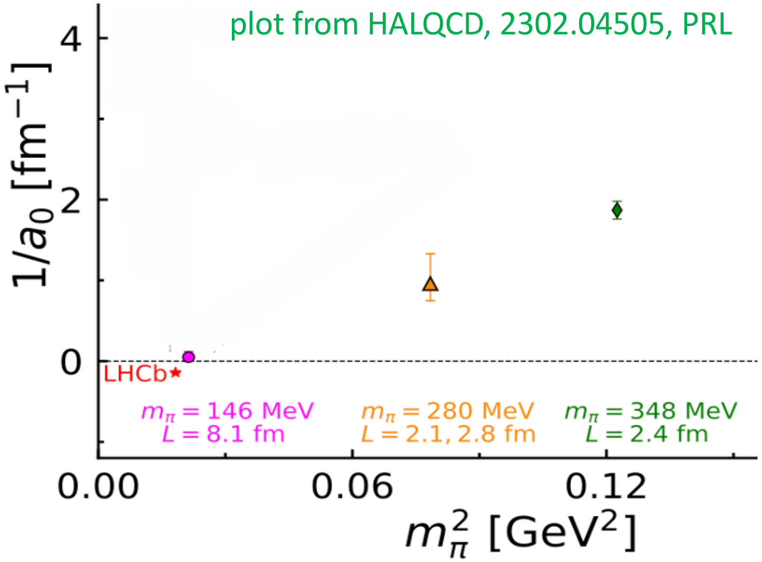


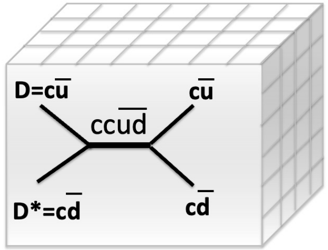
pole

$$\bar{m}_D^{\rm crit} = 2.71(^{+34}_{-26})\ \text{GeV},$$
$$m_r^{\rm crit} = 1.35(^{+17}_{-13})\ \text{GeV}.$$

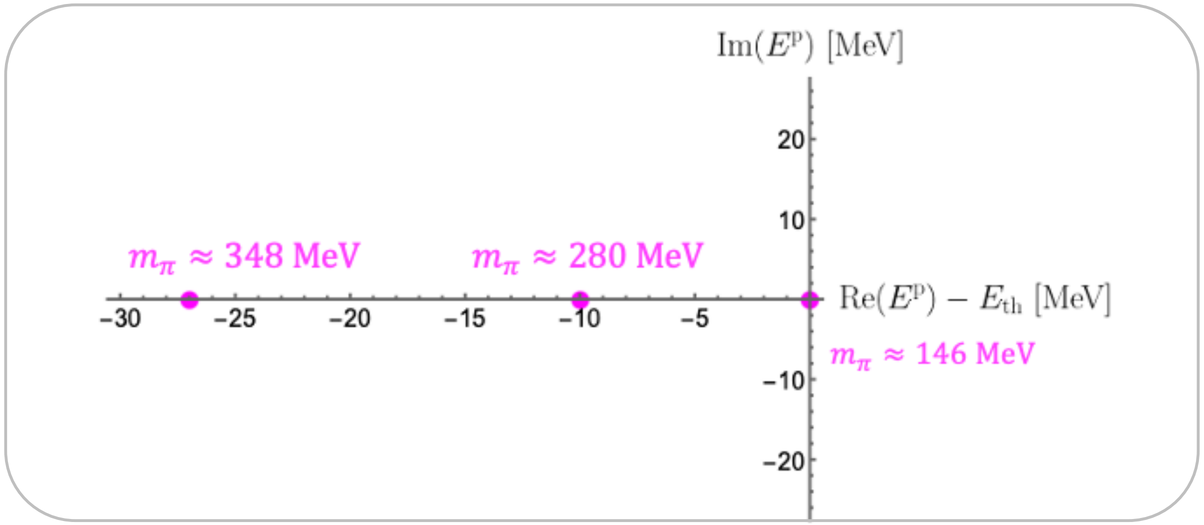
T_{bc}: $m_r(B^*D) = 1.38$ GeV

T_{cc} assuming effective range expansion: **pole trajectory**





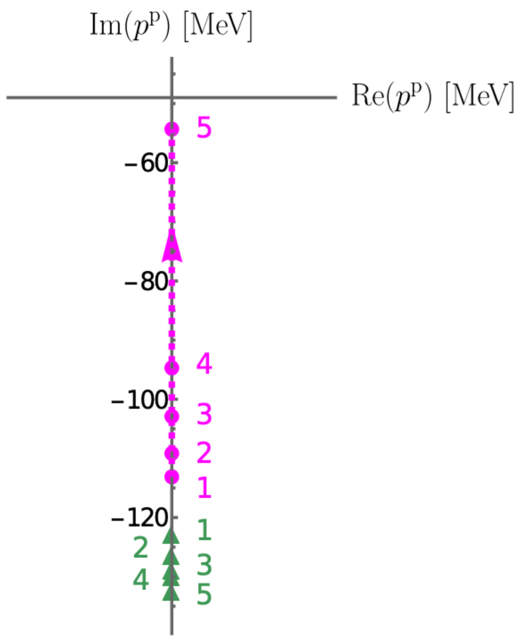
virtual state pole

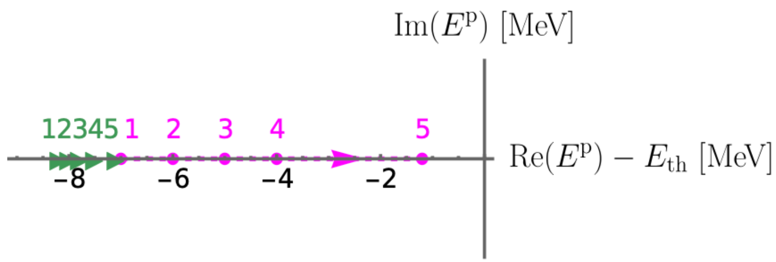


effective

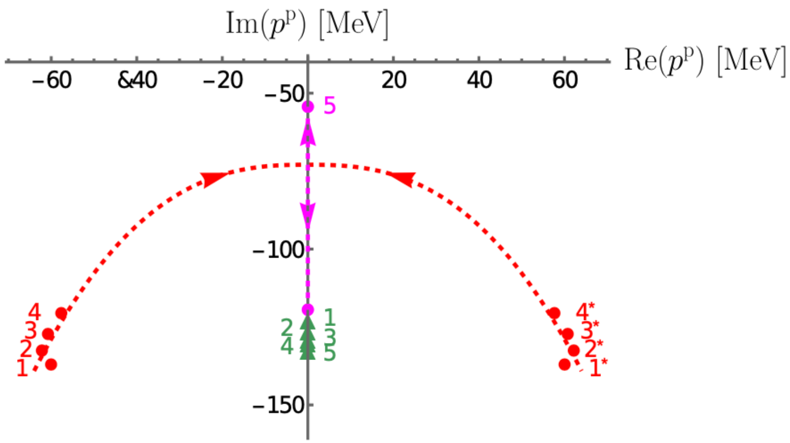
range

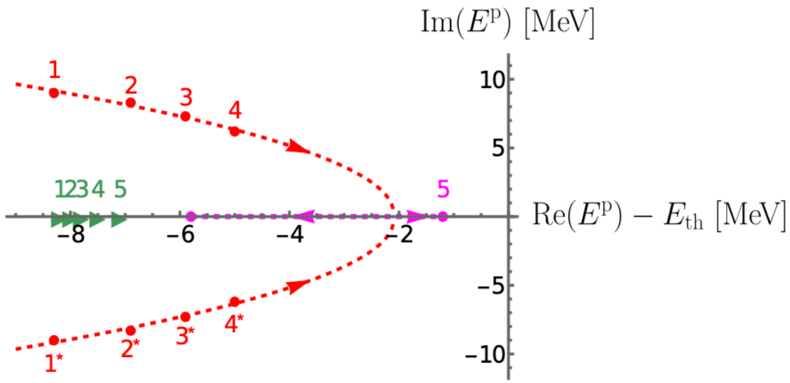
expansion





EFT



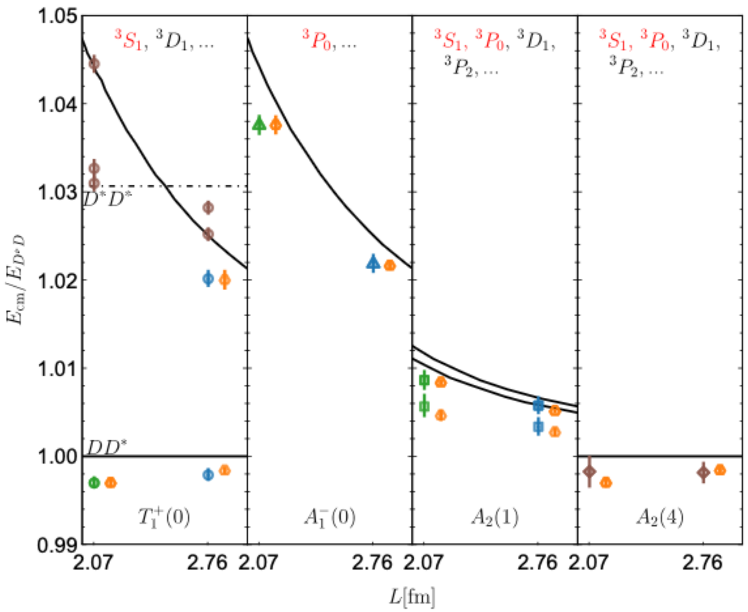


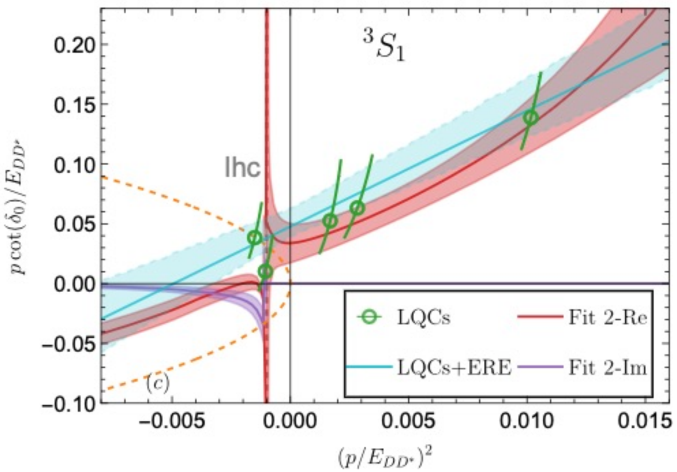
T_{cc}: plane wave approach

mpi~280 MeV, m_c^{ph}

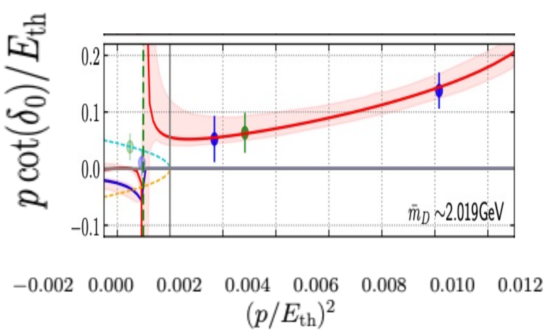
Meng, Baru, Epelbaum et al., 2312.01930,

orange: reconstructed levels, blue, green: lattice levels

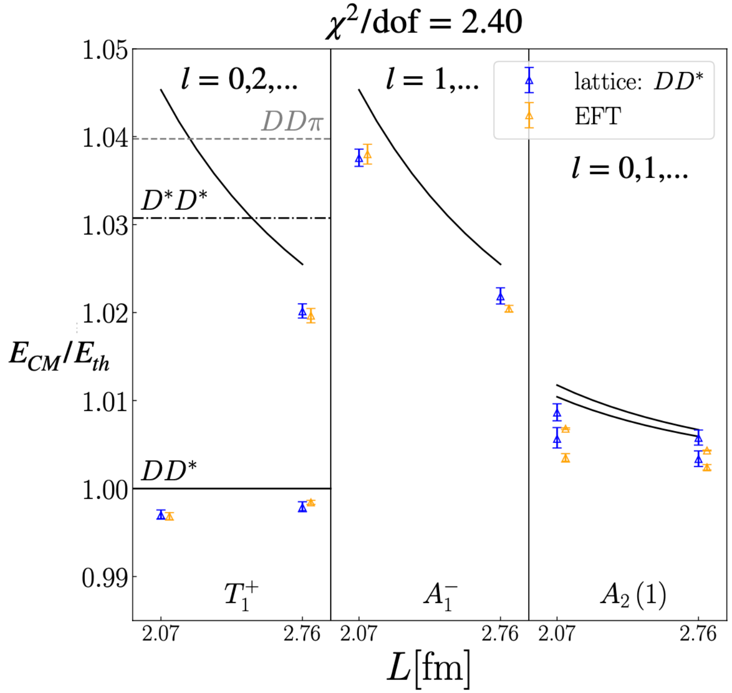


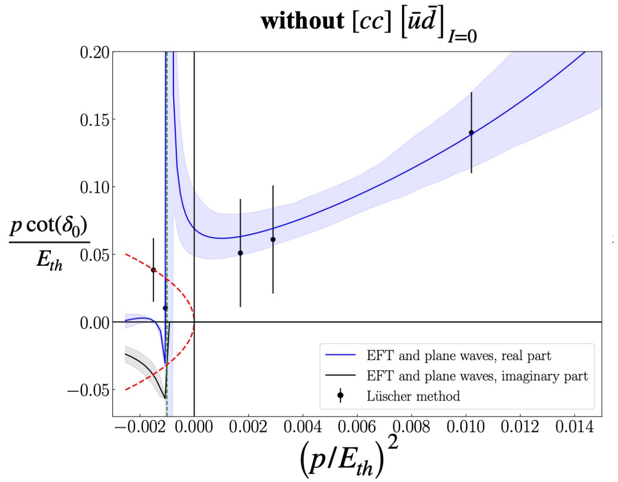


this talk, 2402.14715

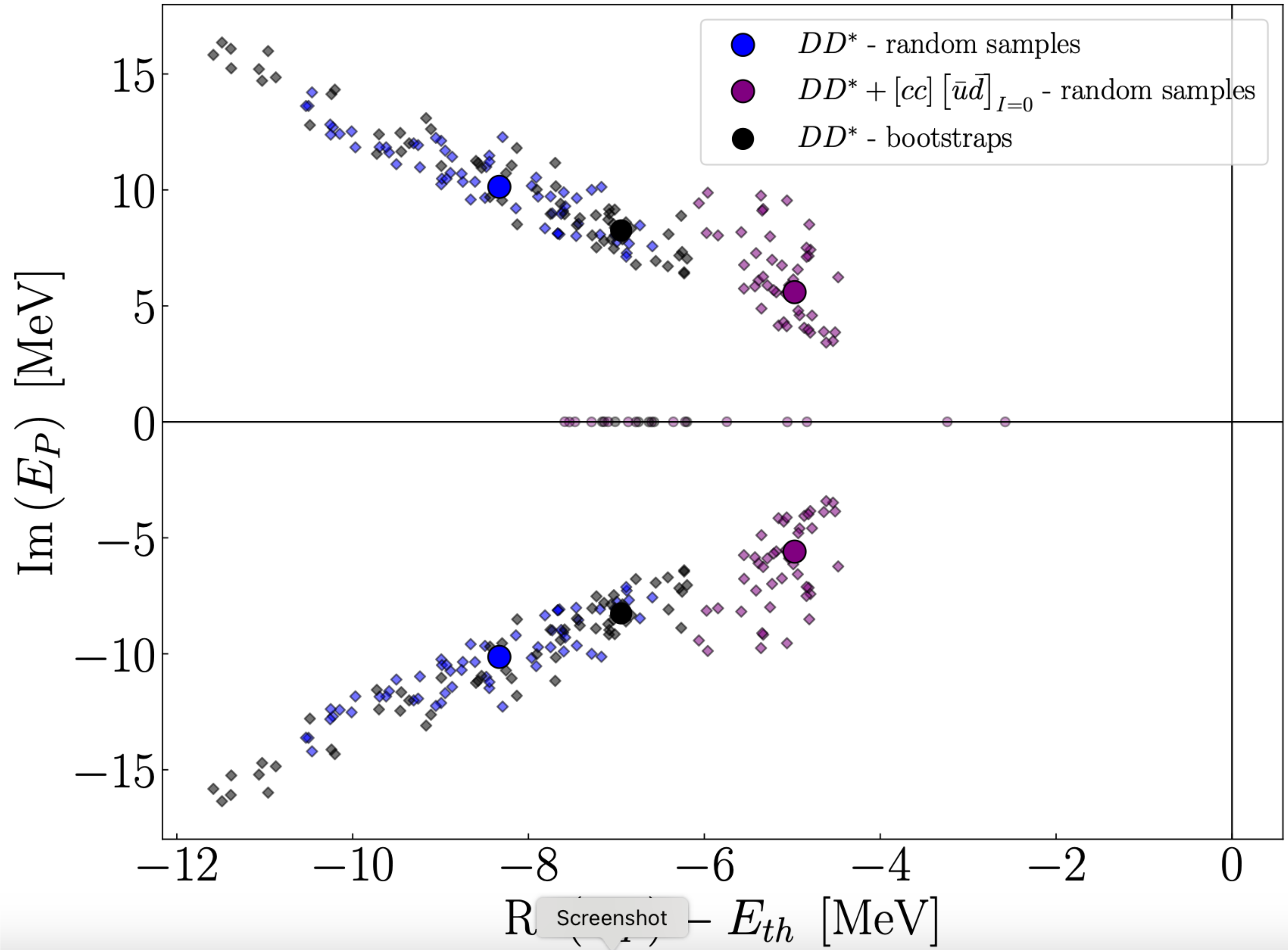


talk by Ivan Vujmilovic @ lat24





talk by Ivan Vujmilovic @ lat24



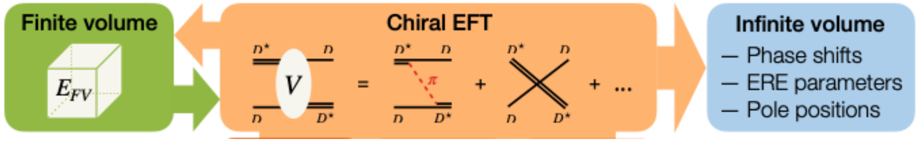
this talk

plane waves

plane waves

T_{cc}: plane wave approach

Meng, Baru, Epelbaum et al., 2312.01930, PRD
formalism: Meng, Epelbaum, 2108.02709;
lattice data: Padmanath, SP. 2202.10110, *PRL*



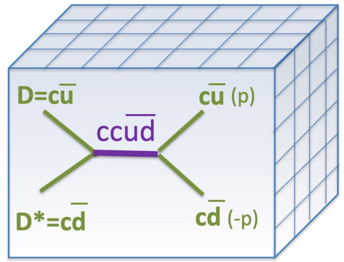
$$H = \frac{p^2}{2m_r} + V_\pi + V_{CT}$$

$$Hv = Ev$$

$$H_\Gamma v = E_\Gamma v$$

T_{cc}: dependence on $m_{u/d}$

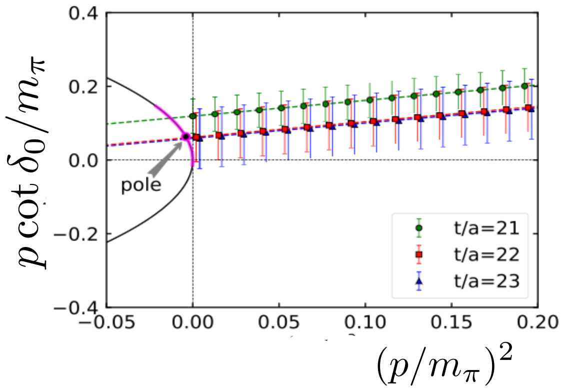
$$p \cot \delta_0 = \frac{1}{a_0} + \frac{1}{2}\, r_0\, p^2$$



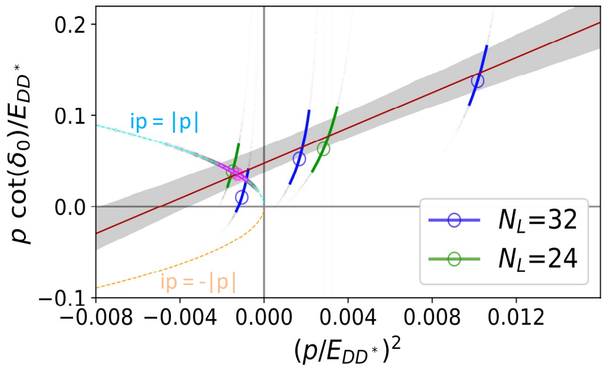
$m_{u,d}$

LHCb

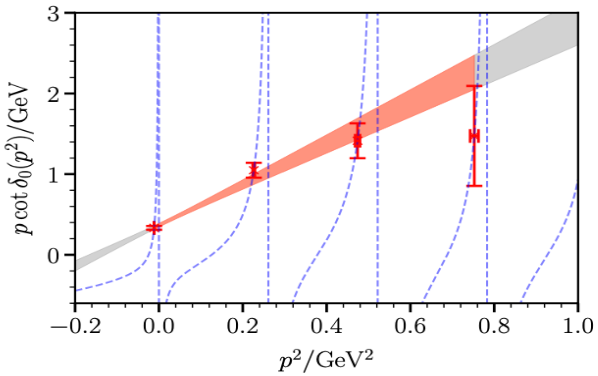
HALQCD method, 2302.04505, $m_\pi \approx 146$ MeV



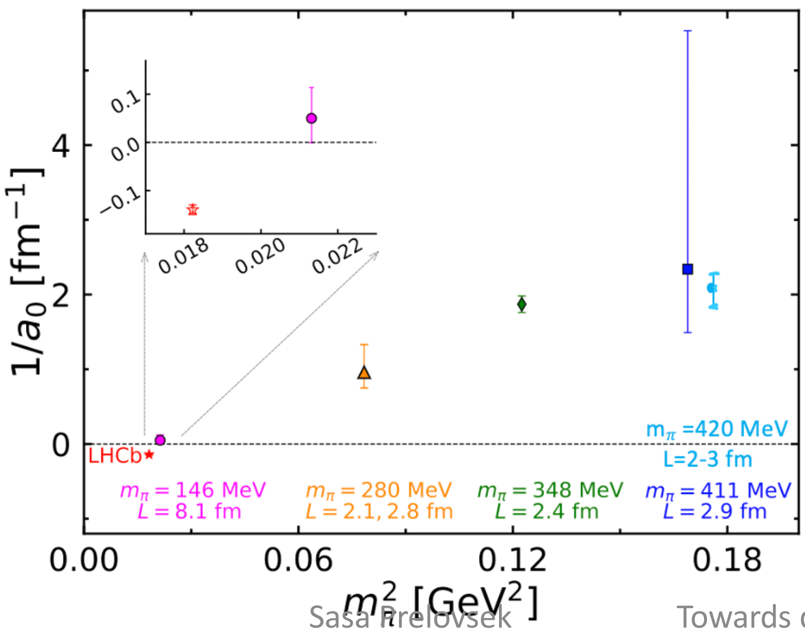
Padmanath, SP: 2202.10110, PRL, $m_\pi \approx 280$ MeV



CLQCD 2206.06185, PLB, $m_\pi \approx 348$ MeV

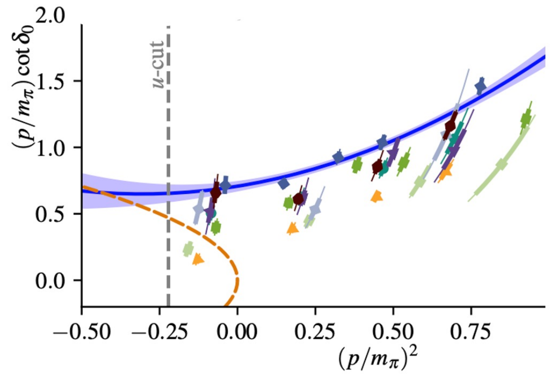


adapted from 2302.04505



several a

Green et al, Mainz, Lat 2023, $m_\pi \approx 420$ MeV

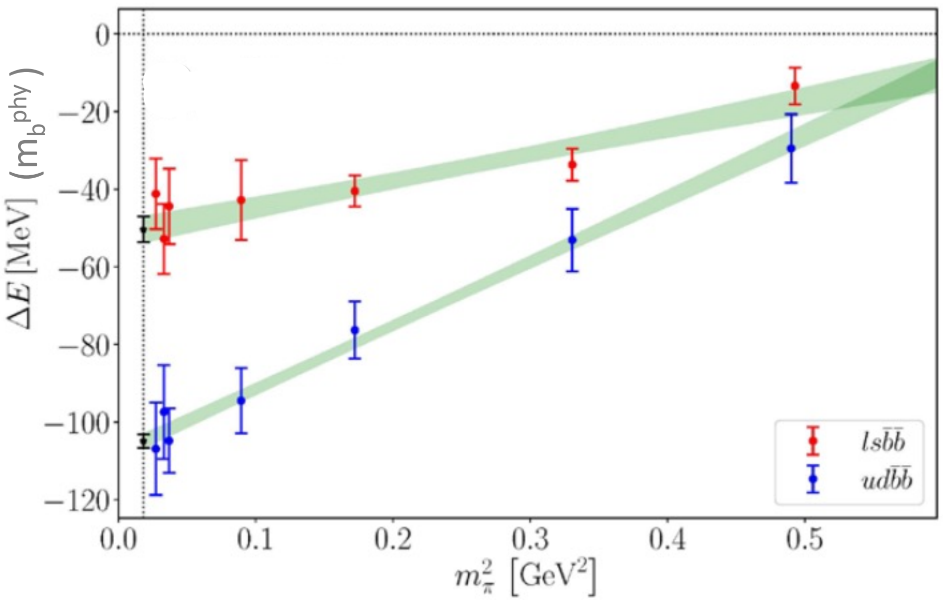


Doubly bottom tetraquarks

$bb\bar{d}\bar{u}$ $bb\bar{s}\bar{u}$ $I=0,\ J^P=1^+$

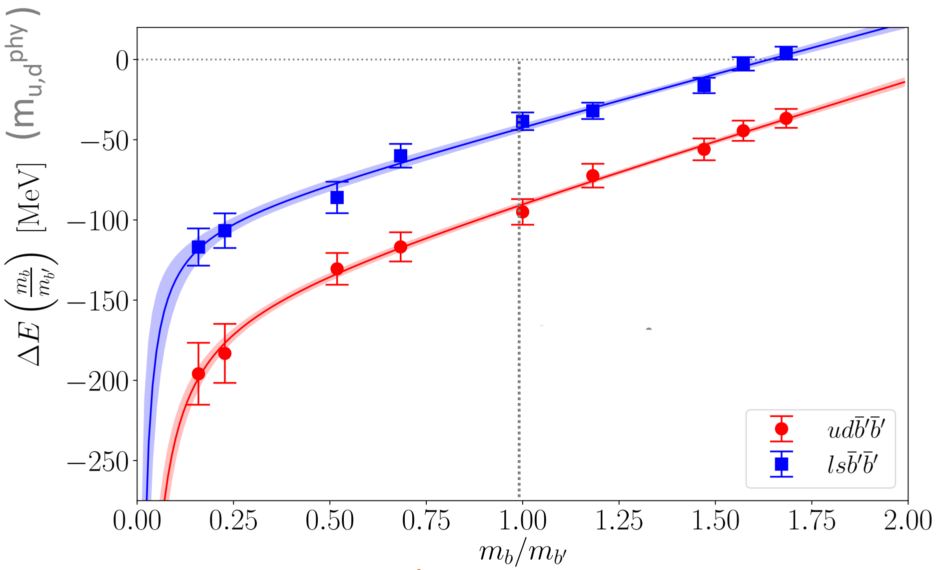
bound states

Frances, Colquhoun, Lewis, Maltman, Hudspith
PoS LATTICE2021 (2022) 144



$m_{u/d}$

$m_{u,d}$ increases →



m_b

$m_{b'}$ decreases →