T_{cc}^{+} via plane wave approach and including diquark-antidiquark operators

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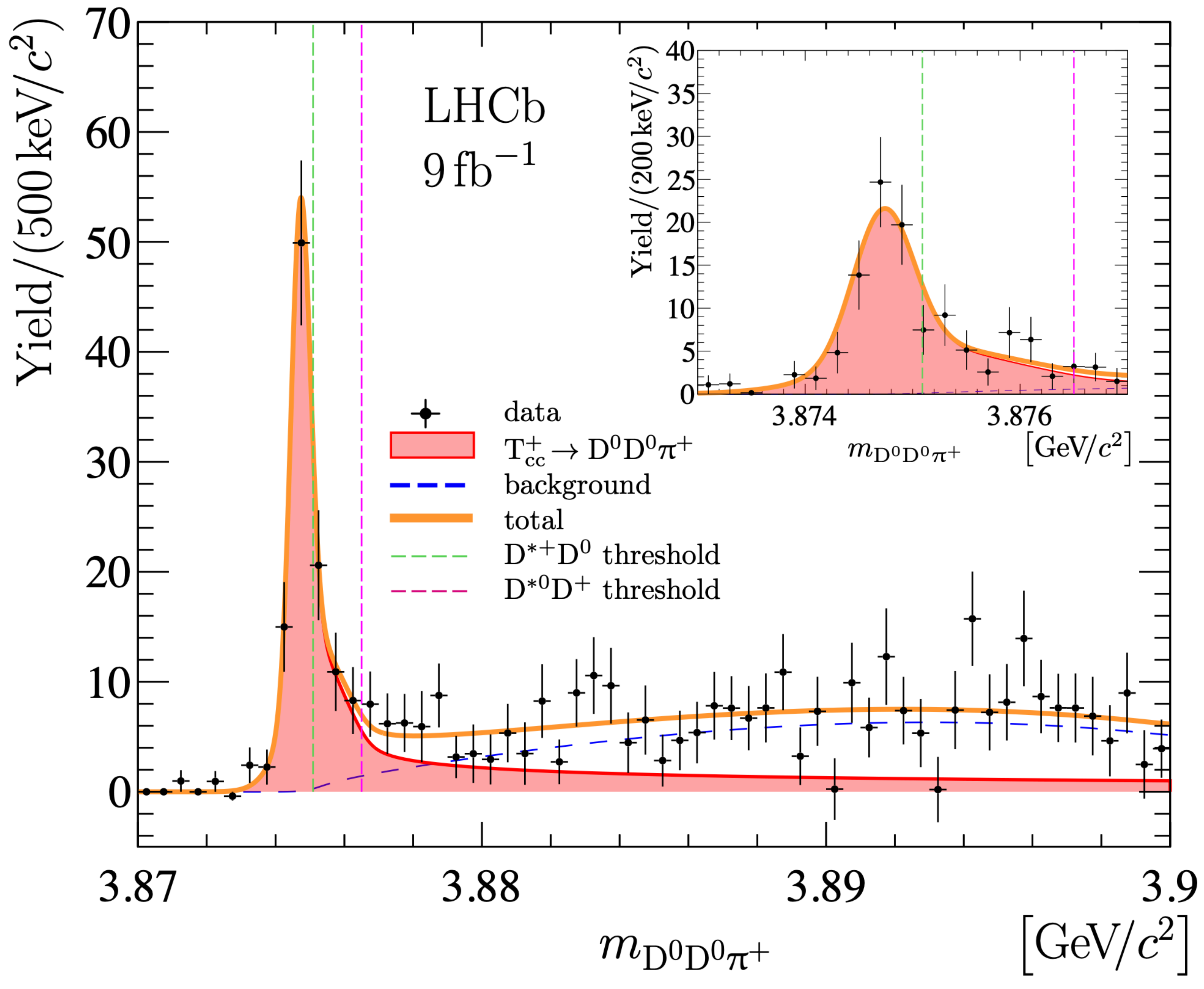
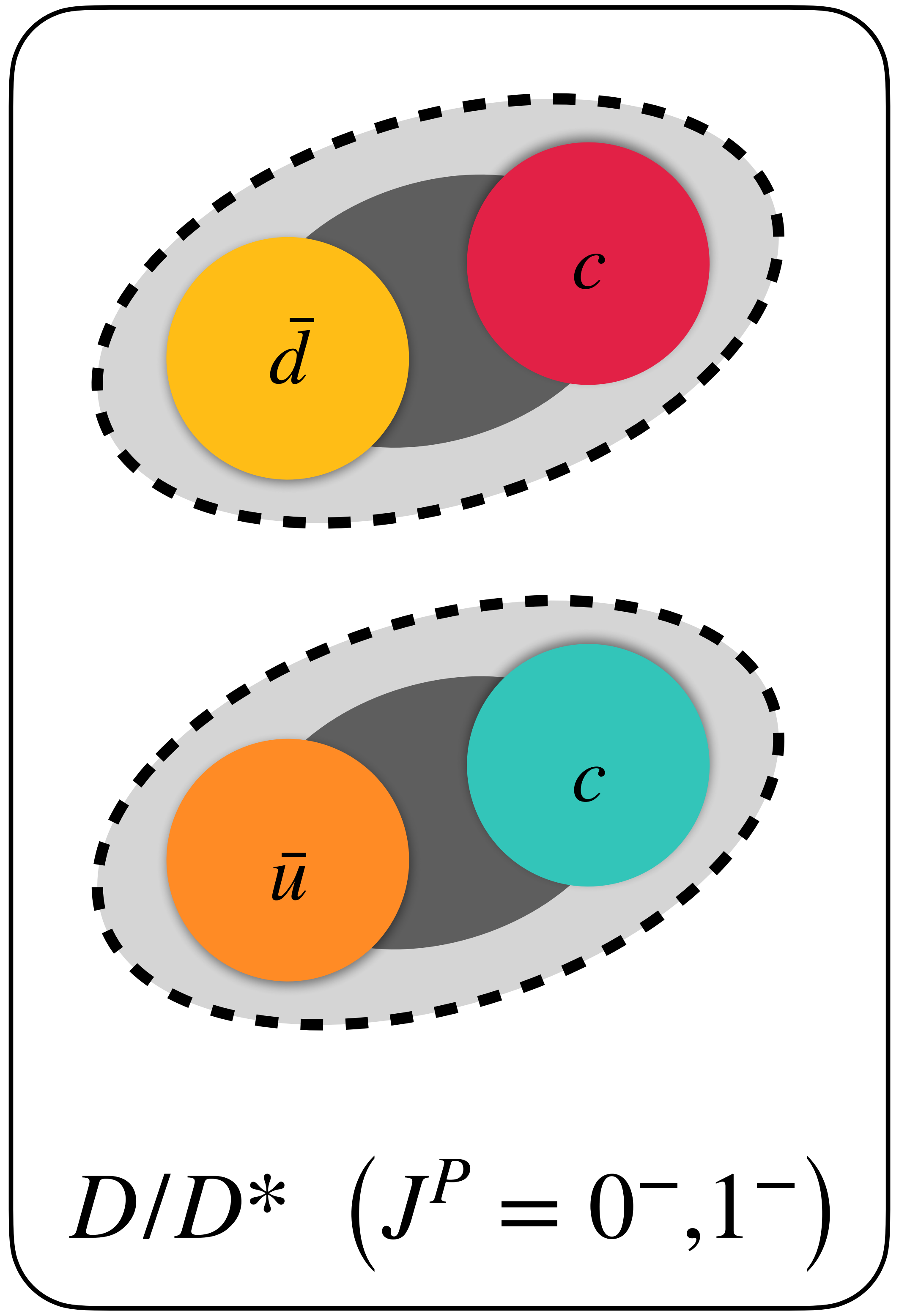
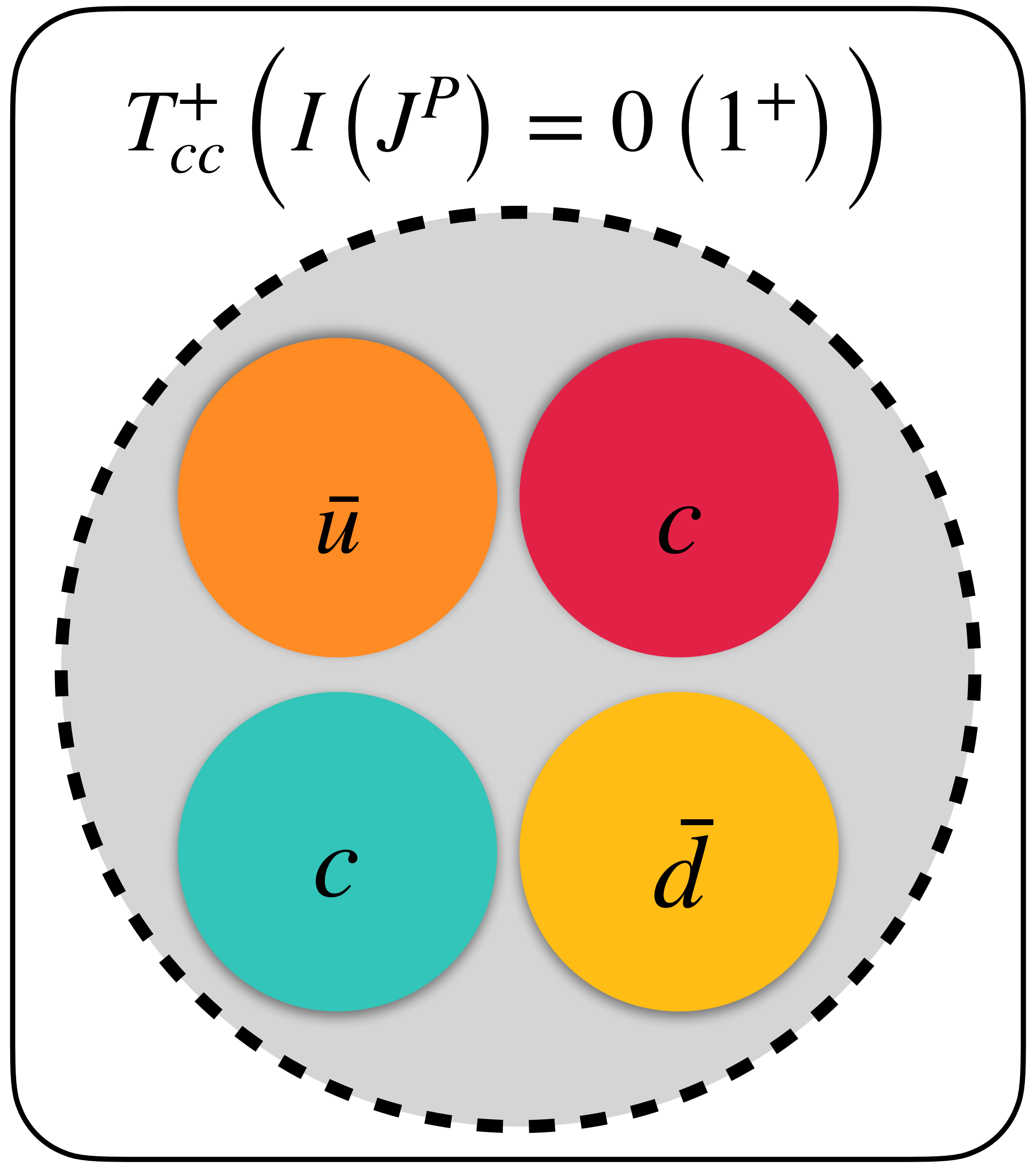
A short intro

$$\delta m_{\text{pole}} = m_{T_{cc}^+} - \left(m_{D^{*+}} + m_{D^0}\right),$$

$$\delta m_{\text{pole}} = -360 \pm 40\,^{+4}_{-0}\ \text{keV}/c^2\,,$$
$$\Gamma_{\text{pole}} = 48 \pm 2\,^{+0}_{-14}\,\text{keV}$$







- doubly charmed tetraquark ($cc\bar{u}\bar{d}$)
- recently observed by LHCb
- most frequent approach in LQCD:

1. simulate DD^* scattering correlators
2. extract finite-volume energies
3. apply Lüscher's QC to get the amplitude

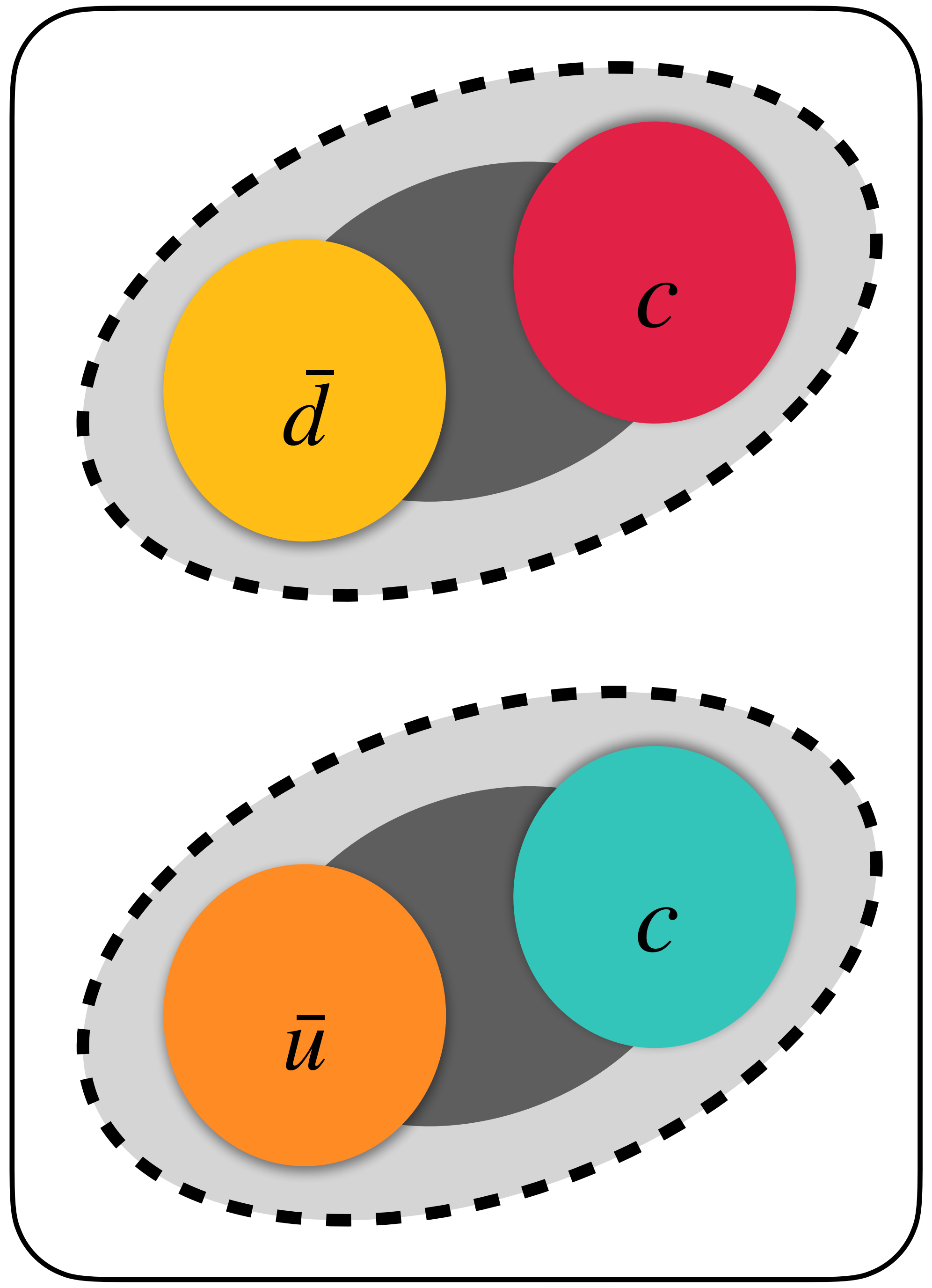
Addition of diquark-antidiquark operators

- basic building block for the scattering operators:

$$\mathcal{O}^{DD^*}_{I=0}\left(\vec{p}_1,\vec{p}_2\right) = \sum_{\vec{x}_1,\vec{x}_2} e^{i\vec{p}_1\cdot\vec{x}_1} e^{i\vec{p}_2\cdot\vec{x}_2}\cdot\left[\bar{u}(x_1)\Gamma_V c(x_1)\right]\left[\bar{d}(x_2)\Gamma_P c(x_2)\right] - \{\bar{u}\leftrightarrow\bar{d}\}$$

- inclusion of $[cc]\left[\bar{u}\bar{d}\right]_{I=0}$ operators in analysis:

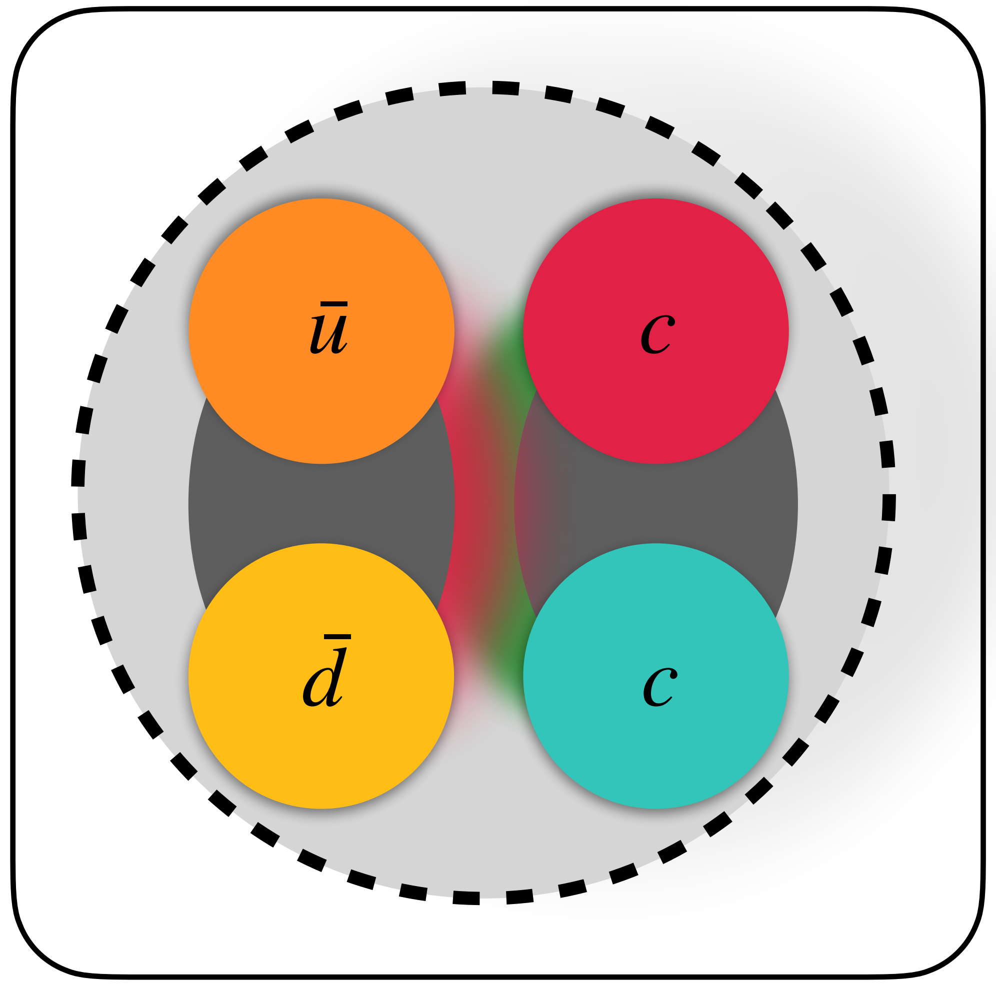
$$\mathcal{O}^{[cc]\left[\bar{u}\bar{d}\right]}_{I=0}\left(\vec{p}\right) = \sum_{\vec{x}} e^{i\vec{p}\cdot\vec{x}}\cdot\epsilon_{abc}\left[c^{\alpha}_{b}(x)(C\gamma_i)^{\alpha\beta}c^{\beta}_{c}(x)\right]\epsilon_{ade}\left[\bar{u}^{\gamma}_{d}(x)(C\gamma_5)^{\gamma\delta}\bar{d}^{\delta}_{e}(x)\right]$$



- its effects are generally dependent on the heavy-quark mass

- ensembles used: U101, H105 (CLS)
  - distillation $\rightarrow N_V = 60,\ 90$

$$\begin{cases} N_L = 24,\ 32 \\ N_f = 2+1 \\ m_\pi = 280(3)\ \text{MeV} \\ a = 0.08636(98)(40)\ \text{fm} \end{cases}$$

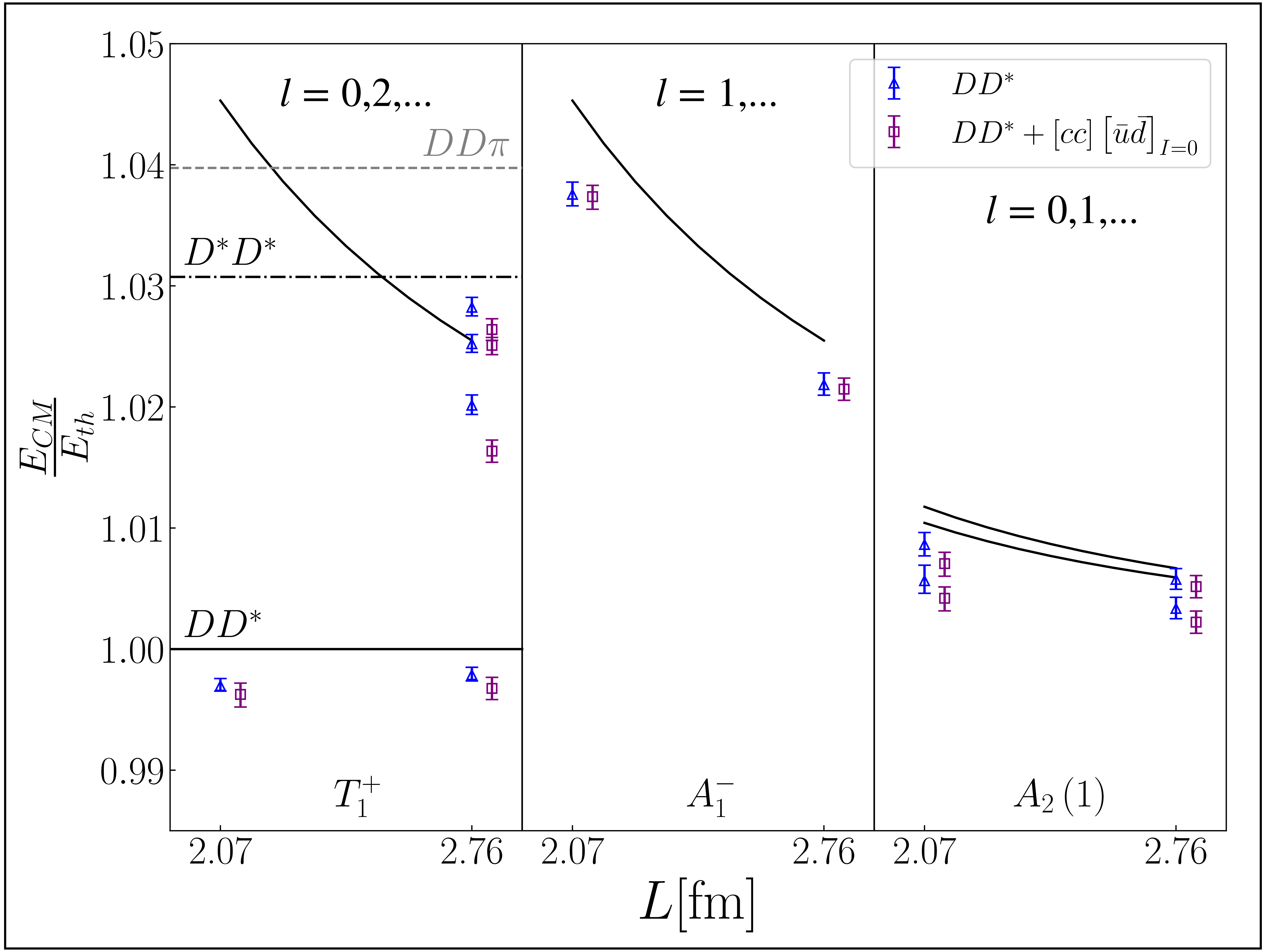


Finite-volume energy shifts

$$m_c^{lat} \sim m_c^{phys}$$

T_1^+ operator basis
$\mathcal{O}_1, \mathcal{O}_2 \sim D(0)D^*(0)$
$\mathcal{O}_3 = \left[D(1)D^*(-1)\right]_{l=0}$
$\mathcal{O}_4 = \left[D(1)D^*(-1)\right]_{l=2}$
$\mathcal{O}_5 = D^{*0}(0)D^{*+}(0)$
$\mathcal{O}_6 = [cc]\left[\bar{u}\bar{d}\right]_{I=0}$

Preliminary results



Overlap factors

$\mathcal{O}_1, \mathcal{O}_2 \sim D(0)D^*(0)$

$\mathcal{O}_3 = \left[D(1)D^*(-1)\right]_{l=0}$

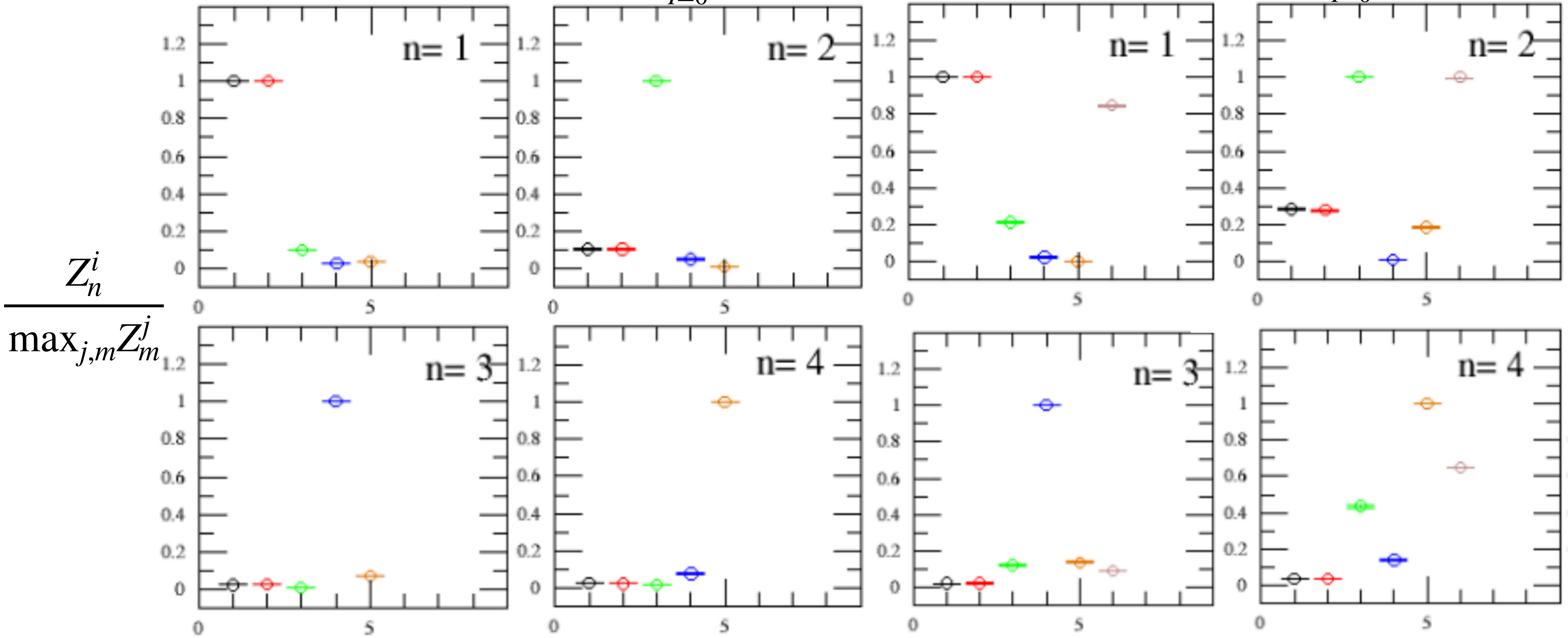
$\mathcal{O}_4 = \left[D(1)D^*(-1)\right]_{l=2}$

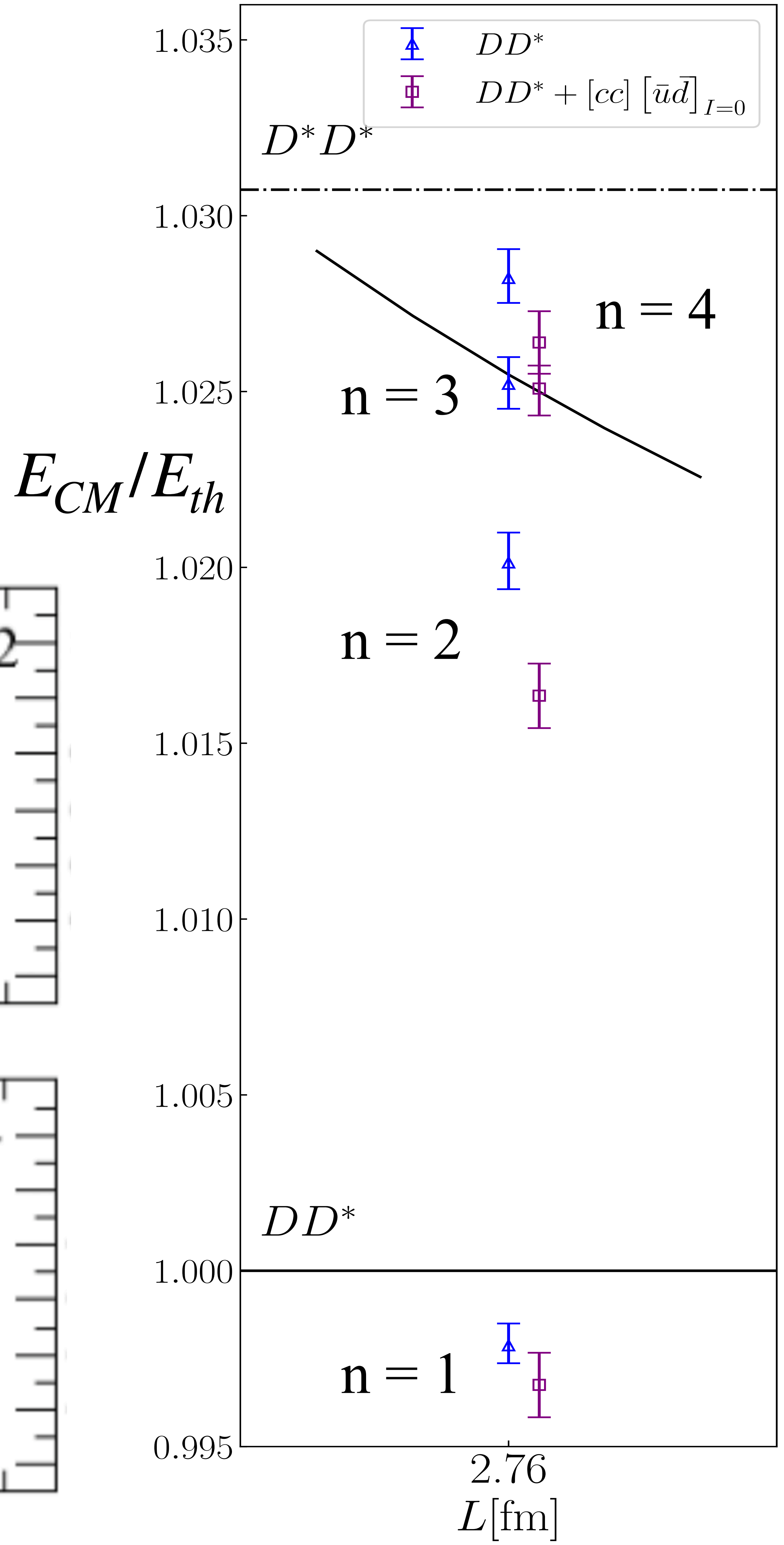
$\mathcal{O}_5 = D^{*0}(0)D^{*+}(0)$

$\mathcal{O}_6 = [cc]\,[\bar{u}\bar{d}]_{I=0}$

$$Z_n^j = \langle n | \mathcal{O}_j | 0 \rangle$$

without $[cc]\,[\bar{u}\bar{d}]_{I=0}$ — **with** $[cc]\,[\bar{u}\bar{d}]_{I=0}$





- analysis of the results with $m_b^{lat} \sim m_b^{phys}$: $[bb]\,[\bar{u}\bar{d}]_{I=0}$ introduces significant mixing between BB^* and B^*B^* channels

EFT: DD^* elastic scattering

$$\mu^2 = m_\pi^2 - (m_{D^*} - m_D)^2$$
$$\vec{k} = \vec{p} + \vec{p}'$$

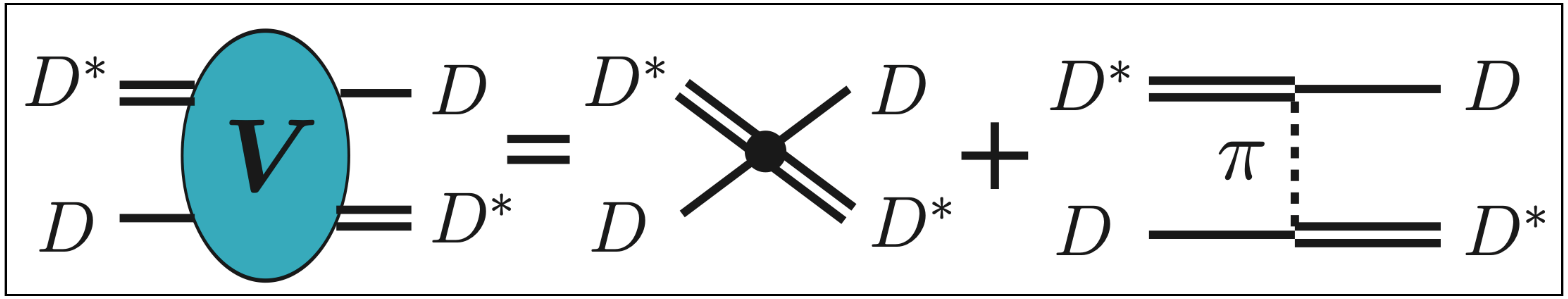
✦ effective potential V derived from chiral EFT, up to $\mathcal{O}(Q^2)$:

$$V\left(\vec{p},\vec{p}'\right) = \left(2c_{S0} + 2\left(\vec{p}^2 + \vec{p}'^2\right)c_{S2}\right)\left(\vec{\epsilon}\cdot\vec{\epsilon}'^*\right) + 2\left(\vec{p}'\cdot\vec{\epsilon}'^*\right)\left(\vec{p}\cdot\vec{\epsilon}\right)c_{P2} - \frac{3g^2}{4f_\pi^2}\frac{(\vec{k}\cdot\vec{\epsilon})(\vec{k}\cdot\vec{\epsilon}'^*)}{\vec{k}^2 + \mu^2}$$

One pion exchange

❖ low energy constants (LECs) c_{S0}, c_{S2}, c_{P2} are treated as fit parameters

❖we employ cutoff to each term in the potential: $F(p,p';\Lambda,n) = \exp\left(-\frac{p^n + p'^n}{\Lambda^n}\right)$



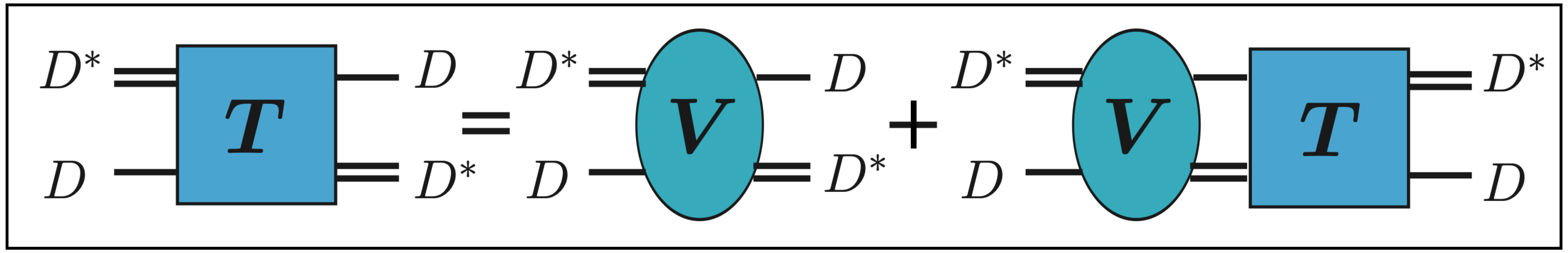
Lippmann-Schwinger equation

$\hat{T}$ - scattering matrix

$\hat{V}$ - EFT potential

$\hat{G}$ - propagator

$$\hat{T} = \hat{V} + \hat{V}\hat{G}\hat{T}$$



in nonrelativistic regime: **projected to various lattice irreps Λ:**

poles: $\det\left(\hat{G}^{-1} - \hat{V}\right) = 0 \longrightarrow \det\left(\hat{H} - E\hat{I}\right) = 0 \longrightarrow \det\left(\hat{H}_\Lambda - E_\Lambda \hat{I}\right) = 0$

L. Meng, E. Eppelbaum, 2108.02709

Plane wave basis

$$\vec{p} = \frac{2\pi}{L}\vec{n},\ \vec{n} \in Z^3$$

$$i = x, y, z$$

$$\hat{H} = \frac{\hat{p}^2}{2m_r} + \hat{V} \rightarrow$$ well defined in **plane wave basis**

$$|\vec{p}_1\rangle \otimes |\vec{p}_2, i\rangle$$

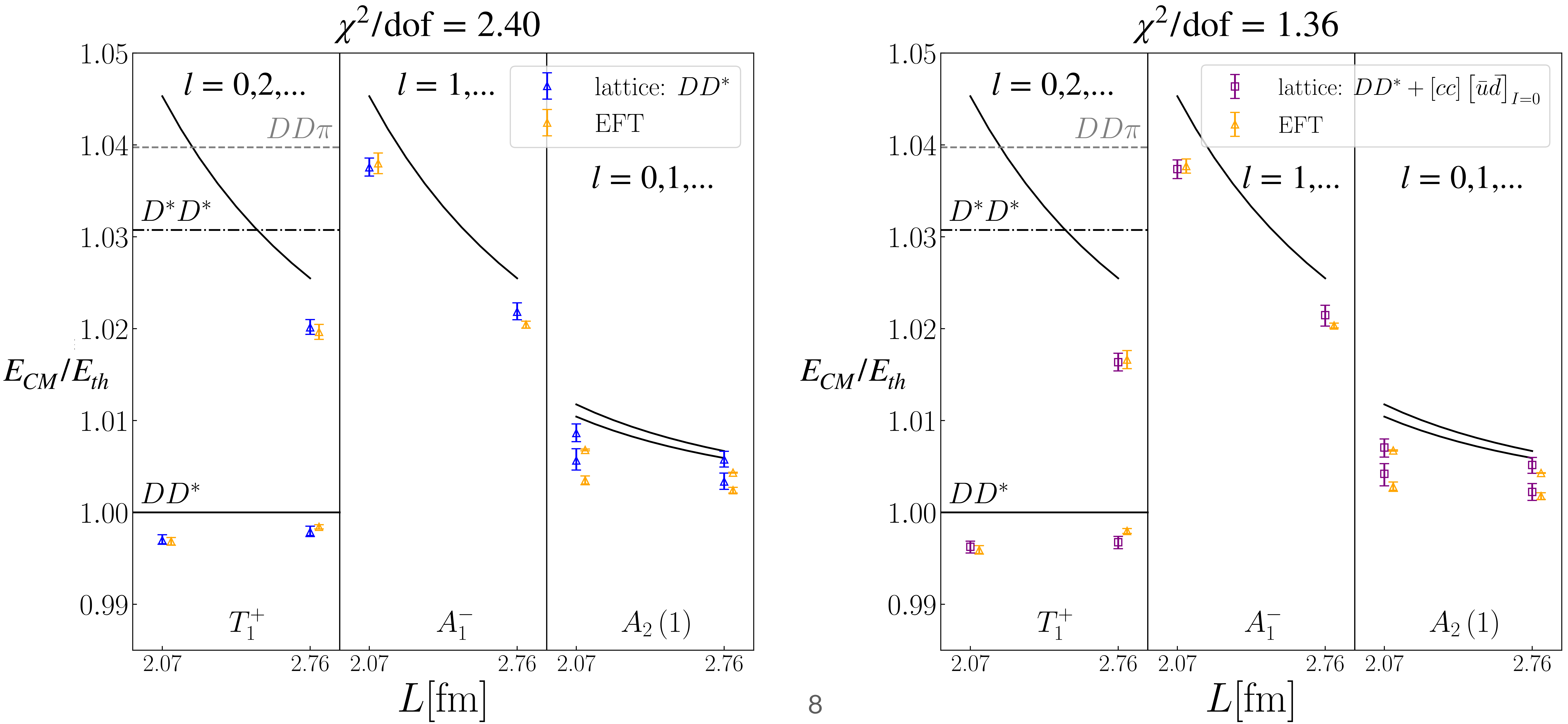
additional constraints: T_1^+, A_1^-

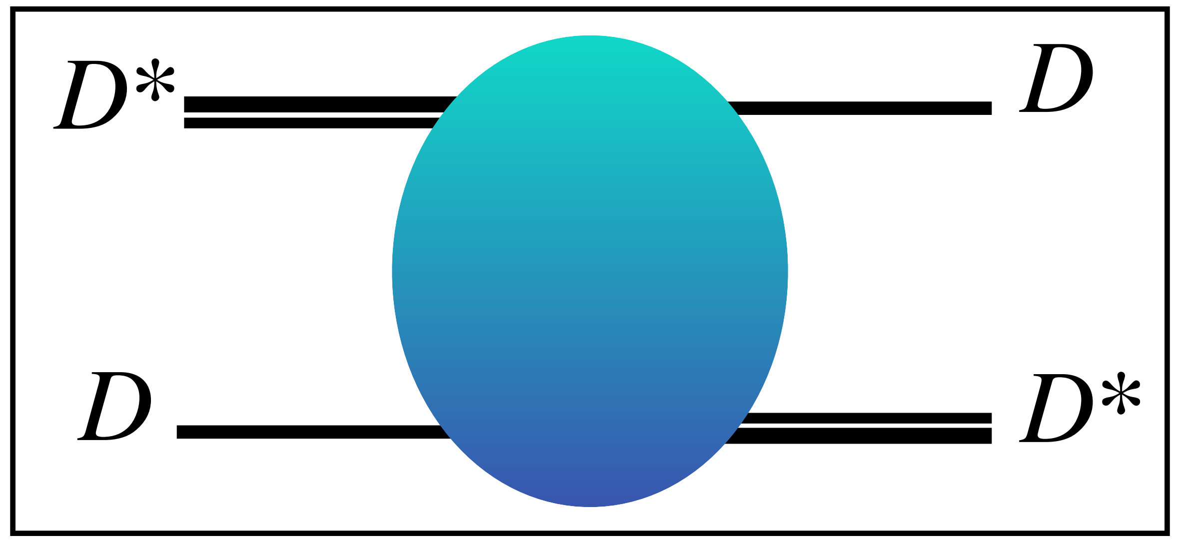
$$\vec{p}_1 + \vec{p}_2 = \vec{0},\ \frac{2\pi}{L}(0,0,1)\ \ A_2(1)$$

Fitting low energy constants: c_{S0}, c_{S2}, c_{P2}

- sharp cutoff: $\Lambda = 0.65$ GeV, $n = 40$

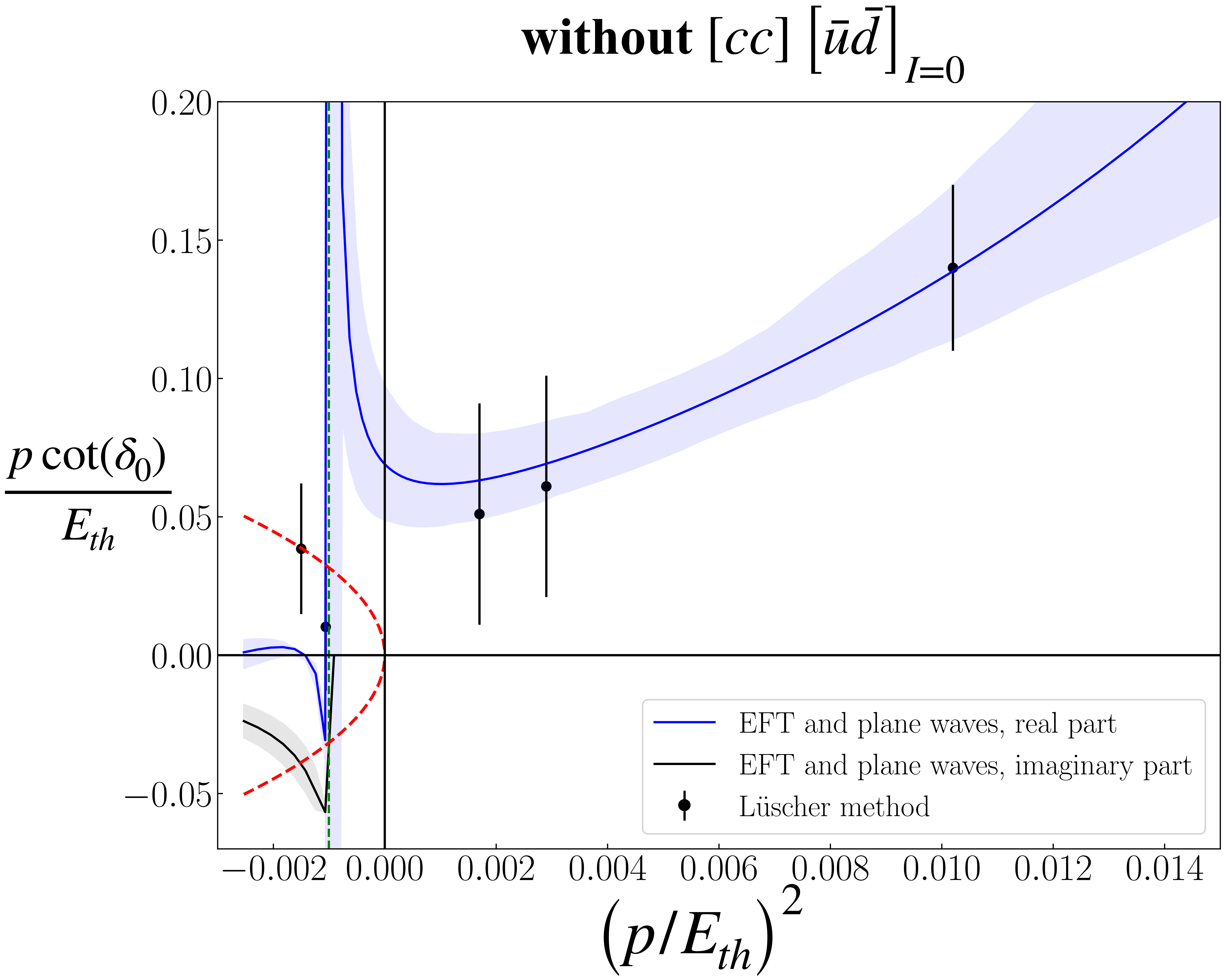
Preliminary results

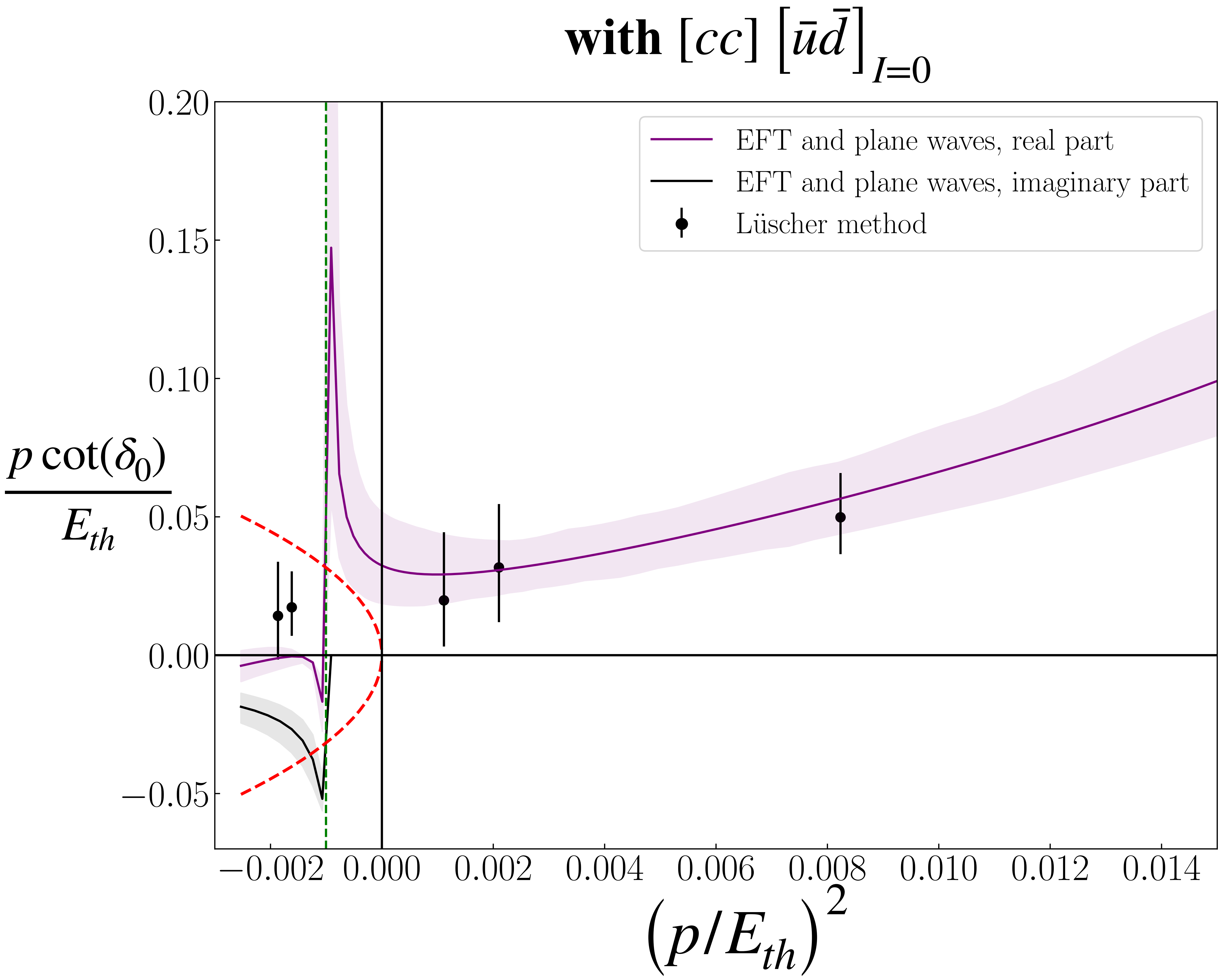




Plane waves and Lüscher:
a comparison

Preliminary results





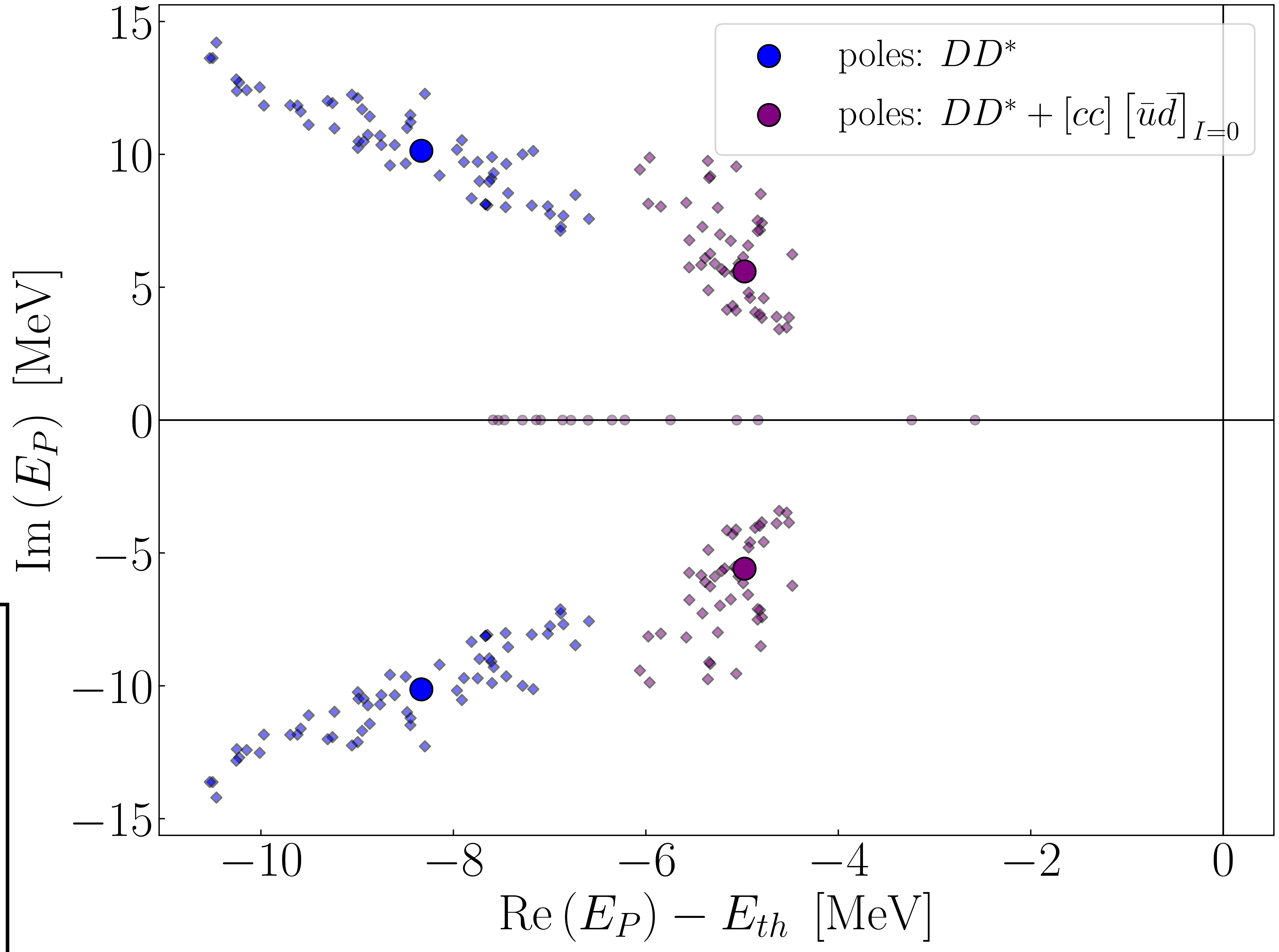
T_{cc} pole

- subthreshold resonant state in both cases

$$\mathrm{Re}\left(E_P\right) - E_{th} = -\,8.33^{+1.79}_{-2.20}\ \mathrm{MeV}$$
$$\mathrm{Im}\left(E_P\right) = -\,10.13^{+3.03}_{-4.07}\ \mathrm{MeV}$$

$$\mathrm{Re}\left(E_P\right) - E_{th} = -\,4.99^{+0.56}_{-0.95}\ \mathrm{MeV}$$
$$\mathrm{Im}\left(E_P\right) = -\,5.60^{+1.97}_{-3.55}\ \mathrm{MeV}$$

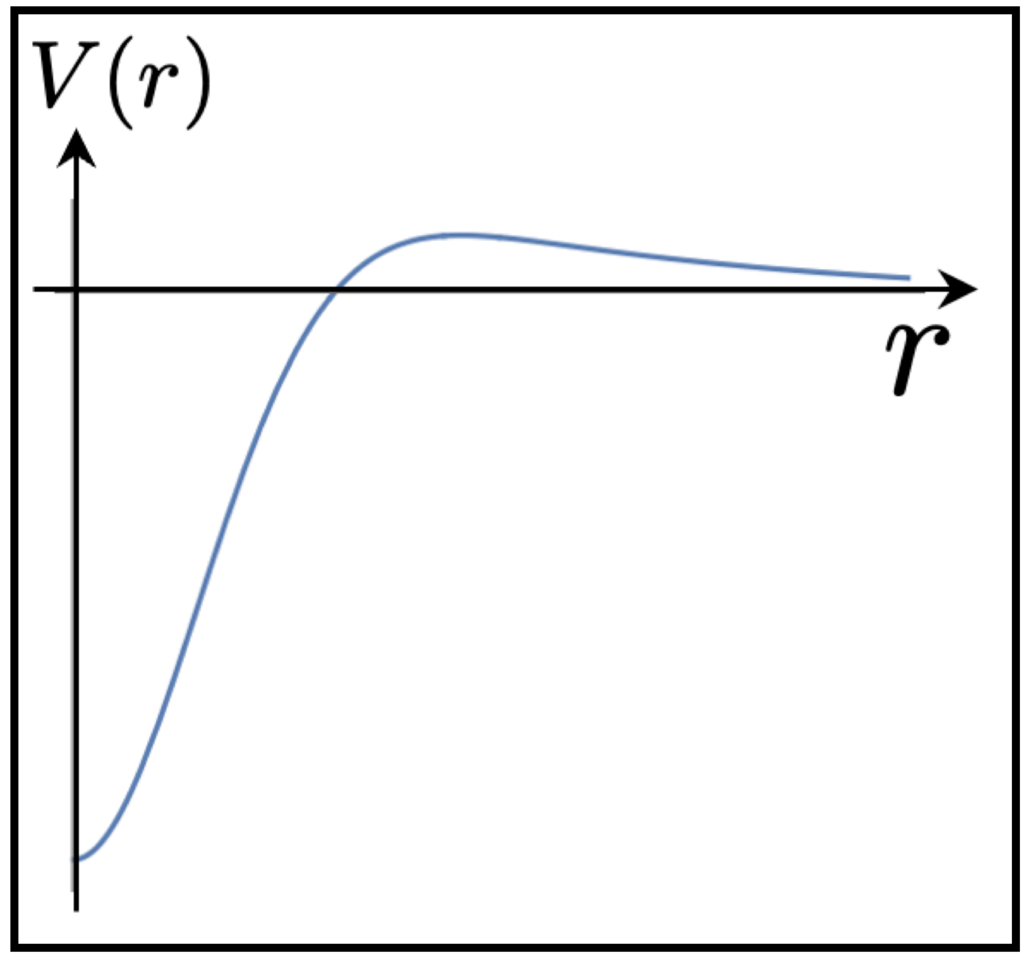
+ complex conjugate poles



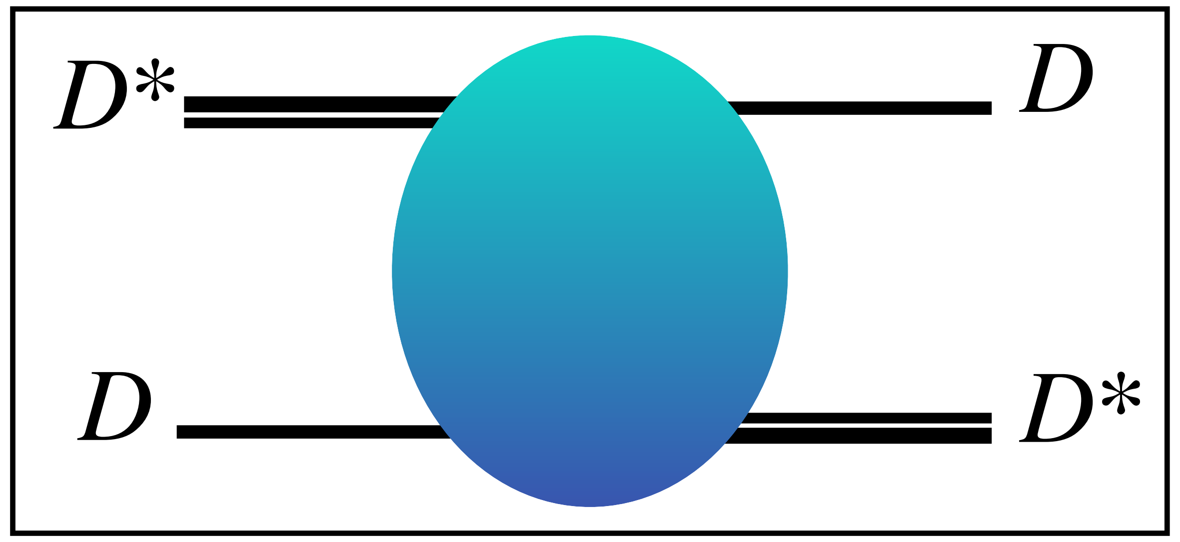
- Contact terms → short range attraction

- One-pion exchange → long range repulsion

$$m_\pi = 280\ \mathrm{MeV}$$



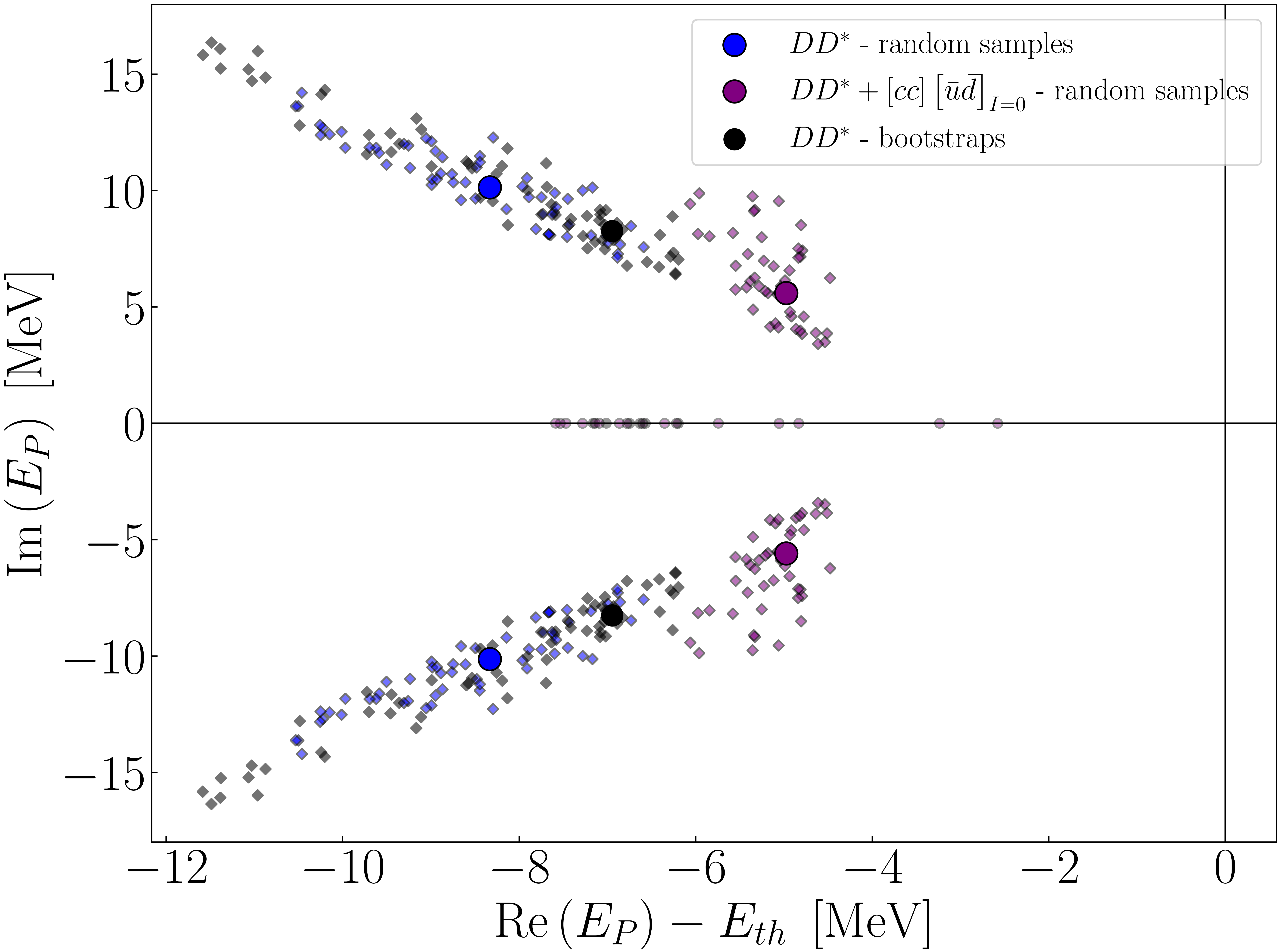
S. Collins, A. Nefediev, M. Padmanath, S. Prelovsek; 2402.14715



Summary

❖ study of the T_{cc} pole:

- addition of local diquark-antidiquark interpolators: **energy shifts, overlap factors**
- explicit accounting for the left-hand cut: **effective potential** featuring OPE
- in both cases: subthreshold resonance
  - shift towards the real line with the addition of $[cc]\left[\bar{u}\bar{d}\right]_{I=0}$



DD^* - random samples
$DD^* + [cc]\left[\bar{u}\bar{d}\right]_{I=0}$ - random samples
DD^* - bootstraps
$\mathrm{Im}\,(E_P)$ [MeV]
$\mathrm{Re}\,(E_P) - E_{th}$ [MeV]
15
10
5
0
−5
−10
−15
−12
−10
−8
−6
−4
−2
0