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T_{cc} from coupled $DD^* - D^*D^*$ scattering, including left-hand cuts and local operators

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$T_{cc}(3875)^+$ – summary of current status

- narrow $DD\pi$ resonance, just below $D^{*+}D^0$ thr.

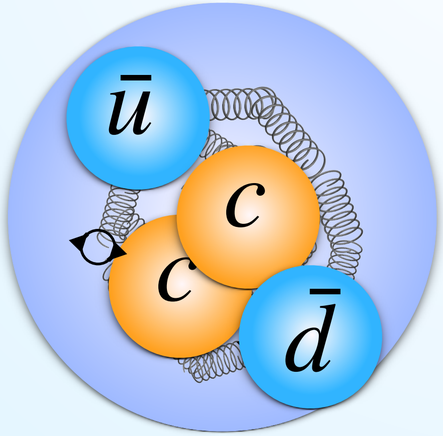
$$cc\bar{u}\bar{d},\ I(J^P) = 0(1^+)$$

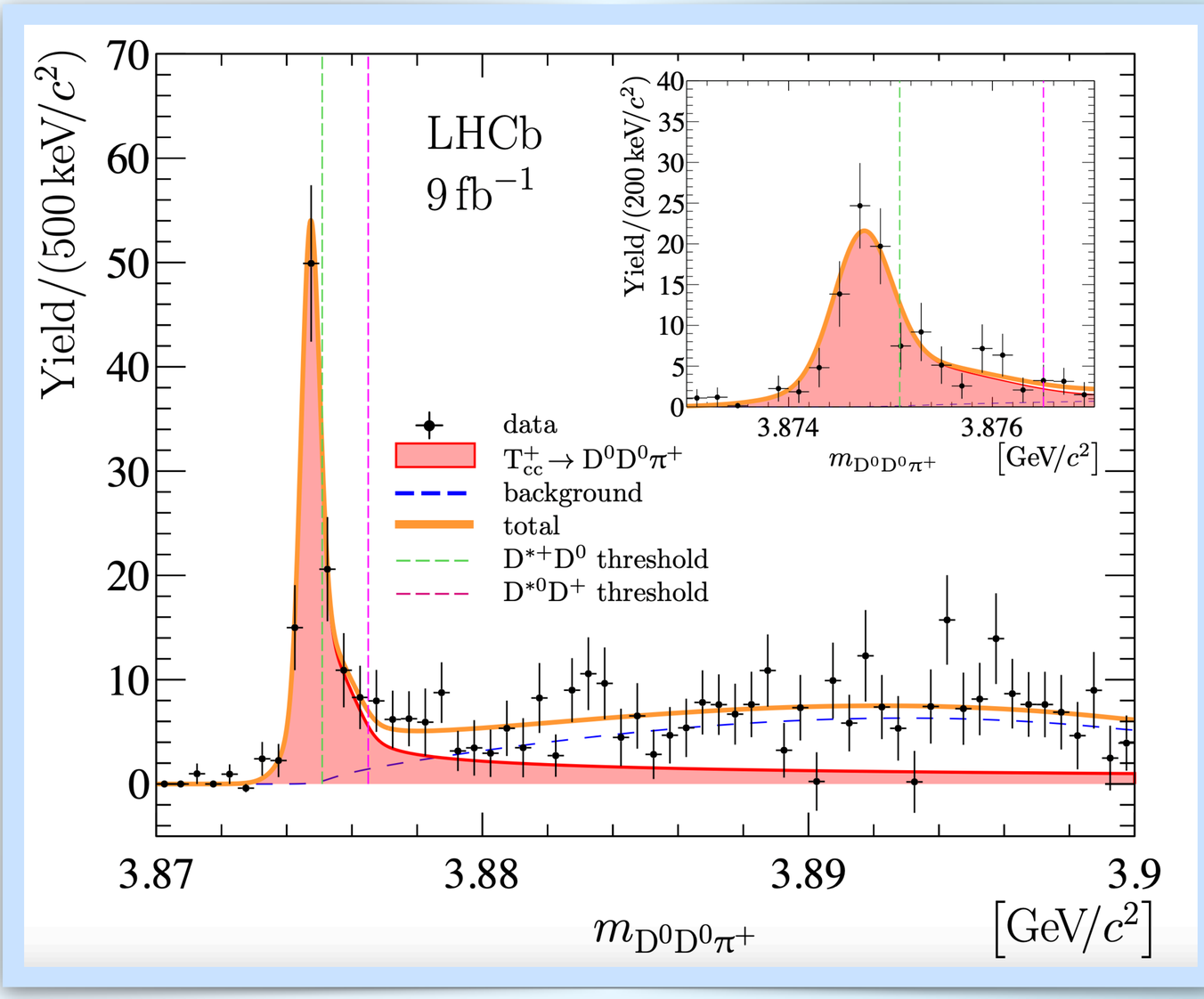
- as soon as m_π^{latt} slightly greater than m_π^{phys}:

$D^* \to D\pi$ forbidden

$$m_\pi^{phys} \leftrightarrow m_\pi^{latt}$$

$$DD\pi \leftrightarrow DD^*$$





$T_{cc}(3875)^+$ – summary of current status

- narrow $DD\pi$ resonance, just below $D^{*+}D^0$ thr.

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

- extremely active subject of LQCD studies:

i. Luscher, DD^* 2202.10110

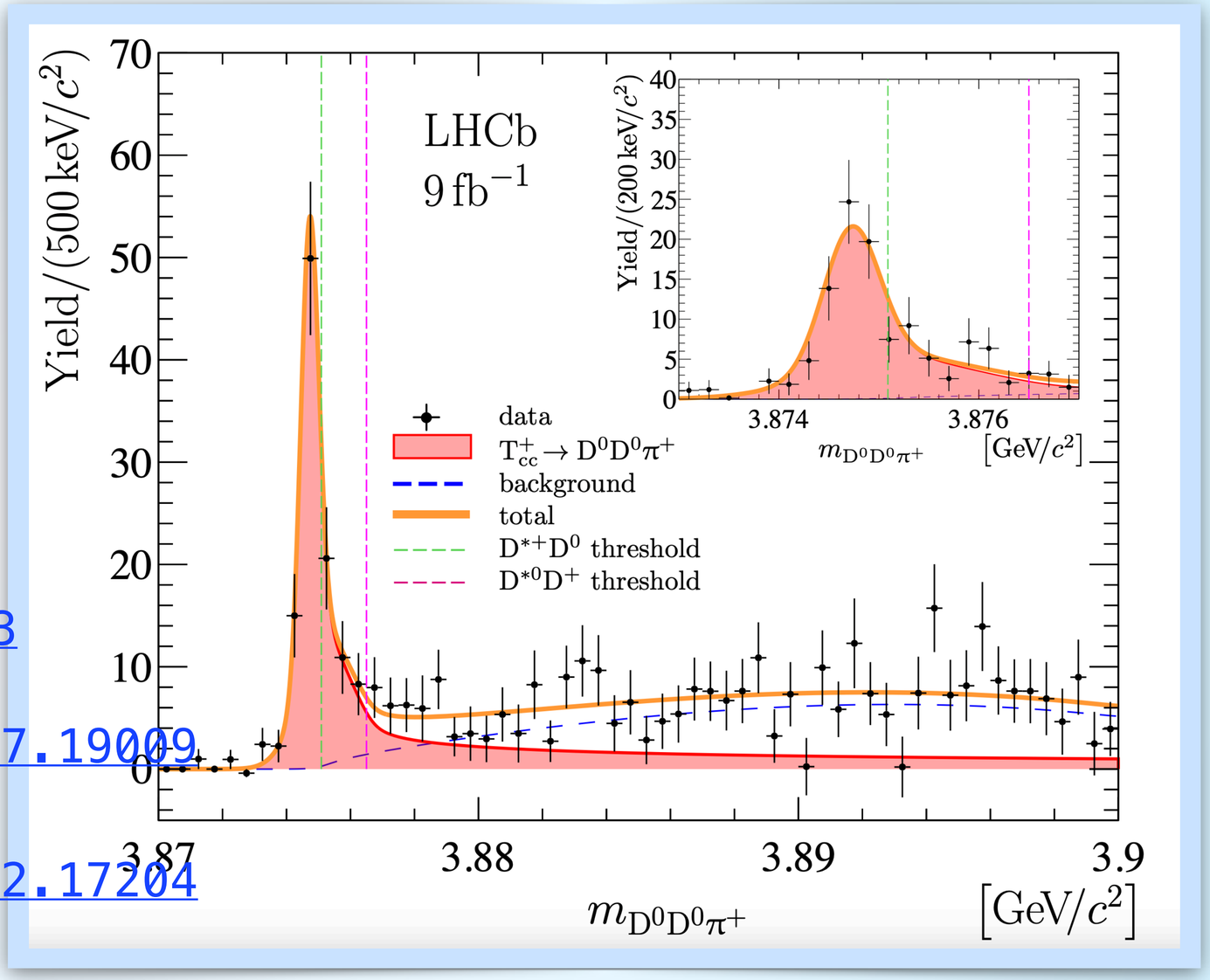
ii. Luscher, $DD^* + D^*D^*$ 2405.15741

iii. LSE+EFT+plane-waves, DD^* 2504.03473

iv. Baião-Raposo–Hansen approach, DD^* 2607.19009

v. RFT 3-body formalism, $DD\pi$ - ongoing 2602.17204

(list not exhaustive)



Lattice setup

ens.	$N_L^3 \times N_T$	a (fm)	m_π (MeV)	m_D (MeV)	m_{D^*} (MeV)	N_V (MM)	N_V (loc.)
F32P30	$32^3 \times 96$	0.07746(18)	305.81(71)	1891.1(1.3)	2015.5(2.3)	100	60
F48P30	$48^3 \times 96$	0.07746(18)	304.98(50)	1892.62(66)	2017.6(1.4)	200	60

- 2 ensembles generated by the CLQCD collaboration ($N_f = 2 + 1$)
- Wilson-Clover light quarks
- RHQ action for the charm quark
- stable D^*
- distilled quark fields

Operator basis

i. basis with good overlap to scattering states below $DD\pi$ thr.

ii. irreps containing information on DD^*, D^*D^* int. in lowest partial waves

- DD^*: T_1^+ ($l = 0,2$), A_1^- ($l = 1$) and E^- ($l = 1,3$)
- D^*D^*: T_1^+ ($s = 1, l = 0,2$) and E^- ($s = 2, l = 3$)

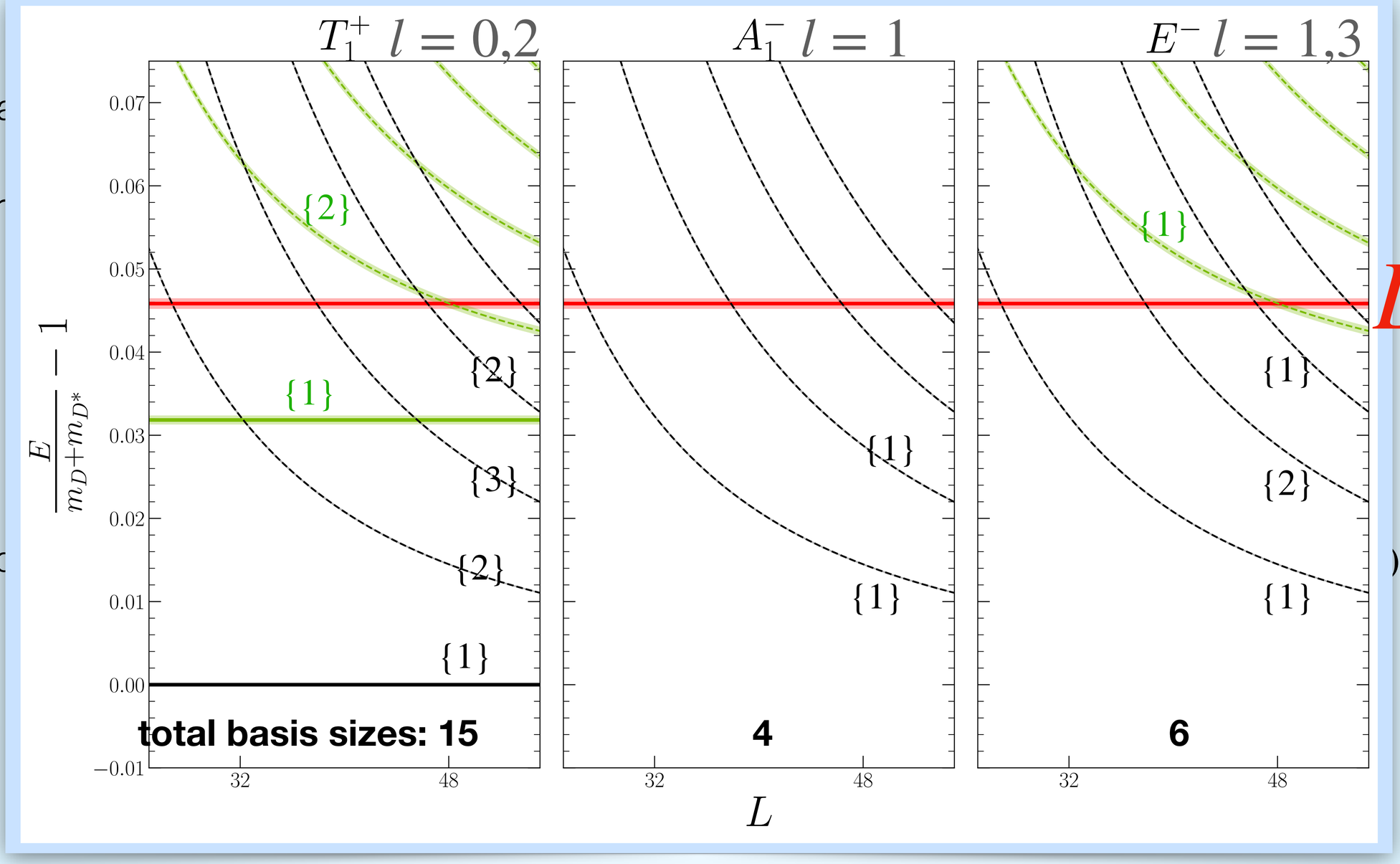
iii. add local diquark-antidiquark ops. into the basis $\mathcal{O}_{4q} = \sum_{\vec{x}} \epsilon^{abc}\epsilon^{ade}[c_b(x)C\gamma_z c_c(x)][\bar{u}_d(x)C\gamma_5\bar{d}_e(x)]$

Operator basis

i. ba

ii. irr

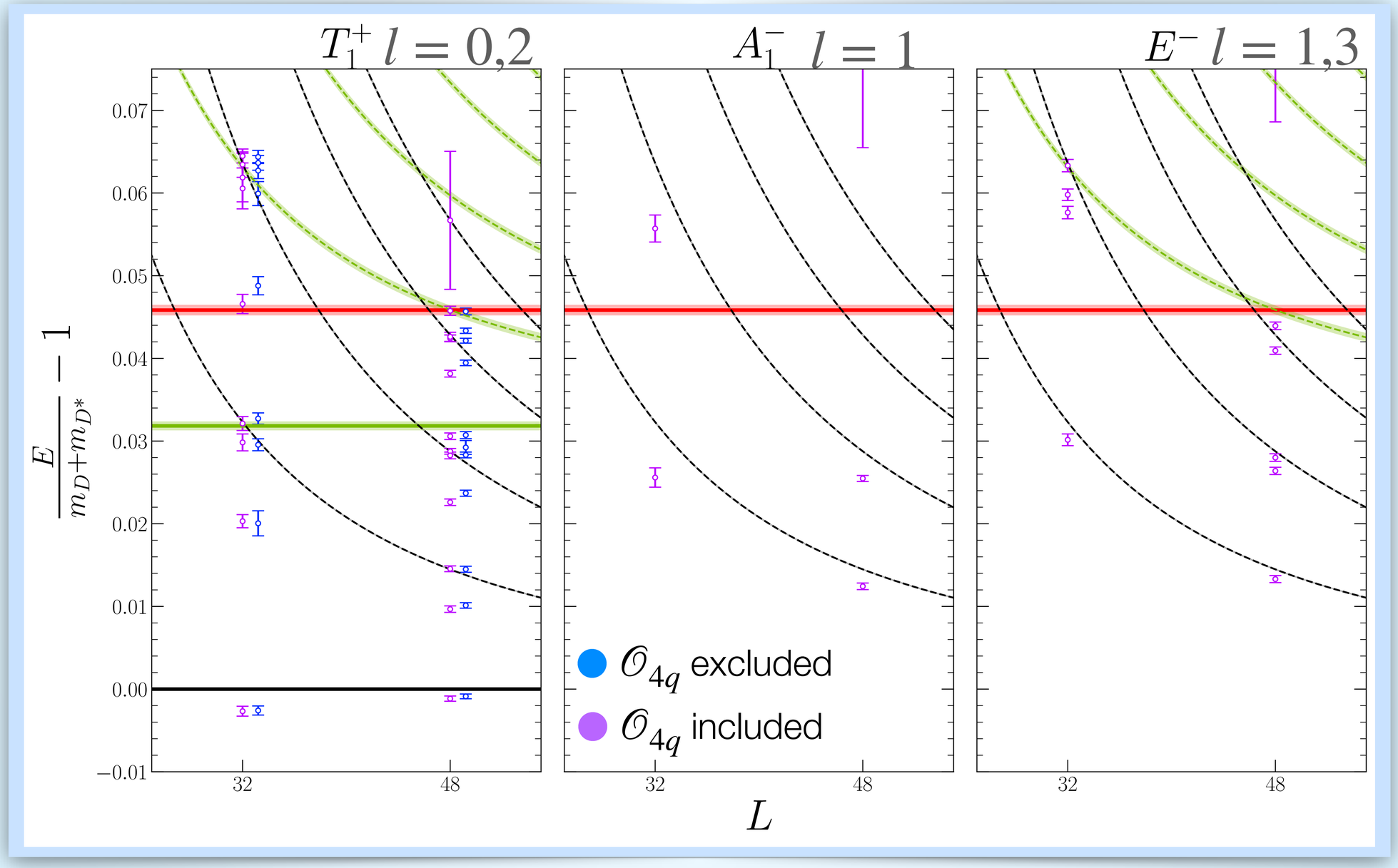
iii. ac



$DD\pi$

$)C\gamma_5\bar{d}_e(x)]$

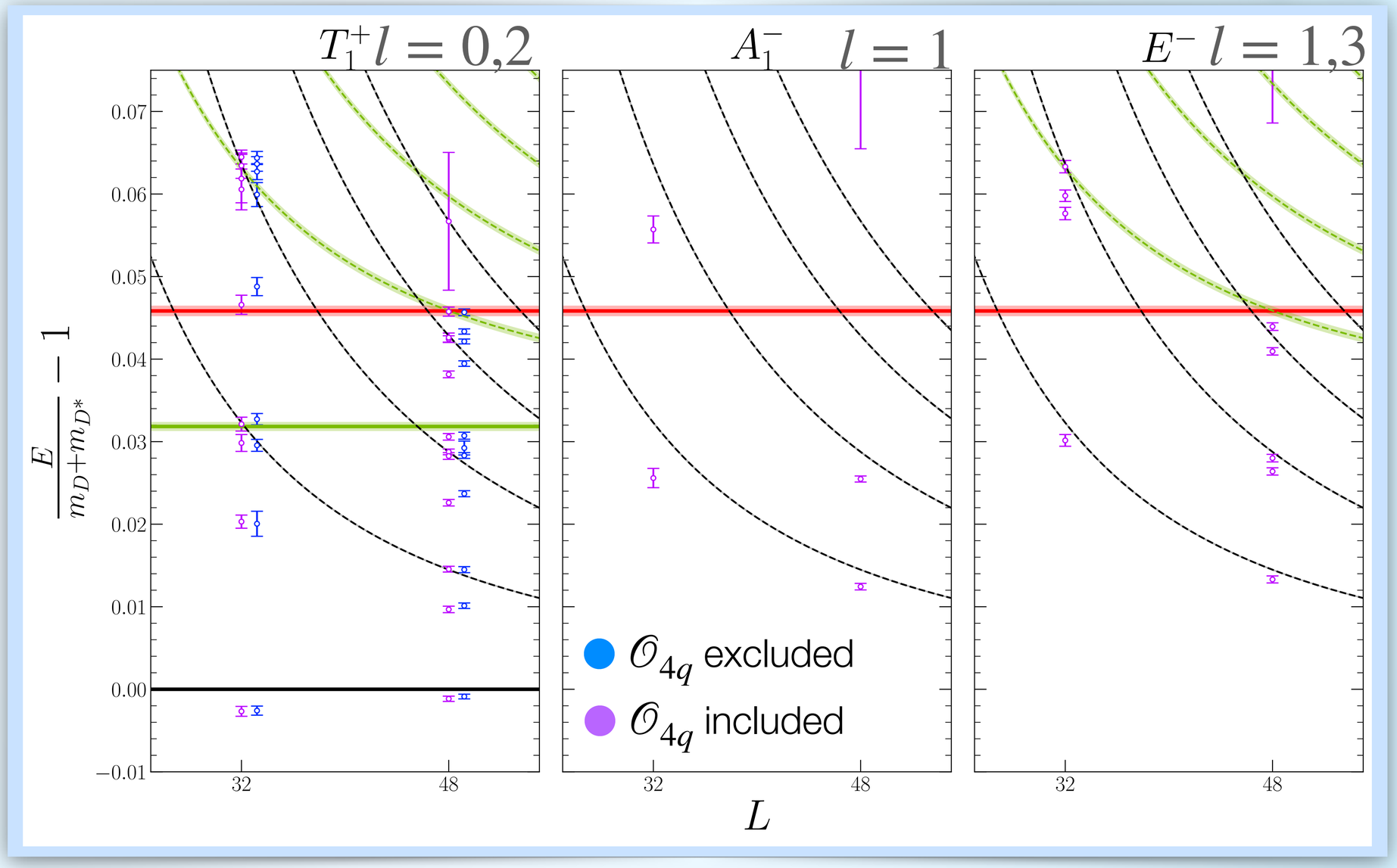
Finite-volume spectrum



Finite-volume spectrum

i. very mild influence of $\mathcal{O}_{4q}$

on the FV spectrum



Finite-volume spectrum

i. very mild influence of $\mathcal{O}_{4q}$

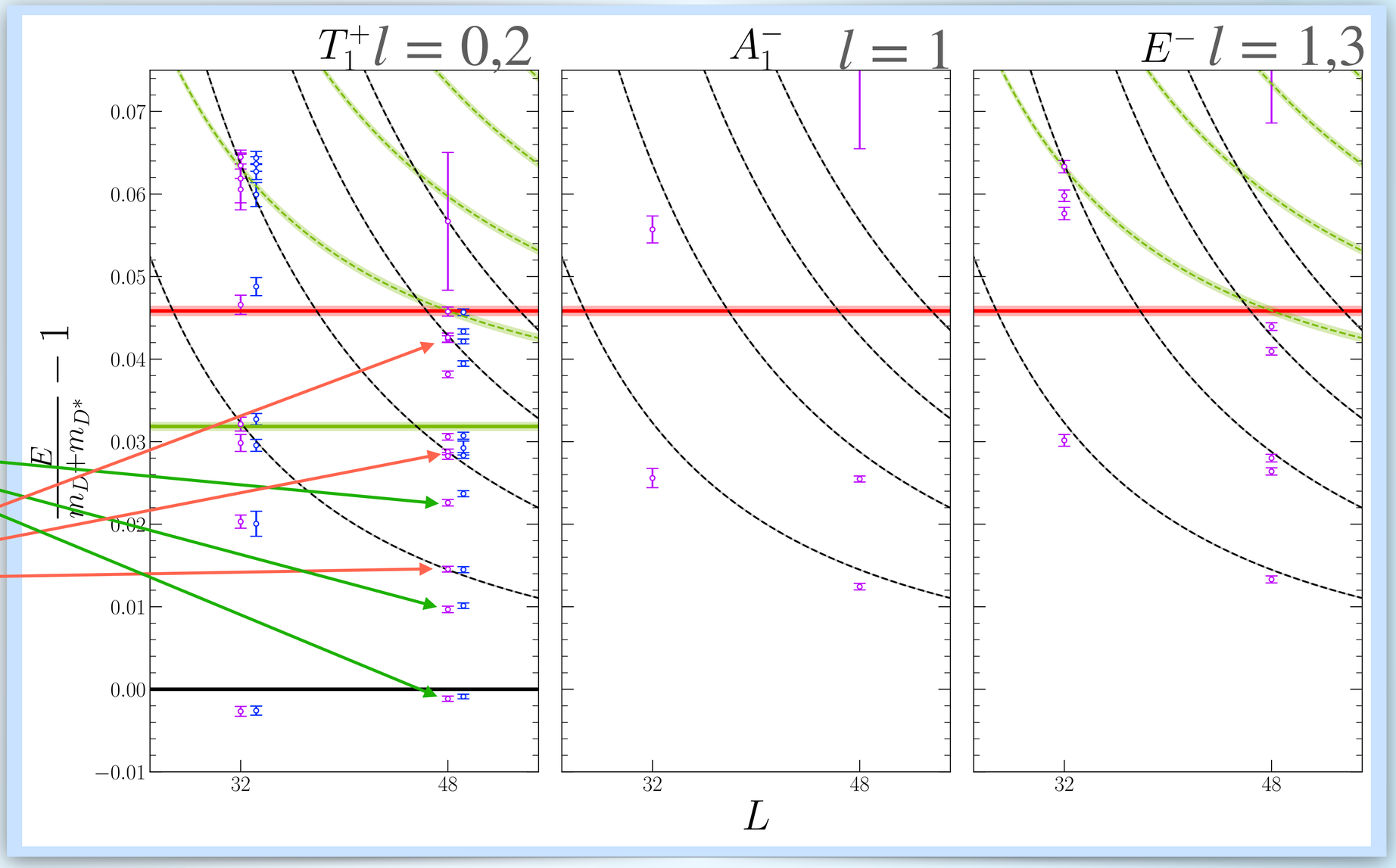
on the FV spectrum

ii. using overlap factors:

attractive $s-$wave int. in

both channels, largely

nonint. $d-$wave levels



Finite-volume spectrum

i. very mild influence of $\mathcal{O}_{4q}$

on the FV spectrum

ii. using overlap factors:

attractive $s-$wave int. in

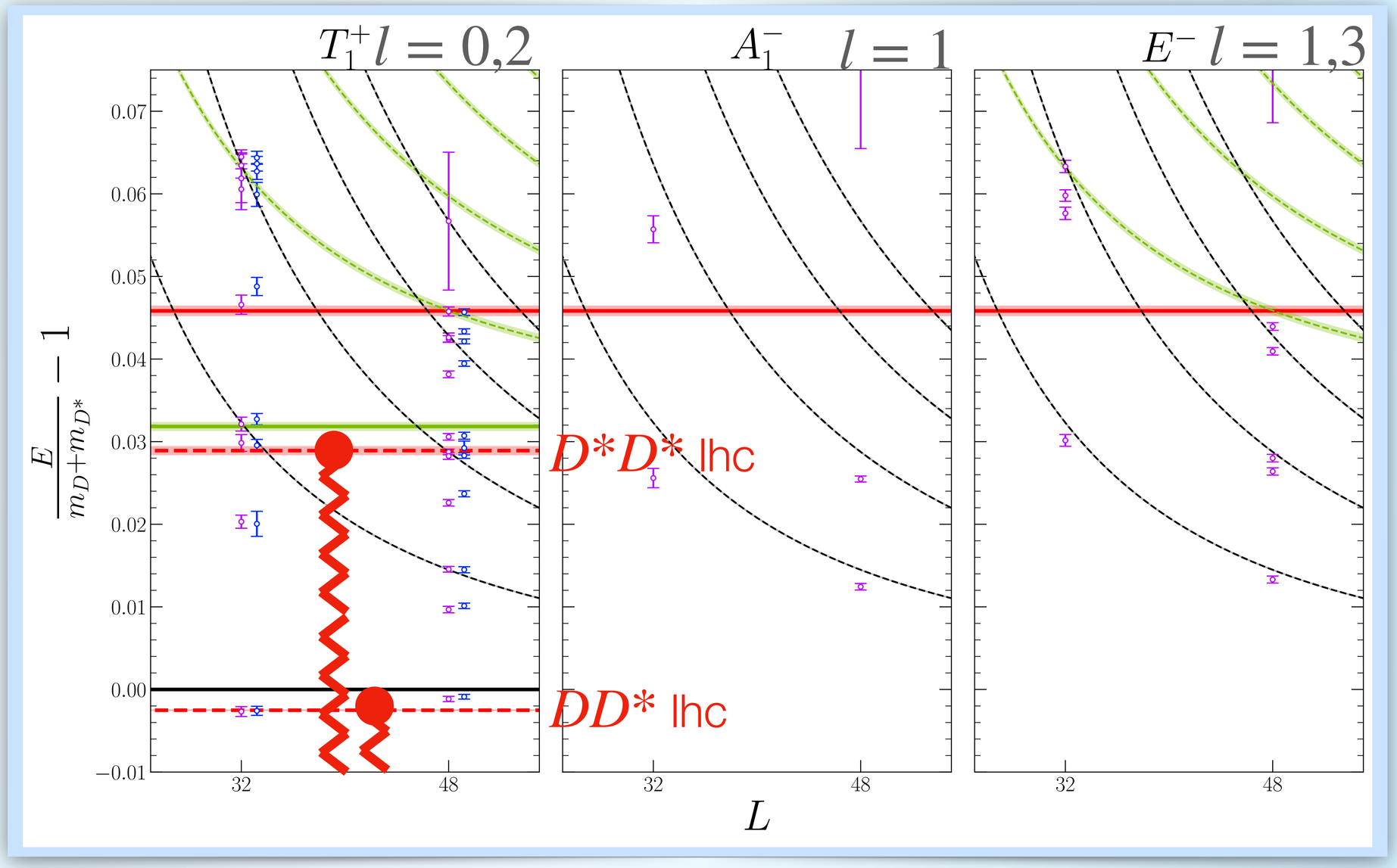
both channels, largely

nonint. $d-$wave levels

iii. crucial $D(0)D^*(0)$ and

$D^*(0)D^*(0)$ levels sitting

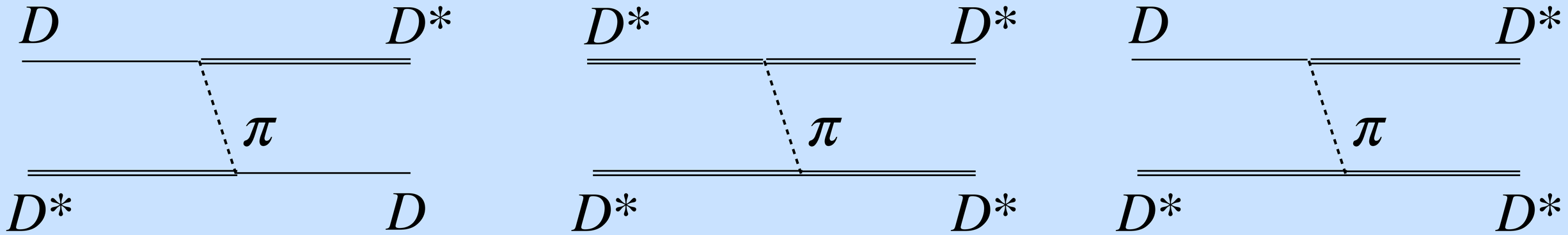
at/below the lhcs



Finite- to infinite-volume pipeline

- ultimate goal: obtain $\begin{pmatrix} T_{DD^*\to DD^*} & T_{DD^*\to D^*D^*} \\ T_{D^*D^*\to DD^*} & T_{D^*D^*\to D^*D^*} \end{pmatrix}$ in infinite-volume

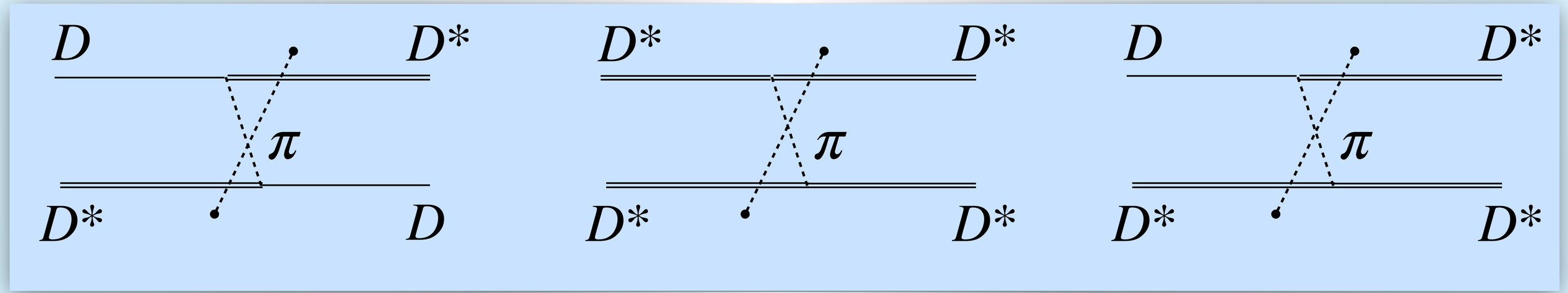
- **complication**: left-hand branch cuts in partial-wave projected scatt. amplitudes, starting from one pion exchange



- (one of several) solution(s): use a quantization condition **not** formulated in partial-wave space

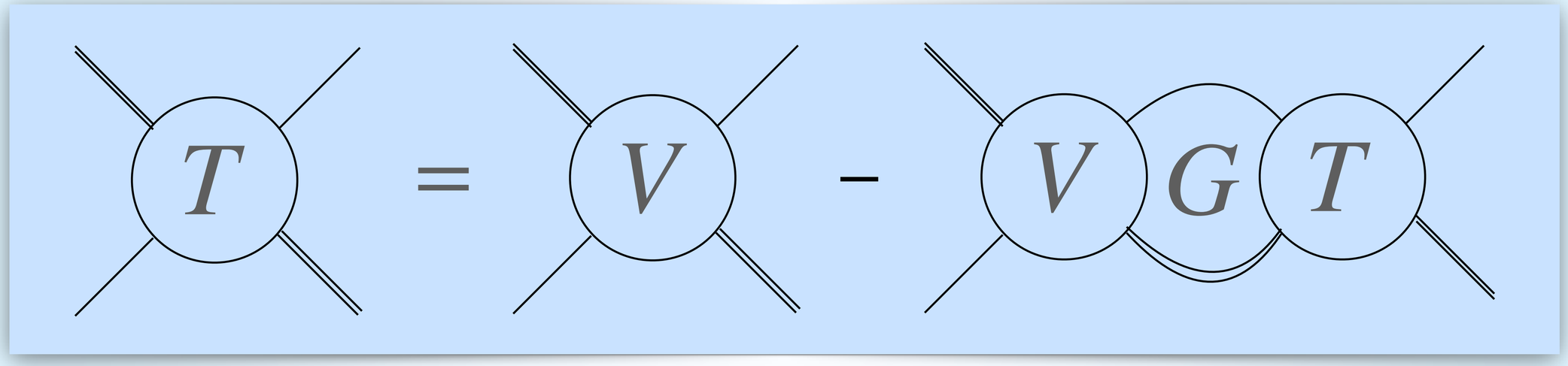
Finite- to infinite-volume pipeline

- **finite-volume unitarity QC** - originally derived for 3-body scattering, readily adaptable for 2-body problems [1709.08222]
- equivalent to Luscher's QC + **can** handle left-hand cuts [1107.3988]



Finite- to infinite-volume pipeline

$$T = V - VGT$$



V : Bethe-Salpeter kernel

G : two-body loop function

$$V^{\infty} = V^{L} + \mathcal{O}(e^{-m_{\pi}L})$$

$$\equiv \frac{1}{k^2 - m_1^2 + i\epsilon} \frac{1}{(P-k)^2 - m_2^2 + i\epsilon}$$

Finite- to infinite-volume pipeline

$$\det\left(2L^3\omega_1(p^2)\left((P-k)^2-m_2^2\right)\Big|_{k^0=\omega_1(p^2)} - V\right) = 0$$

helicity plane-wave basis: $|D(\vec{p})D^*(-\vec{p},\lambda)\rangle,\ |D^*(\vec{p},\lambda_1)D^*(-\vec{p},\lambda_2)\rangle$

↳ **project plane-waves to definite irreps**

det. index runs over channel indices and plane-waves in definite irrep up to some momentum shell p - **roots correspond to FV energies**

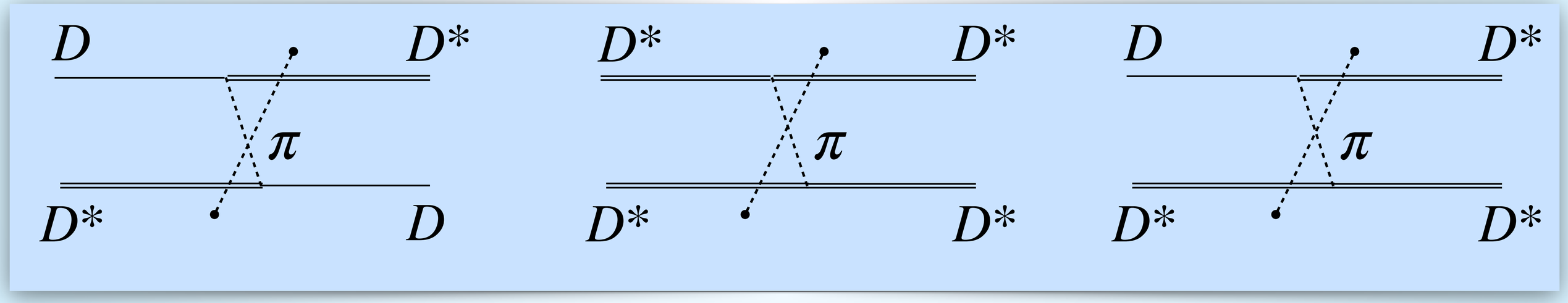
Finite- to infinite-volume pipeline

$$\det\left(2L^3\omega_1(p^2)\left((P-k)^2-m_2^2\right)\Big|_{k^0=\omega_1(p^2)} - V\right) = 0$$

$$V = B + C$$

- one-pion exchange B: tree-level expressions, fixed by HMχPT

1008.0383



- contact term C: smooth, expanded in several lowest partial waves

Finite- to infinite-volume pipeline

- one-pion exchange B: tree-level expression, fixed by HMχPT [1008.0383]

- contact term C: smooth, expanded in several lowest partial waves

regulated: $c_{L'L} \to \left(\frac{\Lambda^2}{\Lambda^2 + p'^2}\right)^{L'+1} c_{L'L} \left(\frac{\Lambda^2}{\Lambda^2 + p^2}\right)^{L+1}$

channel	irrep	J^P	L	parametrization
$DD^* \to DD^*$	T_1^+	1^+	s, d	$c_{ss} + c'_{ss}(p^2 + p'^2), c_{sd}p^2, c_{dd}p^2p'^2$
	A_1^-	0^-	p	$c_{pp}p$
	E^-	2^-	p	$c_{pp}p$
$DD^* \to D^*D^*$	T_1^+	1^+	s	c_{ss}
$D^*D^* \to D^*D^*$	T_1^+	1^+	s	c_{ss}

Fits with OPE – T_1^+

i. good: DD^* $s-$wave

LECs very robust with

respect to Λ variation

ii. higher channel more

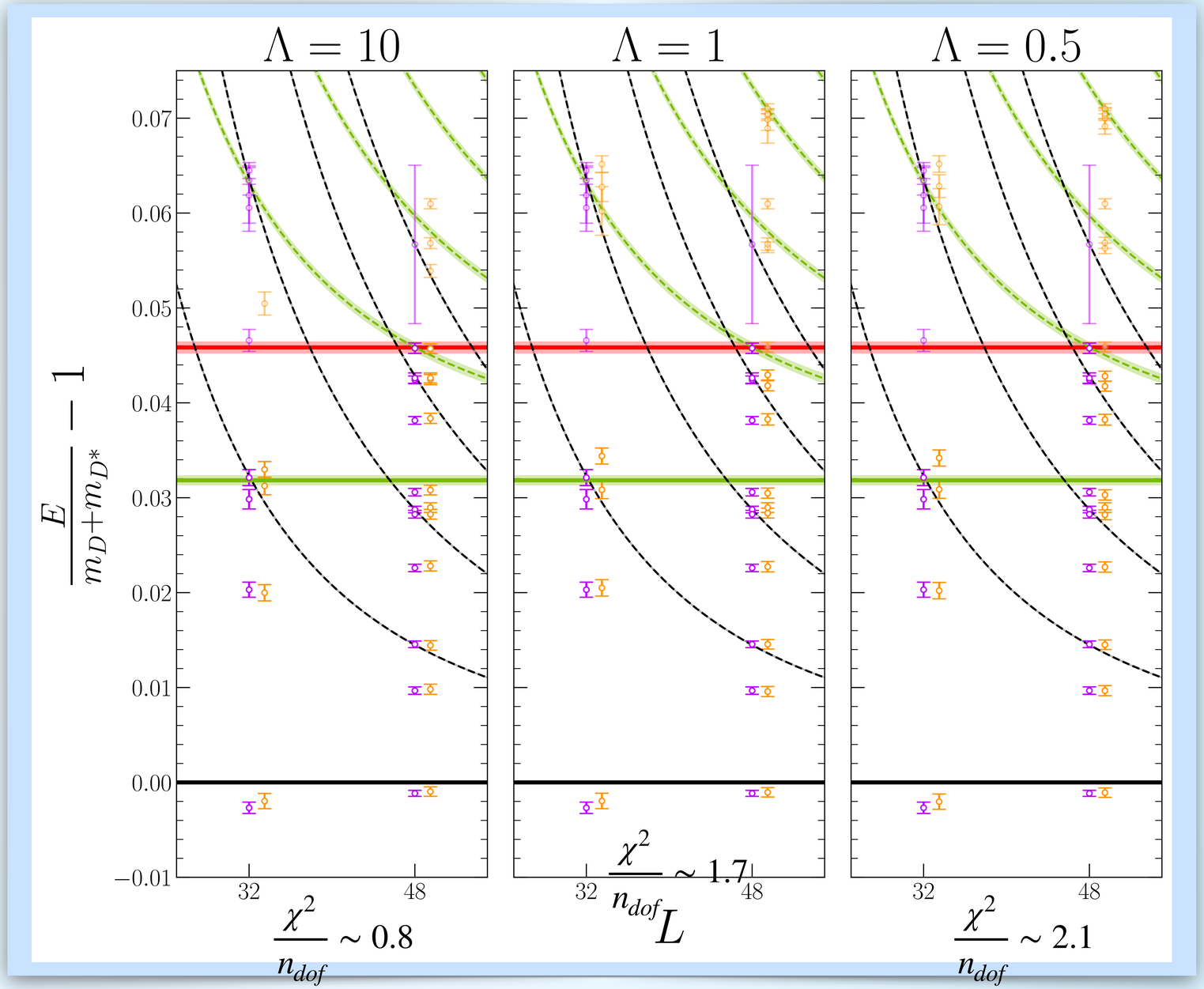
affected by cutoff

$c_{ss}^{DD^*\to D^*D^*}(\Lambda = 10) = 0$

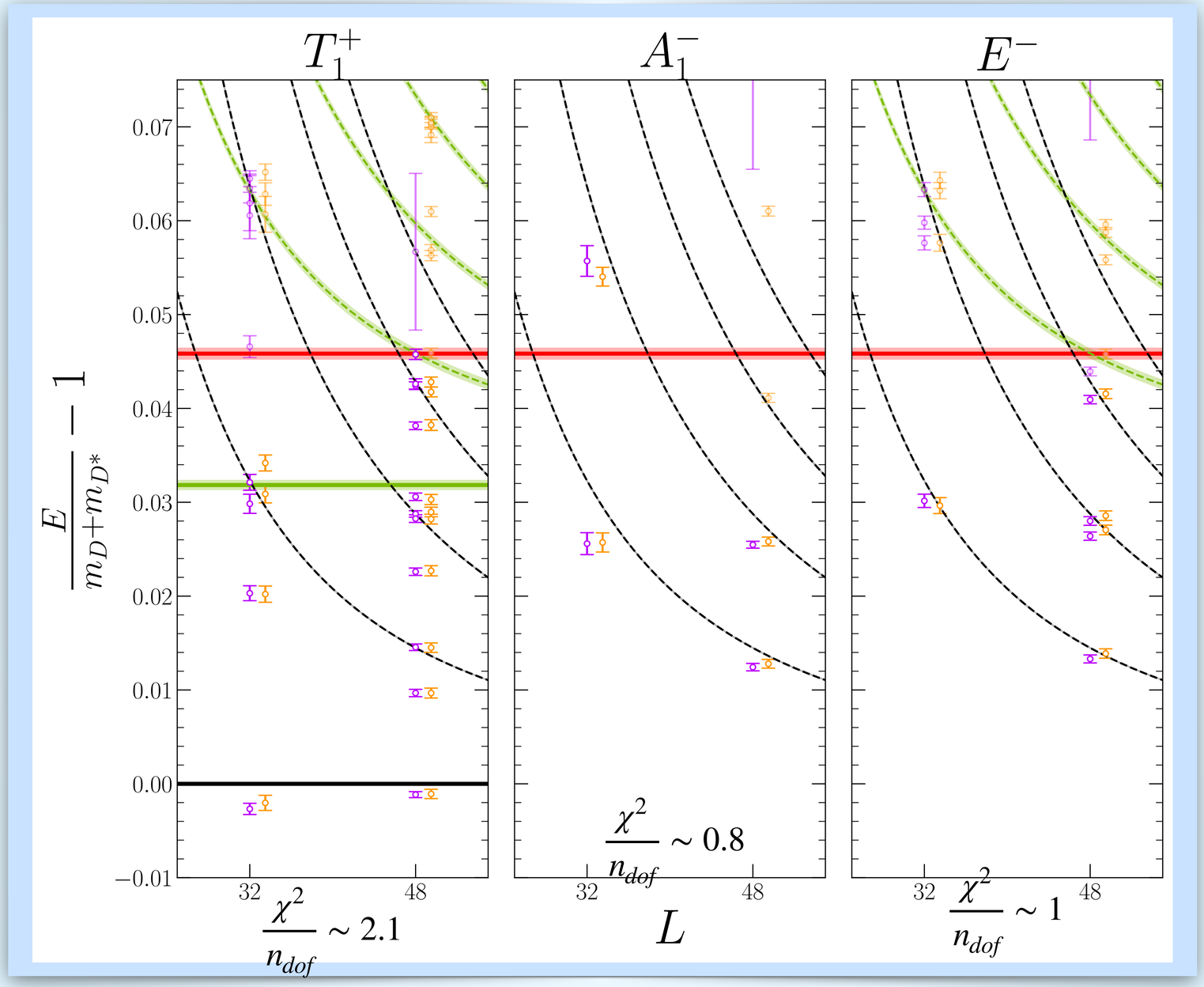
$c_{ss}^{DD^*\to D^*D^*}(\Lambda = 0.5) \ll 0$

$c_{ss}^{D^*D^*\to D^*D^*}$ also significantly

decreases as $\Lambda \to 0$



Fits with OPE $\Lambda = 0.5$



Fits without OPE $\Lambda = 0.5$

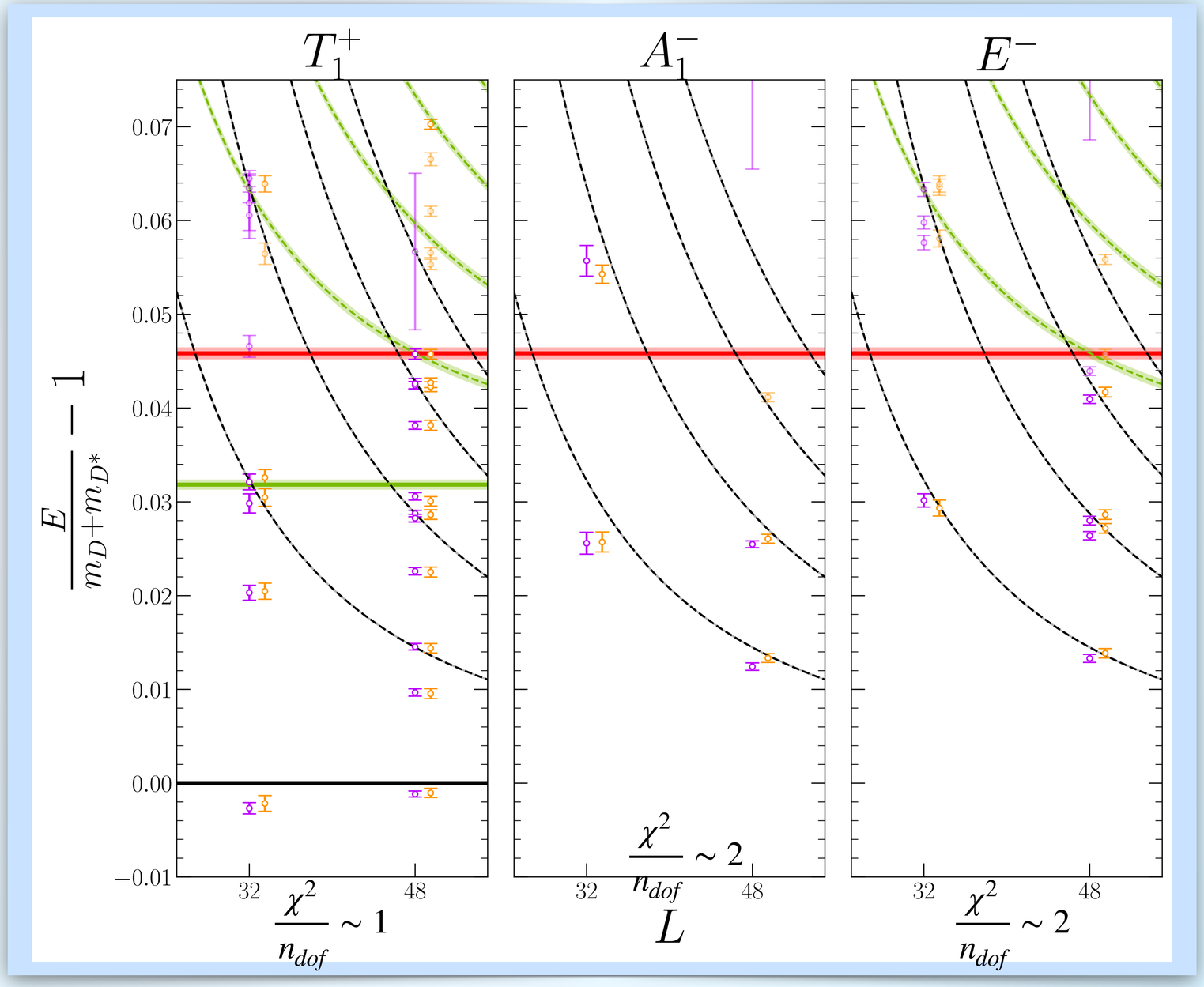
i. no partial-wave mixing and

no $d-$wave energy shifts

with OPE set to zero →

can set c_{sd}, c_{dd} to zero

and get good fits in T_1^+



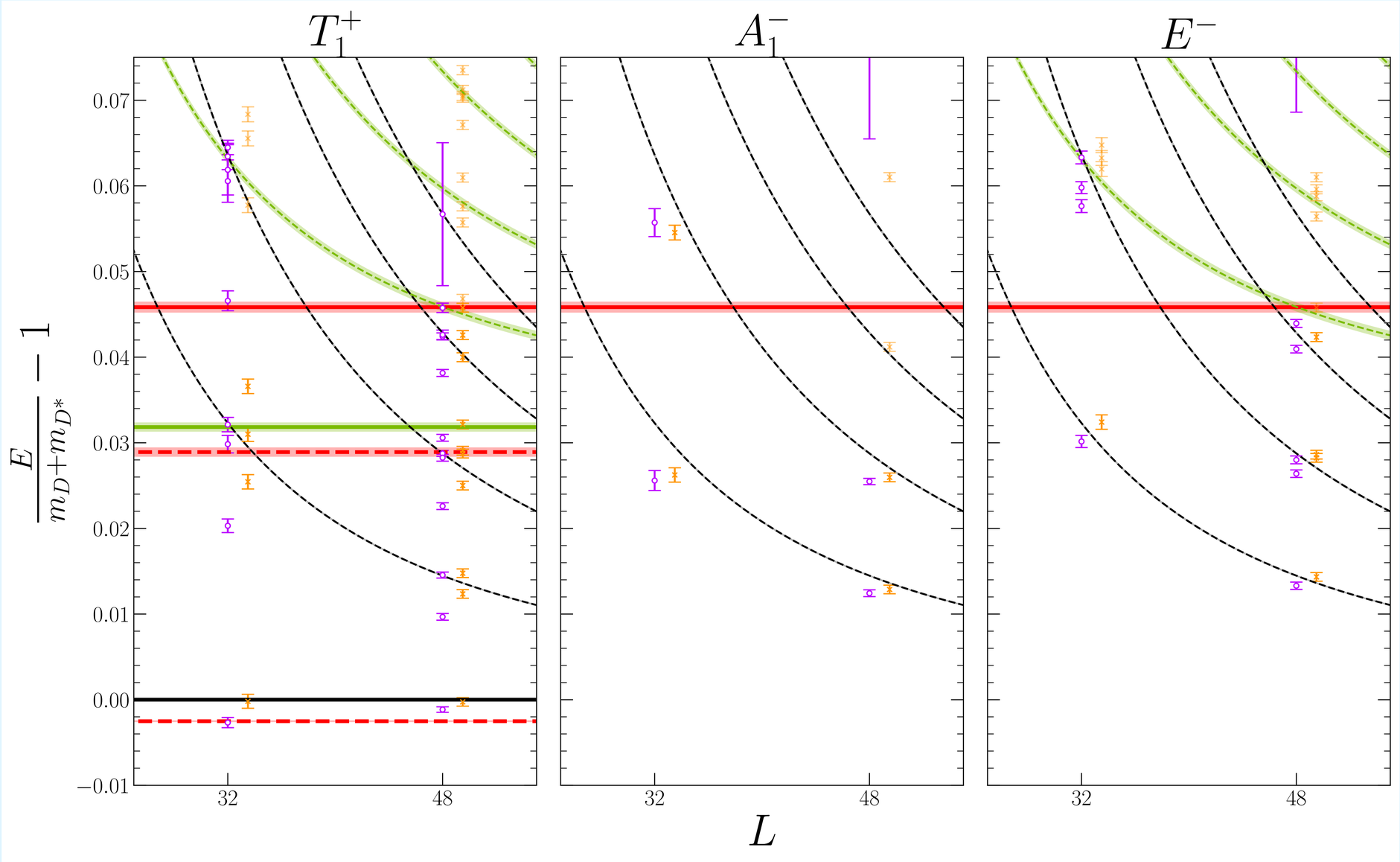
Summary and outlook

- searching for T_{cc} (and T'_{cc}) in coupled-channel $DD^* - D^*D^*$ scattering
- left-hand branch cuts avoided/accounted for - finite-volume unitarity QC
- **preliminary** fits to FV spectrum with(out) one-pion exchange:
    i. robust DD^* $s-$wave low-energy constants with respect to cutoff Λ
    ii. higher channel interactions more affected
- further constrain low-energy constants by using FV from a smaller lattice + moving frame irreps → solve BSE
- start moving towards physical m_π

Thank you!

Backup

OPE spectrum, $C = 0$



F32P30 – levels 2 & 3

- $D(0)D^*(0)$
- $D(1)D^*(-1)_{L=0}$
- $D(1)D^*(-1)_{L=2}$
- $D(2)D^*(-2)_{L=0}$
- $D(2)D^*(-2)_{L=2}$
- $D(2)D^*(-2)_{J=3;L=2}$
- $D(3)D^*(-3)_{L=0}$
- $D(3)D^*(-3)_{L=2}$
- $D^*(0)D^*(0)$
- $D^*(1)D^*(-1)_{L=0}$
- $D^*(1)D^*(-1)_{L=2}$
- $D(0)D^*(0)(\gamma_i\gamma_t, \gamma_5\gamma_t)$
- $D(1)D^*(-1)_{L=0}(\gamma_i\gamma_t, \gamma_5\gamma_t)$
- $D^*(0)D^*(0)(\gamma_i\gamma_t, \gamma_j\gamma_t)$
- $O_{4q}(0)$