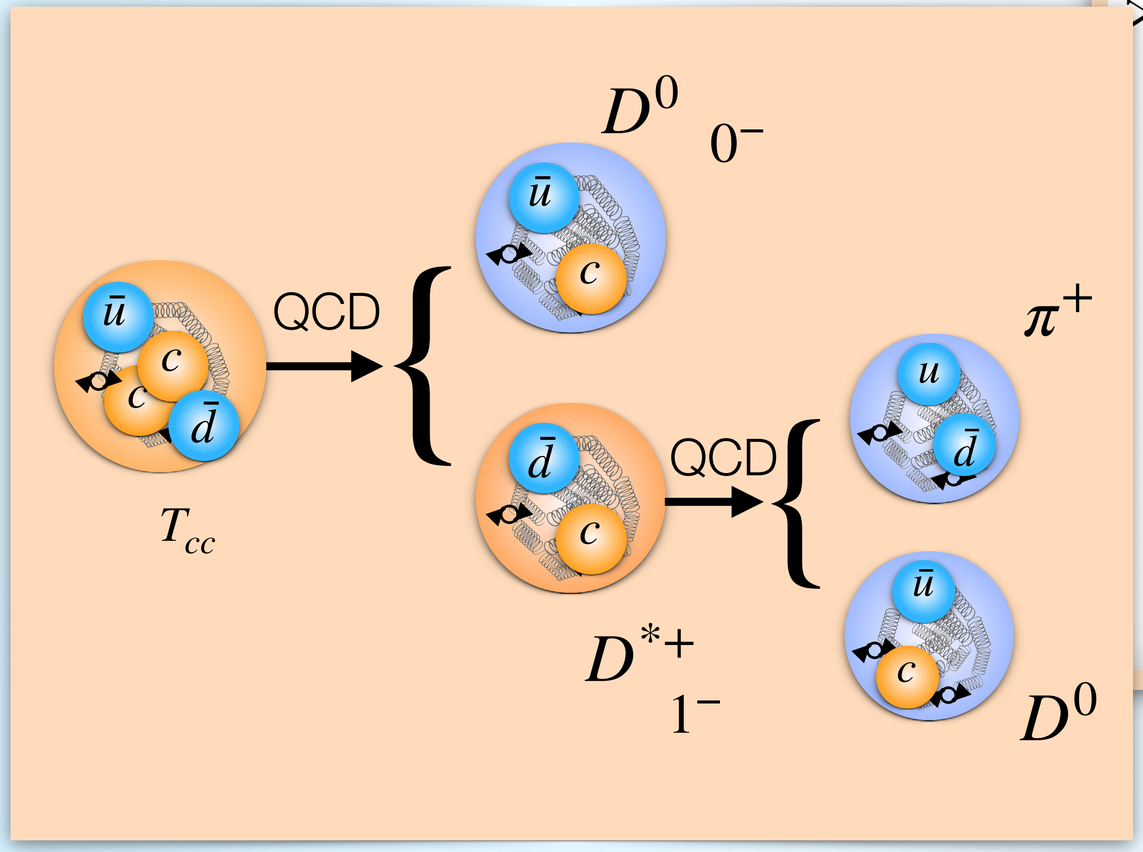
Doubly-charmed tetraquark from coupled $DD^* - D^*D^*$ scattering on the lattice

in collaboration with: **Feng-Kun Guo, Liuming Liu, Maxim Mai, Sasa Prelovsek, Haobo Yan** and **Xu Zhang**

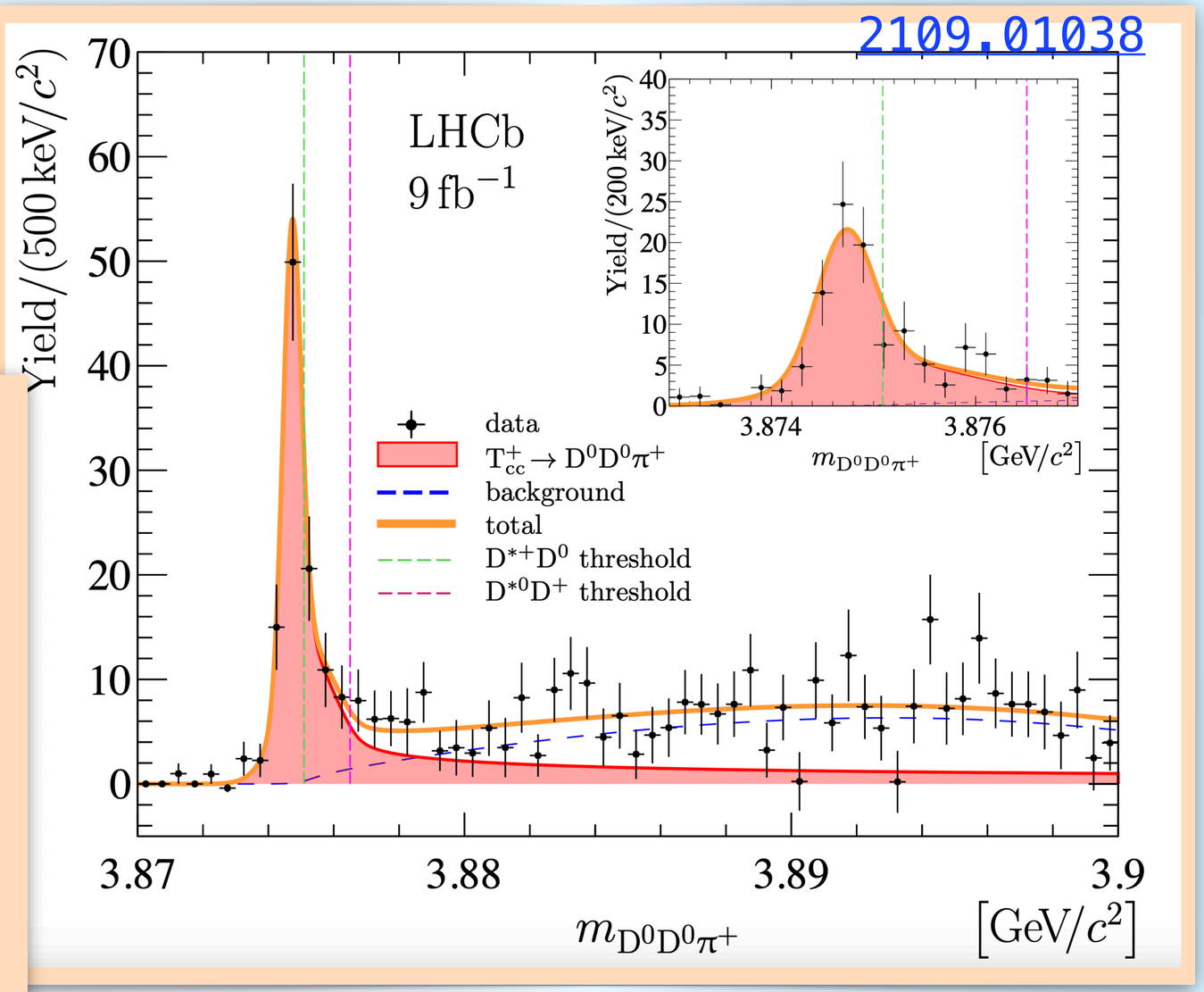
BRDA 2026: Challenges in particle physics and cosmology
October 16th, 2026

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

- LHCb, 2021
- manifestly exotic: $cc\bar{u}\bar{d}, I(J^P) = 0(1^+)$
- narrow $DD\pi$ resonance, just below $D^{*+}D^0$ thr.
- $T_{cc} \to DD^* \to DD\pi$



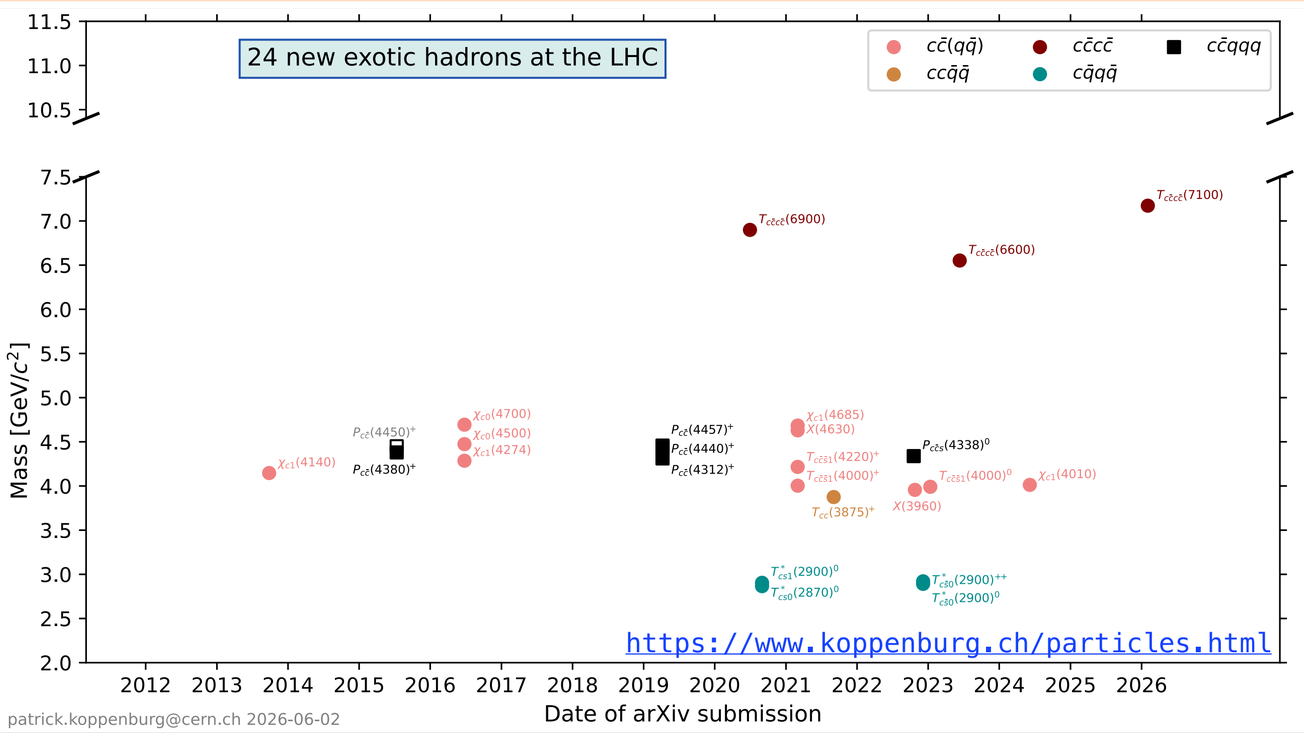
2109.01038

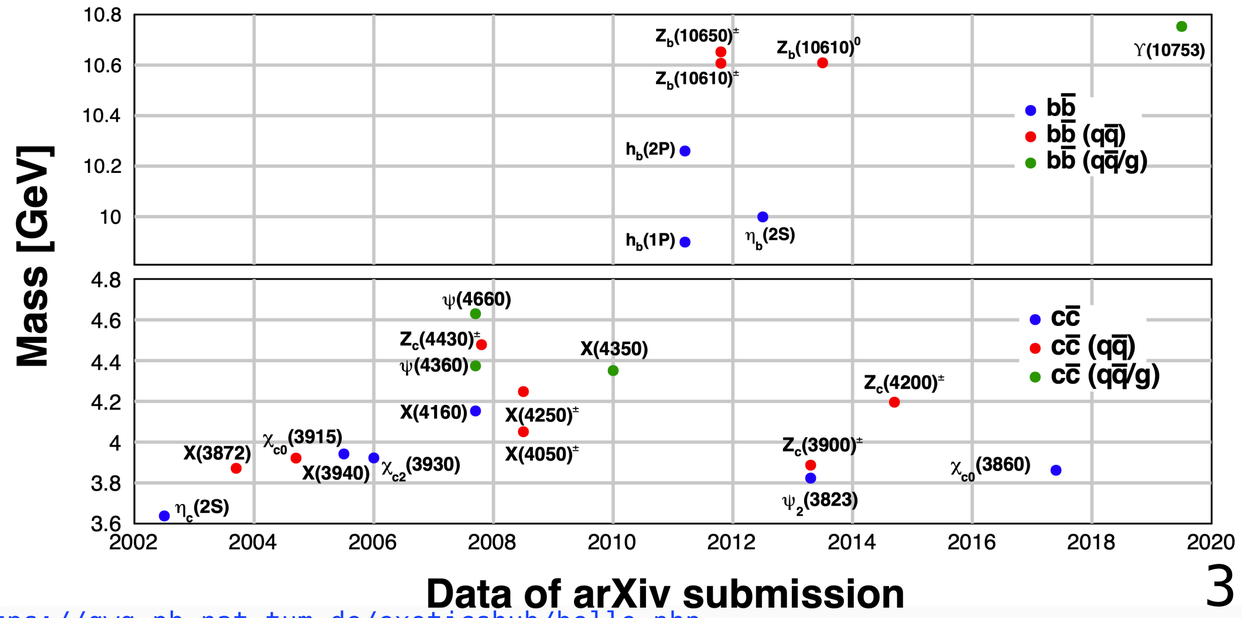


Motivation

- exotic hadron
- known experimentally to exist
- long-lived
- somewhat simpler to study than most other

  exotics of type $c\bar{c}X, b\bar{b}X$





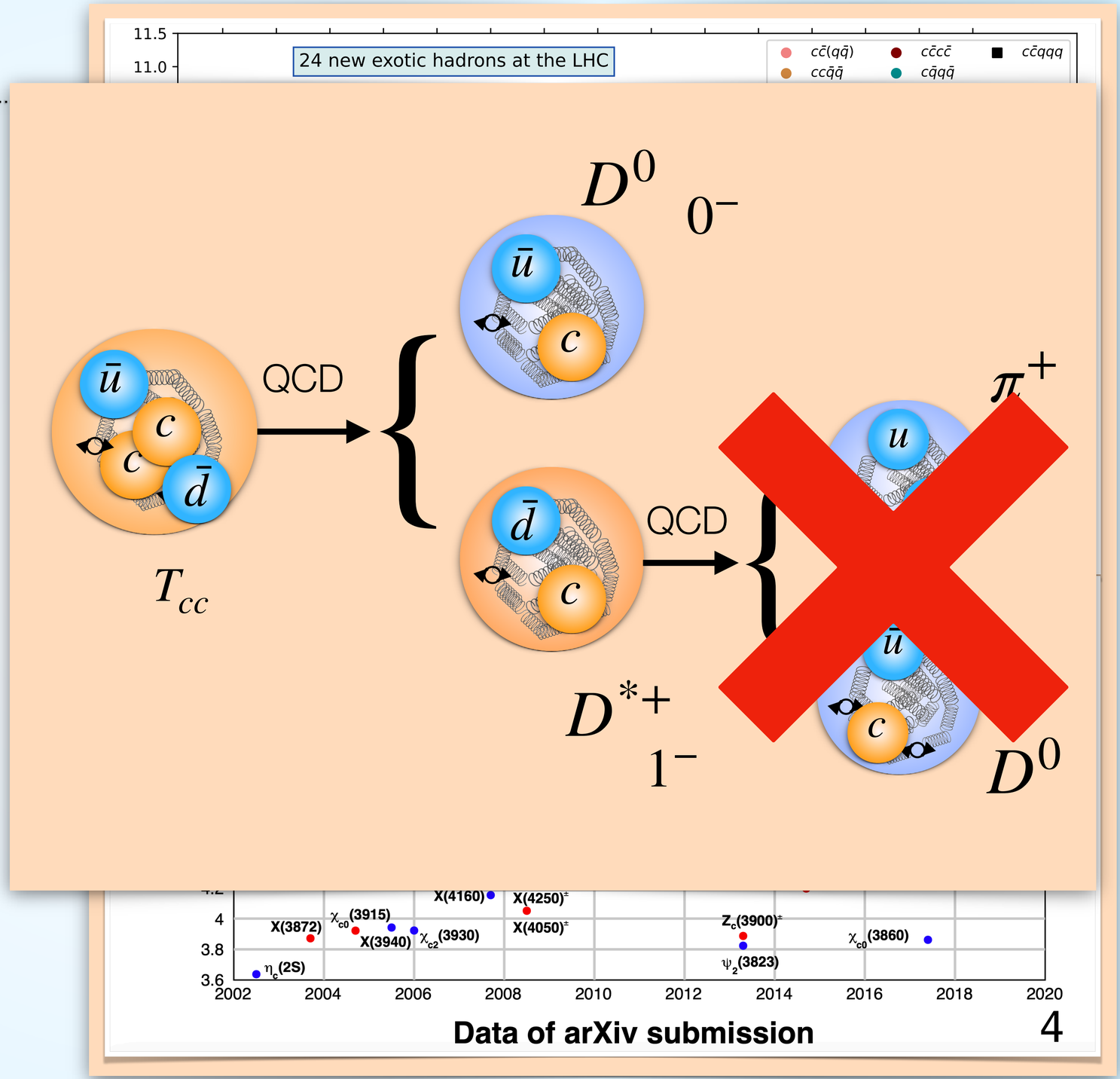
https://qwg.ph.nat.tum.de/exoticshub/belle.php

Motivation

- exotic hadron
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  exotics of type $c\bar{c}X, b\bar{b}X$

- on the lattice:
  - usually $m_\pi^{latt} > m_\pi^{phys} \approx 135$ MeV
  - $(m_{D^*} - m_D)_{phys} \approx 140$ MeV
  - $D^* \to D\pi$ decay forbidden on the lattice
    - $2-$**body problem!** DD^* **scattering**



Motivation

* in the infinitely heavy quark mass limit: D, D^*

  become degenerate — **existence of T'_{cc} in the**

  D^*D^* spectrum?

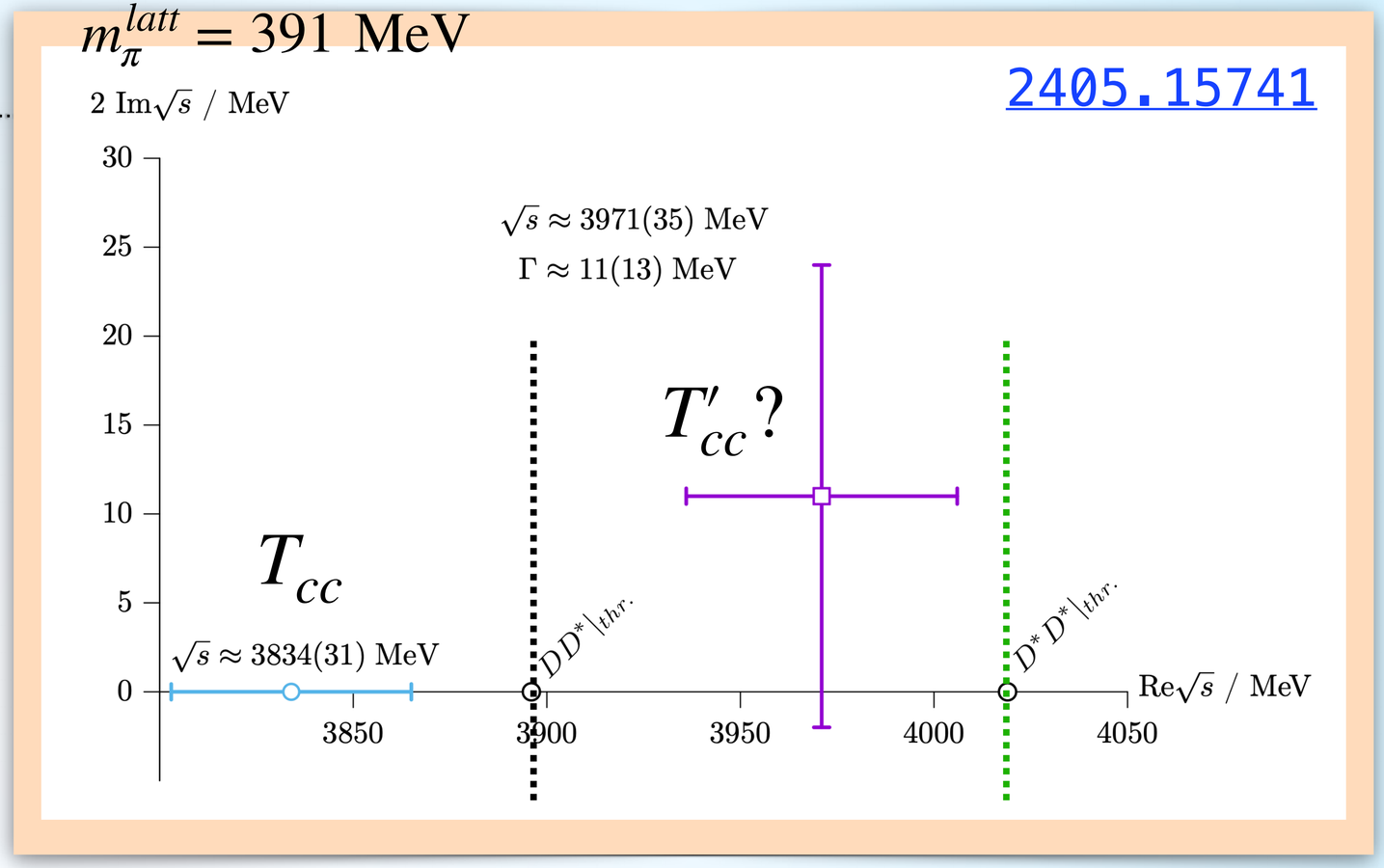
* extremely active subject of LQCD studies:

  i. M. Padmanath, S. Prelovsek 2202.10110

  ii. Hadron Spectrum Collaboration

  iii. S. Prelovsek, E. Ortiz-Pacheco, S. Collins, L. Leskovec, M. Padmanath, I. V. 2504.03473

(many other works missing)



improvements of the current project:

i. study at smaller $m_\pi^{latt} \approx 300$ MeV

ii. in addition to scattering operators, use local operators

iii. account for the left-hand branch cuts in the scatt. amplitudes

Motivation

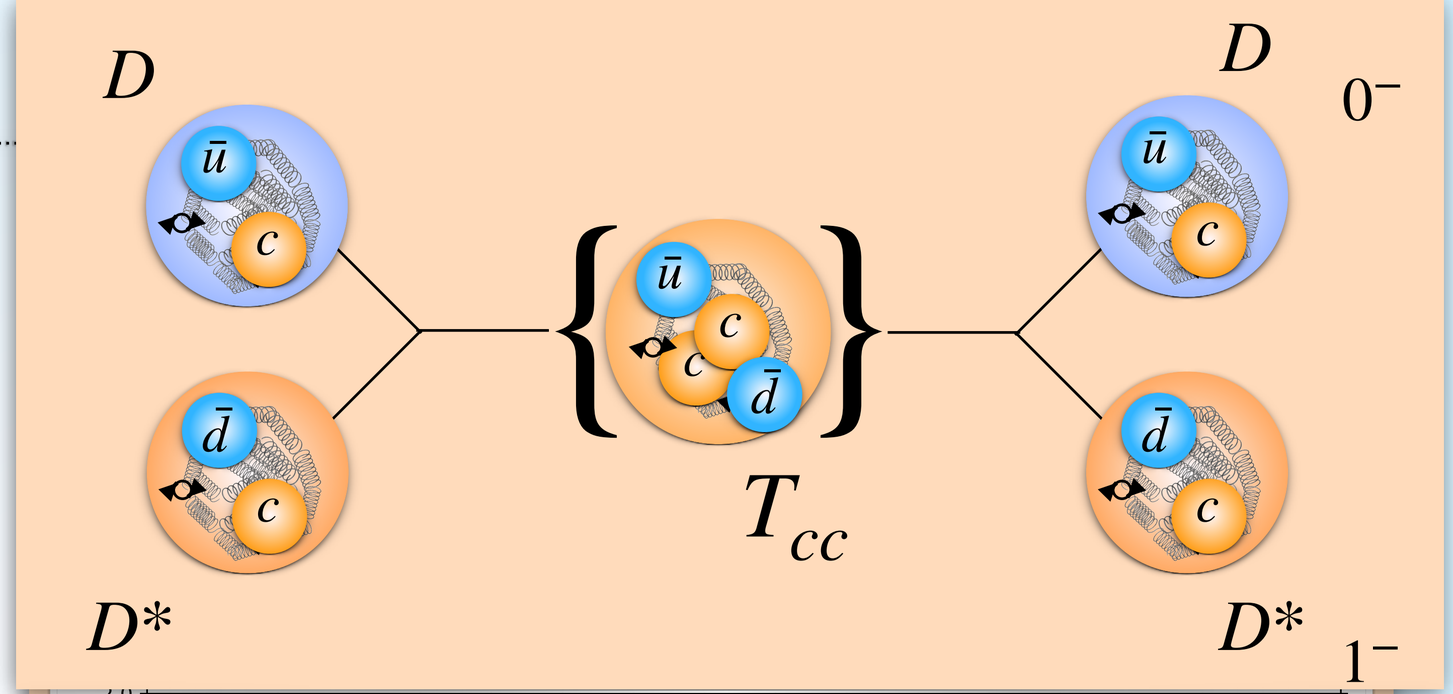
workflow:

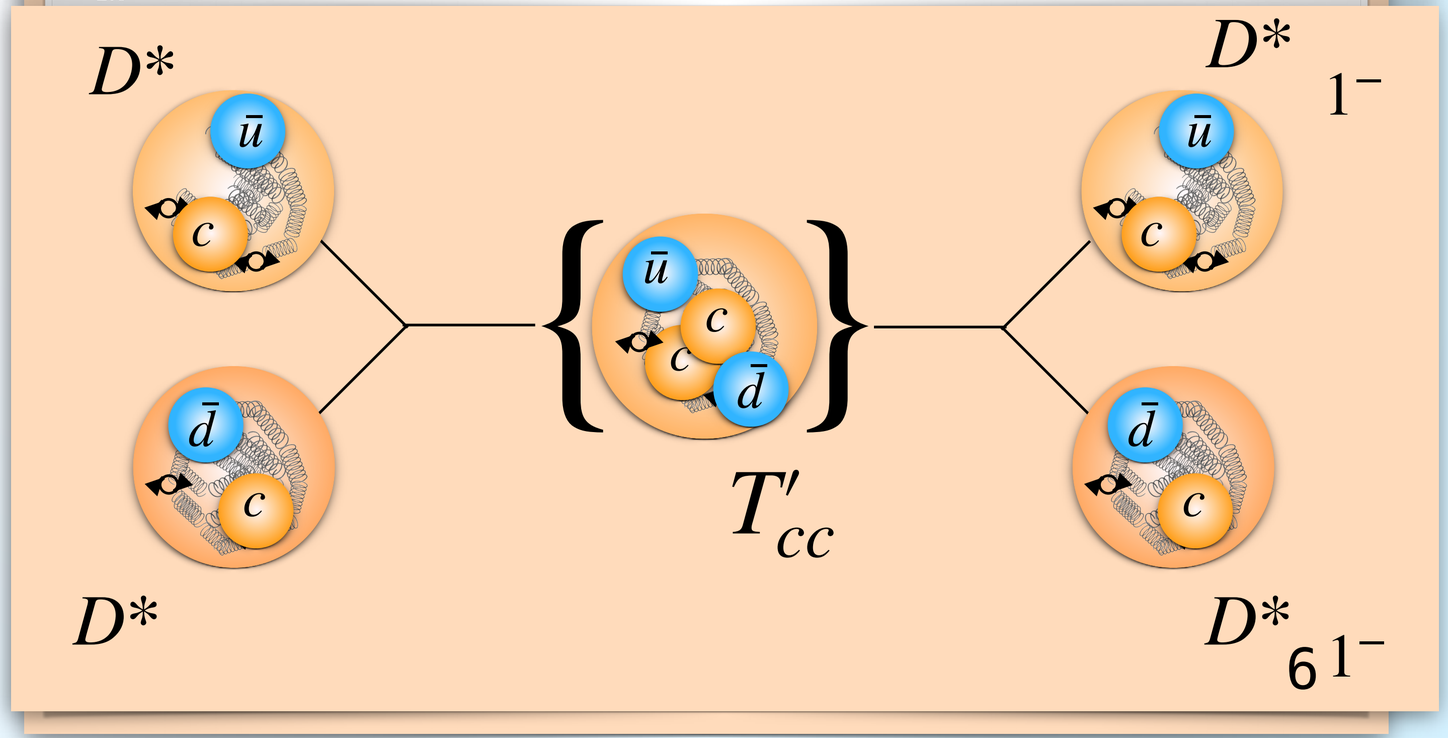
i. simulate coupled $DD^* - D^*D^*$ scattering on the lattice

ii. use finite-volume data to constrain $s-$wave interactions

iii. search for T_{cc}, T'_{cc} poles in scattering amplitudes

$$\begin{pmatrix} T_{DD^*\to DD^*} & T_{DD^*\to D^*D^*} \\ T_{D^*D^*\to DD^*} & T_{D^*D^*\to D^*D^*} \end{pmatrix}$$





Intro to lattice QCD

- starting point: continuum QCD $\quad S(\bar{q}_f, q_f, G) = \int \mathscr{L}_{QCD}(x)\mathrm{d}^4x$

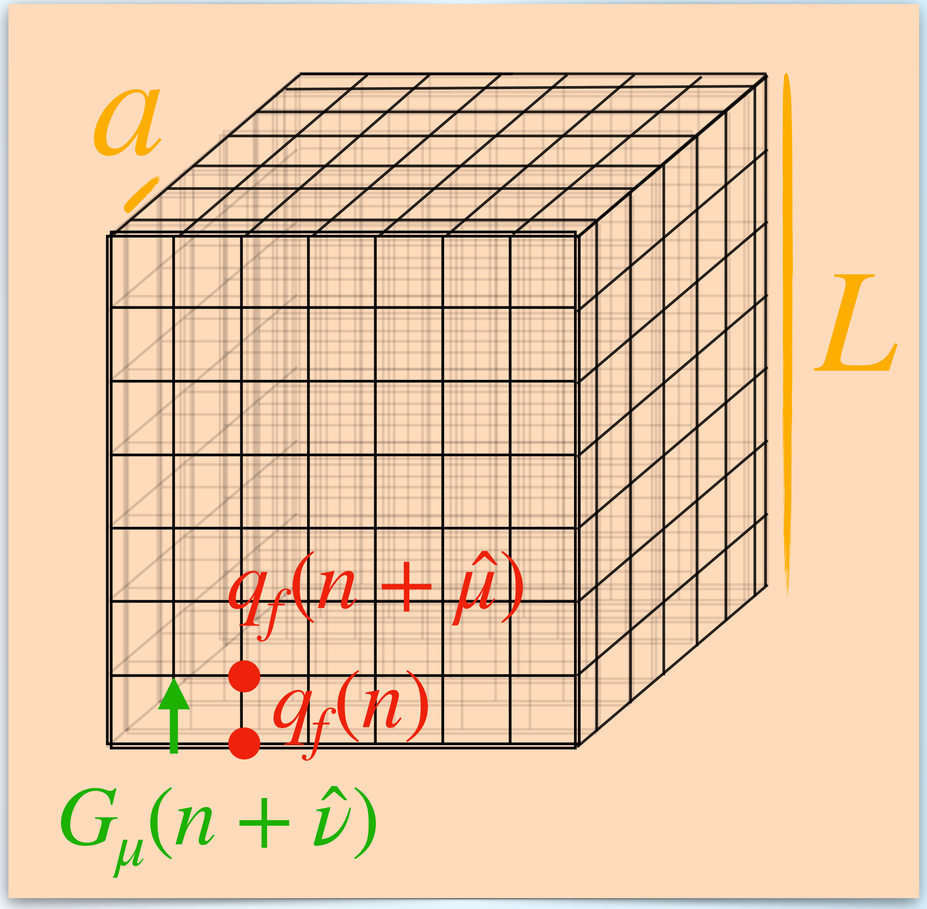
$$\mathscr{L}_{QCD}(x) = \sum_f \bar{q}_f(x)\left(i\gamma^\mu\partial_\mu - g_S\gamma^\mu G^a_\mu(x)t_a - m_f\right)q_f(x) - \frac{1}{4}F^a_{\mu\nu}(x)F^{\mu\nu}_a(x)$$

i. discretize the action S

ii. path integral: perform Wick rotation $t \to -it_E$

$$\langle\hat{O}\rangle \equiv \langle\Omega\,|\,\hat{O}\,|\,\Omega\rangle = \frac{1}{Z}\int DGD\bar{q}_f Dq_f\; O(\bar{q}_f, q_f, G)e^{iS(\bar{q}_f,q_f,G)}$$

$$Z \equiv \int DGD\bar{q}_f Dq_f\; e^{iS(\bar{q}_f,q_f,G)}$$



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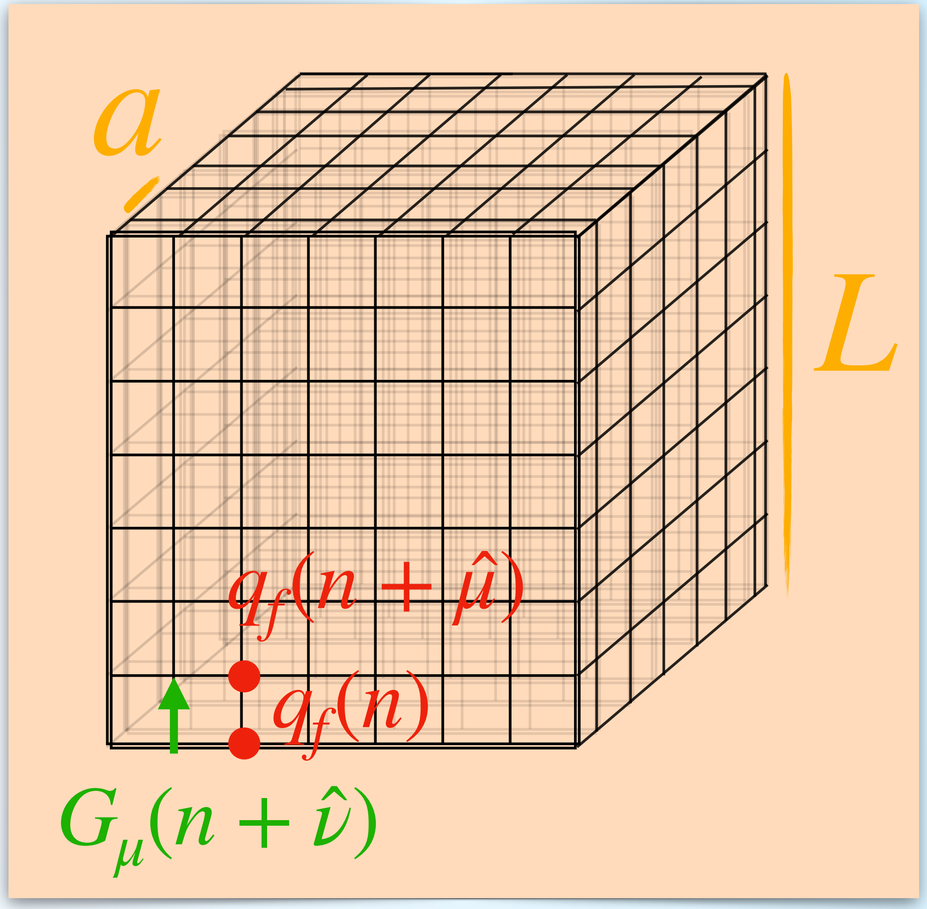
$$\mathscr{L}_{QCD}(x) = \sum_f \bar{q}_f(x)\left(i\gamma^\mu\partial_\mu - g_S\gamma^\mu G_\mu^a(x)t_a - m_f\right)q_f(x) - \frac{1}{4}F_{\mu\nu}^a(x)F_a^{\mu\nu}(x)$$

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$$\langle\hat{O}\rangle_E \equiv \langle\Omega\,|\,\hat{O}\,|\,\Omega\rangle = \frac{1}{Z}\int DGD\bar{q}_fDq_f\ O(\bar{q}_f, q_f, G)e^{-S_E(\bar{q}_f,q_f,G)}$$

$$Z \equiv \int DGD\bar{q}_fDq_f\ e^{-S_E(\bar{q}_f,q_f,G)}$$



$$\frac{e^{-S_E(\bar{q}_f,q_f,G)}}{\int DGD\bar{q}_fDq_f\ e^{-S_E(\bar{q}_f,q_f,G)}} \equiv \text{probability density} \to \langle\hat{O}\rangle_E \text{ numerically calculable}$$

Hadron spectroscopy in lattice QCD

$$C_{2ij}(\vec{p},t) = \langle \Omega | O_i(\vec{p},t) O_j^\dagger(\vec{p},t_0) | \Omega \rangle$$

- $O_j^\dagger(\vec{p},t), O_i(\vec{p},t)$: hadronic creation(annihilation)

  operators with well defined quantum numbers

$$C_2(\vec{p},t) = \left(1 = \sum_n |n\rangle\langle n|\right) = \sum_n \langle \Omega | O(\vec{p}) | n \rangle \langle n | O^\dagger(\vec{p}) | \Omega \rangle e^{-E_n(t-t_0)}$$

$$= \sum_n |\langle \Omega | O(\vec{p}) | n \rangle|^2 e^{-E_n(t-t_0)}$$

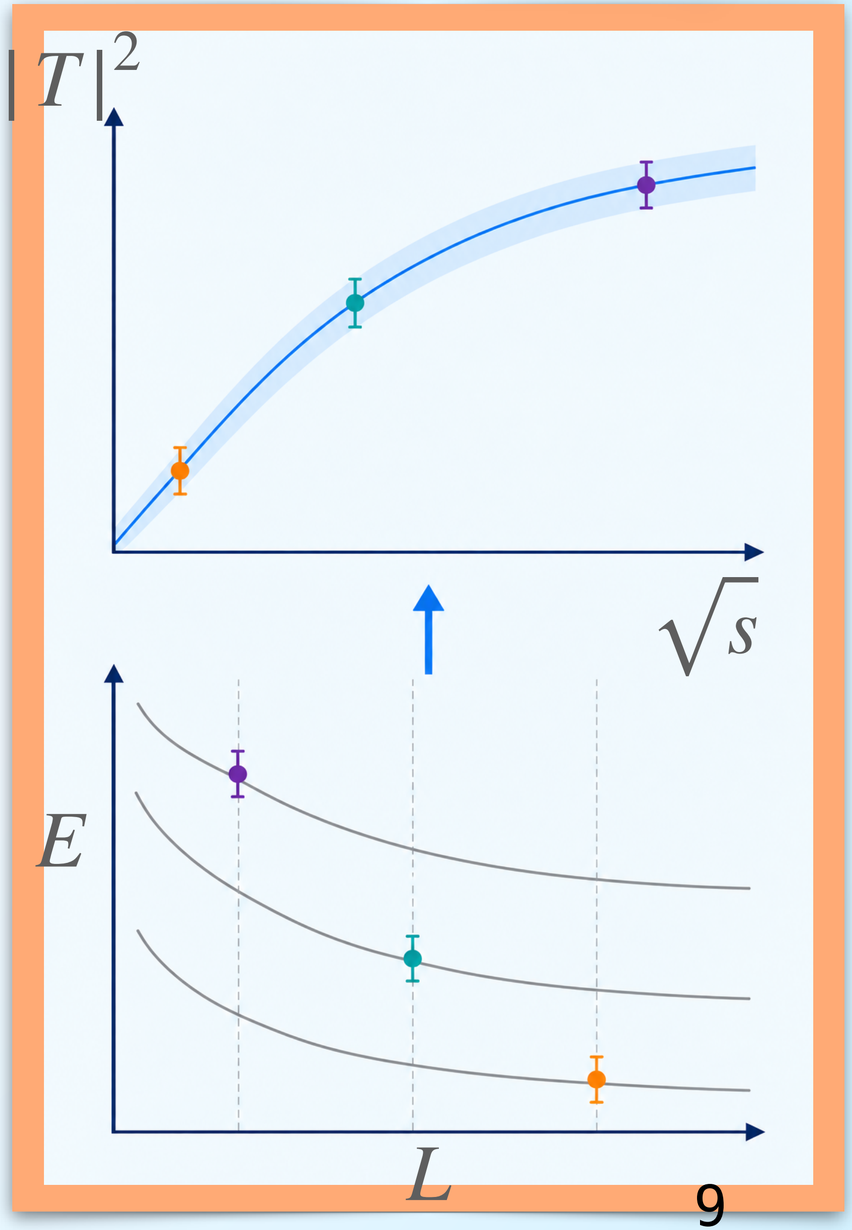
overlap factors

energy levels E_n

$$\hat{H}_{QCD} |n\rangle = E_n |n\rangle$$

Quantization conditions in lattice QCD: energies in the

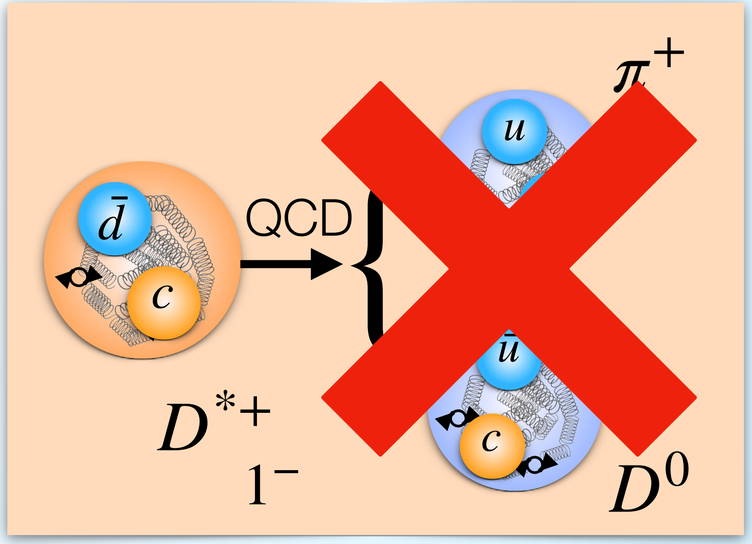
finite-volume constrain the infinite-volume scattering amplitude



Lattice setup

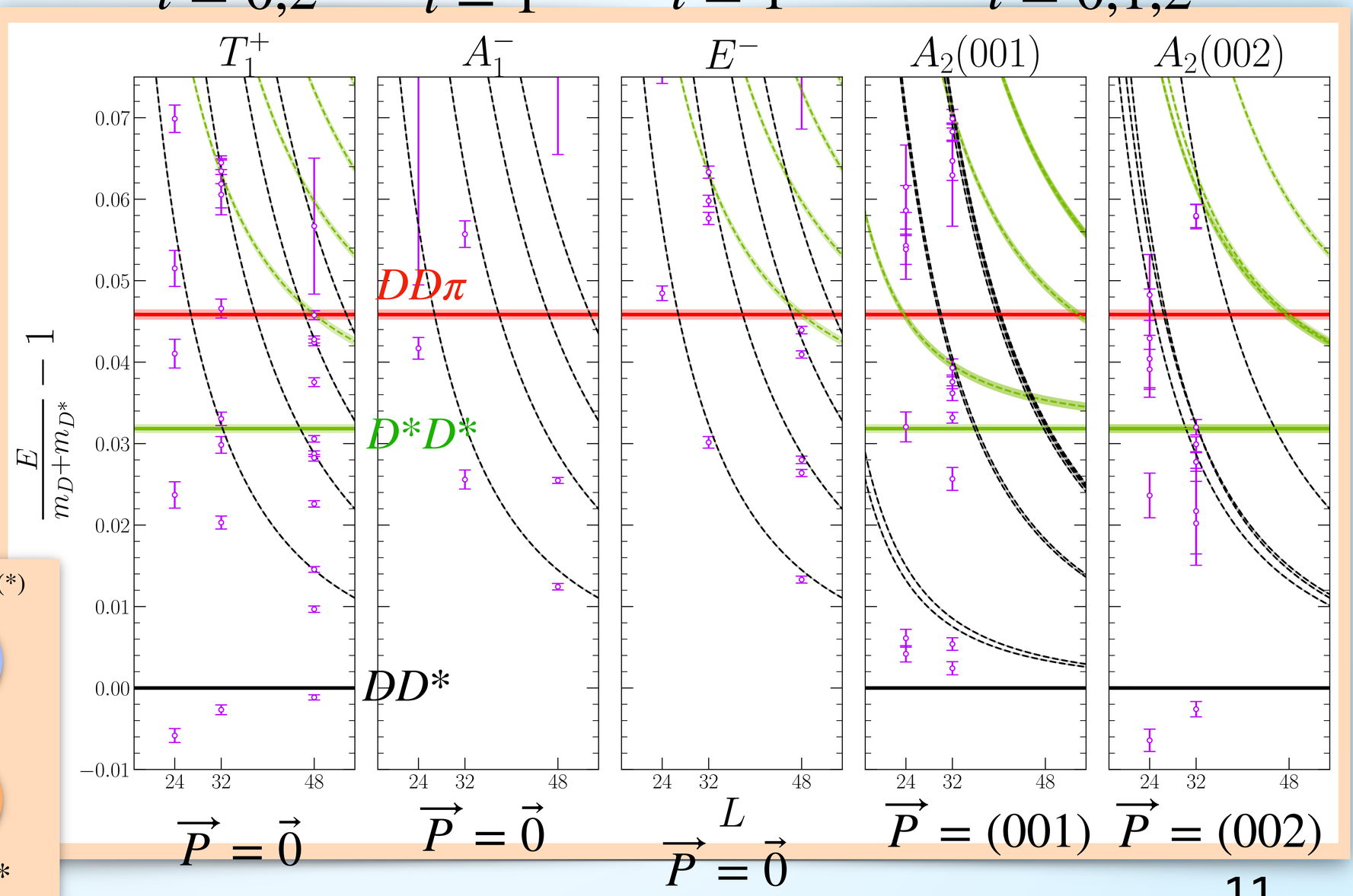
ensemble	$L^3 \times T$	a (fm)	m_π (MeV)	m_D (MeV)	m_{D^*} (MeV)
F24P30	$24^3 \times 72$	0.07746(18)	315.5(1.9)	1900.0(1.0)	2030.3(3.2)
F32P30	$32^3 \times 96$	0.07746(18)	305.81(71)	1891.1(1.3)	2015.5(2.3)
F48P30	$48^3 \times 96$	0.07746(18)	304.98(50)	1892.62(66)	2017.6(1.4)

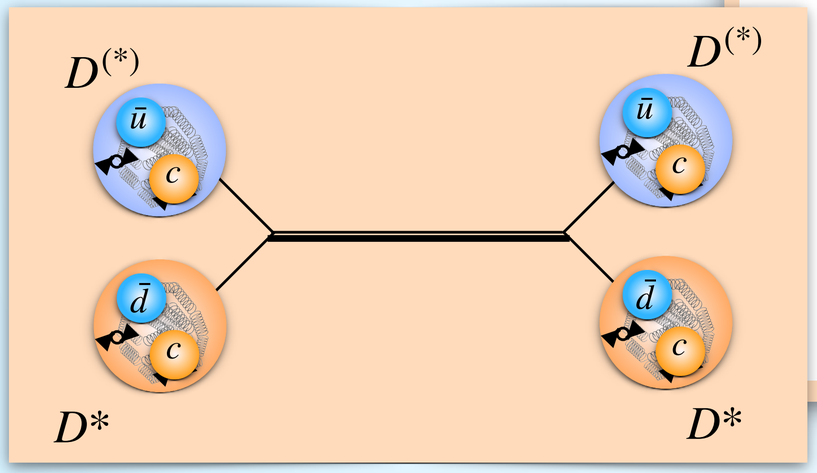
- 3 ensembles generated by the CLQCD collaboration
- stable D^*



Finite-volume spectrum

- finite-volume spectrum from ensembles of size $L = 24,32,48$
- continuous lines: noninteracting DD^*, D^*D^*, $DD\pi$ levels
- discrete points: interacting spectrum

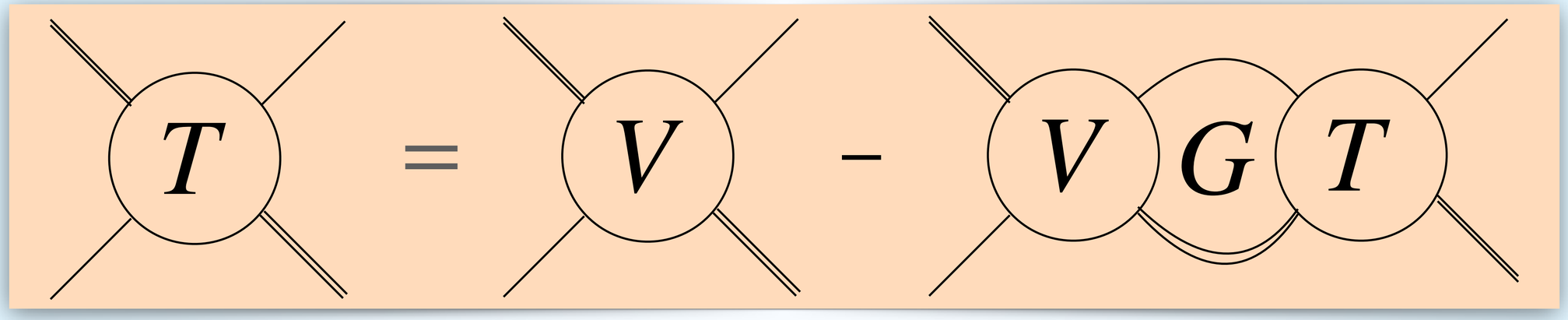




Finite- to infinite-volume pipeline

- **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

- **Quantization condition:** based on the Bethe-Salpeter equation $T = V - VGT$



V : Bethe-Salpeter kernel

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

- reduces to the potential in the NR limit

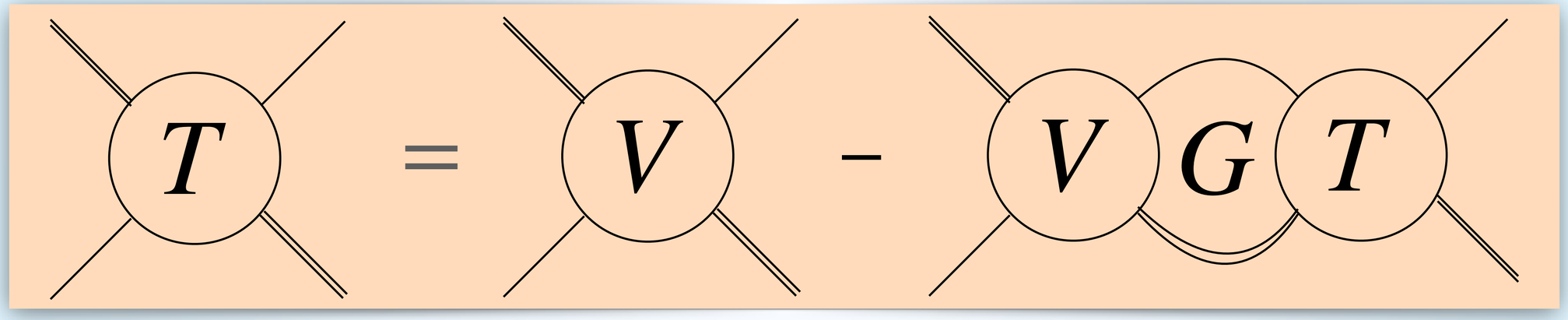
G : two-body loop function

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

Finite- to infinite-volume pipeline

- **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

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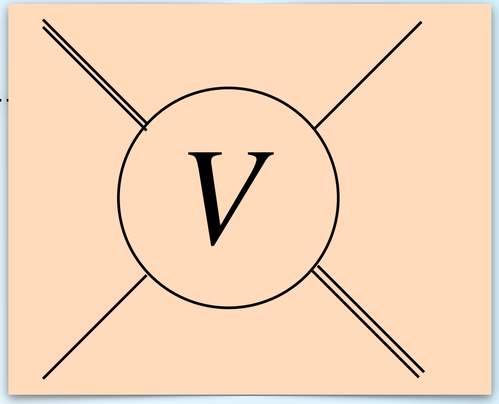
  - in the infinite-volume: integral equation

  - in the **finite-volume**: matrix equation in the basis $|D(\vec{p})D^*(-\vec{p},\lambda)\rangle,\ |D^*(\vec{p},\lambda_1)D^*(-\vec{p},\lambda_2)\rangle$

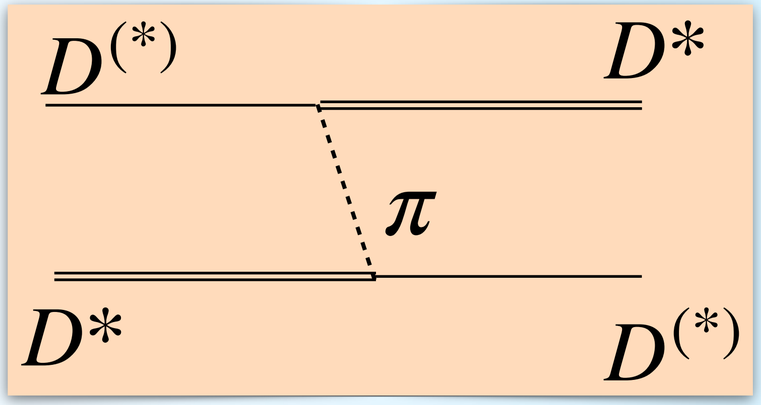
$$T = G^{-1}(G^{-1} + V)^{-1}V$$

finite-volume energy levels occur $\leftrightarrow$ T is singular : $\det(G^{-1} + V) = 0$

Interactions



- parametrization of the kernel/potential V:
  - $V = V_\pi + V_{CT}$
  - V_π : one-pion exchange - calculated from the heavy-meson χPT [1008.0383]
    - responsible for the left-hand branch cut in the DD^*, D^*D^* scattering amplitudes
  - V_{CT} : smooth contact term - generic low-energy interaction, parametrized in lowest partial waves:

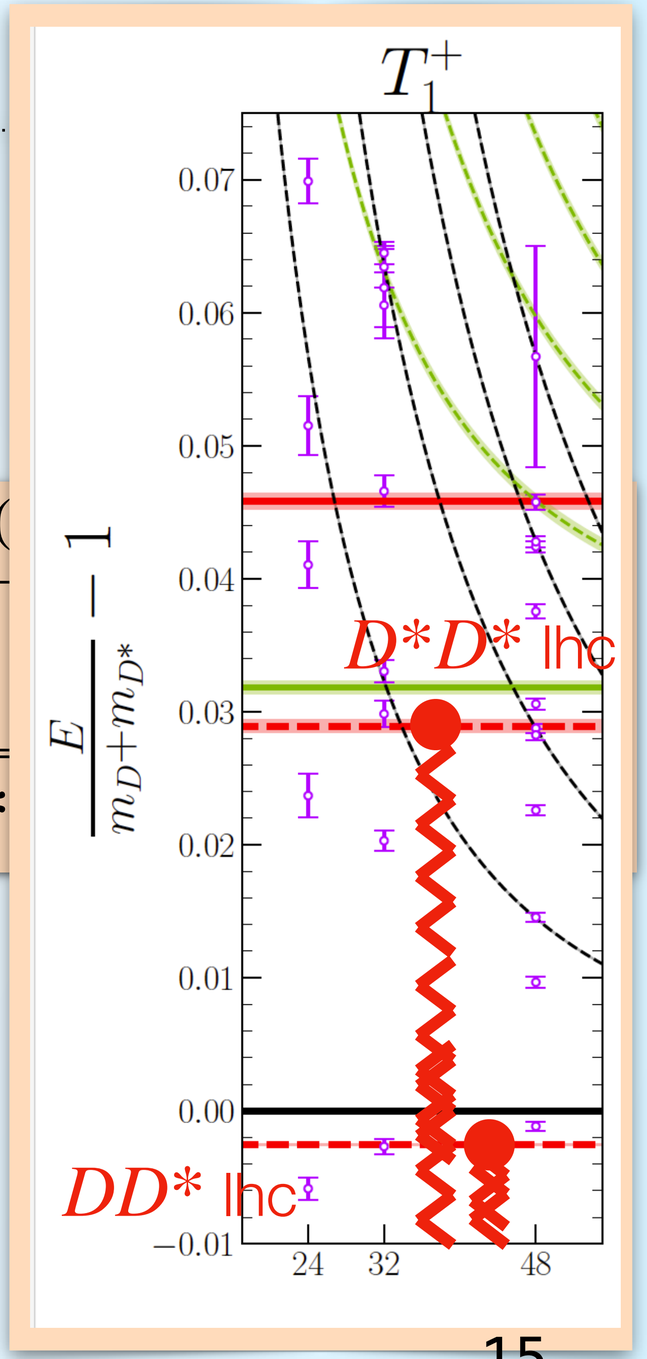


$$\begin{pmatrix} c_{11} + c'_{11}(p^2 + p'^2) & c_{12} \\ c_{12} & c_{22} \end{pmatrix}_{L=0}$$

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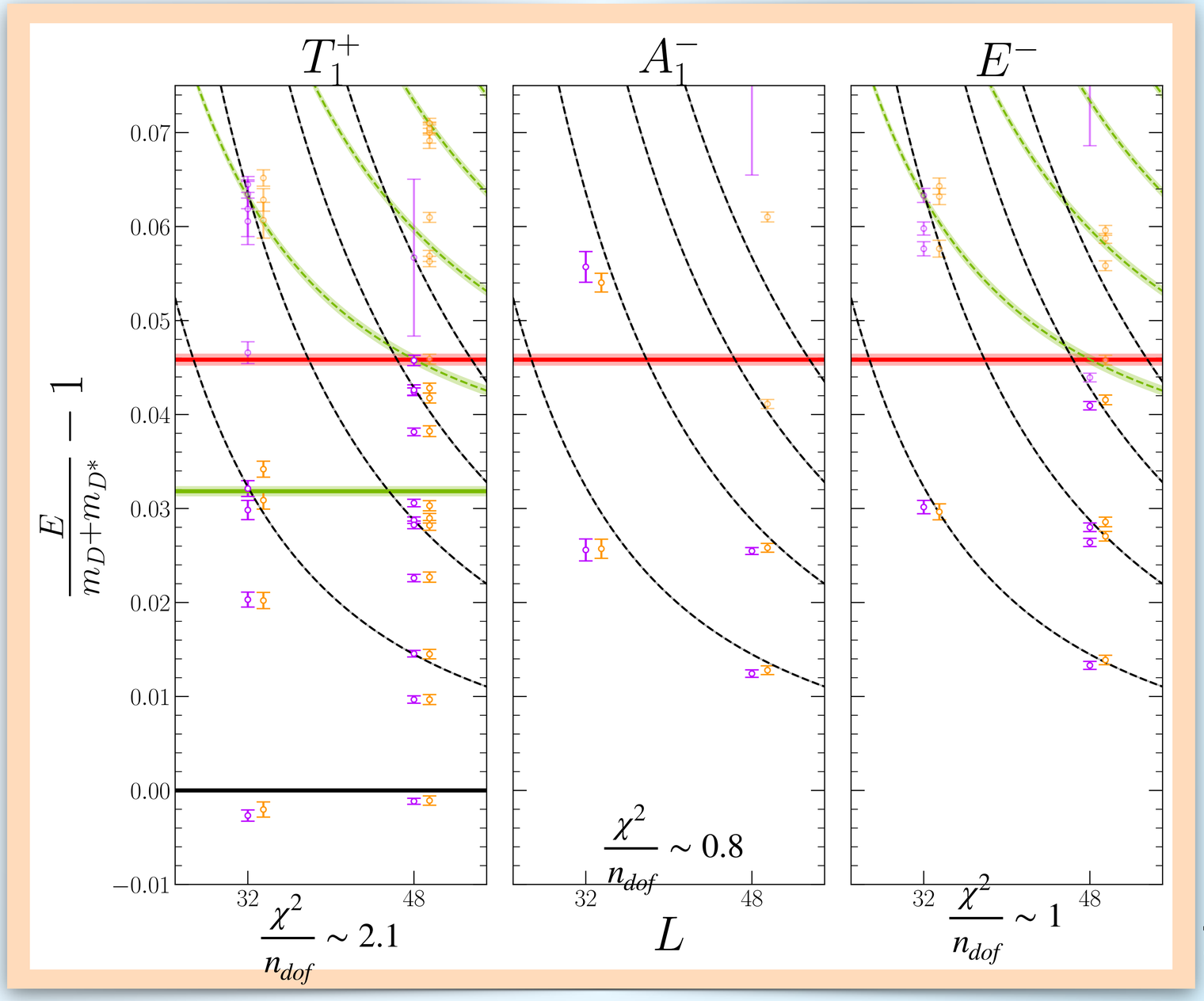


Fits to CMF data

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

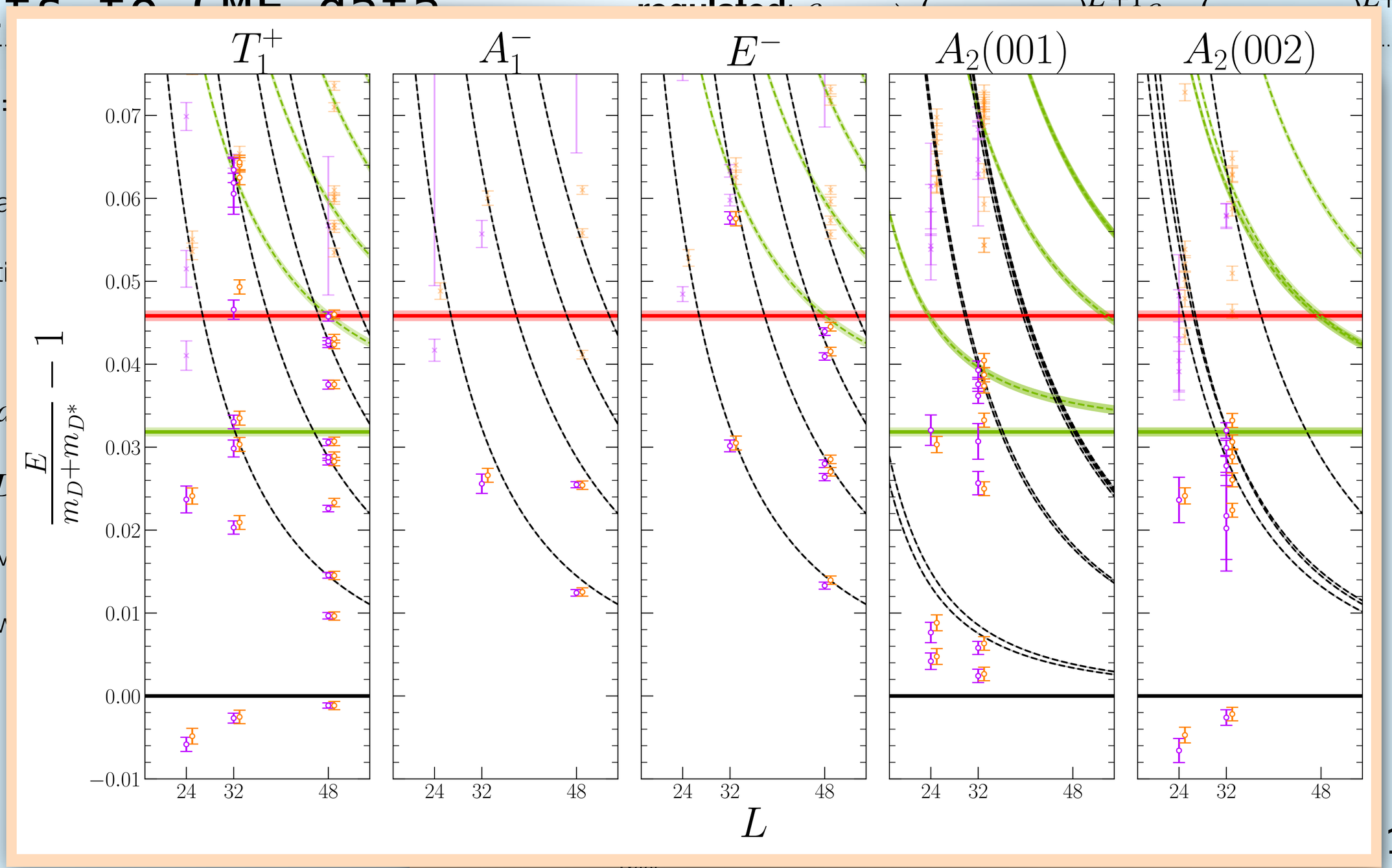
$$\Lambda = 1.27 \text{ GeV}$$

- CMF data constrains $s-$ and $p-$wave interactions in both channels
- several weakly shifted mysterious levels: $d-$wave?
- good: DD^* and D^*D^* exhibit attractive interaction in all analyzed partial waves



Fits to CMF data

- CMF da
- interacti
- several
- levels: d
- good: L
- attractiv
- partial w



Summary and outlook

i. simulate coupled $DD^* - D^*D^*$ scattering on the lattice

ii. use finite-volume data to constrain $s-$wave interactions

iii. search for T_{cc}, T'_{cc} poles in scattering amplitudes

- left-hand branch cuts accounted for
- start moving towards physical m_π
- analyze other challenging exotics

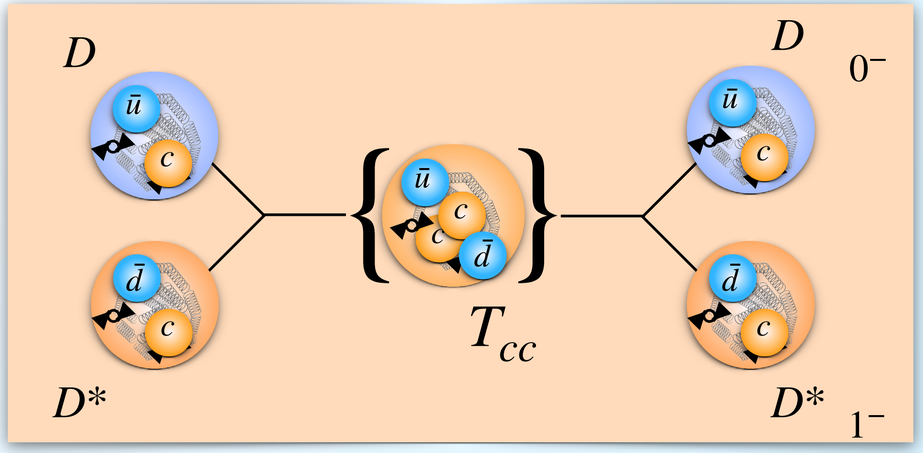
almost completely done for three volumes $L = 24,32,48$

~60 levels below $DD\pi$ threshold, ~120 levels in total

fitting machinery in place for CMF, moving frame data

preliminary fits shown

integral-equation solving machinery in place, awaiting succesful fits



Thank you!