Excited charm/charmonium mesons and exotics from lattice QCD

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ECT* workshop on "*Glueballs and Charmonium, Lattice QCD, Experiment and Phenomenology*"
2 – 6 March 2026

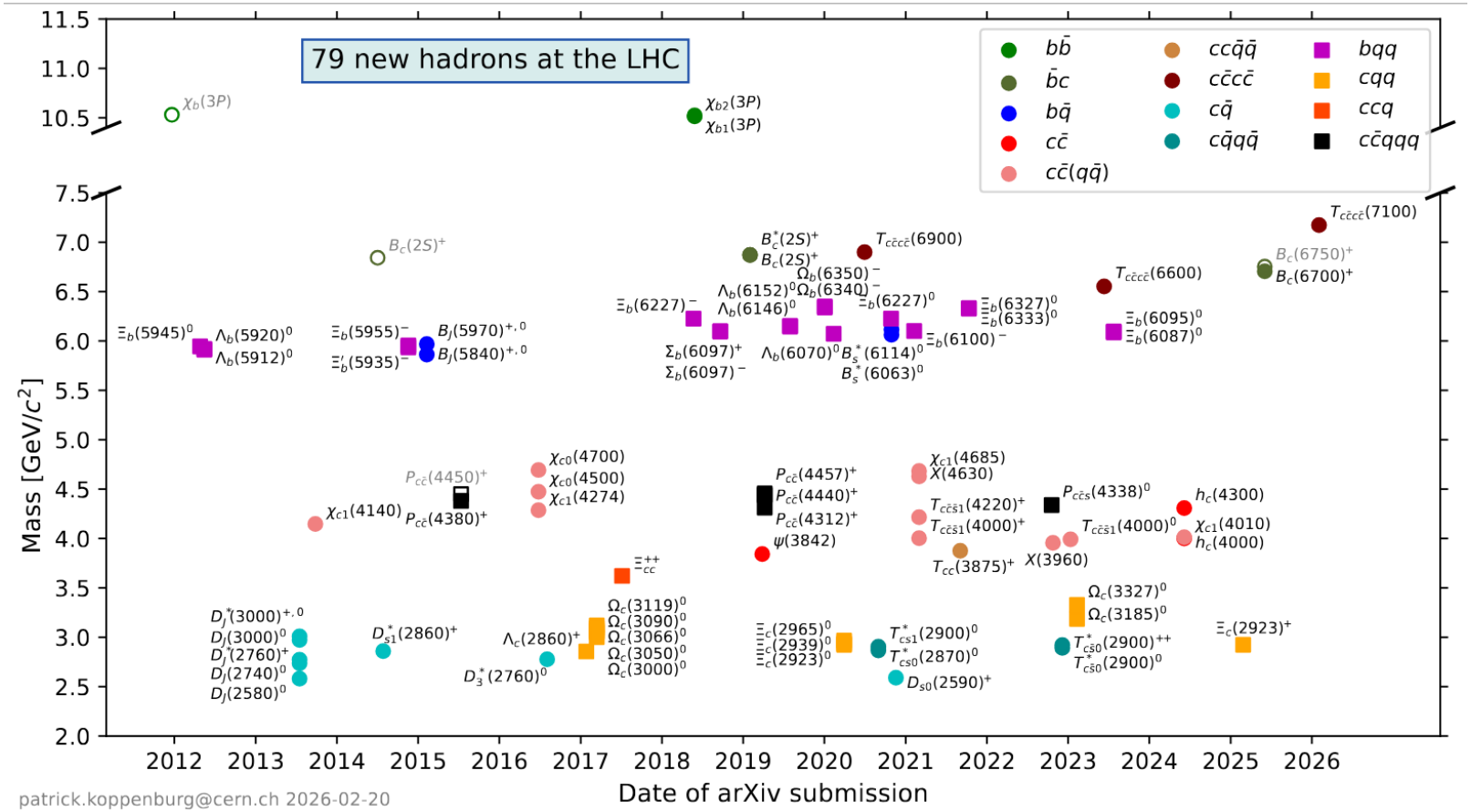


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hadspec

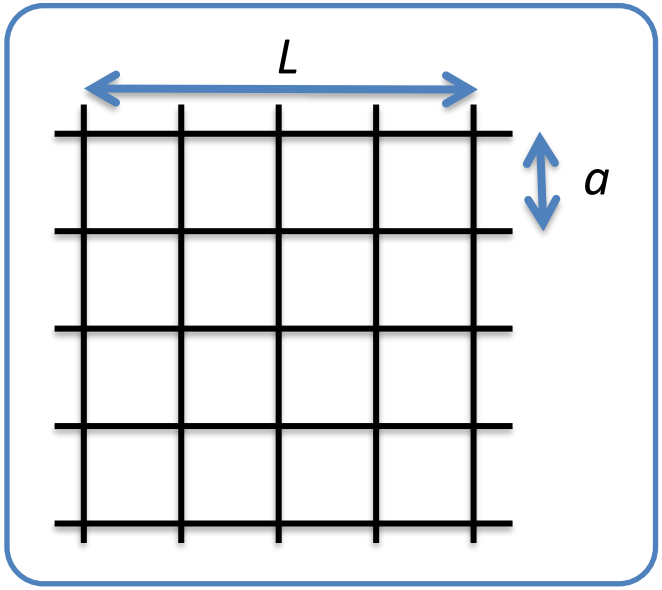
Hadron spectroscopy

Intriguing observations, e.g. $X(3872)$, $Y(4230)$, $Z_c^+(4430)$, $Z_c^+(3900)$, $X(6900)$, $T_{cc}(3875)$, $D_{s0}(2317)$, $T_{cs}(2900)$, Z_b^+, light scalars, $\pi_1(1600)$ [$J^{PC} = 1^{-+}$], P_c , Roper, other baryon resonances



Lattice QCD

Systematically-improvable
first-principles calculations in QCD



- **Discretise** spacetime in a **finite volume**
- Compute correlation fns. numerically
  (Euclidean time, $t \rightarrow i\,t$)

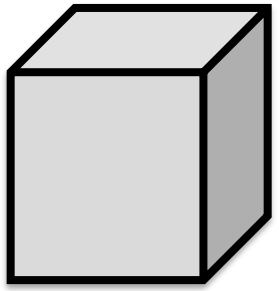
Note:

- Finite a and L
- Possibly heavy u, d quarks
  ($\rightarrow$ unphysical m_π)





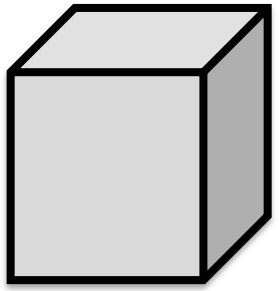
Lattice QCD spectroscopy



Finite-volume energy eigenstates from:

$$C_{ij}(t) = \left\langle 0 \left| \mathcal{O}_i(t) \mathcal{O}_j^\dagger(0) \right| 0 \right\rangle$$

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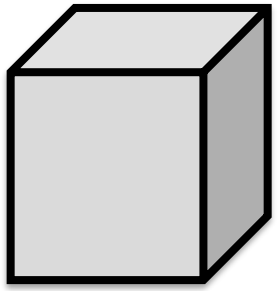


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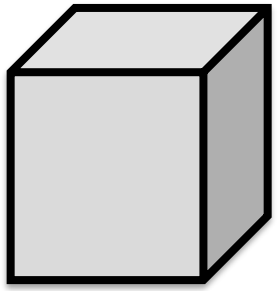
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Lower-lying hadrons in each flavour sector are well determined (including isospin breaking, QED).

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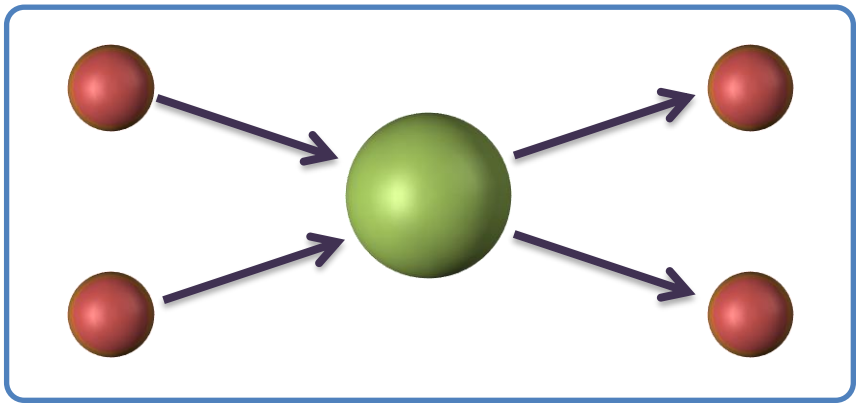
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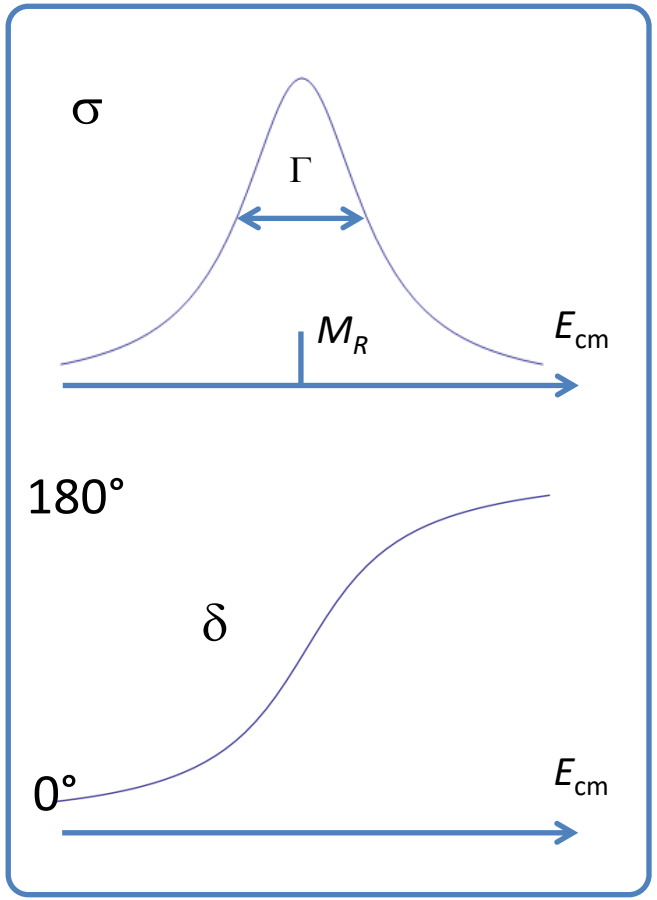
Excited states: in each symmetry channel compute matrix of correlators for **large bases of interpolating operators** with appropriate variety of structures.

Variational method (generalised eigenvalue problem) → $\{E_n\}$

Scattering and resonances in infinite-volume continuum

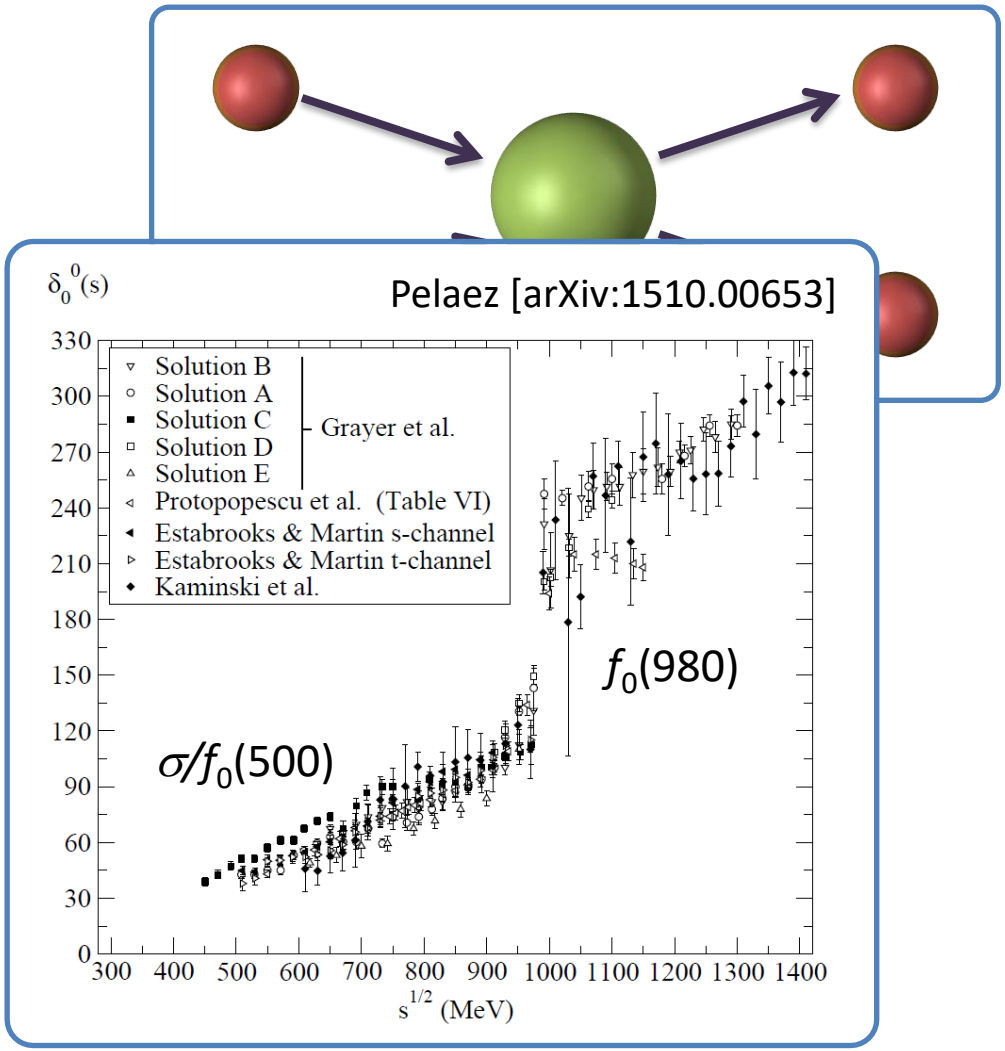
Most hadrons are resonances and decay strongly to lighter hadrons

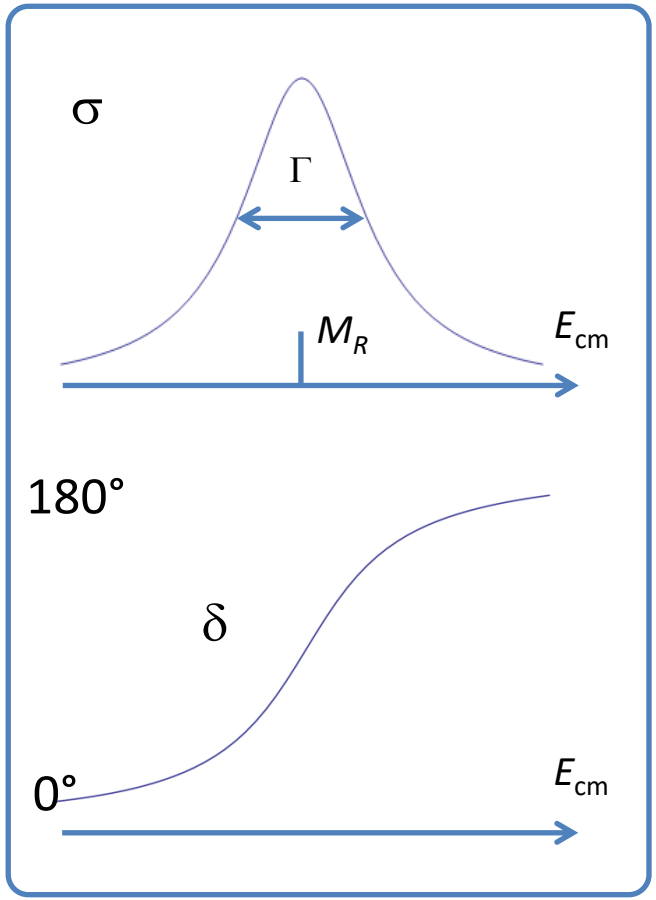




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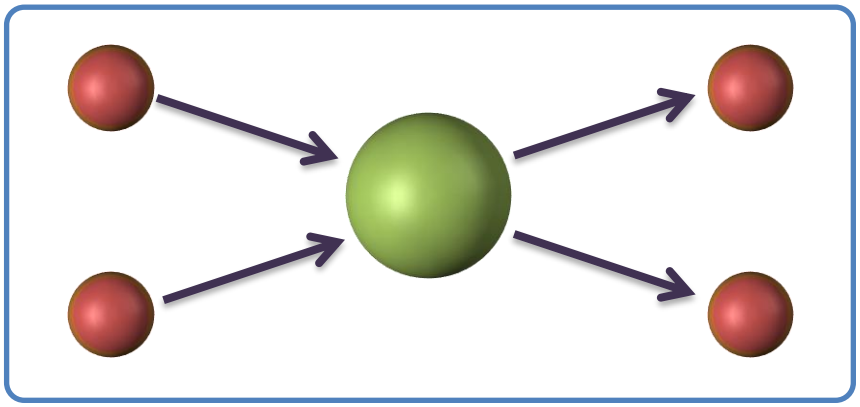
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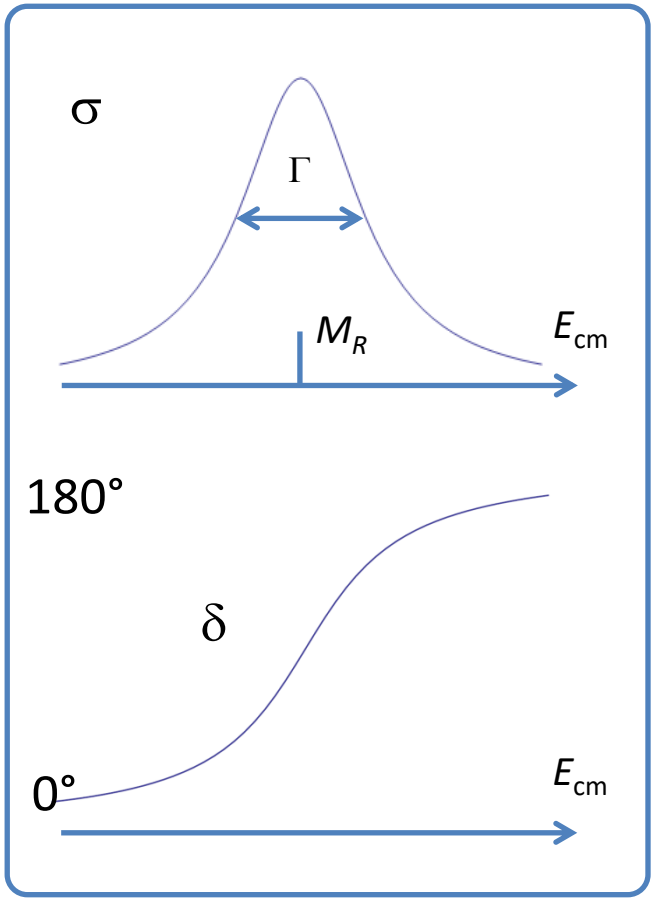




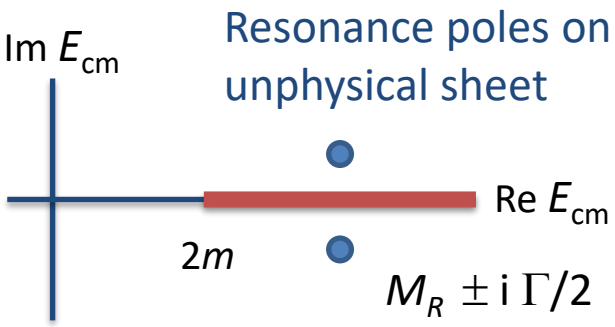
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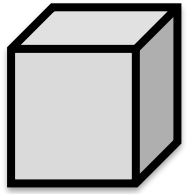
Singularity structure of scattering matrix (poles → state content)



Scattering and resonances in lattice QCD

Can't directly compute scattering amplitudes in lattice QCD

Lüscher method [NP B354, 531 (1991)] and extensions: relate discrete set of **finite-volume energy levels** $\{E_{\text{cm}}\}$ to **infinite-volume scattering *t*-matrix**.

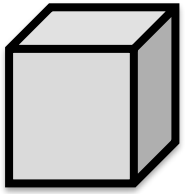


$$\vec{p} = \frac{2\pi}{L}(n_x, n_y, n_z)$$

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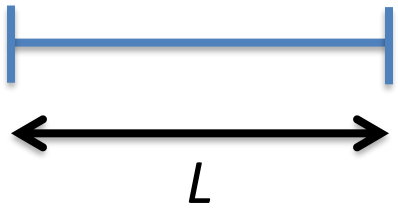
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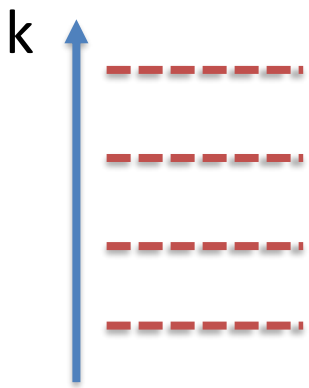
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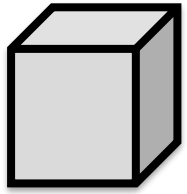




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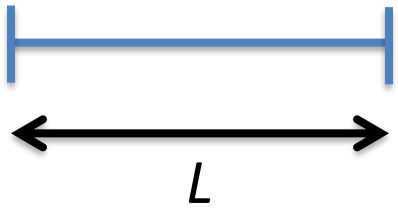
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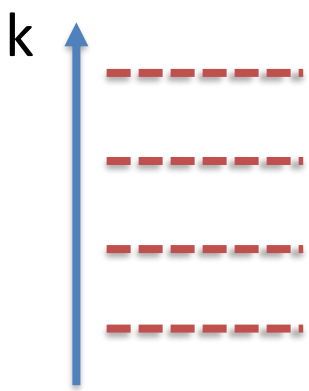
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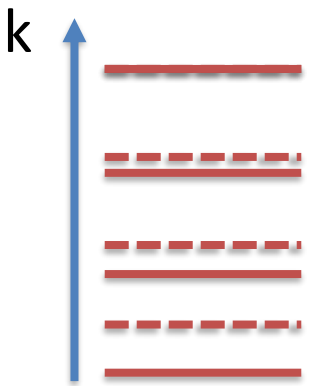


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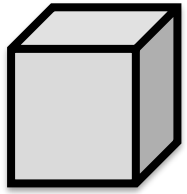




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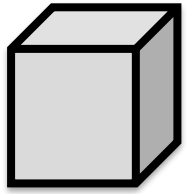
Infinite-volume scattering *t*-matrix
$S = 1 + 2i\sqrt{\rho}\,t\,\sqrt{\rho}$

Effect of finite volume (including reduced sym.)

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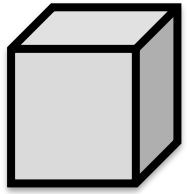
Elastic scattering: one-to-one mapping $E_{\text{cm}} \leftrightarrow t(E_{\text{cm}})$

[Complication: reduced sym. of lattice vol. → mixing of partial waves]

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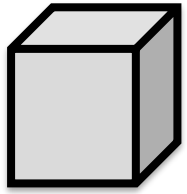
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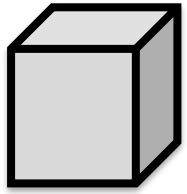
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But we need: spectrum → $\boldsymbol{t}(E_{\text{cm}})$ – under-constrained problem
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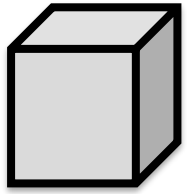
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→ Parametrize $t(E_{\text{cm}})$ using various forms (*K*-matrix forms, …)
[see e.g. review Briceño, Dudek, Young, Rev. Mod. Phys. 90, 025001 (2018)]

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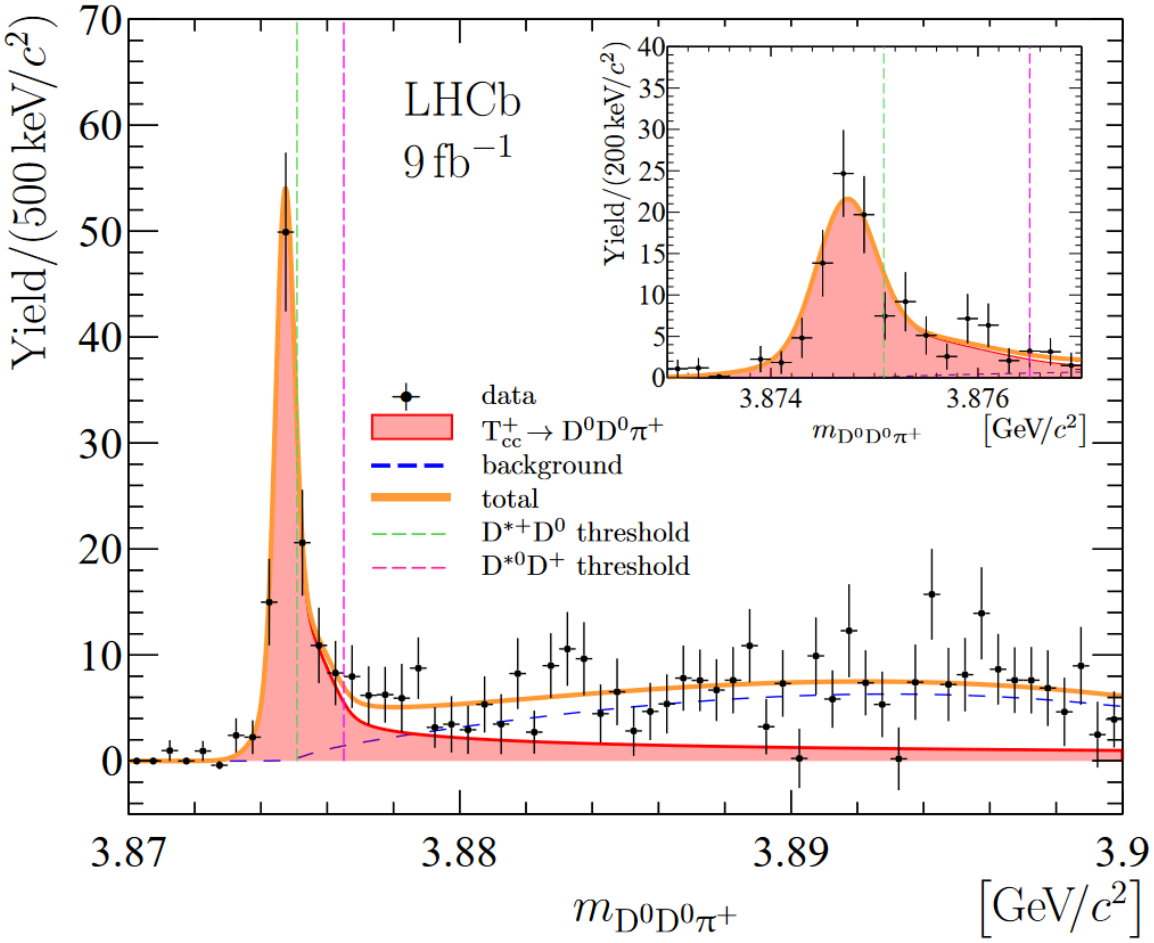
Analytically continue $t(E_{\text{cm}})$ in complex E_{cm} plane, look for poles.

Demonstrated in calcs. of ρ and many other channels.

T_{cc}

T_{cc}^{+} seen in $D^0D^0\pi^+$ at LHCb [2109.01038, 2109.01056]

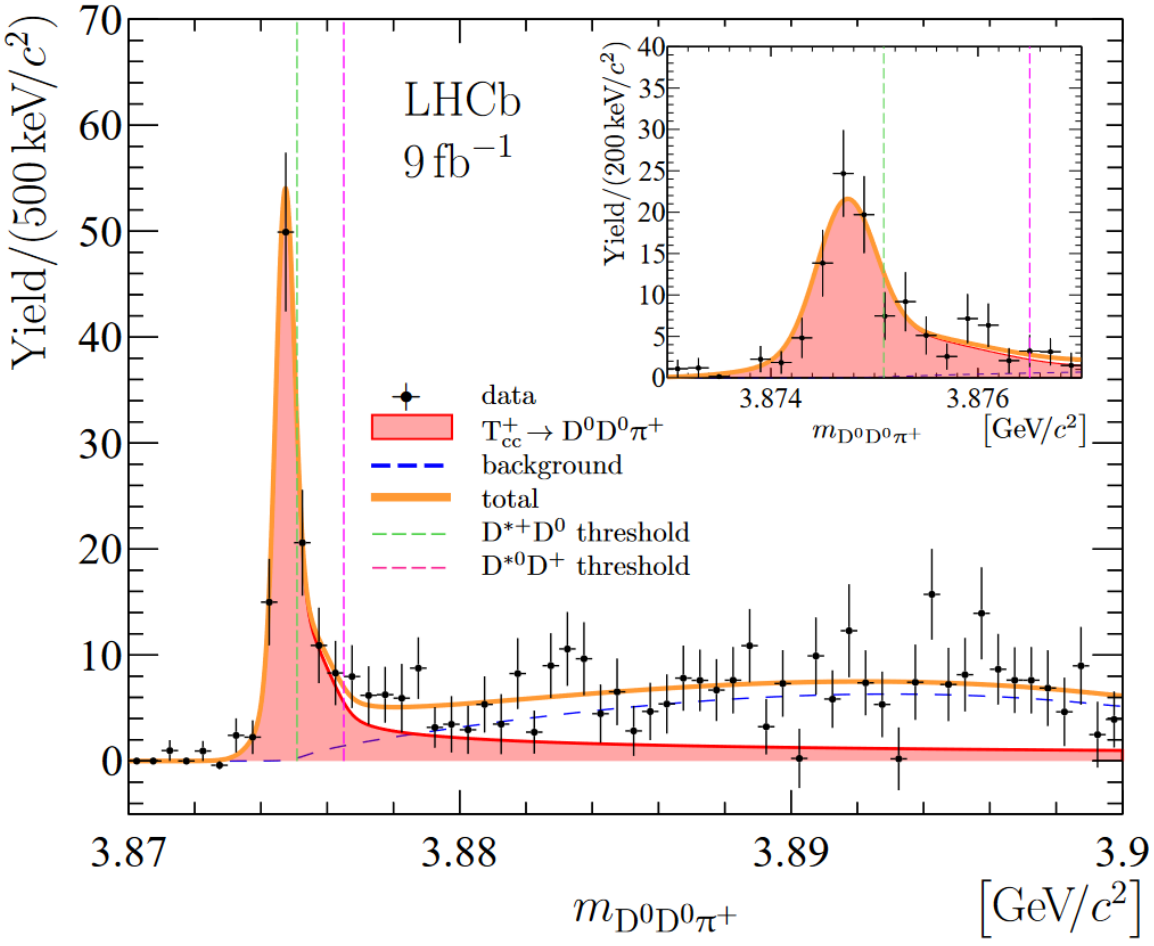
Close to DD^* threshold, $J^P=1^+$, I=0, **exotic flavour** ($cc\bar{u}\bar{d}$)



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Close to DD^* threshold, $J^P=1^+$, I=0, **exotic flavour** ($cc\bar{u}\bar{d}$)



What about higher energies (coupled DD^*, D^*D^*)?

Other lattice calcs:

- Padmanath & Prelovsek [2202.10110, PRL];
- Chen *et al* [2206.06185, PLB];
- Lyu *et al* (HAL QCD) [2302.04505, PRL];
- Collins *et al* [2402.14715, PRD];
- Prelovsek *et al* [2504.03473, PRD]
- Nagatsuka, Sasaki [2507.20712, PRD]
- Stump, Green [2510.26459, PRD]

See also:

- Du *et al* [2303.09441, PRL];
- Meng *et al* [2312.01930, PRD].
- Gil-Domínguez & Molina [2409.15141, PRD].
- Dawid *et al* [2409.17059, JHEP & 2505.05466, JHEP].
- Meng *et al* [2411.06266, PRD];

Coupled DD^*, D^*D^* scattering ($I = 0$)

First lattice QCD calculation of coupled DD^*, D^*D^* scattering

$m_\pi \approx 391$ MeV, $m_D \approx 1890$ MeV,
$m_{D^*} \approx 2010$ MeV (D^* stable),
3 volumes ($L \approx 2 - 3$ fm),
one lattice spacing (anisotropic)

Matrices of corr. fns. with many meson-meson-like DD^* and D^*D^* ops (I = 0)
['optimised' D and D^* ops, 'distillation' to compute corrs.]

[**Travis Whyte**, Wilson, Thomas (HadSpec), 2405.15741 (PRD)]

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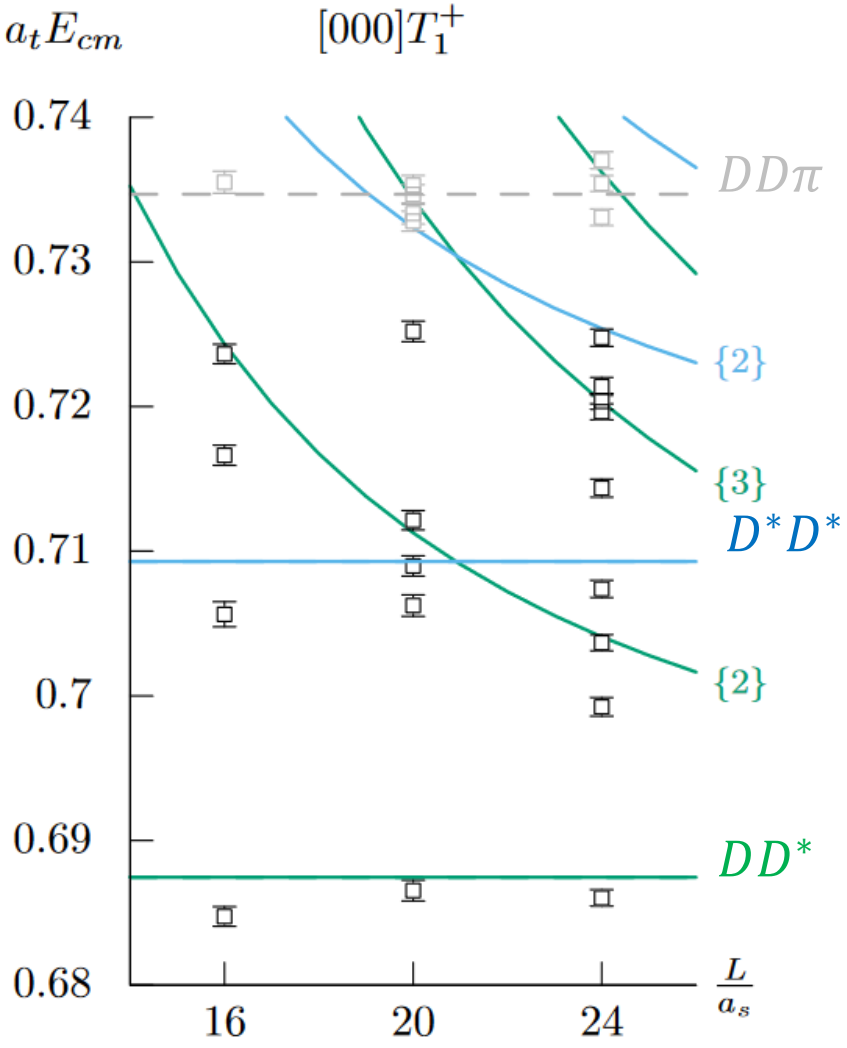
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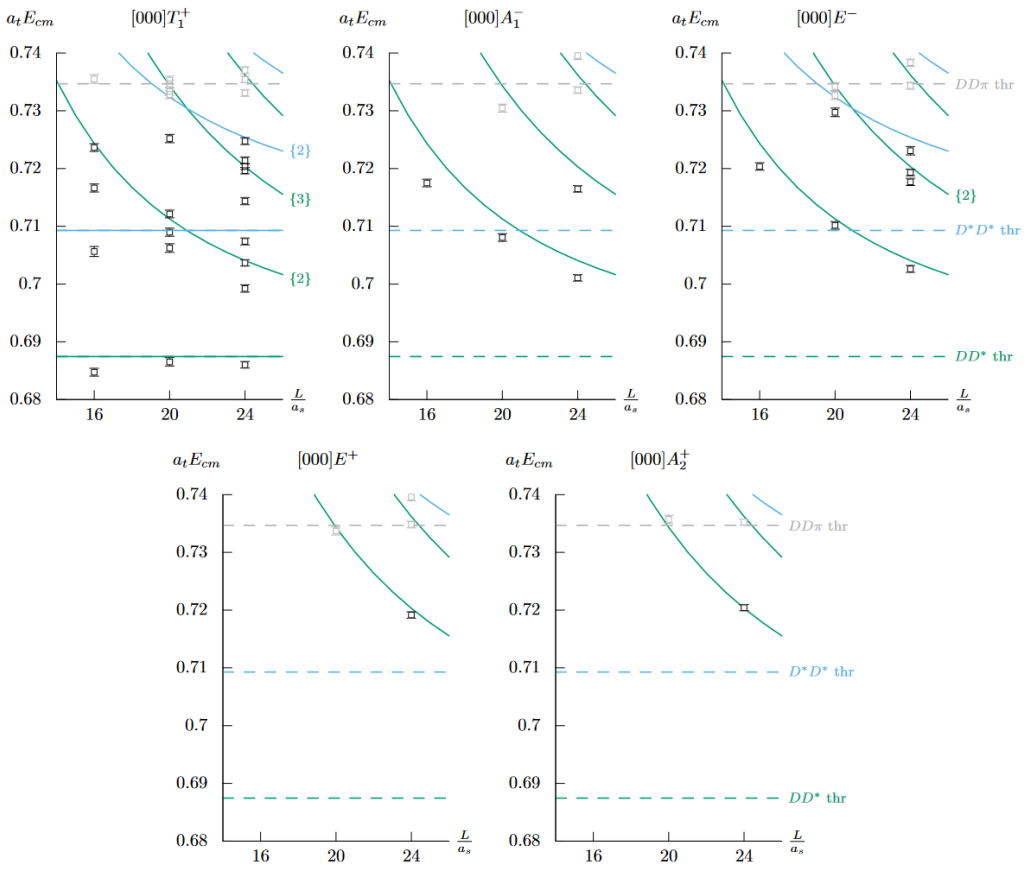
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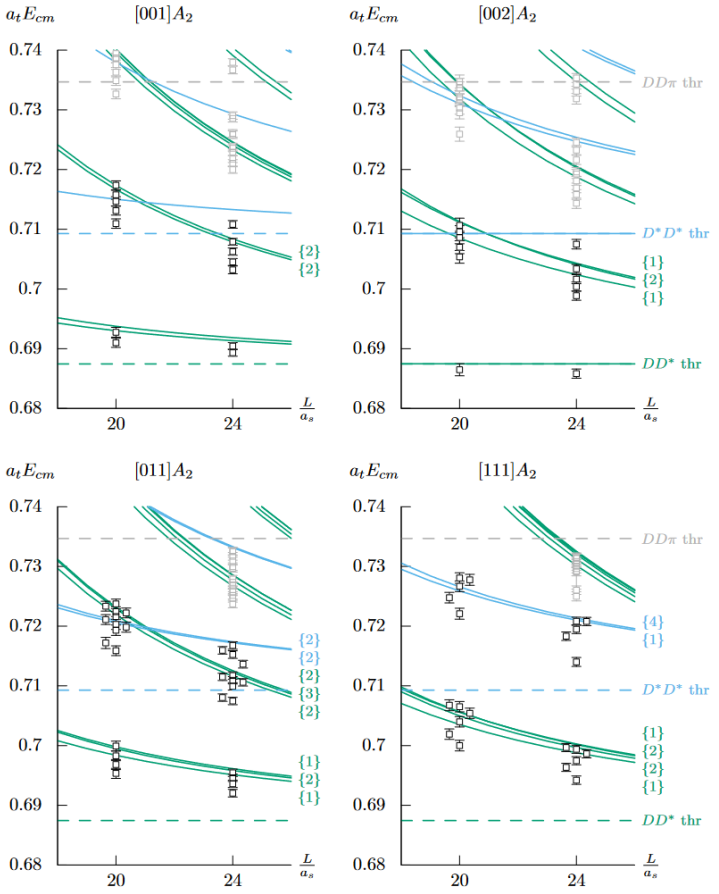
P = [0,0,0] $J^P = 1^+, \ldots$



Coupled DD^*, D^*D^* scattering ($I = 0$)

[2405.15741]





Use 109 energy levels

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Partial wave amplitudes for $J^P = 1^+$:

DD^* $^3\mathrm{S}_1$ $(l = 0, S = 1)$, $^3\mathrm{D}_1$ $(l = 2, S = 1)$

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and 'background' partial waves

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and 'background' partial waves

K-matrix param. – respects unitarity (conserve prob.) and flexible

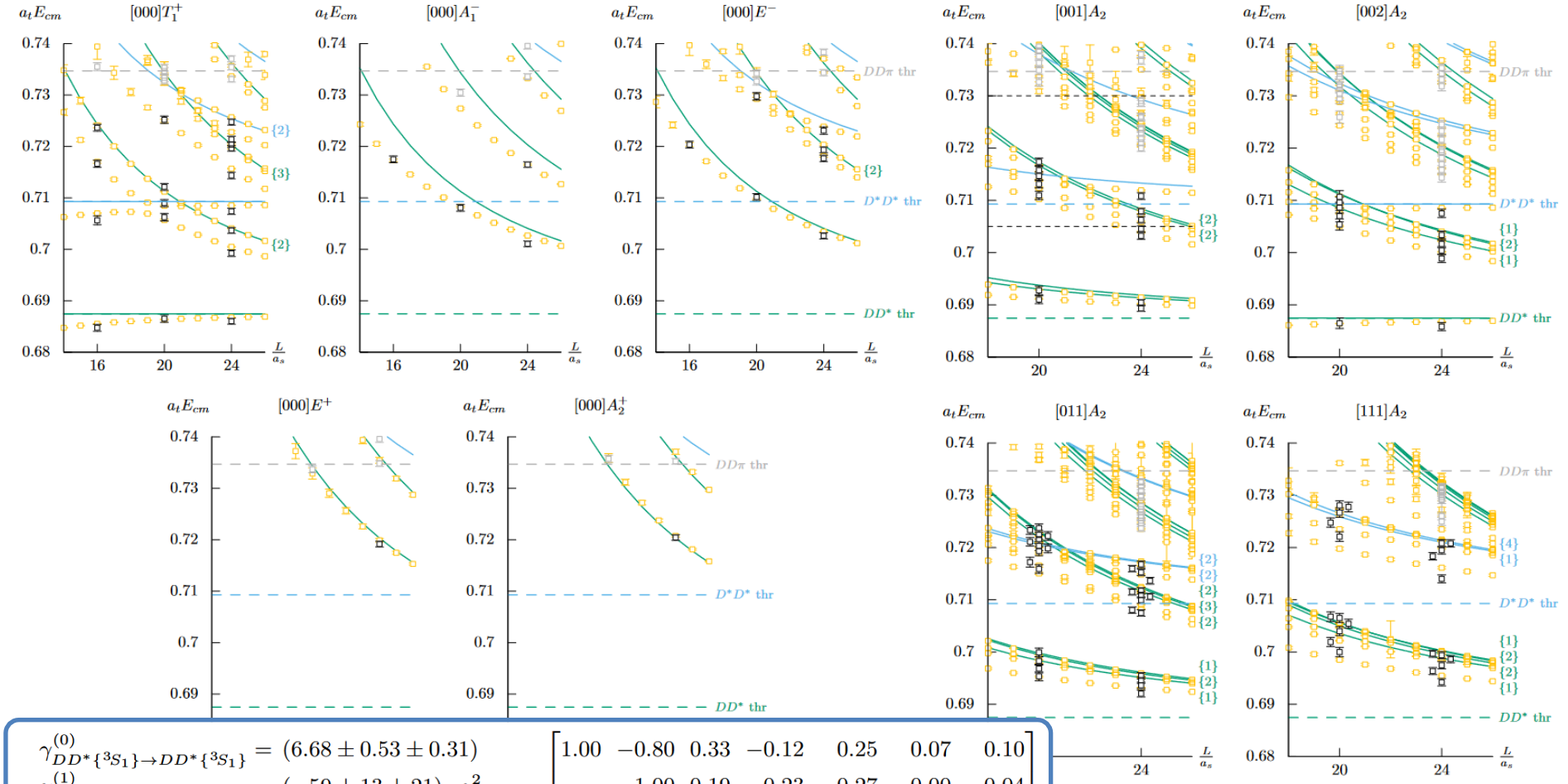
$$t_{ij}^{-1}(s) = \frac{1}{(2k_i)^\ell} K_{ij}^{-1}(s) \frac{1}{(2k_j)^\ell} + I_{ij}(s) \qquad \mathrm{Im}[I_{ij}(s)] = -\delta_{ij}\rho_i(s)$$

$$\rho_i(E_{\mathrm{cm}}) = \frac{2k_i}{E_{\mathrm{cm}}}$$

In this work $K(s)_{\ell SJa,\ell' S' Jb} = \sum_n \gamma^{(n)}_{\ell SJa,\ell' S' Jb} s^n$,

Coupled DD^*, D^*D^* scattering ($I = 0$)

[2405.15741]



$$\gamma^{(0)}_{DD^*\{^3S_1\}\to DD^*\{^3S_1\}} = (6.68 \pm 0.53 \pm 0.31)$$
$$\gamma^{(1)}_{DD^*\{^3S_1\}\to DD^*\{^3S_1\}} = (-59 \pm 13 \pm 21) \cdot a_t^2$$
$$\gamma^{(0)}_{DD^*\{^3S_1\}\to D^*D^*\{^3S_1\}} = (4.11 \pm 0.51 \pm 0.94)$$
$$\gamma^{(0)}_{D^*D^*\{^3S_1\}\to D^*D^*\{^3S_1\}} = (12.7 \pm 2.5 \pm 2.8)$$
$$\gamma^{(1)}_{D^*D^*\{^3S_1\}\to D^*D^*\{^3S_1\}} = (-122 \pm 53 \pm 71) \cdot a_t^2$$
$$\gamma^{(0)}_{DD^*\{^3D_1\}\to DD^*\{^3D_1\}} = (149 \pm 63 \pm 42) \cdot a_t^4$$
$$\gamma^{(0)}_{D^*D^*\{^3D_1\}\to D^*D^*\{^3D_1\}} = (-504 \pm 178 \pm 1095) \cdot a_t^4$$

$$\begin{bmatrix} 1.00 & -0.80 & 0.33 & -0.12 & 0.25 & 0.07 & 0.10 \\ & 1.00 & 0.19 & 0.23 & -0.27 & -0.00 & -0.04 \\ & & 1.00 & 0.27 & -0.04 & 0.06 & 0.09 \\ & & & 1.00 & -0.95 & 0.04 & 0.06 \\ & & & & 1.00 & -0.03 & -0.02 \\ & & & & & 1.00 & 0.03 \\ & & & & & & 1.00 \end{bmatrix}$$

K-matrix param.

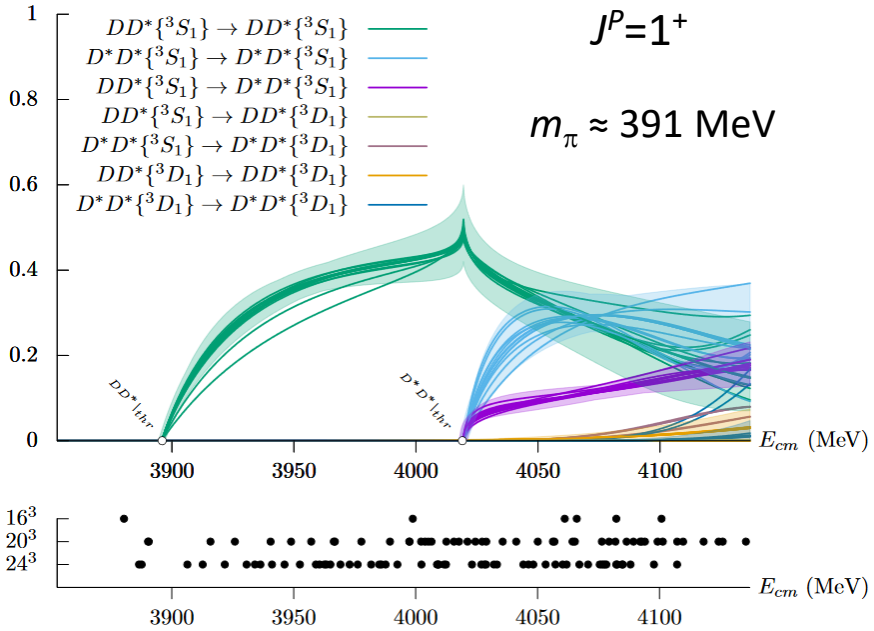
$$K(s)_{\ell SJa,\ell' S' Jb} = \sum_n \gamma^{(n)}_{\ell SJa,\ell' S' Jb} s^n,$$

$$\chi^2/N_{\text{dof}} = \frac{121.3}{109-14} = 1.28$$

T_{cc} and T'_{cc} in coupled DD^*, D^*D^* scattering

[2405.15741]

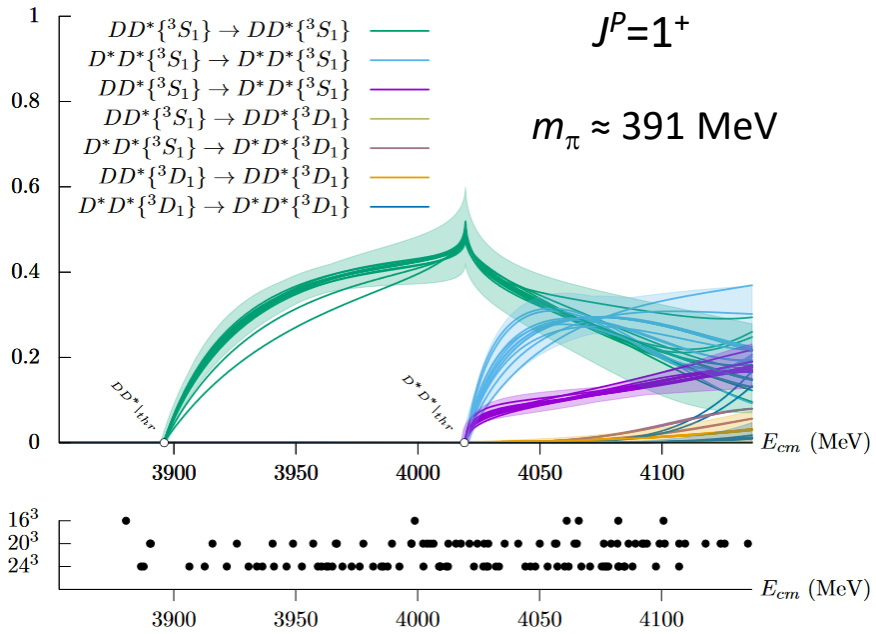
~ |amp|^2

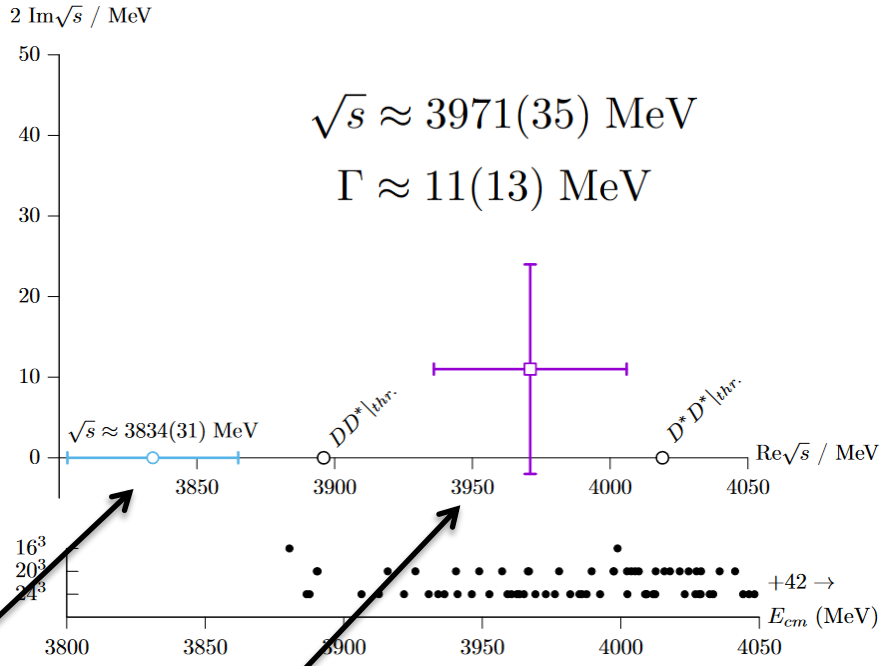


T_{cc} and T'_{cc} in coupled DD^*, D^*D^* scattering

[2405.15741]

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Virtual bound state (T_{cc}) below DD^* threshold

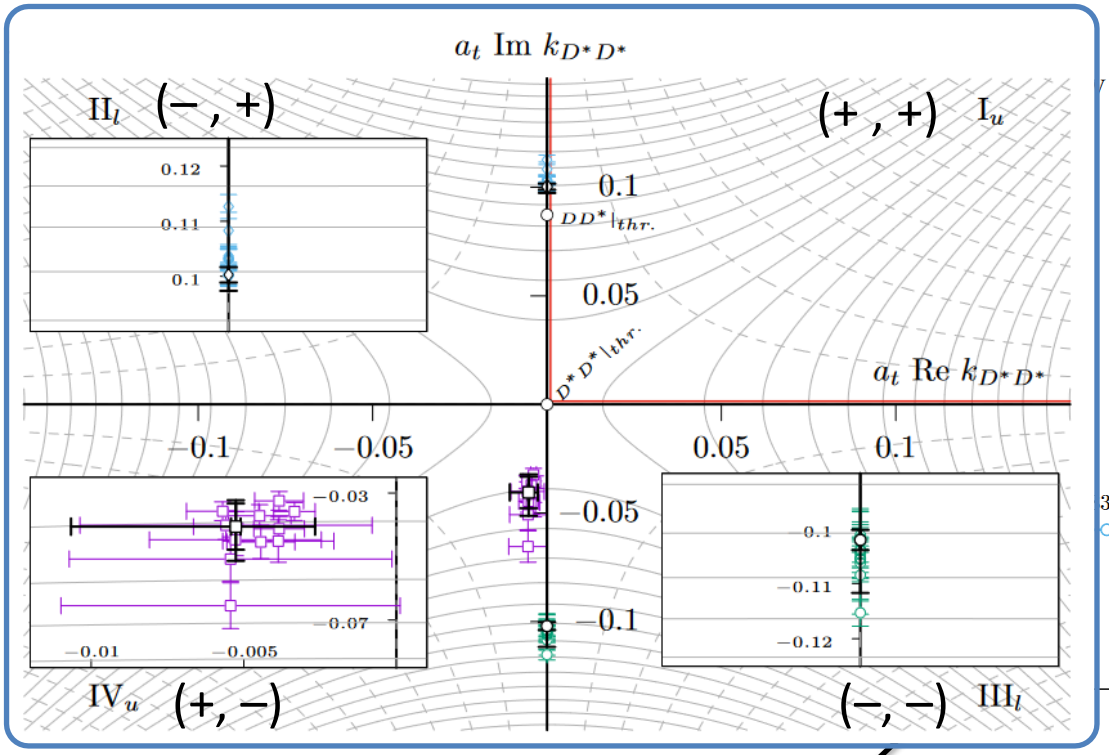
$\sqrt{s} \approx 3834(31)$ MeV

Resonance (T'_{cc}) pole on (+ , –) sheet below D^*D^* threshold – prediction of new state

(might be seen in DD, $DD\pi$ because low mom. π/γ can escape detection)

T_{cc} and T'_{cc} in coupled DD^*, D^*D^* scattering

[2405.15741]

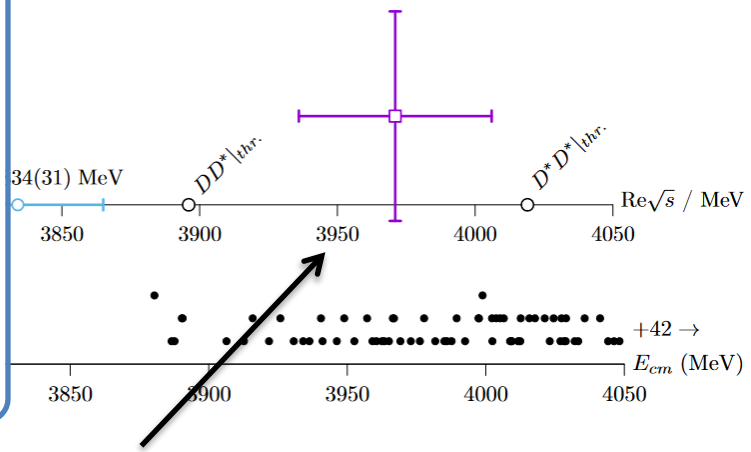


Virtual bound state (T_{cc}) below DD^* threshold

$\sqrt{s} \approx 3834(31)$ MeV

$\sqrt{s} \approx 3971(35)$ MeV

$\Gamma \approx 11(13)$ MeV



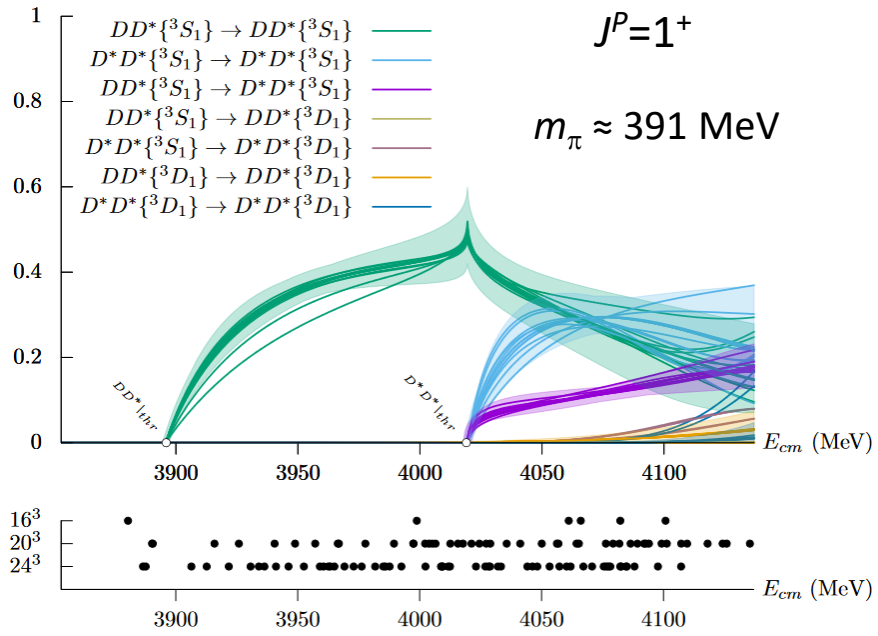
Resonance (T'_{cc}) pole on (+ , −) sheet below D^*D^* threshold – prediction of new state

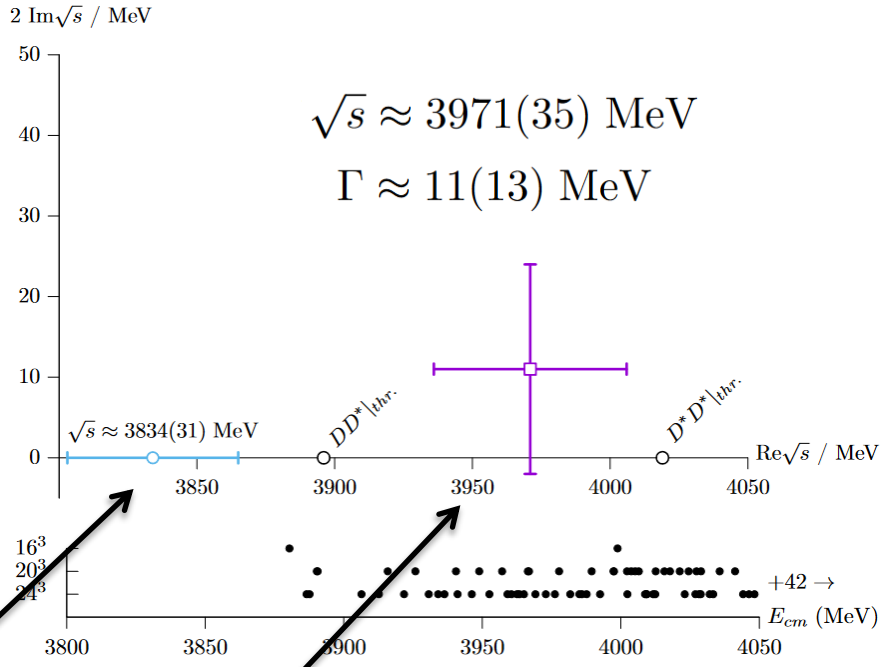
(might be seen in DD, $DD\pi$ because low mom. π/γ can escape detection)

T_{cc} and T'_{cc} in coupled DD^*, D^*D^* scattering

[2405.15741]

~ |amp|^2





Virtual bound state (T_{cc}) below DD^* threshold

$\sqrt{s} \approx 3834(31)$ MeV

Resonance (T'_{cc}) pole on (+ , –) sheet below D^*D^* threshold – prediction of new state

Dependence on m_π?

Effect of left hand cut from π exchange (≈18 MeV below DD^* thresh)?

Coupled DD, DD^*, D^*D^* scattering ($I = 1$)

$J^P = 0^+, 1^+, 2^+$

Same setup as previous calculation

[**Nelson Lachini**, Thomas, Wilson (HadSpec), 2505.01363 (PRD)]

Coupled DD, DD^*, D^*D^* scattering ($I = 1$)

$J^P = 0^+, 1^+, 2^+$

Same lattice setup as previous calculation

Weak repulsive interactions,
except weak attraction for S-wave D^*D^* with $J^P = 0^+$

No sign of bound states or resonances in energy region considered

Consistent with T_{cc} having isospin 0

[**Nelson Lachini**, Thomas, Wilson (HadSpec), 2505.01363 (PRD)]

Charmonium scalar (0^{++}) and tensor (2^{++}) resonances

Experimental situation:

- Ground state $\chi_{c0}(1P)$ (0^{++}) and $\chi_{c2}(1P)$ (2^{++}) below $D\bar{D}$ threshold. Above that it is less clear…

Charmonium scalar (0^{++}) and tensor (2^{++}) resonances

Experimental situation:

- Ground state $\chi_{c0}(1P)$ (0^{++}) and $\chi_{c2}(1P)$ (2^{++}) below $D\overline{D}$ threshold. Above that it is less clear…

- $\chi_{c0}(3860) \to D\overline{D}$ (Belle). Not seen in $B^+ \to D^+D^-K^+$ (LHCb). Theoretical reanalyses: may be from pole below $D\overline{D}$ thresh.
- $\chi_{c0}(3930) \to D\overline{D}$ (LHCb)
- $\chi_{c0}(3960) \to D_s\overline{D}_s$ (LHCb)
- $X(3915) \to J/\psi\omega$ (Belle)

  } $\chi_{c0}(3915)$

- $\chi_{c2}(3930) \to D\overline{D}$ (Belle, BABAR, LHCb)

Charmonium 0^{++} and 2^{++} resonances

$m_\pi \approx 391$ MeV,
3 lattice volumes ($L \approx 2 - 3$ fm)
No c - $\bar{c}$ annihilation.

Use many
fermion-bilinear ($\bar{c}\,\Gamma\,\mathrm{D}\,\ldots\,c$)
and meson-meson-like ops
($\eta_c\eta$, $D\bar{D}$, $\eta_c\eta'$, $D_s\bar{D}_s$, $D\bar{D}^*$, $D_s\bar{D}_s^*$, $\psi\omega$, $D^*\bar{D}^*$, $\psi\phi$, $\eta_c\sigma$, $\chi_{c0,2}\sigma$, …)

First ‘complete’ lattice study
of this energy region.

[**David Wilson**, Thomas, Dudek, Edwards (HadSpec), 2309.14070 (PRL), 2309.14071 (PRD)]

Charmonium 0^{++} and 2^{++} resonances

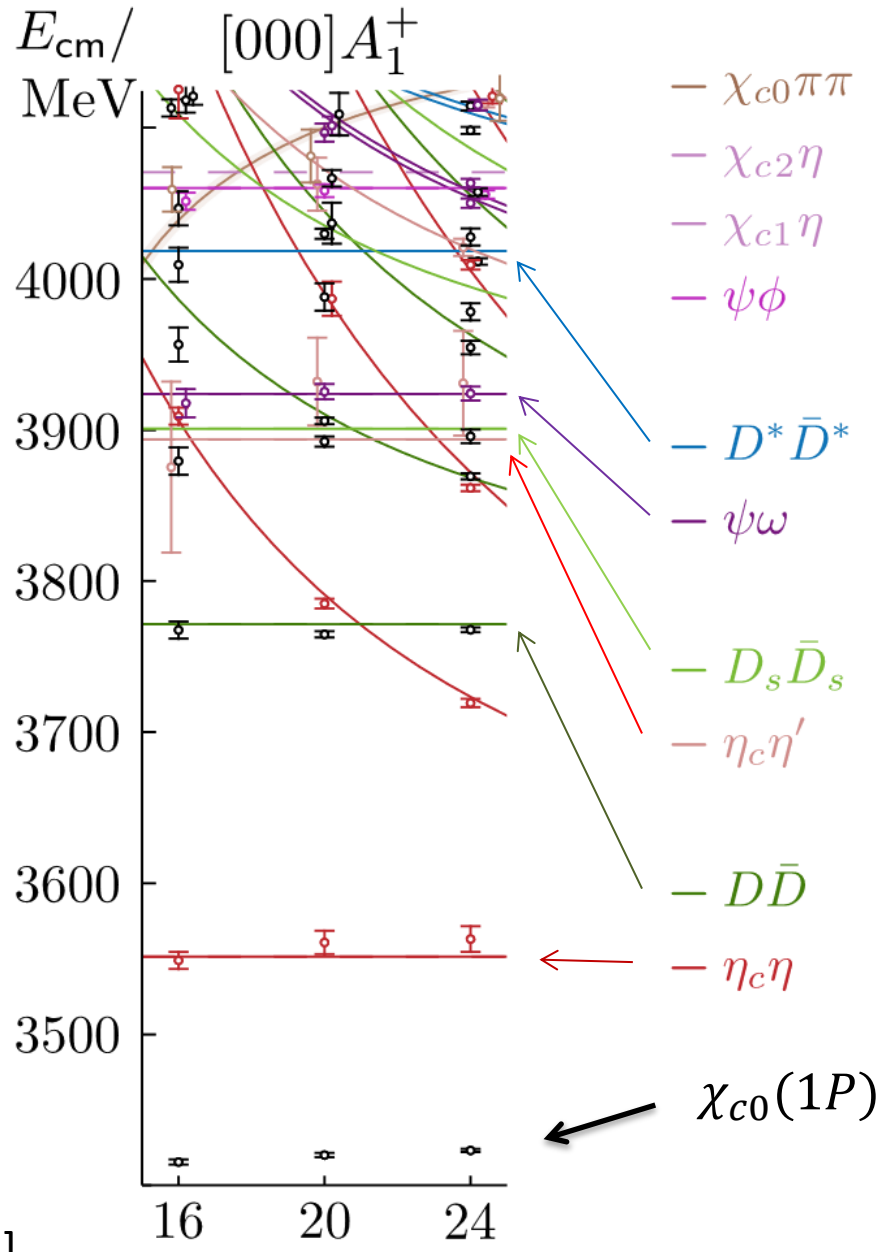
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First ‘complete’ lattice study of this energy region.

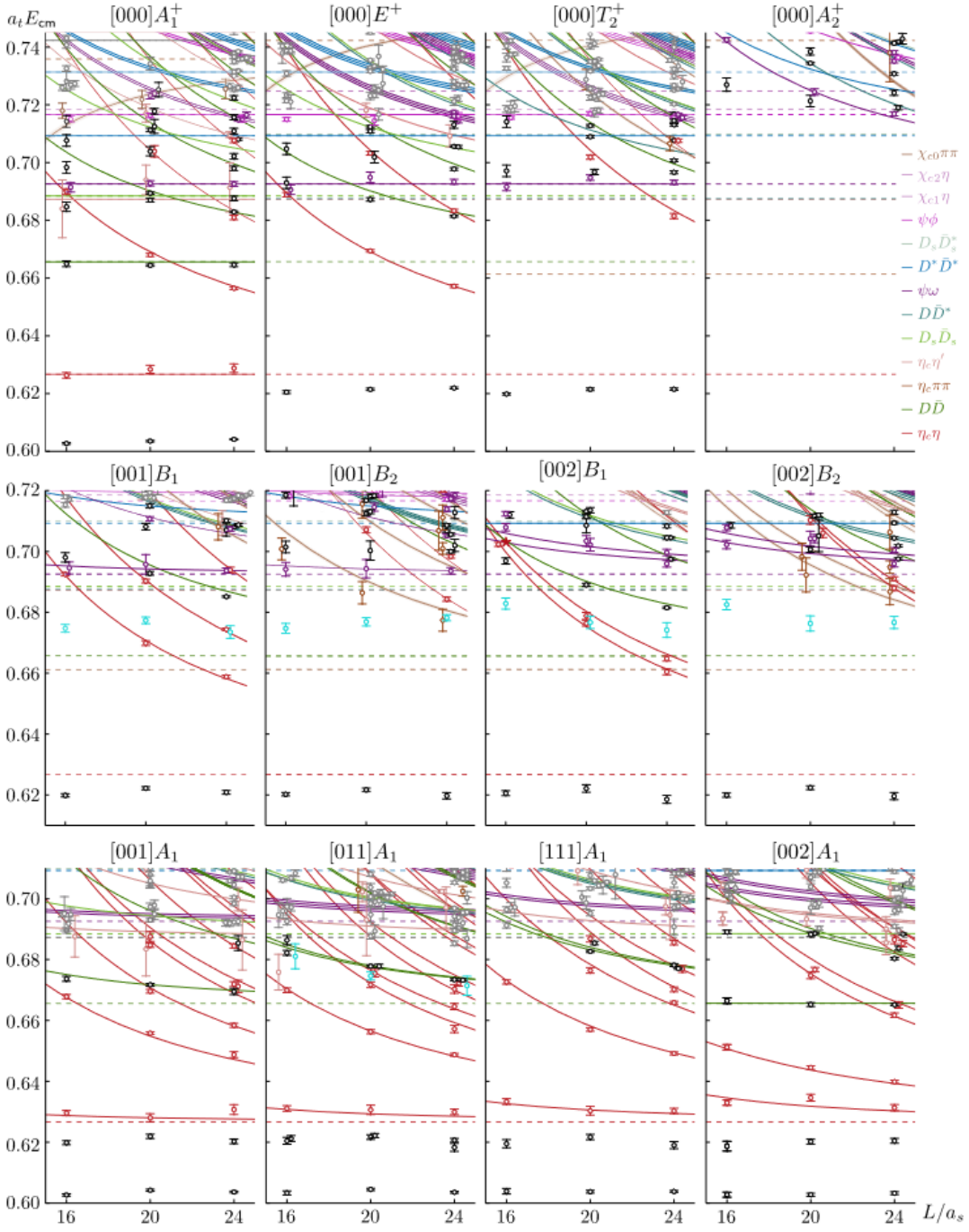
[**David Wilson**, Thomas, Dudek, Edwards (HadSpec), 2309.14070 (PRL), 2309.14071 (PRD)]

P = [0,0,0] $J^P = 0^+, (4^+, \ldots)$



Charmonium 0^{++} and 2^{++} resonances

Use more than 200 energy levels



[2309.14070, 2309.14071]

Scattering amplitudes

0^{++} $\eta_c\eta, D\bar{D}, \eta_c\eta', D_s\bar{D}_s, \psi\omega, D^*\bar{D}^*, \psi\phi\{^1S_0\}$

2^{++} $\eta_c\eta, D\bar{D}, [\eta_c\eta'], D_s\bar{D}_s\{^1D_2\}; D\bar{D}^*, [D_s\bar{D}_s^*]\{^3D_2\}$
$\psi\omega, D^*\bar{D}^*, \psi\phi\{^5S_2\}$

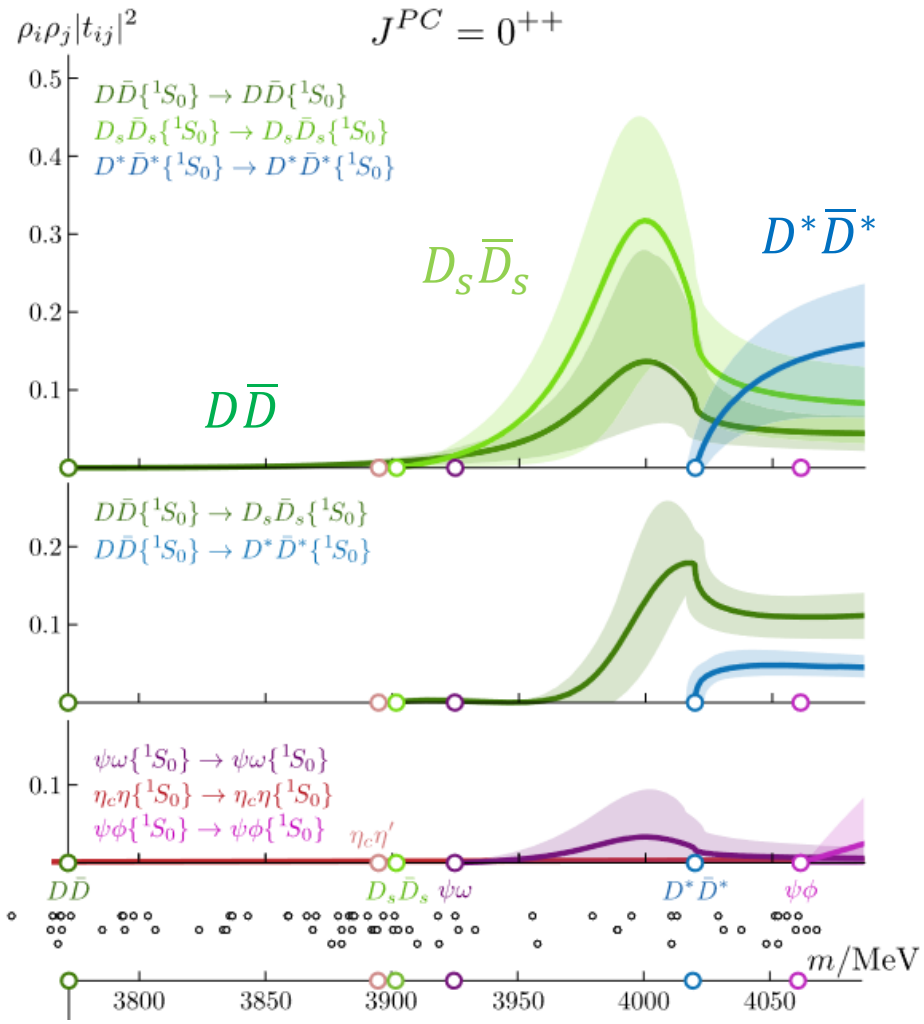
3^{++} $D\bar{D}^*, \psi\omega, D_s\bar{D}_s^*, \psi\phi\{^3D_3\}; [\eta_c\sigma\{^1F_3\}]$
$\psi\omega, D^*\bar{D}^*, [\psi\phi, D_s^*\bar{D}_s^*]\{^5D_3\}$

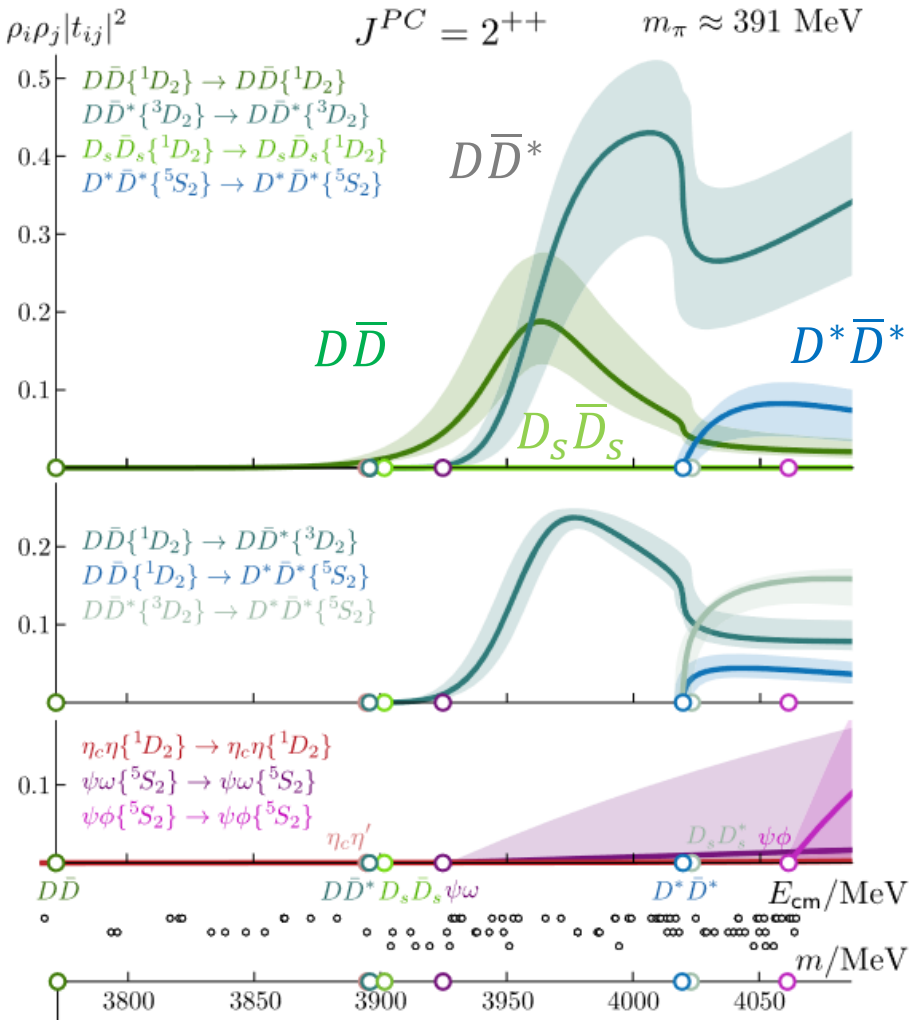
and ‘background’ 1^{-+}, 2^{-+}, 3^{-+} amplitudes

$$K_{ij} = \sum_p \frac{g_i^{(p)} g_j^{(p)}}{m_p^2 - s} + \sum_a \gamma_{ij}^{(a)} s^a$$

[2309.14070, 2309.14071]

0^{++} and 2^{++} scattering amplitudes





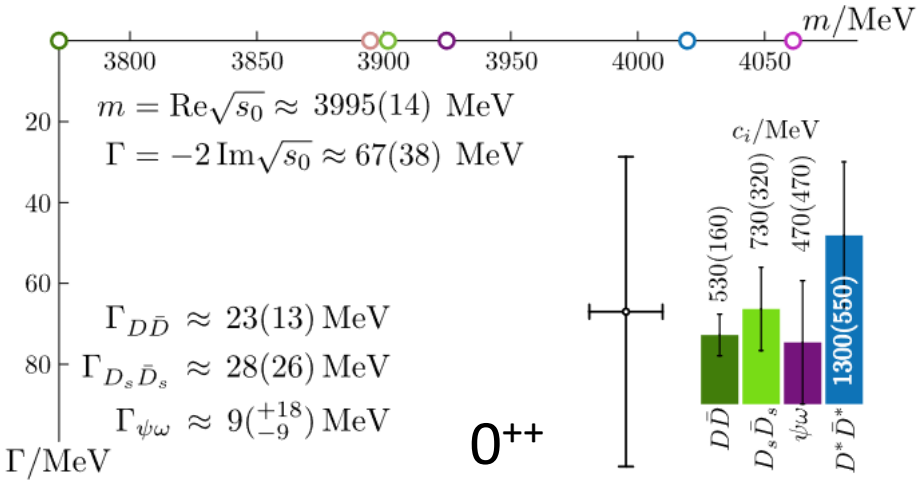
[2309.14070, 2309.14071]

Use more than 200 energy levels

Charmonium 0^{++} and 2^{++} resonances

[2309.14070, 2309.14071]

$m_\pi \approx 391$ MeV

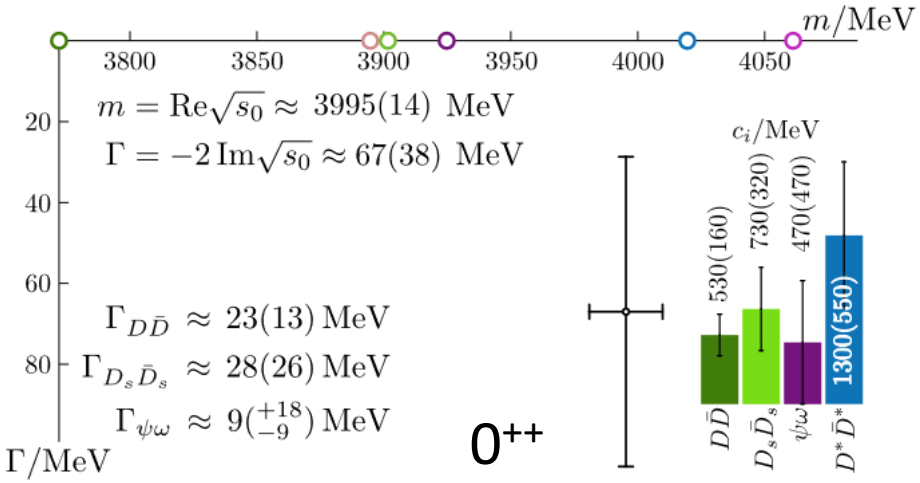


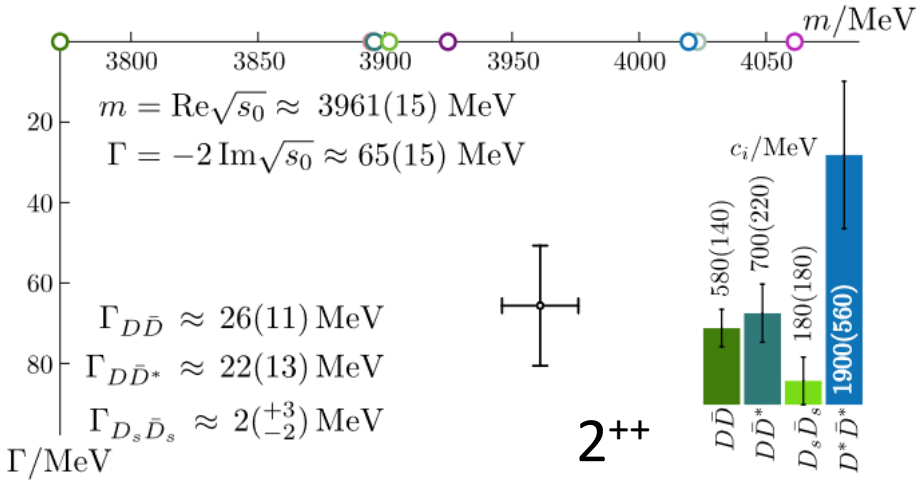
$$t_{ij} \sim \frac{c_i c_j}{(s_0 - s)}$$

Charmonium 0^{++} and 2^{++} resonances

[2309.14070, 2309.14071]

$m_\pi \approx 391$ MeV



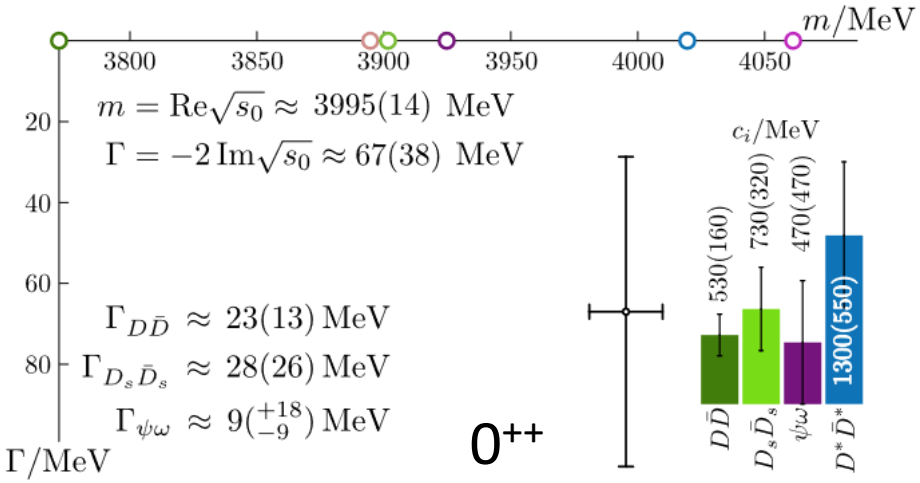


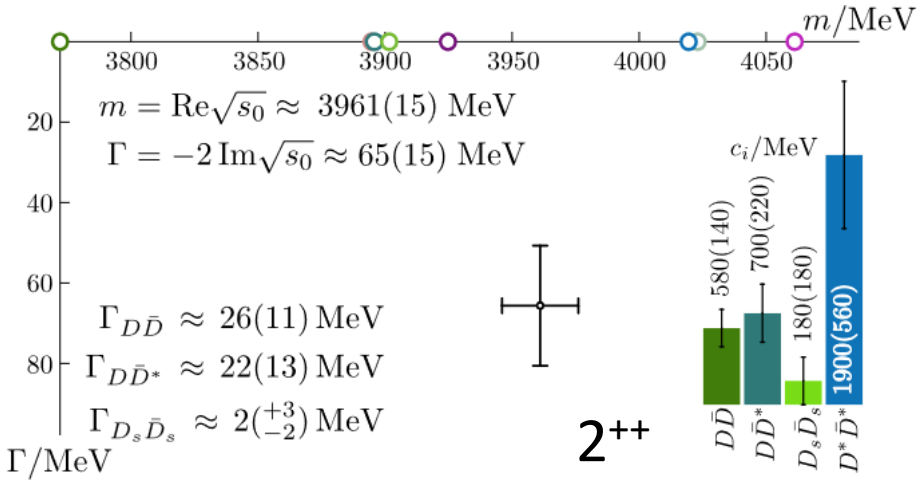
$$t_{ij} \sim \frac{c_i c_j}{(s_0 - s)}$$

Charmonium 0^{++} and 2^{++} resonances

[2309.14070, 2309.14071]

$m_\pi \approx 391$ MeV





- **Simple picture:** only one 0^{++} and one 2^{++} resonance $\lesssim 4.1$ GeV, c.f. $\chi_{c0}(3915)$, $\chi_{c2}(3930)$ and quark model (2P states)
- No large scattering amps in channels with $\bar{c}c$ + light meson (OZI)
- Above ground state χ_{c0} no other 0^{++} bound states or near-$D\bar{D}$ / $D_s\bar{D}_s$ threshold resonances. C.f. claims for extra $\chi_{c0}(3860)$ by Belle [1704.01872], lattice calc ($m_\pi \approx 280$ MeV) [Prelovsek *et al,* 2011.02542 – talk on Mon.], some models, …)
- (Also bound state in 2^{-+} and narrow resonance in 3^{++}.)

Near-threshold $D\bar{D}$ scattering

What about reducing the light-quark mass?

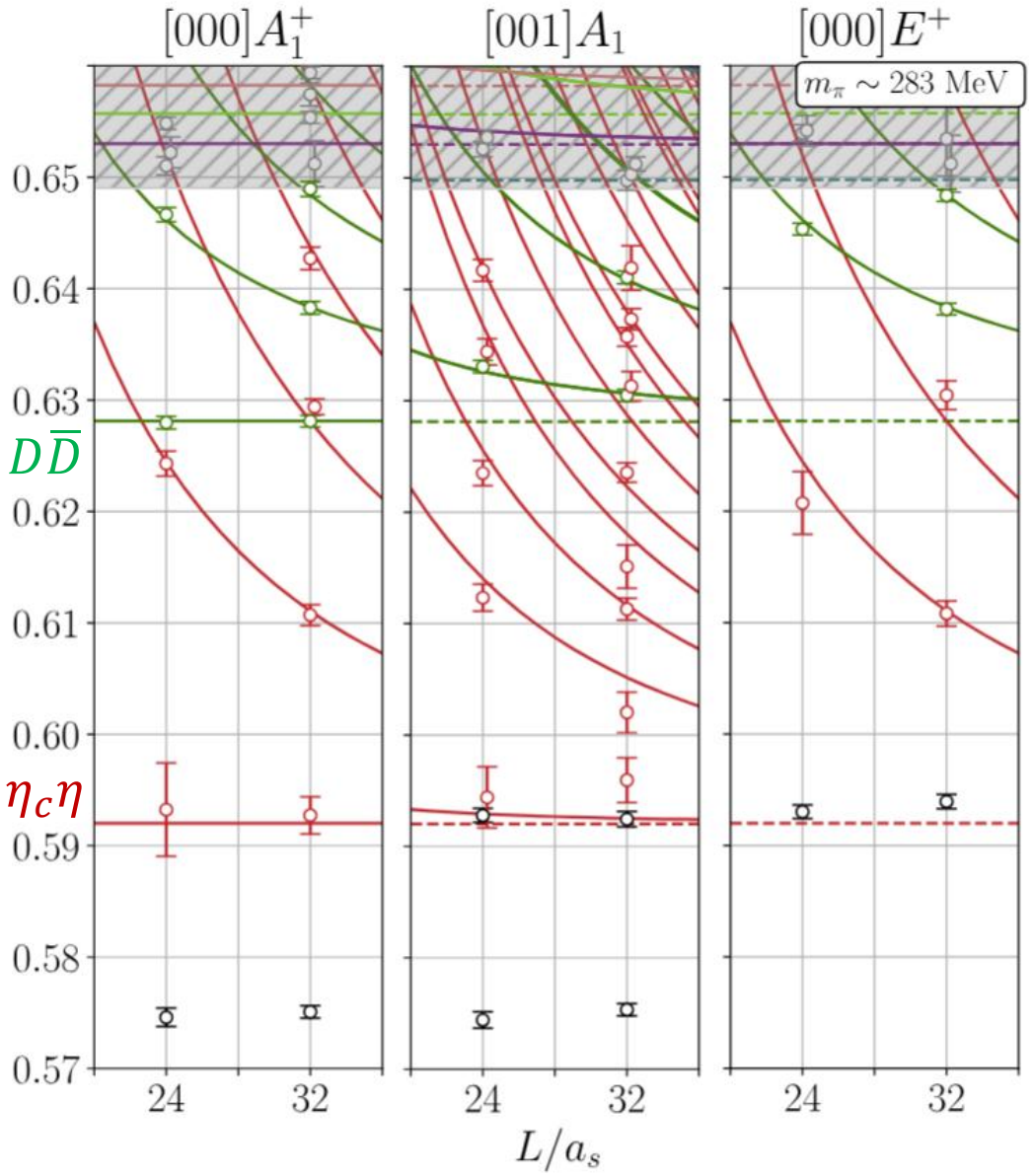
$m_\pi \approx$ 239 MeV, 283 MeV, 330 MeV (previous calc. 391 MeV)

Consider $\eta_c\eta$, $D\bar{D}$ $(I = 0)$ scattering
in *S*-wave and *D*-wave near $D\bar{D}$ threshold

[**David Wilson**, Dudek, Edwards, Thomas (HadSpec), 2602.09862]

Near-threshold $D\bar{D}$ scattering

[2602.09862]



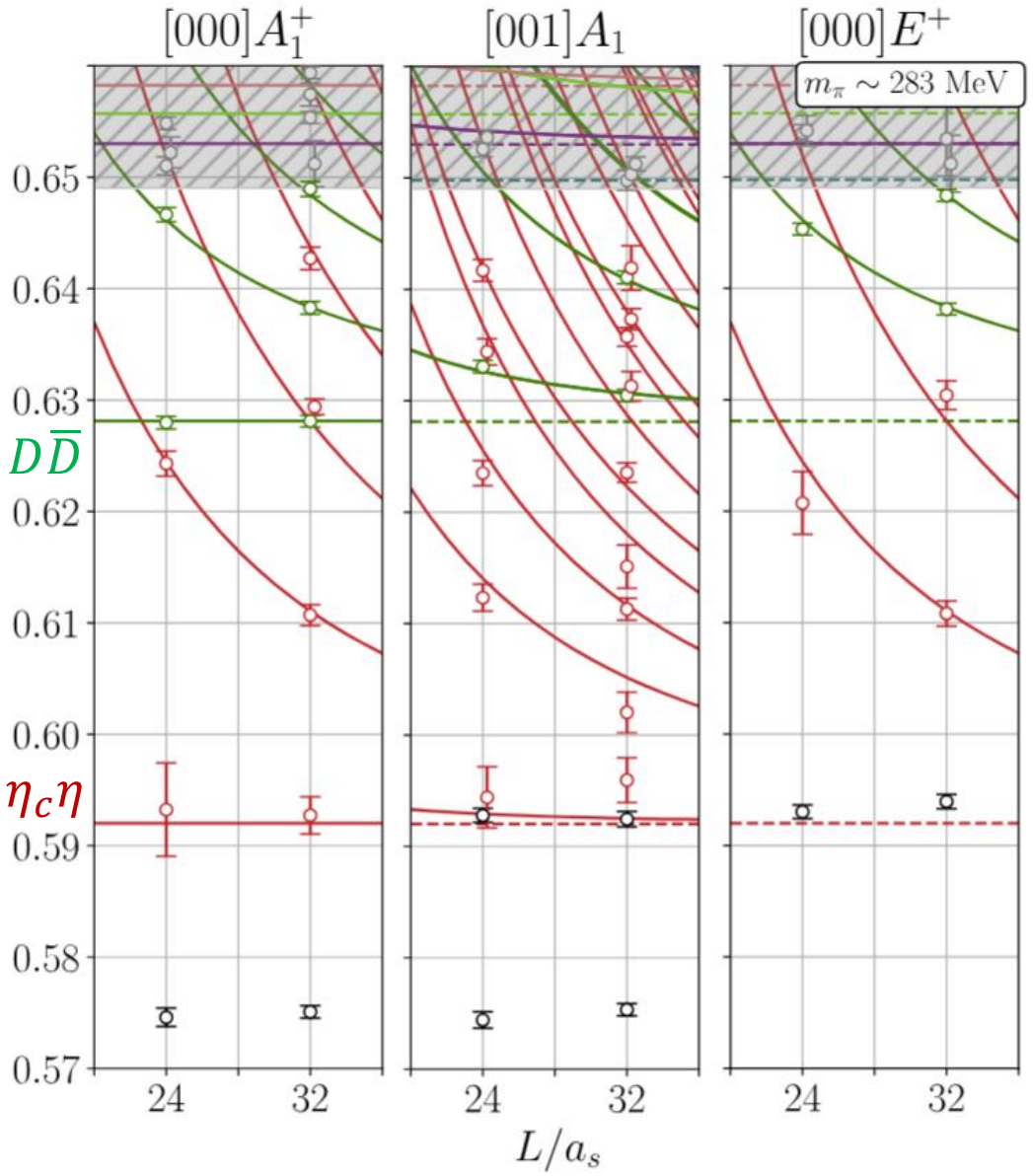
$m_\pi \approx 283$ MeV (2 volumes):
42 energy levels
[including 8 associated with stable $\chi_{c0,2}(1P)$]

$\chi_{c2}(1P)$

$\chi_{c0}(1P)$

Near-threshold $D\overline{D}$ scattering

[2602.09862]



$m_\pi \approx 283$ MeV (2 volumes):
42 energy levels
[including 8 associated with stable $\chi_{c0,2}(1P)$]

$m_\pi \approx 239$ MeV, 330 MeV
(1 volume each):
22, 19 energy levels
[including 4 for $\chi_{c0,2}(1P)$]

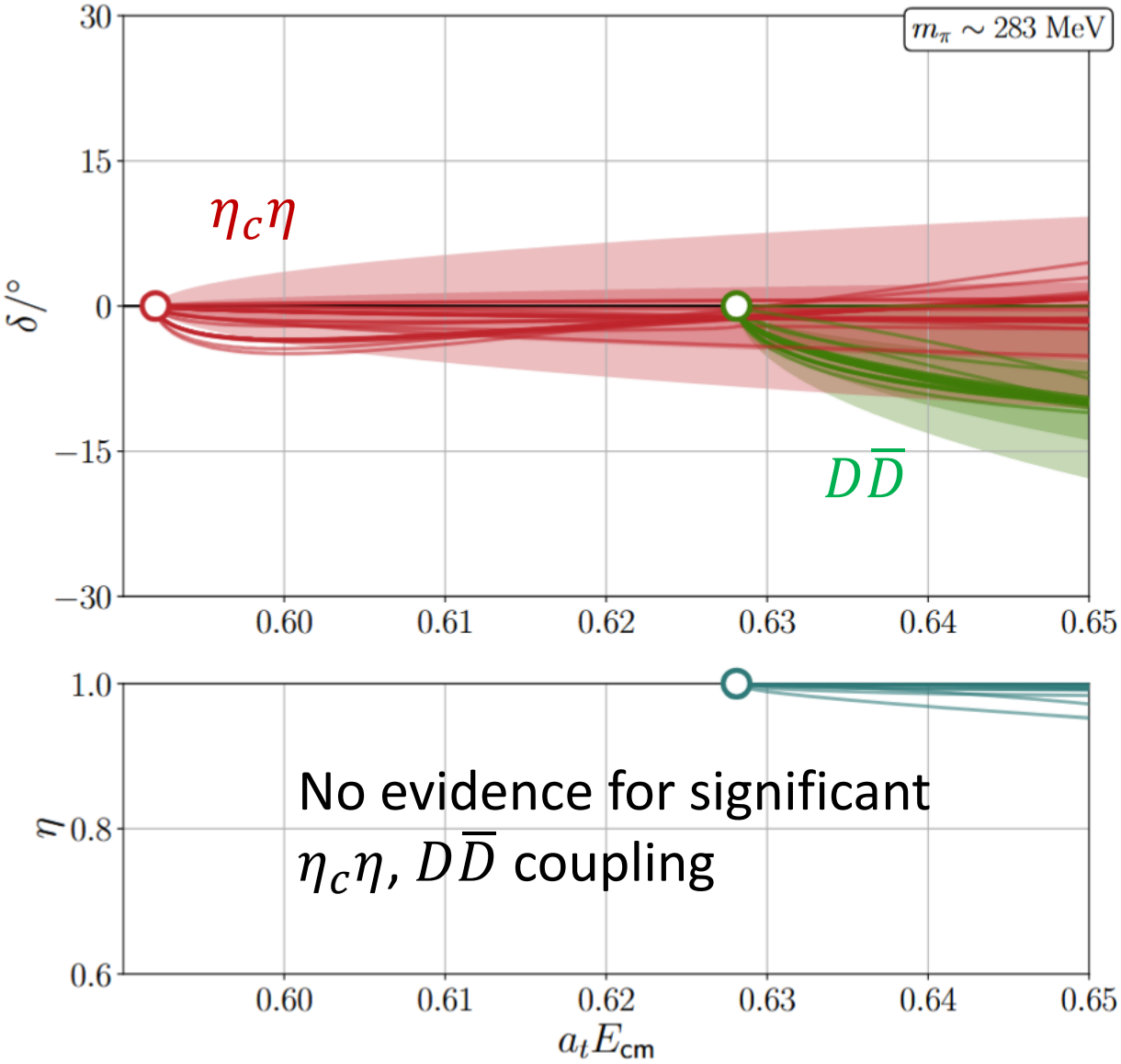
$\chi_{c2}(1P)$

$\chi_{c0}(1P)$

Near-threshold $D\bar{D}$ scattering

$m_\pi \approx 283$ MeV

[2602.09862]

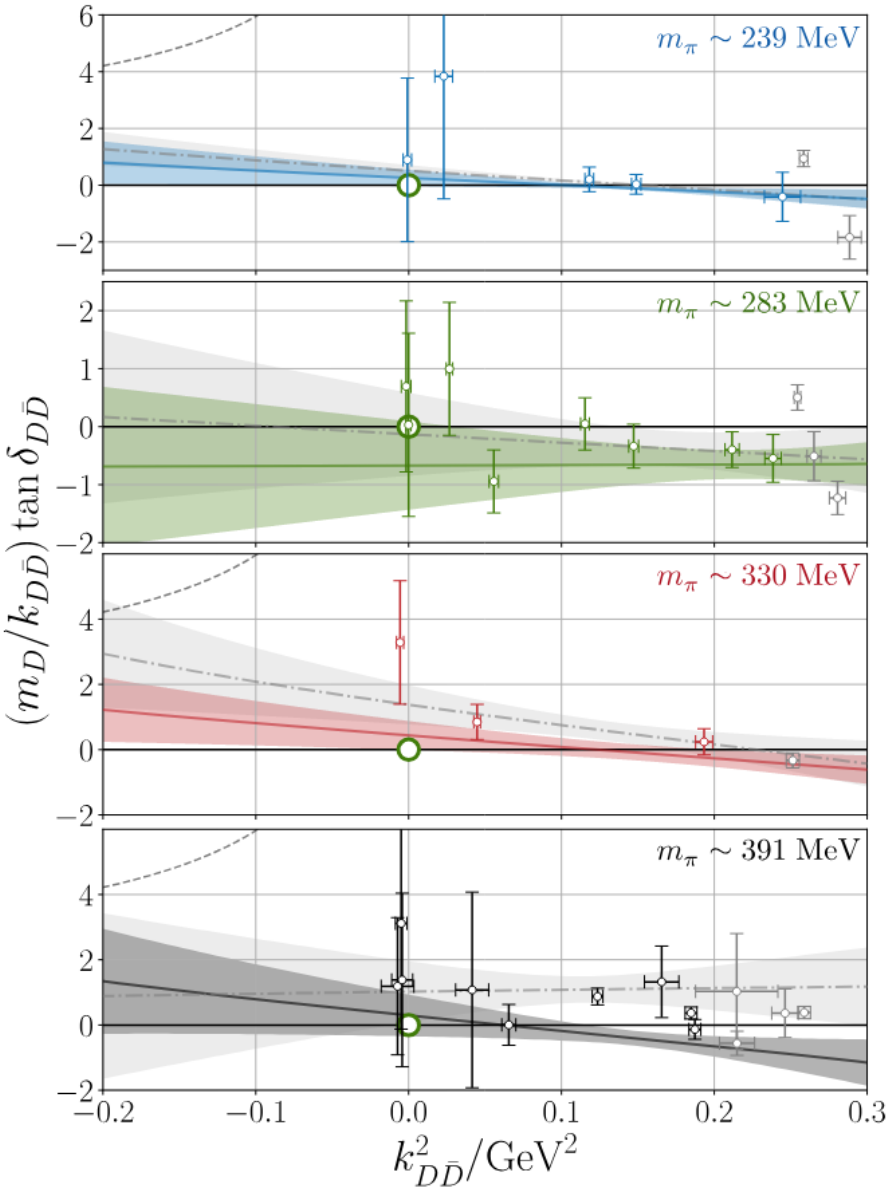


$$t_{ij} = \begin{cases} \frac{\eta\, e^{2i\delta_i} - 1}{2i\,\rho_i} & (i = j) \\ \frac{\sqrt{1-\eta^2}\, e^{i(\delta_i+\delta_j)}}{2\sqrt{\rho_i\,\rho_j}} & (i \neq j) \end{cases}$$

No evidence for significant $\eta_c\eta$, $D\bar{D}$ coupling

Near-threshold $D\bar{D}$ scattering

[2602.09862]



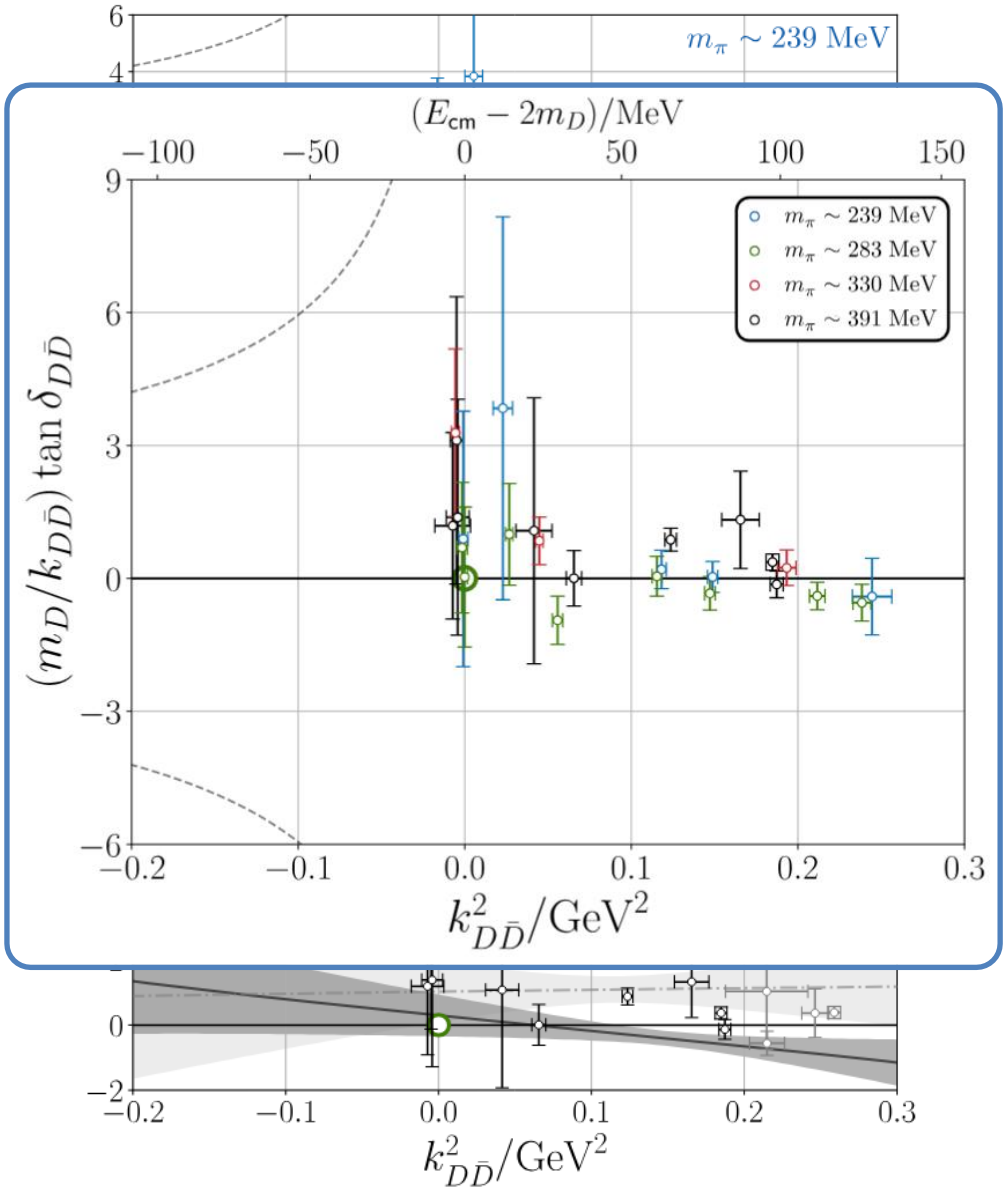
Reducing light-quark mass doesn't appear to change picture:

Near-threshold $D\bar{D}$ scattering is weak.

No sign of near-threshold bound state, virtual bound state or resonance [c.f. $\chi_{c0}(3860)$]

Near-threshold $D\bar{D}$ scattering

[2602.09862]



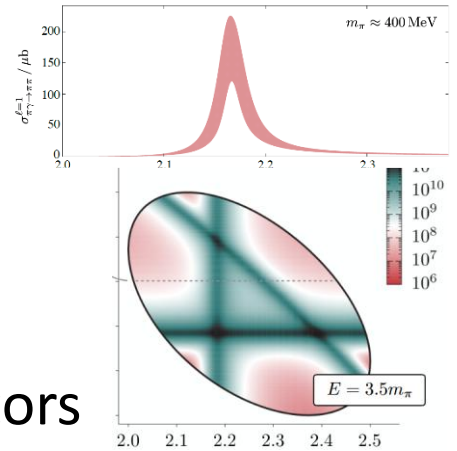
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Summary

- Some recent LQCD calculations of charm/charmonium mesons:
  - T_{cc} and T'_{cc} in coupled DD^*, D^*D^* scattering
  - Scalar (0^{++}) and tensor (2^{++}) charmonia – simple picture
  - Reduce light-quark mass: picture doesn't change, near-threshold $D\overline{D}$ interactions are weak
- Many other calcs, e.g. D_0, D_{s0}, π_1 (exotic 1^{-+}), light scalars
- Outlook:
  - Other channels and vary light-quark mass
  - Effect of left-hand cut?
  - Three (or more!?) hadron scattering
  - Probe structure, e.g. transitions and form factors



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