

Excited heavy mesons and exotics from lattice QCD

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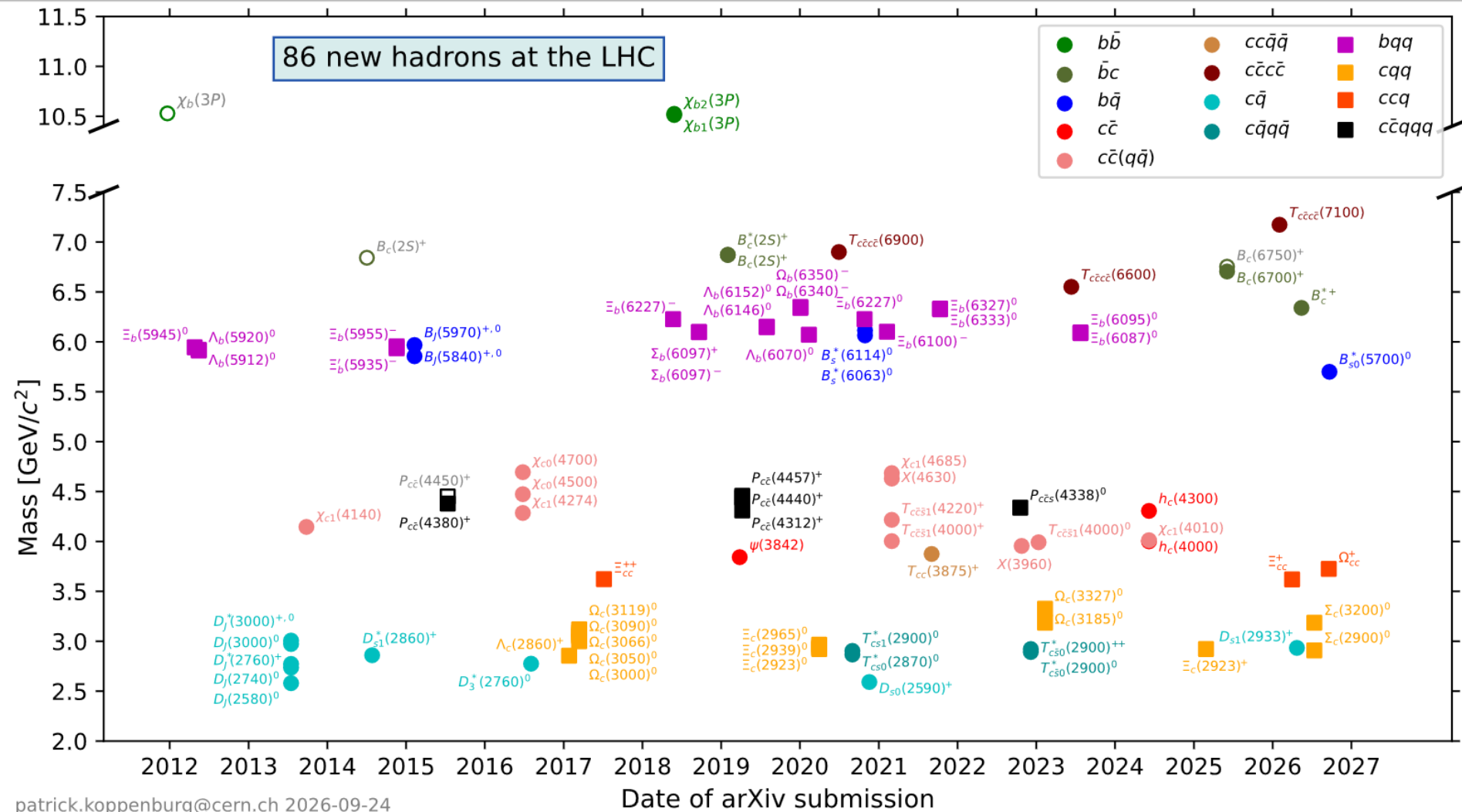
QCD@LHC, Oxford,
28 Sept – 2 Oct 2026



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had spec

Hadron spectroscopy



First-principles calculations in QCD → lattice QCD

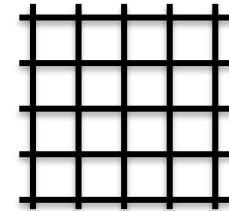
Lattice QCD spectroscopy

Systematically-improvable
first-principles calculations

Discretise spacetime in a finite volume.

[Finite a and L , possibly unphysically-heavy u, d quarks]

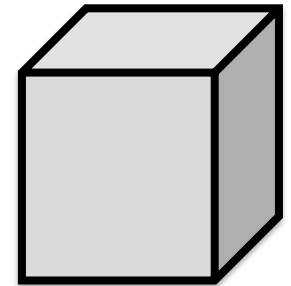
Compute correlation functions numerically.



Finite-volume energy eigenstates $\{E_n\}$ from

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

[Large bases of operators with appropriate structures.]



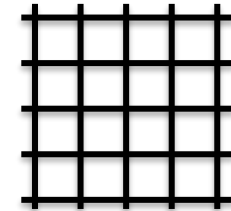
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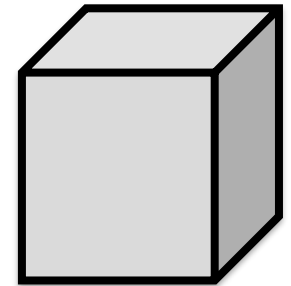
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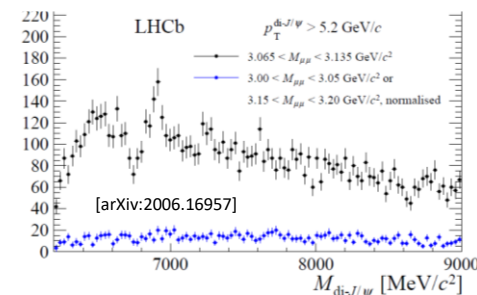
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Most hadrons are resonances (not asymptotic states).



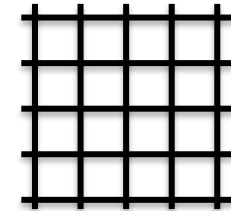
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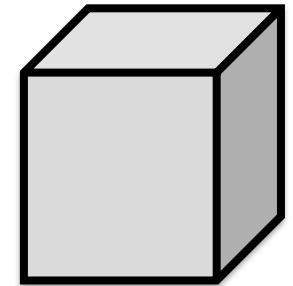
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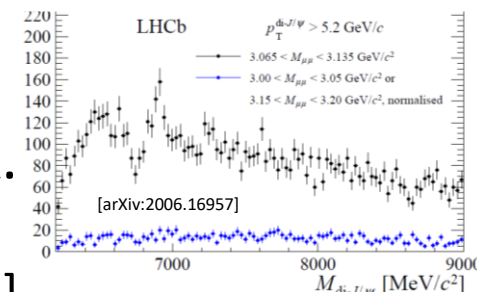
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Use Lüscher method and extensions:

relate $\{E_n\}$ to **infinite-volume scattering t -matrix**.

[Each E_{cm} constrains t -matrix at that $E_{\text{cm}} \rightarrow$

parametrize $t(E_{\text{cm}})$ using various forms (K -matrix forms, ...)]



Analytically continue $t(E_{\text{cm}})$ in complex E_{cm} plane, look for poles $\rightarrow$ **resonance/bound-state content**.

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...

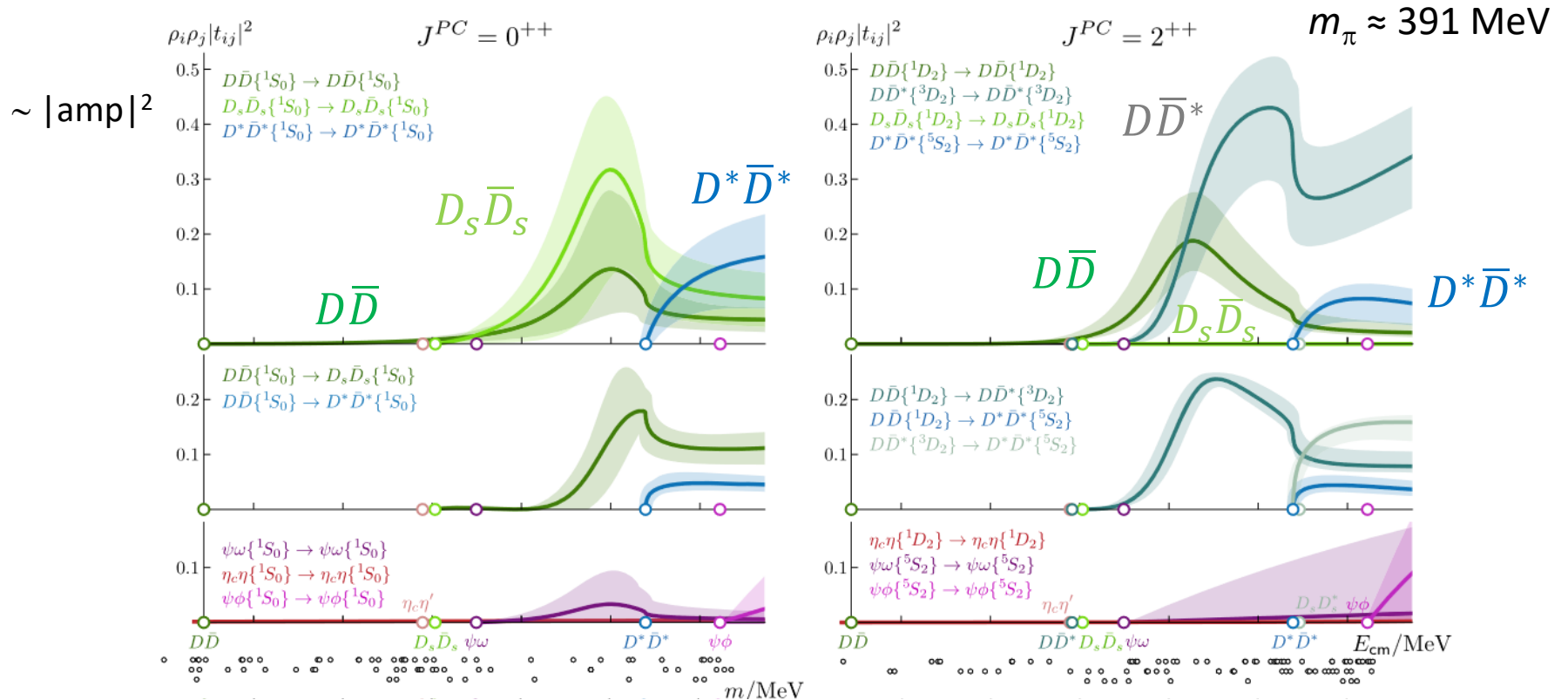
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Experimental situation:

- Ground state $\chi_{c0}(1P)$ (0^{++}) and $\chi_{c2}(1P)$ (2^{++}) below $D\bar{D}$ threshold. Above that it is less clear...
 - $\chi_{c0}(3860) \rightarrow D\bar{D}$ (Belle). Not seen in $B^+ \rightarrow D^+ D^- K^+$ (LHCb).
 - $\chi_{c0}(3930) \rightarrow D\bar{D}$ (LHCb)
 - $\chi_{c0}(3960) \rightarrow D_s \bar{D}_s$ (LHCb)
 - $X(3915) \rightarrow J/\psi \omega$ (Belle)
 - $\chi_{c2}(3930) \rightarrow D\bar{D}$ (Belle, BABAR, LHCb)
- } $\chi_{c0}(3915)$

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

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

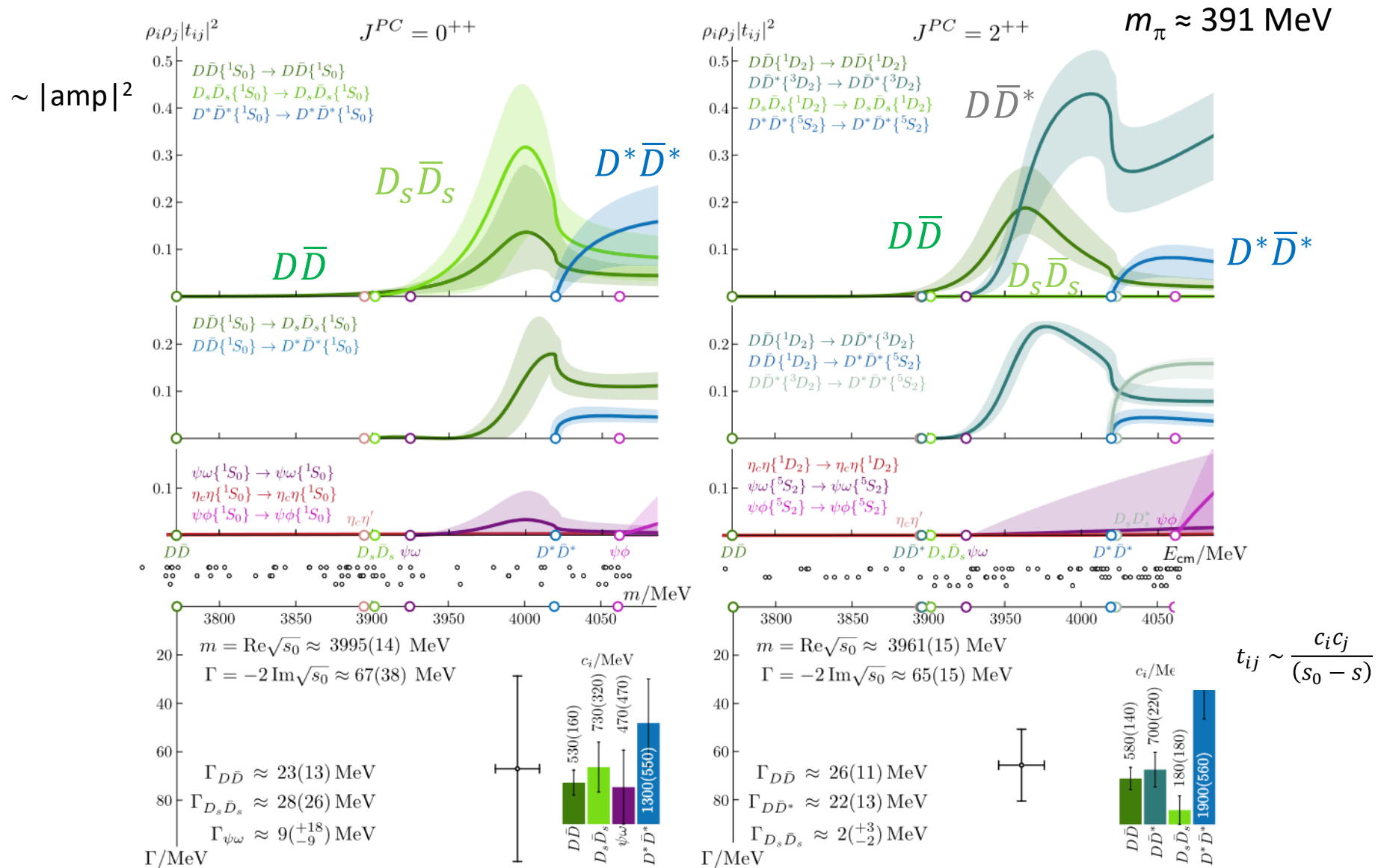


First ‘complete’ lattice study of this energy region
Use more than 200 energy levels

$(\eta_c \eta, D\bar{D}, \eta_c \eta', D_s \bar{D}_s, D\bar{D}^*, D_s \bar{D}_s^*, \psi\omega, D^* \bar{D}^*, \psi\phi, \eta_c \sigma, \chi_{c0,2} \sigma, \dots)$

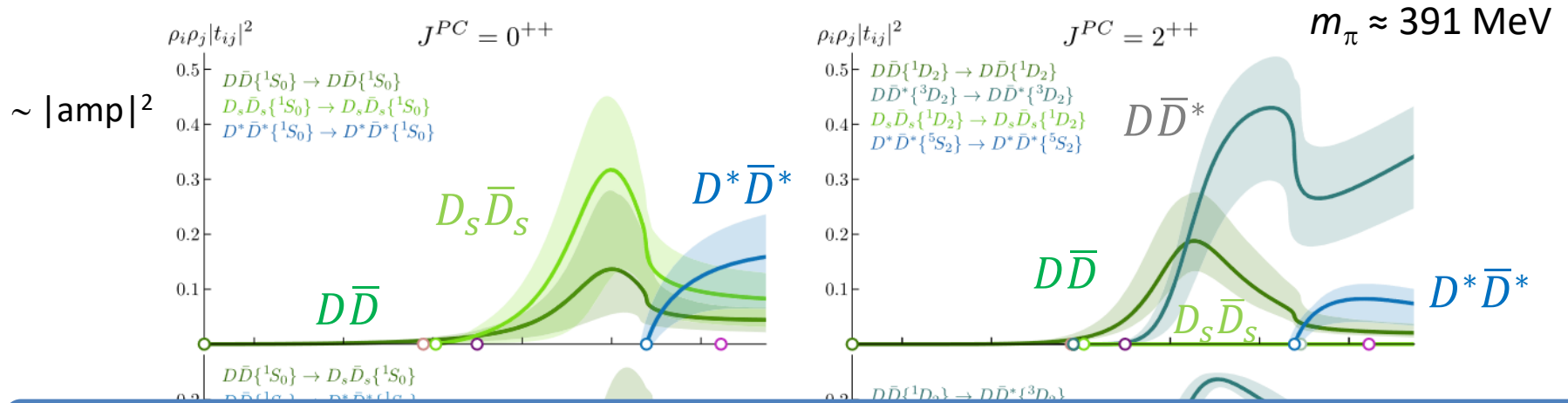
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Charmonium 0^{++} and 2^{++} resonances

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

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

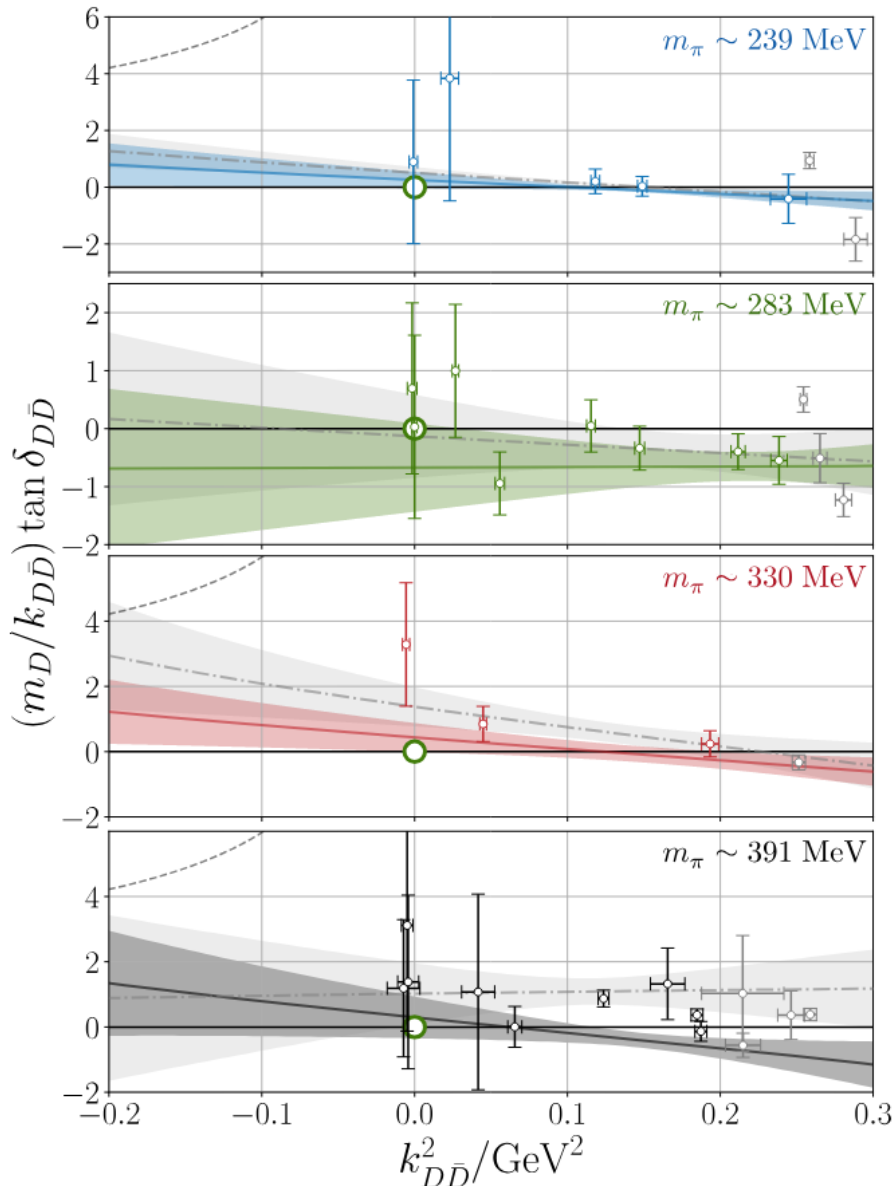
[**David Wilson**, Dudek, Edwards,
Thomas (HadSpec), 2602.09862 (PRD)]

What about reducing the light quark mass? Consider $\eta_c\eta$, $D\bar{D}$ in S and D -wave near $D\bar{D}$ thresh.

$m_\pi \approx 239, 283, 330$ MeV
(previous 391 MeV)
[42, 22, 19 energy levels]

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$m_\pi \approx 239, 283, 330 \text{ MeV}$
(previous 391 MeV)
[42, 22, 19 energy levels]

Picture doesn't change:

Near-threshold $D\bar{D}$ scattering is weak. No near $D\bar{D}$ threshold bound state, virtual bound state or resonance [c.f. $\chi_{c0}(3860)$].

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

Charm (D) and charm-strange (D_s) mesons

Longstanding questions about $J^P = 0^+$ charm mesons:

- $D_0^*(2300)$ [$c\bar{l}$] (above $D\pi$ threshold)
- $D_{s0}^*(2317)$ [$c\bar{s}$] (below DK threshold)

Exotic structures seen in LHCb ~ 2900 MeV

$J^P = 0^+$: $T_{cs0}^*(2870)$ [$cs\bar{u}\bar{d}$], $T_{c\bar{s}0}^*(2900)$ [$c\bar{s}ud\bar{d}$, $c\bar{s}d\bar{u}$]

$J^P = 1^-$: $T_{cs1}^*(2900)$ [$cs\bar{u}\bar{d}$]

Other calculations

Some other lattice QCD work on DK and/or $D\pi$ scattering:

- Mohler *et al* [PR D87, 034501 (2013), 1208.4059];
- Liu *et al* [PR D87, 014508 (2013), 1208.4535];
- Mohler *et al* [PRL 111, 222001 (2013), 1308.3175];
- Lang *et al* [PR D90, 034510 (2014), 1403.8103];
- Bali *et al* (RQCD) [PR D96, 074501 (2017), 1706.01247];
- Alexandrou *et al* (ETM) [PR D101 034502 (2020), 1911.08435];
- Yan *et al* [PR D111, 014503 (2025), 2404.13479].
- Gregory *et al* [EPJ A 61, 226 (2025), 2503.23954]

Also:

- Martínez Torres *et al* [JHEP 05 (2015) 153, 1412.1706];
- Albaladejo *et al* [PL B767, 465 (2017), 1610.06727];
- Du *et al* [PR D98, 094018 (2018), 1712.07957];
- Guo *et al* [PR D98, 014510 (2018), 1801.10122];
- Guo *et al* [EPJ C79, 13 (2019), 1811.05585];
- Lutz, Guo, Heo, Korpa [PR D106, 114038 (2022), 2209.10601];
- Korpa *et al* [PR D107, L031505 (2023), 2211.03508];
- Asokan *et al* [PR D107, L031505 (2023), 2212.07856];
- Gil-Domínguez, Molina [PR D109, 096002 (2024), 2306.01848].

$SU(3)_F$ flavour symmetry ($m_u=m_d=m_s$)

$D_{\bar{3}}(c\bar{q}) \eta_8(q\bar{q})$ scattering: $\bar{\mathbf{3}} \otimes \mathbf{8} = \bar{\mathbf{3}} \oplus \mathbf{6} \oplus \overline{\mathbf{15}}$
(S -wave, $J^P = 0^+$)

$m_\pi (m_{\eta_8}) \approx 700 \text{ MeV}$

[See also PR D87, 014508 (2013) (1208.4535); PL B767, 465 (2017) (1610.06727); PR D98, 094018 (2018) (1712.07957); PR D98 014510 (2018) (1801.10122); EPJ C79, 13 (2019) (1811.05585); arXiv:2106.15391; PR D107, L031505 (2023); EPJ A61, 226 (2025) (2503.23954)]

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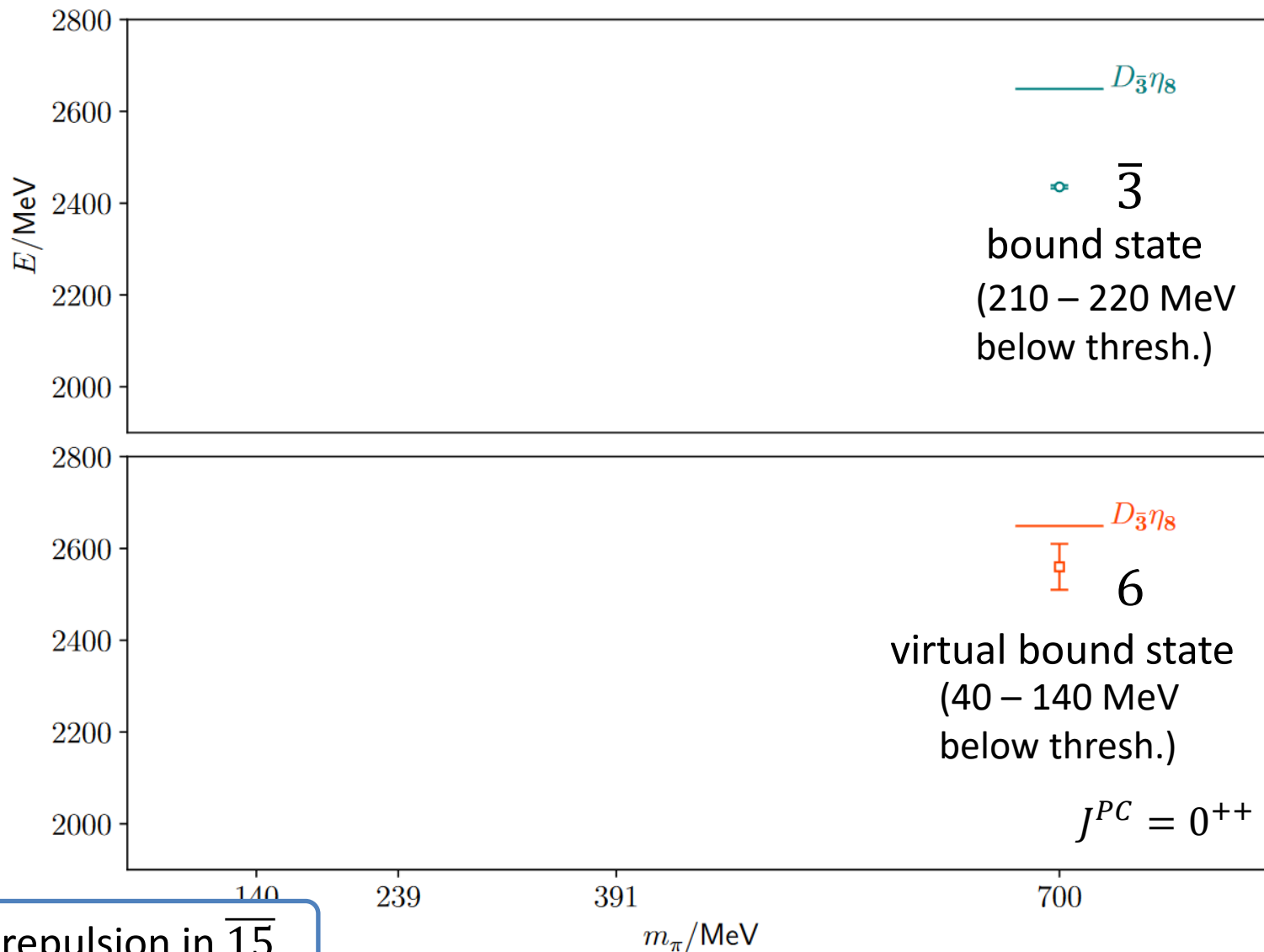
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Exotic flavour
(can't be just $c\bar{q}$,
e.g. $cs\bar{l}\bar{l}$, $l=1$ $cl\bar{s}\bar{l}$)

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DK/π with $SU(3)_F$ sym

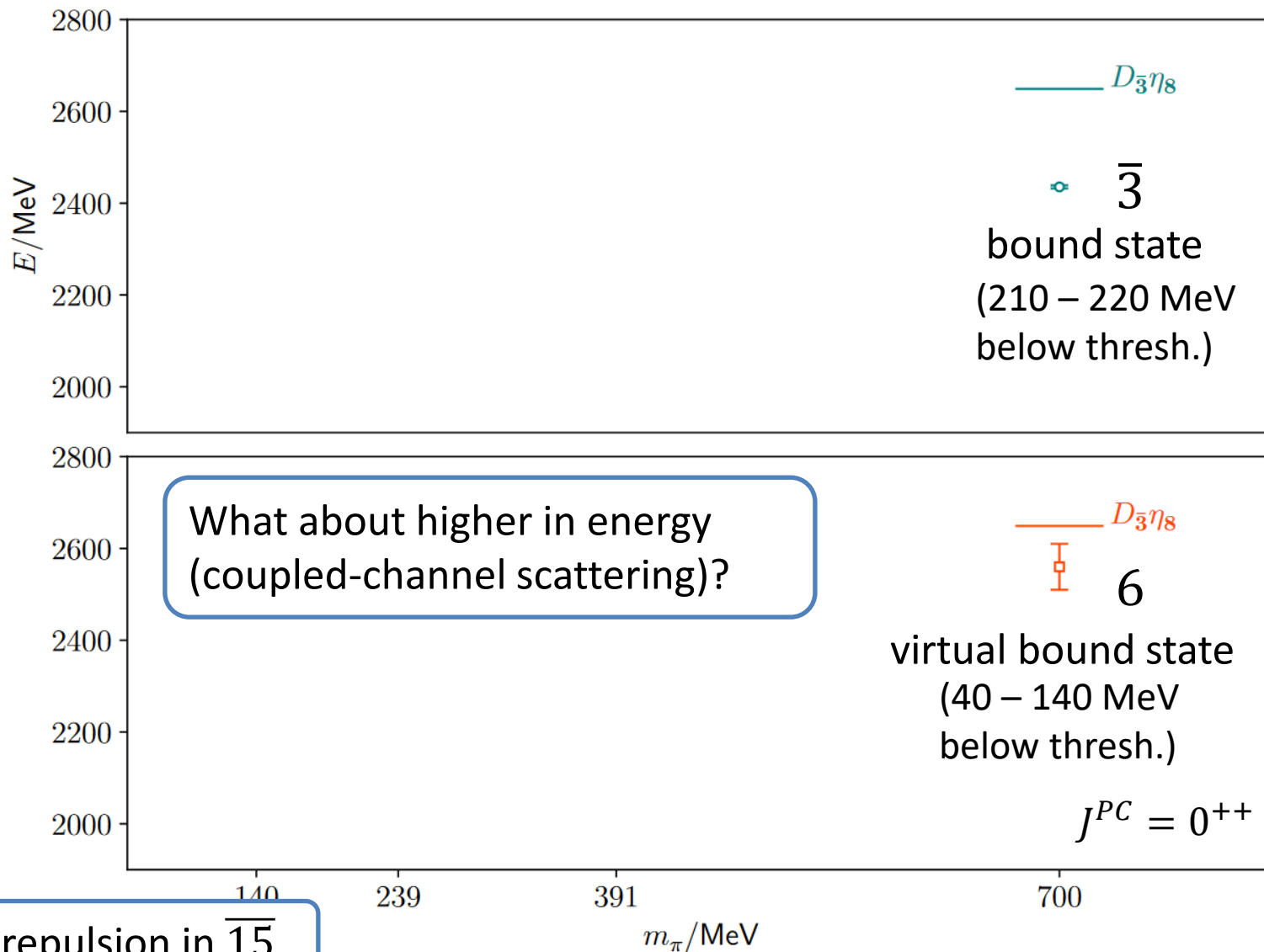
[Daniel Yeo, Thomas, Wilson
(HadSpec), 2403.10498 (JHEP)]



Weak repulsion in $\bar{15}$

DK/π with $SU(3)_F$ sym

[Daniel Yeo, Thomas, Wilson
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Coupled-channel scattering with $SU(3)_F$ sym

$$D_{\bar{3}} \eta_8, D_{\bar{3}}^* \eta_8, D_{\bar{3}} \omega_8, D_{\bar{3}}^* \omega_8$$

in S and D -wave

$$J^P = 0^+, 1^+, 2^+, 3^+, 4^+$$

(and consider other
potentially-relevant channels)

5 lattice volumes

46 + 58 + 82 + 22 energy levels
(for $J^P = 0^+ \text{ \& } 4^+, 1^+, 2^+, 3^+$)

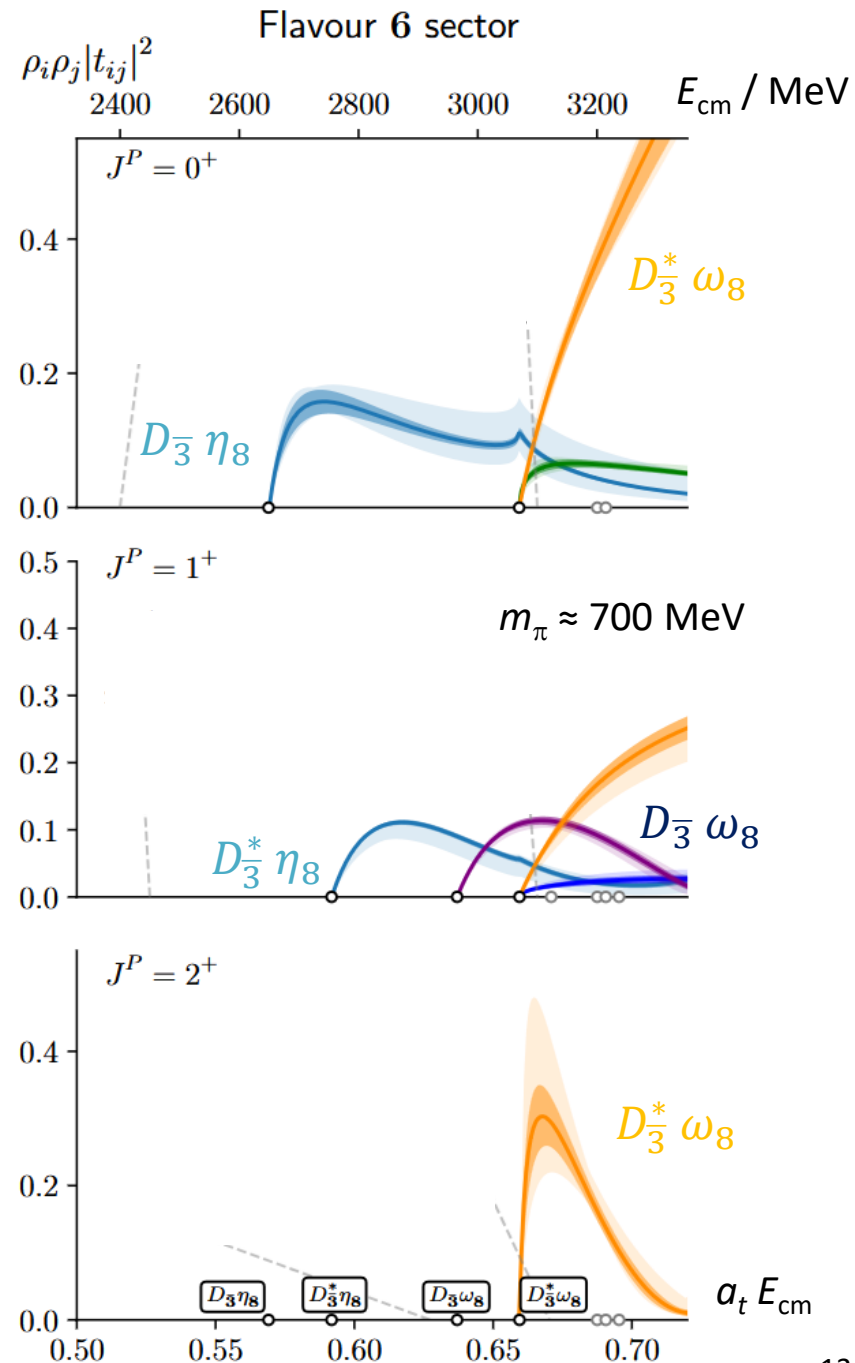
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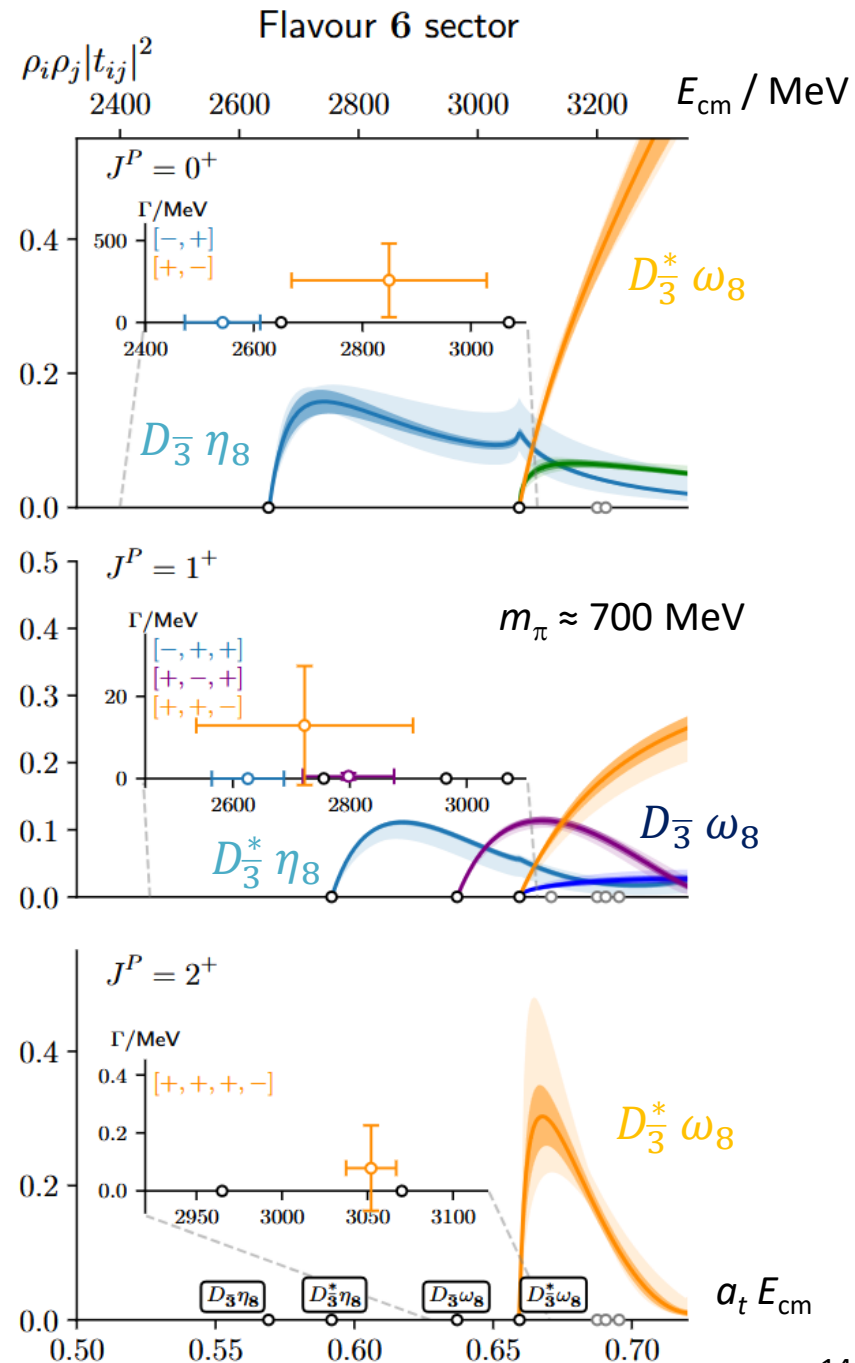
[Daniel Yeo, Thomas, Wilson
(HadSpec), 2604.19553]



Coupled-channel scattering with $SU(3)_F$ sym

In flavour 6: pole on 'hidden' sheet associated with each S-wave channel ($0^+, 1^+, 2^+$; not $3^+, 4^+$) below the corresponding threshold.

[Daniel Yeo, Thomas, Wilson
(HadSpec), 2604.19553]

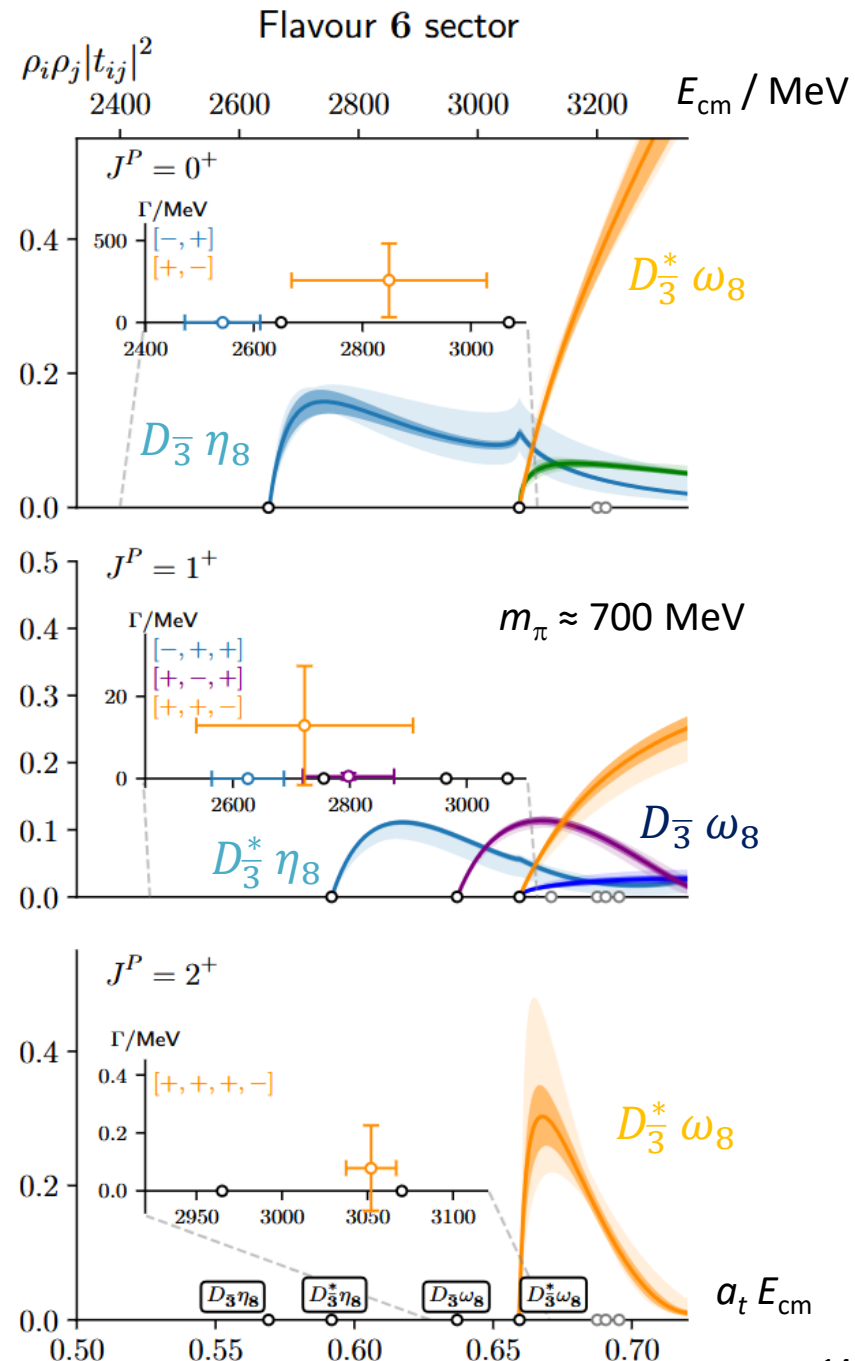


Coupled-channel scattering with $SU(3)_F$ sym

In flavour **6**: pole on ‘hidden’ sheet associated with each S-wave channel ($0^+, 1^+, 2^+$; not $3^+, 4^+$) below the corresponding threshold.

In $\overline{15}$ at most slight repulsion or slight attraction, no poles consistently found.

[Daniel Yeo, Thomas, Wilson
(HadSpec), 2604.19553]



Coupled-channel scattering with $SU(3)_F$ sym

[2604.19553]

In flavour **6**: a pole associated with each S -wave channel.

J^P	$m \pm \frac{i}{2}\Gamma / \text{ MeV}$	$SU(3)_f$	$^{2S+1}\ell_J$
0^+	2540(70)	$D_{\bar{\mathbf{3}}}\eta_8$	1S_0
0^+	$2850(180) \pm \frac{i}{2}250(230)$	$D_{\bar{\mathbf{3}}}^*\omega_8$	1S_0
1^+	2630(60)	$D_{\bar{\mathbf{3}}}^*\eta_8$	3S_1
1^+	$2800(80) \pm \frac{i}{2}0.5(0.8)$	$D_{\bar{\mathbf{3}}}\omega_8$	3S_1
1^+	$2720(190) \pm \frac{i}{2}13(14)$	$D_{\bar{\mathbf{3}}}^*\omega_8$	3S_1
2^+	$3052(15) \pm \frac{i}{2}0.08(15)$	$D_{\bar{\mathbf{3}}}^*\omega_8$	5S_2

$m_\pi \approx 700 \text{ MeV}$

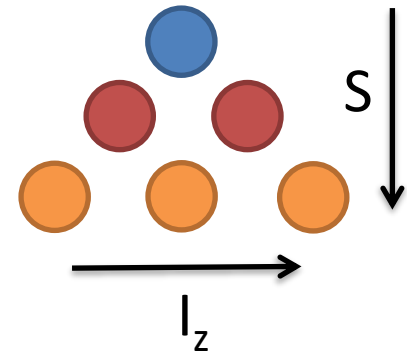
Coupled-channel scattering with $SU(3)_F$ sym

[2604.19553]

In flavour **6**: a pole associated with each S-wave channel.

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0^+	2540(70)	$D_{\bar{\mathbf{3}}}\eta_8$	1S_0	$T_{cs0}^*: D\bar{K}$	$D_0^{*'}: D\pi - D\eta - D_s\bar{K} - D\eta'$	$T_{c\bar{s}0}^*: D_s\pi - DK$
0^+	$2850(180) \pm \frac{i}{2}250(230)$	$D_{\bar{\mathbf{3}}}\omega_8$	1S_0	$T_{cs0}'^*: D^*\bar{K}^*$	$D_0^{*''}: D^*\rho - D^*\omega - D_s^*\bar{K}^* - D^*\phi$	$T_{c\bar{s}0}'^*: D_s^*\rho - D^*K^*$
1^+	2630(60)	$D_{\bar{\mathbf{3}}}^*\eta_8$	3S_1	$T_{cs1}: D^*\bar{K}$	$D_1^{*'}: D^*\pi - D^*\eta - D_s^*\bar{K} - D^*\eta'$	$T_{c\bar{s}1}: D_s^*\pi - D^*K$
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2^+	$3052(15) \pm \frac{i}{2}0.08(15)$	$D_{\bar{\mathbf{3}}}^*\omega_8$	5S_2	$T_{cs2}^*: D^*\bar{K}^*$	$D_2^{*'}: D^*\rho - D^*\omega - D_s^*\bar{K}^* - D^*\phi$	$T_{c\bar{s}2}^*: D_s^*\rho - D^*K^*$
$m_\pi \approx 700 \text{ MeV}$				$cs\bar{l}\bar{l} \text{ (6)}$	$cl\bar{l}\bar{l} \text{ (6 + } \bar{\mathbf{3}} + \bar{\mathbf{15}})$	$cl\bar{s}\bar{l} \text{ (6 + } \bar{\mathbf{15}})$

Each $SU(3)$ **6** pole has 3 different
(strangeness, isospin) components: 1 + 2 + 3 states



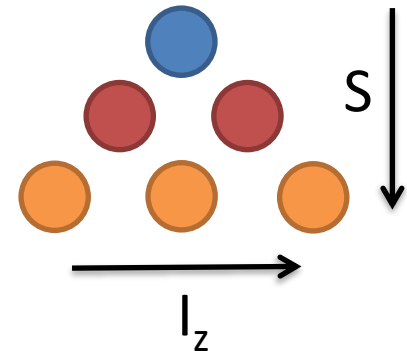
Coupled-channel scattering with $SU(3)_F$ sym

[2604.19553]

In flavour **6**: a pole associated with each S-wave channel.

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Each $SU(3)$ **6** pole has 3 different
(strangeness, isospin) components: 1 + 2 + 3 states
How do the poles evolve as lower light-quark mass?



Coupled-channel scattering with $SU(3)_F$ sym

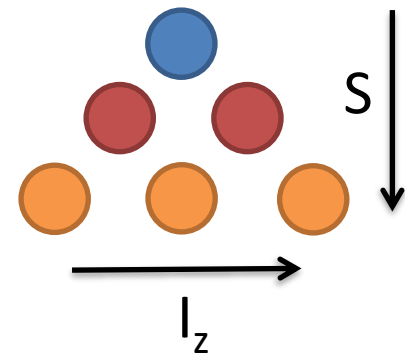
[2604.19553]

In flavour **6**: a pole associated with each S-wave channel.

Studied in previous lattice calculations

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$m_\pi \approx 700 \text{ MeV}$				$cs\bar{l}\bar{l} \text{ (6)}$	$cl\bar{l}\bar{l} \text{ (6 + } \bar{3} + \bar{15})$	$cl\bar{s}\bar{l} \text{ (6 + } \bar{15})$

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(strangeness, isospin) components: 1 + 2 + 3 states
How do the poles evolve as lower light-quark mass?



Coupled-channel scattering with $SU(3)_F$ sym

[2604.19553]

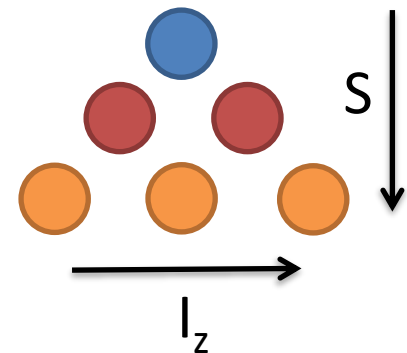
In flavour **6**: a pole associated with each S-wave channel.

Studied in previous lattice calculations

J^P	$m \pm \frac{i}{2}\Gamma / \text{MeV}$	$SU(3)_f$	$^{2S+1}\ell_J$	$(-1, 0)$	$(0, \frac{1}{2})$	$(1, 1)$
0^+	2540(70)	$D_{\bar{3}}\eta_8$	1S_0	$T_{cs0}^*: D\bar{K}$	$D_0^{*'}: D\pi - D\eta - D_s\bar{K} - D\eta'$	$T_{c\bar{s}0}^*: D_s\pi - DK$
0^+	$2850(180) \pm \frac{i}{2}250(230)$	$D_{\bar{3}}\omega_8$	1S_0	$T_{cs0}^{*'}: D^*\bar{K}^*$	$D_0^{*''}: D^*\rho - D^*\omega - D_s^*\bar{K}^* - D^*\phi$	$T_{c\bar{s}0}^{*'}: D_s^*\rho - D^*K^*$
1^+	2630(60)	$D_{\bar{3}}^*\eta_8$	3S_1	$T_{cs1}: D^*\bar{K}$	$D_1^{*''}: D^*\pi - D^*\eta - D_s^*\bar{K} - D^*\eta'$	$T_{c\bar{s}1}: D_s^*\pi - D^*K$
1^+	$2800(80) \pm \frac{i}{2}0.5(0.8)$	$D_{\bar{3}}^*\omega_8$	3S_1	$T_{cs1}': D\bar{K}^*$	$D_1^{*'''}: D\rho - D\omega - D_s\bar{K}^* - D\phi$	$T_{c\bar{s}1}': D_s\rho - DK^*$
1^+	$2720(190) \pm \frac{i}{2}13(14)$	$D_{\bar{3}}^*\omega_8$	3S_1	$T_{cs1}'': D^*\bar{K}^*$	$D_1^{*''''}: D^*\rho - D^*\omega - D_s^*\bar{K}^* - D^*\phi$	$T_{c\bar{s}1}'': D_s^*\rho - D^*K^*$
2^+	$3052(15) \pm \frac{i}{2}0.08(15)$	$D_{\bar{3}}^*\omega_8$	5S_2	$T_{cs2}^*: D^*\bar{K}^*$	$D_2^{*'}: D^*\rho - D^*\omega - D_s^*\bar{K}^* - D^*\phi$	$T_{c\bar{s}2}^*: D_s^*\rho - D^*K^*$
$m_\pi \approx 700 \text{ MeV}$				$cs\bar{l}\bar{l} \text{ (6)}$	$cl\bar{l}\bar{l} \text{ (6 + } \bar{3} + \bar{15})$	$cl\bar{s}\bar{l} \text{ (6 + } \bar{15})$

$T_{cs0}^*(2870)$ (isospin 0) and $T_{c\bar{s}0}^*(2900)$ (isospin 1)?
Expect 1^+ , 2^+ partners.

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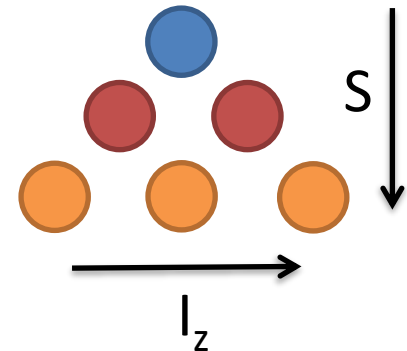
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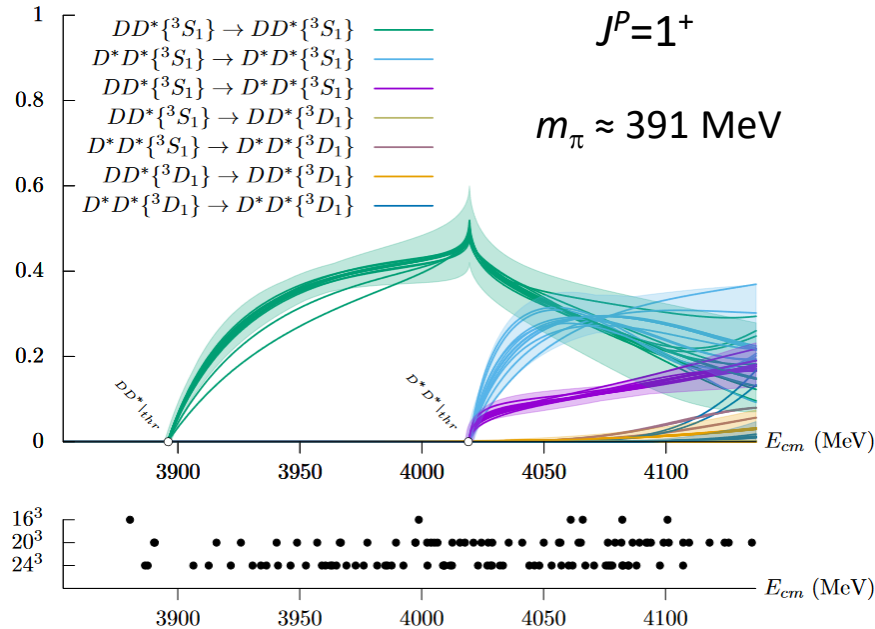
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T_{cc} and T'_{cc} in coupled DD^* , D^*D^* ($I=0$) scattering

$\sim |\text{amp}|^2$

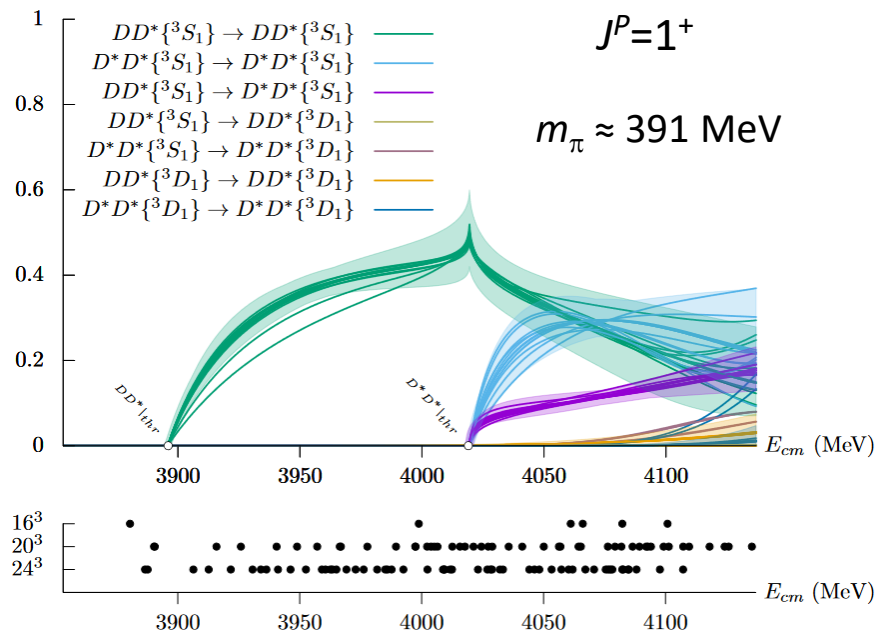
Use 109 energy levels



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

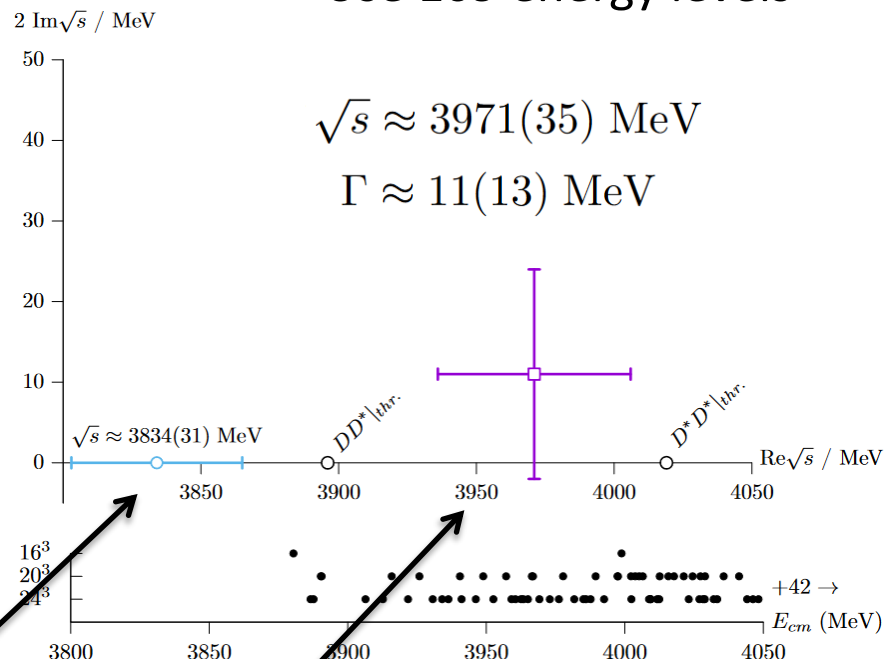
T_{cc} and T'_{cc} in coupled DD^* , D^*D^* ($l=0$) scattering

$\sim |\text{amp}|^2$



Virtual bound state (T_{cc})
below DD^* threshold
 $\sqrt{s} \approx 3834(31)$ MeV

Use 109 energy levels

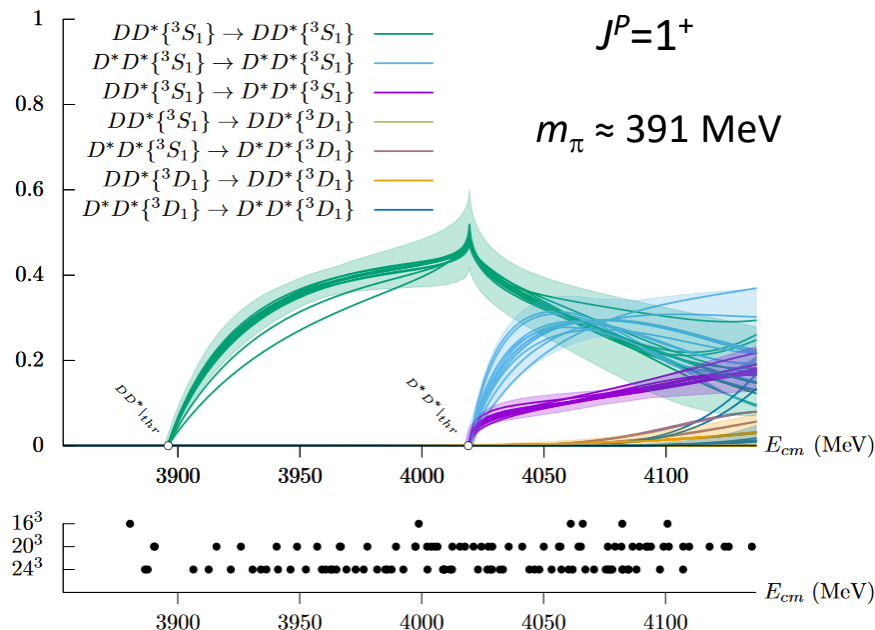


Resonance (T'_{cc}) pole on (+, -)
sheet below D^*D^* threshold
– prediction of new state
(might be seen in DD , $DD\pi$ because
low mom. π/γ can escape detection)

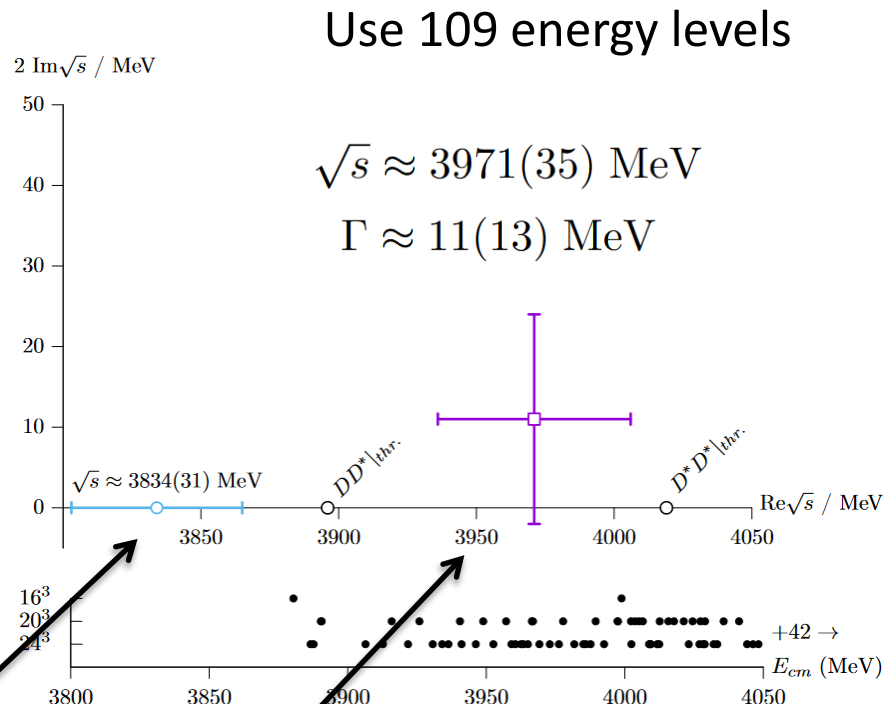
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T_{cc} and T'_{cc} in coupled DD^* , D^*D^* ($l=0$) scattering

$\sim |\text{amp}|^2$



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



Resonance (T'_{cc}) pole on (+, -)
sheet below D^*D^* threshold

Effect of left-hand cut from π exchange (≈ 18 MeV below DD^* thresh)?
[see e.g. 2607.19009 and refs therein]
Dependence on m_π ?

Summary

- Some recent lattice QCD calculations of charm(onium) mesons:
 - Scalar (0^{++}) and tensor (2^{++}) charmonia – simple picture
 - Near-threshold $D\bar{D}$ interactions are weak
 - Exotic-flavour charm mesons, c.f. $T_{c\bar{s}0}^*(2870)$, $T_{c\bar{s}0}^*(2900)$
 - T_{cc} and T'_{cc} in DD^* , D^*D^*
- Many other calculations!
- Outlook:
 - Other channels and vary light-quark mass
 - Possible effects of left-hand cut
 - Three (or more!?) hadron scattering
 - Probe structure, e.g. transitions and form factors

