Open charm spectroscopy from lattice QCD

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hadspec

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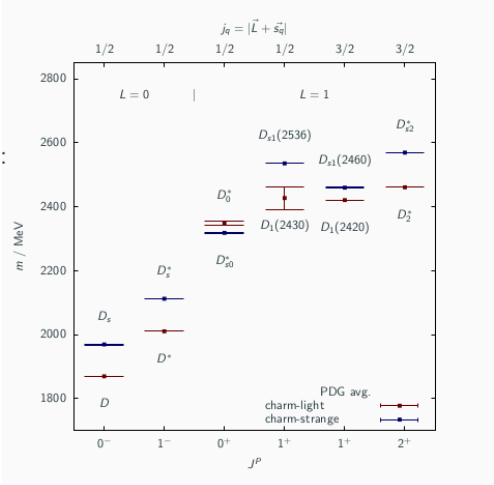
Open charm - a rich arena with puzzles & challenges

- Excited and hybrid mesons in D and D_s spectra.
- The D_0^* and the D_{s0}^* - a lattice perspective
  - D_0^* lightest scalar charm-light resonance: $m_{D_0^*} \sim 2343$MeV, broad enhancement.
  - PDG average: D_{s0}^* lies below D_0^* - what can lattice say about this puzzling hierarchy?



An active field

Selection of other lattice QCD studies of $D\pi$ and DK scattering

- Mohler et al. PRD87 034501 (2013), 1208.4059
- Liu et al. PRD87 014508 (2013), 1208.4535
- Mohler et al. PRL 111, 222001 (2013), 1308.3175
- Lang et al. PRD90, 034510 (2014), 1403.8103
- Bali et al. PRD96, 074501 (2017), 1706.01247
- Alexandrou et al PRD101 034502 (2020), 1911.08435
- Gregory et al. 2106.15391

Other work

- Martínez Torres et al. JHEP 05 (2015) 153, 1412.1706
- Albaladejo et al. PLB767, 465 (2017), 1610.06727
- Du et al. PRD98 094018 (2018), 1712.07957
- Guo et al. PRD98 014510 (2018), 1801.10122
- Guo et al. EPJ C79, 13 (2019), 1811.05585

Lattice calculations

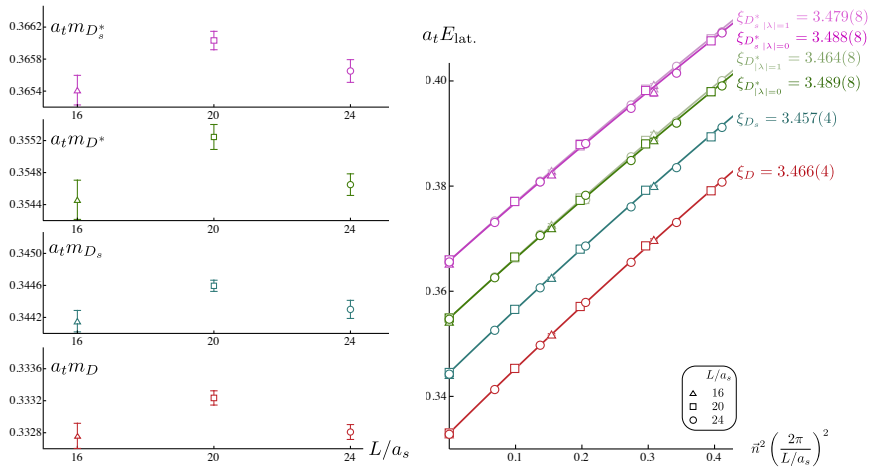
- Earlier lattice study of D_0^* in $D\pi$ scattering found a resonance close to the PDG average [Mohler et al, 1208.4059]
- HadSpec objective: determine pole positions, understand mass ordering and light-quark mass dependence of the two states. This talk draws results from
  - D and D_s spectroscopy [1610.01073]
  - $D_0^*(2300)$ in $D\pi \to D\pi$ at $m_\pi = 239, 391$ MeV [2102.04973]
  - $D_{s0}^*(2317)$ in $DK \to DK$ at $m_\pi = 239, 391$ MeV [2008.06432]

- Anisotropic lattice: $a_s/a_t \sim 3.5$, $a_s \sim 0.12$ fm on a range of volumes.
- $N_f = 2 + 1$, Wilson (clover) fermions with 2 pion masses and $a_t^{-1}(m_\Omega)$.
- Large operator bases including: fermion bilinears $\bar{\Psi}\Gamma\Psi$ and meson-meson operators e.g. DK using optimised D and K operators; projected to irreps of the lattice

a_s	~ 0.11 fm
$a_t^{-1}(m_\Omega)$	~ 5.7 GeV
m_π	239, 391 MeV
$m_\pi L$	4-6
N_f	2+1

Cheung, Thomas, Wilson, Moir, Peardon, SR JHEP 02 (2021) 100 [2008.06432]
Gayer, Lang, SR, Tims, Thomas. Wilson JHEP 07 (2021) 123 [2102.04973]

Dispersion relations - sanity checks!



- Parameters (m_c, ξ) tuned once for η_c.
- Agreement across volumes and for pseudoscalar and vectors in D and D_s.

The method (briefly)

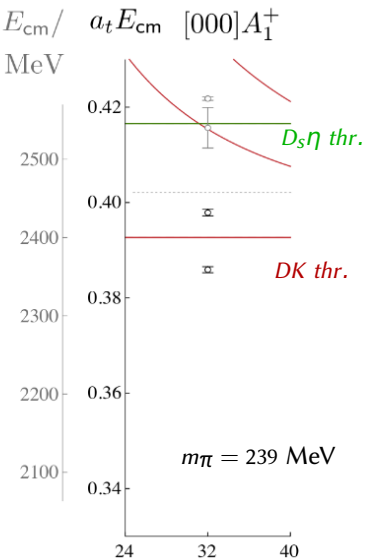
- Using distillation - compute correlation functions

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

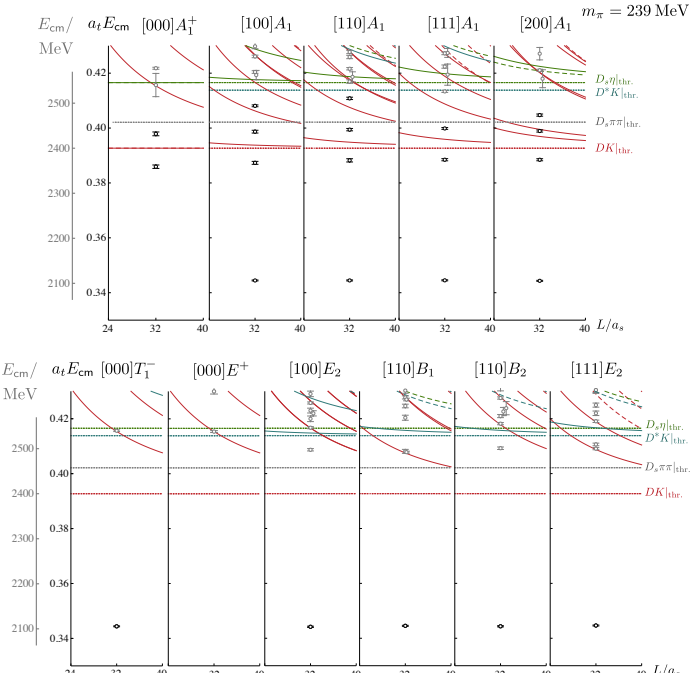
with a large basis of operators including relevant structures

$$\bar{\Psi}\Gamma D \ldots \Psi; \quad \sum_{\vec{p}_1,\vec{p}_2} C\left(\vec{P},\vec{p}_1,\vec{p}_2\right)\Omega_{M_1}(\vec{p}_1)\Omega_{M_2}(\vec{p}_2)$$

- Solve as a GEVP $C_{ij}(t)v_j^{(n)} = \lambda_n(t,t_0)C_{ij}(t_0)v_j^{(n)}$ to yield E_n via fits to sums of exponentials.



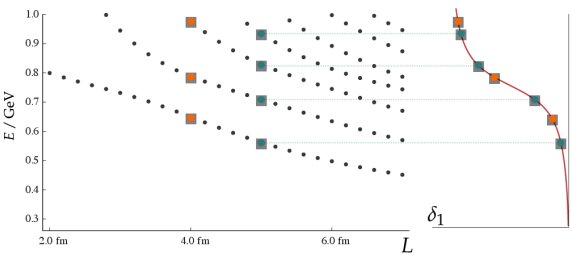
The finite energy levels - example from DK I=0



Energy spectrum → infinite volume amplitudes

- Lüscher method (and extensions) relate energy levels in finite volume to scattering information (t-matrix) in infinite volume.
  $det\,[1 + i\rho(s) \cdot \mathbf{t}(s) \cdot (1 + i\mathcal{M}(s, L))] = 0$
- Elastic scattering → one-to-one map
  $E_{cm} \longleftrightarrow t(E_{cm})$

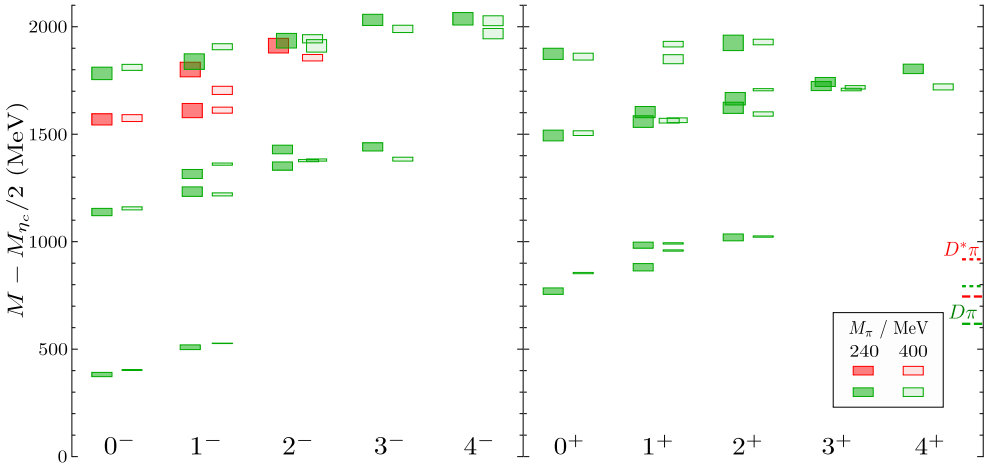
- Parametric form of **t**-matrix undetermined by Lüscher condition but unitarity, causality, analyticity provide constraints.
- Use a range of parameterisations of t: K-matrix, effective range, ...
- Analytically continue **t** in complex (E_{cm}) plane and look for poles.



The D and Ds Spectrum

Precision spectroscopy of single-hadron states including hybrid mesons

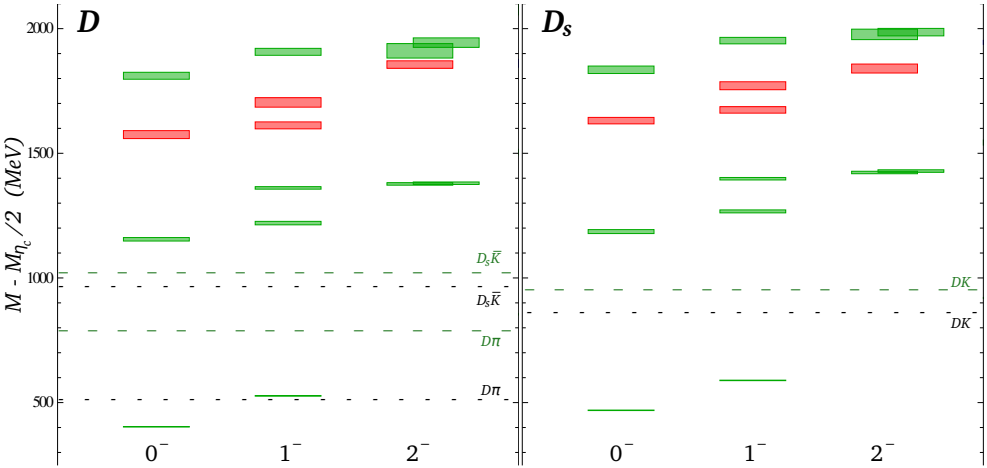
Open charm spectrum (D meson) for $J \leq 4$



- Single hadron operators only, including hybrid-like operators.

JHEP12 (2016) 089

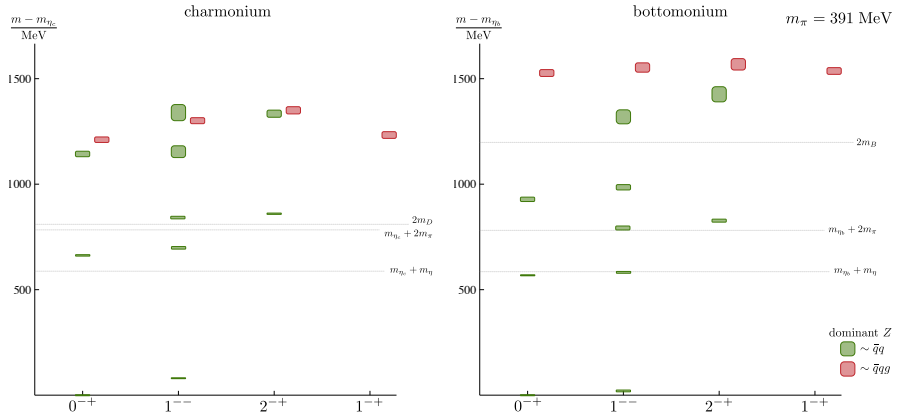
An open-charm hybrid supermultiplet



- This is $m_\pi \sim 391$ MeV. Similar pattern for $m_\pi \sim 236$ MeV.

JHEP05 (2013) 021

Similar patterns in quarkonia

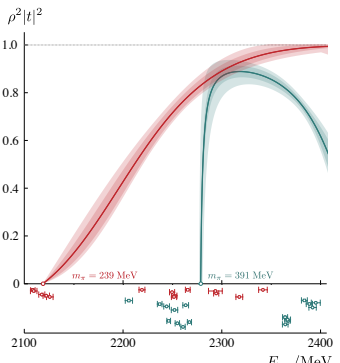


Lightest hybrid supermultiplets[*HadSpec*:2008.02656]: same pattern and scale in -onia and light[*HadSpec*:1106.5515] sectors.

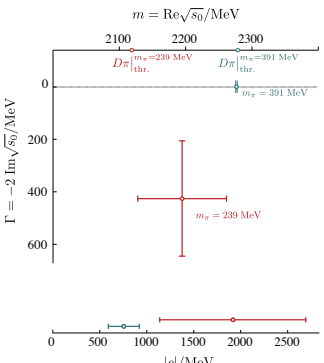
$D\pi$ scattering & the D_0^*

$D\pi$ (I=1/2) and the D_0^*

- First HadSpec study of $D\pi \to D\pi$ at $m_\pi = 391$ MeV: shallow bound state ($\sim 2 \pm 1$ MeV below threshold)
- At $m_\pi = 239$ MeV: pole migrates into complex plane ($\sim 77 \pm 64$ MeV above threshold)

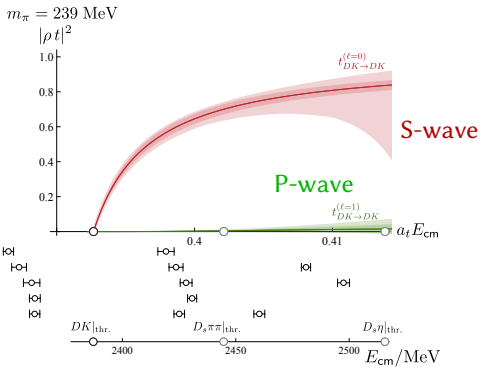


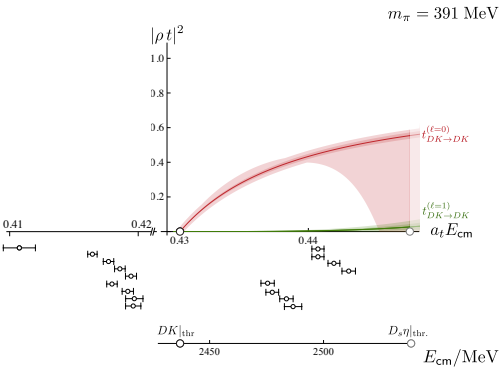
- Find D_0^* resonance pole, $m = (2194 \pm 64)$ MeV, $\Gamma = (425 \pm 224)$ MeV.
  Mass below reported experimental value (despite unphysical light quarks)
- Strong coupling of poles to $D\pi$ channel in both cases.



DK scattering and the D_{s0}^{*}

DK (I=0) amplitudes

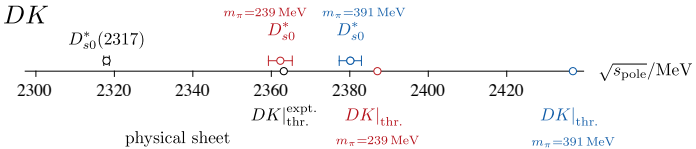




Elastic DK scattering in S and P-wave
Sharp turn-on in S-wave at threshold

From 22 energy levels ($m_\pi = 239$ MeV) &
34 energy levels ($m_\pi = 391$ MeV)

DK I=0 S-wave poles



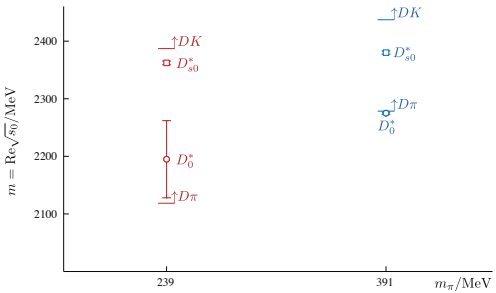
Also find a deeply bound state in P-wave, D_s^*, but not strongly influencing DK scattering at these energies

Bound-state pole strongly coupled to S wave DK
$\Delta E = 25(3)$ MeV for $m_\pi \sim 239$ MeV. $Z \lesssim 0.11$
$\Delta E = 57(3)$ MeV for $m_\pi \sim 391$ MeV. $Z \sim 0.13(6)$
c.f. experiment $\Delta E \sim 45$ MeV (decays to $D_s\pi^0$)

Weinberg compositeness, $0 \leq Z \leq 1$ assuming binding sufficiently weak

Summary: the $D_0^* - D_{s0}^*$ mass hierarchy

- mapped out the energy-dependence of scattering amplitudes using lattice QCD
- Isospin 0, DK:
  S-wave bound state, $D_{s0}^*(2317)$
- Isospin 1/2, $D\pi$:
  S-wave bound state/resonance,
  $D_0^*(2300)$
- Locations of poles follow expectations from SU(3) symmetry. Puzzling D_0^* heavier than D_{s0}^* not reproduced by this study.



- Exotic flavour isospin 0 $D\bar{K}$: S-wave virtual bound state?
- Further investigation of light quark mass dependence?
- Higher up in energy, inelastic (3-hadron) scattering effects?

Summary

- QCD describes the properties of observed matter in terms of fundamental variables and their interactions.
- Significant progress in lattice calculations in the last 10 years although many open questions and unsolved problems.
- Extensive analyses by HadSpec of excited and exotic spectroscopy and scattering in light, heavy-light and heavy quark regimes.
- Just a snapshop of activity ... ongoing work in different quark mass regimes, pion masses and including three-particle thresholds from HadSpec.

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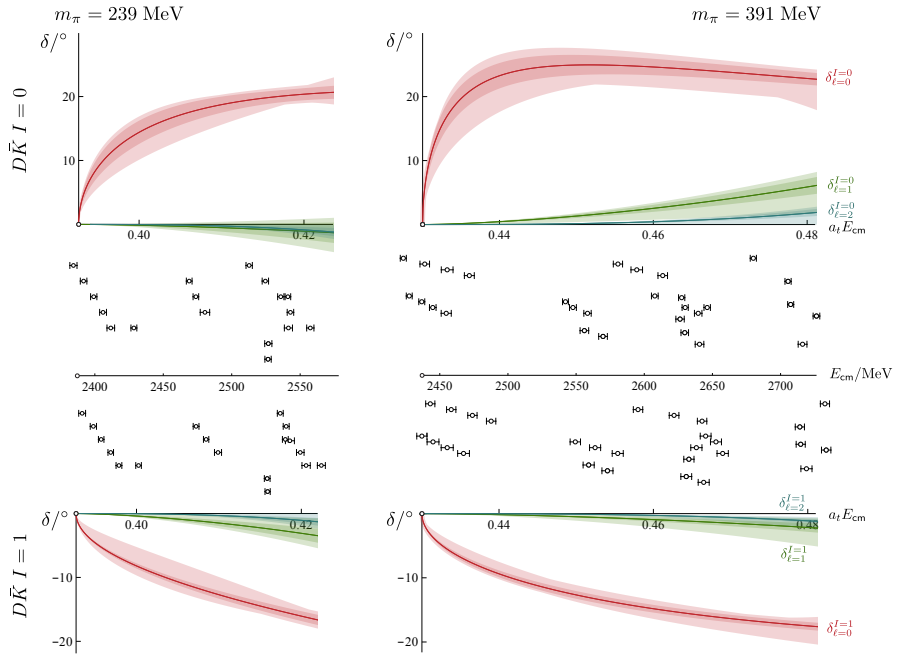
Thanks for listening!

$D\bar{K}$ (I=0,1) ... exotic flavour ($\bar{l}\bar{l}cs$)



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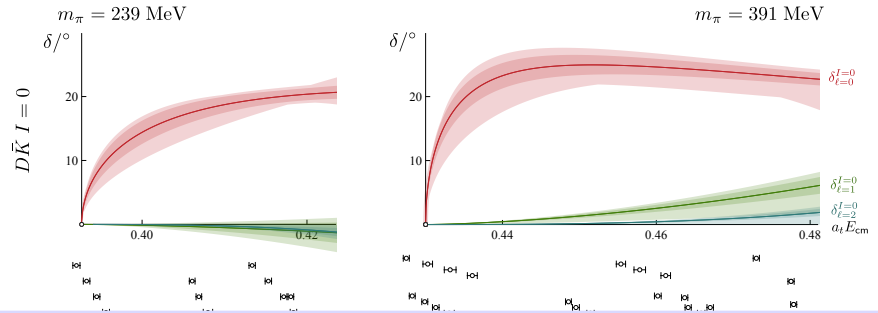

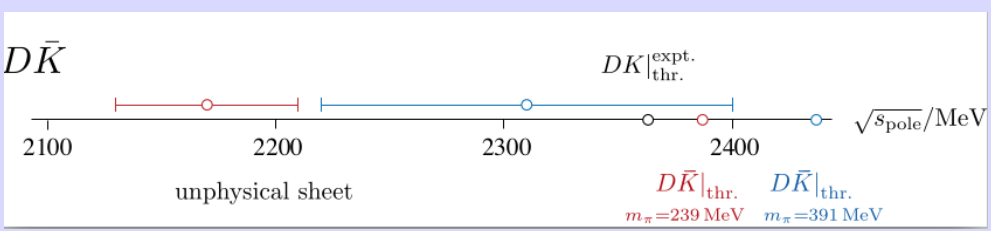

Suggestion of virtual bound-state pole (exotic flavour)