Charm mesons on the lattice

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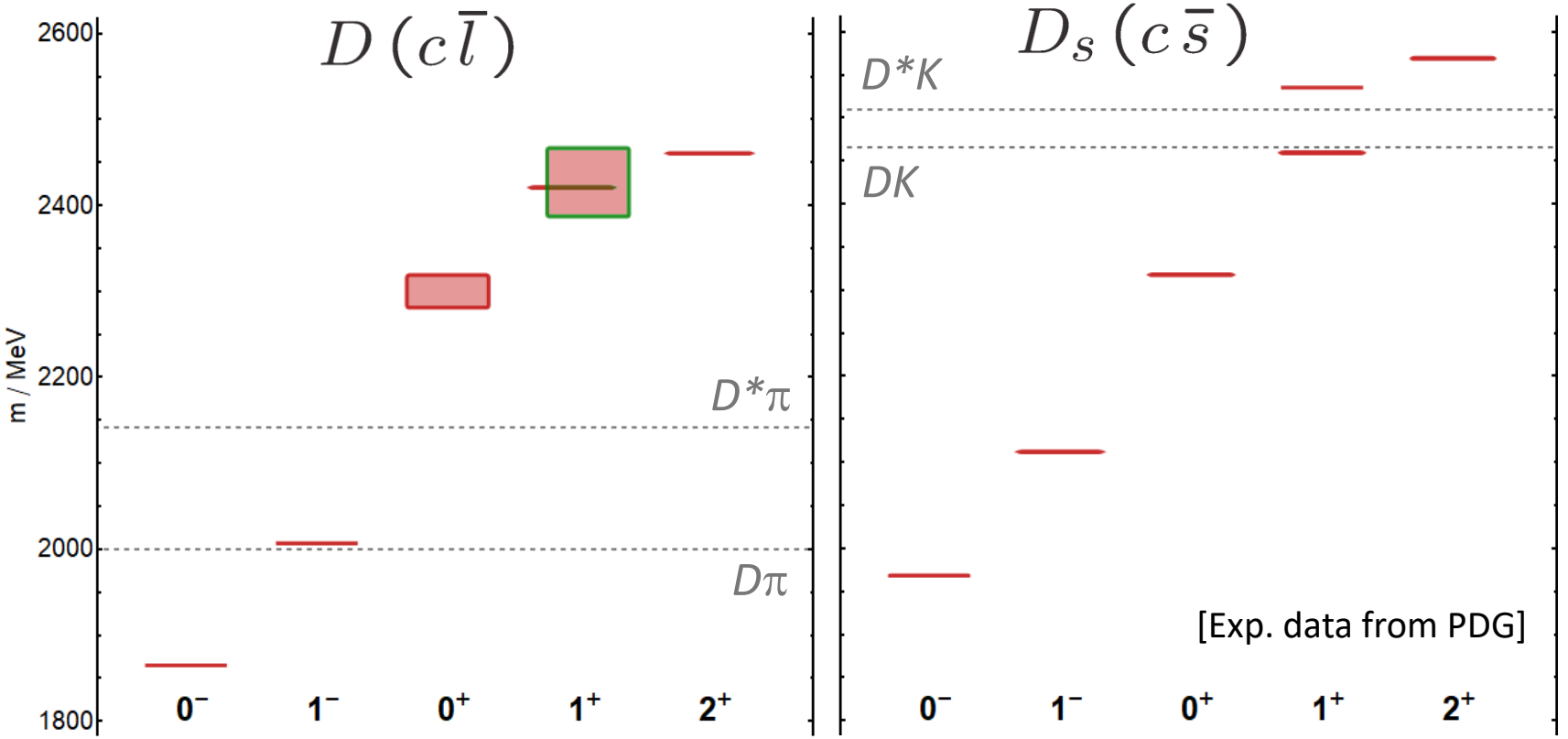
31 May – 4 June 2021

UNIVERSITY OF CAMBRIDGE

hadspec

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



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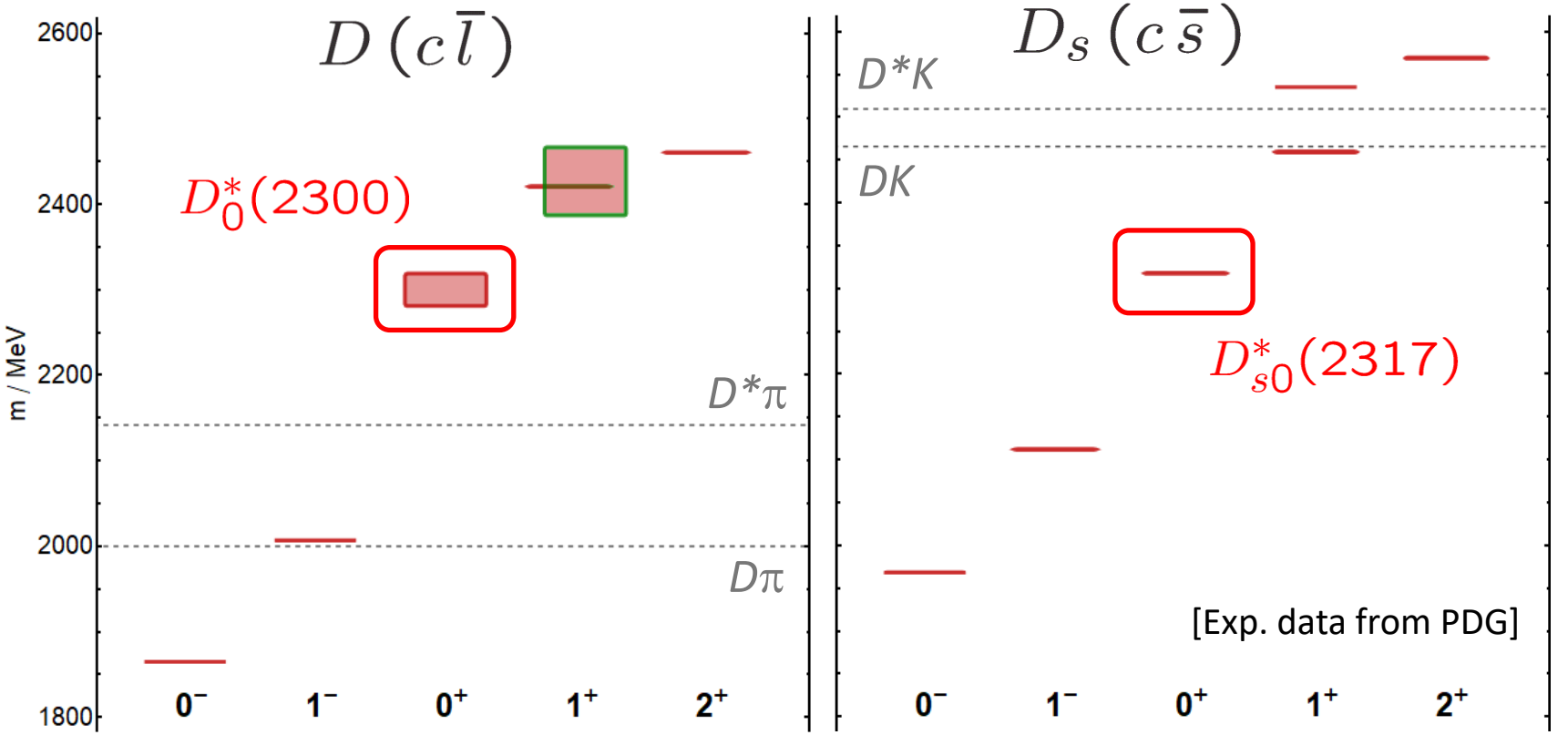

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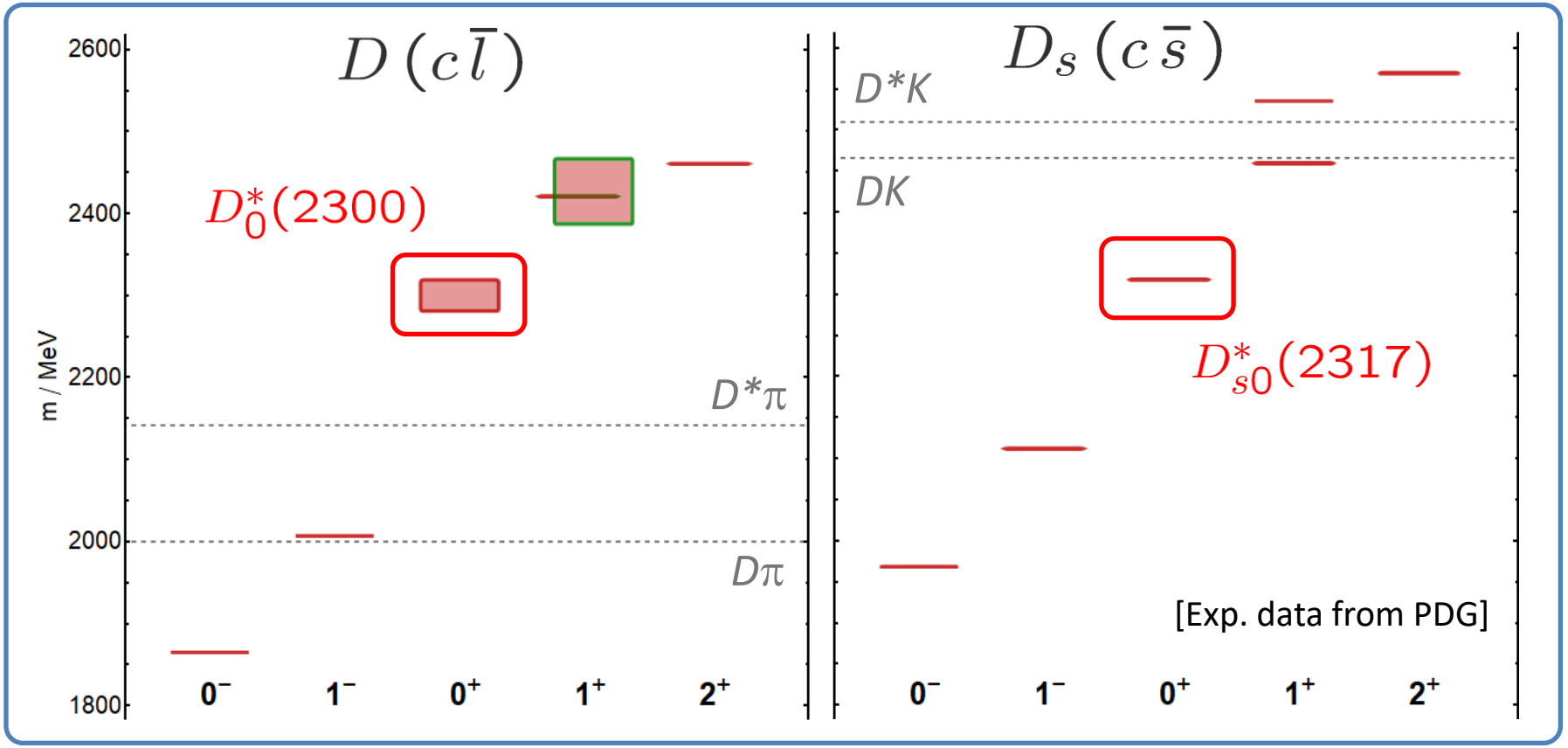

Most hadrons appear as resonances in scattering of lighter hadrons (poles in scattering amplitudes for complex E_{cm})

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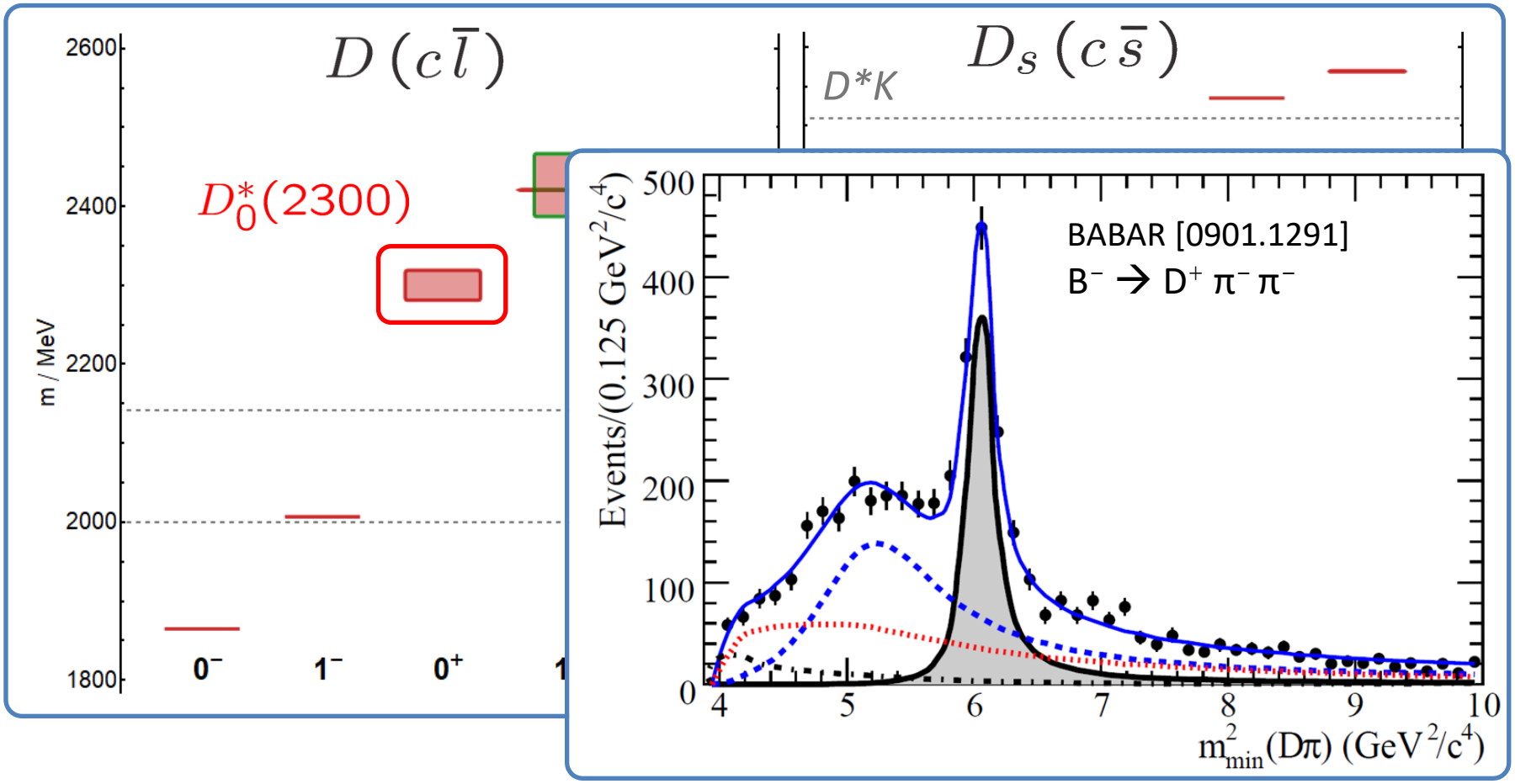

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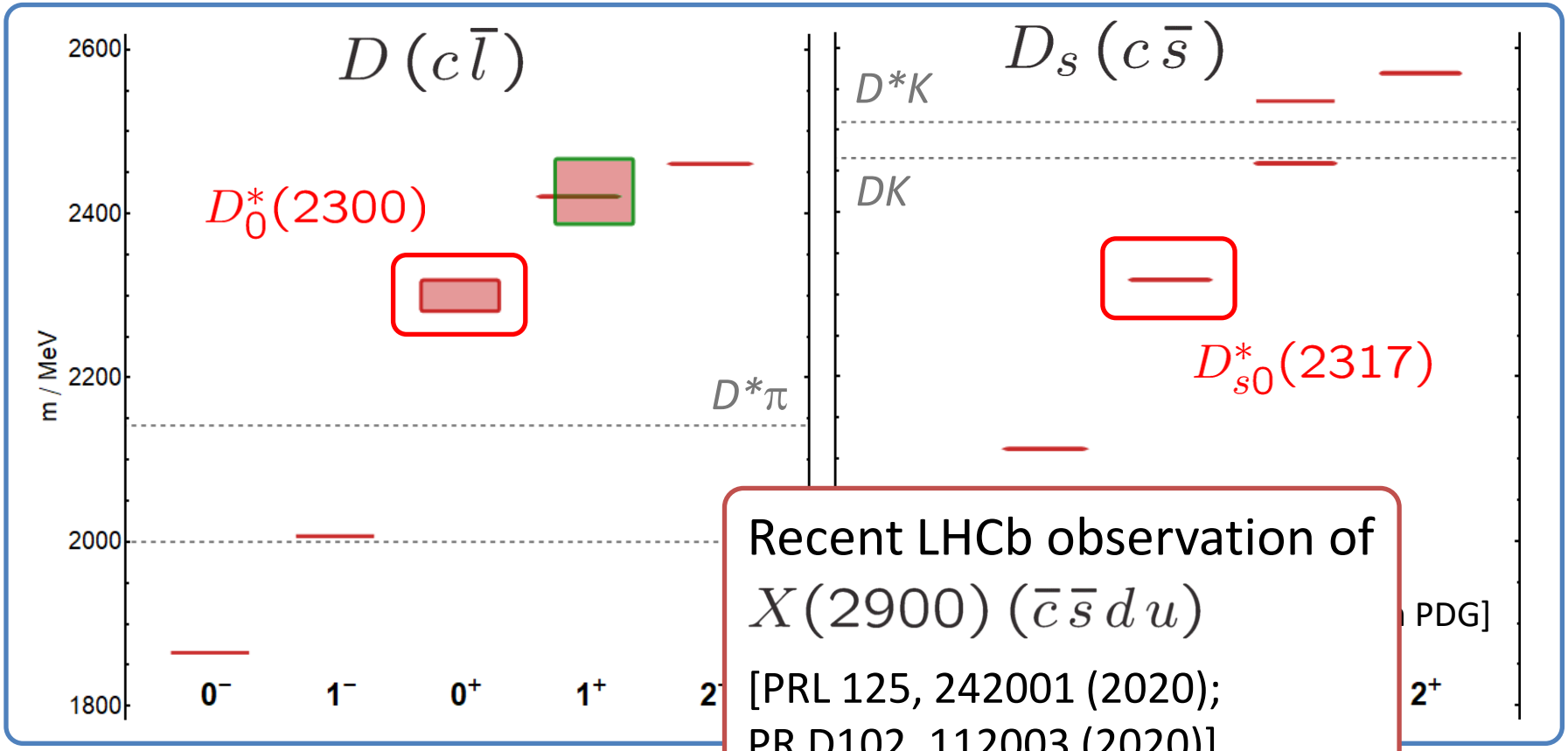

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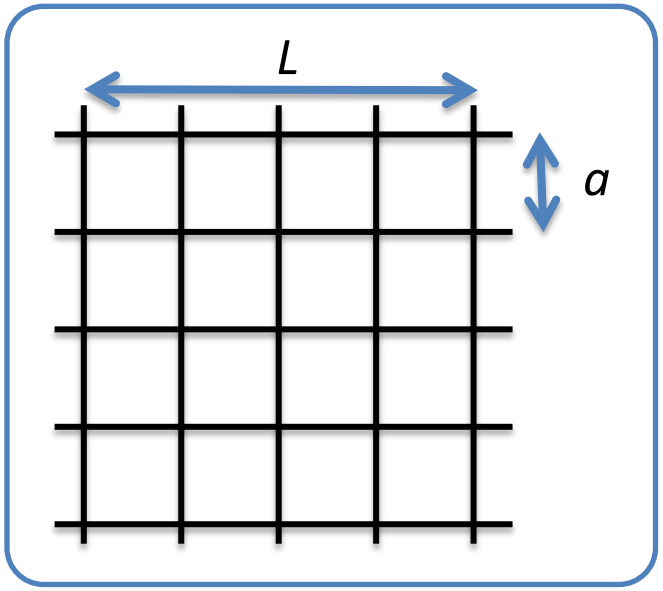
Lattice QCD spectroscopy

Systematically-improvable
first-principles calculations



- **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)

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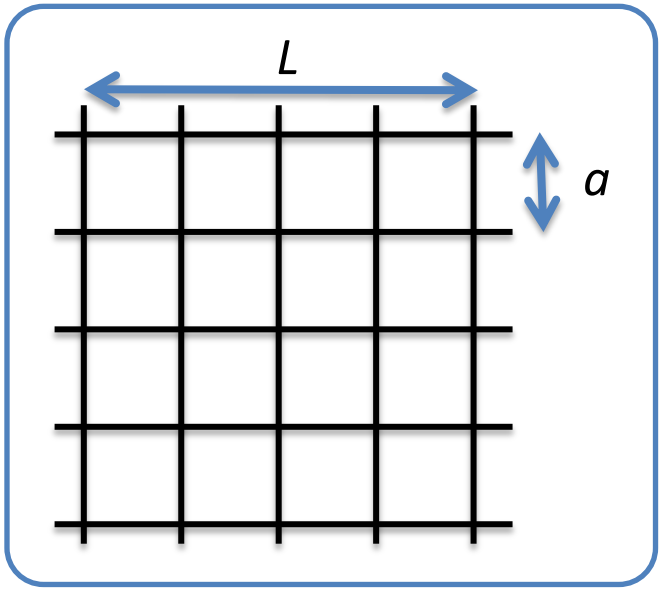

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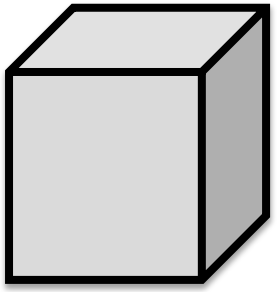
Finite-volume energy eigenstates from:

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

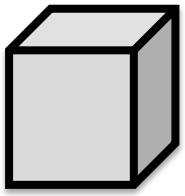
Interpolating operators with appropriate structures



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**.



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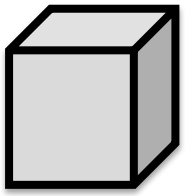

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Elastic scattering: one-to-one mapping $E_{cm} \leftrightarrow t(E_{cm})$

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

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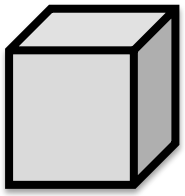

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Coupled channels: under-constrained problem
(each E_{cm} constrains *t*-matrix at that E_{cm})
Param. $t(E_{cm})$ using various *K*-matrix forms, effective range, …

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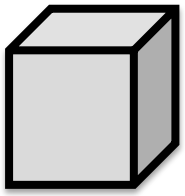

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(each E_{cm} constrains *t*-matrix at that E_{cm})
Param. $t(E_{cm})$ using various *K*-matrix forms, effective range, …

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

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

Charm mesons on the lattice

This talk: some recent lattice QCD calculations of

- *S*-wave $D\,K$ scattering and the $D_{s0}^*(2317)$
- *S*-wave $D\,\pi$ scattering and the $D_0^*(2300)$

with $m_\pi \approx 239$ MeV and 391 MeV

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with $m_\pi \approx 239$ MeV and 391 MeV

Some other LQCD work on $D\,K$ 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]

Also: Martínez Torres *et al* [JHEP 05 (2015) 153, 1412.1706]; Albaladejo *et al* [PL B767, 465 (2017), 1610.06727]; Guo et al [*PR D*98 014510 (2018), 1801.10122]; Du *et al* [PR D98, 094018 (2018), 1712.7957]; Guo *et al* [EPJ C79, 13 (2019), 1811.05585]

DK (isospin=0)

[Cheung, CT, Wilson, Moir, Peardon, Ryan (HadSpec), JHEP 02 (2021) 100, arXiv:2008.06432]

Use many different fermion-bilinear

$$\sim \bar{\psi}\Gamma D \ldots \psi$$

and *DK*, ... operators

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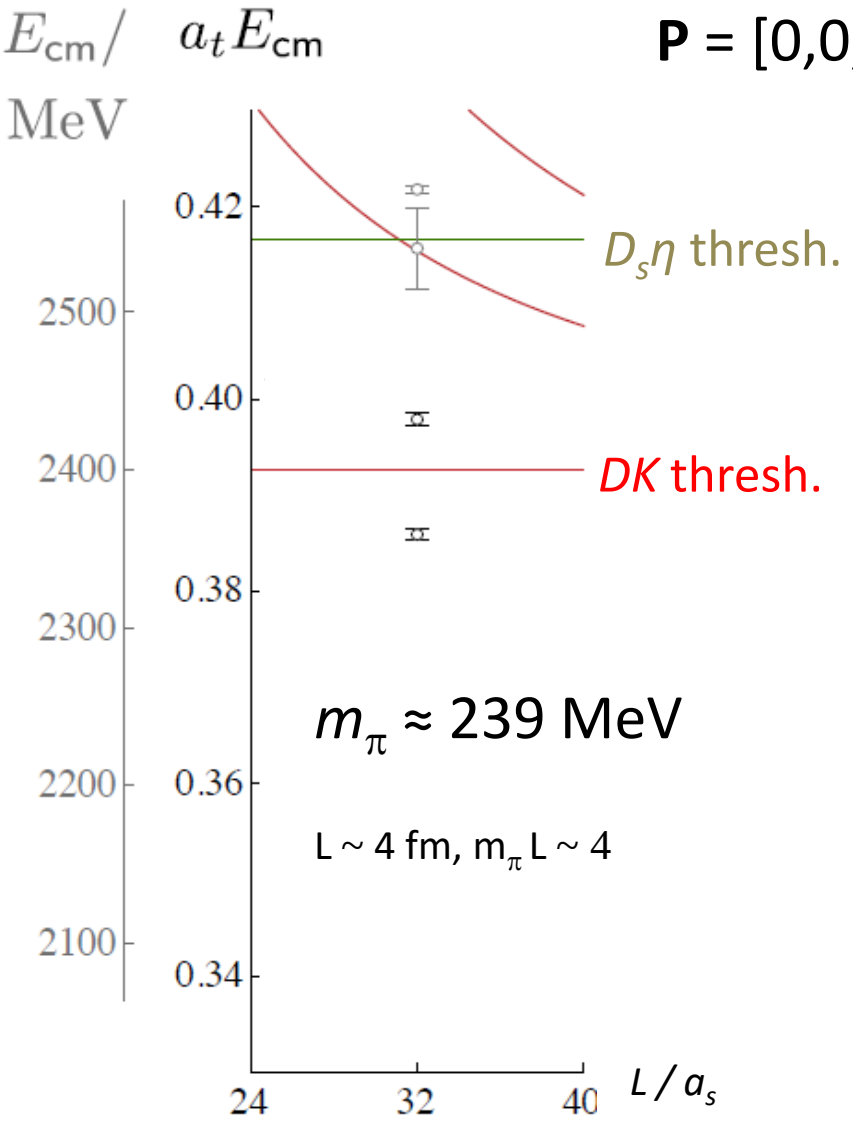
P = [0,0,0] $J^P = 0^+, (4^+, \ldots)$



$m_\pi \approx 239$ MeV

L ~ 4 fm, m_π L ~ 4

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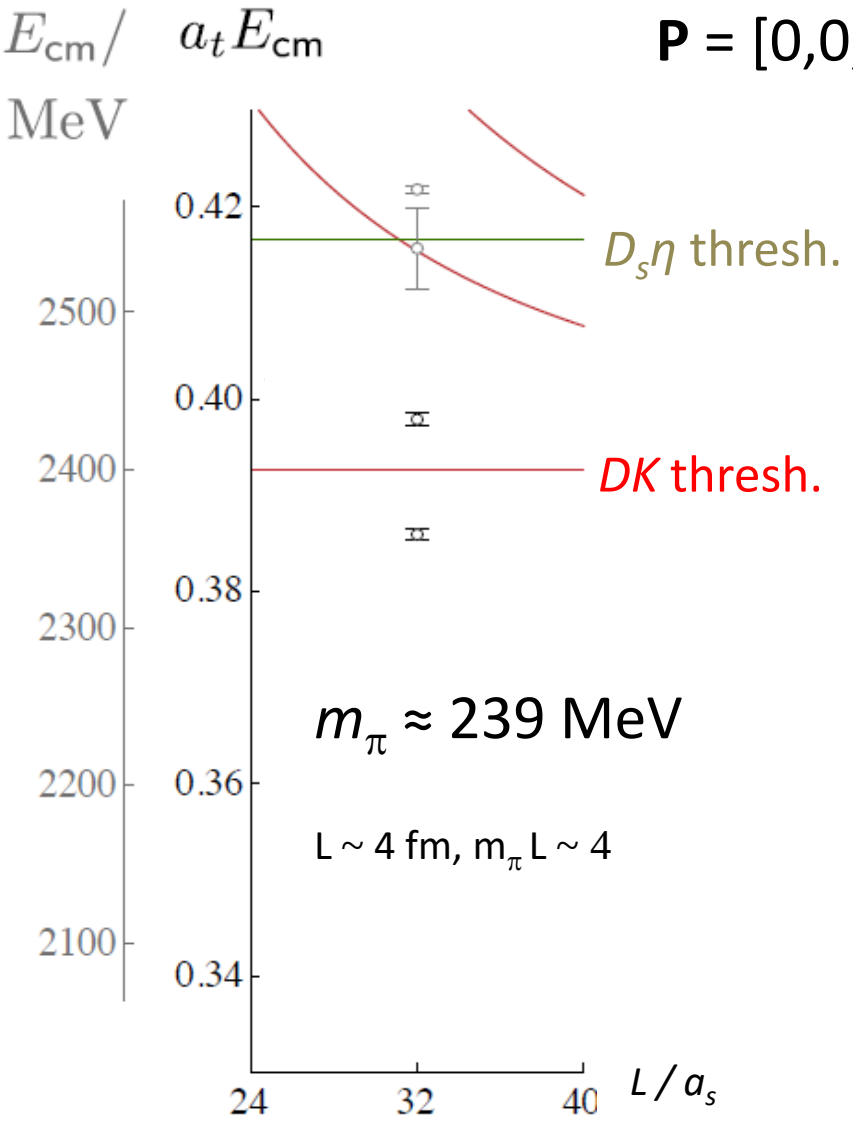
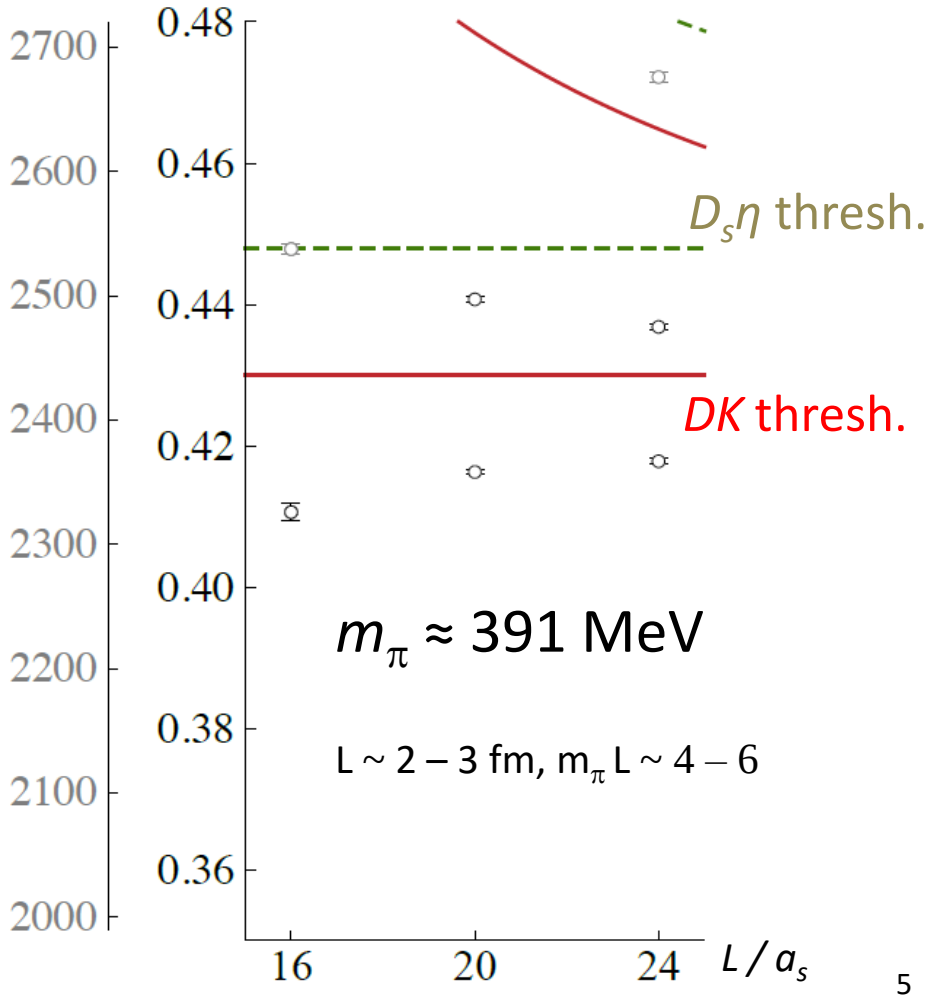
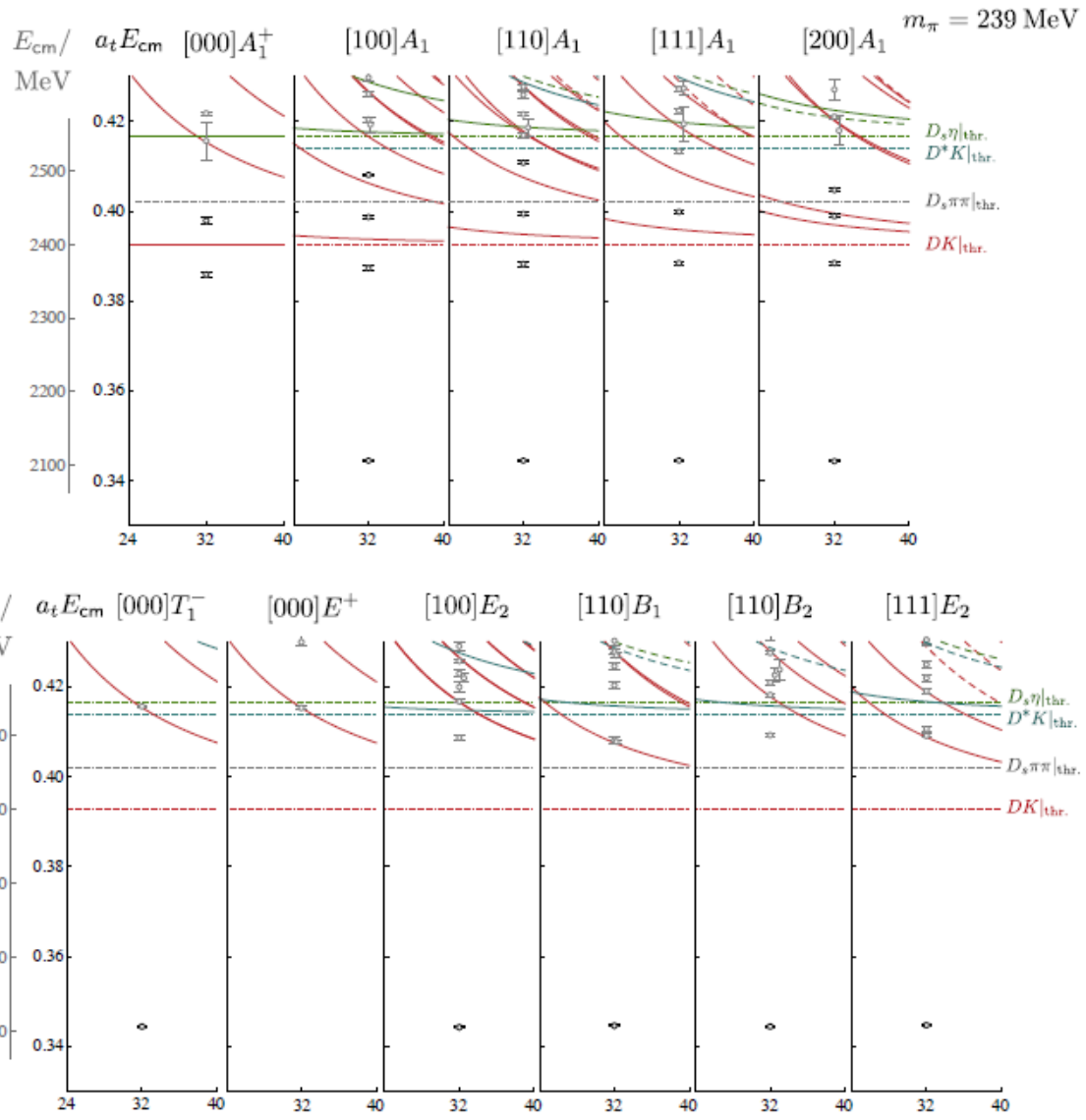




DK (isospin=0) – spectra

[JHEP 02 (2021) 100]

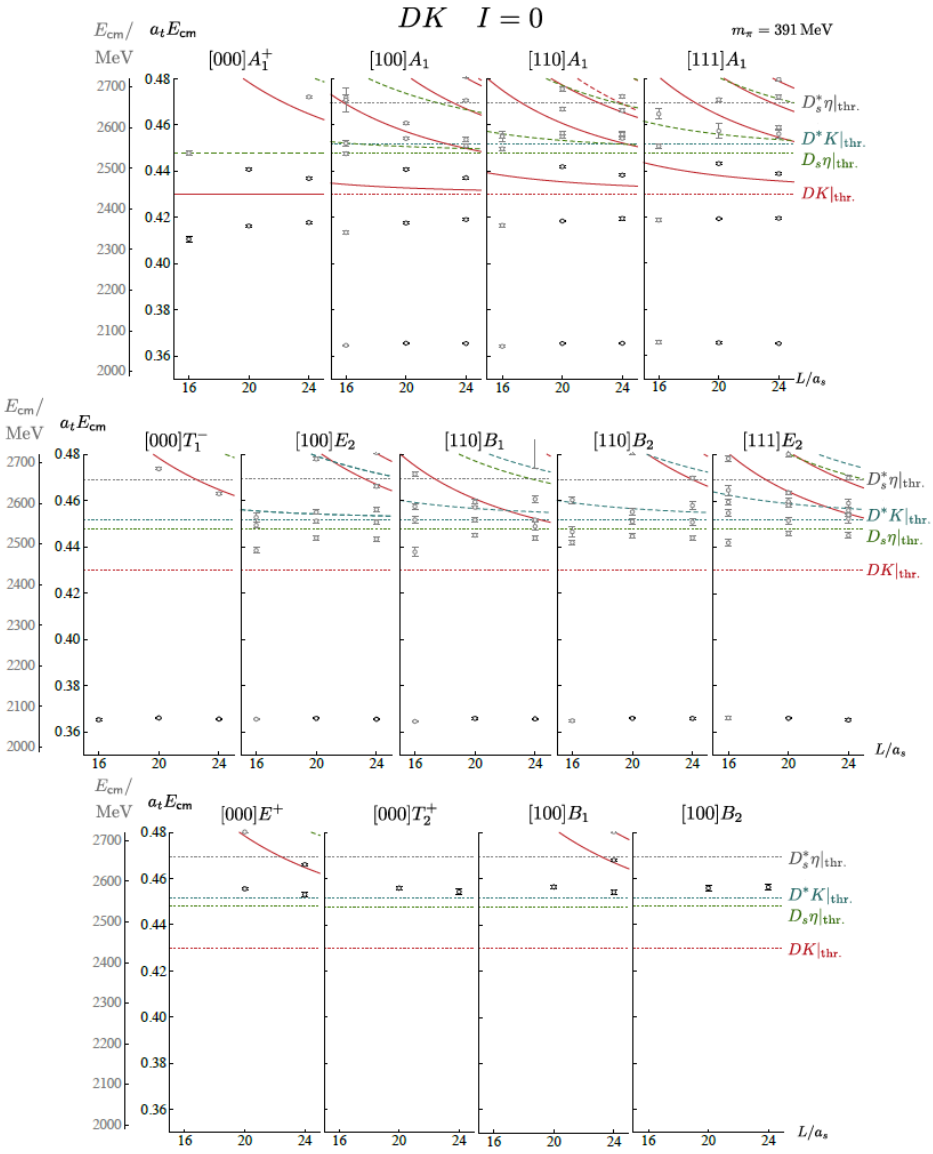


$m_\pi \approx 239$ MeV

Use 22 energy levels for $\ell = 0, 1$

DK (isospin=0) – spectra

[JHEP 02 (2021) 100]



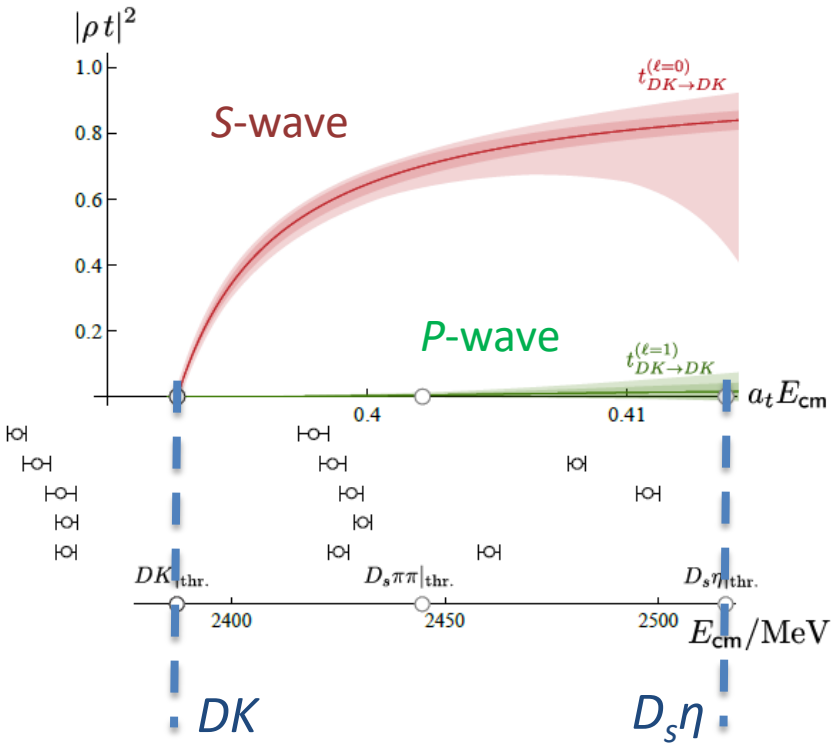
$m_\pi \approx 391$ MeV

Use 34 energy levels for $\ell = 0, 1$

DK (isospin=0) – amplitudes

[JHEP 02 (2021) 100]

$m_\pi \approx 239$ MeV



~ |amp|^2

Elastic *DK* scattering in *S* and *P*-wave

Sharp turn-on in *S*-wave at threshold

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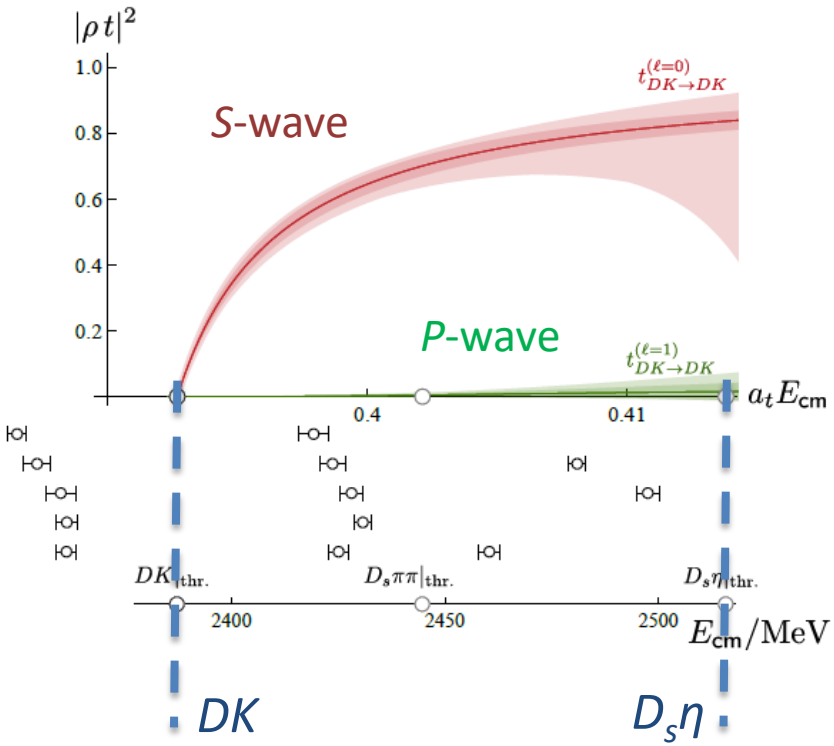

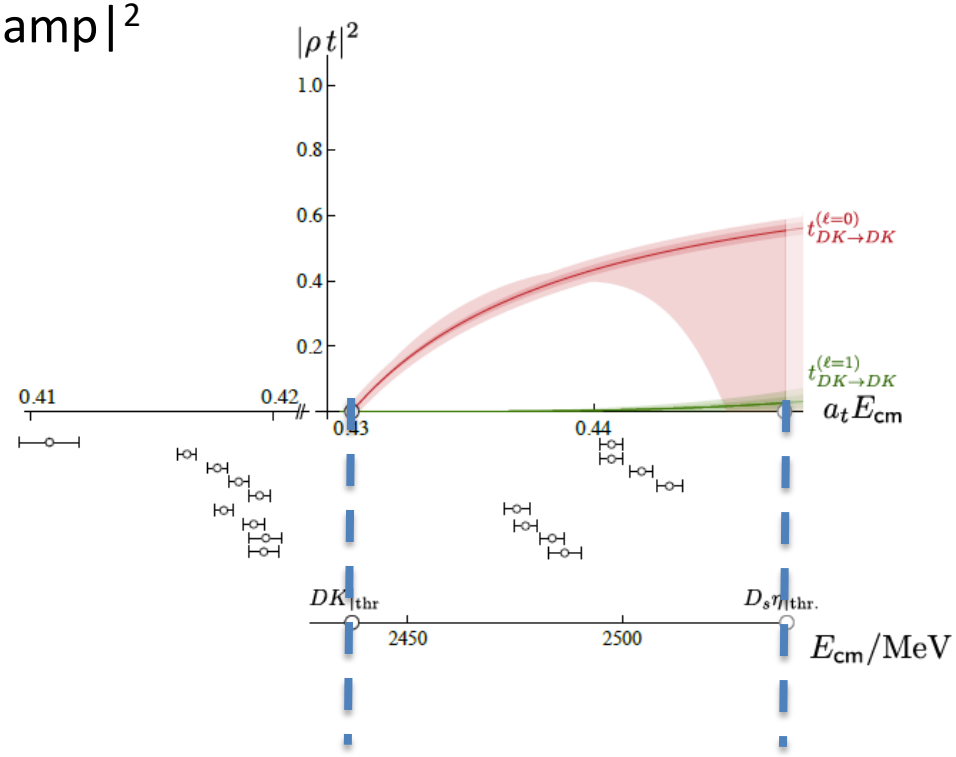

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DK (isospin=0) – *S*-wave poles

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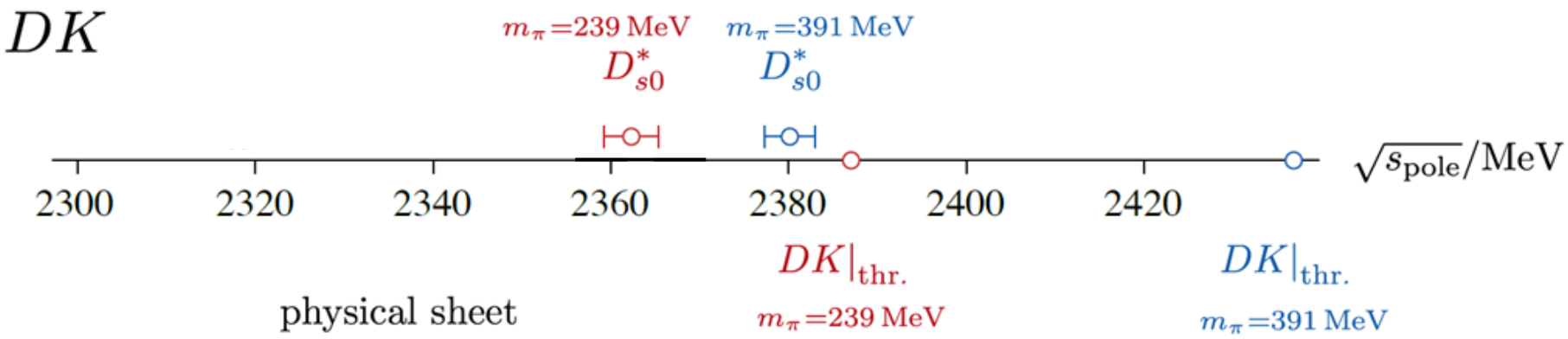

Bound-state pole strongly coupled to *S*-wave *DK*

ΔE = 25(3) MeV for $m_\pi \approx 239$ MeV

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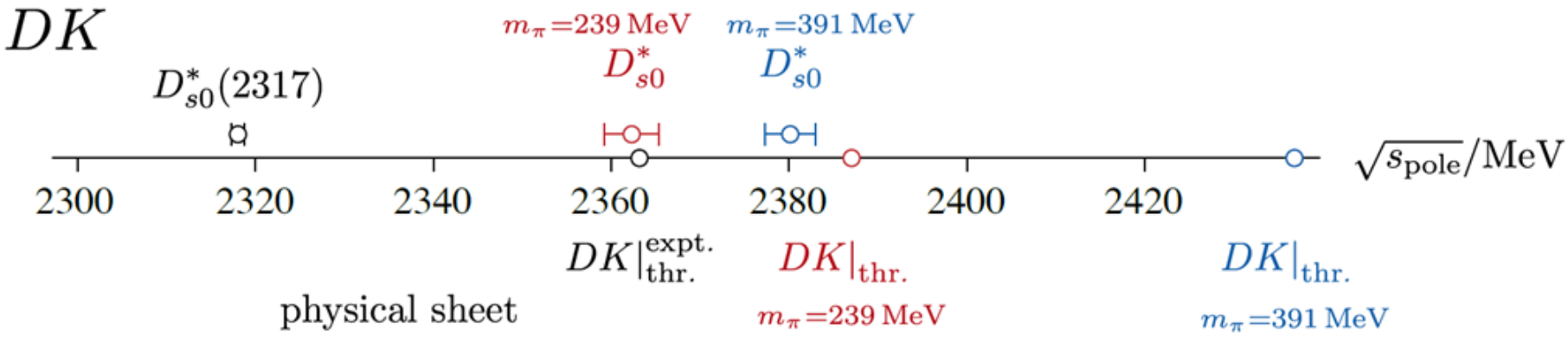

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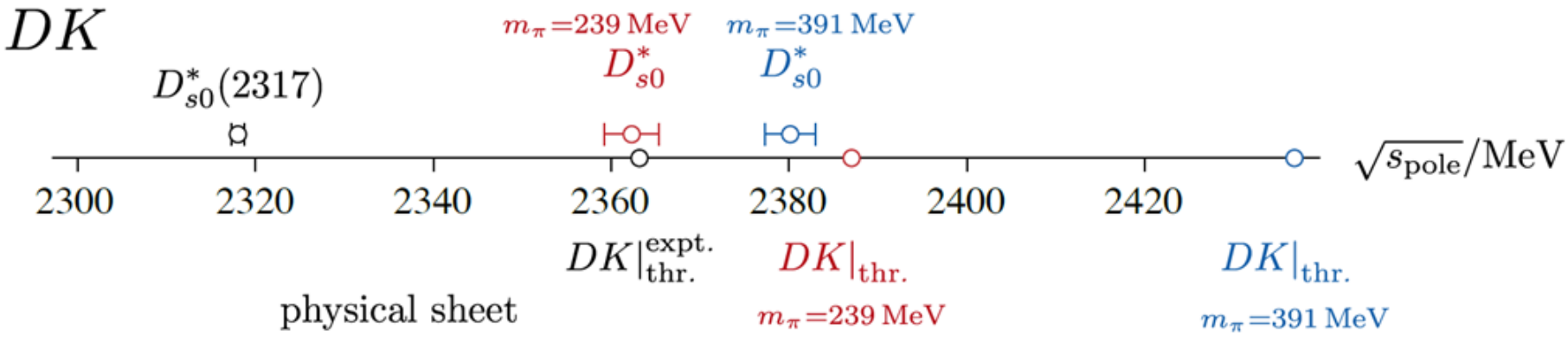

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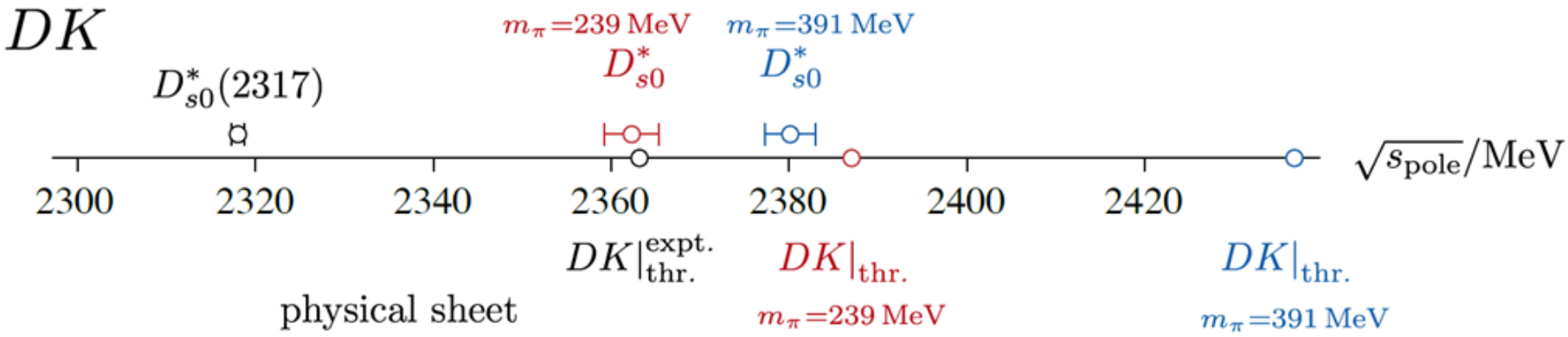
Weinberg [PR 137, B672 (1965)] compositeness, $0 \le Z \le 1$
(assuming binding is sufficiently weak)

DK (isospin=0) – *S*-wave poles

[JHEP 02 (2021) 100]



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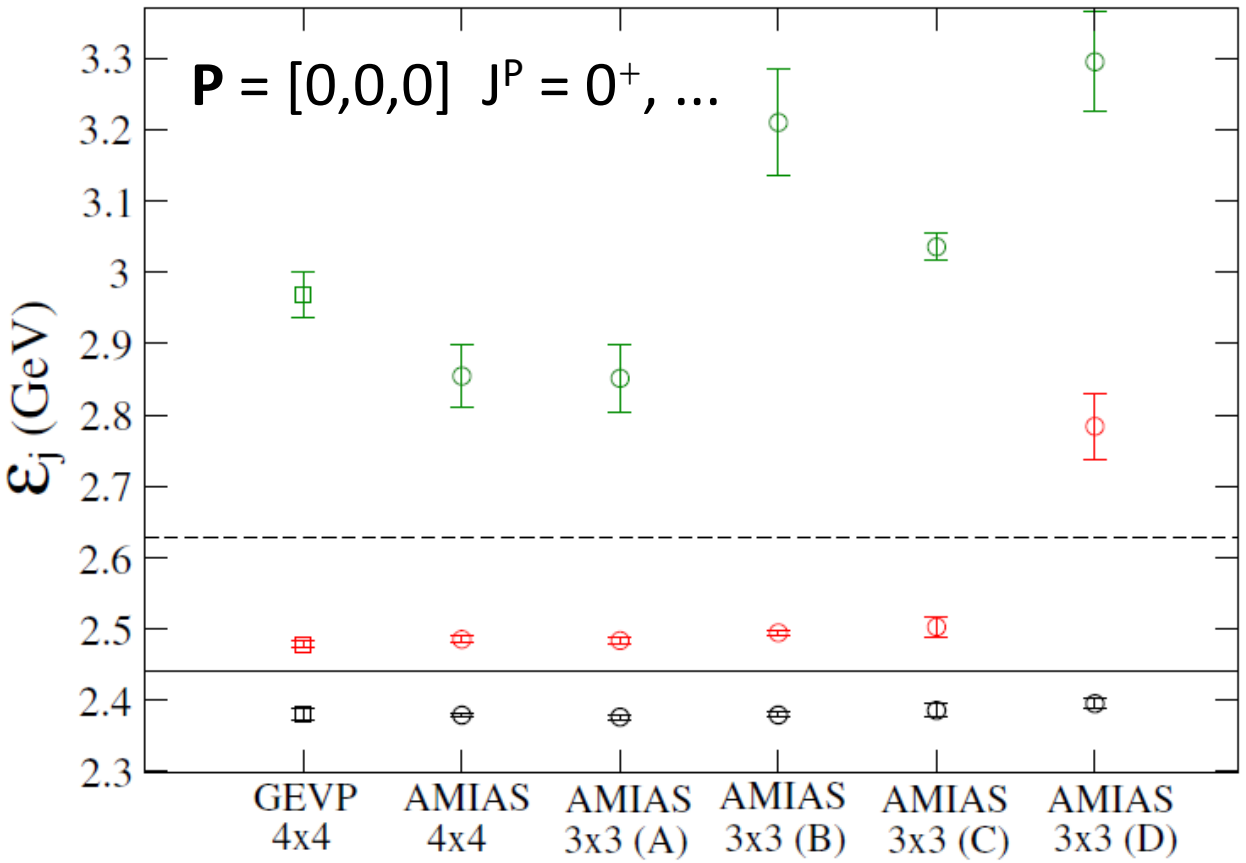
Also deeply bound state in *P*-wave, D_s^*, but doesn't strongly influence *DK* scattering at these energies

DK (isospin=0)



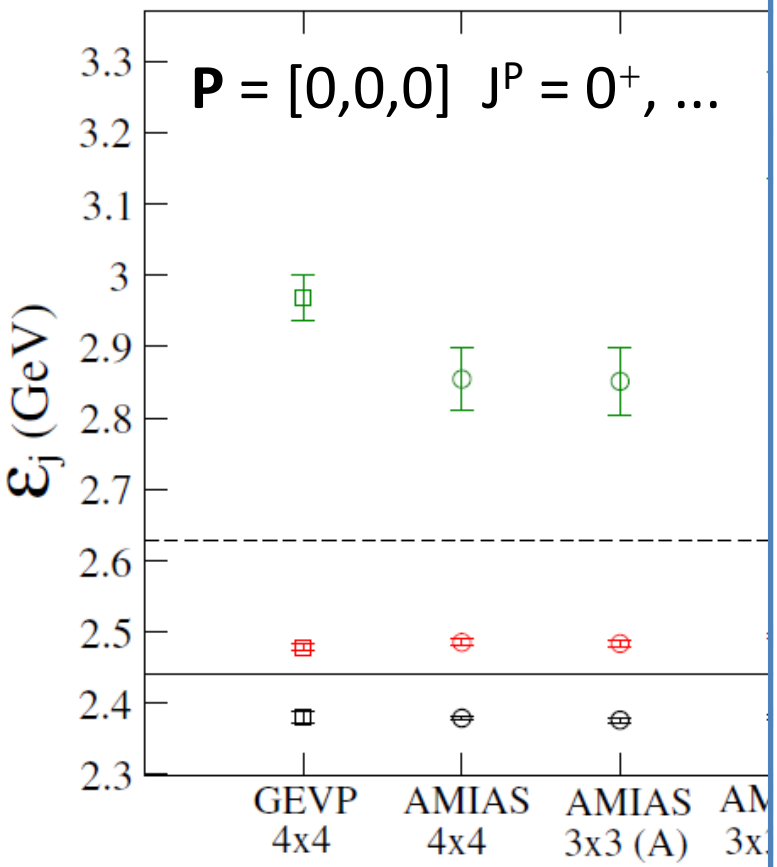
D(1)*K*(-1)

DK threshold

$m_\pi \approx 296$ MeV

Alexandrou *et al* (ETM)
[PR D101, 034502 (2020), 1911.08435]

DK (isospin=0)



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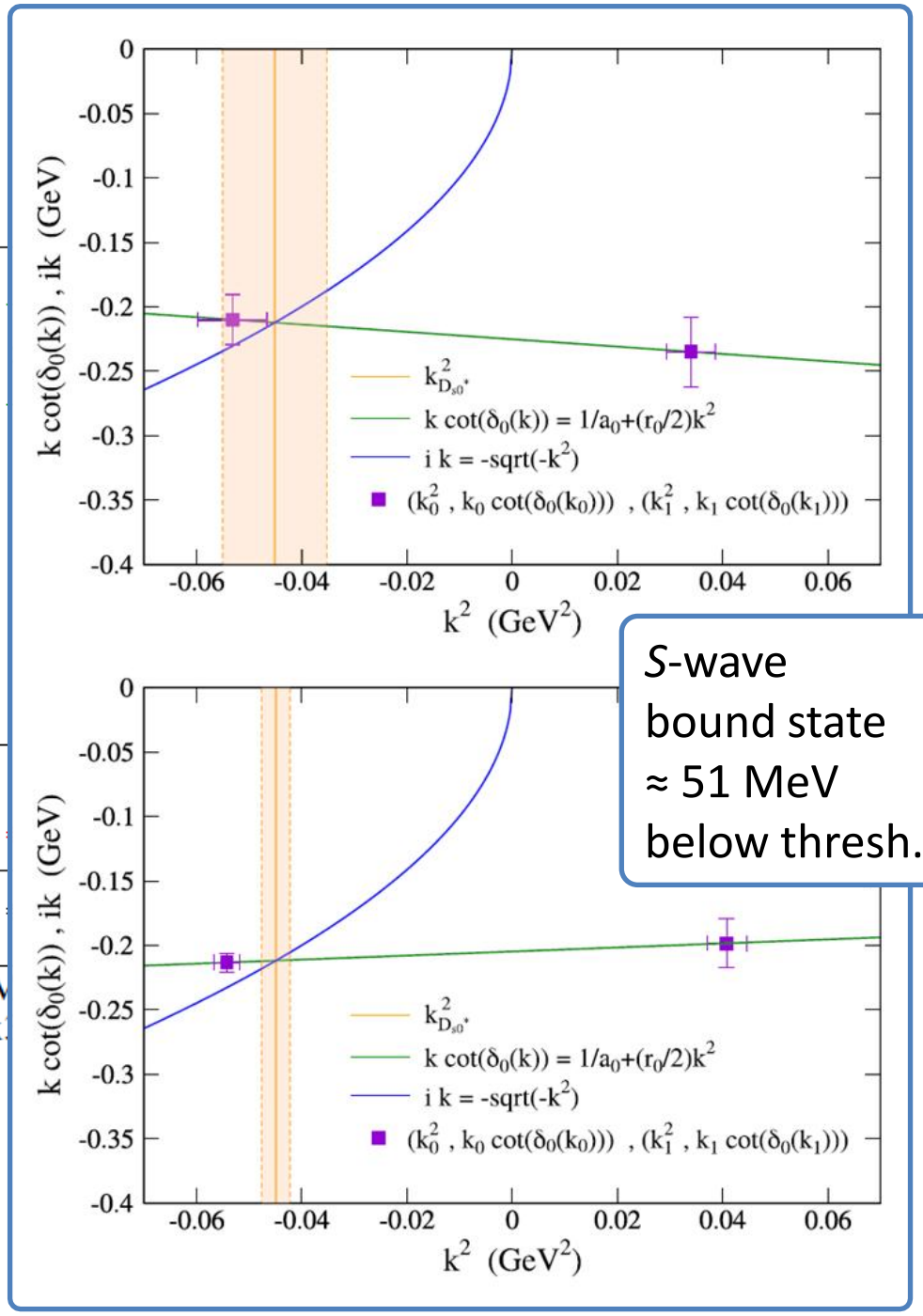


S-wave bound state ≈ 51 MeV below thresh.

Alexandrou *et al* (ETM)
[PR D101, 034502 (2020), 1911.08435]

$D\bar{K}$ (isospin=0,1)

Exotic flavour $(\bar{l}\bar{l}\,c\,s)$

[JHEP 02 (2021) 100]

Use many operators,

$\sim D\bar{K}$

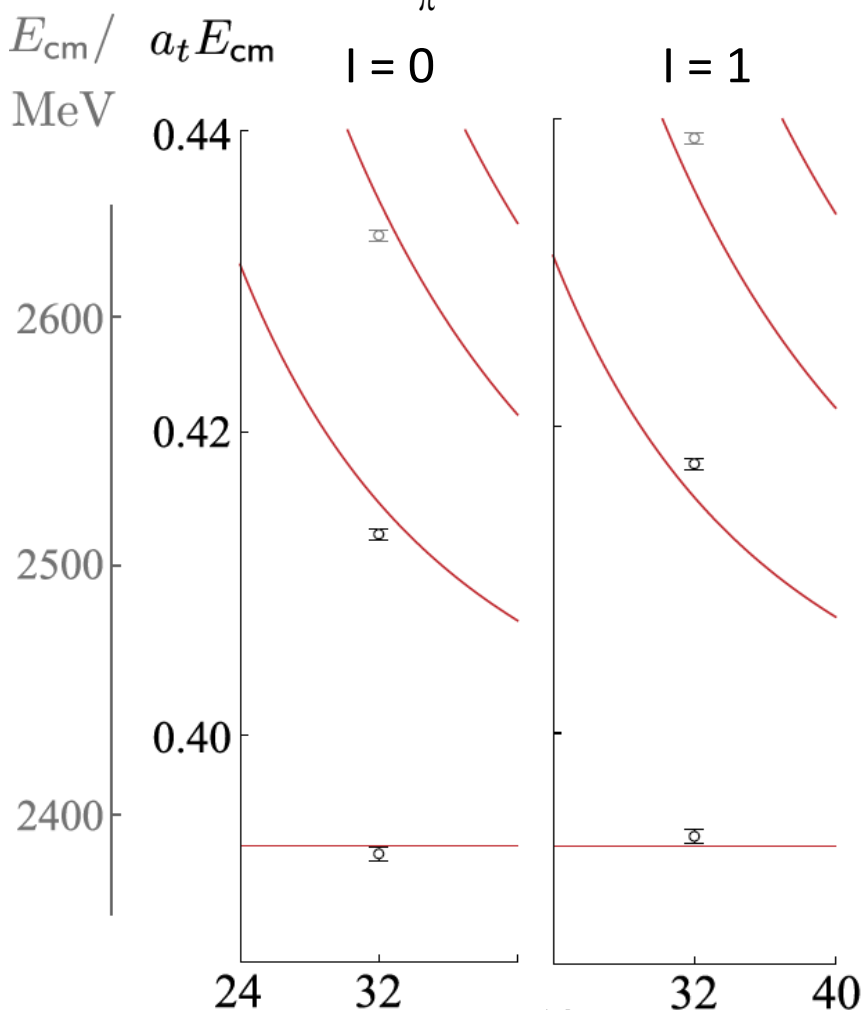
$D\bar{K}$ (isospin=0,1)

Exotic flavour $(\bar{l}\bar{l}cs)$

[JHEP 02 (2021) 100]

[0,0,0] $J^P = 0^+$, ...

$m_\pi \approx 239$ MeV



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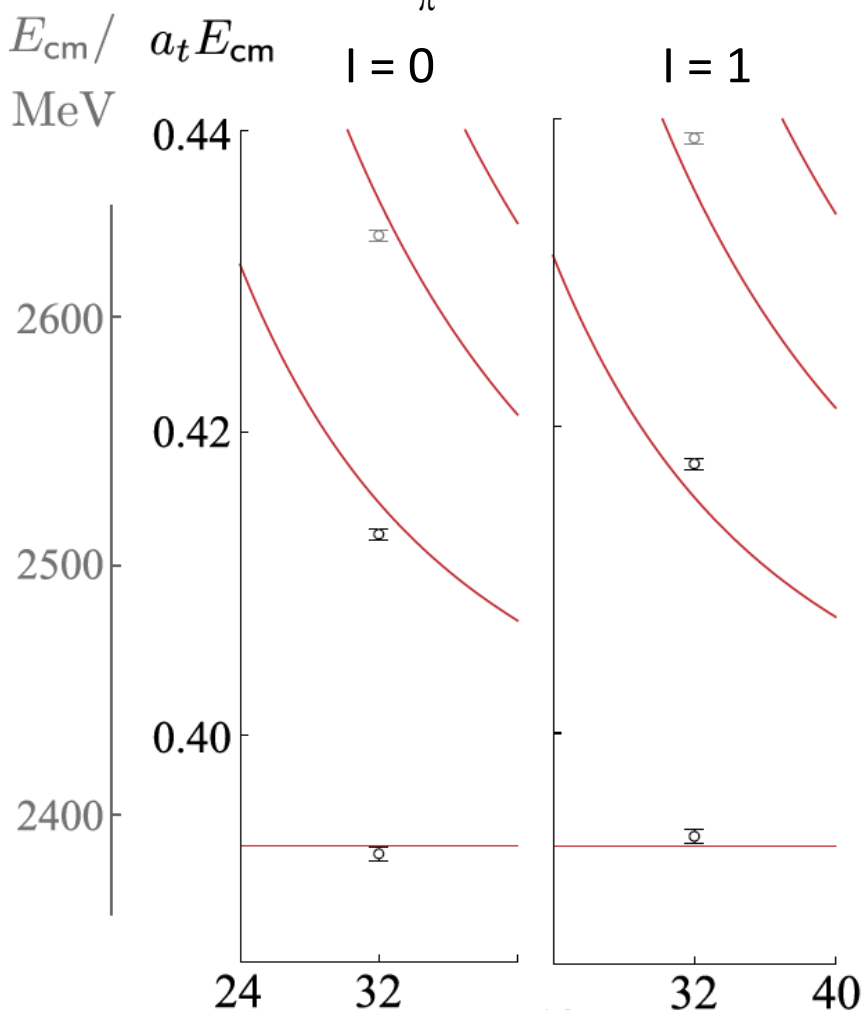
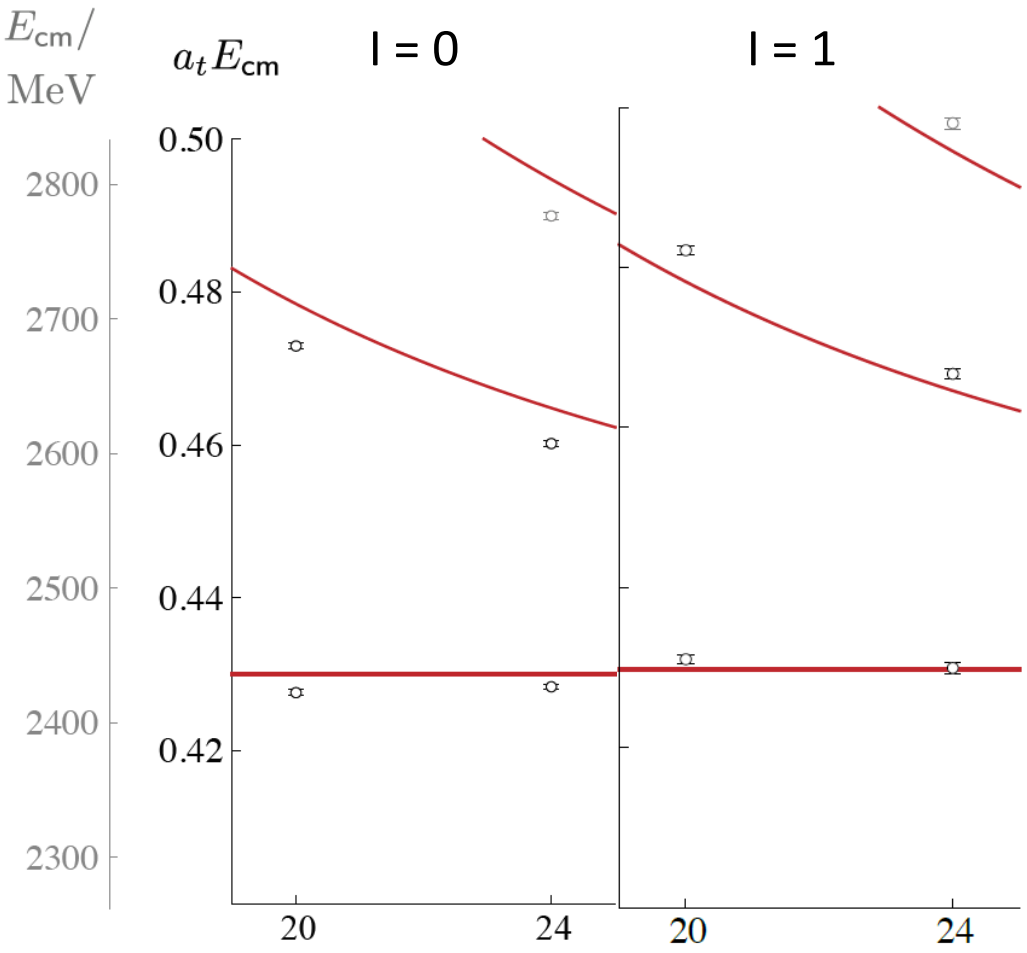


$m_\pi \approx 391$ MeV

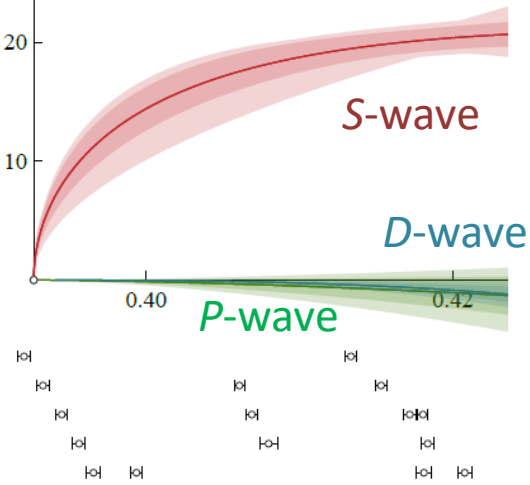


$D\bar{K}$ (isospin=0,1) – amplitudes

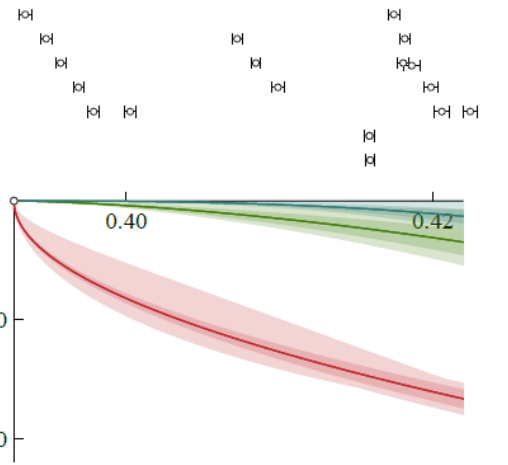
[JHEP 02 (2021) 100]

δ / ° $m_\pi \approx 239$ MeV

I = 0



(18, 18 levels for I=0,1)



I = 1

Elastic scattering in *S*, *P*, *D*-wave

Weak attraction in *S*-wave I=0

Weak repulsion in *S*-wave I=1

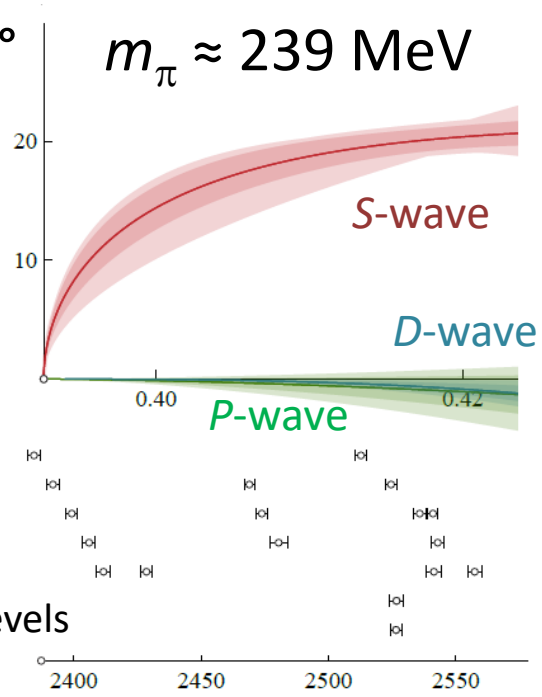
$D\bar{K}$ (isospin=0,1) – amplitudes

[JHEP 02 (2021) 100]

δ / °

$m_\pi \approx 239$ MeV

I = 0



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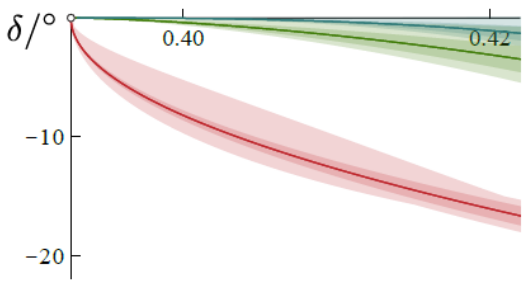

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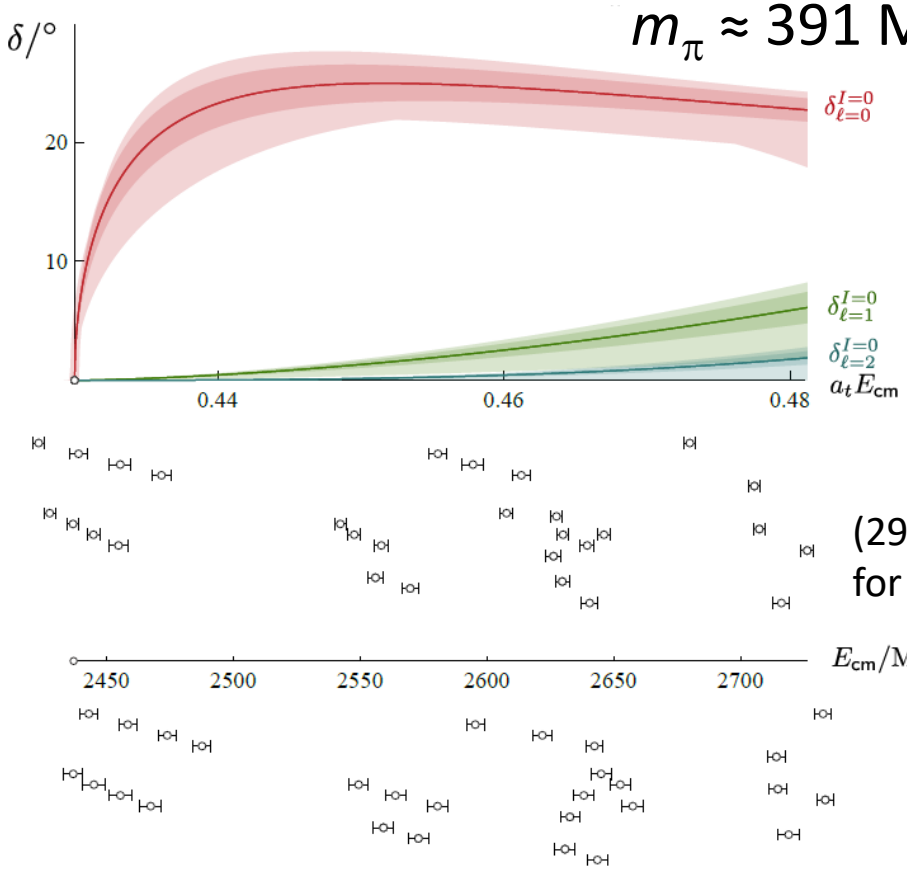
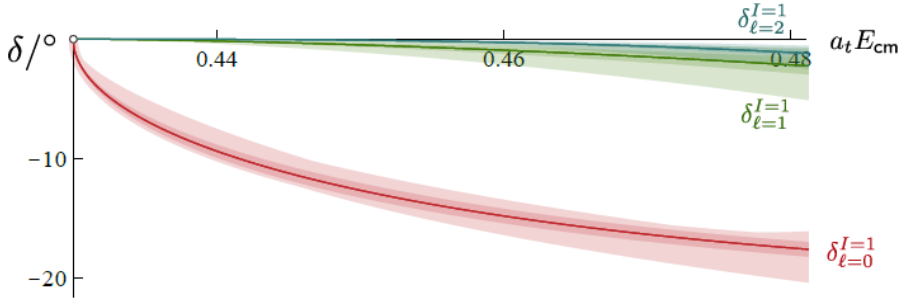
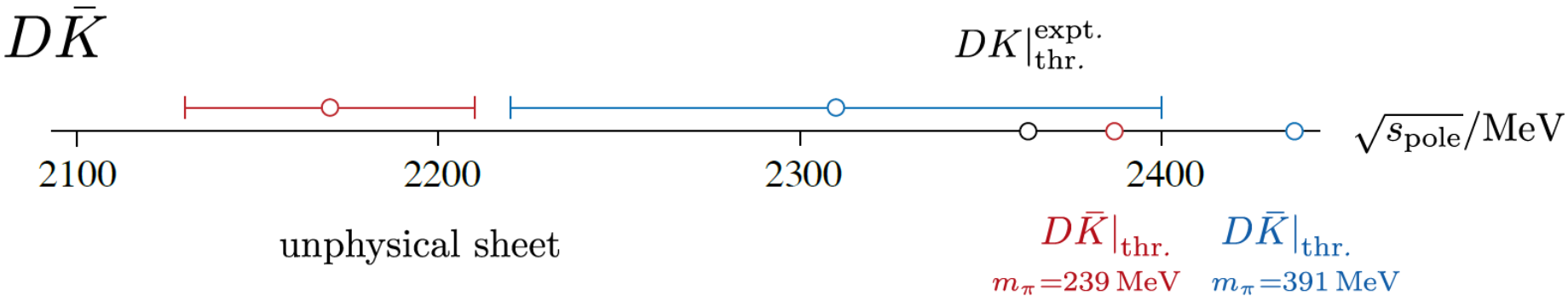


(29,28 levels for I=0,1)



$D\bar{K}$ (isospin=0) – poles

[JHEP 02 (2021) 100]



Suggestion of a **virtual bound-state** pole in *S*-wave I=0 (**exotic flavour**)

Dπ (isospin=1/2) – S-wave

[Gayer, Lang, Ryan, Tims, CT, Wilson (HadSpec), arXiv:2102.04973]

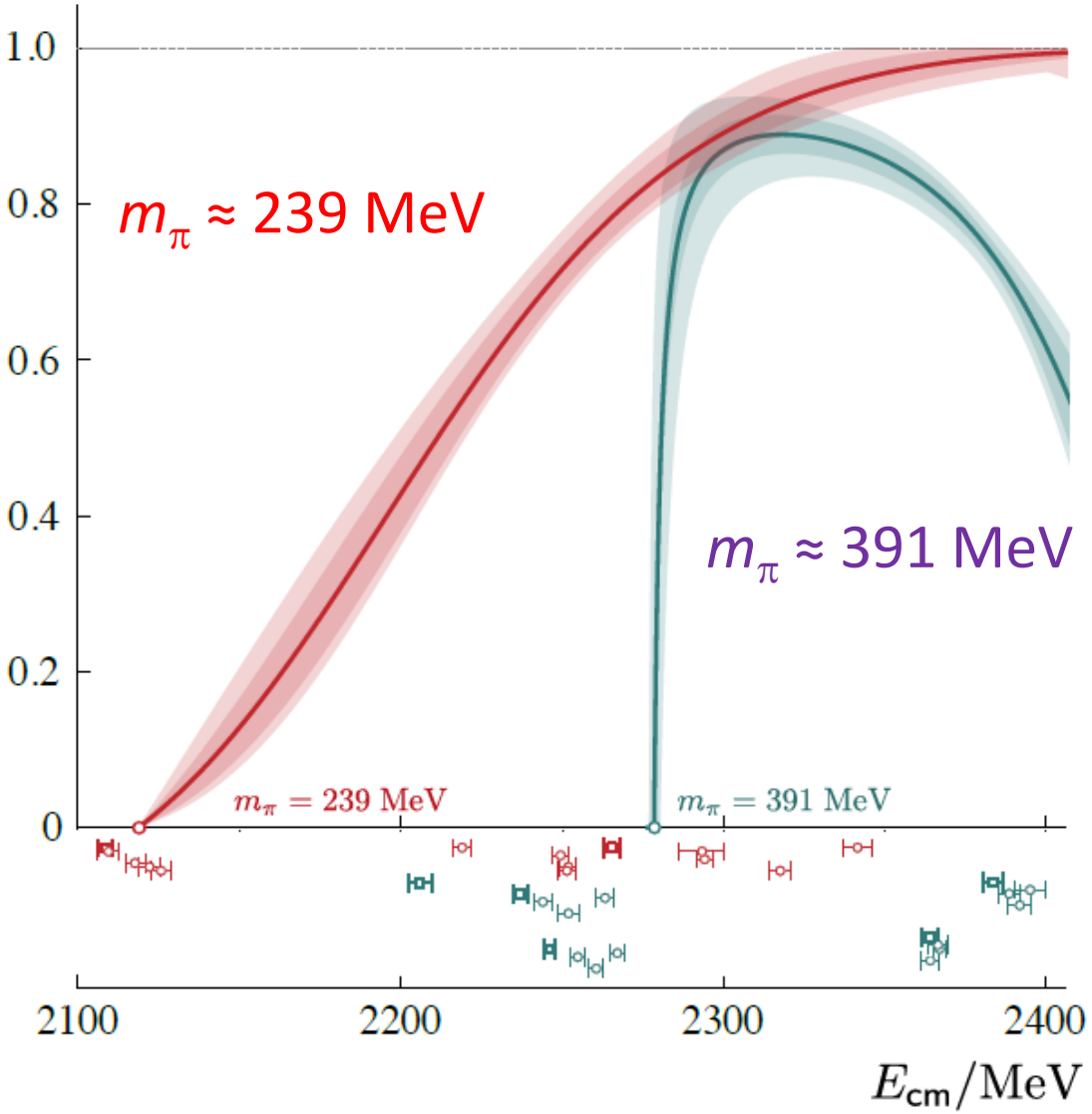
[Moir, Peardon, Ryan, CT, Wilson (HadSpec) JHEP 1610, 011 (2016)]

Dπ (isospin=1/2) – S-wave

[Gayer, Lang, Ryan, Tims, CT, Wilson (HadSpec), arXiv:2102.04973]

[Moir, Peardon, Ryan, CT, Wilson (HadSpec) JHEP 1610, 011 (2016)]

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



$m_\pi \approx 239$ MeV
29 energy levels
(1 volume)

$m_\pi \approx 391$ MeV
47 energy levels
(3 volumes)

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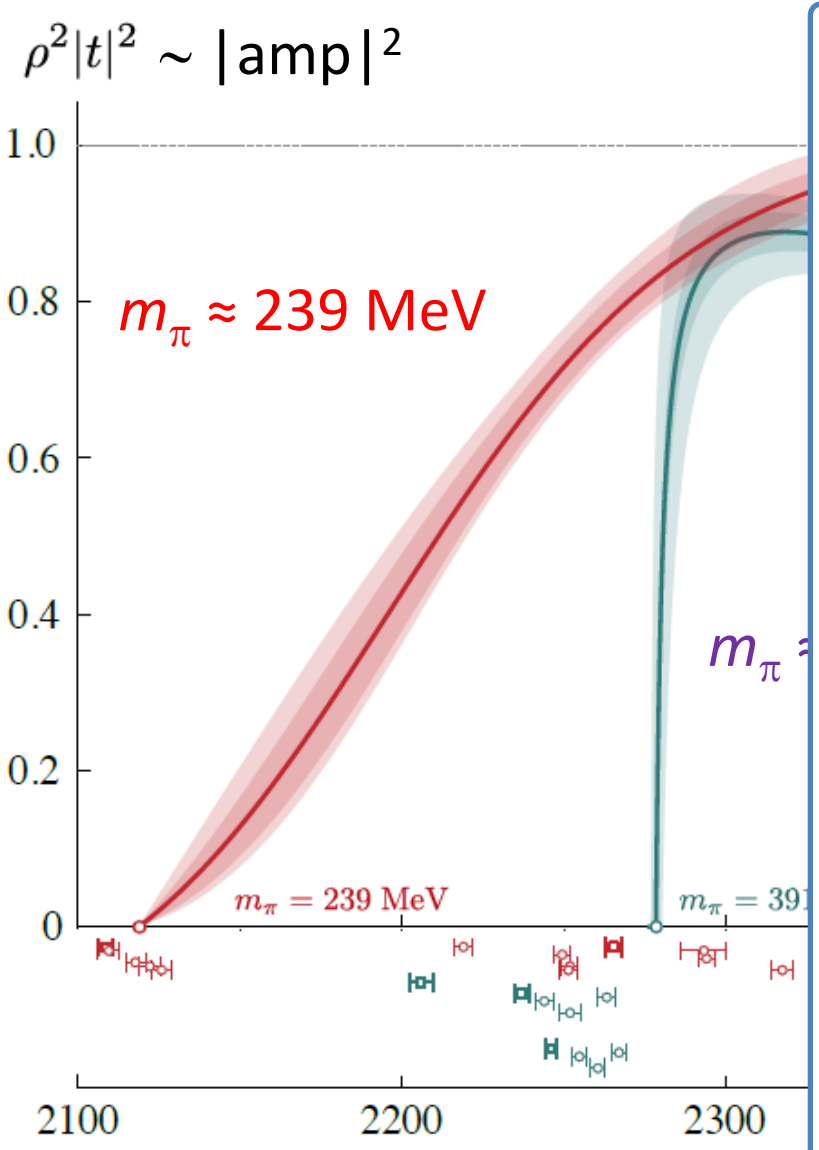

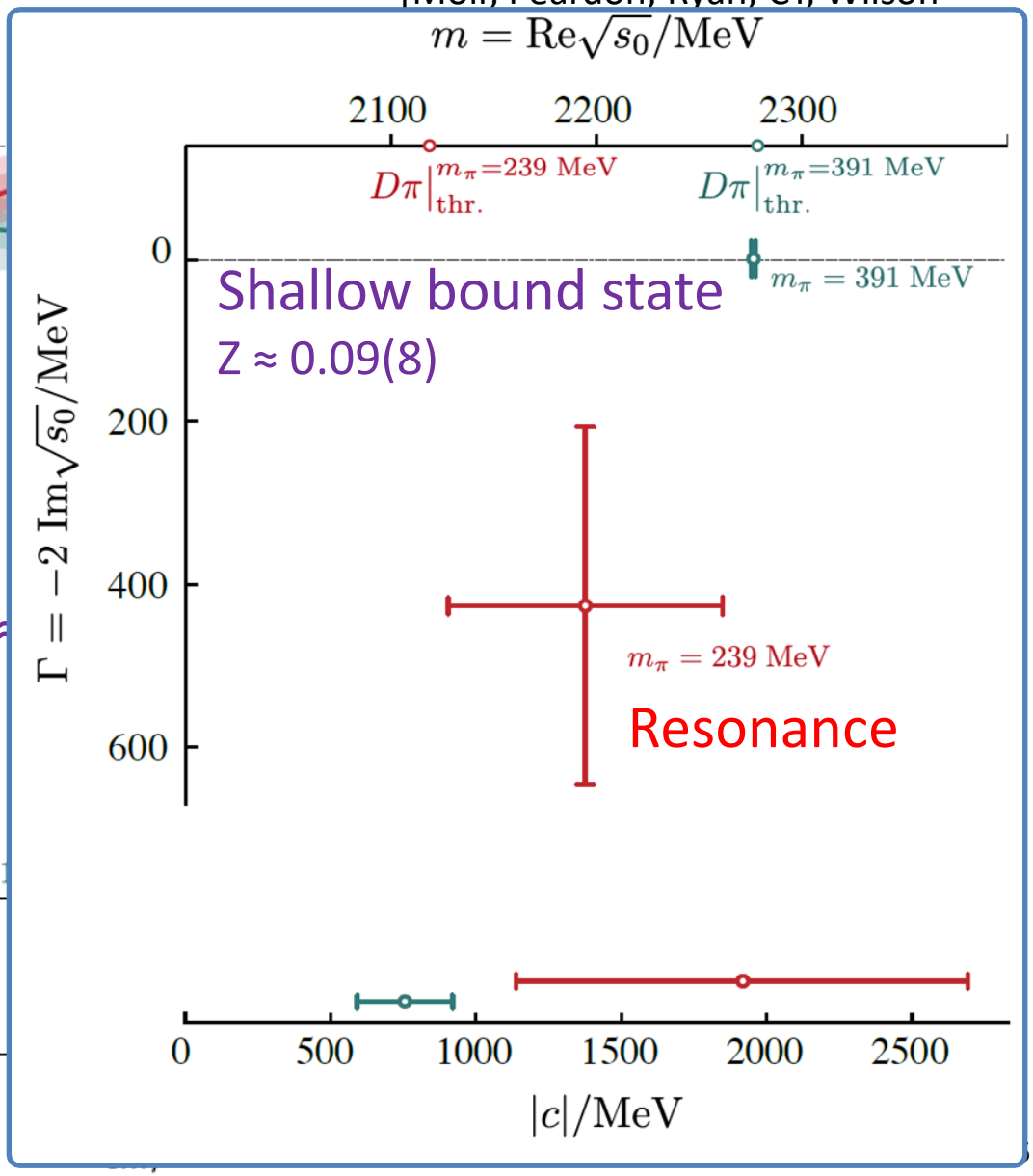

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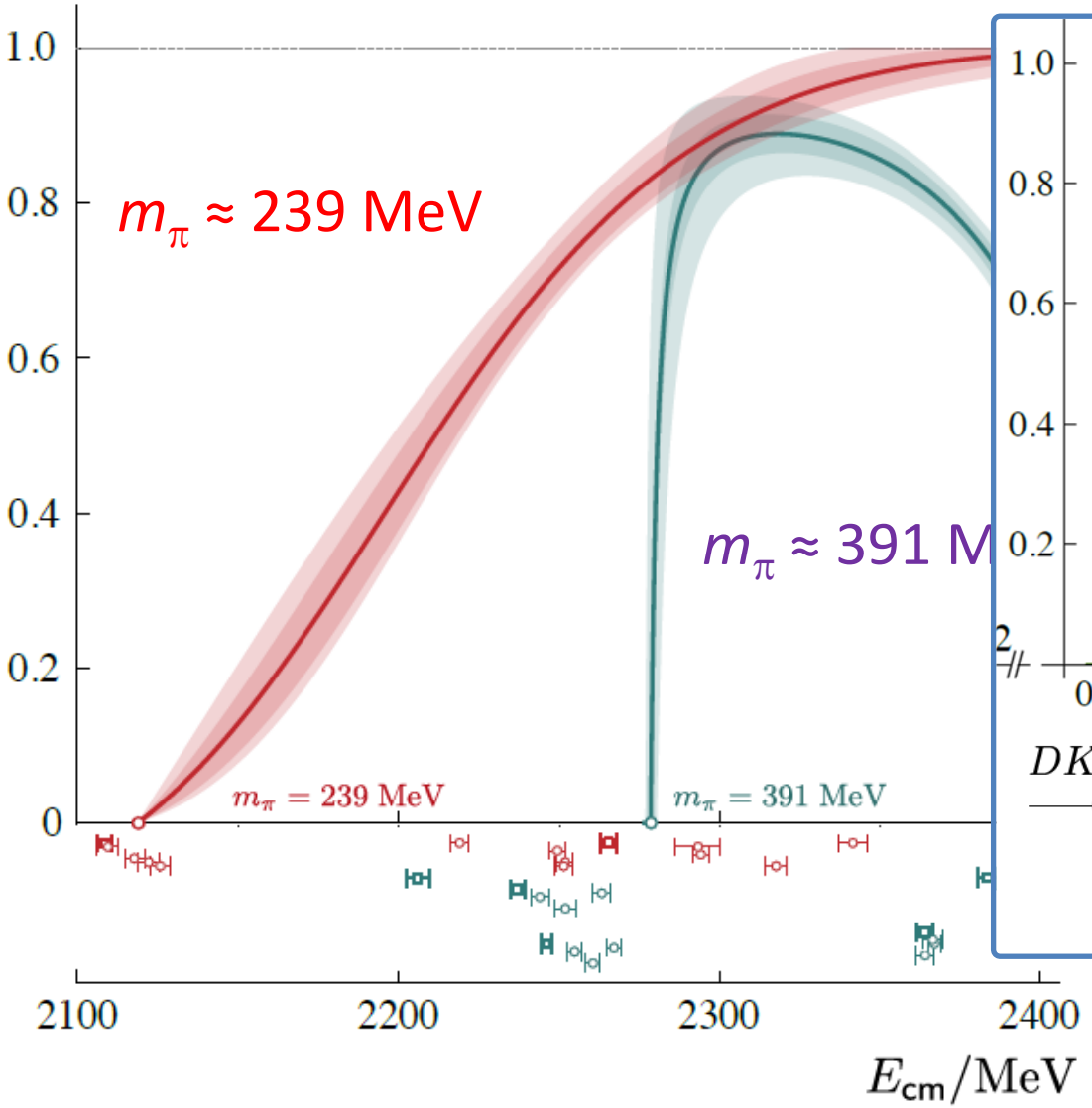
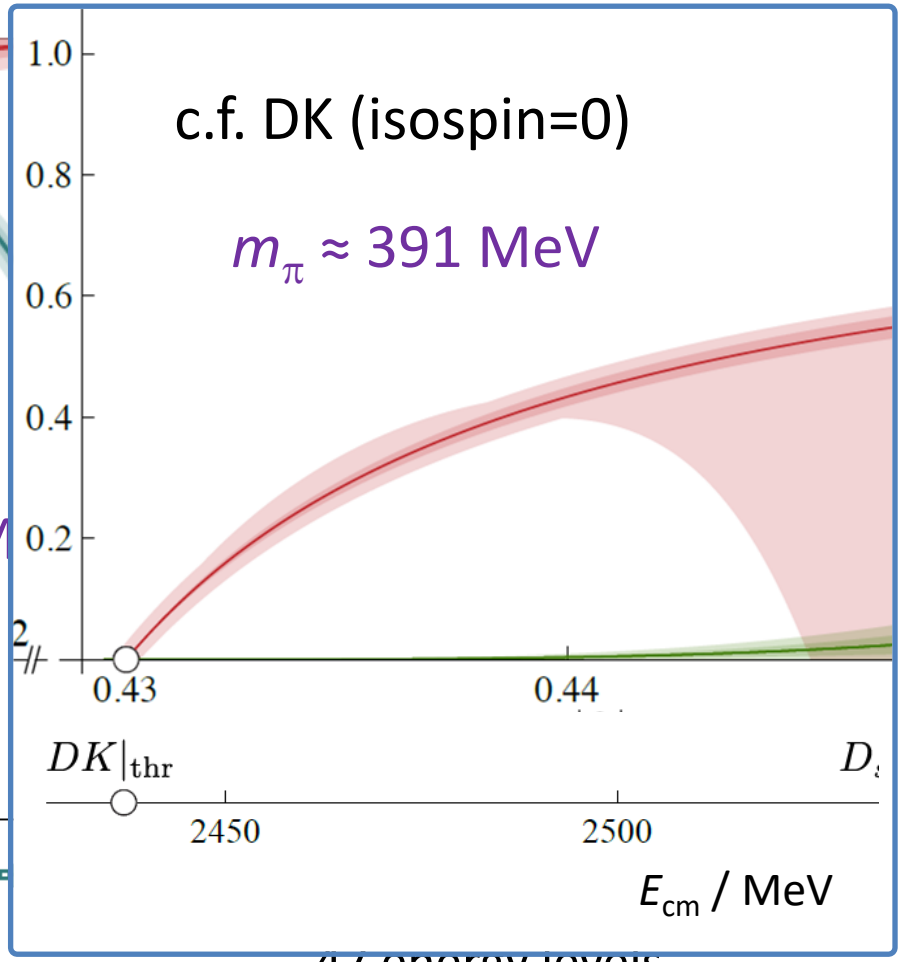
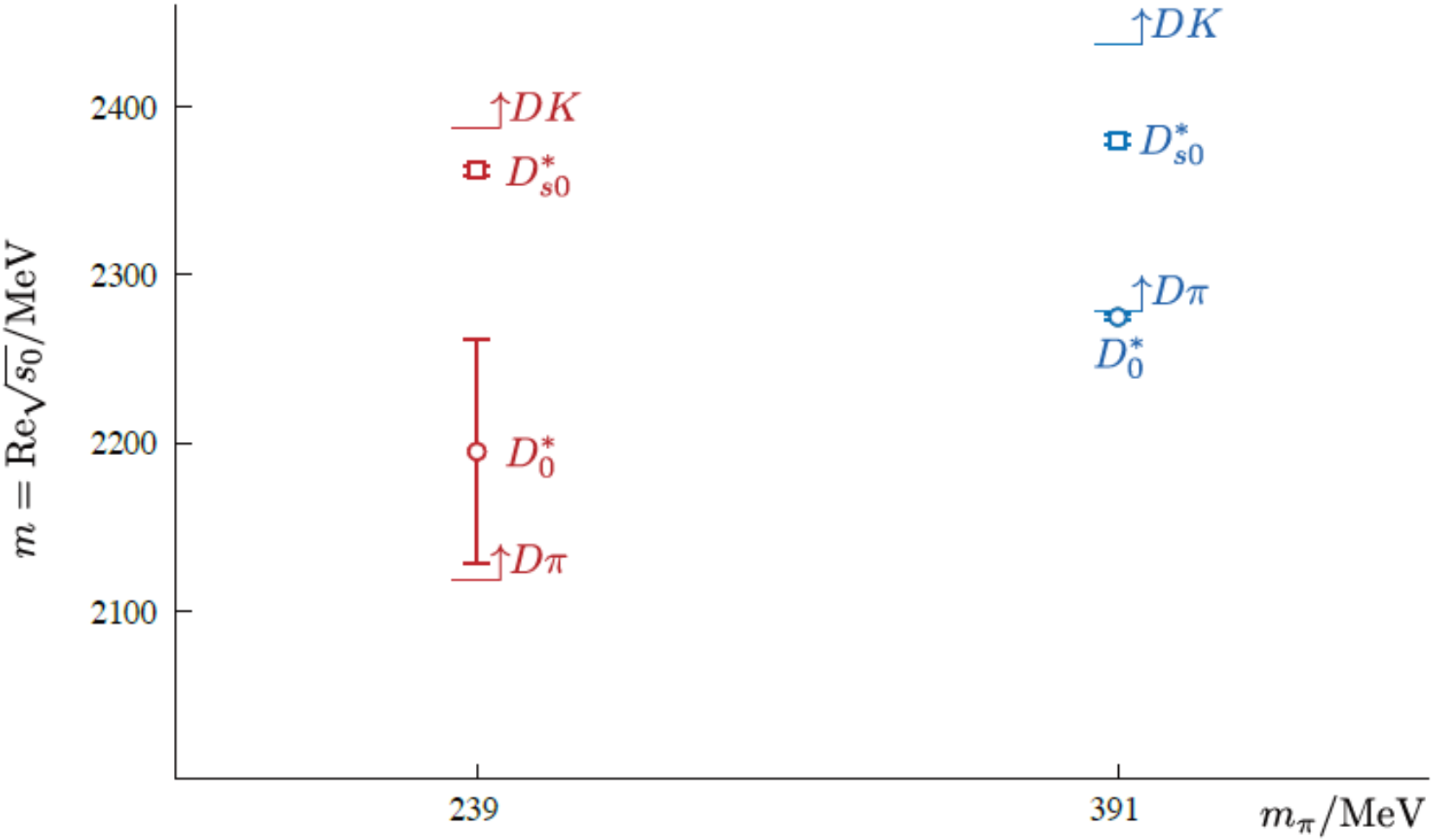




47 energy levels
(3 volumes)

DK and Dπ – S-wave poles

[arXiv:2102.04973]



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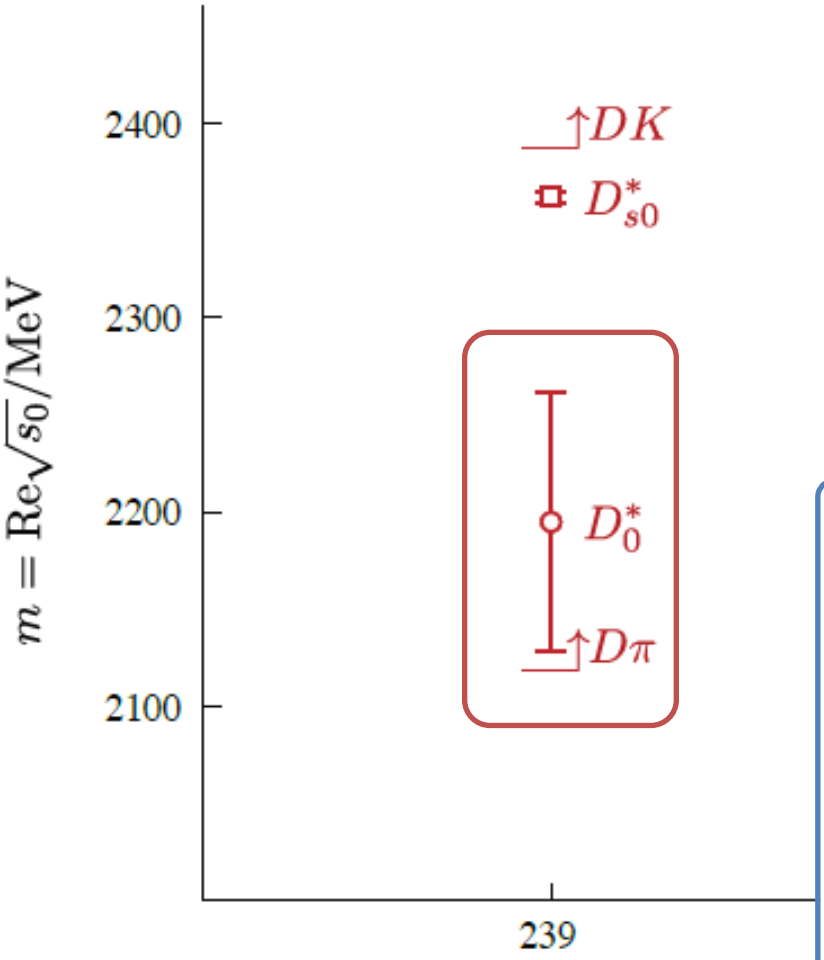
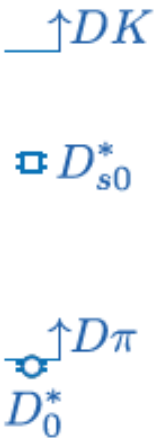
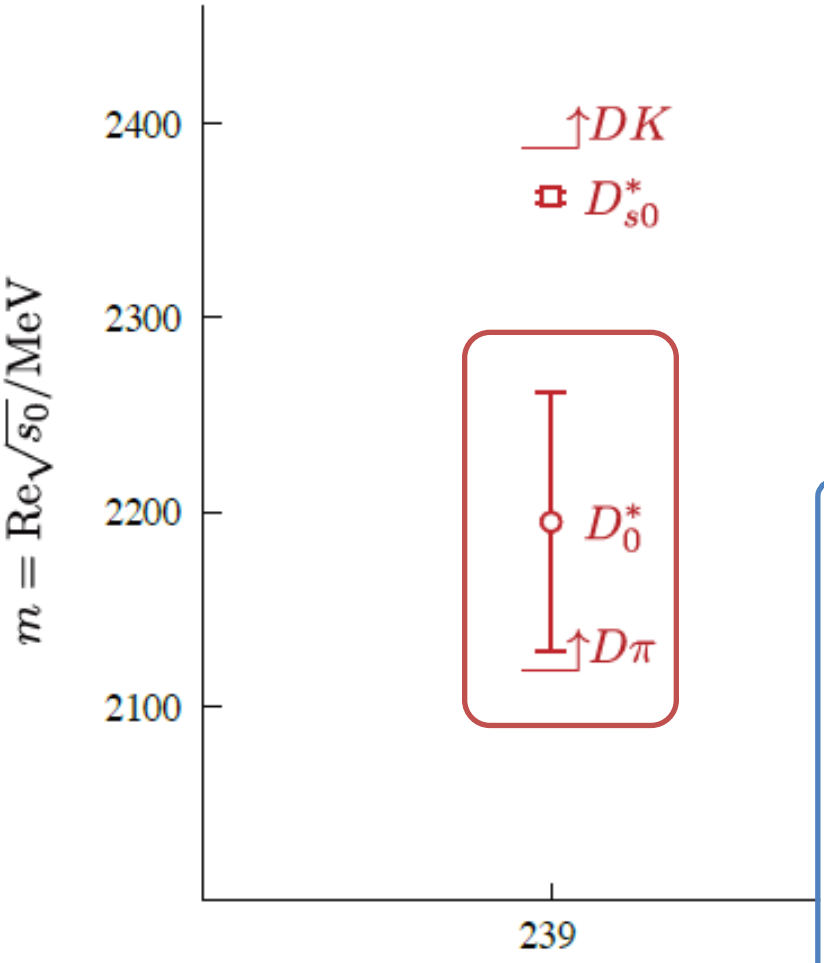


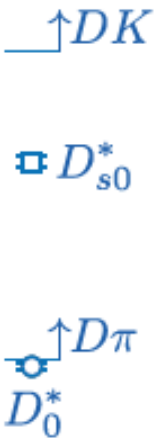


m_π/MeV	239	391
m_D/MeV	1880	1887
m_{BW}/MeV	2380(36)	2206(32)
g_{BW}	5.39(56)	7.62(75)
$\frac{\chi^2}{N_{\mathrm{dof}}}$	$\frac{14.6}{20-4}$	$\frac{36.0}{29-5}$
$\mathrm{Re}\sqrt{s_0}$/MeV	2189(72)	2275(1)
$-2\,\mathrm{Im}\sqrt{s_0}$/MeV	510(97)	-
$\lvert c\rvert$/MeV	2391(411)	826(133)

DK and Dπ – S-wave poles

[arXiv:2102.04973]





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D_0^* pole position may be lower than currently reported exp. value.
(See also Du *et al*, PRL 126, 192001 (2021), 2012.04599)

SU(3) flavour symmetry

[JHEP 02 (2021) 100]

SU(3) flavour symmetry

[JHEP 02 (2021) 100]

SU(3) multiplets:

$D_{(s)}$ $\overline{\mathbf{3}}$ Light/strange meson $\mathbf{8}$ or $\mathbf{1}$

$$\overline{\mathbf{3}} \otimes \mathbf{8} \to \overline{\mathbf{3}} \oplus \mathbf{6} \oplus \overline{\mathbf{15}}, \quad \overline{\mathbf{3}} \otimes \mathbf{1} \to \overline{\mathbf{3}}$$

SU(3) flavour symmetry

[JHEP 02 (2021) 100]

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$(I = 0)$ DK-$D_s\eta$: $\overline{\mathbf{3}} \oplus \overline{\mathbf{15}}$ $(I = \frac{1}{2})$ $D\pi$-$D\eta$-$D_s\bar{K}$: $\overline{\mathbf{3}} \oplus \mathbf{6} \oplus \overline{\mathbf{15}}$

$(I = 1)$ DK-$D_s\pi$: $\mathbf{6} \oplus \overline{\mathbf{15}}$ $(I = 0)$ $D\bar{K}$: $\mathbf{6}$

$(I = \frac{1}{2})$ D_sK, $(I = 1)$ $D\bar{K}$, $(I = \frac{3}{2})$ $D\pi$: $\overline{\mathbf{15}}$

SU(3) flavour symmetry

[JHEP 02 (2021) 100]

SU(3) multiplets:

$D_{(s)}$ $\overline{\mathbf{3}}$ Light/strange meson $\mathbf{8}$ or $\mathbf{1}$

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$(I=\frac{1}{2})$ D_sK, $(I=1)$ $D\bar{K}$, $(I=\frac{3}{2})$ $D\pi$: $\overline{\mathbf{15}}$

$(I=\frac{1}{2})$ $D\pi$-$D\eta$-$D_s\bar{K}$: $\overline{\mathbf{3}} \oplus \mathbf{6} \oplus \overline{\mathbf{15}}$

$(I=0)$ $D\bar{K}$: $\mathbf{6}$

S-wave results [broken SU(3)] suggest:

$\overline{\mathbf{3}}$ resonance/bound state

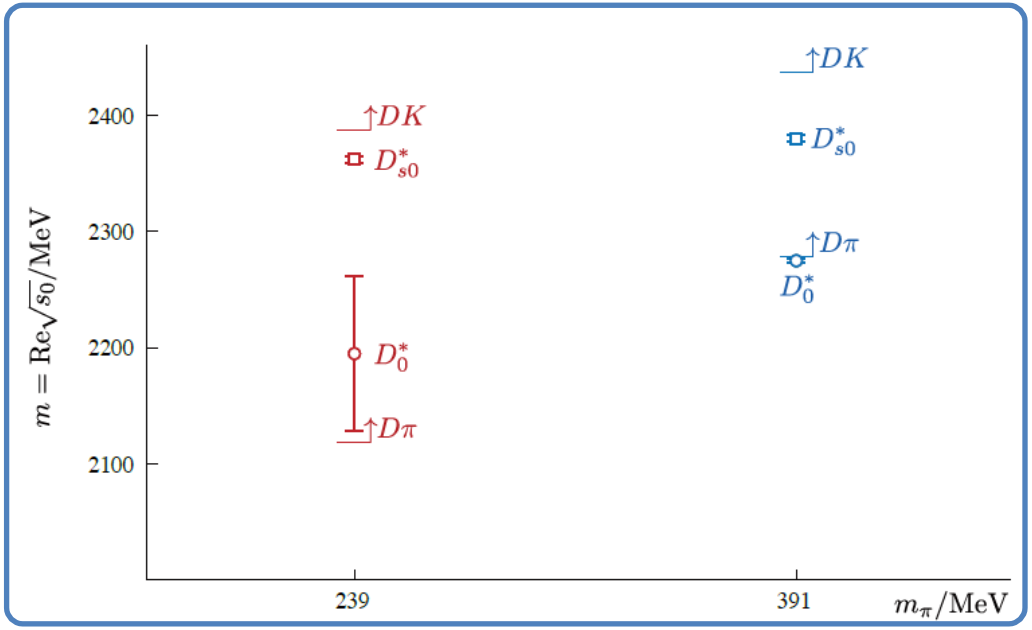
$\mathbf{6}$ virtual bound state

$\overline{\mathbf{15}}$ weak repulsion

[See also PR D87, 014508 (2013) (1208.4535); PL B767, 465 (2017) (1610.06727); PR D98, 094018 (2018) (1712.07957); *EPJ C79, 13 (2019)* (1811.05585)]

Summary

- First principles lattice QCD calcs: **mapping out energy-dependence** of **scattering amplitudes**



- Isospin-0 *DK*: *S*-wave bound state, $D^*_{s0}(2317)$
- Isospin-1/2 *Dπ*: *S*-wave bound state/resonance, $D^*_0(2300)$
- **Exotic-flavour** isospin-0 $D\bar{K}$: *S*-wave virtual bound state?

- Lighter (or heavier) light quarks? With SU(3) flavour sym?
- Further up in energy, inelastic scattering (3-hadron scattering)

Acknowledgements

Hadron Spectrum Collaboration

[*www.hadspec.org*]

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Edinburgh, UK: Max Hansen; Tata Institute, India: Nilmani Mathur