# $DK$ and $D\bar{K}$ scattering and the $D_{s0}^*(2317)$ from lattice QCD

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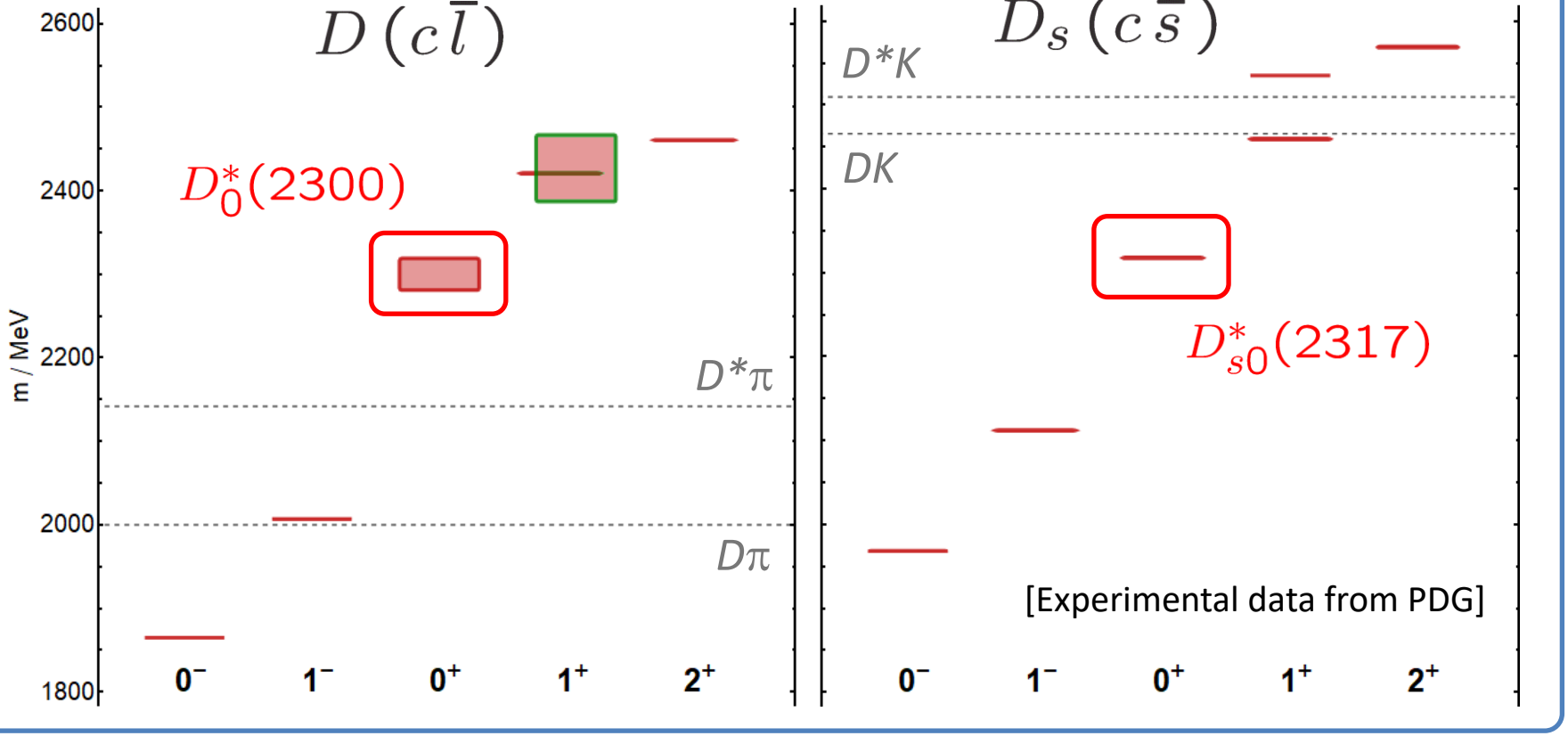
38th International Symposium on Lattice Field Theory (Lattice 2021),
26 – 30 July 2021

UNIVERSITY OF CAMBRIDGE

hadspec

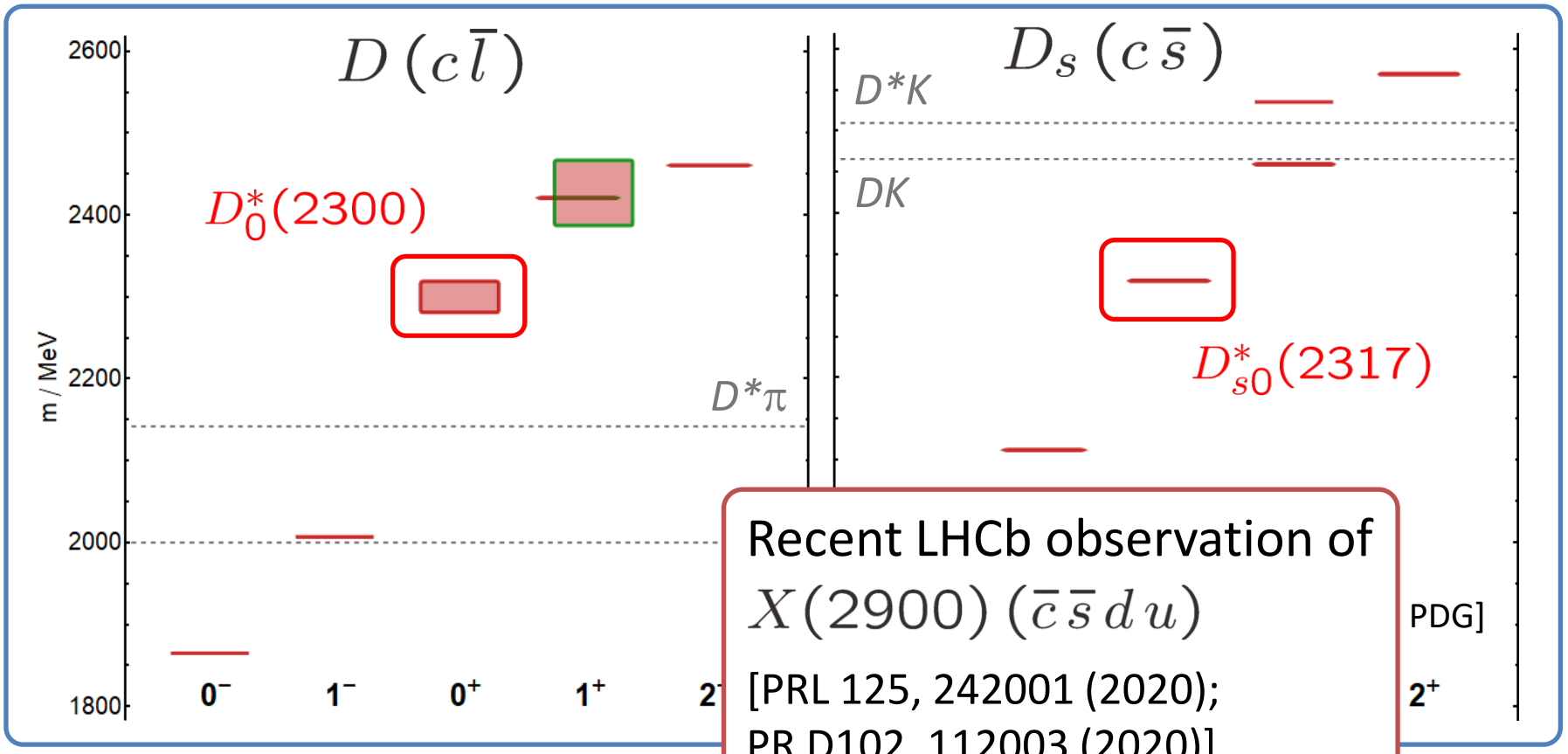
# Charm ($D$) and charm-strange ($D_s$) mesons




Nicolas Lang (earlier): $D\,\pi$ scattering and the $D_0^*(2300)$

This talk: $D\,K$ scattering and the $D_{s0}^*(2317)$

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




Recent LHCb observation of $X(2900)\ (\bar{c}\,\bar{s}\,d\,u)$

[PRL 125, 242001 (2020); PR D102, 112003 (2020)]

Nicolas Lang (earlier): $D\,\pi$ scattering and the $D_0^*(2300)$

This talk: $D\,K$ scattering and the $D_{s0}^*(2317)$

# Other calculations

Some other lattice QCD 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];
- Gregory *et al* [2106.15391]

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 D*98 014510 (2018), 1801.10122];
- Guo *et al* [EPJ C79, 13 (2019), 1811.05585]

# Outline of method

Use *distillation* to compute correlation functions

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

involving *large bases of operators* (appropriate structures)

$$\bar{\psi} \Gamma D \ldots \psi \qquad \sum_{\vec{p}_1, \vec{p}_2} C(\vec{P}, \vec{p}_1, \vec{p}_2) M_1(\vec{p}_1) M_2(\vec{p}_2)$$

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

Lüscher method (and extensions): relate **finite-volume energy levels** to **infinite-volume scattering *t*-matrix**.

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

Param. $t(E_{\text{cm}})$ using various $K$-matrix forms, effective range, …

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

# $DK$ (isospin=0)

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

Anisotropic lattices,
$a_s/a_t \approx 3.5$, $a_s \approx 0.12$ fm,
various volumes.

$N_f = 2+1$,
Wilson-clover fermions,
$m_\pi \approx 239$ MeV & 391 MeV.

Use many different fermion-bilinear

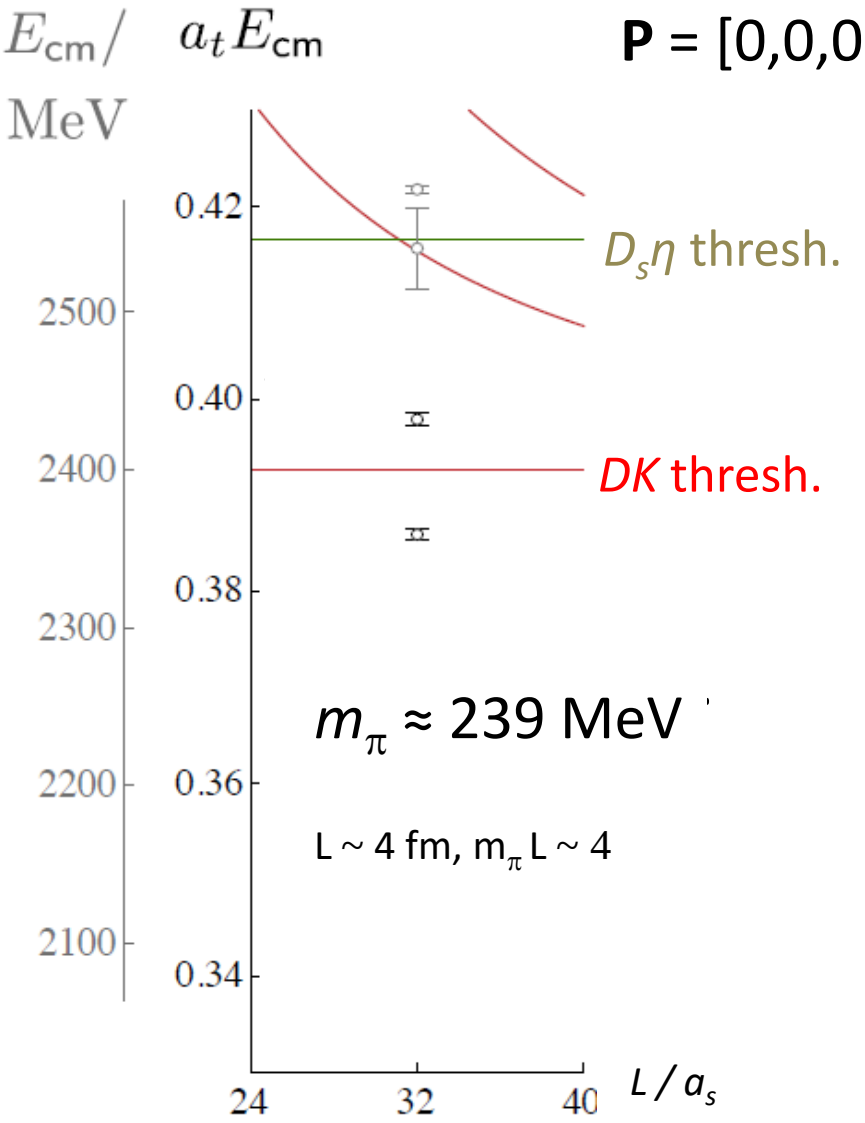
$$\sim \bar{\psi} \Gamma D \ldots \psi$$

and *DK*, ... operators (built from optimised *D* and *K* operators)

# $DK$ (isospin=0)

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

**P** = [0,0,0] $A_1^+$ ($J^P = 0^+, 4^+, \ldots$)




$m_\pi \approx 239$ MeV

L ~ 4 fm, $m_\pi$ L ~ 4

Use many different fermion-bilinear

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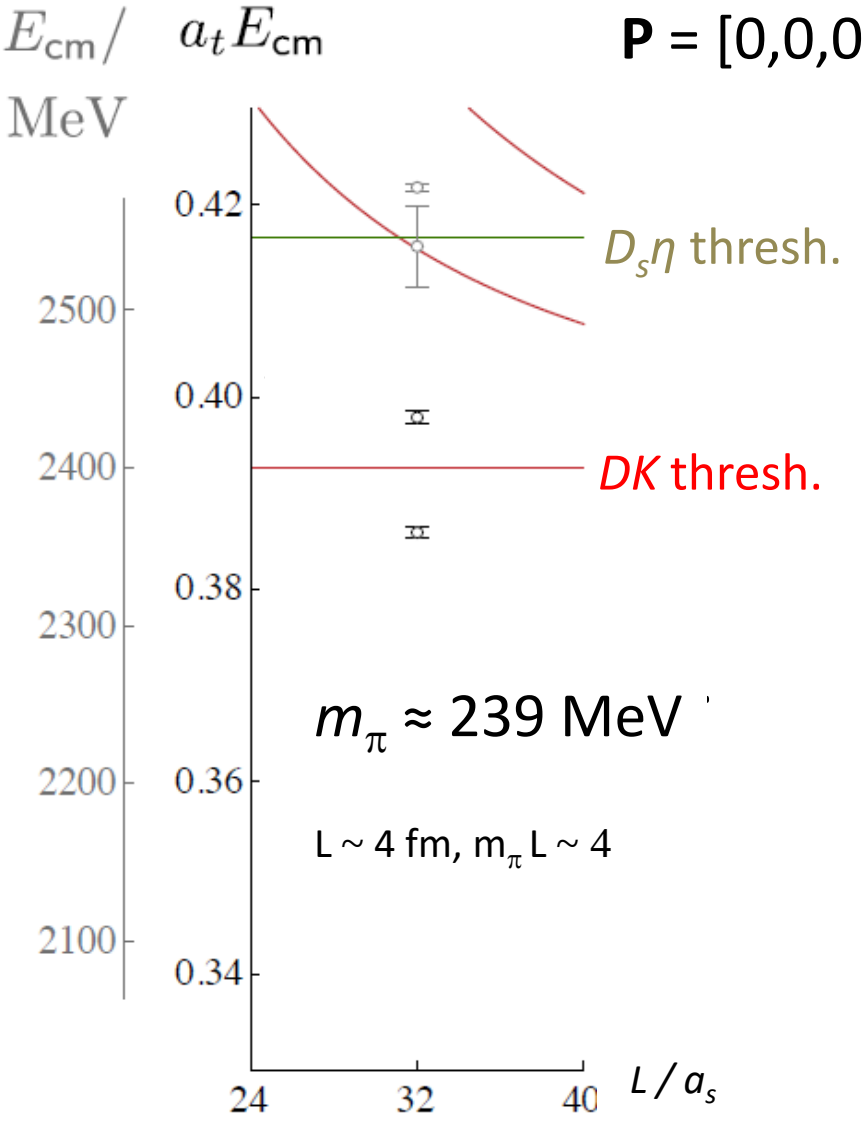
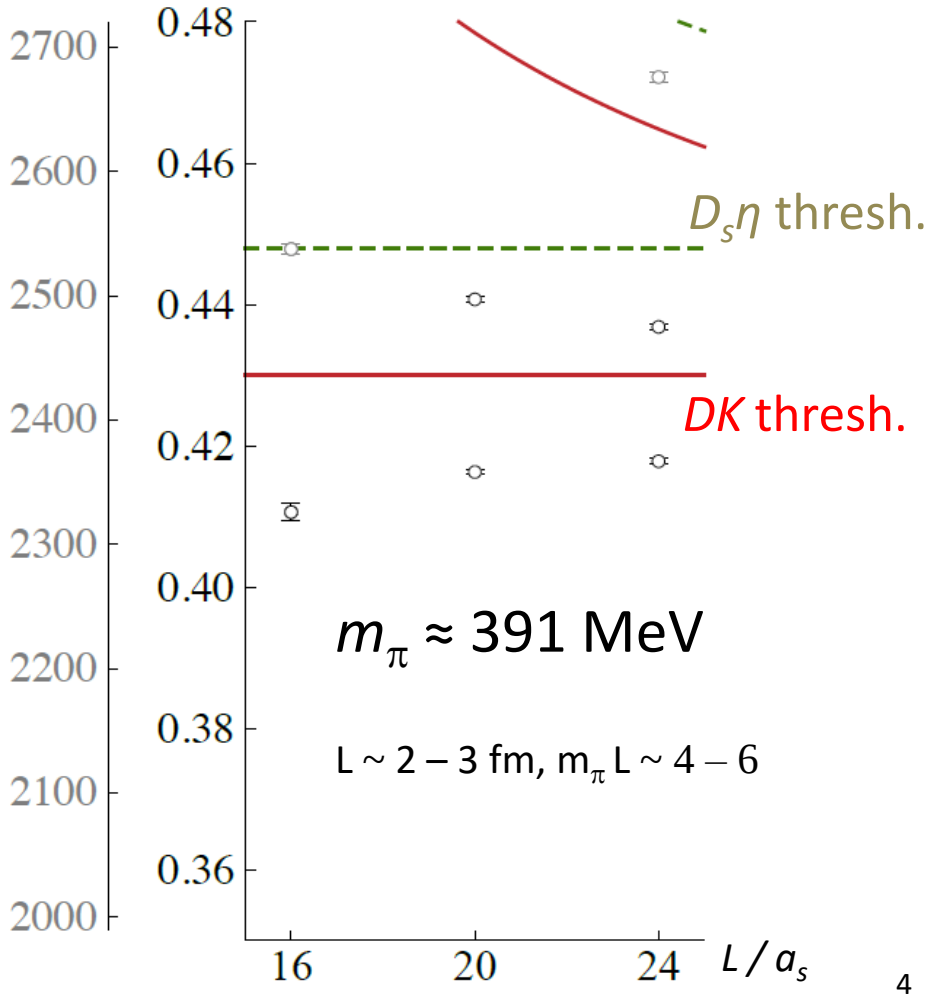
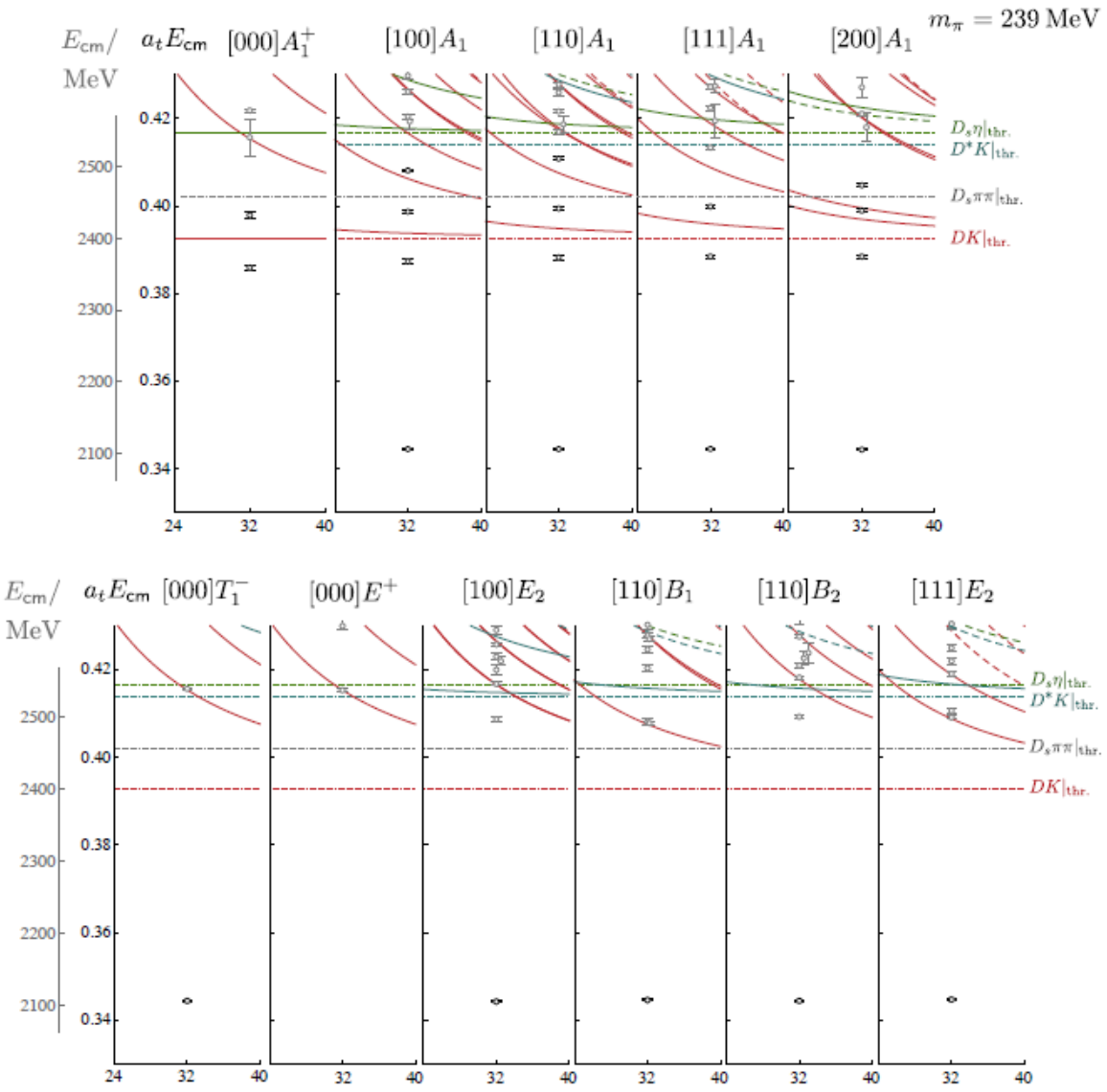


# $DK$ (isospin=0) – spectra

[JHEP 02 (2021) 100]




$m_\pi \approx 239$ MeV

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

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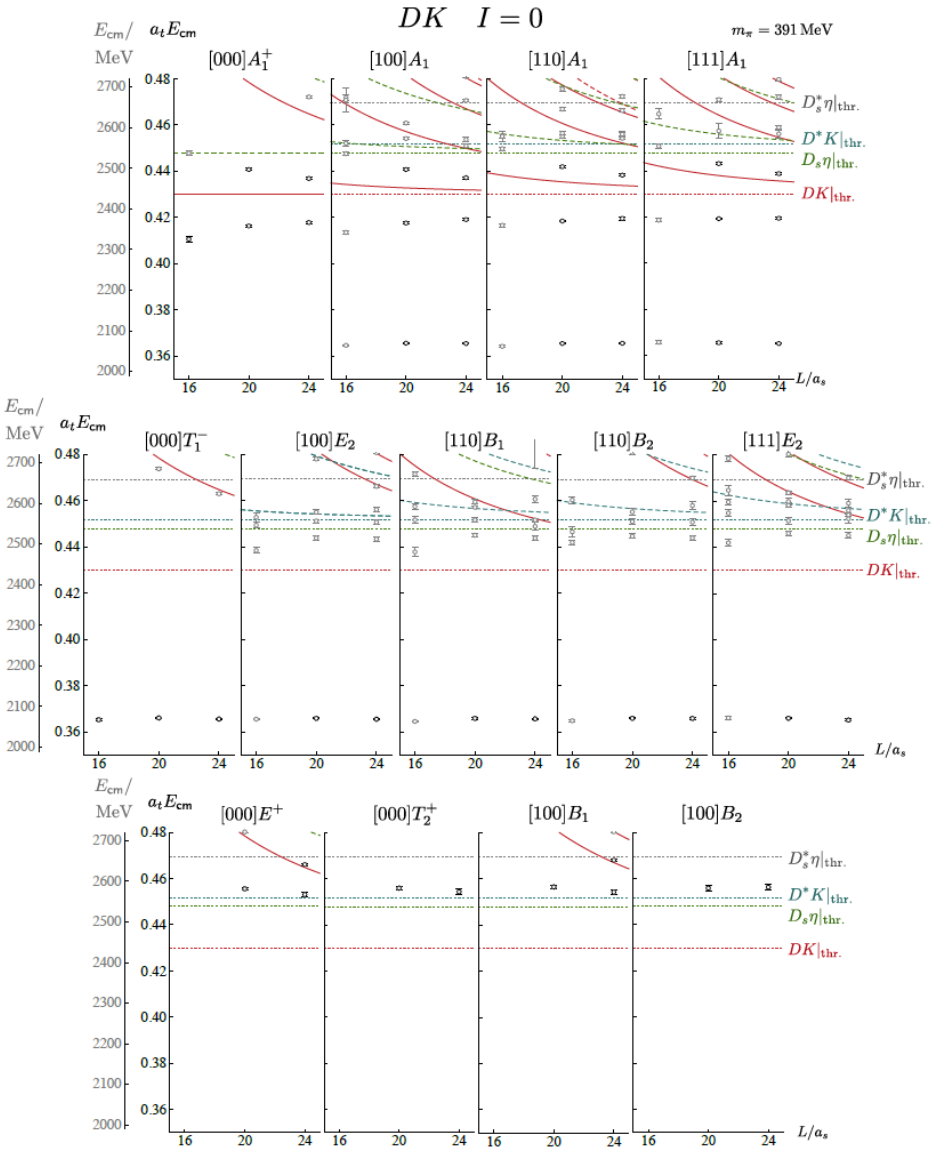



$m_\pi \approx 391$ MeV

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

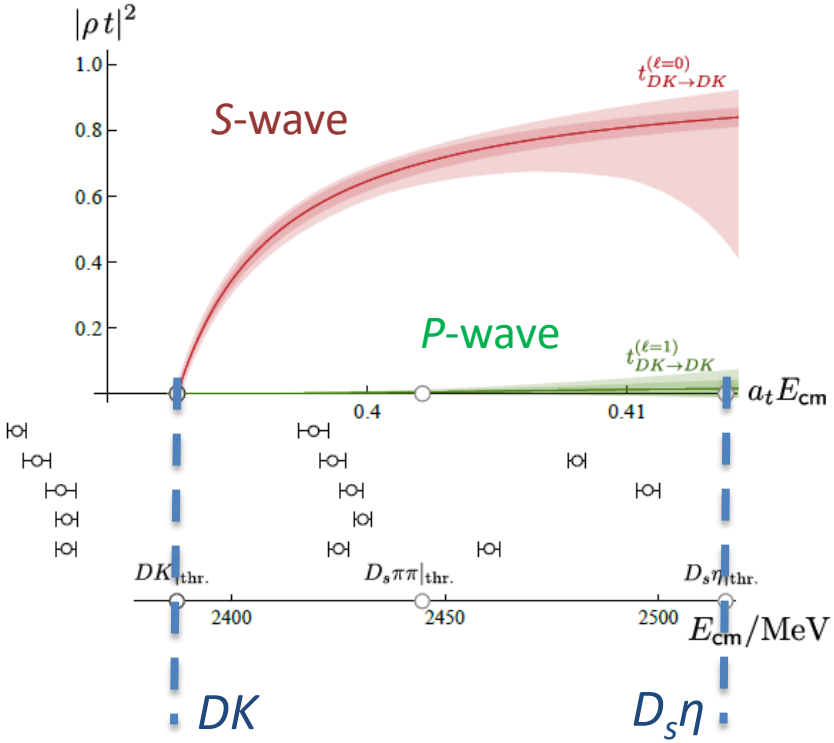
# $DK$ (isospin=0) – amplitudes

[JHEP 02 (2021) 100]

$m_\pi \approx 239$ MeV

(22 energy levels)

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




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

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

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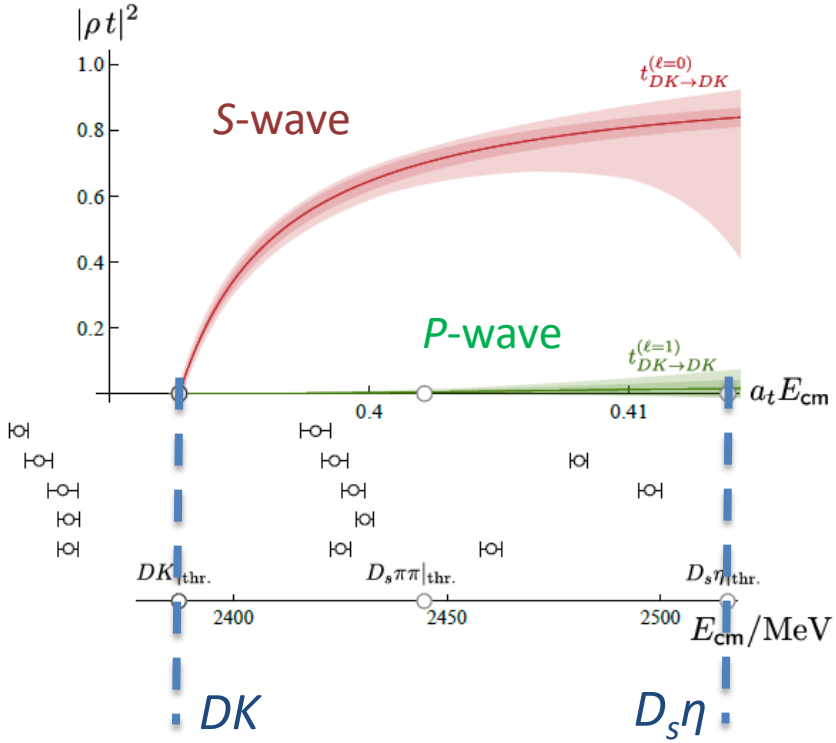


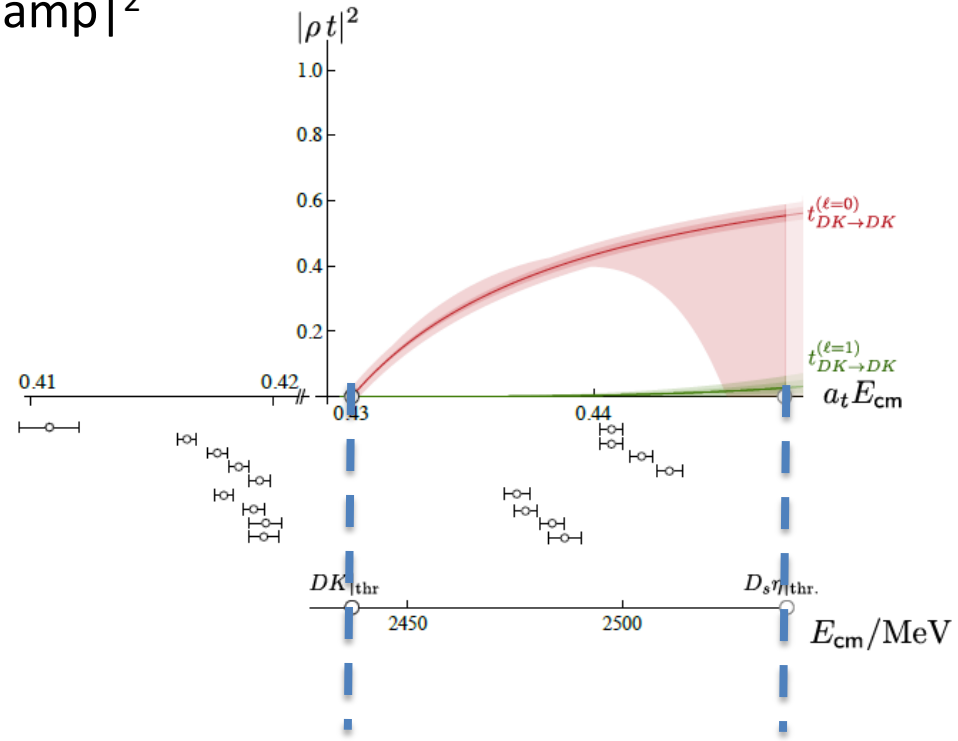


Elastic *DK* scattering in *S* and *P*-wave

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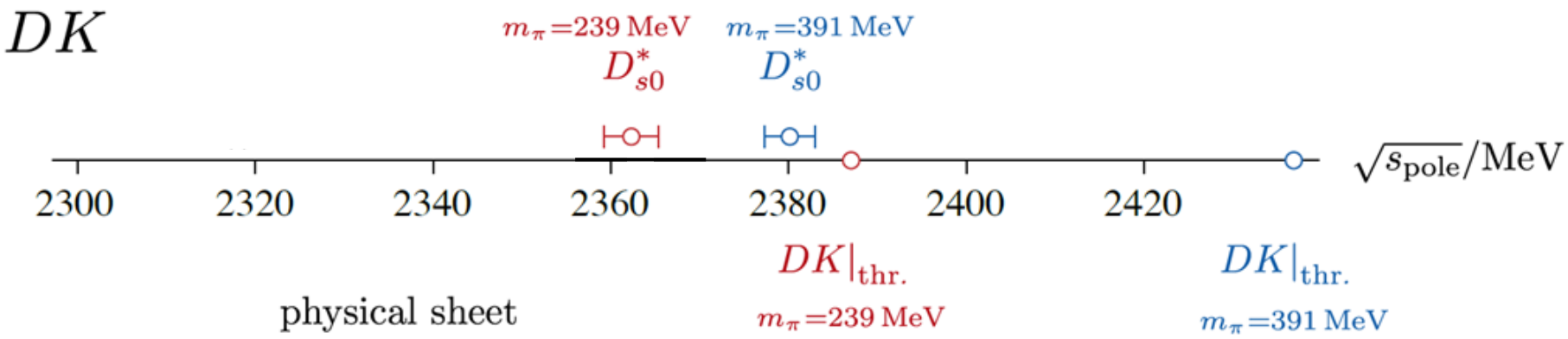
# $DK$ (isospin=0) – *S*-wave poles

[JHEP 02 (2021) 100]




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

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

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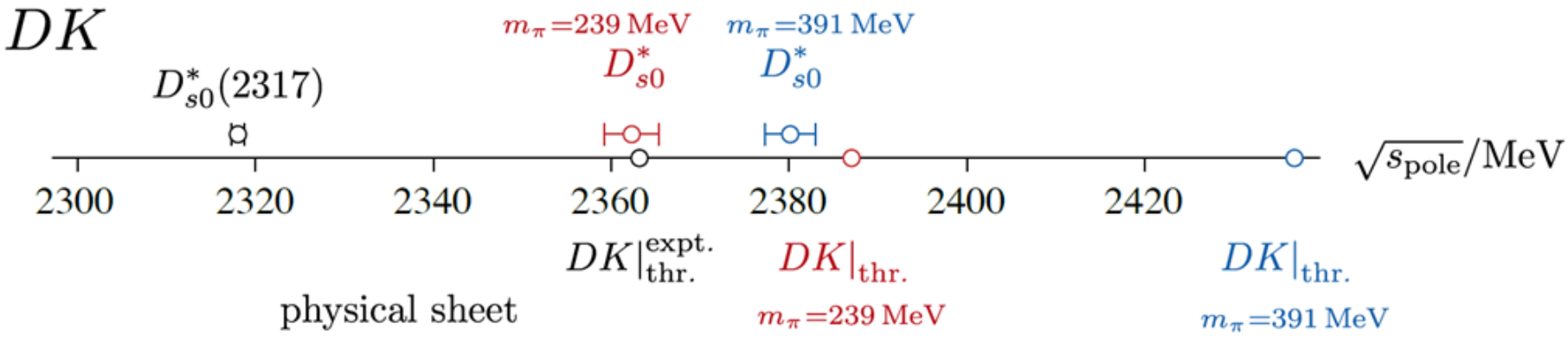


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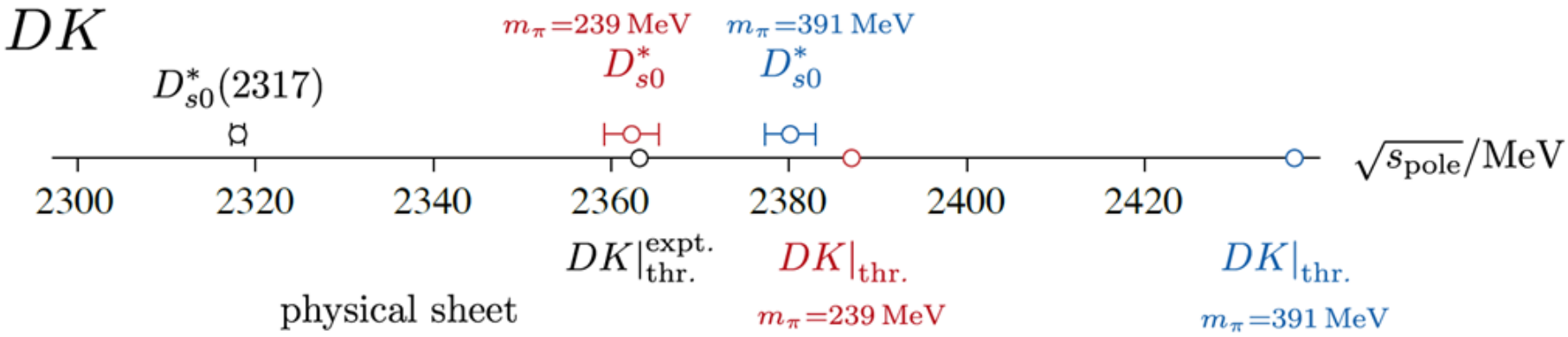


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ΔE = 25(3) MeV for $m_\pi \approx 239$ MeV $\quad Z \lesssim 0.11$

ΔE = 57(3) MeV for $m_\pi \approx 391$ MeV $\quad Z \approx 0.13(6)$

c.f. experiment ΔE ≈ 45 MeV (decays to $D_s\pi^0$)

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

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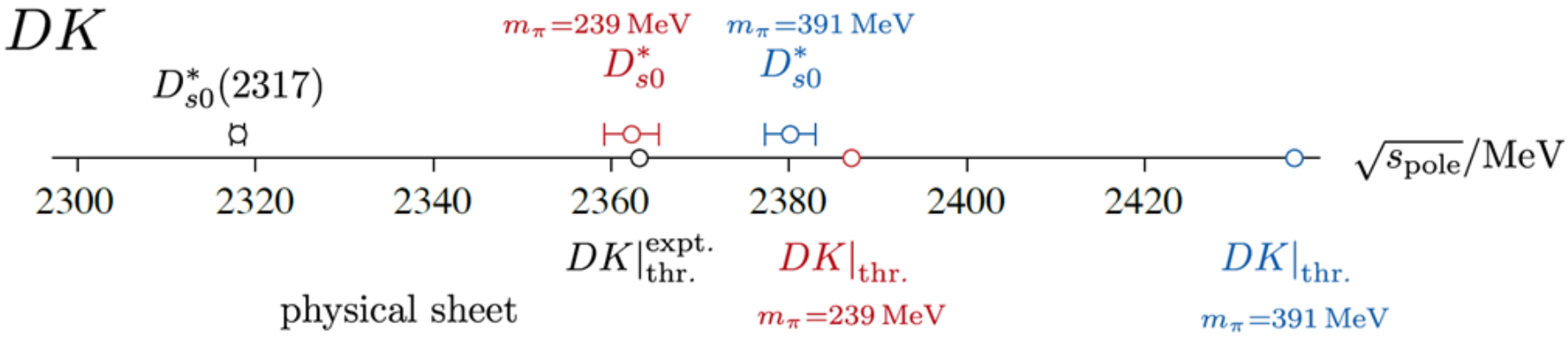
[JHEP 02 (2021) 100]

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c.f. experiment ΔE ≈ 45 MeV (decays to $D_s\pi^0$)

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

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

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

[JHEP 02 (2021) 100]

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

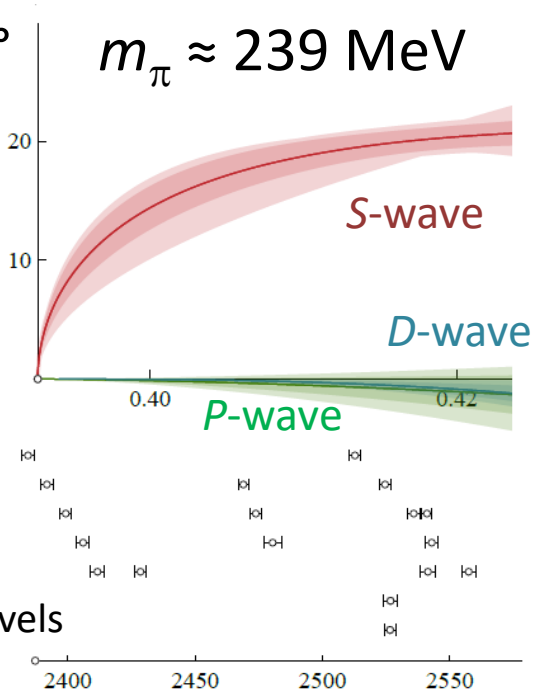
## Exotic flavour $(\bar{l}\bar{l}cs)$

[JHEP 02 (2021) 100]

δ / °

$m_\pi \approx 239$ MeV

I = 0




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

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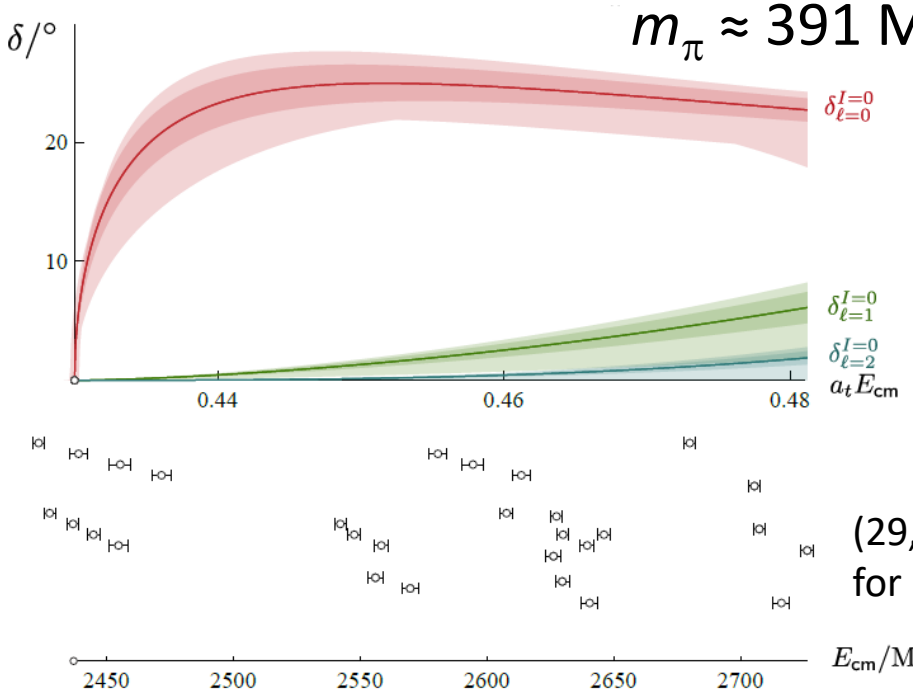


(29,28 levels for I=0,1)

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

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[JHEP 02 (2021) 100]

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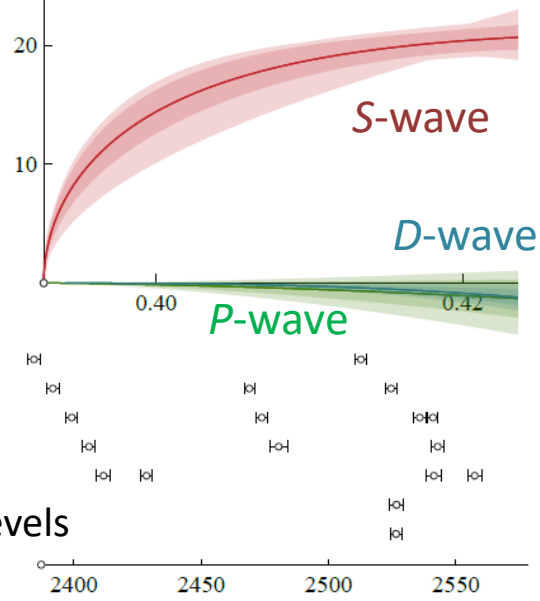
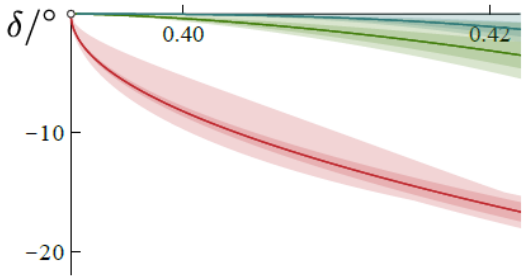






(18, 18 levels for I=0,1)

I = 1

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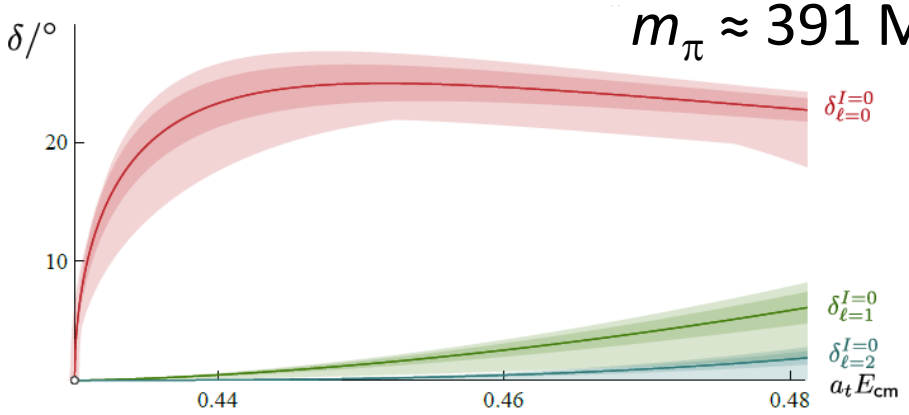


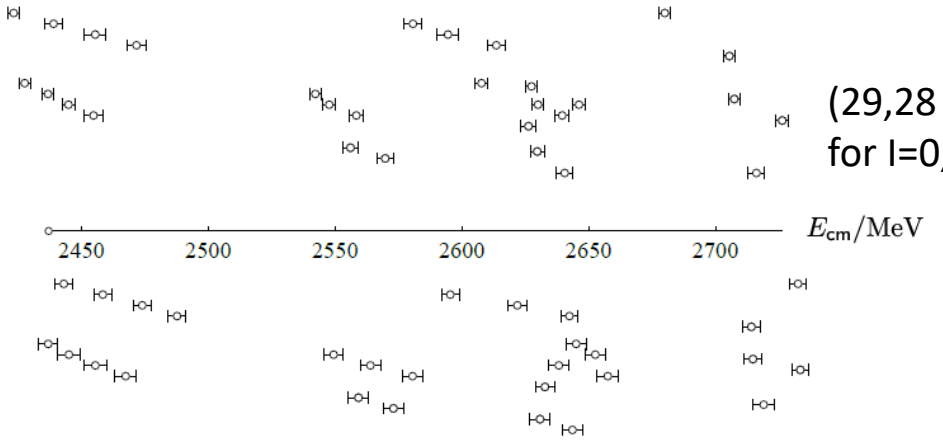


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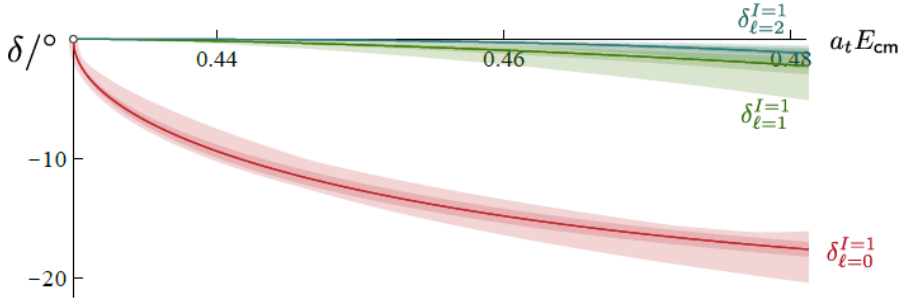

# $D\bar{K}$ (isospin=0,1)

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

[JHEP 02 (2021) 100]

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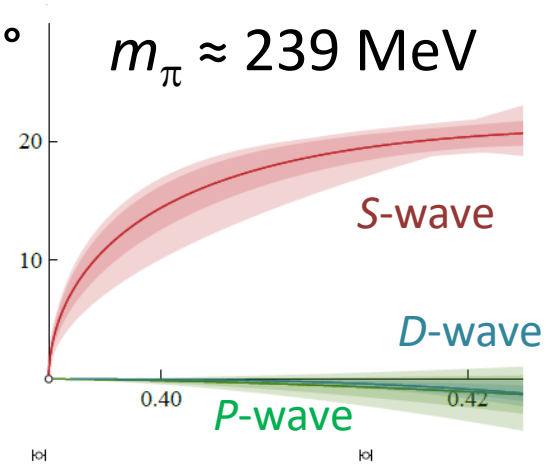
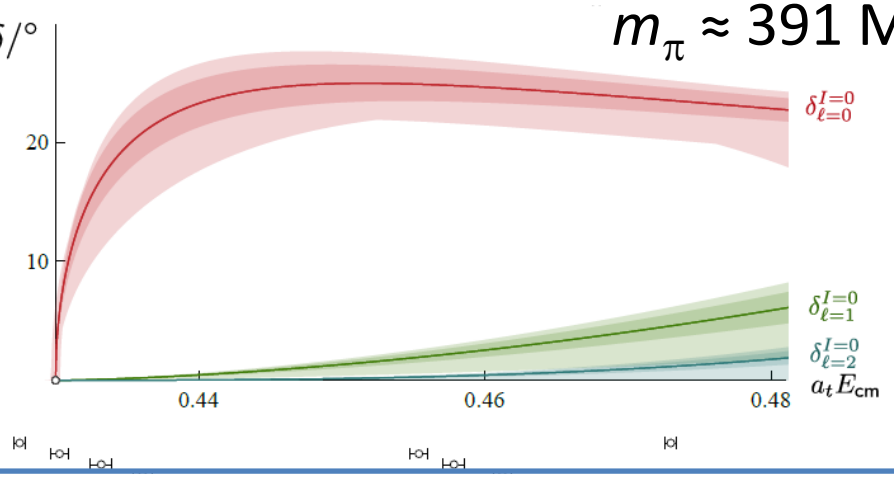
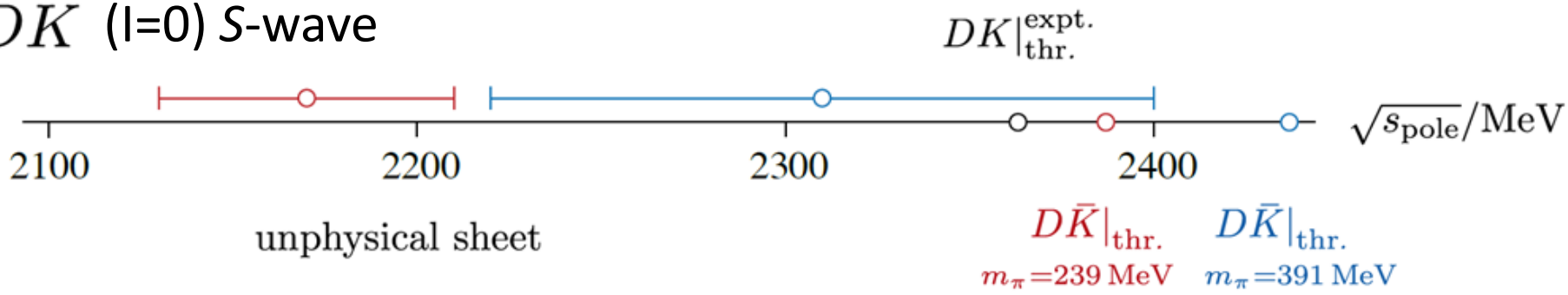



$D\bar{K}$ (I=0) *S*-wave




Suggestion of a **virtual bound-state** pole (**exotic flavour**)

# SU(3) flavour symmetry

[JHEP 02 (2021) 100]

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SU(3) multiplets:

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

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

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$(I=0)$ $DK$-$D_s\eta$: $\overline{\mathbf{3}} \oplus \overline{\mathbf{15}}$

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

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

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

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

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

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

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

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

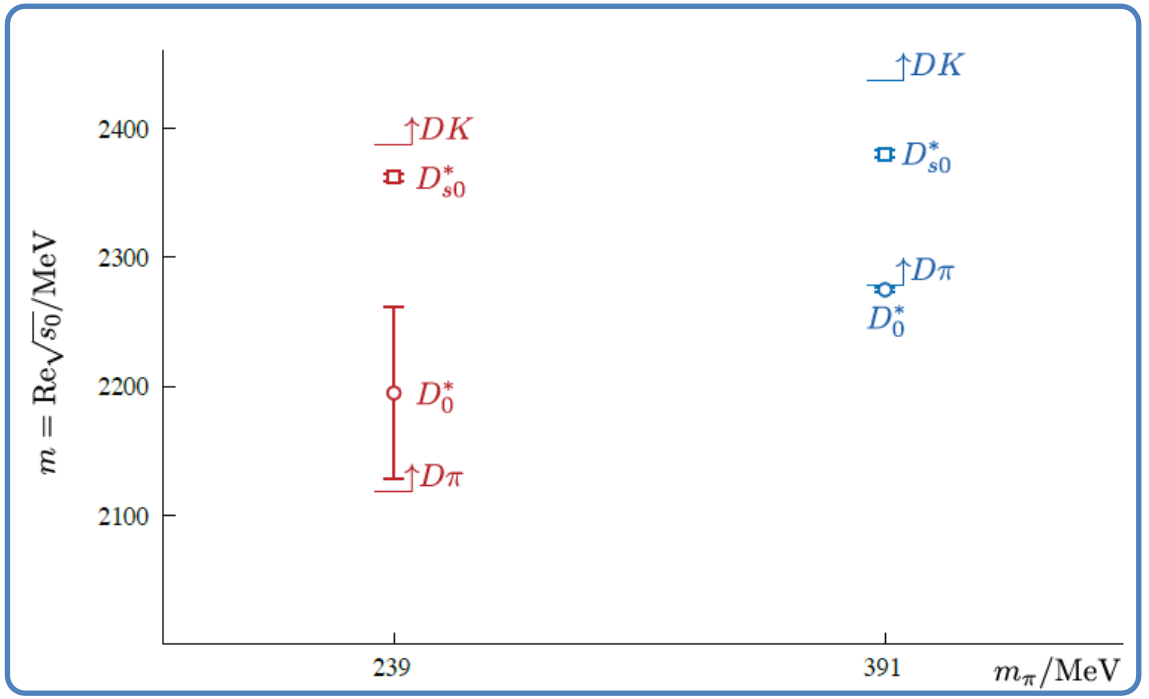
$\mathbf{6}$ virtual bound state

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

[See also PR D87, 014508 (2013) (1208.4535); PL B767, 465 (2017) (1610.06727); PR D98, 094018 (2018) (1712.07957); *PR D*98 014510 (2018) (1801.10122); *EPJ C79, 13 (2019)* (1811.05585); arXiv:2106.15391]

# Summary

- **Mapped out the energy-dependence** of **scattering amplitudes** using lattice QCD




- 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*]

Jefferson Lab and surroundings, USA:

JLab: Robert Edwards, Jie Chen, Frank Winter; ORNL: Bálint Joó

W&M: Jozef Dudek[1], Arkaitz Rodas, *Christopher Johnson*, *Archana Radhakrishnan, Felipe Ortega* ([1] and Jefferson Lab)

ODU: Raúl Briceño[1], Andrew Jackura, Luka Leskovec

Trinity College Dublin, Ireland:

Michael Peardon, Sinéad Ryan, *Nicolas Lang*

University of Cambridge, UK:

CT, Bipasha Chakraborty, David Wilson, *James Delaney*

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