Excited mesons and resonances from lattice QCD

– charm/charmonium

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"Bound states in strongly coupled systems", GGI
12 – 16 March 2018

Excited lattice QCD spectroscopy

Finite-volume energy eigenstates from:

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

Use many different interpolating operators

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Excited charmonia
[JHEP 1612, 089 (2016)]

Large bases of fermion-bilinear operators $\sim \bar{\psi} \Gamma D \ldots \psi$

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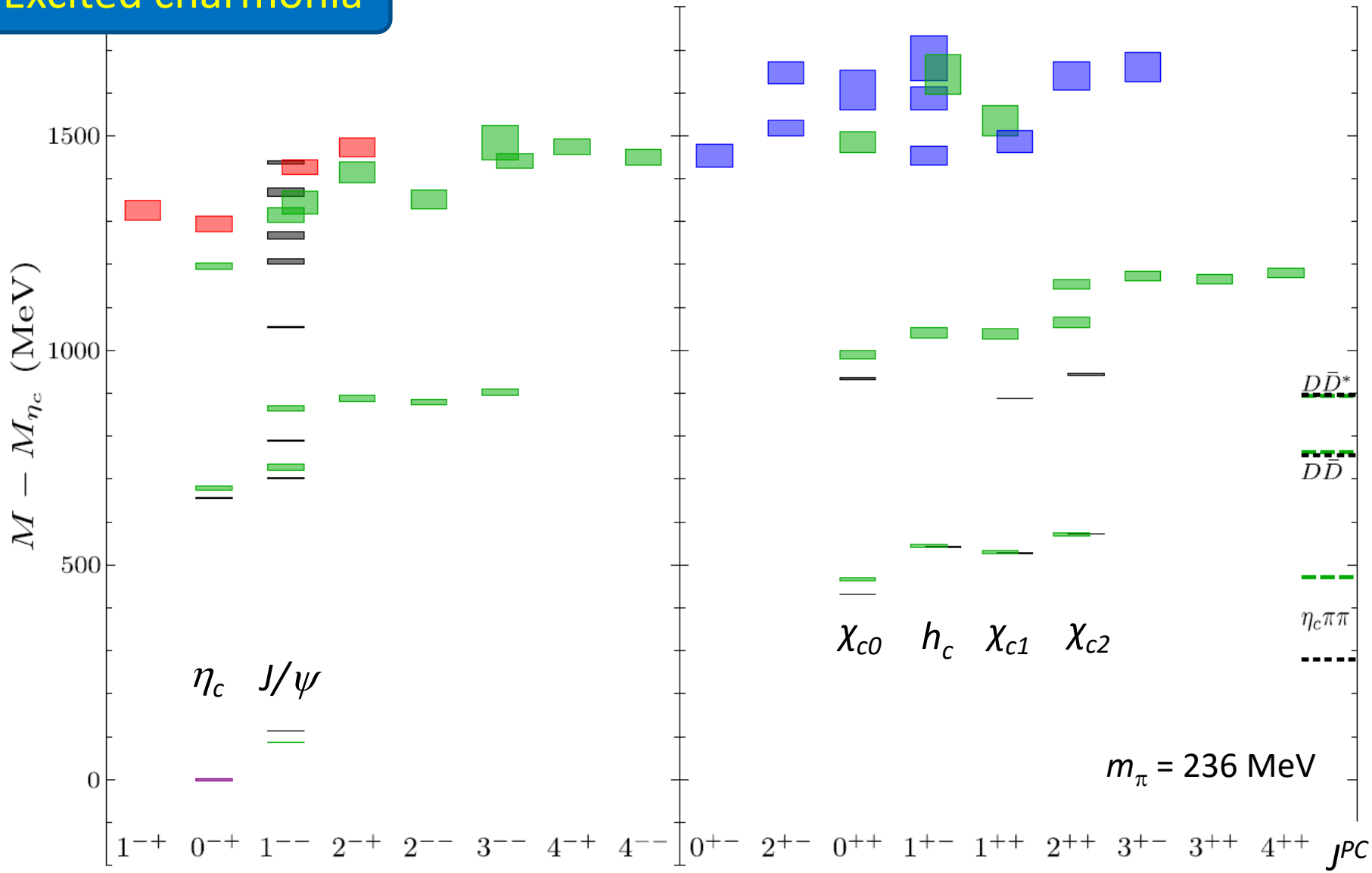

One lattice spacing and volume [Cheung *et al* (HadSpec), JHEP 1612, 089 (2016)]
(similar pattern to older m_π = 391 MeV, 1 lattice spacing and 3 volumes)

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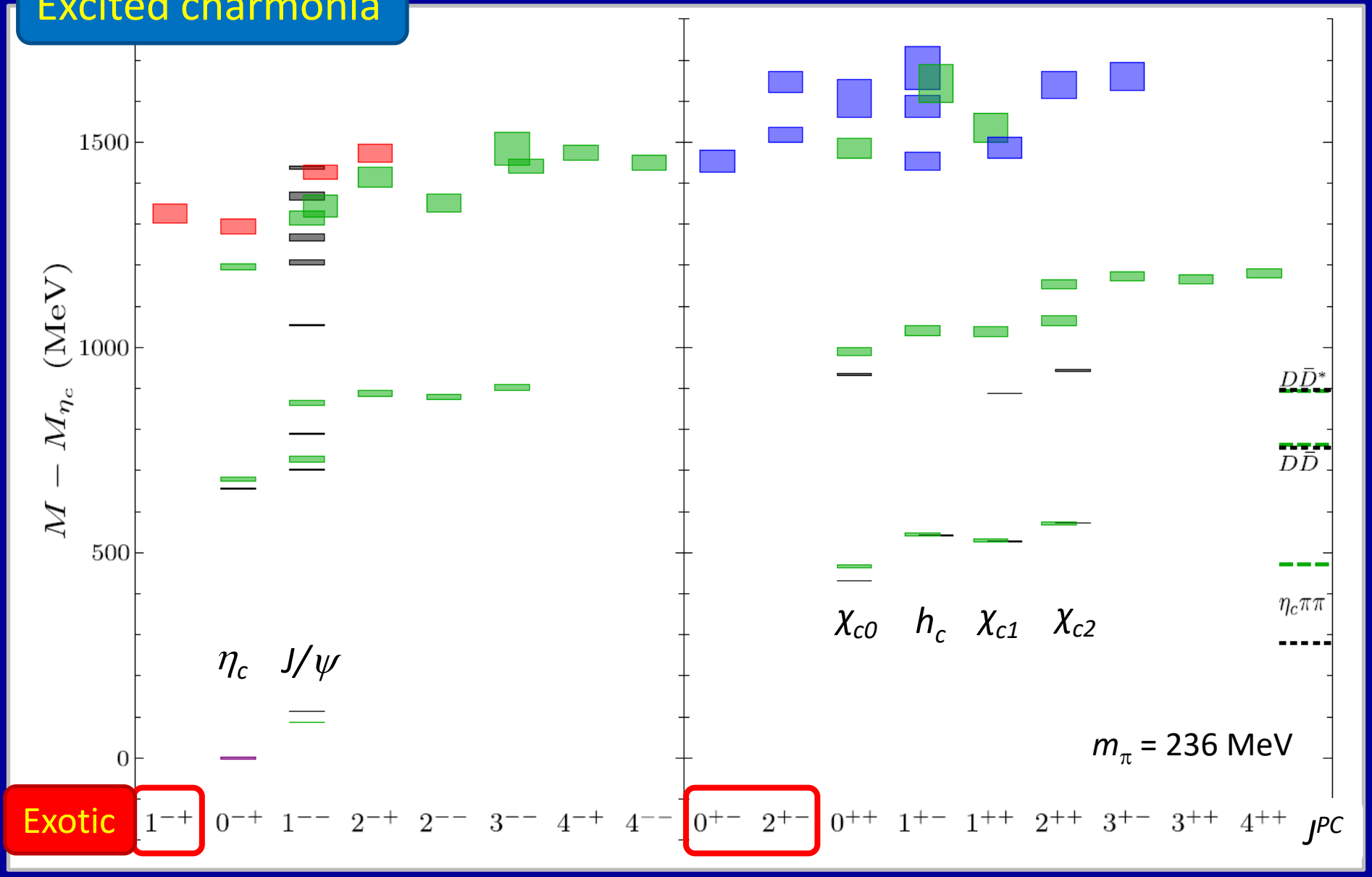

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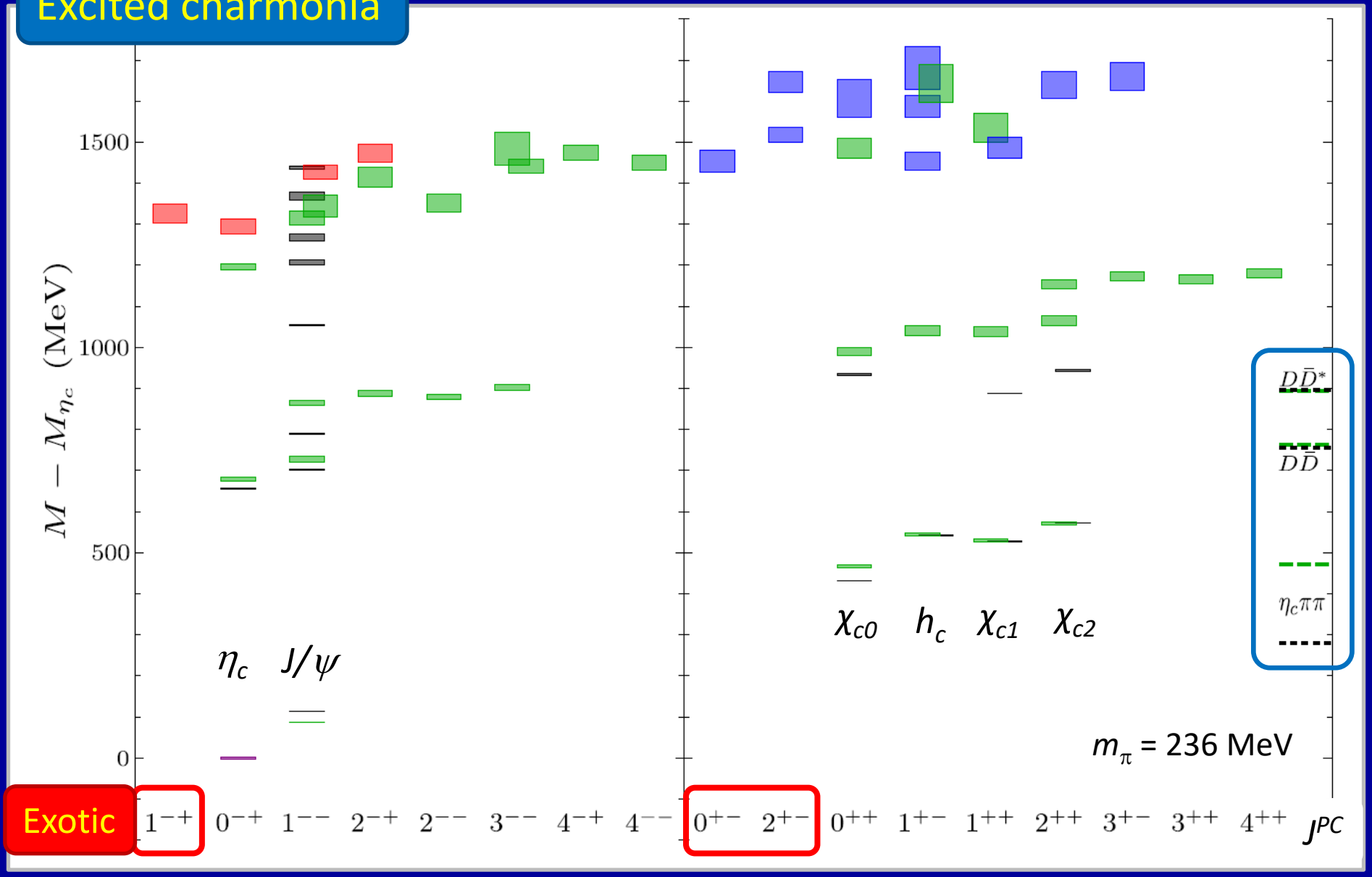

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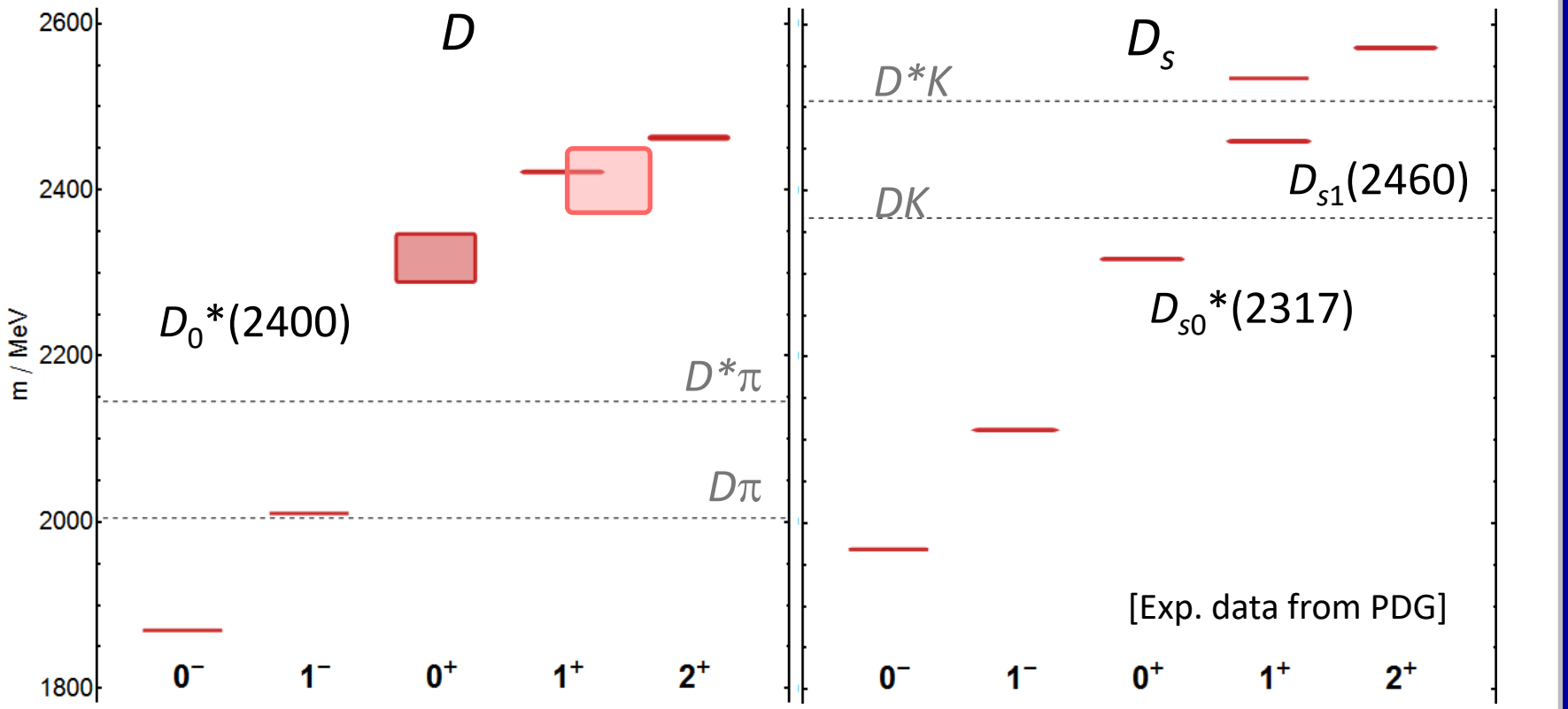
Charm-light (D) and charm-strange (D_s) mesons



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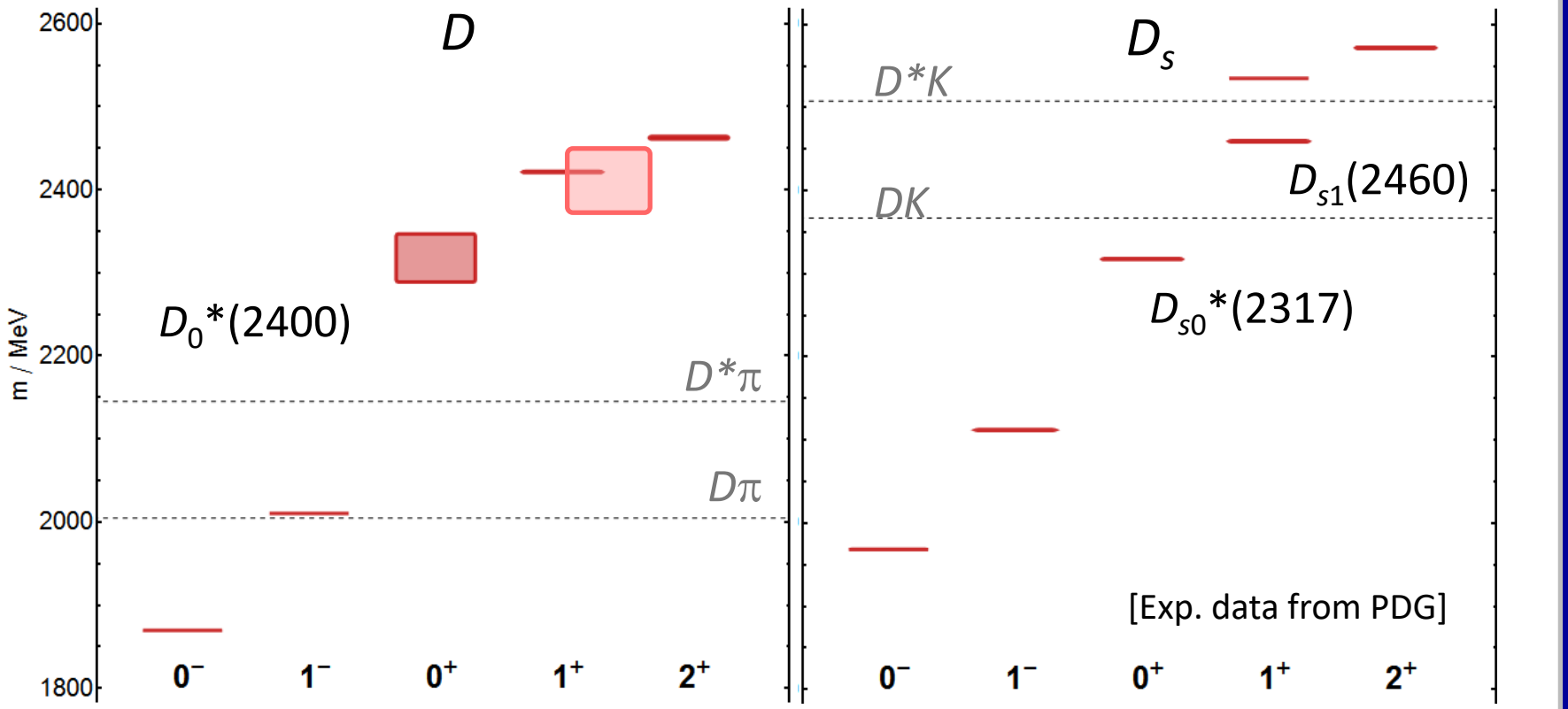

Some other LQCD studies:

- Mohler *et al* [PR D87, 034501 (2012)] – 0^+ $D\,\pi$ and 1^+ $D^*\,\pi$ resonances
- Mohler *et al* [PRL 111, 222001 (2013)] – 0^+ $D_{s0}(2317)$ below $D\,K$ threshold
- Lang *et al* [PRD 90, 034510 (2014)] – 0^+ $D_{s0}(2317)$ and 1^+ $D_{s1}(2460)$, $D_{s1}(2536)$
- Bali *et al* (RQCD) [PRD D96, 074501 (2017)] – 0^+ $D_{s0}(2317)$ and 1^+ $D_{s1}(2460)$

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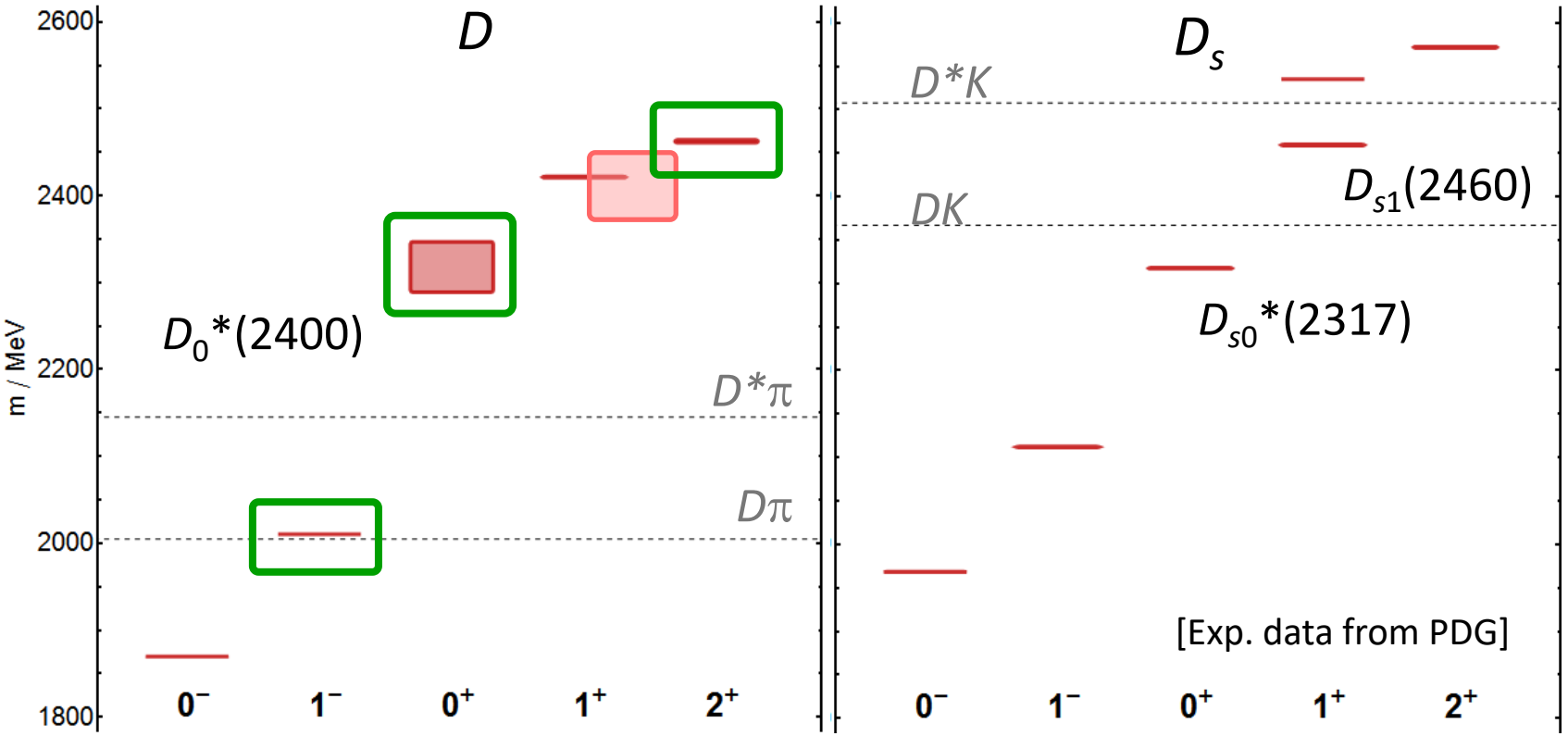

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$D\pi$, $D\eta$, $D_s\bar{K}$ ($I=\frac{1}{2}$)

Isospin = ½
Strangeness = 0
Charm = 1

Use many different fermion-bilinear operators,

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

and $D\pi$, $D\eta$, $D_s\bar{K}$ 'meson-meson' operators

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

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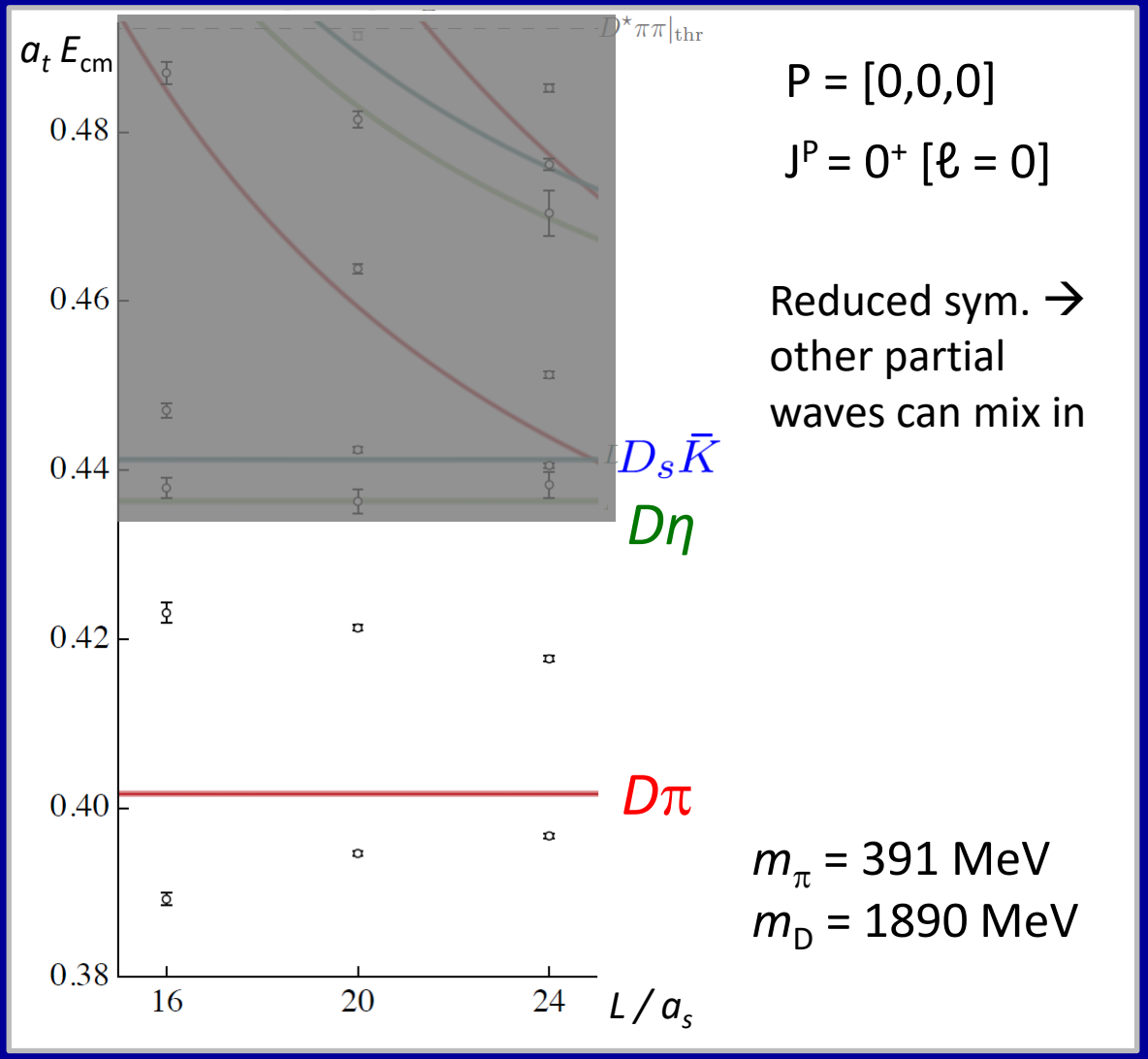

P = [0,0,0]

$J^P = 0^+$ [$\ell = 0$]

Reduced sym. → other partial waves can mix in

m_π = 391 MeV
m_D = 1890 MeV

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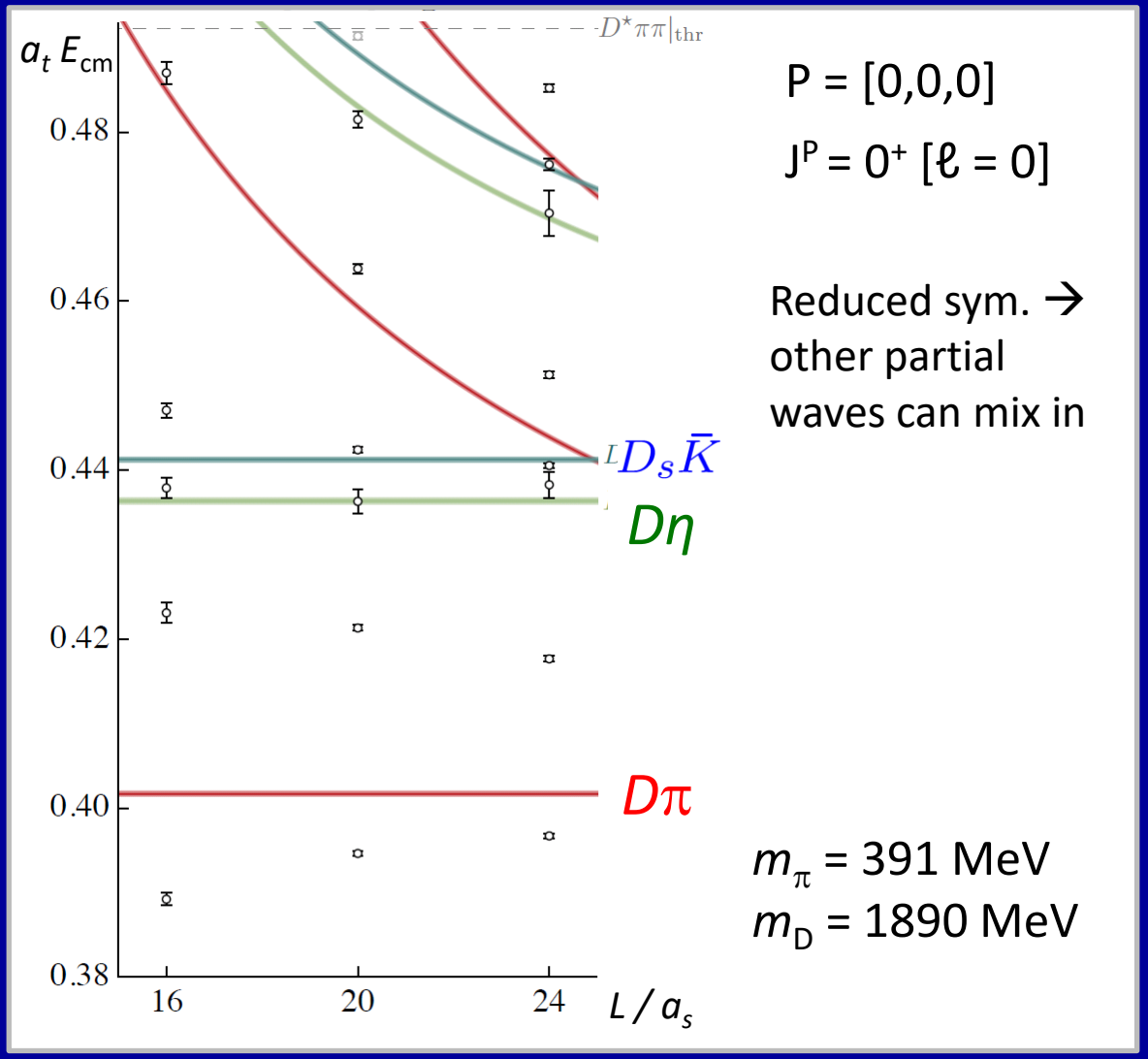

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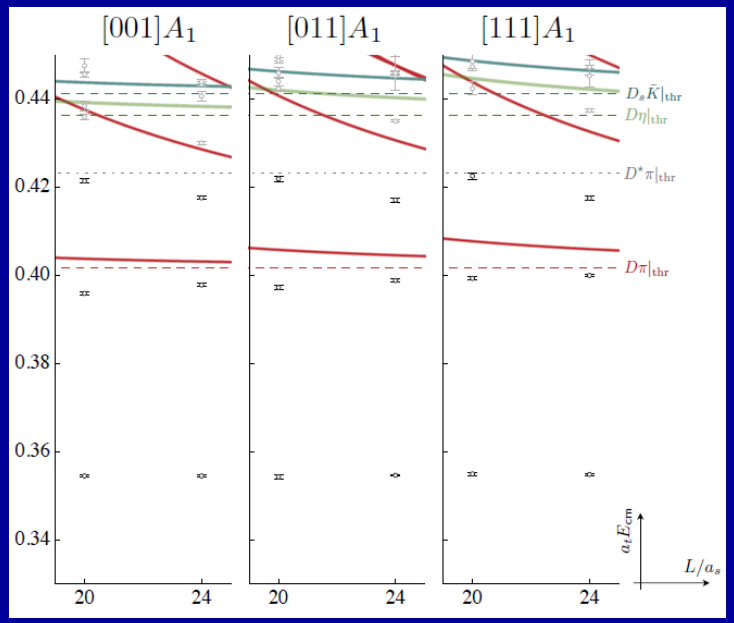
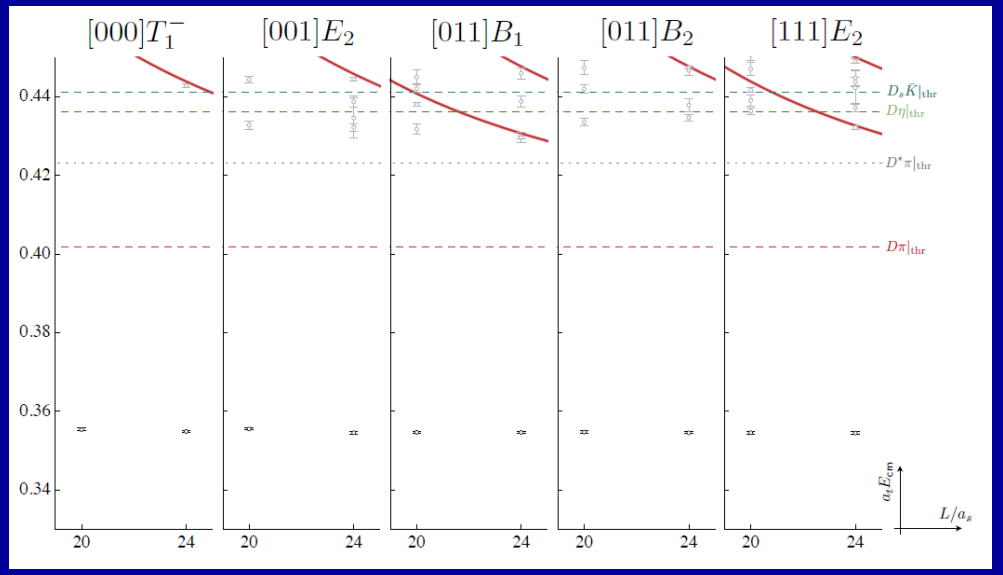
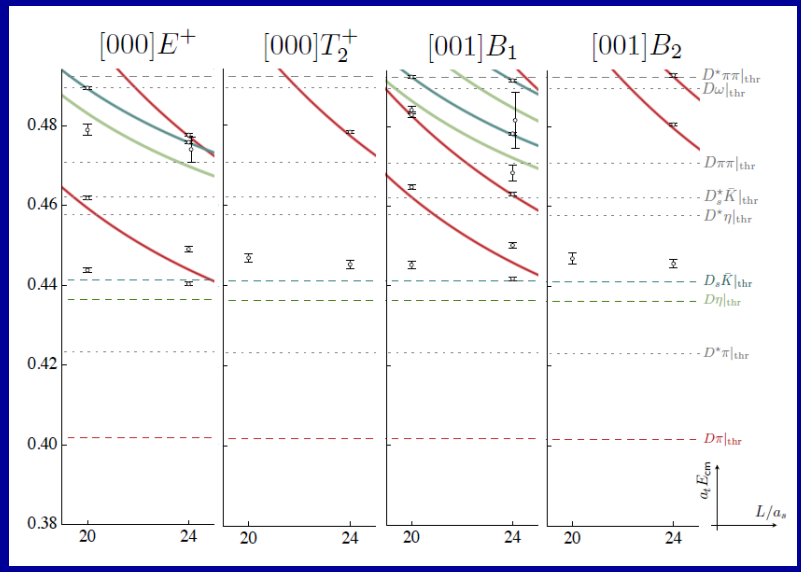
$D\pi$, $D\eta$, $D_s\bar{K}$ (I=½): spectra

[JHEP 1610, 011 (2016)]



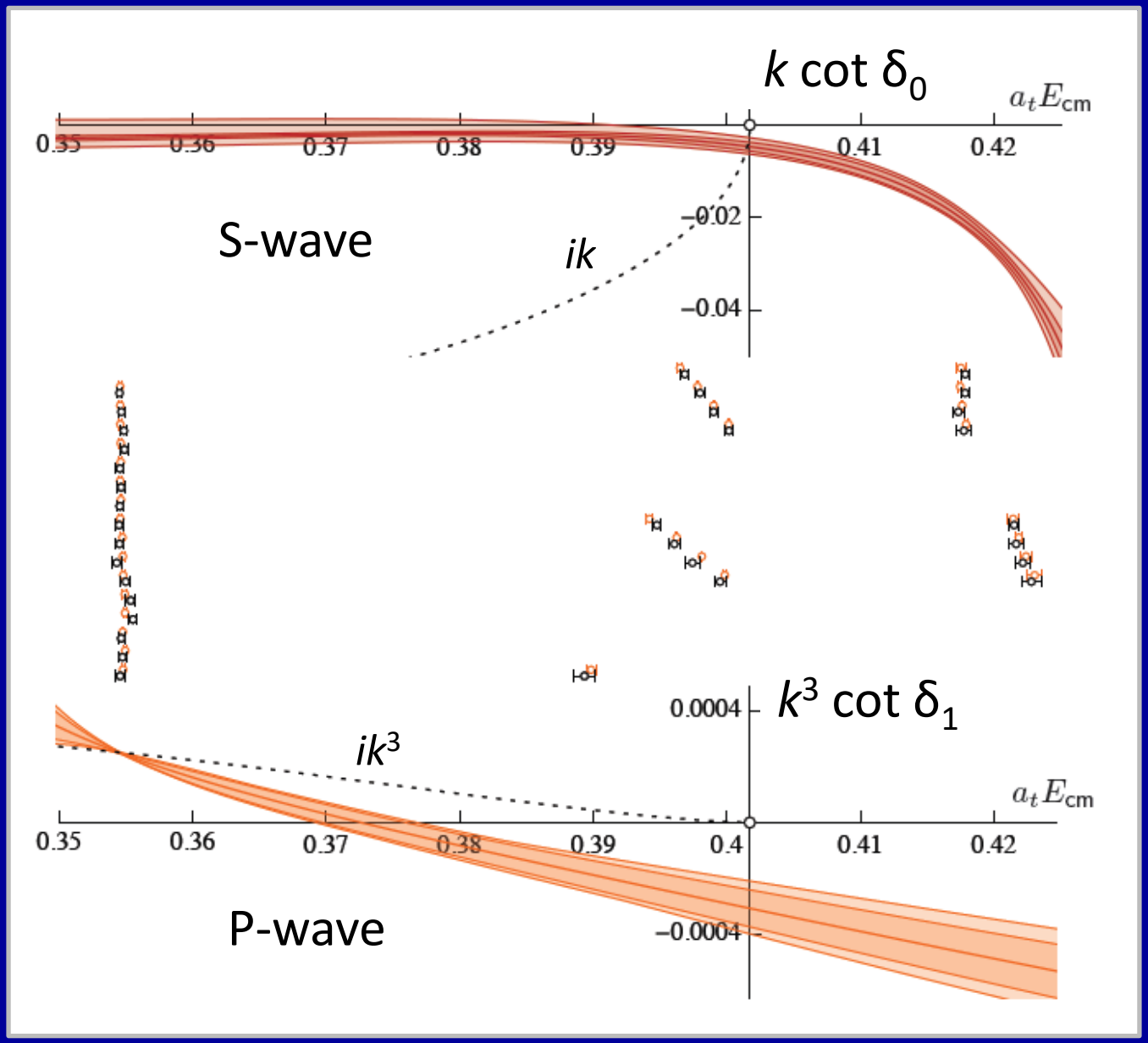


Use 47 energy levels for ℓ = 0, 1 and 18 for ℓ = 2



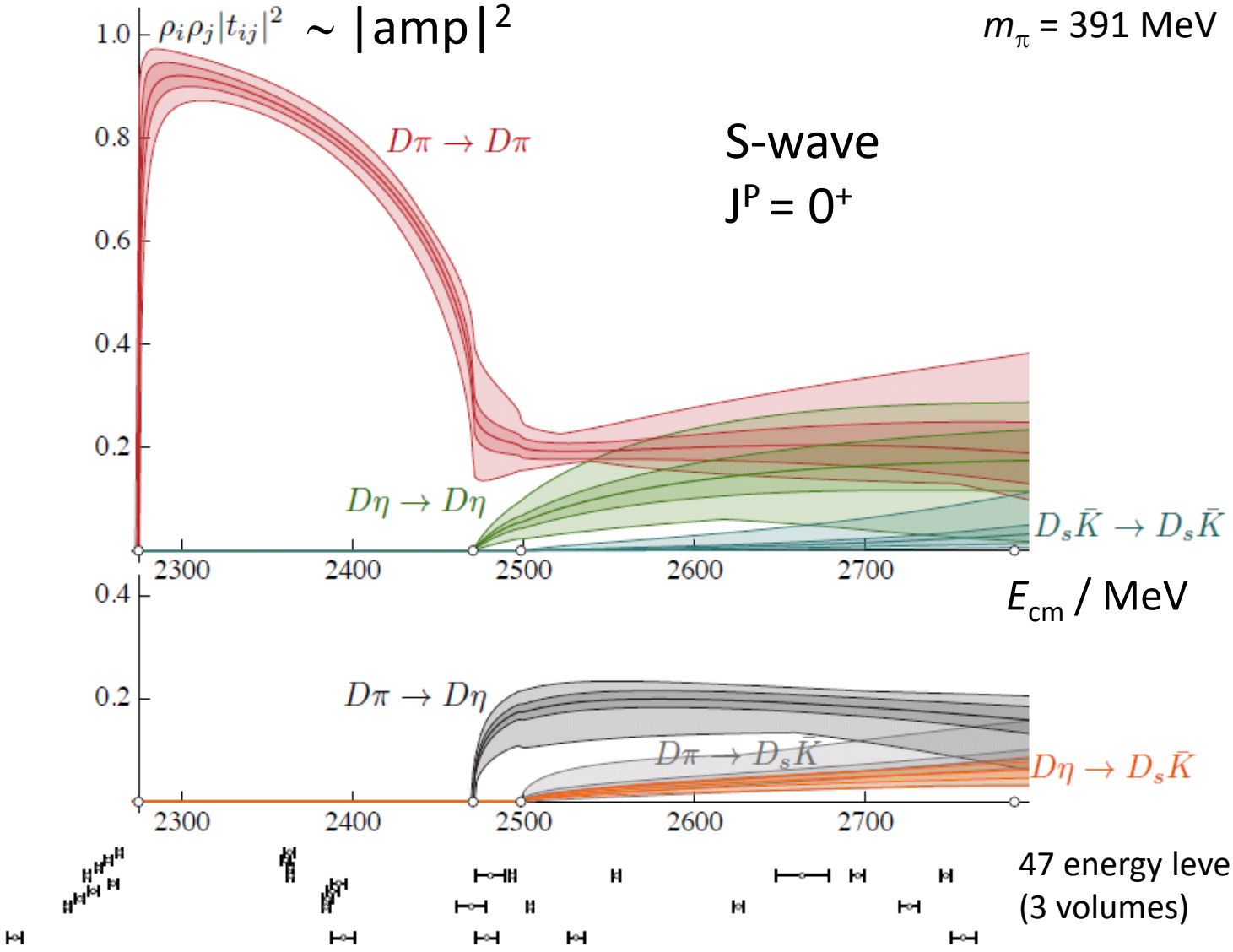
Elastic Dπ (I=½): ℓ = 0,1

[JHEP 1610, 011 (2016)]



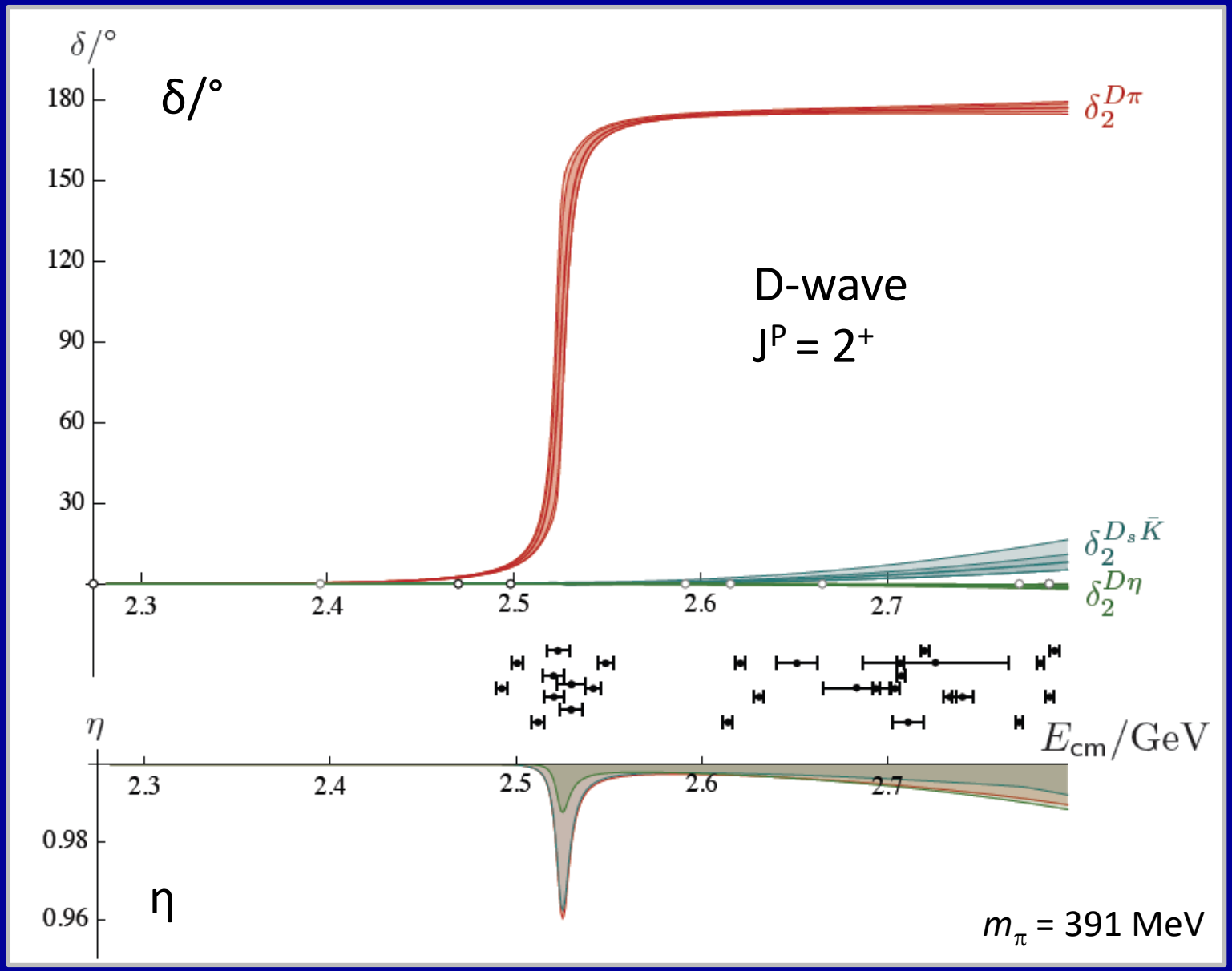
$D\pi$, $D\eta$, $D_s\bar{K}$ ($I=\frac{1}{2}$): $\ell = 0$

[JHEP 1610, 011 (2016)]



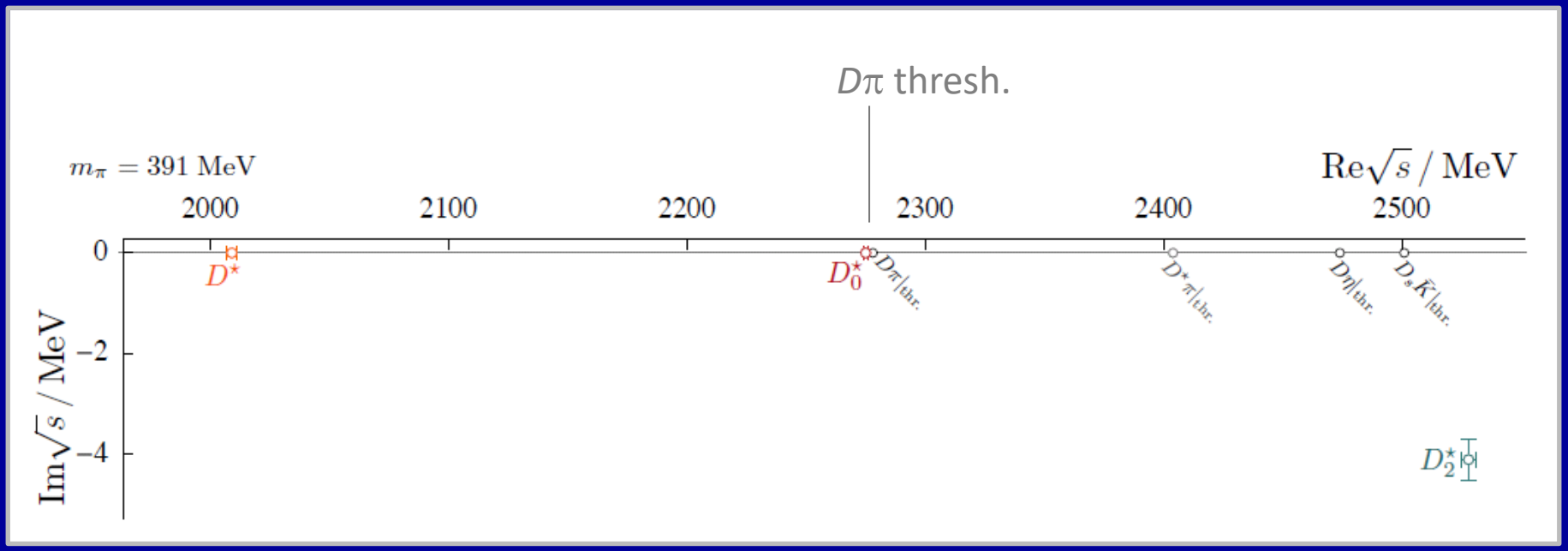
$D\pi$, $D\eta$, $D_s\bar{K}$ (I=½): $\ell = 2$

[JHEP 1610, 011 (2016)]



$D\pi$, $D\eta$, $D_s\bar{K}$ (I=½): poles of *t*-matrix

[JHEP 1610, 011 (2016)]



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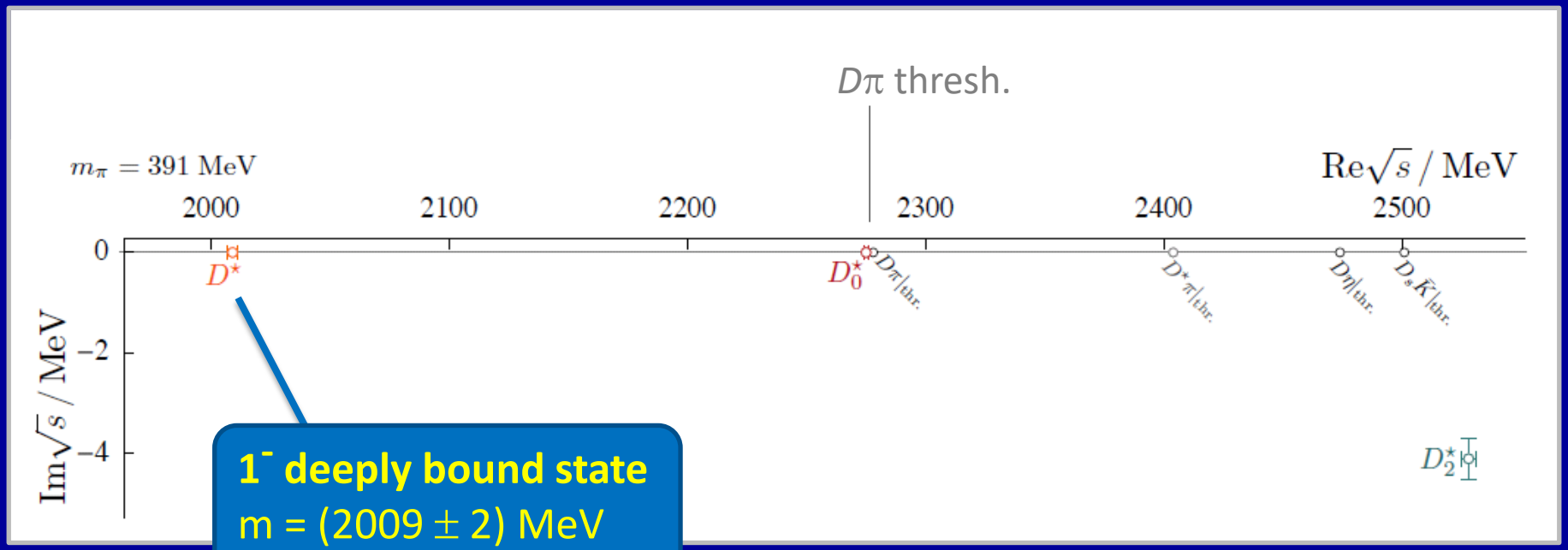


1^- deeply bound state

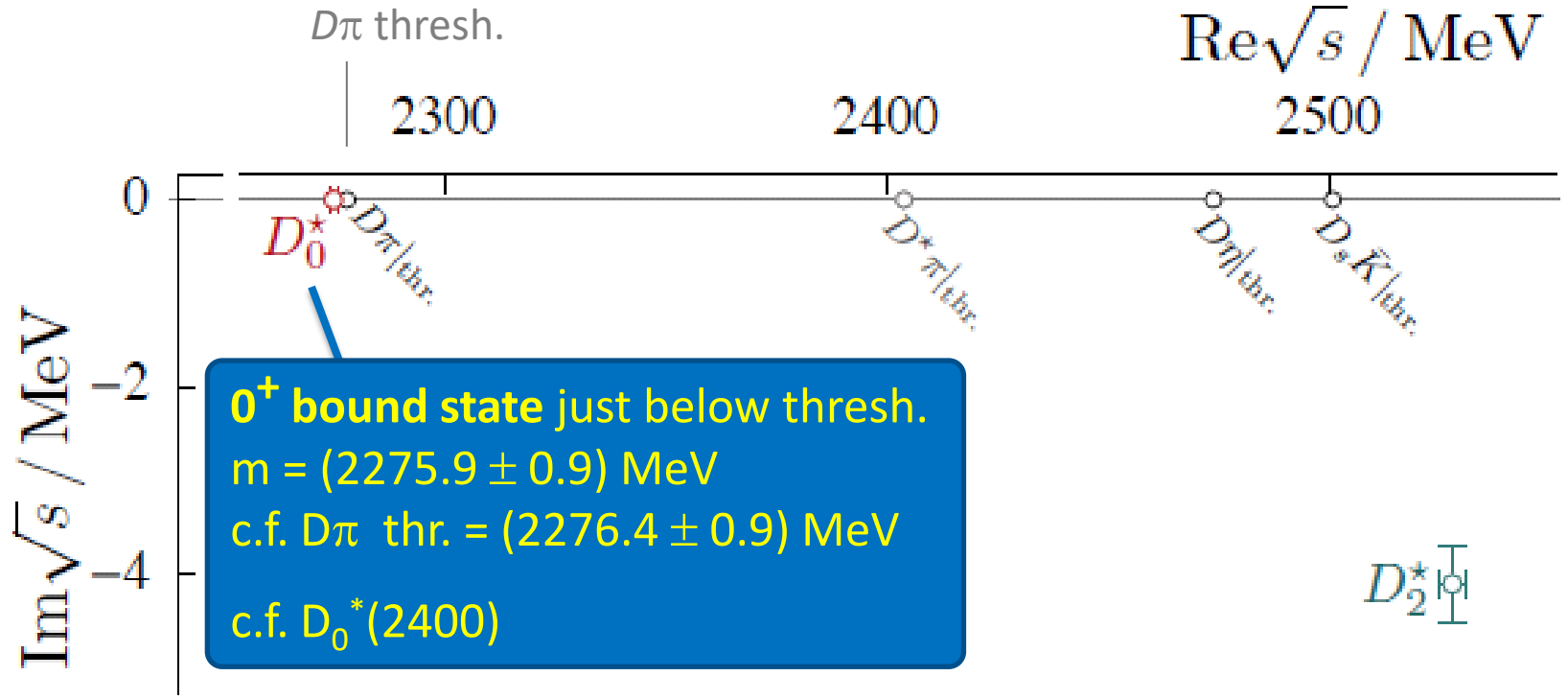
m = (2009 ± 2) MeV

c.f. $D^*(2007)$

Dπ, Dη, $D_s\bar{K}$ (I=½): poles of *t*-matrix

[JHEP 1610, 011 (2016)]

m_π = 391 MeV

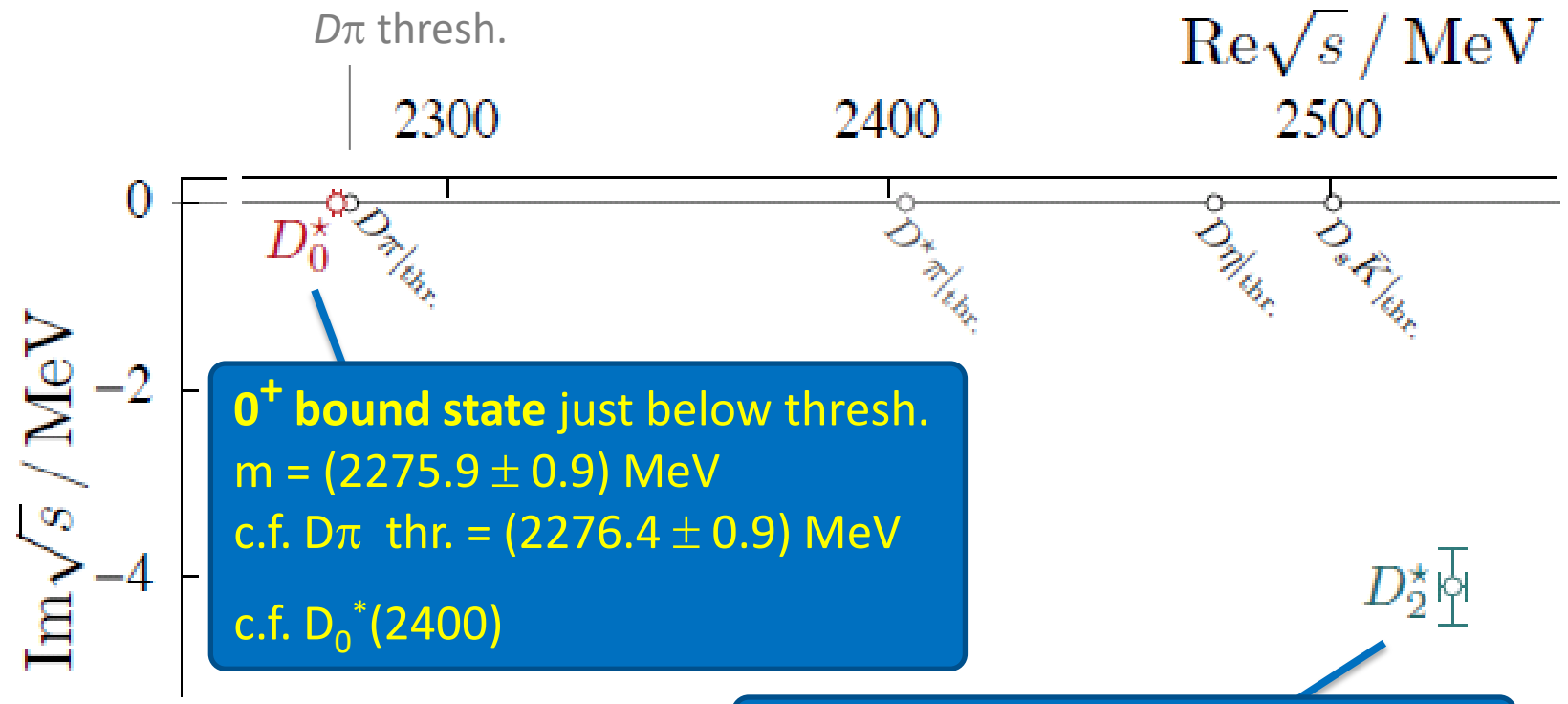


0^+ bound state just below thresh.
m = (2275.9 ± 0.9) MeV
c.f. Dπ thr. = (2276.4 ± 0.9) MeV

c.f. $D_0^*(2400)$

Dπ, Dη, $D_s\bar{K}$ (I=½): poles of *t*-matrix

[JHEP 1610, 011 (2016)]



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m = (2275.9 ± 0.9) MeV
c.f. Dπ thr. = (2276.4 ± 0.9) MeV

c.f. $D_0^*(2400)$

2^+ narrow resonance
m = (2527 ± 3) MeV
Γ = (8.2 ± 0.7) MeV

c.f. $D_2^*(2460)$ (also couples to $D^*\pi$)

Charm tetraquarks

Cheung, CT, Dudek, Edwards (HadSpec) [JHEP 1711, 033 (2017)]

Compute spectra in some **exotic-flavour** channels

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

Use a range of **'meson-meson' operators**,

$$\sim \sum_{\hat{p}_1, \hat{p}_2} \left[\bar{q}\, \Gamma_1\, q\right](\vec{p}_1) \;\; \left[\bar{q}\, \Gamma_2\, q\right](\vec{p}_2)$$

and **'tetraquark' (diquark-antidiquark) operators**,

$$\sim \sum_{a,d} C_{ad} \;\; \left[c_{abc}\, q_a^T\, \Gamma_1\, q_b\right] \;\; \left[c_{def}\, \bar{q}_e\, \Gamma_2\, \bar{q}_f^T\right]$$

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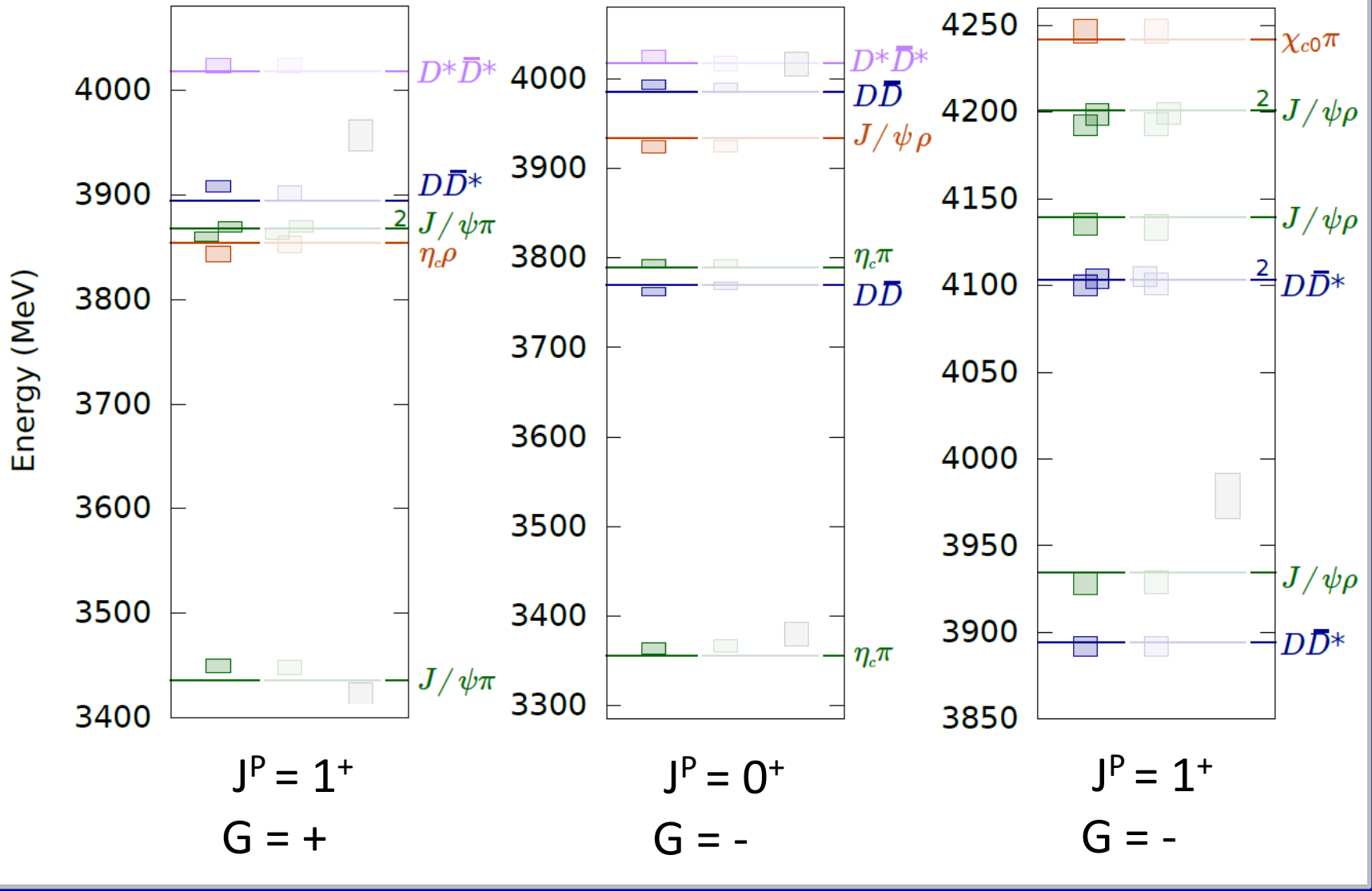
One lattice spacing

1 volume (≈ 2 fm)

m_π = 391 MeV

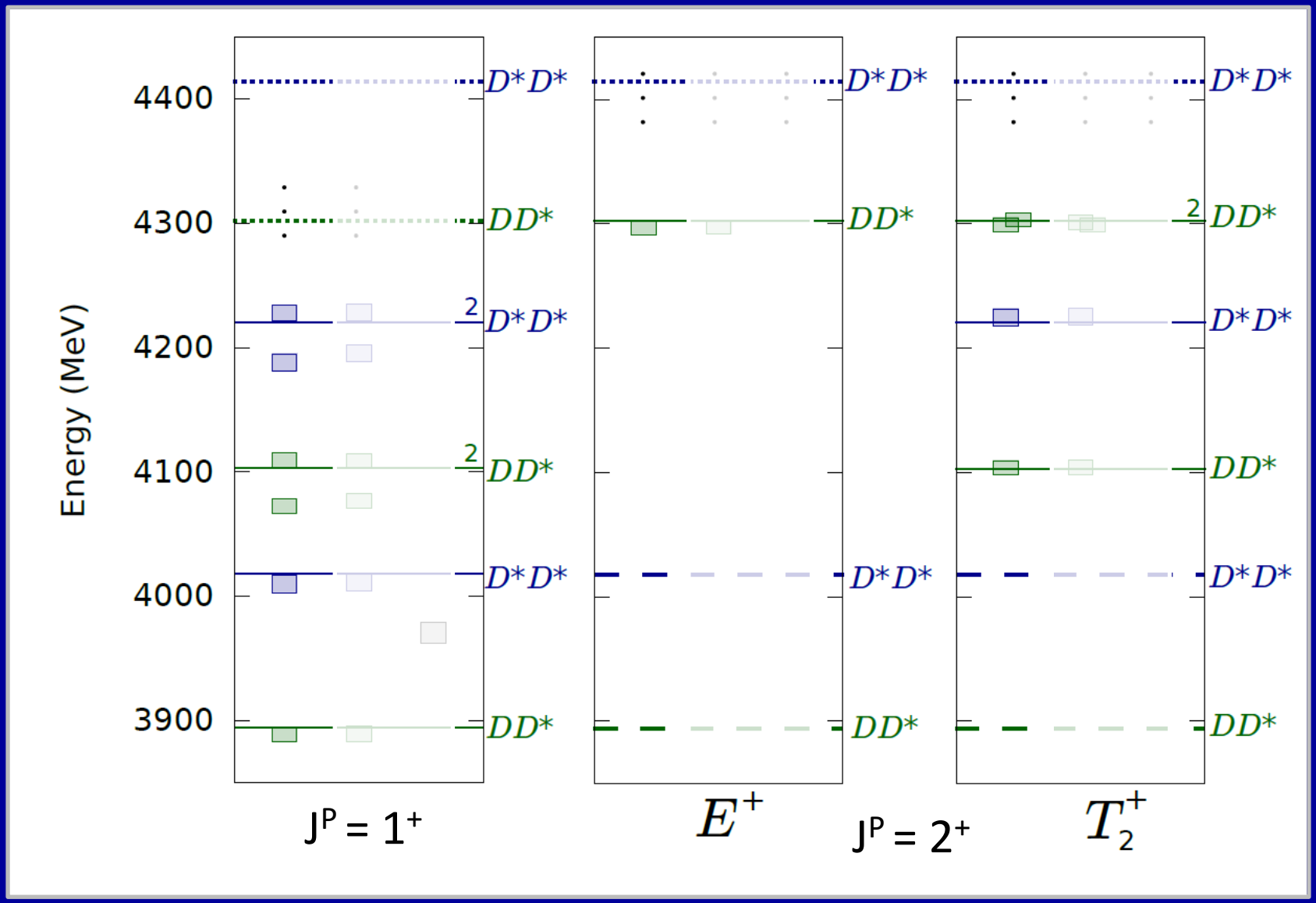
Hidden-charm I=1 ($c\bar{c}l\bar{l}$)

[JHEP 1711, 033 (2017)]



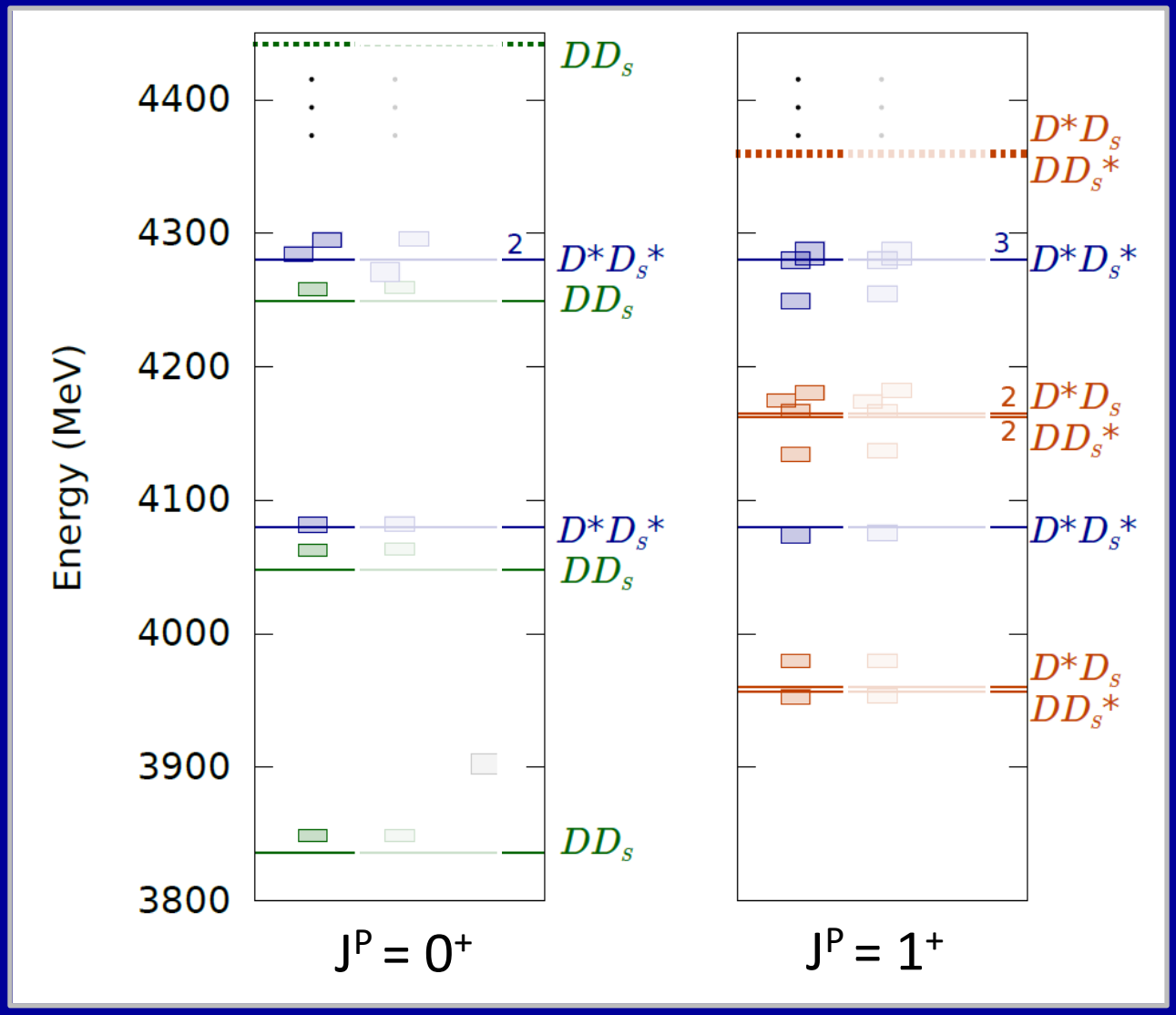
Doubly-charmed I=0 ($cc\bar{l}\bar{l}$)

[JHEP 1711, 033 (2017)]



Doubly-charmed I=½ ($cc\bar{l}\bar{s}$)

[JHEP 1711, 033 (2017)]



Summary

- Significant progress in LQCD calculations of excited hadrons, resonances, near-threshold states, etc.
- Examples of recent work (see also Raul's talk earlier):
  - $D\pi$, $D\eta$, $D_s\bar{K}$ I=½ scattering (also I=3/2 $D\pi$)
  - Exotic-flavour channels (tetraquarks)
- Work in progress on other channels and different m_π
- Use m_π dependence as a tool to probe structure
- Ongoing work on formalism (e.g. 3-hadron scattering)

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Science & Technology Facilities Council

Hadron Spectrum Collaboration

Jefferson Lab and surroundings, USA:

Raúl Briceño[1], Jozef Dudek[2], Robert Edwards, Bálint Joó, David Richards, Frank Winter, Bipasha Chakraborty

([1] and Old Dominion University, [2] and William & Mary)

W&M: *Christopher Johnson*, *Archana Radhakrishnan*

Trinity College Dublin, Ireland:

Michael Peardon, Sinéad Ryan, David Wilson, *Cian O'Hara*, *David Tims*

University of Cambridge, UK:

CT, Graham Moir, *Gavin Cheung, Antoni Woss*

Tata Institute, India:

Nilmani Mathur

www.hadspec.org