Excited mesons and resonances from lattice QCD

Christopher Thomas, University of Cambridge

c.e.thomas@damtp.cam.ac.uk

Hadron 2017, Salamanca, Spain,
25 – 29 September 2017

UNIVERSITY OF CAMBRIDGE

Hadron Spectrum Collaboration

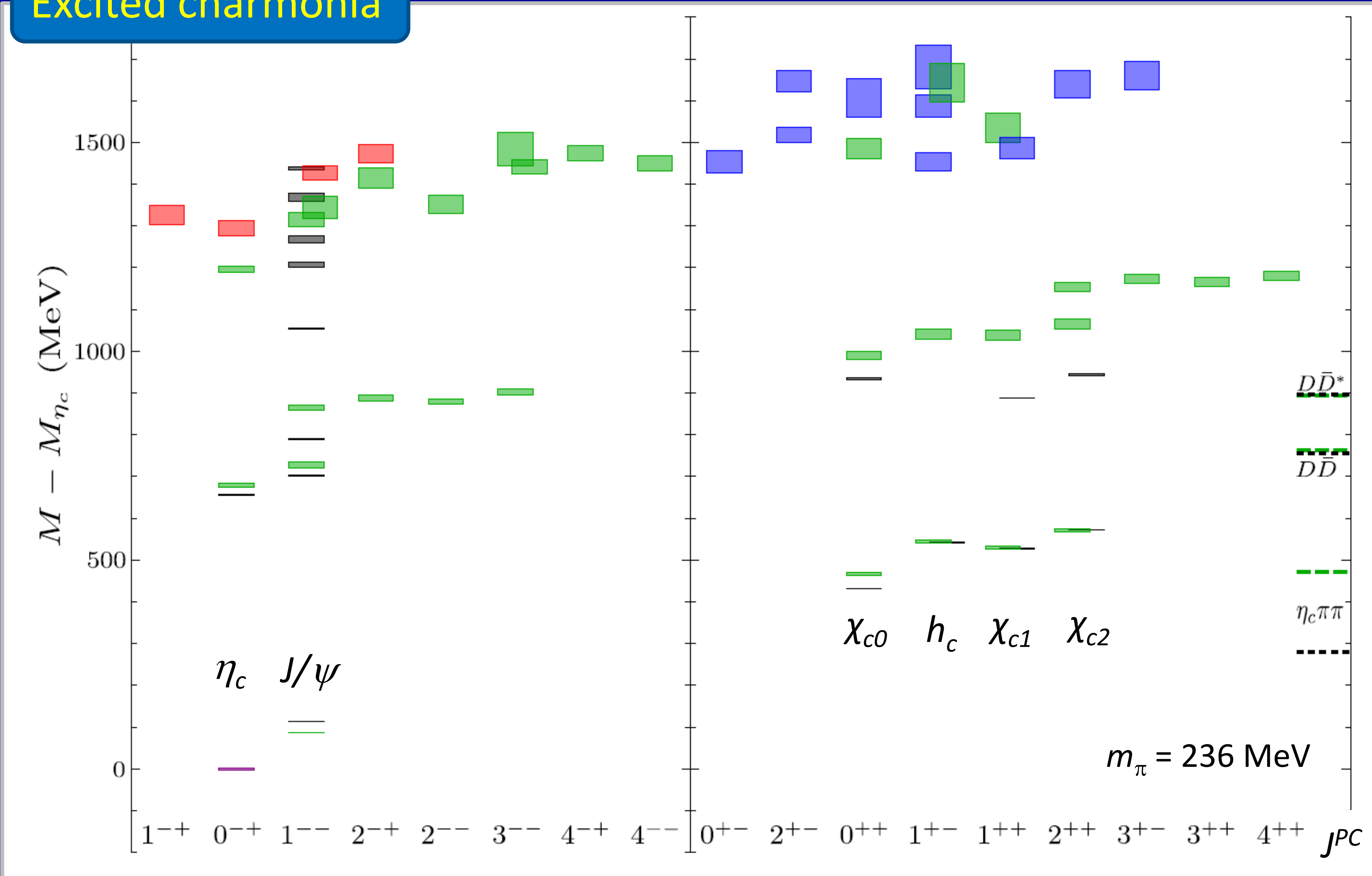
Excited lattice QCD spectroscopy

Finite-volume energy eigenstates from:

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

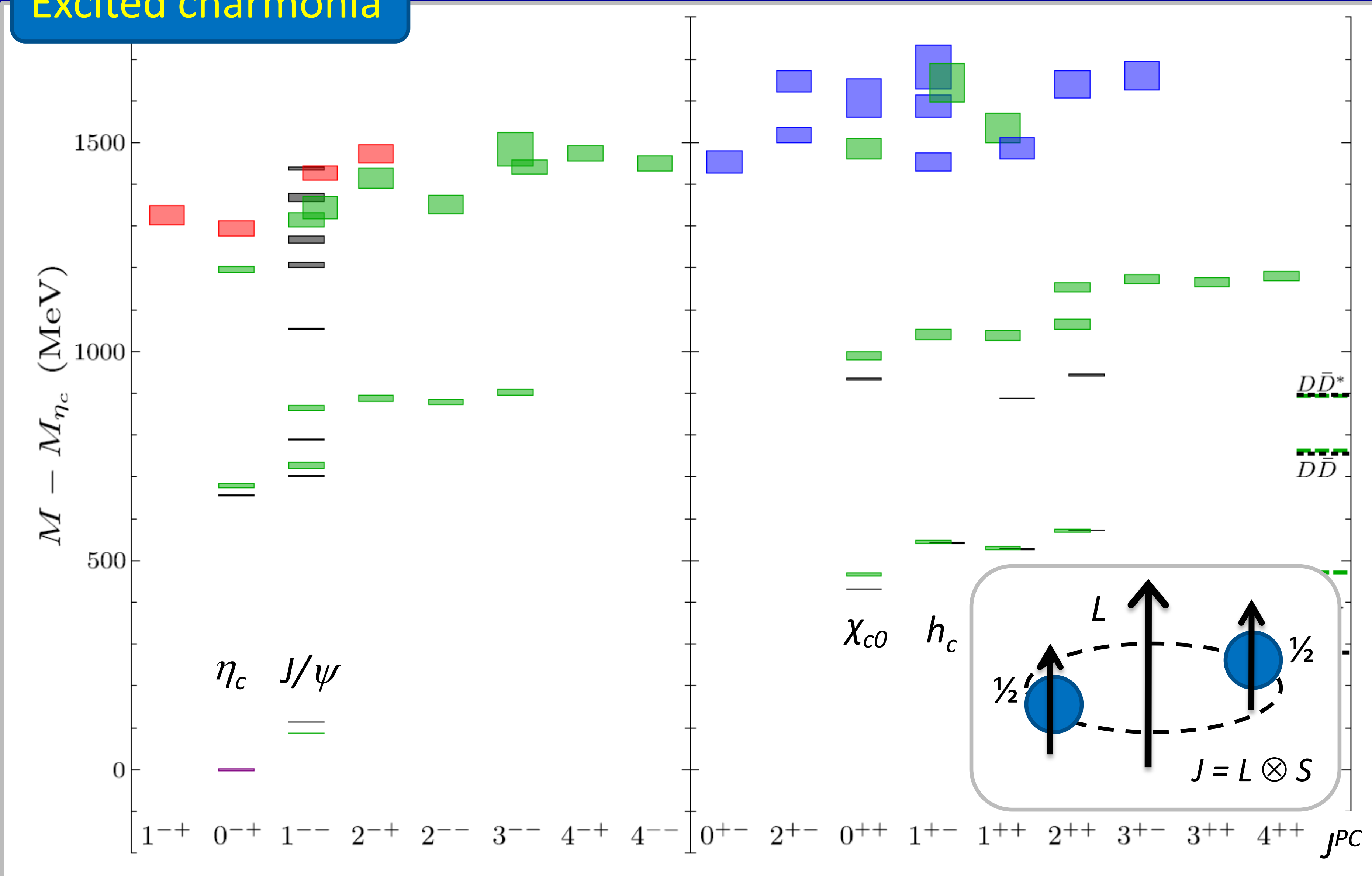
Use many different interpolating operators

Excited charmonia



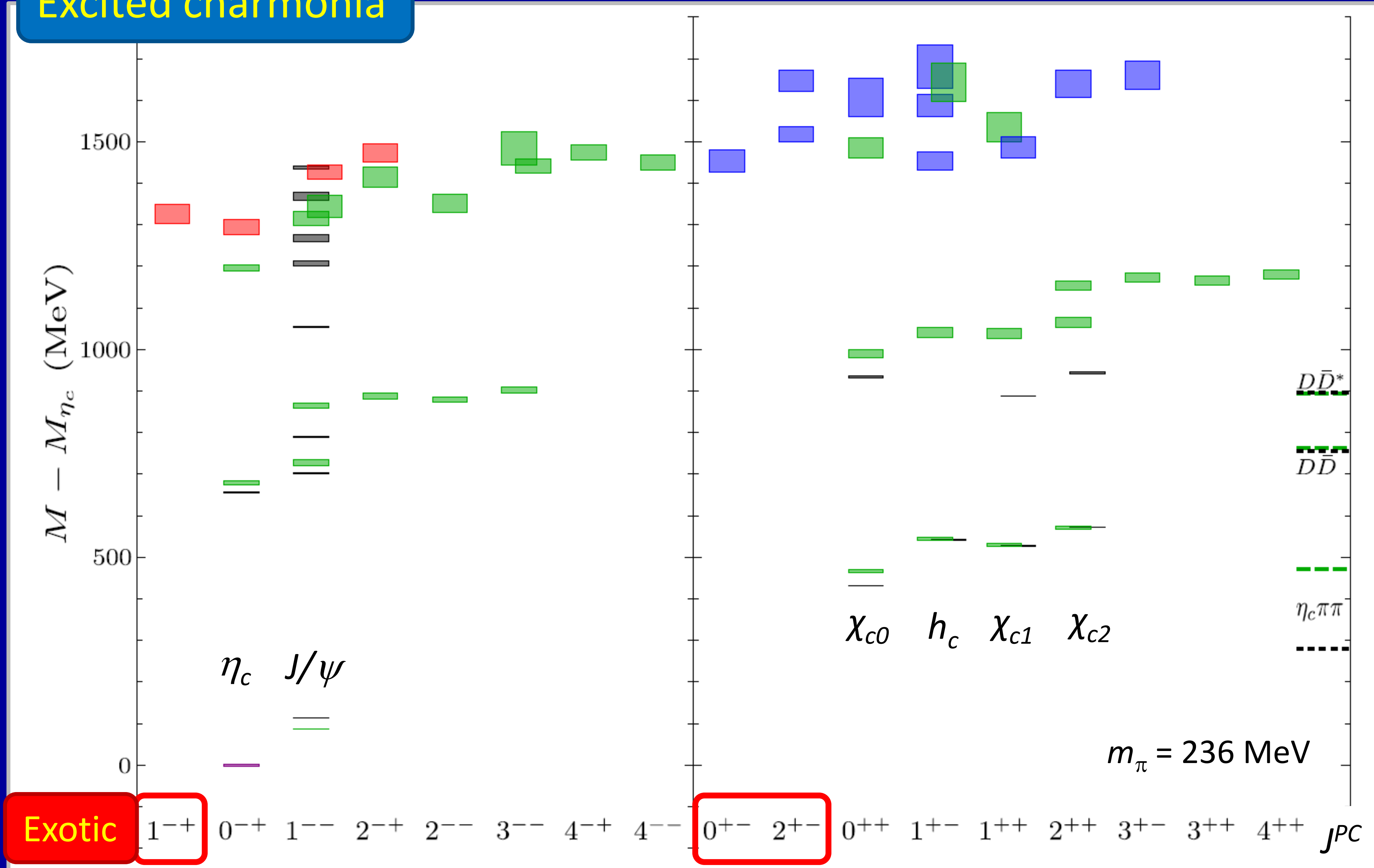
m_π = 236 MeV, one lattice spacing and volume [Cheung *et al* (HadSpec), JHEP 12 (2016) 089]
(similar pattern to older m_π = 391 MeV, 1 lattice spacing and 3 volumes)

Excited charmonia



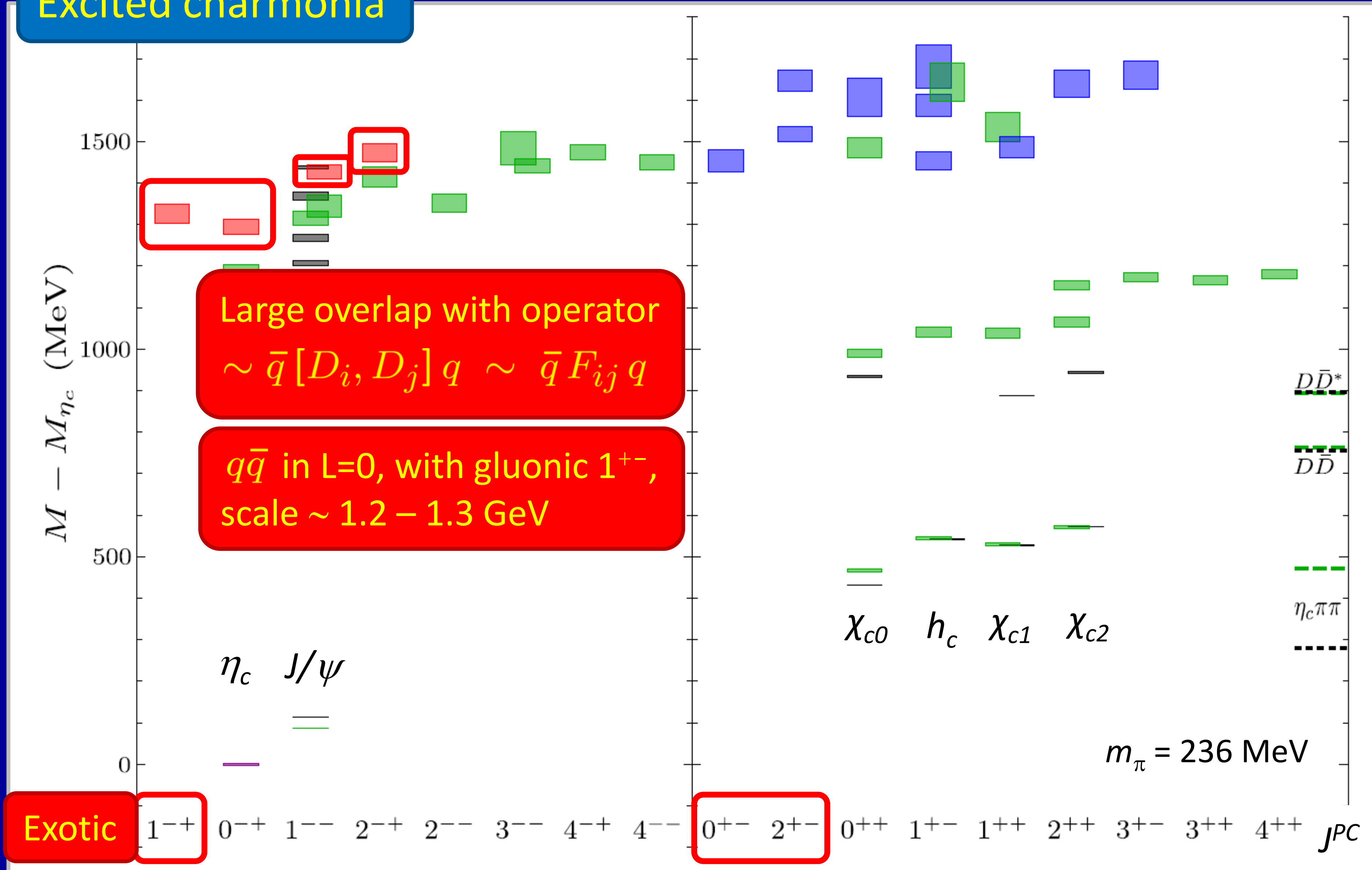
m_π = 236 MeV, one lattice spacing and volume [Cheung *et al* (HadSpec), JHEP 12 (2016) 089]
(similar pattern to older m_π = 391 MeV, 1 lattice spacing and 3 volumes)

Excited charmonia



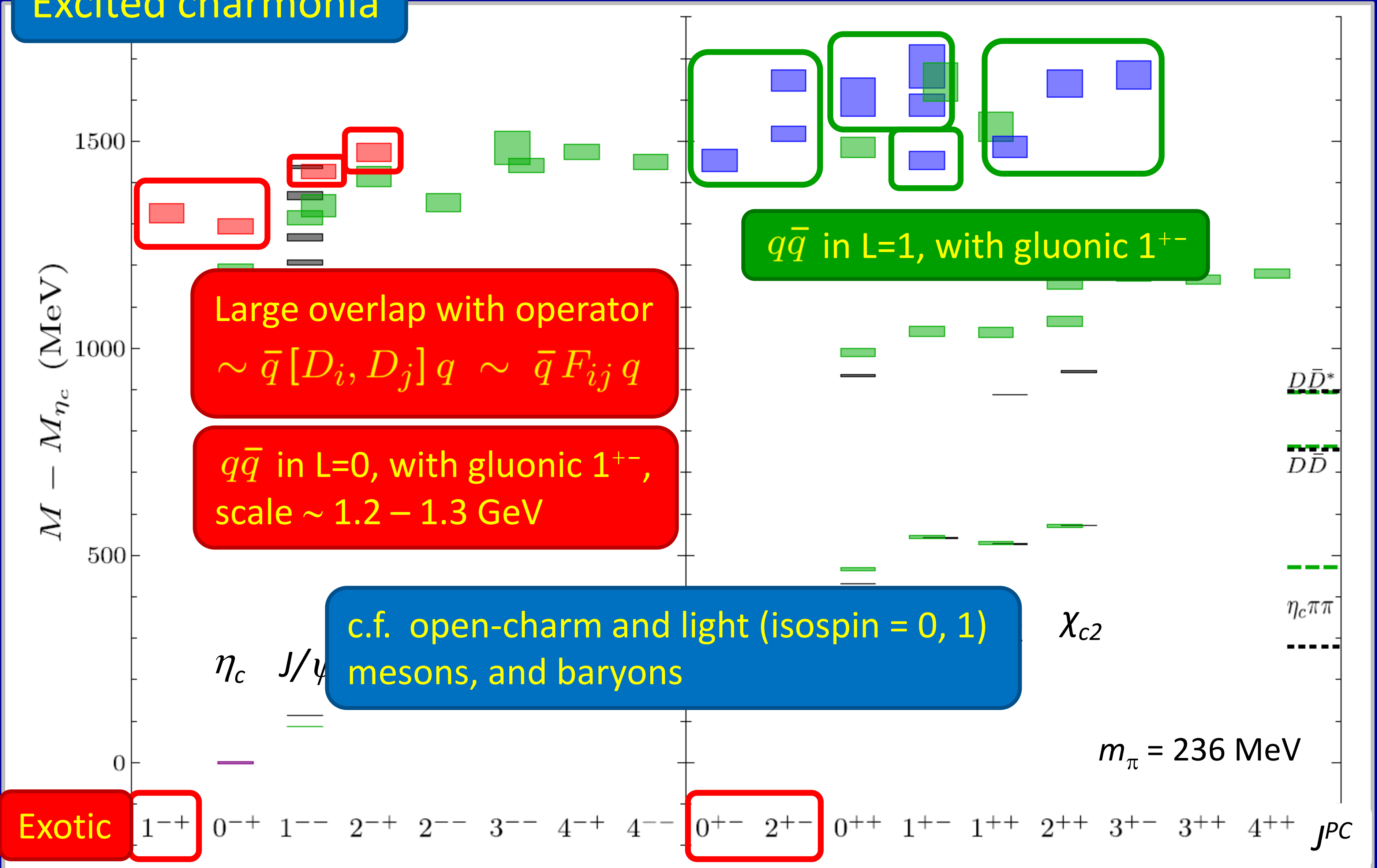
m_π = 236 MeV, one lattice spacing and volume [Cheung *et al* (HadSpec), JHEP 12 (2016) 089]
(similar pattern to older m_π = 391 MeV, 1 lattice spacing and 3 volumes)

Excited charmonia



m_π = 236 MeV, one lattice spacing and volume [Cheung *et al* (HadSpec), JHEP 12 (2016) 089]
(similar pattern to older m_π = 391 MeV, 1 lattice spacing and 3 volumes)

Excited charmonia



Large overlap with operator $\sim \bar{q}\,[D_i, D_j]\,q \;\sim\; \bar{q}\,F_{ij}\,q$

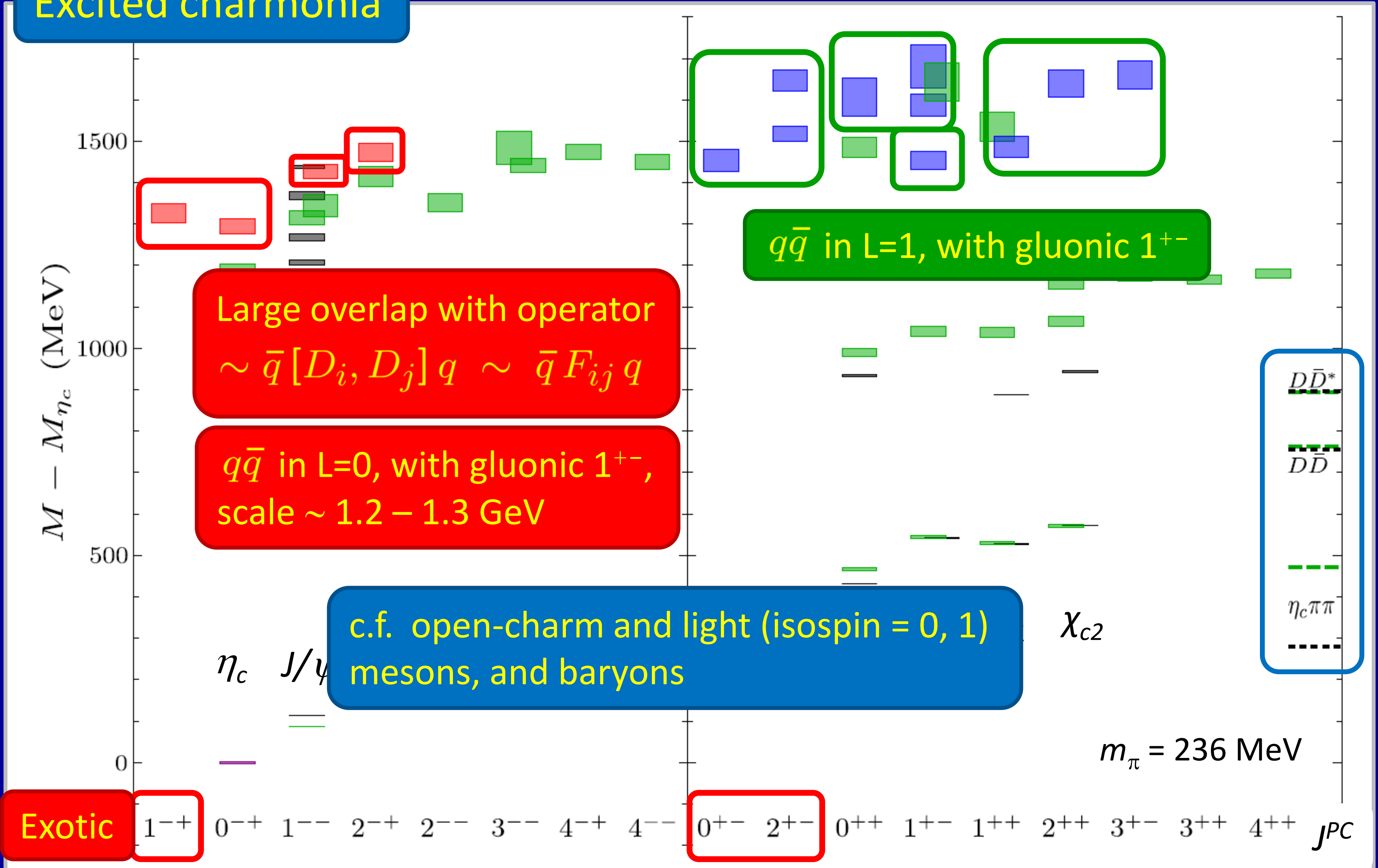
$q\bar{q}$ in L=0, with gluonic 1^{+-}, scale ~ 1.2 – 1.3 GeV

$q\bar{q}$ in L=1, with gluonic 1^{+-}

c.f. open-charm and light (isospin = 0, 1) mesons, and baryons

m_π = 236 MeV, one lattice spacing and volume [Cheung *et al* (HadSpec), JHEP 12 (2016) 089]
(similar pattern to older m_π = 391 MeV, 1 lattice spacing and 3 volumes)

Excited charmonia



$q\bar{q}$ in L=1, with gluonic 1^{+-}

Large overlap with operator
$\sim \bar{q}\,[D_i, D_j]\,q \;\sim\; \bar{q}\,F_{ij}\,q$

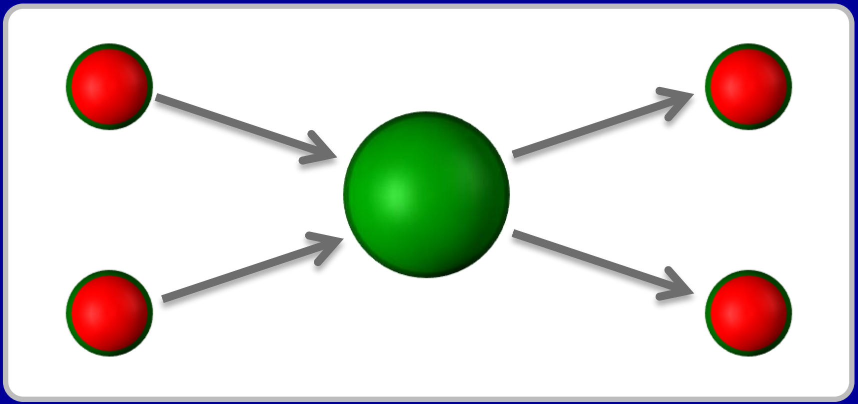
$q\bar{q}$ in L=0, with gluonic 1^{+-},
scale ~ 1.2 – 1.3 GeV

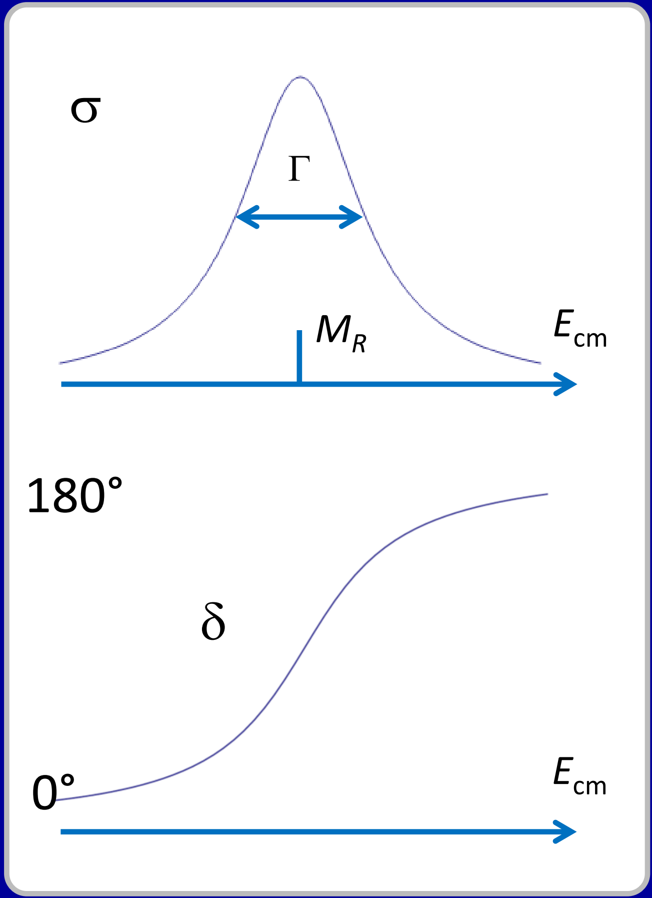
c.f. open-charm and light (isospin = 0, 1)
mesons, and baryons

m_π = 236 MeV, one lattice spacing and volume [Cheung *et al* (HadSpec), JHEP 12 (2016) 089]
(similar pattern to older m_π = 391 MeV, 1 lattice spacing and 3 volumes)

Scattering and resonances

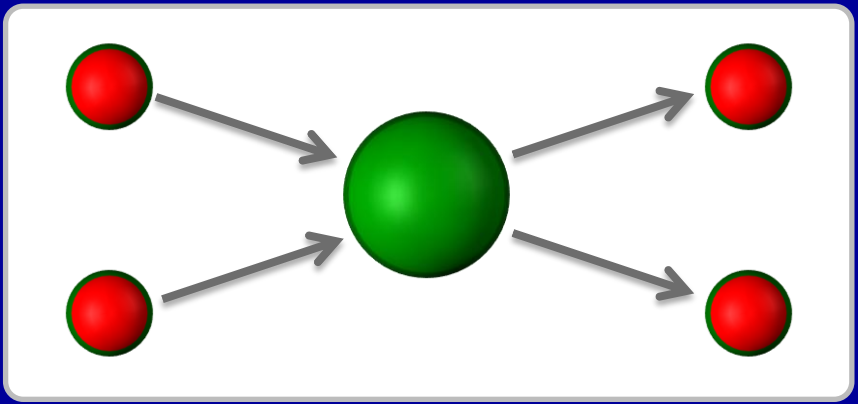
Most hadrons appear as resonances in scattering of lighter hadrons



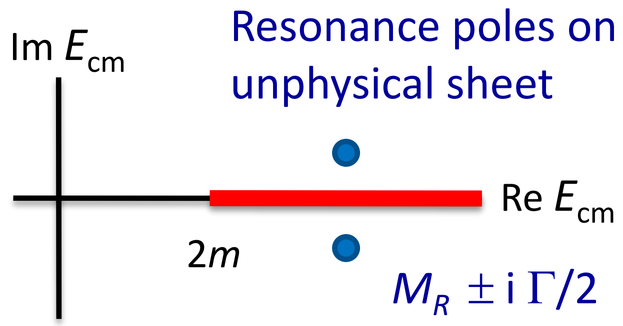


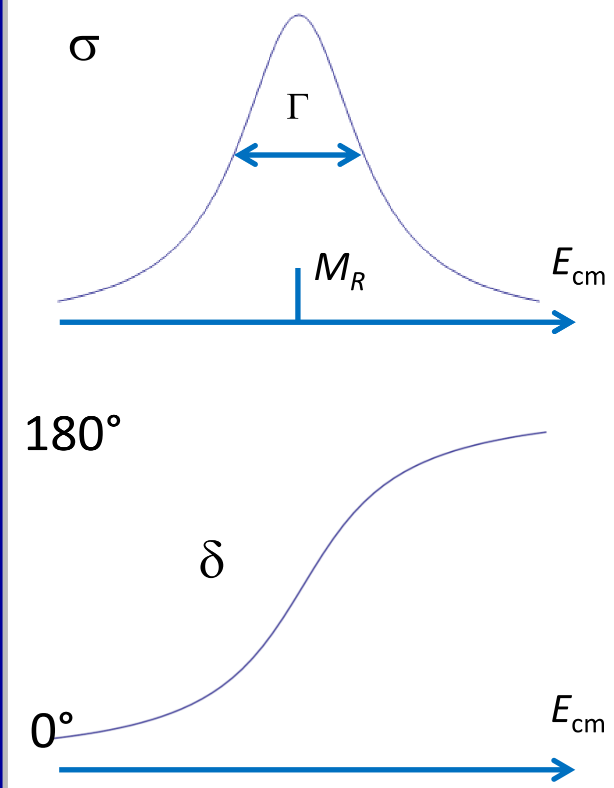
Scattering and resonances

Most hadrons appear as resonances in scattering of lighter hadrons



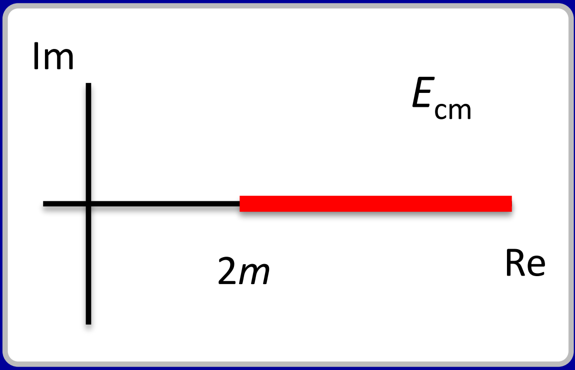
Singularity structure of scattering matrix





Scattering in lattice QCD

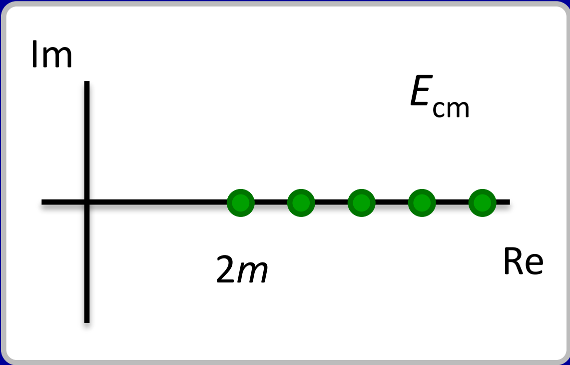
Infinite volume – contin. spectrum above thresh.

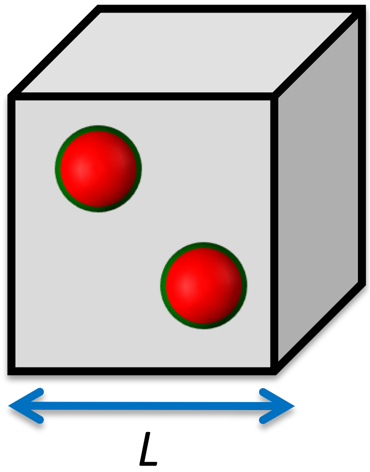


Scattering in lattice QCD

Infinite volume – contin. spectrum above thresh.

Finite volume – discrete spectrum





Non-interacting: $\vec{k}_{A,B} = \frac{2\pi}{L}(n_x, n_y, n_z)$

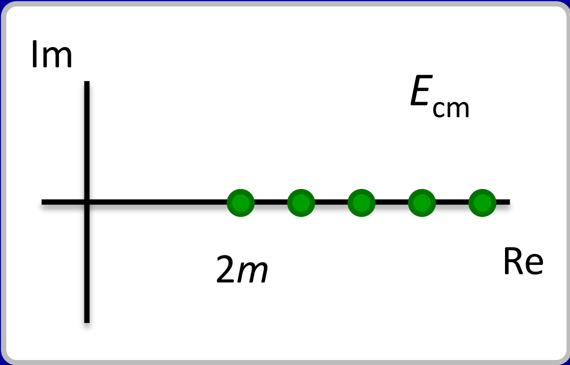
Interacting: $\vec{k}_{A,B} \neq \frac{2\pi}{L}(n_x, n_y, n_z)$

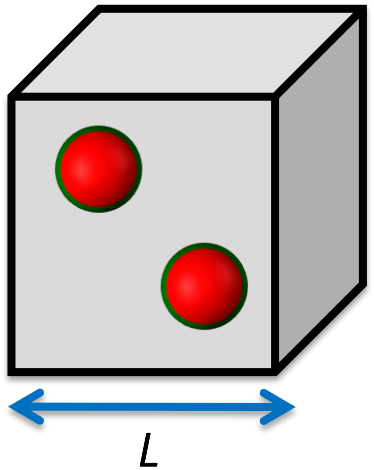
[periodic b.c.s]

Scattering in lattice QCD

Infinite volume – contin. spectrum above thresh.

Finite volume – discrete spectrum





Non-interacting: $\vec{k}_{A,B} = \frac{2\pi}{L}(n_x, n_y, n_z)$

Interacting: $\vec{k}_{A,B} \neq \frac{2\pi}{L}(n_x, n_y, n_z)$

$$\mathrm{t}(E_{\mathrm{cm}}) = \begin{pmatrix} t_{\pi\pi\to\pi\pi}(E_{\mathrm{cm}}) & t_{\pi\pi\to K\bar{K}}(E_{\mathrm{cm}}) \\ t_{K\bar{K}\to\pi\pi}(E_{\mathrm{cm}}) & t_{K\bar{K}\to K\bar{K}}(E_{\mathrm{cm}}) \end{pmatrix}$$

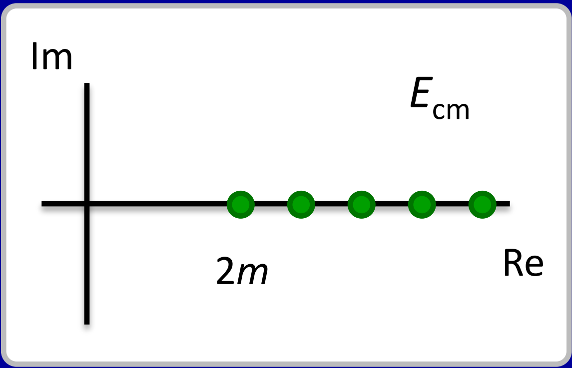
Lüscher method (and extensions): relate **finite-volume energy levels** to **infinite-volume scattering *t*-matrix**.

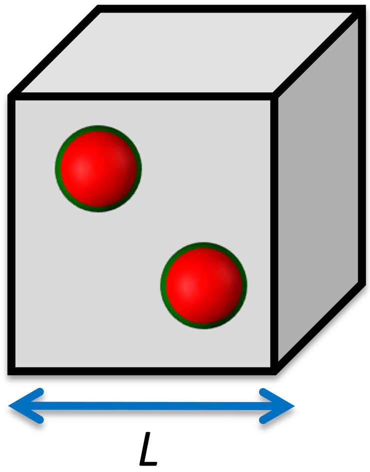
Elastic scattering: 1-to-1 correspondence (ignoring partial-wave mixing).
But **in general under-constrained problem** (determinant equ. at each E_{cm})
→ parameterize E_{cm} dependence of *t*-matrix and fit $\{E_{lat}\}$ to $\{E_{param}\}$
Consider many different parameterizations (e.g. *K*-matrix, eff. range, B.W.)

Scattering in lattice QCD

Infinite volume – contin. spectrum above thresh.

Finite volume – discrete spectrum





Non-interacting: $\vec{k}_{A,B} = \frac{2\pi}{L}(n_x, n_y, n_z)$

Interacting: $\vec{k}_{A,B} \neq \frac{2\pi}{L}(n_x, n_y, n_z)$

$$\mathrm{t}(E_{\mathrm{cm}}) = \begin{pmatrix} t_{\pi\pi\to\pi\pi}(E_{\mathrm{cm}}) & t_{\pi\pi\to K\bar{K}}(E_{\mathrm{cm}}) \\ t_{K\bar{K}\to\pi\pi}(E_{\mathrm{cm}}) & t_{K\bar{K}\to K\bar{K}}(E_{\mathrm{cm}}) \end{pmatrix}$$

Lüscher method (and extensions): relate **finite-volume energy levels** to **infini**

Elas

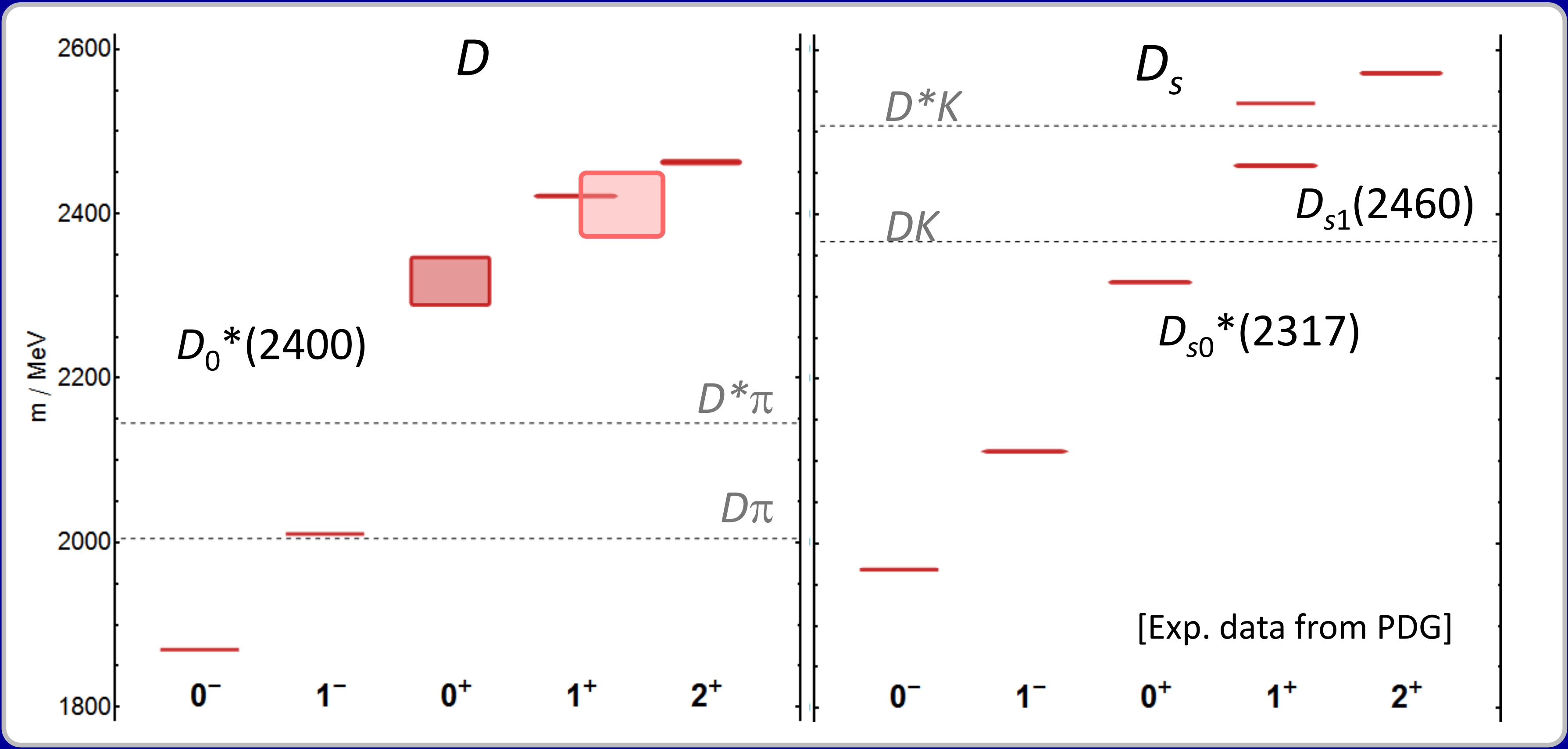
But

Con

Currently limited to hadron-hadron scattering – progress being made on formalism for channels with > 2 hadrons.

See plenary by Raul Briceño at 10:10am on Tuesday and recent review [Briceño, Dudek, Young. arXiv:1706.06223]

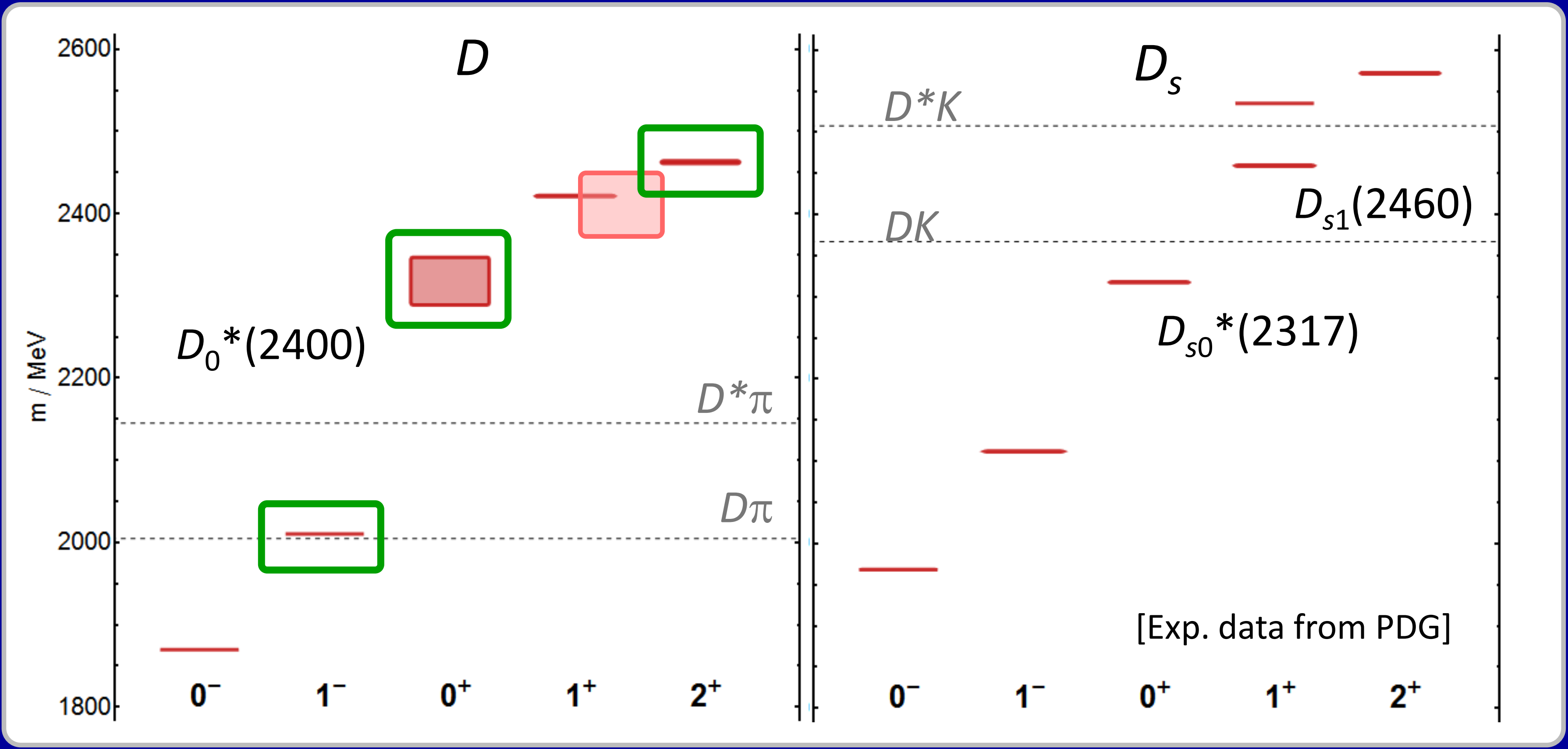
Charm-light (D) and charm-strange (D_s) mesons



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) [arXiv:1706.01247] – 0^+ $D_{s0}(2317)$ and 1^+ $D_{s1}(2460)$

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

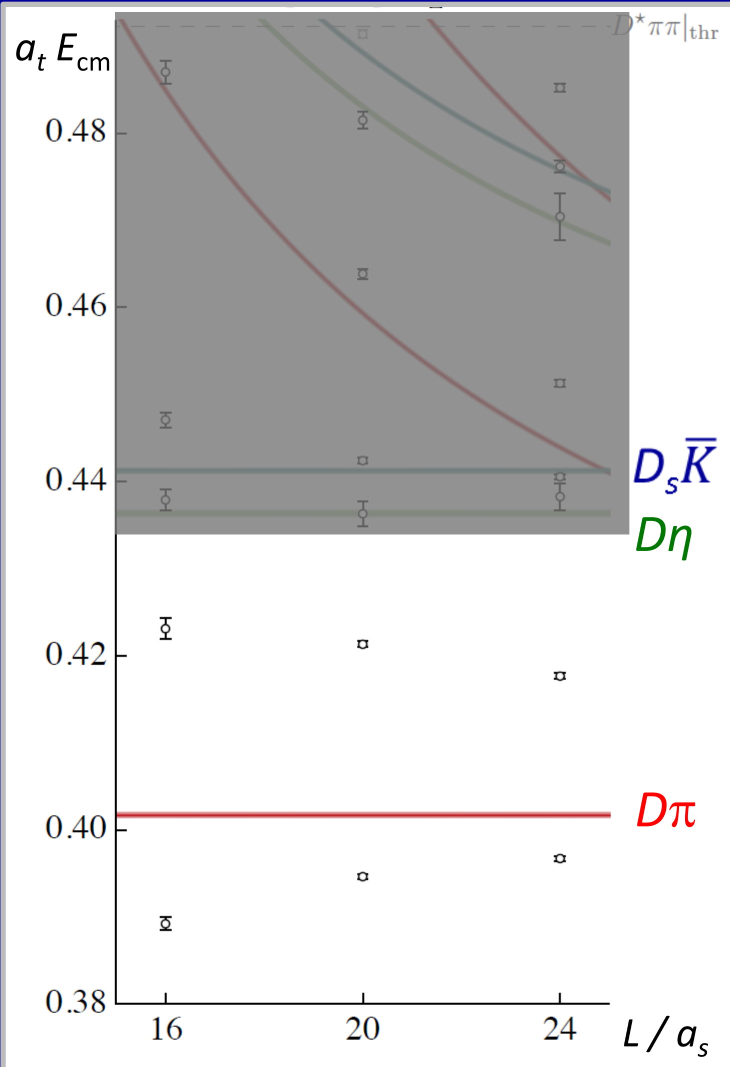


Some other LQCD studies:

- 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) [arXiv:1706.01247] – 0^+ $D_{s0}(2317)$ and 1^+ $D_{s1}(2460)$

Dπ, Dη, $D_s\bar{K}$ (I=½)

Isospin = ½
Strangeness = 0
Charm = 1



P = [0,0,0]

$J^P = 0^+$ [ℓ = 0]

Reduced sym. → other partial waves can mix in

m_π = 391 MeV
m_D = 1890 MeV

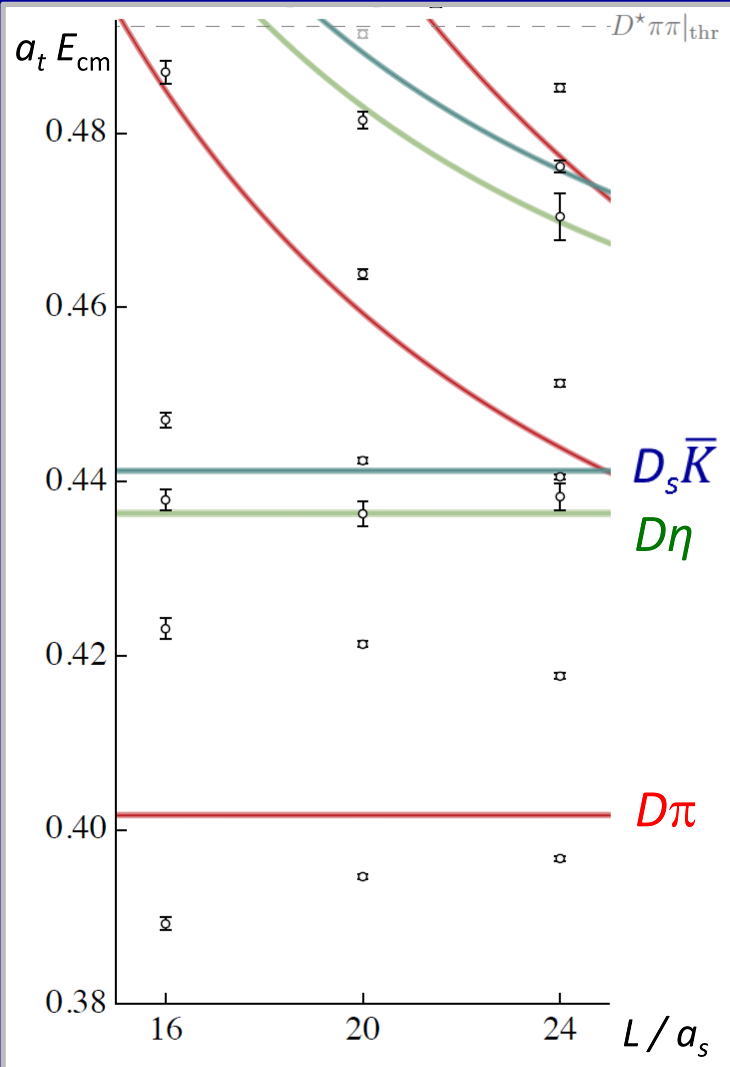
One lattice spacing

3 volumes (2 – 3 fm)
(L / a_s = 16,20,24)

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

$D\pi$, $D\eta$, $D_s\bar{K}$ (I=½)

Isospin = ½
Strangeness = 0
Charm = 1



P = [0,0,0]

$J^P = 0^+$ [ℓ = 0]

Reduced sym. → other partial waves can mix in

m_π = 391 MeV
m_D = 1890 MeV

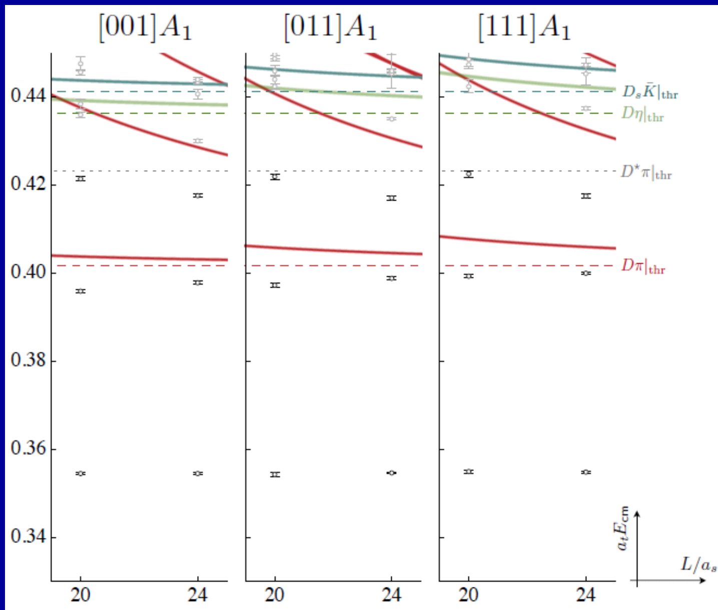
One lattice spacing

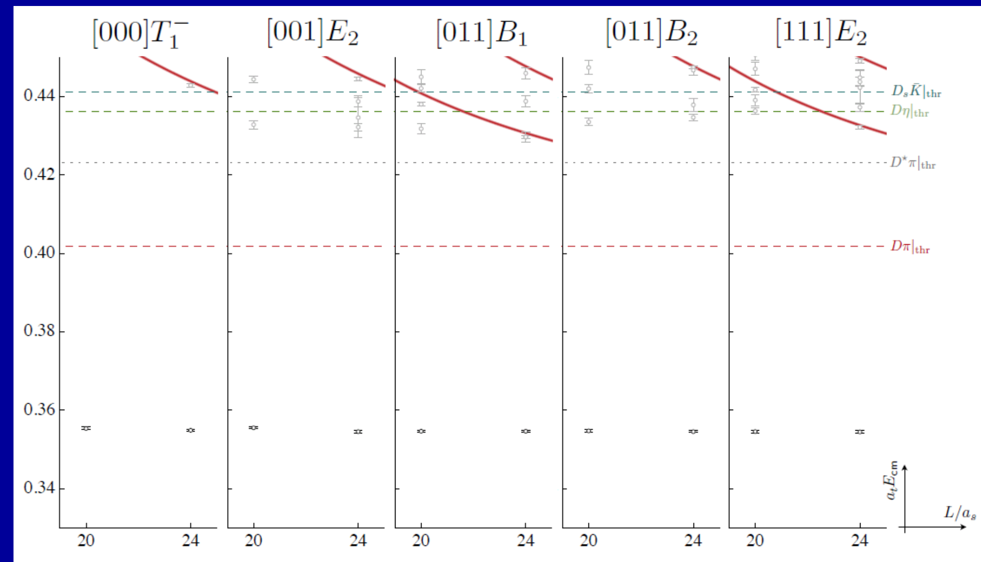
3 volumes (2 – 3 fm)
(L / a_s = 16,20,24)

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

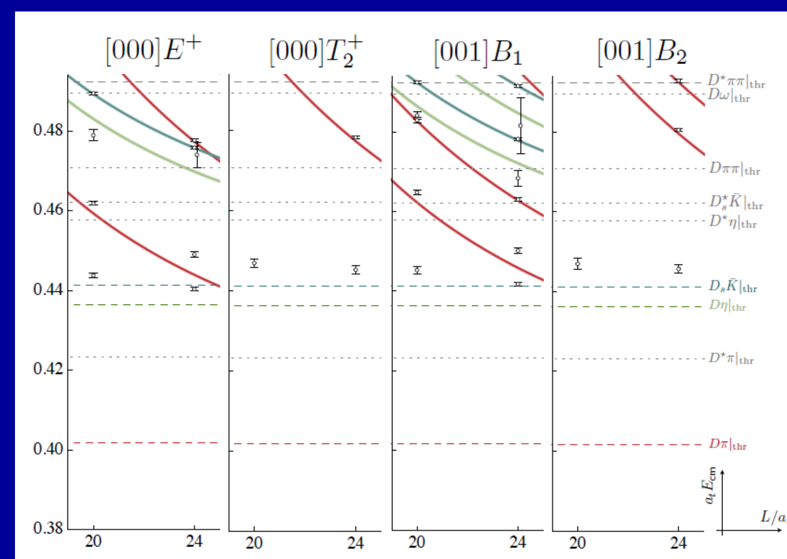
$D\pi$, $D\eta$, $D_s\bar{K}$ (I=½): spectra

[JHEP 1610, 011 (2016)]



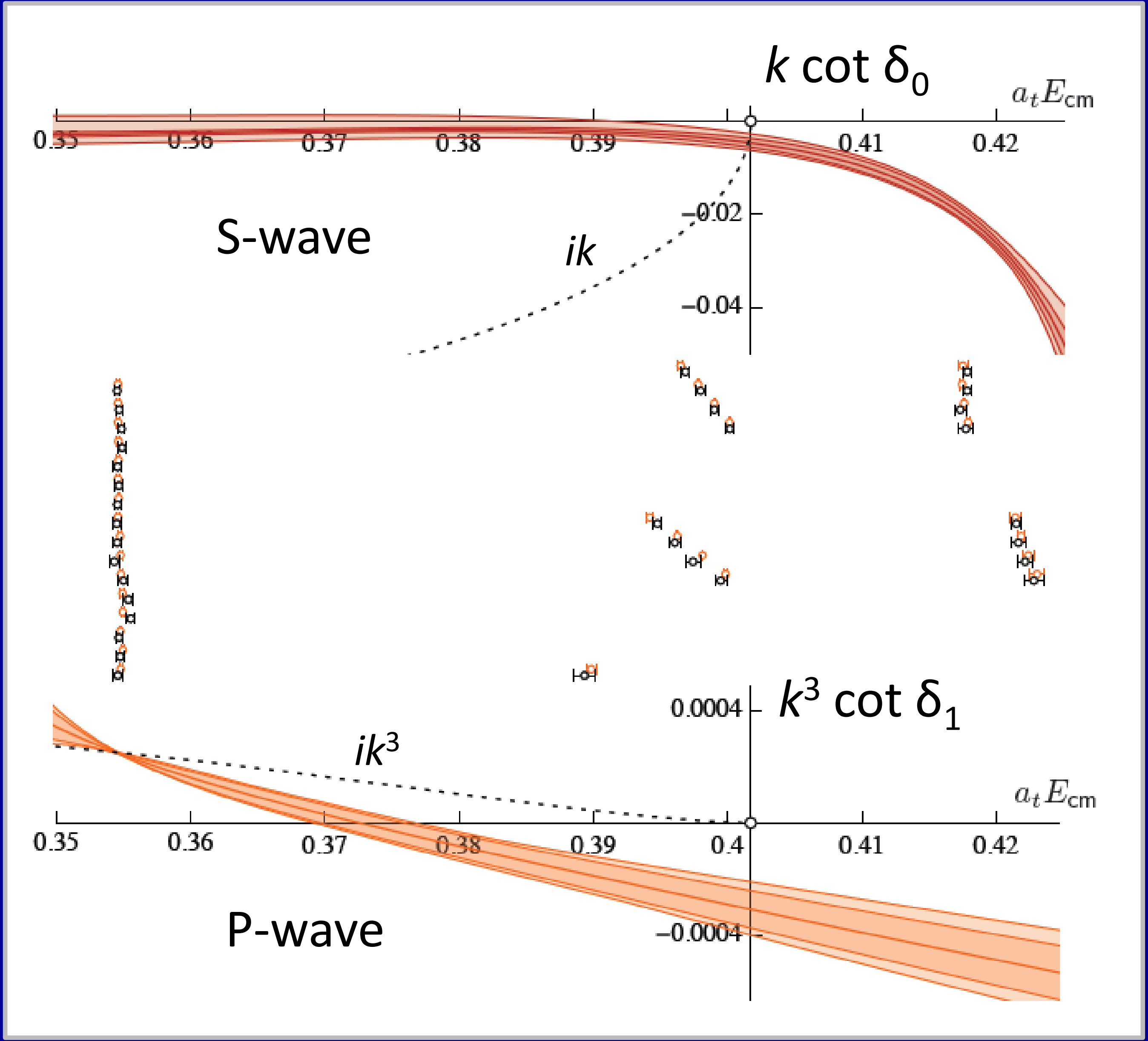


Use 47 energy levels for ℓ = 0, 1 and 18 for ℓ = 2



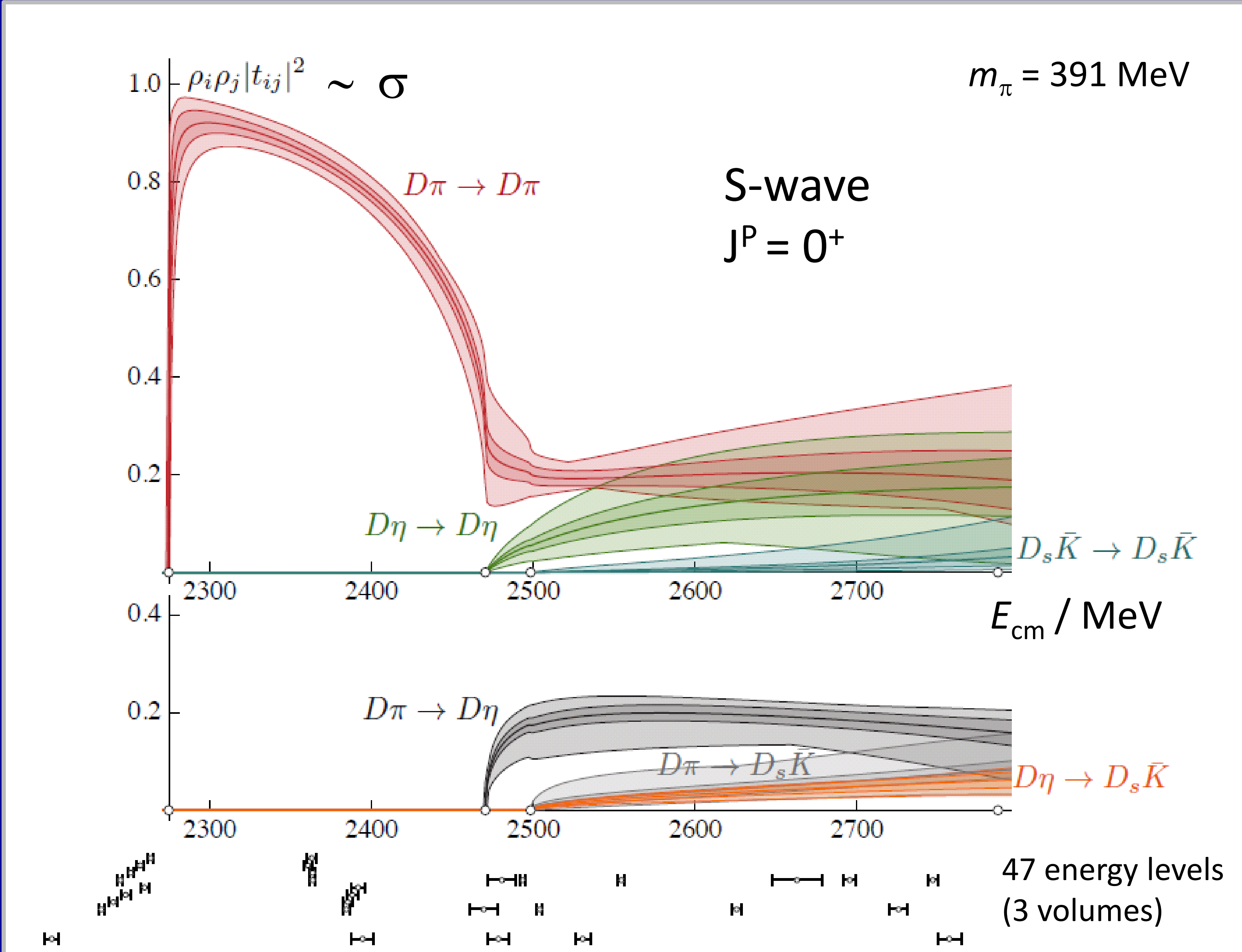
Elastic Dπ (I=½): ℓ = 0,1

[JHEP 1610, 011 (2016)]



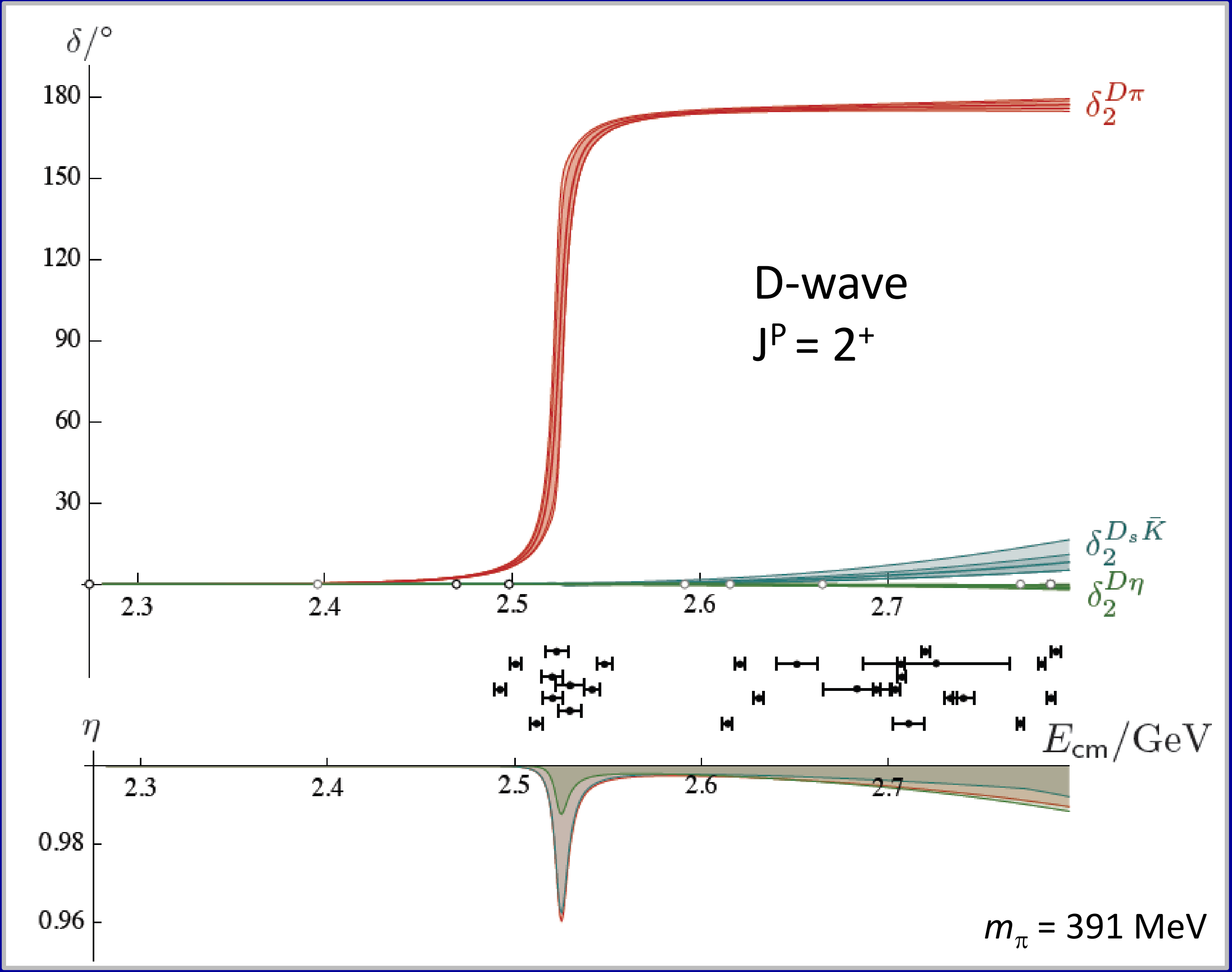
Dπ, Dη, $D_s\bar{K}$ (I=½): ℓ = 0

[JHEP 1610, 011 (2016)]



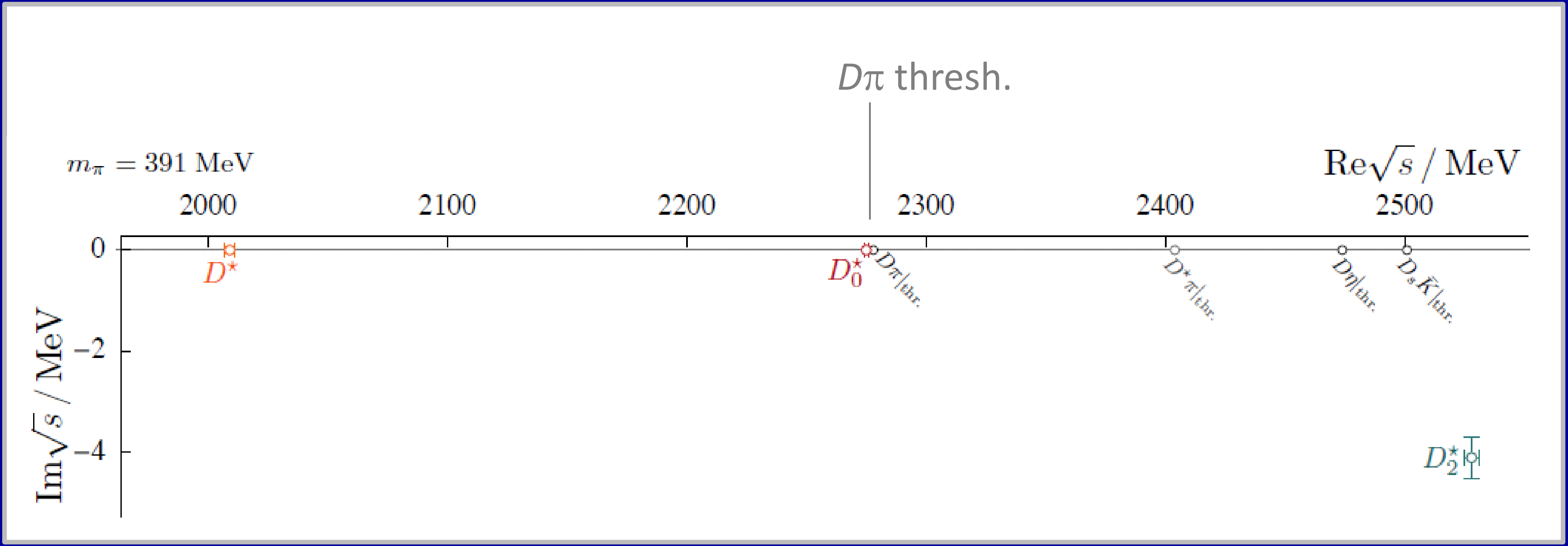
Dπ, Dη, $D_s\bar{K}$ (I=½): ℓ = 2

[JHEP 1610, 011 (2016)]



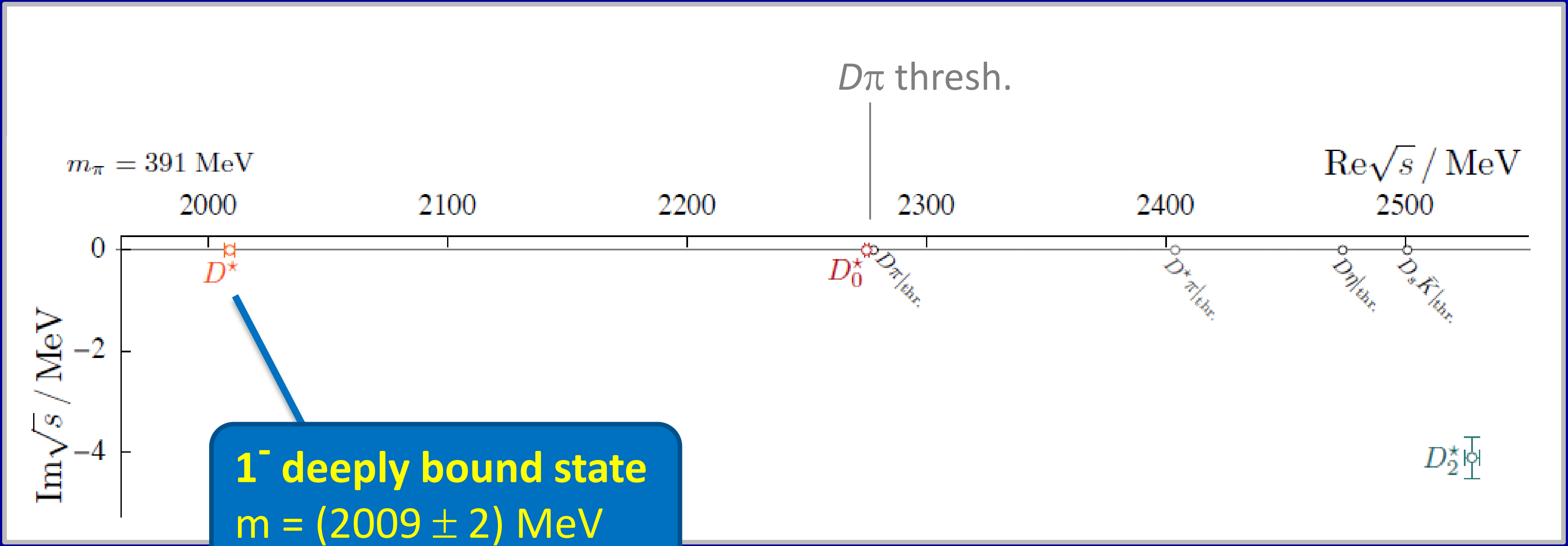
Dπ, Dη, $D_s\bar{K}$ (I=½): poles of *t*-matrix

[JHEP 1610, 011 (2016)]



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

[JHEP 1610, 011 (2016)]



1⁻ deeply bound state

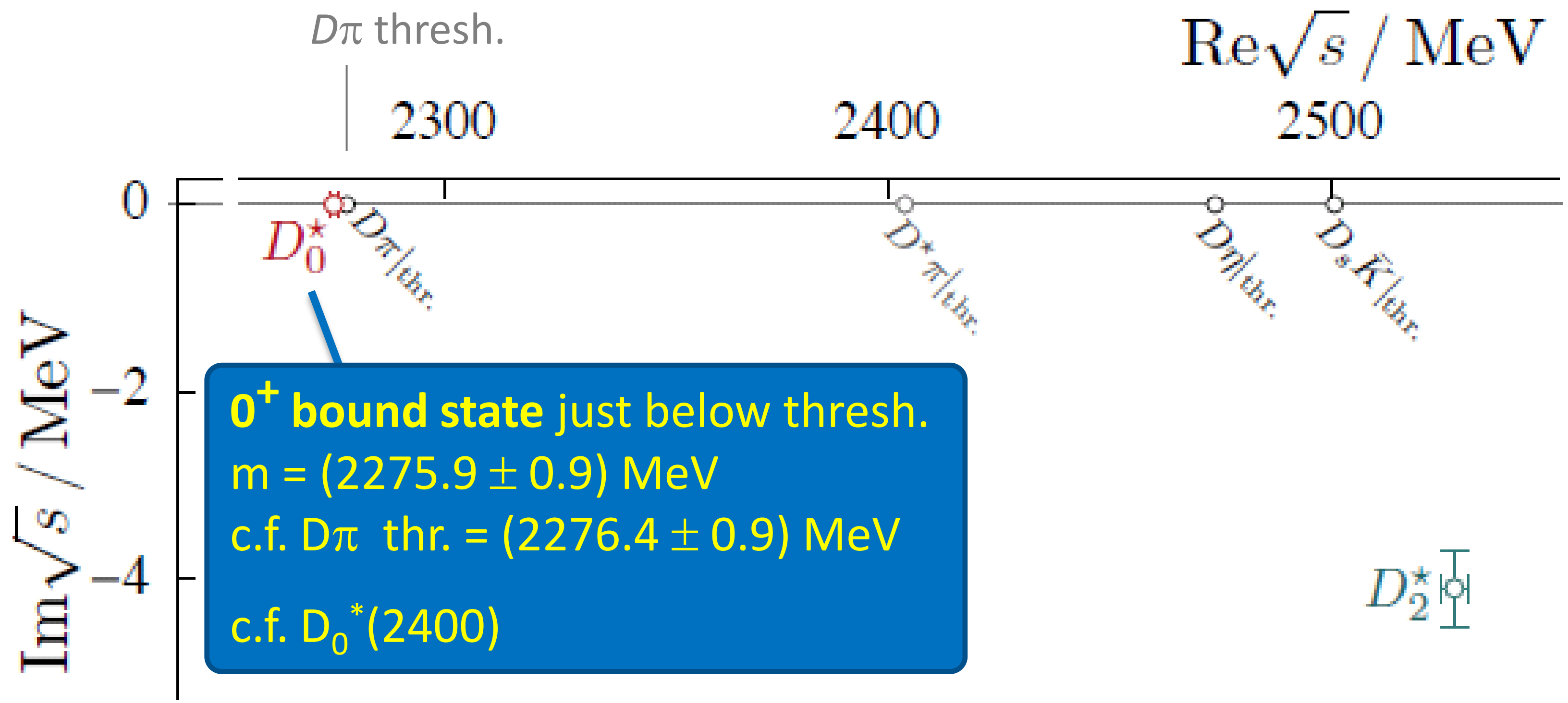
m = (2009 ± 2) MeV

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

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

[JHEP 1610, 011 (2016)]

m_π = 391 MeV

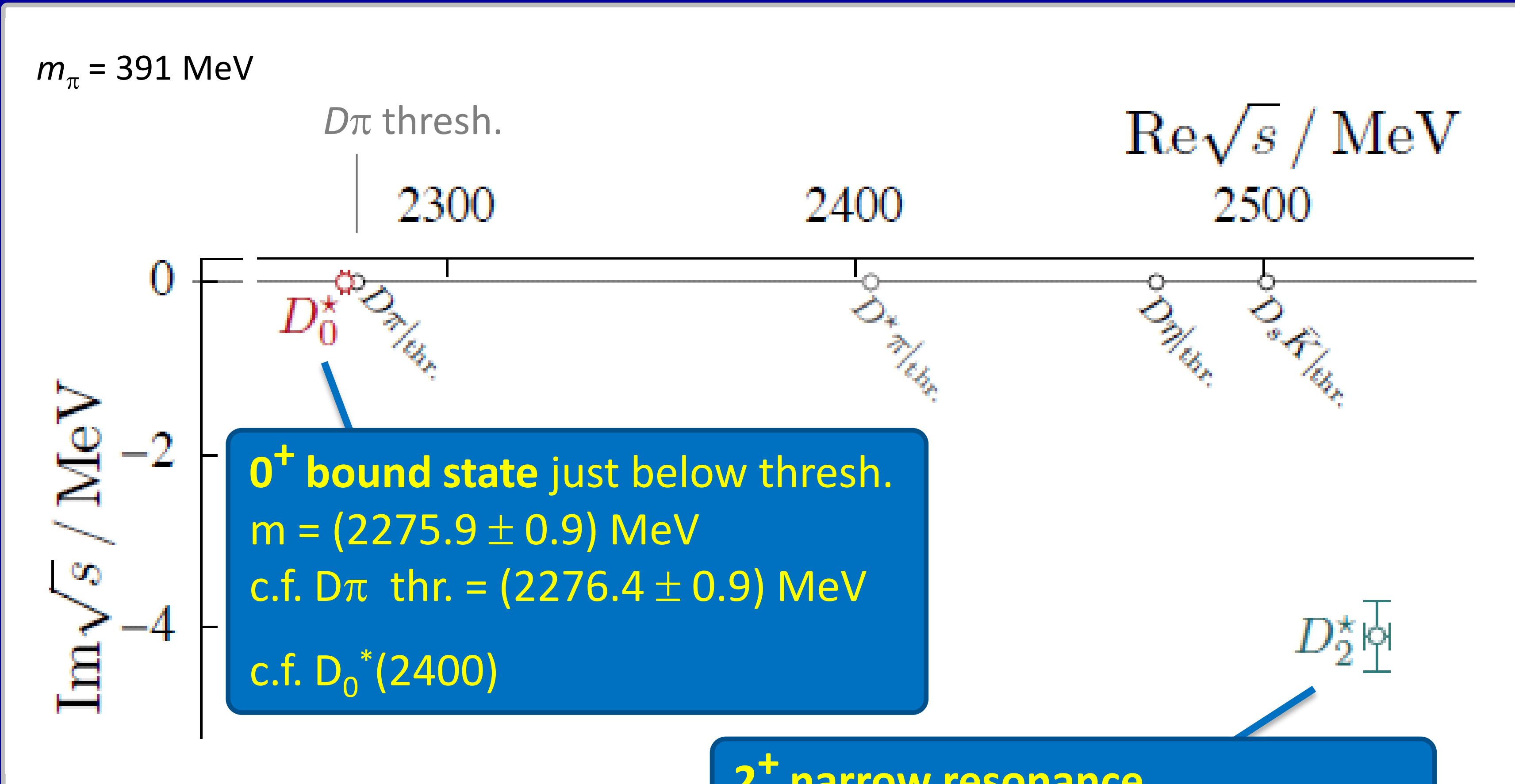


0^+ bound state just below thresh.
m = (2275.9 ± 0.9) MeV
c.f. Dπ thr. = (2276.4 ± 0.9) MeV

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

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

[JHEP 1610, 011 (2016)]



0^+ bound state just below thresh.
m = (2275.9 ± 0.9) MeV
c.f. $D\pi$ 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 $D^*\pi$)

Summary

- **Significant progress** in LQCD calculations of **resonances**, near-threshold states, etc – **map out scattering amps**.
- Example of some recent work in the open-charm sector
- Other talks with Hadron Spectrum Collaboration results:
  - Raul Briceño [10:10 TUES, plenary] – light hadrons, ...
  - Gavin Cheung [11:40 WEDS, exotics session]
    – charm tetraquarks (exotic-flavour channels)
- Ongoing work on other channels
- Use m_π dependence as tool to probe structure
- Extensions of formalism to e.g. 3-hadron scattering

UNIVERSITY OF CAMBRIDGE

Science & Technology Facilities Council

Hadron Spectrum Collaboration

Jefferson Lab, USA:

Bipasha Chakraborty, Jozef Dudek[1], Robert Edwards, David Richards, Raul Briceño[2]

([1] and W&M, [2] and ODU)

Trinity College Dublin, Ireland:

Mike 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