Excited heavy mesons from lattice QCD

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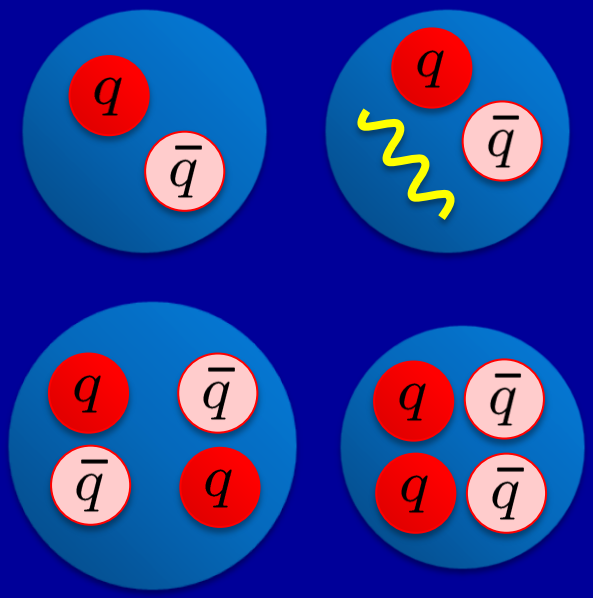
UNIVERSITY OF CAMBRIDGE

Hadron Spectrum Collaboration

Excited heavy-meson spectroscopy



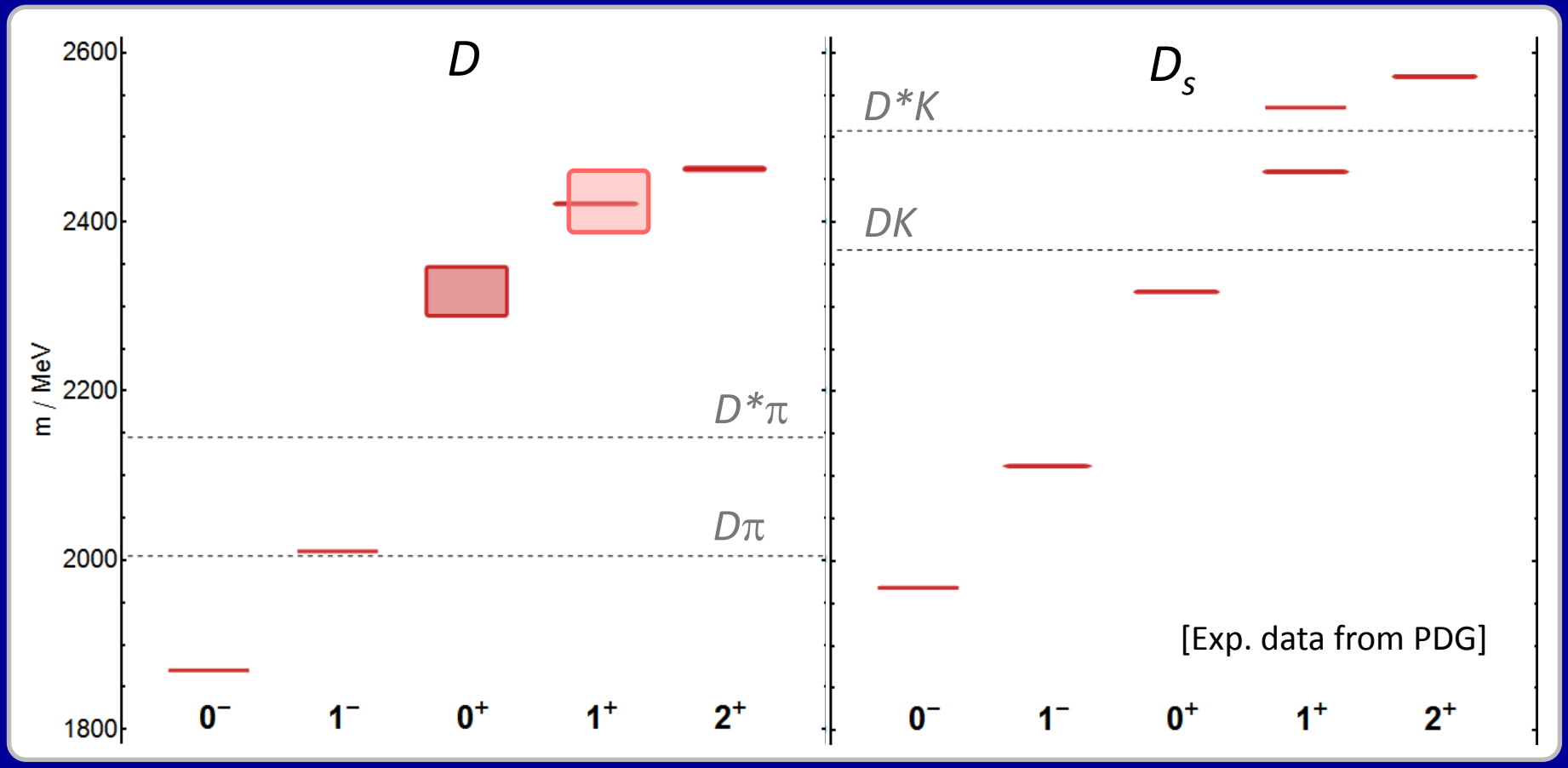
Experiments

$X(3872)$, $Y(4260)$, $Z^+(4430)$, $Z_c^+(3900)$, Z_b^+, $X(5568)$, $D_s(2317)$, ...

Exotic flavour or **exotic** J^{PC} (0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, ...) quantum numbers – can't just be a $q\bar{q}$ pair

First-principles calculations → lattice QCD

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



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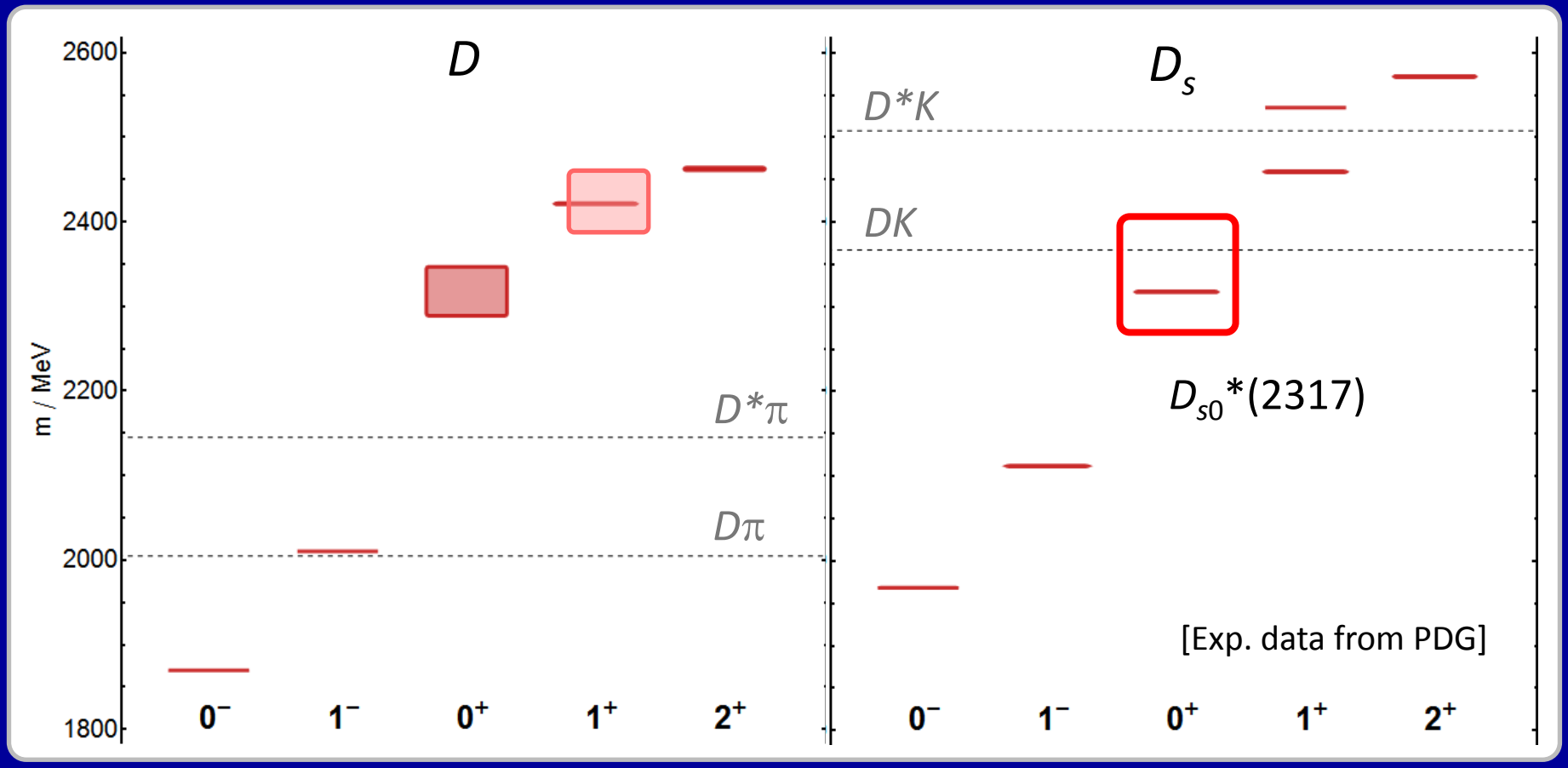

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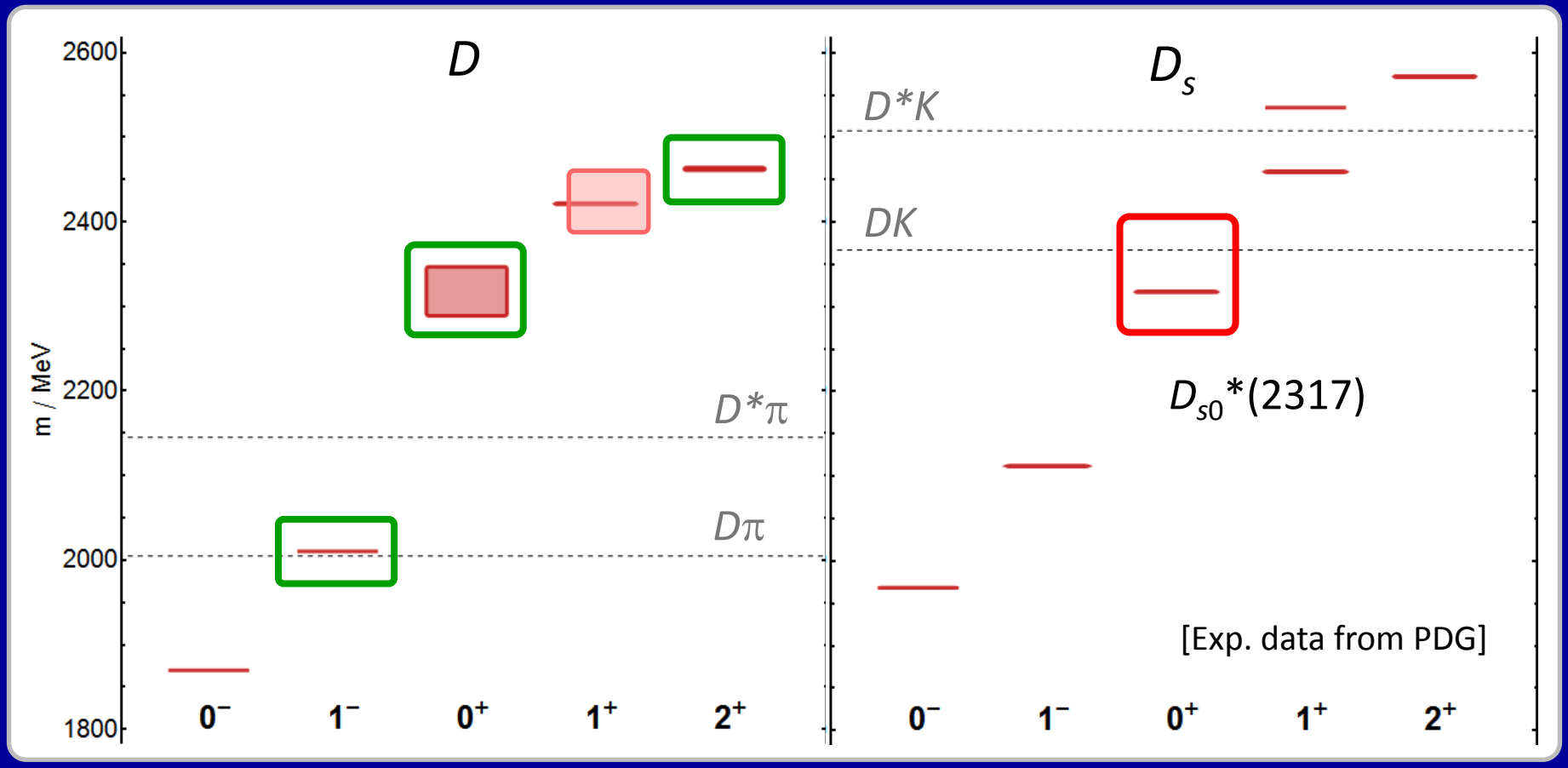
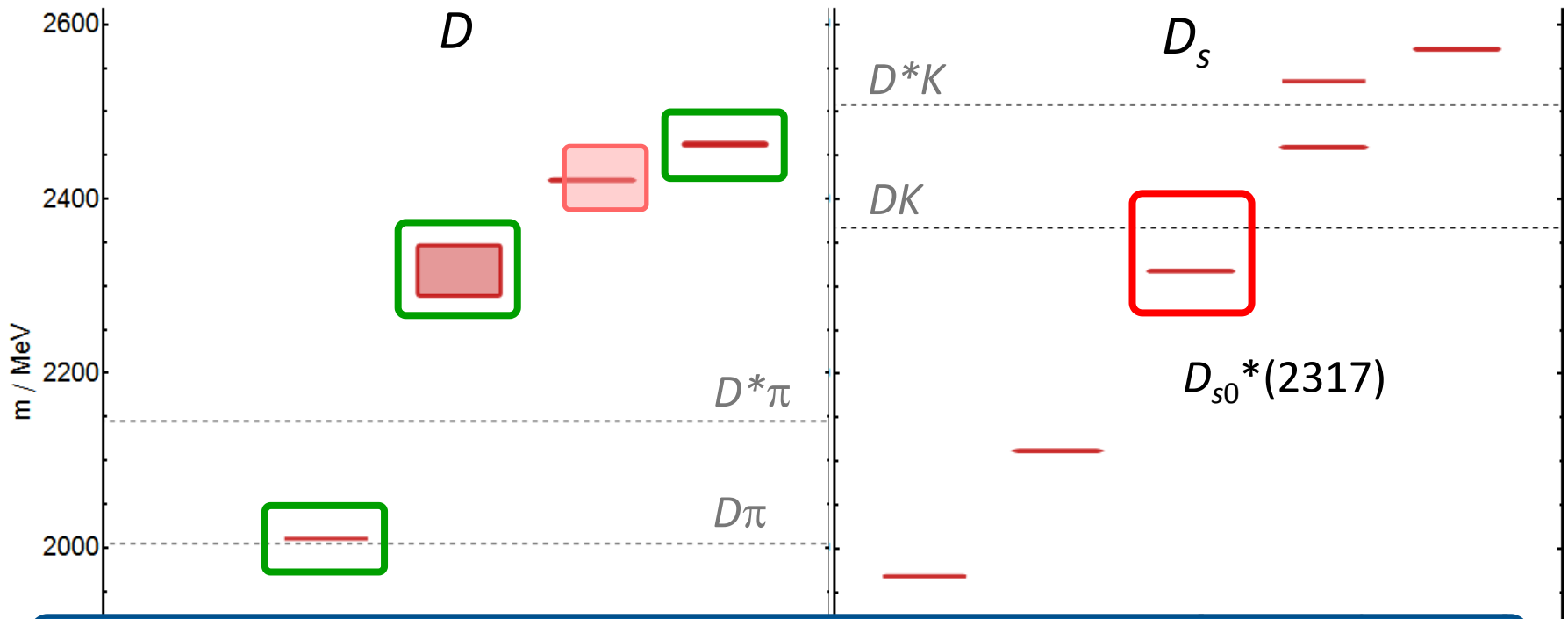


Focus here on states that appear in $D\,\pi$ (isospin=½): $J^P = 0^+, 1^-, 2^+, \ldots$

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



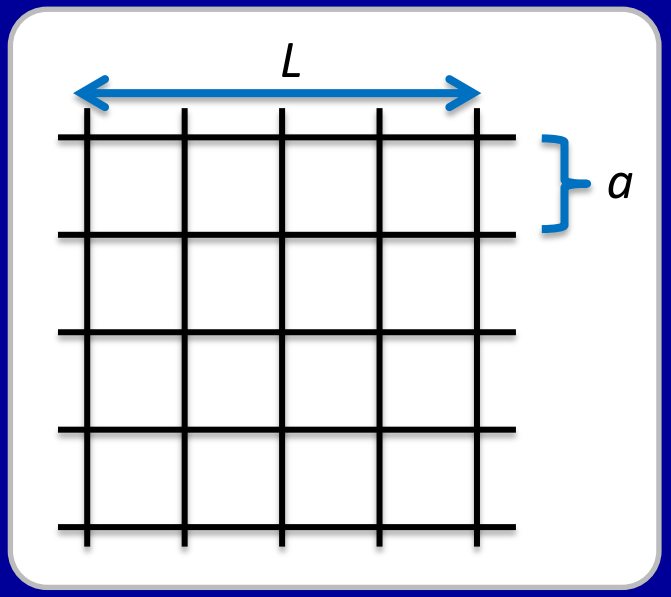
Some previous LQCD studies (of charm resonances/near-threshold states):

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

Excited D and D_s mesons (not allowing for unstable nature):

Moir *et al* (HadSpec) [JHEP 05 (2013) 021]

Lattice QCD Spectroscopy



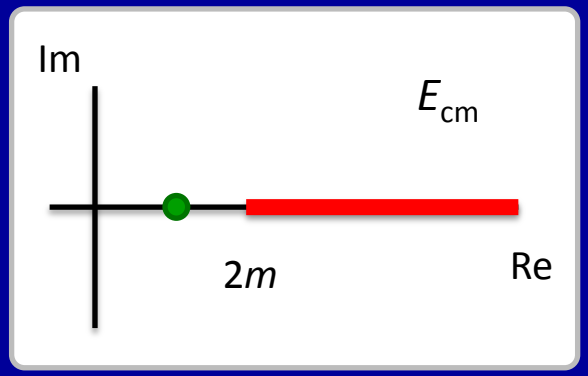
Finite-volume **energy eigenstates** from:

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

$$= \sum_n \frac{e^{-E_n t}}{2\ E_n} Z_i^{(n)} Z_j^{(n)*}$$

Lattice QCD Scattering

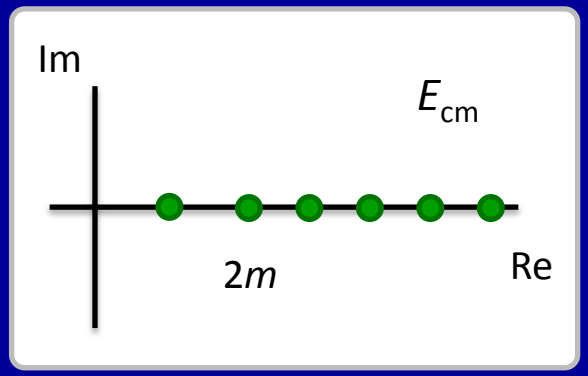
Infinite volume – contin. spectrum above thresh.

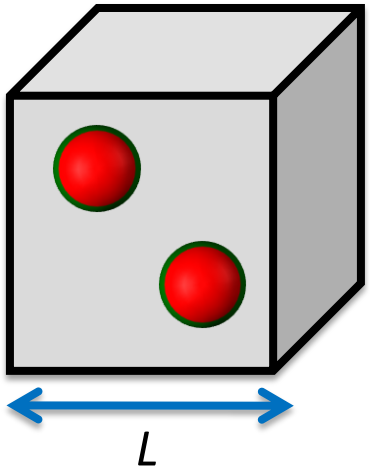


Lattice QCD Scattering

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]

Lattice QCD Scattering

Infinite volume – contin. spectrum above thresh.

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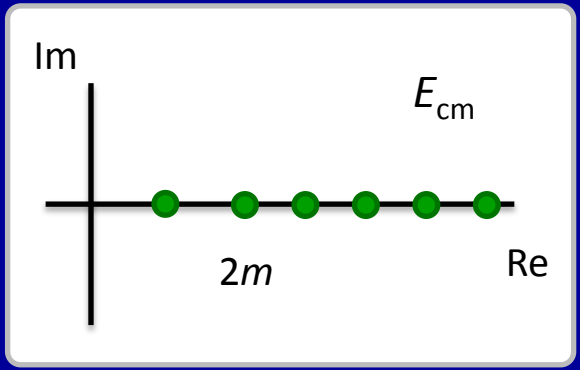

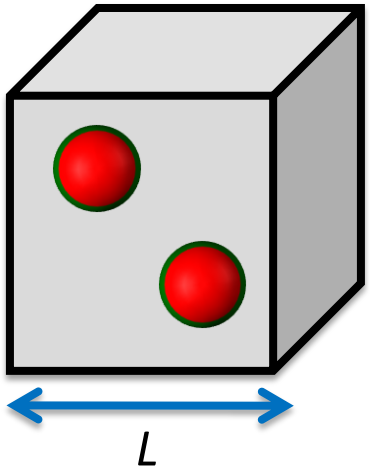

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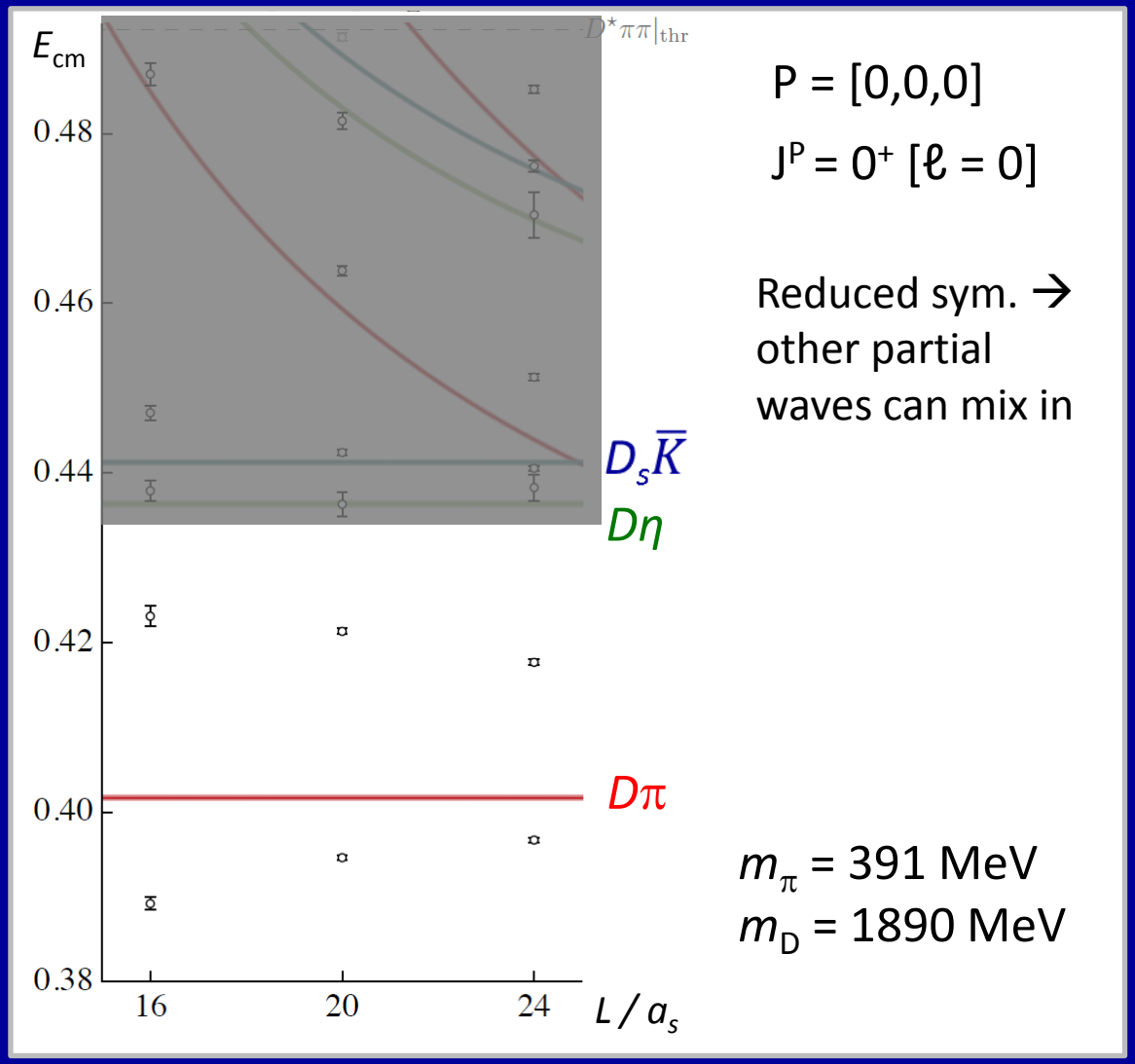
$$\mathrm{t}(E_{\mathrm{cm}}) = \begin{pmatrix} t_{D\pi\to D\pi}(E_{\mathrm{cm}}) & t_{D\pi\to D\eta}(E_{\mathrm{cm}}) \\ t_{D\eta\to D\pi}(E_{\mathrm{cm}}) & t_{D\eta\to D\eta}(E_{\mathrm{cm}}) \end{pmatrix}$$

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

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.)

$D\pi$, $D\eta$, $D_s\bar{K}$ (isospin-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)

m_π = 391 MeV

Moir, Peardon, Ryan, CT, Wilson (HadSpec) [arXiv:1607.07093]

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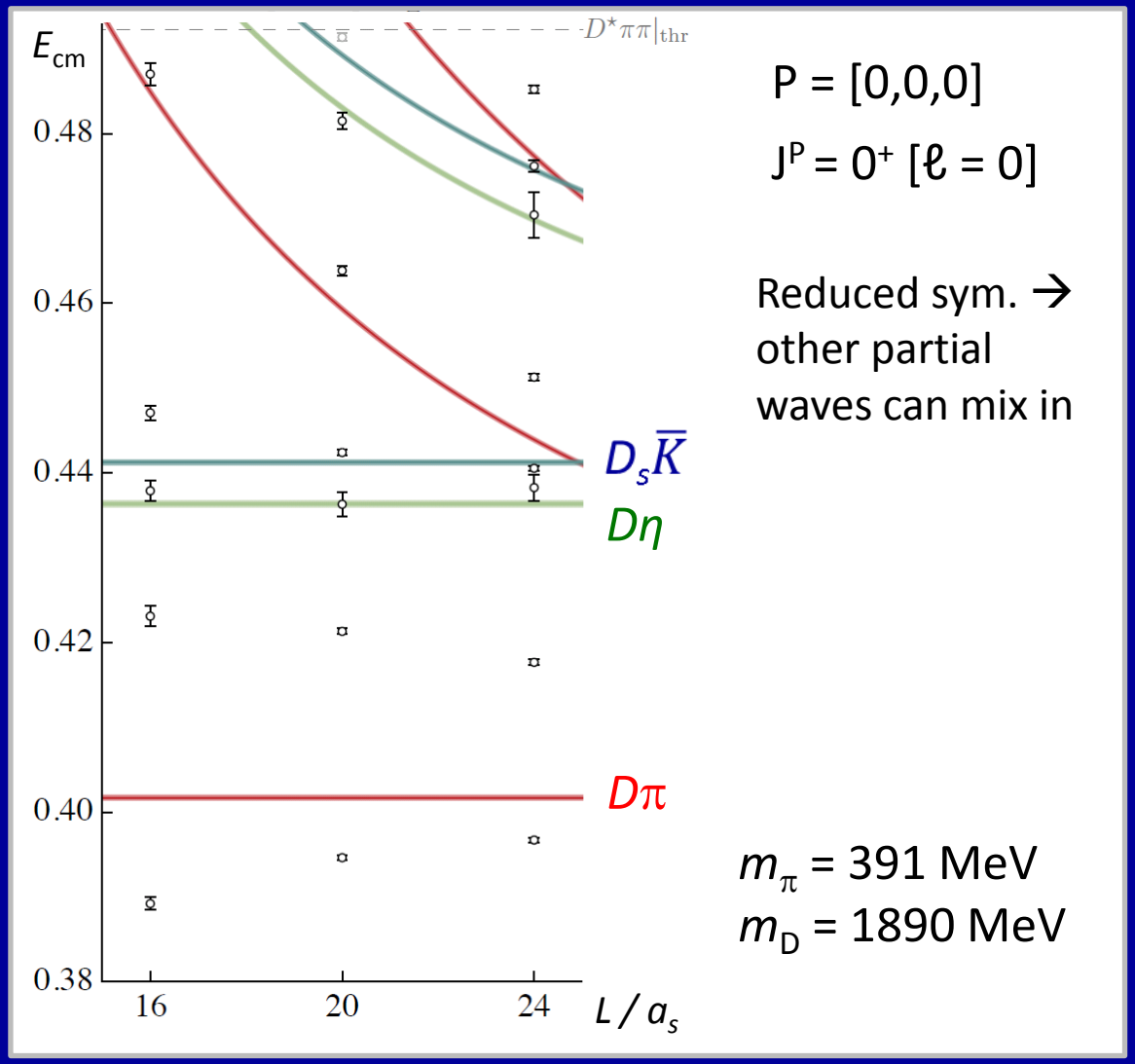

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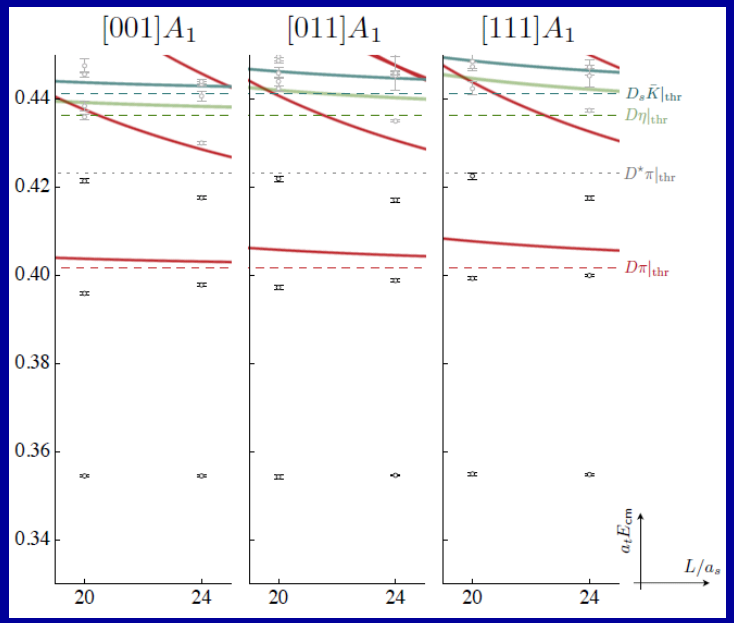
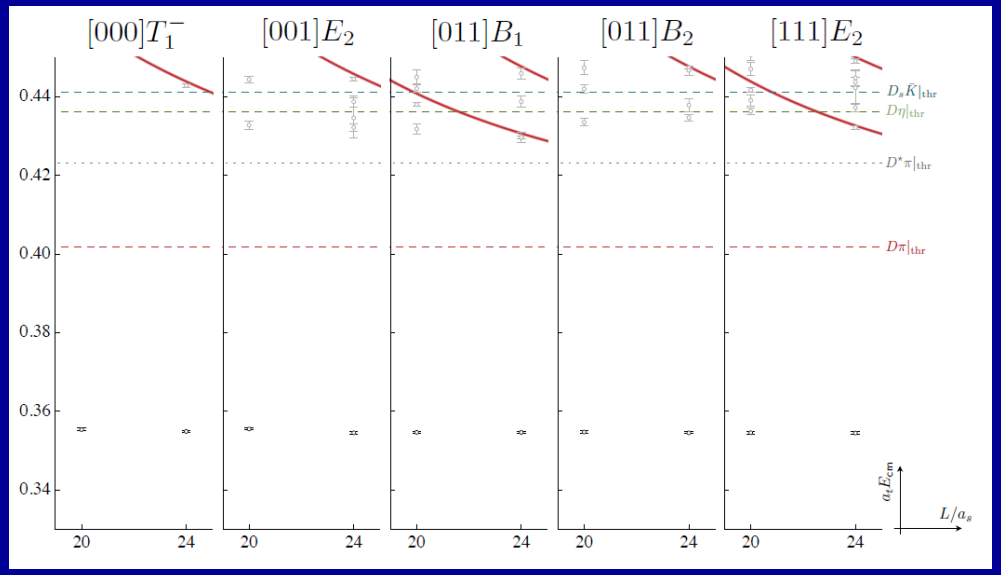
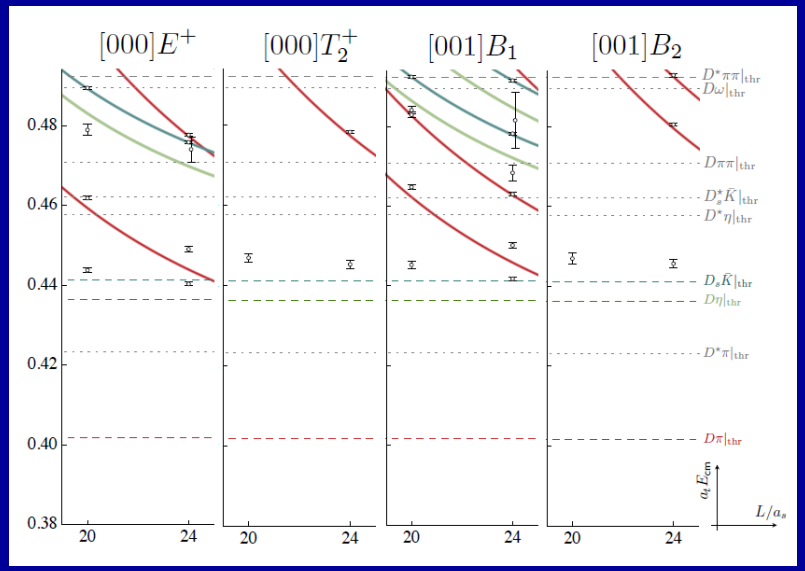
$D\pi$, $D\eta$, $D_s\bar{K}$ (isospin-½): spectra

[arXiv:1607.07093]



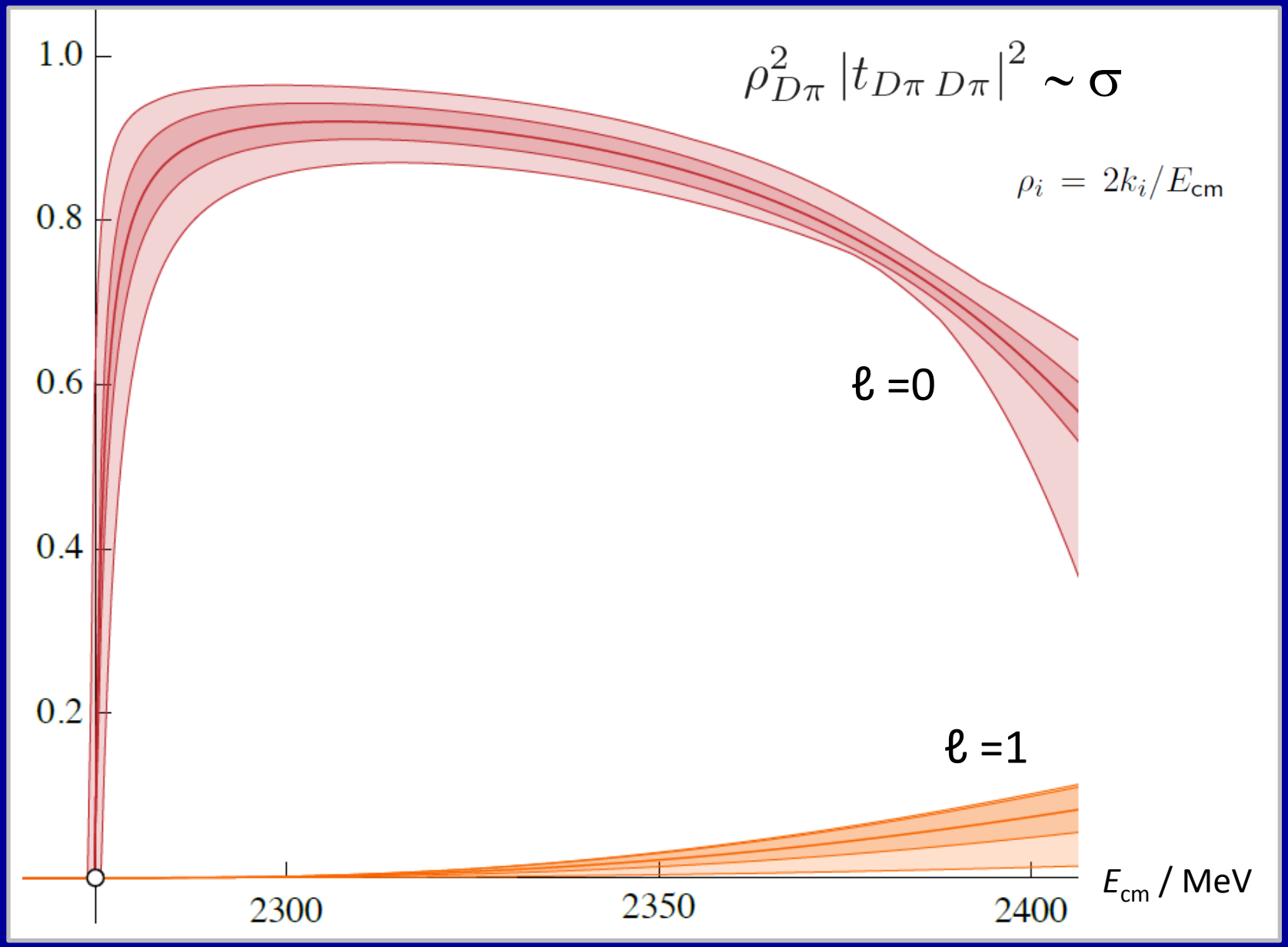


Use 47 energy levels for ℓ = 0, 1 and 18 for ℓ = 2



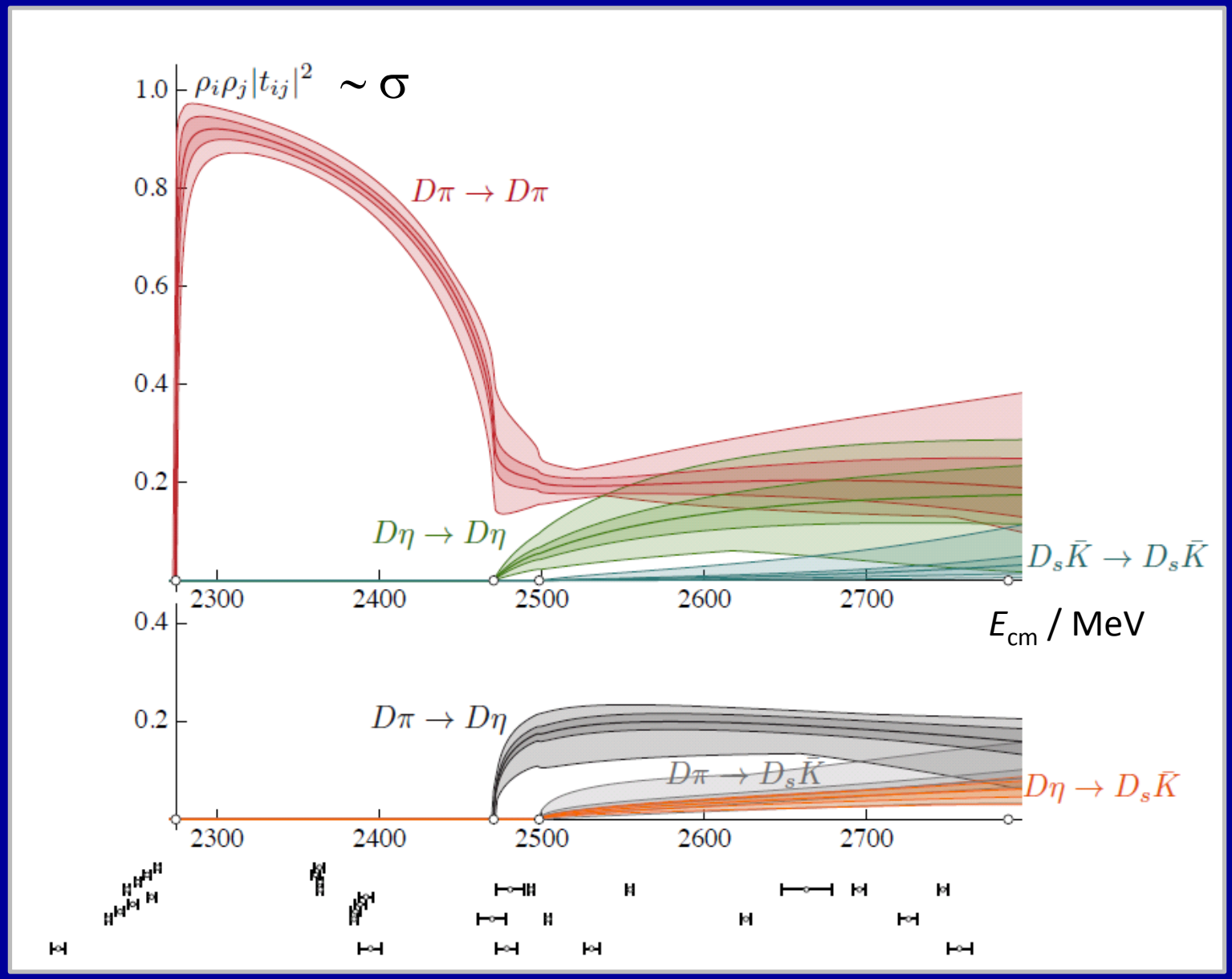
Elastic Dπ (I=½): ℓ = 0,1

[arXiv:1607.07093]



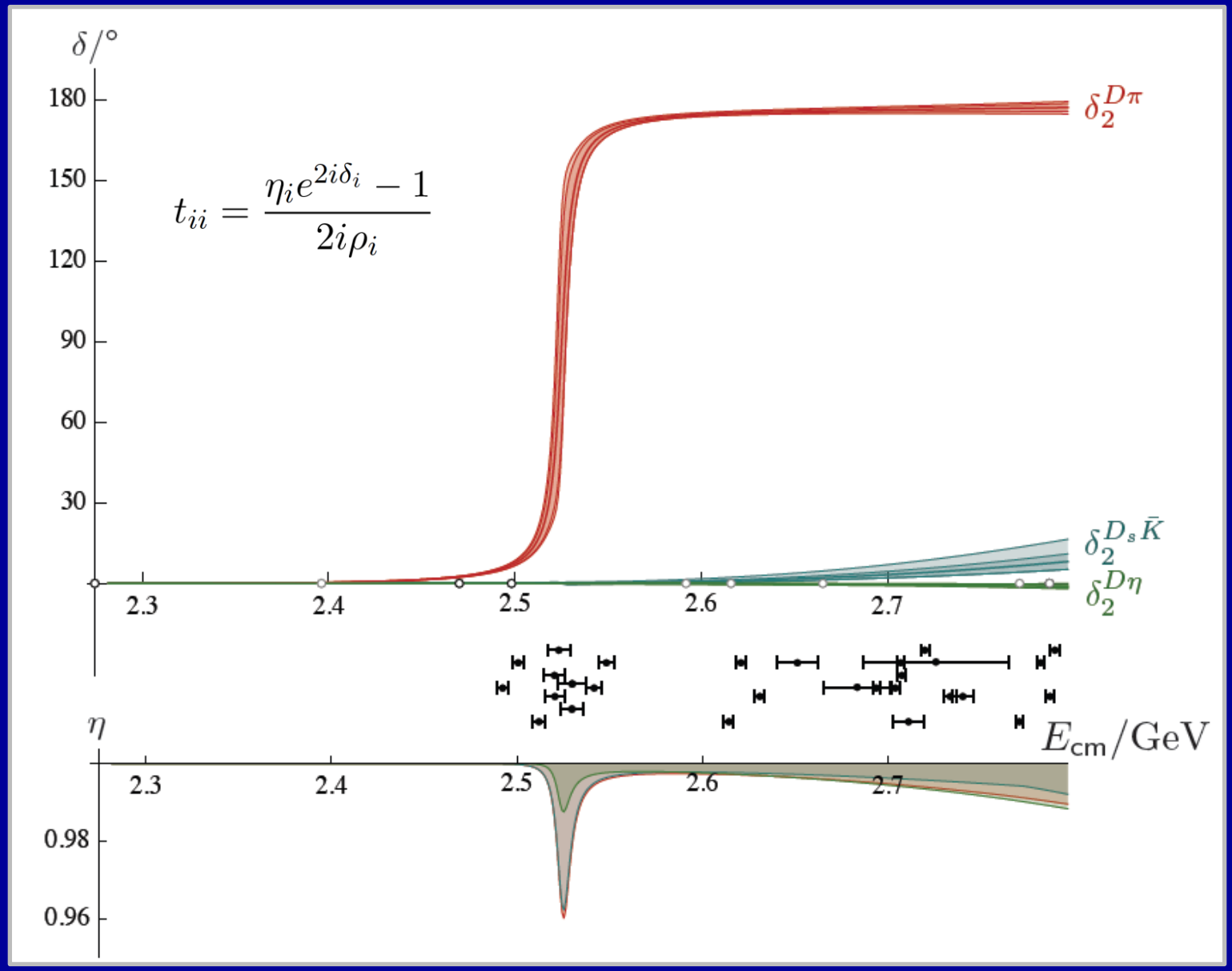
$D\pi$, $D\eta$, $D_s\bar{K}$ ($I=½$): $\ell = 0$

[arXiv:1607.07093]



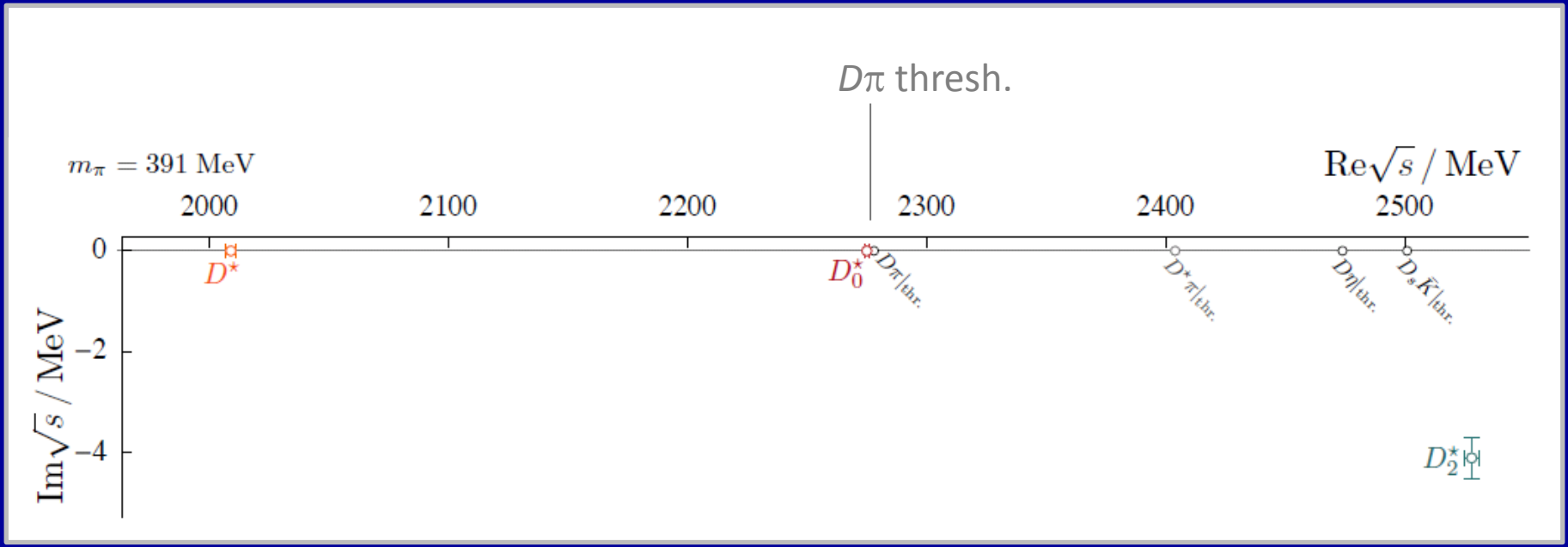
$D\pi$, $D\eta$, $D_s\bar{K}$ (I=½): $\ell = 2$

[arXiv:1607.07093]



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

[arXiv:1607.07093]



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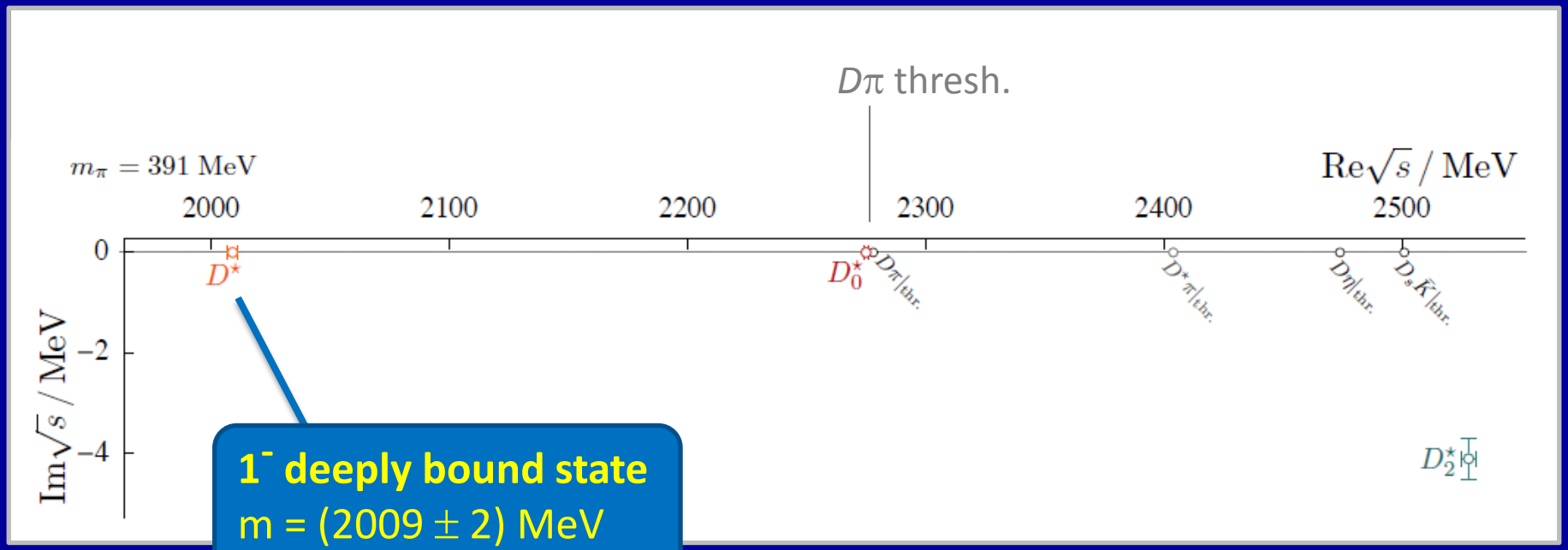

1^- deeply bound state

m = (2009 ± 2) MeV

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

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

[arXiv:1607.07093]

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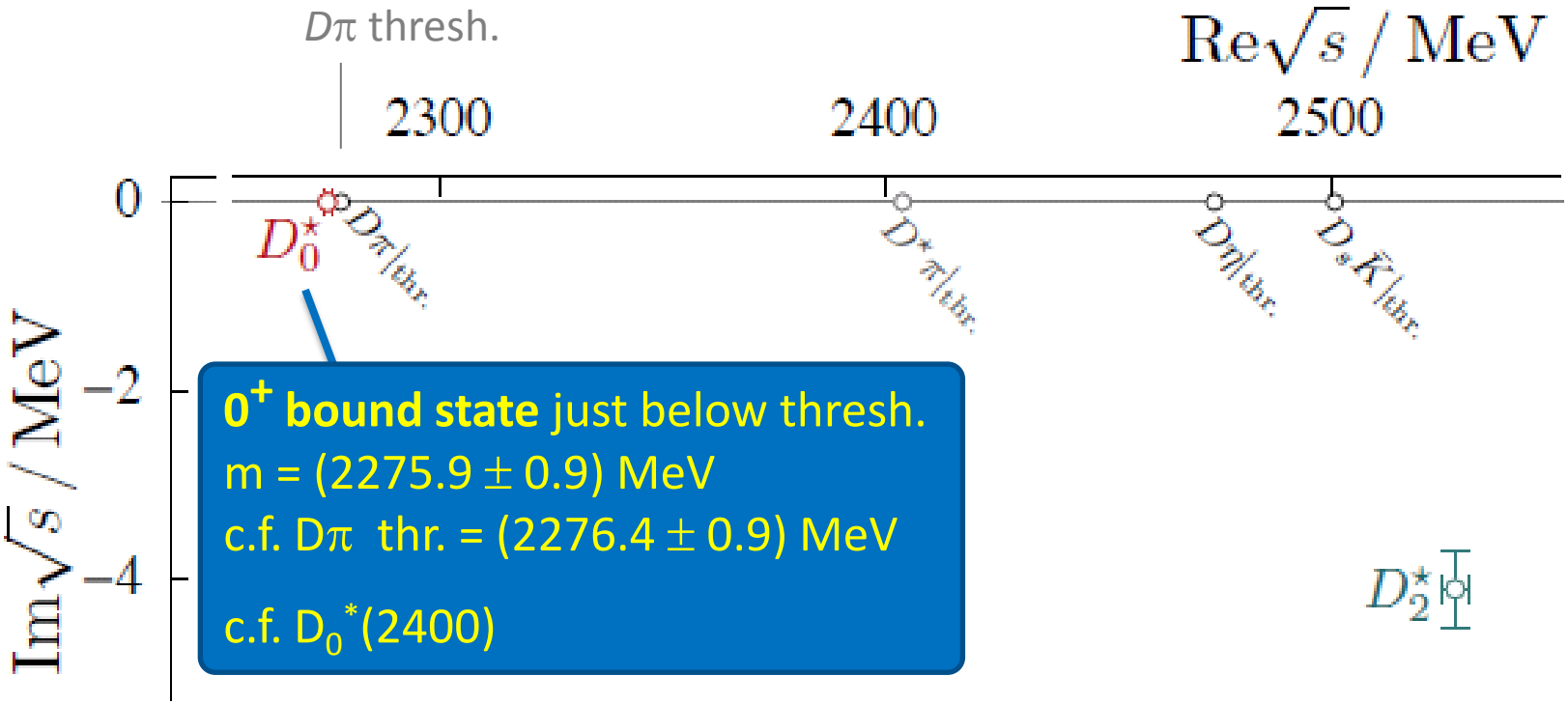

0^+ bound state just below thresh.
m = (2275.9 ± 0.9) MeV
c.f. $D\pi$ thr. = (2276.4 ± 0.9) MeV

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

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

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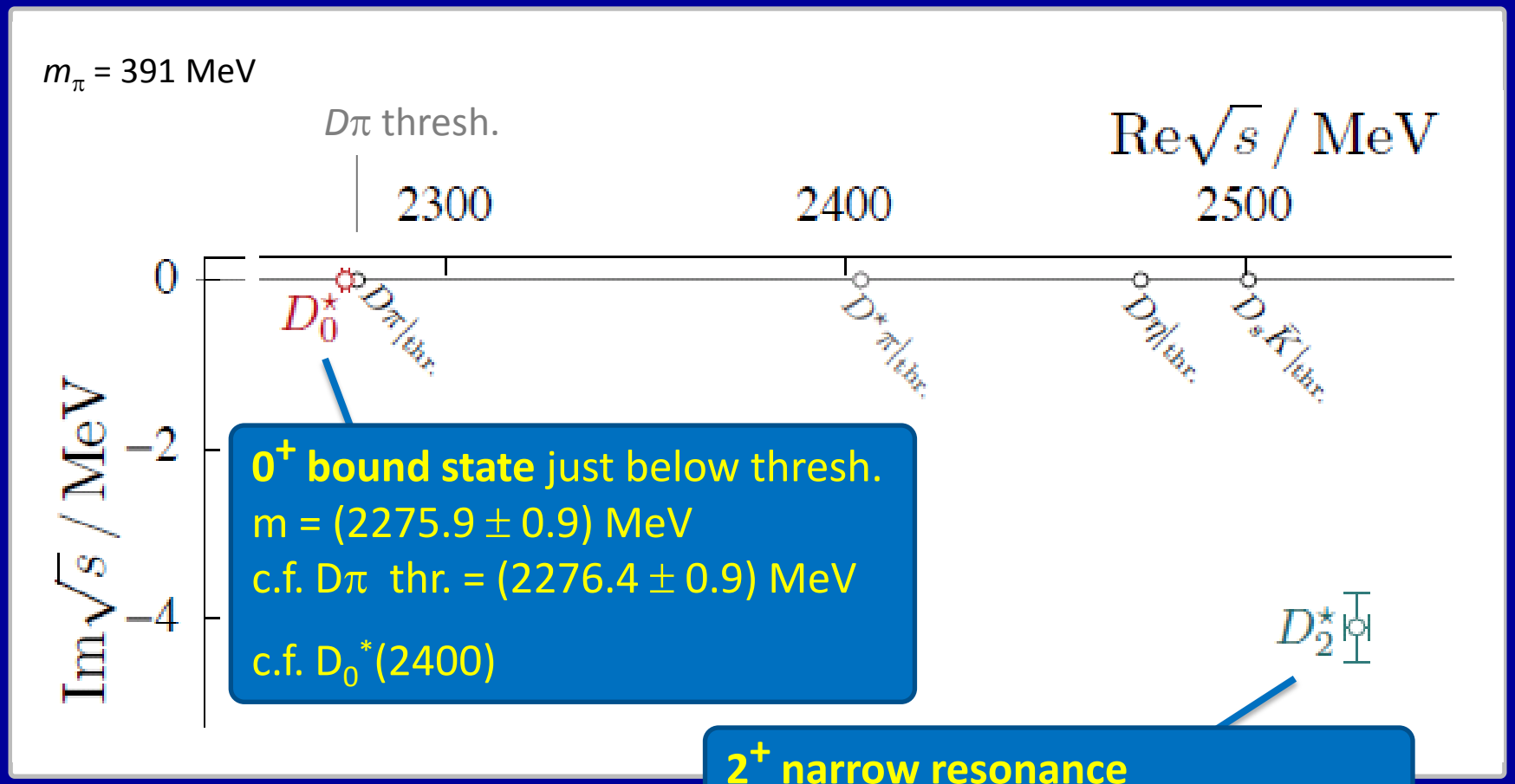


0^+ bound state just below thresh.
m = (2275.9 ± 0.9) MeV
c.f. $D\pi$ thr. = (2276.4 ± 0.9) MeV

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

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

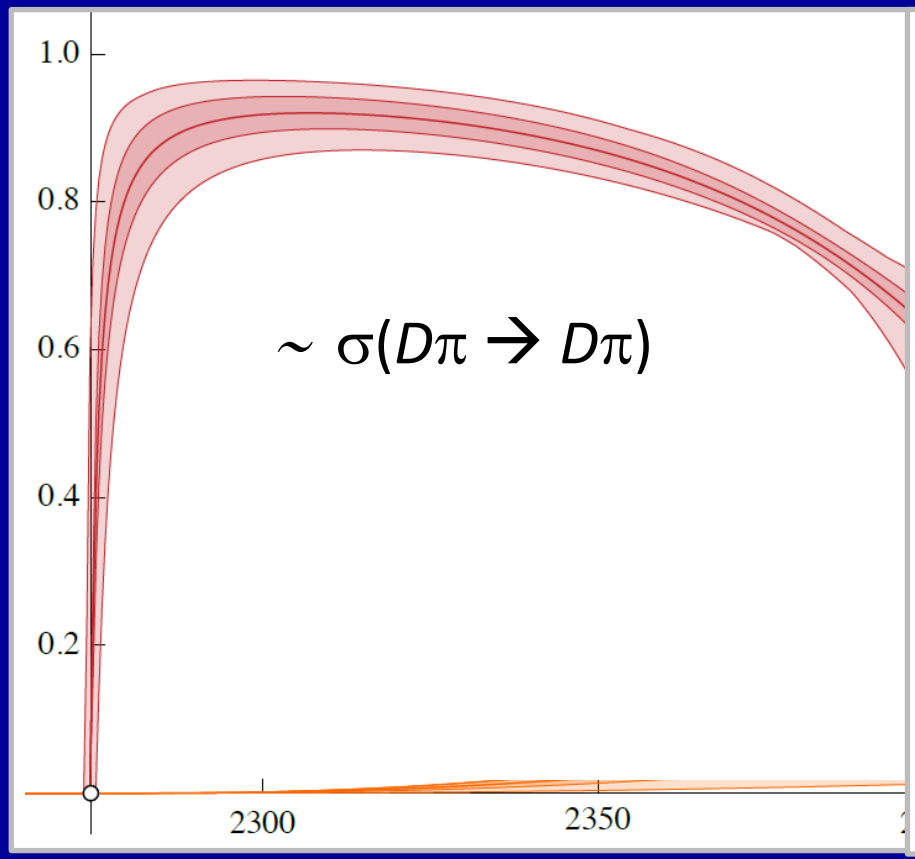
c.f. $D_2^*(2460)$ (also couples to $D^*\pi$)

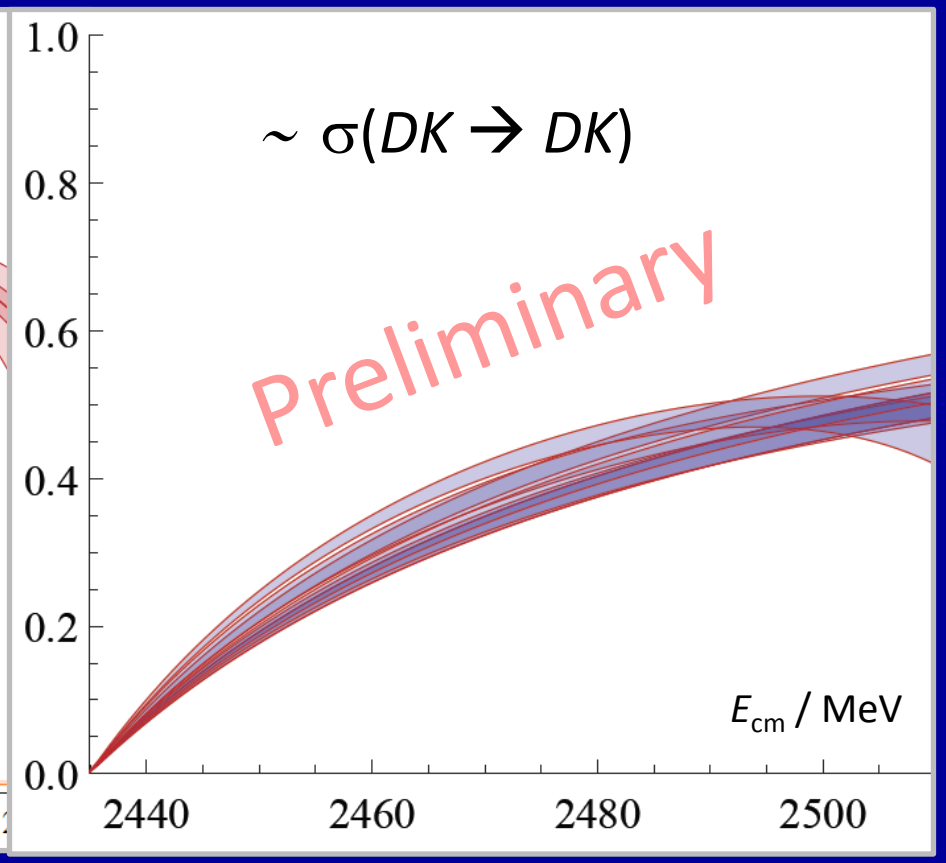
Dπ (I=½) c.f. DK (I=0): ℓ = 0

m_π = 391 MeV

0^+ in Dπ at (2275.9 ± 0.9) MeV
c.f. Dπ threshold (2276.4 ± 0.9) MeV

0^+ in DK at ≈ 2380 MeV
c.f. DK threshold ≈ 2430 MeV





Summary and outlook

- **Significant progress** in using LQCD to study scattering, resonances, etc (**map out scattering amplitudes**)
- First LQCD study of coupled-channel $D\pi$, $D\eta$, $D_s\bar{K}$ scattering:

  0^+ bound state very close to threshold, 1^- very bound, narrow 2^+ resonance
- C.f. DK and $D_{s0}^*(2317)$
- See **Dave Wilson's talk at 2pm on Saturday** for:

  $\eta\pi, K\bar{K}$ (I=1) and the a_0; $\pi\pi$ (I=0) and the σ

  $K\pi$, $K\eta$ and the κ; $\pi\pi$ (I=1) and the ρ
- Also transitions, e.g. ρ resonance $(\pi\pi) \rightarrow \pi\gamma$

  [PRL 115, 242001; PR D93, 114508]
- Many other interesting (coupled-) channels