Hadron Spectroscopy from Lattice QCD

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hadspec
hadspec.org

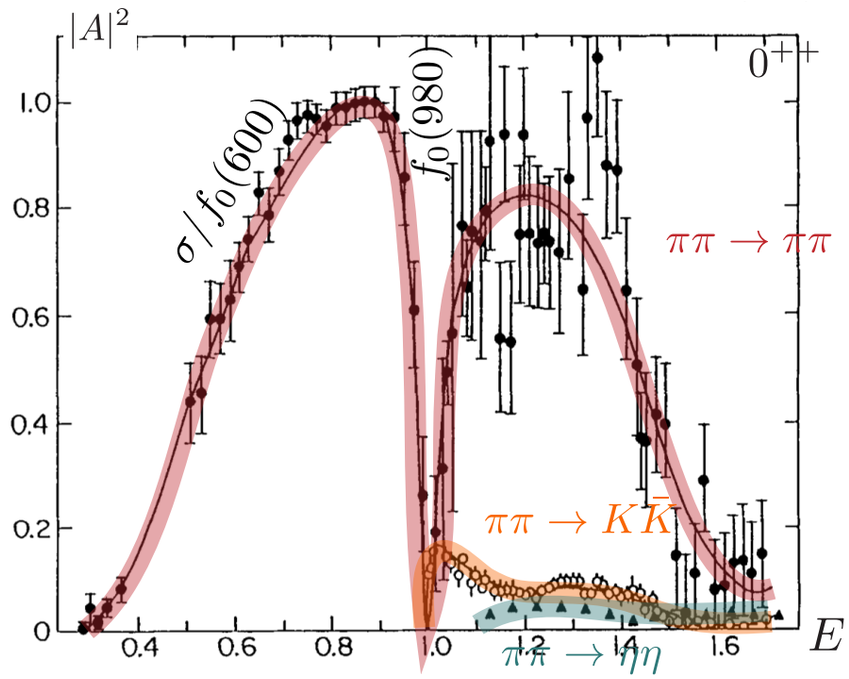
Opportunities with JLab Energy and Luminosity Upgrade
27 September 2022

UNIVERSITY OF CAMBRIDGE

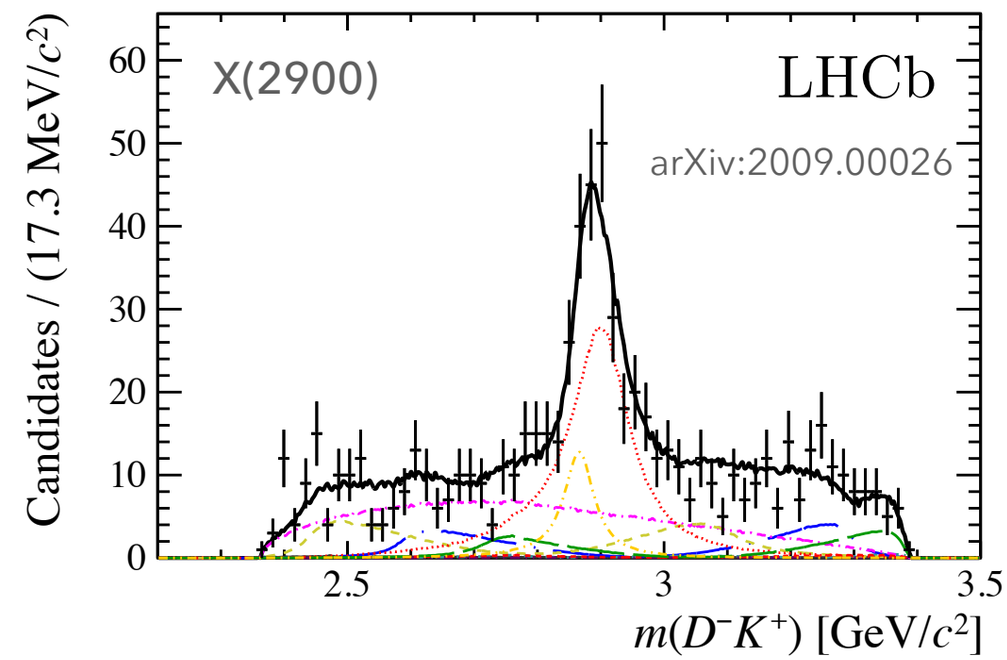
THE ROYAL SOCIETY

spectroscopy from first-principles is a hard problem

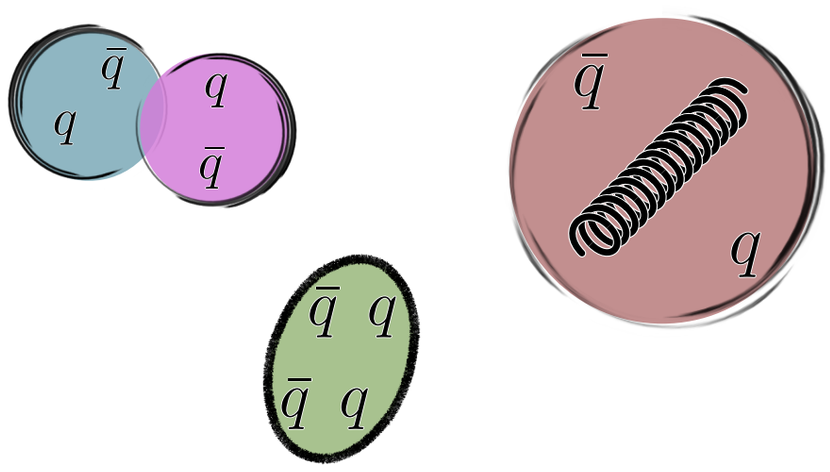
CERN-Munich, ANL, BNL



many puzzles - new and old



the quark model is a good guide for low-lying states



models are useful, but what does **QCD** say?

Lattice QCD provides a rigorous approach to hadron spectroscopy

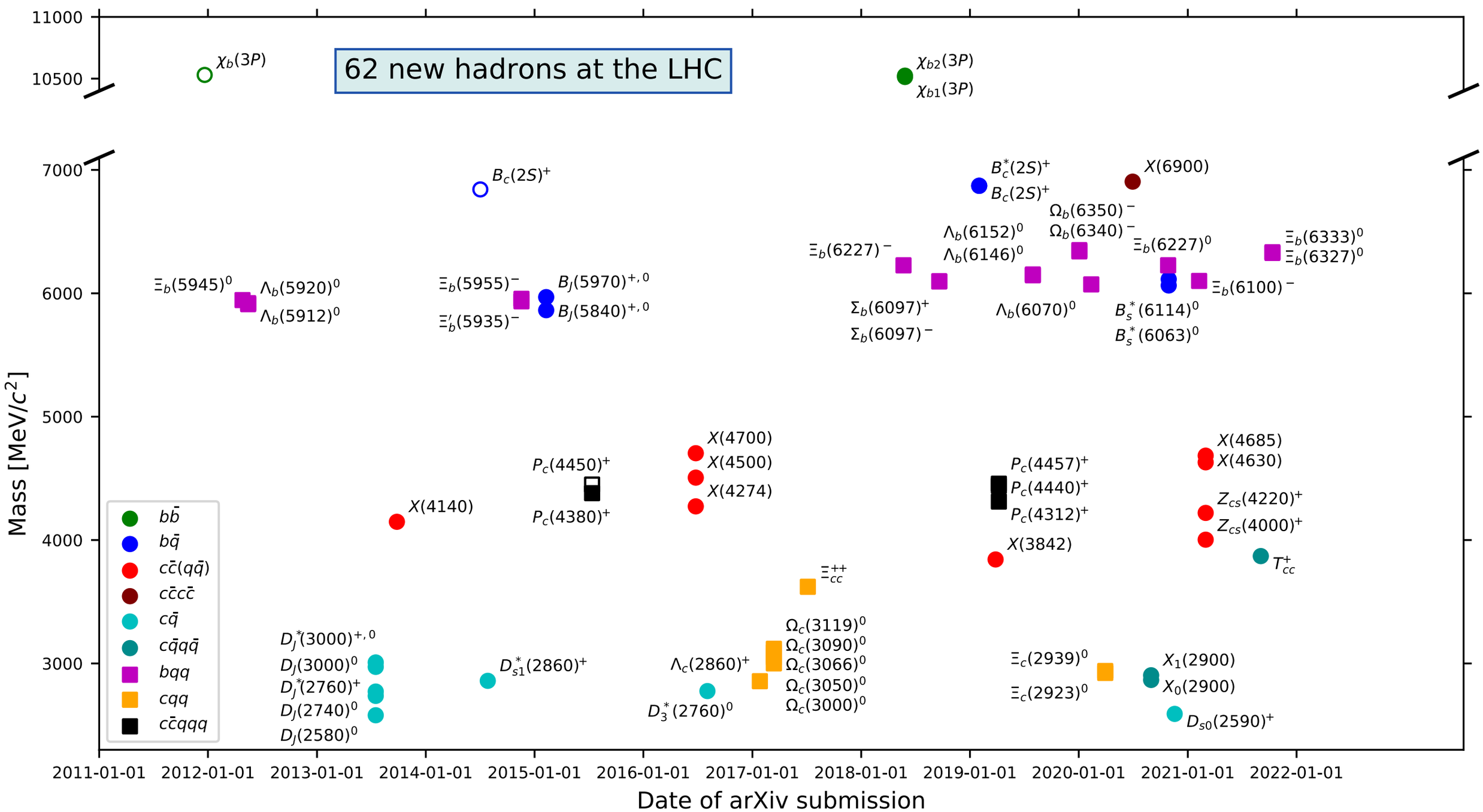
- as **rigorous** as possible
- **all** necessary **QCD** diagrams are computed
- **excited states** appear as **unstable resonances** in a scattering amplitude

tremendous progress in recent years
but not yet ready for precision comparisons

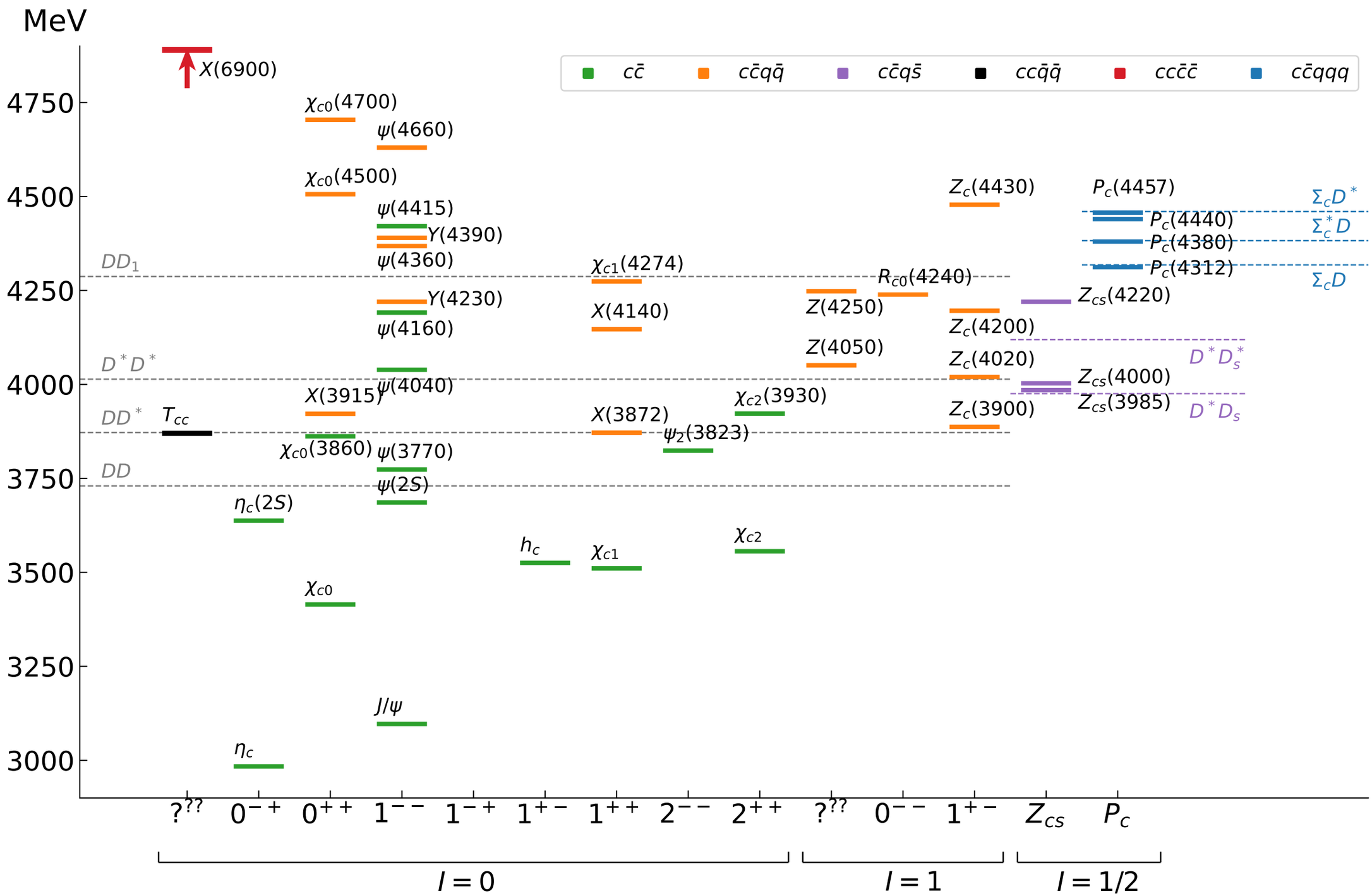
- physical pions are very light
- most interesting states can decay to **many** pions
- control of light-quark mass is a useful tool
- small effects not considered in general:

  finite lattice spacing, isospin breaking, EM interactions

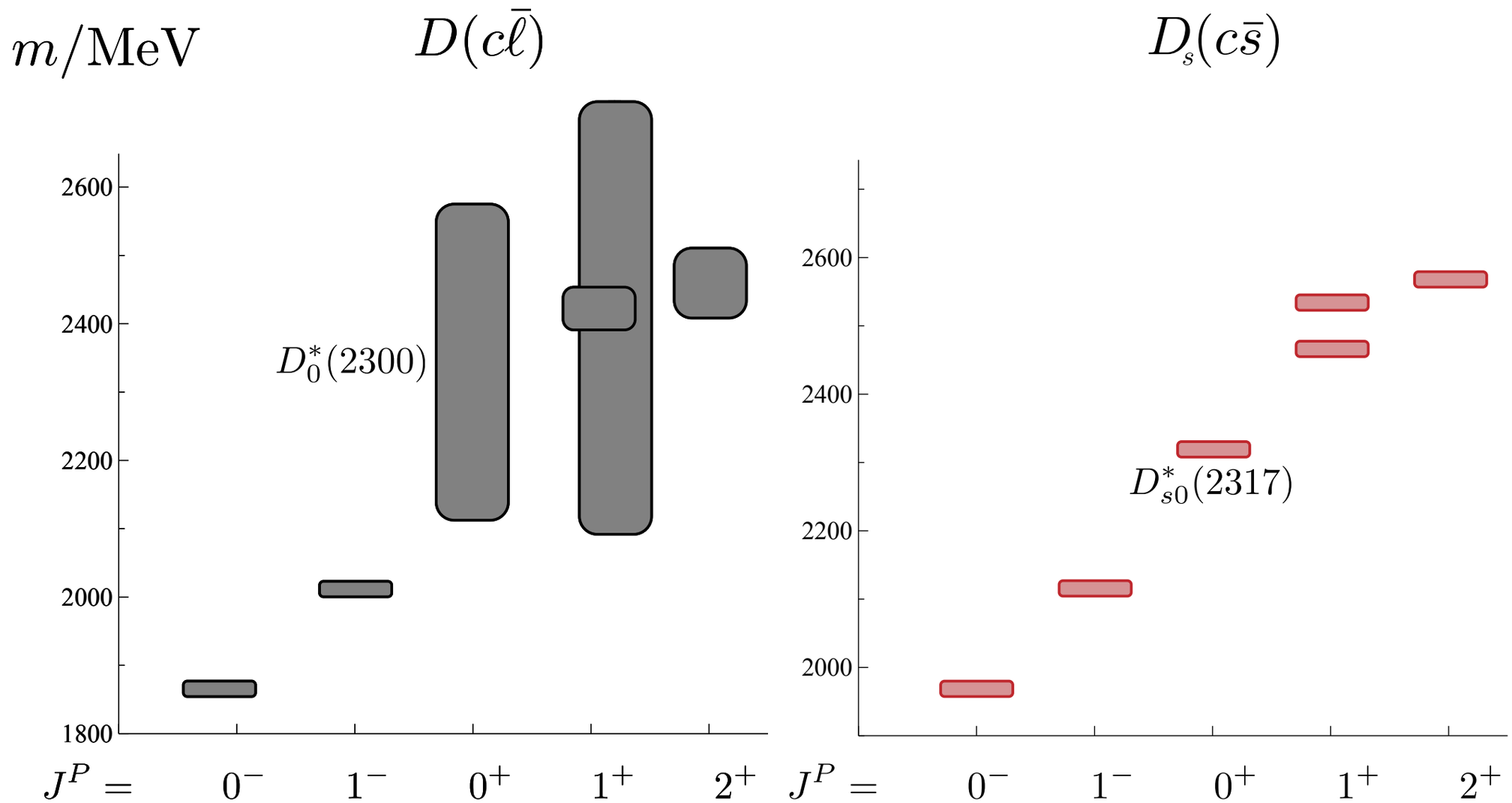
goal: what does **QCD** say about the excited hadron spectrum?



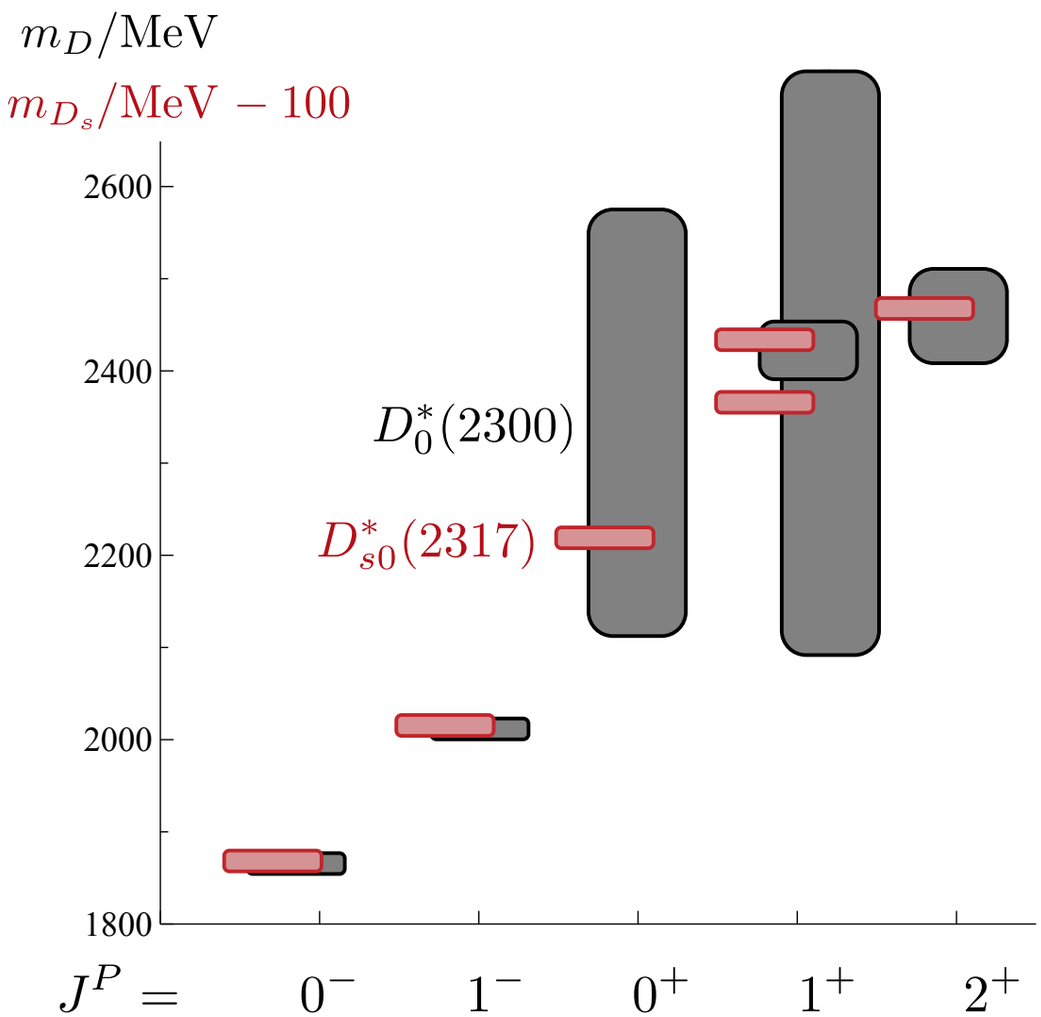
LHCb arXiv:2206.15233



JPAC arXiv:2112.13436



[masses, widths from PDG]



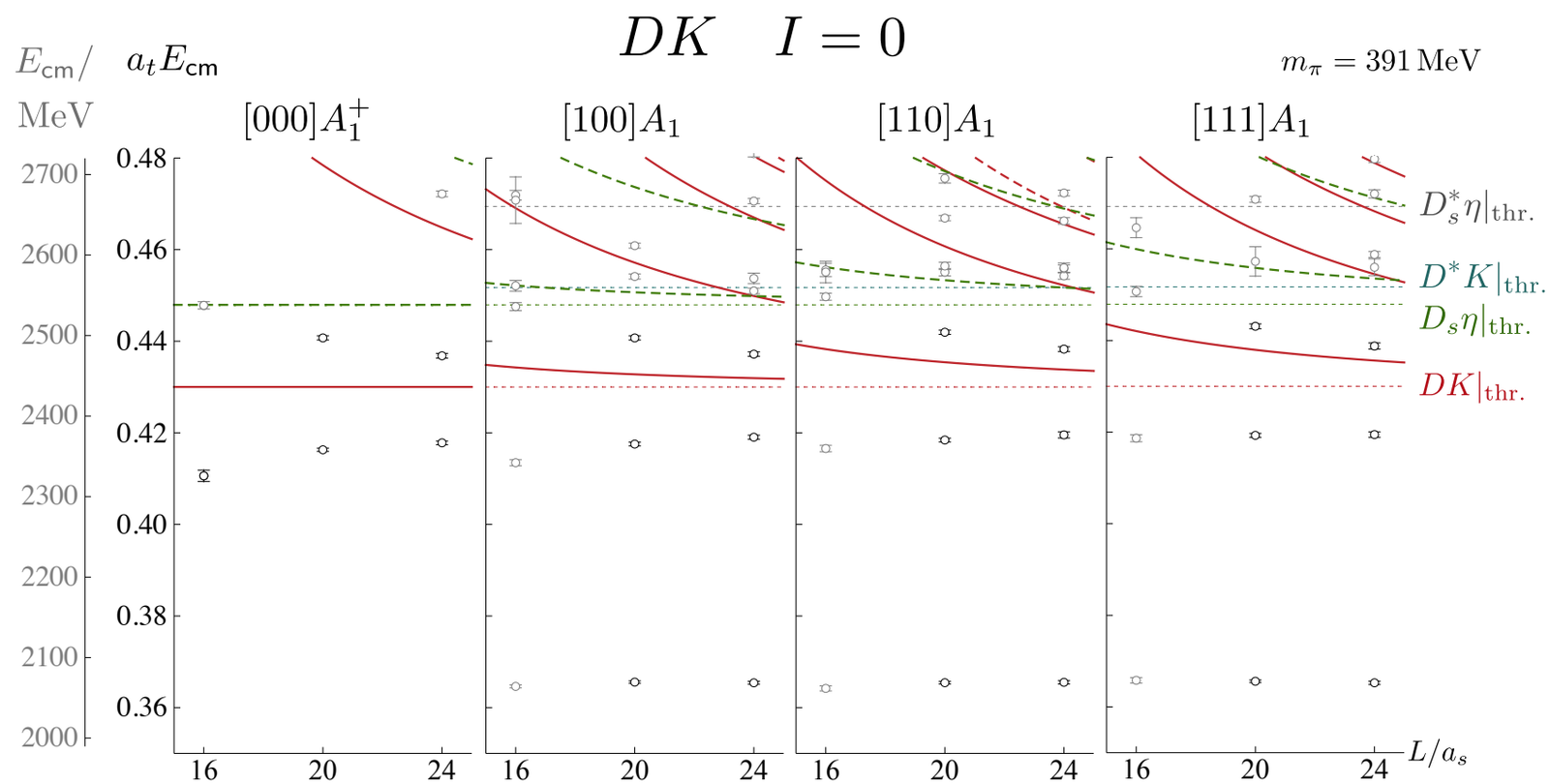
[masses, widths from PDG]

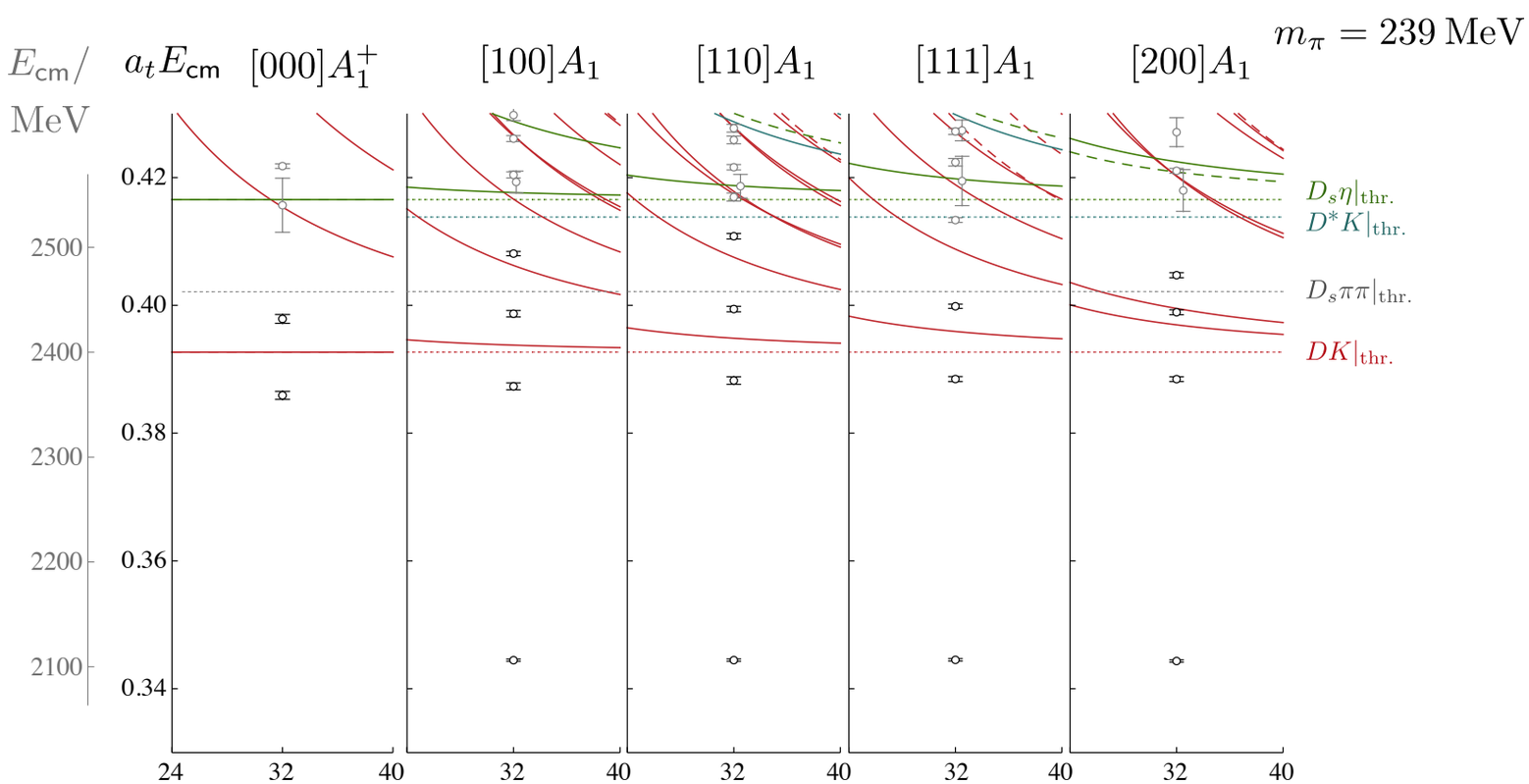
$D_0^*(2300)$ & $D_{s0}^*(2317)$

what is the mass ordering?

why are the masses so close?

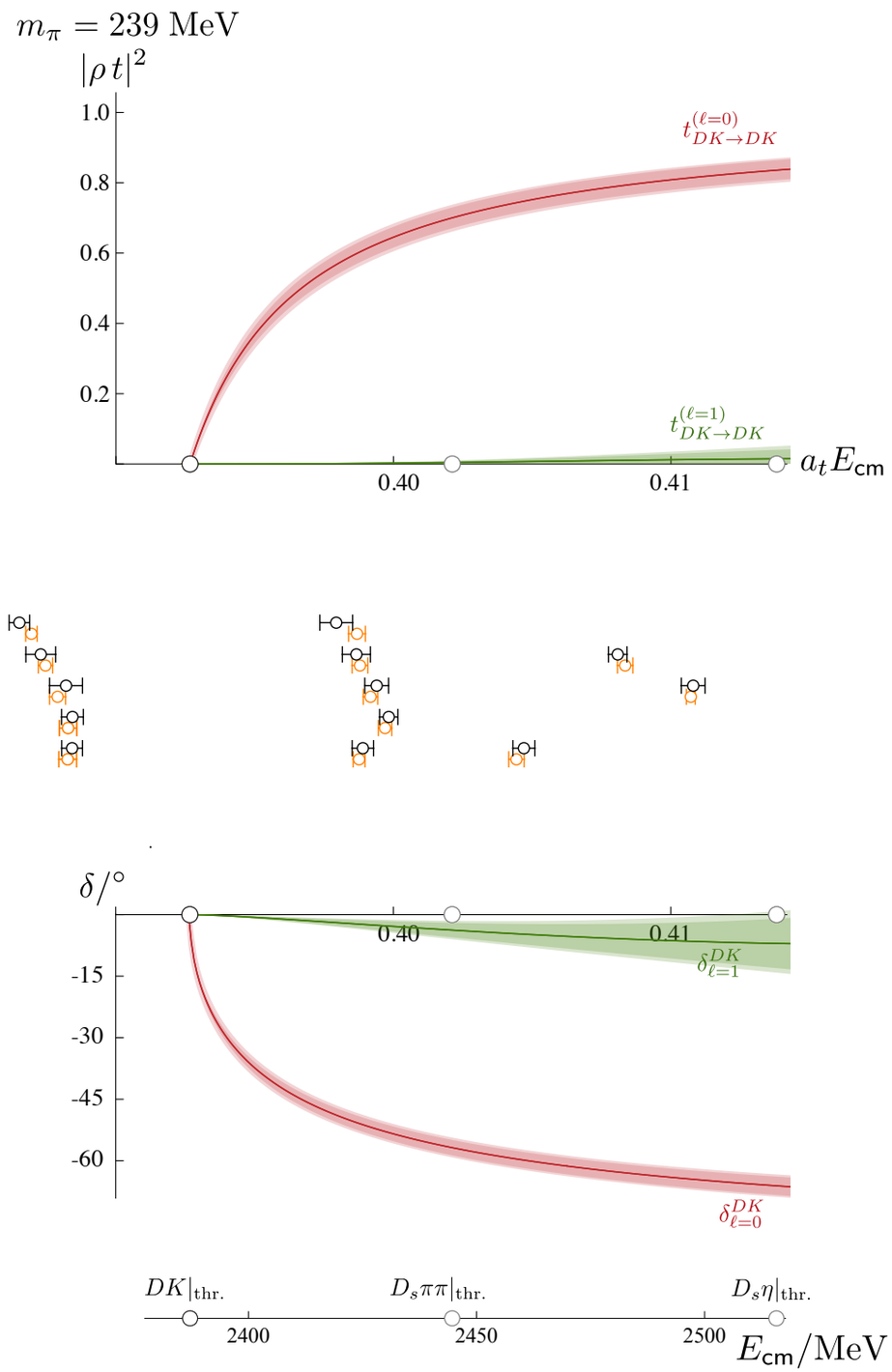
why are the widths so different?

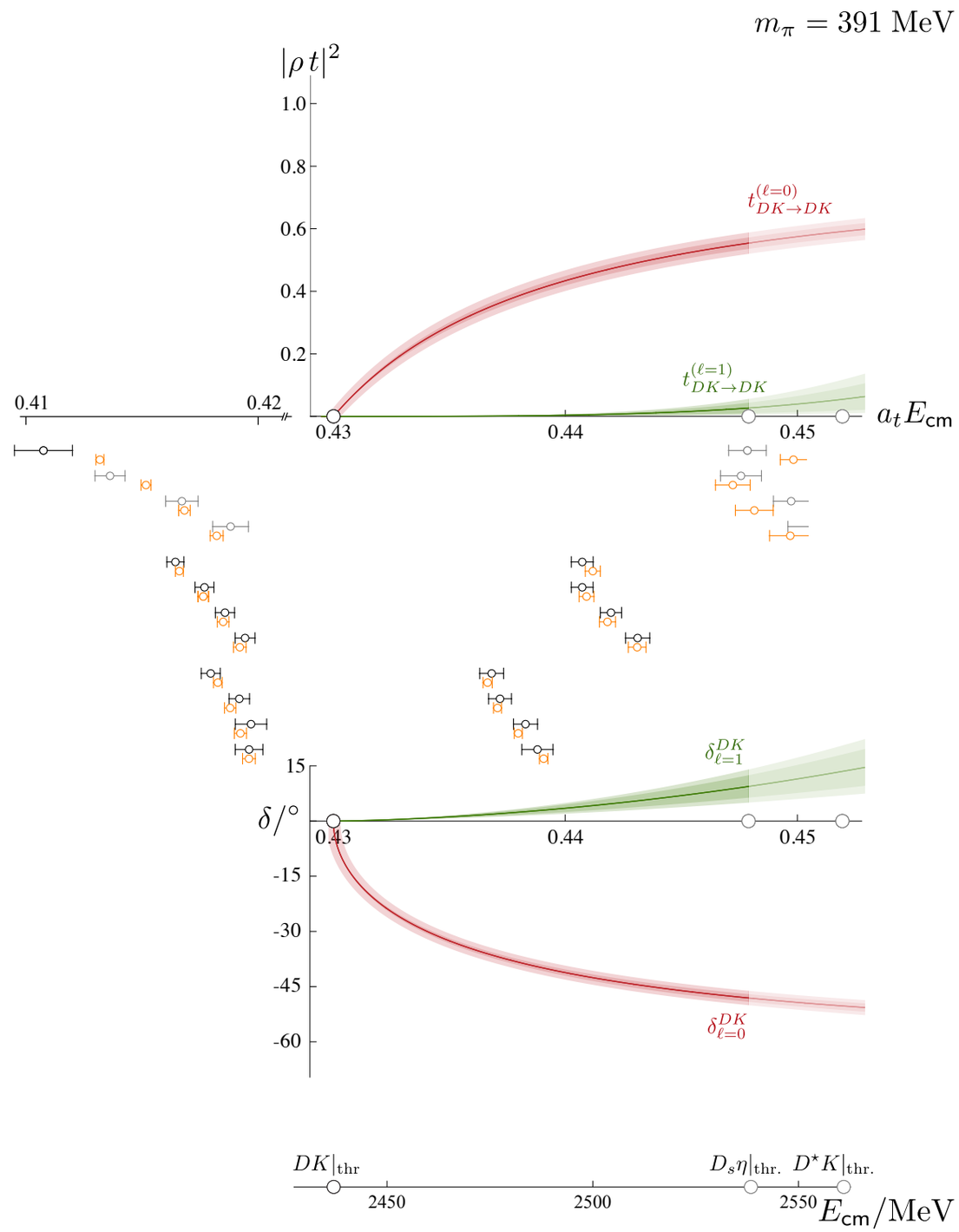

$DK \quad I = 0$
$m_\pi = 391$ MeV
E_{cm}/ MeV
$a_t E_{\mathrm{cm}}$
$[000]A_1^+$
$[100]A_1$
$[110]A_1$
$[111]A_1$
$D_s^*\eta|_{\mathrm{thr.}}$
$D^*K|_{\mathrm{thr.}}$
$D_s\eta|_{\mathrm{thr.}}$
$DK|_{\mathrm{thr.}}$
L/a_s


$m_\pi = 239$ MeV
E_{cm}/ MeV
$a_t E_{\mathrm{cm}}$
$[000]A_1^+$
$[100]A_1$
$[110]A_1$
$[111]A_1$
$[200]A_1$
$D_s\eta|_{\mathrm{thr.}}$
$D^*K|_{\mathrm{thr.}}$
$D_s\pi\pi|_{\mathrm{thr.}}$
$DK|_{\mathrm{thr.}}$

G. Cheung et al (HadSpec), JHEP 02 (2021) 100 arXiv: 2008.06432

$D_{s0}(2317)$

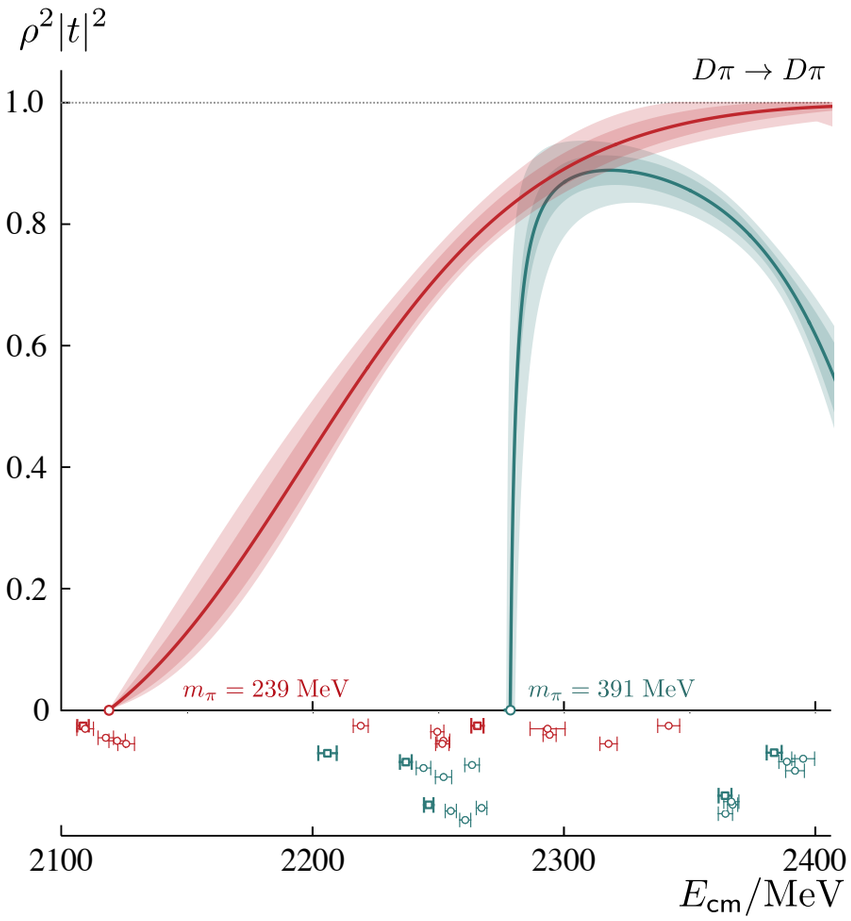




bound states in DK amplitude at both masses

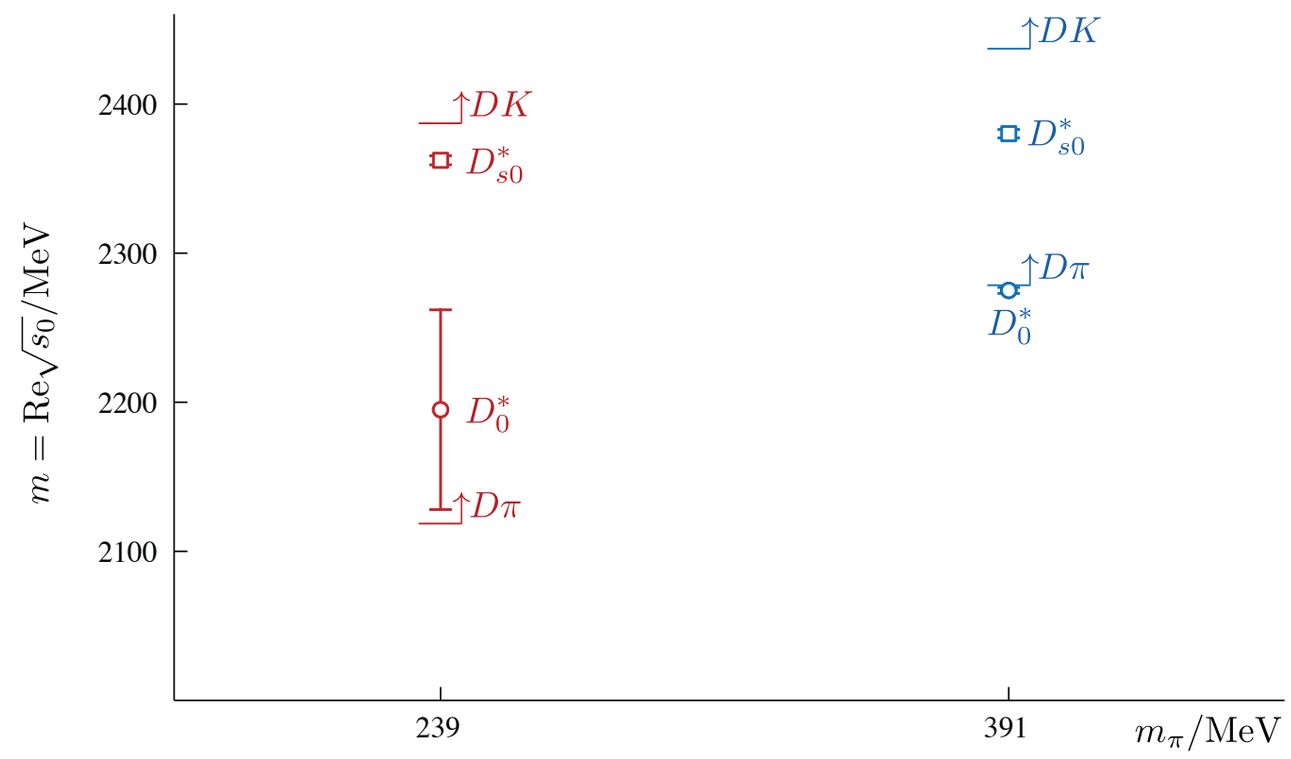
similar couplings c~1400 MeV

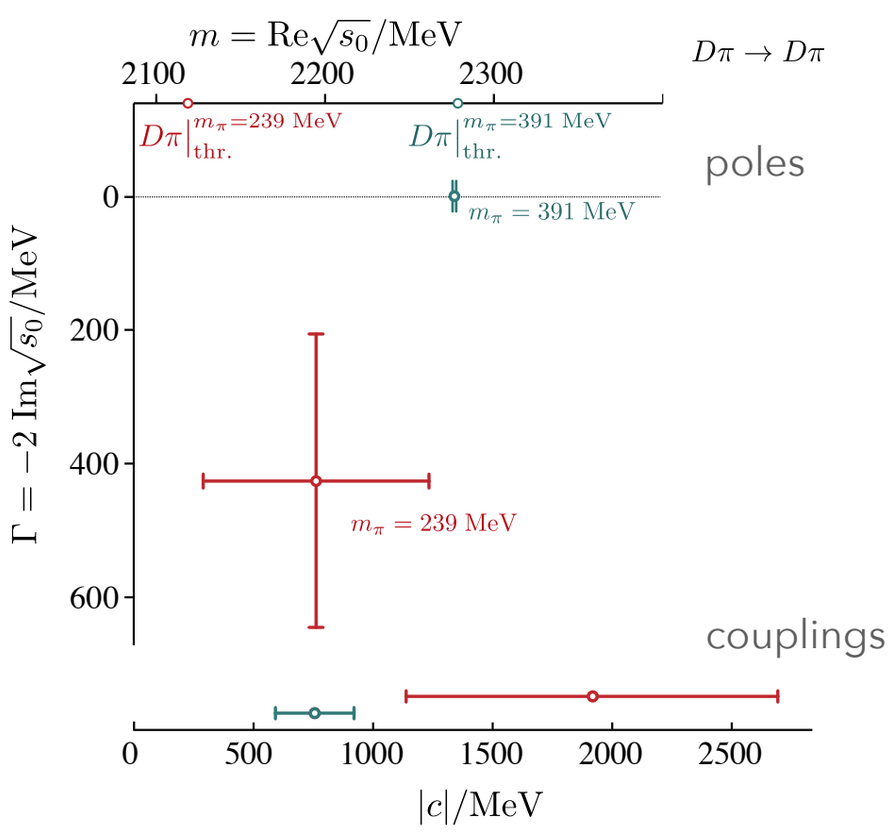
L. Gayer, N. Lang et al (HadSpec), arXiv:2102.04973



$$t \sim \frac{c^2}{s_{\rm pole} - s} \qquad \sqrt{s_{\rm pole}} = m \pm \tfrac{i}{2}\Gamma$$

suggestive of a much lighter D_0^* compared with the D_{s0}^*





natural mass ordering: given light, strange constituents

likely hypothesis: D_0^* pole position is lower, m~2100-2200 MeV ?

see also LHCb data+ChiPT+unitarity: Du et al, PRL 126, 192001

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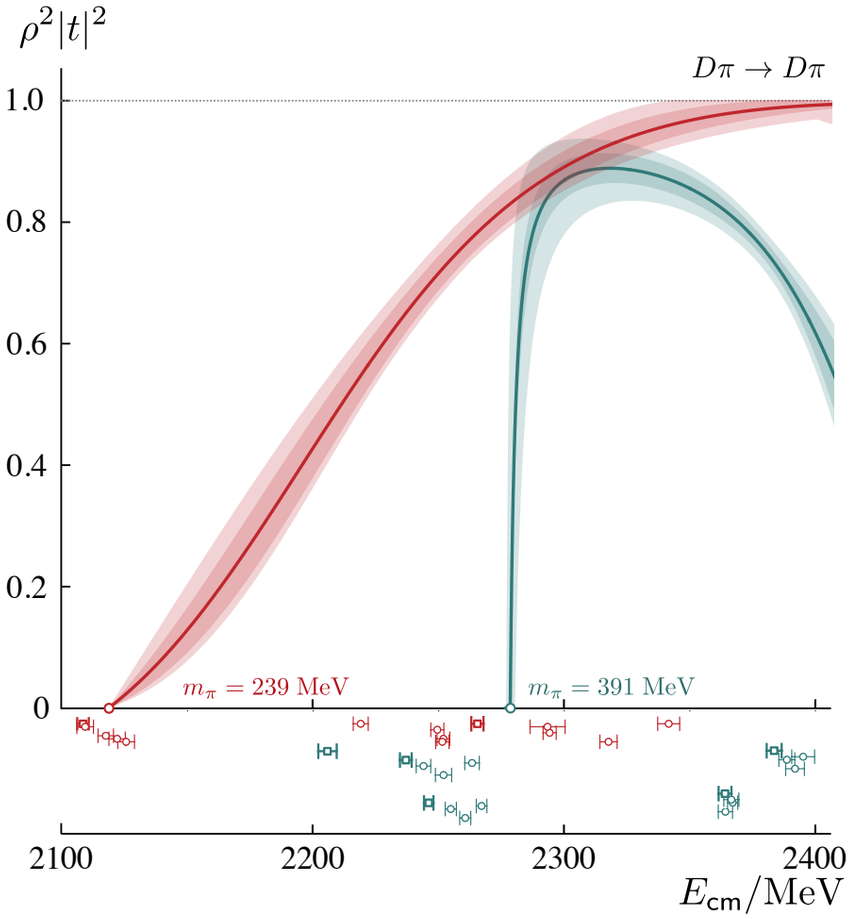

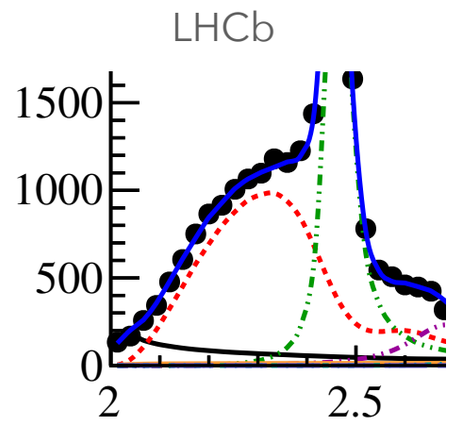

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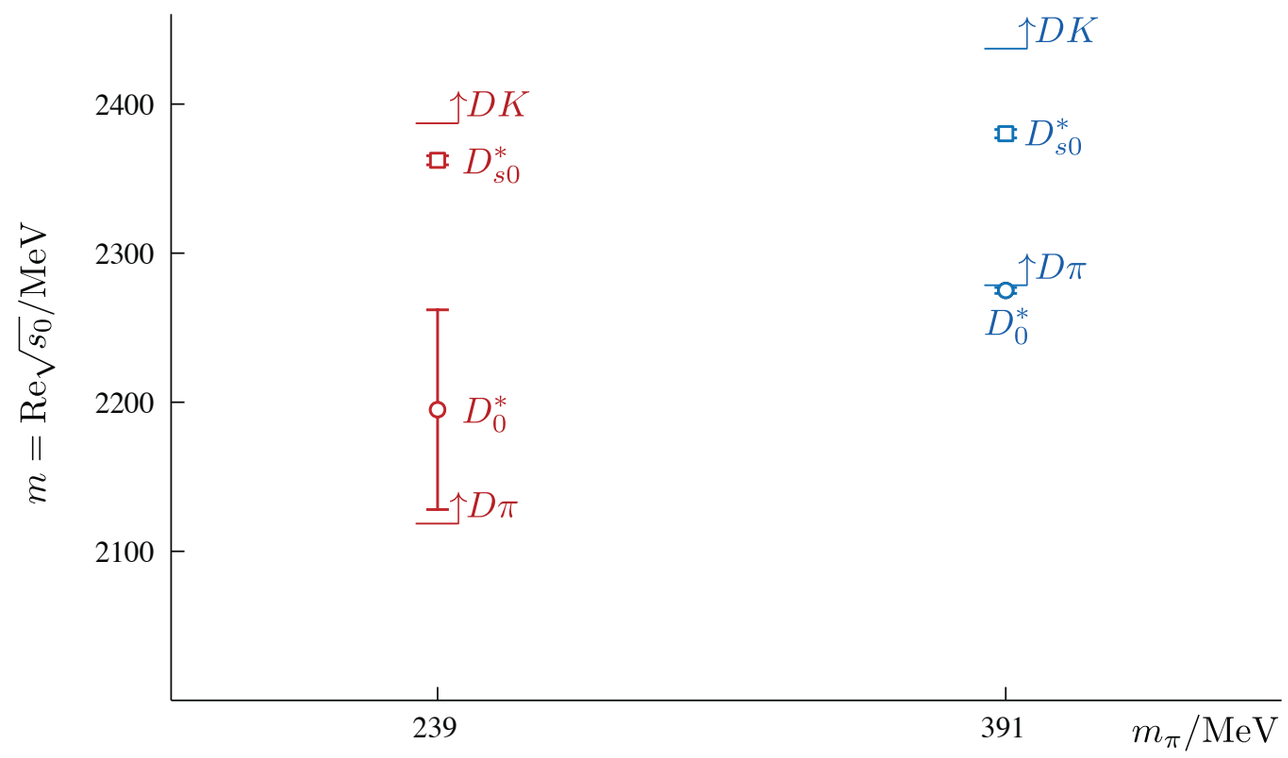

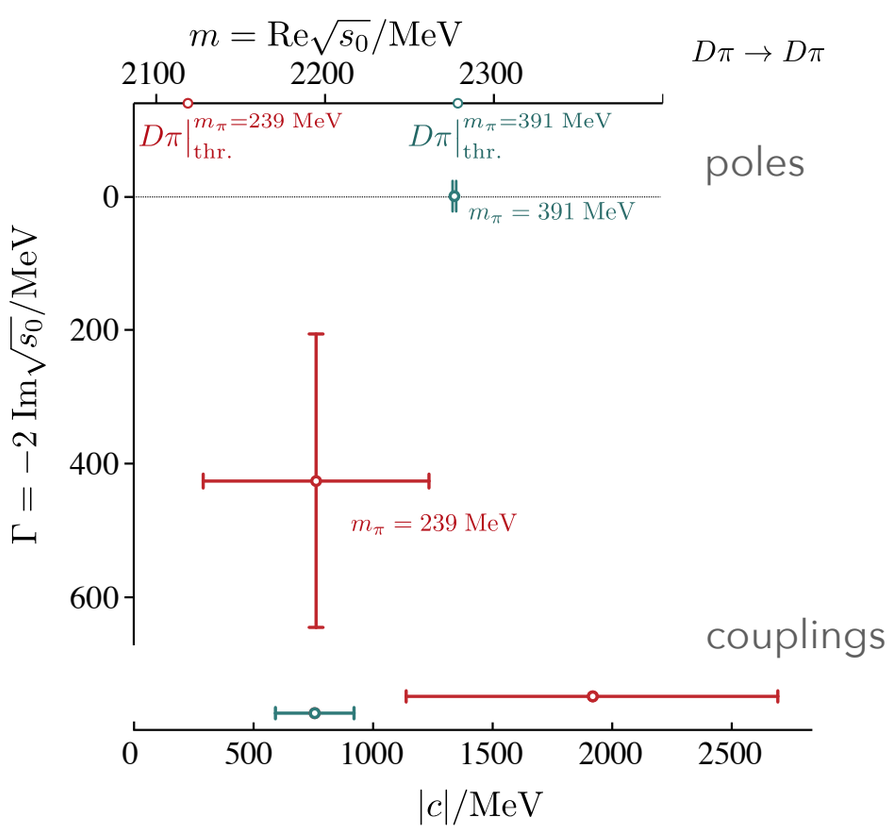

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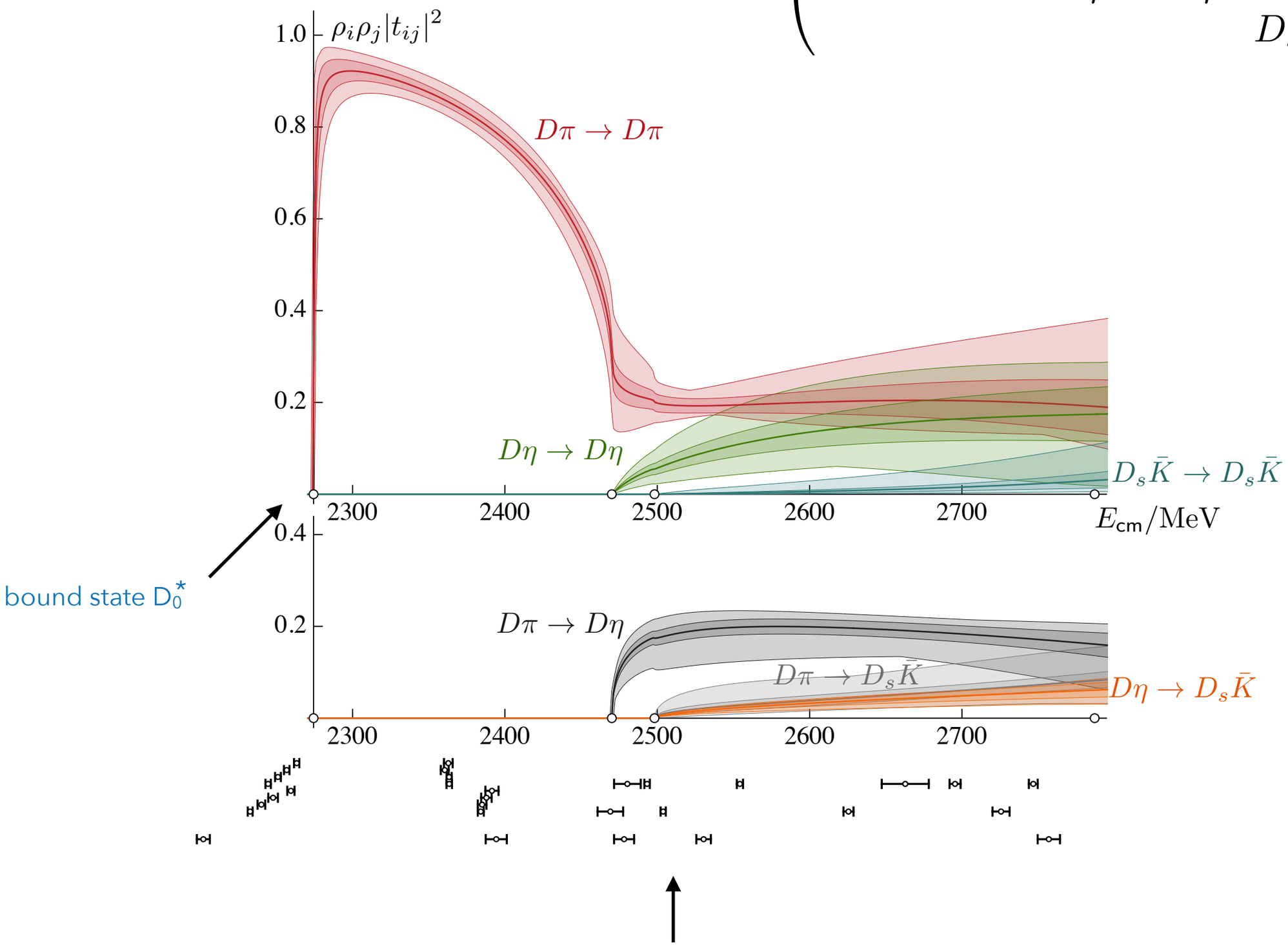
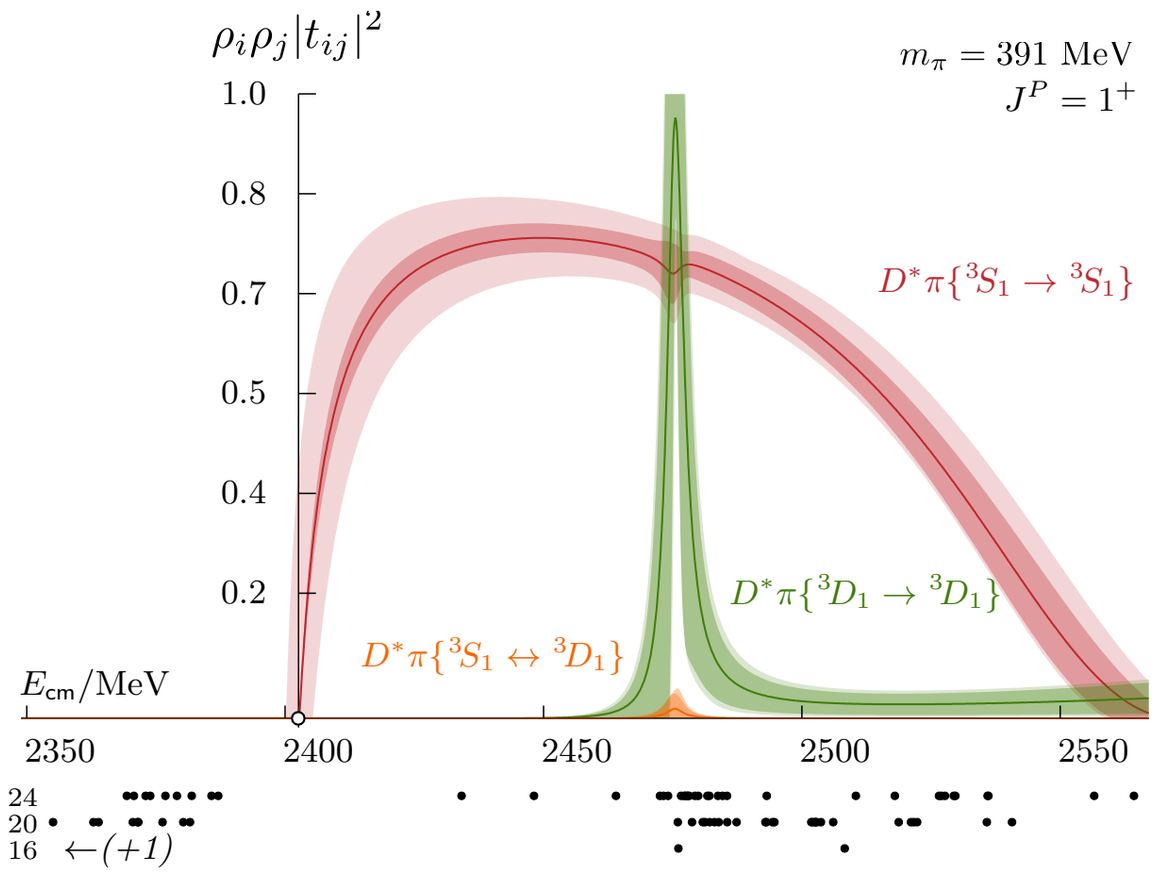
$m_\pi = 391\,\mathrm{MeV}$

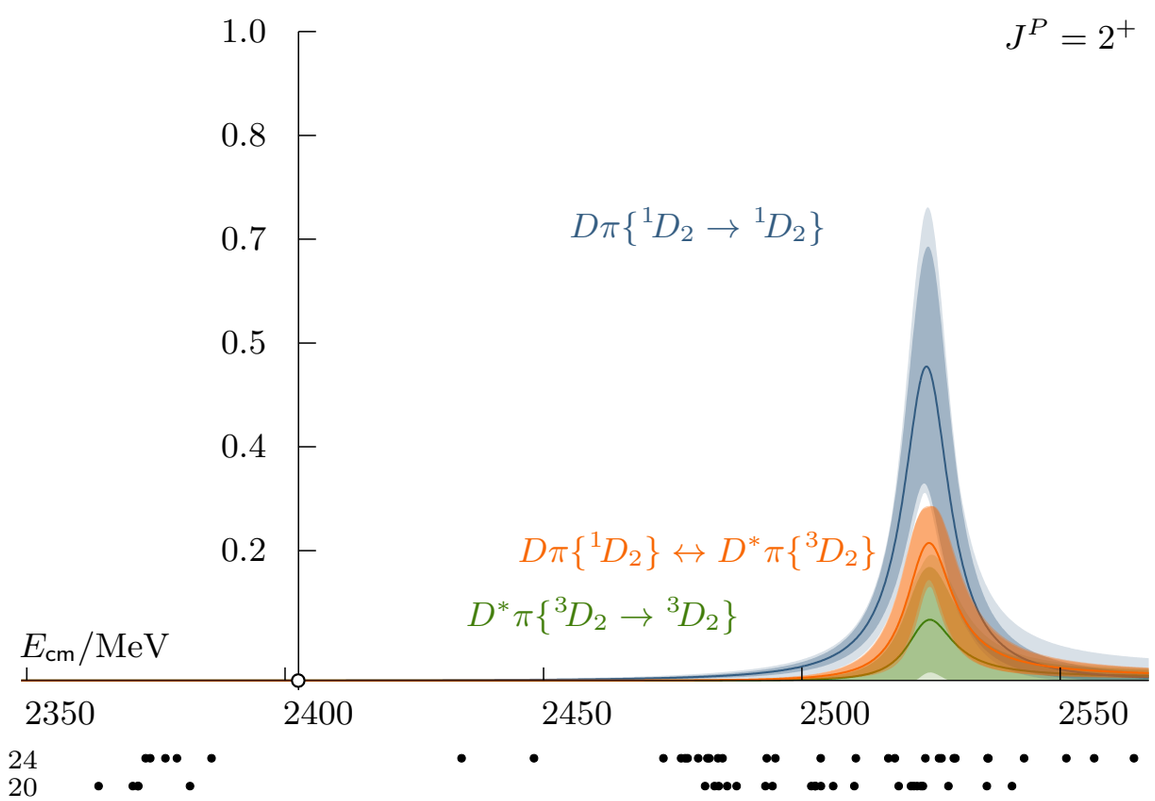
$$\boldsymbol{t} = \begin{pmatrix} D\pi \to D\pi & D\pi \to D\eta & D\pi \to D_s\bar{K} \\ & D\eta \to D\eta & D\eta \to D_s\bar{K} \\ & & D_s\bar{K} \to D_s\bar{K} \end{pmatrix}$$



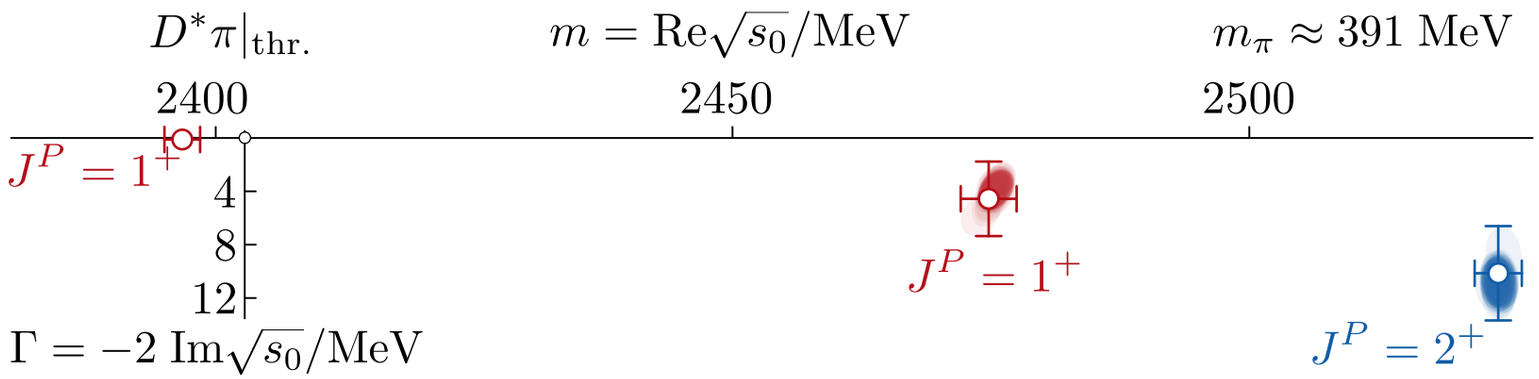
G. Moir et al (HadSpec),
JHEP 10 (2016) 011

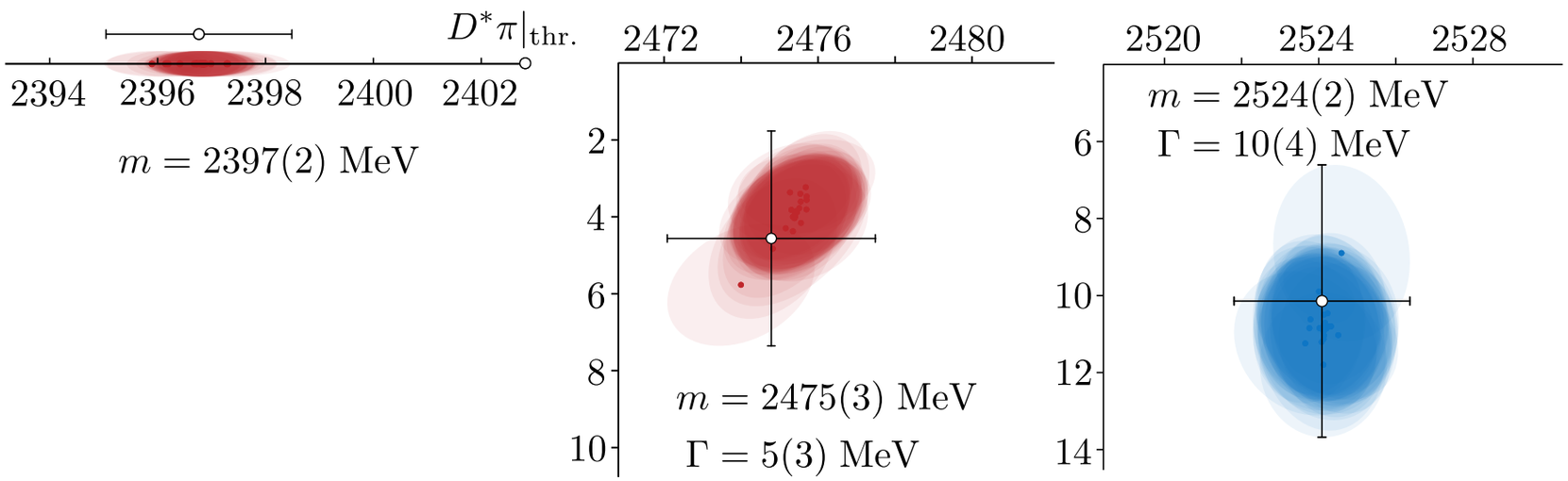


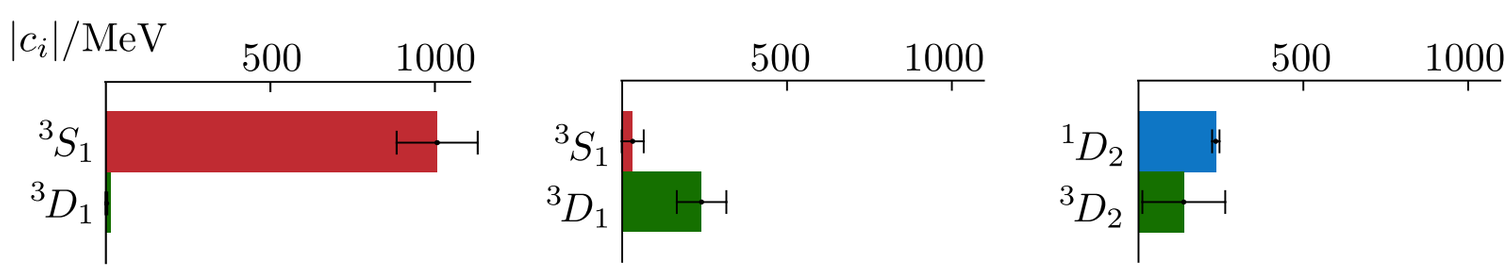
$$\boldsymbol{t} = \begin{pmatrix} D^*\pi\{^3S_1\} \to D^*\pi\{^3S_1\} & D^*\pi\{^3S_1\} \to D^*\pi\{^3D_1\} \\ & D^*\pi\{^3D_1\} \to D^*\pi\{^3D_1\} \end{pmatrix}$$

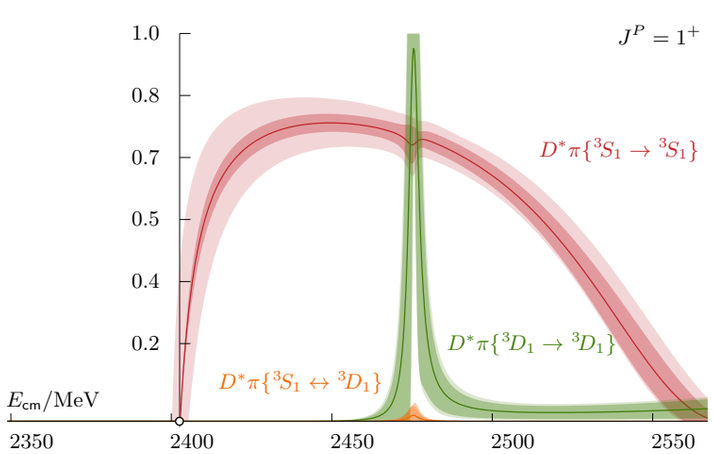


$$\boldsymbol{t} = \begin{pmatrix} D\pi\{^1D_2\} \to D\pi\{^1D_2\} & D\pi\{^1D_2\} \to D^*\pi\{^3D_2\} \\ & D^*\pi\{^3D_2\} \to D^*\pi\{^3D_2\} \end{pmatrix}$$

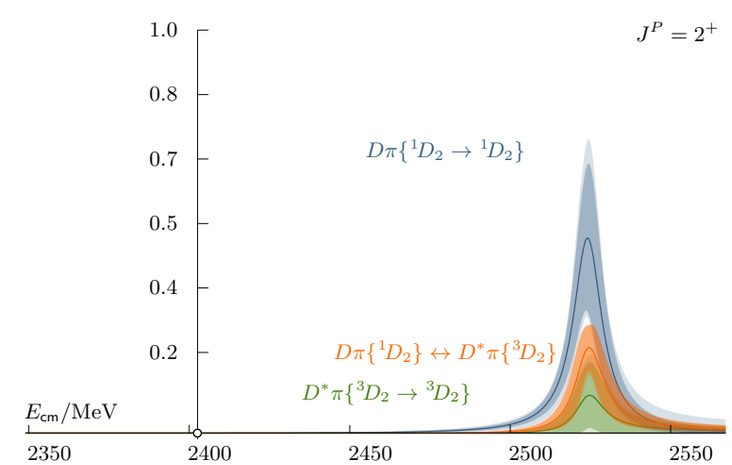








$$t_{ij} \sim \frac{c_i c_j}{s_0 - s}$$



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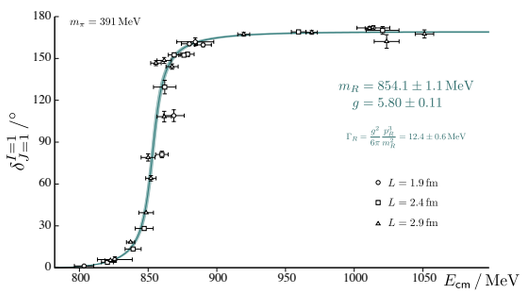
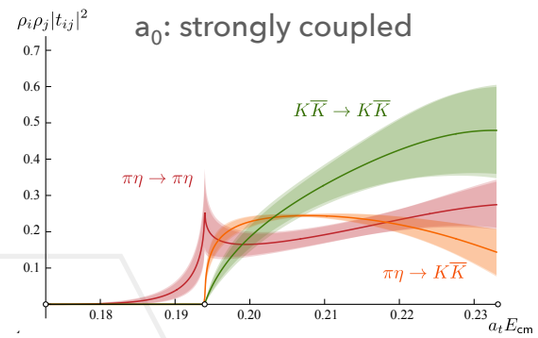
2012 2014 2016 2018 2020

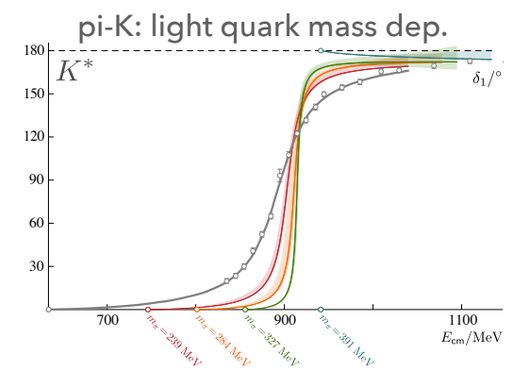
applications: (a biased sample)

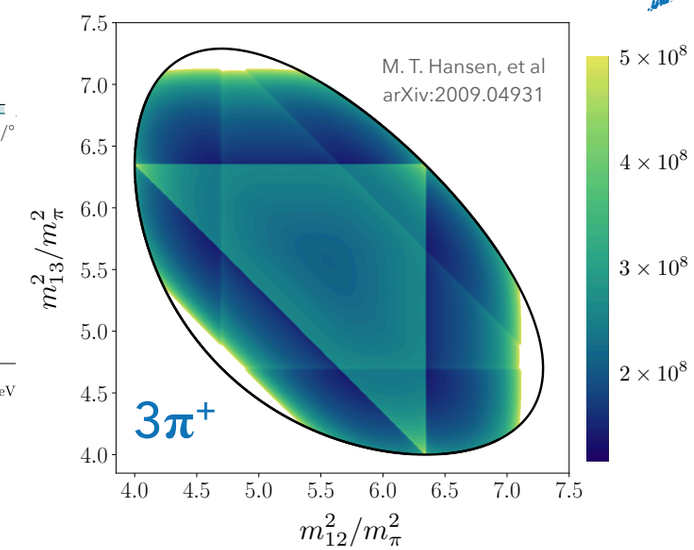


elastic scattering:
rho resonance

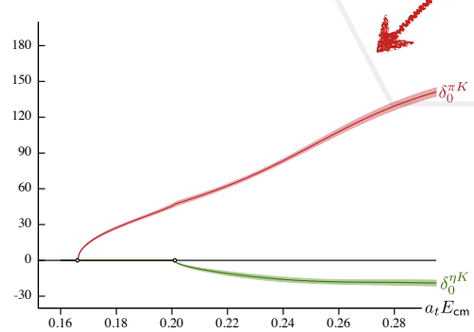


J. Dudek et al, PRD 93 (2016) 9, 094506

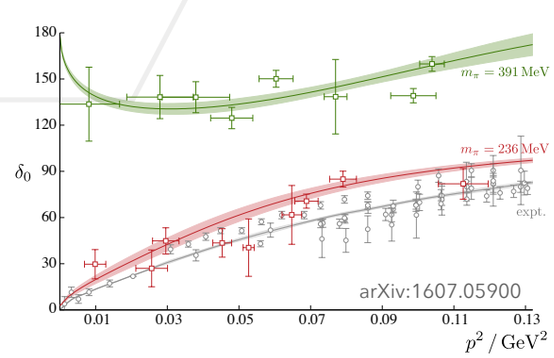




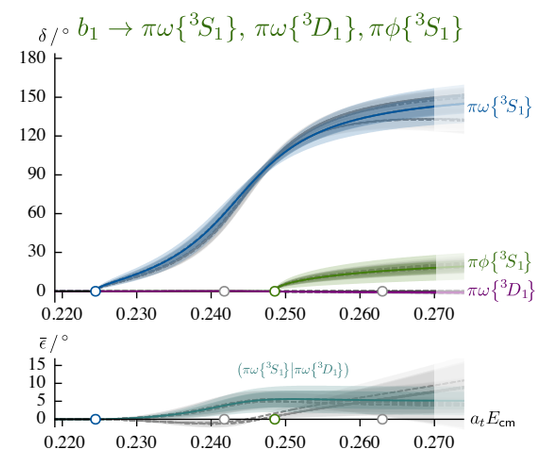
coupled-channel scattering



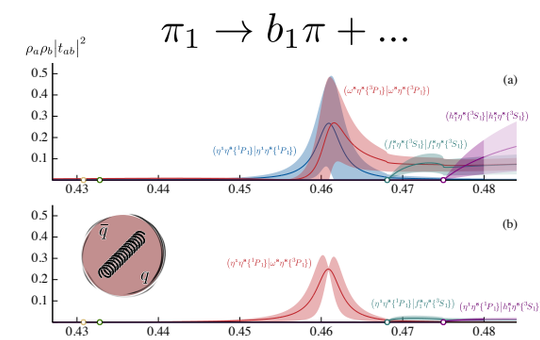
pi-K: almost decoupled,
first ever application



elastic scattering:
sigma resonance,
light quark mass dep.



scattering of
hadrons with spin



π_1 decays, SU(3) flavour,
11 active channels

formalism/theory developments:

pseudocalar two-body coupled-channel scattering

resonance transition FFs

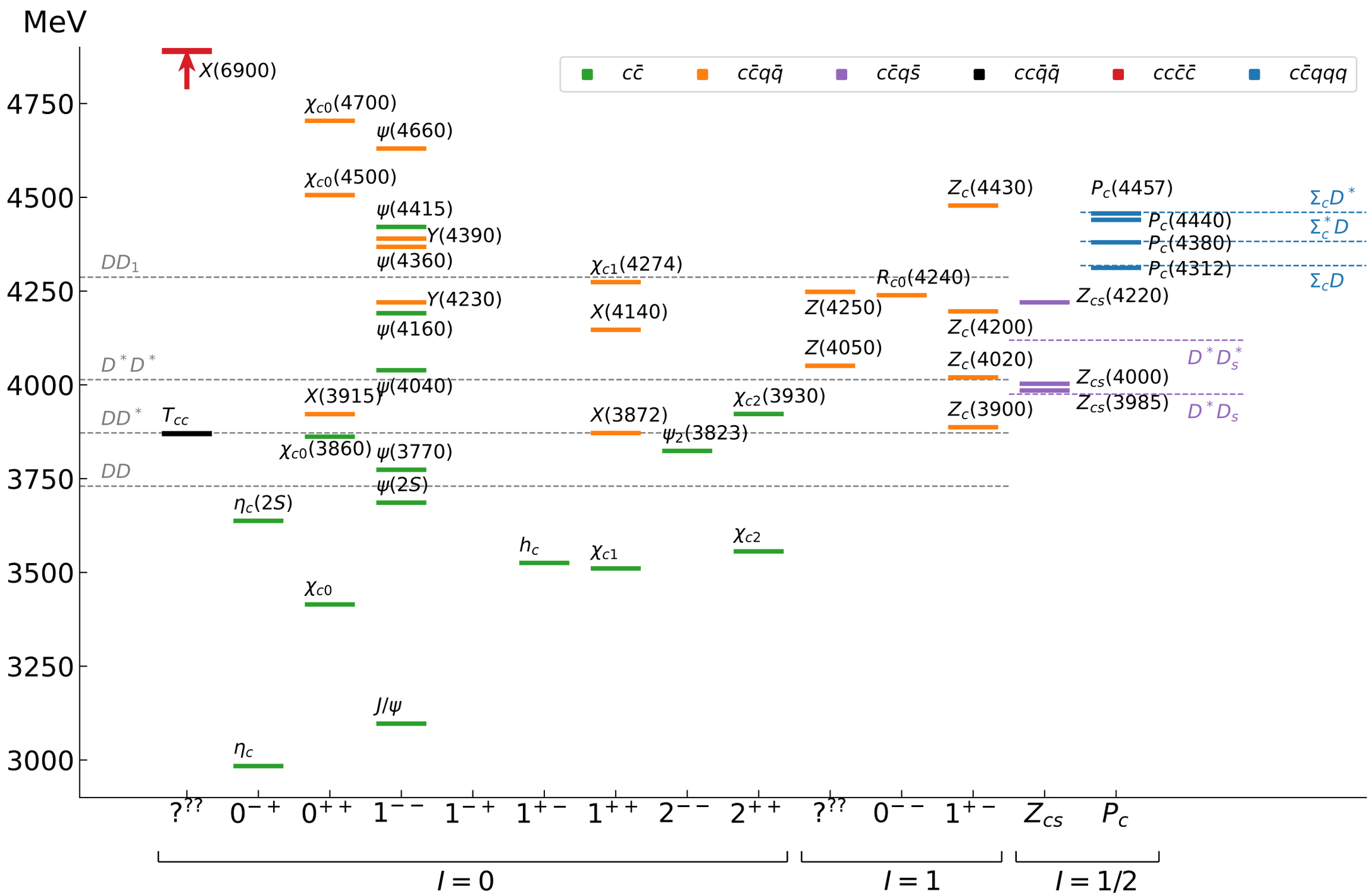
three-body scattering

general three-body scattering

scattering of hadrons with spin

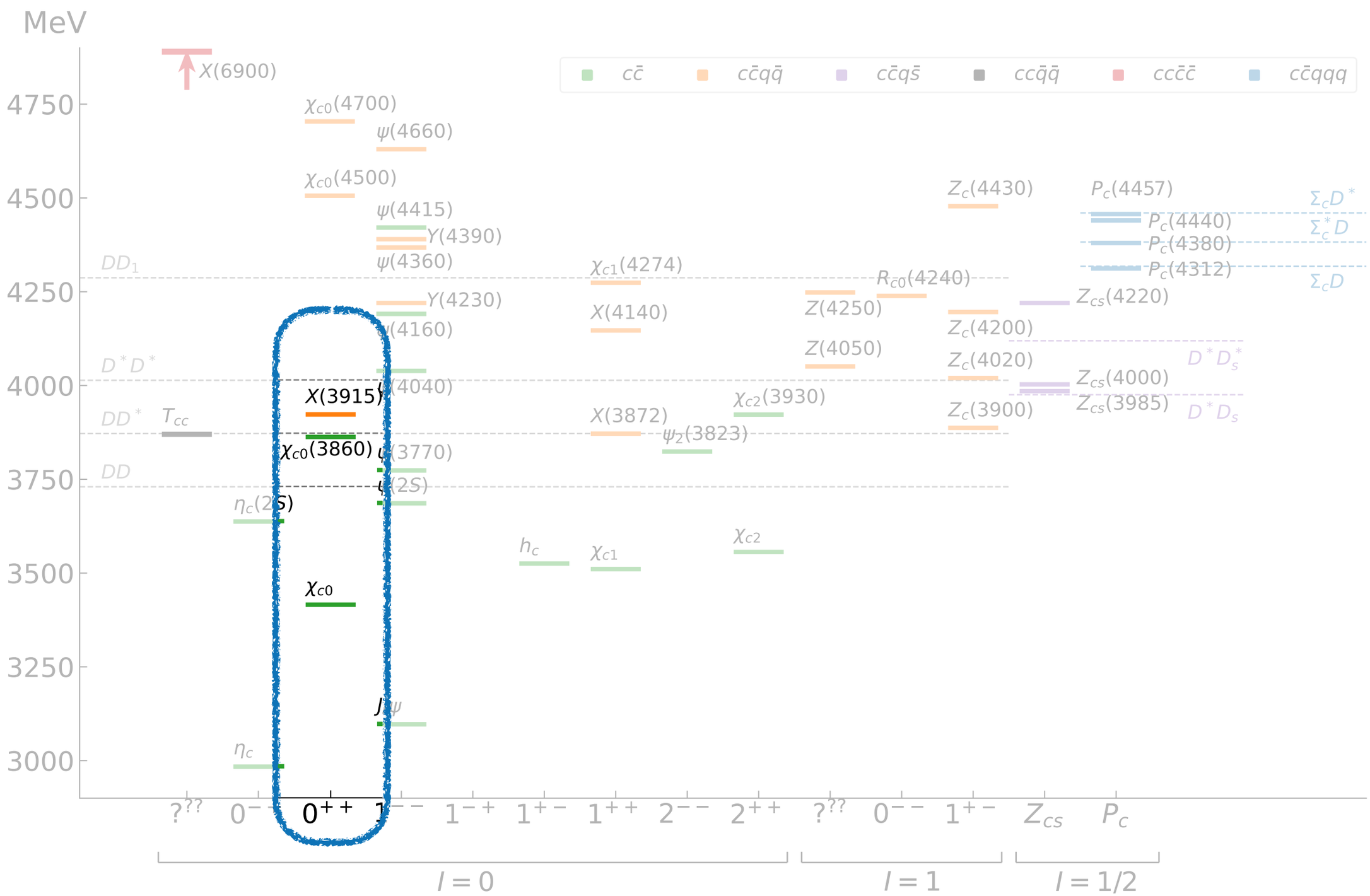
form factors of resonances

more general processes: two currents, …



JPAC arXiv:2112.13436

prospects for near-threshold charmonia



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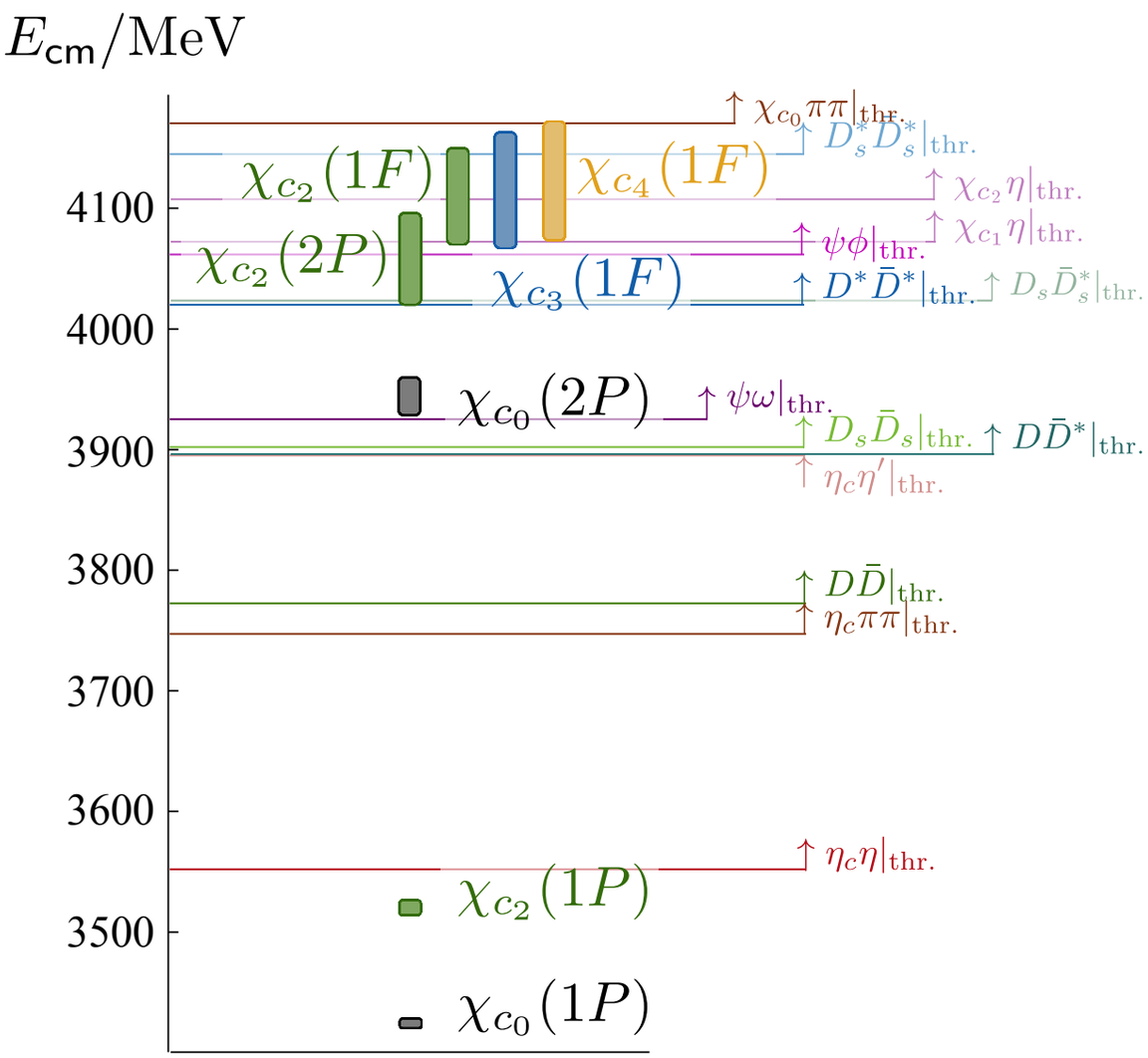
χ_{c0} & χ_{c2}



spectra from qqbar operators only, Liu et al JHEP 1207 (2012) 126
no meson-meson-like operators (essential for scattering)
indicates energy regions where resonance effects are likely

many-channel scattering - not easy

feasible to consider the limit where charm annihilation is forbidden

have to consider all allowed decays, pions are light

only studies to-date consider one or two hadron-hadron channels (see eg JHEP06 (2021) 035)

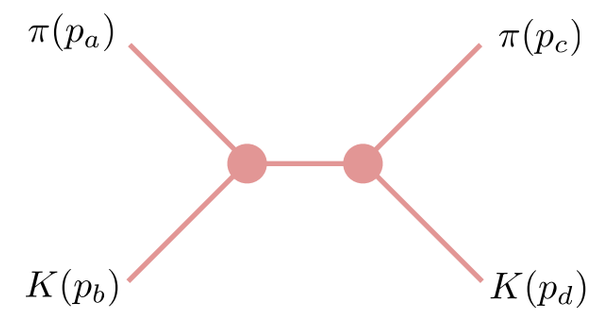
expect new results very soon (~2022)
light-quark mass dependence to follow

later: resonance form factors for spatial structure

expect several calculations of several charmonia below about 4200 MeV soon

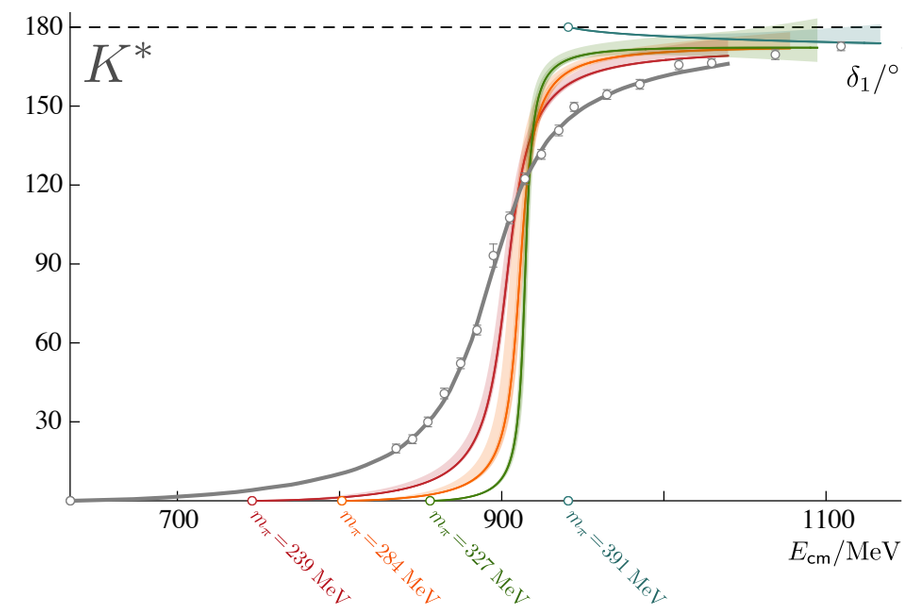
s-channel scattering

- complicated heavy-hadron multiparticle decay process
- many puzzling XYZ states seen in three-body processes



determine the complete S-matrix

- unitarity, causality, analyticity, …
- no missing channels
  (can compute obscure things like ηK to ηK)

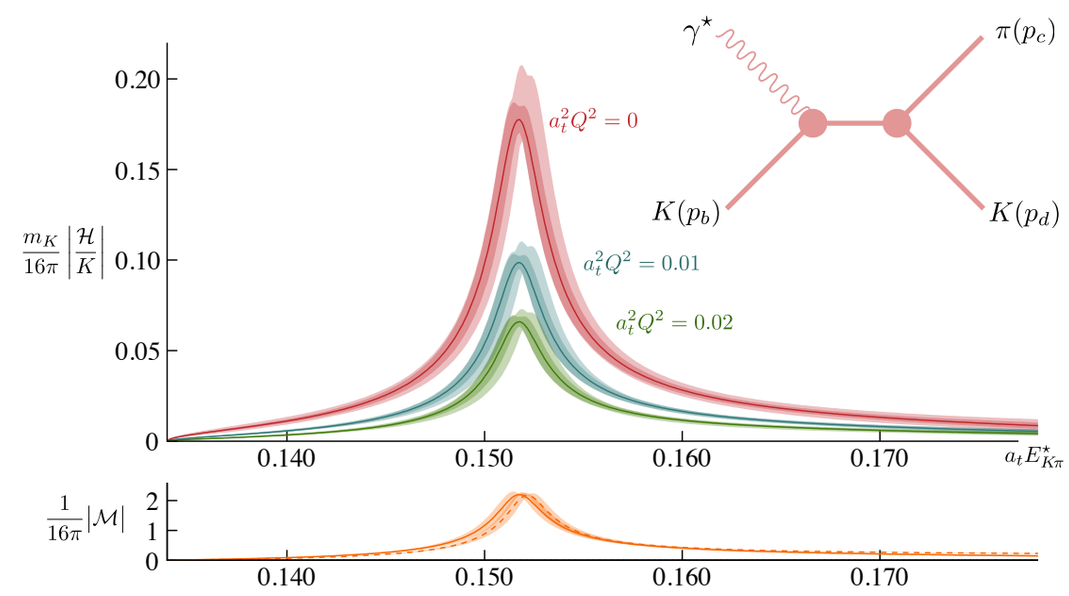


light-quark mass dependence

- help understand resonance-threshold interplay
- eg X(3872), Tcc(3875) DD*
- "hadronic molecule" vs "compact tetraquark" vs "qqbar"

resonance elastic and transition form-factors

- theory is ready
- early applications appearing: 2105.02017, 2208.13755



Lattice QCD provides a **first-principles** tool to do **hadron spectroscopy**

D and Ds systems

- readily accessible in lattice QCD calculations
- useful place to compare lattice with experiment & other theoretical approaches

These methods are widely applicable

- coupled-channel scattering
- baryons
- charmonium, b-quarks
- form factors, radiative transitions (incl. resonances)

…

Control of 3+ body effects needed for

- lighter pion masses
- higher resonances

significant recent progress in every area