Charmonium-like channels 1^{+-} and 1^{++} with isospin 1

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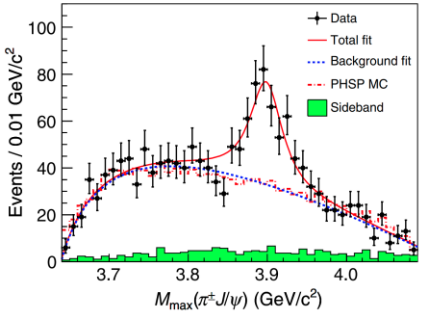
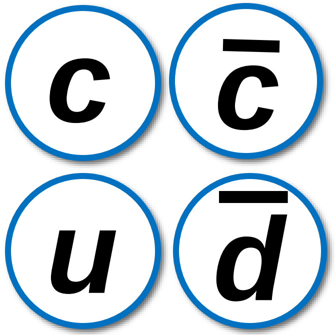
Motivation

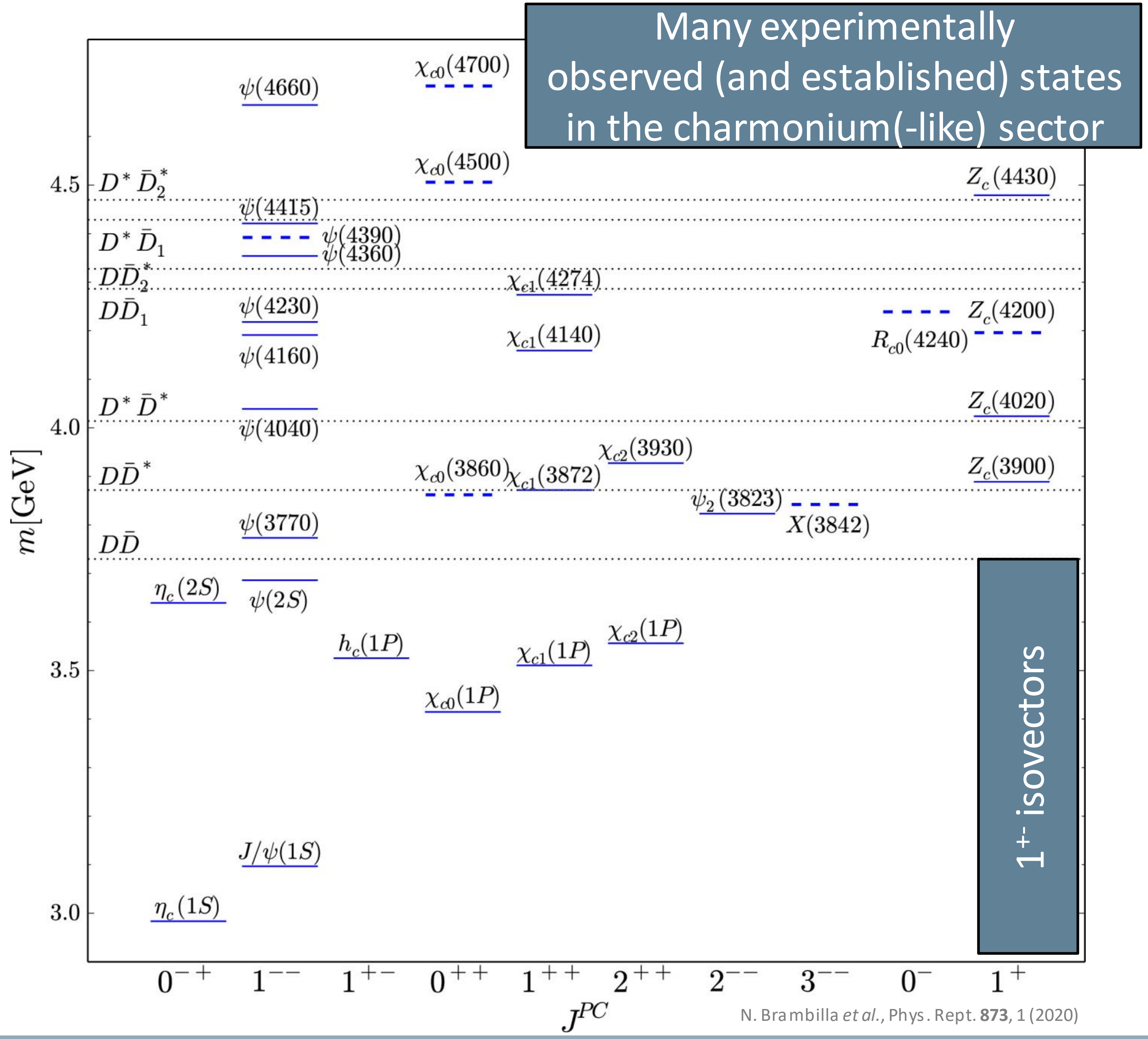
Our focus:

- Charmonium-like resonances
- $I(J^{PC})$:
  - $1(1^{+-})$ (observed Z_c states):
    - Manifestly exotic
    - First discoveries of $Z_c(3900)$:
      - M. Ablikim *et al.* (BESIII), PRL **110**, 252001 (2013)
      - Z. Q. Liu *et al.* (Belle), PRL **110**, 252002 (2013)
      - Lying on the $D\bar{D}^*$ threshold



M. Ablikim *et al.* (BESIII), PRL **110**, 252001 (2013)



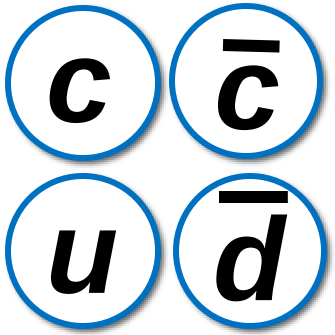


N. Brambilla *et al.*, Phys. Rept. **873**, 1 (2020)

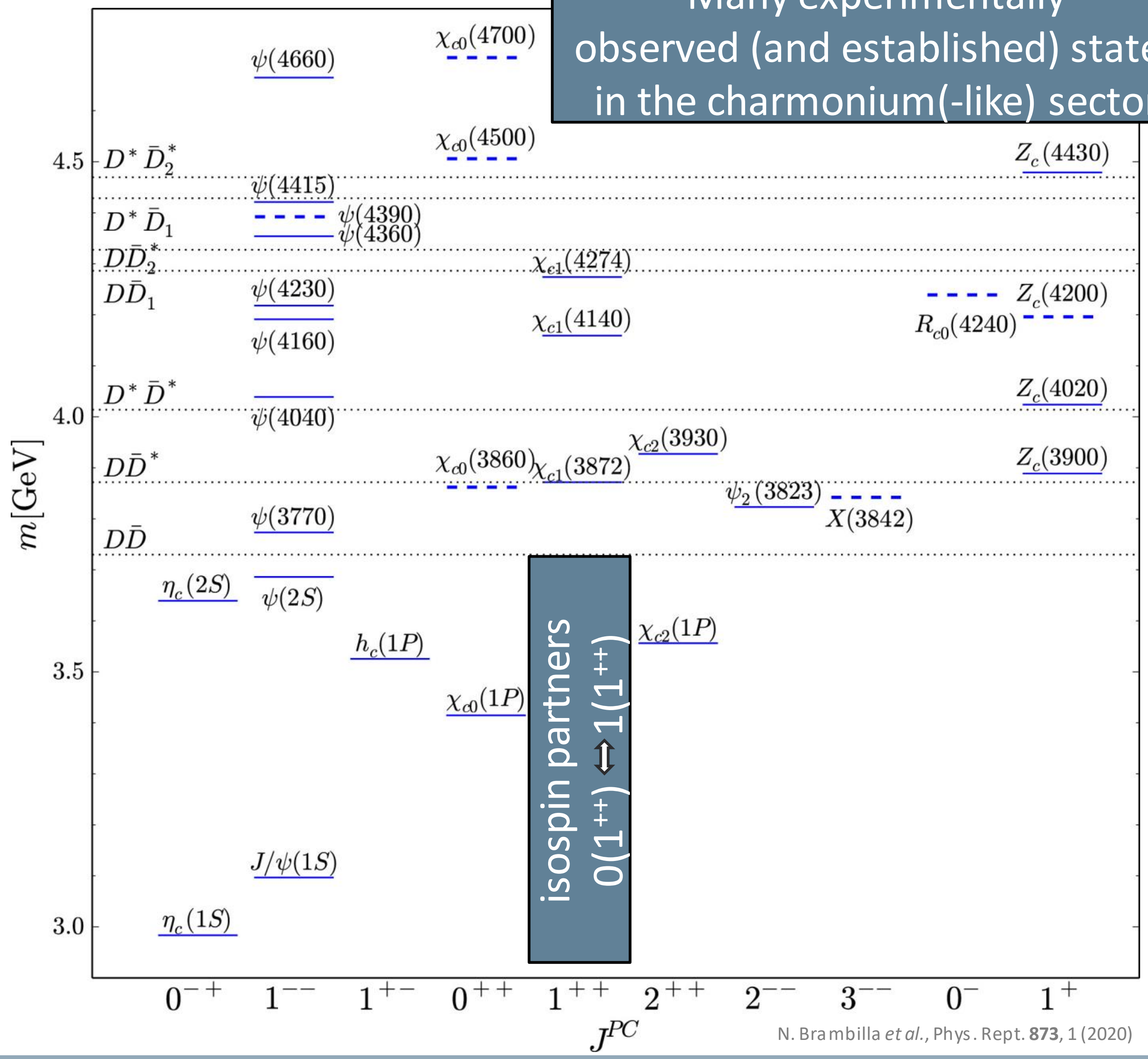
Motivation

Our focus:

- Charmonium-like resonances
- I(J^{PC}):
  - 1(1^{+-})
  - 1(1^{++}):
    - No experimentally established state
    - A candidate is an isospin partner of χ_{c1}(3872) expected in the diquark-antidiquark models
    - Possible candidates (observed but not established; 1($?^{?+}$):
      - X(4050)
      - X(4250)

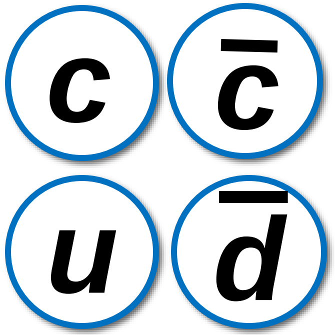


Many experimentally observed (and established) states in the charmonium(-like) sector



N. Brambilla *et al.*, Phys. Rept. **873**, 1 (2020)

Lattice studies so far



$I(J^{PC}) = 1(1^{+-})$ - Z_c states:

- Lattice studies find almost non-interacting $D\bar{D}^*$ and $J/\psi\pi$ eigen-energies:
  - S. Prelovsek and L. Leskovec, Phys. Lett. B **727**, 172 (2013)
  - S. Prelovsek *et al.*, PRD **91**, 014504 (2015)
  - Y. Chen *et al.* (CLQCD), PRD **89**, 094506 (2014)
  - S.-h. Lee *et al.* (Fermilab Lattice, MILC), (2014), arXiv:1411.1389
  - G. K. C. Cheung *et al.* (HSC), JHEP **11**, 033 (2017)
  - T. Chen *et al.* (CLQCD), Chin. Phys. **C43**, 103103 (2019)
- HAL QCD lattice study aimed at $Z_c(3900)$ – claiming that $Z_c(3900)^+$ is a threshold cusp suggesting the importance of cross-channel interaction:
  - Y. Ikeda *et al.*, PRL **117**, 242001 (2016)
  - Y. Ikeda, J. Phys **G45**, 024002 (2018)

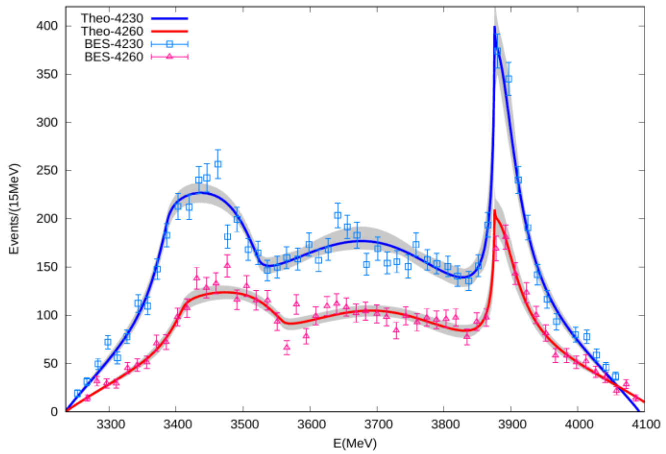
$I(J^{PC}) = 1(1^{++})$:

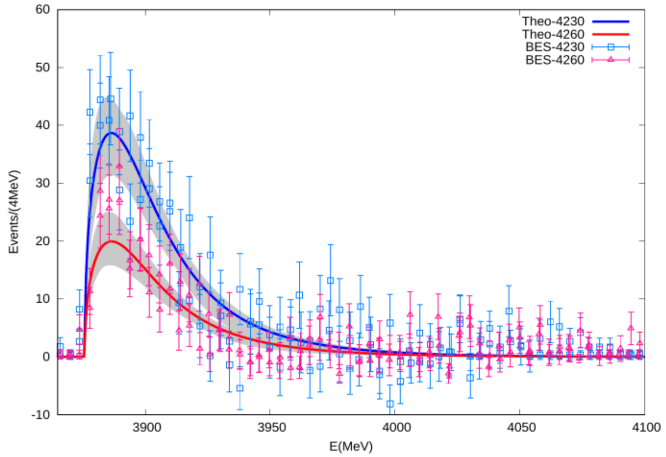
- Studies find almost non-interacting $D\bar{D}^*$ eigen-energies:
  - S. Prelovsek and L. Leskovec, PRL **111** 192001 (2013)
  - M. Padmanath, C. B. Lang and S. Prelovsek, PRD **92**, 034501 (2015)

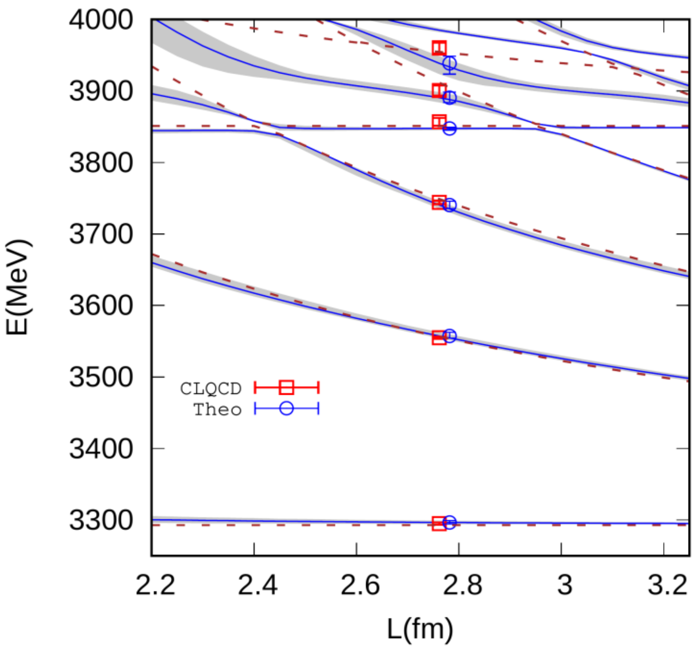
The latest study on $Z_c(3900)$

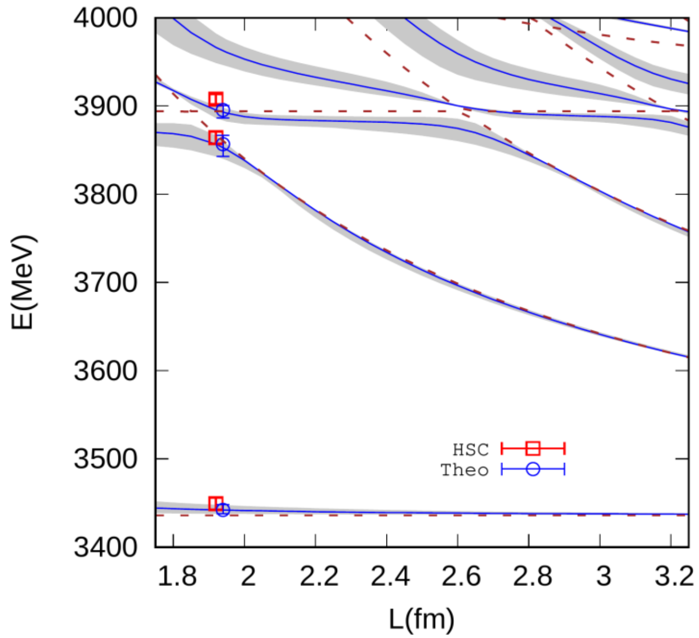
L.-W. Yan, Z.-H. Guo, F.-K. Guo, D.-L. Yao, Z.-Y. Zhou, (2023), arXiv:2307.12283

- The $J/\psi\pi$ and $D\bar{D}^*$ **coupled-channel** system within a covariant framework
- The $J/\psi\pi$ and $D\bar{D}^*$ invariant-mass distributions (BESIII) and lattice QCD[1] energy levels are successfully simultaneously fitted
- Interaction between $J/\psi\pi$ and $D\bar{D}^*$ important for the explanation of the $Z_c(3900)$ peaks
- Used lattice data do not preclude the existence of $Z_c(3900)$









[1]Fitted lattice data from:
- G. K. C. Cheung *et al.* (HSC), JHEP **11**, 033 (2017)
- T. Chen *et al.* (CLQCD), Chin. Phys. **C43**, 103103 (2019)

Overview of our study

- Meson-meson interpolators:
  - Charmonium + light meson

    $\bar{c}c$ $\bar{d}u$

  - $D + \bar{D}^*$ / $\bar{D} + D^*$

    $\bar{c}u$ $\bar{d}c$

- No diquark-antidiquark interpolators
  - very little influence found when including them:

    M. Padmanath, C. B. Lang and S. Prelovsek, PRD **92**, 034501 (2015)

    S. Prelovsek *et al.*, PRD **91**, 014504 (2015)

- 2 different charge parities (C = +, –)
- 2 ensembles (N_L = 24, 32)
- 2 lattice irreps:
  - P = (0,0,0): $\Lambda^P = T_1^+$
  - P = (0,0,1): $\Lambda = A_2$

Note that continuum quantum numbers $J^P = 1^+$ contribute to those irreps

This is the first lattice study that incorporates 2 different lattice sizes and additionally to P = (0,0,0) also P = (0,0,1)

CLS lattice ensembles

	dynamical quarks
N_F	2 + 1
a	0.08636(98)(40) fm
m_π	280(3) MeV
m_c	slightly heavier than physical
M_{av}	3103(3) MeV
m_D	1927(1) MeV
m_{D*}	2049(2) MeV

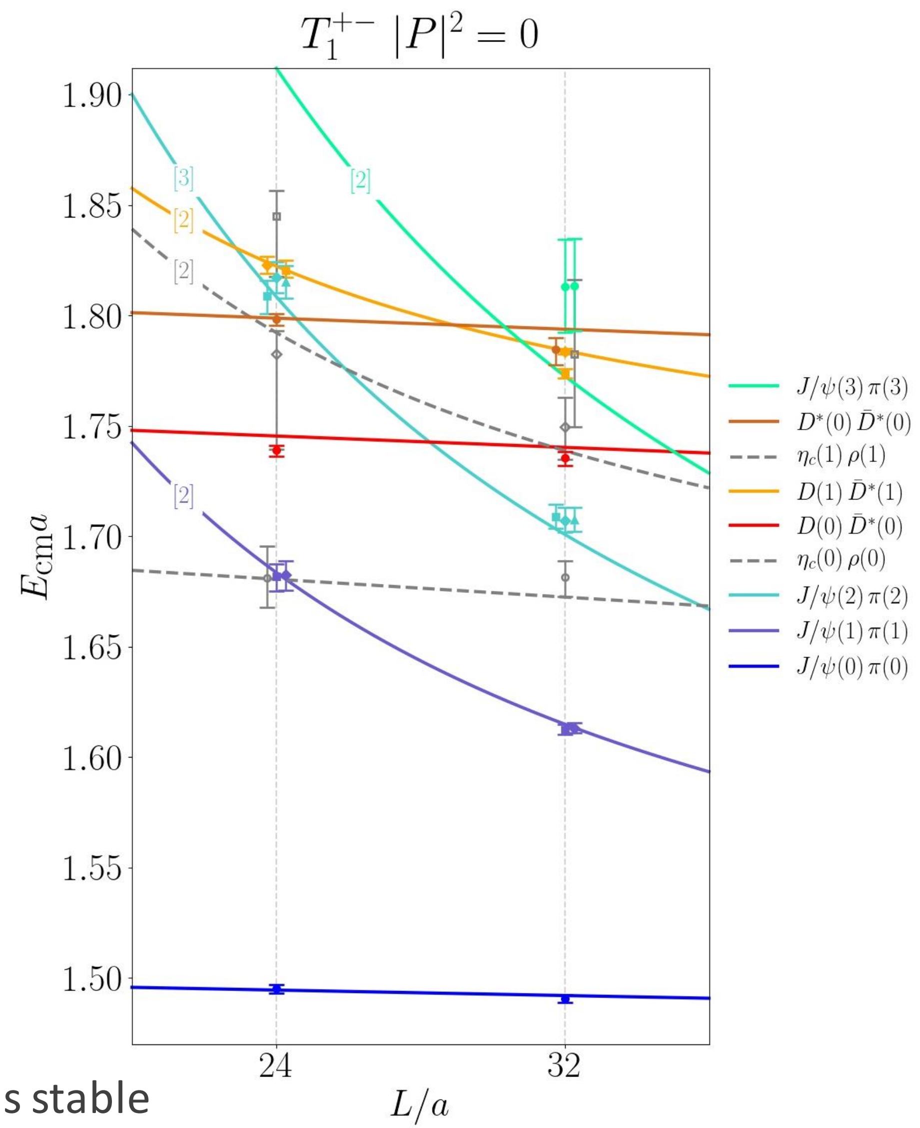
ensembles	U101	H105
$N_L^3 \times N_T$	$24^3 \times 128$	$32^3 \times 96$
configurations	255	492
Laplacian eigenvectors (quark fields are smeared with the ‘Distillation’ method)	90	100

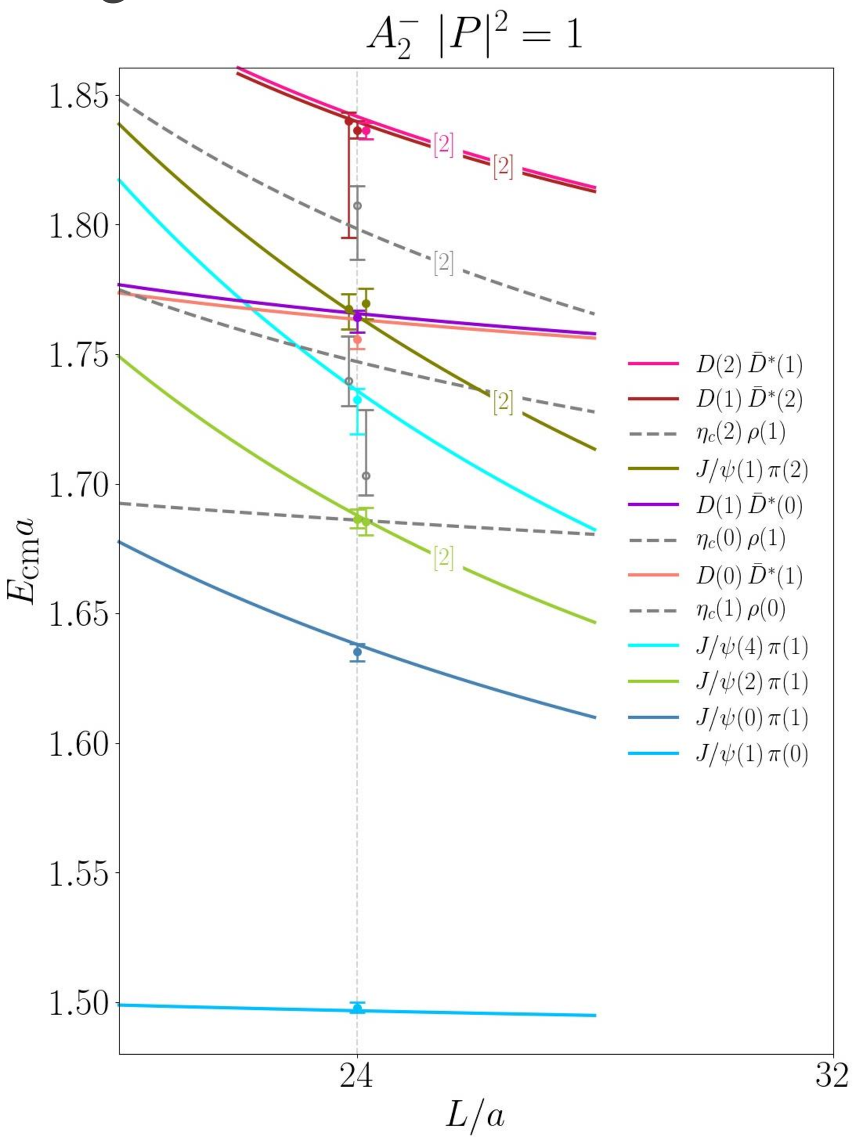
Lattice spectra (C = – , Z_c)

N_L = 24
15 inter-polators

N_L = 32
21 inter-polators

$J/\psi(0)\pi(0)$
$J/\psi(0)\pi(0)$
$J/\psi(1)\pi(1)$
$J/\psi(1)\pi(1)$
$J/\psi(2)\pi(2)$
$J/\psi(2)\pi(2)$
$J/\psi(2)\pi(2)$
$\eta_c(0)\rho(0)$
$\eta_c(1)\rho(1)$
$\eta_c(1)\rho(1)$
$\bar{D}^*(0)D(0)$
$\bar{D}^*(0)D(0)$
$\bar{D}^*(1)D(1)$
$\bar{D}^*(1)D(1)$
$\bar{D}^*(0)D^*(0)$
$J/\psi(3)\pi(3)$
$J/\psi(3)\pi(3)$
$\eta_c(2)\rho(2)$
$\eta_c(2)\rho(2)$
$\eta_c(2)\rho(2)$
$h_c(1)\pi(1)$





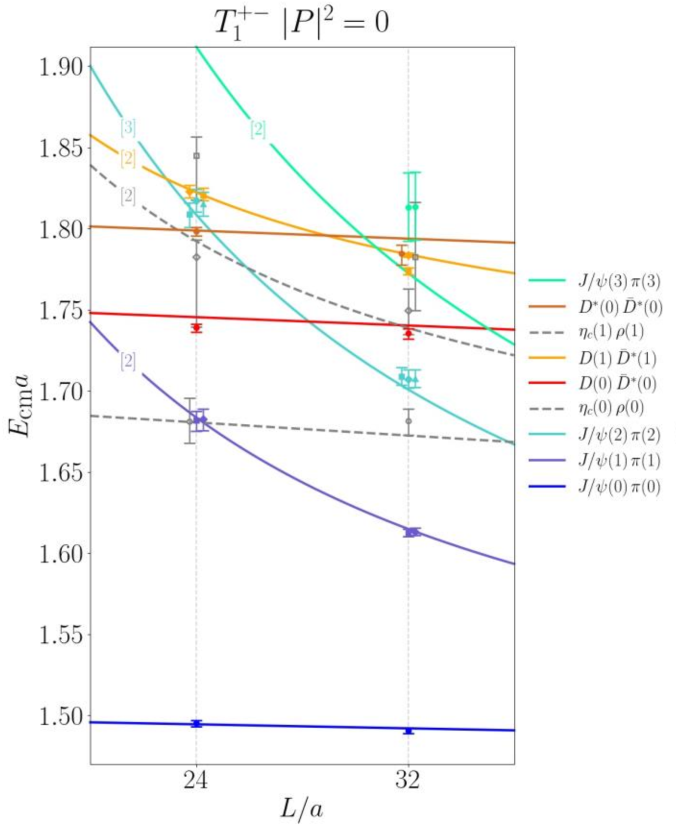
$J/\psi(1)\pi(0)$
$J/\psi(0)\pi(1)$
$J/\psi(1)\pi(0)$
$J/\psi(0)\pi(1)$
$J/\psi(2)\pi(1)$
$J/\psi(2)\pi(1)$
$J/\psi(1)\pi(2)$
$J/\psi(1)\pi(2)$
$J/\psi(4)\pi(1)$
$\eta_c(1)\rho(0)$
$\eta_c(0)\rho(1)$
$\eta_c(2)\rho(1)$
$\eta_c(2)\rho(1)$
$\bar{D}^*(0)D(1)$
$\bar{D}^*(1)D(0)$
$\bar{D}^*(0)D(1)$
$\bar{D}^*(1)D(0)$
$\bar{D}^*(1)D(2)$
$\bar{D}^*(1)D(2)$
$\bar{D}^*(2)D(1)$
$\bar{D}^*(2)D(1)$

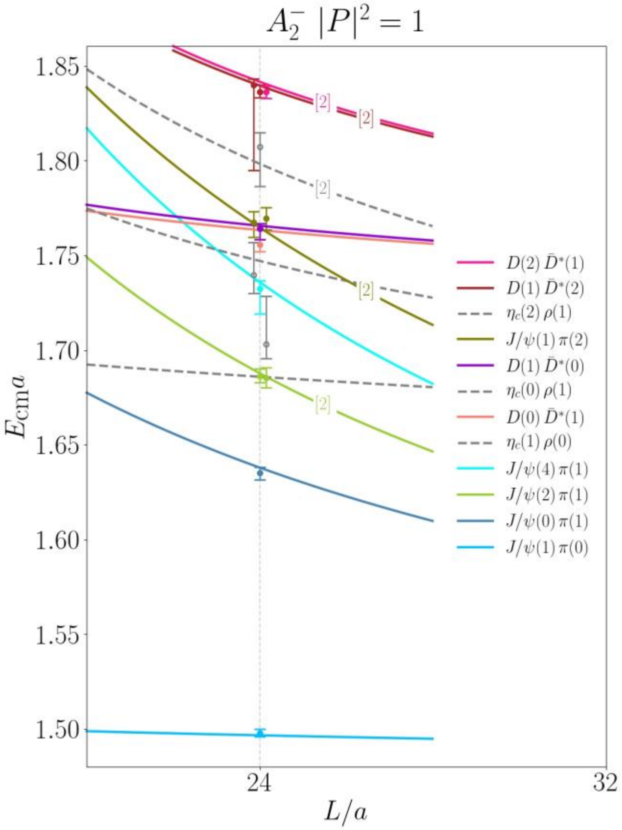
N_L = 24
21 inter-polators

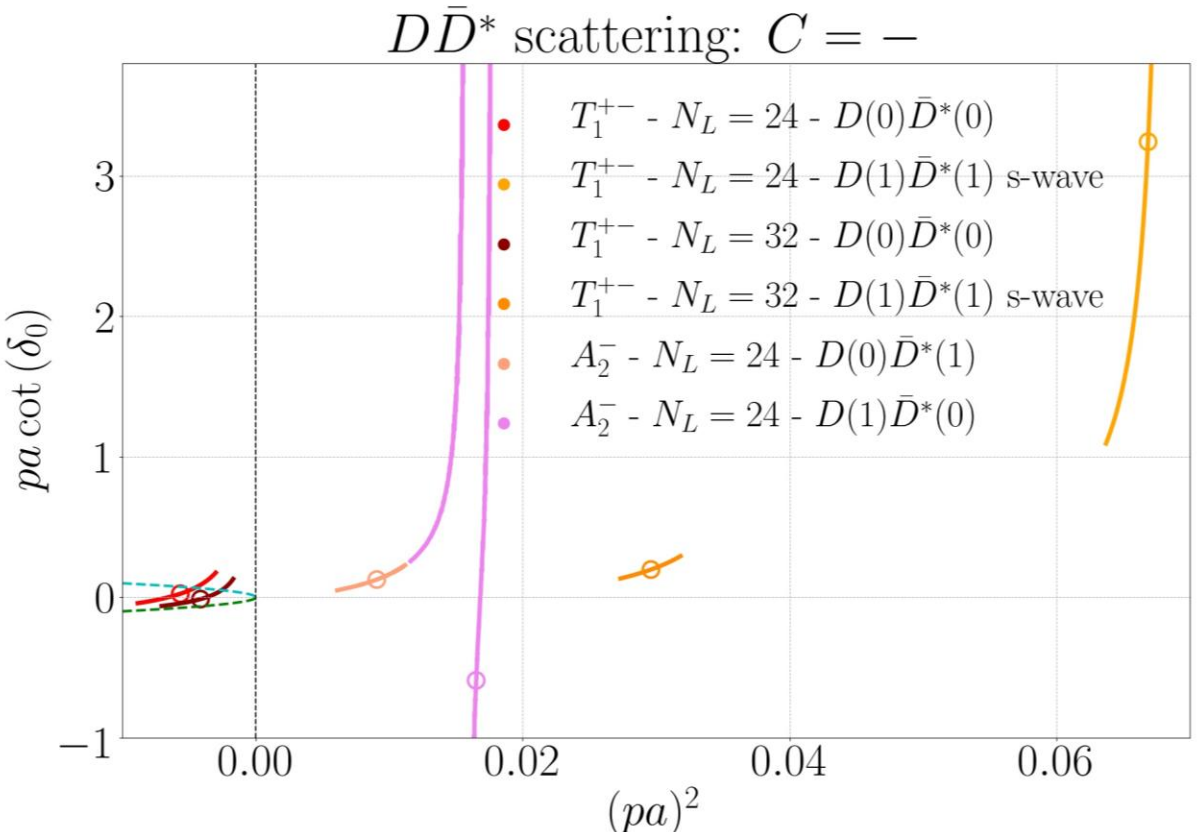
Note: ρ treated as stable

Elastic $D\bar{D}^*$ scattering ($C = -$, Z_c)

Phase shift plots are obtained assuming negligible coupling to $J/\psi\pi$ and $\eta_c\rho$





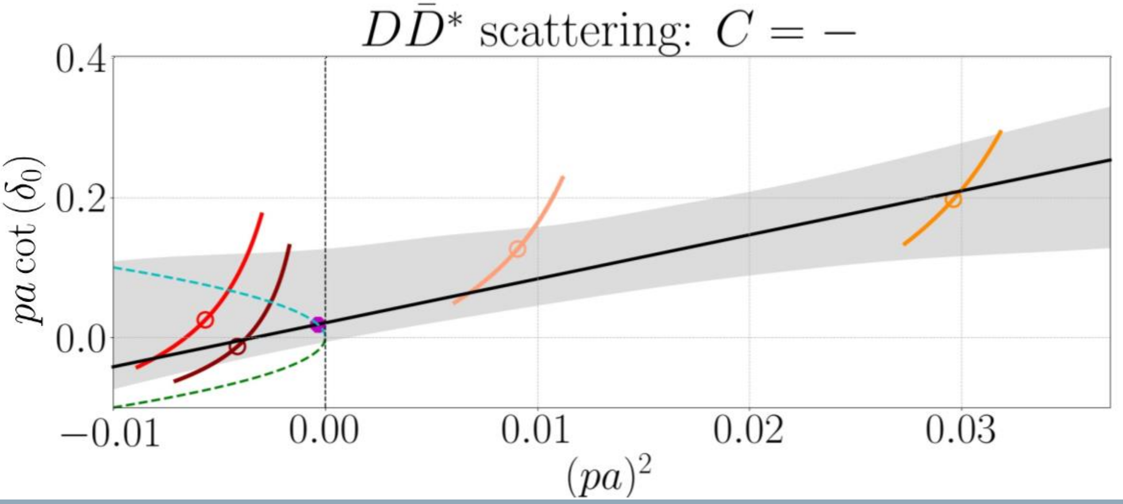


Elastic $D\bar{D}^*$ scattering amplitude ($C = -$, Z_c)

$$p \cot(\delta_0(p)) = \frac{1}{a_0} + \frac{1}{2} r_0 p^2 + \ldots$$

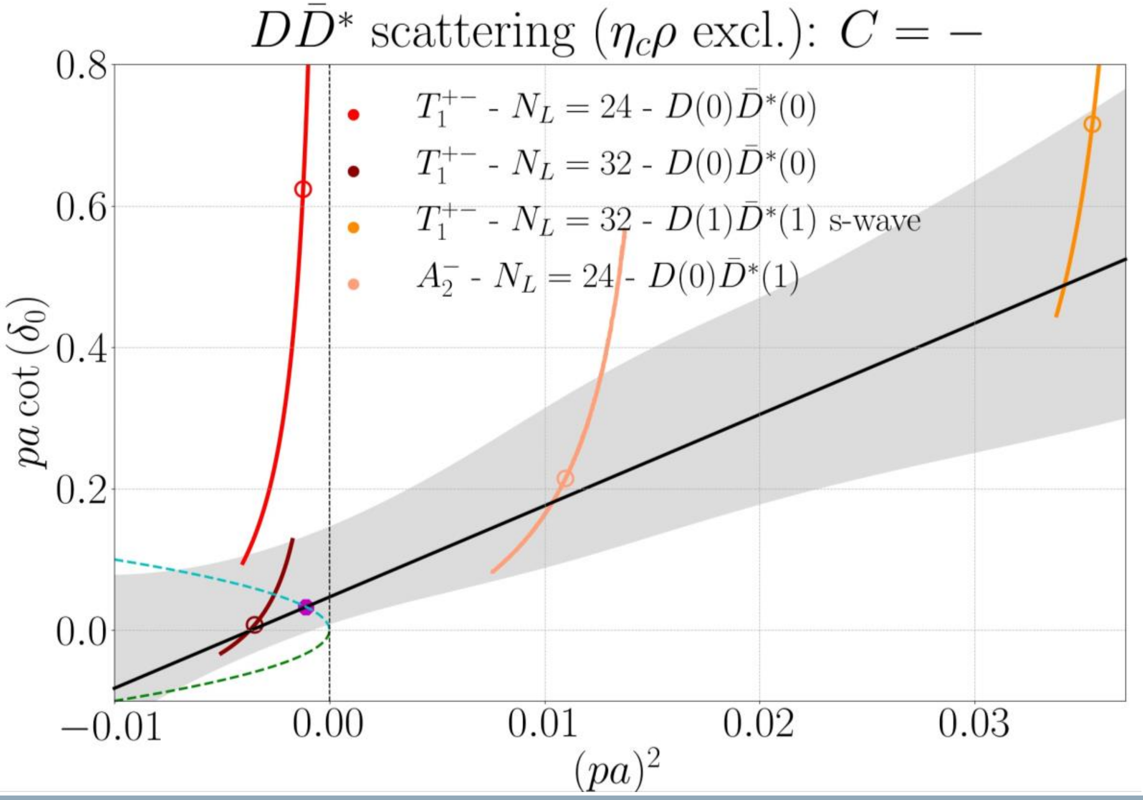
$$1/a_0 = 0.24 \left(^{+1.21}_{-0.30}\right) \text{ fm}^{-1}$$

$$r_0 = 1.08 \left(^{+0.32}_{-0.93}\right) \text{ fm}$$

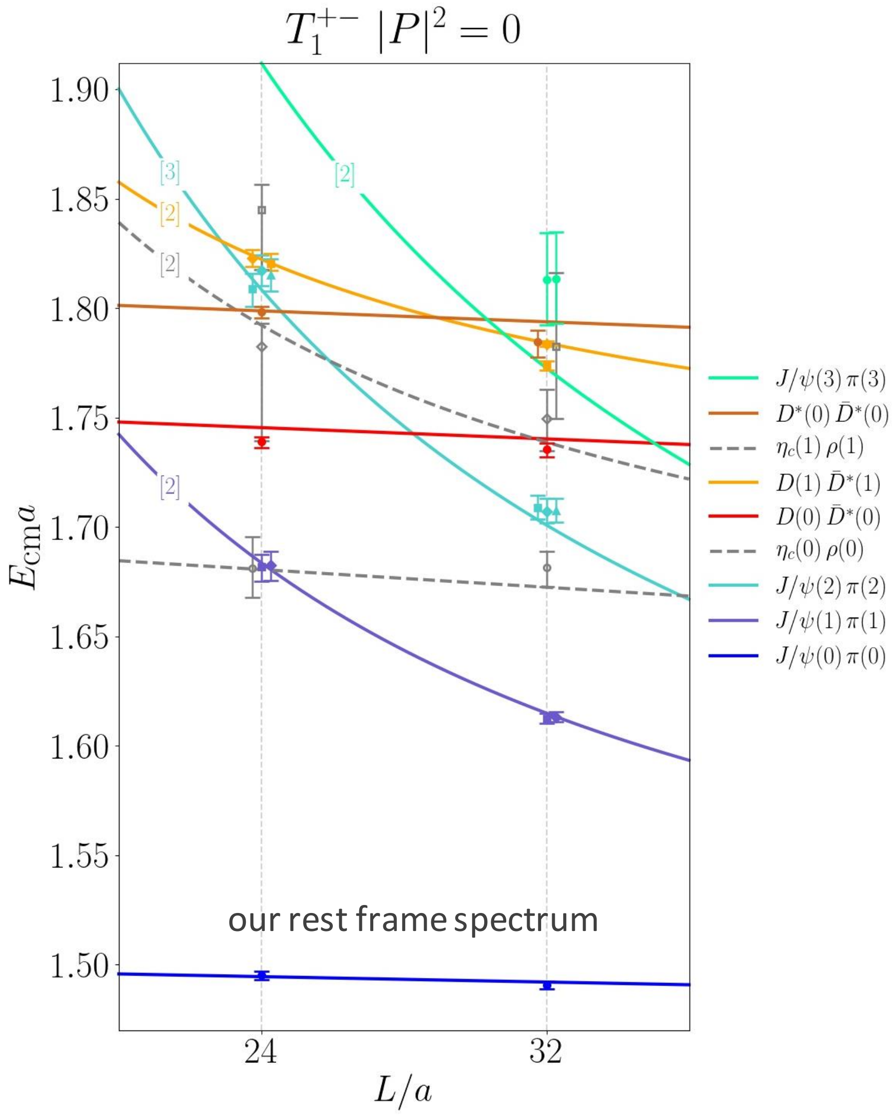


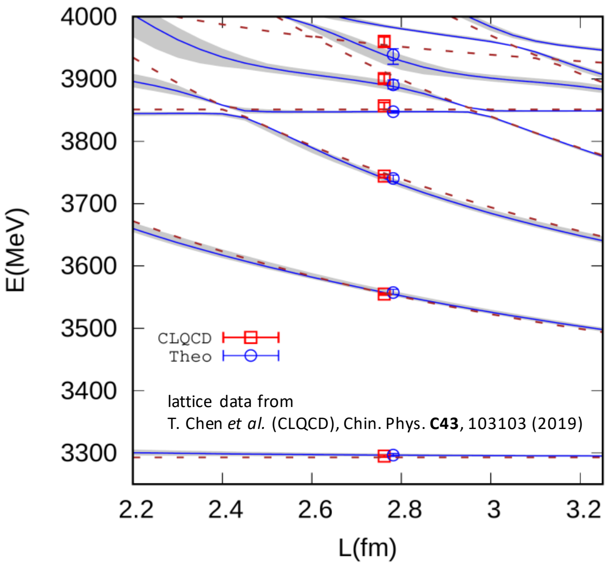
$$1/a_0 = 0.54 \left(^{+1.07}_{-0.44}\right) \text{ fm}^{-1}$$

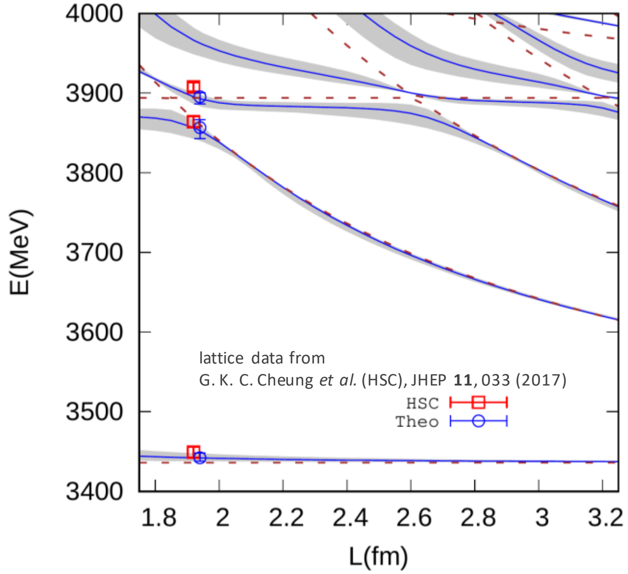
$$r_0 = 2.23 \left(^{+0.95}_{-1.08}\right) \text{ fm}$$



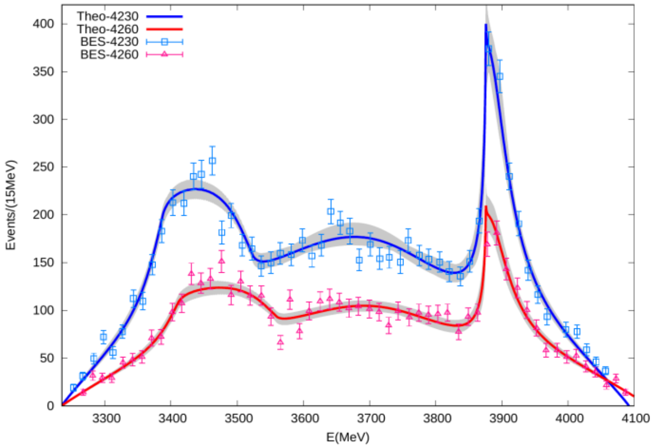
Reconciling experiment and lattice results of $Z_c(3900)$

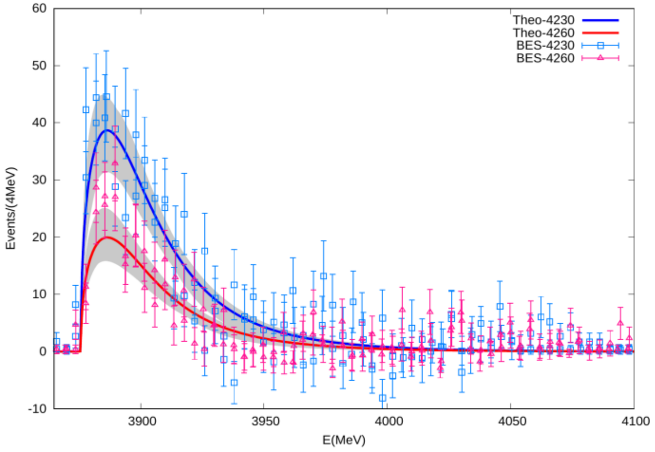






L.-W. Yan, Z.-H. Guo, F.-K. Guo, D.-L. Yao, Z.-Y. Zhou, (2023), arXiv:2307.12283



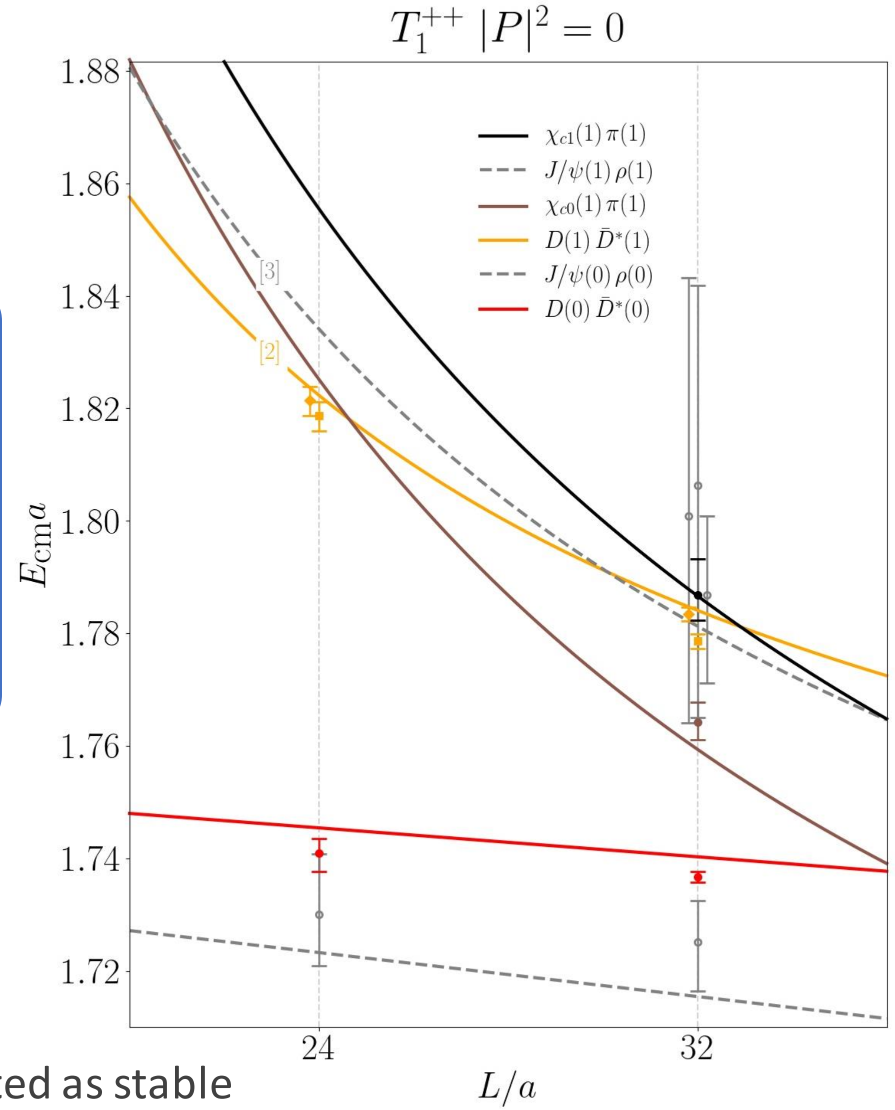


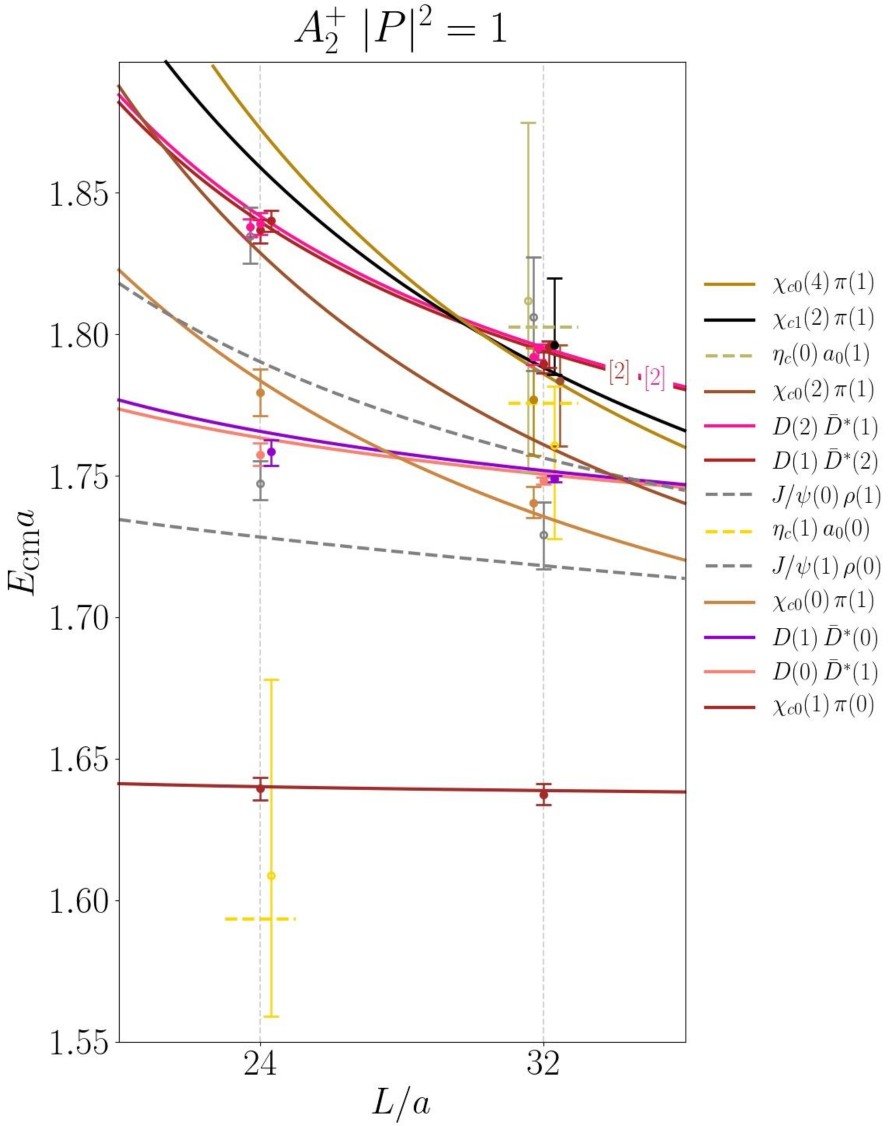
Lattice spectra (C = +, isospin partner of $\chi_{c1}(3872)$)

$N_L = 24$
5 inter-polators

$N_L = 32$
10 inter-polators

$J/\psi(0)\rho(0)$
$\bar{D}^*(0)D(0)$
$\bar{D}^*(0)D(0)$
$\bar{D}^*(1)D(1)$
$\bar{D}^*(1)D(1)$
$J/\psi(1)\rho(1)$
$J/\psi(1)\rho(1)$
$J/\psi(1)\rho(1)$
$\chi_{c0}(1)\pi(1)$
$\chi_{c1}(1)\pi(1)$





$\eta_c(1)a_0(0)$
$\chi_{c0}(1)\pi(0)$
$\chi_{c0}(0)\pi(1)$
$J/\psi(1)\rho(0)$
$J/\psi(0)\rho(1)$
$\bar{D}^*(0)D(1)$
$\bar{D}^*(1)D(0)$
$\bar{D}^*(0)D(1)$
$\bar{D}^*(1)D(0)$
$\bar{D}^*(1)D(2)$
$\bar{D}^*(1)D(2)$
$\bar{D}^*(2)D(1)$
$\bar{D}^*(2)D(1)$
$\eta_c(0)a_0(1)$
$\chi_{c0}(2)\pi(1)$
$\chi_{c0}(4)\pi(1)$
$\chi_{c1}(2)\pi(1)$

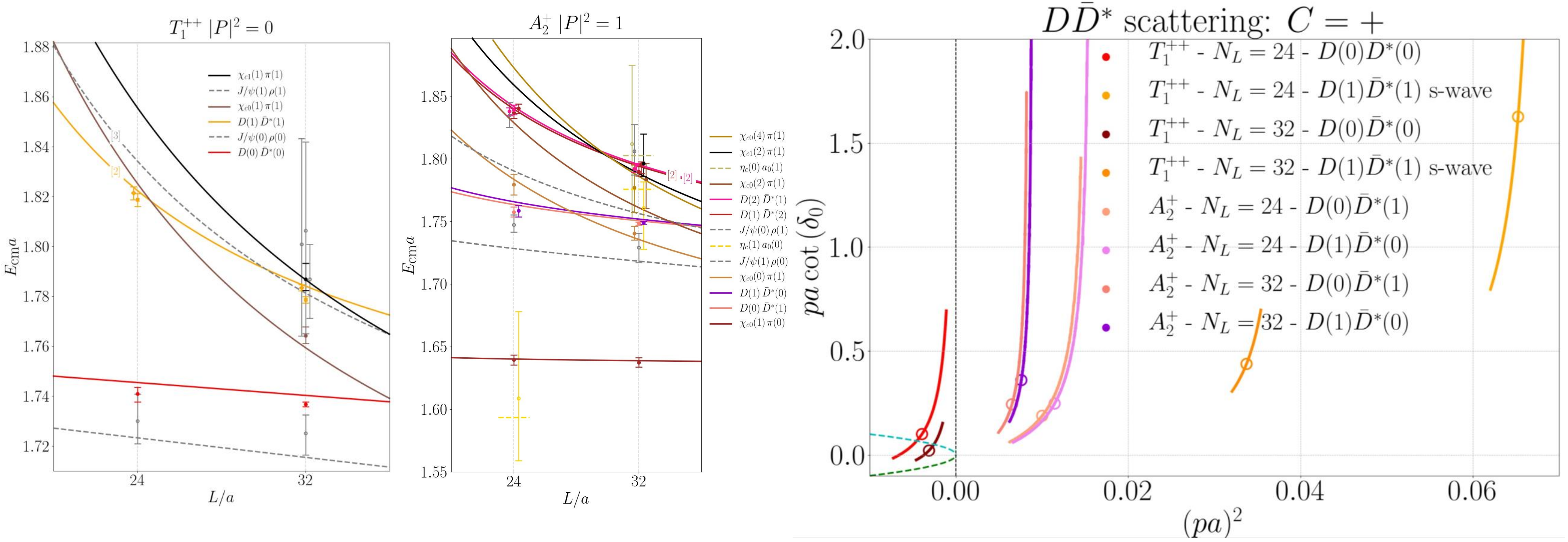
$N_L = 24$
13 inter-polators

$N_L = 32$
17 inter-polators

Note: ρ, a_0 treated as stable

Elastic $D\bar{D}^*$ scattering (C = +, isospin partner of $\chi_{c1}(3872)$)

Phase shift plots are obtained assuming negligible coupling to J/ψρ



Elastic $D\bar{D}^*$ scattering amplitude
(C = +, isospin partner of $\chi_{c1}(3872)$)

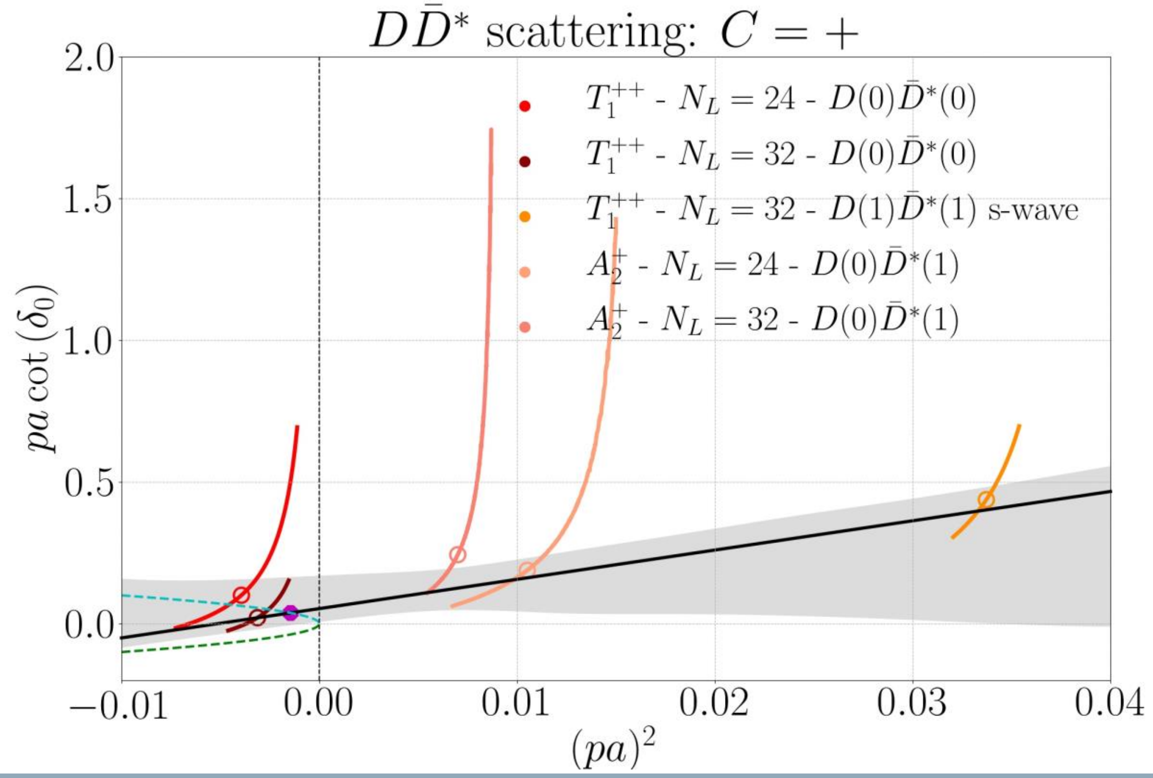
$$1/a_0 = 0.62\left(^{+1.30}_{-0.51}\right)\ \mathrm{fm}^{-1}$$

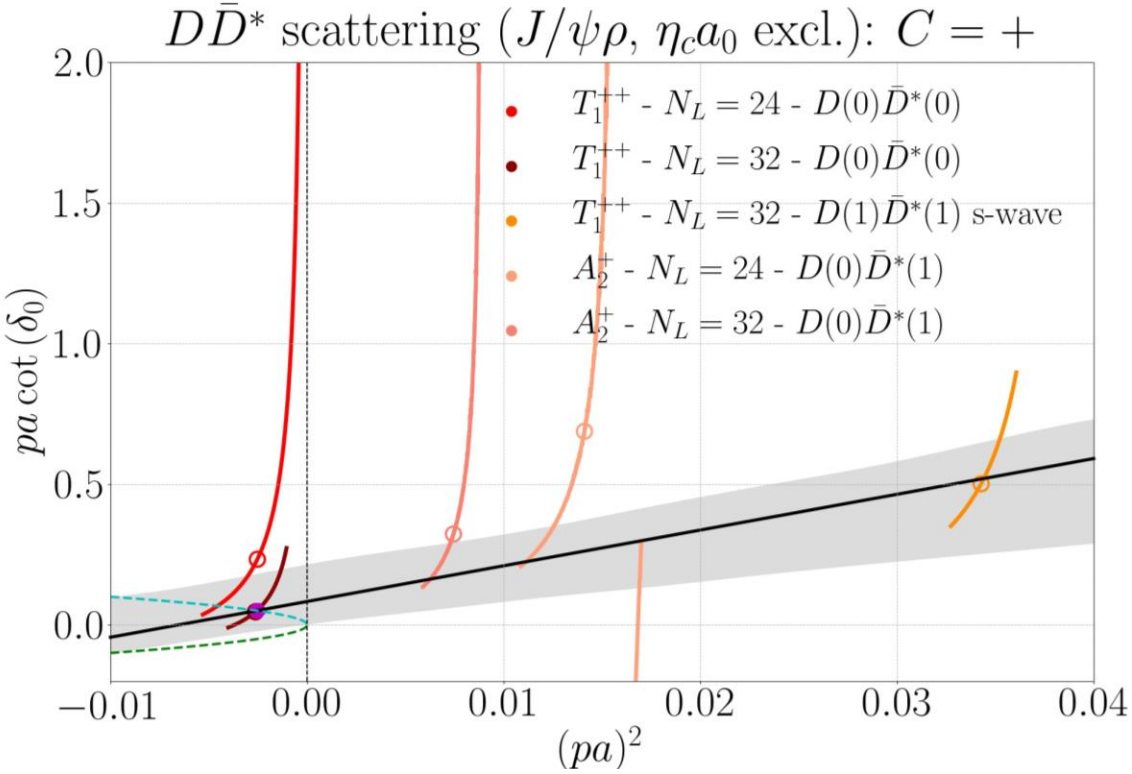
$$r_0 = 1.78\left(^{+0.25}_{-2.44}\right)\ \mathrm{fm}$$

$$p\cot(\delta_0(p)) = \frac{1}{a_0} + \frac{1}{2}r_0 p^2 + \dots$$

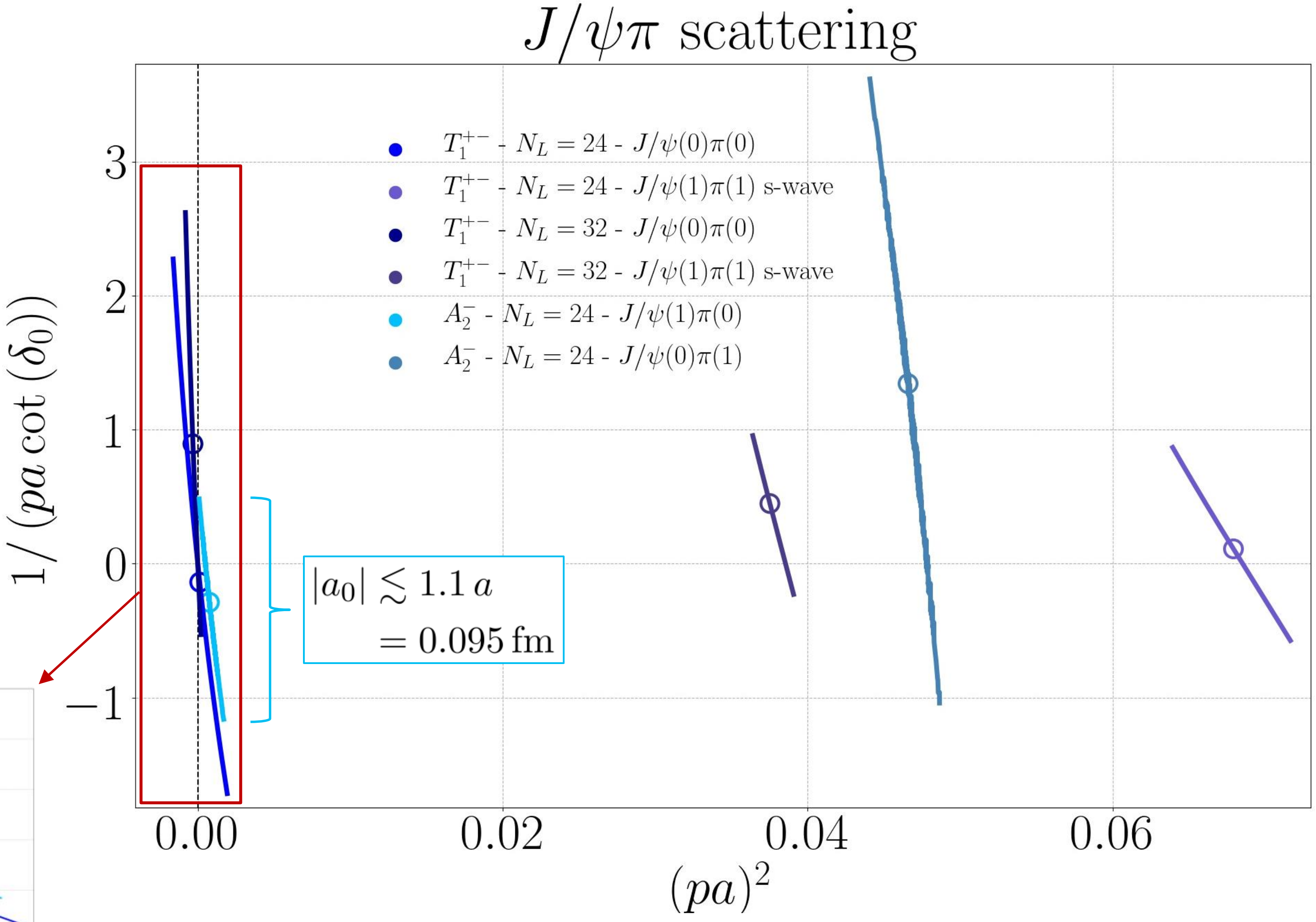
$$1/a_0 = 0.96\left(^{+1.42}_{-0.91}\right)\ \mathrm{fm}^{-1}$$

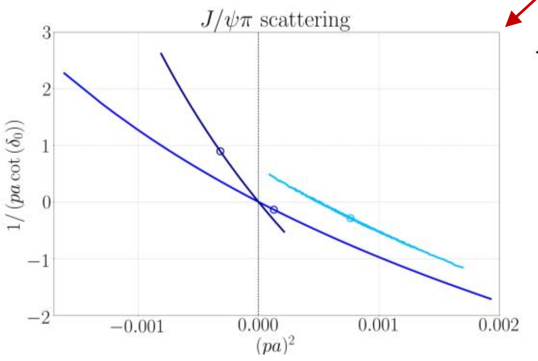
$$r_0 = 2.19\left(^{+0.36}_{-1.00}\right)\ \mathrm{fm}$$





One-channel J/ψπ scattering in the $I(J^{PC}) = 1(1^{+-})$ channel

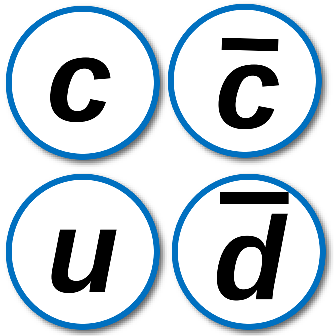




- J/ψπ meson-meson states have negligible energy shift
- These results already constrain the upper bound of $|a_0|$

$$p\cot(\delta_0(p)) = \frac{1}{a_0} + \ldots$$

Conclusions



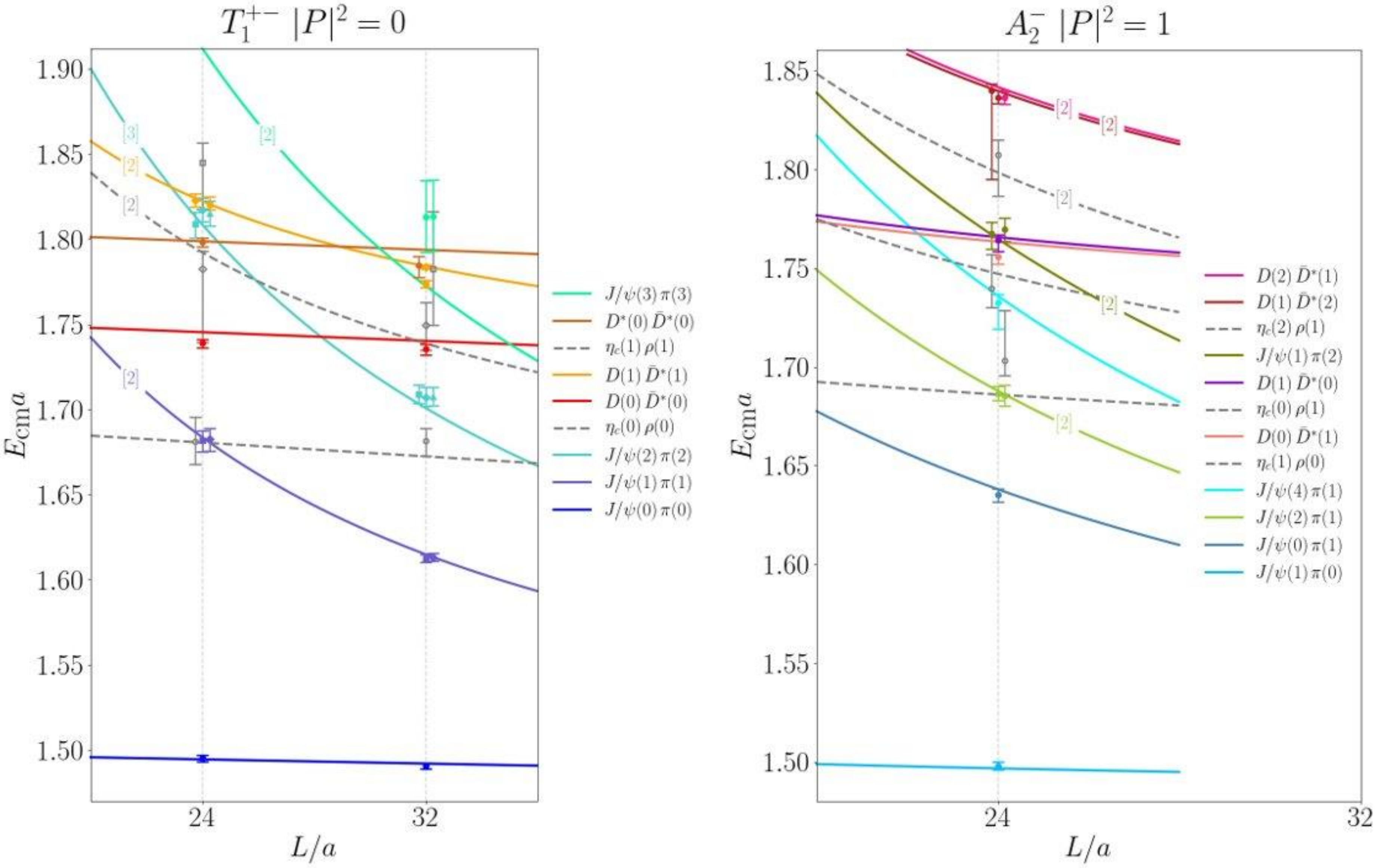
- Investigation of the exotic charmonium-like spectrum $1(1^{+\pm})$
  - Scattering amplitude assuming **decoupled** $D\bar{D}^*$ scattering close to the threshold
- Thresholds $J/\psi\pi$, $\eta_c\rho$ ($J/\psi\rho$) in the 1^{+-} (1^{++}) channel lie below the $D\bar{D}^*$ threshold
  - Large uncertainties of higher-lying $D\bar{D}^*$ eigen-energies
  - Large uncertainties of the scattering amplitude
- Previous and current lattice studies find relatively non-interacting eigen-energies
  - but according to a recent paper arXiv:2307.12283, lattice data which were jointly fitted with the experiment in a $J/\psi\pi$, $D\bar{D}^*$ **coupled-channel** framework do not preclude the existence of $Z_c(3900)$

> Our data show slightly more attraction compared to previous lattice data

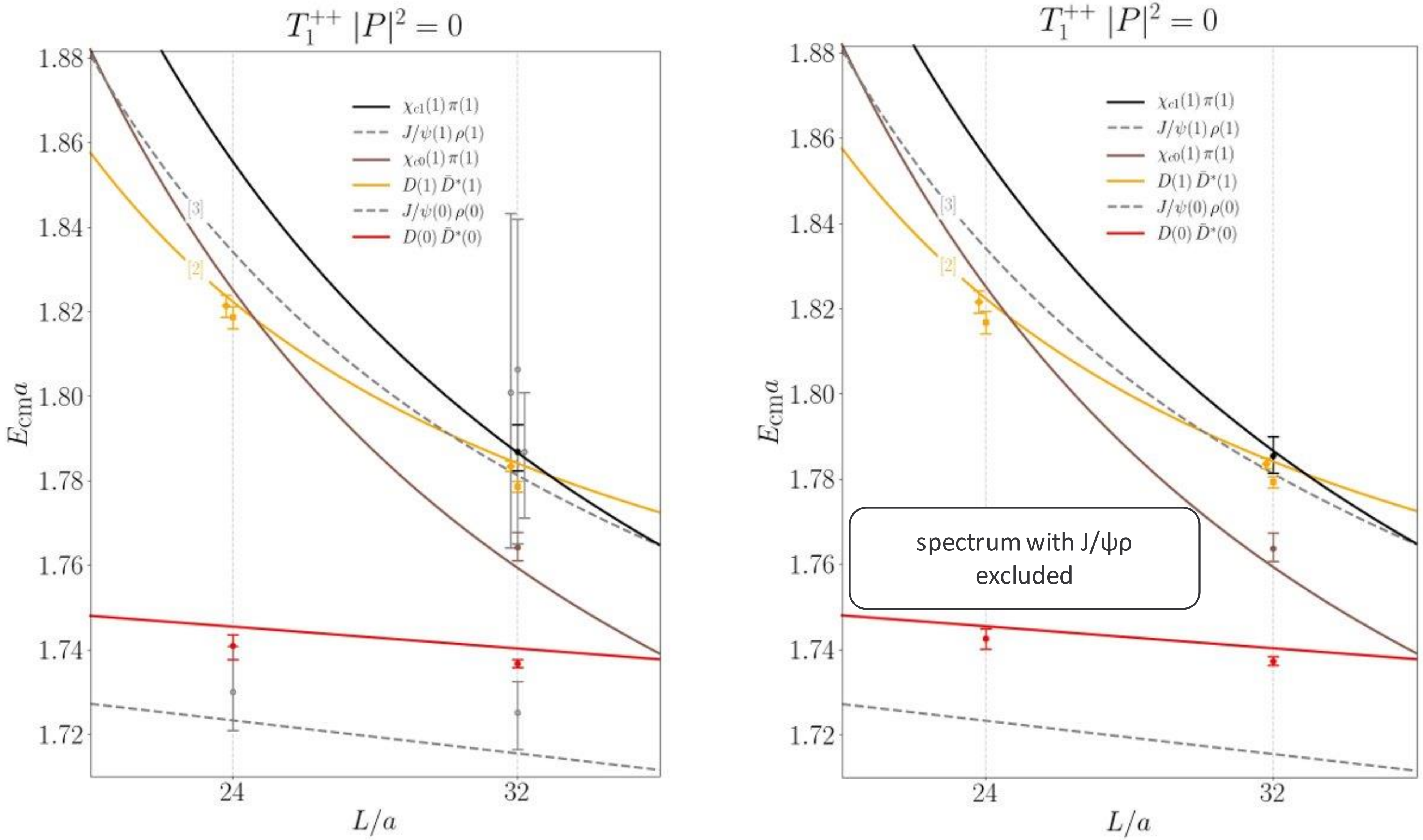
> OUTLOOK: It will be interesting to see whether our spectra reconcile with the experiment

Thank you for your attention

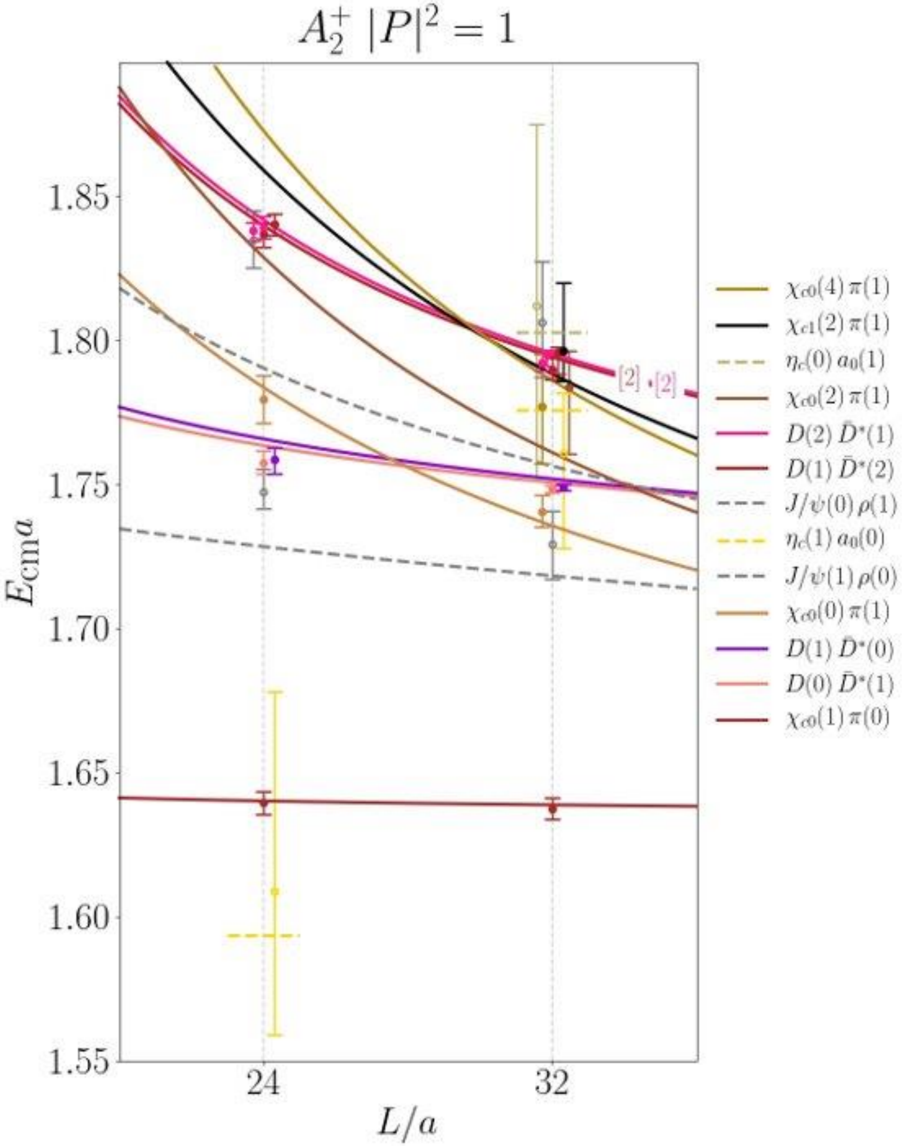
Backup – spectra

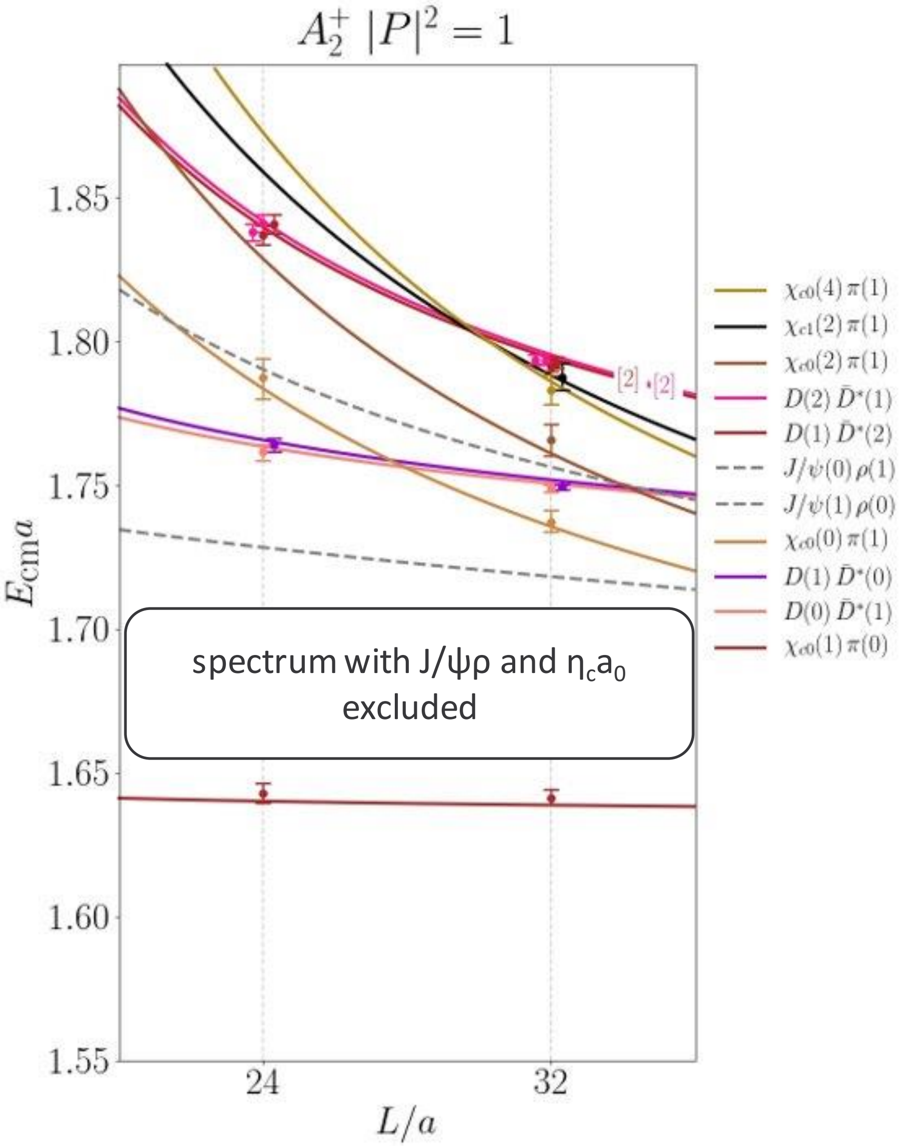


Backup – spectra



Backup – spectra





Backup – our procedure

- Extract the finite volume spectrum (in 2 inertial frames and for 2 different lattice volumes):
  - Eigen-energies from the single-exponential fits to the eigenvalues $\lambda^{(n)}(t) \propto e^{-E_n^{\text{lat}} t}$

    of the from generalized eigenvalue problem $C(t)v^{(n)}(t) = \lambda^{(n)}(t)C(t_0)v^{(n)}(t)$

- Consider only single channel (*s*-wave) $D\bar{D}^*$ scattering
  - Assume elastic scattering near the threshold

- Fit effective range parameters $p\cot(\delta_0(p)) = \frac{1}{a_0} + \frac{1}{2}r_0 p^2 + \ldots$

  to $p\cot(\delta_l(p)) = \dfrac{2\mathcal{Z}_{00}^{\mathbf{d}}\left(1, \left(\frac{pL}{2\pi}\right)^2\right)}{\gamma\sqrt{\pi}L}$

  determined via Lüscher relation from lattice energy levels E_{cm}

  We minimize χ^2 with the residue $\Omega(E_{cm}) = \dfrac{\det(A)}{\det((\mu^2 + AA^\dagger)^{1/2})}$, where $A(E_{cm}) = \tilde{K}^{-1}(E_{cm}) - B(E_{cm})$

  according to determinant residual method proposed by C. Morningstar *et al.*, Nucl. Phys. B **924**, 477 (2017)

Utilized interpolators

P = (0,0,0), $\Lambda^{PC} = T_1^{+-}$

N_L = 24
15 interpolators

N_L = 32
21 interpolators

$J/\psi(0)\pi(0)$
$J/\psi(0)\pi(0)$
$J/\psi(1)\pi(1)$
$J/\psi(1)\pi(1)$
$J/\psi(2)\pi(2)$
$J/\psi(2)\pi(2)$
$J/\psi(2)\pi(2)$
$\eta_c(0)\rho(0)$
$\eta_c(1)\rho(1)$
$\eta_c(1)\rho(1)$
$\bar{D}^*(0)D(0)$
$\bar{D}^*(0)D(0)$
$\bar{D}^*(1)D(1)$
$\bar{D}^*(1)D(1)$
$\bar{D}^*(0)D^*(0)$
$J/\psi(3)\pi(3)$
$J/\psi(3)\pi(3)$
$\eta_c(2)\rho(2)$
$\eta_c(2)\rho(2)$
$\eta_c(2)\rho(2)$
$h_c(1)\pi(1)$

P = (0,0,1), $\Lambda^{C} = A_2^{-}$

N_L = 24
21 interpolators

$J/\psi(1)\pi(0)$
$J/\psi(0)\pi(1)$
$J/\psi(1)\pi(0)$
$J/\psi(0)\pi(1)$
$J/\psi(2)\pi(1)$
$J/\psi(2)\pi(1)$
$J/\psi(1)\pi(2)$
$J/\psi(1)\pi(2)$
$J/\psi(4)\pi(1)$
$\eta_c(1)\rho(0)$
$\eta_c(0)\rho(1)$
$\eta_c(2)\rho(1)$
$\eta_c(2)\rho(1)$
$\bar{D}^*(0)D(1)$
$\bar{D}^*(1)D(0)$
$\bar{D}^*(0)D(1)$
$\bar{D}^*(1)D(0)$
$\bar{D}^*(1)D(2)$
$\bar{D}^*(1)D(2)$
$\bar{D}^*(2)D(1)$
$\bar{D}^*(2)D(1)$

P = (0,0,0), $\Lambda^{PC} = T_1^{++}$

N_L = 24
5 interpolators

N_L = 32
10 interpolators

$J/\psi(0)\rho(0)$
$\bar{D}^*(0)D(0)$
$\bar{D}^*(0)D(0)$
$\bar{D}^*(1)D(1)$
$\bar{D}^*(1)D(1)$
$J/\psi(1)\rho(1)$
$J/\psi(1)\rho(1)$
$J/\psi(1)\rho(1)$
$\chi_{c0}(1)\pi(1)$
$\chi_{c1}(1)\pi(1)$

P = (0,0,1), $\Lambda^{C} = A_2^{+}$

N_L = 24
13 interpolators

N_L = 32
17 interpolators

$\eta_c(1)a_0(0)$
$\chi_{c0}(1)\pi(0)$
$\chi_{c0}(0)\pi(1)$
$J/\psi(1)\rho(0)$
$J/\psi(0)\rho(1)$
$\bar{D}^*(0)D(1)$
$\bar{D}^*(1)D(0)$
$\bar{D}^*(0)D(1)$
$\bar{D}^*(1)D(0)$
$\bar{D}^*(1)D(2)$
$\bar{D}^*(1)D(2)$
$\bar{D}^*(2)D(1)$
$\bar{D}^*(2)D(1)$
$\eta_c(0)a_0(1)$
$\chi_{c0}(2)\pi(1)$
$\chi_{c0}(4)\pi(1)$
$\chi_{c1}(2)\pi(1)$