

# Charmonium-like states with $J^P=1^+$ and isospin 1

Mitja Šadl (Faculty of Mathematics and Physics, University of Ljubljana)

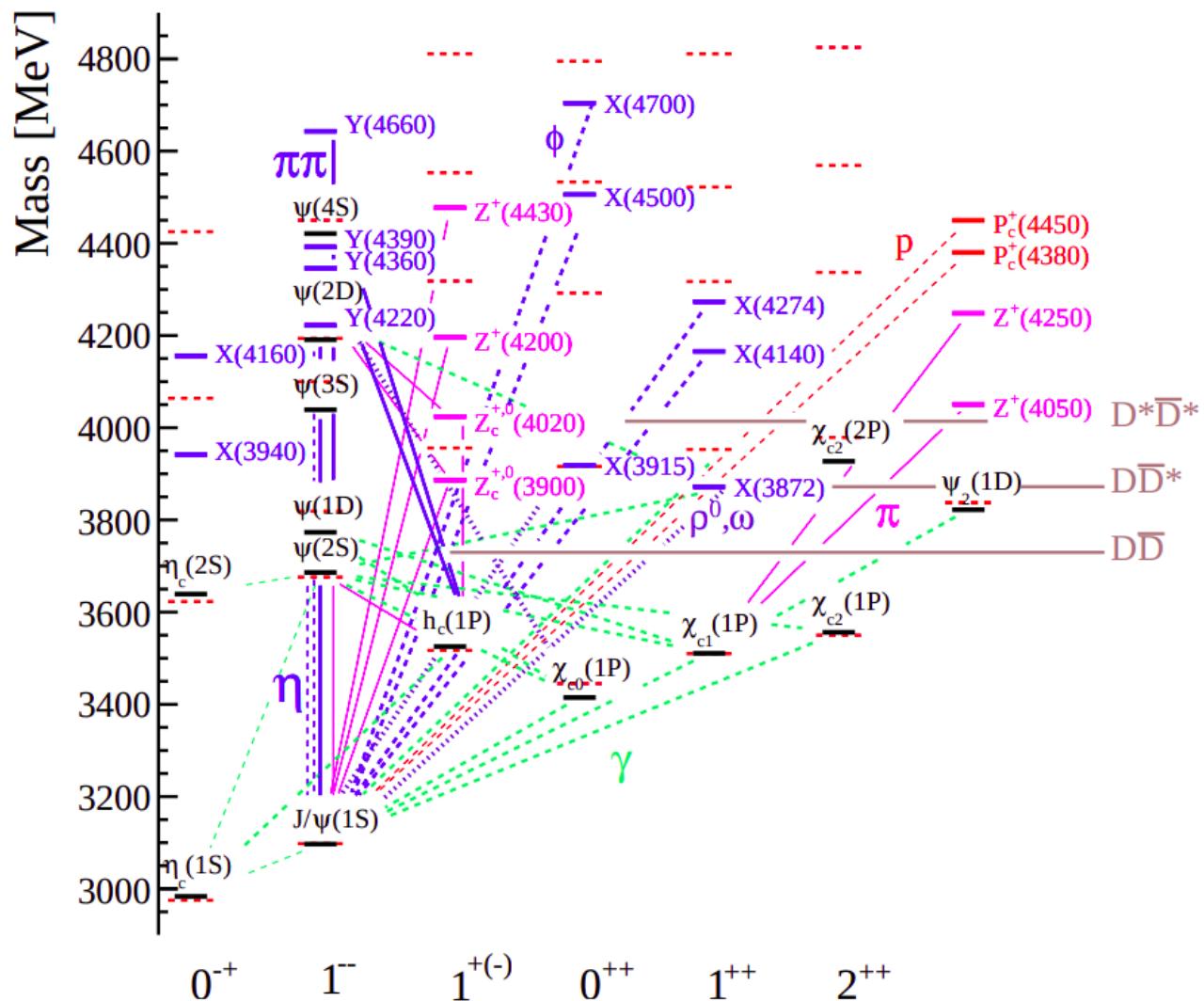
Sara Collins (University of Regensburg),

M. Padmanath (Helmholtz Inst., Mainz),

Saša Prelovšek (University of Ljubljana, Jozef Stefan Institute)

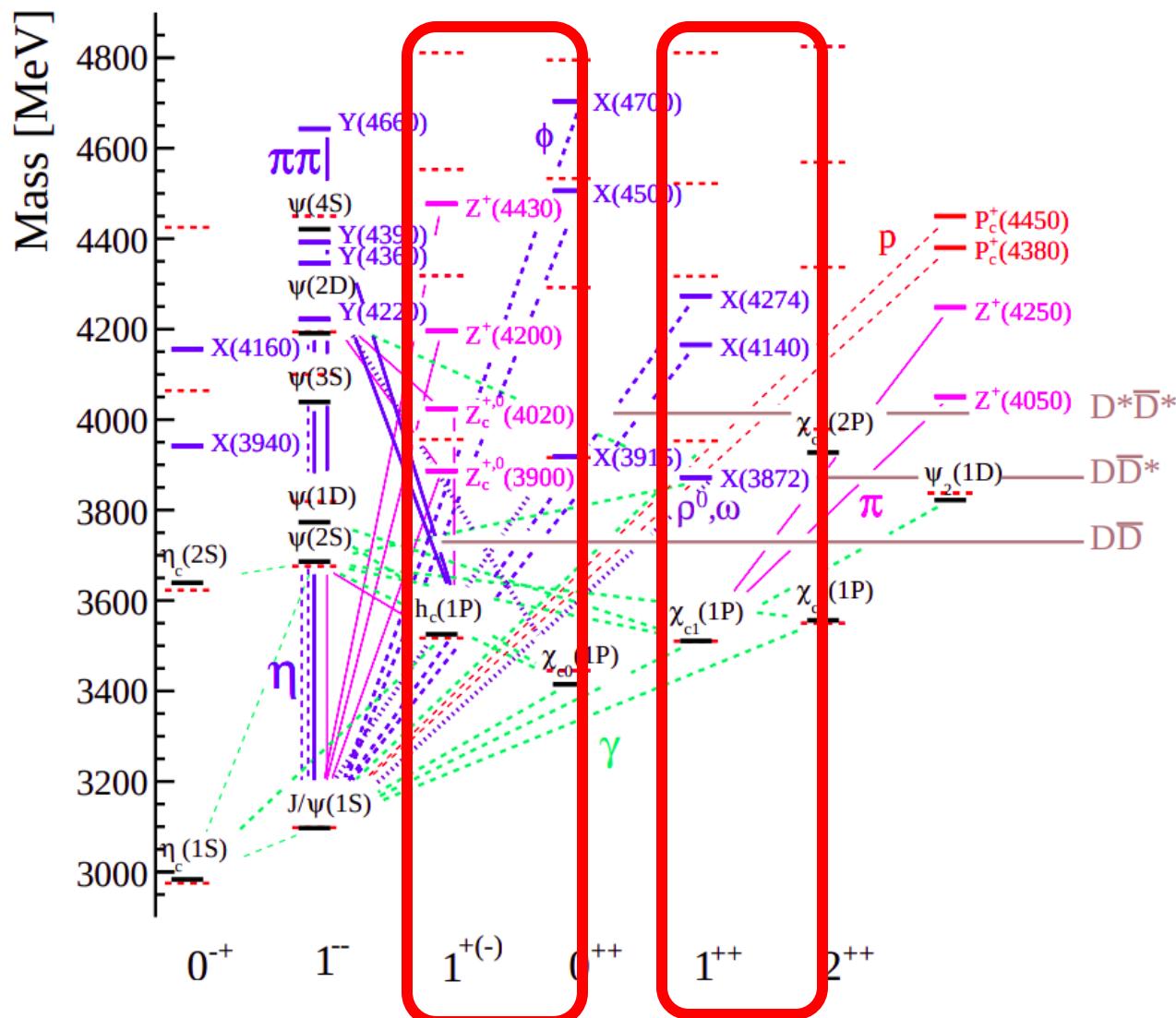
THE 39TH INTERNATIONAL SYMPOSIUM ON LATTICE FIELD THEORY (LATTICE 2022)

# Motivation – charmonium-like resonances



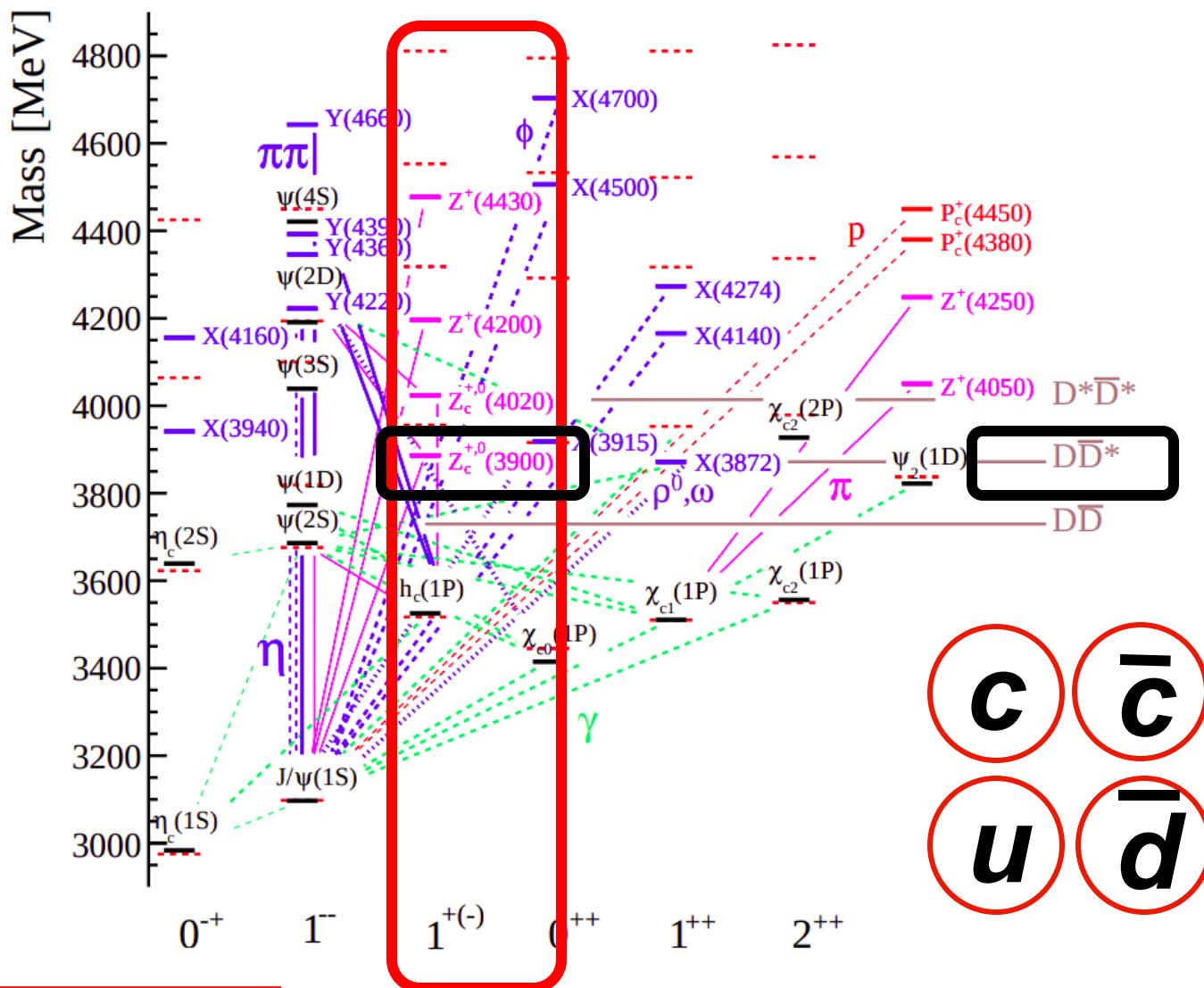
- Many **conventional** and **exotic** charmonium(-like) states experimentally discovered

# Motivation – charmonium-like resonances

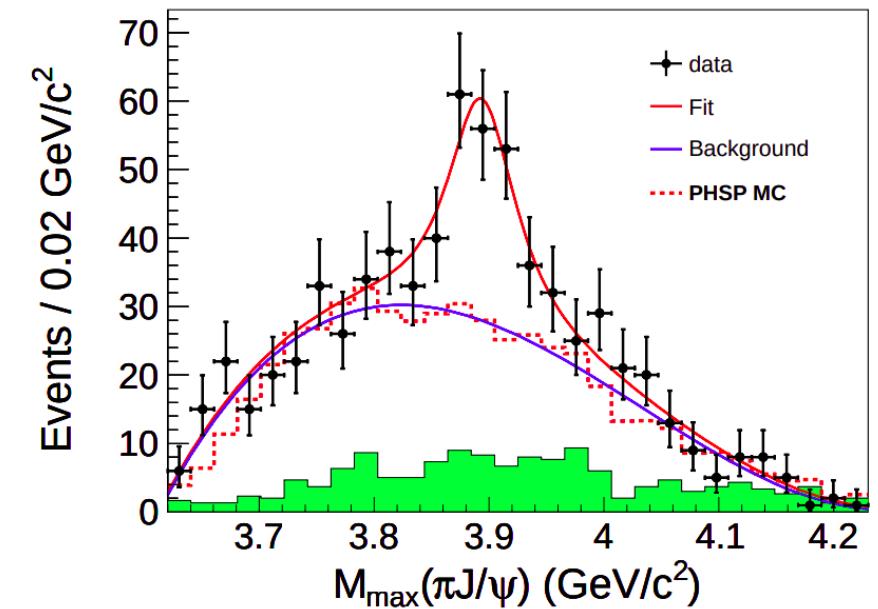


- Many **conventional** and **exotic** charmonium(-like) states experimentally discovered
- We consider sectors:
  - $I(J^{PC})=1(1^{+-})$
  - $I(J^{PC})=1(1^{++})$

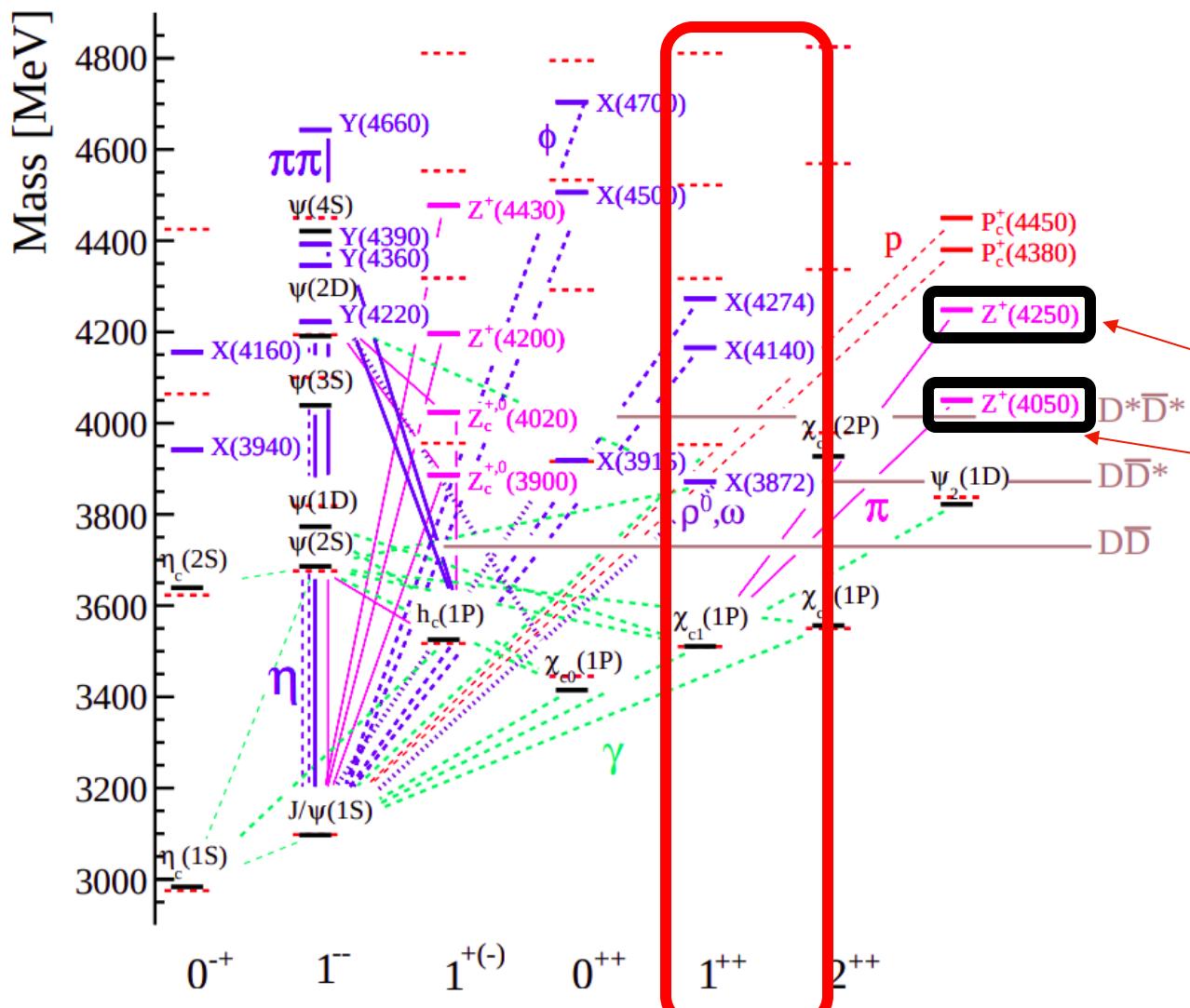
# Motivation – charmonium-like resonances



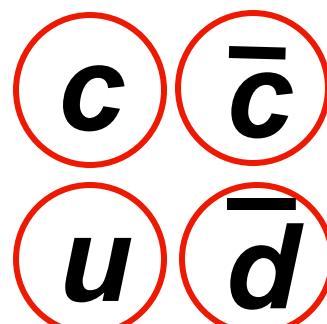
- $I(J^{PC})=1(1^{+-}) \sim Z_c$  states
  - Charged states discovered
  - Manifestly exotic
  - First discoveries of  $Z_c(3900)$ :
    - M. Ablikim *et al.* (BESIII), PRL **110**, 252001 (2013)
    - Z. Q. Liu *et al.* (Belle), PRL **110**, 252002 (2013)
    - Lying on the  $D\bar{D}^*$  threshold



# Motivation – charmonium-like resonances

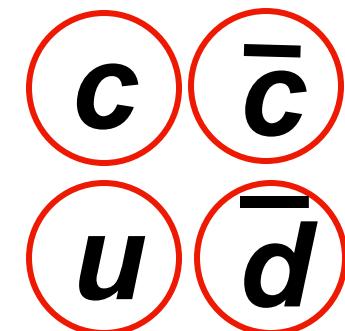


- $I(J^{PC})=1(1^{++})$
- Candidate is an isospin partners of  $X(3872)$  ( $\chi_{c1}(3872)$ )
- No experimentally discovered state
- Possible observed candidates (quantum numbers not reliably determined):
  - $X(4250)$
  - $X(4050)$



# Previous lattice studies

- $I(J^{PC})=1(1^{+-}) \sim Z_c$  states
  - $Z_c(3900)$  and  $Z_c(4020)$  – HQSS (heavy quark spin symmetry) partners - L. Meng *et al.*, PRD **102**, 111502 (2020)
    - The interactions on the spin of the heavy quark are independent
  - Lattice studies aimed at  $Z_c(3900)$  – existence not confirmed:
    - 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)
    - M. Albaladejo *et al.*, Eur. Phys. J. C **76**, 573 (2016)
    - S.-h. Lee *et al.* (Fermilab Lattice, MILC), (2014), arXiv:1411.1389
    - G.K.C. Cheung *et al.*, JHEP **11**, 033 (2017)
  - HAL QCD lattice study aimed at  $Z_c(3900)$  – a pole is found and claiming that  $Z_c(3900)^+$  is a threshold cusp:
    - Y. Ikeda *et al.*, PRL **117**, 242001 (2016)
    - Y. Ikeda, J. Phys **G45**, 024002 (2018)
    - The above scenario is not supported by two-channel effective range expansion via Lüscher's formalism: T. Chen *et al.* (CLQCD), Chin. Phys. **C43**, 103103 (2019)
- $I(J^{PC})=1(1^{++})$ 
  - Studies do not see any new candidates in the spectrum:
    - S. Prelovsek and L. Leskovec, PRL **111**, 192001 (2013)
    - M. Padmanath, C. B. Lang and S. Prelovsek, PRD **92**, 034501 (2015)



# The procedure

- Choose and calculate sets of interpolating operators
- Extract the finite volume spectrum (in 2 inertial frames and for 2 different lattice volumes):
  - Correlation matrix:  $C_{ij}(t) = \langle O_i(t_{\text{src}} + t)O_j^\dagger(t_{\text{src}}) \rangle$
  - Eigen-energies from the single-exponential fits to the eigenvalues  $\lambda^{(n)}(t) \propto e^{-E_n^{\text{lat}} t}$  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
  - Via Lüscher relation determine
- Constraining effective range parameters

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

$$T_l = \frac{1}{p \cot(\delta_l(p)) - ip}$$

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

$I(J^P)=1(1^+)$   
Charmonium-like states

# CLS lattice ensembles

	<b>U101</b>	<b>H105</b>
$N_L^3 \times N_T$	$24^3 \times 128$	$32^3 \times 96$
	dynamical quarks	
$N_F$	2+1	
$a$	0.08636(98)(40) fm	
$m_\pi$	280(3) MeV	
$M_{av}$	3103(3) MeV	
$m_D$	1927(1) MeV	
$m_{D^*}$	2049(2) MeV	
configurations	255	492
Laplacian eigenvectors (quark fields are smeared with the 'Distillation' method)	90	100

$m_c$  heavier than physical

(quark fields are smeared  
with the 'Distillation' method)

# Used interpolator types

- No  $\bar{c}c$  interpolators:
  - $I = 1$  – for sure four quark states:
- No diquark-antidiquark interpolators:
  - very little influence found when including them – M. Padmanath, C. B. Lang and S. Prelovsek, PRD **92**, 034501 (2015)
- Only meson-meson interpolators:

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

Note that  $J^P = 1^+$  is contained  
in irreps:

- $\mathbf{d} = (0,0,0)$ :  $\Lambda^P = T_1^+$
- $\mathbf{d} = (0,0,1)$ :  $\Lambda = A_2$

$I(J^P)=1(1^+)$   
Charmonium-like states

$\bar{c}c$

$\bar{d}u$

$\bar{c}u$

$\bar{d}c$

# Used interpolators

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

- 2 ensembles and
- 2 irreps

**$N_L = 24$**

**15 interpolators**

**$N_L = 32$**

**21 interpolators**

considered energy region:

$E_{cm} < 4100$  MeV

while the  $D\bar{D}^*$  threshold is in our  
case at 3976 MeV

- $\mathbf{d} = (0,0,0)$ ,  $\Lambda^{PC} = \mathbf{T}_1^{+-}$

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

$J/\psi(3)\pi(3)$   
 $J/\psi(3)\pi(3)$   
 $\eta_c(2)\rho(2)$   
 $\eta_c(2)\rho(2)$   
 $\eta_c(2)\rho(2)$   
 $h_c(1)\pi(1)$

- $\mathbf{d} = (0,0,1)$ ,  $\Lambda^C = \mathbf{A}_2^-$

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

**$N_L = 24$**

**21 interpolators**

**$N_L = 32$**

**too many  
interpolators,  
not constructed**

# Used interpolators

$|(J^{PC})=1(1^{++})$

- 2 ensembles and
- 2 irreps

**N<sub>L</sub> = 24**  
5 interpolators

**N<sub>L</sub> = 32**  
10 interpolators

■  $\mathbf{d} = (0,0,0)$ ,  $\Lambda^{PC} = \mathbf{T}_1^{++}$

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

■  $\mathbf{d} = (0,0,1)$ ,  $\Lambda^C = \mathbf{A}_2^+$

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

**N<sub>L</sub> = 24**  
13 interpolators

**N<sub>L</sub> = 32**  
17 interpolators

considered energy region:

$$E_{cm} < 4100 \text{ MeV}$$

while the  $D\bar{D}^*$  threshold is in our case at 3976 MeV

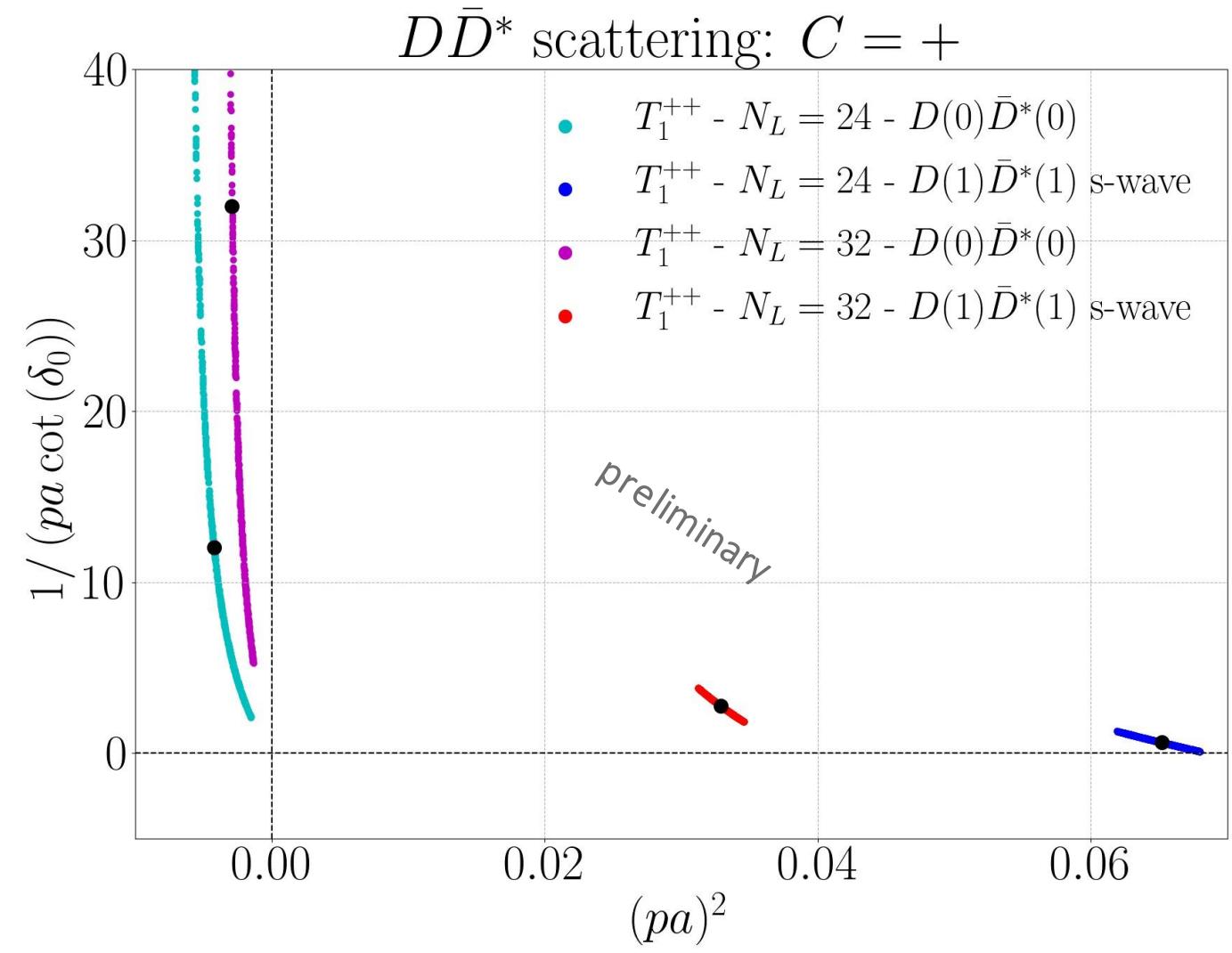
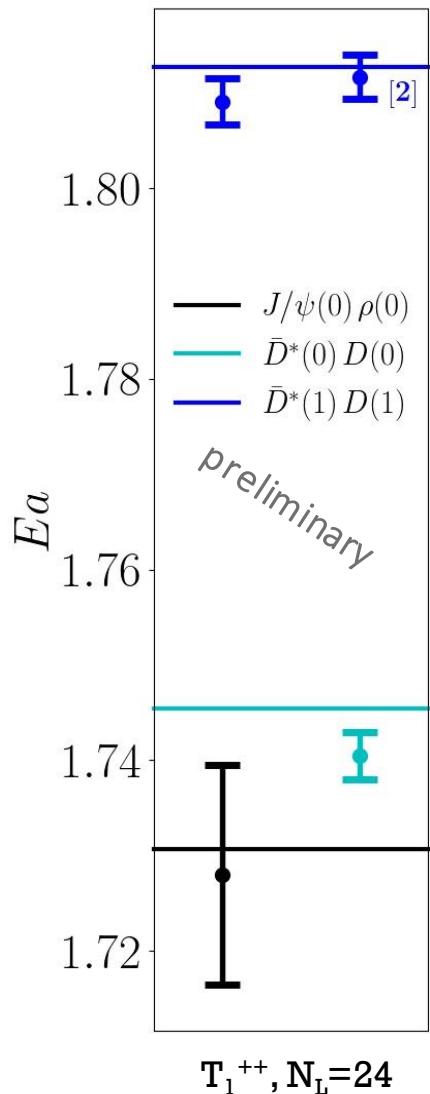
$\bar{c}c$

$\bar{d}u$

$\bar{c}u$

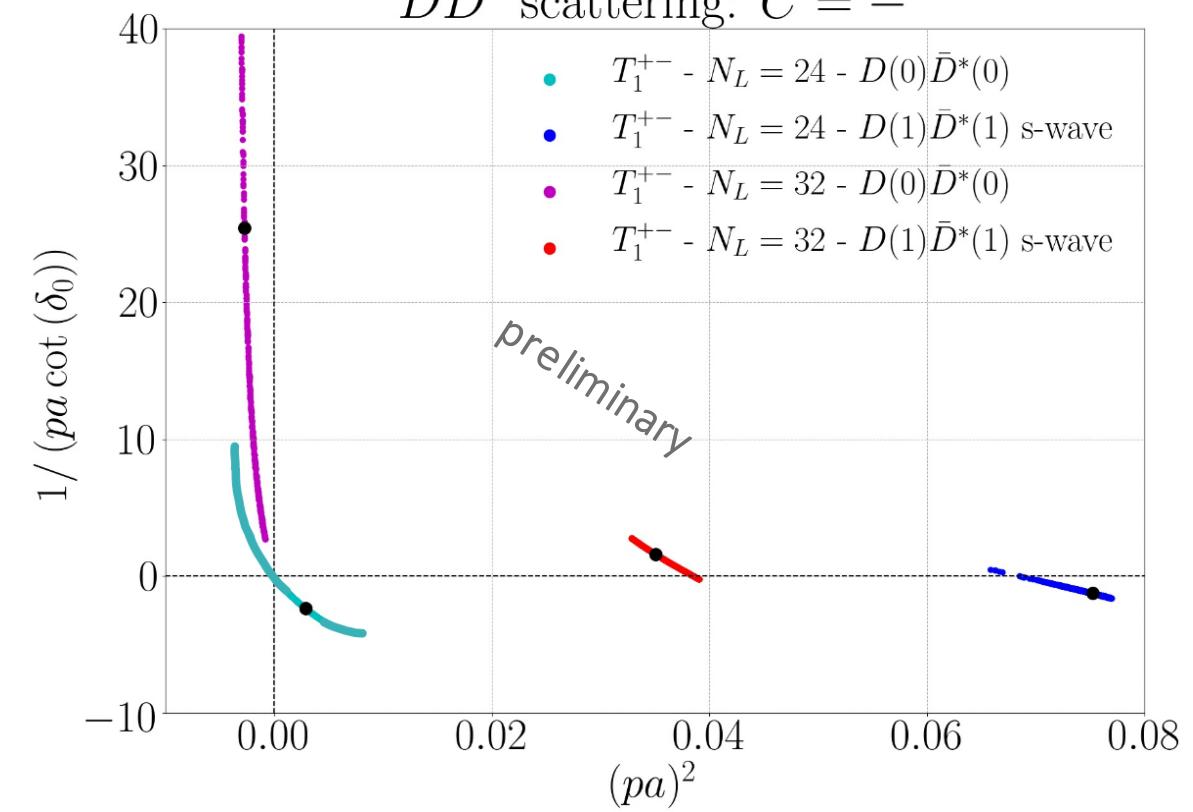
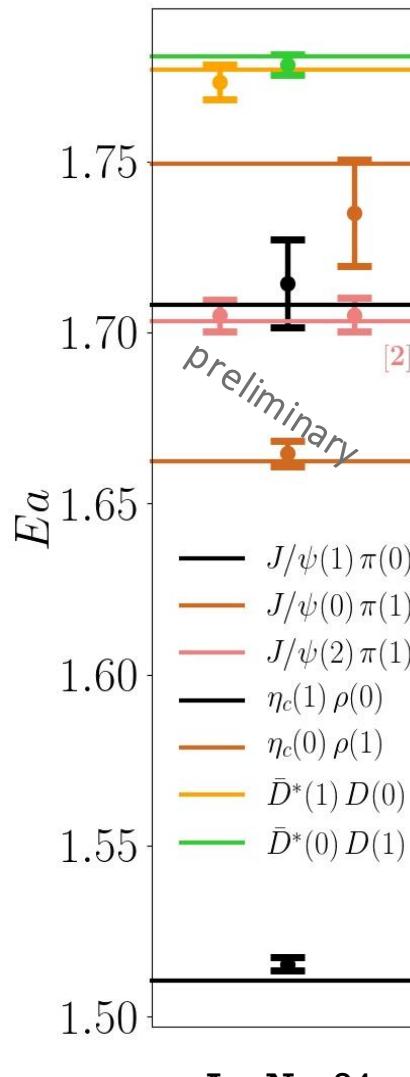
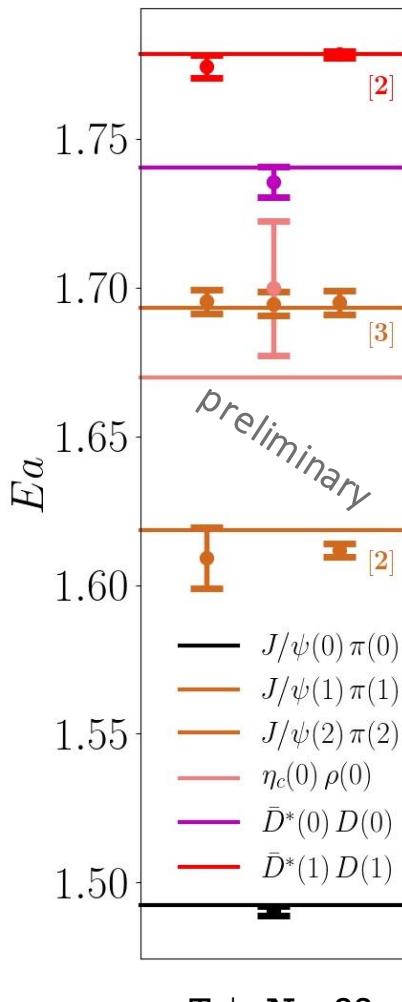
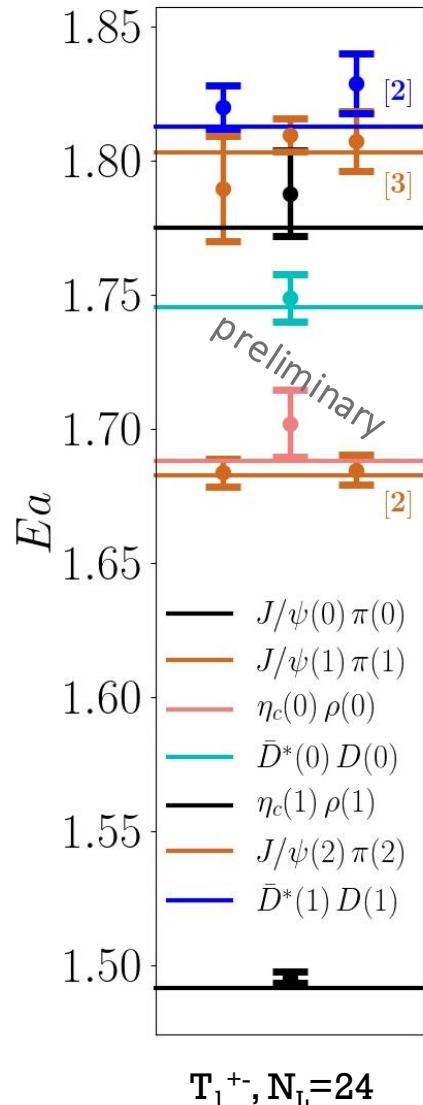
$\bar{d}c$

# Preliminary results – $I(J^{PC})=1(1^{++})$



$I(J^P)=1(1^+)$   
Charmonium-like states

# Preliminary results – $I(J^{PC})=1(1^{+-})$

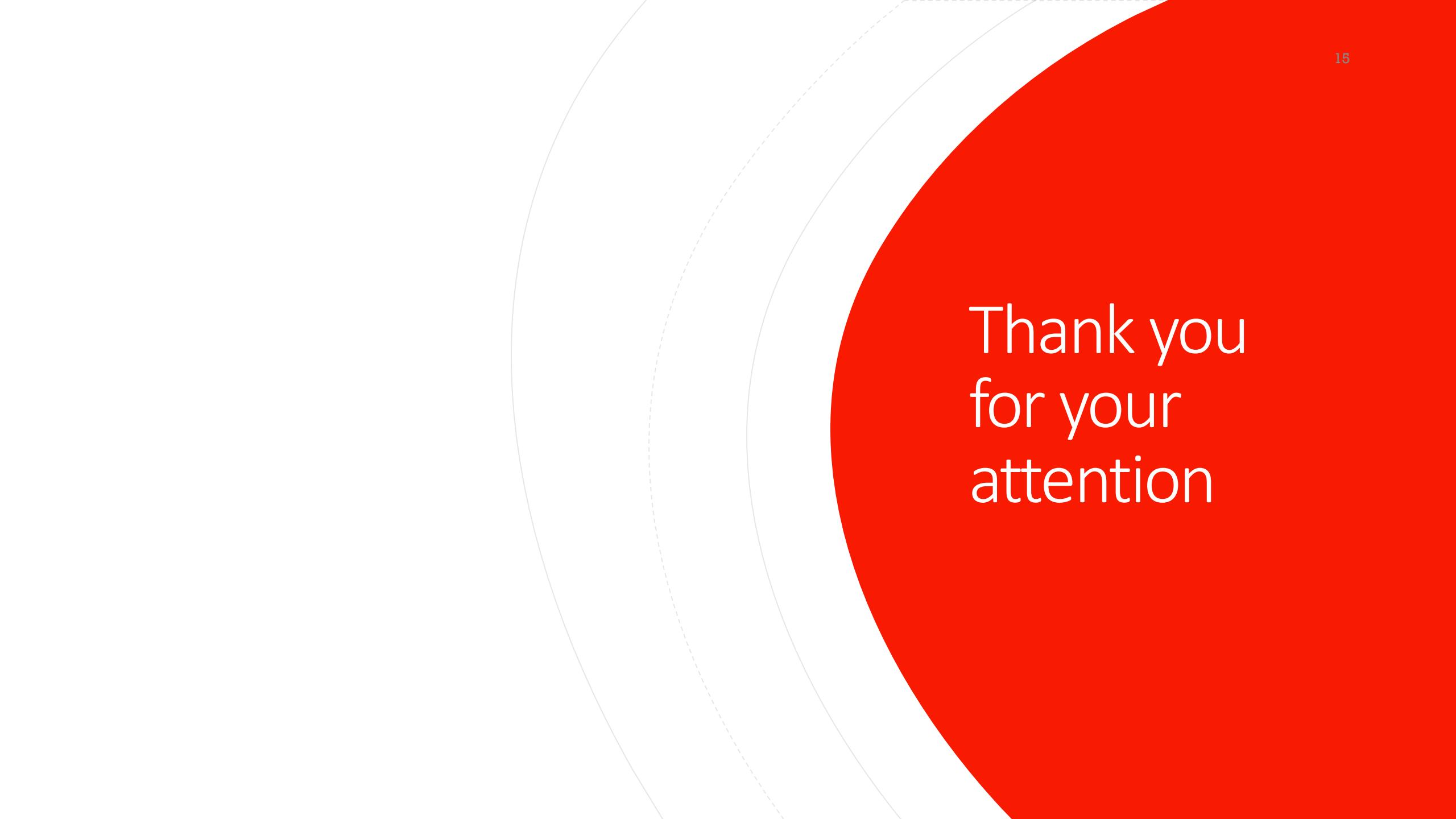


## Conclusion

- We investigate the spectrum of exotic charmonium-like mesons with  $I = 1$  and  $J^P = 1^+$
- Preliminary results show a very small interaction between mesons
- For these two channels, a non-zero total momentum calculation (on 2 volumes) was done for the first time
- A complete determination should already constrain some models and interpretations

## Outlook

- Our primary goal was to determine the  $D\bar{D}^*$  scattering phase shift
- Since some attraction is rarely seen, we will make a comparison with the phenomenological approaches and put constraints on the scattering length.

The background features a minimalist design with three overlapping circles. A large, solid white circle is positioned in the upper left. Overlaid on its lower right is a smaller, dashed light-gray circle. To the right of the dashed circle is a medium-sized, solid light-gray circle. The area where all three circles overlap is white, while the rest of the slide is a plain, light gray.

Thank you  
for your  
attention