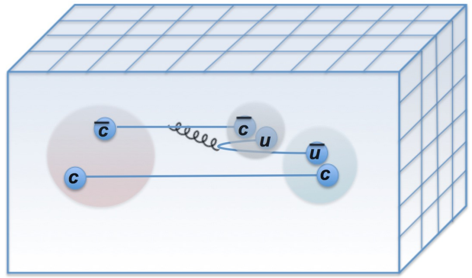
Conventional and exotic charmonia from lattice QCD

$\bar{c}c\,,\ \bar{c}q\bar{q}c$



Sasa Prelovsek University of Ljubljana & Jozef Stefan Institute, Slovenia

(guest professor at Regensburg and member of SFB, 2016-2021)

QCD on and off the lattice, Regensburg University, 18th September, 2023

Sara Collins, Daniel Mohler, M. Padmanath, Stefano Piemonte, SP

1811.04116, PRD 2019 : with **Andreas Schafer** and Simon Weishaeupl

1905.03506, PRD2019

2011.02542, JHEP 2021

2111.02934 : review

Outline : Conventional and exotic charmonia

$\bar{c}c$, $\bar{c}q\bar{q}c$

- motivation
- glimpse of the results
- path to the results
- results (again)

  comparison to exp, implications

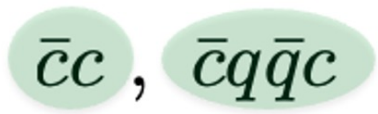
  .....

  - challenges & how we addressed them

  - challenges that remain open

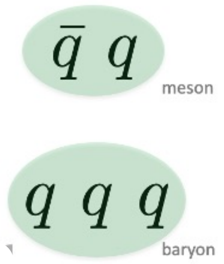
Motivation

Charmonium(like) states

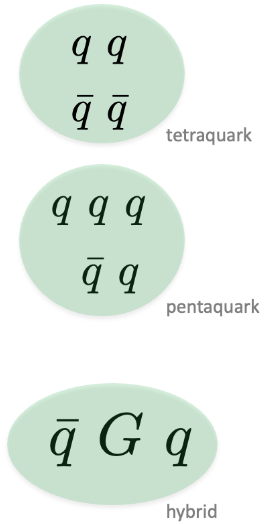


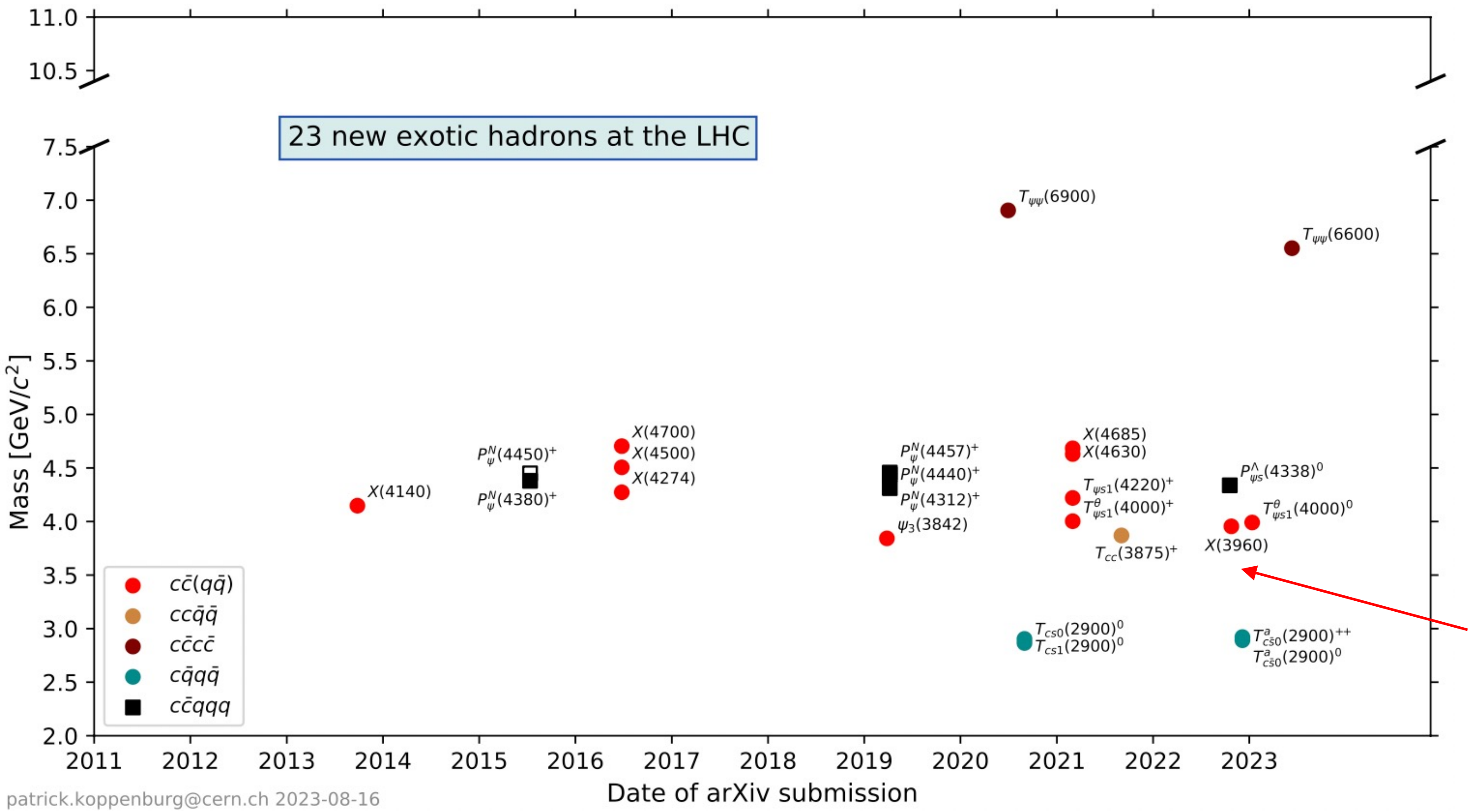
majority of exotic hadrons contain $c\bar{c}$

conventional hadrons



exotic hadrons



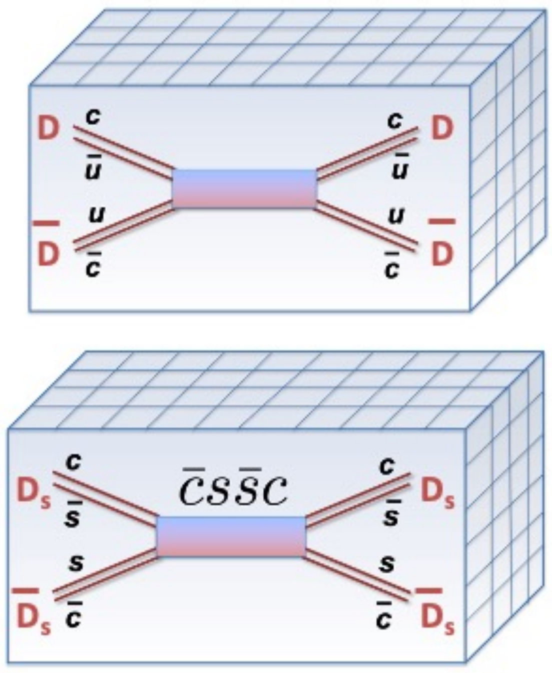


https://www.nikhef.nl/~pkoppenb/particles.html

Charmonium(like) states

$\bar{c}c\bar{d}u$ I=1

$\bar{c}c\ ,\ \bar{c}c\bar{q}q \quad (\bar{q}q = \bar{u}u + \bar{d}d,\ \ \bar{s}s)$ I=0



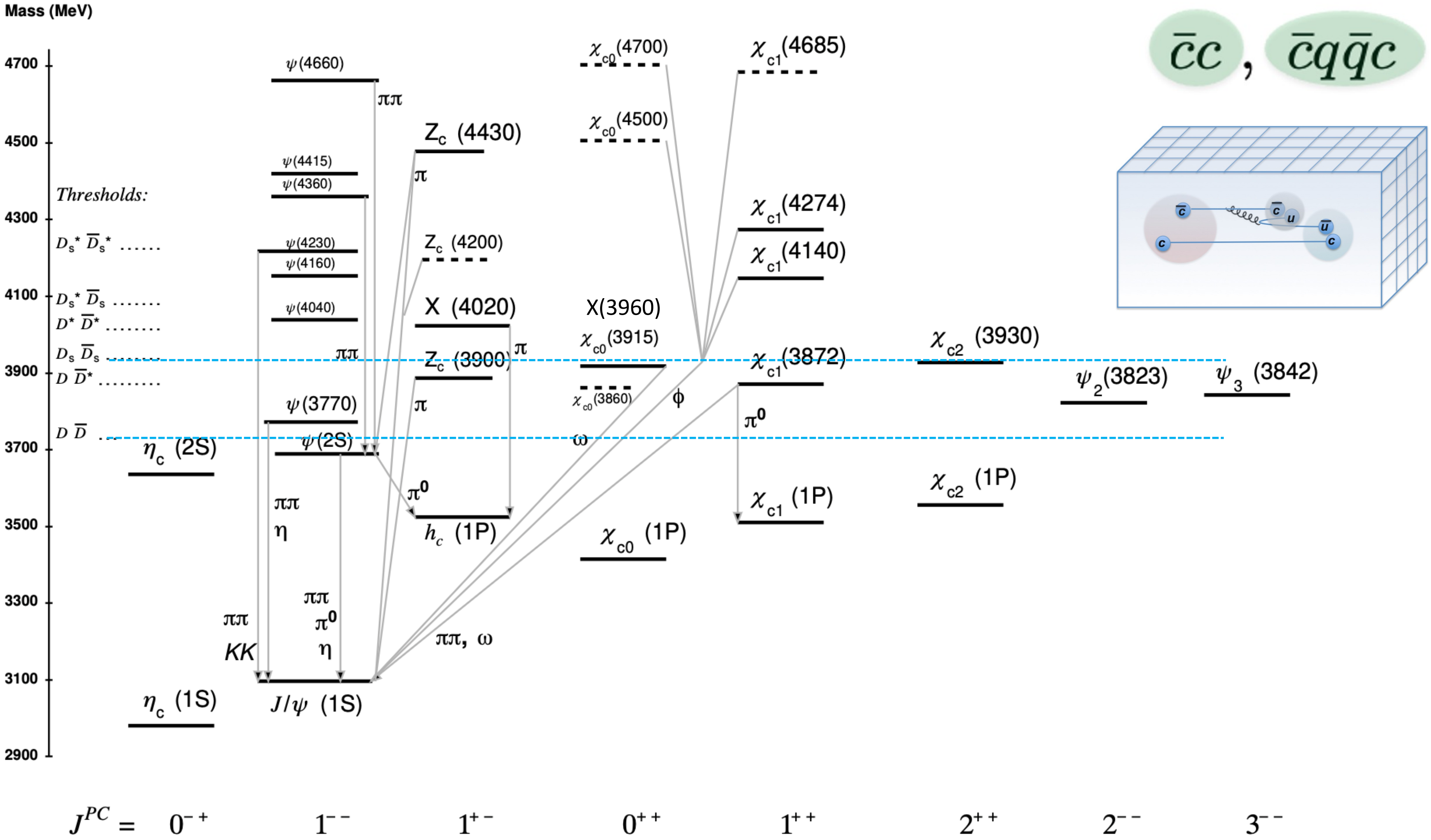
$D\bar{D} - D_s\bar{D}_s$ scattering

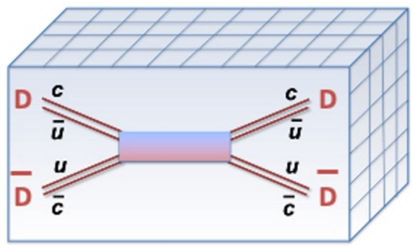
discussed in this talk

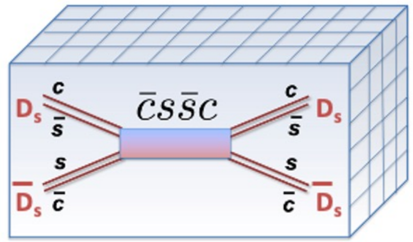
I=0, $J^{PC}=0^{++},1^{--},2^{++},3^{--}$

Charmonium(like) system: experimental status (PDG)

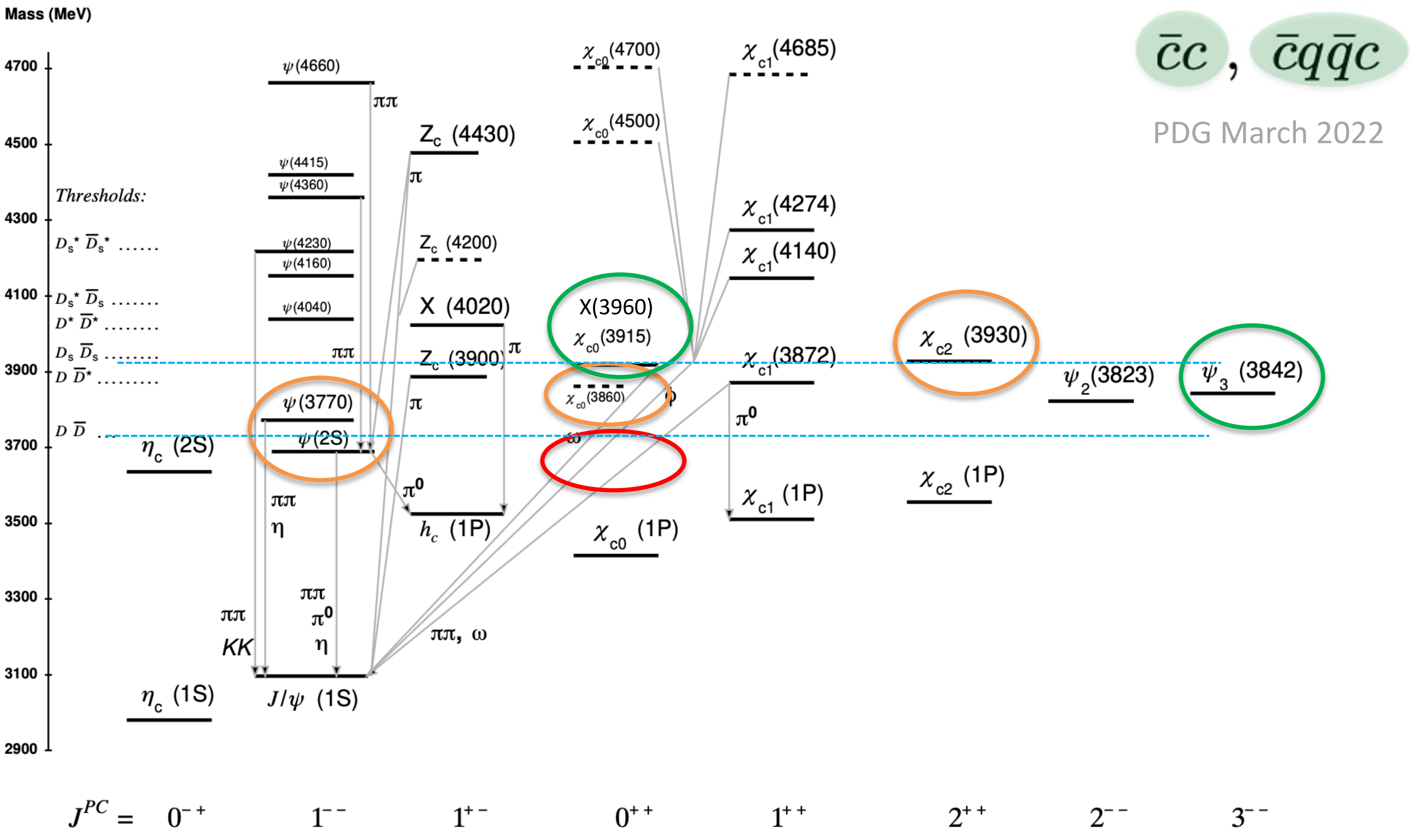
PDG March 2022







Charmonium(like) system: experimental status (PDG) and summary of our lattice results

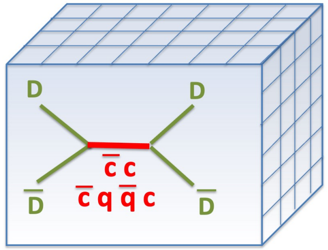


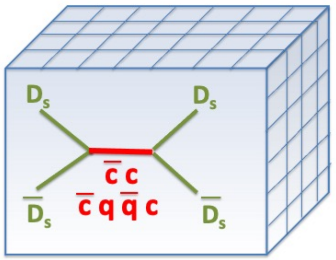
our lattice study: postdicted | predicted, exp discovered | predicted, exp not (yet) discovered

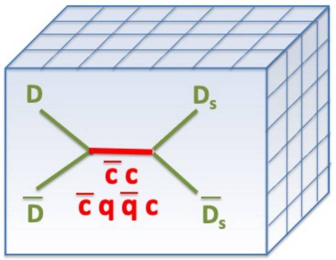
Outline of results:

$$\frac{|c^2_{D\bar{D}}|}{|c^2_{D_s\bar{D}_s}|} = 0.02\ ^{+0.02}_{-0.01}$$

$$T_{ij}(E_{cm}) \sim \frac{c_i\ c_j}{E^2_{cm} - m^2}$$

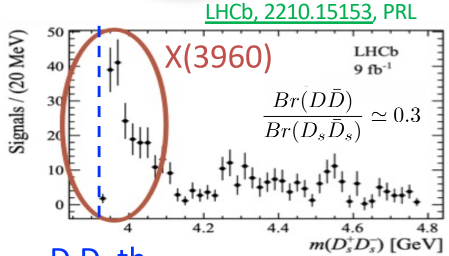






$\bar{D}D - \bar{D}_sD_s$

$\bar{D}_sD_s$ $J^P=0^+$ state



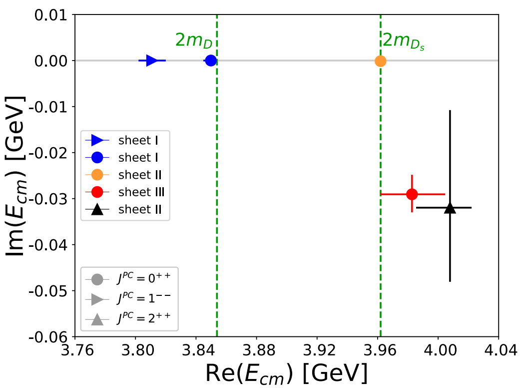
D_sD_s th.

$\bar{D}D$ $J^P=0^+$ state

predicted in models [Oset et al, 0612179 PRD, Guo et al 2101.01021]

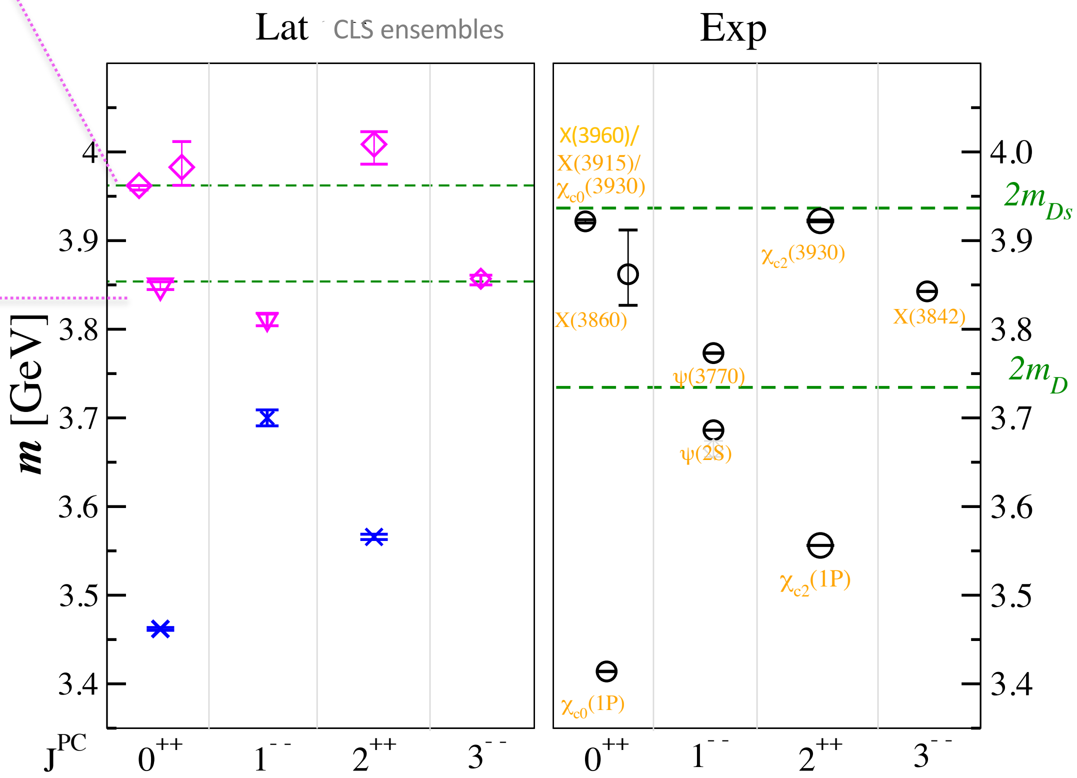
seen in re-analysis of exp. [Danilkin et al 2111.15033, Ji, F.K. Guo et al., 2212.00613]

+ expected conventional charmonia



$\bar{c}c\ ,\ \bar{c}q\bar{q}c$ $\quad$ q=u,d,s $\quad$ $I=0$

$m_\pi \simeq 280$ MeV $\quad$ $m_D \simeq 1927$ MeV



Charmonium(like) resonances and bound states

Path to results

Lattice setup

CLS ensembles with u/d, s dynamical quarks

a≃0.086 fm, **m_π =280(3) MeV**

L = 2.1 fm, 2.7 fm

U101 H105

lat exp

$m_{u/d} > m_{u/d}^{exp}$

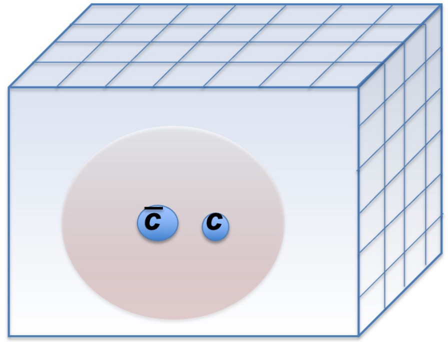
$m_s < m_s^{exp}$

$m_u+m_d+m_s = m_u^{exp} + m_d^{exp} + m_s^{exp}$

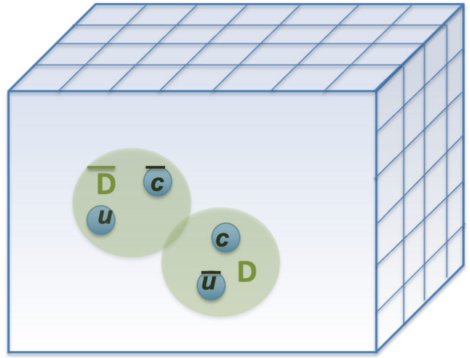
two values of m_c (relativistic charm quarks)

	m_D [MeV]	$\frac{1}{4}(m_{\eta_c}+3m_{J/\psi})$ [MeV]
lat ($m_c \gtrsim m_c^{exp}$)	1927(1)	3103(3)
lat ($m_c \lesssim m_c^{exp}$)	1762(1)	2820(3)
exp	1864.85(5)	3068.6(1)

Quantity extracted from lattice: eigen-energy E_n



$$C_{ij}(t) = \langle 0 | \mathcal{O}_i(t)\ \mathcal{O}_j^{+}(0) | 0 \rangle = \sum_n Z_i^n\ Z_j^{n*}\ e^{-E_n t}$$



- correlators evaluated using distillation method [Peardon et al, 2009]
- eigen-energies extracted using GeVP
- for strongly stable state well below threshold : $E_n(P=0) = m$
- in general : $$E_n^{cm} \rightarrow T(E_n^{cm})$$

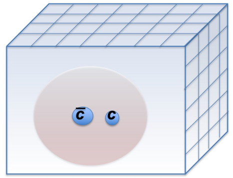
Luscher's relation

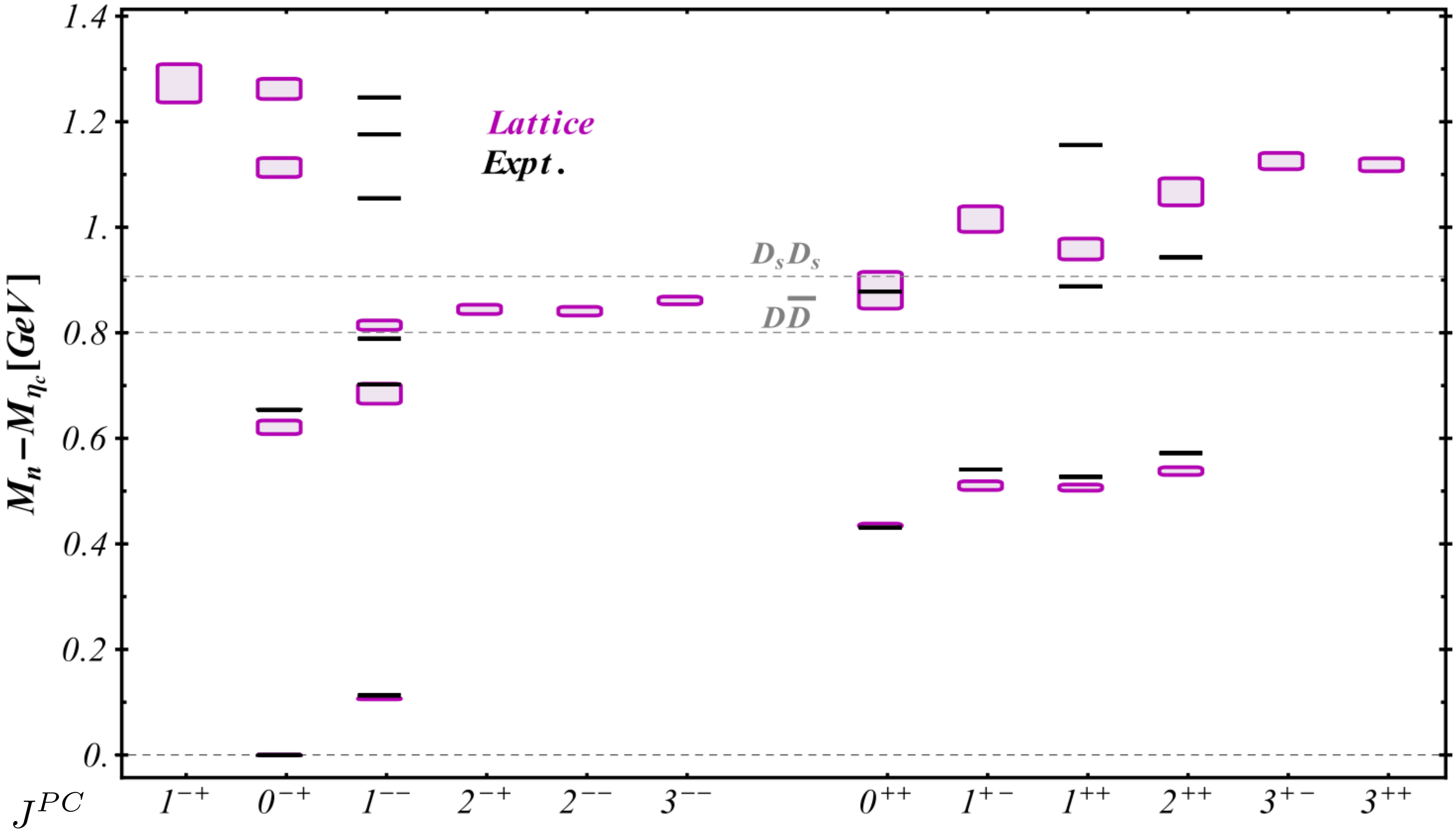
- Initial step: consider charmonia to be strongly stable

$\mathcal{O}$: $\bar{c}(x)\Gamma c(x)$, $\bar{c}(x)\Gamma \overleftrightarrow{D}_j c(x)$, $\bar{c}(x)\Gamma \overleftrightarrow{D}_j \overleftrightarrow{D}_k c(x)$.

(up to 30 interpolators in given irrep)

- Charmonia at rest $E_n(P=0) = m$





- Initial step: consider charmonia to be strongly stable

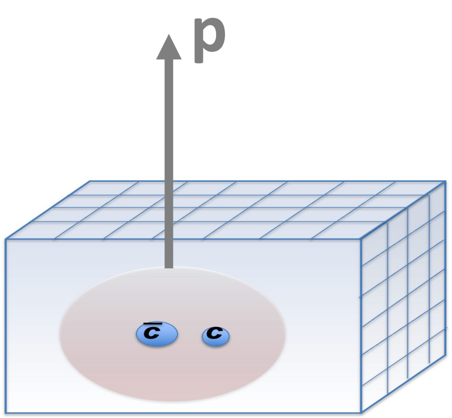
➢ Charmonia with momentum p≠0 : Challenge

$$E_n^{cm}=\sqrt{(E_n^{cm})^2-P^2}$$

Motivation to study p≠0: extraction of scattering matrix

$$E_n^{cm}\to T(E_n^{cm})$$

Challenge: identify J^P of charmonium in flight

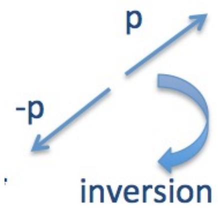


Symmetries: p≠0

continuum

C: good

P: NOT good



Rotations/reflections:

transformations that leave p invariant

rotations around p; little group U(1)

spin J: not good

helicity : good $\lambda = \frac{\vec{J}\cdot\vec{p}}{|\vec{p}|}$

$\tilde{\eta}$: good (only for λ=0 states)

$$\Pi\,|p,J^P,\lambda\rangle = \tilde{\eta}\,|p,J^P,-\lambda\rangle$$

$$\tilde{\eta} \equiv P(-1)^J$$

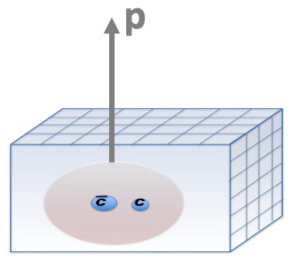
cubic lattice

C: good

P: NOT good

Rotations/reflections:

transformations that leave box and p invariant:



p=(0,0,1): group Dic_4 , 8 elements

TABLE VII. Choice of representation matrices for the Dic_4 little group. I denotes the identify transformation, $R(\phi)$ denotes a rotation around the z-axis by ϕ and Π denotes a reflection in the yz plane ($x \to -x$).

Irrep	I	$R(\pi)$	$R(3\pi/2)$	$R(\pi/2)$	Π	$R(\pi)\Pi$	$R(\pi/2)\Pi$	$R(3\pi/2)\Pi$

p=(1,1,0); group Dic_2 , 4 elements

Irrep	I	$R(\pi)$	Π	$R(\pi)\Pi$

irreps: good quantum numbers

helicity: not good

$\tilde{\eta}$: good (only for λ=0 states)

The challenge to determine J^P

$|\lambda| <= J$ $\qquad \lambda = \frac{\vec{J}\cdot\vec{p}}{|\vec{p}|}$

refers to J^P in charmonium's rest frame

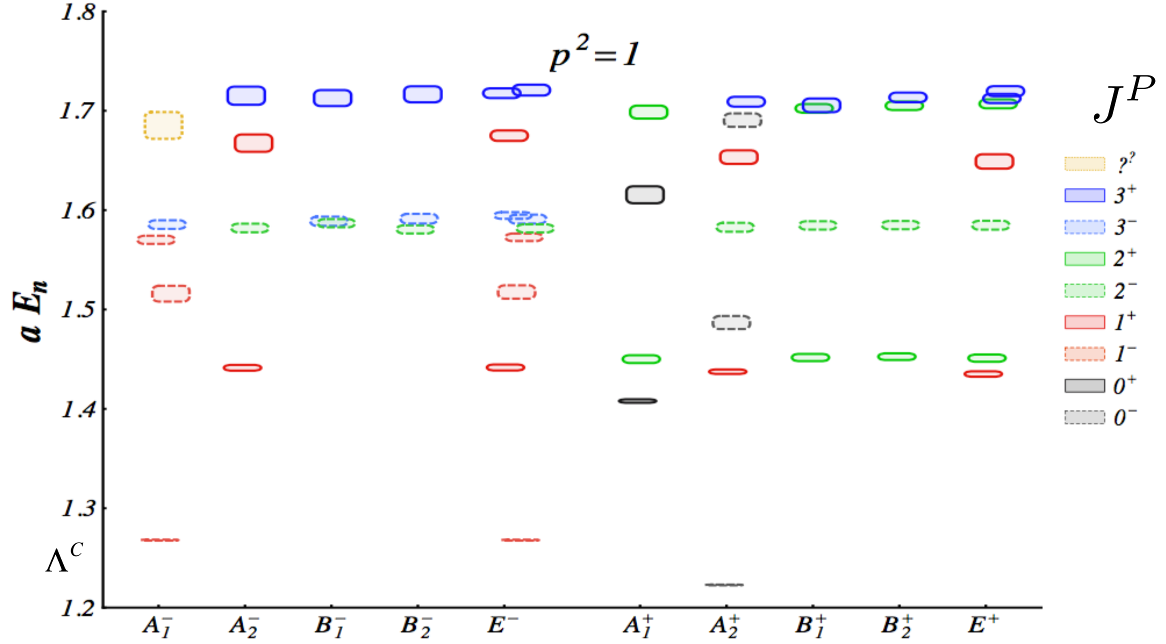
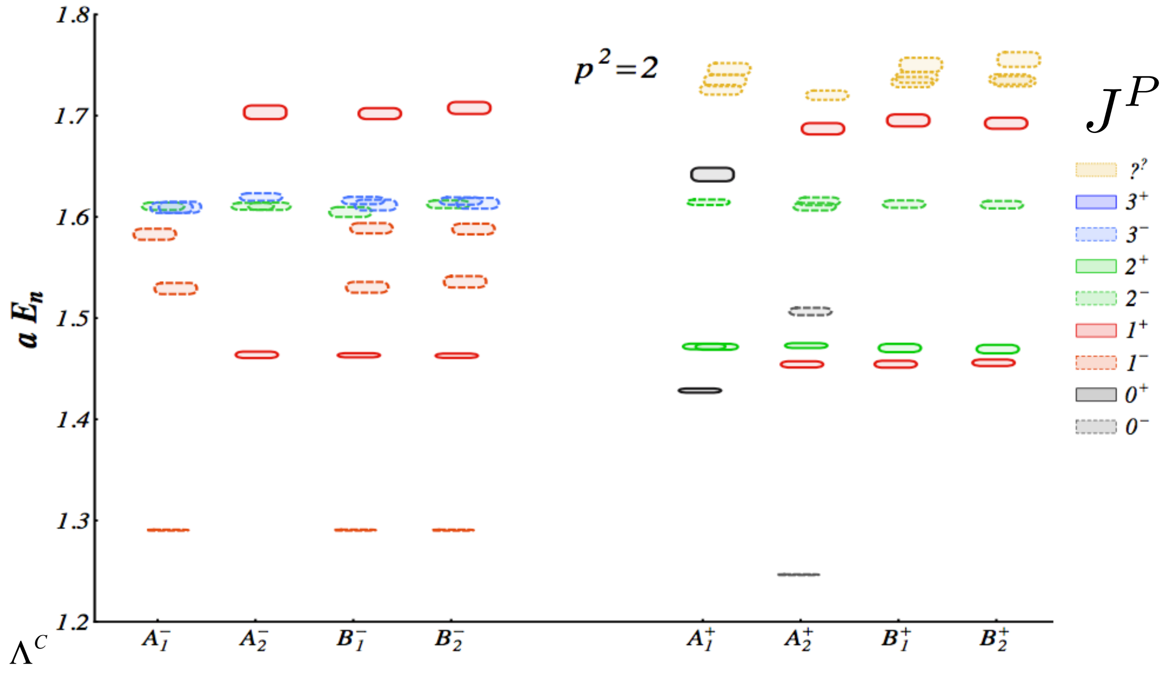


FIG. 11. J^P-identified charmonium spectrum in the moving frame with $\mathbf{p} = (0,0,1)$. Irreps Λ^C of group Dic_4 are presented



$\mathbf{p} = (0,0,1)$, Dic_4		
Λ (dim)	$\|\lambda\|^{\tilde{\eta}}$	J^P (at rest)
A_1 (1)	0^+	$0^+,\ 1^-,\ 2^+,\ 3^-$
A_2 (1)	0^-	$0^-,\ 1^+,\ 2^-,\ 3^+$
E (2)	1	$1^\pm,\ 2^\pm,\ 3^\pm$
	3	$3^\pm$
B_1 (1)	2	$2^\pm,\ 3^\pm$
B_2 (1)	2	$2^\pm,\ 3^\pm$

$\mathbf{p} = (1,1,0)$, Dic_2		
Λ (dim)	$\|\lambda\|^{\tilde{\eta}}$	J^P (at rest)
A_1 (1)	0^+	$0^+,\ 1^-,\ 2^+,\ 3^-$
	2	$2^\pm,\ 3^\pm$
A_2 (1)	0^-	$0^-,\ 1^+,\ 2^-,\ 3^+$
	2	$2^\pm,\ 3^\pm$
B_1 (1)	1	$1^\pm,\ 2^\pm,\ 3^\pm$
	3	$3^\pm$
B_2 (1)	1	$1^\pm,\ 2^\pm,\ 3^\pm$
	3	$3^\pm$

state with J has $|\lambda|<=J$

state with $|\lambda|$ can have $|\lambda|<=J$

Identifying J^P for hadrons in flight

following strategy by HadSpec employed for light mesons PRD 2012

$$\bar{c}\, \Gamma D..c$$

$$O_i^{J^{PC},\lambda}(\mathbf{p}) = \sum_M \mathcal{D}^{(J)*}_{M,\lambda}(R)\; O_i^{J^{PC},M}(\mathbf{p})$$

$$O_{\Lambda,\mu} = \sum_{R\in Dic_{2,4}} T^{\Lambda}_{\mu\mu}(R)^*\, RO$$

$$O^{[J^{PC},|\lambda|]}_{i,\Lambda^C}$$

construction of operators

criteria :

$$\langle O^{[J^{PC},|\lambda|]}_{i,\Lambda^C} | \mathbf{p}, J^{PC}, \lambda\rangle > \langle O^{[J^{PC},|\lambda|]}_{i,\Lambda^C} | \mathbf{p}, J'^{P'C}, \lambda\rangle$$

$$\langle O^{[J^{PC},|\lambda|]}_{i,\Lambda_1^C} | \mathbf{p}, J^{PC}, \lambda\rangle \simeq \langle O^{[J^{PC},|\lambda|]}_{i,\Lambda_2^C} | \mathbf{p}, J^{PC}, \lambda\rangle$$

considering

overlaps of eigenstates

$$\langle O | n \rangle$$

Why these results are valuable ?

$\mathcal{O}: \ \bar{c}c,$

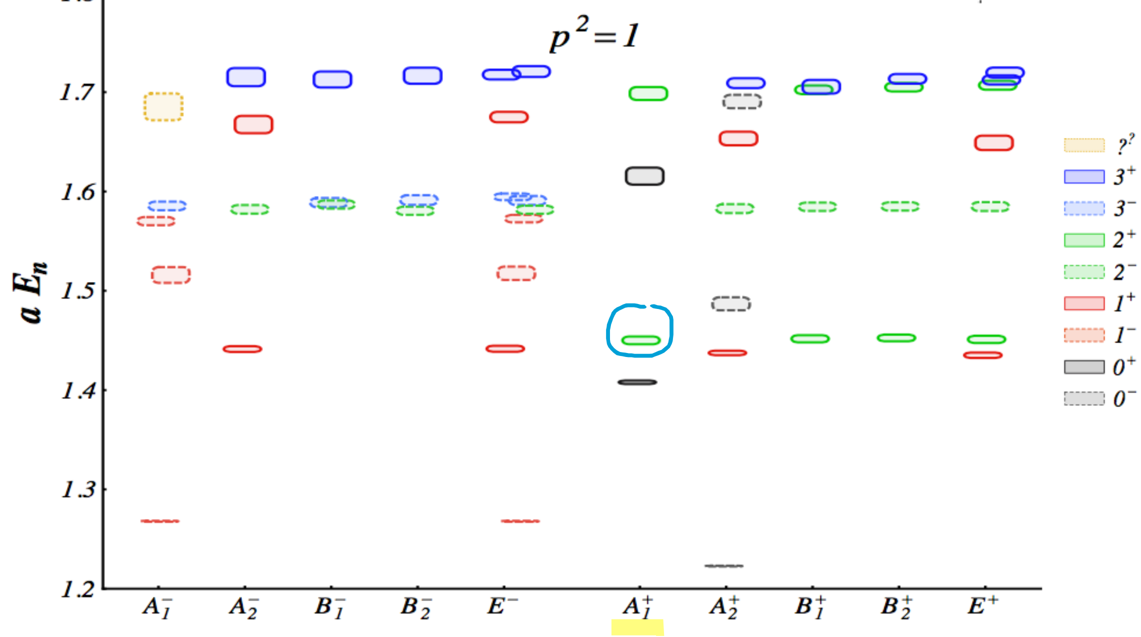
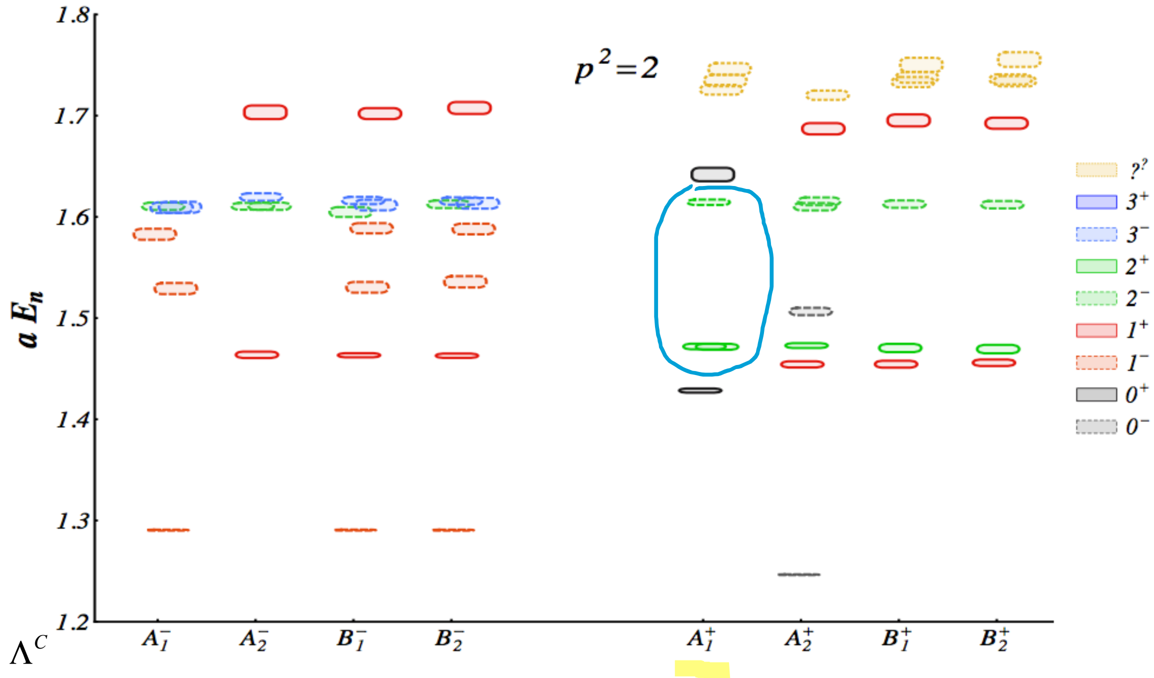
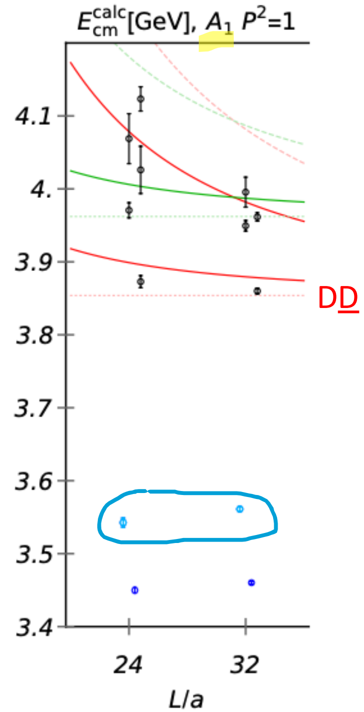


FIG. 11. J^P-identified charmonium spectrum in the moving frame with $\mathbf{p} = (0,0,1)$. Irreps Λ^C of group Dic_4 are presented. The colors indicate J^P of states according to the color-coding (21).

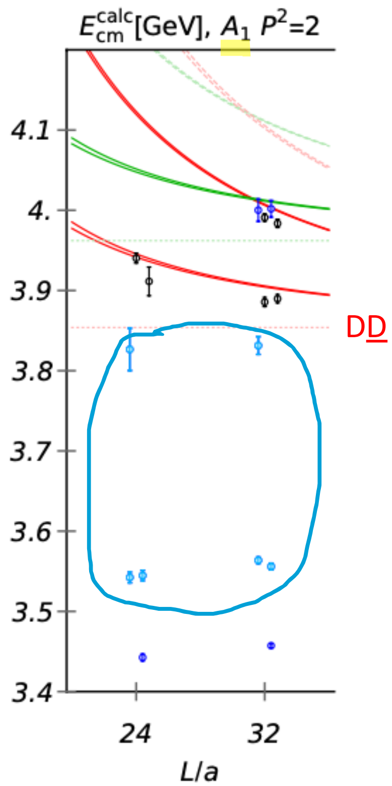




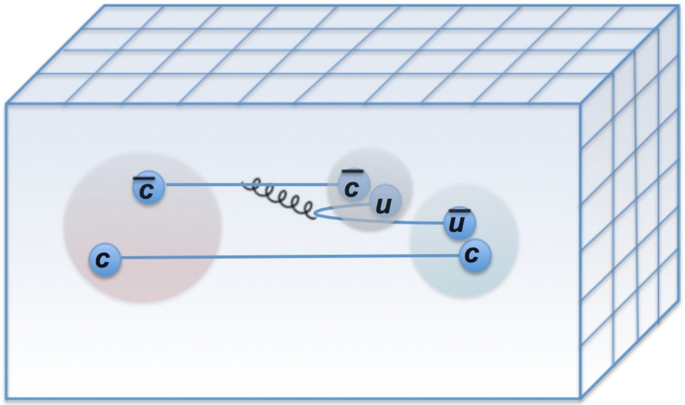
$\mathcal{O}: \ \bar{c}c, \bar{D}D$

En in scat. study

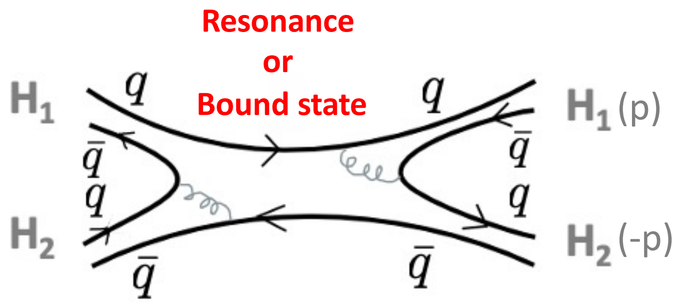
aimed at scalars in A1



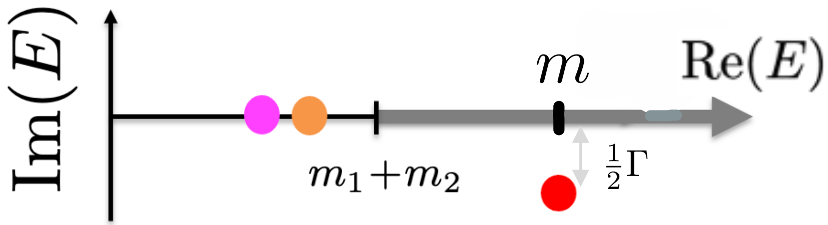
Taking strong decays into account



Extract resonances and (virtual) bound states from H_1 H_2 scattering



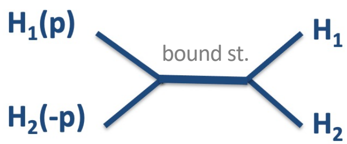
scattering matrix T(E)

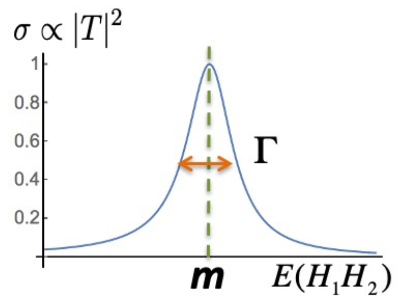


Virtual bound st.	Bound st.	Resonance
p = - i |p|	p = i |p|	

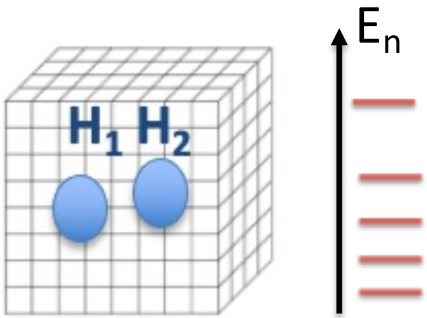
$$T(E) \propto \frac{1}{E^2 - m^2}$$

$$T(E) \propto \frac{1}{E^2 - m^2 + iE\Gamma}$$





Scattering matrix T(E) from lattice QCD



periodic b.c.

real E — for real E — for complex E

$$E \rightarrow T(E) \rightarrow T(E^c)$$

analytic relation: Luscher 1991

analytic contin. to complex E

simple argument: next slide

Relation between E and δ(E) , T(E): 1D quantum mechanics

$$S(E) = e^{2i\delta(E)} = 1 + 2i\,\frac{2p}{E}\,T(E)$$

$$E \to T(E)$$

V≠ 0: outside the region of potential

$E=p^2/2m$

$$\psi(x) = A\cos(p|x|+\delta) = \begin{cases} A\cos(px+\delta) & x>R \\ A\cos(-px+\delta) & x<-\frac{R}{2} \end{cases}$$

- this form already ensures $\psi(L/2) = \psi(-L/2)$
- the other BC: $\psi'(L/2) = \psi'(-L/2)$

  this requires

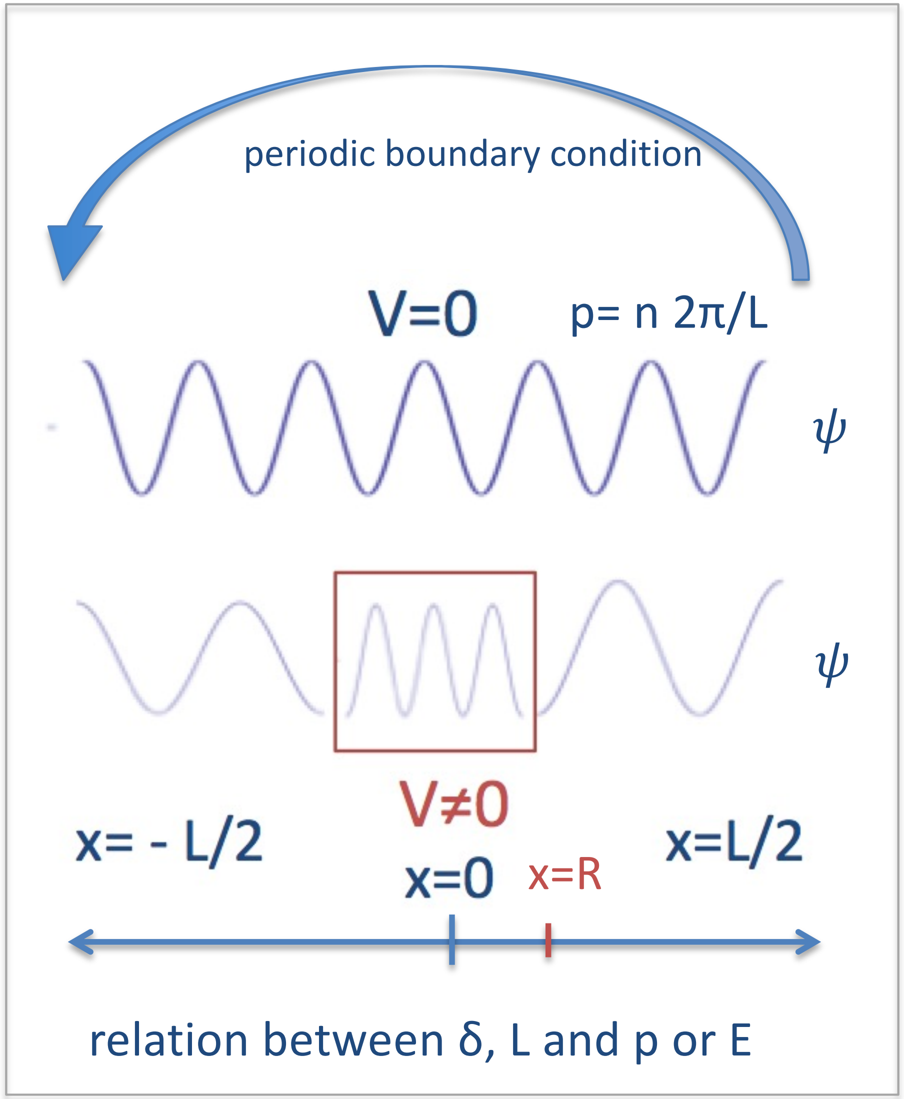
  $$Ap\sin\left(p\left(\tfrac{L}{2}\right)+\delta\right) = -Ap\sin\left(-p\left(-\tfrac{L}{2}\right)+\delta\right)$$

  $$\to \psi'(L/2)=0\ ,\quad \sin\left(p\tfrac{L}{2}+\delta\right)=0$$

$$p\frac{L}{2}+\delta = m\pi \qquad \boxed{p = m\frac{2\pi}{L} - \frac{2}{L}\delta}$$

relation between δ, L

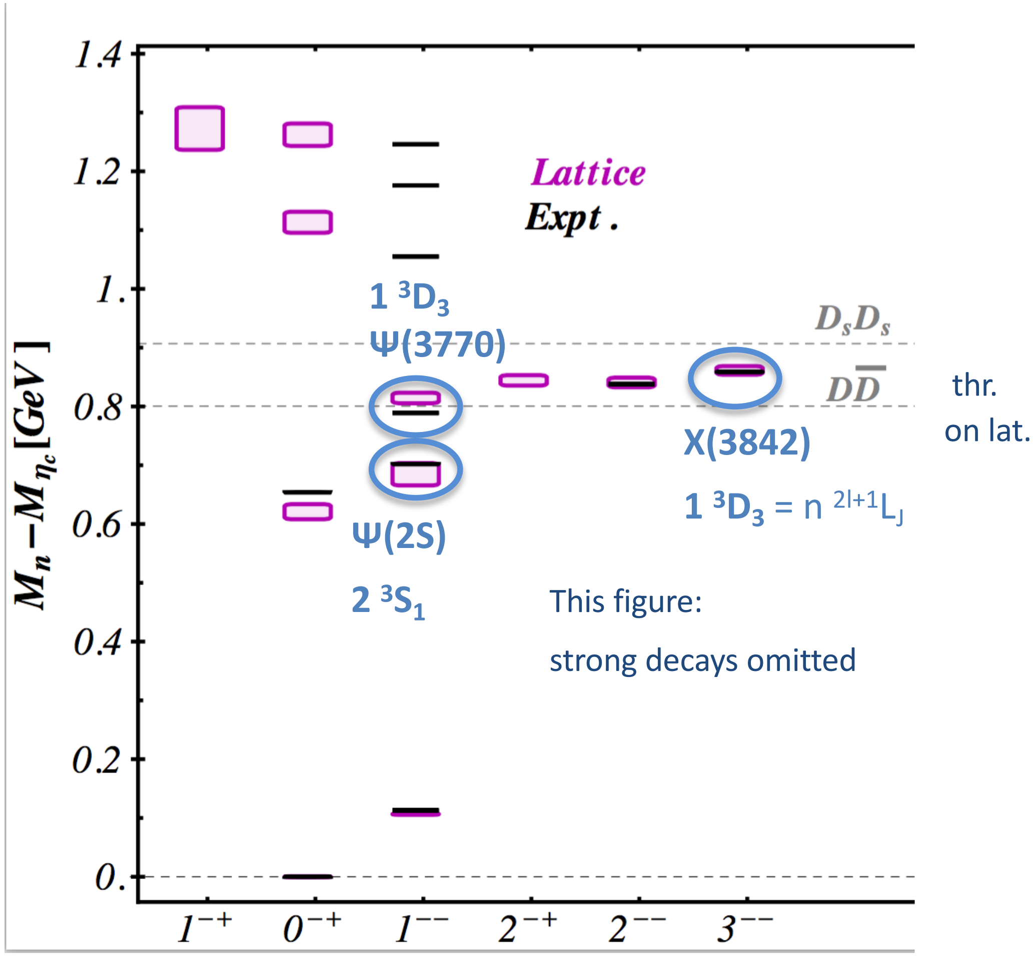
$E=p^2/2m$

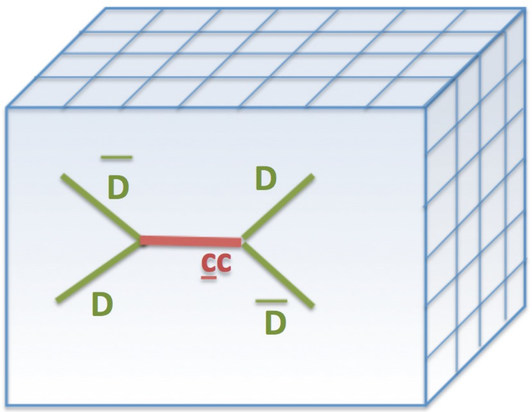


Charmonia with $J^{PC}=1^{--}$ and 3^{--}

from one-channel $\underline{D}D$ scattering

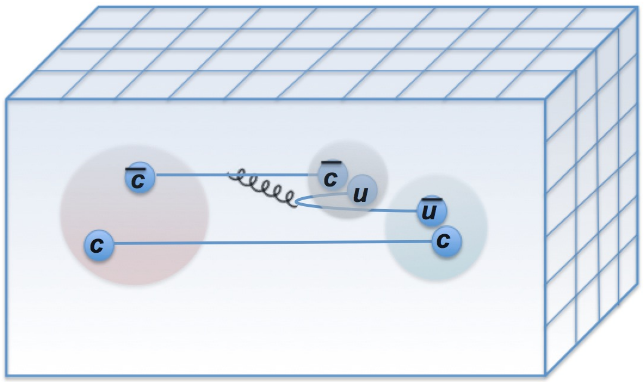
Charmonia with $J^{PC}=1^{--}$ and 3^{--} from one-channel DD scattering



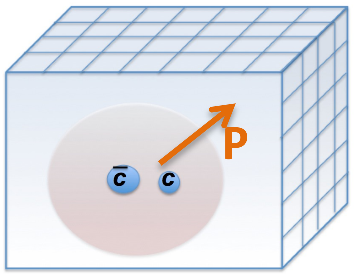


E

strong decay



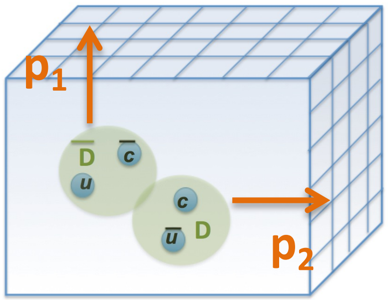
Operators



$$\mathcal{O}^{\bar{c}c} = (\bar{c}\Gamma c)_{\vec{P}}$$

$$\mathcal{O}^{\bar{D}D} = (\bar{c}\Gamma_1 q)_{\vec{p}_1} (\bar{q}\Gamma_2 c)_{\vec{p}_2}$$

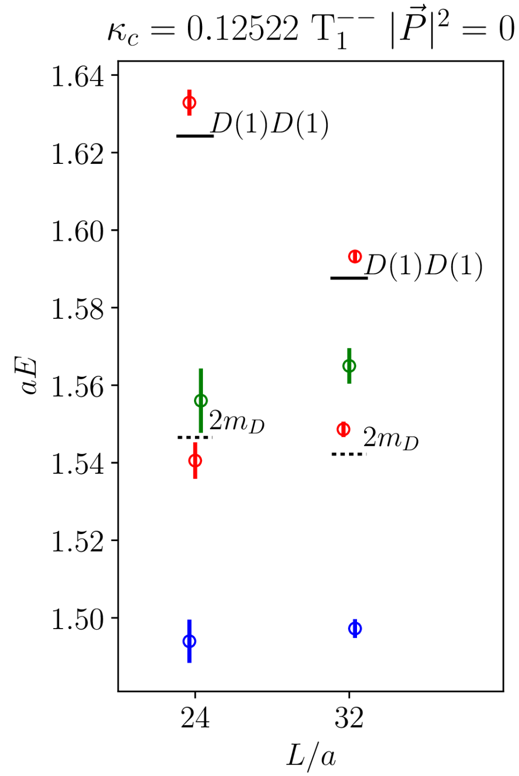
$$= \bar{D}(\vec{p}_1) D(\vec{p}_2)$$

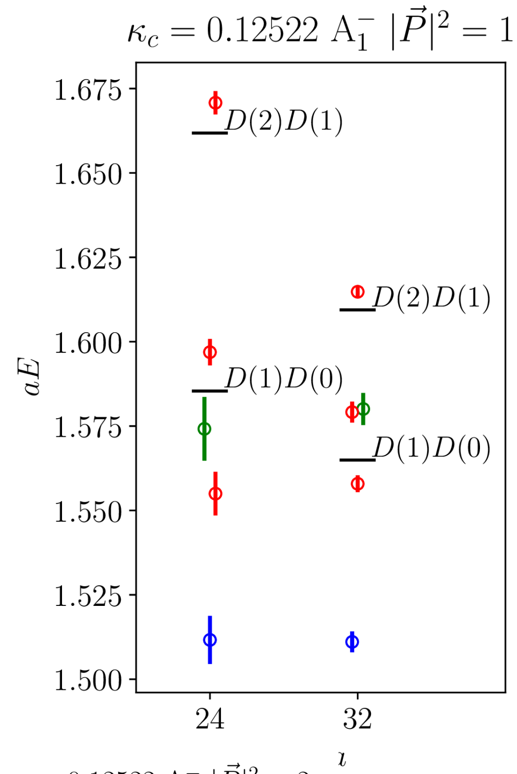


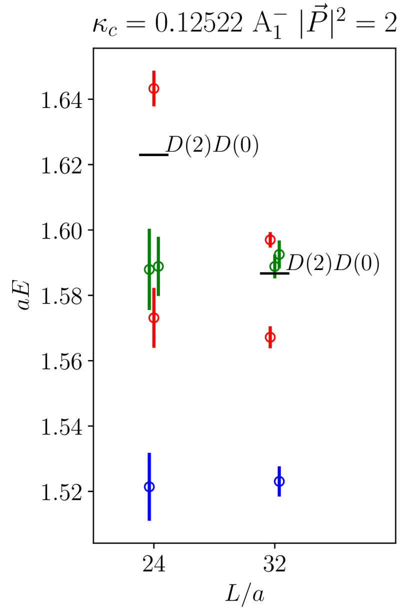
$\vec{P} = \vec{p}_1 + \vec{p}_2$ P: 0
(0,0,1) $2\pi/N_L$
(1,1,0) $2\pi/N_L$

$$C_{ij}(t) = \langle 0 | \mathcal{O}_i(t)\ \mathcal{O}_j^{+}(0) | 0 \rangle = \sum_n Z_i^n\ Z_j^{n*}\ e^{-E_n t}$$

Eigen-energies E_n





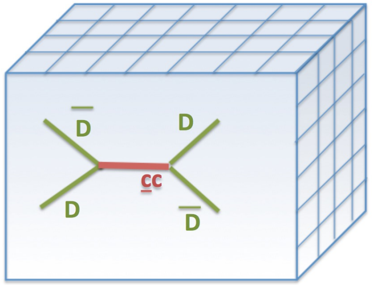


Plots for

$m_D \approx 1762$ MeV

Charmonia with $J^{PC}=1^{--}$ and 3^{--} from one-channel $D\bar{D}$ scattering

l=1 and $m_D \approx 1762$ MeV



p = D-meson momentum in CMF

$$\frac{p^{2l+1}\cot(\delta_l)}{\sqrt{s}} = \frac{m^2 - s}{G^2}$$ Breit Wigner

Ψ(2S) Ψ(3770)

l=1 $$\frac{p^3\cot(\delta_1)}{\sqrt{s}} = \left(\frac{G_1^2}{m_1^2 - s} + \frac{G_2^2}{m_2^2 - s}\right)^{-1}$$

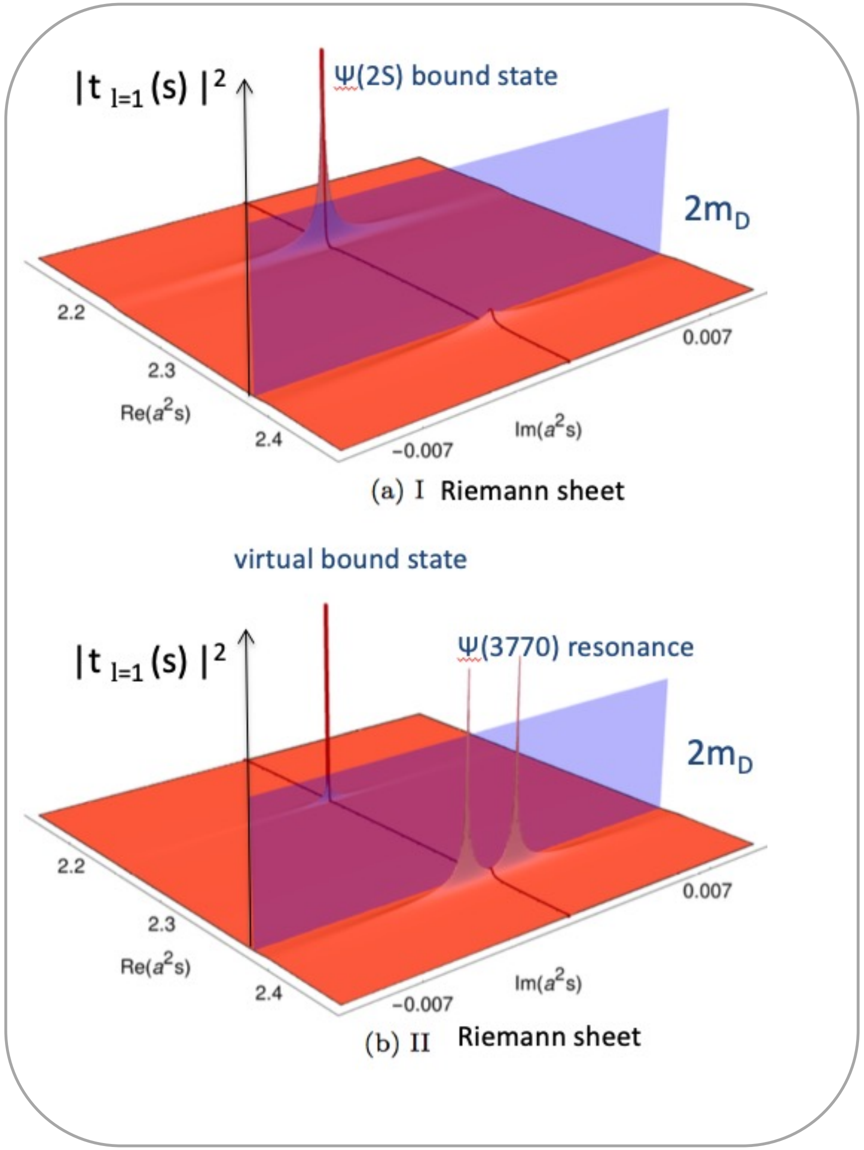
l=3 $$\frac{p^7\cot(\delta_3)}{\sqrt{s}} = \frac{m_3^2 - s}{g_3^2}$$

X(3842)

$$\Gamma = \frac{g^2}{6\pi}\frac{p^3}{s}$$

Ψ(3770)

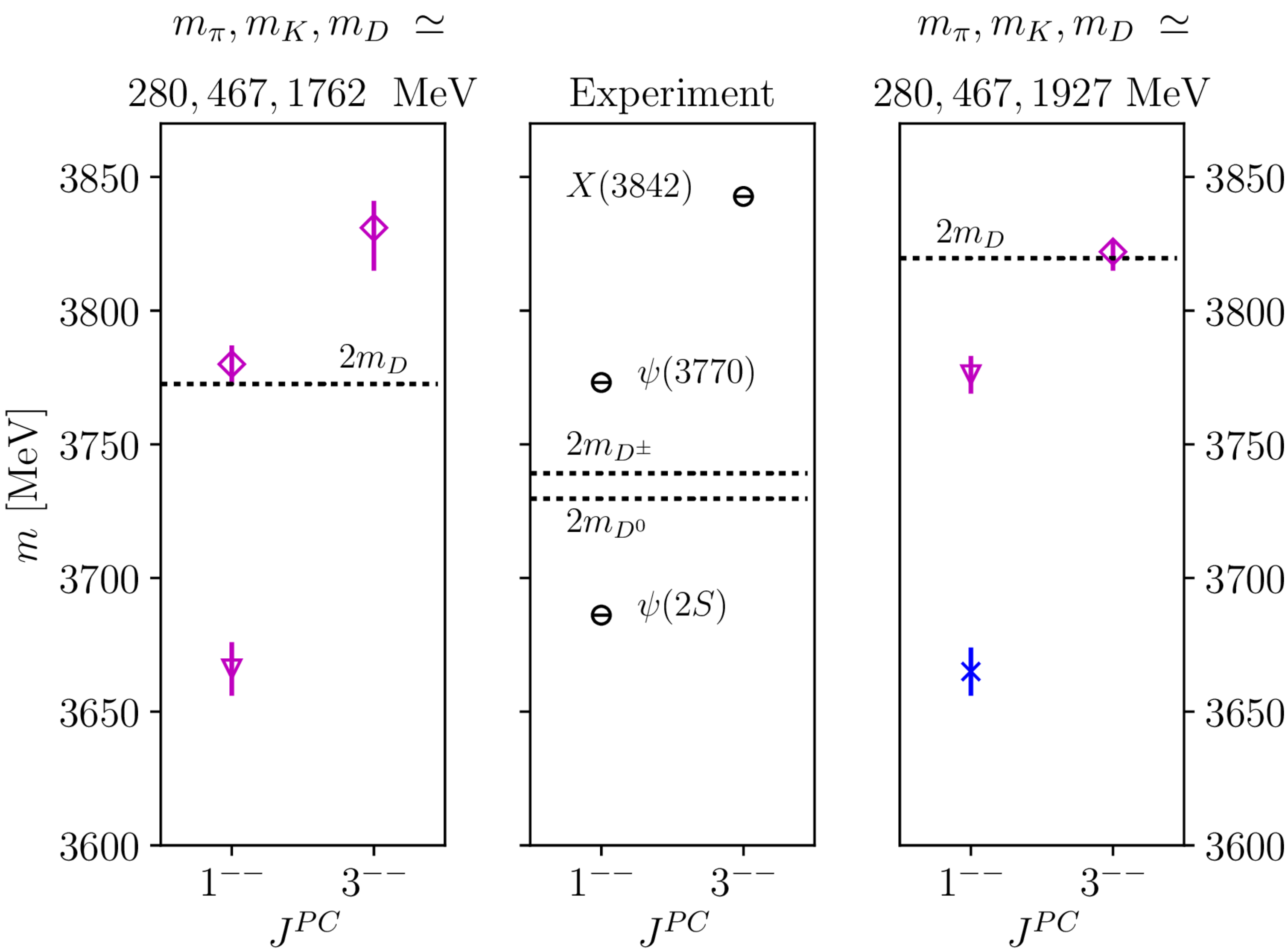
	g
lat	$16.0^{+2.1}_{-0.2}$
exp	18.7 ± 0.9



Masses of charmonium resonances and bound states

$$M_{\rm av} = \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$$

$$m = m^{\rm lat} - M_{\rm av}^{\rm lat} + M_{\rm av}^{\rm exp}$$

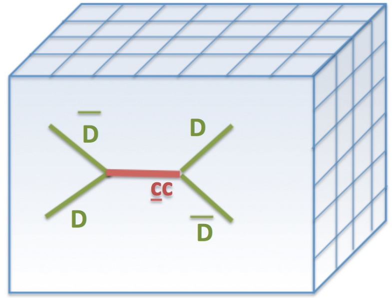


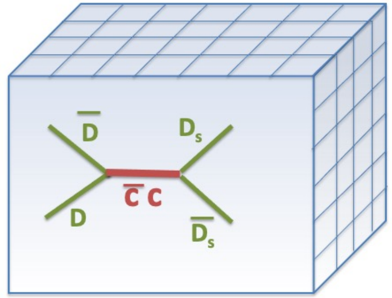
Charmonium(like) states with $J^{PC}=0^{++}$ and 2^{++}

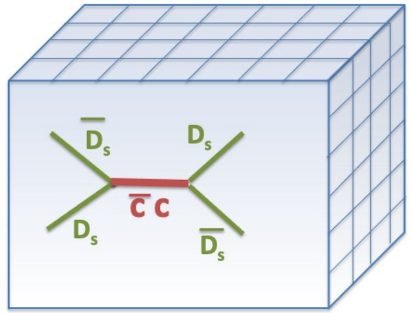
from coupled-channel scattering $D\bar{D} - D_s\bar{D}_s$

the only available coupled-channel study for charmonia with I=0

Charmonia with $J^{PC}=0^{++}$ and 2^{++}
from coupled-channel scattering $D\bar{D} - D_s\bar{D}_s$

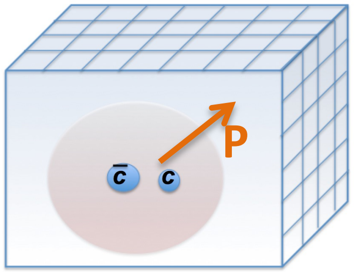




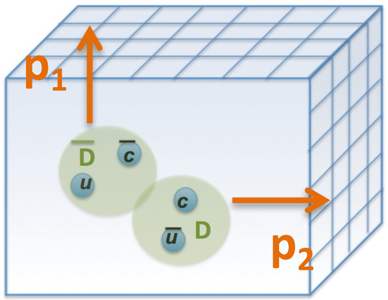


Operators

$$\mathcal{O}^{\bar{c}c} = (\bar{c}\Gamma c)_{\vec{P}}$$



$$\mathcal{O}^{\bar{D}D} = (\bar{c}\Gamma_1 q)_{\vec{p}_1} (\bar{q}\Gamma_2 c)_{\vec{p}_2} = \bar{D}(\vec{p}_1) D(\vec{p}_2)$$



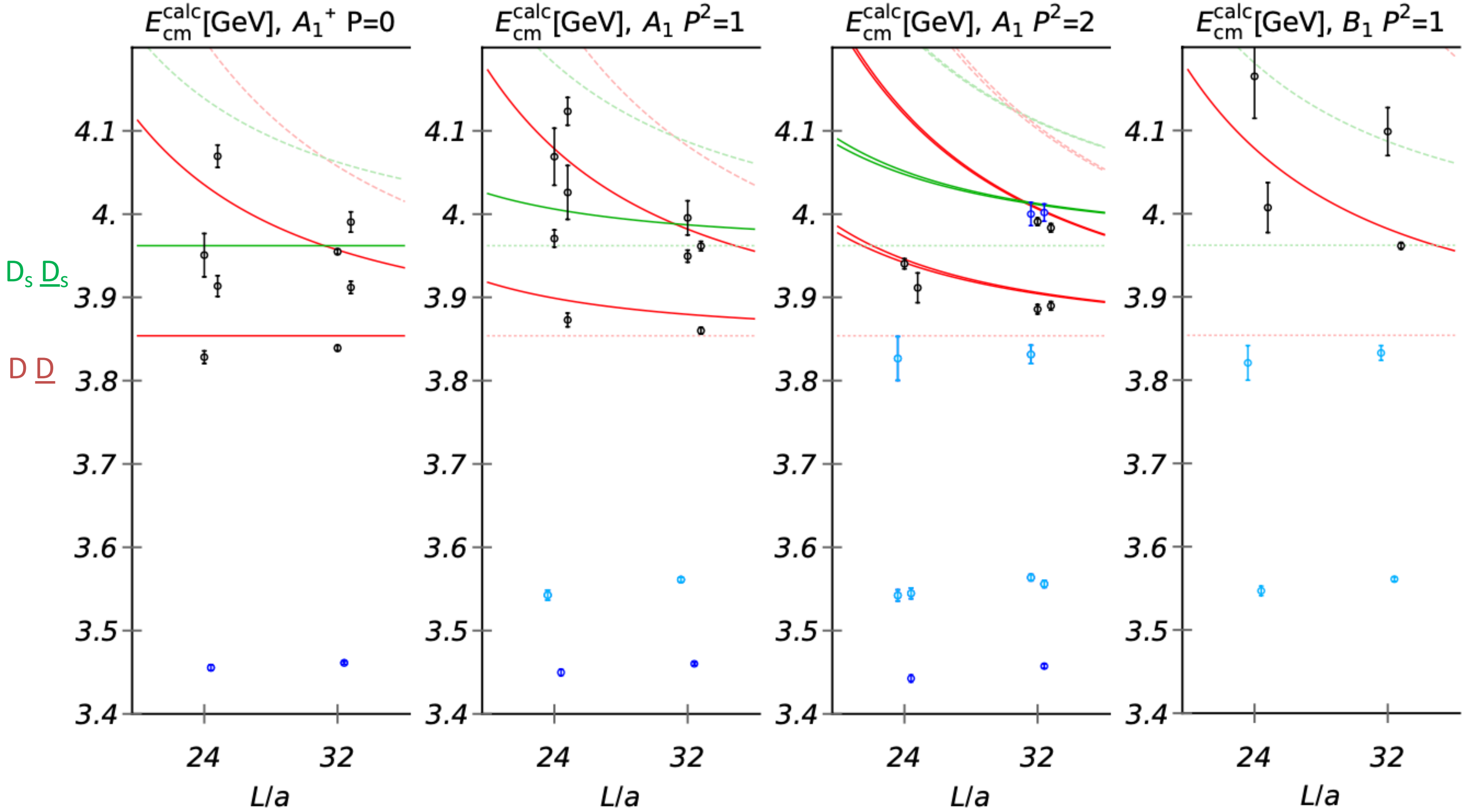
$$\mathcal{O}^{\bar{D}_s D_s} = (\bar{c}\Gamma_1 s)_{\vec{p}_1} (\bar{s}\Gamma_2 c)_{\vec{p}_2} = \bar{D}_s(\vec{p}_1) D_s(\vec{p}_2)$$

$\vec{P} = \vec{p}_1 + \vec{p}_2$

P: 0
(0,0,1) $2\pi/N_L$
(1,1,0) $2\pi/N_L$

NL=24,32

Energies of eigen-states E_n in irreps that contain $J^{PC}=0^{++}, 2^{++}$



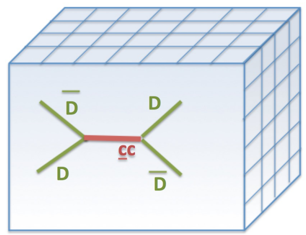
non-interacting energies denoted

D $\underline{D}$

D_s $\underline{D}_s$

$J^{PC}=0^{++}$

$J^{PC}=2^{++}, 2^{-+}$



$E \not\rightarrow t(E)$

$$S_{ij}(E_{cm}) = 1 + 2i\ \rho\ t_{ij}(E_{cm})$$

Extraction of matrix t(E) : NOT straightforward !

$$t(E_{cm}) = \begin{vmatrix} t_{11}(E_{cm}) & t_{12}(E_{cm}) \\ t_{12}(E_{cm}) & t_{22}(E_{cm}) \end{vmatrix}$$

1: $\underline{D}$D, 2: $\underline{D}$sDs

$$det[1 + i\ t(E_{cm})\ F(E_{cm})] = 0$$

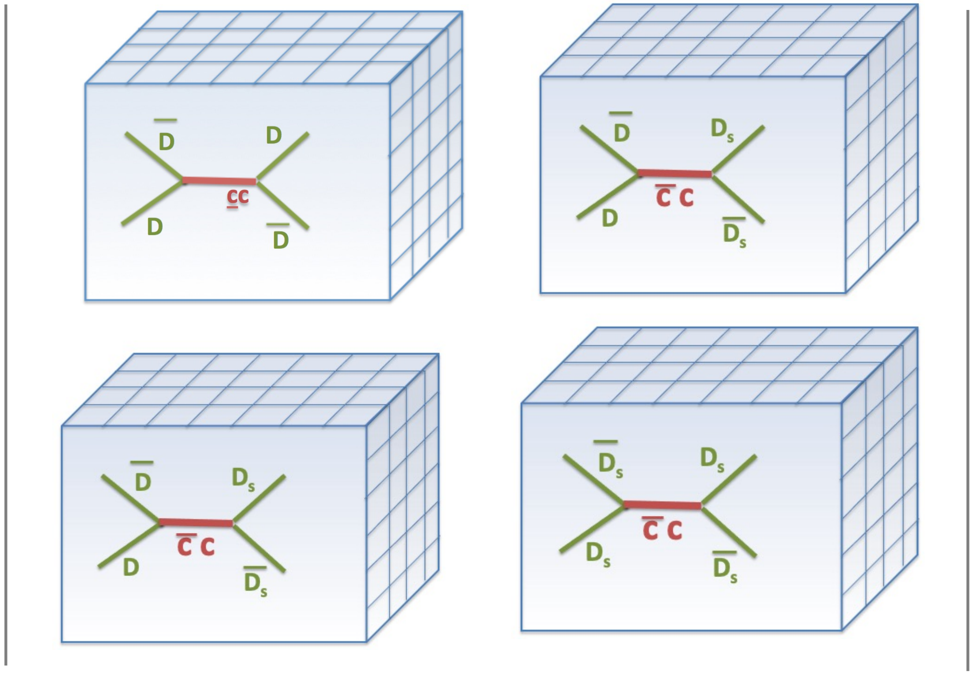
known 2x2 matrix

one equation, three unknowns (at each E_{cm})

$$(t^{-1})_{ij} = \frac{2}{E_{cm}\ p_i^l p_i^l}\ (\tilde{K}^{-1})_{ij} - i\ \rho_i\ \delta_{ij} \qquad \frac{\tilde{K}^{-1}_{ij}(s)}{\sqrt{s}} = a_{ij} + b_{ij} s$$

$$\rho_i \equiv 2p_i/E_{cm} \qquad s = E^2_{cm}$$

Challenge: determine coupled-channel scattering matrix



1: DD, 2: DsDs

$$t(E_{cm}) = \begin{vmatrix} t_{11}(E_{cm}) & t_{12}(E_{cm}) \\ t_{12}(E_{cm}) & t_{22}(E_{cm}) \end{vmatrix}$$

Challenge: parametrization of scattering matrix

$\rho_i \equiv 2p_i/E_{cm}$

$s = E_{cm}^2$

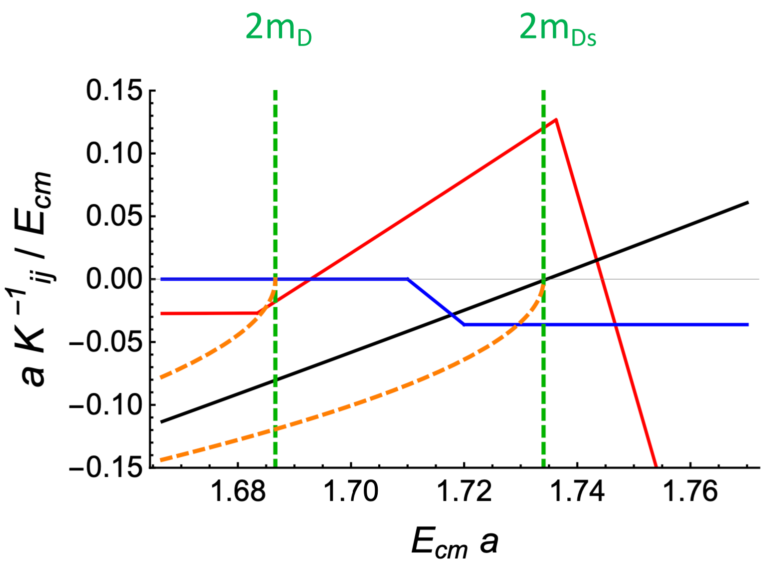
$$t(E_{cm}) = \begin{vmatrix} t_{11}(E_{cm}) & t_{12}(E_{cm}) \\ t_{12}(E_{cm}) & t_{22}(E_{cm}) \end{vmatrix}$$

$$(t^{-1})_{ij} = \frac{2}{E_{cm}\, p_i^l p_j^l} (\tilde{K}^{-1})_{ij} - i\, \rho_i\, \delta_{ij}$$

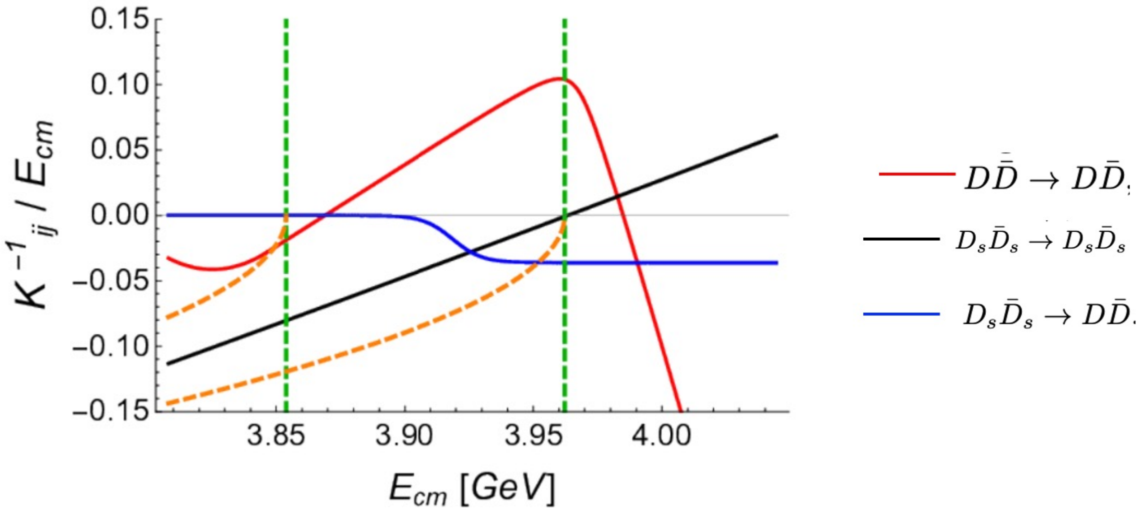
$$\frac{\tilde{K}_{ij}^{-1}(s)}{\sqrt{s}} = a_{ij} + b_{ij} s$$

linear parametrization

for low and high energy regions

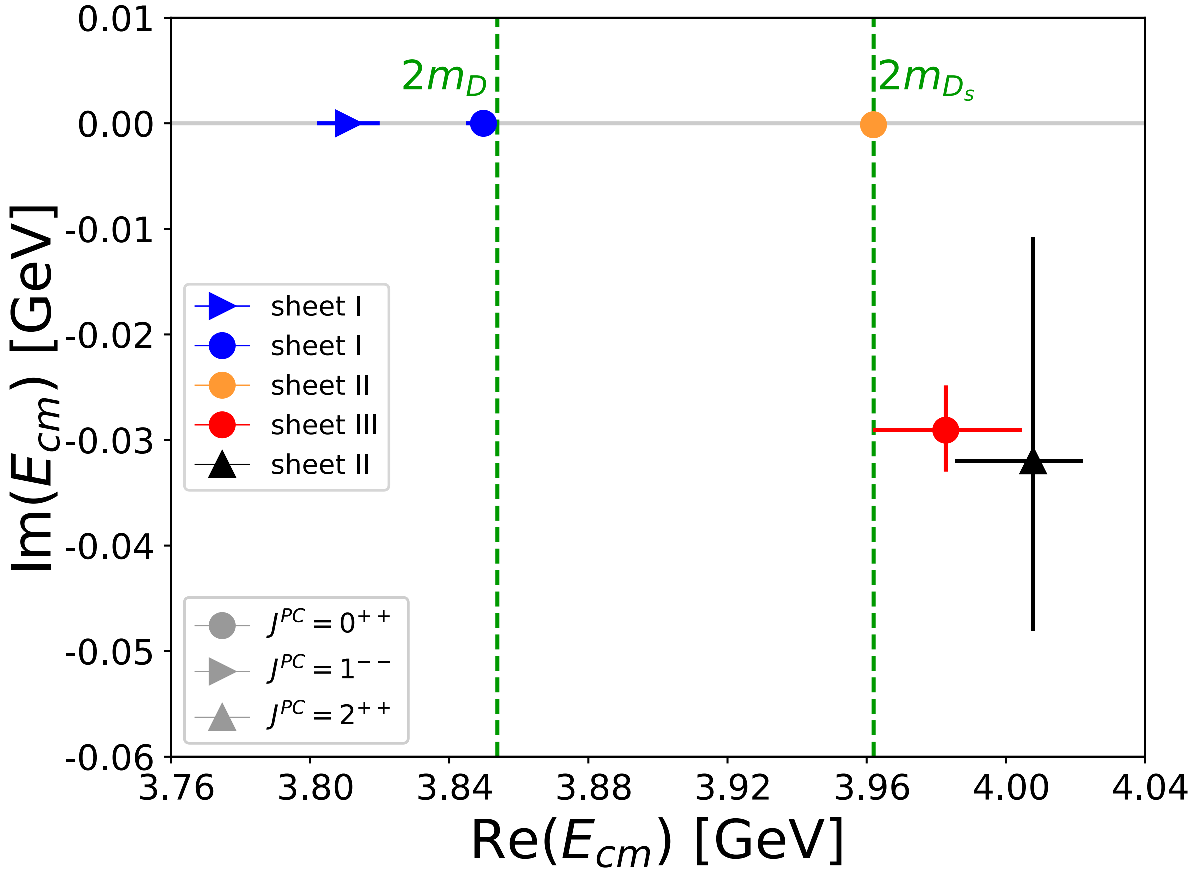


"gluing" via hyperbolas



Poles of the scattering amplitude $D\bar{D} - D_s\bar{D}_s$

$\bar{c}c$, $\bar{c}q\bar{q}c$ q=u,d,s $I=0$

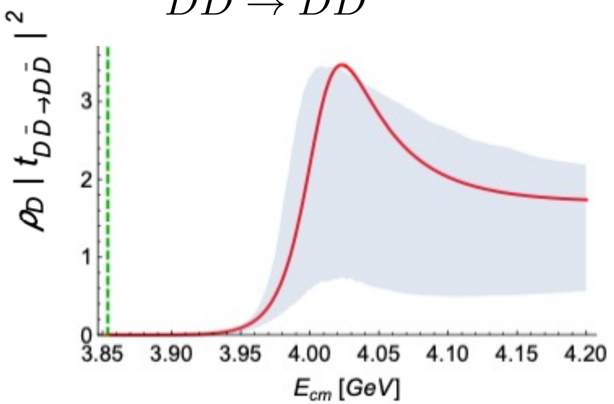


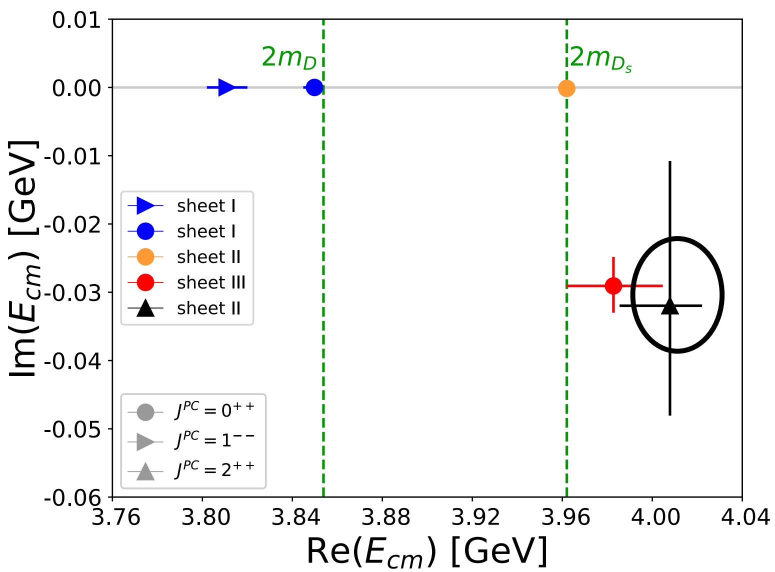
$$\text{sheet I}: \ \text{Im}(\rho_D) > 0, \text{Im}(\rho_{D_s}) > 0\,, \quad \text{sheet II}: \ \text{Im}(\rho_D) < 0, \text{Im}(\rho_{D_s}) > 0\,, \quad (\rho_i = 2p_i/E_{\rm cm})$$
$$\text{sheet III}: \ \text{Im}(\rho_D) < 0, \text{Im}(\rho_{D_s}) < 0\,, \quad \text{sheet IV}: \ \text{Im}(\rho_D) > 0, \text{Im}(\rho_{D_s}) < 0\,.$$

$J^{PC}=2^{++}$: conventional resonance

D-wave (L=2, $J^{PC}=2^{++}$)

$D\bar{D} \to D\bar{D}$





- 2++ resonance

$$\Gamma \equiv g^2 p_D^{2l+1}/m^2$$

$$lat: m = 3973^{+14}_{-22}\ MeV \quad g = 4.5^{+0.7}_{-1.5}\ GeV^{-1}$$

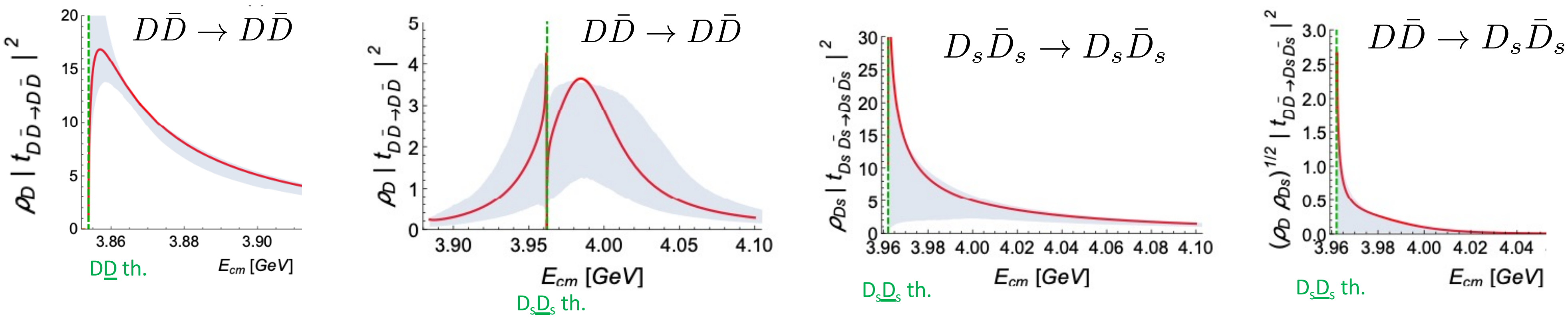
$$\chi_{c2}(3930): m = 3923 \pm 1\ \mathrm{MeV} \quad g = 2.65 \pm 0.12\ \mathrm{GeV}^{-1}$$

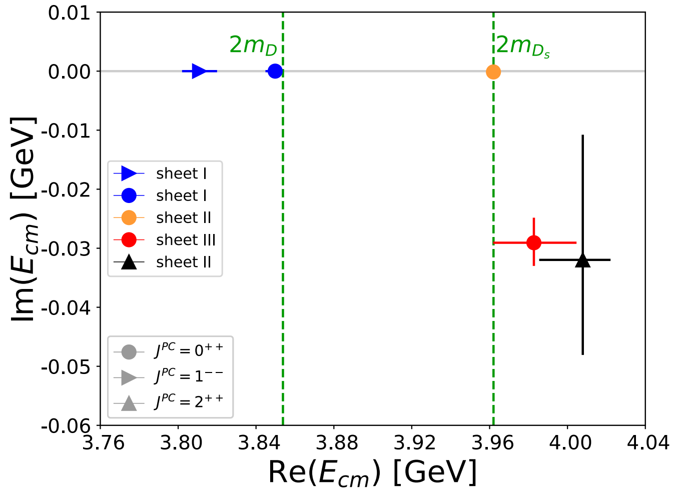
PDG

$J^{PC}=0^{++}$: some expected and unexpected states found

$$D\bar{D} - D_s\bar{D}_s$$

S-wave (L=0, $J^{PC}=0^{++}$)





near pole $$t_{ij} \sim \frac{c_i\ c_j}{(E^p_{cm})^2 - E^2_{cm}}$$

- broad resonance coupling mostly to DD

candidate for $\chi_{c0}(2P)$

$$lat: m = 3949^{+28}_{-20}\ MeV \quad g = 1.35^{+0.04}_{-0.08}\ GeV$$

$$X(3860): m = 3862^{+48}_{-35}\ MeV \quad g = 2.5^{+1.2}_{-0.9}\ GeV$$

Belle 2017

$$\Gamma \equiv g^2 p_D^{2l+1}/m^2$$

- state near D_sD_s threshold coupling mostly to D_sD_s

$$\frac{|c^2_{D\bar D}|}{|c^2_{D_s\bar D_s}|} = 0.02\ {}^{+0.02}_{-0.01}$$

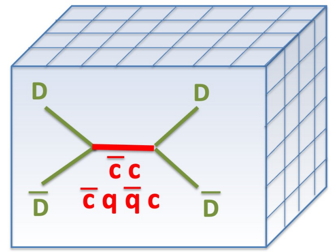
lat $: m - 2m_{D_s} = -0.2\ {}^{+0.16}_{-4.9}\ \mathrm{MeV}\ , \quad g = 0.10\ {}^{+0.21}_{-0.03}\ \mathrm{GeV}$

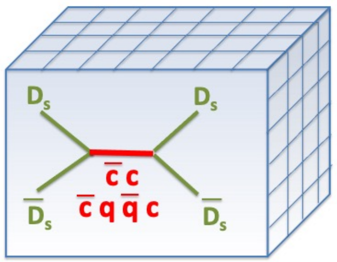
- state near DD threshold

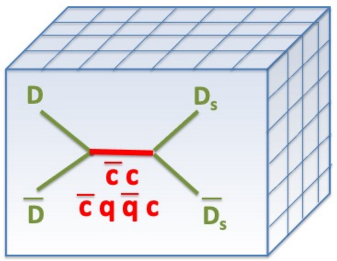
Charmonium(like) states: poles and masses

$$\frac{|c^2_{D\bar{D}}|}{|c^2_{D_s\bar{D}_s}|} = 0.02\ ^{+0.02}_{-0.01}$$

$$T_{ij}(E_{cm}) \sim \frac{c_i\ c_j}{E^2_{cm} - m^2}$$

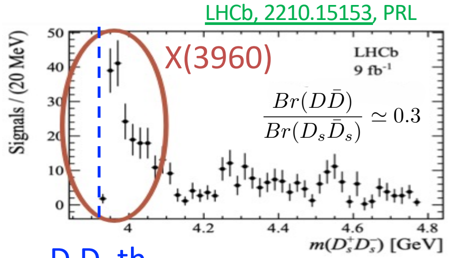






$\bar{D}D - \bar{D}_sD_s$

$\bar{D}_sD_s$ $J^P=0^+$ state



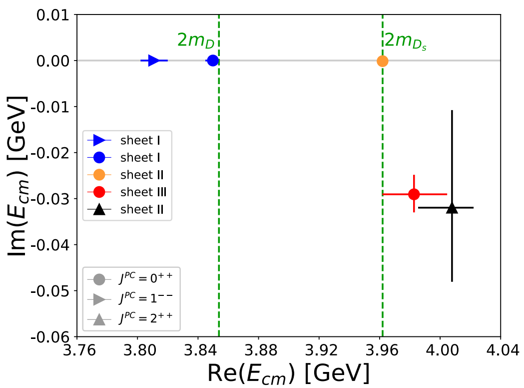
D_sD_s th.

$\bar{D}D$ $J^P=0^+$ state

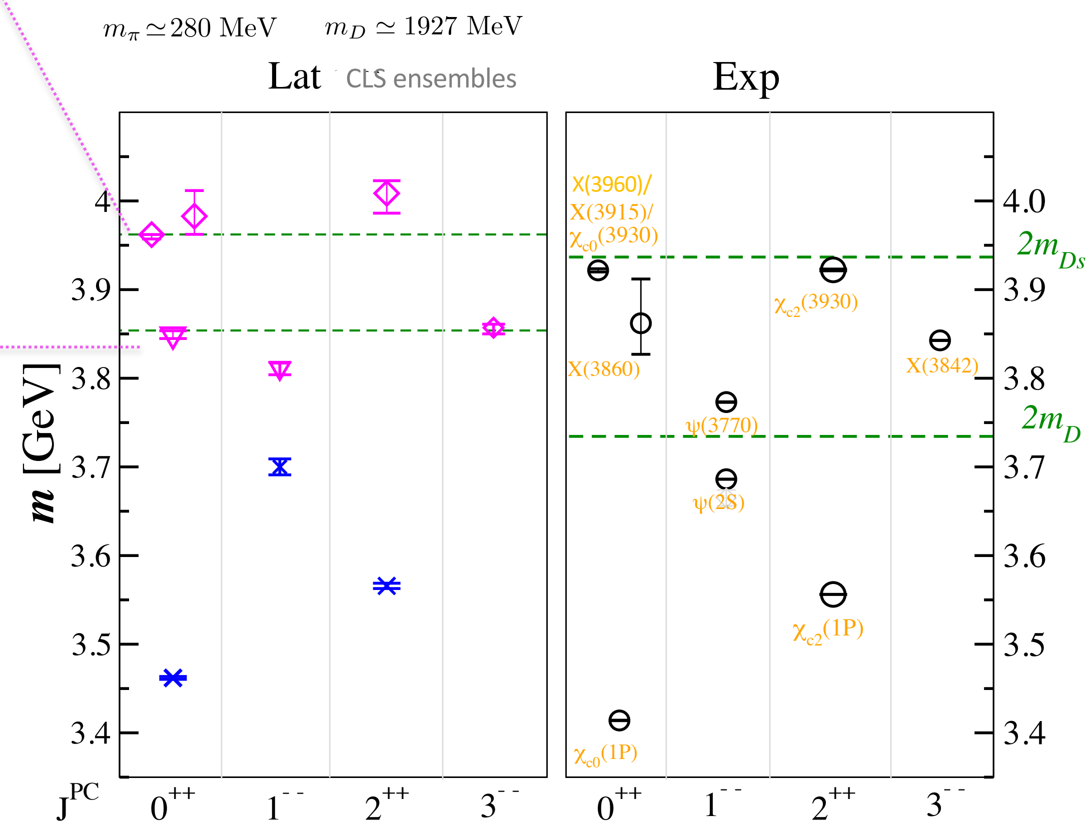
predicted in models [Oset et al, 0612179 PRD, Guo et al 2101.01021]

seen in re-analysis of exp. [Danilkin et al 2111.15033, Ji, F.K. Guo et al., 2212.00613]

+ expected conventional charmonia

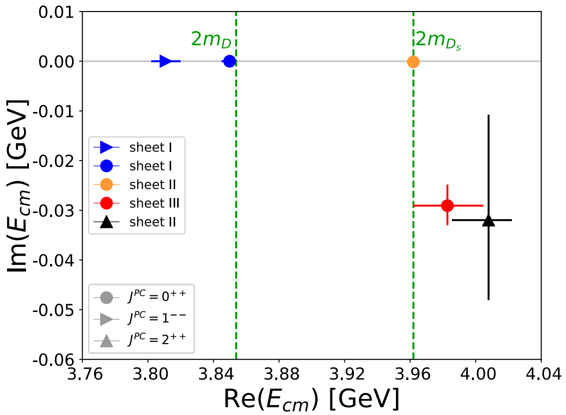


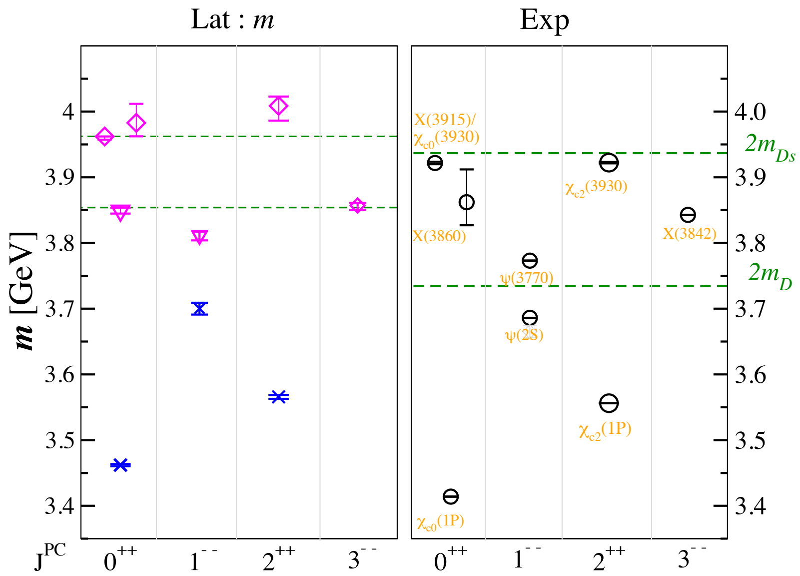
$\bar{c}c$, $\bar{c}q\bar{q}c$ q=u,d,s $I=0$



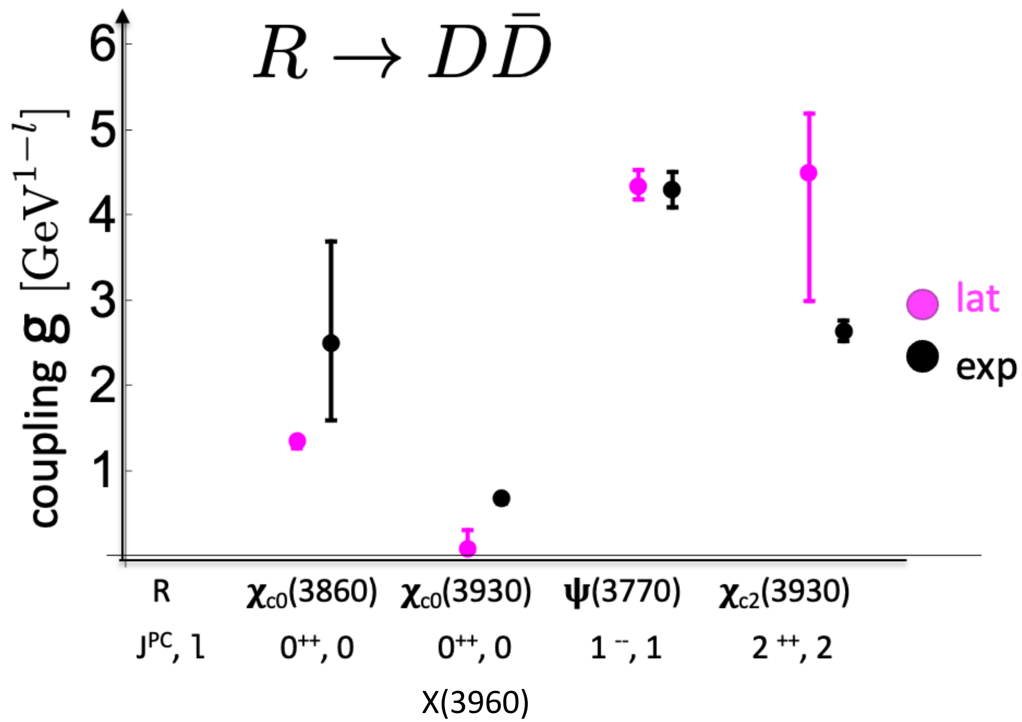
Charmonium(like) resonances and bound states

Charmonium(like) states: widths and masses





$$\Gamma \equiv g^2 \, \frac{p_D^{2l+1}}{m^2}$$



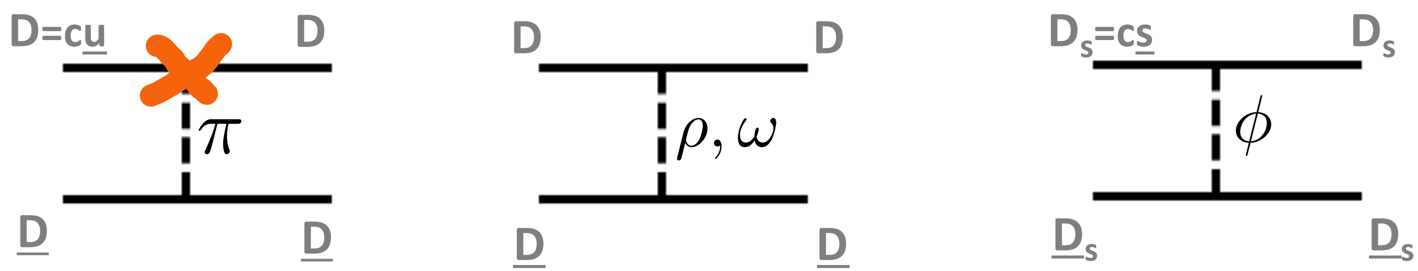
Possible interpretation of some near-threshold states:

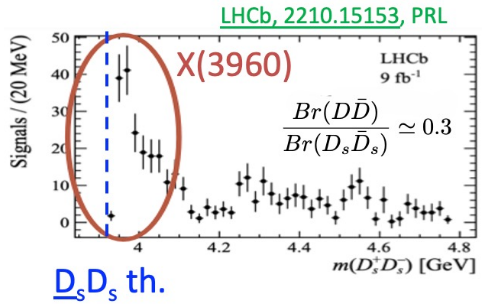
"molecules" attracted by V exchange

a number of pheno studies
Oset et al, 0612179 PRD,
Wu, Molina, Oset, Zou, 1007.0573, PRL
Guo et al, 2101.01021,...

$\bar{c}q\bar{q}c$ $I=0$ $J^P=0^+$

$\bar{D}D$ $\bar{D}_sD_s$

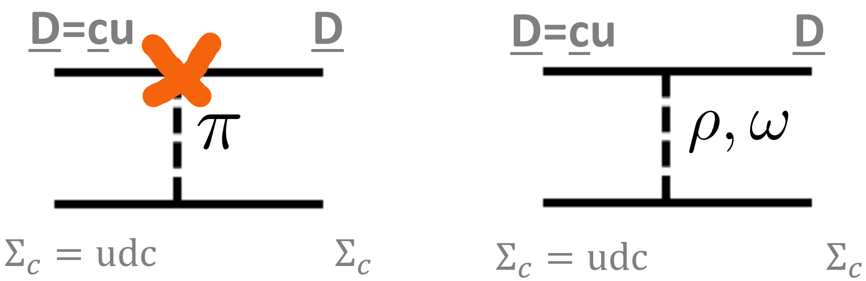


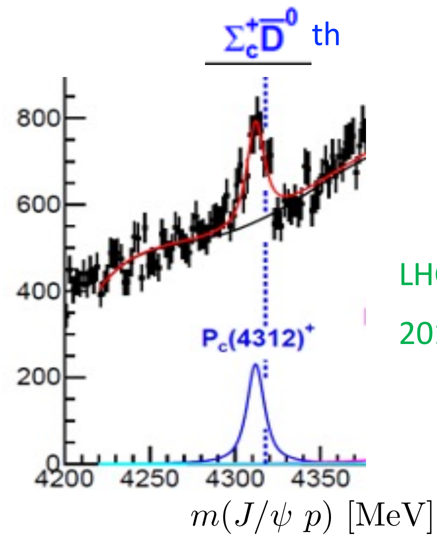


now support also from lattice

$c\bar{c}uud$

$\bar{D}\Sigma_c$





LHCb
2019

currently to challenging for lattice

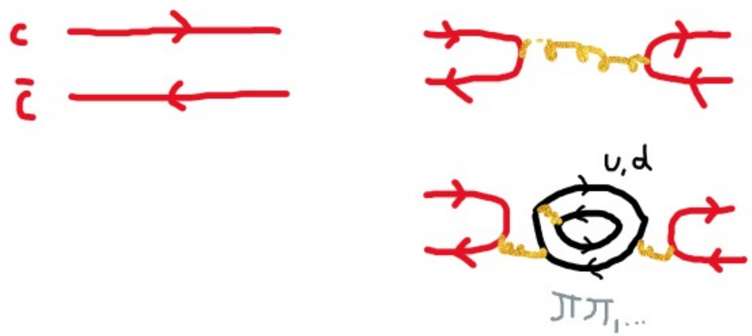
Challenges, caveats, ...

see: Assumptions and simplifications (Section 5, 2011.02542, JHEP 2021)

- caveat: lattice simulation at unphysical quark masses and single lattice spacing

- further channels:
  - incorporated with interpolators, treated as decoupled: $J/\psi\ \omega, \quad D^*\bar{D}^*$
  - omitted $\eta_c\ \eta$

- charm annihilation omitted



Instead of conclusions

$\bar{c}c$, $\bar{c}c\bar{q}q$ $(\bar{q}q = \bar{u}u + \bar{d}d,\ \bar{s}s)$ $I = 0$ this talk

---

$\bar{c}c\bar{d}u$ $I = 1$

further exciting studies with Regensburg group

$cc\bar{d}\bar{u}$

....

Thanks to prof. Andreas Schafer for

involvement, support, effort, patience, enthusiasm, ... !

Backup

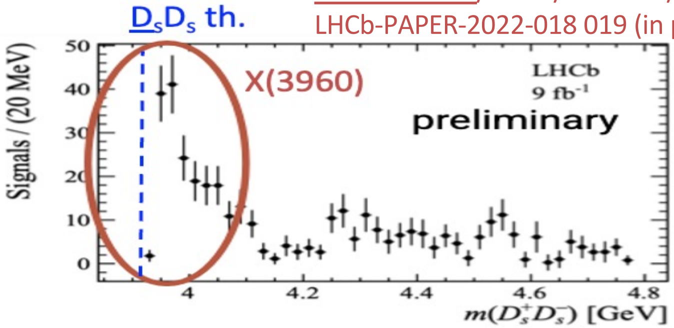
$J^{PC}=0^{++}$ $\bar{c}s\bar{s}c$ likely related to X(3915) / χ_{c0}(3930) / X(3960)

lat: $\frac{|c^2_{D\bar{D}}|}{|c^2_{D_s\bar{D}_s}|} = 0.02 \, ^{+0.02}_{-0.01}$

all three likely the same state
currently named χ_{c0}(3914) in PDG

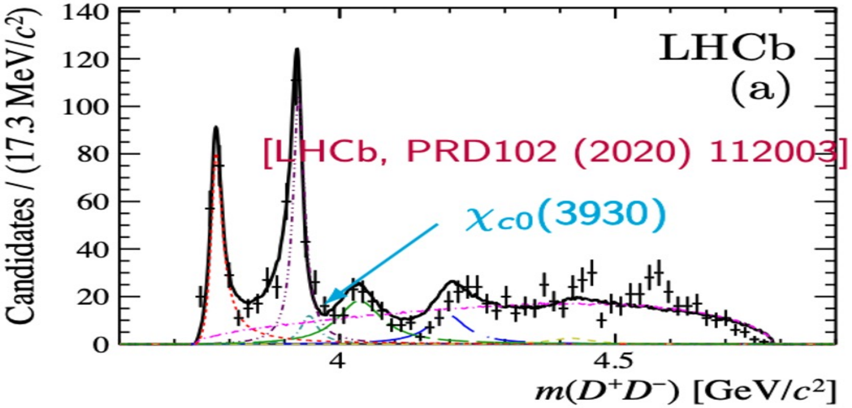
indico.cern.ch/event/1176505/ july 2022
LHCb-PAPER-2022-018 019 (in preparation)

talk by
Chen Chen
today

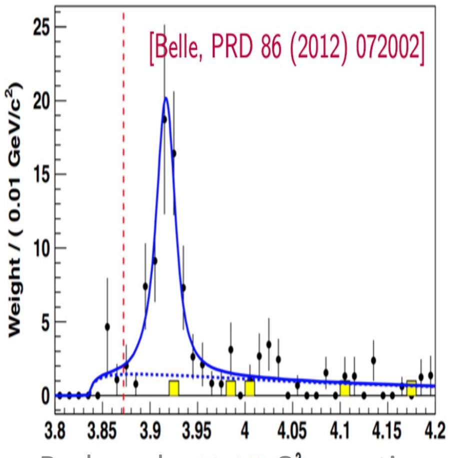


$$X(3960) \to D_s\bar{D}_s$$

$$\text{exp: } \frac{Br(D\bar{D})}{Br(D_s\bar{D}_s)} \simeq 0.3$$



$$\chi_{c0}(3930) \to D\bar{D}$$



$$X(3915) \to J/\psi \; \omega$$

$$(\Delta E^{\mathrm{lat}}) = (E^{\mathrm{lat}}) - (E^{\mathrm{lat}}_{H_1(\vec{p}_1)}) - (E^{\mathrm{lat}}_{H_2(\vec{p}_2)}) \ ,$$

$$(E^{\mathrm{calc}}) = (\Delta E^{\mathrm{lat}}) + \left(E^{\mathrm{cont}}_{H_1(\vec{p}_1)}\right) + \left(E^{\mathrm{cont}}_{H_2(\vec{p}_2)}\right)$$