Charmonium resonances (from lattice QCD)

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Torino, 13-17 May 2019

M. Padmanath, S. Collins, D. Mohler, S. Piemonte, S.P., A. Schafer, S. Weishaeupl : 1811.04116, PRD 2019

S. Piemonte, S. Collins, M. Padmanath, D. Mohler, S.P. : 1905.03506

Regensburg collaboration RQCD (mostly)

Outline

Lattice QCD study of

- Ground and excited conventional charmonia

- charmonia with all J^{PC} ($J \leq 3$), momenta P=0 and P≠0

  omitting strong decays

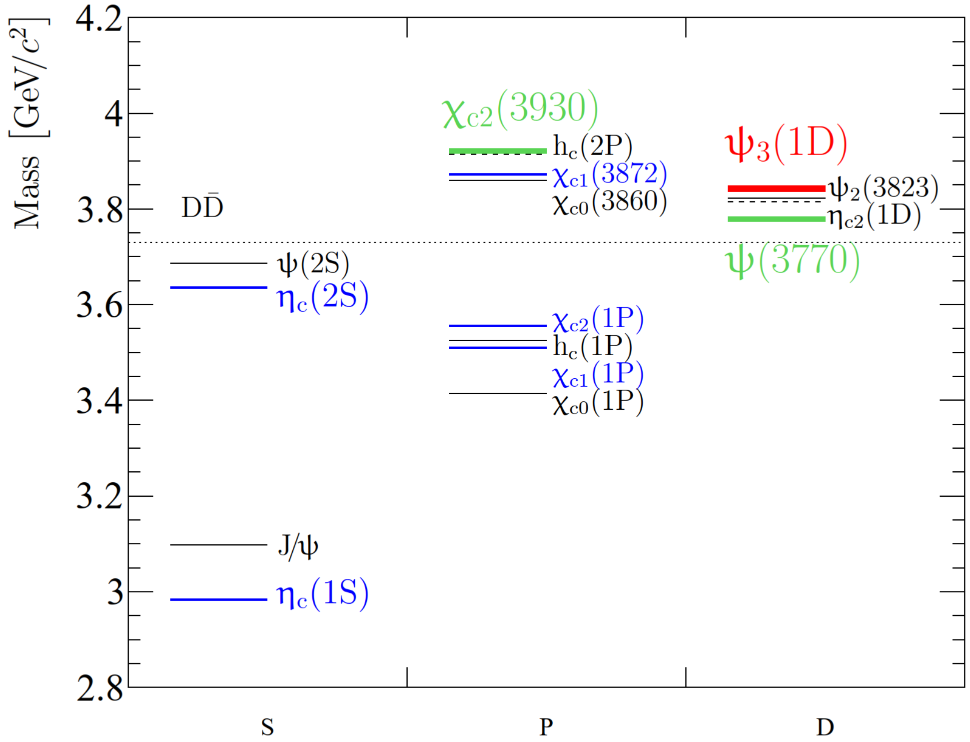
  determine : m or E, J^{PC}

- charmonium resonances with $J^{PC} = 1^{--}$ [Ψ(3770)] and 3^{--} [X(3842)],

  taking strong decays to DD into account (applying Luscher's method)

  determine: m and Γ , J^{PC}

- Very briefly on exotic quarkonium-like channels:
- pentquark P_c channel
- tetraquark Z_b channel



aken from
/lhcb-public.web.cern.ch/lhcb-public

Conventional charmonia
below and above open-charm threshold DD

One of the motivations for lattice QCD study:

Verify lattice QCD treatment of conventional charmonia

Only then apply analogous treatment for more challenging charmonium-like states

First discovery of a charmonium with spin J=3

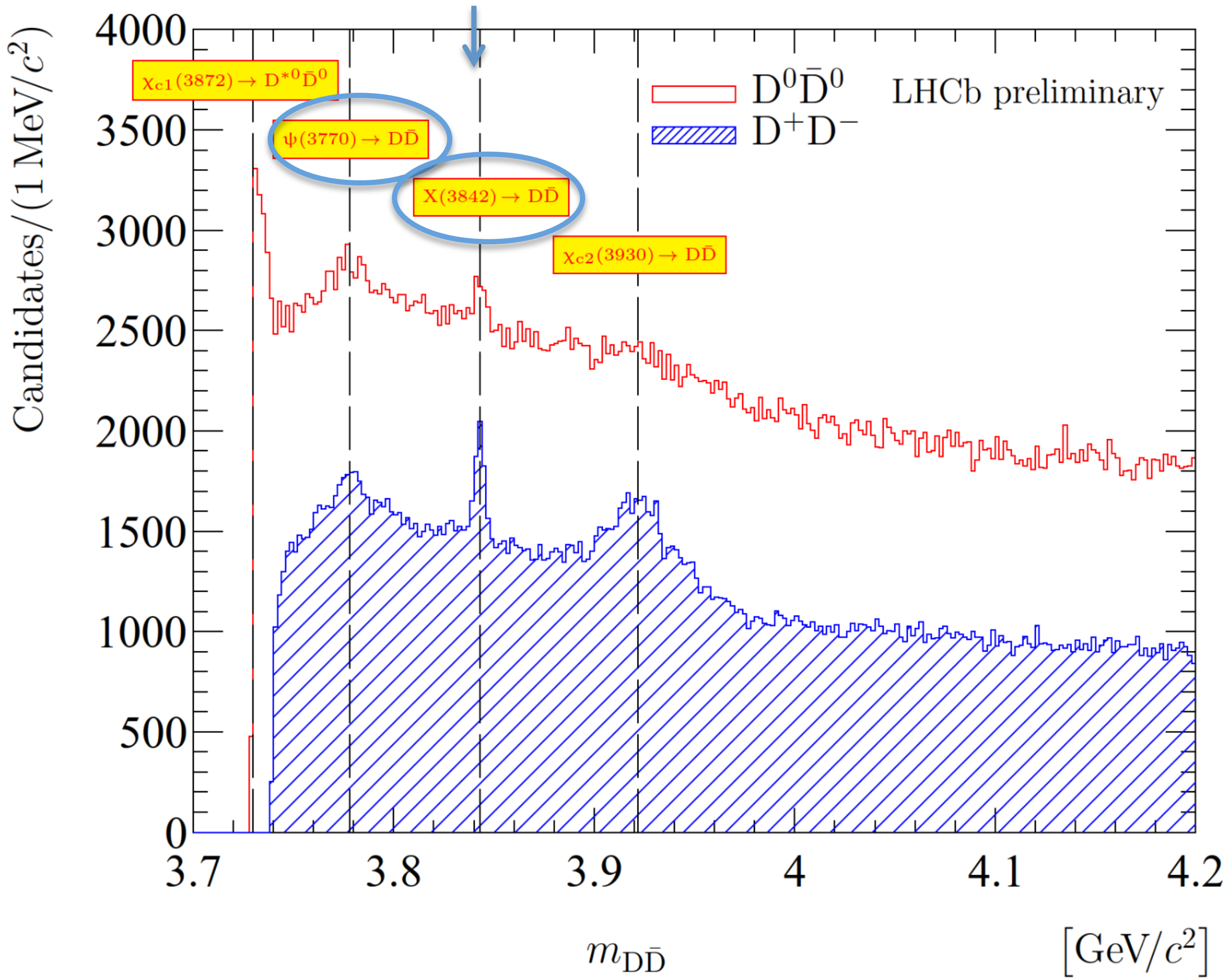
$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\mathrm{MeV}/c^2\,,$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\mathrm{MeV}\,,$$

LHCb 2019

1903.12240

JHEP 2019

$J^{PC}=3^{--}$



J^{PC} not experimentally measured

LHCb paper:

"The narrow natural width and the mass of the X(3842) state suggest the interpretation as charmonium state with $J^{PC} = 3^{--}$"

Quark model quantum numbers:

$$n\,^{2s+1}l_J = 1\,^3D_3$$

Lattice ensembles

- CLS ensembles with dynamical u/d and s quarks: $m_\pi \approx 280$ MeV, $m_K \approx 467$ MeV
- two values of m_c to explore dependence of charmonia on the position of $\bar{D}D$ thresholds:
  $m_D \approx 1762$ MeV, 1927 MeV ($m_D^{exp}=1867$ MeV)

  $a \approx 0.086$ fm, $N_L=24$ & 32

|n> denotes eigenstate of H_{QCD}

Info from lattice : E_n , Z^n_i

$$Z_i^n \equiv \langle 0 | \mathcal{O}_i | n \rangle$$

Large number (15-30) of operators with the quantum numbers of desired channel

quantum number : in continuum: J^{PC}

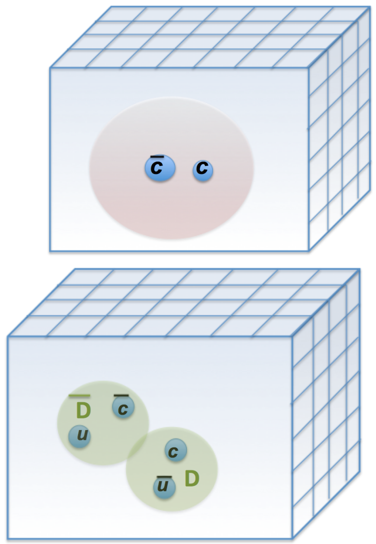
on the lattice: lattice irrep Λ

$$\mathcal{O}^{\bar{c}c} = \bar{c}\Gamma c$$

$$\mathcal{O}^{\bar{D}D} = (\bar{c}\Gamma_1 q)(\bar{q}\Gamma_2 c) = \bar{D}D$$

charm annihillation omitted

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



M. Padmanath, S. Collins, D. Mohler, S. Piemonte, S.P., A. Schafer, S. Weishaeupl : 1811.04116, PRD 2019

charmonia with all J^{PC} ($J \le 3$) omitting strong decays

employing only operators $\mathcal{O}^{\bar{c}c} = \bar{c}\,\Gamma c$

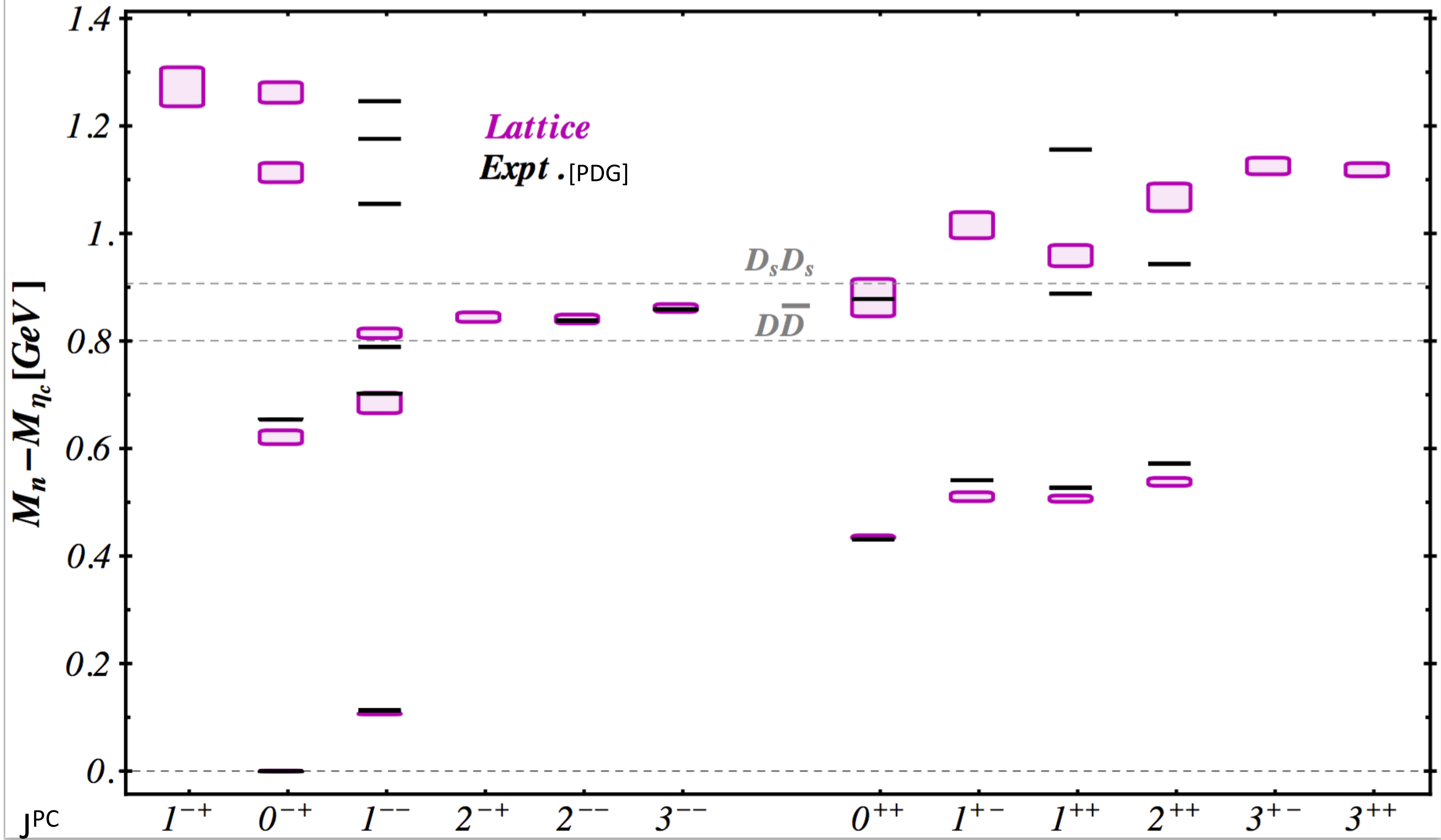
(10-30 for quantum number)

m and J^{PC} of charmonia with P=0

$\bar{c}c$

(extensive spectra using similar approach HSC: 1610.01073)

1811.04116, PRD 2019



exotic J^{PC}

hybrid candidate

agrees with
Belle 2013
BESIII 2015

agrees with
LHCb X(3842)
1903.12240

agrees with
Belle X(3860)
1704.01872

X(3872) too high without
DD* threshold effect

Charmonia with P≠0 : determining E and J^{PC}

refers to quantum numbers in charmonium's rest frame

- Experiment: charmonium -> H_1 H_2
- Lorentz transformation of decay products to charmonium's rest frame
- observed partial wave and q.n. of H_1 and H_2 render J^{PC} of charmonium in its rest frame

- Lattice: Above strategy can not be followed on the lattice
- Strategy : following [HSC, Thomas et al, 1107.1930] used for light isovectors

  each irrep Λ contains several J^P ; for example: A_1 irrep for P=1 x $2\pi/N_L$ contains J^P= 0+, 1- , 2+, 3-

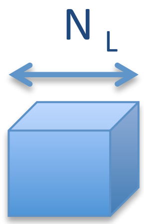
$$\mathcal{O}^{J^{PC}} = \bar{c}\Gamma c \xrightarrow{\text{boost to P}} \mathcal{O}^{J^{PC},\lambda} \xrightarrow{\text{subduce to lattice irrep } \Lambda} \mathcal{O}_\Lambda^{[J^{PC},\lambda]}$$

good q.n. at rest in continuum — good helicity λ at mom. P in continuum — operator on the lat.

- determine overlaps $Z_i^n \equiv \langle 0 | \mathcal{O}_i^{[J^{PC},\lambda]} | n \rangle$ from lattice

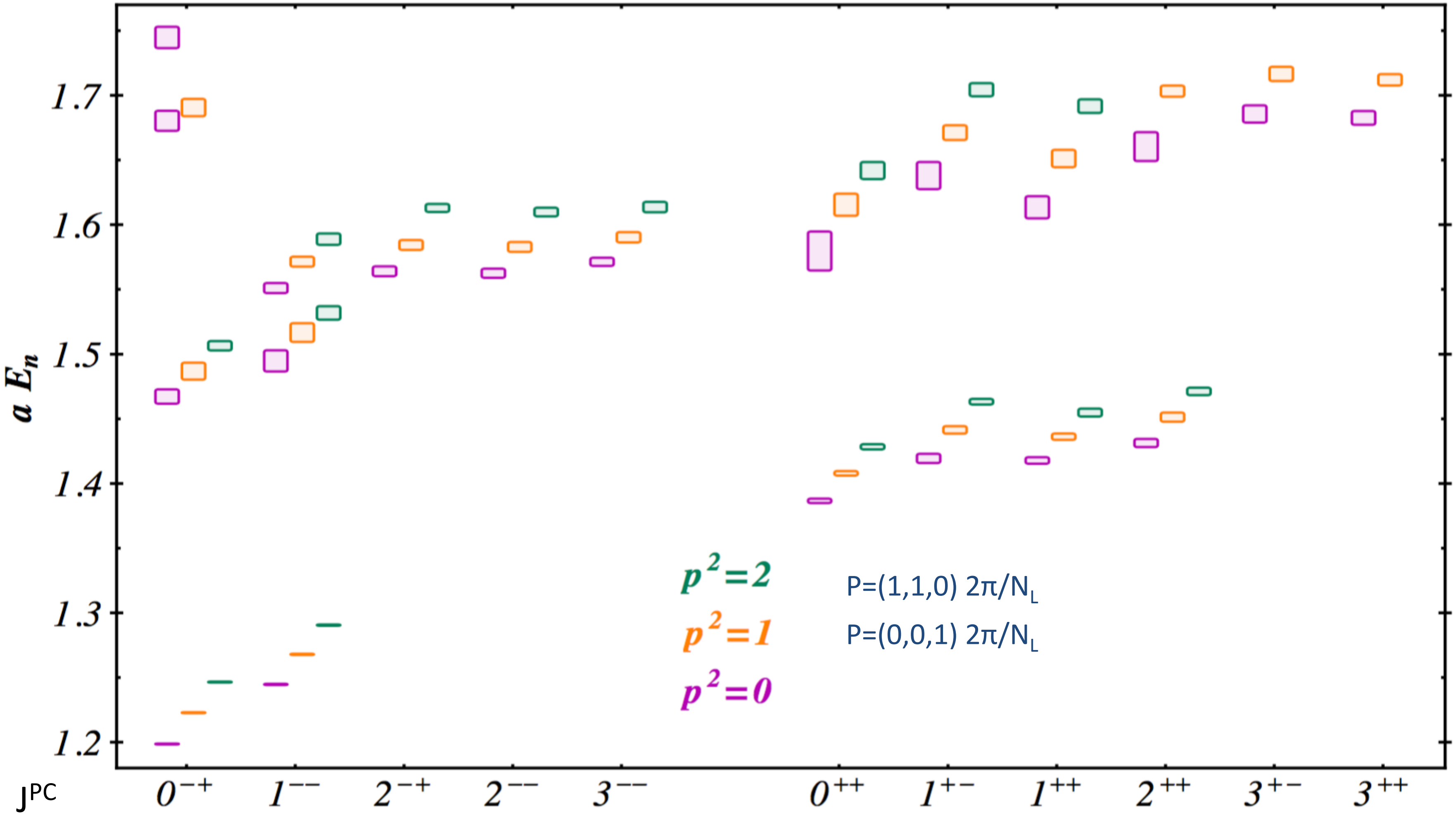
- eigen-state $|J^P,\lambda\rangle$ couples better to $O^{[J,\,P,\,\lambda]}$ than to $O^{[J',\,P',\,\lambda']}$

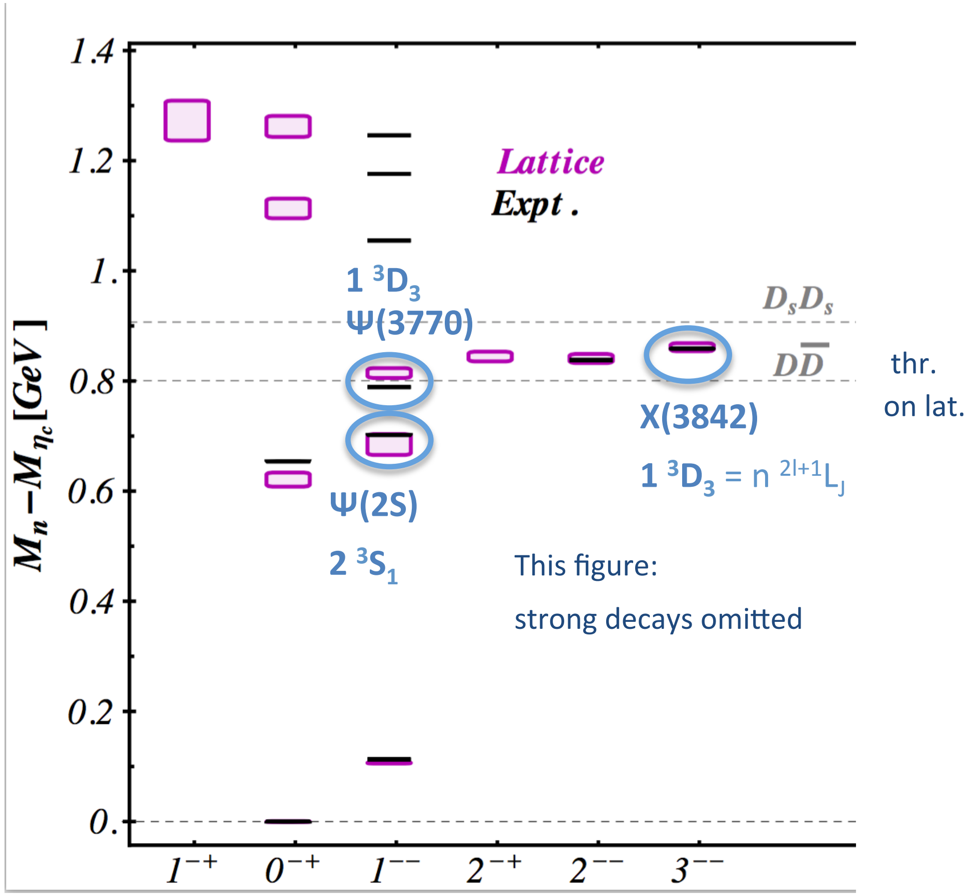
E and J^{PC} of charmonia at P=0 and P≠0

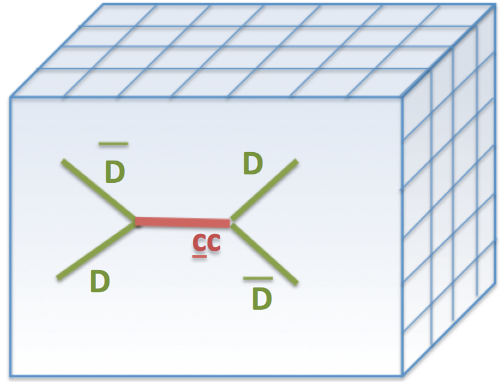


$E \approx \sqrt{m^2 + P^2}$

J^{PC} denote quantum numbers in particle's rest frame







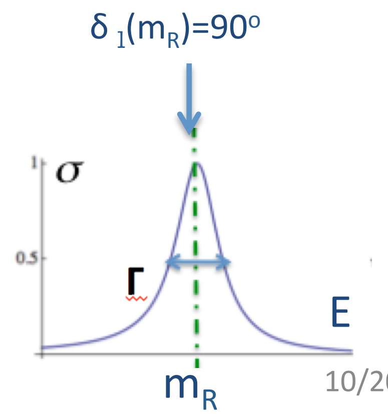
Strategy

- simulate $D\bar{D}$ scattering on the lattice
- determine scattering amplitude

$$S_l(E) = \exp[2i\delta_l(E)], \quad l = 1,3$$

$$\sigma(E) \propto |S(E)-1|^2 \propto |t(E)|^2$$

- m_R and Γ_R from Breit-Wigner type fits

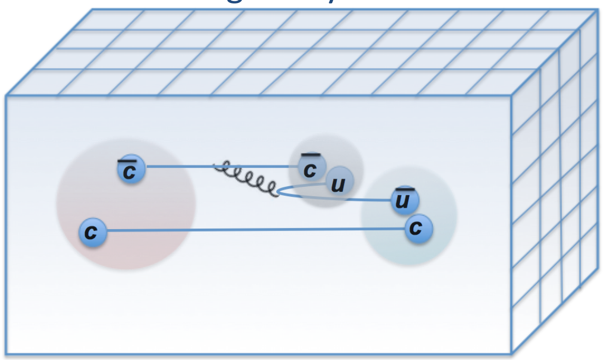


Charmonia with $J^{PC}=1^{--}$ and 3^{--}

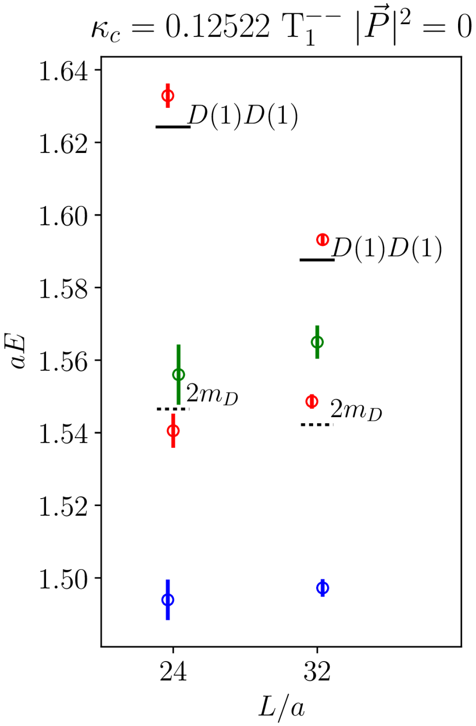
taking into account their strong transitions to $D\bar{D}$

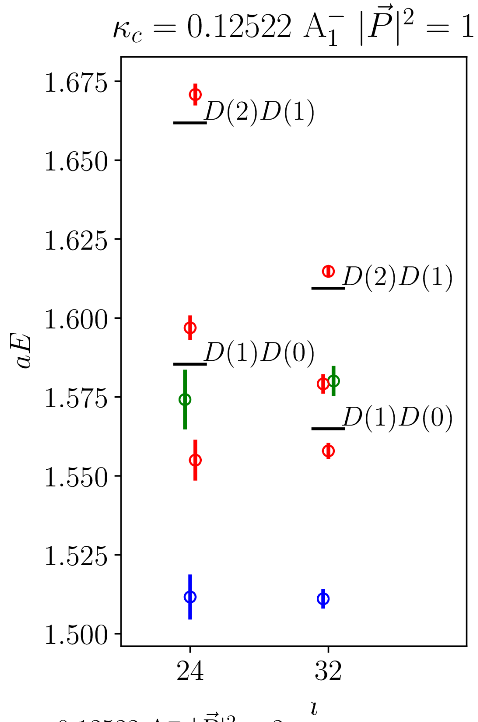
- only 1 previous lattice study extracted width of charmonium resonances (0^{++} and 1^{--})
  Lang, Leskovec, Mohler, S.P. , 1503.05363, JHEP 2015
- Present work:
  S. Piemonte, S. Collins, M. Padmanath, D. Mohler, S.P. : 1905.03506

strong decay

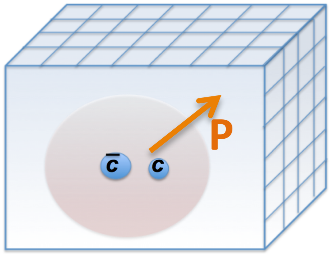


Eigen-energies E_n





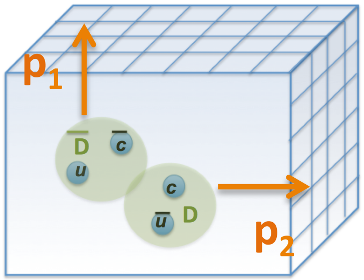
Operators

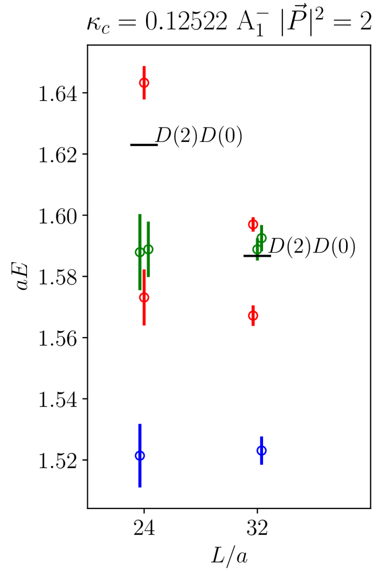


$$\mathcal{O}^{\bar{c}c} = (\bar{c}\Gamma c)_{\vec{P}}$$

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

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





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

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

Plots for
$m_D \approx 1762$ MeV

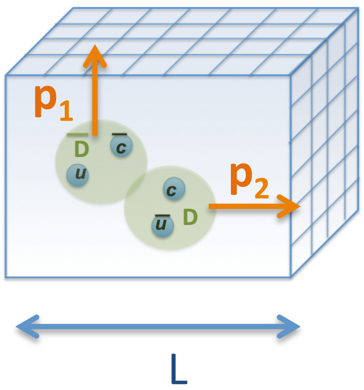
$$C_{ij}(t) = \langle 0 | \mathcal{O}_i(t)\ \mathcal{O}_j^{+}(0) | 0 \rangle = \sum_n Z_i^n\ Z_j^{n*}\ e^{-E_n t}$$

Luscher 1991

Relation between eigen-energies E and $S_l(E)=\exp[2i\,\delta_l(E)]$

P=0 or P≠0, 3D space

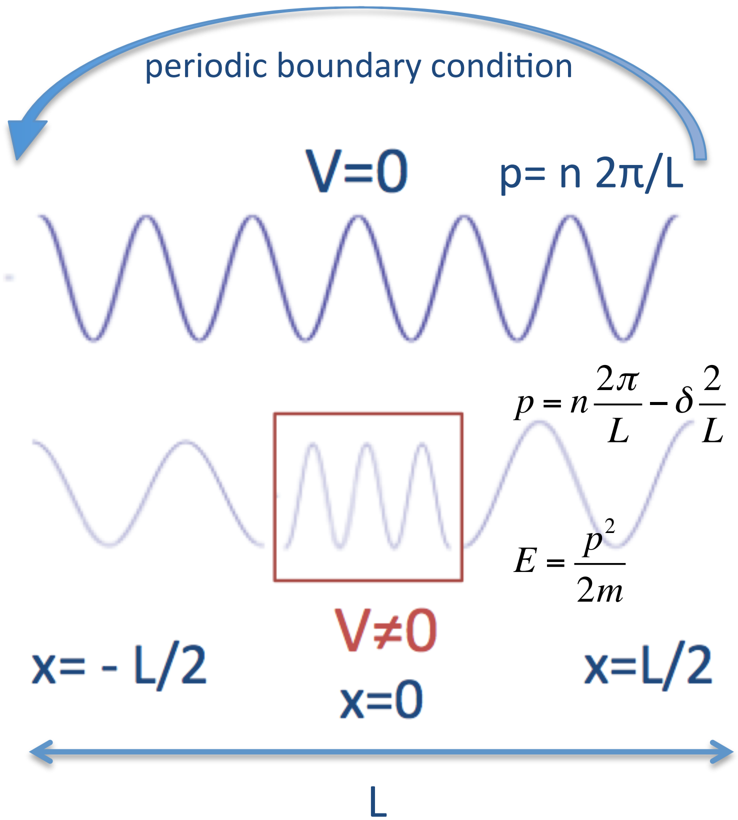
$$E \to E_{cm}$$



l=1,3 appear together due to finite cubic lattice (lattice artifact)

$$f^{\Lambda,\vec{P}}(\delta_1(E_{cm}),\delta_3(E_{cm}),E_{cm},L)=0$$

1D space, quantum mechanics



$$f(\delta(E),E,L)=0 \qquad E \to \delta(E)$$

known functions

Fit of phase shifts for l=1,3 from E_n

$$E_{cm} = \sqrt{s} = 2\sqrt{m_D^2 + p^2}$$

p = relative momenta of D-mesons in CMF

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

$\delta_1(m_R)=90^o$

Fit forms:

Ψ(2S) Ψ(3770)

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

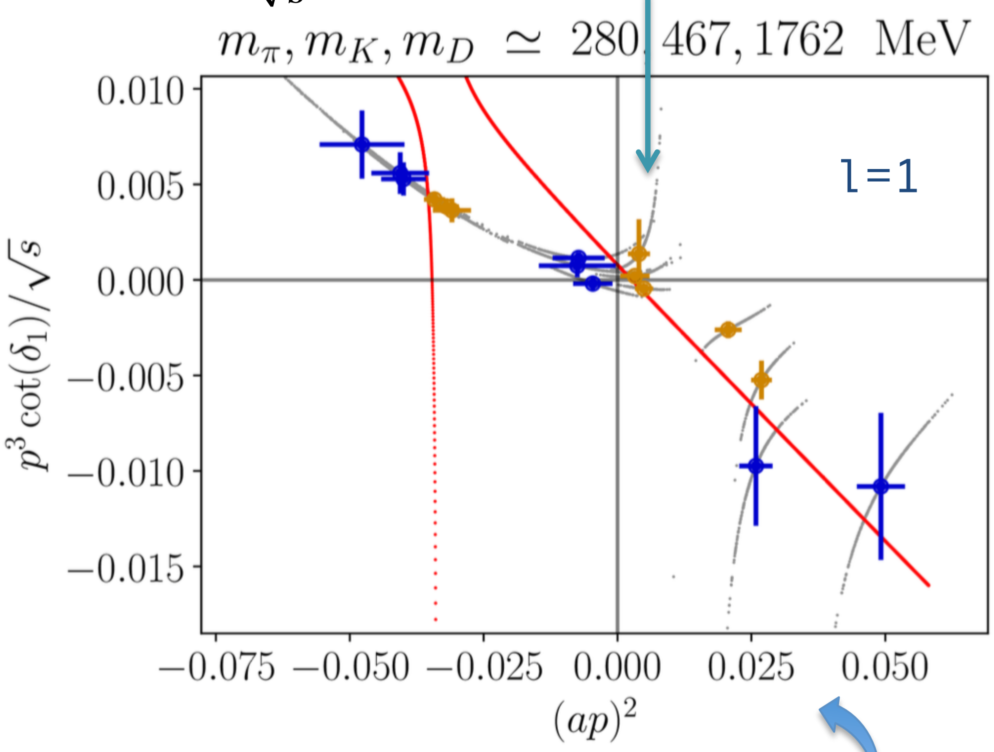
l=3 $$\frac{p^7\cot(\delta_3)}{\sqrt{s}} = \frac{m_3^2 - s}{g_3^2}$$

X(3842)

$$\frac{p^3\cot(\delta_1)}{\sqrt{s}}$$

δ=90⁰, cot δ=0

Ψ(3770) resonance



Result:

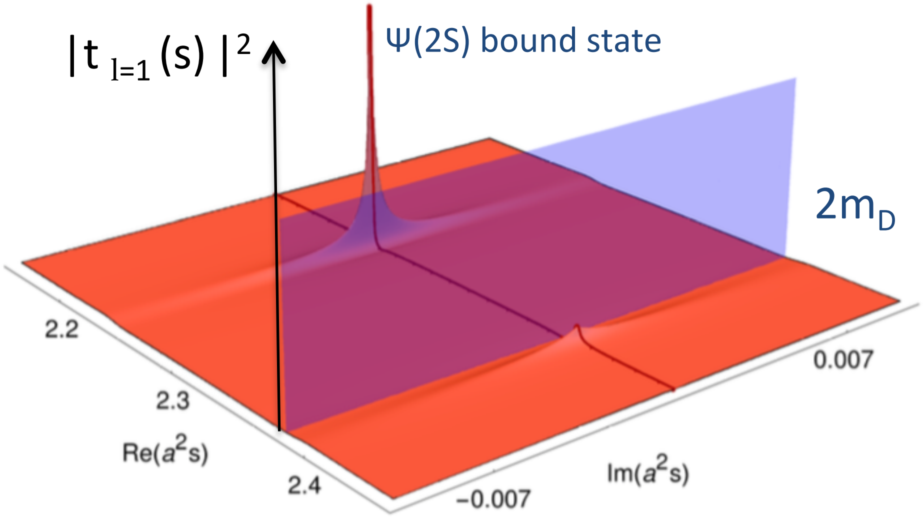
$$\frac{p^{2l+1}\cot(\delta)}{\sqrt{s}} = \begin{cases} \left(\frac{[0.63(33)]^2}{[1.4966(30)]^2 - s} + \frac{[3.69(37)]^2}{[1.5457(32)]^2 - s}\right)^{-1} & l=1 \\ \frac{[1.568(11)]^2 - s}{[0.07(3)]^2} & l=3 \end{cases}$$

Scattering amplitude t(E) in complex energy plane

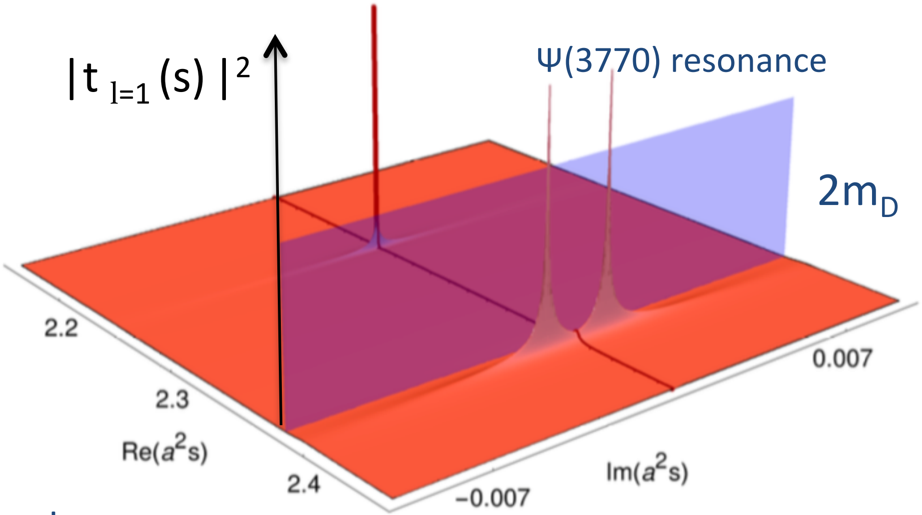
$$S_l(E) = \exp[2i\delta_l(E)] = 1 + 2i\rho\, t_l(E)$$

$$t_l(s) = \frac{1}{\rho\ \cot(\delta_l) - i\ \rho}$$

$$\rho = \frac{2p}{\sqrt{s}} = \sqrt{1 - 4\frac{m_D^2}{s}}\ .$$



(a) I Riemann sheet



(b) II Riemann sheet

poles in t(s) related to

resonance and bound states

Fig for l=1 and $m_D \approx$1762 MeV:

one resonance, one bound state, one virtual bound state

Results at m_D=1762 MeV

Resonances

Ψ(3770) $J^{PC}=1^{--}$, l=1

X(3842) $J^{PC}=3^{--}$, l=3

Mass:

$\delta_1(E_{cm}=m_R)=90^o$

$\cot[\delta_1(m_R)]=0$

Width or coupling g:

Ψ(3770) → $D\bar{D}$, l=1

$$\frac{p^3 \cot\delta_1}{\sqrt{s}}\Big|_{s\simeq m^2} = \frac{6\pi}{g^2}(m^2-s)$$

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

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

X(3842): to narrow to resolve

Bound state

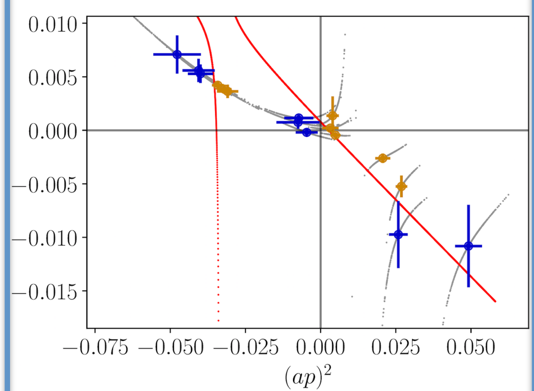
Ψ(2S) $J^{PC}=1^{--}$, l=1

Mass:

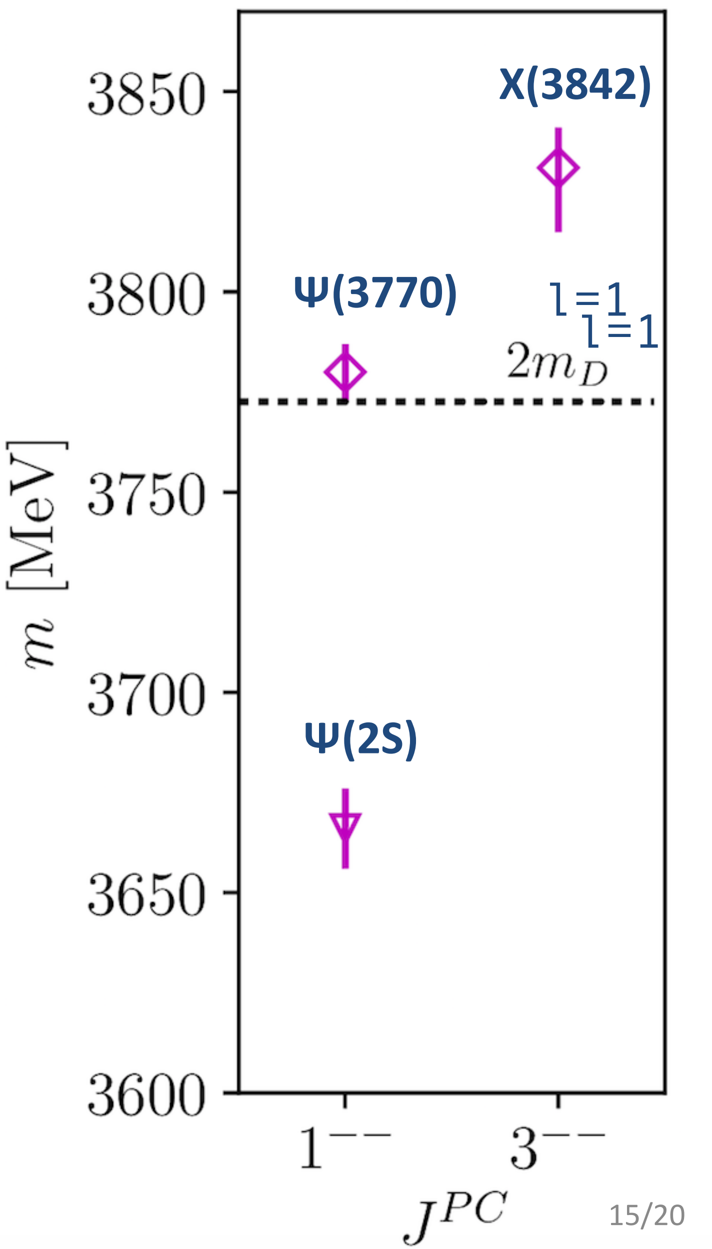
$|t(E_{cm}=m_B)| = \infty$

m_B given by the pole on the first sheet

$$\frac{p^3\cot(\delta_1)}{\sqrt{s}}$$

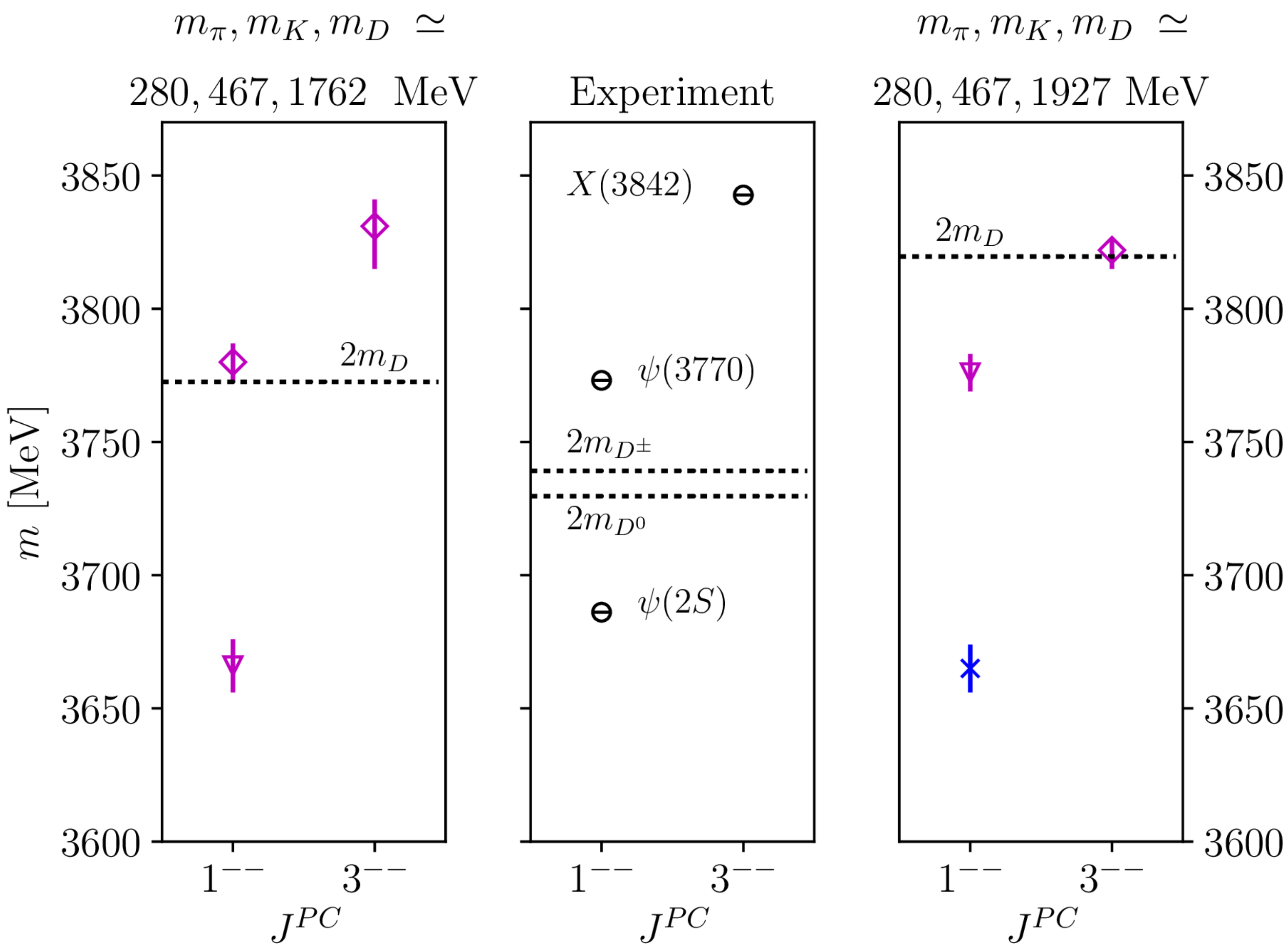


$m_\pi, m_K, m_D \simeq$ 280, 467, 1762 MeV



$$m = m^{\text{lat}} - M_{\text{av}}^{\text{lat}} + M_{\text{av}}^{\text{exp}} \qquad M_{\text{av}} = \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$$

Masses of charmonium resonances and bound states



1905.03506

Investigated conventional charmonia are not very sensitive to position of DD threshold.

Briefly on exotic quarkonium-like channels

Lattice study of P_c pentaquark channel

$$P_c = uud\bar{c}c \rightarrow (uud)\,(\bar{c}c)$$

light-baryon charmonium

$$\rightarrow (uuc)\,(\bar{c}d)$$

charmed-baryon charmed-meson

Question we address: Do Pc resonances appear in one-channel p J/ψ scattering on the lattice (in approximation where this channel is decoupled from other channels)

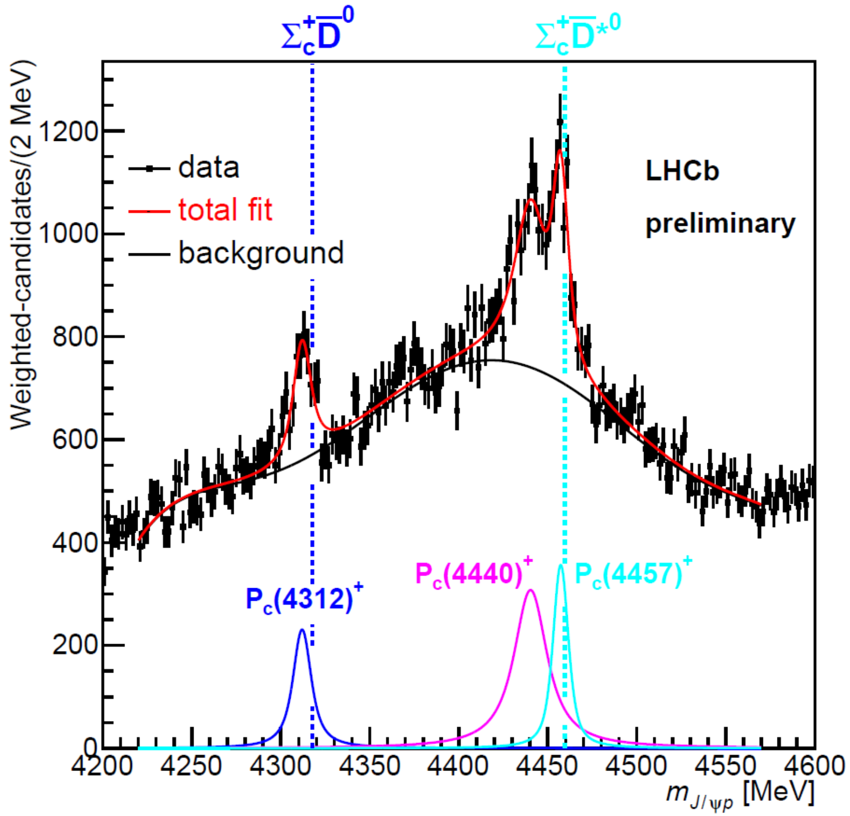
$$p\ \ J/\psi \rightarrow P_c \rightarrow p\ \ J/\psi$$

We simulate this scattering and cover also the energy region of P_c for the first time.

The answer from our lattice simulation : No.

U. Skerbis, S. Prelovsek, 1811.02285 to appear in PRD

This indicates that the coupling of p J/ψ channel with other two-hadron channels is likely responsible for Pc resonances in experiment.



This is in line with LHCb results, where Pc's are found near other thresholds. This by itself indicates that other channels are important.

Lattice study of Z_b tetraquark channel

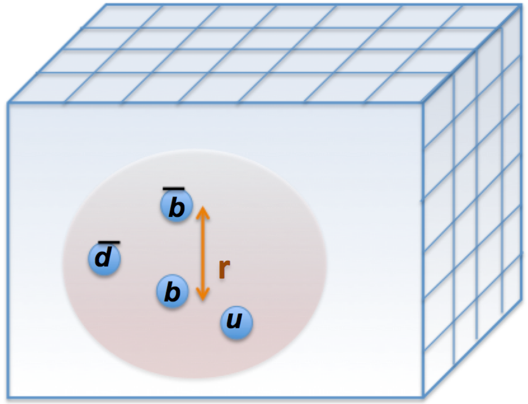
Lattice simulation of Zb channel with static b and b̲

Inspired by Bicudo, Peters, Wagner [1602.07621, 1709.03306]

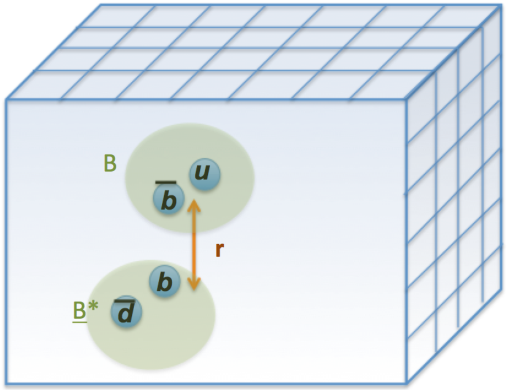
Extracted $E_n(r)$

ongoing study with J. Petkovic and H. Bahtiyar

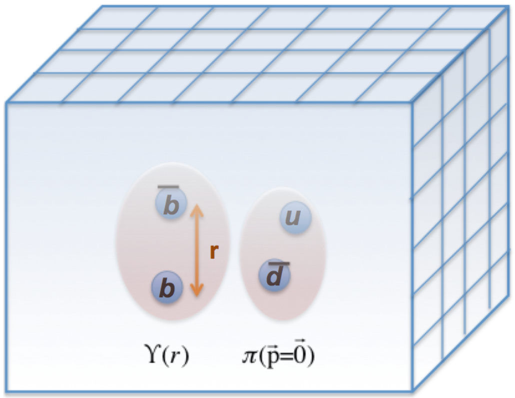
conclusions concerning Z_b from this approach: coming soon

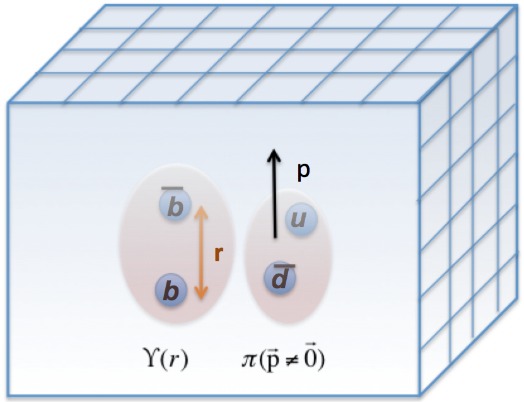


Fock components incorporated:



sizable attraction
found in this channel



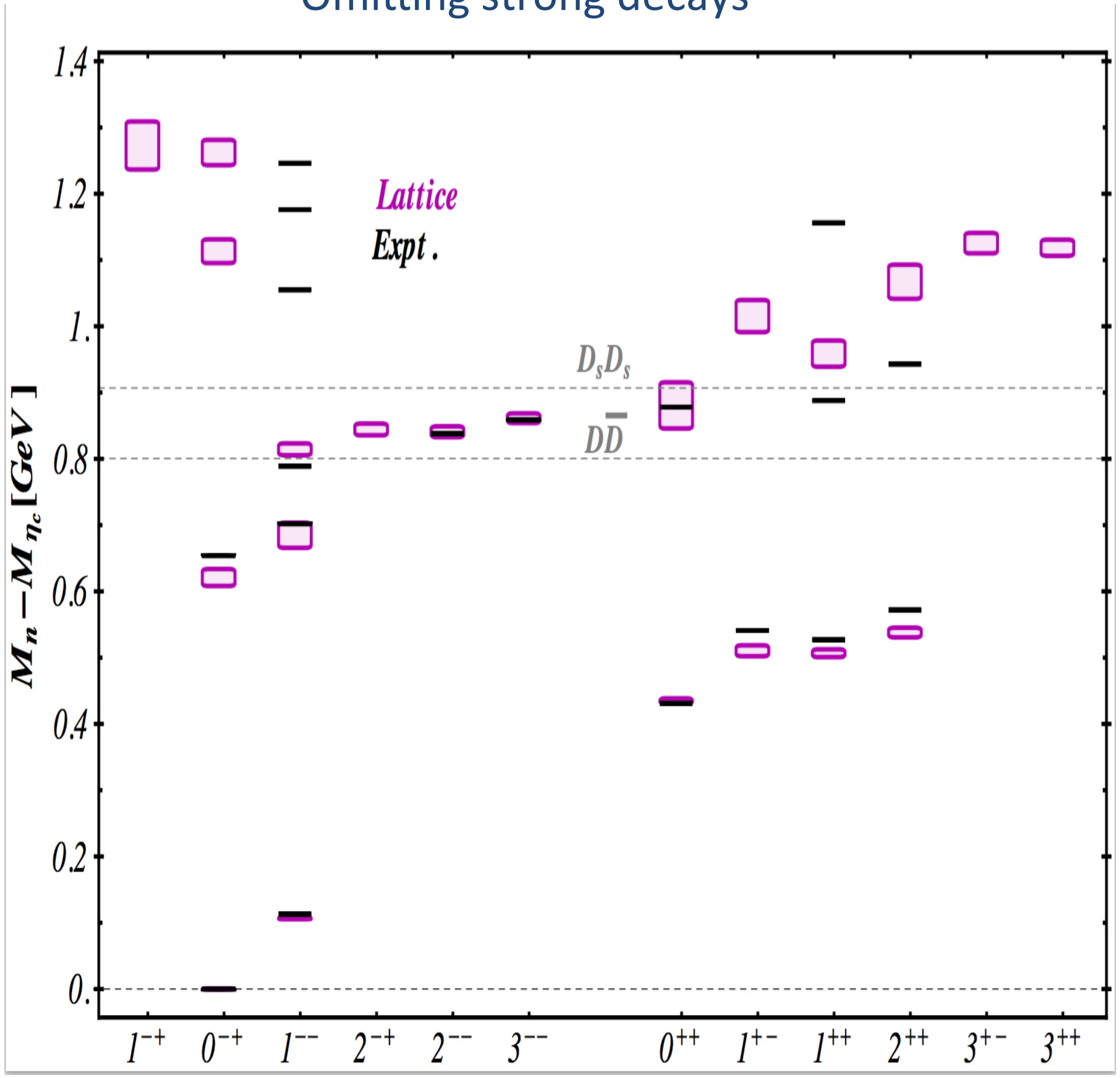


new

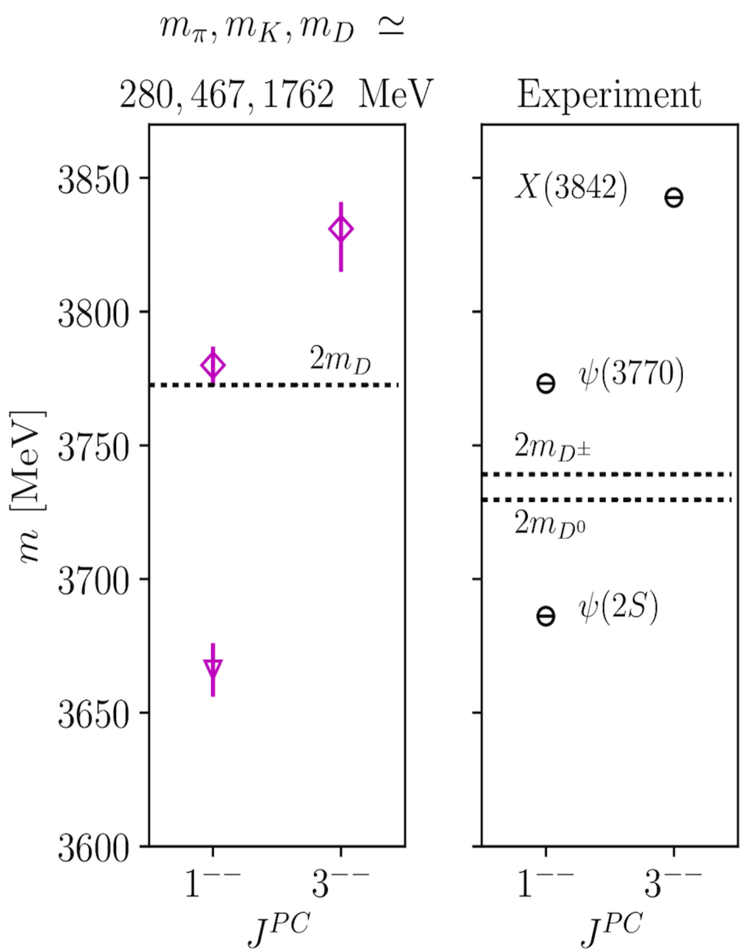
Conclusions

Charmonium spectrum from a lattice study at a single lattice spacing and m_π ≈280 MeV (not extrapolated to physical point)

Omitting strong decays



Including strong transitions to DD



Ψ(3770) → DD coupling/width in agreement with exp

Backup

PDG 2018

$n\,^{2s+1}\ell_J$ J^{PC}		I = 0 $c\bar{c}$	I = 0 $b\bar{b}$
$1\,^1S_0$	0^{-+}	$\eta_c(1S)$	$\eta_b(1S)$
$1\,^3S_1$	1^{--}	$J/\psi(1S)$	$\Upsilon(1S)$
$1\,^1P_1$	1^{+-}	$h_c(1P)$	$h_b(1P)$
$1\,^3P_0$	0^{++}	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$
$1\,^3P_1$	1^{++}	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$
$1\,^3P_2$	2^{++}	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$
$1\,^3D_1$	1^{--}	$\psi(3770)$	
$1\,^3D_3$	3^{--}	X(3842)	
$2\,^1S_0$	0^{-+}	$\eta_c(2S)$	$\eta_b(2S)$
$2\,^3S_1$	1^{--}	$\psi(2S)$	$\Upsilon(2S)$

S. Piemonte, S. Collins, M. Padmanath, D. Mohler, S.P. : 1905.03506

	J^{PC}	lat (present work) $\kappa_c = 0.12522$	lat (present work) $\kappa_c = 0.12315$	exp $\bar{D}^0 D^0 / D^+ D^-$	lat [16]
m_D [MeV]		1762(2)	1927(2)	$\bar{m}_D \simeq 1867$ MeV	1763(22)(18)*
m_{D_s} [MeV]		1818(1)	1981(1)	1968.34(7)	
$M_{\rm av}$ [MeV]		2820(3)	3103(3)	3068.6(2)	3119(9)(33)*
m_π [MeV]		280	280	$\bar{m}_\pi \simeq 137$ MeV	266
$\boldsymbol{\psi(3770)}$	1^{--}	resonance	bound st.	resonance [44]	resonance
g		$\mathbf{16.0(^{+2.1}_{-0.2})}$	$\mathbf{18.9(^{+0.8}_{-0.7})}$	**18.7(9)**	13.2(1.2)
$m - M_{\rm av}$ [MeV]		711(7)	707(7)	704.25(35)	715(7)
$m - 2m_D$ [MeV]		9(7)	-43(8)	38.52(35)	
$\boldsymbol{m}$ **[MeV]**		**3780(7)**	**3776(7)**	**3773.13(35)**[a]	3784(7)
$\boldsymbol{\psi(2S)}$	1^{--}	bound st.	bound st.	bound st. [44]	bound st.
$m - M_{\rm av}$ [MeV]		597(10)	596(9)	617.347(25)	605(6)
$m - 2m_D$ [MeV]		-105(11)	-154(10)	-48.383(25)	
$\boldsymbol{m}$ **[MeV]**		**3666(10)**	**3665(9)**	**3686.097(25)**	3674(6)
$\boldsymbol{X(3842)}$	3^{--}	resonance	resonance	resonance [21]	
$m - M_{\rm av}$ [MeV]		$762(^{+10}_{-16})$	$754(^{+4}_{-7})$	773.9(2)	
$m - 2m_D$ [MeV]		$59(^{+11}_{-16})$	$4(^{+9}_{-3})$	108.2(2)	
$\boldsymbol{m}$ **[MeV]**		$\mathbf{3831(^{+10}_{-16})}$	$\mathbf{3822(^{+4}_{-7})}$	**3842.7(2)**	

The challenge to determine J^P

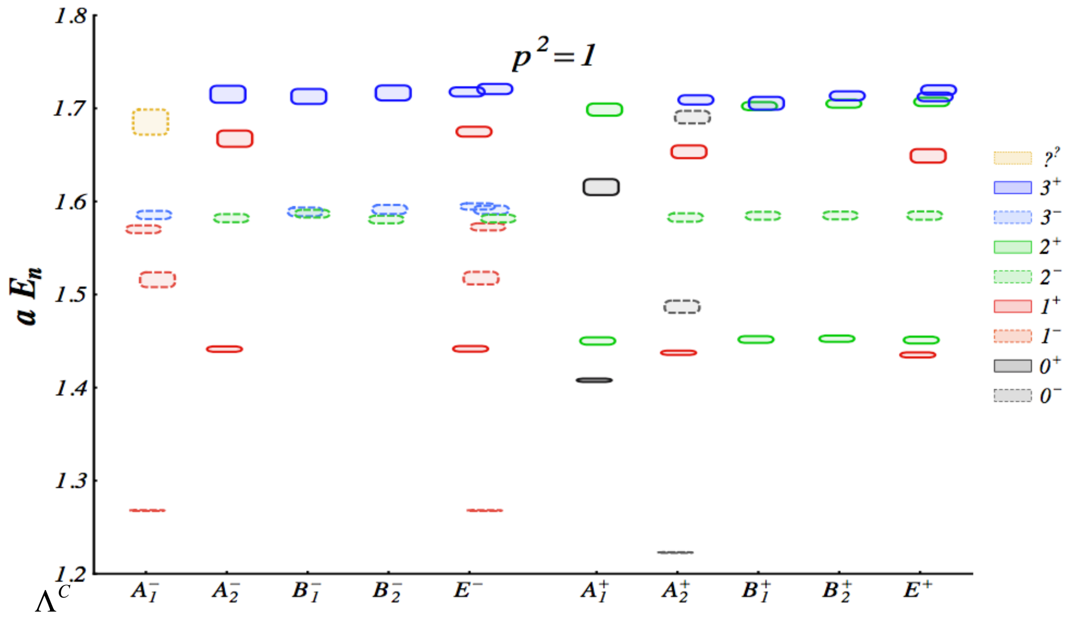
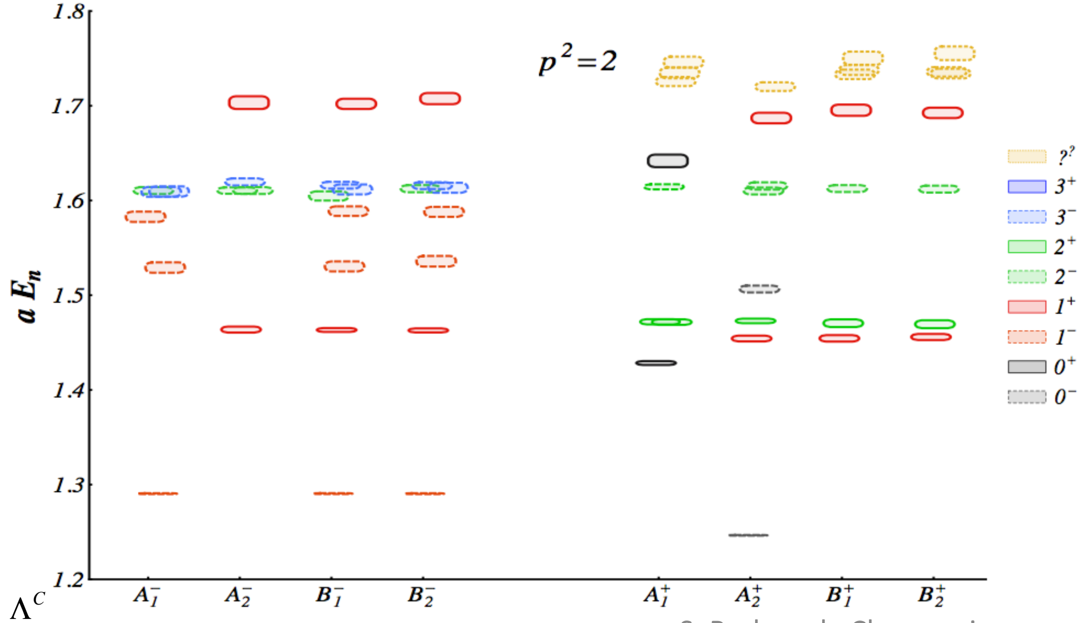


FIG. 11. J^P-identified charmonium spectrum in the moving frame with $\mathbf{p} = (0,0,1)$. Irreps Λ^C of group Dic_4 are presented. The colors indicate J^P of states according to the color-coding (21).

$\mathbf{p} = (0,0,1)$, Dic_4		
Λ (*dim*)	$\lvert\lambda\rvert^{\tilde{\eta}}$	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	$2^\pm,\ 3^\pm$

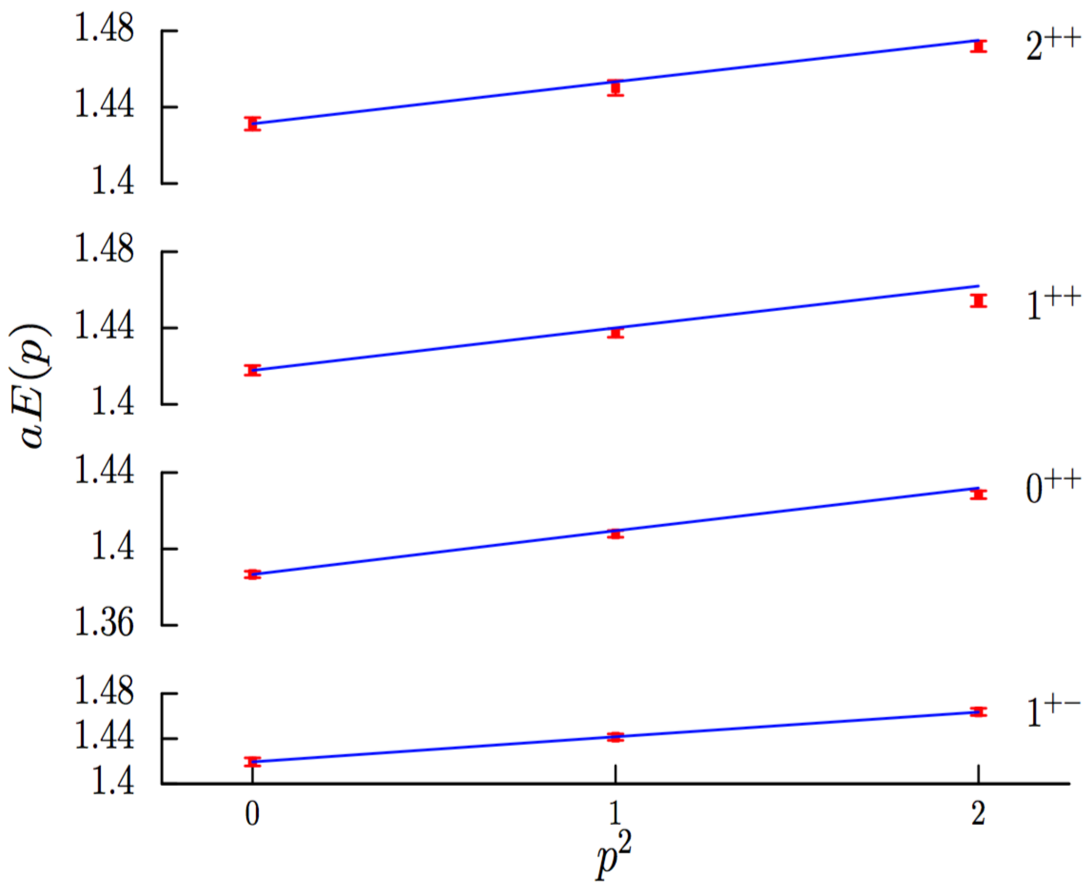


$\mathbf{p} = (1,1,0)$, Dic_2		
Λ (*dim*)	$\lvert\lambda\rvert^{\tilde{\eta}}$	J^P (at rest)
A_1 (1)	0^+	$0^+,\ 1^-,\ 2^+,\ 3^-$
	2	$2^\pm,\ 3^\pm$
A_2 (1)	0^-	$0^-,\ 1^+,\ 2^-,\ 3^+$
	2	$2^\pm,\ 3^\pm$
B_1 (1)	1	$1^\pm,\ 2^\pm,\ 3^\pm$
	3	$3^\pm$
B_2 (1)	1	$1^\pm,\ 2^\pm,\ 3^\pm$
	3	$3^\pm$

1811.04116, PRD 2019

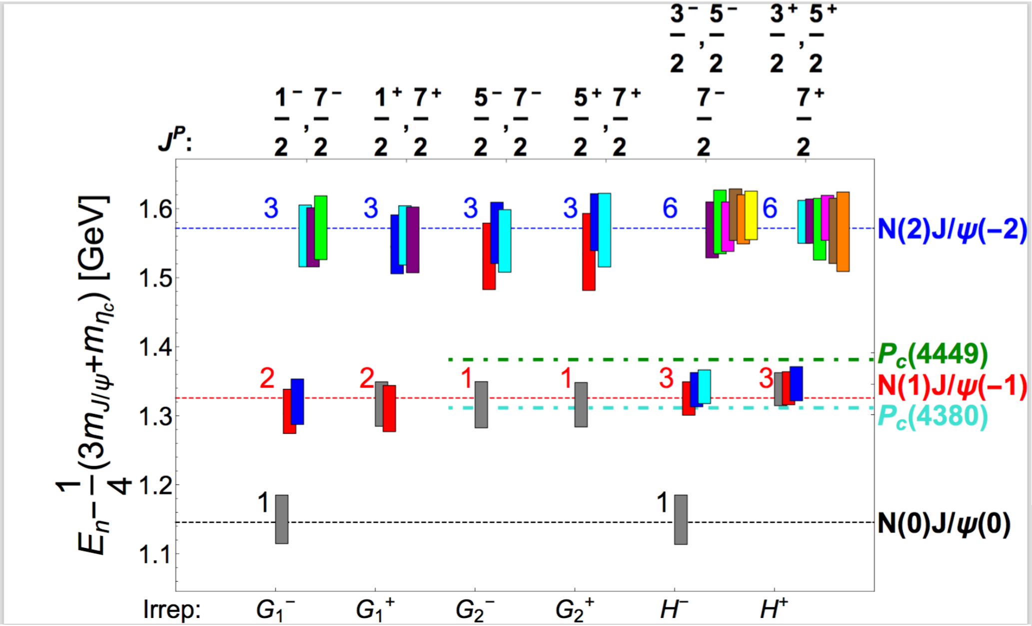
$$\cosh(bE(\mathbf{p})) = \cosh(bM) + \sum_{i=x,y,z}\left[2\sin\left(\frac{bp_i}{2}\right)\right]^2$$

$$E(\mathbf{p}) = \sqrt{M^2 + \mathbf{p}^2} \text{ for } b \to 0$$



1811.04116, PRD 2019

proton J/Ψ scattering in lattice QCD in Pc channels



U. Skerbis, S. Prelovsek, 1811.02285