Lattice QCD study

of Zb tetraquark channel

+ two other quarkonium(like) channels

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Zb: S. Prelovsek, H. Bahtiyar, J. Petkovic, 1912.02656

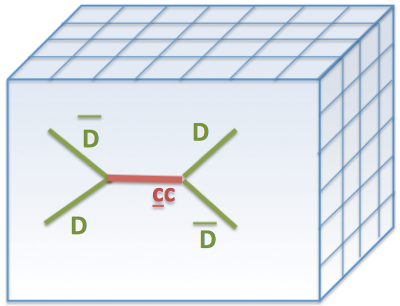
charmonium resonances: S. Piemonte, S. Collins, M. Padmanath, D. Mohler, S.P. : 1905.03506, PRD 2019

Pc: U. Skerbis, S. Prelovsek, 1811.02285, PRD 2019

Outline

Lattice QCD study of

1) conventional charmonium resonances above $\underline{D}D$ threshold $\bar{c}\,c$



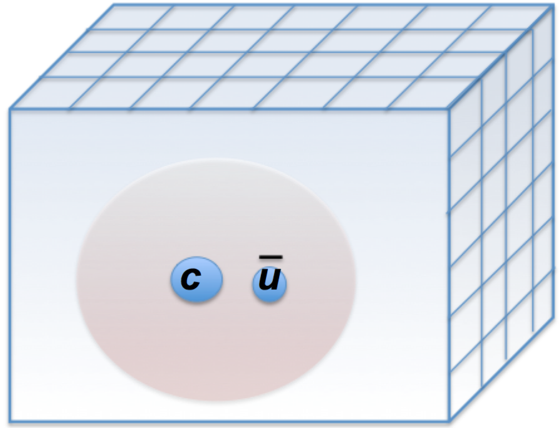
$J^{PC} = 1^{--}$ $\Psi(3770)$ know for long time

$J^{PC} = 3^{--}$ $X(3842)$ discovered at LHCb 2019

2) pentquark P_c channel discovered at LHCb 2015,2019 $\bar{c}\,c\,u\,u\,d$

3) tetraquark Z_b channel discovered at Belle 2011 $\bar{b}\,b\,\bar{d}\,u$

Lattice QCD



$$L_{QCD} = -\tfrac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q} i \gamma_\mu (\partial^\mu + i g_s G^\mu_a T^a) q - m_q \bar{q} q$$

input: g_s , m_q

Numerical evaluation of QFT Feynman path integrals on discretized Eucledian space-time

$$\int DG\, Dq\, D\bar{q}\; e^{-S_{QCD}/\hbar}$$

$$J^{PC} \qquad \mathcal{O} = \bar{q}\Gamma q, \quad (\bar{q}\Gamma_1 q)(\bar{q}\Gamma_2 q), \quad [\bar{q}\Gamma_3 \bar{q}][q\Gamma_4 q], \ldots$$

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

Extracted quantity: E_n = energy of QCD eigenstate with given quantum numbers

$E_1(p=0, J^P=0^-) = m_D$

$\bar{c}\ c$

(1) Conventional charmonia

S. Piemonte, S. Collins, M. Padmanath, D. Mohler, S.P. : 1905.03506, PRD 2019

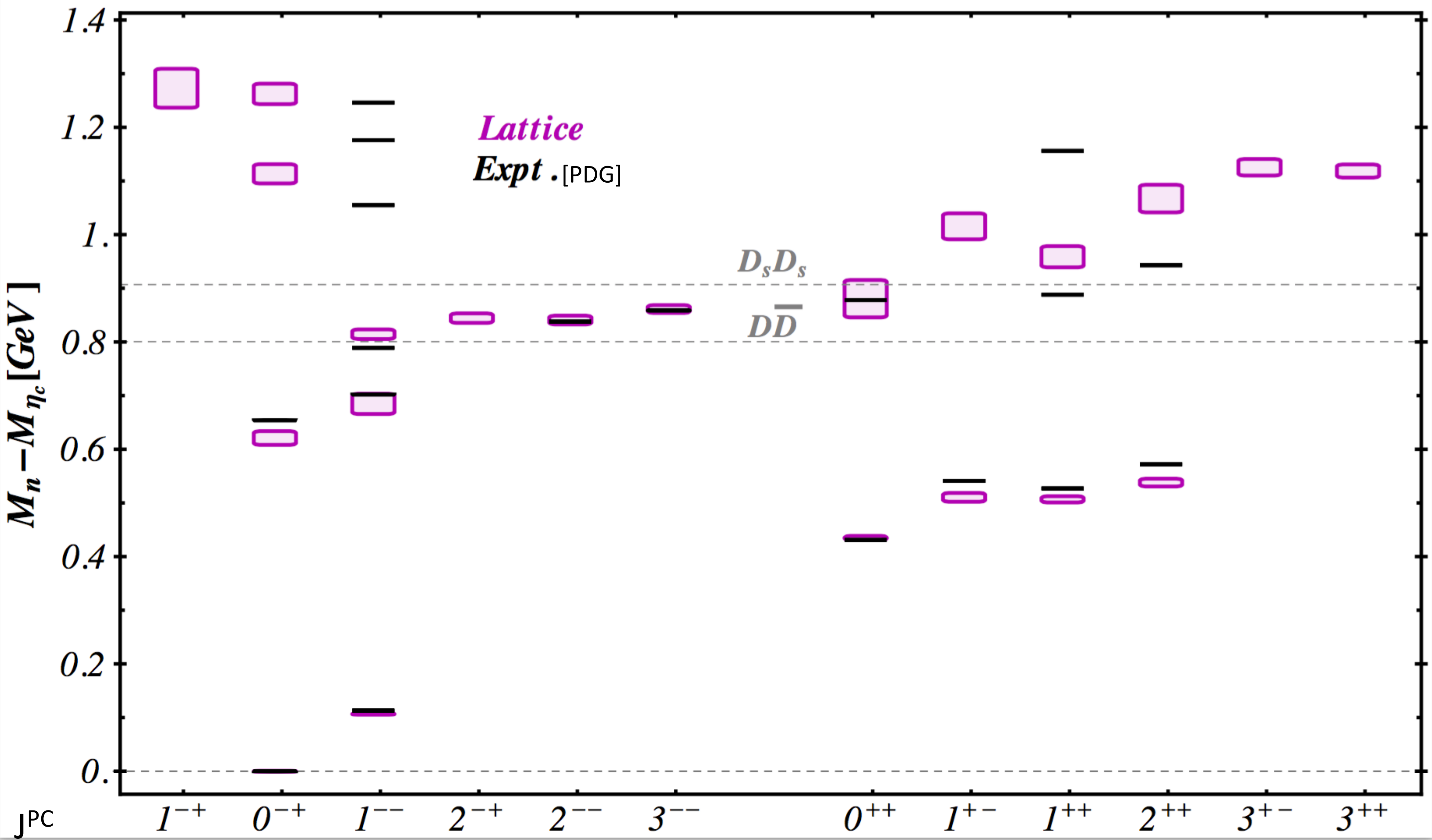
M. Padmanath, S. Collins, D. Mohler, S. Piemonte, S.P., A. Schafer, S. Weishaeupl : 1811.04116, PRD 2019

(Regensburg group)

m and J^{PC} omitting strong decays

$\bar{c}c$ $\quad \bar{c}\Gamma_i c,\ \bar{c}\Gamma_i D_j c, \ldots$

Lattice: 1811.04116, PRD 2019: Nf=2+1, $m_\pi \approx 280$ MeV, N_L=24



exotic J^{PC}
hybrid candidate

agrees with
Belle 2013
BESIII 2015

agrees with
LHCb X(3842)
1903.12240

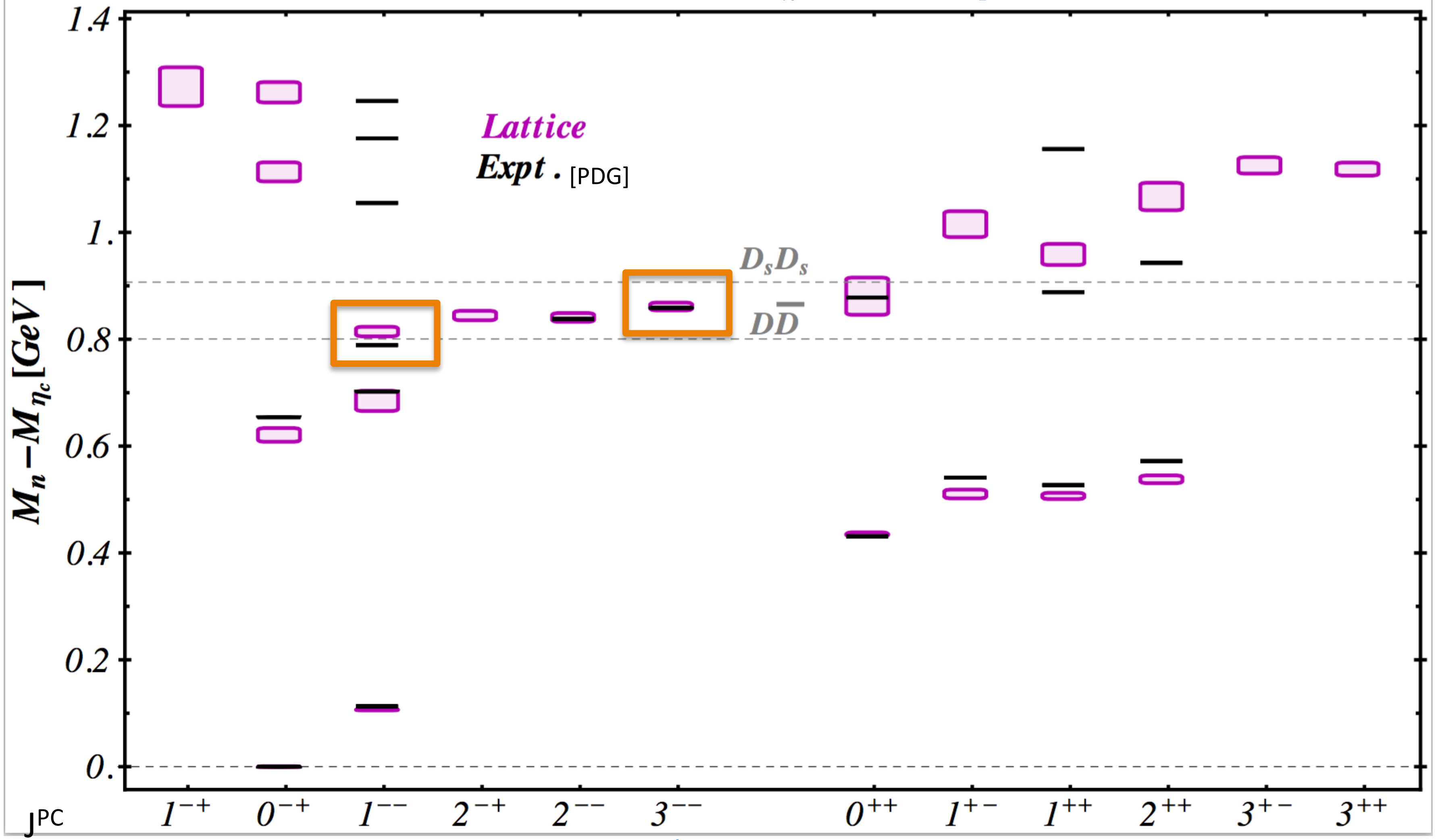
agrees with
Belle X(3860)
1704.01872

X(3872) too high without
DD* threshold effect

Next: strong decays of resonances to $D\bar{D}$

$\bar{c}c$

Lattice: 1811.04116, PRD 2019: Nf=2+1, $m_\pi \approx 280$ MeV, $N_L=24$



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1903.12240

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1704.01872

X(3872) too high without
DD* threshold effect

First exp. discovery of a charmonium with spin J=3

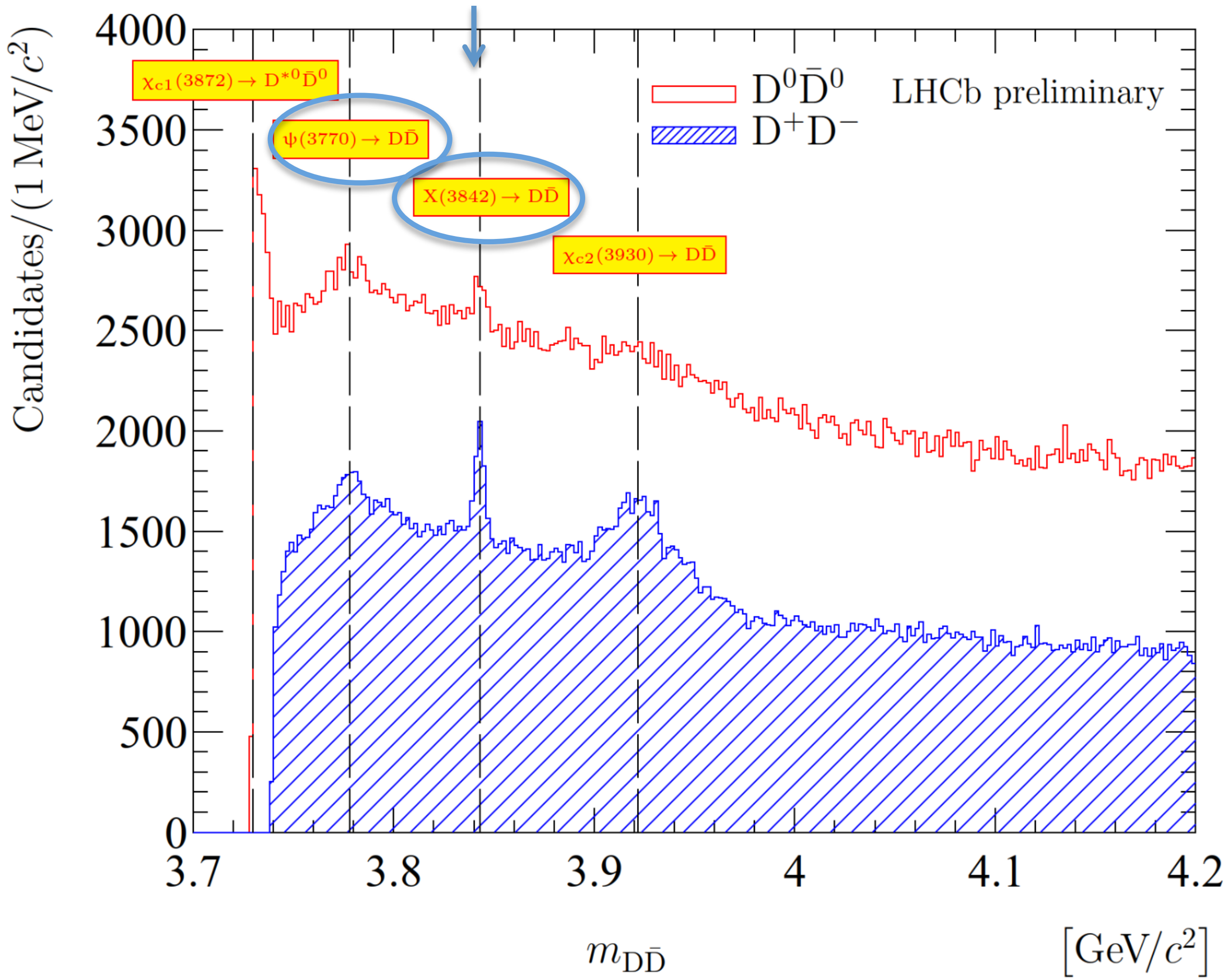
$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\mathrm{MeV}/c^2\,,$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\mathrm{MeV}\,,$$

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

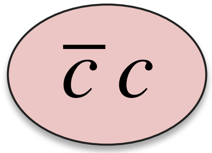
Quark model quantum numbers:

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

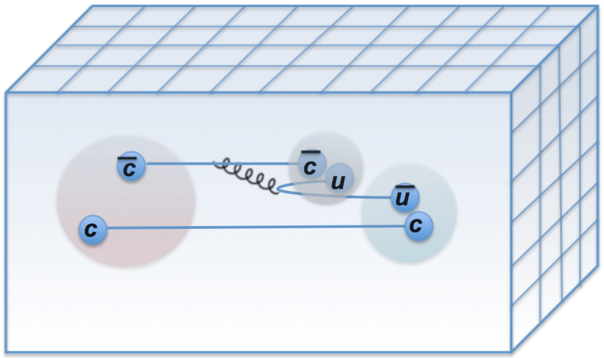
$$\bar{c}c \to \bar{D}D$$

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

taking into account strong transitions to DD



Strategy



- simulated DD scattering on the lattice
- determined scattering amplitude

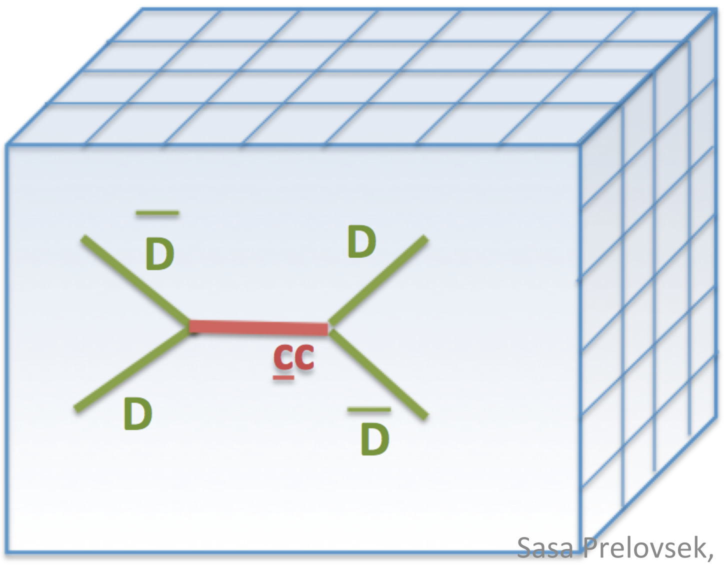
$$S_l(E) = \exp[2i\delta_l(E)]\,, \quad l = 1,3$$

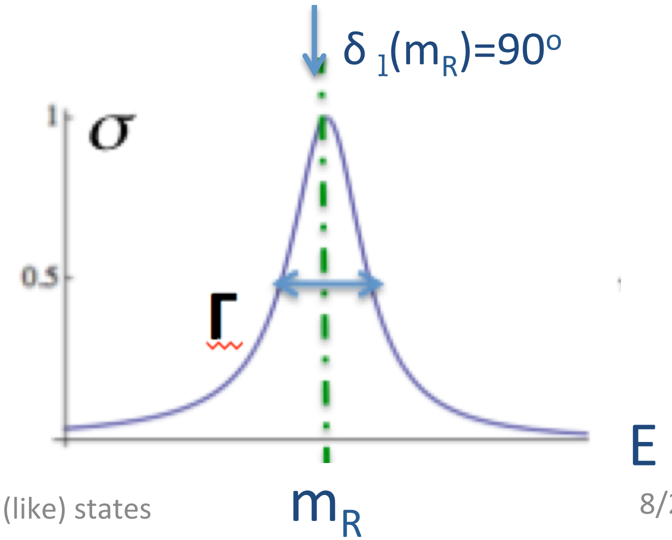
$$\sigma(E) \propto |S(E)-1|^2 \propto |t(E)|^2$$

- only 1 previous lattice study extracted width of charmonium resonances (0^{++} and 1^{--})

  Lang, Leskovec, Mohler, S.P. , 1503.05363, JHEP 2015

- m_R and Γ_R from Breit-Wigner type fits

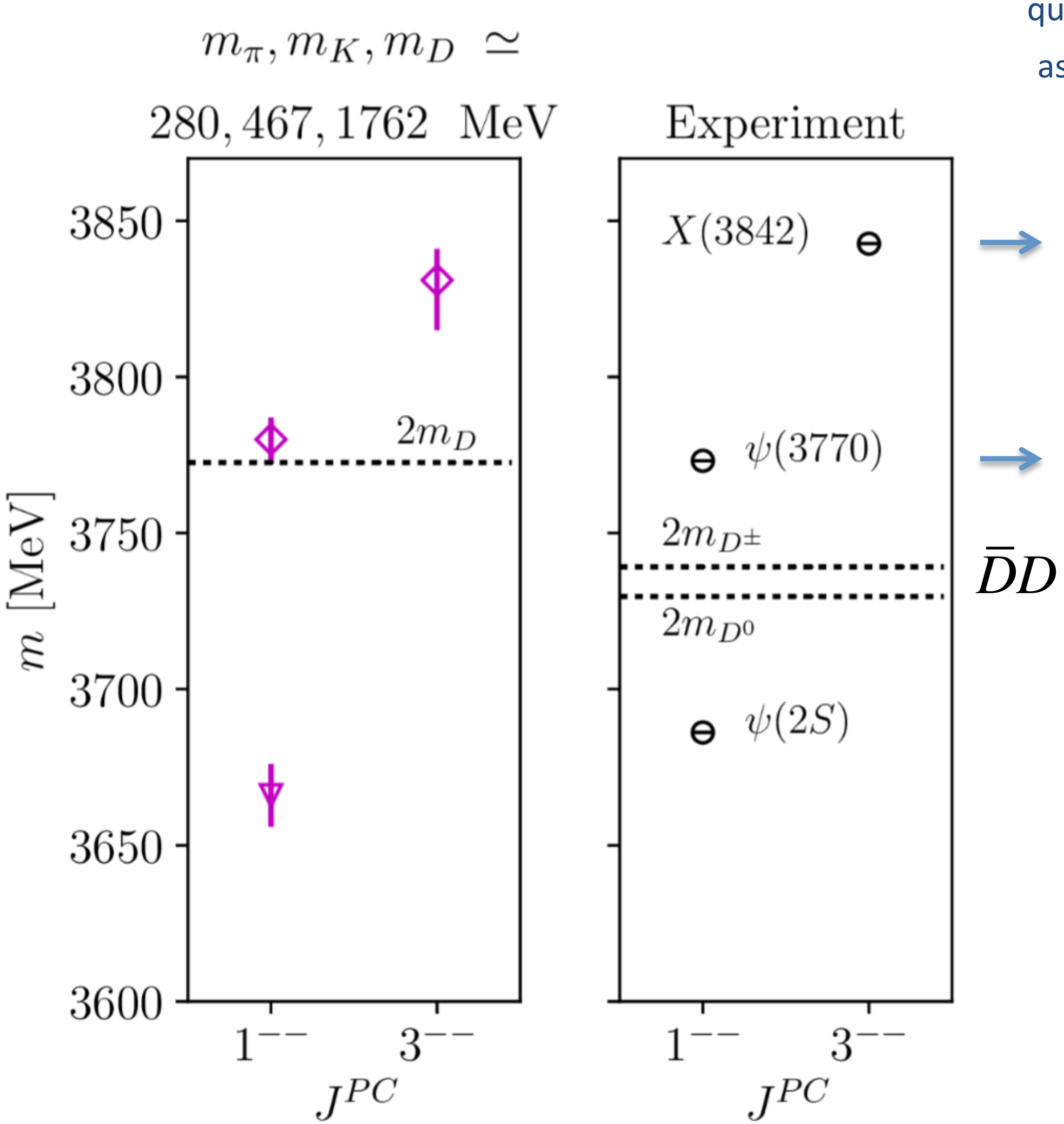




Lattice results for charmonium resonances

$\bar{c}\,c$

1905.03506, PRD 2019



quark model assignment

$n^{2S+1}L_J$

→ 1^3D_3

→ 1^3D_1

widths of resonances:

- ψ(3770)

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

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

- X(3842)

  to narrow to

resolve in this lat. sim.

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

(2) P_c pentaquark channel

U. Skerbis, S.P., 1811.02285, PRD 2019

Lattice study of P_c pentaquark channel

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

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

light-baryon charmonium

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

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)

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

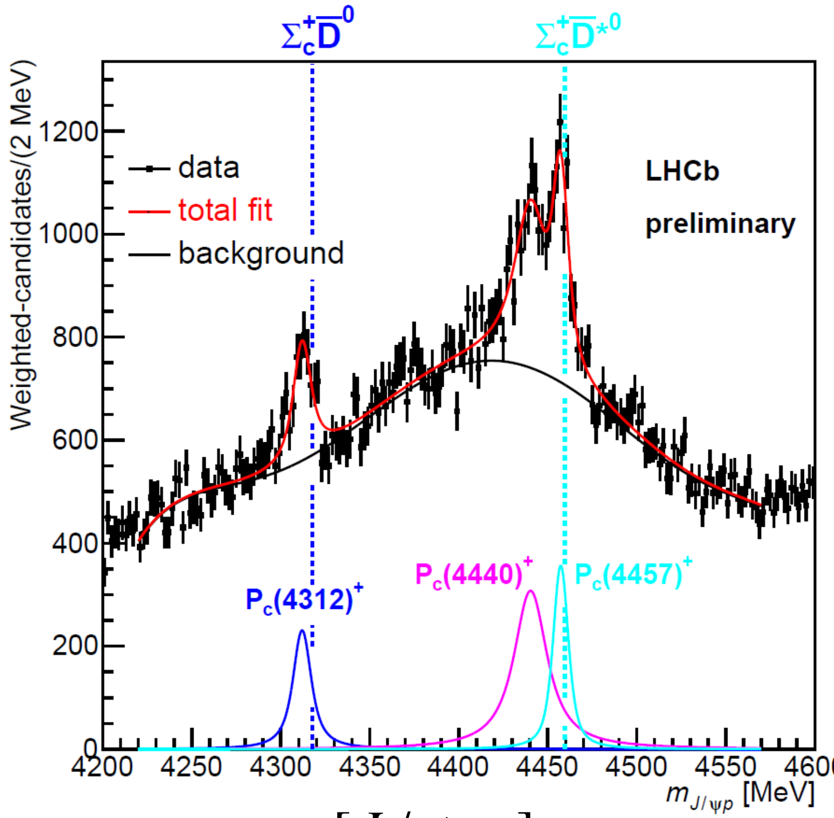
We simulate this scattering and cover also

the energy region of P_c for the first time.

U. Skerbis, S.P., 1811.02285, PRD 2019

The answer from our lattice simulation : No.

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



$m[J/\psi \;\; p]$

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

$\bar{b}b\,\bar{d}u$

(3) Z_b^+ tetraquark channel

S.P., H. Bahtiyar, J. Petkovic, 1912.02656

Zb in experiment

discovered by Belle in 2011 [PRL 108 (2012) 122001]

$$Z_b^+ \rightarrow \Upsilon \;\; \pi^+$$

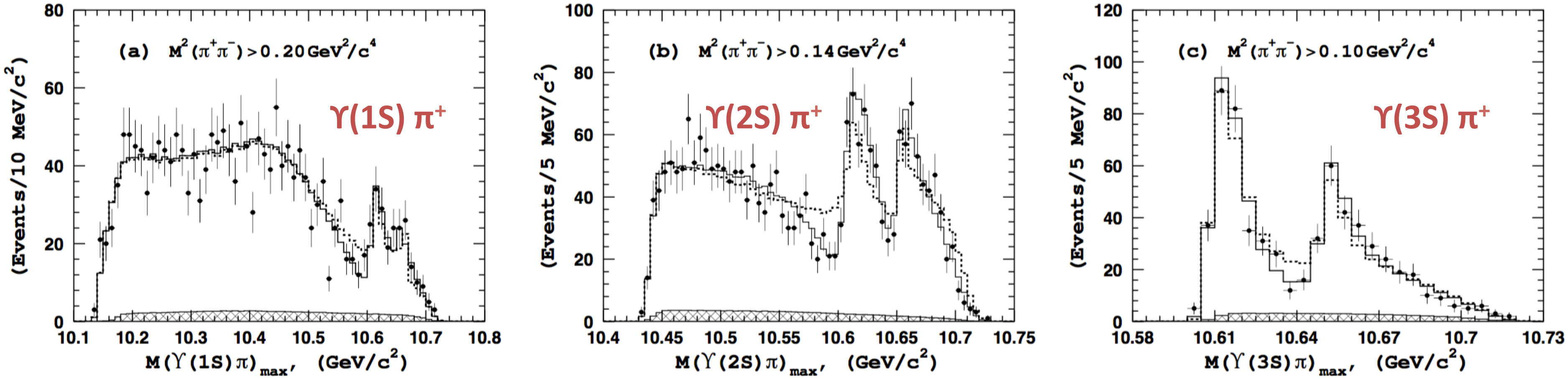
$$\bar{b}b\,\bar{d}u$$

$Z_b^+(10610)$, $Z_b^+(10650)$

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

Z_b observed in decays $\Upsilon(1S)\,\pi$, $\Upsilon(2S)\,\pi$, $\Upsilon(3S)\,\pi$
$h_b(1S)\,\pi$, $h_b(2S)\,\pi$
B <u>B</u>* , B* <u>B</u>*

Belle PRD 91 (2015) 072003



↑ $m_B+m_{B^*}$

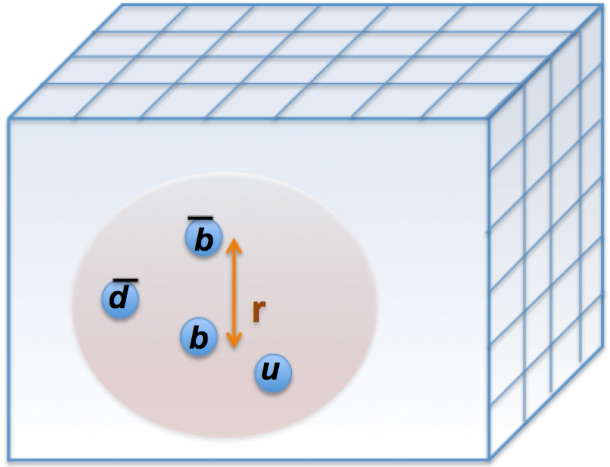
Z_b on the lattice with static b and $\bar{b}$

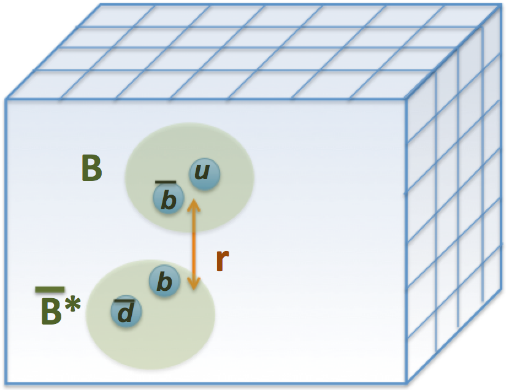
Only previous lat study

Bicudo, Cichy, Peters, Wagner [proceedings Lat16: 1602.07621
proceedings Lat17: 1709.03306]

Born-Oppenheimer approach

Fock components incorporated for $S_{\bar{b}b} = 1$

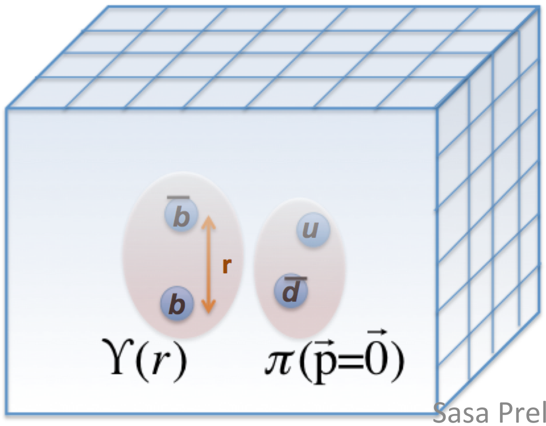


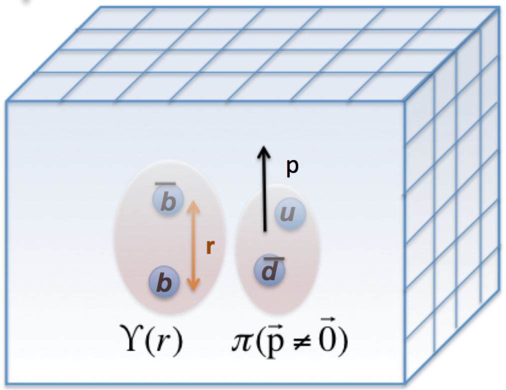


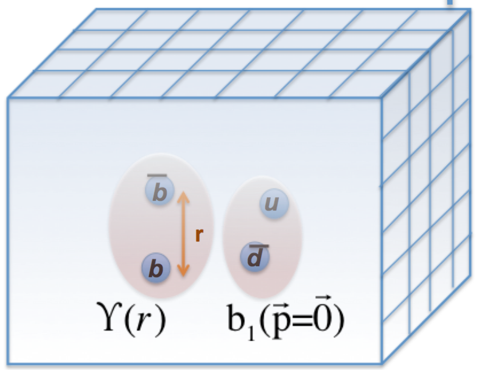
- main aim: extract static potential V(r) between B and $\bar{B}$*
- momentum of light degrees of freedom not conserved

in presence of static quarks

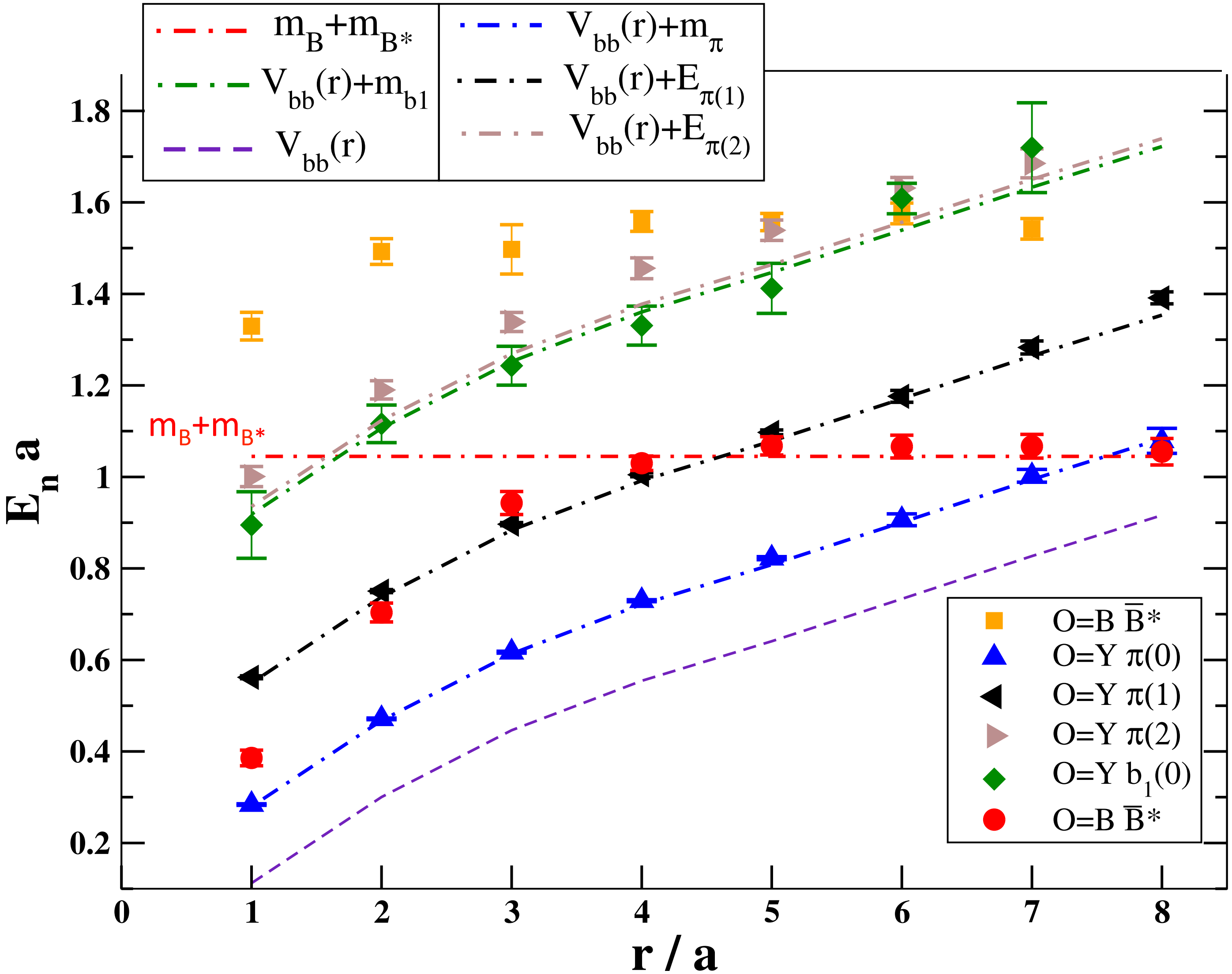
not incorporated before

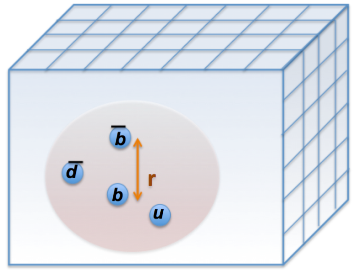






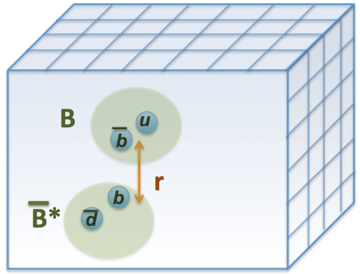
Eigen-energies of Z_b system

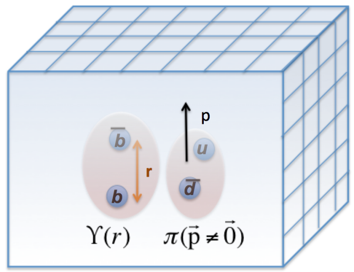


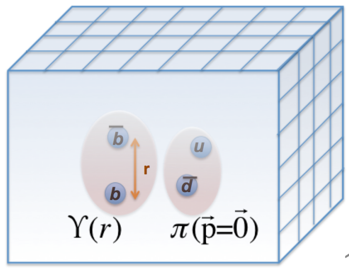


dot-dashed-lines:

$E_n^{\text{non-int}}$

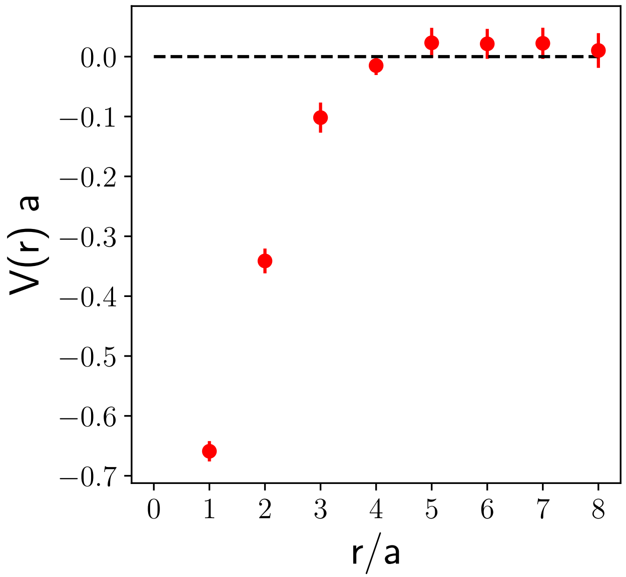


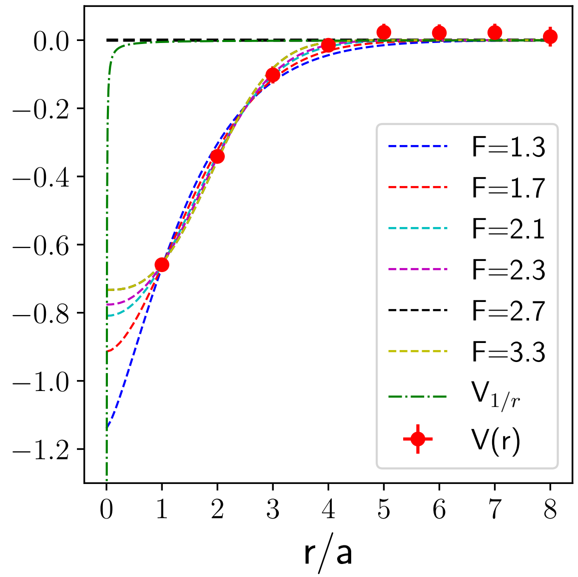


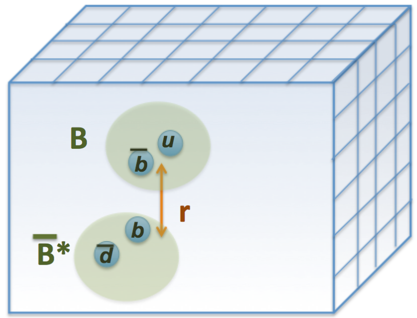


Static potential V(r) for interaction between B and B*

We assume that B B* eigenstate is decoupled from other channels (overlaps support that).







Need for theory input !

- analytic form of potential
- behavior at very small r

V(r<1) = ?

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2}+\frac{\hbar^2 L(L+1)}{2\mu r^2}+V(r)\right]u(r)=Eu(r)$$

$$\mu=\tfrac{1}{2}m_B^{\exp},\quad \psi\propto\frac{u}{r}Y_{LM}$$

We focus on most relevant : s-wave (L=0)

Born-Oppenheimer approach: B and B* move in

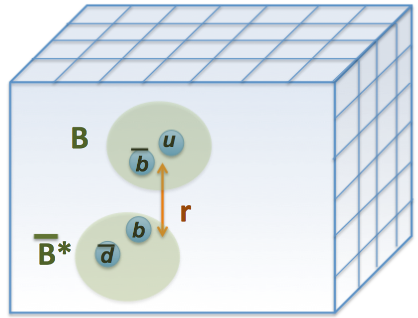
$V(r)= E_n(r) - m_B - m_{B*}$ $(m_{B*}=m_B)$

parametrizing V(r) by

$$V(r)=-A\exp[-(\tfrac{r}{d})^F]$$

Results on Zb based on extracted V(r)

$\bar{b}b\,\bar{d}u$



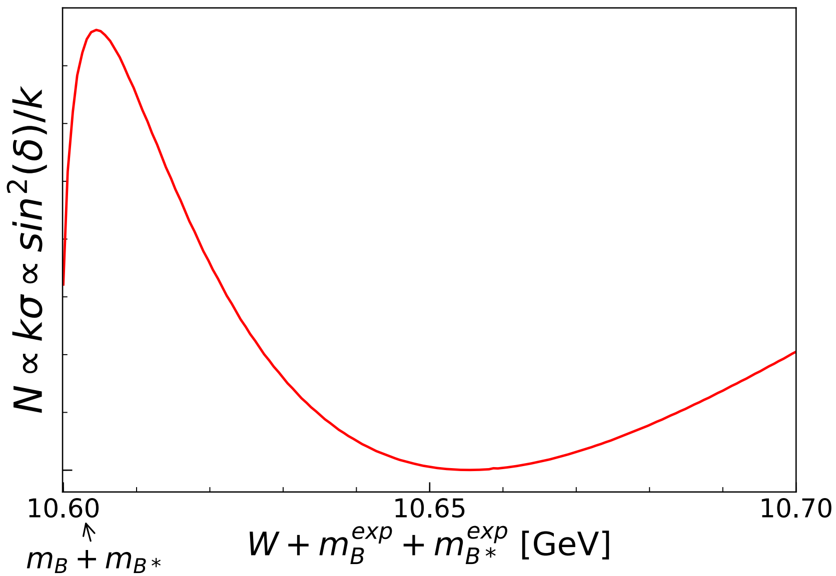
$$V(r) = -A\exp[-(\tfrac{r}{d})^F]$$ for F=1.3

Zb found to be virtual bound state (pole of S-matrix for k=- i|k|)

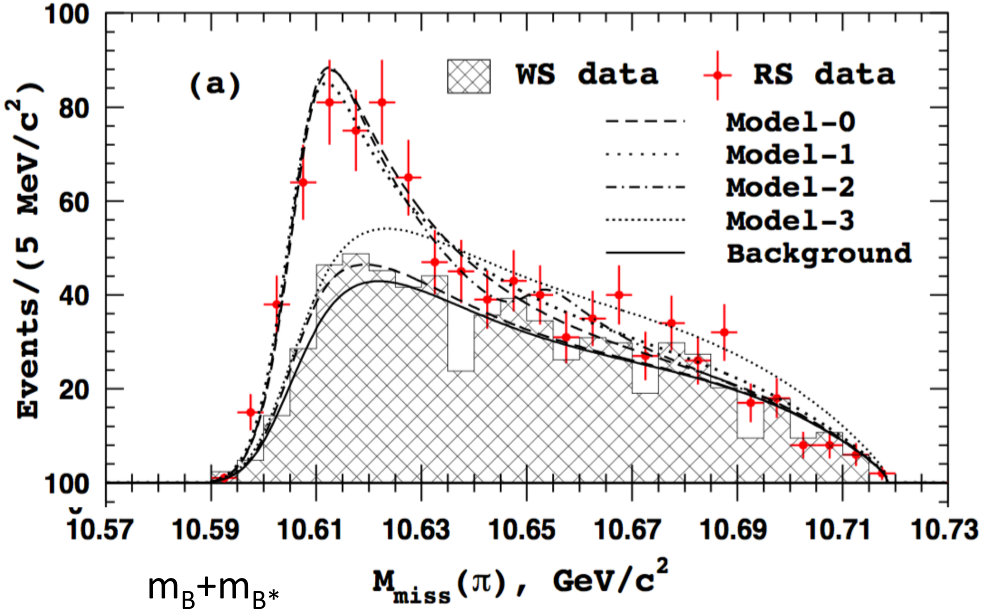
$$M_{Zb} = m_B + m_{B^*} - 13 \pm 10 \text{ MeV}$$

Zb peak is a consequence of virtual bound state

BB* rate from lattice study



BB* rate from Belle 2015



$$M \approx m_B + m_{B*} - 400\ \mathrm{MeV}$$

$$M_{Zb} \approx m_B + m_{B*} - 13\ \mathrm{MeV}$$

lattice

A possible deep bound state !?

If it exist: it could be perhaps visible only in Υ(1S) π, since it is located below all other thresholds.

virtual bound state

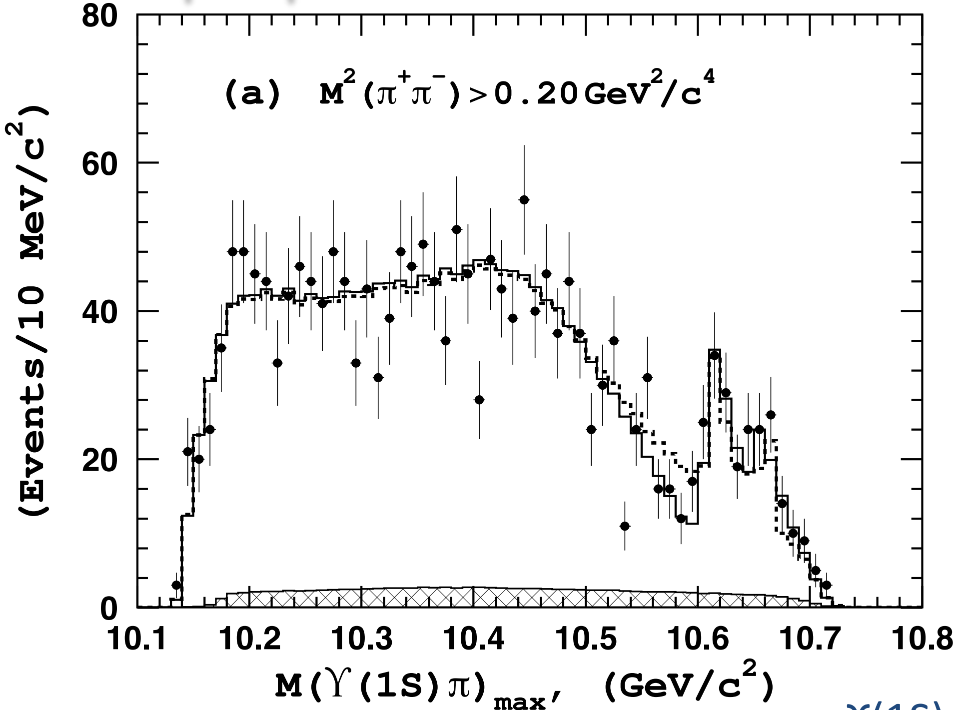
experiment

Belle PRD 91 (2015) 072003

nothing claimed by Belle; significant "bump" could perhaps emerge at higher statistics

exp Z_b res

Relating lattice results to Belle experiment



Υ(1S) π

$m_B + m_{B*}$ - 400 MeV

$m_B + m_{B*}$

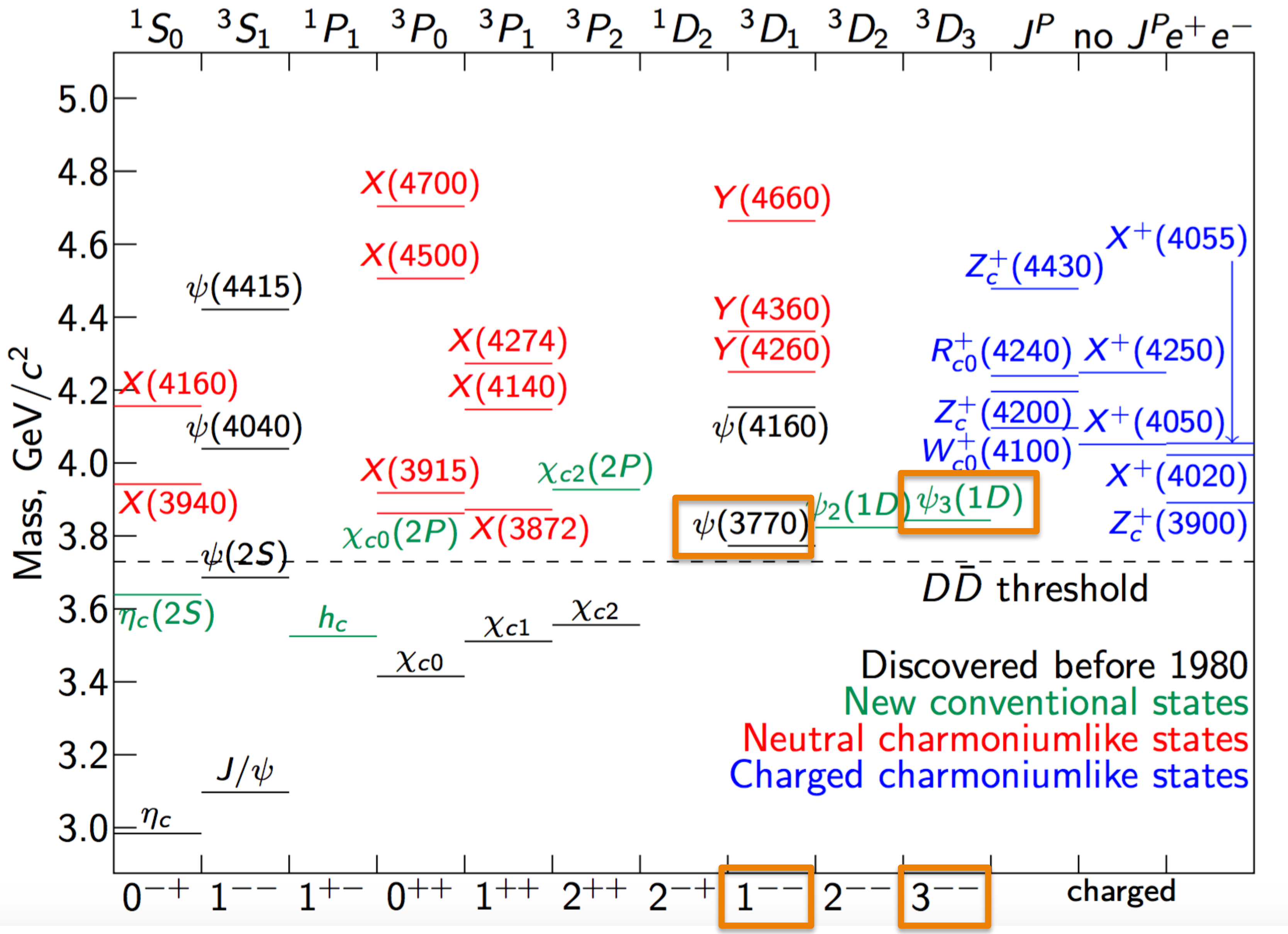
LHCb: try to look for Zb in B<u>B</u>* final state (exclusive or inclusive)

Conclusions

Backup

Charmonium (like) states

plot taken from K.Chilikin, excited QCD 2020



Charmonium resonances in DD scattering
fits of phase shifts for l=1,3

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

p = relative momenta of D-mesons in CMF

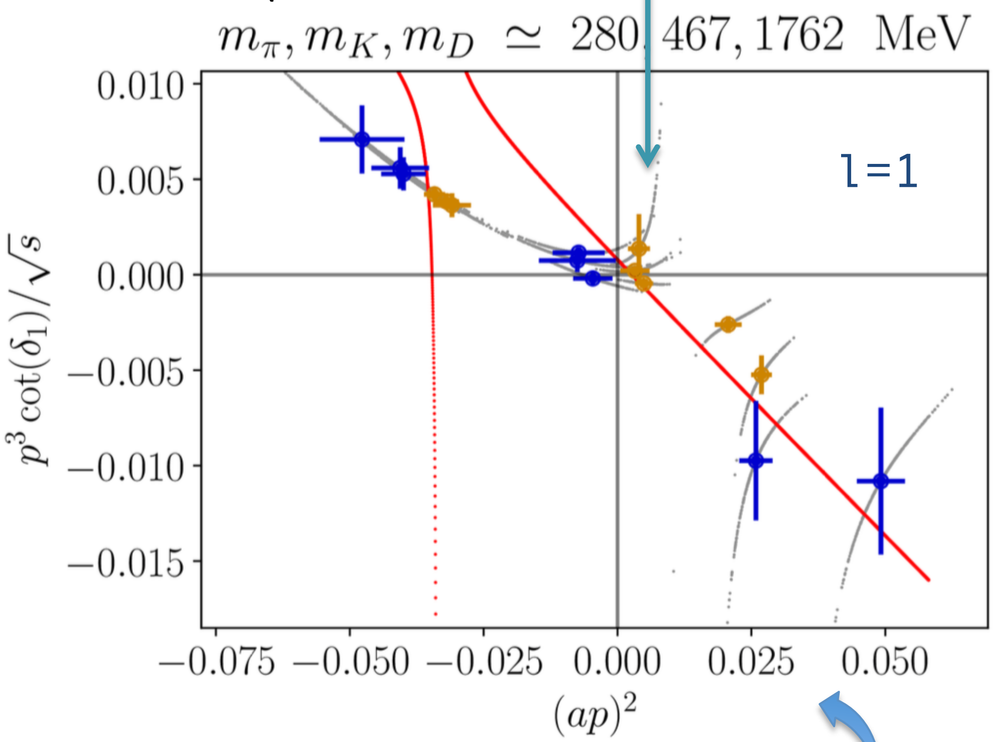
$$\frac{p^{2l+1}\cot(\delta_l)}{\sqrt{s}} = \frac{m^2 - s}{G^2}$$ Breit-Wigner

$\delta_1(m_R)=90^o$

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

δ=90⁰, cot δ=0

Ψ(3770) resonance



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)

Result:

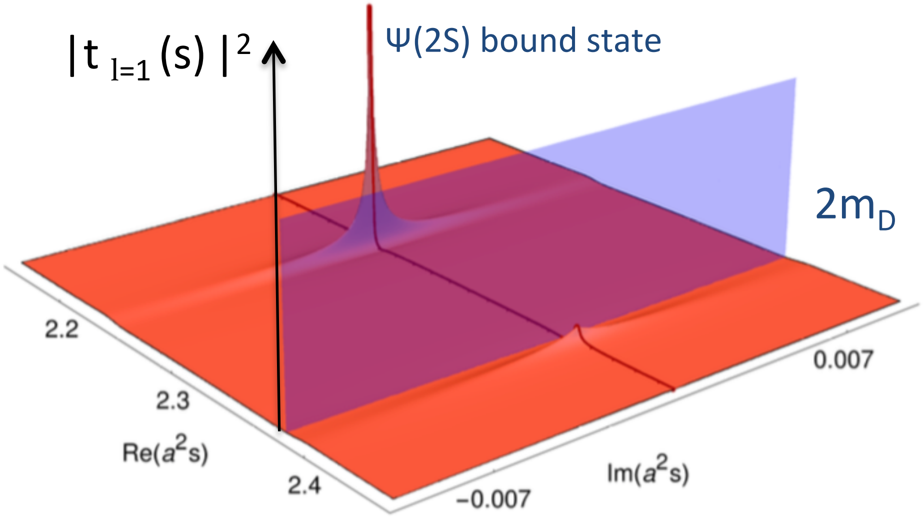
$$\frac{p^{2l+1}\cot(\delta)}{\sqrt{s}} = \begin{cases} \left(\frac{[0.63(33)]^2}{[1.4966(30)]^2 - s} + \frac{[3.69(37)]^2}{[1.5457(32)]^2 - s}\right)^{-1} & l=1 \\ \frac{[1.568(11)]^2 - s}{[0.07(3)]^2} & l=3 \end{cases}$$

Scattering amplitude t(E) in complex energy plane

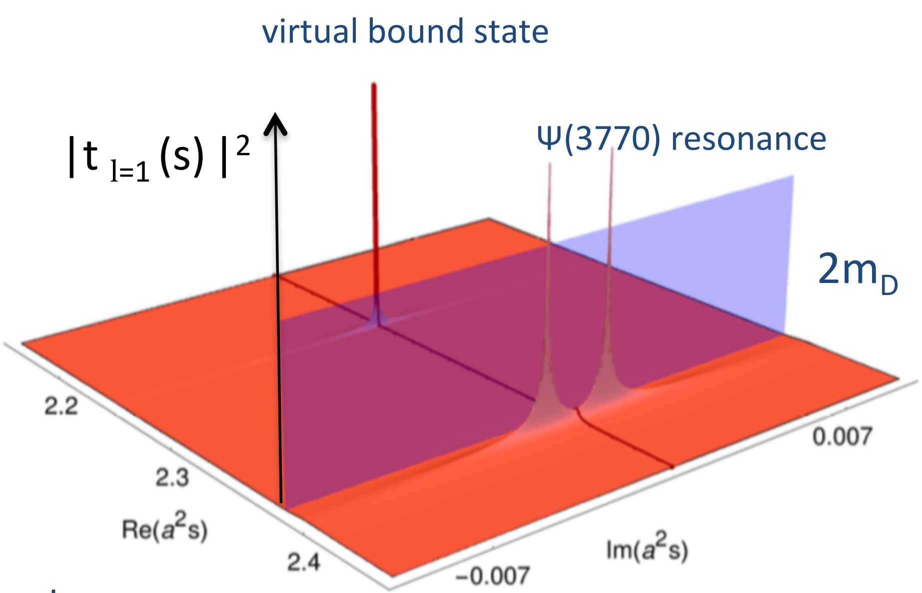
$$S_l(E) = \exp[2i\delta_l(E)] = 1 + 2i\rho\, t_l(E)$$

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

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



(a) I Riemann sheet



(b) II Riemann sheet

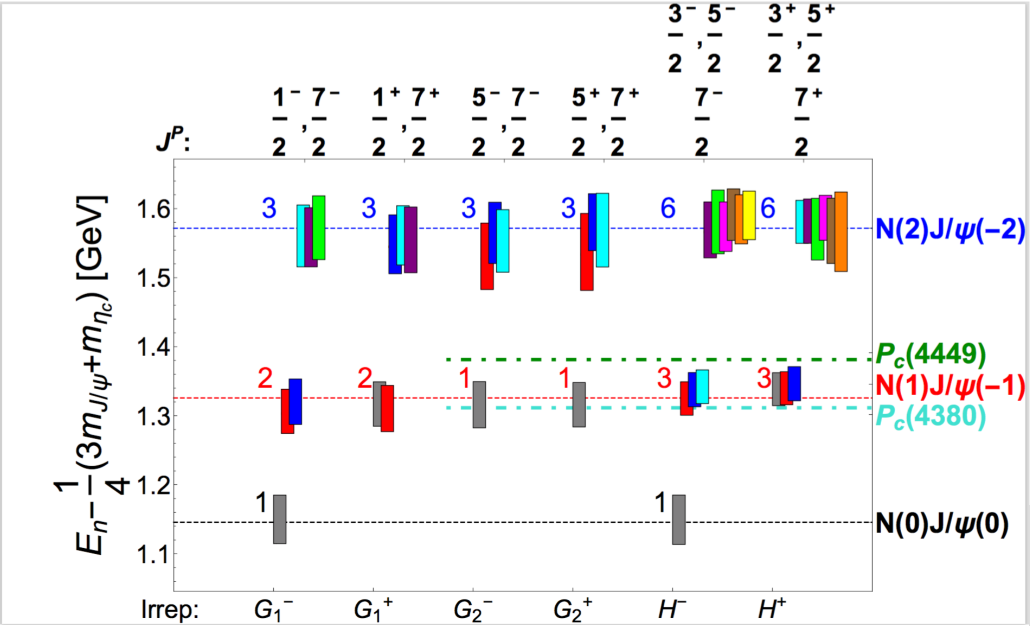
poles in t(s) related to

resonance and bound states

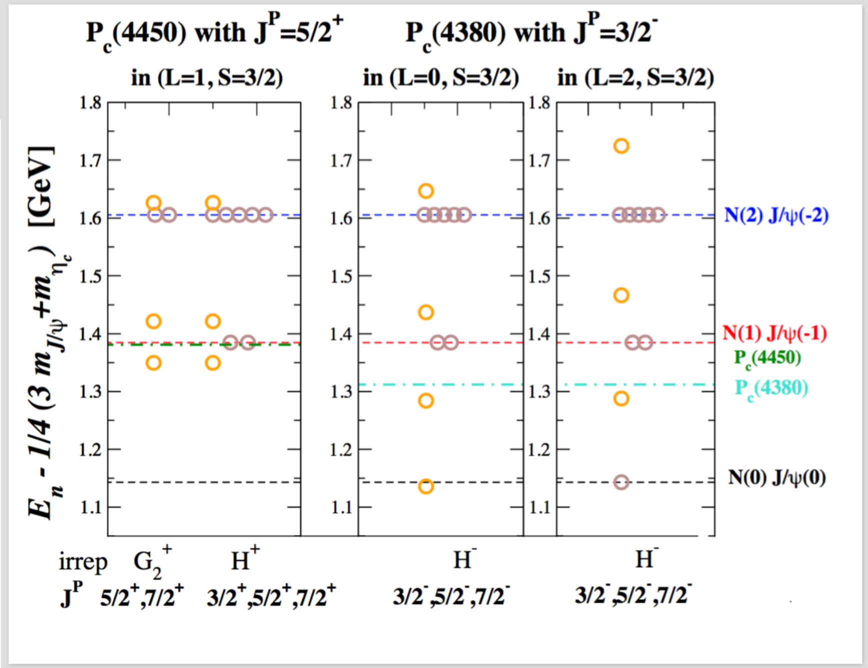
Fig for l=1 and $m_D \approx 1762$ MeV:

one resonance, one bound state, one virtual bound state

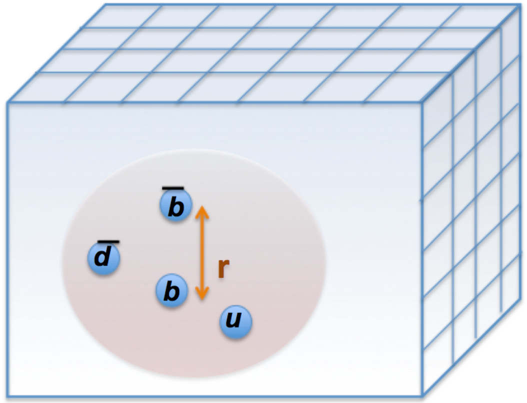
proton J/Ψ scattering in lattice QCD in Pc channels

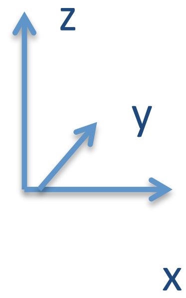


U. Skerbis, S. Prelovsek, 1811.02285



Zb with static b $\underline{b}$





Good symmetries and quantum numbers:

I=1 I_3=0 (consider neutral Z_b)

S_{heavy}=1 $(Sz)_{heavy}$=0 $\bar{b}(\uparrow)b(\downarrow)-\bar{b}(\downarrow)b(\uparrow)$ heavy quark can not flip spin via gluon exchange

note: transition is not possible to final states with S_{heavy}=0 (η_b, h_b)

$(Jz)_{light}$ =0 [Jx and Jy not conserved]

C•P= -1 (P= inversion over midpoint between b and $\underline{b}$)

R_{light}= reflection over yz plane = P_{light} * $R_{light}(y,\pi)$: ε=-1

momentum of light degrees of freedom: not conserved

Masses of bound states in Zb channel

V(r)