Lattice results on exotics with hidden charm and bottom

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Implications of LHCb measurements and future prospects

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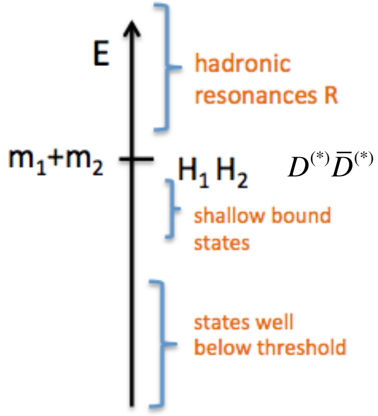
Outline

$\bar{Q}Q\bar{q}q$ $\bar{Q}Q\,qqq$ $\bar{Q}\ glue\ Q$ $\bar{Q}Q$ $Q = c, b$

exotic



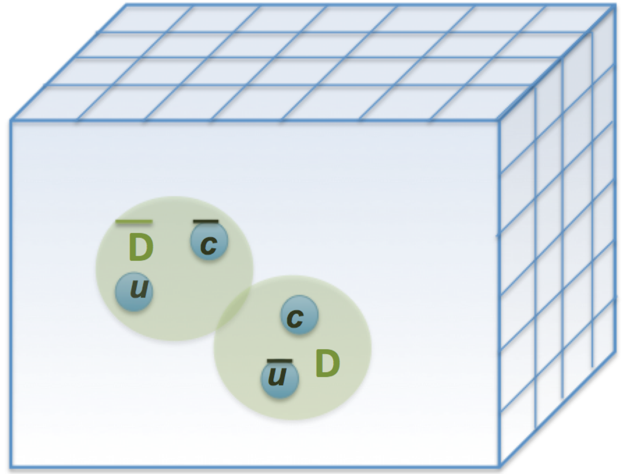
Hadrons with hidden charm and bottom; focus on exotic and lattice results:

- states well below strong decay threshold or treated as strongly stable "doable"
- states above or just below one threshold "more difficult, but doable"
- state above several threshold (Z_c, Z_b, P_c ,...) "challenging"

➢ lattice predictions of yet undiscovered exotic hadrons (but with different flavor than indicated above)

Lattice QCD

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



$$\langle C \rangle = \int DG\, Dq\, D\bar{q}\, C\, e^{-S_{QCD}/\hbar}$$

discretized finite Eucledian space-time

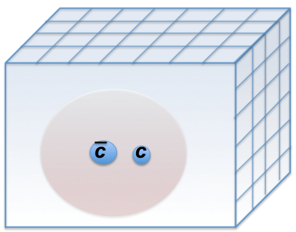
Determine energies of eigenstates E_n and overlaps

$$\text{charmonium}: \quad J^{PC}: \quad \bar{c}\Gamma c\,, \quad (\bar{c}\Gamma_1 u)(\bar{u}\Gamma_2 c) = D\bar{D}\,, \qquad [\bar{c}\Gamma_3 \bar{u}][c\Gamma_4 u]$$

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

overlap

energy of eigenstate |n>



$$J^{PC} = 1^{--}: \quad E_1(\vec{p}=0) = m_{J/\psi}$$

cc and bb annihilation omitted for all result in this talk.

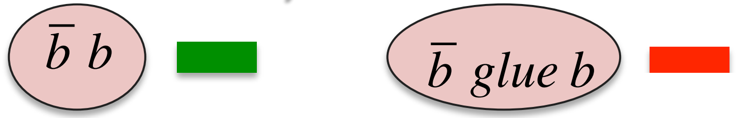
Then hadrons below DD or BB are strongly stable

$$E_n(\vec{p}=0) = m_n$$

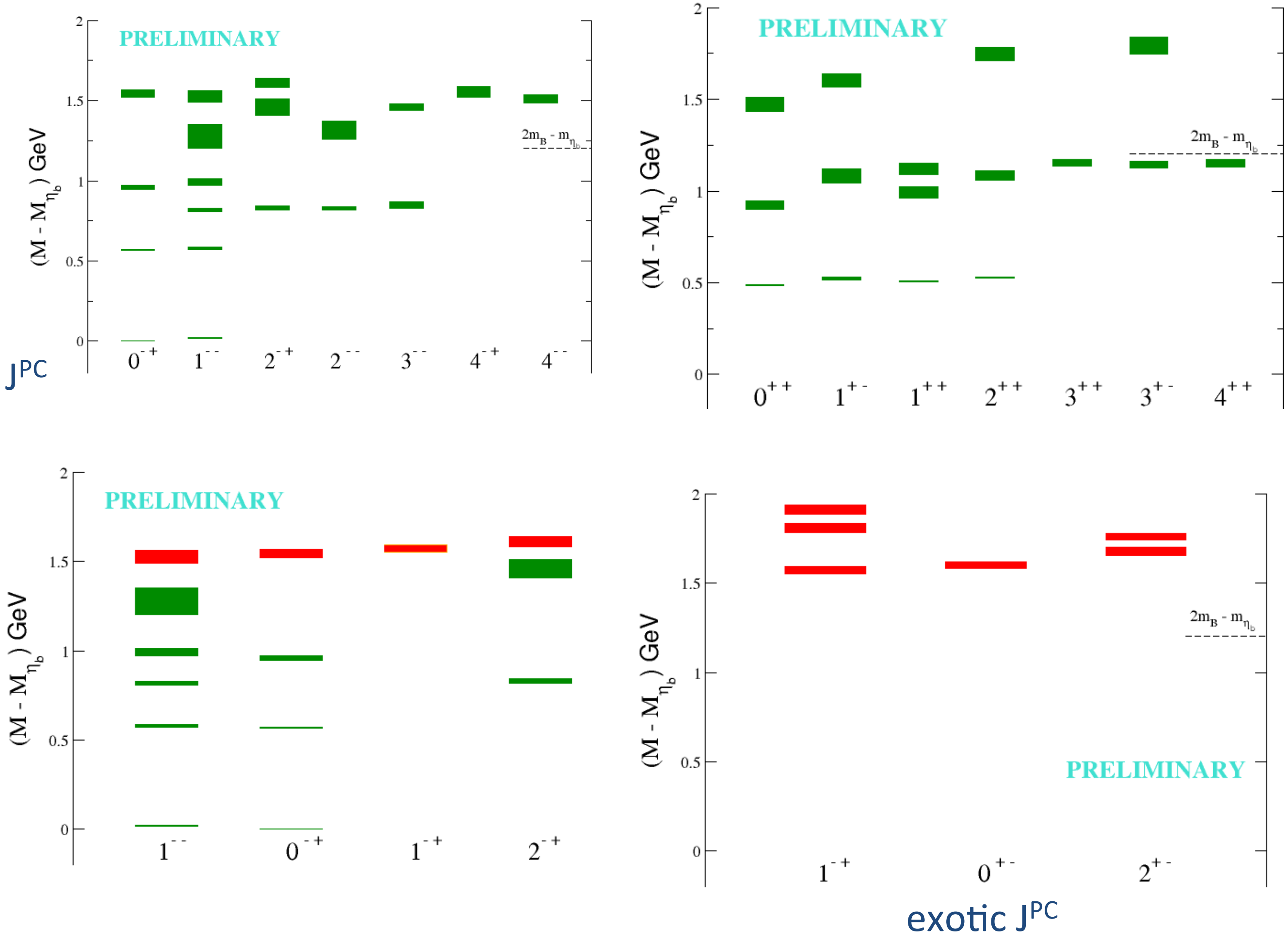
States well below thresholds
or
treated as strongly stable

"doable"

Excited bottomonia, bottomonium hybrids



$m_{hybrid} \geq 10.9$ GeV



S. Ryan & D. Wilson,
Hadron Spectrum Coll,
private communication
details in Lattice2019 talk
(to appear)

lattice QCD: $m_\pi \approx 400$ MeV

relativistic b-quark:

main challenge a m_b errors

states above BB threshold

treated as strongly stable

most of states below B B

experimentally discovered

previous lattice results on
excited bb spectrum

[Wurtz, Lewis, Woloshyn,

1505.04410, PRD]

EFT+lattice prediction of
hybrids [Brambilla, Lai,
Segovia, Castella, Vario,
1805.07713, PRD 2019]

charmonium hybrids:
backup slides

Non-existence of strongly stable fully beautiful tetraquark

$\bar{b}b\bar{b}b$

Lattice QCD: No indication for strongly stable state (below threshold) with

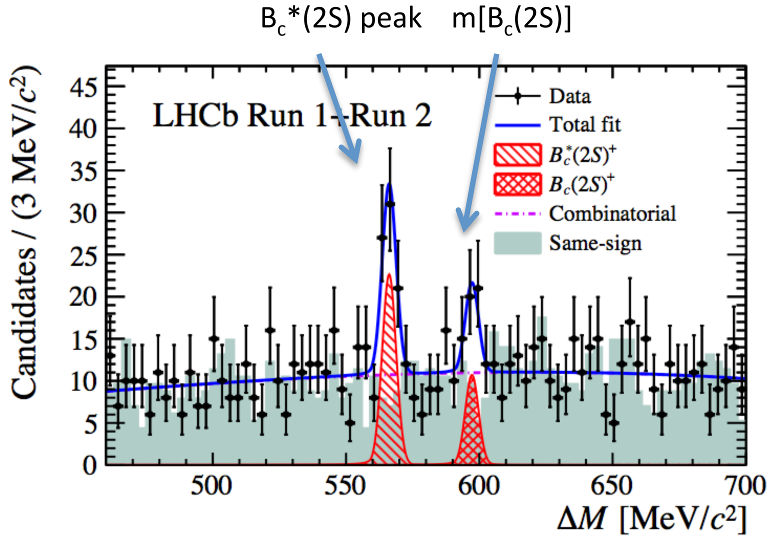
J^{PC} =	0^{++} ,	1^{+-} ,	2^{++}
threshold	$\eta_b\eta_b$	$\eta_b\Upsilon$	$\Upsilon\Upsilon$

[Hughes, Eichten, Davies, HPQCD, 1710.03236, PRD 2018]

Discovery of $B_c^*(2S)$ & confirmation of $B_c(2S)$

$\bar{b}c$

[LHCb, 1904.00081, PRL]



$$m[B_c(2S)]: \quad 6872.1(1.3)(0.1)(0.8)\ \text{MeV}$$

$$B_c^*(2S) \text{ peak at } M = m[B_c(2S)] - \Delta M \quad 6841.2(0.6)(0.1)(0.8)\ \text{MeV}$$

agrees with [CMS, 1902.00571, PRL]

$$B_c^*(2S) \to B_c^* \pi^+\pi^-, \quad B_c^* \to B_c \gamma$$

photon undetected

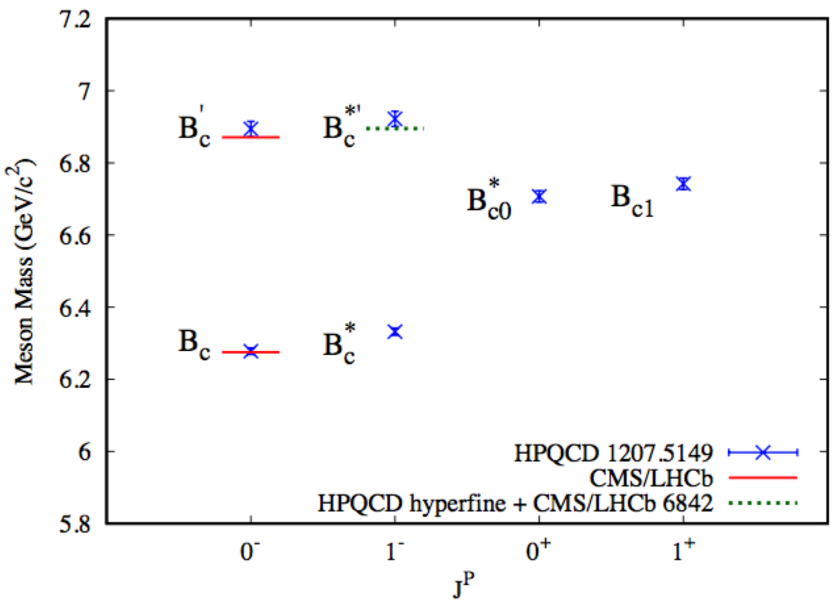
Lattice QCD:

[HPQCD, 1207.5149,

Lytle, talk at QWG19]

c: relativistic

b: NRQCD



$$\Delta M = \{m[B_c^*] - m[B_c]\} - \{m[B_c^*(2S)] - m[B_c(2S)]\}$$

m[$B_c^*(2S)$] determined using

ΔM from experiment and

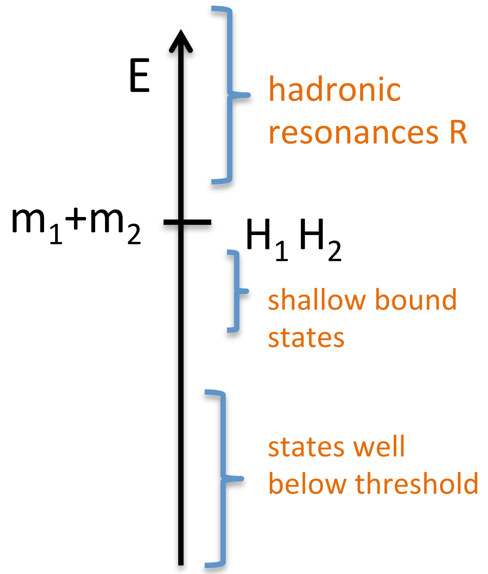
m(Bc*)-m(Bc) from lattice (HPQCD)

$c\bar{c}$ and $b\bar{b}$ annihilation omitted for all result in this talk.

Then hadrons below $D\bar{D}$ or $B\bar{B}$ are strongly stable

strong decay threshold:

$D^{(*)}\bar{D}^{(*)}, \quad B^{(*)}\bar{B}^{(*)}$

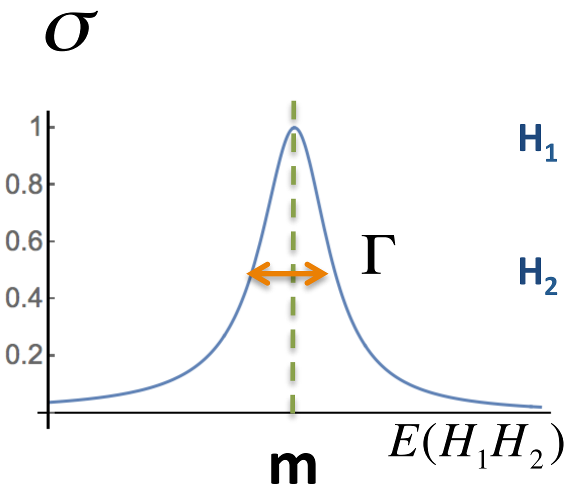


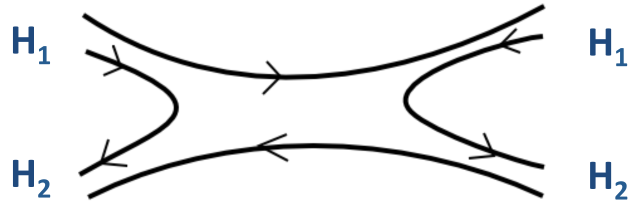
States above or slightly below one threshold

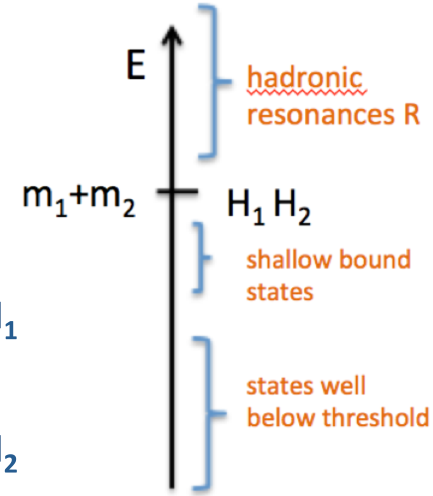
"more difficult, but doable"

All experimentally discovered exotic hadrons are strongly decaying resonances !

Hadronic resonances and shallow bound states from lattice (near/above one threshold)



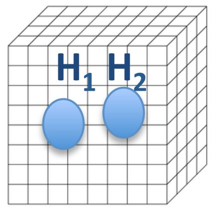




$$T_B(E) \propto \frac{1}{E^2 - m_B^2} \qquad T_R(E) = \frac{-m_R\,\Gamma}{E^2 - m_R^2 + i\,m_R\,\Gamma}$$

$$T_B(E = m_B) = \infty$$

$$\sigma(E) \propto |T(E)|^2$$



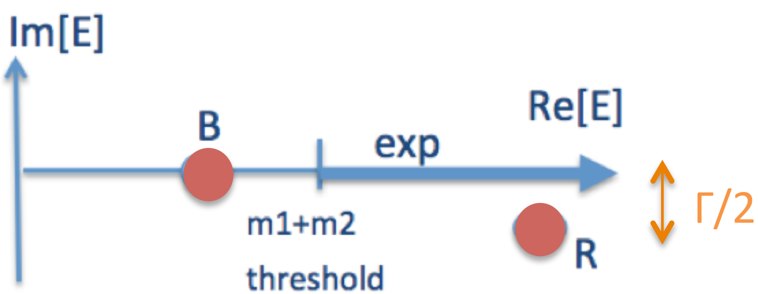
energy of eigenstate

scattering matrix for real E

E → $T(E)$

analytic relation: Luscher 1991

continuation to complex E



location of poles in complex E plane

$E=E_{cm}$

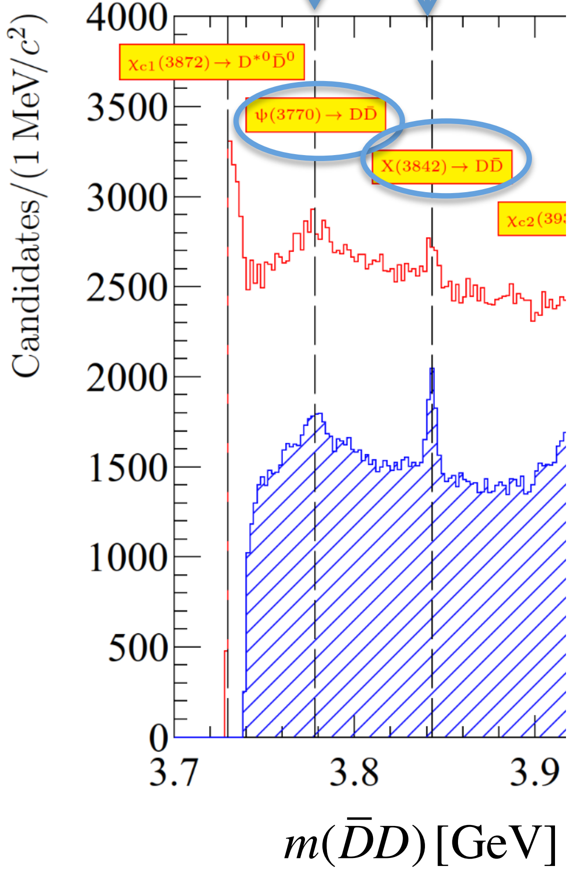
Charmonia with $J^{PC}=3^{-}$ and 1^{--}

$\bar{c}\,c$ conventional

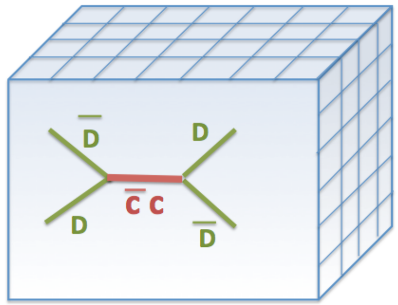
$n\,^{2s+1}l_J = 1\,^3D_3,\ 1\,^3D_1$

LHCb 2019, 1903.12240, JHEP 2019

$J^{PC}=1^{--}$ 3^{--}

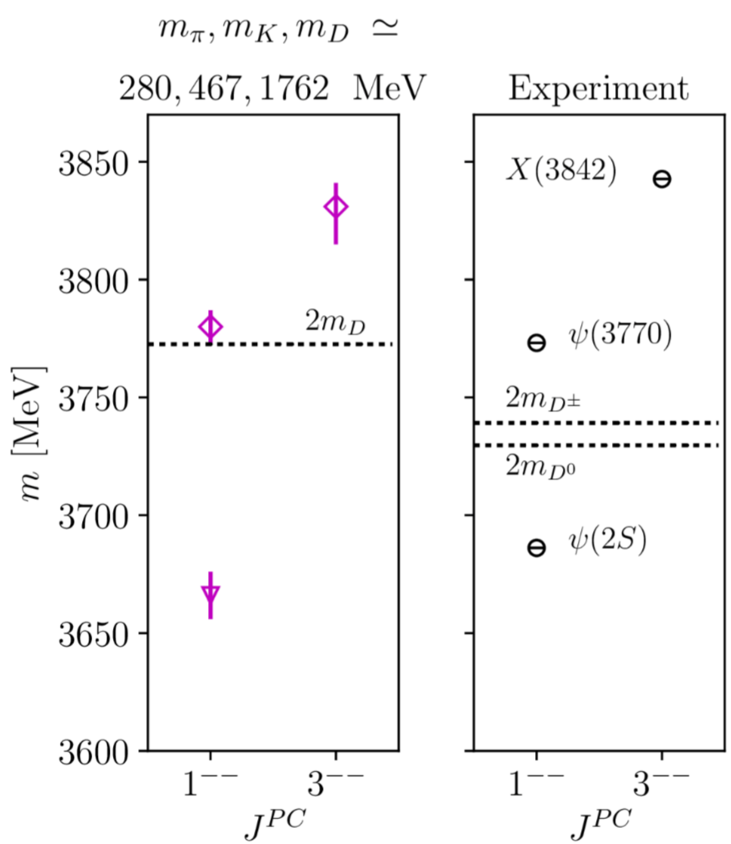


first discovery of charmonium with J=3



partial waves L=3 and L=1

Lattice QCD: Piemonte, Collins, Padmanath, Mohler, S.P. : 1905.03506, PRD 2019



widths of resonances:

- ψ(3770)

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

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

- X(3842)

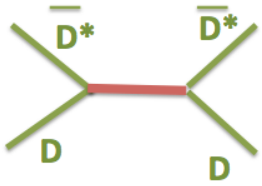
  to narrow to resolve in this lat. sim.

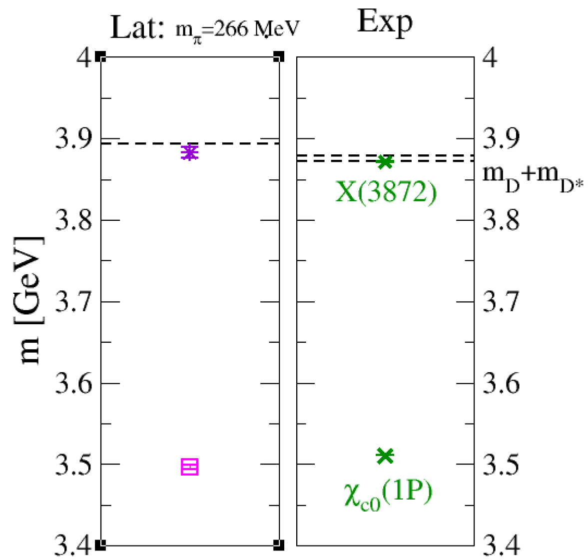
χ_{c1}(2P) aka X(3872)

$\bar{c}c + \bar{c}q\bar{q}c$

[Belle, 2003]

Aim: look for poles in D$\bar{\text{D}}$* scattering matrix





- Lattice QCD
- first evidence [S.P.,Leskovec, 1307.5172, PRL 2013]
- Fock components: [Padmanath, Lang, S.P., 1503.03257, PRD 2015]

  crucial: $D\bar{D}^*$, $\bar{c}c$, less important: $(\bar{c}q)(cq)$

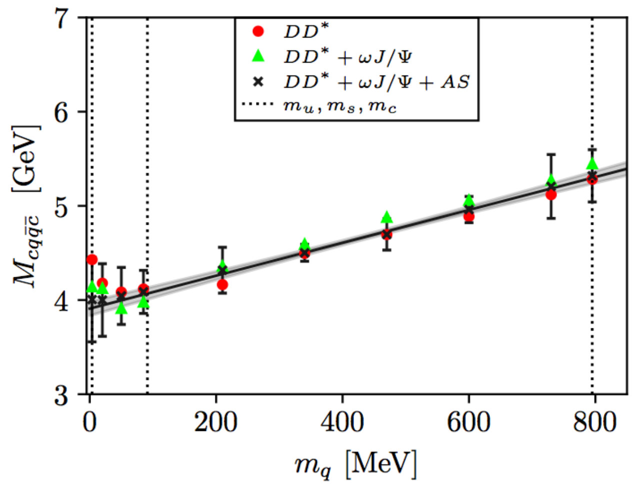
  no charged partner found up to m=4.2 GeV (in agreement with exp)

  unfortunately, no other published lattice paper on X(3872) till now

- Dyson-Schwinger / Bethe-Salpeter approach

  [Wallbott, Eichmann, Fischer, 1905.02615, PRD 2019]

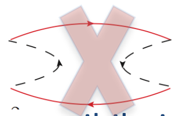
  location of pole in the scattering matrix



$$M_{1^{++}}^{cq\bar{q}\bar{c}} = 3916(74)\ \text{MeV}$$

mass not accurate enough to determine whether below or above D$\bar{\text{D}}$* threshold

- pole for X found although



  $\bar{c}$c Fock component omitted, $\bar{q}$q annihilation omitted

  (in contrary: lattice studies find that $\bar{c}$c is crucial for getting pole related to X)

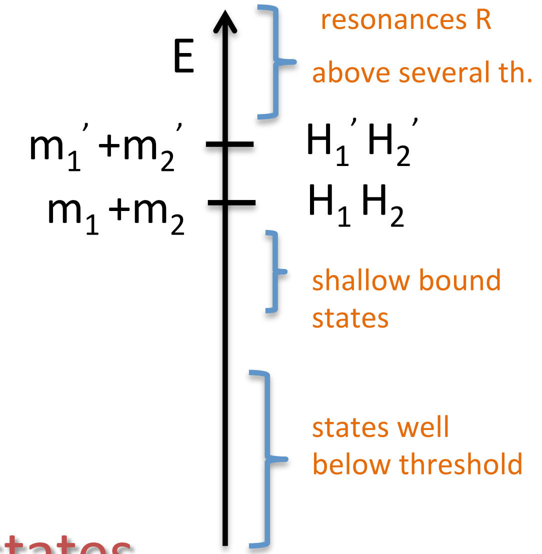
- exp evidence that X is not completely molecular:

  ideal combination of I=0,1 (molecule) would lead to completely dominant rate to J/Ψ ρ (since J/Ψ ω is 7 MeV above and ω is very narrow), while exp rates are comparable

  $\bar{c}c : (I=0)$

  molecule: $(I=0)+(I=1)$

  $X \to J/\psi\ \omega,\ J/\psi\ \rho$



Hadrons that strongly decay to several final states

Scattering in two or more channels

"challenging"

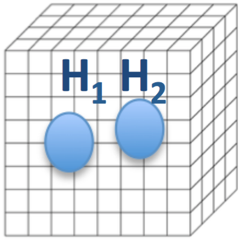
examples: all experimentally discovered Zc, Zb, Pc

Extracting scattering matrix from lattice

Resonance above one threshold

$$R \rightarrow H_1 H_2 \qquad T(E) \quad \leftarrow E_n$$

Luscher's method



Lattice simulation of one-channel scattering via Luscher's method: doable

Resonance above two or more thresholds

most of exotic hadrons are above more than one threshold, for example Zc(4430)

$$R \rightarrow H_1 H_2,\; H_1' H_2'$$

channel a : $H_1 H_2$

channel b : $H_1' H_2'$

a -> a a -> b

$$T(E) = \begin{bmatrix} T_{aa}(E) & T_{ab}(E) \\ T_{ab}(E) & T_{bb}(E) \end{bmatrix} \quad \leftarrow E_n$$

b->a b -> b

Luscher's method

Lattice simulation of coupled-channel scattering via Luscher's method: challenging

- several coupled channels studied in the light-quark sector (Hadron Spectrum collaboration)
- only simulations for hadrons with heavy quarks

  excited D mesons [Moir, Peardon, Ryan, Thomas, Wilson, 1607.07093, JHEP 2016]

  Z_c channel [Chen et al., CLQCD, 1907.03371]
- final conclusions on many interesting states therefore not available (yet)

P_c pentaquarks

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

J^P not determined from exp.

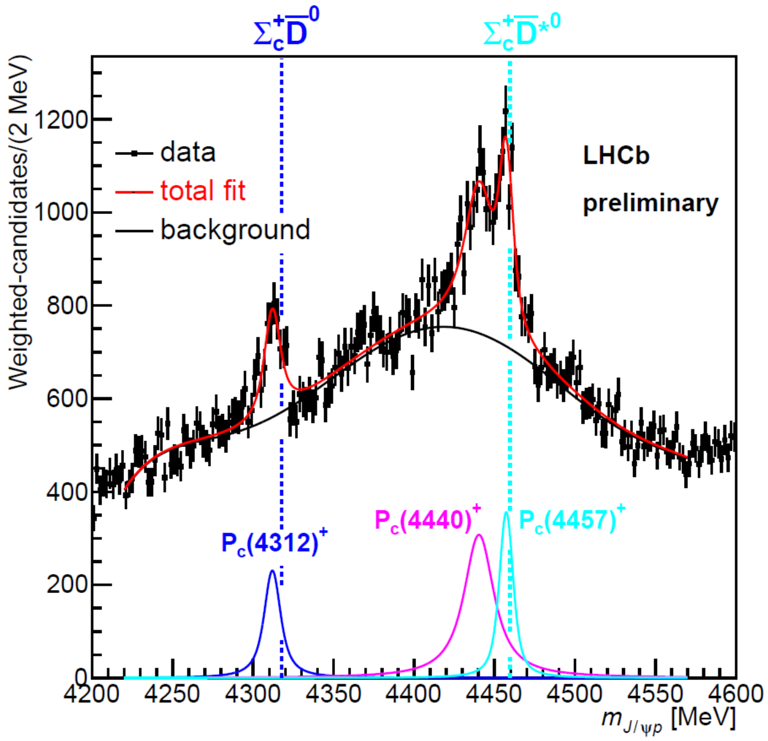
Expected J^P for molecule in s-wave:

$\Sigma_c(\frac{1}{2}^+)\bar{D}(0^-) \to J^P = \frac{1}{2}^-$ $\Sigma_c(\frac{1}{2}^+)\bar{D}^*(1^-) \to J^P = \frac{1}{2}^-, \frac{3}{2}^-$

$P_c = \text{uud}\bar{\text{c}}\text{c} \to (\text{uud})\,(\bar{\text{c}}\text{c})\text{: p J}/\Psi,\ldots$

$\to (\text{udc})\,(\bar{\text{c}}\text{u})\text{: } \Sigma_c^+\,\bar{D}^0,\ldots$

[LHCb 2019, 1904.03947, PRL]



Indications that $\Sigma_c^+ \underline{D}^{(*)}$ **molecular** component is important:

- **experiment** finds them slightly below those thresholds
- supported by **phenomenological models** with ρ/ω exchange

  predicted 2010-2012 [Wu, Molina, Oset, Zou, 1007.0573, PRL; Wu et al., 1202.1036. PRC, Yang et al, 1105.2901, Wang et al, 1101.0453, PRC]

- **Lattice QCD** addressed simplified question:

Do Pc resonances appear in one-channel

$$p\ \ J/\psi \to P_c \to p\ \ J/\psi$$

scattering if it is decoupled from other channels ?

Answer: No [Skerbis, S. P., 1811.02285, PRD 2019]

T(E)≈0 within large errors, small interaction, no resonance

This indicates that coupling of p J/ψ channel with other two-hadron channels is likely responsible for Pc in experiment (in line with LHCb result)

$Z_c^+(3900)$ $\bar{c}c\,\bar{d}u$ $J^P=1^+$

$Z_c^+ \to J/\psi\ \pi^+, \cdots$ [BES III, Belle, 2013]

Consensus on the nature of Zc(3900) has not been achieved

- re-analysis of all experimental data is compatible with several scenaria
  resonance pole above th., bound state, virtual bound state,
  kinematical enhancement via triangular diagram
  [Pilloni et al, 1612.06490, PLB 2017]

- Lattice QCD :
  extract scattering matrix for coupled channel scattering $J/\psi\ \pi\ ,\ D\bar{D}*$

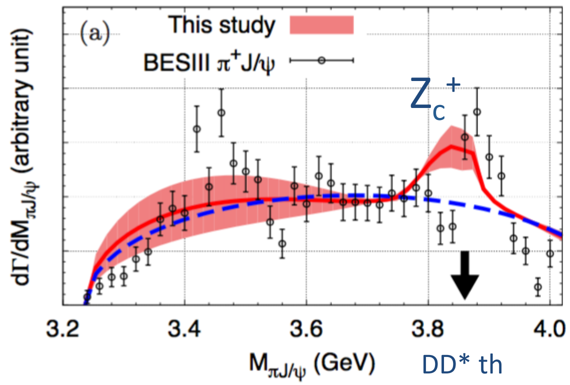
➢ [Ikeda et al., HALQCD, 1602.03465, PRL]
  HALQCD method (which was not verified yet on any conventional resonance)

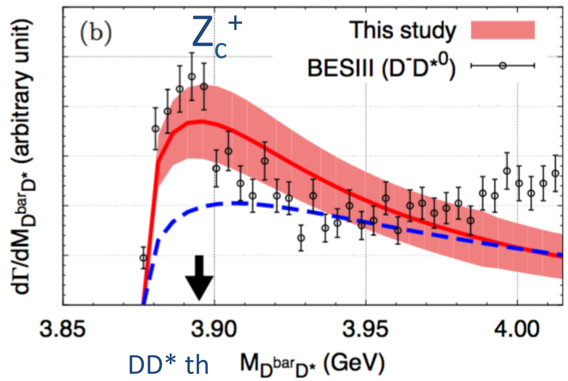
- Z_c*(3900) coupled-channel effect due to sizable J/Ψ π and DD* coupling, not genuine resonances (i.e. pole on the unphysical sheet above DD* th.)

➢ [Chen et al., CLQCD, 1907.03371]

- Luscher's method : T(E) ≈ small, small interaction
  no narrow resonance behavior found near DD* th.
- in line with previous lattice study that did not extract the scattering matrix
  [S.P. et al, 1401.7623, PRD 2015 & HSC, 1709.01417, JHEP 2017]

[Ikeda et al., HALQCD, 1602.03465, PRL]



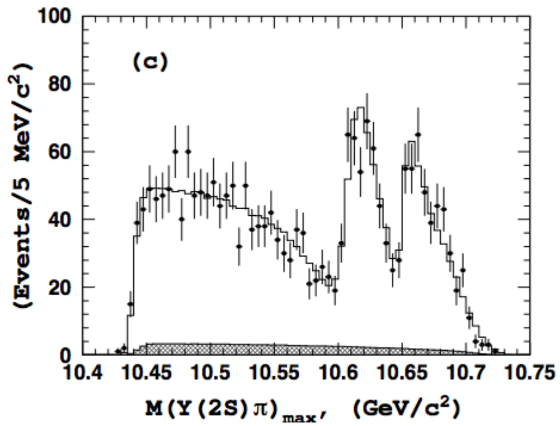


differential rate from lattice

rate from lattice if coupling between J/Ψ π and DD* channels set to zero by hand

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

$\bar{b}\, b\, \bar{d}\, u$ $J^P=1^+$



$\downarrow$ m_B+m_{B*}

$$Z_b^+ \rightarrow \Upsilon(1S,2S,3S)\pi^+, \quad h_b(1S,2S)\pi^+, B^{(*)}\bar{B}*$$

[Belle, 1110.2251, PRL 2012]

Indications that molecular B $\underline{B}^*$ in $Z_b^+(10610)$ is crucial:

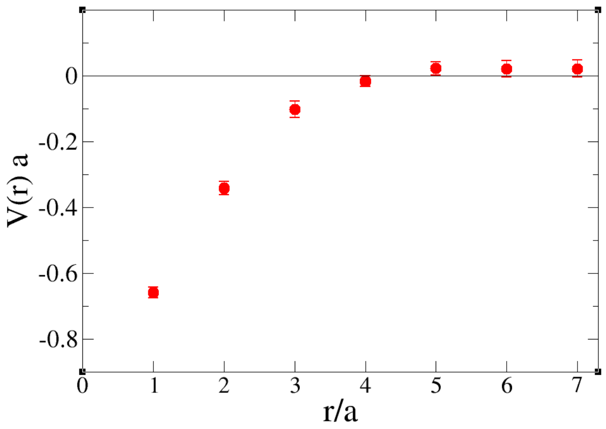
- lies near mB+mB* threshold
- Br(B $\underline{B}^*$)≈85 % although this mode is phase space suppressed
- molecule $(S_{\bar{b}b}=1)\otimes(S_{\bar{q}q}=0)\pm(S_{\bar{b}b}=0)\otimes(S_{\bar{q}q}=1)$

  this makes it natural that Z_b decays comparably to ϒ ($S_{\underline{b}b}$=1) and h_b ($S_{\underline{b}b}$=0)

- Exploratory (!) lattice study of $(S_{\bar{b}b}=1)\otimes(S_{\bar{q}q}=0)$ component with static b-quarks

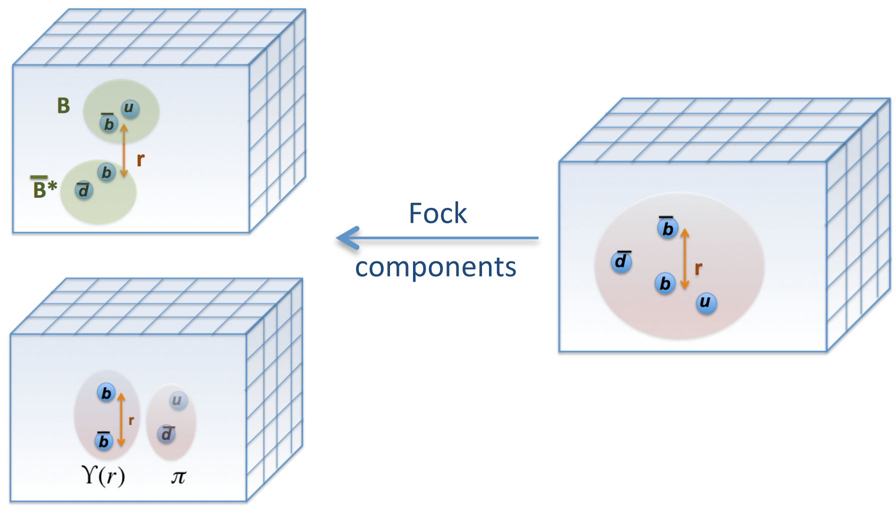
  [S.P., Bahtiyar, Petkovic, 1909.02356], inspired by [Peters, Bicudo, Wagner, 1602.07621]

eigen energies E_n render potential between B and $\underline{B}$*



a=0.12 fm

Strong attraction between B and $\underline{B}$* for r=0.1-0.4 fm. Might be responsible for existence of Zb

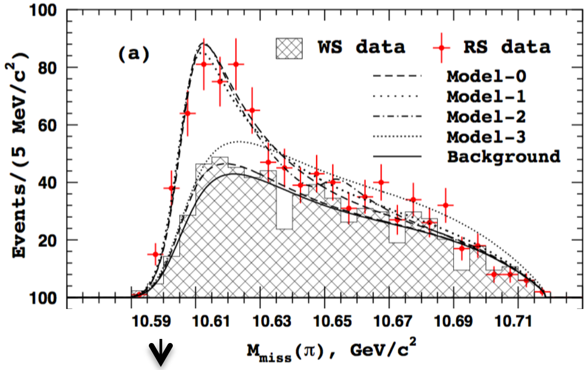


$Z_b^+(10610)$, $Z_b^+(10650)$

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

[Belle, 1512.07419, PRL 2016]

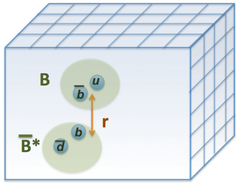
$Z_b(10610)$ in B$\underline{\text{B}}$* decay mode



mB+mB*

- Lattice study, continued

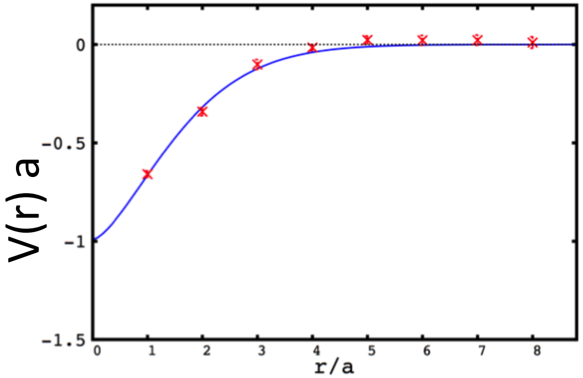
  [S.P., Bahtiyar, Petkovic, 1909.02356]



V(r) between B and $\underline{\text{B}}$*

a=0.12 fm

V(r<0.1 fm) = ?

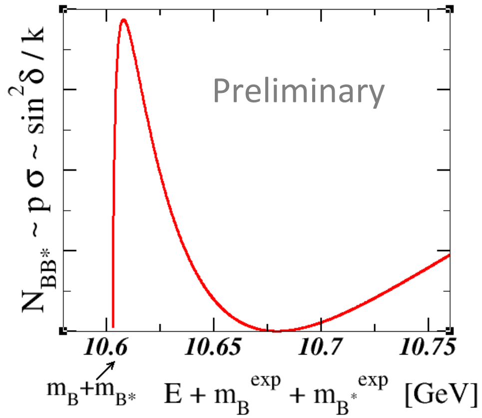


Solving Schrodinger equation for B$\underline{\text{B}}$* system with this V(r).

Observed attraction leads to virtual B $\underline{\text{B}}^*$ bound state slightly below threshold

$$\mathrm{Re}[E_{Zb}] = -32^{+29}_{-5}\ \mathrm{MeV}$$

This pole leads to peak in N_{BB^*} above threshold (similar to exp) →



- Virtual bound state consistent with reanalysis of exp data

  [Wang, Baru, Filin, Hanhart, Nefediev, Wynen, 1805.07453, PRD 2018]

- So far Z_b found only by Belle
- Could LHCb search for Zb in inclusive final state with $B\bar{B}^*$?

pole of T(W) at W_B

p= + i |p| for bound state

p= - i |p| for virtual bound state

$$W_B = \sqrt{m_B^2 + p^2} + \sqrt{m_{B^*}^2 + p^2} < m_B + m_{B^*}$$

Lattice predictions of yet unobserved hadrons

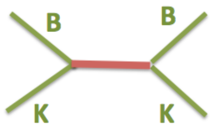
- there are no reliable lattice PREdictions for yet-unobserved $\bar{Q}Q\bar{q}q, \quad \bar{Q}Qqqq \quad (Q = c, b)$
  since these states likely lie above several thresholds (very challenging)

- Instead, I list predictions of interesting states with different quark content
  that lie below strong threshold (doable)

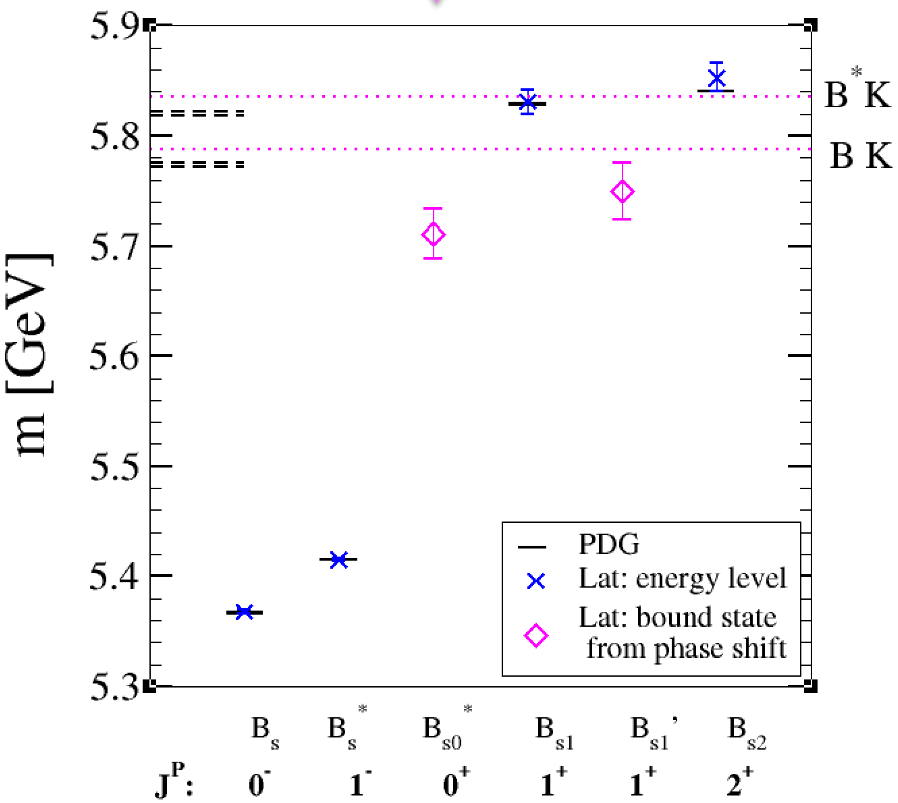
Scalar B_{s0} and axial B_{s1}

partner of scalar $D_{s0}(2317)$

$\bar{s}b$



bound state B_{s0}^* found



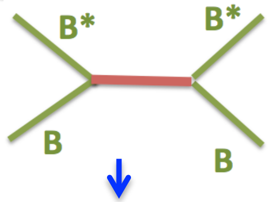
lattice QCD, taking into account effects of $BK^{(*)}$ threshold

[C. Lang, D. Mohler, S.P. , R. Woloshyn: 1501.0164, PLB2015]

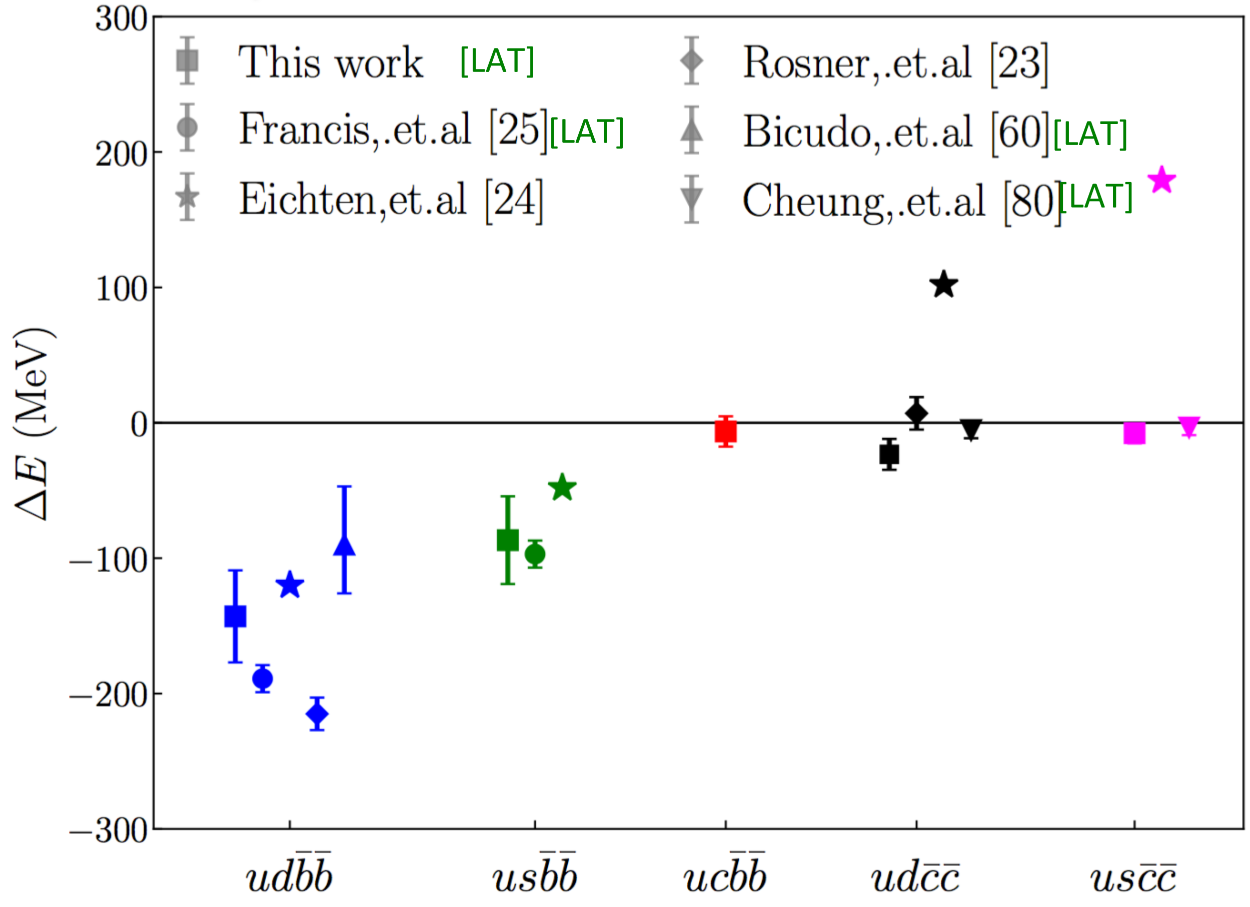
Strongly stable doubly bottom tetraquarks

$\overline{bb}ud \quad (J^P = 1^+, I = 0)$

$\overline{bb}us \quad (J^P = 1^+)$



most firm prediction of a manifestly exotic hadron from lattice and other approaches

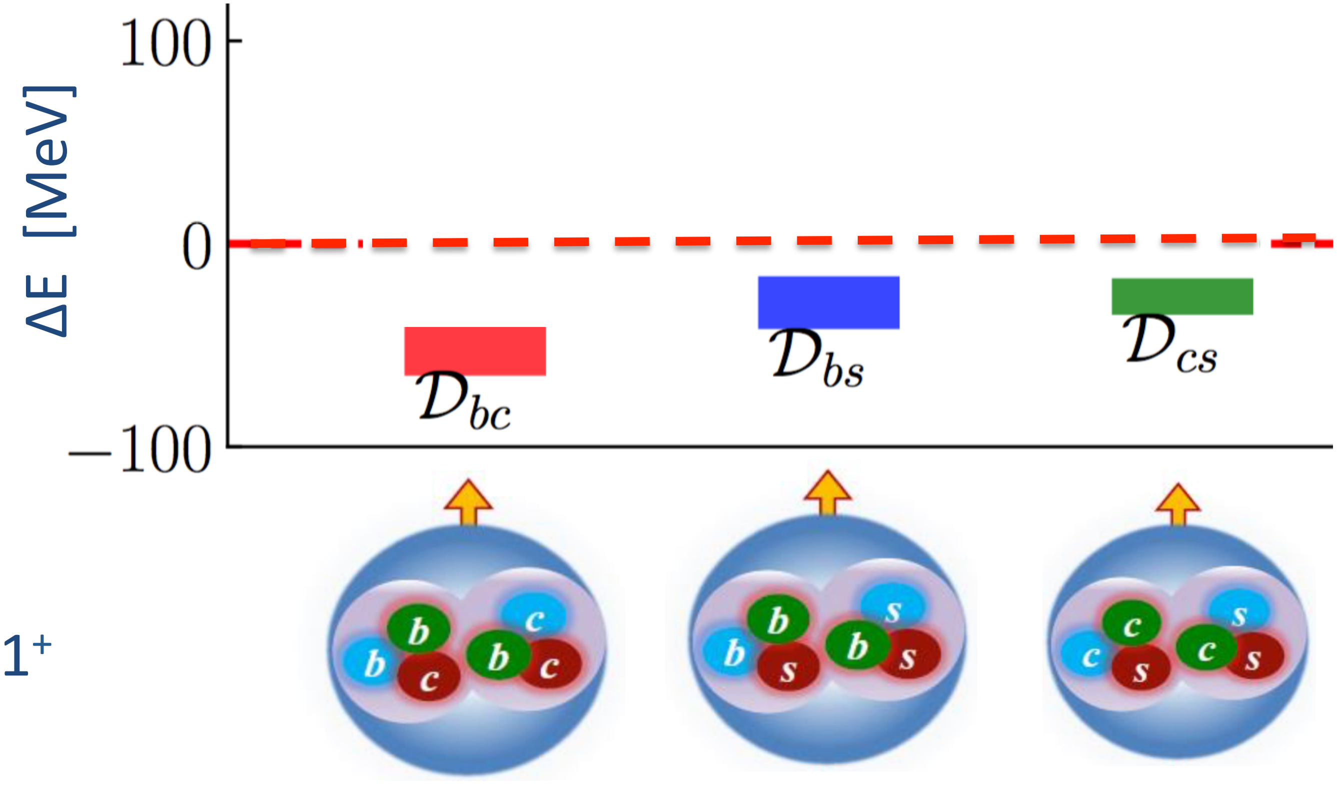


Taken from Junnarkar, Mathur, Padmanath [1810.12285]

strong decay threshold $\quad BB^* \quad B_s B^*$

Strongly and EM stable di-baryons

lattice QCD: Junnarkar, Mathur, [1906.06054, PRL 2019]



$J^P=1^+$

deuterium-like

strong decay threshold

$\Omega^{J=3/2}_{ccc}\Omega^{J=3/2}_{bbb}$ $\Omega^{J=3/2}_{sss}\Omega^{J=3/2}_{bbb}$ $\Omega^{J=1/2}_{css}\Omega^{J=1/2}_{ccs}$

Conclusions

- Compliments to experimental colleagues for discovering a number of conventional and unconventional hadrons !

- Masses of ground and excited hadrons: lattice results and exp agree well

- Lattice QCD can extract scattering matrices for scattering of hadrons:
  their poles give information on resonances, bound states and virtual bound states

- predictions for many yet undiscovered hadrons

- understanding conventional and exotic states above several thresholds requires
  extraction of coupled-channel scattering matrices from lattice ...
  Challenging, but hopefully forthcoming

Backup

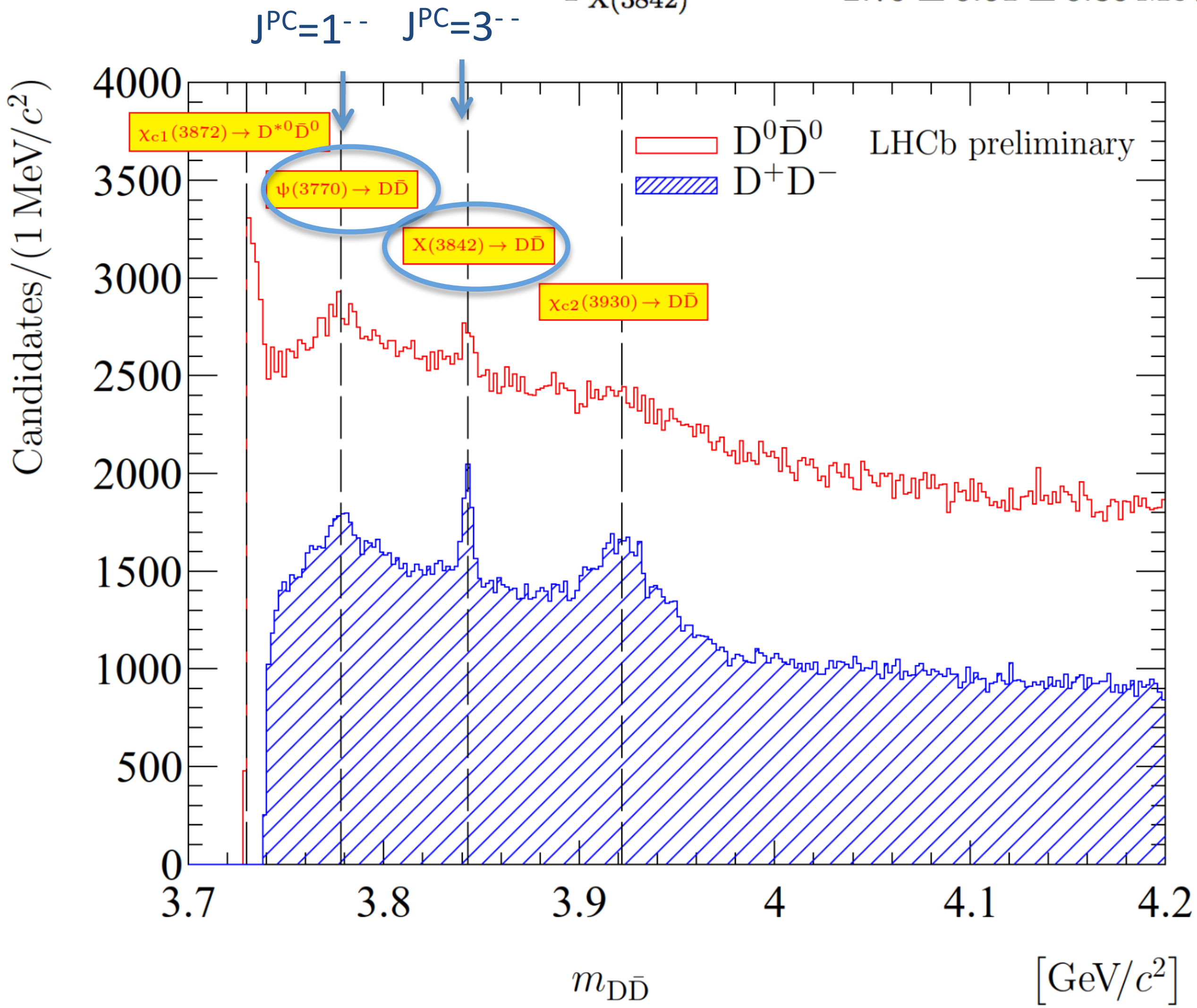
Charmonium resonances in $D\bar{D}$ from LHCb: first discovery of charmonium with J=3

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

LHCb 2019

1903.12240

JHEP 2019



J^{PC} not experimentally measured

LHCb paper:

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

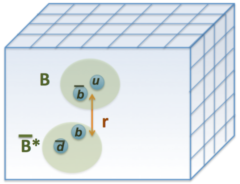
Quark model quantum numbers:

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

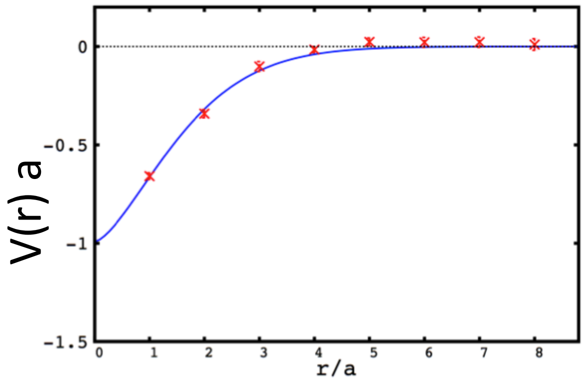
$Z_b^+(10610)$, $Z_b^+(10650)$

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

- Lattice study, continued
  [S.P., Bahtiyar, Petkovic, 1909.02356]



V(r) between B and B*
a=0.12 fm
V(r<0.1 fm) = ?

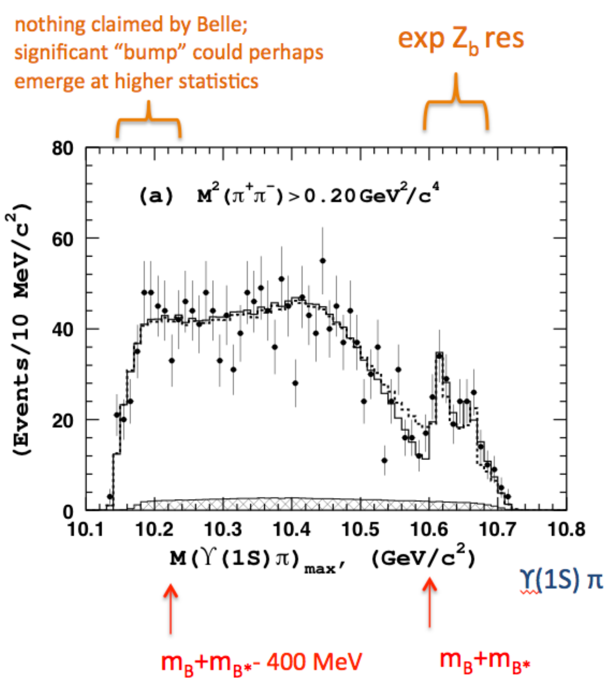


Solving Schrodinger equation for BB* system with this V(r).
Observed attraction leads to

a virtual bound state just below threshold $\mathrm{Re}[E_{Zb}] = -32^{+29}_{-5}\ \mathrm{MeV}$

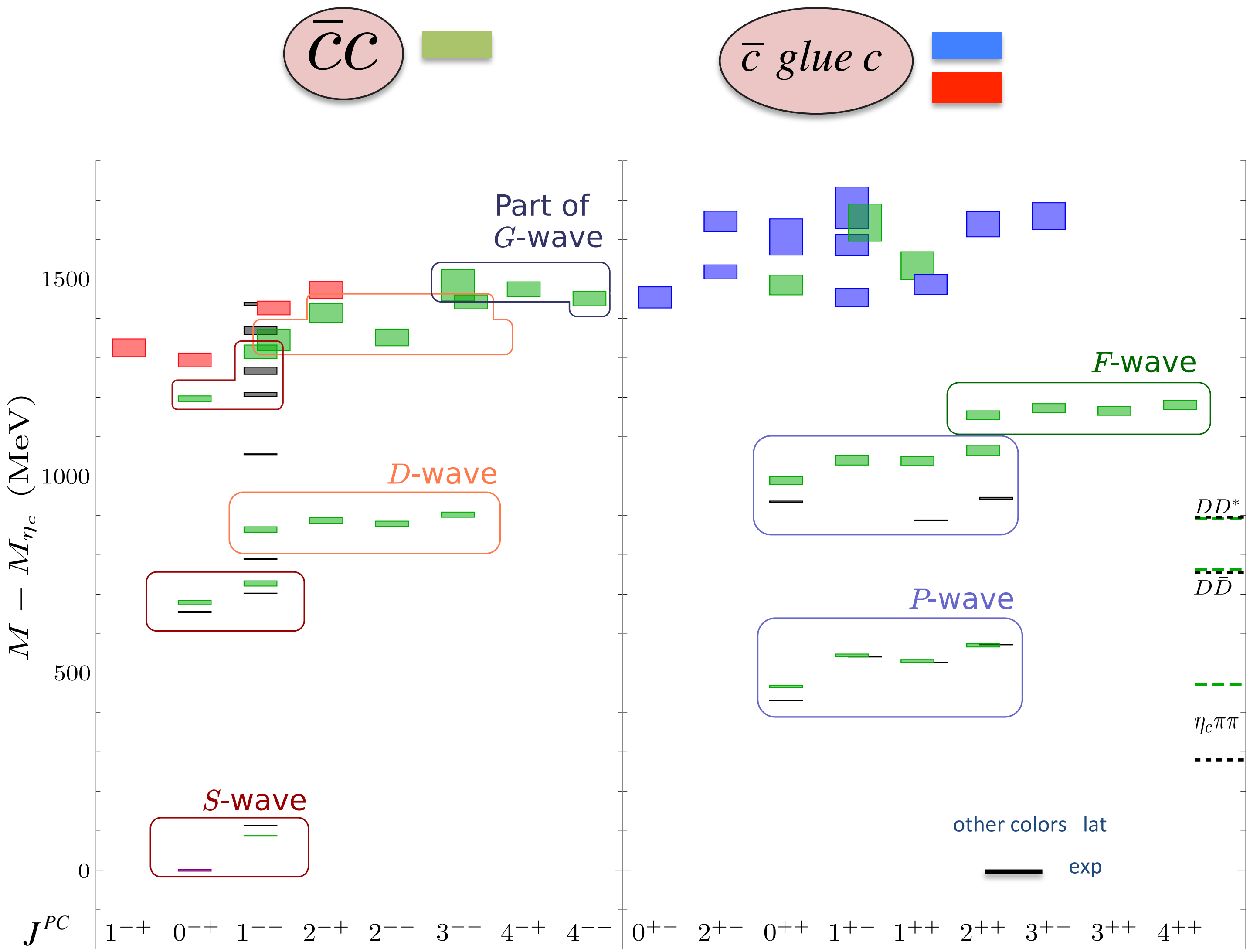
and also to a deep bound state $\mathrm{Re}[E_{Zb}] = -403 \pm 70\ \mathrm{MeV}$

Belle PRD 91 (2015) 072003



- Could LHCb search for Zb in inclusive final state with $B\bar{B}^*$?

Excited charmonia, charmonium hybrids



[Hadron Spectrum Coll, JHEP 2016, 1610.01073]

lattice QCD: m_π=240 MeV

states above $D\underline{D}$ threshold treated as strongly stable; effects of thresholds not taken into account

red and blue are candidates for hybrids with excited glue

most of these states (J=3,4 or exotic $J^{PC}=1^{-+},2^{+-}$,..) yet to be experimentally discovered !!

masses of hybrids in rough agreement with EFT+lattice [Brambilla, Lai, Segovia, Castella, Vario, 1805.07713, PRD 2019]

prediction also for $b\underline{b}$ hybrids