Lattice Spectroscopy (focus on exotics)

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Outline

Theoretical spectrum of hadrons containing b and c quarks (focus on lattice QCD results)

Hadrons

- Recently discovered/confirmed in experiment

$$\text{excited } \Omega_c, \quad \bar{c}c \text{ with } J=3, \; P_c, \; B_c(2S), \quad \Lambda_b$$

- Long-standing challenges for theory

$$Z_c, \quad Z_b, \quad X(3872)$$

- Predictions, yet undiscovered

$$bb\overline{q}\overline{q}', \text{highly excited } \overline{\text{b}}\text{b and } \overline{\text{c}}\text{c}, \overline{\text{b}}\text{Gb and } \overline{\text{c}}\text{Gc hybrids, scalar B, beautiful baryons}$$

A number of interesting experimentally discovered exotic states (for example Zc(4430)) will not be discussed – those are typically to challenging for ab-initio lattice treatment

Some recent reviews

The *XYZ* states: experimental and theoretical status and perspectives
N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C.-P. Shen, C. Thomas, A. Vairo, C.-Z. Yuang
1907.07583, submitted to Physics Reports

The Belle II Physics book, Quarkonium(like) Physics (chapter 14)
N. Brambilla, B. Fulsom, C. Hanhart, Y. Kiyo, R. Mizuk, R. Mussa, A. Polosa, S. Prelovsek, C. P. Shen
1808.10567, Progress of Theoretical and Experimental Physics

Multiquark Hadrons
A. Ali, L. Maiani, A. D. Polosa
Cambridge University Press, 2019, doi:10.1017/9781316761465

Hadronic molecules
F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou
1705.00141, Rev. Mod. Phys. 90 (2018) 015004

Pentaquark and Tetraquark states
Y.-R. Liu, H.-X. Chen,W. Chen, X. Liu, S.-L. Zhu
1903.11976, Progress in Particle and Nuclear Physics 107 (2019) 237

The hidden-charm pentaquark and tetraquark states
H.-X. Chen, W. Chen, X. Liu, S.-L. Zhu
1601.02092, Physics Reports 639 (2016) 1

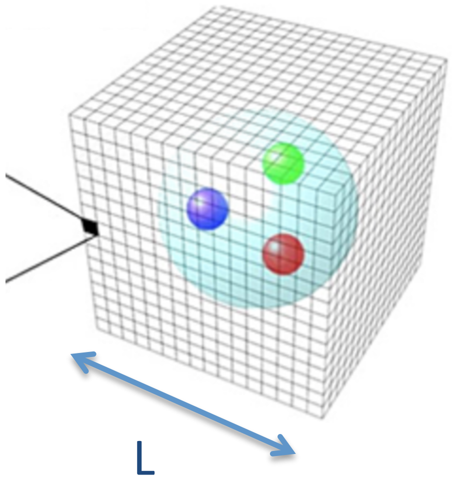
Heavy-Quark QCD Exotica
R. F. Lebed, R. E. Mitchell, E. S. Swanson
1610.04528, Progress in Particle and Nuclear Physics 93 (2017)

Multiquark Resonances
A. Esposito, A. Pilloni, A.D. Polosa
1611.07920, Physics Reports 668 (2017) 1-97

Exotics: Heavy Pentaquarks and Tetraquarks
A. Ali, J. Lange, S. Stone
1706.00610, Progress in Particle and Nuclear Physics (2019) 237

Lattice QCD

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



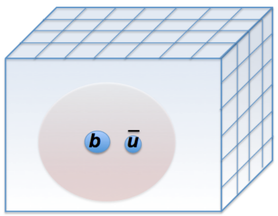
input: g_s , m_q

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

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

$$S_{QCD} = \int d^4x\, L_{QCD}[G(x), q(x), \bar{q}(x)]$$

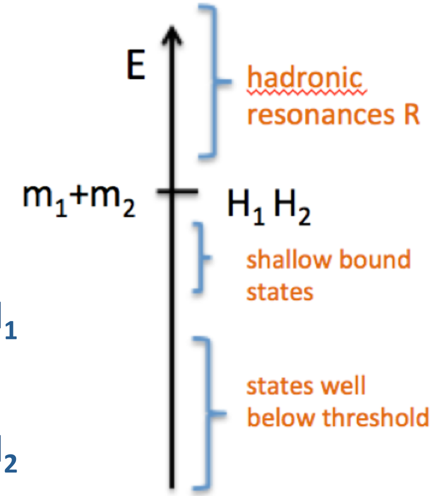
Extracted quantity: E_n = energy of QCD eigenstate with given quantum numbers

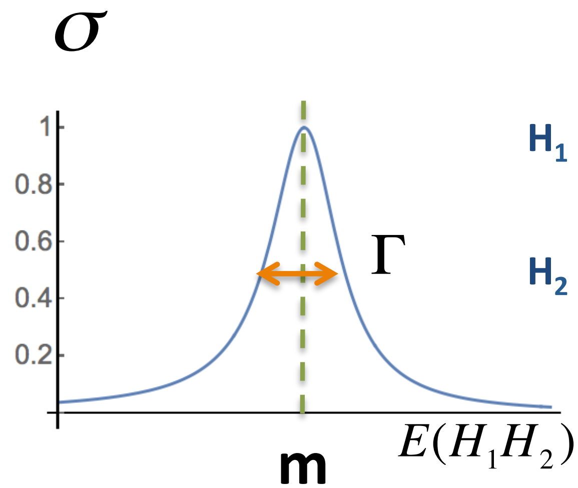


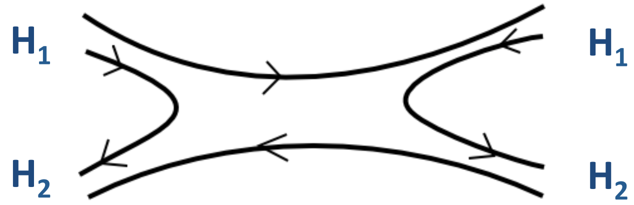
$E_1(p=0, J^P=0^-) = m_B$

Most of hadrons and all experimentally discovered exotic hadrons are strongly decaying resonances !

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

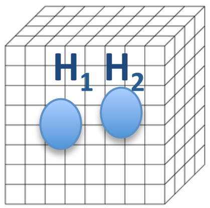






$$T_B(E) \propto \frac{1}{s - m_B^2} \qquad T_R(E) = \frac{-m_R \Gamma}{E^2 - m_R^2 + i m_R \Gamma}$$

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



energy of eigenstate

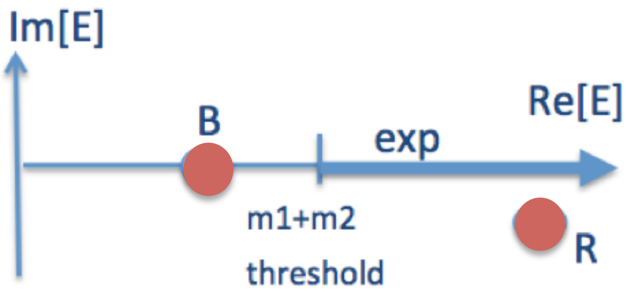
scattering matrix for real E

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

E → $T(E)$

analytic relation:
Luscher 1991

continuation to complex E



location of poles in complex E plane

Hadrons that were recently discovered/confirmed in exp

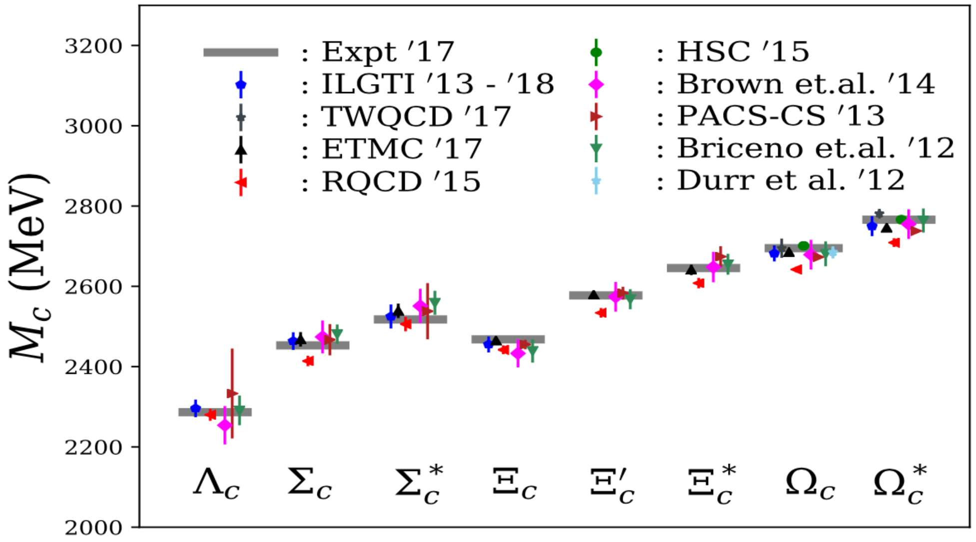
Baryons with charm quark

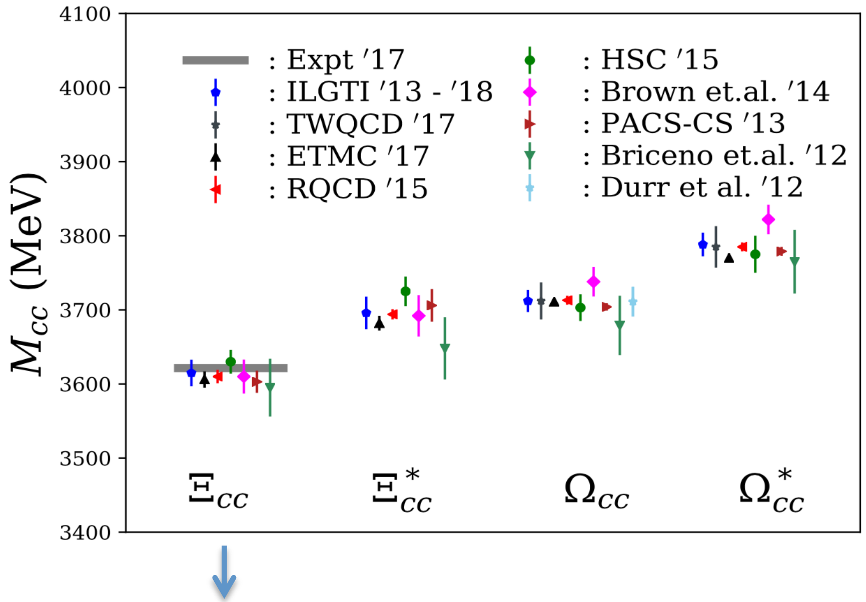
exp vs. lattice

colors

cqq

ccq





[LHCb, 2017]

plot taken from M. Padmanath, 1905.09651

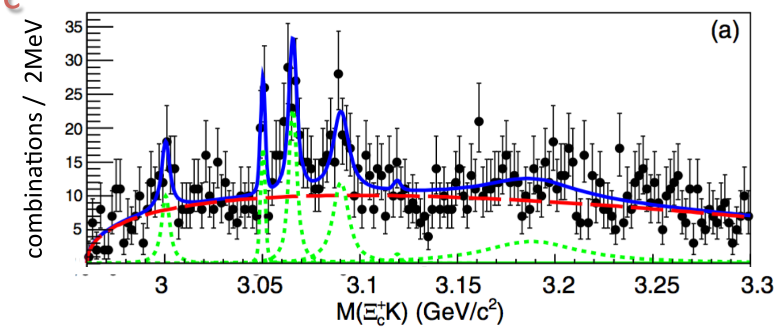
New excited Ω_c^*

CSS

conventional

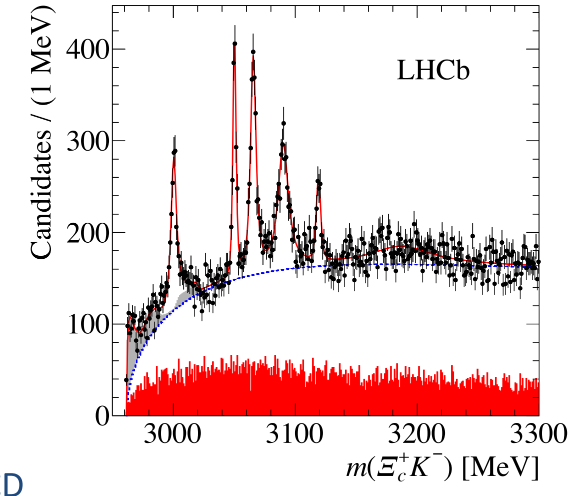
[Belle 2017, 1711.07927, PRD (2018)]

confirmation of lowest 4 resonance peaks

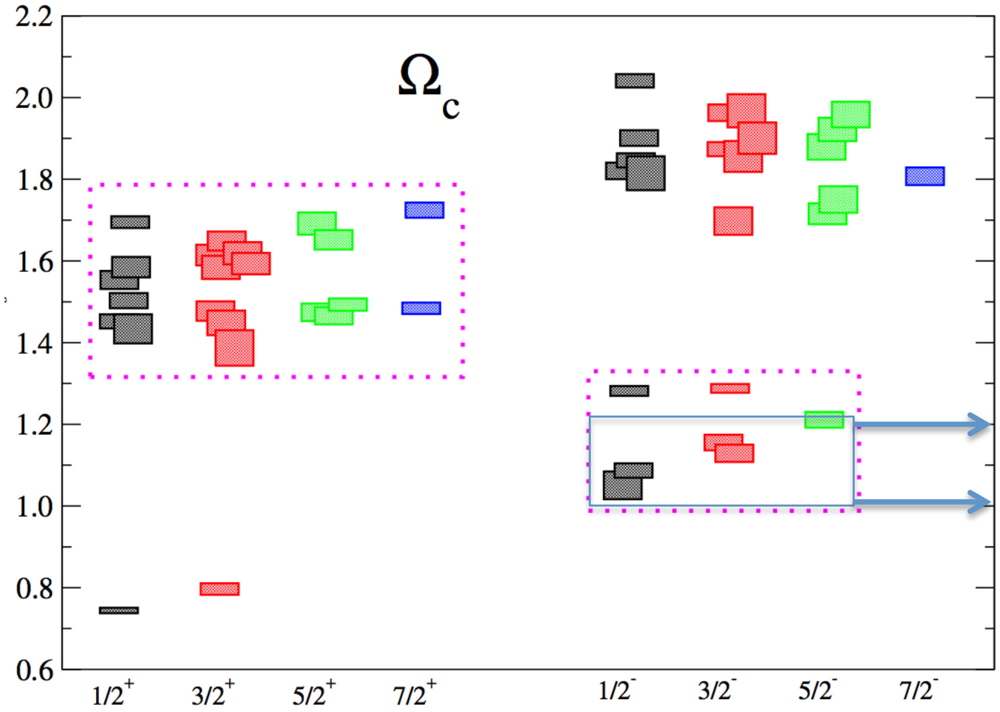


[LHCb 2017, 1703.04639, PRL 2017]

J^P are not measured in exp



$m - m_{Ds}$ [GeV]



Padmanath et al. 2013

[1311.4806, proc. CHARM2013]

1/2- 3/2- 5/2-

J^P

3.2 GeV

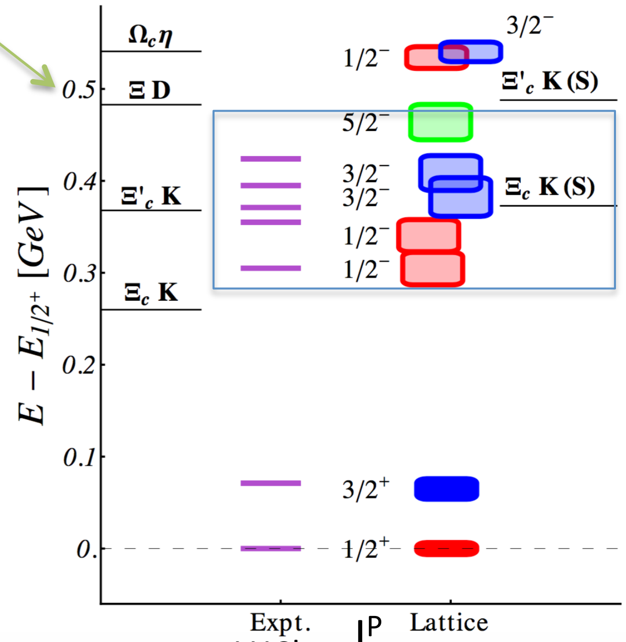
3.0 GeV

prediction of states and J^P from lattice QCD

(ignoring strong decays)

same results

Padmanath, Mathur, 1704.00259, PRL



LHCb J^P

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

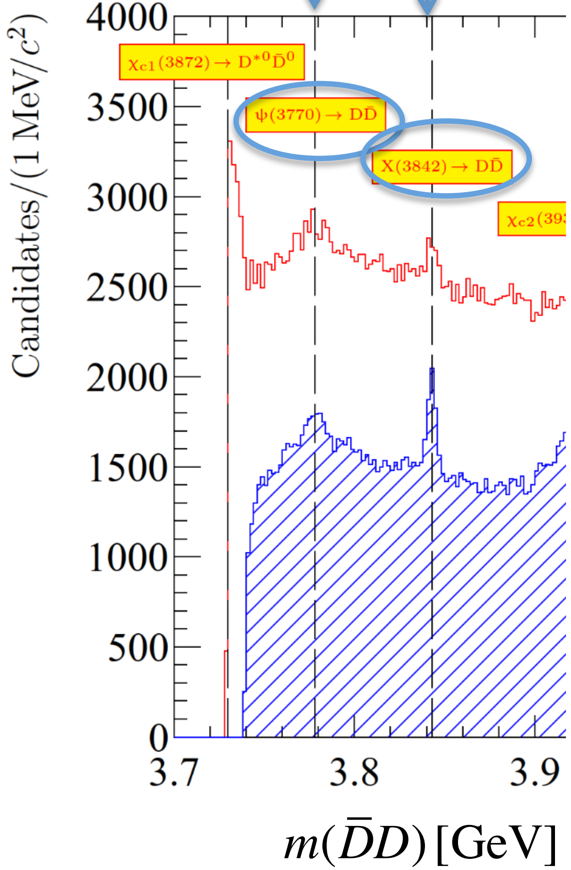
$\bar{c}\,c$ conventional

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

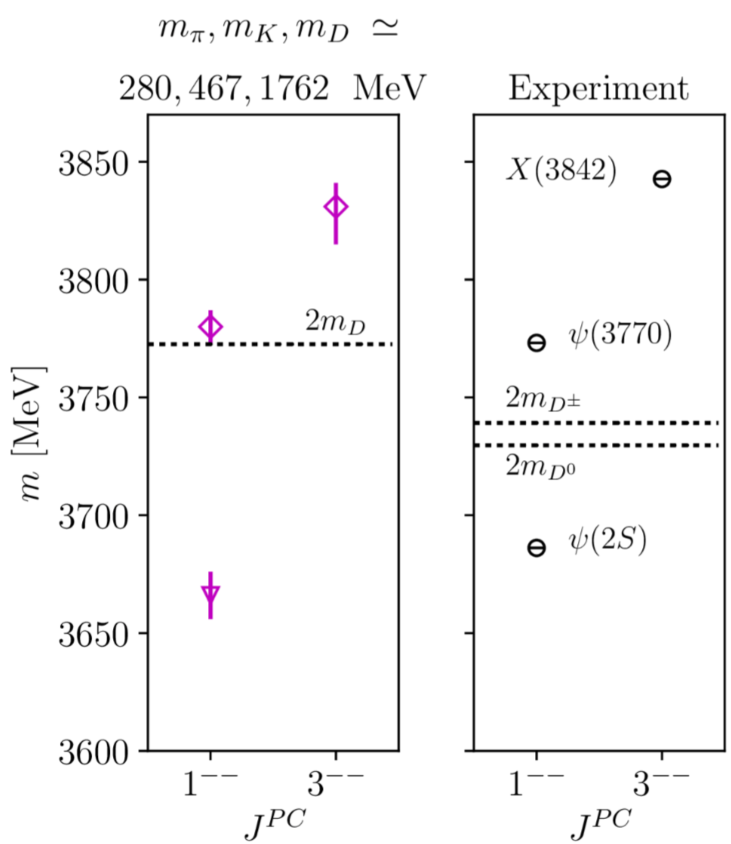
first discovery of charmonium with J=3

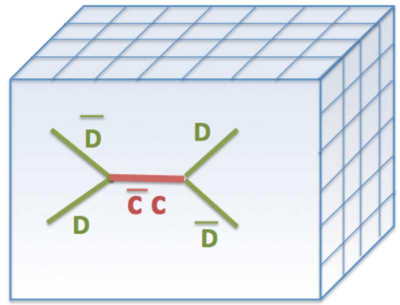
LHCb 2019, 1903.12240, JHEP 2019

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



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





partial waves L=3 and L=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.

P_c pentaquarks $\bar{c}cuud$

J^P not determined from exp.

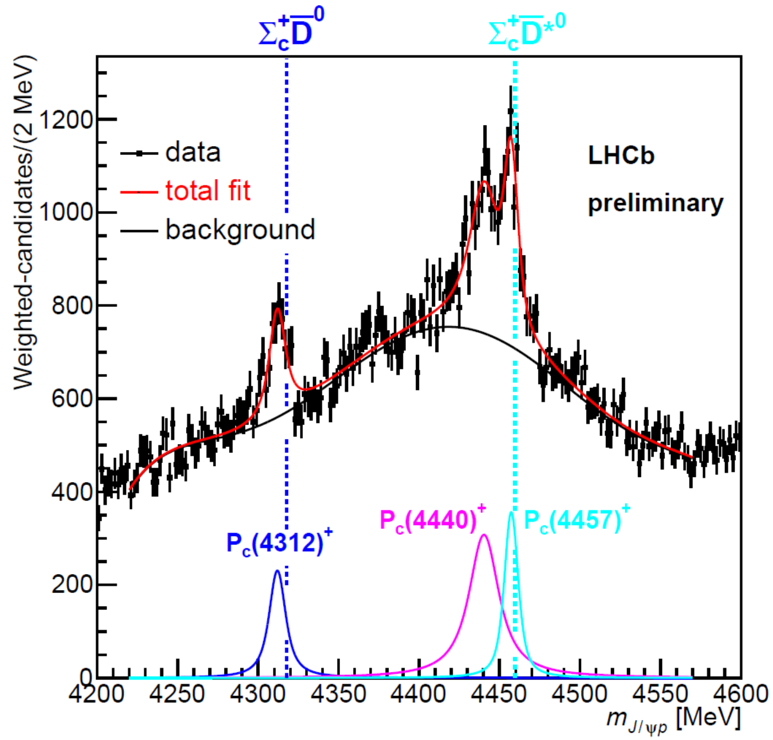
Expected J^P for molecule in s-wave:

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

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

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

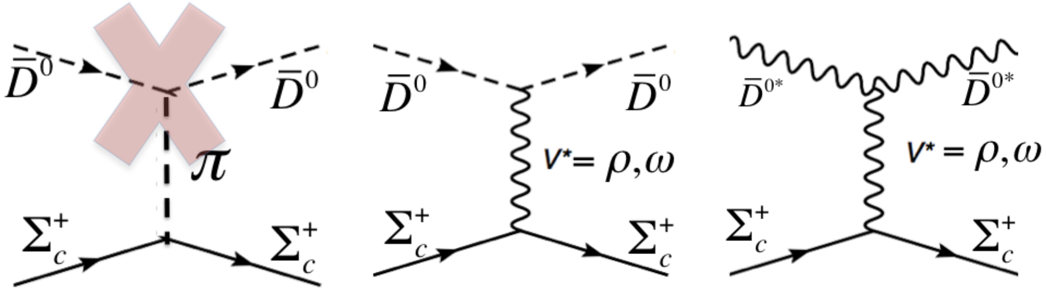
[LHCb 2019, 1904.03947, PRL]



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

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

Karliner & Rosner, 1506.06386, PRL2015



these effective models at hadron level PREdicted (2010-2012) Pc slightly below **Σ_c^+D** and **Σ_c^+D*** thresholds, with masses roughly compatible with exp

[Wu, Molina, Oset, Zou, 1007.0573, PRL; Wu et al., 1202.1036. PRC, Yang et al, 1105.2901]

Chiral quark model incorporating ρ/ω exchange also support Pc below **Σ_c^+D** [Wang et al, 1101.0453, PRC]

Some of those models predict other states that have not been experimentally confirmed (yet).

- **Lattice QCD** addressed simplified question:

Do Pc resonances appear in one-channel

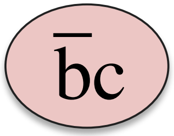
$$p\ \ J/\psi \rightarrow P_c \rightarrow p\ \ J/\psi$$

scattering where it is decoupled from other channel ?

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

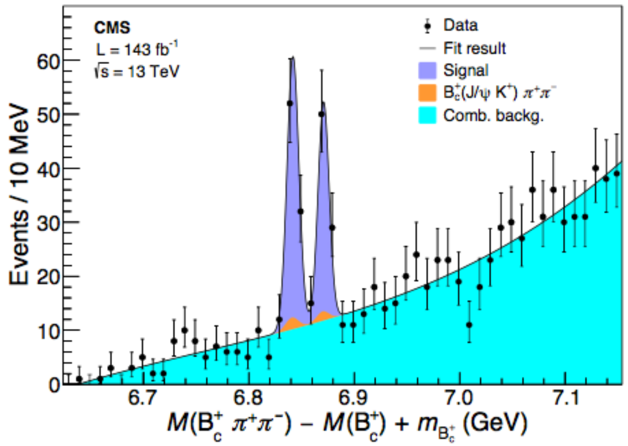
This indicates that coupling of p J/ψ channel with other two-hadron channels is responsible for Pc in experiment (in line with LHCb result)

$B_c(2S)$

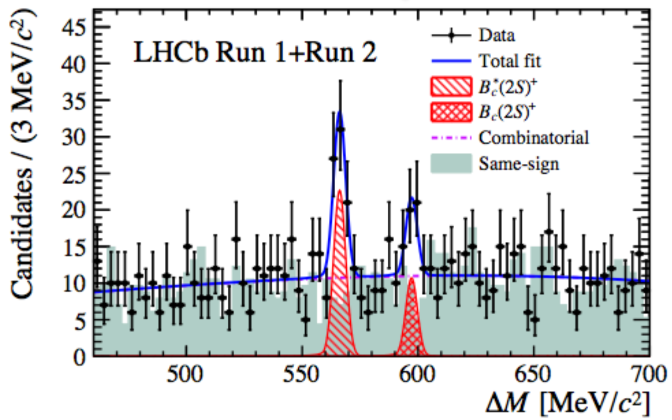


discovery [ATLAS, PRL 2014]

[CMS, 1902.00571, PRL]

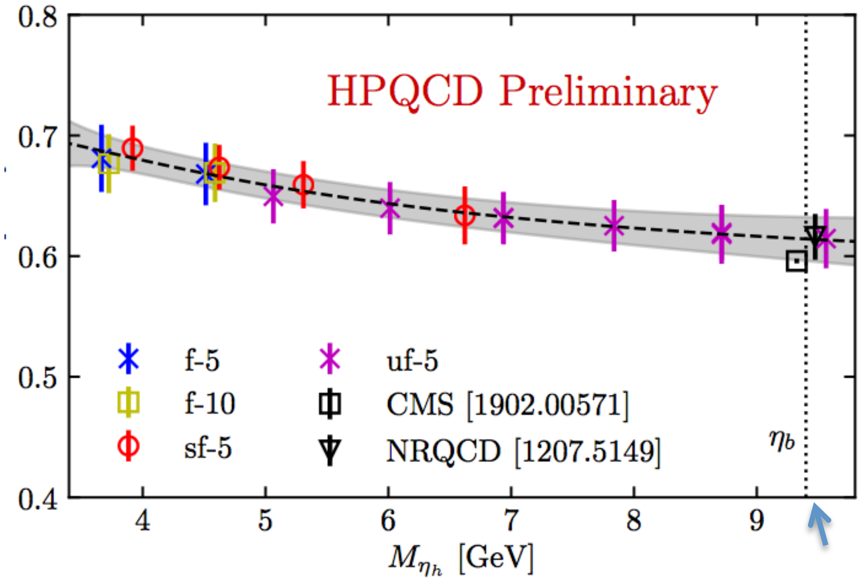


[LHCb, 1904.00081, PRL]



$$m[B_c(2S)]: \quad 6871(1.2)(0.8)(0.8)\ \text{MeV} \qquad 6872.1(1.3)(0.1)(0.8)\ \text{MeV}$$

$$m[B_c(2S)] - m[B_c(1S)] \quad [\text{GeV}]$$



$m_b = m_b^{phy}$

Lattice QCD:

[HPQCD, 1811.09448, A. Lytle, talk at QWG19]

$m_c = m_c^{phy}$

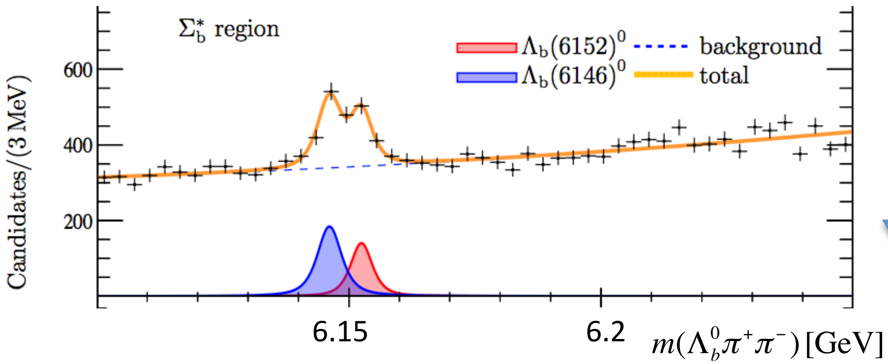
m_b varried

$B_c^*(2S)$ in backup-slides

New excited Λ_b^0

bdu

[LHCb, 1907.13598]



PDG

	J^P (exp)
Λ_b^0 m=5619 MeV	½ +
$\Lambda_b^0(5912)$	½ -
$\Lambda_b^0(5920)$	3/2 -
$\Lambda_b^0(6146)$	?
$\Lambda_b^0(6152)$	?

quark model predictions

Table taken from Chen et. al. 1406.6561, EPL 2015

Chen et al. — Ebert et al. — Roberts & Pervin — Capstick & Isgur

$J^P(nL)$	Exp. [1]	This work	Ref. [9]	Ref. [50]	Ref. [51]
$\frac{1}{2}^+(1S)$	5619.4	5619	5620	5612	5585
$\frac{1}{2}^-(1P)$	5912.0	5911	5930	5939	5912
$\frac{3}{2}^-(1P)$	5919.8	5920	5942	5941	5920
$\frac{3}{2}^+(1D)$		6147	6190	6181	6145
$\frac{5}{2}^+(1D)$		6153	6196	6181	6165
$\frac{5}{2}^-(1F)$		6346	6408	6206	6205
$\frac{7}{2}^-(1F)$		6351	6411		6360
$\frac{7}{2}^+(1G)$		6523	6598	6433	6445
$\frac{9}{2}^+(1G)$		6526	6599		6580

new Λ_b likely have $J^P=3/2^+, 5/2^+$

- Quark models favor $3/2^+$ and $5/2^+$
- Masses of excited Λ_b^0 have not been determined by lattice QCD (to my knowledge).
- Masses of excited Λ_c^0 in lattice QCD preliminary: Padmanath et al. 2013 [1311.4806, proc. CHARM2013]
- splittings between $m(\Lambda_b^0)$ and $m(\Lambda_c^0)$ differ in $1/m_Q$ contributions

Hadrons that are long-standing challenges for theory

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

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

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

[Belle, 1110.2251, PRL 2012]

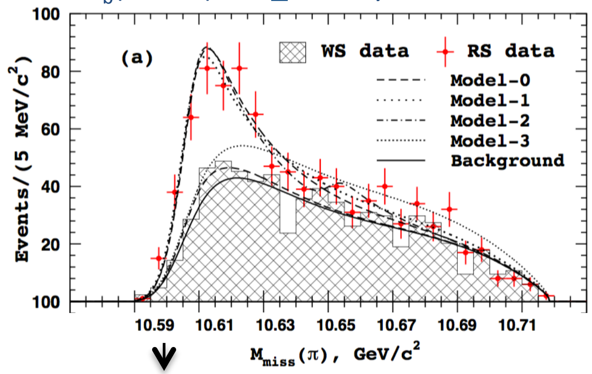
Indications that molecular B $\underline{B}^*$ in $Z_b^+(10610)$ is crucial:

- 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 to ϒ ($S_{\underline{b}b}$=1) and h_b ($S_{\underline{b}b}$=0) comparably

[Belle, 1512.07419, PRL 2016]

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



mB+mB*

- reanalysis of exp data finds virtual B $\underline{B}^*$ bound state slightly below threshold

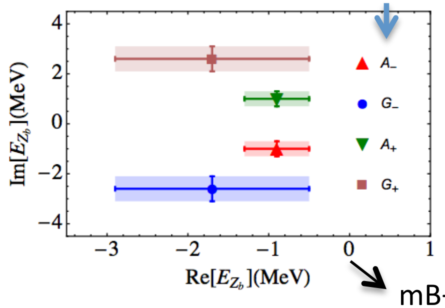
  [Wang, Baru, Filin, Hanhart, Nefediev, Wynen, 1805.07453, PRD 2018]

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

p= + i |p| for bound state

p= - i |p| for virtual bound state

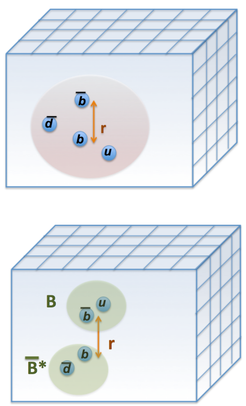
various schemes



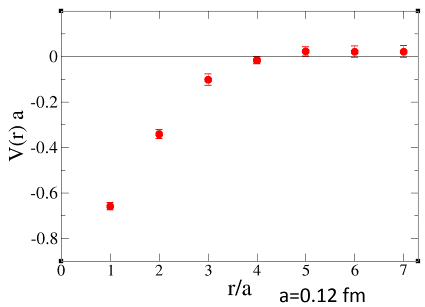
mB+mB*

- 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]



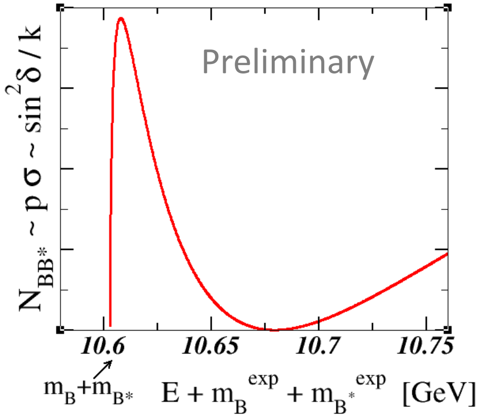
extracted potential between B and $\underline{B}$*



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

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

This leads to peak above th.



$Z_c^+(3900)$

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

$Z_c^+ \to J/\psi\,\pi^+,\cdots$ [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 $J/\psi\,\pi\,,\ D\bar{D}*$

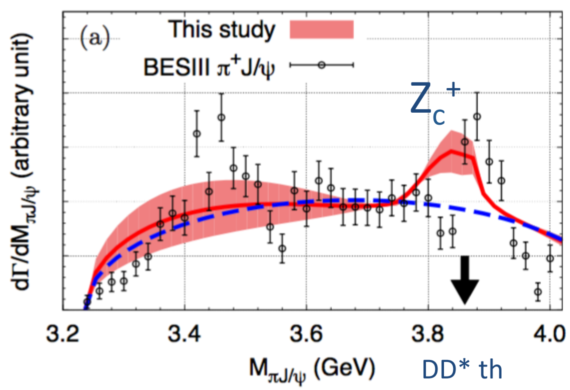
➢ [Ikeda et al., HALQCD, 1602.03465, PRL]
  HALQCD method (which was not verified yet on any conventional resonance)

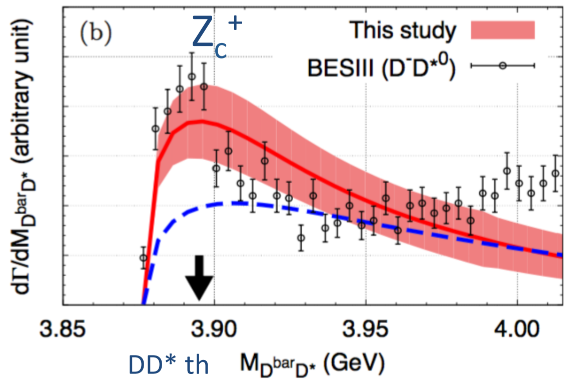
- Z_c*(3900) coupled-channel effect due to sizable J/Ψ π and DD* coupling, not genuine resonances (i.e. pole on the unphysical sheet above DD* th.)

➢ [Chen et al., CLQCD, 1907.03371]

- Luscher's method : 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]

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





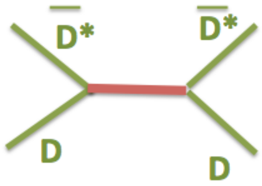
differential rate from lattice differential

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

χ_{c1}(2P) aka X(3872)

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

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

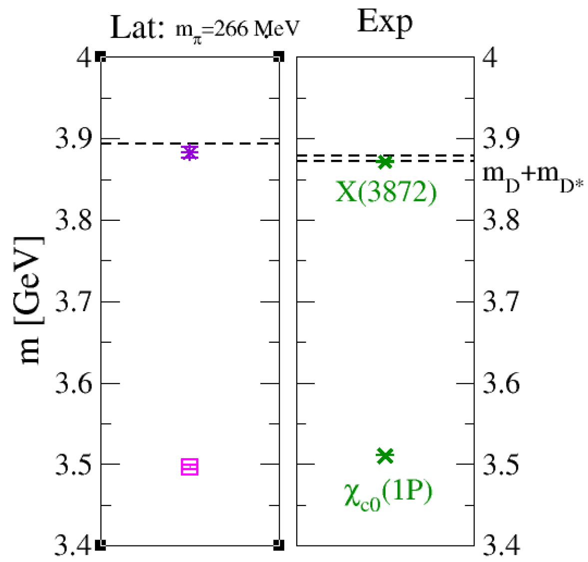


➢ Lattice QCD

- 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: $(\bar{c}\bar{q})(cq)$

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



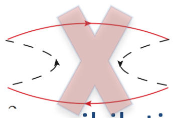
➢ Dyson-Schwinger / Bethe-Salpeter approach

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

new developments of formalism [Williams, 1804.11161]

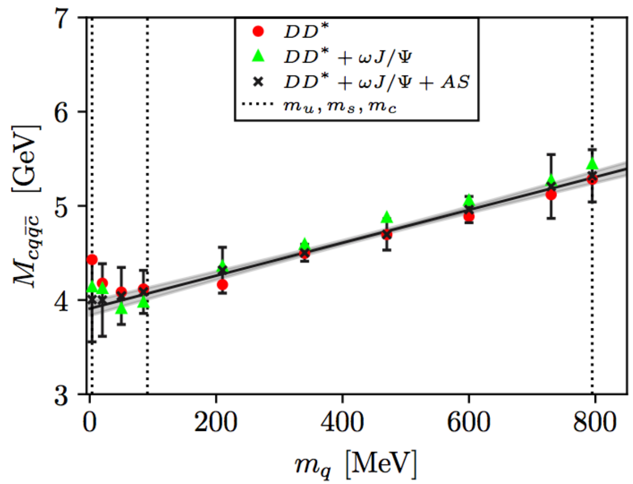
location of pole in the scattering matrix

- pole for X found although



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

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



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

mass not accurate enough to determine whether it is a bound state below th.

➢ exp indication 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: $(I=0)+(I=1)$

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

Theoretical predictions of yet undiscovered hadrons

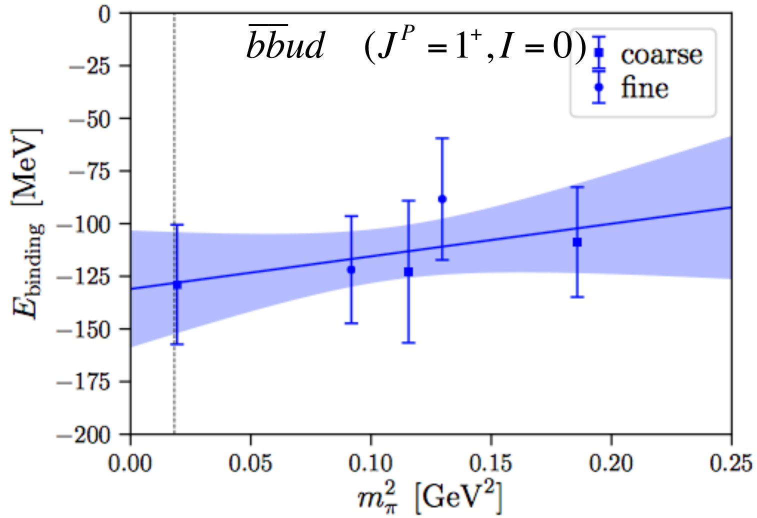
Strongly stable doubly bottom tetraquarks

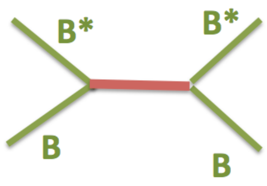
$\overline{b}\overline{b}ud$ $(J^P = 1^+, I = 0)$

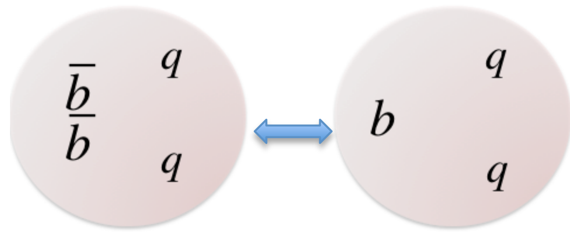
$\overline{b}\overline{b}us$ $(J^P = 1^+)$

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

$\Delta E = m - m_B - m_{B^*}$ location of the bound state pole below BB*
[Leskovec et al, 1904.04197, PRD, 2019]





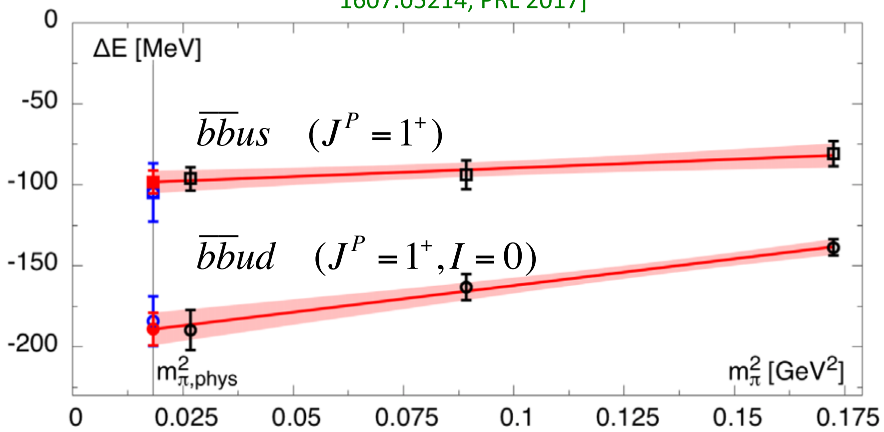


$(\overline{b}\overline{b})_{3_c}$
compact

$$\bar{Q}\bar{Q} \approx Q$$

$$m(\bar{Q}\bar{Q}qq) - m(\bar{Q}\bar{Q}\bar{q}) \approx m(Qqq) - m(Q\bar{q})$$

$\Delta E = m - m_B - m_{B^*_{(s)}}$ assuming $E_{\text{ground-state}} = E_{\text{pole}}$
[Francis, Hudspith, Lewis, Maltman, 1607.05214, PRL 2017]



Eichten, Quigg, 1707.09575, PRL 2017

Karliner, Rosner, 1707.07666, PRL 2017

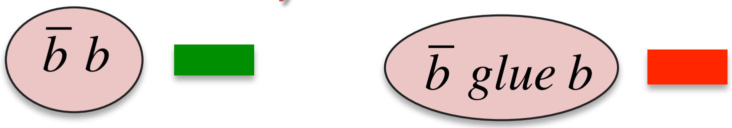
Observation of Ξ_{cc} implies existence of $\underline{bb}ud$

Is some doubly-heavy tetraquark with c stable?

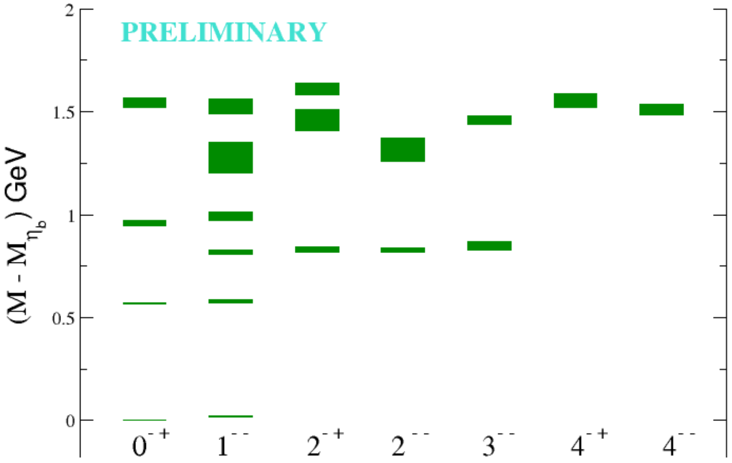
Final consensus has not been reached.

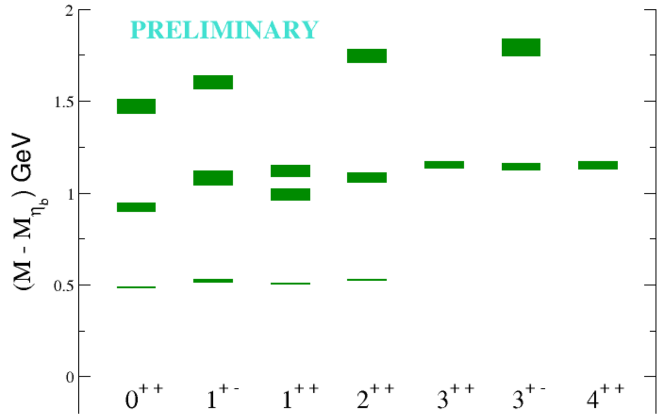
They are much less bound or unbound.

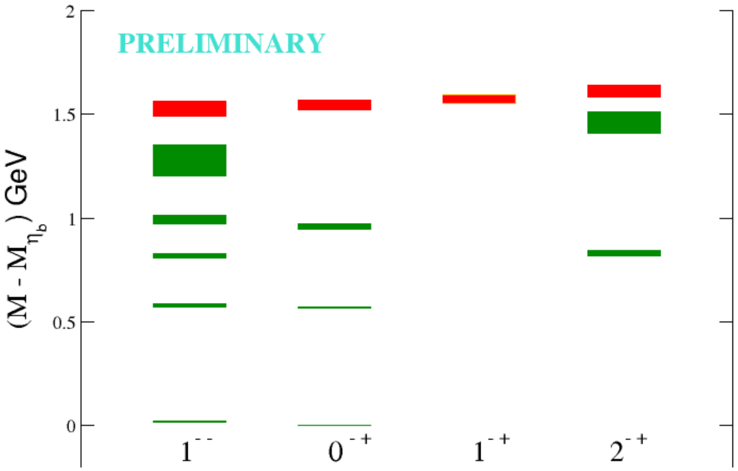
Excited bottomonia, bottomonium hybrids

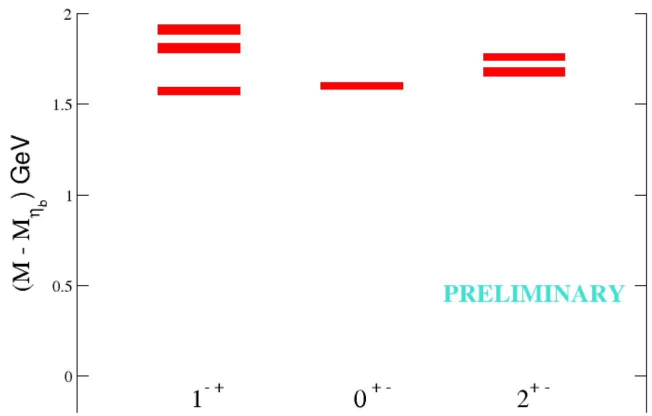


$m_{hybrid} \geq 10.9$ GeV









exotic J^{PC}

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 B$\underline{\text{B}}$ threshold

treated as strongly stable

$$2M_B - M_{\eta_b} \approx 1.2\,\text{GeV}$$

most of states below B $\underline{\text{B}}$

experimentally discovered

previous lattice results on
excited $\underline{\text{b}}$b spectrum

[Wurtz, Lewis, Woloshyn,

1505.04410, PRD]

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

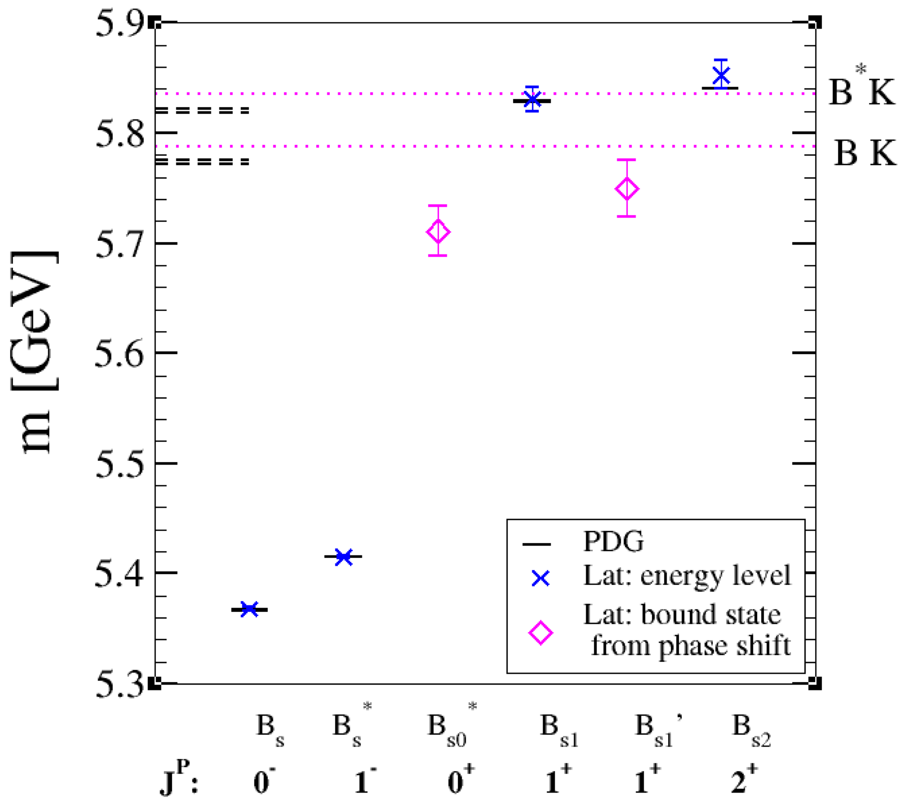
 charmonium and charmonium hybrids: see backup

Scalar B_{s0} and axial B_{s1}

$\bar{s}b$

↓

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



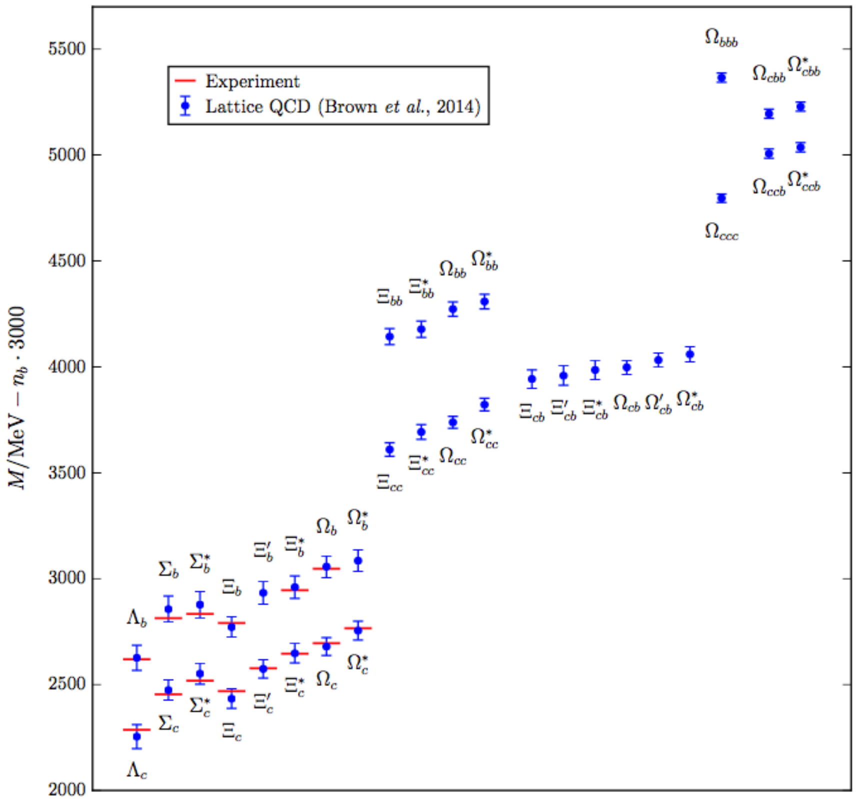
lattice QCD, taking into account effects of $BK^{(*)}$ threshold

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

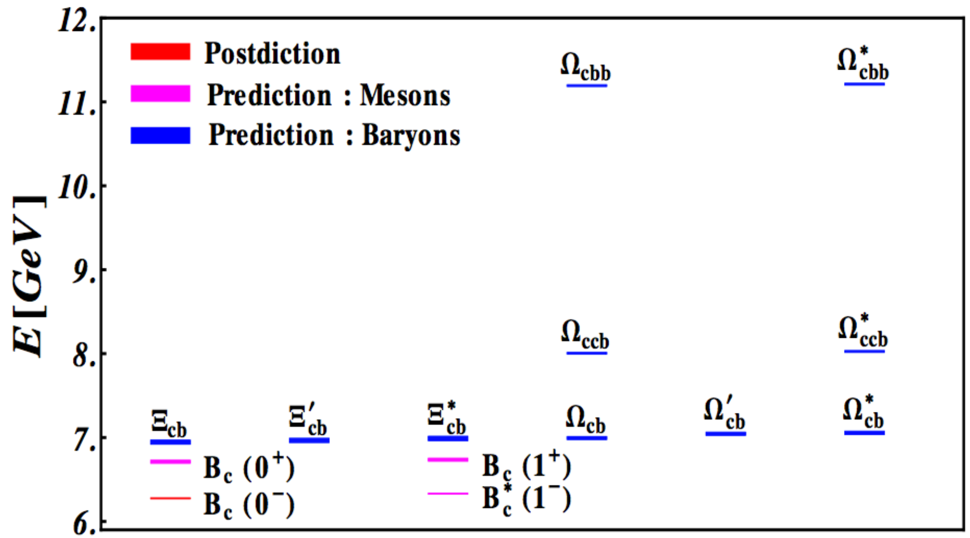
Baryons with b and/or c

lattice QCD, omitting strong decays

[Brown, Detmold, Meinel, Orginos, 1409.0497]



[Mathur, Padmanath, Mondal, 1806.04151, PRL]



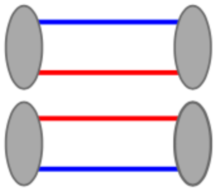
Non-existence of strongly stable fully beautiful tetraquark

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

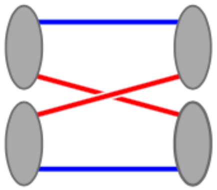
Lattice QCD: No indication for strongly stable state with $J^{PC}=0^{++}, 1^{++}, 2^{++}$

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

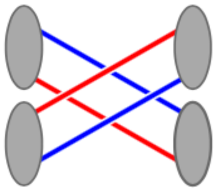
Lesson: all Wick contractions (expect for $\underline{b}b$ annihilation) need to be taken into account, otherwise false bound state emerges



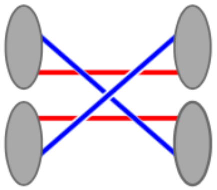
(a) Direct1



(b) Xchange2



(c) Direct3

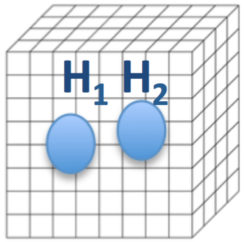


(d) Xchange4

Extracting scattering matrix from lattice

Resonance above one threshold

$$R \to H_1 H_2 \qquad T(E) \xleftarrow[\text{Luscher's method}]{} E_n$$



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)

$$R \to H_1 H_2,\ H_1' H_2'$$

channel a : $H_1 H_2$

channel b : $H_1' H_2'$

$$T(E) = \begin{bmatrix} T_{aa}(E) & T_{ab}(E) \\ T_{ab}(E) & T_{bb}(E) \end{bmatrix} \xleftarrow[\text{Luscher's method}]{} E_n$$

(a -> a, a -> b; b->a, b -> b)

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]

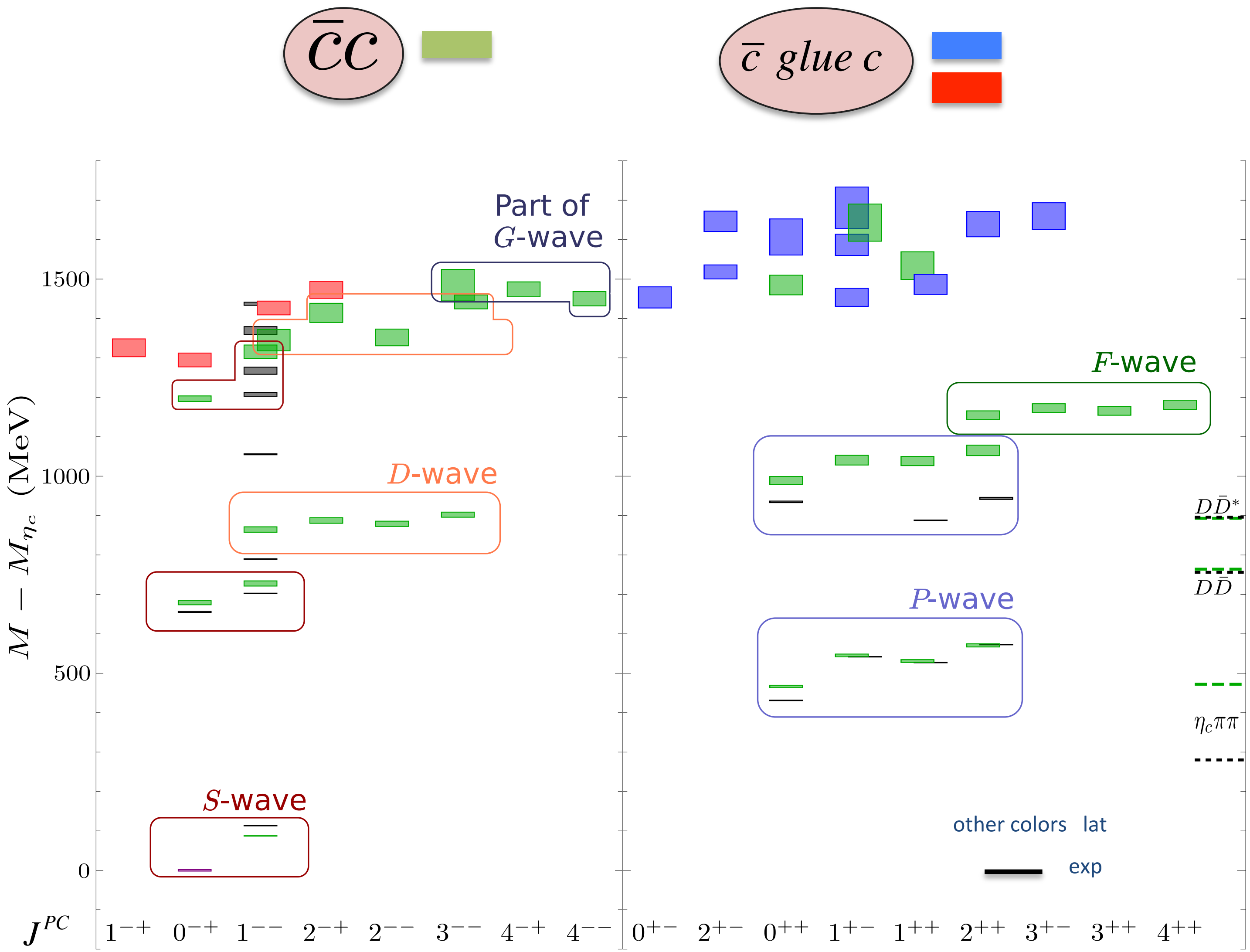
  Z_c channel [Chen et al., CLQCD, 1907.03371]

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
- Dyson-Schwinger approach has also started to look for poles in the scattering matrices
- predictions for many yet undiscovered hadrons
- look for strongly stable double-bottom tetraquarks if possible ... $\bar{b}\bar{b}ud, \quad \bar{b}\bar{b}us$
- understanding conventional and exotic states above several thresholds requires extraction of coupled-channel scattering matrices from lattice ... Challenging, but hopefully forthcoming

Backup

Excited charmonia, charmonium hybrids



[Hadron Spectrum Coll, JHEP 2016, 1610.01073]

lattice QCD: m_π=240 MeV

states above DD 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 bb hybrids

Excited Ω_c^*

CSS

[LHCb 2017, 1703.04639, PRL 2017]

5 resonance peaks discovered by LHCb

TABLE I. Results of the fit to $m(\Xi_c^+ K^-)$ for the mass, width, yield, and significance for each resonance. The subscript fd indicates the feed-down contributions described in the text. For each fitted parameter, the first uncertainty is statistical and the second systematic. The asymmetric uncertainty on the $\Omega_c(X)^0$ arising from the Ξ_c^+ mass is given separately. Upper limits are also given for the resonances $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ for which the width is not significant.

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		<1.2 MeV, 95% C.L.		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		<2.6 MeV, 95% C.L.		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\rm fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\rm fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\rm fd}$			$190 \pm 70 \pm 20$	

[Belle 2017, 1711.07927, PRD (2018)]

TABLE I. Yields of the six resonances, and comparison of the mass measurements to the LHCb values. In rows 4 and 5, the units are MeV/c^2. None of the mass measurements include the uncertainty in the ground-state Ξ_c^+ which is common to both experiments.

Ω_c Excited state	3000	3050	3066	3090	3119	3188
Yield	37.7 ± 11.0	28.2 ± 7.7	81.7 ± 13.9	86.6 ± 17.4	3.6 ± 6.9	135.2 ± 43.0
Significance	3.9σ	4.6σ	7.2σ	5.7σ	0.4σ	2.4σ
LHCb mass	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.5 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$	$3119 \pm 0.3 \pm 0.9$	$3188 \pm 5 \pm 13$
Belle mass (with fixed Γ)	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$	$\cdots$	$3199 \pm 9 \pm 4$

lowest 4 resonance peaks confirmed by Belle

Non-observation of $\Omega_c(3119)$ is not in disagreement with LHCb

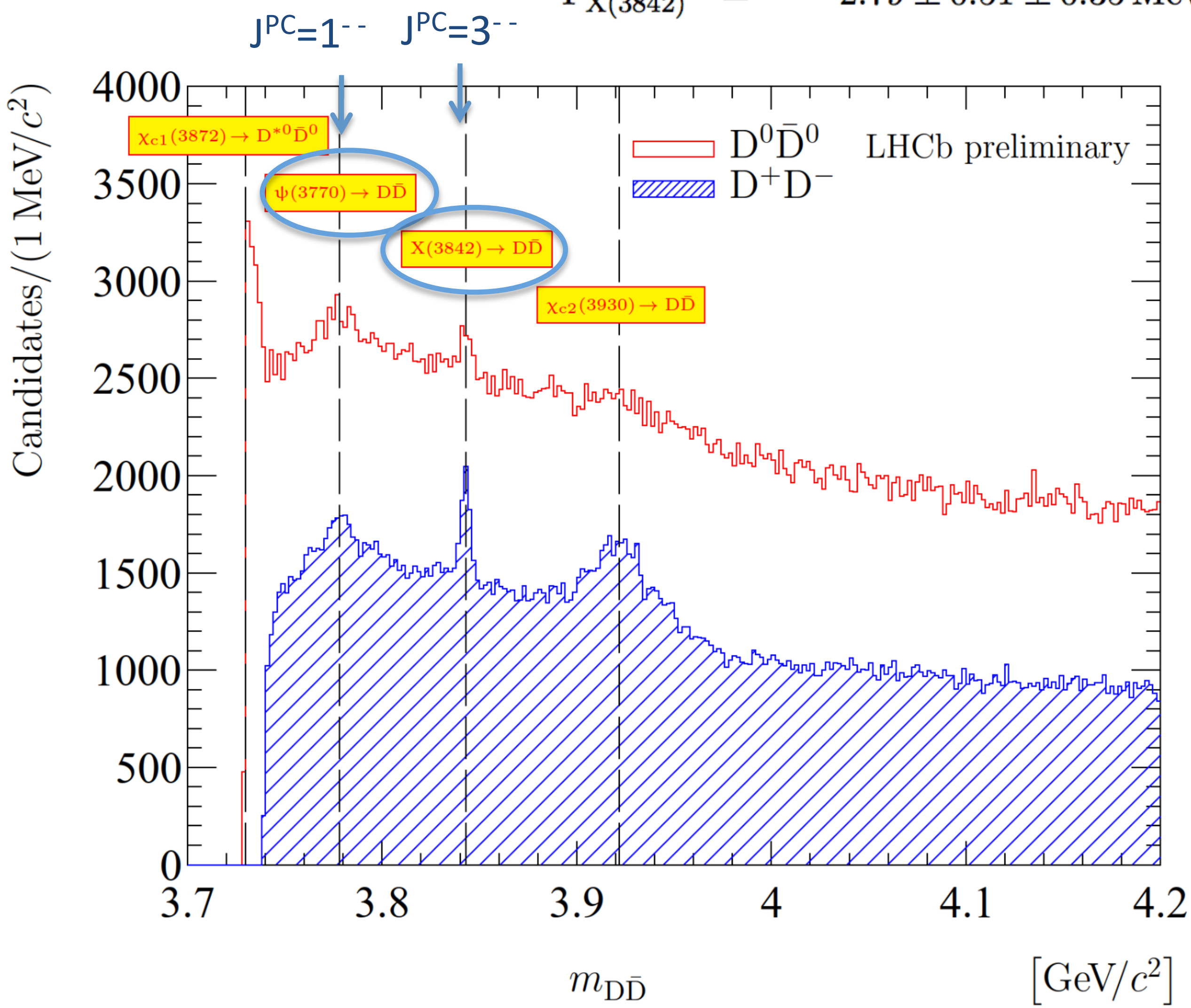
Charmonium resonances in D$\bar{D}$ from LHCb: first discovery of charmonium with J=3

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

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 $J^{PC} = 3^{--}$“

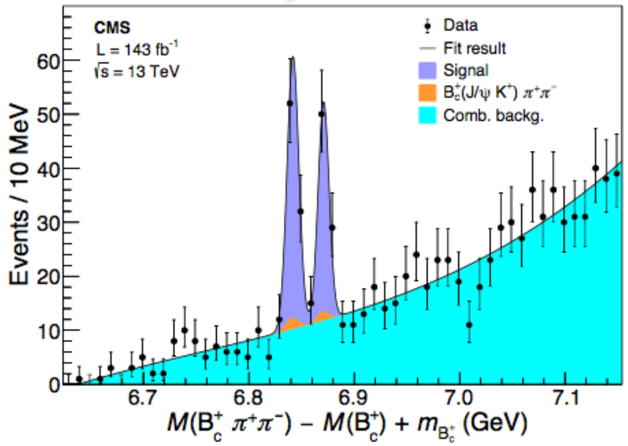
Quark model quantum numbers:

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

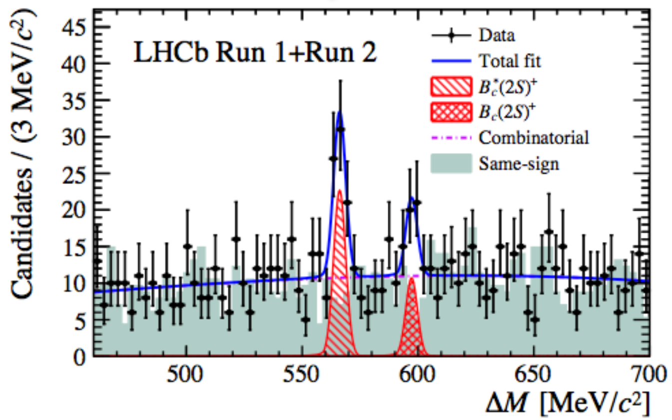
B_c*(2S)

$\bar{b}c$

[CMS, 1902.00571, PRL]



[LHCb, 1904.00081, PRL]

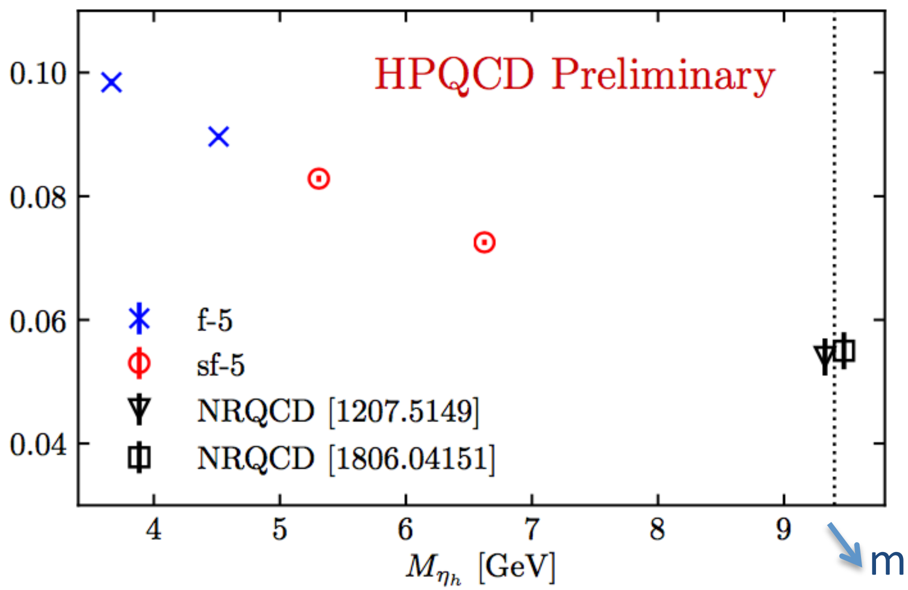


$B_c^*(2S)$ peak at $M = m[B_c(2S)] - \Delta M$ $\quad 6842(2)$ MeV $\quad 6841.2(0.6)(0.1)(0.8)$ MeV

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

photon undetected

$m[B_c^*] - m[B_c]$ [GeV]



$m_b = m_b^{phy}$

Lattice QCD:

[HPQCD, 1811.09448, A. Lytle, talk at QWG19]

$m_c = m_c^{phy}$

m_b varried

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

m[B_c*(2S)] can be determined using ΔM from experiment and m(Bc*)-m(Bc) from lattice