What's left to learn from Mesons with Heavy Quarks?

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Outline

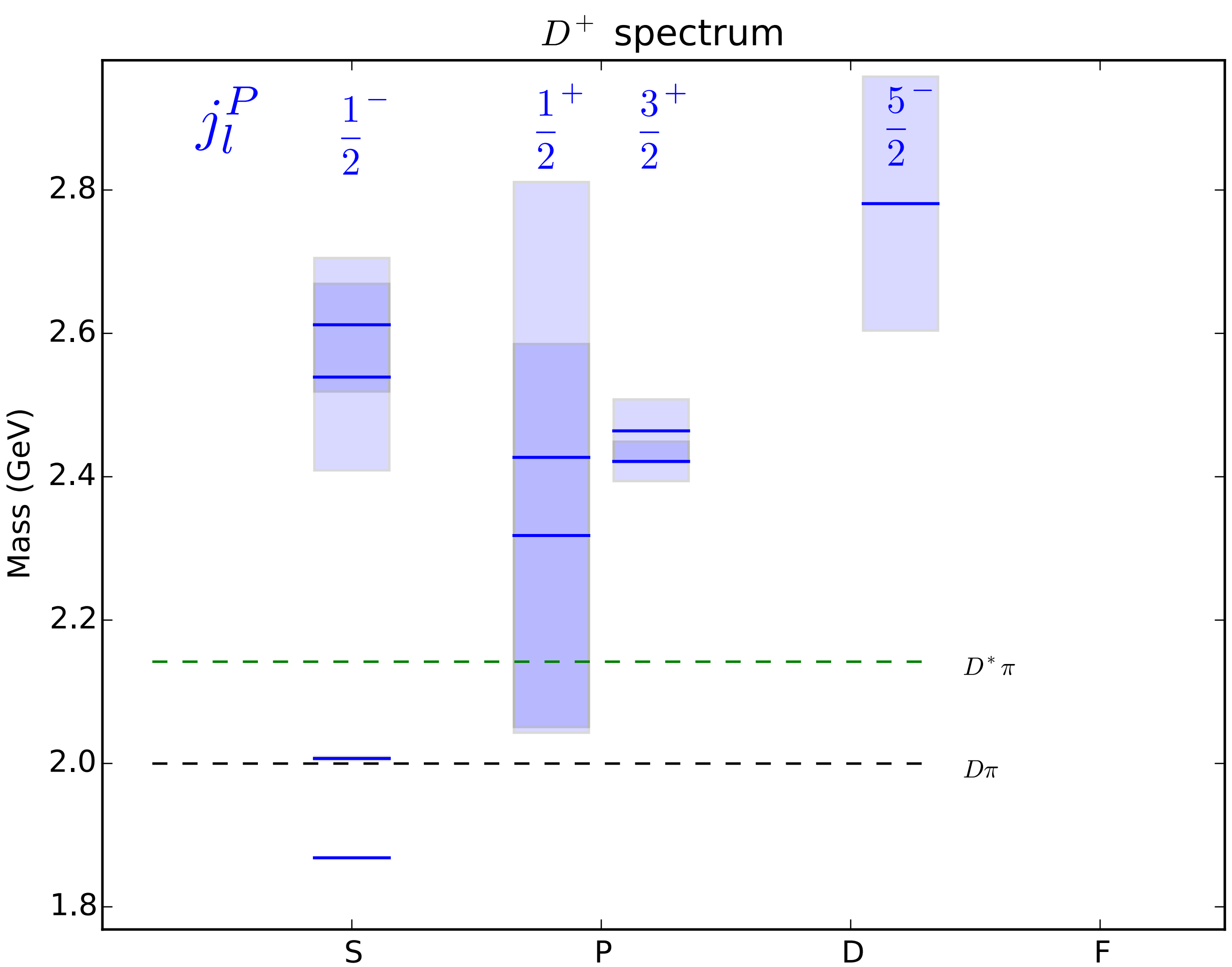
- Heavy-light Mesons $(Q\bar{q})$
- Quarkonium Mesons $(Q\bar{Q}')$
- Disentangling States Near Threshold
- Summary

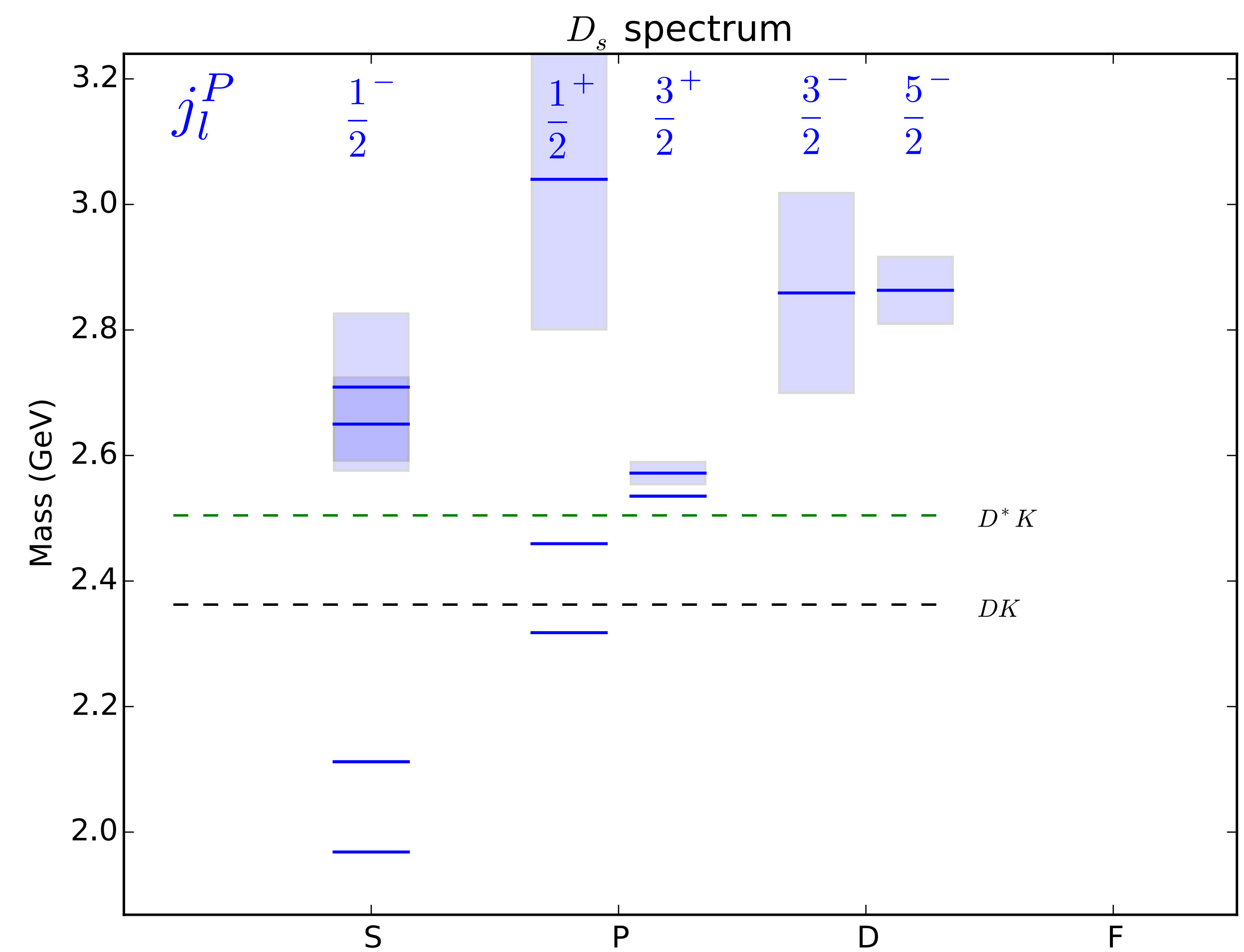
- QCD dynamics greatly simplifies for heavy quarks ($m_Q \gg \Lambda_{QCD}$)
- For systems with heavy quarks and light quarks:
  - HQET: systematic expansion in powers of Λ_{QCD}/m_Q
  - Heavy-light systems: $(c\bar{q})$, $(b\bar{q})$, (cqq), (bqq), (ccq), (cbq), (bbq) for q=u,d or s
  - HQS relations between excitation spectrum in [$(c\bar{q})$,$(b\bar{q})$,(ccq), (bcq) and (bbq)] and between [(cqq) and (bqq)]
  - QED analog - hydrogen atom (e^-p)
- For non relativistic $(Q\bar{Q})$: bound states form with masses M near $2m_Q$:
  - NRQCD: systematic expansion in powers of v/c
  - Quarkonium systems: $(c\bar{c})$, $(b\bar{b})$, $(b\bar{c})$
  - heavy quark velocity: $p_Q/m_Q \approx v/c \ll 1$
  - binding energy: $2m_Q - M \approx m_Q\, v^2/c^2$
  - QED analogs - positronium (e^+e^-), (true) muonium ($\mu^-\mu^+$), muonium ($e^-\mu^+$)

Heavy Quark Symmetry

- As $m_Q \to \infty$ the spectrum of heavy-light mesons becomes doubly degenerate.
  - $J = j_l + s_Q$ where j_l the total angular momentum of the light degrees of freedom.
  - Corrections of order $1/m_Q$ do three things:
    - split the spin degeneracy: $C_1(j_l \cdot s_Q)/m_Q$
    - spin independent shift center of gravity: $C_2(\nabla_Q \cdot \nabla_Q)/m_Q$
    - mix states with same J^P different j_l : $C_3[(j_l \cdot r_l)(s_Q \cdot r_l) - 1/3(j_l \cdot s_Q)(r_l \cdot r_l)]/m_Q$
      eg. mix $j_l = 1/2, 3/2$ with $J^P = 1^+$ P states
  - This symmetry doesn't depend on the QCD dynamics of the light degrees of freedom.
    - Implications for the P states of the heavy-light system
      - Independent of dynamic nature of the (0+, 1+) $j_l = 1/2$ P states of the B, D system
      - HQS does not require the four P states to be degenerate as $m_Q \to \infty$, as expected in leading order of NR limit.
  - Can see this behavior in the excitation spectrum of the the B, D systems

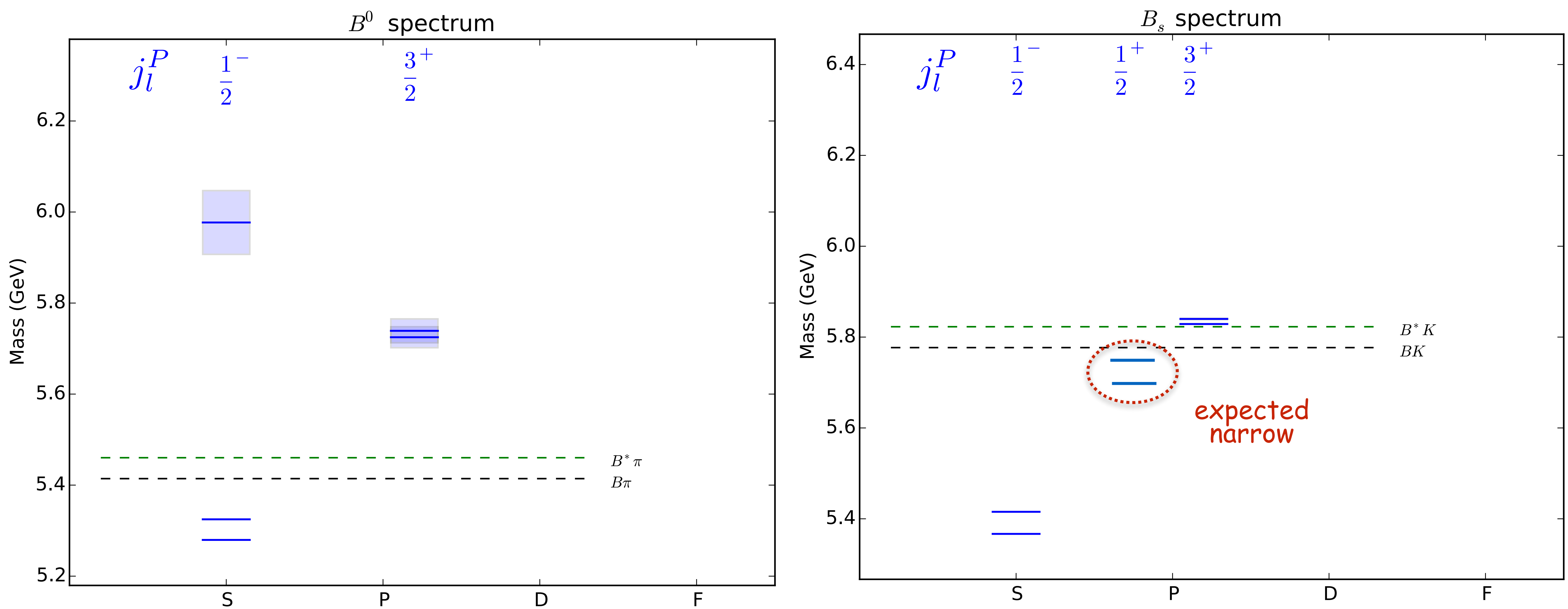
Observed States in D Spectrum





- HQS determines the ratios of hadronic transitions - very useful in distinguishing excited states
- Various proposals for the shifts of the $D_s^*(2317)$ and $D_s(2460)$:
  - Influence of the nearby decay channels.
  - Chiral multiplets $(0^-, 0^+)$.
  - Threshold bound states of DK and D*K respectively.

Observed states in B meson system



- HQS relates the excitation spectrum in the D system to the B system.
- Various models will be disentangled when the narrow B_s ($j^P = \frac{1}{2}^+$) states are observed.

Important to observe the B_s ($j^P = \frac{1}{2}^+$) states

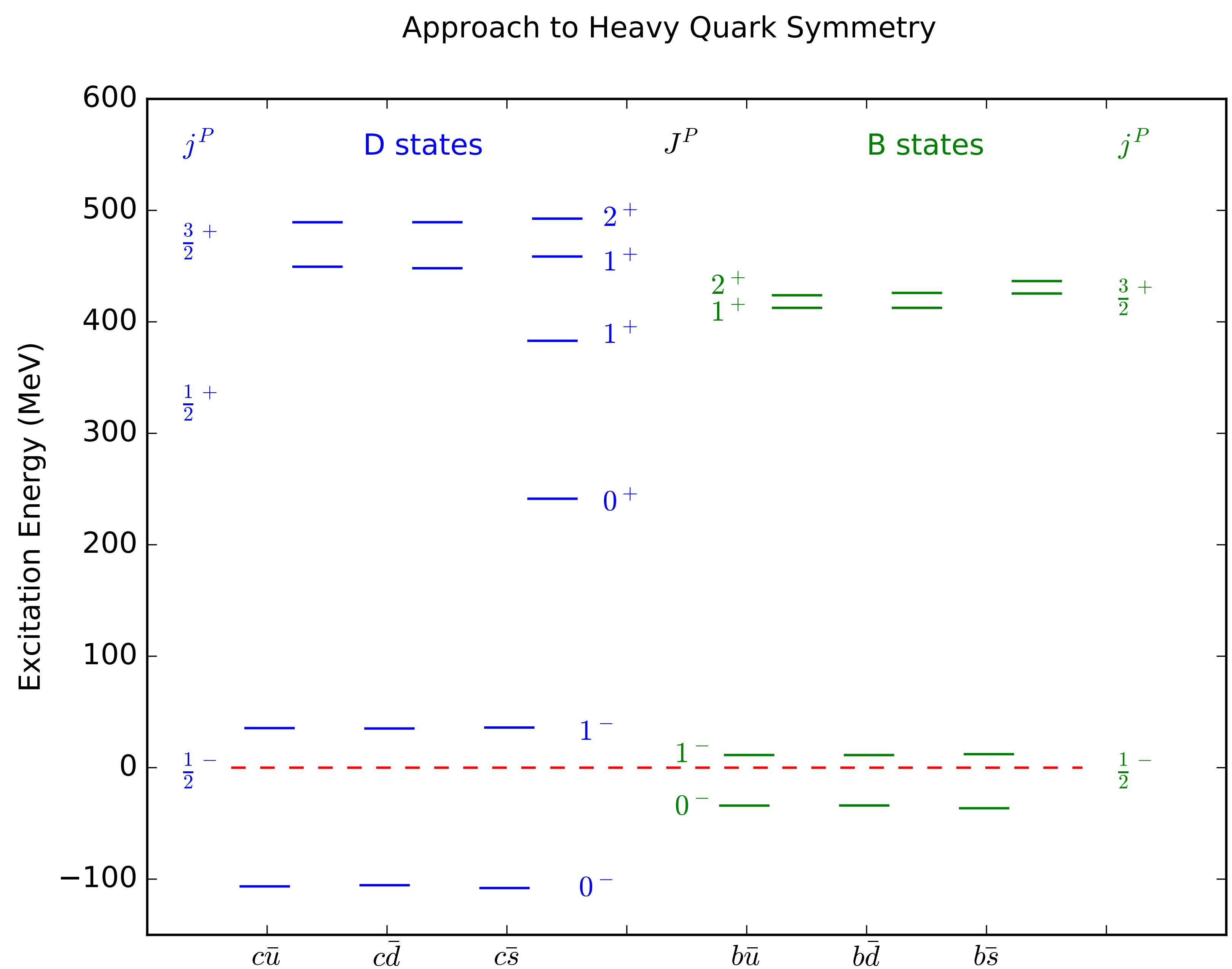
- Spin splittings (MeV)

Multiplet	D Mesons			B Mesons		
j_l^P	u	d	s	u	d	s
$\frac{1}{2}^-$	142.0	140.6	144.0	45.4	45.2	48.5
$\frac{1}{2}^+$	−−	−−	141.7	−−	−−	−−
$\frac{3}{2}^+$	39.9	41.3	34.0	11.3	13.4	11.2

- Shift of CoG (relative)

Multiplet	D Mesons			B Mesons		
j_l^P	u	d	s	u	d	s
$\frac{1}{2}^+$	−−	−−	348	−−	−−	−−
$\frac{3}{2}^+$	479	479	484	423	421	434

- Need $j_l^P = \frac{1}{2}^+$ B_s states to extrapolate to HQS limit for P states
- Will allow to distinguish various models of the QCD dynamics of these states.



- Mass predictions: Bs ($j_l^P = \frac{1}{2}^+$)
  - Approaches to QCD dynamics
    - LQCD
    - Chiral multiplets (0^+, 0^-)
    - K matrix: $B+K^{(*)}$ scattering
    - Tetraquarks
    - RQM with coupled channels
  - Splitting (from HQS)
    - $[m(1^+) - m(0^+)]_b \approx [m(1^+)-m(0^+)]_c\, M(J/\psi)/M(\Upsilon)$ ≈ 46 MeV
    - All valid approaches should agree [RQM looks low]
  - CoG = $[3\ m(1^+) + m(0^+)]/4$
    - QCD dynamics dependent: C_2, C_3
    - See a wide variation in models as expected.
    - If C_2 same as for D system: CoG = 5837 MeV
    - Need experimental determination. [Belle 2, LHC] $B_s\, B_{s0}^*$ Threshold ~ 11.130

C. B. Lang, Daniel Mohler, Sasa Prelovsek, R. M. Woloshyn [arXiv:1501.01646]

Table 5: Comparison of masses from this work to results from various model based calculations; all masses in MeV.

J^P	0^+	1^+
Covariant (U)ChPT [24]	5726(28)	5778(26)
NLO UHMChPT [19]	5696(20)(30)	5742(20)(30)
LO UChPT [17, 18]	5725(39)	5778(7)
LO χ-SU(3) [16]	5643	5690
HQET + ChPT [20]	5706.6(1.2)	5765.6(1.2)
Bardeen, Eichten, Hill [15]	5718(35)	5765(35)
rel. quark model [5]	5804	5842
rel. quark model [22]	5833	5865
rel. quark model [23]	5830	5858
HPQCD [30]	5752(16)(5)(25)	5806(15)(5)(25)
this work	5713(11)(19)	5750(17)(19)

LQCD calculation includes the mixing of the two meson thresholds.

Table 2. Predicted masses of the 0^+ and 1^+ heavy-strange mesons, and poles given as $(M, \Gamma/2)$ for the 0^+ and 1^+ heavy-nonstrange mesons. Here M and Γ are the mass and the total decay width, respectively. For comparison, the RPP values [13] and latest lattice QCD results are also shown. All values are in units of MeV.

	Prediction	RPP	Lattice QCD
D_{s0}^*	2315^{+18}_{-28}	2317.7 ± 0.6	2348^{+7}_{-4} [44]
D_{s1}	2456^{+15}_{-21}	2459.5 ± 0.6	2451 ± 4 [44]
B_{s0}^*	5720^{+16}_{-23}	–	5711 ± 23 [64]
B_{s1}	5772^{+15}_{-21}	–	5750 ± 25 [64]
D_0^*	$\left(2105^{+6}_{-8}, 102^{+10}_{-11}\right)$, $\left(2451^{+35}_{-26}, 134^{+7}_{-8}\right)$	$(2318 \pm 29, 134 \pm 20)$	–
D_1	$\left(2247^{+5}_{-6}, 107^{+11}_{-10}\right)$, $\left(2555^{+47}_{-30}, 203^{+8}_{-9}\right)$	$\left(2427 \pm 40, 192^{+65}_{-55}\right)$	–
B_0^*	$\left(5535^{+9}_{-11}, 113^{+15}_{-17}\right)$, $\left(5852^{+16}_{-19}, 36 \pm 5\right)$	–	–
B_1	$\left(5584^{+9}_{-11}, 119^{+14}_{-17}\right)$, $\left(5912^{+15}_{-18}, 42^{+5}_{-4}\right)$	–	–

- Branching fractions
  - Both D and B systems can be used to distinguish models.
  - Need to measure (H = D or B) branching fractions.
    - $R_1(H)$ =Br(H_s(0+) -> H_s(0-) + γ)/Br(H_s(0+) -> H_s(0-) + π^0)
    - $R_2(H)$ =Br(H_s(1+) -> H_s(1-) + γ)/Br(H_s(1+) -> H_s(1-) + π^0)
    - $R_3(H)$ =Br(H_s(1+) -> H_s(0-) + γ)/Br(H_s(1+) -> H_s(1-) + π^0)
    - $R_4(H)$ = Br(H_s(1+) -> H_s(1-) + 2π)/Br(H_s(1+) -> H_s(1-) + π^0)
  - Expect R_1(D) << R_1(B) - cancelling c and s quark terms for E1 transition.
  - R_2(B) distinguishes models.
  - R_2(H)/R_3(H) measures mixing of the J=1 states.
  - HQS assures that the
    - Γ(H_s(0+) -> H_s(0-) + π^0) = Γ(H_s(1+) -> H_s(1-) + π^0)

Table 1: The hadronic and electromagnetic transition rates for narrow $j_l^P = 1/2^+$ heavy-light P states.

system	transition	Q(keV)	dependency	width (keV)	exp BR
$(c\bar{s})$	$0^+ \to 1^- + \gamma$	212	m_s^*, m_c^*	1.74	$(< 5)\%$
	$0^+ \to 0^- + \pi^0$	297	$G_A\delta_{\eta\pi 0}$	21.5	$(100^{+0}_{-20})\%$
	total			23.2	
$(c\bar{s})$	$1^+ \to 0^+ + \gamma$	323	m_s^*, m_c^*, θ_c	0.43	$(3.7^{+5.0}_{-2.4})\%$
	$1^+ \to 1^- + \gamma$	323	m_s^*, m_c^*, θ_c	3.49	$(< 8)\%$
	$1^+ \to 0^- + \gamma$	442	m_s^*, m_c^*, θ_c	7.62	$(18 \pm 4)\%$
	$1^+ \to 1^- + \pi^0$	298	$G_A\delta_{\eta\pi 0}$	21.5	$(48 \pm 11)\%$
	$1^+ \to 1^- + 2\pi$	221	$g_A\delta_{\sigma_1\sigma_3}$	9.7	
	total			42.7	
$(b\bar{s})$	$0^+ \to 1^- + \gamma$	293	m_s^*, m_b^*	58.3	
	$0^+ \to 0^- + \pi^0$	297	$G_A\delta_{\eta\pi 0}$	21.5	
	total			79.8	
$(b\bar{s})$	$1^+ \to 0^+ + \gamma$	335	m_s^*, m_b^*, θ_b	0.15	
	$1^+ \to 1^- + \gamma$	335	m_s^*, m_b^*, θ_b	42.3	
	$1^+ \to 0^- + \gamma$	381	m_s^*, m_b^*, θ_b	58.3	
	$1^+ \to 1^- + \pi^0$	298	$G_A\delta_{\eta\pi 0}$	21.5	
	$1^+ \to 1^- + 2\pi$	125	$g_A\delta_{\sigma_1\sigma_3}$	0.24	
	total			123.8	

W.Bardeen, E.E., C. Hill PR D68 054024 (2003)

[hep-ph/0305049]

Hadronic and electromagnetic transition rates for narrow B_{s1} heavy-light P states. Results for various other models: B^*K bound state in Heavy Chiral Unitary [hep-ph/0801.1932,hep-ph/0803.1223] and Light-Cone QCD sum rules[hep-ph/0711.2559], $\mathcal{L}_{eff}(1)$ [hep-ph/0801.2232] and (2) [hep-ph/1405.2242], Bethe-Salpeter [arXiv:1906.09002] approaches; and Relativistic quark model with mixing to four quark (two meson) states[hep-ph/0711.2359]. (Results in keV)

Approach	$\Gamma(B_{s1} \to B_s^*\pi)$	$\Gamma(B_{s1} \to B_s\gamma)$	$\Gamma(B_{s1} \to B_s^*\gamma)$
Heavy Chiral Unitarity	10.36	$3.2 - 15.8$	$0. - 6.1$
Light Cone Sum Rules	$5.3 - 20.7$	106.5(60.7)	75.6(6.0)
Bethe-Salpeter	$27.5 - 39.2$	$45.2 - 79.8$	$0.4 - 2.6$
$\mathcal{L}_{eff}(1)$	$57.0 - 94.0$	$2.0 - 2.67$	$0.04 - 0.18$
$\mathcal{L}_{eff}(2)$	1.8 ± 1.8	4.1 ± 10.9	46.9 ± 33.6

- QCD dynamics greatly simplifies for heavy quarks ($m_Q \gg \Lambda_{QCD}$)
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  - Heavy-light systems: $(c\bar{q})$, $(b\bar{q})$, (cqq), (bqq), (ccq), (cbq), (bbq) for q=u,d or s
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  - heavy quark velocity: $p_Q/m_Q \approx v/c \ll 1$
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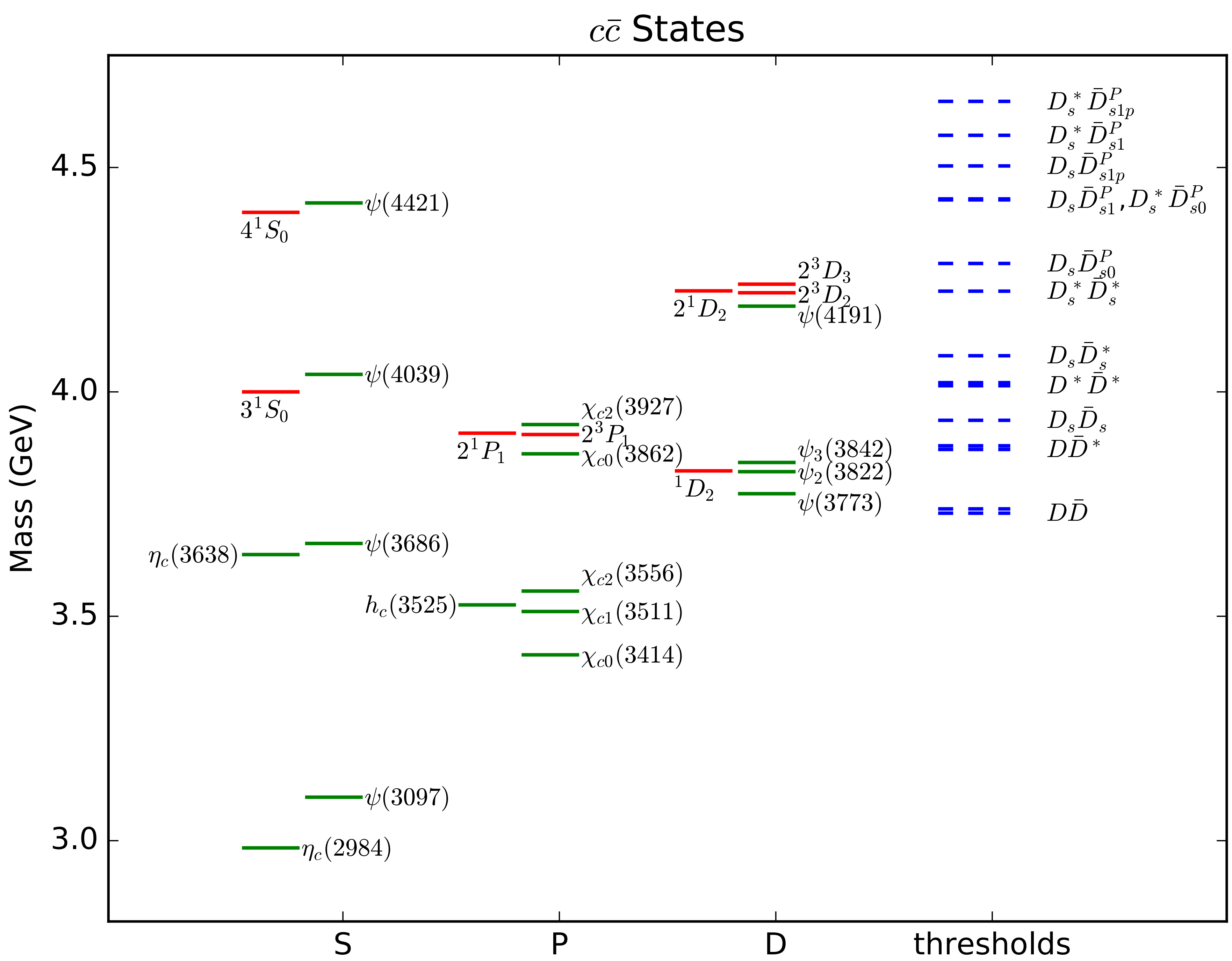
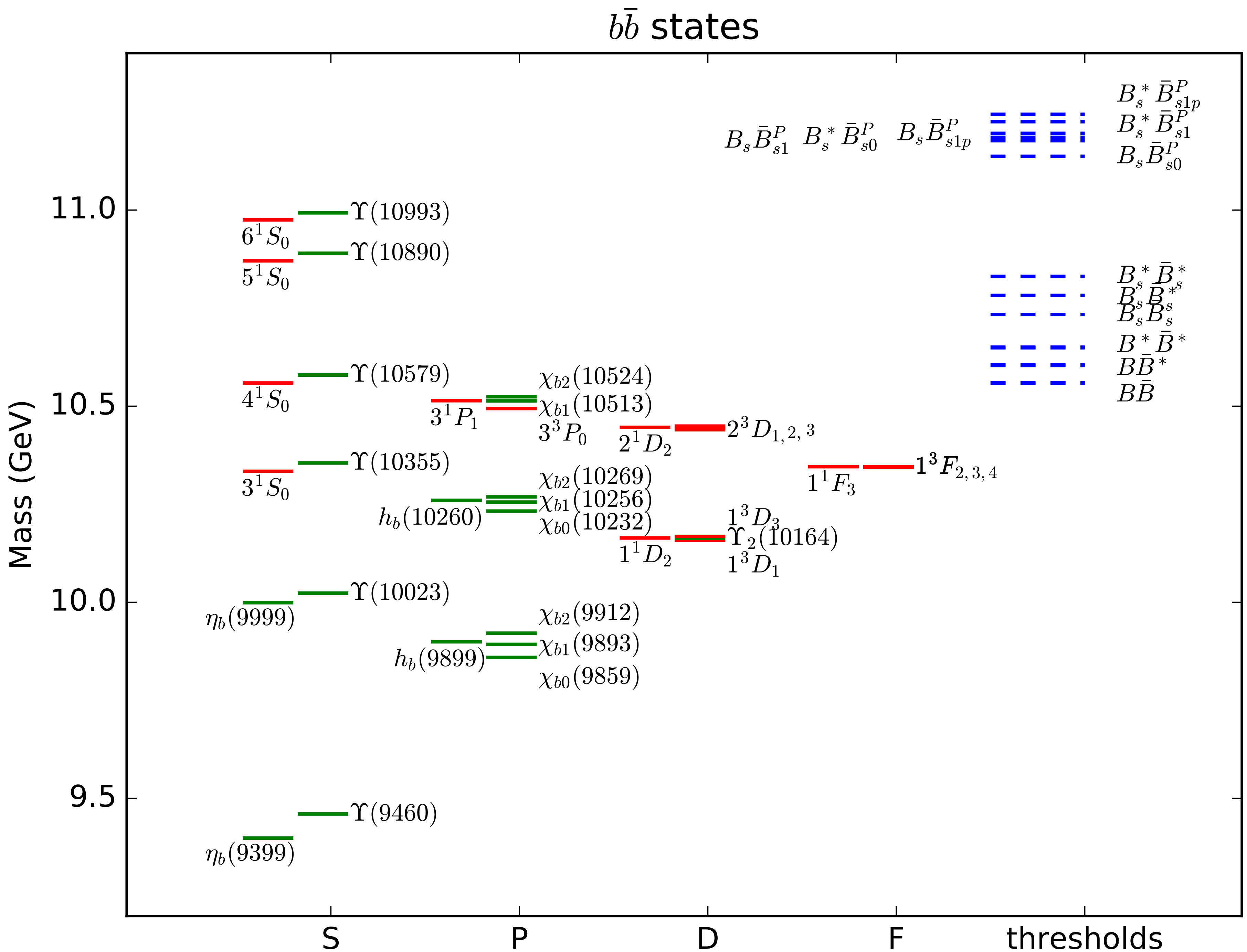
  - QED analogs - positronium (e^+e^-), (true) muonium ($\mu^-\mu^+$), muonium ($e^-\mu^+$)

Narrow States Below Threshold

- For charmonium system:
  - experiment theory
  - Below threshold only
    $^1D_2$ state unobserved.
  - Two body thresholds
  - Charmed mesons:
    $\Gamma < 1$ MeV

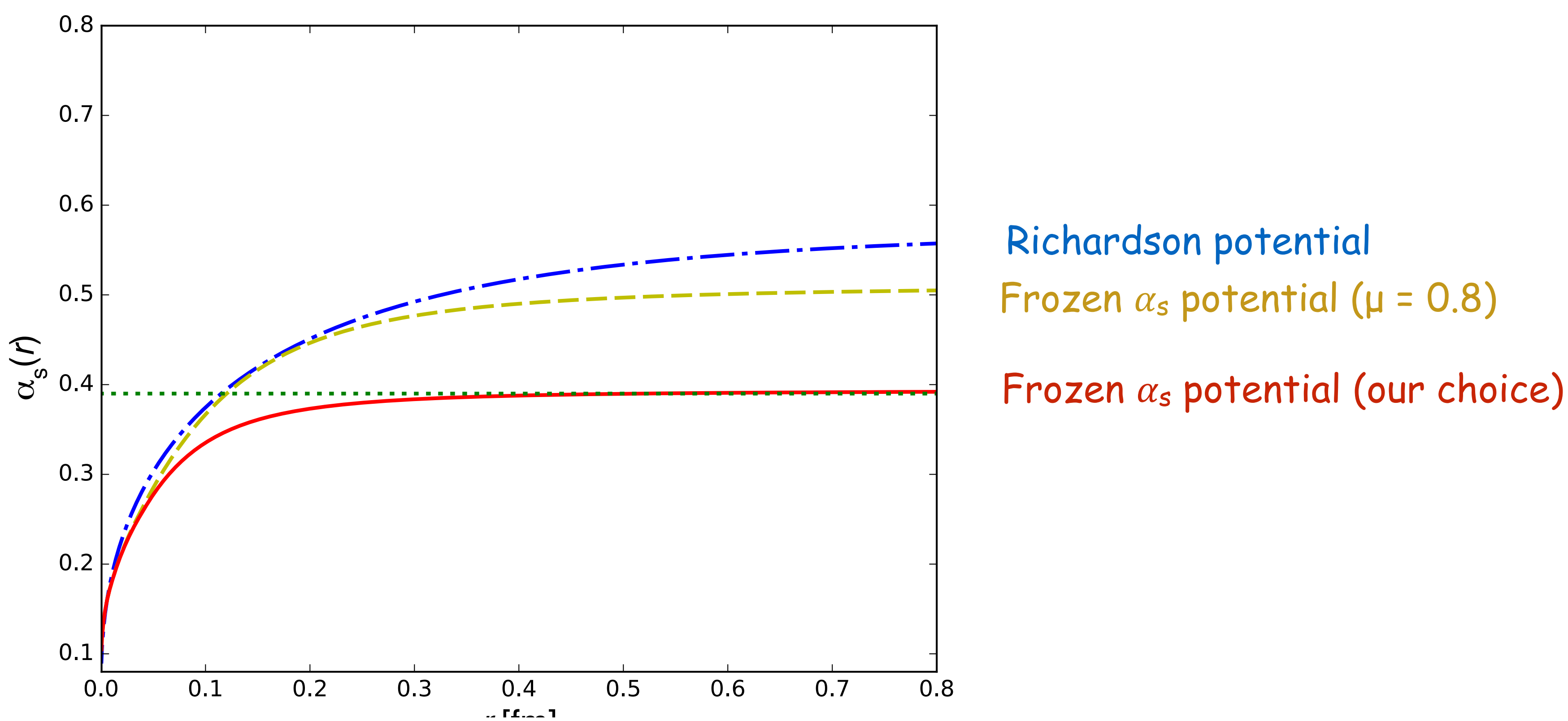


- For bottomonium system:
  - experiment theory
  - Below threshold
    14 state unobserved.
  - Two body thresholds
  - Beauty mesons:
    Γ< 1 MeV
  - Pattern of thresholds affected by smaller spin-splitings

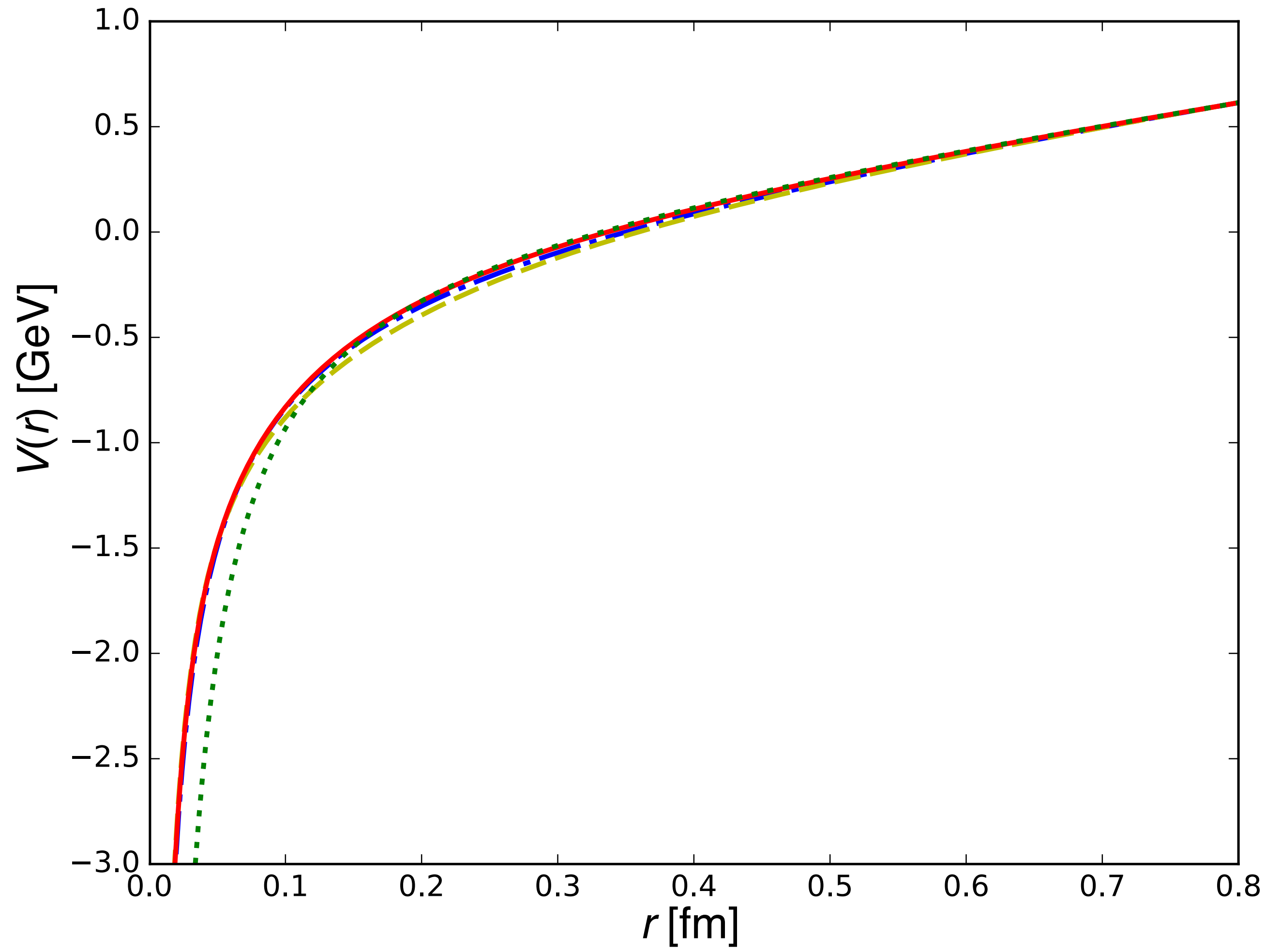


B_c System

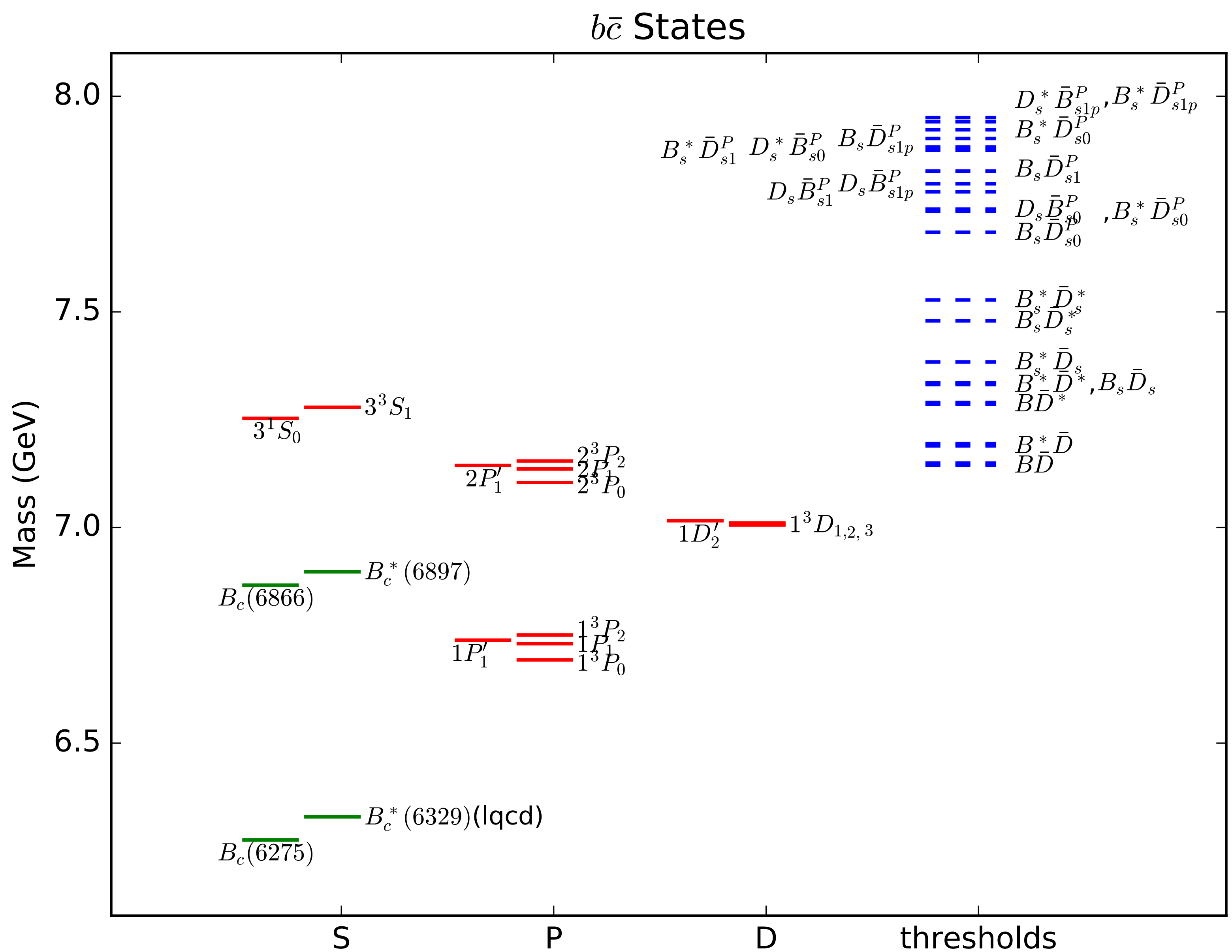
- Only other quarkonium system with narrow states is the $(b\bar{c})$
  - Has been studied theoretically for many years. I will report on a recent update. (E.E and C. Quigg [1902.09735])
  - Starting point a QCD inspired variation of Cornell potential:
    - $V(r) = -4/3\ \alpha_s(r)/r + r/a^2$ with $a = 2.34\ \mathrm{GeV}^{-1}$; $m_c = 1.84$ GeV, $m_b = 5.18$ GeV
    - $\alpha_s(r)$ the four loop QCD running coupling at short distance but becoming frozen at large distance [as suggest by Gribov for light mesons: $\alpha_s \to (3\pi/4)(1-\sqrt{(2/3)}) \approx 0.44$)]



- Results
  - potential
    - Frozen alpha (red)
    - original Cornell (green)
    - Richardson (blue)
  - The spin-dependent terms determined from fits to observed (cc) and (bb) systems



- B_c is the unique heavy-heavy meson that only has weak decays.
  - A rich excitation spectrum of states.
  - All the excited states below BD threshold decay to B_c.
    - Bc(2S) -> Bc(1S) +ππ.
    - The P-states have photon transitions to lower S and D states
  - Many states observable at the LHC and a future TevaZ factory.



EE & C. Quigg [arXiv:1902.09735]

- Spin splittings unequal mass
  - General form

$$H_{\text{eff}} = [\frac{L\cdot s_1}{2m_1^2} + \frac{L\cdot s_2}{2m_2^2}]T_1 + \frac{L\cdot(s_1+s_2)}{m_1m_2}T_2 + \frac{s_1\cdot s_2}{m_1m_2}T_3 + \frac{S_{12}}{m_1m_2}T_4$$

  - The spin singlet state is shifted from the center of gravity of the spin triplets states.

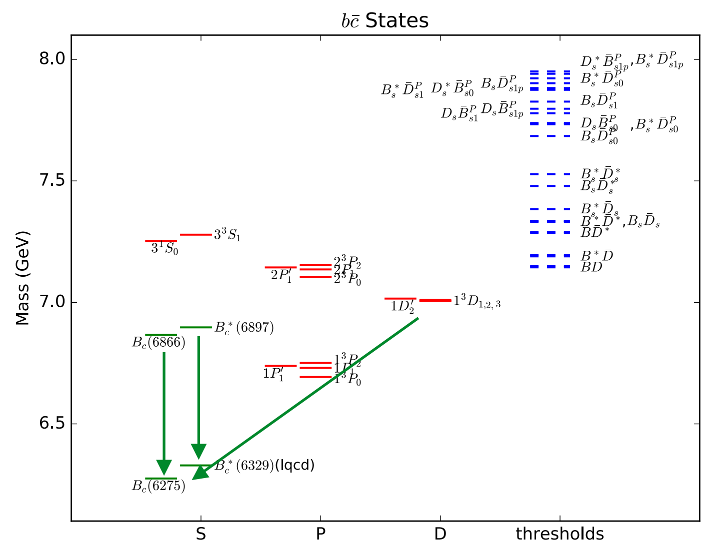
(S=1, S=0)

$$H(spin\ orbit) \;=\; \left[\frac{1}{4}(\frac{1}{m_1^2}+\frac{1}{m_2^2})T_1 + \frac{1}{m_1m_2}T_2\right] \begin{array}{c} \begin{array}{cccc} \text{L+1,} & \text{L,} & \text{L,} & \text{L-1} \end{array} \\ \begin{pmatrix} L & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -(L+1) \end{pmatrix} \end{array} +$$

$$\frac{1}{4}(\frac{1}{m_1^2}-\frac{1}{m_2^2})T_1 \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \sqrt{L(L+1)} & 0 \\ 0 & \sqrt{L(L+1)} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

  - Can be measured from the 1P spin splittings

- Decay rates of excited (bc) narrow states:
  - 12 to 15 narrow states depending exact position of the 2P states
  - notable 2π hadronic transitions



  - notable photon transitions

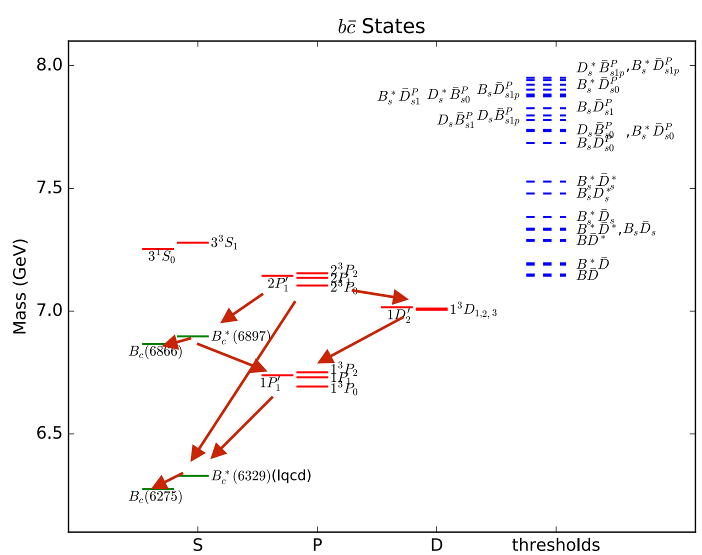


TABLE VI. Total widths Γ and branching fractions $\mathcal{B}$ for principal decay modes of $(c\bar{b})$ states below threshold, updating Table IX of Ref. [6]. Dissociation into BD, etc., will dominate over the tabulated decay modes for states above threshold.

Decay Mode	k_γ [keV]	Branching Fraction (%)
1^1S_0 (6275) : weak decays		
1^3S_1 (6329) : $\Gamma = 0.144$ keV		
$1^1S_0 + \gamma$	54	100
2^3P_0 (6692) : $\Gamma = 53.1$ keV		
1^3S_1 (6329)	354	100
$2P_1$ (6730) : $\Gamma = 72.5$ keV		
1^3S_1 (6329)	389	86.2
1^1S_0 (6275)	440	13.7
$2P_1'$ (6738) : $\Gamma = 99.9$ keV		
1^1S_0 (6275)	448	92.4
1^3S_1 (6329)	397	7.51
2^3P_2 (6750) : $\Gamma = 79.7$ keV		
1^3S_1 (6329)	409	100
2^1S_0 (6866) : $\Gamma = 73.1$ keV		
$1^1S_0 + \pi\pi$		81.1
$2P_1'$ (6738)	126	16.5
$2P_1$ (6730)	134	2.24
2^3S_1 (6897) : $\Gamma = 76.8$ keV		
$1^3S_1 + \pi\pi$		65.0
2^3P_0 (6692)	201	7.66
$2P_1$ (6730)	165	11.5
$2P_1'$ (6738)	157	1.13
2^3P_2 (6750)	145	14.6
$3D_2$ (7005) : $\Gamma = 93.7$ keV		
$1^1S_0 + \pi\pi$		12.2
$1^3S_1 + \pi\pi$		9.0
$2P_1$ (6730)	270	29.1
$2P_1'$ (6738)	262	42.3
2^3P_2 (6750)	250	7.24
3^3D_1 (7006) : $\Gamma = 117$ keV		
$1^3S_1 + \pi\pi$		17.0
2^3P_0 (6692)	306	53.4
$2P_1$ (6730)	270	25.3
$2P_1'$ (6738)	262	2.62
2^3P_2 (6750)	251	1.51
3^3D_3 (7010) : $\Gamma = 87.2$ keV		
$1^3S_1 + \pi\pi$		22.9
2^3P_2 (6750)	255	77.0
$3D_2'$ (7015) : $\Gamma = 92.1$ keV		
$1^1S_0 + \pi\pi$		9.2
$1^3S_1 + \pi\pi$		12.4
$2P_1'$ (6738)	272	37.2
$2P_1$ (6730)	279	41.0
3^3P_0 (7104) : $\Gamma = 60.9$ keV		
1^3S_1 (6329)	733	46.4
2^3S_1 (6897)	204	45.0
3^3D_1 (7006)	97	8.44
$3P_1$ (7135) : $\Gamma = 87.1$ keV		
1^3S_1 (6329)	761	32.6
1^1S_0 (6275)	809	6.24
2^3S_1 (6897)	234	40.4
2^1S_0 (6866)	264	8.39
$3D_2$ (7005)	129	4.74
$3D_2'$ (7015)	119	4.55
3^3D_1 (7006)	128	2.88
$3P_1'$ (7143) : $\Gamma = 113$ keV		
1^1S_0 (6275)	816	32.9
1^3S_1 (6329)	768	3.88
2^1S_0 (6866)	272	47.0
2^3S_1 (6897)	242	5.15
$3D_2'$ (7015)	127	4.22
$3D_2$ (7005)	137	6.72
3^3P_2 (7154) : $\Gamma = 100$ keV		
1^3S_1 (6329)	777	35.2
2^3S_1 (6897)	252	49.2
$3D_2$ (7005)	147	1.09
$3D_2'$ (7015)	137	1.18
3^3D_1 (7006)	146	0.16
3^3D_3 (7010)	142	13.0
$4F_3$ (7221) : $\Gamma = 77.6$ keV		
$3D_2$ (7005)	213	52.4
$3D_2'$ (7015)	203	42.8
3^3D_3 (7010)	208	4.71
4^3F_4 (7223) : $\Gamma = 79.9$ keV		
3^3D_3 (7010)	210	100
4^3F_2 (7233) : $\Gamma = 95.3$ keV		
$3D_2$ (7005)	225	6.73
$3D_2'$ (7015)	215	7.96
3^3D_1 (7006)	224	84.8
3^3D_3 (7010)	220	0.42
$4F_3'$ (7237) : $\Gamma = 89.9$ keV		
$3D_2'$ (7015)	218	47.4
$3D_2$ (7005)	228	52.5

- Strong Decays for states above threshold.
  - 3S states above threshold and have significant decay widths

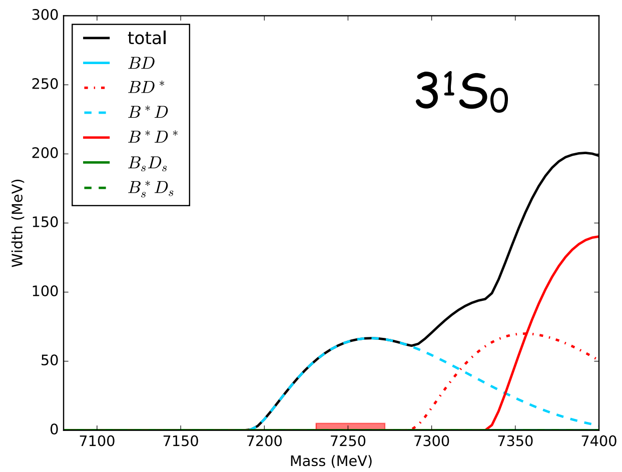
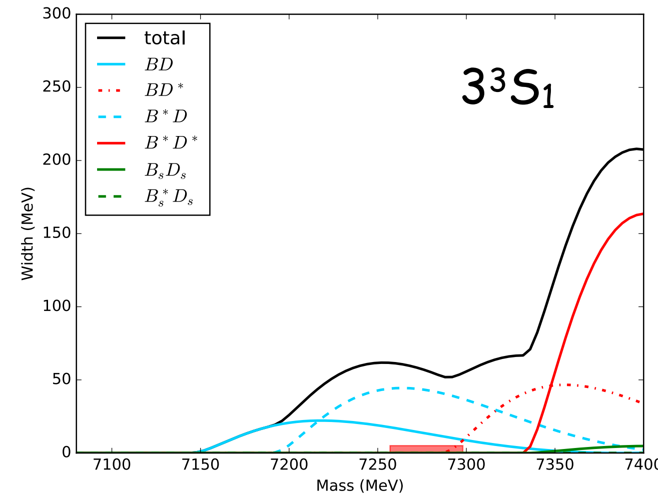
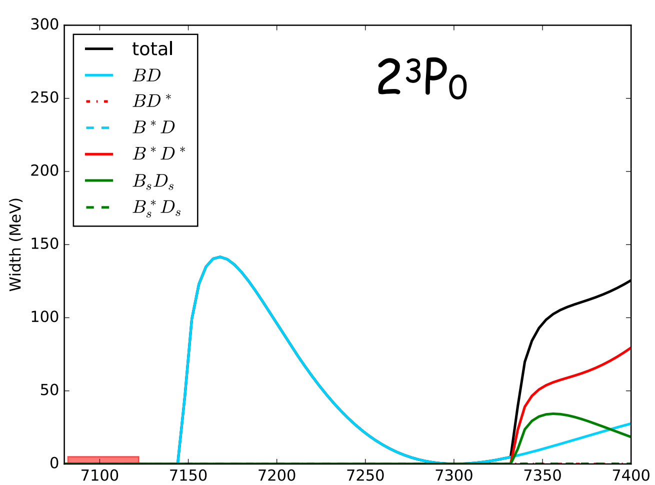
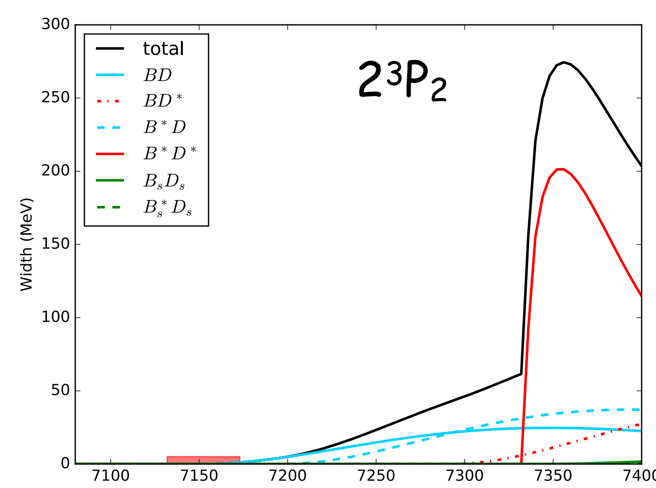


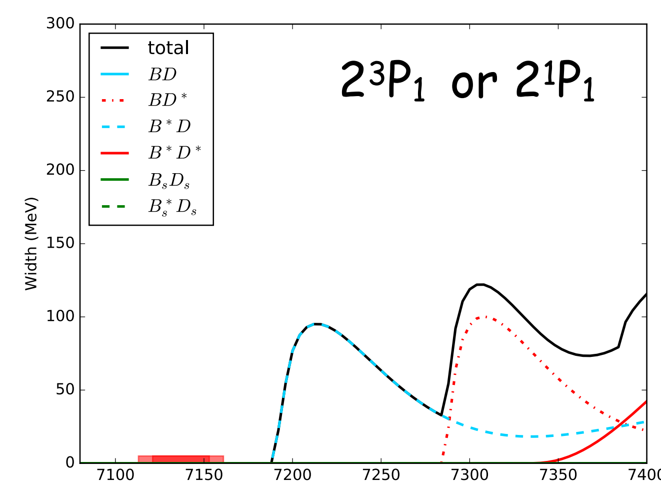
FIG. 9. Strong decay widths of the 3^1S_0 $(c\bar{b})$ level near open-flavor threshold. The shaded band on the mass axis indicates ± 20 MeV around our nominal value for the mass of this state, 7253 MeV.



  - 2P states just below threshold and may have significant mixing







- Production at hadron colliders
  - Use BCVEGPY 2.2 [hep-ph/05504017]
    Chao-Hsi Chang, Jian-Xiong Wang, Zing-Gang Wu
  - No calculation for D states (expected small)
  - p_T and rapidity distributions nearly state independent.

TABLE VIII. Production rates (in nb) for $(c\bar{b})$ states in pp collisions at the LHC. The production rates were calculated using the BCVEGPY2.2 generator of Ref. [45], extended to include the production of $3P$ states. Color-octet contributions to s-wave production are small; we show them (following |) only for the $1S$ states.

$(c\bar{b})$ level	$\sigma(\sqrt{s}=8$ TeV)	$\sigma(\sqrt{s}=13$ TeV)	$\sigma(\sqrt{s}=14$ TeV)
1^1S_0	46.8 | 1.01	80.3 | 1.75	88.0 | 1.90
1^3S_1	123.0 | 4.08	219.1 | 6.97	237.0 | 7.55
2^3P_0	1.113	1.959	2.108
2^3P_1	2.676	4.783	5.214
2^1P_1	3.185	5.702	6.166
2^3P_2	6.570	11.57	12.64
2^1S_0	9.58	16.94	18.45
2^3S_1	23.46	41.72	45.53
3^3P_0	0.915	1.642	1.806
3^3P_1	2.263	4.082	4.478
3^1P_1	2.695	4.817	5.287
3^3P_2	5.53	9.98	10.90
3^1S_0	4.23	7.53	8.08
3^3S_1	10.16	18.21	19.83

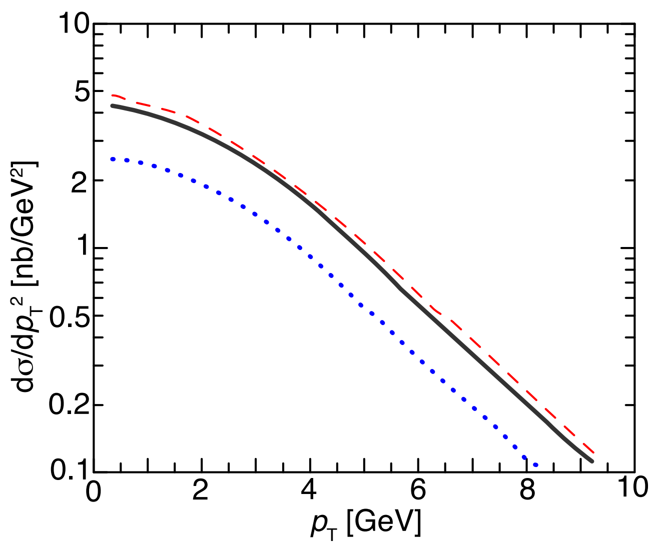


FIG. 5. Transverse momentum distribution of B_c produced in pp collisions at $\sqrt{s}=8$ TeV (dotted blue curve), $\sqrt{s}=13$ TeV (solid black curve), and $\sqrt{s}=14$ TeV (dashed red curve), calculated using BCVEGPY2.2 [45] Small shape variations are statistical fluctuations.

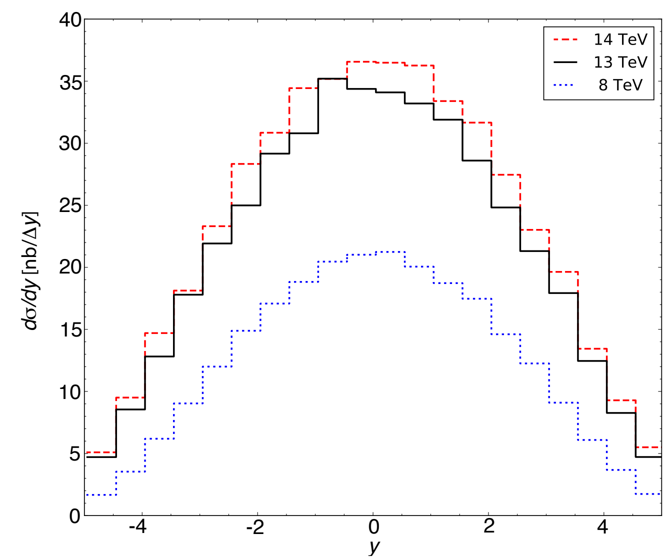
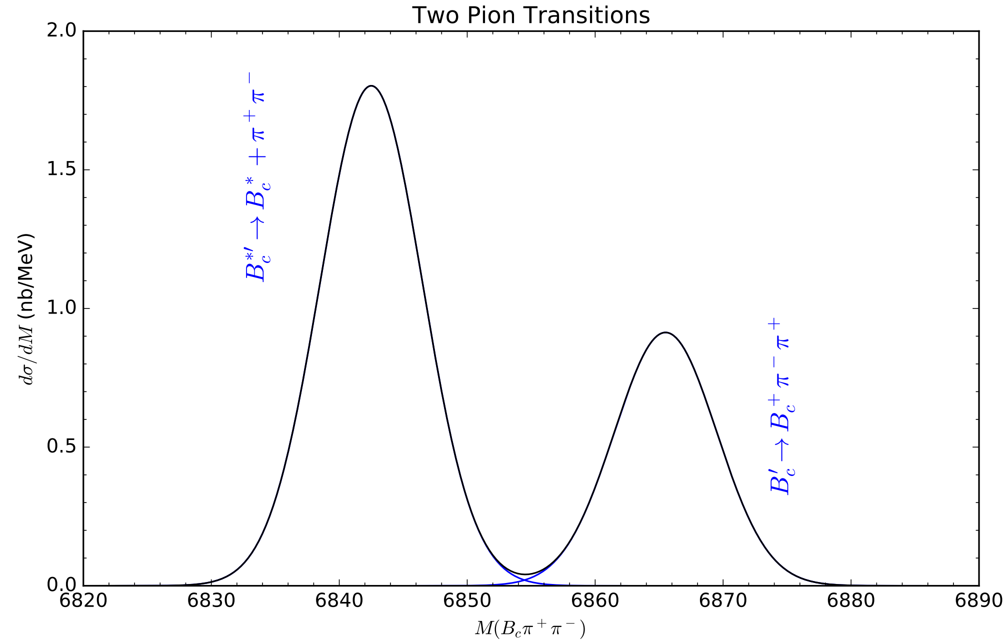
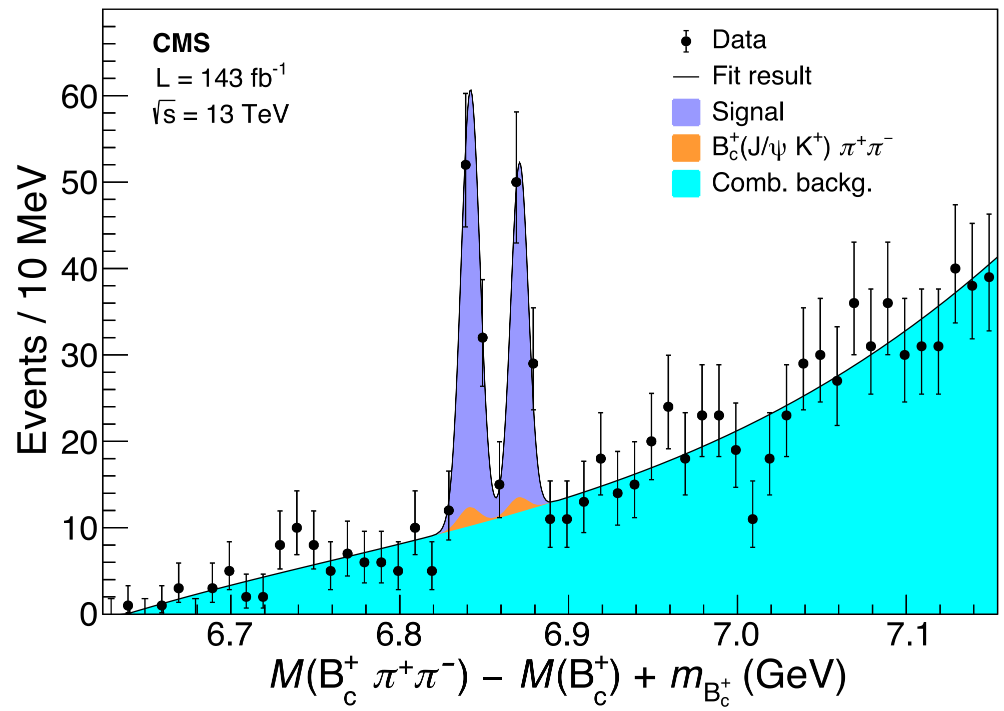


FIG. 4. Rapidity distribution for production of B_c^* in pp collisions at $\sqrt{s}=8$ TeV (dotted blue curve), $\sqrt{s}=13$ TeV (solid black curve), and $\sqrt{s}=14$ TeV (dashed red curve), calculated using BCVEGPY2.2 [45]. The bin width is $\Delta y = 0.5$. The mild asymmetries are statistical fluctuations.

- B_c spectrum
- 2S -> ππ + 1S transitions has been observed ATLAS, CMS, LHCb
- theory
  - Combine theoretically expected production rates with the branching fractions for the ππ transitions.
  - results in expectations for ππ transition rates.
- experiment
  - 2S -> ππ + 1S transitions has been observed ATLAS, CMS, LHCb
  - the gamma transition $B_c^* \to \gamma\, B_c$ is unobserved

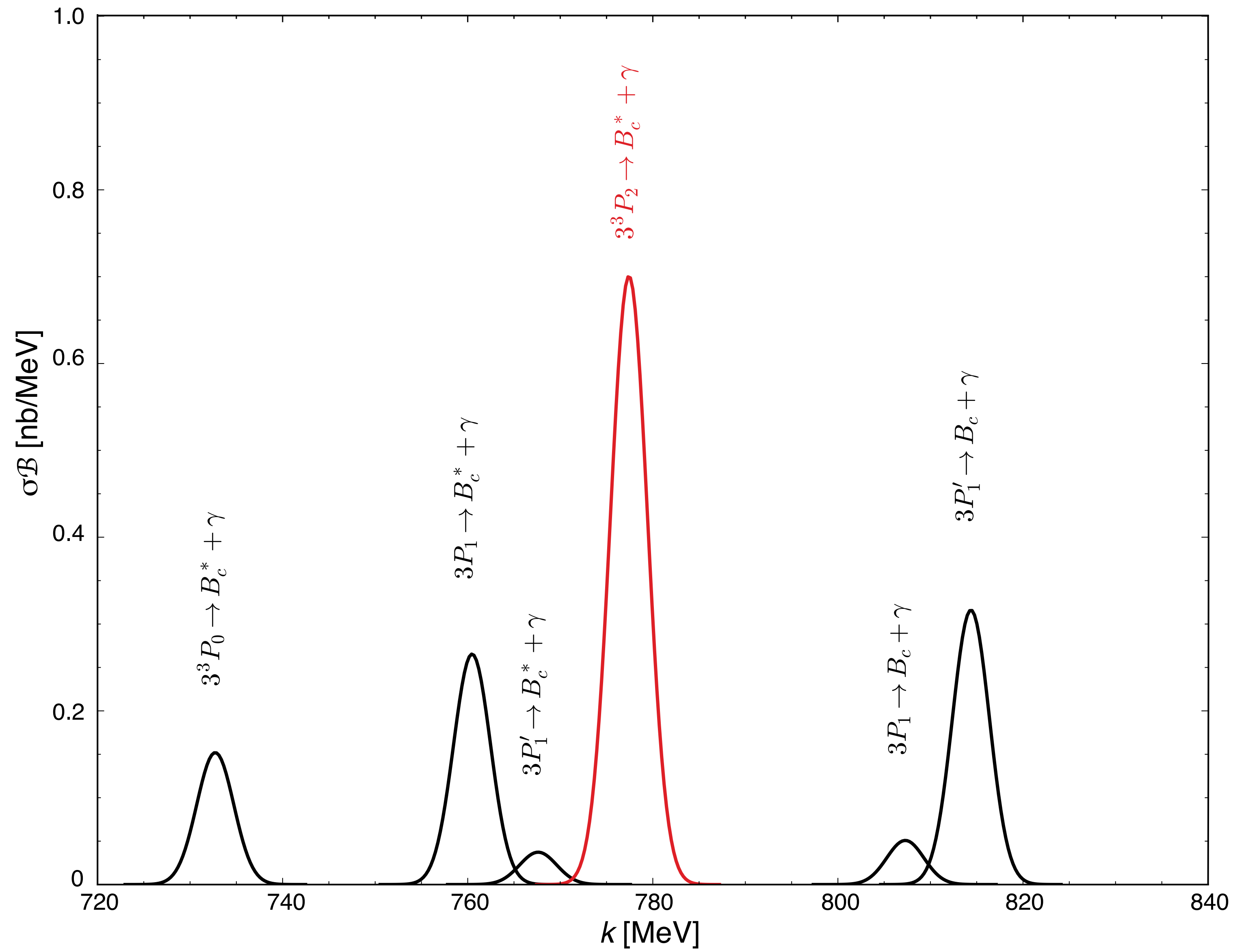


EE & C. Quigg [arXiv:1902.09735]



CMS [arXiv;1902.00571]

- The excited P states
  - The 2P states very close to decay thresholds.
  - Various models tested as analogs of X(3872).
  - Combining theoretically expected production rates and decay fractions yield the rates for the photon transitions.
- E1 transition photons observable:
  CMS, LHCb, Atlas

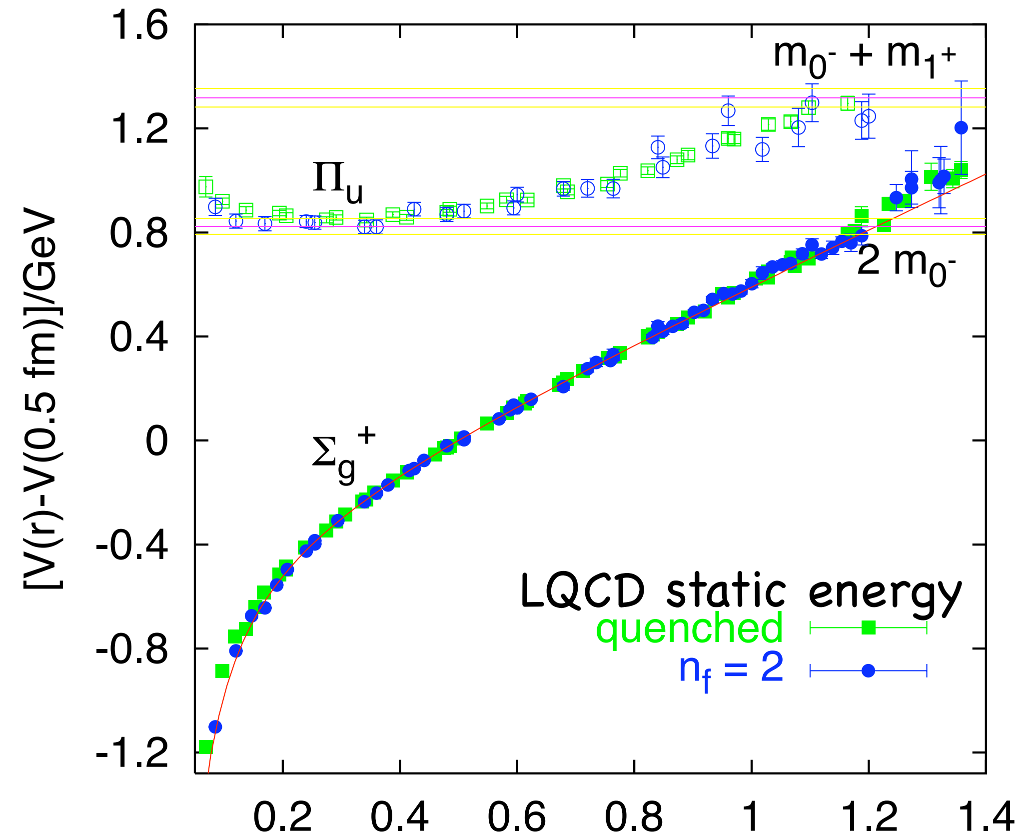


EE & C. Quigg [arXiv:1902.09735]

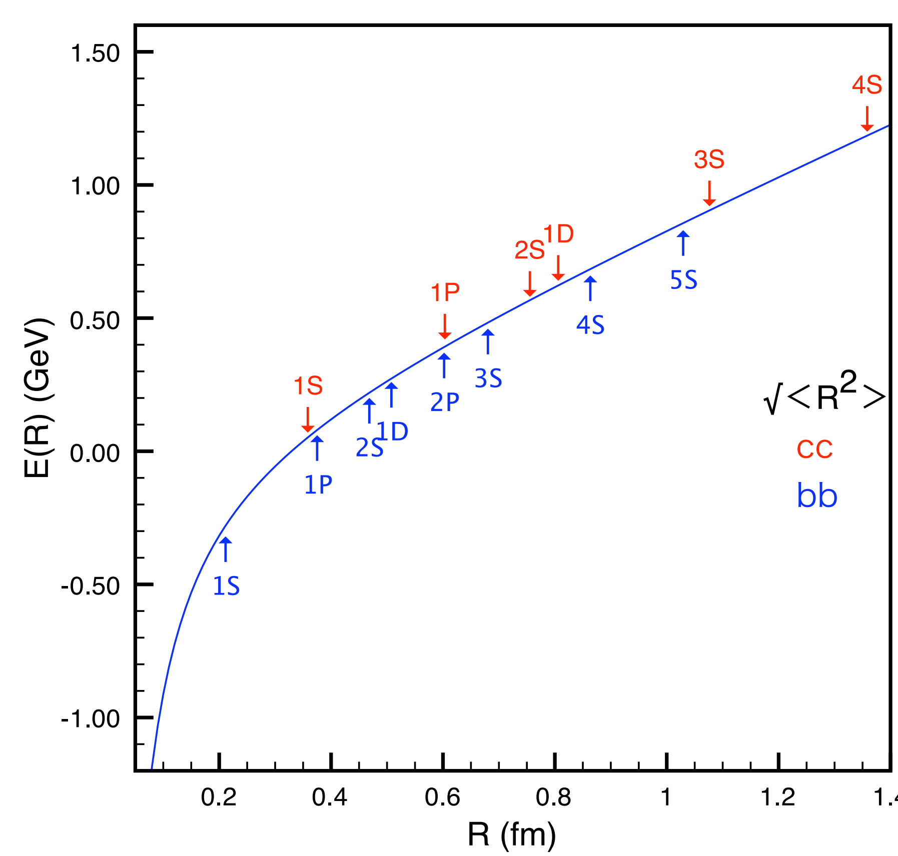
Why it works so well

- Lattice calculation V(r), then SE

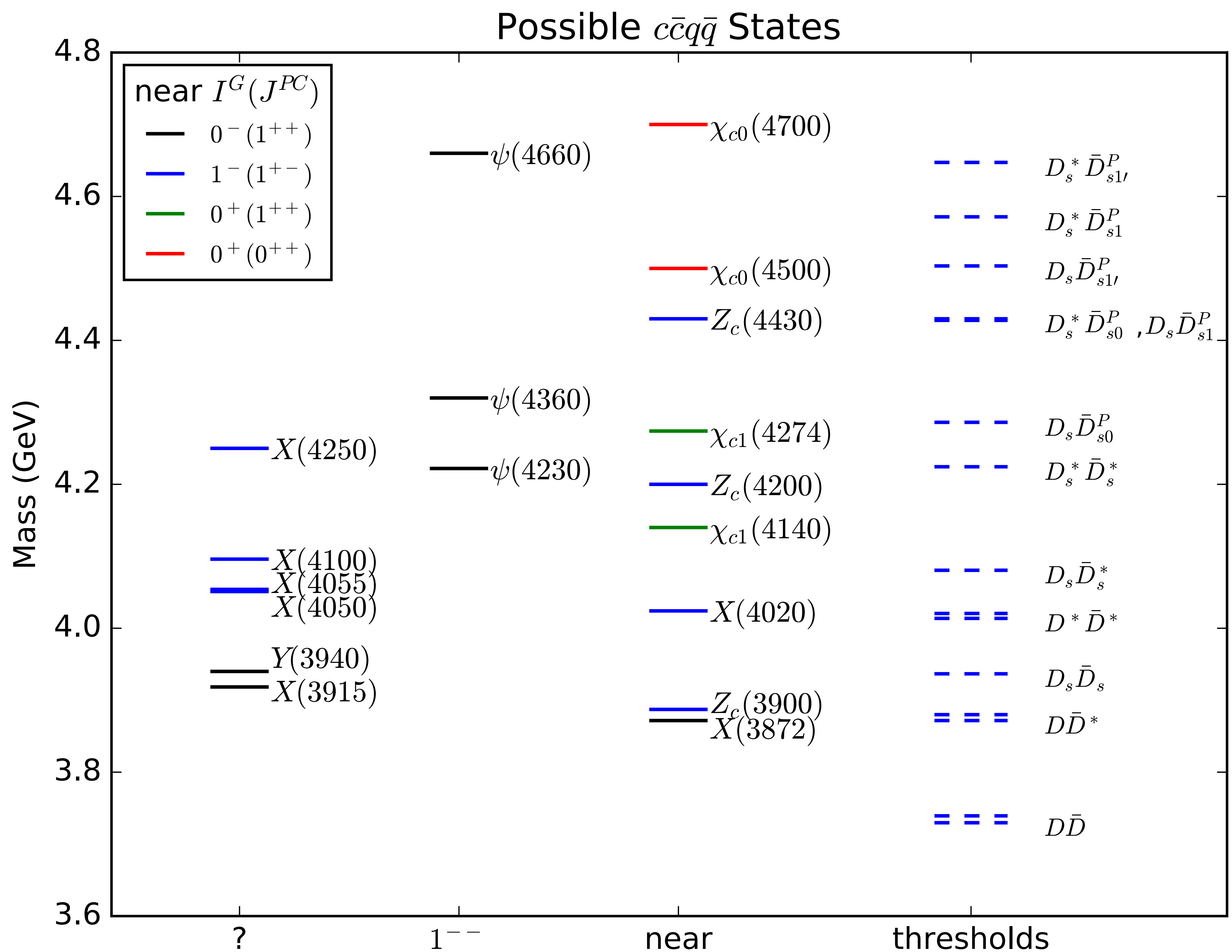
$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2}+\left\{\frac{\langle \boldsymbol{L}^2_{Q\bar{Q}}\rangle}{2\mu r^2}+V_{Q\bar{Q}}(r)\right\}u(r)=E\,u(r)$$



- What about the gluon and light quark degrees of freedom of QCD?
- Two thresholds:
  - Usual $(Q\bar{q})+(q\bar{Q})$ decay threshold
  - Excite the string - hybrids
- Tetraquarks may appear.
- Hybrid states will appear in the spectrum associated with the potential Π_u, ...
- In the static limit this occurs at separation: $r \approx 1.2$ fm.
- Between 3S-4S in $(c\bar{c})$; near the 5S in $(b\bar{b})$.



- Present status of states that don't fit as ordinary charmonium states
  - "?" states need info
  - if $J^{PC} = 0^{++}$ X(3915) ? 2^3P_2 state
  - ψ(4660) ? 5S state
  - ψ(4230), ψ(4360) ? hybrids ?
  - "near" states possible molecules
  - All the states at at or above threshold



X(3872)

- X(3872) - $J^{PC} = 1^{++}$ M= 3871.69 ± 0.17 Γ< 1.2 MeV from J/ψ ππ mode
  - $M_X - M_D - M_{D^*}$ = 0.01 ± 0.17 MeV
  - Large isospin violation
  - Decays observed:

$\pi^+\pi^- J/\psi(1S)$	$> 3.2\%$	large Isospin violation
$\rho J/\psi(1S)$		
$\omega J/\psi(1S)$	$> 2.3\%$	
$D^0\bar{D}^0\pi^0$	$> 40\%$	suggests molecule
$\bar{D}^{*0}D^0$	$> 30\%$	
$\gamma J/\psi$	$> 0.7\%$	
$\gamma\psi(2S)$	$> 4\%$	suggests 2P state

  - LHCb [arXiv:1404.0275]

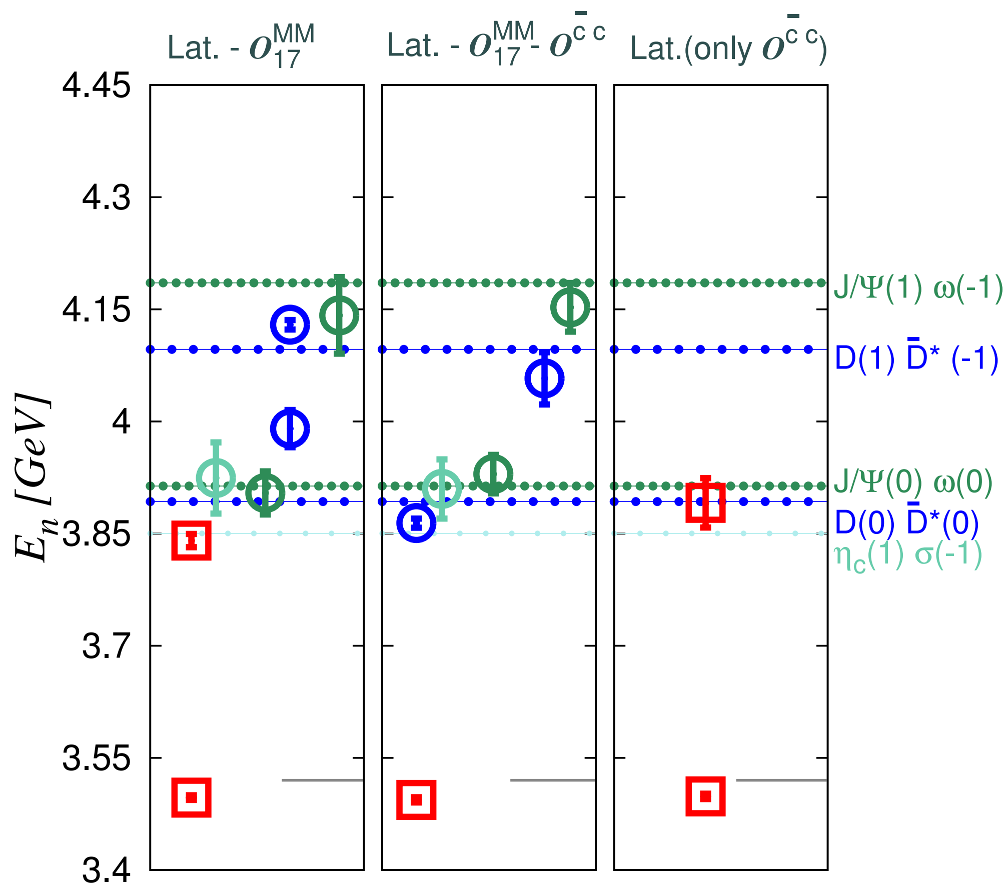
$$\frac{\mathcal{B}(\mathrm{X}(3872) \to \psi(2\mathrm{S})\gamma)}{\mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

  - Mixed state with sizable quarkonium component likely.
  - BES III (Chang-Zheng Yuan talk LATTICE 2019)

mode	$D^{*0}\bar{D}^0 + c.c.$	$\gamma J/\psi$	$\gamma\psi'$	γD^+D^-	$\omega J/\psi$	$\pi^0\chi_{c1}$
ratio	14.81 ± 3.80	0.79 ± 0.28	< 0.42	< 0.99	$1.7^{+0.4}_{-0.3} \pm 0.2$ [27]	$0.88^{+0.33}_{-0.27} \pm 0.10$ [37]

  - For LQCD: Where is the $\chi'_{c0}(2^3P_0)$ state?

- LQCD approaches need to include the $2^3P_1(c\bar{c})$ state to observe a X(3872) state



Alexandrou et al. arXiv:1212.1418
Prelovsek et al. arXiv:1405.7623 *
Guerrieri et al. arXiv:1411.2247
Padmanath et al. arXiv:1503.03257
Francis et al. arXiv:1607.05214

Prelovsek et al. arXiv:1405.7623
Caveats:
(1) m_π = 266 MeV
(2) limited spacings and volumes
(3) must include all states below and in region of possible new 4Q states

- BESIII [arXiv:1901.03992]
  - X(3872) -> π^0 ^3P_J

TABLE I. Final results for the normalization and search channels and their ratios. Individual efficiencies are reported without considering ISR in the MC (no ISR) and are for illustration only. Efficiency ratios are for the search channels divided by the normalization channel and include effects due to ISR (with ISR), which nearly cancel in the ratio. Numbers in parentheses are 90% C.L. upper limits. The first errors are statistical and the second are systematic.

	$\pi^+\pi^- J/\psi$	$\pi^0\chi_{c0}$	$\pi^0\chi_{c1}$	$\pi^0\chi_{c2}$
Event yield	$84.1^{+10.1}_{-9.4}$	$1.9^{+1.9}_{-1.3}$	$10.8^{+3.8}_{-3.1}$	$2.5^{+2.3}_{-1.7}$
Signal significance (σ)	16.1	1.6	5.2	1.6
Efficiency (no ISR) (%)	32.3	8.8	14.1	12.8
Efficiency ratio (with ISR)	...	0.272	0.435	0.392
$\mathcal{B}(\chi_{cJ} \to \gamma J/\psi) \times \mathcal{B}(\pi^0 \to \gamma\gamma)$ (%)	...	1.3	33.5	19.0
Total systematic error (%)	...	17.0	11.9	9.4
$\mathcal{B}(X \to \pi^0\chi_{cJ})/\mathcal{B}(X \to \pi^+\pi^- J/\psi)$	...	$6.6^{+6.5}_{-4.5} \pm 1.1$ (19)	$0.88^{+0.33}_{-0.27} \pm 0.10$	$0.40^{+0.37}_{-0.27} \pm 0.04$ (1.1)

  - Rate for a conventional 2^3P_1 expected to be small but unknown.
  - Ratios :

	J=0	J=1	J=2
• 2^3P_1 -> ^3P_J	0	5	2.14
• D^0 D^{*0} molecule	7.76	3	3.56

S. Dubynskiy and M. B. Voloshin, Phys. Rev. D 77, 014013 (2008).

  - Might be a better discriminator
- Can use polarization in prompt production (p p) of X(3872) to distinguish 2^3P_1 or molecule. Model suggests dominantly 2^3P_1 production.

M. Butenschoen, Zhi-Guo He, B. Kniehl, [arXiv:1906.0853]

- After 15 years we still are not sure of the mixture: X(3872) = cos(θ) $|D^0D^{*0}\rangle$ + sin(θ) $|2^3P_1\rangle$

Summary

- Much left to understand in mesons containing heavy quarks
- A few of the most exciting opportunities are:
- For heavy-light systems:
  - Fully characterized the nature of the $j_l^P=\frac{1}{2}^+$ narrow ($Q\bar{s}$) P states.
    - masses: (B_{s0}^*, B_{s1}) Belle 2, LHCb
    - decay branching fractions: (B_{s0}^*, B_{s1}), (D_{s0}^*, D_{s1}) Belle 2, LHCb, BES III
    - relative strengths of photon and π^0 transitions are sensitive probes
- For quarkonium systems:
  - The B_c excited states provides new insights: LHC, TeraZ
    - States below threshold are all extremely narrow.
    - Probe the spin structure for unequal masses.
    - 2 P states very near threshold - possible X(3872) analogs
  - Disentangling states near threshold offers best hope for understanding the new exotic states in QCD.