

## QUARKONIUM: NEW DEVELOPMENTS

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### Abstract

To illustrate the campaign to understand heavy quarkonium systems, I focus on a puzzling new state,  $X(3872) \rightarrow \pi^+\pi^-J/\psi$ . Studying the influence of open-charm channels on charmonium properties leads us to propose a new charmonium spectroscopy: additional discrete charmonium levels that can be discovered as narrow resonances of charmed and anticharmed mesons. I recall some expectations for a new spectroscopy of mesons with beauty and charm, the  $B_c$  ( $b\bar{c}$ ) system. Throughout, I call attention to open issues for theory and experiment.

## 1 The Renaissance in Hadron Spectroscopy

We live in exciting times for hadron spectroscopy. Over the past two years, experiments have uncovered a number of new narrow states that extend our knowledge of hadrons and challenge our understanding of the strong interaction. First came the discovery in the Belle experiment of  $\eta'_c$  in exclusive  $B \rightarrow KK_S K^- \pi^+$  decays<sup>1)</sup>. CLEO<sup>2)</sup>, BaBar<sup>3)</sup>, and Belle<sup>4)</sup> have confirmed and refined the discovery of  $\eta'_c$  in  $\gamma\gamma$  collisions, fixing its mass and width as  $M(\eta'_c) = 3637.7 \pm 4.4$  MeV and  $\Gamma(\eta'_c) = 19 \pm 10$  MeV<sup>5)</sup>. The unexpectedly narrow  $D_{sJ}$  states discovered by Babar<sup>6)</sup>, CLEO<sup>7)</sup>, and Belle<sup>8)</sup> provided the next surprise. Evidence for  $\Theta^+(1540)$ , a baryon state with  $K^+n$  quantum numbers that do not occur in the simple  $qqq$  quark-model description of baryons, captured headlines around the world. And finally (for now!) comes the discovery by Belle<sup>9)</sup> of  $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ , rapidly confirmed by CDF<sup>10)</sup> and DØ<sup>11, 12)</sup>. Each of these new states raises questions of interpretation, and offers opportunities.

The puzzle of  $X(3872)$  will be the centerpiece of this talk, so I summarize the Belle, CDF, and DØ observations in Figure 1.

The outstanding issue for the  $^1S_0$   $\eta'_c$ , compared to potential-model expectations, is the small splitting from its  $^3S_1$  hyperfine partner  $\psi'$ , which we shall examine presently. The  $D_{sJ}(2317)$  and  $D_{sJ}(2463)$  are apparently the  $0^{++}$  and  $1^{++}$  levels of the  $c\bar{s}$  system, corresponding to the  $j_\ell = \frac{1}{2}$  doublet in the heavy-quark-symmetry classification. They surprised us by being lighter than their  $j_\ell = \frac{3}{2}$  counterparts—so light that the expected strong decays into  $KD^*$  are kinematically forbidden. Chiral symmetry<sup>13)</sup> relates the  $0^{++}-1^{++}$  doublet to the  $0^{-+}-1^{-}$  ground-state doublet; we await detailed experimental tests. Assuming that  $\Theta^+(1540)$  is confirmed, we need to learn the nature of this apparent pentaquark state. Is it best viewed as a chiral soliton, as uncorrelated  $uudd\bar{s}$ , or as correlated  $[ud][ud]\bar{s}$  or other configurations involving diquarks?

Questions for  $X(3872)$  include its mass, which differs from the simplest expectations for the  $^3D_2$  charmonium state, and the nonobservation of radiative transitions. It is tantalizing that  $X(3872)$  lies almost precisely at the  $D^0 \bar{D}^{*0}$  threshold. We will now take up the challenges of  $X(3872)$  in detail.

## 2 Charmonium in the Wake of the $\eta'_c$ Discovery

Charmonium is a fertile field that continues to draw our interest for many reasons<sup>1)</sup>. Including the interthreshold region between  $2M(D)$  and  $M(D)+M(D^*)$ , we expect about ten or eleven narrow levels, of which at least seven are already known. Including higher states within 800 MeV of charm threshold, we expect perhaps sixty states, to be observed either as discrete levels or through their

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<sup>1)</sup>Vaia Papadimitriou's La Thuile talk<sup>14)</sup> offers numerous concrete examples.

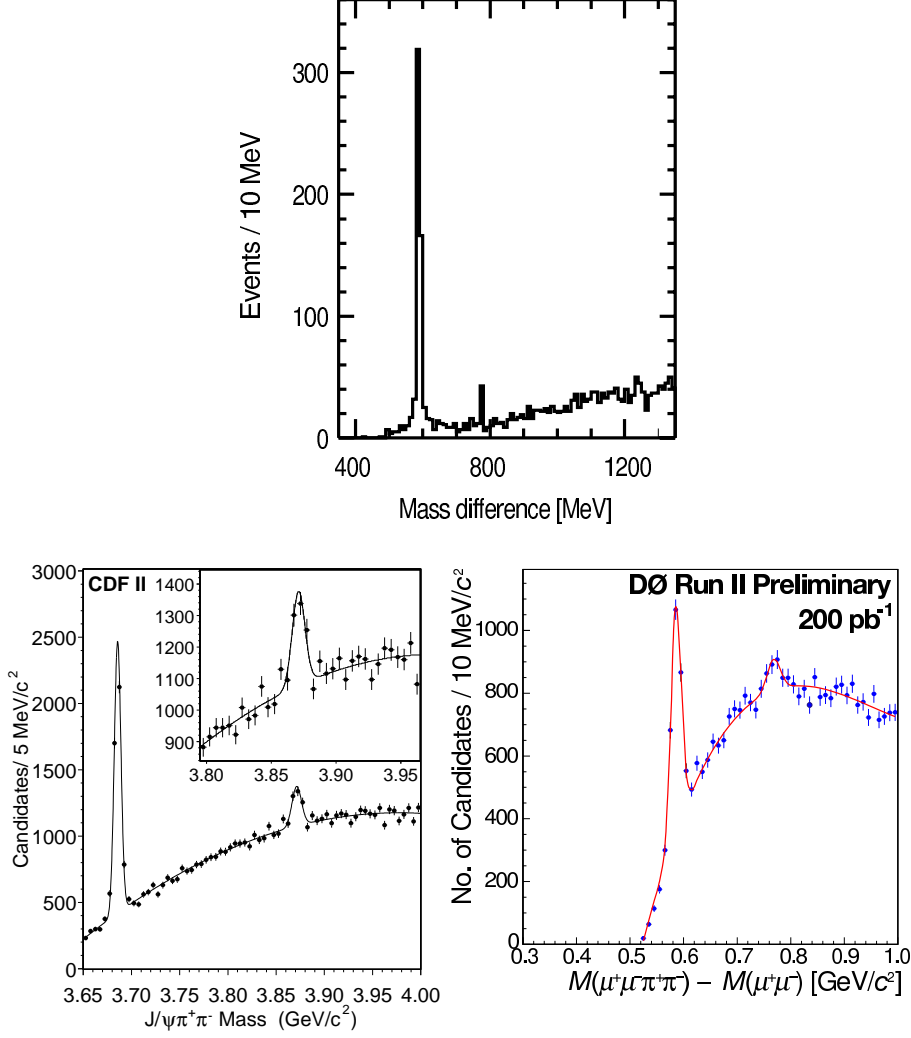


Figure 1: Evidence for  $X(3872) \rightarrow \pi^+\pi^- J/\psi$ , from Belle <sup>9)</sup> (top panel), CDF <sup>10)</sup> (bottom left), and DØ <sup>11)</sup> (bottom right). The prominent peak on the left of each panel is  $\psi'(3686)$ ; the smaller peak near  $\Delta M \equiv M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) \approx 775$  MeV,  $M(J/\psi\pi^+\pi^-) \approx 3.87$  GeV is  $X(3872)$ . The CDF and DØ samples are restricted to dipion masses  $> 500$  and  $520$  MeV, respectively.

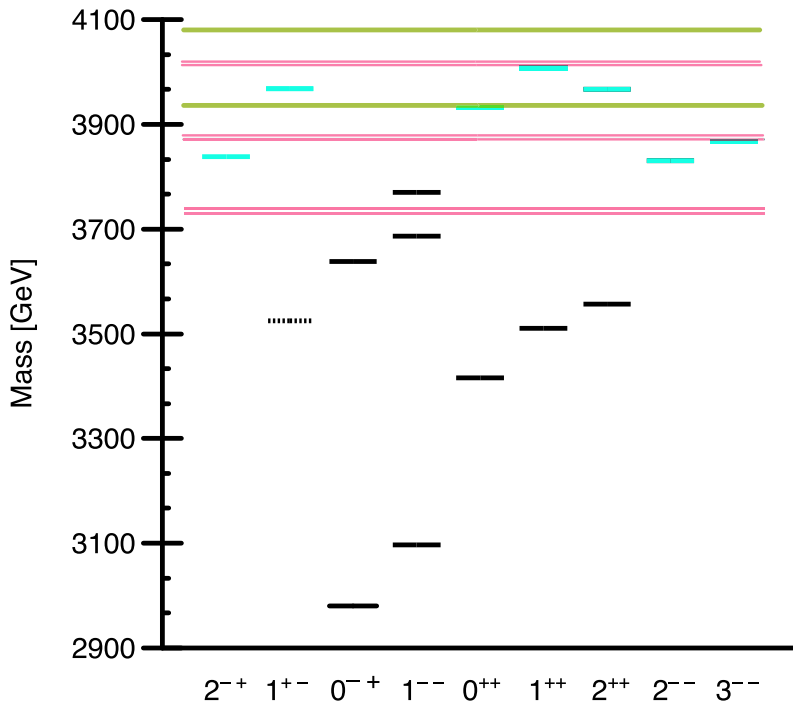


Figure 2: Grotrian diagram for the charmonium spectrum. States marked by heavy black lines are well established. The  ${}^1P_1 h_c$  level is indicated by the dashed line at the  ${}^3P_J$  centroid. Thresholds are shown, in order of increasing mass, for  $D^0\bar{D}^0$ ,  $D^+D^-$ ,  $D^0\bar{D}^{*0}$ ,  $D^+\bar{D}^{*-}$ ,  $D_s\bar{D}_s$ ,  $D^{*0}\bar{D}^{*0}$ ,  $D^{*+}\bar{D}^{*-}$ , and  $D_s\bar{D}_s^*$ . Some predicted states above threshold are depicted as faint lines.

collective effect on the total cross section for  $e^+e^- \rightarrow$  hadrons. A portion of the charmonium spectrum is shown in Figure 2. Nonrelativistic potential models historically have given a good account of the spectrum, but they cannot be the whole story. They are truncated, single-channel treatments that do not contain the full richness of quantum chromodynamics. We are coming closer to a complete theoretical treatment: lattice QCD is increasingly capable for quarkonium spectroscopy—and improvements are coming swiftly. Charmonium states are being seen in electron-positron annihilations, in  $B$  decay, in two-photon collisions, and in hadronic production. This circumstance gives us access to a very broad variety of quantum numbers  $J^{PC}$ , and makes for a lively conversation among experiments and a fruitful dialogue between theory and experiment.

Stimulated by Belle’s discovery of  $\eta'_c$ , my colleagues Estia Eichten, Ken

Lane, and I sketched a coherent strategy to explore  $\eta'_c$  and the remaining charmonium states that do not decay into open charm,  $h_c(1^1P_1)$ ,  $\eta_{c2}(1^1D_2)$ , and  $\psi_2(1^3D_2)$ , through  $B$ -meson gateways<sup>15)</sup>. We argued that radiative transitions among charmonium levels and  $\pi\pi$  cascades to lower-lying charmonia would enable the identification of these states. Ko, Lee and Song<sup>16)</sup> discussed the observation of the narrow D states by photonic and pionic transitions, and Suzuki<sup>17)</sup> emphasized that the cascade decay  $B \rightarrow h_c K^{(*)} \rightarrow \gamma \eta_c K^{(*)}$  offers a promising technique to look for  $h_c$ .

We noted that, according to current understanding of charmonium formation in  $B$ -decays<sup>16, 18, 19, 20)</sup>, the states in question all should be produced at a level of  $\approx \frac{1}{2}\%$ . Moreover, the  $1^3D_2$  states should indeed be narrow, if their masses lie below  $D\bar{D}^*$  threshold. Our 2002 estimates of the gluonic decay rates of all the 1D states, and of their  $\pi\pi$  cascade rates to the charmonium ground state are given in Table 1. The annihilation rates were computed using standard expressions of perturbative QCD. We used the Wigner-Eckart theorem of the color-multipole expansion to set all the 1D cascade rates to a common value, normalized to an old estimate of the  $\psi(3770) \rightarrow \pi\pi J/\psi$  decay rate. Both parts of this statement are weaknesses: the Wigner-Eckart relation for E1-E1 transitions does not take into account kinematic differences that arise when the initial 1D states or the final 1S states are not degenerate in mass, and the normalizing rate is poorly known. Here at La Thuile we have heard a final determination<sup>21, 22)</sup> from the current BES data set,  $\mathcal{B}(1^3D_1 \rightarrow \pi^+\pi^- J/\psi) = (0.338 \pm 0.137 \pm 0.082)\%$ , or  $\Gamma(1^3D_1 \rightarrow \pi^+\pi^- J/\psi) = 80 \pm 32 \pm 21$  keV. This value is challenged by a CLEO- $c$  limit<sup>5)</sup>,  $\mathcal{B}(1^3D_1 \rightarrow \pi^+\pi^- J/\psi) < 0.26\%$  at 90% C.L. This is a ter-

Table 1: Hadronic decay widths of charmonium 1D states in the single-channel potential model with 2002 inputs, from Ref.<sup>15)</sup>.

Level	Mass (MeV)	Transition	Partial Width (keV)
$1^1D_2$	3815	$\eta_{c2} \rightarrow gg$	110 keV
		$\eta_{c2} \rightarrow \pi\pi\eta_c$	$\approx 45$ keV
$1^3D_1$	3770	$\psi \rightarrow ggg$	216 keV
		$\psi \rightarrow \pi\pi J/\psi$	$43 \pm 15$ keV
$1^3D_2$	3815	$\psi_2 \rightarrow ggg$	36 keV
		$\psi_2 \rightarrow \pi\pi J/\psi$	$\approx 45$ keV
$1^3D_3$	3815	$\psi_3 \rightarrow ggg$	102 keV
		$\psi_3 \rightarrow \pi\pi J/\psi$	$\approx 45$ keV

ribly hard measurement, but a precise normalization for the 1D properties is urgently needed!

Although the  $\pi\pi$  cascades promised plausible rates for the observation of  $\eta_{c2}$  and  $\psi_2$ , our estimates of the radiative (E1) transition rates were markedly larger. We computed, for example,  $\Gamma(1^3D_2 \rightarrow \chi_{c2}\gamma) = 56$  keV,  $\Gamma(1^3D_2 \rightarrow \chi_{c1}\gamma) = 260$  keV. and  $\Gamma(1^1D_2 \rightarrow h_c\gamma) = 303$  keV. Normalizing to the 45-keV  $\pi\pi$  cascade rate, we anticipated that  $\mathcal{B}(h_c \rightarrow \eta_c\gamma) \approx \frac{2}{5}$ ,  $\mathcal{B}(\eta_{c2} \rightarrow h_c\gamma) \approx \frac{2}{3}$ , and  $\mathcal{B}(\psi_2 \rightarrow \chi_{c1,2}\gamma) \approx \frac{4}{5}$ , of which  $\mathcal{B}(\psi_2 \rightarrow \chi_{c1}\gamma) \approx \frac{2}{3}$ .

### 3 What We Know about $X(3872)$

The  $X(3872)$  did indeed show itself in a search for narrow charmonium states such as  $1^3D_2$ , but the observed mass of  $3871.7 \pm 0.6$  MeV is considerably higher than the pre-discovery expectation of 3815 MeV. CDF and DØ have not yet determined the prompt (as opposed to  $B$ -decay) fraction of  $X$  production, but it is highly plausible<sup>14, 12)</sup> that prompt production is not negligible. Belle's discovery paper<sup>9)</sup> compares the rates of  $X$  and  $\psi'$  production in  $B$  decays,

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ X)\mathcal{B}(X \rightarrow \pi^+\pi^- J/\psi)}{\mathcal{B}(B^+ \rightarrow K^+ \psi')\mathcal{B}(\psi' \rightarrow \pi^+\pi^- J/\psi)} = 0.063 \pm 0.014. \quad (1)$$

Belle has searched in vain for radiative transitions to the  $1^3P_1$  level; their 90% C.L. upper bound<sup>9, 23)</sup>,

$$\frac{\Gamma(X(3872) \rightarrow \gamma\chi_{c1})}{\Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi)} < 0.89, \quad (2)$$

conflicts with our single-channel potential-model expectations for the  $1^3D_2$  state<sup>15)</sup>, while the limit<sup>23)</sup>

$$\frac{\Gamma(X(3872) \rightarrow \gamma\chi_{c2})}{\Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi)} < 1.1, \quad (3)$$

is problematic for both the  $1^3D_2$  and  $1^3D_3$  interpretations. The theoretical estimate of the  $\pi\pi J/\psi$  rate is highly uncertain, however.

Just before we met in La Thuile, Belle<sup>23)</sup> presented the first information about the decay angular distribution of  $J/\psi$  produced in  $X \rightarrow \pi^+\pi^- J/\psi$ . It does not yet determine  $J^{PC}$ , but the  $2^1P_1$   $h'_c$  (or  $1^{+-}$  charm molecule) assignment is ruled out. For more on the diagnostic capabilities of decay angular distributions, see Jackson's classic Les Houches lectures<sup>24)</sup> and the recent paper on  $X(3872)$  by Pakvasa and Suzuki<sup>25)</sup>. A BES limit<sup>26)</sup> on the electronic width of  $X(3872)$  argues against a  $1^{--}$  assignment.

## 4 Alternatives to Charmonium

The notion that charm molecules might be formed by attractive pion exchange between  $D$  and  $\bar{D}^*$  mesons has a long history, and has been invoked as a possible interpretation for  $X(3872)$  by Törnqvist<sup>27)</sup> and others<sup>28, 29, 30)</sup>. A maximally attractive channel analysis suggests that deuteron-analogue “deusons,” as Törnqvist likes to call them, should be  $J^{PC} = 0^{-+}$  or  $1^{++}$  states. Parity conservation forbids the decay of these levels into  $(\pi\pi)_{I=0}J/\psi$ ; the isospin-violating  $(\pi\pi)_{I=1}J/\psi$  mode is required. Although an isovector dipion might account for the observed preference for high dipion masses, it remains to be seen whether the decay rate is large enough. (The  $D^+-D^0$  and  $D^{*+}-D^{*0}$  mass splitting means that the molecule is not a pure isoscalar state.) Törnqvist has suggested that the dissociation  $X(3872) \rightarrow (D^0\bar{D}^{*0})_{\text{virtual}} \rightarrow D^0\bar{D}^0\pi^0$  should be a prominent decay mode of a charm molecule, with a partial width of perhaps 50 keV. The Belle Collaboration’s limit<sup>31)</sup>,

$$\mathcal{B}(B^+ \rightarrow K^+ X(3872)) \mathcal{B}(X(3872) \rightarrow D^0\bar{D}^0\pi^0) < 6 \times 10^{-5}, \quad (4)$$

is perhaps an order of magnitude from challenging this expectation.

Braaten & Kusunoki<sup>32)</sup> conjecture that a charm molecule that lies very close to threshold has universal properties determined by an unnaturally large scattering length that is inversely proportional to the reduced mass and the binding energy. Both production and decay rates would be suppressed by a factor of  $(\text{scattering length})^{-1}$ . The same authors<sup>33)</sup> have calculated the probability for charmed mesons produced in  $\Upsilon(4S)$  decay to coalesce into a lightly bound  $D\bar{D}^*$  molecule by the mechanism shown in Figure 3. The leading contribution is a universal form proportional to  $(\Gamma(B \rightarrow \text{all})/M_B)^2$  that depends only on hadron masses and on the width and branching fractions of the  $B$  meson, and on the binding energy  $E_b$  of the molecule. For light binding, they find

$$\frac{\Gamma(\Upsilon(4S) \rightarrow X(3872)hh')}{\Gamma(\Upsilon(4S) \rightarrow D^0\bar{D}^{*0}hh') + \Gamma(\Upsilon(4S) \rightarrow \bar{D}^0D^{*0}hh')} \approx 10^{-24}, \quad (5)$$

which may hold the distinction of being the smallest strong-interaction branching fraction ever calculated!

Hybrid states such as  $c\bar{c}g$  that manifest the gluonic degrees of freedom might also appear in the charmonium spectrum, and should be examined as interpretations of  $X(3872)$ <sup>34)</sup>. It is fair to say that dynamical calculations of hybrid-meson properties are in a primitive state, but heuristic arguments do offer some guidance. A picture based on chromoelectric flux tubes suggests that the lowest-lying states might have quantum numbers  $J^{PC} = (0, 1, 2)^{++}$  or  $1^{+-}$ ; for chromomagnetic flux tubes,  $J^{PC} = (0, 1, 2)^{-+}$  or  $1^{--}$  prevail. Ground-state  $c\bar{c}g$  masses are anticipated around  $4100 \pm 200$  MeV, rather higher than

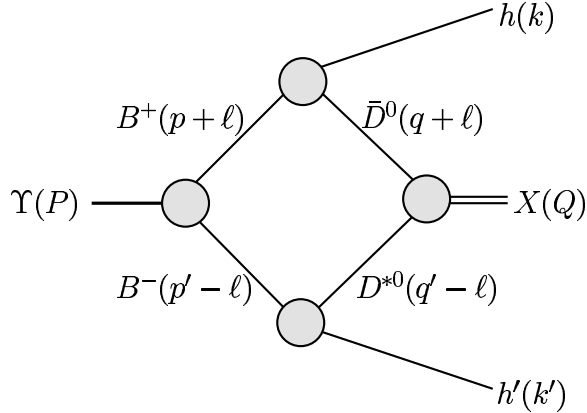


Figure 3: Formation of charm molecule  $X(3872)$  by coalescing  $\bar{D}^0$  and  $D^{*0}$ .

$X(3872)$ , but the estimates are not reliable enough to lead us immediately to dismiss the hybrid interpretation. The valence gluon in the hybrid wave function leads to the speculation that the  $\eta J/\psi$  mode might be quite prominent. The Babar experiment <sup>35)</sup> has found no sign of  $X \rightarrow \eta J/\psi$  and quoted a limit,

$$\mathcal{B}(X(3872) \rightarrow \eta J/\psi) < 2\mathcal{B}(\psi' \rightarrow \eta J/\psi) , \quad (6)$$

that does not favor a privileged role for the  $\eta J/\psi$  mode.

## 5 Coupling to Open-Charmed Channels

The Cornell group showed long ago that a very simple model that couples charmonium to charmed-meson decay channels confirms the adequacy of the single-channel  $c\bar{c}$  analysis below threshold and gives a qualitative understanding of the structures observed above threshold <sup>36, 37)</sup>. Eichten and Lane and I recently have employed the Cornell coupled-channel formalism to analyze the properties of charmonium levels that populate the threshold region between  $2M_D$  and  $2M_{D^*}$  <sup>38)</sup>.

Our command of quantum chromodynamics is inadequate to derive a realistic description of the interactions that communicate between the  $c\bar{c}$  and  $c\bar{q} + \bar{c}q$  sectors. The Cornell formalism generalizes the  $c\bar{c}$  model without introducing new parameters, writing the interaction Hamiltonian in second-quantized form as

$$\mathcal{H}_I = \frac{3}{8} \sum_{a=1}^8 \int : \rho_a(\mathbf{r}) V(\mathbf{r} - \mathbf{r}') \rho_a(\mathbf{r}') : d^3r d^3r' , \quad (7)$$

where  $V$  is the charmonium potential and  $\rho_a(\mathbf{r}) = \frac{1}{2} \psi^\dagger(\mathbf{r}) \lambda_a \psi(\mathbf{r})$  is the color current density, with  $\psi$  the quark field operator and  $\lambda_a$  the octet of SU(3)



Table 2: Charmonium spectrum, including the influence of open-charm channels. All masses are in MeV. The penultimate column holds an estimate of the spin splitting due to tensor and spin-orbit forces in a single-channel potential model. The last column gives the spin splitting induced by communication with open-charm states, for an initially unsplit multiplet.

State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
$1^1S_0$	2979.9	3067.6	-90.5	+2.8
$1^3S_1$	3096.9		+30.2	-0.9
$1^3P_0$	3415.3	3525.3	-114.9	+5.9
$1^3P_1$	3510.5		-11.6	-2.0
$1^1P_1$	3525.3		+1.5	+0.5
$1^3P_2$	3556.2		-31.9	-0.3
$2^1S_0$	3637.7	3673.9	-50.4	+15.7
$2^3S_1$	3686.0		+16.8	-5.2
$1^3D_1$	3769.9	(3815)	-40	-39.9
$1^3D_2$	3830.6		0	-2.7
$1^1D_2$	3838.0		0	+4.2
$1^3D_3$	3868.3		+20	+19.0
$2^3P_0$	3931.9	3968	-90	+10
$2^3P_1$	4007.5		-8	+28.4
$2^1P_1$	3968.0		0	-11.9
$2^3P_2$	3966.5		+25	-33.1

matrices. To generate the relevant interactions,  $\psi$  is expanded in creation and annihilation operators (for charm, up, down, and strange quarks), but transitions from two mesons to three mesons and all transitions that violate the Zweig rule are omitted. It is a good approximation to neglect all effects of the Coulomb piece of the potential in (7).

The basic coupled-channel interaction (7) is spin-independent, but the hyperfine splittings of  $D$  and  $D^*$ ,  $D_s$  and  $D_s^*$ , induce spin-dependent forces that affect the charmonium states. These spin-dependent forces give rise to S-D mixing that contributes to the  $\psi(3770)$  electronic width, for example, and are a source of additional spin splitting, shown in the rightmost column of Table 2. To compute the induced splittings, we adjust the bare centroid of the spin-triplet states so that the physical centroid, after inclusion of coupled-channel

effects, matches the value in the middle column of Table 2. As expected, the shifts induced in the low-lying 1S and 1P levels are small. For the other known states in the 2S and 1D families, coupled-channel effects are noticeable and interesting.

In a simple potential picture, the  $\eta'_c(2^1S_0)$  level lies below the  $\psi'(2^3S_1)$  by the hyperfine splitting given by  $M(\psi') - M(\eta'_c) = 32\pi\alpha_s|\Psi(0)|^2/9m_c^2$ . Normalizing to the observed 1S hyperfine splitting,  $M(J/\psi) - M(\eta_c) = 117$  MeV, we would find

$$M(\psi') - M(\eta'_c) = 67 \text{ MeV} , \quad (8)$$

which is larger than the observed  $48.3 \pm 4.4$  MeV, as is typical for potential-model calculations. The 2S induced shifts in Table 2 draw  $\psi'$  and  $\eta'_c$  closer by 20.9 MeV, substantially improving the agreement between theory and experiment. It is tempting to conclude that the  $\psi'$ - $\eta'_c$  splitting reflects the influence of virtual decay channels, but compare the analysis of Ref. <sup>39)</sup>.

We peg the 1D masses to the observed mass of the  $1^3D_1$   $\psi(3770)$ . In our model calculation, the coupling to open-charm channels increases the  $1^3D_2$ - $1^3D_1$  splitting by about 20 MeV, but does not fully account for the observed 102 MeV separation between  $X(3872)$  and  $\psi(3770)$ . It is noteworthy that the position of the  $3^{--} 1^3D_3$  level turns out to be very close to 3872 MeV. For the 2P levels, we have no experimental anchor, so we adjust the bare centroid so that the  $2^1P_1$  level lies at the centroid of the potential-model calculation.

The physical charmonium states are not pure potential-model eigenstates. To compute the E1 radiative transition rates, we must take into account both the standard  $(c\bar{c}) \rightarrow (c\bar{c})\gamma$  transitions and the transitions between (virtual) decay channels in the initial and final states. Our expectations for E1 decays of the  $1^3D_2$  and  $1^3D_3$  candidates for  $X(3872)$  are shown in Table 3.

Once the position of a resonance is given, the coupled-channel formalism yields reasonable predictions for the other resonance properties. The  $1^3D_1$  state  $\psi''(3770)$ , which lies some 40 MeV above charm threshold, offers an important benchmark: we compute  $\Gamma(\psi''(3770) \rightarrow D\bar{D}) = 20.1$  MeV, to be compared

Table 3: Calculated rates for E1 radiative decays of some 1D levels. *Values in italics* result if the influence of open-charm channels is not included.

Transition ( $\gamma$ energy in MeV)	Partial width (keV)
$1^3D_2(3872) \rightarrow \chi_{c2} \gamma(303)$	<i>85</i> $\rightarrow$ 45
$1^3D_2(3872) \rightarrow \chi_{c1} \gamma(344)$	<i>362</i> $\rightarrow$ 207
$1^3D_3(3872) \rightarrow \chi_{c2} \gamma(304)$	<i>341</i> $\rightarrow$ 299

with the Particle Data Group’s fitted value of  $23.6 \pm 2.7$  MeV<sup>40)</sup>. The variation of the  $1^3D_1$  width with mass is shown in the top left panel of Figure 4.

Barnes & Godfrey<sup>41)</sup> have estimated the decays of several of the charmonium states into open charm, using the  $^3P_0$  model of  $q\bar{q}$  production first applied above charm threshold by the Orsay group<sup>42)</sup>. They did not carry out a coupled-channel analysis, and so did not determine the composition of the physical states, but their estimates of open-charm decay rates can be read against ours as a rough assessment of model dependence.

The long-standing expectation that the  $1^3D_2$  and  $1^1D_2$  levels would be narrow followed from the presumption that these unnatural parity states should lie between the  $D\bar{D}$  and  $D\bar{D}^*$  thresholds, and could not decay into open charm. At 3872 MeV, both states can decay into  $D^0\bar{D}^{*0}$ , but the partial widths are quite small. We show the variation of the  $1^3D_2$  partial width with mass in the top right panel of Figure 4; over the region of interest, it does not threaten the Belle bound,  $\Gamma(X(3872)) < 2.3$  MeV. The range of values is quite similar to the range estimated for  $\Gamma(1^3D_2 \rightarrow \pi\pi J/\psi)$ , so we expect roughly comparable branching fractions for decays into  $D^0\bar{D}^{*0}$  and  $\pi^+\pi^- J/\psi$ . If  $X(3872)$  does turn out to be the  $1^3D_2$  level, we expect  $M(1^1D_2) = 3880$  MeV and  $\Gamma(1^1D_2 \rightarrow D^0\bar{D}^{*0}) \approx 1.7$  MeV.

The natural-parity  $1^3D_3$  state can decay into  $D\bar{D}$ , but its  $f$ -wave decay is suppressed by the centrifugal barrier factor, so the partial width is less than 1 MeV at a mass of 3872 MeV. Although estimates of the hadronic cascade transitions are uncertain, the numbers in hand lead us to expect  $\Gamma(1^3D_3 \rightarrow \pi^+\pi^- J/\psi) \lesssim \frac{1}{4}\Gamma(1^3D_3 \rightarrow D\bar{D})$ , whereas  $\Gamma(1^3D_3 \rightarrow \gamma\chi_{c2}) \approx \frac{1}{3}\Gamma(1^3D_3 \rightarrow D\bar{D})$ , if  $X(3872)$  is identified as  $1^3D_3$ . The variation of  $\Gamma(1^3D_3 \rightarrow D\bar{D})$  with mass is shown in the middle left panel of Figure 4. Note that if  $1^3D_3$  is not to be identified with  $X(3872)$ , *it may still be discovered as a narrow  $D\bar{D}$  resonance*, up to a mass of about 4000 MeV.

In their study of  $B^+ \rightarrow K^+\psi(3770)$  decays, the Belle Collaboration<sup>31)</sup> has set 90% CL upper limits on the transition  $B^+ \rightarrow K^+X(3872)$ , followed by  $X(3872) \rightarrow D\bar{D}$ . Their limits imply that

$$\begin{aligned} \mathcal{B}(X(3872) \rightarrow D^0\bar{D}^0) &\lesssim 4\mathcal{B}(X \rightarrow \pi^+\pi^- J/\psi), \\ \mathcal{B}(X(3872) \rightarrow D^+D^-) &\lesssim 3\mathcal{B}(X \rightarrow \pi^+\pi^- J/\psi). \end{aligned} \tag{9}$$

This constraint is already intriguingly close to the level at which we would expect to see  $1^3D_3 \rightarrow D\bar{D}$ .

The constraint on the total width of  $X(3872)$  raises more of a challenge for the  $2^1P_1$  candidate, whose  $s$ -wave decay to  $D^0\bar{D}^{*0}$  rises dramatically from threshold, as shown in the middle right panel of Figure 4. Within the current uncertainty ( $3871.7 \pm 0.6$  MeV) in the mass of  $X$ , the issue cannot be settled, but the  $2^1P_1$  interpretation is viable only if  $X$  lies below  $D^0\bar{D}^{*0}$  threshold. If a light  $2^1P_1$  does turn out to be  $X(3872)$ , then its  $2^3P_J$  partners should

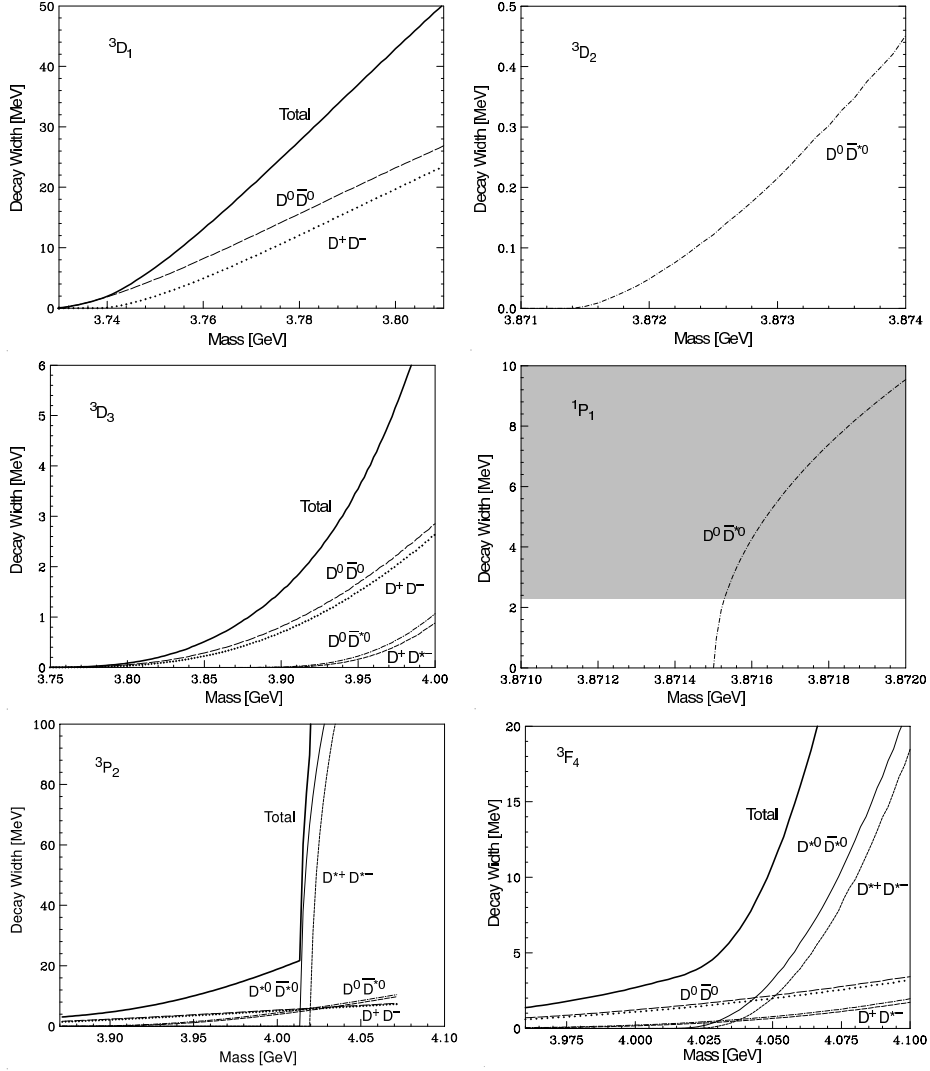


Figure 4: Partial and total widths near threshold for decay of charmonium states into open charm, computed in the Cornell coupled-channel model. Long dashes:  $D^0\bar{D}^0$ , dots:  $D^+D^-$ , dot-dashes:  $D^0\bar{D}^{*0}$ , dashes:  $D^+D^{*-}$ , thin line:  $D^{*0}\bar{D}^{*0}$ , short dashes:  $D^{*+}D^{*-}$ , widely spaced dots:  $D_s\bar{D}_s$ , thick line: sum of open-charm channels. Belle's 90% C.L. upper limit <sup>9)</sup>,  $\Gamma(X(3872)) < 2.3$  MeV, is indicated on the  $^1P_1$  window. For  $DD^*$  modes, the sum of  $DD^*$  and  $\bar{D}\bar{D}^*$  is always implied.

lie nearby. In that case, they should be visible as relatively narrow charm-anticharm resonances. At 3872 MeV, we estimate  $\Gamma(2^3P_1 \rightarrow D\bar{D}^*) \approx 21$  MeV and  $\Gamma(2^3P_2 \rightarrow D\bar{D}) \approx 3$  MeV. The bottom left panel in Figure 4 shows that the  $2^3P_2$  level remains relatively narrow up to the opening of the  $D^*\bar{D}^*$  threshold.

I point out one more candidate for a narrow resonance of charmed mesons: The  $1^3F_4$  level remains narrow ( $\Gamma(1^3F_4 \rightarrow \text{charm}) \lesssim 5$  MeV) up to the  $D^*\bar{D}^*$  threshold, as illustrated in the bottom right panel of Figure 4. Its allowed decays into  $D\bar{D}$  and  $D\bar{D}^*$  are inhibited by  $\ell = 4$  barrier factors, whereas the  $D^*\bar{D}^*$  channel is reached by  $\ell = 2$ .

## 6 Following up the Discovery of $X(3872)$

On the experimental front, the first order of business is to establish the nature of  $X(3872)$ . Determining the spin-parity of  $X$  will winnow the field of candidates. The charmonium interpretation and its prominent rivals require that  $X(3872)$  be a neutral isoscalar. Are there charged partners? A search for  $X(3872) \rightarrow \pi^0\pi^0 J/\psi$  will be highly informative. As Barnes & Godfrey<sup>41)</sup> have remarked, observing a significant  $\pi^0\pi^0 J/\psi$  signal establishes that  $X$  is odd under charge conjugation. Voloshin has commented<sup>43)</sup> that the ratio  $\mathcal{R}_0 \equiv \Gamma(X \rightarrow \pi^0\pi^0 J/\psi)/\Gamma(X \rightarrow \pi^+\pi^- J/\psi)$  measures the dipion isospin. Writing  $\Gamma_I \equiv \Gamma(X \rightarrow (\pi^+\pi^-)_I J/\psi)$ , we see that  $\mathcal{R}_0 = \frac{1}{2}/(1 + \Gamma_1/\Gamma_0)$ , up to kinematic corrections. Deviations from  $\mathcal{R}_0 = \frac{1}{2}$  signal the isospin-violating decay of an isoscalar, or the isospin-conserving decay of an isovector. Radiative decay rates and the prompt (as opposed to  $B$ -decay) production fraction will provide important guidance. Other diagnostics of a general nature have been discussed in Refs.<sup>34, 41, 25, 44)</sup>

Within the charmonium framework,  $X(3872)$  is most naturally interpreted as the  $1^3D_2$  or  $1^3D_3$  level, both of which have allowed decays into  $\pi\pi J/\psi$ . The  $2^{--} 1^3D_2$  state is forbidden by parity conservation to decay into  $D\bar{D}$  but has a modest  $D^0\bar{D}^{*0}$  partial width for masses near 3872 MeV. Although the uncertain  $\pi\pi J/\psi$  partial width makes it difficult to estimate relative branching ratios, the decay  $X(3872) \rightarrow \chi_{c1} \gamma(344)$  should show itself if  $X$  is indeed  $1^3D_2$ . The  $\chi_{c2} \gamma(303)$  line should be seen with about  $\frac{1}{4}$  the strength of  $\chi_{c1} \gamma(344)$ . In our coupled-channel calculation, the  $1^3D_2$  mass is about 41 MeV lower than the observed 3872 MeV. In contrast, the computed  $1^3D_3$  mass is quite close to 3872 MeV, and  $1^3D_3$  does not have an E1 transition to  $\chi_{c1} \gamma(344)$ . The dominant decay of the  $3^{--} 1^3D_3$  state should be into  $D\bar{D}$ ; a small branching fraction for the  $\pi\pi J/\psi$  discovery mode would imply a large production rate. One radiative transition should be observable, with  $\Gamma(X(3872) \rightarrow \chi_{c2} \gamma(303)) \gtrsim \Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi)$ . I underscore the importance of searching for the  $\chi_{c1} \gamma(344)$  and  $\chi_{c2} \gamma(303)$  lines.

Beyond pinning down the character of  $X(3872)$ , experiments can search for additional narrow charmonium states in radiative and hadronic transitions to lower-lying  $c\bar{c}$  levels, as we emphasized in Ref. <sup>15)</sup>, and in neutral combinations of charmed mesons and anticharmed mesons. The coupled-channel analysis presented in our most recent paper <sup>38)</sup> sets up specific targets.

More broadly, it is worth reminding ourselves that a search for structure in channels including  $J/\psi$  and any readily detectable hadron, including  $J/\psi + \pi^\pm, \eta, K^\pm, K_s, p, \Lambda, \dots$  may be rewarding. Some of these combinations are predicted to be there, and others just might exist. We would feel foolish if we failed to look.

On the theoretical front, we need a more complete understanding of the production of the charmonium states in  $B$  decays and by direct hadronic production, including the influence of open-charm channels. Understanding of the production mechanisms for molecular charm or  $c\bar{c}g$  hybrid states is much more primitive. The hybrid-meson hypothesis in particular needs some specific predictions and a decision tree to test the interpretation. We need to improve the theoretical understanding of hadronic cascades among charmonium states, including the influence of open-charm channels. The comparison of charmonium transitions with their upsilon counterparts should be informative. The analysis we have carried out can be extended to the  $b\bar{b}$  system, where it may be possible to see discrete threshold-region states in direct hadronic production. Because the Cornell coupled-channel model is only an approximation to QCD, it would be highly desirable to compare its predictions with those of a coupled-channel analysis of the  $^3P_0$  model of quark pair production. Ultimately, extending lattice QCD calculations into the flavor-threshold region should give a firmer basis for predictions.

In addition to the  $1^1P_1 h_c$ , the now-established  $2^1S_0 \eta'_c$ , and the long-sought  $1^1D_2 \eta_{c2}$  and  $1^3D_2 \psi_2$  states, discrete charmonium levels are to be found as narrow charm-anticharm structures in the flavor-threshold region. The most likely candidates correspond to the  $1^3D_3, 2^3P_2$ , and  $1^3F_4$  levels. If  $X(3872)$  is indeed a charmonium state—the  $^3D_2$  and  $^3D_3$  assignments seem most promising—then identifying that state anchors the mass scale. If  $X(3872)$  is not charmonium, then all the charmonium levels remain to be discovered. Finding these states—and establishing their masses, widths, and production rates—will lead us into new terrain.

## 7 The Next Wave: Mesons with Beauty and Charm

Before closing, I want to make a few remarks about the  $b\bar{c}$  system, which I hope will be studied in some detail in Run II of the Tevatron Collider, and later in ATLAS and CMS at the Large Hadron Collider. Knowing the interquark potential and the masses of the  $b$ - and  $c$ -quarks, we can readily compute the

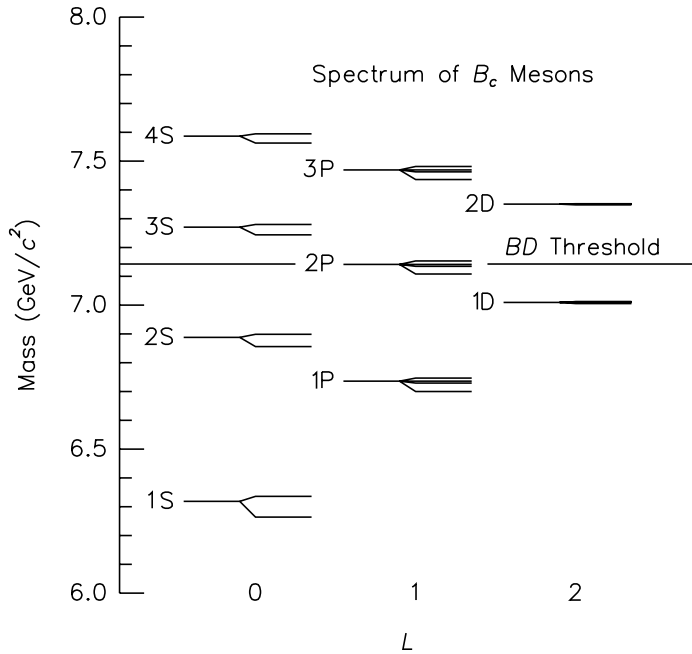


Figure 5: The spectrum of  $b\bar{c}$  mesons, from Ref. <sup>45)</sup>.

spectrum of  $b\bar{c}$  bound states. This has now been done by many people, who find results similar to those displayed in Figure 5, taken from my work with Eichten <sup>45)</sup>. Below the  $B\bar{D}$  threshold, we expect the 1S and 2S doublets as well as the 1P and 1D quartets, and perhaps some of the 2P states. Because the  $b\bar{c}$  mesons have both beauty and charm, all the excited states make radiative or hadronic cascades to the ground state. There are no annihilations into gluons such as we encounter in the charmonium or upsilon families. Among the easily identified decays of  $B_c^+$  should be  $J/\psi \pi^+$ ,  $J/\psi a_1^+$ , and  $J/\psi \ell^+ \nu$ . By considering a universe of reasonable quarkonium potentials, we estimated that the ground-state mass would lie within 20 MeV of 6258 MeV.

We have a number of reasons to want to explore this third system and map out its spectrum. First, it is a wonderful experimental challenge: it will be a remarkable experimental tour-de-force to establish the  $B_c$  ground state and some of the transitions that lead to it. Second, the  $b\bar{c}$  family is intermediate between a heavy-heavy system and a heavy-light system; it should display attributes of both, and theoretical techniques developed for the limiting cases may find interesting challenges here. Third,  $B_c$  and its excited states should be sensitive to relativistic effects and configuration mixing. It is worth noting

that the  $c$ -quark in the  $B_c$  has a much higher velocity than its counterpart in charmonium. Finally, the rich pattern of weak decays:  $b$ -decay,  $c$ -decay, and  $b\bar{c}$  annihilation, should have much to teach us about the interplay of weak and strong interactions.

In 1998, the CDF Collaboration observed <sup>46)</sup> the semileptonic decay  $B_c \rightarrow J/\psi \ell \nu$ , and inferred a ground-state mass  $M_{B_c} = 6.40 \pm 0.39$  (stat.)  $\pm$  0.13 (sys.) GeV. No nonleptonic decay has yet been established. Using the semileptonic sample, CDF measured a lifetime  $\tau(B_c) = 0.46^{+0.18}_{-0.16}$  (stat.)  $\pm$  0.03 (syst.) ps, consistent with theoretical expectations <sup>47)</sup>.

The High-Precision QCD collaboration <sup>48)</sup> has recently reported important progress in the inclusion of dynamical fermions in lattice calculations of quarkonium observables. Their test of lattice predictions consists in tuning the bare  $u$ - and  $d$ -quark masses (set equal), the bare  $s$ -,  $c$ - and  $b$ -masses, and a proxy for the bare QCD coupling, to reproduce  $M_\pi^2$ ,  $2M_K^2 - M_\pi^2$ ,  $M_{D_s}$ ,  $M_\Upsilon$ , and  $M_{\Upsilon'} - M_\Upsilon$ . Having tuned all free parameters, they computed nine other observables. The outcome of their calculations is summarized in Figure 6, which shows the ratio of calculation to measurement for the pion and kaon decay constants, a baryon mass splitting, the  $B_s$ - $\Upsilon$  mass difference, and mass differences between various  $c\bar{c}$  and  $b\bar{b}$  states. The left panel shows ratios from quenched QCD simulations without quark vacuum polarization. These results deviate from experiment by as much as 10–15%. The right panel shows results from unquenched QCD simulations that include realistic vacuum polarization. With no free parameters, the unquenched calculations reproduce experiment to within systematic and statistical errors of 3% or less.

At the recent Aspen Winter Physics Conference, Andreas Kronfeld reported new predictions <sup>49)</sup> for the mass of the  $b\bar{c}$  ground state on behalf of a Glasgow–Fermilab subset of the HPQCD Collaboration. Using quarkonium as a baseline, they quote a preliminary value,  $M_{B_c} = 6307 \pm 2^{+0}_{-10}$  MeV; using a heavy-light baseline, they find  $M_{B_c} = 6253 \pm 17^{+30}_{-50}$  MeV. They are making final studies of the sensitivity to lattice spacing and the sea-quark mass, and expect to present a final result soon.

The new lattice result joins older potential-model estimates as an attractive target for experiment, with the significant added benefit that it includes the full richness of strong-interaction dynamics. We look forward to an early experimental verdict!

## 8 Outlook

The discovery of the narrow state  $X(3872) \rightarrow \pi^+\pi^-J/\psi$  gives quarkonium physics a rich and lively puzzle. We do not yet know what this state is. If the most conventional interpretation as a charmonium state—most plausibly, the  $1^3D_2$  or  $1^3D_3$  level—is confirmed, we will learn important lessons about the



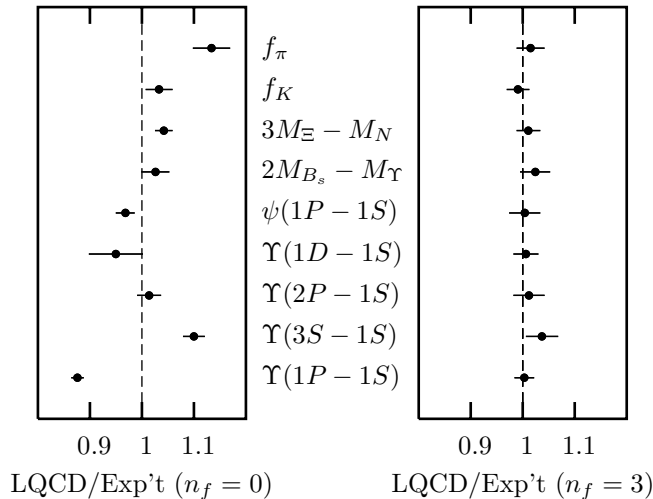


Figure 6: Lattice QCD results divided by experimental results for nine different quantities, without (left panel) and with (right panel) quark vacuum polarization, from Ref. <sup>48</sup>). The top three results are from simulations with lattice spacings of  $\frac{1}{11}$  and  $\frac{1}{8}$  fm; all others are from  $\frac{1}{8}$ -fm simulations.

influence of open-charm states on  $c\bar{c}$  levels. Should the charmonium interpretation not prevail, perhaps  $X(3872)$  will herald an entirely new spectroscopy. In either event, several new charmonium states remain to be discovered through their radiative decays or hadronic transitions to lower  $c\bar{c}$  levels. Another set of  $c\bar{c}$  states promise to be observable as narrow structures that decay into pairs of charmed mesons. In time, comparing what we learn from this new exploration of the charmonium spectrum with analogous states in the  $b\bar{b}$  family will be rewarding. We have seen the first experimental evidence for a third, and rather exotic, quarkonium family, the mesons with beauty and charm of the  $b\bar{c}$  series. A precise determination of the ground-state  $B_c$  mass will test the state of the lattice QCD art, and mapping the spectrum will enhance our understanding of quarkonium systems. The weak decays of  $B_c$  should be highly instructive. For all three quarkonium families, we need to improve our understanding of hadronic cascades. Beyond spectroscopy, we look forward to new insights about the production of quarkonium states in  $B$  decays and hard scattering. I expect continued good fun from the interchange between theory and experiment!

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