The Status and Direction of Hadron Spectroscopy Theory

Richard Lebed

Arizona State University

Snowmass Exercise

Rare Processes and Precision Frontier

Topical Group RF7

July, 2020

Hadron Spectroscopy from 2011-2020

- **36** conventional heavy-quark hadrons discovered:

  $\chi_{c0}(2P), \psi_2(1D), \psi_3(1D),$
  $\chi_{b1}(3P), \chi_{b2}(3P), \eta_b(2S), h_b(1P), h_b(2P),$
  $D^0(2740), D^0(3000),$
  $\Lambda_c(2860), \Xi_c(2923), \Xi_c(2939), \Xi_c(2965),$
  $\Omega_c(3000), \Omega_c(3050), \Omega_c(3065), \Omega_c(3090), \Omega_c(3120),$
  $B_J(5840), B_J(5970),$
  $\Lambda_b(5912), \Lambda_b(5920), \Lambda_b(6146), \Lambda_b(6152),$
  $\Sigma_b(6097), \Xi_b(5935), \Xi_b(5945), \Xi_b(5955), \Xi_b(6227),$
  $\Omega_b(6316), \Omega_b(6330), \Omega_b(6340), \Omega_b(6350),$
  $B_c(2S), \Xi_{cc}$

- And all of these plausibly fit as conventional $q\bar{q}$, qqq hadrons, most with orbital or radial excitations

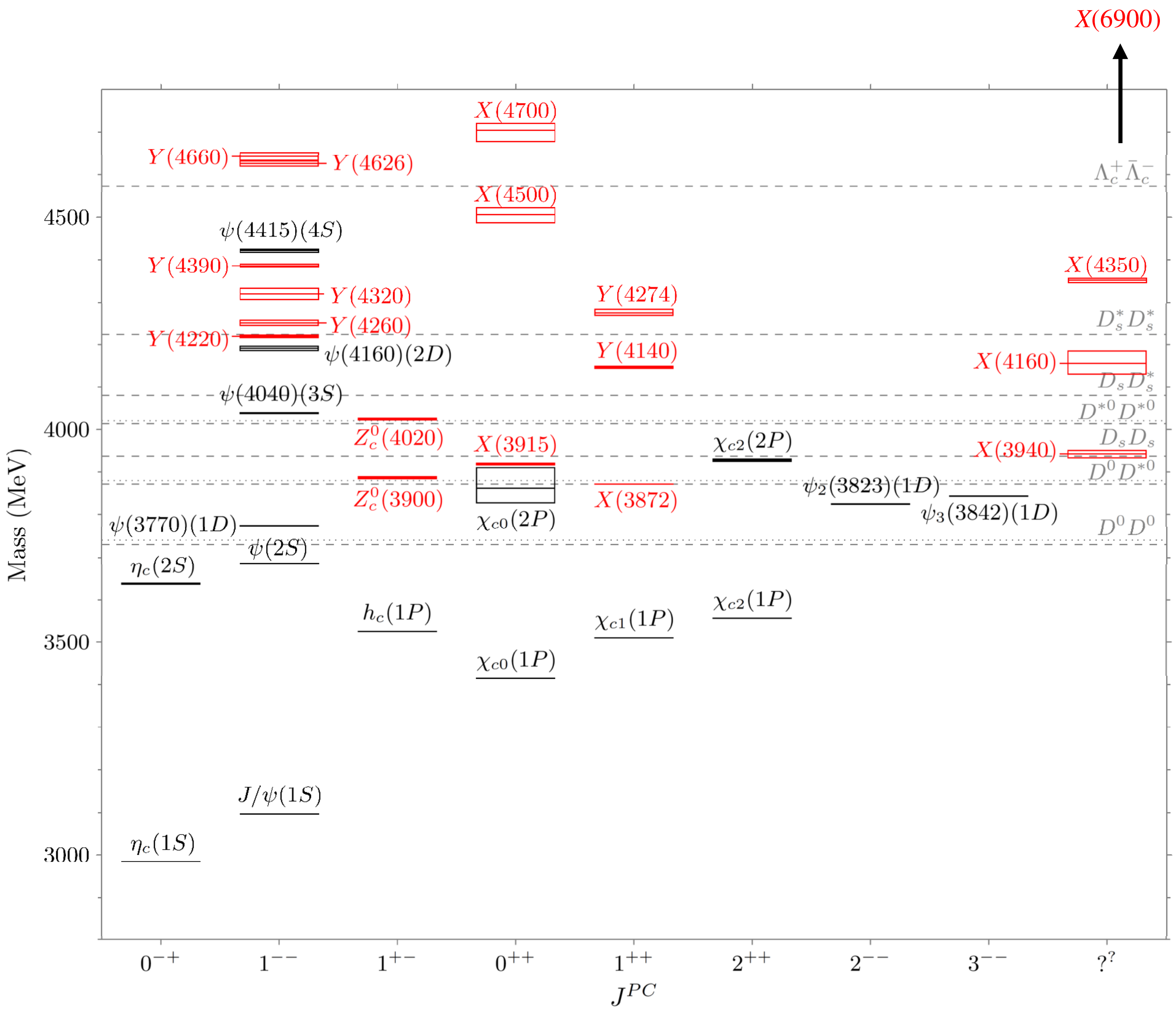
So the conventional side is almost done?

- *Not at all*: For example, there is still one last undiscovered conventional $c\bar{c}$ state, $\eta_{c2}(1D)$ (2^{-+}), that lies below the open-charm threshold, and who knows how many above?
- Many more below open-bottom $b\bar{b}$ states have not yet been observed (missing η_b, h_b, D-wave states)
- And these are the easy ones! Just fit to a simple potential
- The heavy-lights $(D, B, \Lambda_c, \Lambda_b)$ require more finesse, especially for higher excitations (Which potential? Large decay widths!)
- Heavy double-strange baryons Ω_c, Ω_b: unknown before 2017 *e.g.*, does their multiplicity prove the existence of ss diquarks? [Karliner & Rosner, PRD **102** (2020) 014027]
- Double-heavy Ξ_{cc}: How far apart are the cc pair? Hints from weak decays (**RF1**)?

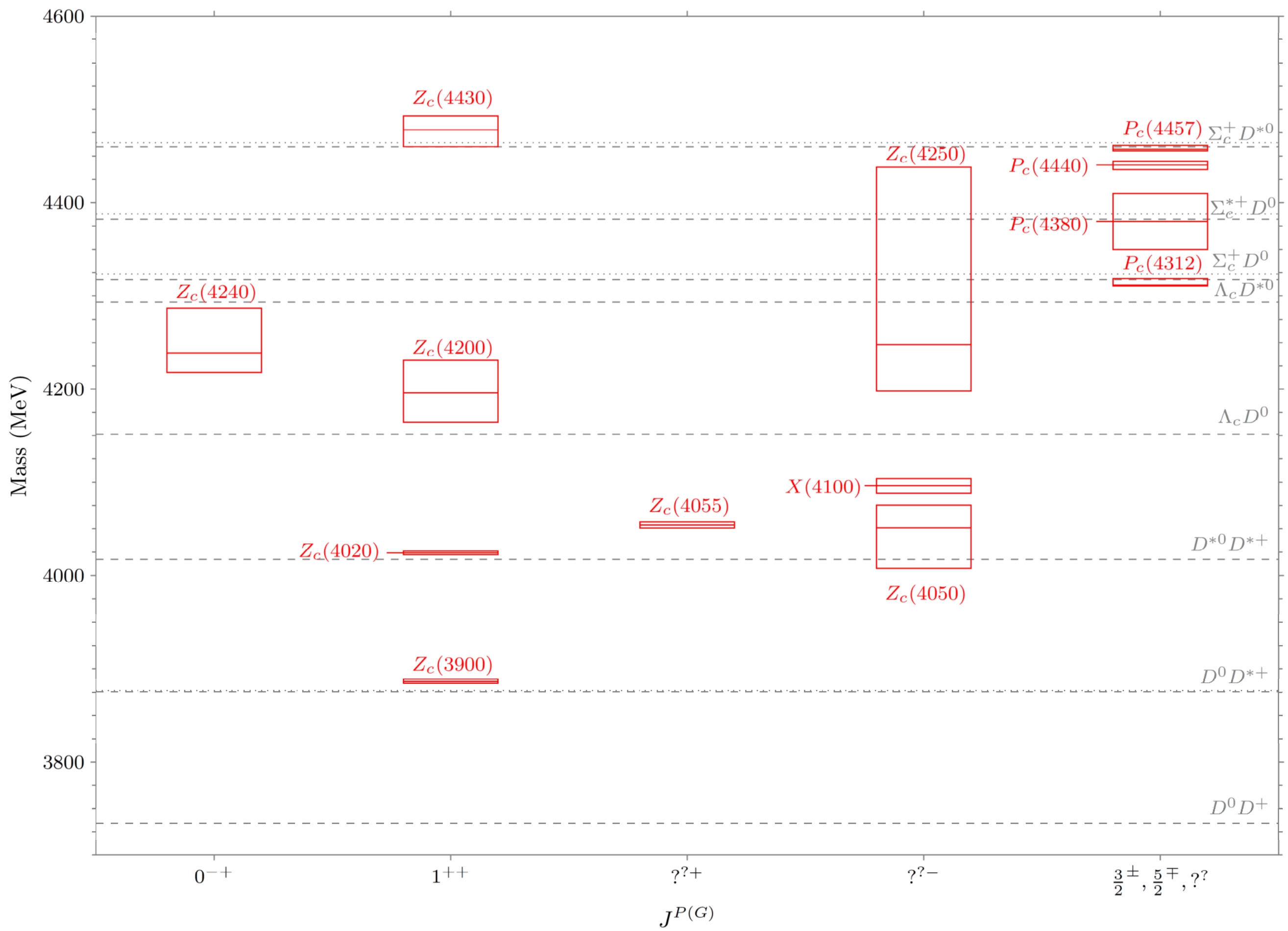
The future for conventional heavy hadrons

- The discovery era is still not finished (Belle II & LHC)
- Once the states are found, only so much can be learned solely from their mass spectrum
- Key observables like radiative & hadronic transition widths are essential to probing their wave functions
- Many of the states listed above are so new that these studies have not yet been carried out, experimentally *or* theoretically
- Is the usual theorists' toolbox (quark potential models, chiral-quark models, lattice simulations, heavy-quark effective theory, QCD sum rules) sufficient, or will mysteries remain?
- If those states not understood, then are we ready for **exotics**?

Neutral charmoniumlike sector, July 2020



Charged charmoniumlike sector, July 2020



The heavy exotics scorecard, July 2020

- **42** observed exotics
  - 35 in charmoniumlike sector (incl. pentaquarks)
  - 1 decaying to di-J/ψ
  - 5 in the (much less explored) bottomonium sector
  - 1 with a single *b* quark (and an *s*, a *u*, and a *d*)
- **15** confirmed [PDG] (& none of other 27 disproved)
- My naïve count estimates over 100 more exotics are waiting to be discovered

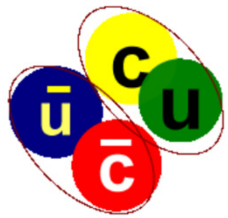
The problems with exotics modeling

- 4- and 5-quark states would be hard to model analytically
  even if all the quarks were heavy, and
  even if the QCD glue interactions were greatly simplified
  - Developing good methods to study multi-electron atoms took <u>decades</u>, and that's just Coulomb interactions and quantum mechanics
- The most physically significant degrees of freedom in the exotics seem to vary from state to state
  - Are their couplings stronger to open-flavor hadrons or to quarkonium?
- Many have same J^{PC} as conventional hadrons & mix w/them
- The world data set is constantly improving
  - Models based upon hints from old data may not bear up under the scrutiny of superior data [*e.g.*, Does the $Y(4260)$ actually exist?]

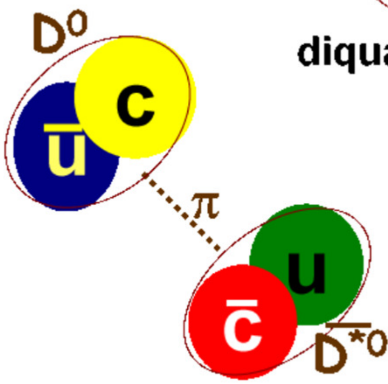
But having heavy quarks helps

- All of the common theoretical pictures for exotics rely in one way or another on $\Lambda_{\mathrm{QCD}}/m_{c,b} \ll 1$:
  - m_Q is nonrelativistic in the state (potential models, lattice simulations)
  - Its Compton wavelength $\hbar/m_Q c$ is smaller than the full hadronic size, making the heavy quarks "discernable" within the state (hybrids, molecular models, diquark models, hadroquarkonium)
  - The scale m_Q is heavy enough to belong to the asymptotic freedom region of QCD, allowing for an operator expansion in powers of $1/m_Q$ (heavy-quark spin effective theory, QCD sum rules)
  - The two-hadron thresholds are spaced further apart than in the forest of overlapping states in the range $1\text{-}2\ \mathrm{GeV}$ (the reason that light-quark exotics are hard to identify)

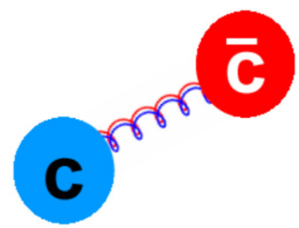
Primary models for heavy exotic hadrons



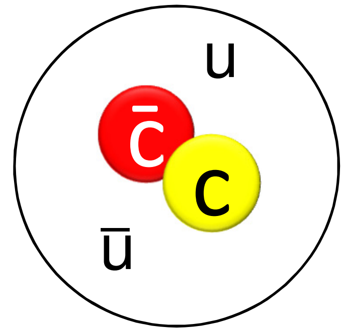
diquark-diantiquark



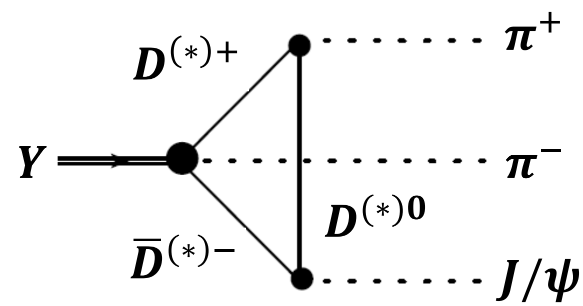
$D^0 - \bar{D}^{*0}$ "molecule"



$q\bar{q}$-gluon"hybrid"



hadrocharmonium



threshold/rescattering/cusp effect

Image adapted from Godfrey & Olsen,
Ann. Rev. Nucl. Part. Sci. **58** (2008) 51

Mesons depicted here, but each model has a baryonic analogue

Spoiler alert

- **None** of these individual models provide a unified picture for explaining all > 40 exotics, in the way that conventional hadrons are explained in the usual quark model
- Example: $m_{X(3872)} - m_{D^{*0}} - m_{D^0} = -0.01 \pm 0.14$ MeV
  That's got to be a $\bar{D}^0 D^{*0}$ molecule!
  But so loosely bound; π exchange would have to be fine-tuned
  It's also produced promptly at colliders, and it has a large b.r. to $\gamma\psi(2S)$: Must have some tightly bound $c\bar{c}$ component
- Nor does lattice QCD yet easily handle problems with several energy/length scales: large masses/small binding energies
- For more details on successes & shortcomings of each approach, see my **EF06** talk at https://indico.fnal.gov/event/43796/

All is not lost: The way forward

- It is becoming increasingly clear that no single theoretical paradigm explains all > 40 heavy-quark exotics
- Threshold effects seem to be essential in several cases, but even those seem to be insufficient if one allows for only a single component [like $\bar{D}D^*$ in $X(3872)$]
- Heavy-quark spin symmetry (most easily probed in decays of exotics to quarkonium) provide important clues on the underlying spin structure of the exotic
- Conventional quarkonium & diquark models provide specific spectra that can be verified or falsified for each observed state
- Transitions between exotic states [like $Y(4220) \to Z_c(3900)$] will be essential in determining which exotics have similar underlying structures

The light-quark exotics

- Why did $X(3872)$ & friends first appear only in the $c\bar{c}$ sector?
- Hints appear lower down in flavor:
  e.g., $D_{s0}^{*}(2317)$ seems too light and too narrow to be purely a conventional $c\bar{s}$ state [Barnes *et al*. PRD **68** (2003) 054006]:
  DK molecule or tetraquark?
- Peculiar states $\phi(2175)$ (only closed-channel $s\bar{s}$ decays so far) and $X(2240)$ in $e^{+}e^{-} \to K^{+}K^{-}$ [BESIII, PRD **99** (2019) 032001] are natural $s\bar{s}q\bar{q}$ candidates
- And the lattice predicts the lowest glueball ~$1.5\ \mathrm{GeV}$ [Review: Ochs, J. Phys. G **40** (2013) 043001], while $\pi_1(1600)$ appears to be a hybrid [JPAC, PRL **122** (2019) 042002], such states as GlueX and COMPASS are designed to study

The light-quark exotics

- ***Q***: But aren't light-quark exotics nowadays essentially nuclear physics, rather than high-energy particle physics?
- ***A***: Particle physics is defined as whatever particle physicists choose to do with their experiments
- ***A***: You don't really understand what heavy-quark exotics are, unless you understand how they emerge as clearly identifiable states when their quarks become heavy

Preliminary Proposal:
Directions for Theory for the 2020's

- The kinds of analysis required by the flood of experimental data that will emerge in the next few years will require broader theoretical efforts:

  – Collaborative endeavors by theorists with differing areas of expertise,
  e.g., lattice simulations and potential models
  e.g., effective field theory and scattering theory
  e.g., medium-energy nuclear theorists and high-energy flavor theorists

  – Collaborative endeavors by theorists working closely
  with particular experiments
  e.g., JPAC [Joint Physics Analysis Center] with connections to GlueX