

The Status and Direction of Hadron Spectroscopy Theory

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Snowmass Exercise

Rare Processes and Precision Frontier

Topical Group RF7

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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**

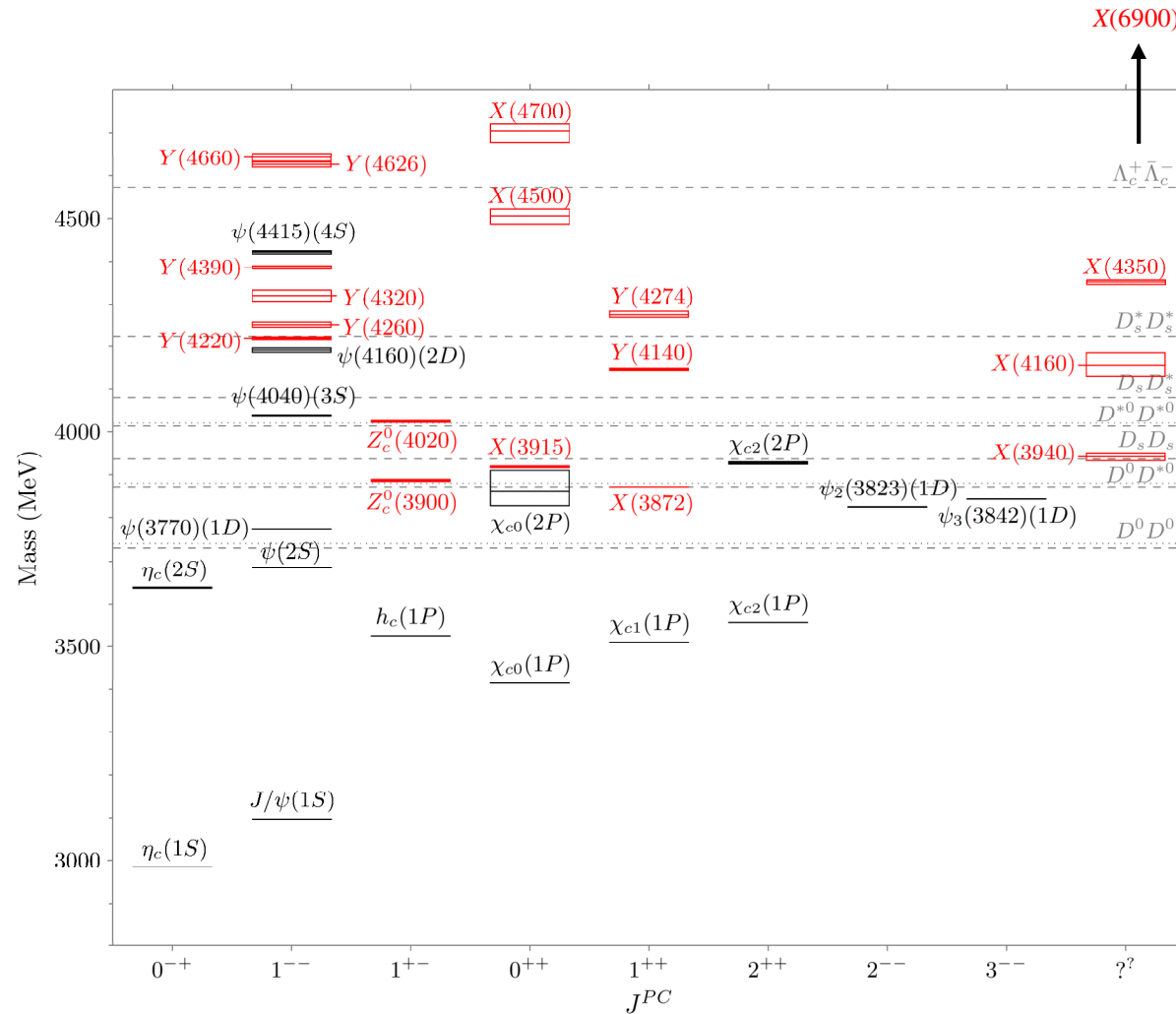
So the conventional side is almost done?

- *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 E_{cc}** : How far apart are the cc pair? Hints from **weak decays (RF1)**?

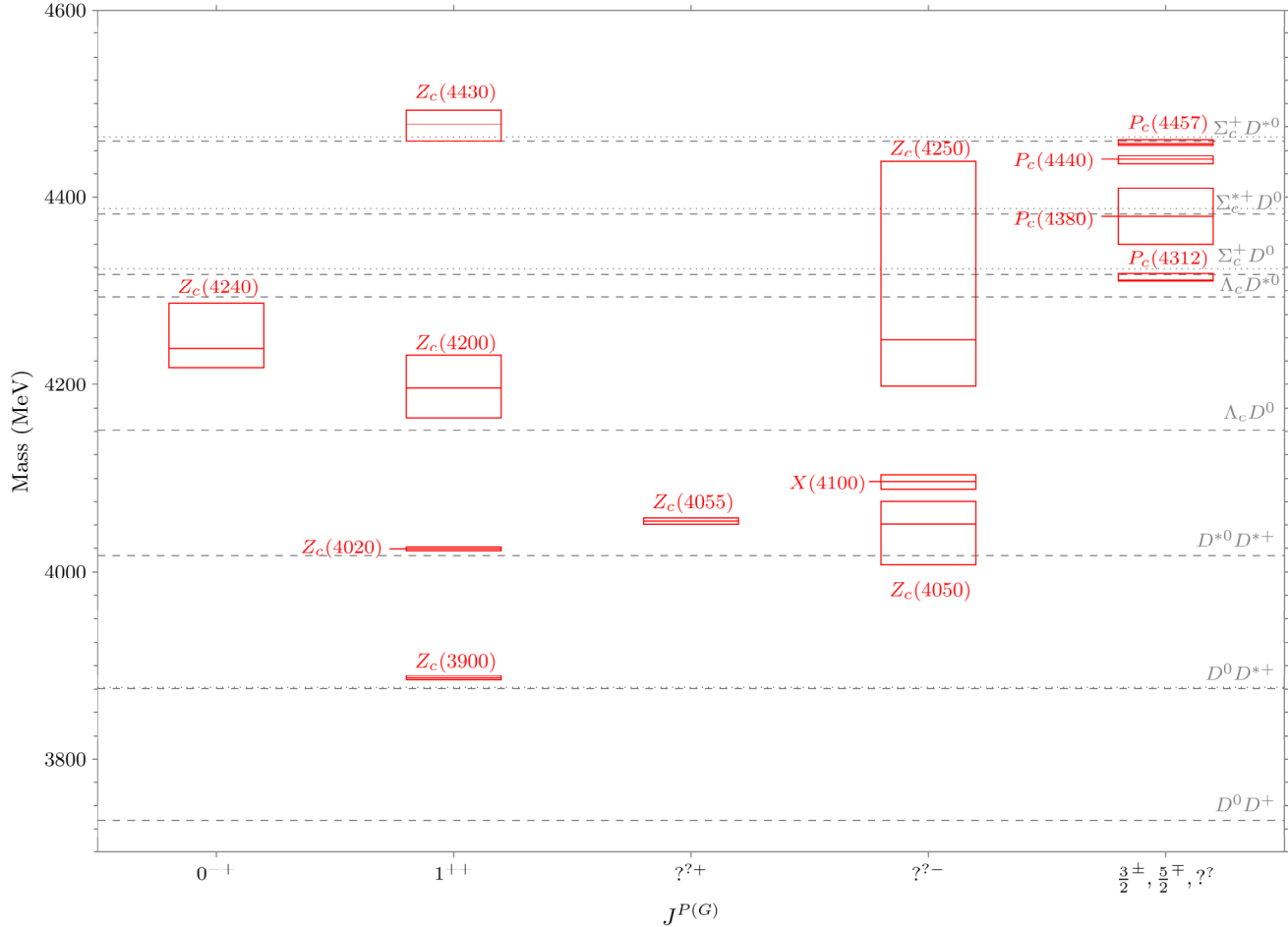
The future for conventional heavy hadrons

- 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 $di\text{-}J/\psi$
 - 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 25 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 decades, 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 $\Lambda_{\text{QCD}}/m_{c,b} \ll 1$:
 - 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 1-2 GeV (the reason that light-quark exotics are hard to identify)

Primary models for heavy exotic hadrons

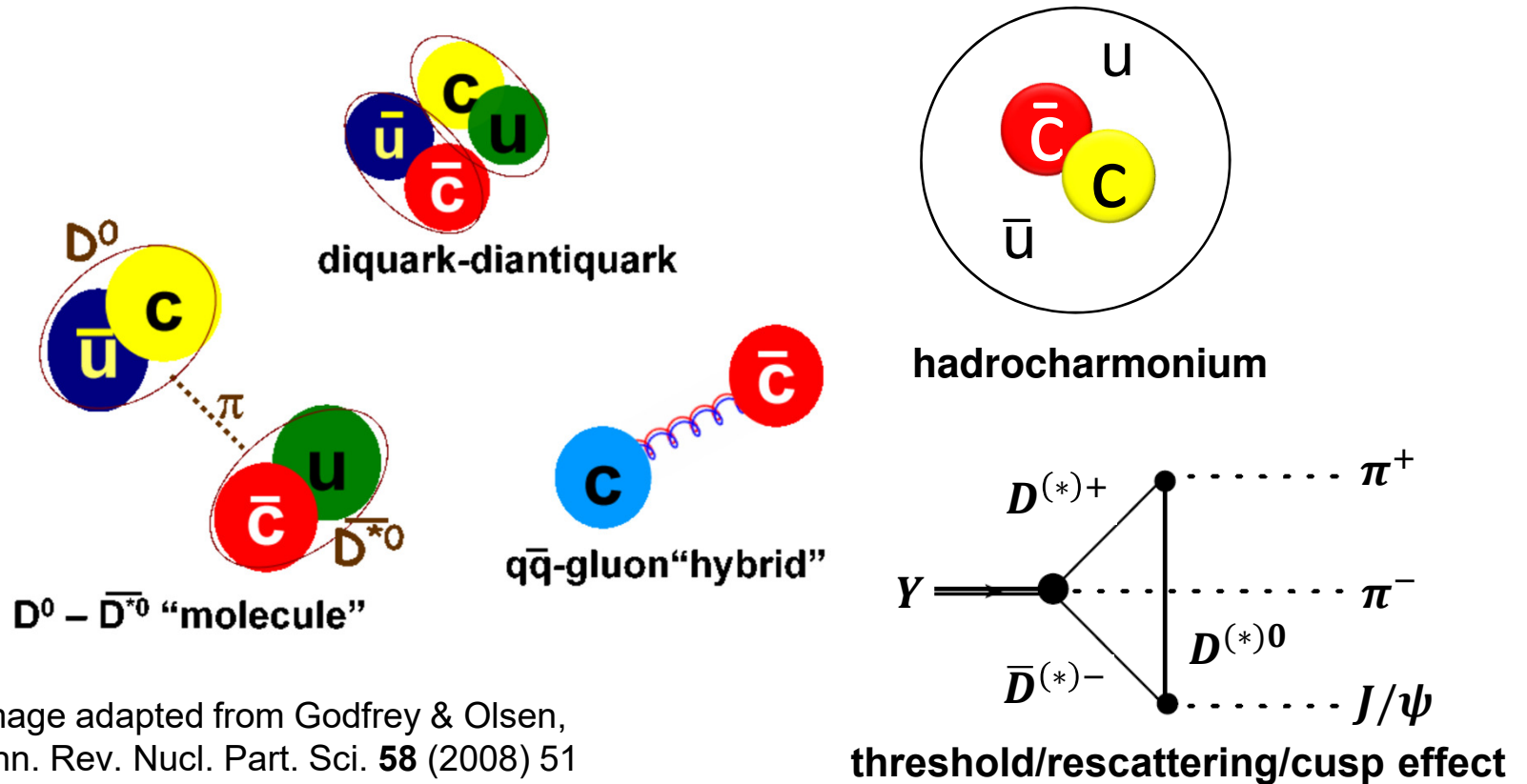


Image adapted from Godfrey & Olsen,
Ann. Rev. Nucl. Part. Sci. **58** (2008) 51

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: $m_{X(3872)} - m_{D^{*0}} - m_{D^0} = -0.01 \pm 0.14 \text{ MeV}$
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 $Y(4220) \rightarrow Z_c(3900)$] 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 $e^+e^- \rightarrow K^+K^-$ [BESIII, PRD **99** (2019) 032001] are natural $s\bar{s}q\bar{q}$ candidates
- And the lattice predicts the lowest glueball ~ 1.5 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**