Future of the Phenomenology of Hadron Spectroscopy

Richard Lebed

Arizona State University

Topical Group RF7, Rare Processes & Precision Physics Frontier

Snowmass Community Summer Study Workshop

University of Washington, Seattle

20 July 2022

Do we really understand hadrons?

- Why was every hadron discovered in the quark model's first 50 years a $q\bar{q}$ meson or qqq baryon? Even Gell-Mann & Zweig saw other options:
  - $q\bar{q}q\bar{q}$, $q\bar{q}q\bar{q}q\bar{q}$, … (*tetraquark, hexaquark, …*)
  - $qqqq\bar{q}$, $qqqqqqq\bar{q}$, … (*pentaquark*, *octoquark*, …)
- And with development of QCD and the discovery of gluons, possibilities with valence glue fields became available:
  - gg, ggg, … (*glueball*)
  - $q\bar{q}g$, $q\bar{q}gg$, … (*hybrid meson*)
- Are diquarks in their attractive color channel important hadron subunits?
- Do molecules of hadrons (analogous to deuterons) form?
- How important are valence gluons?
- **It is quite humbling that after 60 (50) years of the quark model (QCD), we still do not have undisputed answers to these fundamental questions!**

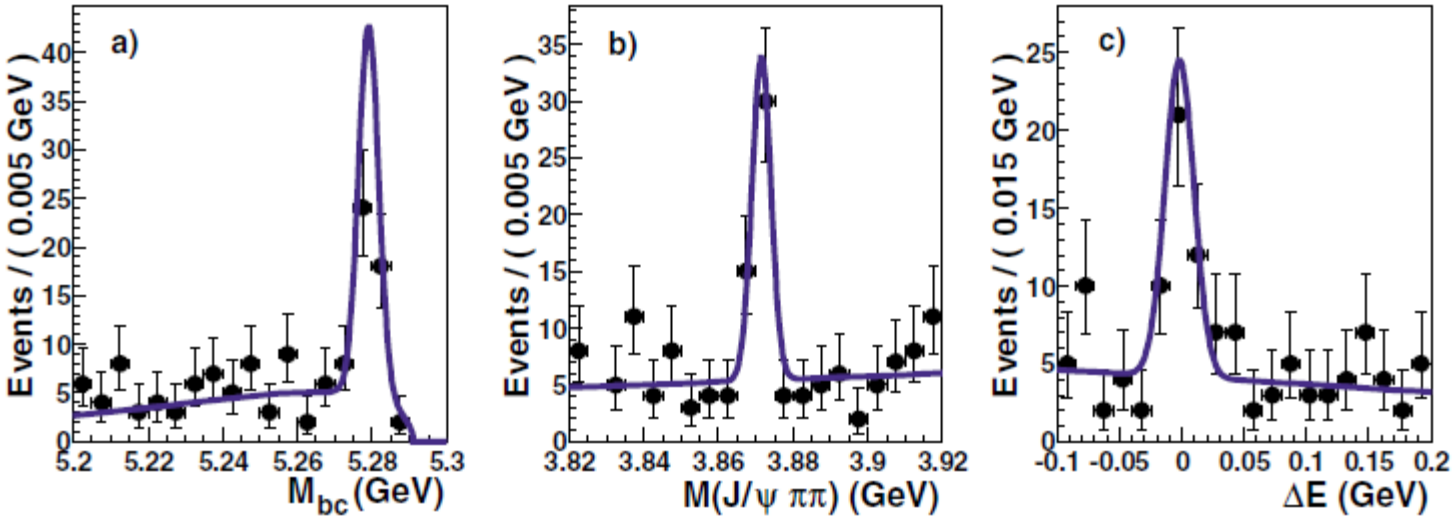
Everything changed in 2003

Belle Collaboration: a narrow new particle, **X(3872)**

In mass range of charmonium, but behaves *very unlike* a pure $c\bar{c}$ state

Almost certainly a hadron of valence quark content $c\bar{c}q\bar{q}$

S.K. Choi *et al.*, Phys. Rev. Lett. **91** (2003) 262001

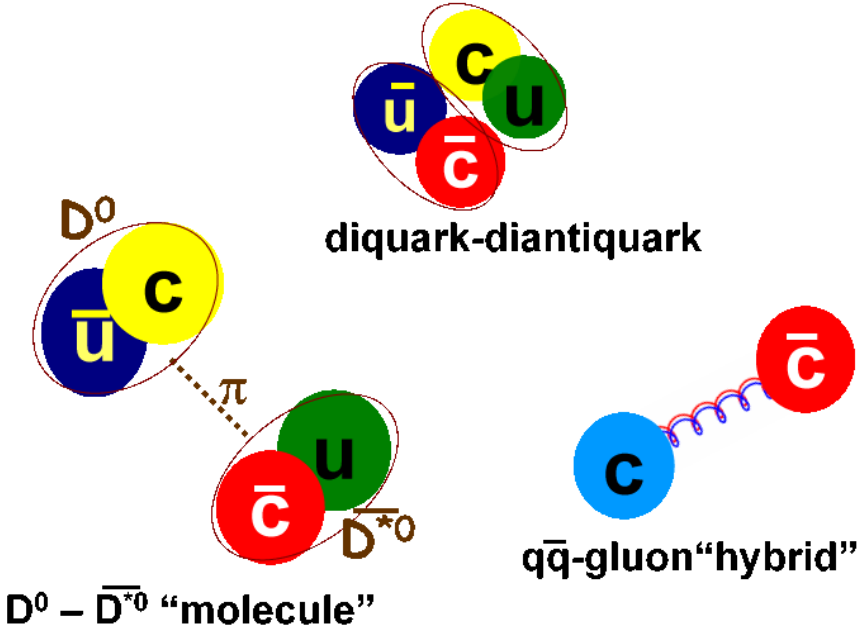


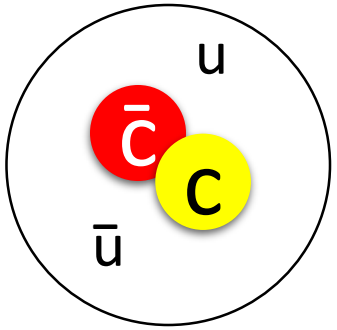
Heavy-quark exotics census: July 2022

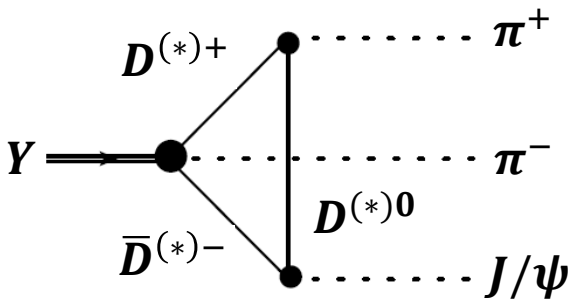
- **57** observed exotics, both tetraquarks and pentaquarks
  - 45 in the charmonium sector (including open-strange)
  - 5 in the (much less explored) bottomonium sector
  - 4 with a single *c* quark (and an *s*, a *u*, and a *d*)
  - 1 with a single *b* quark (and an *s*, a *u*, and a *d*)
  - 1 with all c and $\bar{c}$ quarks (CMS & ATLAS about to announce more!)
  - 1 with two *c* quarks
- A naïve count estimates well over 100 more exotics are waiting to be discovered

Their internal structure is not yet resolved

Mesons depicted here,
but each model has a
baryonic analogue





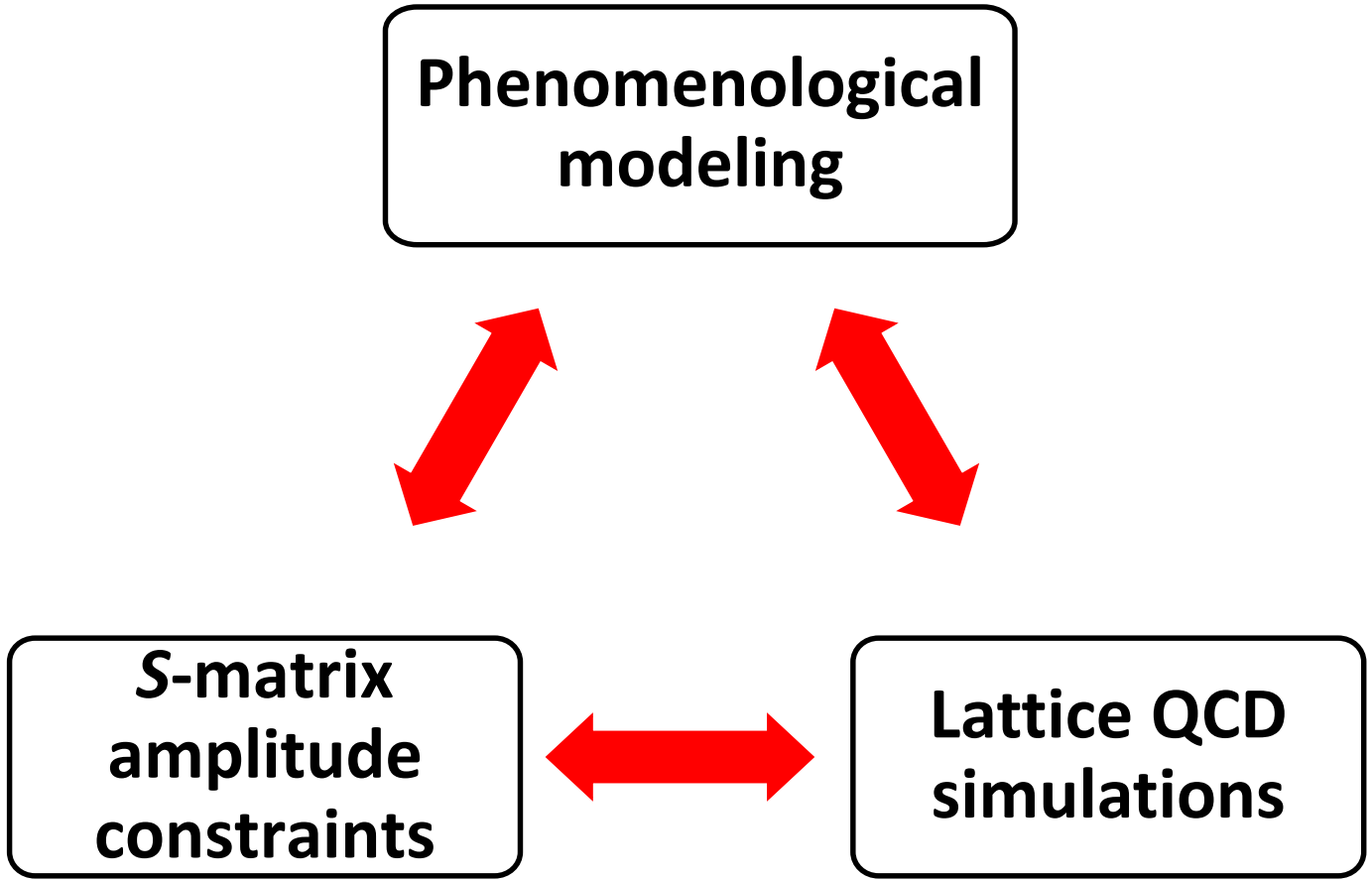


threshold/rescattering/cusp effect

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

No single model accommodates all the new states—
Even mixtures between several types could occur

Modern hadron spectroscopy theory



Phenomenological modeling

- Internal structure of heavy-quark exotics not yet resolved, so multiple approaches must continue to be developed
- Heavy-quark ($m_Q \gg \Lambda_{\mathrm{QCD}}$) hadrons (especially multiquark exotics) admit features not available for light-quark ones:
- Usually fewer prominent decay modes (hence narrower); anomalous decay modes [*e.g.*, $X(3872) \to J/\psi\, \rho$]
- Many of their decay modes make the exotic nature obvious [*e.g.*, $Z_b^+(10610) \to \Upsilon(b\bar{b})\, \pi^+(u\bar{d})$]
- m_Q have small KE, hence heavy quarks nucleates quark clusters (Hadronic molecules? Diquark compounds?)

Phenomenological modeling

- Large m_Q allows for scale separation from lighter $O(\Lambda_{\mathrm{QCD}})$ d.o.f.: effective field theory, Born-Oppenheimer approximation
- Binding between heavy quarks increases with mass: $V_{QQ}, V_{Q\bar{Q}} \propto \alpha_s^2 m_Q$: $bb\bar{u}\bar{d}$ expected to be so strongly bound that it only has weak decays!
- Many candidates lie near di-hadron thresholds [*e.g.*, $X(3872)$ to $D^0\bar{D}^{*0}$] Hadron molecules? Threshold effects? Configuration mixing?
- Do b and c systems have analogous states? Do they form full isospin and SU(3)-flavor multiplets?

Phenomenological modeling

- Rather than review many 100s of papers,
  the white paper "Substructure of Multiquark Hadrons" [2203.16583]
  presents a series of perspectives from top practitioners of the field
- Many different techniques discussed: Molecular models, diquark models, quark-potential models, hybrid models, threshold rescattering effects, QCD sum rules, effective field theories, string/Regge approaches, …
- No single picture simultaneously explains all exotic candidates
  Multiple perspectives needed to develop comprehensive understanding
- Recommendation: Resources for development of U.S. multi-institution consortium to pursue coordinated approach to this hadron spectroscopy

Special thanks to all workshop attendees, all who commented on the Snowmass RF7 report, and especially to…

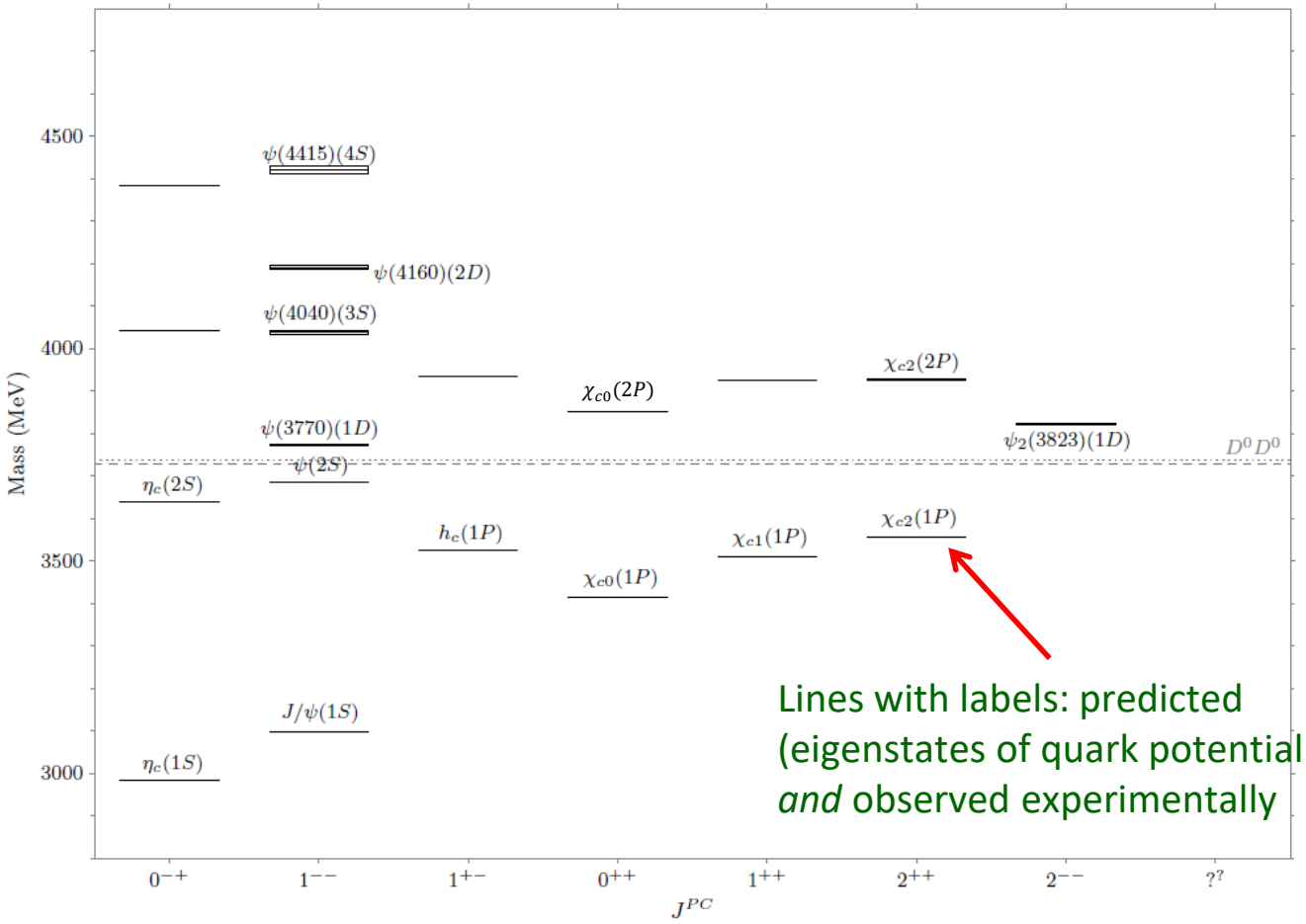
- RF7 subtopic conveners and white paper organizers:
  - Liupan AN (CERN),
  - Sean DOBBS (Florida State U.),
  - Bryan FULSOM (PNNL),
  - Feng-Kun GUO (ITP & U. Chin. Acad. Sci., Beijing),
  - Marek KARLINER (Tel Aviv U.),
  - Ryan MITCHELL (Indiana U.),
  - Alessandro PILLONI (U. Messina & INFN Catania),
  - Alexis POMPILI (U. Bari & INFN Bari),
  - Sasa PRELOVSEK (U. Ljubljana & Jozef Stefan Inst.),
  - Elena SANTOPINTO (INFN Genoa),
  - Justin STEVENS (Coll. William & Mary),
  - Adam SZCZEPANIAK (Indiana U. & Jefferson Lab)

Backup slides

For decades, hadronic spectroscopy was the core of high-energy physics

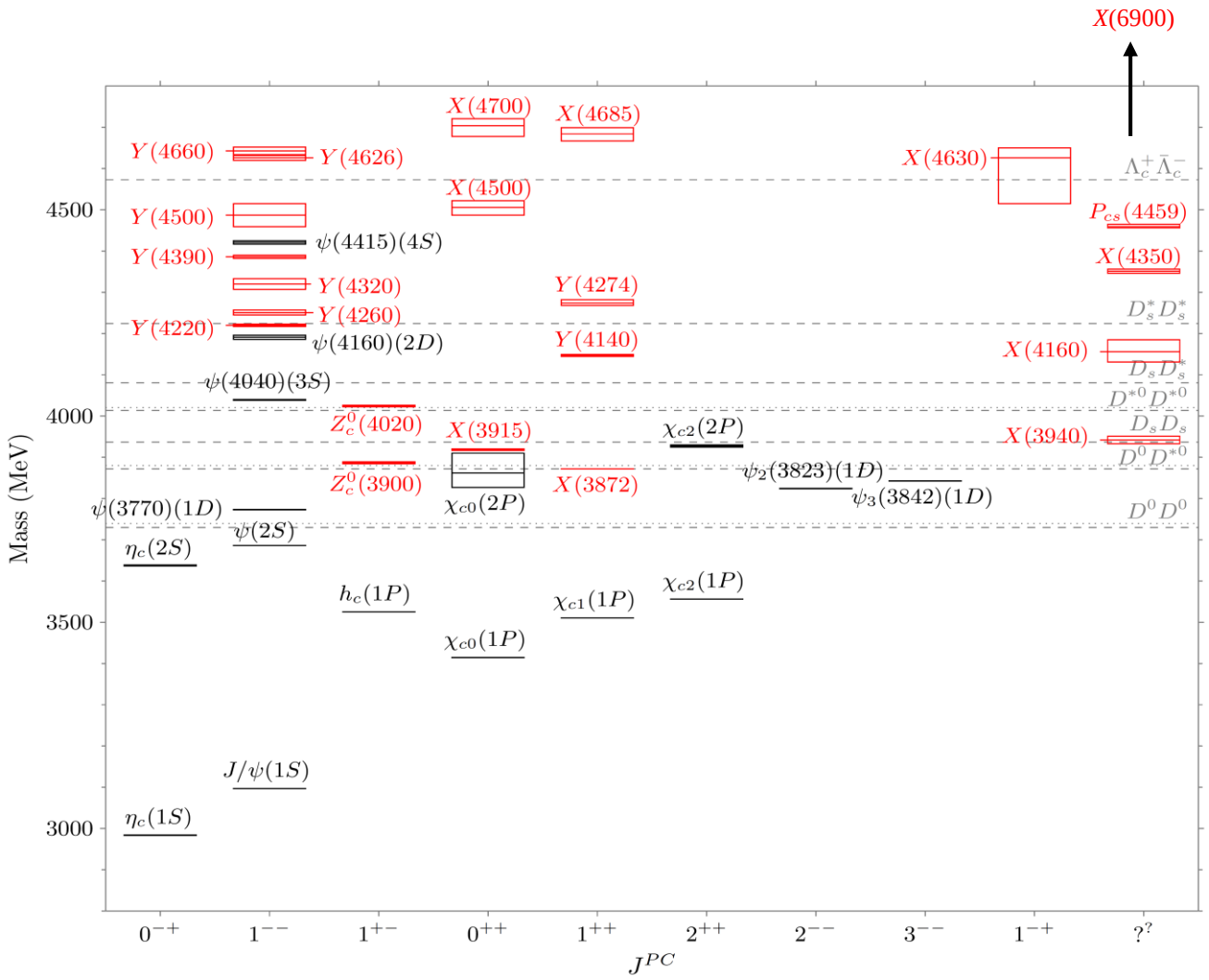
- 1947: Discovery of $\pi^{\pm}$, $K^{\pm}$, K^{0}
- 1950 ~ 1965: The hadron zoo; strangeness; the Eightfold Way; the quark model; color charge
- 1974: Charmonium; evidence for asymptotic freedom & QCD
- 1977: Bottomonium; 3rd generation of quarks needed for CP violation
- 1983: First full reconstruction of B meson decays
- 1983: W & Z bosons. Look for top quark! Look for Higgs! Look for BSM!!
- 1983– Hadron spectroscopy: Fill out the quark-model multiplets 

What the charmonium system should look like



Lines with labels: predicted (eigenstates of quark potential model) *and* observed experimentally

What the charmonium system really looks like



$XYZP$ states have hadronic transitions to narrow charmonium states with surprisingly large rates

Some are explicitly 4-quark effects, *e.g.*, $Z_c^+(3900) \to J/\psi\pi^+$

Not all exotic candidates have heavy quarks

- $\pi_1(1600)$ (discovered 1998) is believed to be a hybrid meson because its $J^{PC} = 1^{-+}$ is not accessible to $q\bar{q}$ states
- $f_0(1710)$ is believed to have a sizeable glueball component because the quark model predicts one fewer 0^{++} states than are seen, and of them $f_0(1710)$ shows up most prominently in J/ψ decays (a glue-rich environment)
- $\phi(2170)$ has a peculiar decay pattern and may be an $s\bar{s}g$ hybrid or the $s\bar{s}q\bar{q}$ tetraquark analogue to the $c\bar{c}q\bar{q}$ state $Y(4230)$
- Exotics studies require high- and low-energy intercommunity dialogue

What kind of “state” is it?

- Not every “bump” in the data is a Breit-Wigner resonance, *i.e.*, corresponds to a pole in one particular region of the complex scattering amplitude
- Distinguishing “resonances” from “virtual states” and “bound states”, not to mention (supposedly) simple “threshold rescattering effects”, requires:

1) Careful determination of amplitude dependence on energy/mass across the resonant region to measure the lineshape in different decay modes
2) Algorithms to model amplitudes in such a way as to obey bedrock quantum-field theory principles like unitarity

Modern hadron spectroscopy analysis will require collaborations featuring frequent interactions between experimentalists and theorists, and the collective work of multiple theory researchers

Why can't lattice simply sort these states out?

- Lattice QCD simulations have known, quantifiable uncertainties, and now predict many observables at the sub-percent level
- But that's for states stable against strong decay— Almost none of the new states are in that category
- There does now exist a technique (Lüscher formalism) for handling unstable states, but many practical complications remain (see below)
- Nevertheless, lattice results can also provide strong constraints on matrix elements and values of amplitudes
- The lattice can be used in coordination with phenomenological modeling and with modeling of amplitudes

Amplitude analysis

[2203.08308; talk by Arkaitz Rodas]

- A "bottom-up" theory approach; no model assumed
  Use only core features of quantum field theory:
  unitarity, analyticity of scattering amplitudes, crossing symmetry
- "Model" amplitudes by using only functions obeying these constraints
- This is a big, intricate job! JPAC (Joint Physics Analysis Center) is a collaboration of theorists & experimentalists (JLab, COMPASS, …) carrying out these complicated calculations
- Examples: $f_0(1710)$ likely dominated by glueball component; $\pi_1(1400)$ hybrid candidate seems to be artifact of true $\pi_1(1600)$ state
- Recommendation: Continued support for collaborations such as JPAC

Lattice QCD simulations

[2203.03230; talk by Sasa Prelovsek]

- Very good results for light, conventional hadrons; conventional quarkonium below open-flavor thresholds; decay constants; *etc*.
- Can study m_q dependence of observables
- …Even with lower values of m_π and unquenching
- Technique (Lüscher formalism) for unstable particles w/ 2-body decays
- Improvements underway/future goals (given sufficient computing resources, researcher support)
  - Decays to particles with nonzero spin
  - Decays with more than one two-body final state (coupled-channel)
  - 3-body decays
  - Isospin breaking, electroweak transitions, …