Status and Future Prospects of Modern Hadron Spectroscopy

Report of Topical Group **RF07**

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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

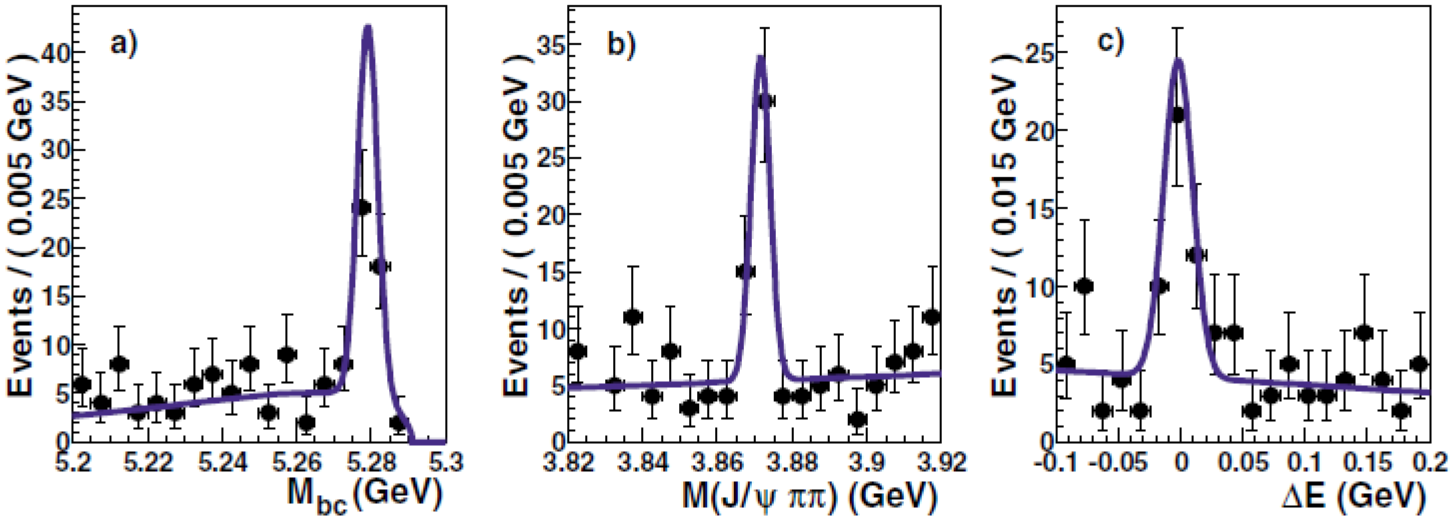
And then, in 2003…

The **Belle Collaboration** at KEK found evidence for a narrow new particle at 3872 MeV

In the broad 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

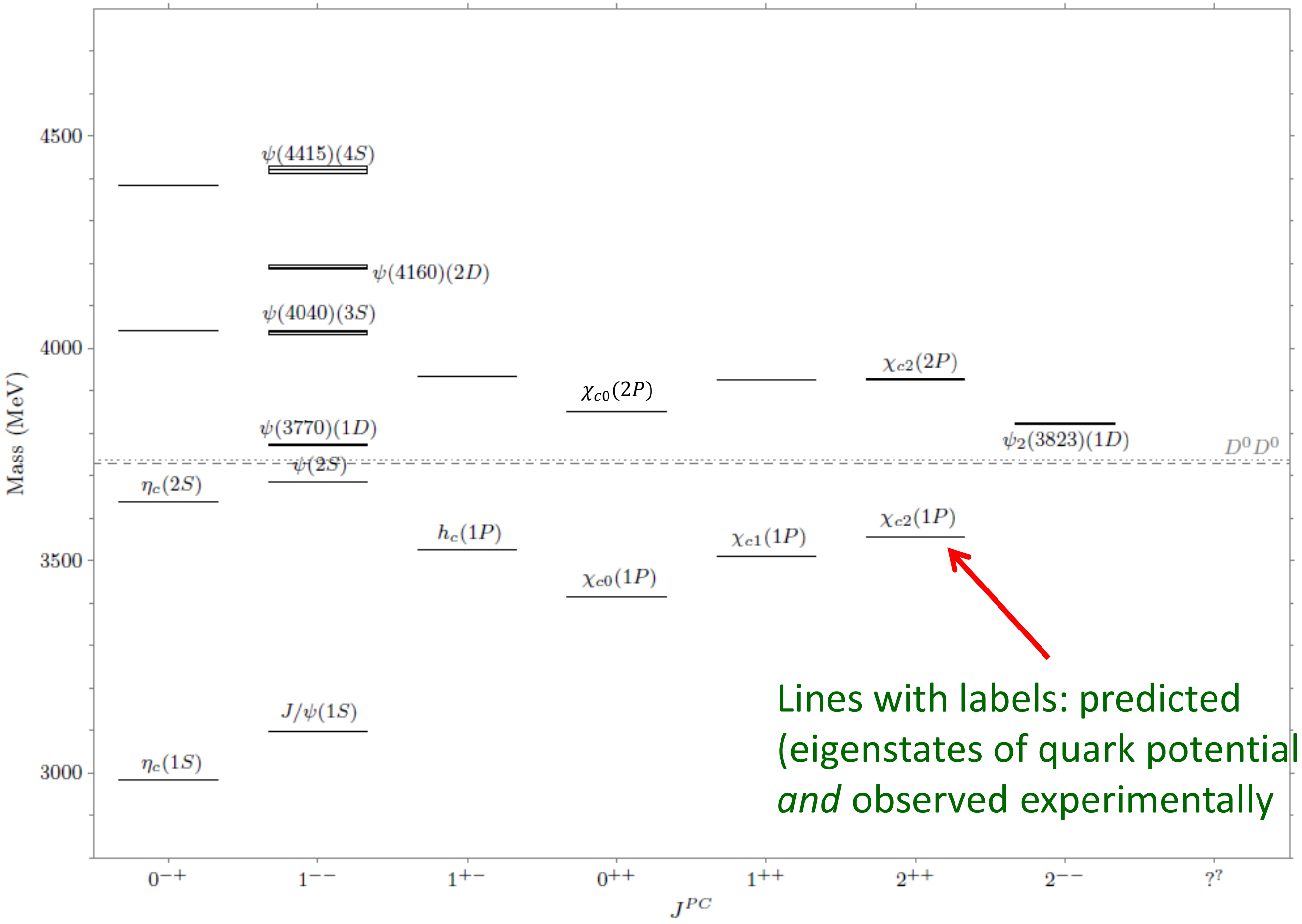


Reminder: The primary goal of Belle was the search for *CP* violation in the *B* system

Do we really understand hadrons?

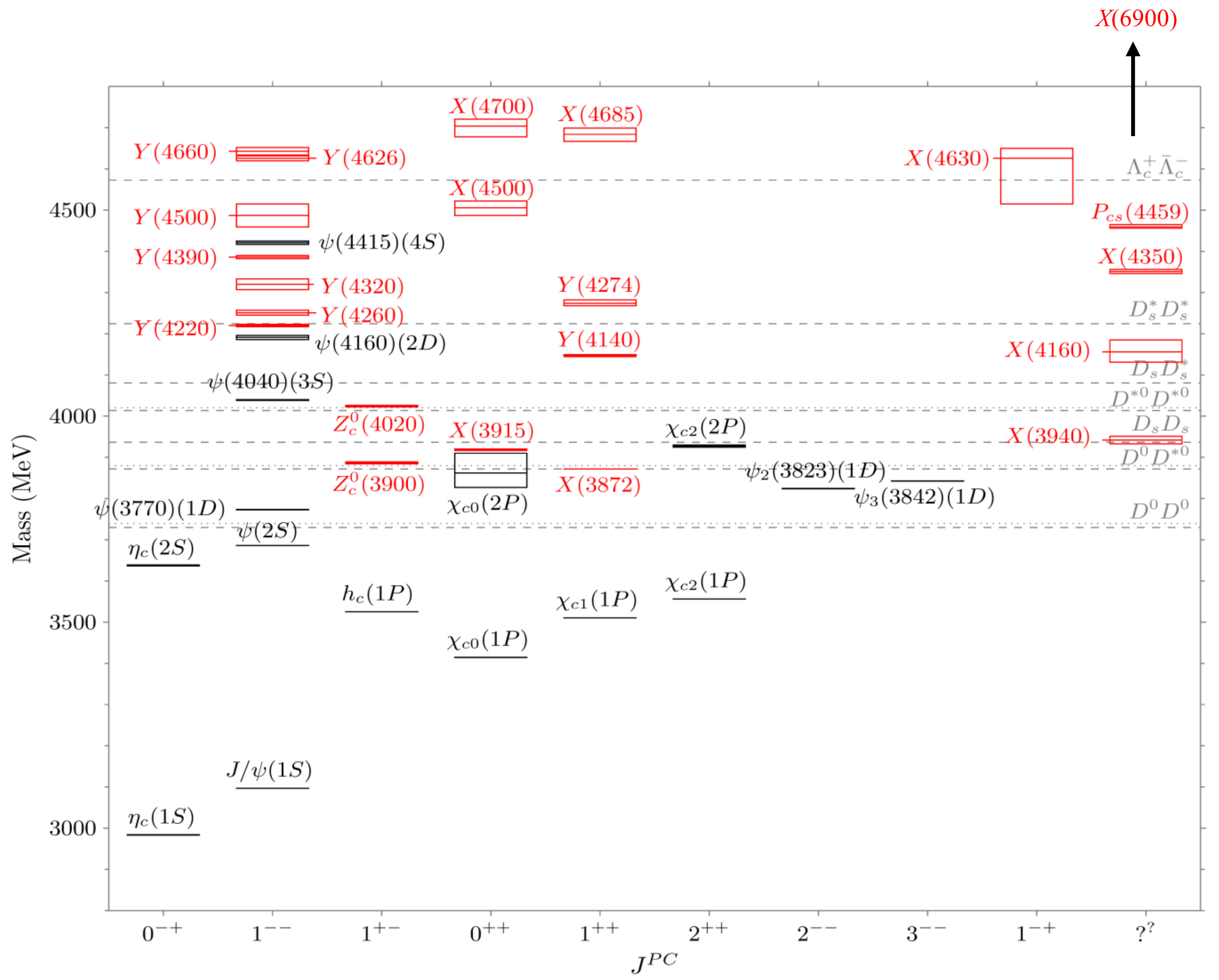
- Why was every hadron discovered in the quark model's first 50 years a $q\bar{q}$ meson or qqq baryon? Even Gell-Mann & Zweig saw other options:
  - $q\bar{q}q\bar{q}$, $q\bar{q}q\bar{q}q\bar{q}$, … (*tetraquark*, *hexaquark*, …)
  - $qqqq\bar{q}$, $qqqqqq\bar{q}$, … (*pentaquark*, *octoquark*, …)
- And with development of QCD and the discovery of gluons, other possibilities became available:
  - gg, ggg, … (*glueball*)
  - $q\bar{q}g$, $q\bar{q}gg$, … (*hybrid meson*)
- Are diquarks in their attractive color channel important hadrons subunits?
- Do molecules of hadrons (like deuterons) involving mesons form?
- **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!**
- Modern hadron spectroscopy aims at settling these issues
- Consequences could be far-ranging:
  - Neutron star models
  - Contributions of hadronic effects in rare B decays (BSM)
  - Phenomenology of *any* strongly coupled theory

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.*, $Z_c^+(3900) \to J/\psi\pi^+$

Heavy-quark exotics census: May 2022

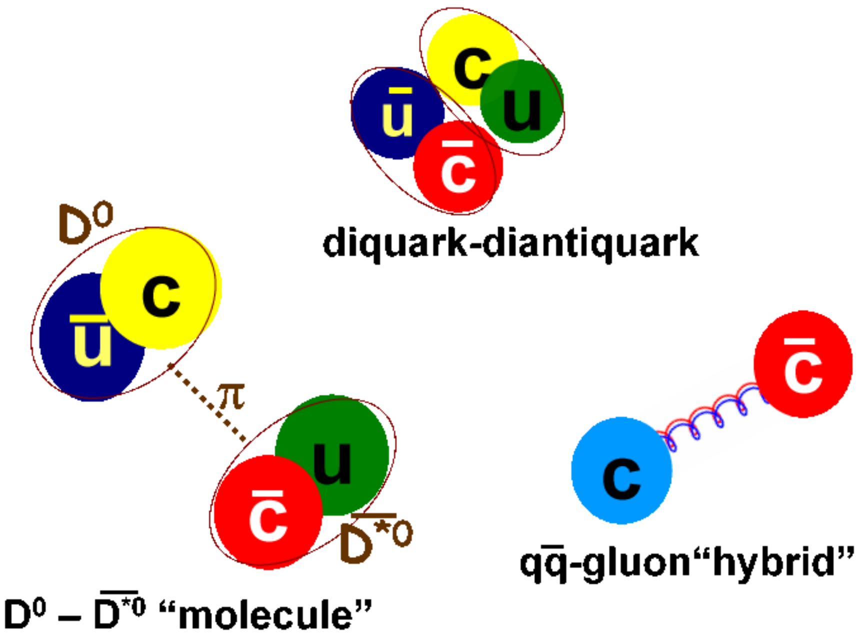
- **54** observed exotics, both tetraquarks and pentaquarks
  - 44 in the charmonium sector (including open-strange)
  - 5 in the (much less explored) bottomonium sector
  - 2 with a single c quark (and an s, a u, and a d)
  - 1 with a single b quark (and an s, a u, and a d)
  - 1 with all c and $\bar{c}$ quarks
  - 1 with two c quarks
- A naïve count estimates well over 100 more exotics are waiting to be discovered
- **Lesson 1**: The currently running experiments need researchers to carry out processing and analysis of large amounts of data

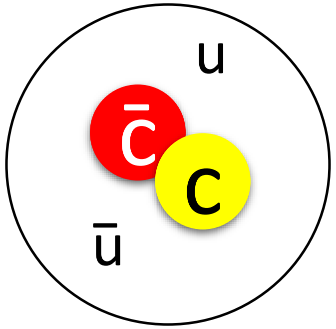
Not all exotic candidates have heavy quarks

- $\pi_1(1600)$ (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 $Y(4230)$
- **Lesson 2**: Exotics studies require high- and low-energy intercommunity dialogue

Their internal structure is not yet resolved

Mesons depicted here, but each model has a baryonic analogue





hadrocharmonium

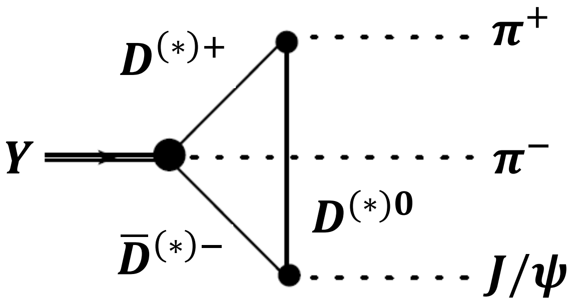


Image adapted from Godfrey & Olsen, Ann. Rev. Nucl. Part. Sci. **58** (2008) 51

threshold/rescattering/cusp effect

Lesson 3: No single model accommodates all the new states—
Even mixtures between several types could occur
All possibilities should be pursued, with an eye toward their unique experimental signatures

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

Lesson 4: 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
- **Lesson 5**: The lattice can be used in coordination with phenomenological modeling and with modeling of amplitudes

The major experiments

Currently ongoing (with future upgrades approved or proposed), hadron spectroscopy is among major goals

- LHCb (CERN, E.U.) ✓
- Belle II (KEK, Japan) ✓
- BESIII (IHEP, China) ✓
- GlueX (JLab, U.S.) ✓

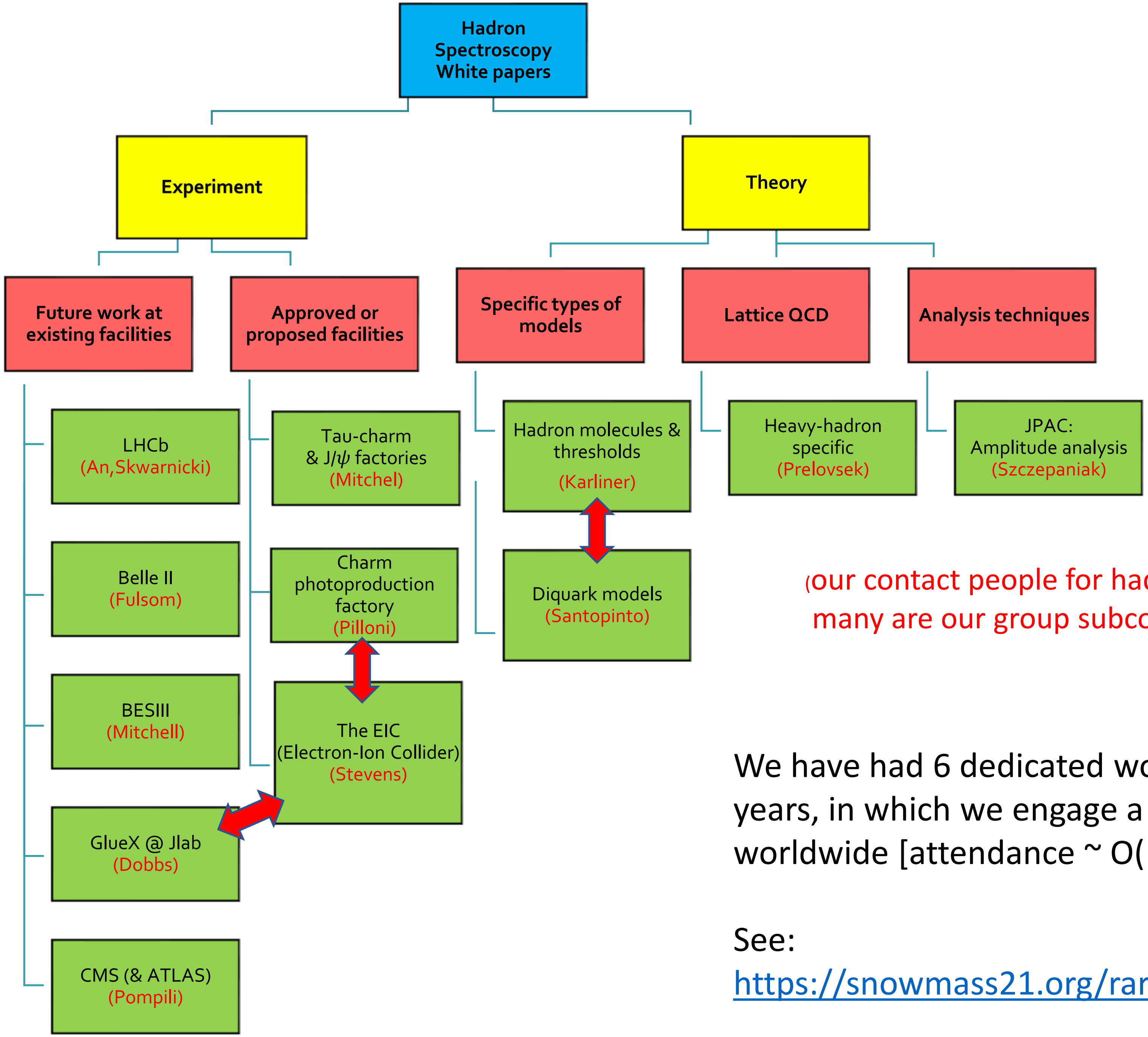
Currently running, hadron spectroscopy is a minor focus

- CMS (CERN, E.U.) ✓
- ATLAS (CERN, E.U.)

Future facilities

- Electron-Ion Collider [EIC] (approved: BNL, U.S.) ✓
- Super Tau-Charm Facility (proposed: China) ✓
- PANDA (planned: FAIR, Germany)

RF7 LoIs/white papers, final structuring



(our contact people for hadron spectroscopy part – many are our group subconveners)

We have had 6 dedicated workshops over the last 2 years, in which we engage a broad community worldwide [attendance ~ O(10^2) physicists]

See: https://snowmass21.org/rare/hadron_spectroscopy

Experimental Facilities

Present & Future

LHCb

[https://cds.cern.ch/record/2806113; talk by Matt Rudolph]

- The LHC experiment, using multi-TeV pp collisions in two runs since 2010 (9 fb^{-1}), made huge numbers of b- and c-containing hadrons (strong production cross section!)
  Very clean final-state signals when produced via subsequent weak decays
- LHCb specializes in studies of b and c physics (forward-angle detection, RICH detectors for charged hadron identification, large dedicated trigger bandwidths, as opposed to high-p_T experiments)
  Runs at intentionally diluted instantaneous luminosity
- With Runs 3 & 4 in next decade, LHC will continue to produce more heavy quarks than any other facility
  LHCb detector upgrades (I ongoing, II next decade)
  designed to take advantage of the instantaneous luminosity already achieved at LHC
- LHCb has discovered more hadrons (conventional & exotic) than any other facility in past decade:
  - Pentaquarks $P_c^+ \to J/\psi\ p$, all-charm tetraquark $X(6900) \to J/\psi\, J/\psi$, open-charm tetraquarks $X(2900) \to D^- K^+$, double-charm tetraquark T_{cc}^+, double-charm baryon Ξ_{cc}^+, *etc. etc. etc.*
  - Many heavy-quark configurations not reachable at other facilities than LHC (b-baryons, bc, bb, …) and important for sorting out different models of multiquark states

LHCb next 2 decades

[https://cds.cern.ch/record/2806113; talk by Matt Rudolph]

- LHCb Upgrade I (2020s): *In commissioning phase as we speak*
  Full software triggering with 40 MHz readout (beam-collision frequency) of all subdetectors. Instantaneous luminosity used is $\sim 10 \times$ better
  Request continued participation of U.S. groups in data taking and analysis
- LHCb Upgrade II (2030s): *Tech Design Report released.* More granular and radiation-hard detector, use timing in subdetectors as 4th dimension in event reconstruction, improved EM calorimeter to fight pile-up that deteriorates detection of neutrals, tracking chambers in the magnet for low-p tracks *etc.* Another factor of ~10 improvement in luminosity
  Request for U.S. involvement in R&D, later detector funds

CMS (& ATLAS)

[2204.06667; talk by Vaia Papadimitriou]

- CMS & ATLAS detectors instead cover central-rapidity region
  & already run at full LHC luminosity
  Since high-p_T detection prioritized, lots of heavy quarks escape
- Trigger efficiencies kick in for higher-p_T muons
  Best sensitivity to double-bottomonium final states $\Upsilon\Upsilon$ with $\Upsilon \to \mu^+\mu^-$,
  in search for $b\bar{b}b\bar{b}$ states (also in $\Upsilon\mu^+\mu^-$ decays)
  Should also play role in verifying the LHCb claims for $J/\psi\, J/\psi$ *etc*.
- No dedicated charged-hadron identification (can't distinguish π^+, K^+, p)
  induces large backgrounds in many channels with ($J/\psi \to \mu^+\mu^-$)+hadrons
- But can identify strangeness in processes involving
  $K_s^0 \to \pi^+\pi^-$ and $\Lambda \to pK^-$ (secondary vertex and mass identifies them)
  Hidden strangeness via $\phi \to K^+K^-$ (very narrow mass peak)
- In such cases, CMS (& ATLAS) can provide complementary results to LHCb
  Examples: $X(4140) \to J/\psi\, \phi$, pentaquark searches in $B^+ \to J/\psi\, p\, \bar{\Lambda}$
- Request for prioritization of collaborations to dedicate enough manpower and computing resources to these topics (dedicated triggers needed)

Belle II (e^+e^- near $b\bar{b}$ threshold)

[https://www.slac.stanford.edu/~mpeskin/Snowmass2021/BelleIIPhysicsforSnowmass.pdf; talk by Bryan Fulsom]

- Data-taking at Belle II began in 2019; as successor to Belle, this e^+e^- experiment has long tradition of uncovering new exotic & conventional states in $c\bar{c}$ and $b\bar{b}$ systems: $X(3872)$, $Z_c^+(4430)$, $Z_b^+(10610)$, *etc.*
- Belle II has reached instantaneous luminosity so far only somewhat exceeding that of Belle, albeit using new, promising e^+e^- machine technology (nanobeams). Major upgrade of interaction point in 2026-27 to reach full design luminosity, about 2 orders of magnitude higher. Expect $40\times$ more data than Belle I by 2031
- Because production cross sections are EM, Belle II cannot compete with LHCb in channels with all charged particles or in simpler final states with neutrals ($\gamma, \pi^0, \eta, \omega$)
  However, in these cases it should have enough sensitivity to verify some claims made by LHCb
- Belle II can edge LHCb in sensitivity in more difficult channels with neutrals (soft γ or π^0, multiple neutrals)
- Tuneable c.m. energy above $B\bar{B}$ threshold gives **unique** access to high-mass $b\bar{b}$, $b\bar{b}q\bar{q}$, $b\bar{b}g$ states (important for hadron spectroscopy!)
- Other unique production processes: $\gamma\gamma \to c\bar{c}$, exclusive double-charmonium production ($J/\psi\, X_{c\bar{c}}$) give access to other narrow charmonium states
- Belle II at full luminosity will be competitive with BESIII on charmonium-like exotics (Y,Z_c states) thanks to initial-state radiation [ISR] ($e^+e^- \to \gamma c\bar{c}$)
- Request continued support to U.S. researchers in data analysis and detector upgrades to cope with increasing luminosity
- Farther future (2030s): Proposal for running with polarized beams and modestly improved luminosity

BESIII (e^+e^- near $c\bar{c}$ threshold)

[2204.08943; talk by Ryan Mitchell]

- Premiere facility for precision e^+e^- tau/charm physics (up to 5 GeV)
- Unlike at B factories, $c\bar{c}$, $c\bar{c}q\bar{q}$, $c\bar{c}g$ states are created directly with better efficiencies in a larger variety of final states. However, dedicated energy scans are needed to map out resonant lineshapes. At present has the most precise method to study vector states (ψ and Y) and narrow Z_c states, a number of them discovered by BESIII
- Observations of transitions between exotic hadrons [*e.g.*, $Y(4230) \rightarrow \gamma X(3872)$] seen nowhere else
- Very large sample of J/ψ (10^{10}) a unique widow to light-hadron spectroscopy (glueballs and hybrids)
- Program to continue 5-10 more years with upgrade of energy to 5.6 GeV and of luminosity (3×)
- Recommend support to U.S. researchers at this unique experiment

The Super Tau-Charm Facility

[2203.07141; talk by Feng-Kun Guo]

- Imagine BESIII with luminosity two orders of magnitude higher ($10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$). Sites have been proposed in China and Russia Data taking in 2030s
- Energy scans would completely map out ψ, Y, narrow Z_c states (beyond any competition from B factories)
- Huge data sets of radiative & hadronic transitions between $c\bar{c}$ and exotic states would become available
- Estimated 3×10^{12} J/ψ means great glue-rich sources for glueballs and light hybrids
- Good potential to produce pentaquarks P_c, P_{cs} and all-heavy ($c\bar{c}c\bar{c}$) tetraquarks
- U.S. participation at this unique facility is desirable (natural transition to researchers trained at BESIII)

Photoproduction Experiments

[2203.08390; talk by Justin Stevens]

- The only major U.S.-based hadron experiments for next decade
- Photoproduction ($\gamma^{(*)}p \to Xp$ or $\gamma^{(*)}A \to XA$) offer clean probes to produce states X without strong-interaction contamination
- Can scan over both c.m. energy (X mass) and γ^* virtuality (X spatial size)
- GlueX (@Jlab), running since 2017: Original purpose is to search for light hybrids, *e.g.*, $\pi_1(1600)$, but can also look for hidden-strangeness exotic candidates like $\phi(2170)$ and P_c pentaquarks in $\gamma^* p \to p\, J/\psi$
- Proposed upgrade of CEBAF facility to higher energy (24 GeV) would make observations of charmonium-like exotics more likely
- EIC (Electron-Ion Collider @BNL) approved to begin construction in 2024, data-taking expected to begin in 2030
  With c.m. energy 20-140 GeV, access to $XYZP$ states likely (at lower EM rates)
- Domestic opportunity for U.S.-based research groups interested in hadron spectroscopy

PANDA

- PANDA (antiProton ANnihilation at DArmstadt): A proposed experiment at FAIR (Facility for Antiproton and Ion Research) in Germany
- FAIR to be commissioned in 2025
- Annihilation of $\bar{p}$ on p in fixed targets ($10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in Phase One) Much higher cross sections than $e^{+}e^{-}$
- Very clean: Make just one mesonic resonance X in formation, $\bar{p}p \to X$, lots of J^{PC} accessible
- High-resolution scans across resonances to obtain detailed lineshapes

Unique experimental capabilities

- LHCb: matchless numbers for b-hadron decays (b-baryons is a unique gateway) reconstructed in charged final states, and in simple channels with neutrals. Exotics in charmonium-like, open-charm, double-charmed and double-charmonium-like configurations already observed Largest impact on hadron spectroscopy in the past decade and best prospects for new discoveries (reaching b-quark exotics?) and improved studies on known states for the next two decades However, some important hadron configurations seen elsewhere have not been detected at LHC
- CMS/ATLAS can play an important role in special channels, in particular for $b\bar{b}b\bar{b}$ spectroscopy.
- Belle II has unique access to $b\bar{b}$-like states, Y_b and Z_b. ISR production of Y_c and narrow Z_c states becomes competitive with BESIII at full luminosity. Unique access to $c\bar{c}$-like states in $\gamma\gamma$ collisions and via double-charmonium production, which is difficult to observe elsewhere
- BESIII has best access to $c\bar{c}$-like states (Y_c and narrow Z_c), and sees transitions among exotic-hadron candidates. Large J/ψ sample a gateway to light glueballs and hybrids
- STCF would increase these capabilities dramatically
- GlueX: dedicated photoproduction experiment to produce light hybrids, making first steps towards charmonium-like spectroscopy in unique production environment. Possible upgrade of CEBAF to make detection of such states more likely. Photoproduction at EIC is also likely to play a role Photoproduction rates are limited by EM cross-sections, but offers special handles to study hadron substructure (energy scans, spatial extent)

Theoretical Approaches

Phenomenological modeling

[2203.16583; talk by Marek Karliner]

- The internal structure of heavy-quark exotics is 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 decay modes (hence narrower); anomalous decay modes (*e.g.*, $X(3872) \to J/\psi\,\rho$); small KE for m_Q hence heavy-quarks nucleates quark clusters (Hadronic molecules? Diquark compounds?)
- Large m_Q allows for scale separation from lighter d.o.f.: effective field theory, Born-Oppenheimer approximation

Phenomenological modeling

[2203.16583; talk by Marek Karliner]

- 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?
- No single picture simultaneously explains all exotic candidates
  Multiple perspectives needed to develop comprehensive understanding
- Recommendation: Funding for development of U.S. multi-institution consortium to pursue coordinated approach to this hadron spectroscopy

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, …

Recommendations from RF07

- No big new experiments called for in the U.S.! All facilities are operating now, approved in U.S., or proposed by other countries
- Human capital: need continued and enhanced support & training of personnel for dedicated data analyses
- Support for research that crosses the traditional particle/nuclear physics divide
- Support for analysis & triggering resources at experiments not originally focused on hadronic physics (*e.g.*, CMS, ATLAS)
- Support for detector equipment enhancements relevant to hadron spectroscopy (*e.g.*, LHCb)

Recommendations from RF07

- Continued & expanded support for researchers at Belle II and BESIII:
  a big U.S. physics footprint for a small U.S. investment;
  training can be carried over to future Super Tau-Charm Facility
- U.S. facilities: support & training for junior researchers at GlueX,
  many of whom will then staff the upcoming EIC or possible JLab24
- Support for U.S. cross experiment/theory initiatives such as JPAC
  to carry out intricate multi-level amplitude analyses
- Support for U.S. multi-institution theory initiatives, including lattice,
  to broaden researchers’ perspectives and generate new collaborations