Heavy Flavor Hadron Spectroscopy

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Experimental highlights since PWA 8 / ATHOS 3 in 2015
Initial impact of heavy flavors on hadron spectroscopy:

Quarks initially treated as mathematical abstraction. Dispute over them ended in 1974.

November revolution of 1974

All excitations above open flavor threshold (no OZI suppression of their widths).
Highly relativistic.
Only qualitative spectroscopy.

Deeper “binding”
A large number of long-lived non-relativistic bound states.
Quantitative spectroscopy.
Heavy-Light Mesons ($Q\bar{q}$): D, D$_s$, B, B$_s$

- Spectroscopy different from that of heavy quarkonia ($Q\bar{Q}$)
  - Light-quark spin-orbit coupling dominates over heavy-quark spin couplings
    \[ \hat{J}_{\bar{q}} = \hat{L} + \hat{S}_{\bar{q}}, \hat{J} = \hat{J}_{\bar{q}} + \hat{S}_Q \text{ vs. } \hat{S} = \hat{S}_Q + \hat{S}_{\bar{Q}}, \hat{J} = \hat{L} + \hat{S} \]
  - Lowest-order invariance with respect to the flavor of the heavy-quark (Heavy Quark Symmetry), as the reduced mass dominated by the light quark
  - Interesting spectroscopy on its own
  - Also impacts studies of possible ($Q\bar{Q}q\bar{q}$), ($Q\bar{Q}qqq$) states via ($Q\bar{q}$), ($\bar{Q}q$), ($Qqqq$) molecules or coupled-channels

- Charm mesons easier to access experimentally than beauty mesons:
  - Lower mass, higher production cross-sections. Reachable at lower beam energies.
  - $b$ to $c$ decays provide an ample source of clean samples of charm hadrons
Recent results on charm spectroscopy

- Amplitude analysis of $B^{-} \rightarrow D^{+}\pi^{-}\pi^{-}$ from LHCb
  - The latest out of 5 similar analyses of $B_{(s)} \rightarrow D\pi\pi$, $DK\pi$ published by LHCb in the last 3 years (Run I data: 3 fb$^{-1}$)
  - High signal statistics (28k), low background (1.5%)
  - Initial and final state particles have no spin resulting in relatively simple matrix element structure (Dalitz plot fit).
  - Isobar approximation (sum over Breit-Wigner $D^{+}\pi^{-}$ resonances), with angular distributions described with Zemach tensors.
  - Large S-wave (with NR and broad $D_{0}^{*}(2400)^{0}$ resonance) parametrized in quasi-model-independent way.

(see talk by Greig Cowan on amplitude fits in LHCb)
Status of D meson spectroscopy

S. Godfrey, K. Moats PR D93, 034035 (2016)

Relativized potential Quark Model (revamp of Godfrey-Isgur 1985).
(Includes predictions for decay widths.)

Hadron Spectrum Collaboration (LQCD $m_q=240$ MeV)
JHEP 1612, 089 (2016) (update of the 2012 results)
(No 4-quark operators included.)

(see talk by Christian Lang yesterday on Excited States on the Lattice)

- $1S, 1P$ and half of $1D$ states have been detected
- Detecting higher excitations is hard (broad, small production rates, many decay channels open)
- Not clear how many of heavier predicted states will ever be detected
- Like for other spectroscopies of short-lived states, theoretical predictions, either phenomenological models or lattice QCD (no couplings to decay channels are simulated above), are qualitative in nature
Status of $D_s$ meson spectroscopy

S. Godfrey, K. Moats PR D93, 034035 (2016)

- No experimental progress in the last 2 years
- Status similar to that of $D$ mesons
- Masses of $D_{s0}^*(2317)$ and one of $D_{s1}^*(2460)$ states are shifted relative the expectations to below the $D K, D^* K$ thresholds. Molecular components?

**Hybrids**

The effect of $D^* K, D K$ thresholds?

Molecular components in $D_{s0}(2460), D_{s0}^*(2317)$?

- Also no recent progress in spectroscopy of $B_{(s)}$ mesons
Heavy-light baryons: excitations of $\Omega_c^0$


• First public presentation of the LHCb study of $\Omega_c^0$ excitations (on arXiv tomorrow).

• Only two ground states ($n=1, L=0$) have been known so far: $\frac{1}{2}^+ \Omega_c^0$, $\frac{3}{2}^+ \Omega_c(2770)^0$

\[ \Omega_c^{**0} \rightarrow \Xi_c^+ K^- \] (Strong decay)

$\Xi_c^+ \rightarrow pK^-\pi^+$

(Cabibbo suppressed $c \rightarrow d$ weak decay)

LHCb 3.3 fb$^{-1}$

$\Xi_c^+$ signal

$\sim$1M events

bkg. $\sim$17%

Significance of each of the narrow resonances $> 10\sigma$
## Interpretation of $\Omega_c$ excitations observed by LHCb

The states newly observed by LHCb are likely $1P$ and $2S$.

None of the models predicted the mass splitting exactly.

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### Table: $M(\Omega_c)$ in [MeV]

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### Diagram

- $\Omega_c$ baryon
- $Q_{qq}$
- $\bar{L}_{qq} = 0$
- $S_{qq} = 0, 1$
- Scalar and axial-vector diquarks
- $\Omega_c(3188)$
- $\Omega_c(3119)$
- $\Omega_c(3090)$
- $\Omega_c(3066)$
- $\Omega_c(3050)$
- $\Omega_c(3000)$

- The states newly observed by LHCb are likely $1P$ and $2S$
- None of the models predicted the mass splitting exactly
• Recent LHCb amplitude analysis of $\Lambda_b^0 \rightarrow D^0 p \pi^-$

First observations

Known before, $J^P$ determined for the first time

\begin{align*}
M(\Lambda_c(2860)^+) &= 2856.1^{+2.0}_{-1.7} \pm 0.5 \text{(syst)}^{+1.1}_{-5.6} \text{(model)} \text{ MeV} \\
\Gamma(\Lambda_c(2860)^+) &= 67.6^{+10.1}_{-8.1} \pm 1.4 \text{(syst)}^{+5.9}_{-20} \text{(model)} \text{ MeV} \\
M(\Lambda_c(2940)^+) &= 2944.8^{+3.5}_{-2.5} \pm 0.4 \text{(syst)}^{+0.1}_{-4.6} \text{(model)} \text{ MeV} \\
\Gamma(\Lambda_c(2940)^+) &= 27.7^{+8.2}_{-6.0} \pm 0.9 \text{(syst)}^{+5.2}_{-10.4} \text{(model)} \text{ MeV} 
\end{align*}
Interpretation of $\Lambda_c$ and of $\Xi_c$ excitations

- Heavy-light charm baryons are excellent systems to study diquark models:
  - Heavy quark spin couplings are suppressed
  - A number of very narrow excitations, with well defined masses up to D-wave states

Molecular $pD^*$ component in $\Lambda_c(2940)$? 

Belle improved measurements of $\Xi_c$ masses (also the first observation of $\Xi_c(3055)^0$). PRD 94, 032002 and PRD 94, 052011 (2016)
**Beauty baryons**

- Recent measurement: precision determination of $\Xi_b^*0 - \Xi_b^-$ mass difference by LHCb ($\Xi_b^*0$ first observed by CMS in 2012):
  
  $$m(\Xi_b^{*0}) - m(\Xi_b^-) - m(\pi^+) = 15.727 \pm 0.068 \text{ (stat)} \pm 0.023 \text{ (syst) MeV/c}^2,$$
  
  $$\Gamma(\Xi_b^{*0}) = 0.90 \pm 0.16 \text{ (stat)} \pm 0.08 \text{ (syst) MeV}.$$ 

- Much fewer excitations known than for charm
- Similar situation for $\Lambda_b, \Sigma_b$
Masses of ground states simulated on lattice agree well with the experimental results.

Preliminary simulations of excited states have been shown at conferences, but not published.

No doubly-heavy baryons established yet. LHCb is approaching the required sensitivity. LHCb upgrade will give a large increase in data statistics.
Charmonium(-like) states

Many new interesting results on unusual states above the flavor threshold

Mass indistinguishable from $D^0\bar{D}^{*0}$
threshold:
$$\Delta M_{th} = M_{X(3872)} - M_{D^0\bar{D}^{*0}} = 0.0 \pm 0.2 \text{ MeV}$$
Is X(3872) a $D\bar{D}^*$ molecule?


  Calculations based on the model of deuteron (np molecule) with scalar and tensor potentials representing single pion exchange forces. $V(r) = -\frac{\pi}{3} \left[ V_D \cdot C(r) + S_D(\gamma) \cdot T(r) \right]$, $\alpha = \frac{\pi^2}{3} \frac{m_{p} m_{n}}{m_{np}^2}$, $T(r) = \alpha \frac{r_0}{r^2} \left( 1 + \frac{3}{4} \gamma^2 \right)$, $\mu^2 = m^2 + (M_D - M_{\pi})^2$

  Predicted the mass and $J^{PC}$ of constituents

  (S-wave interactions)

- Predicted a decade before the X(3872) discovery by Belle!

  The role of pion exchange force in binding such molecule is hotly disputed see e.g. V. Baru et al PR D91, 034002 (2015) but qualitative expectations are generic.

- Decays to charmonium suppressed via spatial separation of c and $\bar{c}$

- The observed X(3872) mass:
  - Consistent with the $D^0\bar{D}^{*0}$ threshold
  - 8MeV below the $D^*\bar{D}^*$ threshold

- As a consequence the molecular model predicts a large isospin violation in its decays:

  - Explains Isospin violation

- The molecular model also predicts a large rate to fall-apart modes

  - Predicted large fall apart rates

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<th>X(3872) WIDTH</th>
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<td>$\mu$ (MeV)</td>
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<th>X(3872) DECAY MODES</th>
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<td>$\Gamma$</td>
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<tr>
<td>$\Gamma_1 = e^+e^-$</td>
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<td>$\Gamma_2 = \pi^+\pi^- + J/\psi(1S)$</td>
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<td>$\Gamma_3 = \omega J/\psi(1S)$</td>
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<td>$\Gamma_4 = D^0\bar{D}^* + D^*\bar{D}$</td>
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<td>$\Gamma_5 = D^<em>\bar{D}^</em> + D\bar{D}^*$</td>
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- Explains narrow width


  Prediction specific to this molecule (large isospin violation in D meson masses)

- Mass of a molecule = mass of constituents + “nuclear binding” O(10$^{0.1}$) MeV + a few MeV for virtual states

- Tail of X(3872)
X(3872) is not a molecule?

- prompt production rate at LHC (and Tevatron) way too large for a loosely-bound molecular object
- at par with prompt production rates for ordinary charmonium states
- or expectations for tightly-bound tetraquark states
Radiative decays of X(3872) in LHCb

LHCb  NP B886 (2014) 665

BR(X(3872)→ψ(2S)γ)/BR(X(3872)→J/ψ(1S)) = 2.48±0.64±0.29 (>0 at 4.4σ)

• X(3872) is likely a mixture of a $\chi_{c1}(2^3P_{1++})$ charmonium state and of $\bar{D}D^*$ molecule


Interplay of quark and meson degrees of freedom in a near-threshold resonance: multi-channel case

Mixing more than one dynamics in one physical state is an important lesson from X(3872)!
**B_c and bottomonium spectroscopy**

- A lot of new results on $B_c^+$ decays
- Getting to excited states is proving difficult at LHC (bkg from primary pp interaction, soft $\gamma$ and $\pi\pi$). $B_c^+$ state still unconfirmed.

- Well understood non-relativistic spectroscopy
- No recent experimental progress, except for $e^+e^-$ scan above the open flavor threshold (see next 2 slides)
Proliferation of near-threshold states: 
$Z_b^{+,0}$ states in bottomonium

Masses a few MeV above the $BB^*$, $B^*B^*$ thresholds

Both $J^P(C) = 1^+(-)$

Charged and neutral versions detected $I^G = 1^+$

Large rate to fall-apart modes observed: Belle PRL116, 212001 (2016)

- Molecular states of $BB^*$, $B^*B^*$ (very weakly bound or slightly virtual) or their coupled-channel cusps [DY.Chen,X.Liu., PR D84, 094003 (2011), E. Swanson PD D91, 034009 (2015)]

Charged $Z_b^+$ states cannot mix with $bb$ states: “smoking gun” for 4-quark effects!
Anomalous $1^-$ states above open beauty threshold?

- Rates for $e^+e^- \rightarrow \Upsilon(5S) \rightarrow \pi\pi\Upsilon(nS)$ are 100 times larger than for $e^+e^- \rightarrow \Upsilon(2,3,4S) \rightarrow \pi\pi\Upsilon(nS)$
- Previously it was speculated that there is an exotic $1^-$ state ["$\Upsilon_b(10890)$"] underneath $\Upsilon(5S)$
- Recent scans by Belle: $\sigma(e^+e^- \rightarrow \pi\pi\Upsilon(nS))$ and $\sigma(e^+e^- \rightarrow \pi\pi\Upsilon_b(nP))$ follow $\sigma(e^+e^- \rightarrow \text{hadrons})$ i.e. are consistent with the $\Upsilon(5S)$ and $\Upsilon(6S)$. Thus, there is no evidence for unexpected states.
- Still the anomalously large decay rates to $\pi\pi\Upsilon(nS)$ and $\pi\pi\Upsilon_b(nP)$ (via $Z_b$ states) are not understood:
  - Admixture of tightly bound tetraquarks? Hybrids?
  - Rescattering of excited B meson pairs offers a “non-exotic” mechanism?

E. Eichten, QWG Workshop
https://indico.hep.pnnl.gov/event/0/session/11/contribution/40/material/slides/0.pdf

See also A.E.Bondar, M.B.Voloshin
PR D93, 094008 (2016)

More scan data (Belle II) with investigation of all possible decay modes will be useful to sort this out
More near-threshold states: many of $Z_c^{+,0}$ charmonium states

- Expected from $Z_b$ states and Heavy Quark Symmetry

Masses a few MeV above the $D\bar{D}^*$, $D^*\bar{D}^*$ thresholds

Large rate to fall-apart modes

$$\frac{\Gamma[Z_c(4025)\rightarrow D^*D^*]}{\Gamma[Z_c(4020)\rightarrow \pi h_c]} \sim 9.$$

$$\frac{\Gamma[Z_c(3900)\rightarrow DD^*]}{\Gamma[Z_c(3900)\rightarrow \pi J/\psi]} = 6.2 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys}}$$

Charged and neutral versions detected $I^G=1^+$

Molecular states of $D\bar{D}^*$, $D^*\bar{D}^*$ (very weakly bound or slightly virtual states, or cusps)

Recent results:
Anomalous $1^-$ states above open charm threshold

First observed by BaBar in 2005

- Y(4260) and Y(4360) do not align with $c\bar{c}$ states
- $\Gamma_{ee}$ widths suppressed by $10^2$-3
- $\Gamma_{\pi\pi}$ widths huge
- Is Y(4660) a $5^3S_1$ $c\bar{c}$ state, baryonium, hexaquark, two different states?

Y(4222)

Y(4260) → $\pi^+\pi^-
\Gamma = 44 \pm 5$ MeV

Y(4260) ?

Y(4360)

Y(4360) ?

Y(4660)

Y(4660)

Γ = 92^{+41}_{-32}$ MeV

Belle PRL 110, 252002 (2013)

BaBar PRD 86, 051102 (2012)

BESIII PRL 115, 112003 (2015)

Belle PRD 91, 112007 (2015)

BESIII PRL 101, 092001 (2017)

Belle PRL 101, 172001 (2008)

Belle PRD 115, 112003 (2015)
Interpretations of $Y(4260), Y(4360)$

- **Hybrid-charmonium:**
  - Masses not too far from the predicted $1^{--}$ hybrid by the lattice QCD:
    - Only one $1^{--}$ hybrid expected in this mass range
    - $\psi(4020), \psi(4160), \psi(4415)$ not well reproduced by lattice
  - $\Gamma_{ee}$ suppressed by a spin-flip needed to produce $c\bar{c}$ in $S=0$ configuration
  - $\pi\pi\psi$ can proceed via $DD^{**}$ rescattering
  - However, expected to decay to $DD^{(*)}\pi$, but not observed [CLEO-c PR D80, 072001(2009)]

- **$\bar{D}D(2420)$ molecule**  
  - The latest mass determination makes it unlikely: ~ -60 MeV binding? [Y(4360) +40 MeV]

- **Tetraquark (diaquarkonium)**
  - Tetraquark $\rightarrow$ tetraquark transitions: $Y(4260) \rightarrow Z_c(3900)\pi$, $Y(4260) \rightarrow X(3872)\gamma$ (possibly observed by BESIII).
  - Predicts many other states which have not been observed
Heavy Flavor Hadron Spectroscopy, PWA/ATHOS 2017, T. Skwarnicki

**$B^0 \to \psi' \pi^+ K^-$**

4D amplitude analysis of masses & decay angles

First observed by Belle
PRL 100, 142001 (2008) (see Kuzmin’s talk)

**$Z_c(4430)^+$** → $\psi' \pi^+$

LHCb PRL 112, 222002 (2014)

**Interpretations:**

- **$D^* (2600)$**
  - $^{13}S_1$
  - $\Gamma_D = 104 \pm 20$ MeV

- **$Z_c(4430)^+$**
  - $1^+$
  - $\Gamma = 181 \pm 31$ MeV
  - Good evidence for resonant character

**Kaon excitations**

- **$K^+(892)$**
  - $J=1$

- **$K^*_{2}(1430)^+$**
  - $J=2$

**Tetraquark or meson-meson molecule**

- **$B^0 \to \psi' \pi^+ K^-$**

**Radial excitation of the $^3S_1$ meson inside meson molecule**

- **$D^* (2600)$**
  - $2^3S_1$

**Radial excitation of tightly bound tetraquark**

- **$D^* (2600)$**
  - $= 104 \pm 20$ MeV
  - (no neutral partner has been observed yet)

(see talk by Anton Poluektov for more details)

L. Maiani et al, PRD 89, 114010 (2014)

L. Maiani et al PR D89, 114010 (2014)
$\mathbf{B^0 \to J/\psi \pi^+ K^-}$

**4D amplitude analysis**

$\mathbf{B^0 \to J/\psi \pi^+ K^-}$

**Argand diagram**

**Some evidence for resonant character**

While it has been suggested $Z_c(4200)^+$ is a tetraquark, no tetraquark model can accommodate it together with $Z_c(4430)^+$

C.Deng et al PR D92, 034027 (2015)

Abundance of $Z_c(3900)^+$ in this channel makes it questionable to pair it up with $Z_c(4430)^+$ (see the previous slide)

With such a large width less likely to be a resonance

$Z_c(4200)^+$ needs confirmation!

No molecular thresholds can explain $Z_c(4200)^+$

No $Z_c(3900)^+$ in this channel makes it questionable to pair it up with $Z_c(4430)^+$ (see the previous slide)
X(4140) was previously observed by CDF, CMS, D0. Hints of X(4274) in CDF data.

X(4140) first observed by CDF PRL 102, 242002 (2009)

6D amplitude analysis

Not enough data to test resonant amplitudes on Argand diagrams.

X(4140) equally well described as a resonance and a tail of $D_s^+D_{s^*}^-$ cusp.
Prompt production of $X \rightarrow J/\psi \phi$ states

Inclusive analysis at Tevatron

$pp \rightarrow (J/\psi \phi) + \ldots$

$J/\psi \rightarrow \mu^+\mu^-$

$\phi \rightarrow K^+K^-$

• There is a significant (4.7$\sigma$) shoulder near 4140 MeV in promptly produced $J/\psi \phi$ candidates, consistent with the $X(4140)$ observed in $B \rightarrow J/\psi \phi K$. This, and $X(3872)$, are the only exotic hadron candidates seen in the prompt production.

• Other $X \rightarrow J/\psi \phi$ states not produced promptly?

• Independent verification of these results is important for the interpretation of these states.
Heavy Flavor Hadron Spectroscopy, PWA/ATHOS 2017, T. Skwarnicki

\[ \Lambda_b^0 \rightarrow J/\psi pK^- \]

5D amplitude analysis

Pentaquark or baryon-meson molecule

\[ \Gamma = 39 \pm 20 \text{ MeV} \]
\[ P_c(4450)^+ \rightarrow J/\psi p \]
\[ P_c(4380)^+ \rightarrow J/\psi p \]
\[ \Gamma = 205 \pm 88 \text{ MeV} \]

No \( \frac{5}{2}^+ \) molecules in this mass range

No \( \pi \)-exchange

\[ \Lambda_b^0 \rightarrow J/\psi pK^- \]

Can accommodate \( \frac{5}{2}^+ \) when at least one diquark in \( S=I \) state

Maiani et al PLB749, 289 (2015) and many others

Such mass difference and the opposite parity can be explained by \( \Delta L=1 \)

JP “preferred” rather than definitely determined

\[ \Lambda_b^0 \rightarrow J/\psi pK^- \]

LHCb
Model independent analysis of $\Lambda_b^0 \rightarrow J/\psi p K^-$

A possible shortcomings of the amplitude analysis:

- Many more $\Lambda^*$ states predicted than included in the fit (see below).
- Non-relativistic formalism. Isobar approximation.
- Non-trivial non-resonant amplitudes/coupled-channels were not considered.

$\Lambda^*$ mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001)

Well-established $\Lambda^*$'s used in the LHCb amplitude analysis

No $\Lambda^*$'s expected here: exclude

No assumptions about resonant or non-resonant Kp contributions, except for excluding a possibility of high-spin contributions at low masses

PRL 117, 082002 (2016)

Maximally attributable to Kp contributions

LHCb data inconsistent at $9\sigma$ with Kp contributions alone

However this method cannot characterize exotic hadrons (their number, masses, widths, $J^P$).

Refining the amplitude analysis with more data will be very important for clarification of the nature of $P_c(4450)^+, P_c(4380)^+$ (see talk by Greig Cowan for more details).
$\Lambda_b^0 \to J/\psi p\pi^-$: Cabibbo suppressed

$\Lambda_b^0 \to J/\psi p\pi^-$ data are consistent with $\Lambda_b^0 \to J/\psi pK^-$ and the expectations from the Cabibbo suppression.

However, no independent confirmation of $P_c(4450)^+, P_c(4450)^+$ because of the limited statistics and the ambiguity between the $P_c(4450)^+, P_c(4450)^+ \to J/\psi p$ and $Z_c(4200)^- \to J/\psi\pi^-$ contributions.

Search for other decay modes of $P_c(4450)^+, P_c(4450)^+$, for other production mechanisms and other states inconclusive so far. LHCb upgrade will bring much higher data samples.

Nucleon excitations...
Summary of recent results

• New states detected for charm mesons. No spectroscopic surprises.
• Five narrow excitations of $\Omega_c^0$ has been just reported by LHCb. Also a new $\Lambda_c^+$ state reported by LHCb. Heavy-light-light baryons a great testing ground for diaquark models. Good experimental prospects with increasing LHC(b) data size and its upgrade program. Doubly-heavy baryons should be soon in reach.
• Spectroscopy of charmonium and bottomonium states below open flavor threshold well established. No recent progress. Spectroscopy of $B_c$ states at LHC hard experimentally.
• Significant developments concerning heavy quarkonium-like exotic hadron candidates, including discovery of pentaquark candidates with hidden charm and family of four tetraquark candidates with hidden charm and strangeness. Also new interesting results on anomalies for vector charmonium and bottomonium states above the open flavor threshold and better understanding of the threshold $D\bar{D}^*$, $D^*\bar{D}^*$, $B\bar{B}^*$, $B^*\bar{B}^*$ states.
• Personal take on status of the heavy exotic hadron spectroscopy on the next few slides.
Status of exotic heavy hadron spectroscopy

• Four- and five-quark structures with hidden charm and beauty have been established beyond any doubts

• The only clear “spectroscopy” which has emerged so far are molecular $J^P=1^+$ structures at every Pseudoscalar-Vector and Vector-Vector isospin-$\frac{1}{2}$ meson thresholds:
  
  – Binding, if any, is extremely weak.
  
  – Possibly just molecular coupled-channel effects
    
    • Future high statistics data (BES-III, Belle-II) will help distinguishing various types of molecular effects
    
    • Only $X(3872)$ is too narrow to be a cusp, but this state appears to exist thanks to mixing of the charmonium $2^3P_1$ state and $D^0\bar{D}^0, D^*D^*$ molecules. There is likely no corresponding $X_b$ state, since $3^3P_1$ states are narrow and ~50 MeV below the $B\bar{B}^*$ threshold!
  
  – $P_c(4450)^+$ might be the most exciting candidate for well bound baryon-meson molecule $(\Sigma_c^+\bar{D}^*0)$. However, alternative explanations exist (e.g. $p\chi_{c1}$ cusp, tightly bound pentaquark). Conclusively pinning down $J^P$ of this state is badly needed.
  
  – There is some evidence for molecular forces also affecting light-quark hadrons with masses close to meson(baryon)-meson thresholds:

$$0^{++} a_0(980), f_0(980) [K\bar{K}], 1^{++} f_1(1420) [K\bar{K}^*], \frac{1}{2}^- \Lambda(1405) [KN], 0^+ D_{s0}^*(2317) [D\bar{K}], 1^+ D_{s1}(2460) [D^*\bar{K}]$$
Status of exotic heavy hadron spectroscopy

- Abundance of structures which don’t fit molecular explanations offers hints that other dynamical effects must be at play

- **Hybrids:**
  - Anomalous behavior/states in $1^-\,$ sector of heavy quarkonia above the open flavor thresholds fall into the mass region expected for the lightest hybrid states
  - Many other hybrids expected in this mass range, including states with manifestly exotic quantum numbers ($1^{++}$).
  - Other explanations of the anomaly are also plausible.
  - High statistics scans of this region at $e^+e^-$ colliders (BES-III, Belle-II) should shed more light into these puzzles.
Status of exotic heavy hadron spectroscopy

• **Tightly bound tetra- and penta-quarks:**
  - Plausible explanation for the anomalies in $1^{--}$ sector
  - Some successes where other models failed:
    - Two nearby $1^{++}$ $X \rightarrow J/\psi \phi$ states.
    - $J=5/2$ $P_c$ state ($5/2$ needs to be confirmed though).
  - However, these models predict a very rich spectrum of states with no experimental evidence for them (so far):
    - I personally find attempts to claim many thresholds states as tetraquarks unconvincing – can’t explain without ad-hoc ansatz why only these masses and only these quantum numbers.
    - Copious prompt production expected but not observed.

• **Theoretical considerations:**
  - In plain diquark model, there is no effective mechanism to prevent rapid fall apart into the constituent quarks confined in smaller groups. Diquark sizes are comparable to diquark separations.
    - **Dynamical diquark formation model:** need to produce diquarks with relatively large relative momentum to facilitate at least temporary suppression of quark rearrangements S.Brodsky,D.Hwang,R.Lebed, PRL 113,112001 (2014).
    - Lots of knobs to turn (types of diquarks, radial and orbital momentum excitations, strengths of couplings) lead to poor predictive power. Postdictions are not too difficult, but predicted states don’t materialize. Diquark schemes change from paper-to-paper. Predictions by different authors vary widely.
  - Yet, QCD predicts attractive forces in color-triplet diquarks, which may play an observable role in ordinary baryons and other multiquark formations, even if not being the exclusive binding force.

For alternative view point on this subject see recent review by

*Multiquark Resonances*,
A. Esposito, A. Pilloni, A.D. Polosa arXiv:1611.07920
Status of exotic heavy hadron spectroscopy

- "Kinematical effects" (they are dynamic…) like coupled-channel cusps and triangular anomalies are often offered as alternative explanations of the observed mass peaks
  - The exact magnitude-and-phase running different than for resonances. High statistics amplitude analyses, with proper coupled-channel treatments should be able to distinguish them.
  - True bound states should manifest themselves in many different decay channels and in many different production mechanisms, with a pattern reflecting their internal structures.
  - More data, including coupled-channels in the fits, and collaboration with theorists when interpreting the data will all be important for firm interpretation of the observed effects.

Status of exotic heavy hadron spectroscopy

A lot of surprises in the data collected in the past decade. Hope for many more and the resolution of the present puzzles in the next decade thanks to BES-III ($e^+e^- \rightarrow c\bar{c}$), Belle-II ($e^+e^- \rightarrow b\bar{b}$, $\gamma c\bar{c}$, $e^+e^- \rightarrow c\bar{c}c\bar{c}$, $\gamma\gamma \rightarrow c\bar{c}$), LHCb upgrade ($pp \rightarrow c\bar{c}, b\bar{b}+\ldots$), PANDA ($pp \rightarrow cc$), JLAB ($\gamma N \rightarrow c\bar{c}$),…

"The story of pentaquarks shows how poorly we understand QCD" – F. Wilczek, 2005 2017
Light and heavy exotic hadrons. Experimental results and theoretical aspects.

Send E-mail to tskwarni@syr.edu if you are interested in contributing.
BACKUP SLIDES
Previously confusing experimental situation concerning $X \to J/\psi \phi$ states

- Some experiments saw narrow $X(4140)$ [i.e. $Y(4140)$], some didn’t.
- Possibly 2nd $J/\psi \phi$ structure in $B$ decays, $X(4274)$, but seen at inconsistent mass. No published claim of its significance.
- Possibly $X(4351)$ state seen in $\gamma \gamma$ collisions.
**B^-\rightarrow J/\psi \phi K^-**  LHCb vs CMS data

- Compare $m_{J/\psi \phi}$ to the CMS data (the previous best sample).
- Non-B background subtracted, corrected for signal efficiency.

![Graph showing data comparison](image)

- LHCb data more precise.
- Qualitative agreement over the full mass range.
Interpretation of J/ψΦ structures?

- P-wave charmonia?

\[
\begin{array}{l}
\chi_{cJ}(nP) \text{ states would couple to } J/\psi \Phi \\
\text{and } J/\psi \omega \text{ the same way.} \\
The J/ψΦ structures do not show up in } J/\psi \omega \text{ spectrum.}
\end{array}
\]

- Not a plausible explanation.
Data preference for opposite parity $P_c^+$ states

- This interference pattern only for states with opposite parity

Positive interference between the $P_c$ states

Negative interference between the $P_c$ states

Events/(20 MeV)

$1.55 < m_{Kp} < 1.70$ GeV

LHCb

Efficiency-corrected, background-subtracted, $\Lambda^*$ fit-component subtracted

from Nathan Jurik
Ph.D. thesis
Syracuse, Aug. 2016
CERN-THESIS-2016-086