Spectroscopy questions for HL/HE LHC

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Hadron spectroscopy and heavy flavors

November revolution of 1974

Quarks are real and mesons are simple $q\bar{q}$ systems!
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Belle 2003

e$^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$

very narrow

$X(3872)$

not all mesons are simple!
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$e^+e^- \rightarrow \psi(2S) \rightarrow B\bar{B}$

very narrow

$\Gamma_{X(3872)} < 1.2$ MeV

$X(3872)$

LHCb 2015

$pp \rightarrow \Lambda_b + \cdots$

$\Lambda_b \rightarrow (pJ/\psi)K$

$P_c(4450)^+$

$P_c(4380)^+$

not all mesons are simple!

neither are all baryons
New particle zoo: charmonium above flavor threshold

Old narrative (before 2003)

Mesons are \(q\bar{q}\) bound states.
New particle zoo: charmonium above flavor threshold

Old narrative (before 2003)

Mesons are $q\bar{q}$ bound states.

All excited light hadrons are above “the open flavor threshold”!

New narrative

Mesons are predominantly $q\bar{q}$ bound states below the open flavor threshold. They are more complex structures above it, and we have not yet understood them.

Figures from Olsen, Skwarnicki, Zieminska, Rev. Mod. Phys. 90, 015003 (2018); arXiv:1708.04012
Hadron spectroscopy at HL/HE LHC?

• Enormous opportunities:
  – Heavy quark production rates orders of magnitude higher than at BESIII ($e^+e^- \rightarrow c\bar{c} + \cdots$) and BelleII ($e^+e^- \rightarrow c\bar{c} + \cdots, b\bar{b} + \cdots$).
  – Exclusive access to $b$-baryons, $B_c$ mesons ($bc$), double-beauty hadrons.

• Come with challenging experimental environment – detector properties become crucially important:
  – Ability to trigger on relevant final states
  – Ability to reduce combinatorial backgrounds ($\pi/K/p$ identification helps a lot)
  – LHCb offers unique capabilities, but CMS and ATLAS can still play important role for simpler final states thanks to higher luminosity
  – Final states with neutrals are hard ($\pi^0, \eta, \gamma$) and will get harder with higher luminosity:
    • New type of EM calorimeter (timing) would be essential for efficient detection. Under consideration in LHCb.
    • Final states with single $\gamma$ can be detected with low efficiency via $\gamma N \rightarrow e^+e^-N$ or via “Dalitz” version of the decay. The latter has superior resolution when instead of $\gamma$ the decay emits $\mu^+\mu^-$. Very promising method for HL samples.
About this talk

• Too many spectroscopy questions for HL/HE LHC to address all in a short talk.
• I will talk about a few selected topics for illustrative purpose.
• No consensus on interpretation of various experimentally observed exotic hadron candidates – be aware of personal biases in any presentation on this topic.
• This talk is not a good sources of references to experimental and theoretical papers – see many recent extensive review articles:


Need to go beyond bump hunting

• Need to explore many different decay modes and different production mechanisms of known exotic hadron candidates to reveal their nature
• The best example – X(3872).
**X(3872): molecular features**

Enhanced isospin violating decays
\[ X(3872) \rightarrow \rho^0 J/\psi \]

Mass near threshold \( D^0 \bar{D}^* \)

Known decay rates:

Huge fall-apart mode from the resonance tail above the \( D^0 \bar{D}^* \) threshold

Only small admixture of \( D^+ \)

Narrow width in decays to \( c\bar{c} \)

\( 0^{-+} \) interacting in S-wave compatible with \( J^{PC}=1^{++} \)
Prompt production of \(X(3872)\)

\[ p\bar{p} \rightarrow X(3872) + \ldots \quad \text{@Tevatron} \]

\[ pp \rightarrow X(3872) + \ldots \quad \text{@LHC} \]

Dispute if large prompt production cross-section is compatible with molecular interpretation:


- and


\(X(3872)/\psi(2S)\) production ratio nearly universal:

- in \(B\) decay modes
- prompt production in \(p\bar{p}\) and \(pp\) including dependence on transverse momentum and rapidity

My own opinion:

- Strong evidence for compact component at short distances (\(c\bar{c}\) or tetraquark?)
- Not necessarily incompatible with \(D\bar{D}^*\) component at large distances
Radiative decays of $X(3872)$

$\text{BR}(X(3872) \rightarrow \psi(2S)\gamma) \quad \text{favored}$

$\text{BR}(X(3872) \rightarrow J/\psi(1S)\gamma) \quad \text{suppressed}$

$= 2.48 \pm 0.64 \pm 0.29 \quad (>0 \text{ at } 4.4\sigma)$

by a factor of $\sim 100!$

Hard to find other mechanism to favor $\psi(2S)\gamma$ over $J/\psi(1S)\gamma$
other than $2P \rightarrow 2S$

$\psi(r)$

$n=1$

$n=2$

Radial wave functions

$|<\psi| r |\psi>|^2 \quad E_\gamma^3$

My own opinion:

- Points to $c\bar{c}(2^3P_{1+})$ component of $X(3872)$
- Does not rule out $D\bar{D}^*$ component at large distances

(F.-K. Guo et al., PL B742, 394 (2015); arXiv:1410.6712)
Can a large molecule mix with a compact charmonium?

$X(3872)$-$\chi'_{c_1}$ mixture $\leftrightarrow$ pretty bizarre

The dispute over the nature of $X(3872)$ continues. More experimental information is highly desired.
Experimental prospects for $X(3872)$

Mass and natural width of $X(3872)$

LHCb

Need to improve statistical errors on radiative decays of $X(3872)$

LHCb, Belle-II

Verify $\gamma X(3872)$

BES-III

$e^+e^- \rightarrow Y(4260) \rightarrow \gamma X(3872)$

Look for:

$X(3872) \rightarrow \pi^+\pi^-, \pi^0\pi^0\chi_{c1}(1P)$

since

$BR(\chi_{b1}(2P) \rightarrow \pi^+\pi^-, \pi^0\pi^0\chi_{c1}(1P))$

$= (0.9 \pm 0.1)\%$

Belle-II, LHCb

More production mechanisms, decay modes? + CMS, ATLAS, ALICE? …

Need to improve statistical errors on $X(3872) \rightarrow \omega J/\psi$

(clarify 2nd peak: $X(3915)$)

LHCb, Belle-II

Study line shape in $D\bar{D}^*$; coupled-channel line-shape fit

LHCb, Belle-II
Charged quarkonium-like near-threshold states

No confusion with quarkonia states (charge!).

Near thresholds. Relatively narrow. Large fall-apart rates. Observable rates to quarkonia.

Molecular states? Tetraquarks interacting with meson-meson thresholds?
Anomalous charmonium-like vector states

- \( Y(4220) \) and \( Y(4320/4360) \) do not align with \( c\bar{c} \) states
- \( \Gamma_{ee} \) widths suppressed by \( 10^{2-3} \)
- \( \Gamma_{\pi\pi\psi} \) widths huge

- **Hybrid-charmonium?**

- **\( D\bar{D}_1(2420) \) molecule?**
  - Q.Wang, C.Hanhart, Q.Zhao, PRL 111 (2013) 132003

- **Tetraquark (diaquarkonium)?**
    - Tetraquark→tetraquark transitions:
      - \( Y(4260)\rightarrow Z_c(3900)\pi, \ Y(4260)\rightarrow X(3872)\gamma \) (possibly observed by BESIII)

Can any of these states be produced at LHC (promptly or in B decays)?
New particle zoo: bottomonium above flavor threshold

Difficult to explore experimentally:
- Not accessible at B-factories
- Prompt production at LHC is the only hope

Figure from Olsen, Skwarnicki, Zieminska
Rev. Mod. Phys. 90, 015003 (2018); arXiv:1708.04012

γN → e⁺e⁻N

γ detected in calorimeter

Figure from Olsen, Skwarnicki, Zieminska
Rev. Mod. Phys. 90, 015003 (2018); arXiv:1708.04012
Charged charmonium-like states in B decays

(Bdominated by $\overline{K}^0 \rightarrow \pi^+ K^-$ resonances)

$Z_c(4200)^+$, $Z_c(4050)^+$, $Z_c(4250)^+$ await confirmation

$Z_c(3900)^+$ and $Z_c(4020)^+$ observed in $e^+ e^- \rightarrow \pi^+ Z_c^-$, not observed in $B \rightarrow K Z_c^+$, (and vice versa).

Sensitivity to production mechanism, points to hadron-level interactions.

No clear explanations.

- Too broad to be molecular bound states?
- No tetraquark model can accommodate all of them.
- Rescattering effects?
- Artifacts of complicated amplitude analyses?

Very high statistics amplitude analyses at HL/HE LHC can study these structures in great detail (e.g. exact phase running).
X(4140) was previously observed by CDF, CMS, D0. Hints of X(4274) in CDF data.

Prospects at HL/HE LHC:
- better amplitude analysis with very high statistics
- analysis of related $B \to J/\psi \phi K^-$
- prompt production of any of these states? (D0 has claimed prompt production of X(4140) at Tevatron)

Postdiction by L. Maiani, A.D. Polosa, V. Riquer
PRD94, 054026 (2016)
Possibly radially excited 0++ tetraquarks. However, only one 1++ state with color triplet diquarks.

Predicted two 1++ tetraquarks in this mass range (S=0,1 diquarks in color triplet and sextet)
Interpretations of $P_c(4450)^+,P_c(4380)^+$?

**Molecules**

$\Sigma_c^+$

$D^*$

$D_c^*$

$P_c(4450)^+$ is too broad to be a molecule

$P_c(4380)^+$

No $\frac{5}{2}^\pm$ molecules in this mass range

Karliner, Rosner PRL115, 122001 (2015) and others

$J^P$ “preferred” rather than definitely determined

Tightly-bound penatquark

Can accommodate $\frac{5}{2}^\pm$ when at least one diquark in $S=1$ state

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

Realistic rescattering mechanisms (cusps, triangle anomalies) have the same $J^P$ selection rules as realistic molecular models (must happen in S-wave)

Prospects at HL/HE LHC:

- better amplitude analysis with very high statistics of ~3M $\Lambda_b \to (p J/\psi)K$ events (firm determination of quantum numbers)
- Investigation of related channels (e.g. 200k events in $\Lambda_b \to (p J/\psi)\pi$)
Heavy-light-light baryons

QCD provides strong motivation for diquarks:

- forces in color anti-triplet $qq$ combinations are attractive
- $qq$ ( $\bar{q}\bar{q}$ ) can substitute $\bar{q}$ ($q$), which are also color anti-triplet ($\text{triplet}$), in well established hadronic structures
- $q\bar{q} \Rightarrow q(qq)$ baryon with diquark substructure
- $q\bar{q} \Rightarrow (\bar{q}\bar{q})(qq)$ tetraquark
- $\bar{q} q \bar{q} q \Rightarrow (qq) (qq) \bar{q}$ pentaquark

- $Qqq$ baryons are a perfect place to study diquark structures as the heavy quark spin decouples from light quark spins

- QCD motivated diquarks need to be in the ground state, $n_{qq}=1$, $L_{qq}=0$, which eliminates a large number of possible excitations:
  - States can be labeled with $n,L$ of the diquark orbiting around the heavy quark, which will be a dominant effect in mass
  - The main mass level hierarchy like among mesons!

In usual diaquark model:

$n_{qq}=1$ \hspace{0.5cm} $L_{qq}=0$

Scalar and axial-vector diquarks

$S_{qq}=0,1$
Why the $\Omega_c^{**0}$ states observed by LHCb are narrow?

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

LHCb PRL 118, 182001 (2017).

$\Omega_c^{**0}$ states observed by LHCb are likely $1P$ and $2S$ of $c$-(ss diquark)

Significance of each of the narrow resonances $> 10\sigma$
Doubly heavy systems

The lightest 1^+ state

Stable tetraquark, will decay weakly

New holy grail of heavy quark spectroscopy

<table>
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<tr>
<th>State</th>
<th>Quark content</th>
<th>M(J = 1/2)</th>
<th>M(J = 3/2)</th>
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<tr>
<td>Ξ^{(*)}_cc</td>
<td>ccq</td>
<td>3627 ± 12</td>
<td>3690 ± 12</td>
</tr>
<tr>
<td>Ξ^{(*)}_{bc}</td>
<td>b[cq]</td>
<td>6914 ± 13</td>
<td>6969 ± 14</td>
</tr>
<tr>
<td>Ξ^{(*)}_{bc}</td>
<td>b(cq)</td>
<td>6933 ± 12</td>
<td>...</td>
</tr>
<tr>
<td>Ξ^{(*)}_{bb}</td>
<td>bbq</td>
<td>10162 ± 12</td>
<td>10184 ± 12</td>
</tr>
</tbody>
</table>

LHCb: 3621 ± 1

Consistent results predicted by LQCD: Francis, Hudspith, Lewis, Maltman PRL 1118,142001 (2017)

Karliner, Rosner PRL 119, 202001 (2017)
Eighten, Quigg PRL 119, 202002 (2017)
See also: Esposito, Papinutto, Pilloni, Polosa, Tantalo PRD88, 054029 (2013)
Observation of double Y production at LHC

- First observation of $b\bar{b} + b\bar{b}$ production at LHC. An example, where high luminosity of CMS, and central region coverage, won over lower muon momentum thresholds in forward region at LHCb.

- $bb$ not in the same hadron yet.

- Can look for $(bb)(\bar{b}\bar{b})$ tetraquark in decays to $Y(1S)Y(1S)$ – some predicted it to be narrow.

- In stable teraquark need to look for $b \rightarrow cW$ decay. Look out for observations of $bbq$ baryons at upgraded LHCb, as signs of reaching sensitivity to detect $(bb)(ud)$
Summary

• New particle zoo for heavy quarkonia families above flavor threshold signals the crisis of the “textbook” quark model \((q\bar{q}, qqq)\).

• Little is agreed on interpretation of the observed exotic hadron candidates

• Enormous production rates of heavy quarks at HL/HE LHC hold a promise of on enormous impact on hadron spectroscopy

• Detector capabilities are a limiting factor.

• Detailed studies of various existing exotic hadron candidates in different decay modes and production mechanisms needed to clarify their nature. Negative searches need to be published more often.

• Studies of conventional baryons with heavy quarks at LHC very important for clarifying the role of diquarks

• Stable \((bb)(\overline{ud})\) tetraquark predicted by both LQCD and phenomenological models. Unique experimental opportunity at HL/HE LHC.

• Many other very interesting spectroscopies I have not had time to talk about (excited D,B,Ds,Bs,Bc,…, light hadrons) can also be explored at HL/HE LHC.

• Judging from the past, future surprises are likely. It is crucially important to preserve data mining capabilities, which may be increasingly difficult in HL/HE era - planning becomes more important.

• Big €¥$ spent on hadron spectroscopy programs at other facilities. Potential of HL/HE LHC in hadron spectroscopy must be fully exploited.