Pentaquarks and Tetraquarks at LHCb

Sheldon Stone on behalf of LHCb

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Why pentaquarks?

- Interest in pentaquarks arises from the fact that they would be new states of matter beyond the simple quark-model picture. Could teach us a lot about QCD.

- There is no reason they should not exist
  - Predicted by Gell-Mann (64), Zweig (64), others later in context of specific QCD models: Jaffe (76), Högaasen & Sorba (78), Strottman (79)

- These would be short-lived $\sim 10^{-23}$ s “resonances” whose presence is detected by mass peaks & angular distributions showing the presence of unique $J^P$ quantum numbers
Prejudices

- No convincing states 51 years after Gell-mann & Zweig proposed $qqq$ and $qqqq\bar{q}$ baryonic states

- Previous “observations” of several pentaquark states have been refuted

- These included
  - $\Theta^+ \rightarrow K^0 p$, $K^+ n$, mass=1.54 GeV, $\Gamma \sim 10$ MeV
  - Resonance in $D^*-p$ at 3.10 GeV, $\Gamma = 12$ MeV
  - $\Xi^- \rightarrow \Xi^- \pi^-$, mass=1.862 GeV, $\Gamma < 18$ MeV

- Generally they were found/debunked by looking for “bumps” in mass spectra circa 2004 [see Hicks Eur. Phys. J. H37 (2012) 1.]

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First looked for in LHCb as a potential background for $B^0 \rightarrow J/\psi K^+ K^-$

Large signal found, used for $\Lambda_b$ lifetime

Dalitz plot showed an unusual feature

[arXiv:1507.03414]

26,000 signal + 5.4% bkgrnd within $\pm 2\sigma$ of peak

$\Lambda_b \rightarrow J/\psi K^- p$
Does this diagram exist?

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Decay amplitude analysis

- Are there “artifacts” that can produce a peak?
  - Many checks done that shows this is not the case: e.g. changing p to K, or π to K allows us to veto misidentified $B_s \rightarrow J/\psi K^- K^+$ & $B^0 \rightarrow J/\psi K^- \pi^+$
  - Clones & ghost tracks eliminated
  - $\Xi_b$ decays checked as a source

- Can interferences between $\Lambda^*$ resonances generate a peak in the $J/\psi p$ mass spectra?
  - Implemented a decay amplitude analysis that incorporates both decay sequences:
Matrix Element

- Two interfering channels:
  \[ \Lambda_b \rightarrow J/\psi \Lambda^*, \]
  \[ \Lambda^* \rightarrow K^- p \]
  &
  \[ \Lambda_b \rightarrow P_c^+ K^-, \]
  \[ P_c^+ \rightarrow J/\psi p \]

- Use \( m(K^- p) \) & 5 decay \( \angle \)'s as fit parameters

- Mass shapes: Breit-Wigner or Flatte

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Models: extended & reduced

- Consider all $\Lambda^*$ states & all allowed L values

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th># Reduced</th>
<th># Extended</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda(1405)$</td>
<td>1/2$^-$</td>
<td>1405.1$^{+1.3}_{-1.0}$</td>
<td>50.5 ± 2.0</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>3/2$^-$</td>
<td>1519.5 ± 1.0</td>
<td>15.6 ± 1.0</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1600)$</td>
<td>1/2$^+$</td>
<td>1600</td>
<td>150</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1670)$</td>
<td>1/2$^-$</td>
<td>1670</td>
<td>35</td>
<td>3</td>
<td>4</td>
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<tr>
<td>$\Lambda(1690)$</td>
<td>3/2$^-$</td>
<td>1690</td>
<td>60</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1800)$</td>
<td>1/2$^-$</td>
<td>1800</td>
<td>300</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1810)$</td>
<td>1/2$^+$</td>
<td>1810</td>
<td>150</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1820)$</td>
<td>5/2$^+$</td>
<td>1820</td>
<td>80</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1830)$</td>
<td>5/2$^-$</td>
<td>1830</td>
<td>95</td>
<td>1</td>
<td>6</td>
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<tr>
<td>$\Lambda(1890)$</td>
<td>3/2$^+$</td>
<td>1890</td>
<td>100</td>
<td>3</td>
<td>6</td>
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<tr>
<td>$\Lambda(2100)$</td>
<td>7/2$^-$</td>
<td>2100</td>
<td>200</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2110)$</td>
<td>5/2$^+$</td>
<td>2110</td>
<td>200</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2350)$</td>
<td>9/2$^+$</td>
<td>2350</td>
<td>150</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(2585)$</td>
<td>?</td>
<td>$\approx 2585$</td>
<td>200</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>

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# parameters 64 146
Results without $P_c$ states

- Use extended model, so all possible known $\Lambda^*$ amplitudes. $m_{Kp}$ looks fine, but not $m_{J/\psi p}$
- Additions of non-resonant, extra $\Lambda^*$'s doesn't help
Extended model with $1 \ P_c$

- Try all $J^P$ up to $7/2^\pm$
- Best fit has $J^P = 5/2^\pm$. Still not a good fit
Reduced model with 2 $P_c$'s

- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred.
Angular distributions

Good fits in the angular variables
In $m(K^-p)$ slices

$P_c$'s cannot appear in first interval as they would be outside of the Dalitz plot boundary.

- **data**
- **total fit**
- **background**

$P_c(4450)$
$P_c(4380)$

- **$\Lambda(1405)$**
- **$\Lambda(1520)$**
- **$\Lambda(1600)$**

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<table>
<thead>
<tr>
<th>$M(K^p)$ range</th>
<th>Events/(20 MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;1.55$ GeV</td>
<td></td>
</tr>
<tr>
<td>$1.55&lt; M(K^p) &lt;1.70$ GeV</td>
<td></td>
</tr>
<tr>
<td>$1.70&lt; M(K^p) &lt;2.00$ GeV</td>
<td></td>
</tr>
<tr>
<td>$2.00$ GeV $&lt; M(K^p)$</td>
<td></td>
</tr>
</tbody>
</table>
Significances

- Fit improves greatly, for 1 $P_c$ $\Delta(-2\ln L)=14.7^2$, adding the 2nd $P_c$ improves by $11.6^2$, for adding both together $\Delta(-2\ln L)=18.7^2$

- Using toy simulations 1st state has significance of $9\sigma$ & 2nd state $12\sigma$, including systematic uncertainties, coming from difference between extended & reduced model results.
### Fit results

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Fit fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4380±8±29</td>
<td>205±18±86</td>
<td>8.4±0.7±4.2</td>
</tr>
<tr>
<td>4449.8±1.7±2.5</td>
<td>39±5±19</td>
<td>4.1±0.5±1.1</td>
</tr>
<tr>
<td>(\Lambda(1405))</td>
<td></td>
<td>15±1±6</td>
</tr>
<tr>
<td>(\Lambda(1520))</td>
<td></td>
<td>19±1±4</td>
</tr>
</tbody>
</table>

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## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th>Fit fractions (%)</th>
<th>$\Lambda(1405)$</th>
<th>$\Lambda(1520)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low</td>
<td>high</td>
<td></td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Extended vs. reduced</td>
<td>21</td>
<td>0.2</td>
<td>54</td>
<td>10</td>
<td>3.14</td>
</tr>
<tr>
<td>$\Lambda^*$ masses &amp; widths</td>
<td>7</td>
<td>0.7</td>
<td>20</td>
<td>4</td>
<td>0.58</td>
</tr>
<tr>
<td>Proton ID</td>
<td>2</td>
<td>0.3</td>
<td>1</td>
<td>2</td>
<td>0.27</td>
</tr>
<tr>
<td>$10 &lt; p_p &lt; 100$ GeV</td>
<td>0</td>
<td>1.2</td>
<td>1</td>
<td>1</td>
<td>0.09</td>
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<tr>
<td>Nonresonant</td>
<td>3</td>
<td>0.3</td>
<td>34</td>
<td>2</td>
<td>2.35</td>
</tr>
<tr>
<td>Separate sidebands</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0.24</td>
</tr>
<tr>
<td>$J^P$ $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$</td>
<td>10</td>
<td>1.2</td>
<td>34</td>
<td>10</td>
<td>0.76</td>
</tr>
<tr>
<td>$d = 1.5 - 4.5$ GeV$^{-1}$</td>
<td>9</td>
<td>0.6</td>
<td>19</td>
<td>3</td>
<td>0.29</td>
</tr>
<tr>
<td>$L_{P_0}^{P_c}$ $\Lambda_b^0 \rightarrow P_c^+$ (low/high) $K^-$</td>
<td>6</td>
<td>0.7</td>
<td>4</td>
<td>8</td>
<td>0.37</td>
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<tr>
<td>$L_{P_c}^P$ $P_c^+$ (low/high) $\rightarrow J/\psi p$</td>
<td>4</td>
<td>0.4</td>
<td>31</td>
<td>7</td>
<td>0.63</td>
</tr>
<tr>
<td>$L_{P_0}^{A_0^<em>}$ $\Lambda_b^0 \rightarrow J/\psi \Lambda^</em>$</td>
<td>11</td>
<td>0.3</td>
<td>20</td>
<td>2</td>
<td>0.81</td>
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<tr>
<td>Efficiencies</td>
<td>1</td>
<td>0.4</td>
<td>4</td>
<td>0</td>
<td>0.13</td>
</tr>
<tr>
<td>Change $\Lambda(1405)$ coupling</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.05</td>
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<tr>
<td>Overall</td>
<td>29</td>
<td>2.5</td>
<td>86</td>
<td>19</td>
<td>4.21</td>
</tr>
<tr>
<td>sFit/cFit cross check</td>
<td>5</td>
<td>1.0</td>
<td>11</td>
<td>3</td>
<td>0.46</td>
</tr>
</tbody>
</table>

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Cross-checks

- Many done, some listed here:
- Signal found using different selections by others
- Two independently coded fitters using different background subtractions (sFit & cFit)
- Split data shows consistency: 2011/2012, magnet up/down, $\bar{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$
- Extended model fits tried without $P_c$ states, but two additional high mass $\Lambda^*$ resonances allowing masses & widths to vary, or 4 non-resonant terms of $J$ up to 3/2
Argand diagrams

Amplitudes for 6 bins between $+\Gamma$ & $-\Gamma$

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Data demands 2 states

- Interference between opposite parity states needed to explain $P_c$ decay angle distribution
- Fit projections

![Graph showing corrected events vs. $\cos(\theta_{P_c})$ with data projections for $P_c(4450)$ and $P_c(4380)$]

- Large $m(K_p)$ region: negative interference
- Small $m(K_p)$ region: positive interference

LHCb

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Pentaquark models

- All models must explain $J^P$ of two states not just one. They also should predict properties of other states: masses, widths, $J^P$. Many models: Let's start with tightly bound quarks ala’ Jaffe

- Two colored diquarks plus the anti-quark, L. Maiani, et. al, [arXiv:1507.04980], ibid [PRD20(1979) 748]

- Colored diquark + colored triquark, R. Lebed [arXiv:1507.05867]

- Bag model, Jaffe; Strings, Rossi & Veneziano [Nucl. Phys. B123 (1977) 507]
Molecular models

- Molecular models, generally with meson exchange for binding
- ala’ Törnqvist [Z. Phys. C61 (1994) 525]
- $\pi$ exchange models usually predict only one state, mainly $J^P=1/2^+$, but could also include $\rho$ exchange…
- Several authors consider $\Sigma_c D(*)$ components (most of these are postdictions)

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Rescattering

- These are all postdictions
- They construct non-BW amplitude that must mimic mass shape & phase variation of a BW
- eg. $\Lambda_b \rightarrow XY(Z) \rightarrow J/\psi pK^-$, especially when $m(XY) = m(P_c)$, hence the word “cusp”
- These models have so far not predicted the size of the rescattering amplitude
- Also difficult to predict two states…

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Some History: The $a_1$

- Is it possible for other processes to mimic resonant effects?
- Example: The Deck effect, a lesson in confusion: $\pi^+ p \rightarrow \pi^+ \rho^0 p$, $\rho^0 \rightarrow \pi^+ \pi^-$, using a 3.65 GeV $\pi^+$ beam, G. Goldhaber et. al, PRL 12, 336 (1964)

Note: BeV $\equiv$ GeV
“Kinematical” effect

- Clear enhancement near threshold. Is it a new resonance as suggested in original paper?
- Theorists, first Deck, suggest that the threshold enhancement can be due to off shell $\pi p$ scattering. 

*R.T. Deck, PRL 13, 169 (1964)*
Deck Effect

- Deck’s fit to data can provide adequate explanation
- $a_1$ then seen in different charge states & different channels, e.g. $K^+ p \rightarrow K^+ \pi^+ \pi^- \pi^0 p$
- Many more sophisticated theory papers
- Controversy continued until observation of $a_1$ in $\tau^- \rightarrow \pi^+ \pi^- \pi^- \nu$ decays, ~1977
- Surmises: a full amplitude analysis may have proved the resonant nature of the $a_1$ earlier. Important to see resonant states in several ways. There never was an unambiguous demonstration of the Deck effect.

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Z(4430)$^+$ tetraquark

- $B^0 \rightarrow \psi' \pi^- K^+$, peak in $m(\psi' \pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$
  - First observed by Belle $M = 4433 \pm 5$ MeV, $\Gamma = 45$ MeV
  - Challenged by BaBar: explanation in terms of $K^*$’s
  - Belle reanalysis using full amplitude fit: $M = 4485 \pm 22^{+28}_{-11}$ MeV, $\Gamma = 200$ MeV, $1^+$ preferred but $0^-$ & $1^-$ not excluded [arXiv:1306.4894]

- LHCb analysis also uses full amplitude fit
  - $M = 4475 \pm 7^{+15}_{-25}$ MeV
  - $\Gamma = 172$ MeV [arXiv:1404.1903]

see also, LHCb-PAPER-2015-038 in preparation

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Full 4D fit to both $K^* \rightarrow K^-\pi^+$ & $Z \rightarrow \psi'\pi^-$ states

$J^P = 1^+$

Unambiguously
Is it a resonance?

- LHCb produced an Argand plot that shows a clear & large phase change.
- There are also attempts at rescattering explanations.
Conclusions

- LHCb has found two resonances decaying into $J/\psi p$ with pentaquark content of $uudc\bar{c}$ arXiv:1507.03414.

- Determination of their internal binding mechanism will require more study. The preferred $J^P$ are $(3/2^-,5/2^+)$, $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$

- Other exotic states have appeared containing $c\bar{c}$ quarks: the $Z^+(4430) \rightarrow \psi'K^-\pi^+$ appears to be a tetraquark with $J^P=1^+$. Is binding stronger for $c\bar{c}$?

- Lattice QCD calculations providing masses would be most welcome

- We look forward to establishing the structure of many other states

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See parallel session talk of Nathan Jurik for more details

The End

US LHCb groups gratefully acknowledge support from the NSF

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Our fit explains $m(J/\psi K^-)$
Extended model with 2 $P_c$'s

(a) LHCb

(b) LHCb

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Other Explanations

- **Molecule:**
  L. Ma et al., [arXiv:1404.3450]
  T. Barnes et al., [arXiv:1409.6651]

- **Same scattering phase as Breit-Wigner**

- **Rescattering:**
  P. Pakhov & T. Uglov
  [arXiv:1408:5295]

- **Opposite phase**

- **Ruled out by LHCb Argand diagram**