Hidden charm pentaquarks in $\Lambda_b \rightarrow J/\Psi\ K^-\ p$

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- Inclusion of more $\Lambda$'s and poor evidence for $P_c(4380)^+$

HADRON 2017, Salamanca, September 28, 2017
The LHCb pentaquarks, $P_c(4450)^+$, $P_c(4380)^+$

The reaction $\Lambda_b \to J/\psi K^- p$ was used to report the existence of two pentaquarks by the LHCb collaboration at CERN.


First claimed hidden-charm baryon

Best fit provides $(J^P(4380), J^P(4450)) = (3/2^+, 5/2^+)$, but also possible $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$.
$P_c(4380)^+$ more controversial:

- No "apparent bump" in the experimental spectra
- Strange Argand plot behaviour
- Breit-Wigner expectation
Only “exotic baryons” quoted in the PDG:

**P_c(4380)^+**

A resonance seen in $\Lambda_b^0 \rightarrow P_c^+ K^-$, then $P_c \rightarrow J/\psi p$, with a significance of 9 standard deviations. The $J/\psi p$ quark content is $uudc\bar{c}$, a pentaquark. See also the $P_c(4450)^+$. In the best amplitude fit, the two states have opposite parity, one having $J = 3/2$, the other $J = 5/2$.

Extraction of the pentaquark signals requires some understanding of the dominant $K^- p$ background. AAIJ 15P used a model-dependent approach. AAIJ 16AG reanalyzed the data making minimal assumptions about the $K^- p$ background, and thus confirmed the strong significance of the pentaquark signals.

**P_c(4450)^+**

A resonance seen in $\Lambda_b^0 \rightarrow P_c^+ K^-$, then $P_c \rightarrow J/\psi p$, with a significance of 12 standard deviations. The $J/\psi p$ quark content is $uudc\bar{c}$, a pentaquark. See also the $P_c(4380)^+$. In the best amplitude fit, the two states have opposite parity, one having $J = 3/2$, the other $J = 5/2$.

Extraction of the pentaquark signals requires some understanding of the dominant $K^- p$ background. AAIJ 15P used a model-dependent approach. AAIJ 16AG reanalyzed the data making minimal assumptions about the $K^- p$ background, and thus confirmed the strong significance of the pentaquark signals.
The $\Lambda(1405)$ in $\Lambda_b \rightarrow J/\psi \; \Lambda(1405)$

Large concentration of strength around threshold $\Lambda(1405)$ relevant
The $\Lambda(1405)$ in $\Lambda_b \rightarrow J/\psi \, \Lambda(1405)$


$\Lambda_b \rightarrow J/\psi \, \pi \Sigma$  $\Lambda_b \rightarrow J/\psi \, \bar{K} \, N$

Meson-baryon amplitudes in coupled channels from chiral unitary approach

$T = [1 - V^G]^{-1} V$

Oset, Ramos'98; Oller, Meissner'01; Jido et al'03, Hyodo et al'03, Garcia-Recio et al.'03, ...
**Two poles in the complex plane**

![Complex plane diagram](image)

- $\Lambda(1405) + 1426 + 16i$
- $1390 + 66i$

**Amplitudes in the real axis:**

![Amplitude graph](image)

**Couplings to different channels:**

<table>
<thead>
<tr>
<th>$z_R$</th>
<th>$1390 + 66i$</th>
<th>$1426 + 16i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(I = 0)$</td>
<td>$g_i$</td>
<td>$</td>
</tr>
<tr>
<td>$\pi \Sigma$</td>
<td>$-2.5 - 1.5i$</td>
<td>2.9</td>
</tr>
<tr>
<td>$\bar{K} N$</td>
<td>$1.2 + 1.7i$</td>
<td>2.1</td>
</tr>
<tr>
<td>$\eta \Lambda$</td>
<td>$0.010 + 0.77i$</td>
<td>0.77</td>
</tr>
<tr>
<td>$K \Xi$</td>
<td>$-0.45 - 0.41i$</td>
<td>0.61</td>
</tr>
</tbody>
</table>

- **Lowest pole dominated by $\pi \Sigma$**
- **Highest pole dominated by $\bar{K} N$**

Recall: no explicit resonances included! (dynamically generated from chiral dynamics and unitarity)

Provide the actual shape of the amplitudes. **Not Breit-Wigners!**

Resonance shape may be different for different reactions!

UChPT as explained before: $\Lambda(1405)$

Poles at $4334 + 19i$ MeV, $4417 + 4i$ MeV and $4481 + 17i$ MeV

with $J^P = 3/2^-$, $I = 1/2$

Dominant coupling to $\bar{D}^* \Sigma_c - \bar{D}^* \Sigma^*_c$ + unitarization
Relative strength between both panels is not trivial at all and is a genuine prediction from the theory.

Results explained with $P_c(4450)^+$ being $J^P=3/2^-$. Experimental fit allows $J^P=5/2^+, 5/2^-, 3/2^-$. 

$\Lambda(1405)$ Range of couplings predicted by the model
Many $\Lambda$ resonances relevant to fit the overall invariant mass spectra

We include:

<table>
<thead>
<tr>
<th>$J^{P}$</th>
<th>$\frac{1}{2}^-$</th>
<th>$\frac{3}{2}^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$</td>
<td>$\Lambda$</td>
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Breit-Wigners with Flatté parametrization of the widths plus proper spin structure
Results of our fit

Quality of the fit almost independent of $J^P$ assignments for the $P_c$'s
Fit without including the lowest mass pentaquak, $P_c(4380)^+$:

- Similar quality of the fit

Effect of the $P_c(4380)^+$ can be accommodated by an increase in a contact term with $5/2^+$ quantum numbers

(original experimental LHCb fit only included up to spin 3/2 nonresonant components)

A tricky issue regarding the $\Lambda(1405)$ and a contact term...

For the $\Lambda(1405)$ channel we have

\[
1 + G_{K^-p}(M_{K^-p}) \, t_{\bar{K}N,\bar{K}N}^{I=0}(M_{K^-p})
\]
Contact term negligible in exp. LHCb fit

However we get a very important contribution

\[
\text{Contradiction?}
\]

\[
\text{NO, (by chance)}
\]
If $V_{12}$ is small:

\[(1 + GT)_{11} \approx \frac{T_{11}}{V_{11}} \propto -T_{11}\]

$T_{11}$ and $T_{12}$ are not proportional.

11: Kbar N $\rightarrow$ Kbar N
12: Kbar N $\rightarrow$ $\pi\Sigma$

and recall the $\Lambda(1405)$ has two poles.
Summary

- $P_c(4450)^+$, $P_c(4380)^+$ are the only exotic baryons quoted by the PDG (1-star status)

- Only seen in one experiment and one reaction: $\Lambda_b \rightarrow J/\psi K^- p$ by LHCb coll. at CERN

- The important role of $\Lambda(1405)$ in $\Lambda_b \rightarrow J/\psi K N$ allows us to check the possible nature of the $P_c(4450)^+$ as a $J^P=3/2^-$ molecule. Results non-trivially compatible with this picture

- Further improvement: Inclusion of more $\Lambda$ resonances and fit to overall spectra:
  - Good fits but similar for different $J^P$ (not conclusive)
  - $P_c(4380)^+$ not essential in the fit

  effect can be mimicked by a non-resonant 5/2 contribution
### Predictions for hidden charm Baryon states


<table>
<thead>
<tr>
<th>$(I, S)$</th>
<th>$z_R$</th>
<th>$\bar{D}^*\Sigma_c$</th>
<th>$\bar{D}^*\Lambda_c^+$</th>
<th>$J/\psi N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1/2, 0)</td>
<td></td>
<td>$4415 - 9.5i$ 2.83 $0.19i$</td>
<td>$-0.07 + 0.05i$</td>
<td>$-0.85 + 0.02i$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{2.83}$</td>
<td>$0.08$</td>
<td>$0.85$</td>
</tr>
</tbody>
</table>

In s-wave: $3/2^-$

**C W Xiao, J Nieves , E. O, PRD 2013 : $D^*\bar{b}ar\Sigma_c$ channel included**

<table>
<thead>
<tr>
<th>$4417.04 + i4.11$</th>
<th>$J/\psi N$</th>
<th>$\bar{D}^*\Lambda_c$</th>
<th>$\bar{D}^*\Sigma_c$</th>
<th>$\bar{D}\Sigma_c^*$</th>
<th>$\bar{D}^<em>\Sigma_c^</em>$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_i$</td>
<td>$0.53 - i0.07$</td>
<td>$0.08 - i0.07$</td>
<td>$2.81 - i0.07$</td>
<td>$0.12 - i0.10$</td>
<td>$0.11 - i0.51$</td>
</tr>
<tr>
<td>$</td>
<td>g_i</td>
<td>$</td>
<td>$0.53$</td>
<td>$0.11$</td>
<td>$2.81$</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>$4481.04 + i17.38$</th>
<th>$J/\psi N$</th>
<th>$\bar{D}^*\Lambda_c$</th>
<th>$\bar{D}^*\Sigma_c$</th>
<th>$\bar{D}\Sigma_c^*$</th>
<th>$\bar{D}^<em>\Sigma_c^</em>$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_i$</td>
<td>$1.05 + i0.10$</td>
<td>$0.18 - i0.09$</td>
<td>$0.12 - i0.10$</td>
<td>$0.22 - i0.05$</td>
<td>$2.84 - i0.34$</td>
</tr>
<tr>
<td>$</td>
<td>g_i</td>
<td>$</td>
<td>$1.05$</td>
<td>$0.20$</td>
<td>$0.16$</td>
</tr>
</tbody>
</table>
Reflects the highest mass \( \Lambda(1405) \) pole

Two different UChPT models:

- Higher order meson-baryon Lagrangians fitted to photoproduction and meson-baryon cross sections
  
  Bruns, Mai, Mei\ss{}ner, Phys.Lett. B697 (2011) 254

- Lowest order chiral Lagrangian with modified kernel
  
  (Our model explained above)

\[
\sum |T|^2 = 3|a|^2 + |b|^2 \frac{3}{2} \frac{\overrightarrow{k}^2}{k} + |c|^2 \frac{3}{2} \overrightarrow{k}^2 + |e|^2 \frac{2}{3} \frac{\overrightarrow{k}^2}{k} + |f|^2 \frac{2}{3} \frac{\overrightarrow{k}^2}{k} \left[ (\overrightarrow{p} \cdot \overrightarrow{k})^2 + \frac{1}{3} \frac{\overrightarrow{k}^2}{p} \overrightarrow{p}^2 \right] - \frac{4}{3} \frac{\overrightarrow{k}^2}{k} \overrightarrow{p} \cdot \overrightarrow{k} \left[ \text{Re}(bf^\ast) - 2 \text{Re}(cf^\ast) \right],
\]

\[
a = \alpha_1 \left( 1 + G_{K^-p(M_{K^-p})} t_{KN,KN}^{t=0} \right) \left( M_{I_{I\psi p}} - m_{c(4450)} + i \frac{\Gamma_{c(4450)}}{2} \right)
+ \delta \frac{1}{\omega} - \frac{1}{2} \alpha_2 G_{I_{I\psi p}} \frac{g_{j_{I\psi p}}^2}{M_{I_{I\psi p}} - m_{c(4450)} + i \frac{\Gamma_{c(4450)}}{2} \overrightarrow{k}^2} + \frac{1}{3} \alpha_6 M_{I_{I\psi p}} - m_{c(4380)} + i \frac{\Gamma_{c(4380)}}{2} \overrightarrow{k}^2 + \frac{1}{3} \alpha_6 M_{I_{I\psi p}} - m_{c(4380)} + i \frac{\Gamma_{c(4380)}}{2} \overrightarrow{k}^2
\]

\[
b = \frac{4}{3} \alpha_5 \frac{1}{M_{K^-p} - m_{\Lambda(1600)} + i \frac{\Gamma_{\Lambda(1600)}}{2} \overrightarrow{k}^2} + \frac{4}{3} \alpha_6 \frac{1}{M_{K^-p} - m_{\Lambda(1600)} + i \frac{\Gamma_{\Lambda(1600)}}{2} \overrightarrow{k}^2} + C_{3/2} \left[ 1 + \delta \frac{1}{\omega} - \frac{1}{2} \alpha_2 G_{I_{I\psi p}} \frac{g_{j_{I\psi p}}^2}{M_{I_{I\psi p}} - m_{c(4450)} + i \frac{\Gamma_{c(4450)}}{2} \overrightarrow{k}^2} + \frac{1}{3} \alpha_6 M_{I_{I\psi p}} - m_{c(4380)} + i \frac{\Gamma_{c(4380)}}{2} \overrightarrow{k}^2 + \frac{1}{3} \alpha_6 M_{I_{I\psi p}} - m_{c(4380)} + i \frac{\Gamma_{c(4380)}}{2} \overrightarrow{k}^2 \right]
\]

\[
c = - \frac{1}{3} \alpha_5 \frac{1}{M_{K^-p} - m_{\Lambda(1600)} + i \frac{\Gamma_{\Lambda(1600)}}{2} \overrightarrow{k}^2} + C_{1/2} \left[ 1 + \delta \frac{1}{\omega} - \frac{1}{2} \alpha_2 G_{I_{I\psi p}} \frac{g_{j_{I\psi p}}^2}{M_{I_{I\psi p}} - m_{c(4450)} + i \frac{\Gamma_{c(4450)}}{2} \overrightarrow{k}^2} + \frac{1}{3} \alpha_6 M_{I_{I\psi p}} - m_{c(4380)} + i \frac{\Gamma_{c(4380)}}{2} \overrightarrow{k}^2 + \frac{1}{3} \alpha_6 M_{I_{I\psi p}} - m_{c(4380)} + i \frac{\Gamma_{c(4380)}}{2} \overrightarrow{k}^2 \right]
\]

\[
de = \alpha_7 \frac{1}{M_{K^-p} - m_{\Lambda(1520)} + i \frac{\Gamma_{\Lambda(1520)}}{2} \overrightarrow{k}^2} + \frac{1}{3} \alpha_6 M_{I_{I\psi p}} - m_{c(4380)} + i \frac{\Gamma_{c(4380)}}{2} \overrightarrow{k}^2 + \frac{1}{3} \alpha_6 M_{I_{I\psi p}} - m_{c(4380)} + i \frac{\Gamma_{c(4380)}}{2} \overrightarrow{k}^2
\]

\[
f = C_{3/2} \left[ 1 + \delta \frac{1}{\omega} - \frac{1}{2} \alpha_2 G_{I_{I\psi p}} \frac{g_{j_{I\psi p}}^2}{M_{I_{I\psi p}} - m_{c(4450)} + i \frac{\Gamma_{c(4450)}}{2} \overrightarrow{k}^2} + \frac{1}{3} \alpha_6 M_{I_{I\psi p}} - m_{c(4380)} + i \frac{\Gamma_{c(4380)}}{2} \overrightarrow{k}^2 + \frac{1}{3} \alpha_6 M_{I_{I\psi p}} - m_{c(4380)} + i \frac{\Gamma_{c(4380)}}{2} \overrightarrow{k}^2 \right].
\]