$b$-baryon decays and the search for exotic hardons at LHCb

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Outline

1. Introduction
2. Studies of $\Lambda_b^0 \rightarrow J/\psi pp\pi^-$ decays
3. Observation of $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decays
4. Summary and future perspective
Both papers mentioned explicitly the possibility for penta-quark states: $qqqq\bar{q}$

Later in context of specific QCD models: Jafee (76), Hogaasen & Sorba (78), Strottman (79)
Pentaquark

No obvious reasons for their non-existence
Fertilize our understanding of QCD
No convinced experimental evidence for light pentaquark
Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi pK^-$ [PRL115(2015)072001]

- 2015: Two pentaquarks discovered by LHCb!!!
- A six-dimensional amplitude fit was done. $9\sigma$ and $12\sigma$ significances for two $P_c$ states.

![Graph showing events vs. $m_{Kp}$ and $m_{J/\psi p}$]"
Search for exotics in $\Lambda^0_b \rightarrow J/\psi p\pi^-$

- Observing the same $P_c$ states in a different decay mode could indicate they are really resonances and not some kinematical effects [PRD 93,094001(2016)]
- Cabibbo-suppressed $\Lambda^0_b$ decays to baryonic exotic resonances are predicted to have

$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda^0_b \rightarrow \pi^-P_c^+)}{\mathcal{B}(\Lambda^0_b \rightarrow K^-P_c^+)}$$

- $R \approx 0.07 - 0.08$ Fig(a)(b) [PRD 92,096009(2015)]
- $R = 0.58 \pm 0.05$ Fig(c) [PLB 572-575,751(2015)]
Studies of $\Lambda_b^0 \to J/\psi p\pi^-$ decays [PRL117, 082003(2016)]

- Analysis: six-dimensional amplitude fit (invariant masses, helicity and decay planes angles)

![Graph 1](image1.png)

$LHCb$

$N_{sig} = 26007$

$\Lambda_b^0 \to J/\psi pK^-$

![Graph 2](image2.png)

$LHCb$

$N_{sig} = 1885 \pm 50$

- Data
- Fit
- Signal
- $\Lambda_b^0 \to J/\psi pK^-$
- Cmb. bkg.
Possible exotic contribution in $\Lambda_b^0 \rightarrow J/\psi p \pi^-$

- More complex due to possible $Z_c^-$ states
- Exotic hadron contributions examined are: $P_c(4380)^+, P_c(4450)^+ \rightarrow J/\psi p$ and $Z_c(4200)^- \rightarrow J/\psi \pi^-$
- $Z_c(4200)^- : m_0 = 4196^{+35}_{-32}$ MeV, $\Gamma_0 = 370^{+99}_{-149}$ MeV
  $J^P = 1^+$ by Belle($6.2\sigma$) in $B^0 \rightarrow J/\psi \pi^- K^+$ decays

[Diagram showing quark configurations and decay processes]
Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

- No obvious structure in $m(J/\psi p)$.
- Breit-Wigners for all resonances. Flatte for $N(1535)$ to account for the threshold of $n\eta$ channel.
- Check consistency with the two $P_c$ states from $\Lambda_b^0 \rightarrow J/\psi pK^-$
Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

- Introduce exotic states can significantly improve $N^*$ fit quality.
- Significance of two $P_c$ is 3.3$\sigma$, if assume production of $Z_c(4200)^-$ is negligible. No independent confirmation of $P_{c^+}$ states.
- Significance of both type of exotics taken together is 3.9$\sigma$, with syst. considered is 3.1$\sigma$
Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

- **15 established $N^*$ states**
- **Reduced(RM):** central values
- **Extended(EM):** syst. + signif.

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th>RM</th>
<th>EM</th>
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<tbody>
<tr>
<td>NR $p\pi$</td>
<td>1/2$^-$</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>4</td>
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<tr>
<td>$N(1440)$</td>
<td>1/2$^+$</td>
<td>1430</td>
<td>350</td>
<td>3</td>
<td>4</td>
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<td>3/2$^-$</td>
<td>1515</td>
<td>115</td>
<td>3</td>
<td>3</td>
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<tr>
<td>$N(1535)$</td>
<td>1/2$^-$</td>
<td>1535</td>
<td>150</td>
<td>3</td>
<td>4</td>
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<tr>
<td>$N(1650)$</td>
<td>1/2$^-$</td>
<td>1655</td>
<td>140</td>
<td>1</td>
<td>4</td>
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<tr>
<td>$N(1675)$</td>
<td>5/2$^-$</td>
<td>1675</td>
<td>150</td>
<td>3</td>
<td>5</td>
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<tr>
<td>$N(1680)$</td>
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<td>1685</td>
<td>130</td>
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<td>$N(1720)$</td>
<td>3/2$^+$</td>
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<td>250</td>
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<td>5</td>
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<tr>
<td>$N(1875)$</td>
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<td>1875</td>
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<td>0</td>
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<td>$N(2190)$</td>
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<td>2190</td>
<td>500</td>
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<td>$N(2220)$</td>
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<td>400</td>
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<td>0</td>
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<td>$N(2600)$</td>
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<td>650</td>
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<td>$N(2300)$</td>
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<tr>
<td>$N(2570)$</td>
<td>5/2$^-$</td>
<td>2570</td>
<td>250</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

- **Without the high-mass and low spin $N^*(N(2300), N(2570)),$ the exotic states have more than $5\sigma$**
- **Better understanding conventional resonances is important for exotic searches.**
Futher results of $\Lambda_0^b \rightarrow J/\psi p\pi^-$

<table>
<thead>
<tr>
<th>State</th>
<th>Fit fraction(%)</th>
<th>$\mathcal{B}(\Lambda_0^b \rightarrow \pi^-P_c^+)/\mathcal{B}(\Lambda_0^b \rightarrow K^-P_c^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(4200^-)$</td>
<td>$7.7 \pm 2.8^{+3.4}_{-4.0}$</td>
<td>--</td>
</tr>
<tr>
<td>$P_c(4380)^+$</td>
<td>$5.1 \pm 1.5^{+2.6}_{-1.6}$</td>
<td>$0.050 \pm 0.016^{+0.026}_{-0.016} \pm 0.025$</td>
</tr>
<tr>
<td>$P_c(4450)^+$</td>
<td>$1.6^{+0.8+0.6}_{-0.6-0.5}$</td>
<td>$0.033^{+0.016+0.011}_{-0.014-0.010} \pm 0.009$</td>
</tr>
</tbody>
</table>

- $R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_0^b \rightarrow \pi^-P_c^+)}{\mathcal{B}(\Lambda_0^b \rightarrow K^-P_c^+)}$ tests $P_c^+$ production mechanism
  - $R \approx 0.07 - 0.08 \checkmark$
  - $R = 0.58 \pm 0.05 \times$

- Overall outlook: $J/\psi p\pi$ data is consistent with $P_c$'s seen in $J/\psi pK$
Search for $\Xi_b^- \rightarrow J/\psi \Lambda K^-$

- $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decays is similar to that of $\Lambda_b^0 \rightarrow J/\psi p K^-$

- A strange hidden-charm pentaquark state, decaying into $J/\psi \Lambda$ can be searched through $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decays. [PRL 105,232001(2010)][PRC 93,065203(2016)]
Analysis strategy for $\Xi_b^- \to J/\psi \Lambda K^-$

- Using 3 fb$^{-1}$ full Run-I data
- Measure the branching fraction related to $\Lambda_b^0 \to J/\psi \Lambda$

$$R = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \times \frac{B(\Xi_b^- \to J/\psi \Lambda K^-)}{B(\Lambda_b^0 \to J/\psi \Lambda)} = \frac{N(\Xi_b^- \to J/\psi \Lambda K^-)}{N(\Lambda_b^0 \to J/\psi \Lambda)} \times \frac{\epsilon_{\Lambda_b^0}^{\text{tot}}}{\epsilon_{\Xi_b^-}^{\text{tot}}}$$

- $f_{\Xi_b^-}/f_{\Lambda_b^0}$ is the ratio of fragmentation fractions
- Fiducial range: $p_T < 25$ GeV, $2.0 < y < 4.5$ on $b$-baryons
- BDTG is used to further discriminate between signal and combinatorial background
- Efficiencies estimated with simulation and data
Signal yield of the two modes

Two types of tracks used to reconstruct $\Lambda$.

Two types of tracks used to reconstruct $\Lambda$.

![Diagram showing signal yield of the two modes with tracks labeled: Upstream track, VELO track, T1, T2, T3, UT (Upstream track), T track, Long track, Downstream track.]

Data Total fit $\Sigma^-$ signal $J/\psi \Sigma^0 K^-$ Comb. bkg

LHCb preliminary

$N_{\text{sig}} = 99 \pm 12$

$N_{\text{sig}} = 209 \pm 17$

$\Delta(2\ln \mathcal{L}) \sim 21\sigma$

Candidates/(6 MeV/c$^2$) [MeV/c$^2$]

$5700$ $5800$ $5900$

$20$ $40$ $60$ $80$

$Xuesong Liu (Tsinghua University)$

Exotic baryons at LHCb

December 18, 2016 15 / 17
Observation of $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decays

- Results

$$R_{\Xi_b^-/\Lambda_b^0} \equiv \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \times \frac{\mathcal{B}(\Xi_b^- \rightarrow J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = (4.19 \pm 0.29\text{(stat.)} \pm 0.14\text{(syst.)}) \times 10^{-2}$$

$$\delta M \equiv M(\Xi_b^-) - M(\Lambda_b^0) = 177.08 \pm 0.47 \pm 0.16 \text{ MeV/c}^2$$

- A simultaneous fit is performed to the four samples, and the fit gives an identical results for the ratio $R_{\Xi_b^-/\Lambda_b^0}$.

- Consistent with the LHCb measurement using open-charm decays: $\delta M = 178.36 \pm 0.46 \pm 0.16 \text{ MeV/c}^2$.

[PRL 113,242002(2014)]

Most precise!!!
Conclusions

- $\Lambda^0_b \rightarrow J/\psi p \pi^- \,$ analysis supports the pentaquark states observed in the amplitude analysis in $\Lambda^0_b \rightarrow J/\psi p K^-$ decays.
- $\Xi^-_b \rightarrow J/\psi \Lambda K^- \,$ decay is first observed, the $\delta M$ between $\Lambda^0_b$ and $\Xi^-_b$ is measured. Full amplitude analysis will perform after LHC Run-II!
- Several analysis processing are digging the structure and physics nature of pentaquarks in LHCb
  - $\Lambda_b \rightarrow J/\psi p \pi K^0_S$
  - $\Lambda_b \rightarrow \chi_{c1}(1P)pK$
  - $\Lambda_b \rightarrow \Lambda^+_c \bar{D}^0 K$
  - ...
- Looking forward to RunII to obtain further exciting results!

Thanks and stay tuned!
Back up
LHCb is single-arm ($2 < \eta < 5$) spectrometer at the LHC

- $CP$ violation measurements, rare decays,
- heavy flavour decays as source for exotic hadrons
- Exploit the correlated production of $b\bar{b}$ pairs in LHC environment

Clean $B$-hadron samples through excellent vertex resolution: $O(\infty \Delta) \leq m(VELO)$

- Flavor tagging, final state discrimination needs excellent particle ID (RICH)
- Highly efficient trigger: di-muons, displaced vertices (topological $B$-hadron), ..
Pentaquark states in $\Lambda_h^0 \rightarrow J/\psi pK^-$ [PRL115(2015)072001]

Extended $\Lambda^*$ model

Extended $\Lambda^*$ model + 1 $P_c^+$

Reduced $\Lambda^*$ model + 2 $P_c^{++}$

<table>
<thead>
<tr>
<th>State</th>
<th>Mass(MeV)</th>
<th>Width(MeV)</th>
<th>Fit fraction(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4380)^+$</td>
<td>4380 ± 8 ± 29</td>
<td>205 ± 18 ± 86</td>
<td>8.4 ± 0.7 ± 4.2</td>
</tr>
<tr>
<td>$P_c(4450)^+$</td>
<td>4449.8 ± 1.7 ± 2.5</td>
<td>39 ± 5 ± 19</td>
<td>4.1 ± 0.5 ± 1.1</td>
</tr>
</tbody>
</table>

- Obtain good fits with reduced $\Lambda^* + 2$ Pentaquarks model.
- Best fits has $J^P = (3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ are preferred.
- Interference of two states of opposite parity required by forward-backward asymmetry in $P_c$ helicity angle.
Some details of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ analysis

- Six-dimensional amplitude fit: resonance invariant mass, three helicities angles, and two differences between decay planes
- Lorentz transformations relates the two helicity representations

- Resonances described by Breit-Wigner
- Angular distribution calculated using helicity formalism.