Overview of latest results on p-J/ψ pentaquarks

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13 December 2019
Key features of LHCb

- Designed primarily to study CP violation and rare decays of b hadrons
  - Forward acceptance
  - Precise vertexing (distinguish displaced vertices)
  - Tracking system providing good momentum resolution
  - Particle identification to distinguish $\pi/K/p$
  - (quasi-)Inclusive trigger scheme

- Fortuitously, these features enable a broad physics programme
  - e.g. study $\Lambda_b \rightarrow J/\psi pK$ as a potential background to $B_s \rightarrow J/\psi KK$
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LHCb data sample

\[ \sigma(pp \rightarrow H_b X) = 72.0 \pm 0.3 \pm 6.8 \, \mu \text{b (7 TeV)}, \ 144 \pm 1 \pm 21 \, \mu \text{b (13 TeV)} \]

$\Lambda_b \rightarrow J/\psi pK^-$

The first (2015) paper, based on Run 1 data (3/fb)


26 007±166 signal candidates (incl. 5.4% bkgs) in signal region
Structure in $m(J/\psi p)$ that cannot be explained by reflections from pK structures

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

![Graphs showing data and phase space comparison](image-url)
Amplitude analysis

Paranoia due to previous pentaquark claims – do the most complete & thorough analysis possible

Amplitude analysis accounting for small background contributions & efficiency variation across phase space resolution effects ignored (no narrow structures)

“Reduced” $\Lambda^*$ model ("extended" $\Lambda^*$ model also considered)
Impossible to describe data without $J/\psi p$ structures

Reasonably good fit obtained with two Breit-Wigner amplitudes, $P_c(4450)$ and $P_c(4380)$

Quantum numbers not determined unambiguously
(four combinations of $3/2^\pm$, $5/2^\pm$)

Additional structure not ruled out
No claim about binding mechanism

“Reduced” $\Lambda^*$ model (“extended” $\Lambda^*$ model also considered)
Additional projections

\[ m(Kp) > 2.00 \text{ GeV} \]
\[ 1.70 < m(Kp) < 2.00 \text{ GeV} \]
\[ m(Kp) < 1.55 \text{ GeV} \]
\[ 1.55 < m(Kp) < 1.70 \text{ GeV} \]

Argand diagrams

Statistically limited & inconclusive
Strongly model dependent (based on best model available at the time)
Model-independent confirmation

Maximal contribution of Kp resonances from the analysis of $\cos(\theta_{Kp})$ moments

LHCb
Follow up studies

• Desire for observation of any new state to be confirmed by >1 experiment and in >1 decay mode
  – Other experiments:
    • Photoproduction (see talk by Peter Pauli), ATLAS (CMS?)
  – Other final states:
    • $\chi_{c1}\rho$ (work in progress on others, e.g. $\Lambda_c\bar{D}$)

• However, $J/\psi p$ final state is golden, especially for LHCb
  • $J/\psi p$ structures in other $b$ hadron decay modes
  • Partner states, e.g. decaying to $J/\psi\Lambda$
  • Update $\Lambda_b \rightarrow J/\psi pK^-$ with more data
\( \Lambda_b \to J/\psi pK^- \) by ATLAS

Difficult to separate signal from both
- combinatorial background
- vertexing resolution not as good as LHCb
- misidentified \( B \to J/\psi h h \) decays
- lack of \( \pi/K/p \) discrimination
Λ_b → J/ψpK− by ATLAS

Comparison of 1D fits to m(J/ψp) (left) without and (right) with P_c states
Preference that P_c states should be included but not conclusive
$\Lambda_b \rightarrow \chi_{c1}pK^-$

First observation with Run 1 data
Amplitude analysis should be possible with Run 1+2 statistics

453±25 $\Lambda_b \rightarrow \chi_{c1}pK^-$ decays
285±23 $\Lambda_b \rightarrow \chi_{c2}pK^-$ decays
\[ \Lambda_b \rightarrow J/\psi p\pi^- \]

Analysis of Run 1 data, signal yield of 1885±50
Evidence for exotic contributions, but could be P\(_c\) (J/\psi p) or Z\(_c\) (J/\psi\pi)
Analysis of Run 1 + some Run 2 data (5.2/fb)

Amplitude analysis may be possible with full Run 1+2

Signal yields of (B^0) 256±22 and 609±31 (B^0_s)

Small phase space → precise B meson mass measurements
Analysis of Run 1 data
Sample separated by whether tracks from $\Lambda$ decay
leave hits in the VELO (LL) or not (DD)
Yields of 99±12 (LL) and 209±17 (DD)
Amplitude analysis may still be marginal with Run 1+2 data (but will be with LHCb Upgrade)
\[ \Lambda_b \rightarrow J/\psi pK^- \]

Update with full Run 1+2 data
Improved selection
Signal yield of 246,000
(9 x Run 1 yield)
+ 6.4% background in signal region
$\Lambda_b \rightarrow J/\psi pK^-$

Previous and new data samples consistent
(some discrepancies between data and model more evident in larger sample)
Mass resolution is 2-3 MeV, while binning is 15 MeV
$\Lambda_b \rightarrow J/\psi pK^-$
$\Lambda_b \rightarrow J/\psi p K^-$

New, narrow structures emerge in larger sample

**Good:** can do simplified (1D) analysis

**Bad:** can no longer ignore resolution effects

(ampplitude analysis becomes much more CPU-intensive)
Example 1D fit (one of many, all consistent)

- Data weighted as function of $\cos(\theta_{Pc})$ to enhance/suppress $P_c/\Lambda^*$ contributions
- Polynomial background model
- 3 Breit-Wigner structures convolved with resolution function

This approach can robustly determine mass and width, but not $J^P$, of narrow states

Cannot determine properties of broad states
(need to wait for amplitude analysis, sorry)

Striking proximity to $\Sigma_c \bar{D}^{(*)}$ thresholds
\[ \Lambda_b \rightarrow J/\psi p K^- \]

<table>
<thead>
<tr>
<th>State</th>
<th>( M ) [MeV]</th>
<th>( \Gamma ) [MeV]</th>
<th>(95% CL)</th>
<th>( \mathcal{R} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_c(4312)^+ )</td>
<td>4311.9 ± 0.7±6.8</td>
<td>9.8 ± 2.7±3.7</td>
<td>(&lt; 27)</td>
<td>0.30 ± 0.07±0.34</td>
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<tr>
<td>( P_c(4440)^+ )</td>
<td>4440.3 ± 1.3±4.1</td>
<td>20.6 ± 4.9±8.7</td>
<td>(&lt; 49)</td>
<td>1.11 ± 0.33±0.22</td>
</tr>
<tr>
<td>( P_c(4457)^+ )</td>
<td>4457.3 ± 0.6±4.1</td>
<td>6.4 ± 2.0±5.7</td>
<td>(&lt; 20)</td>
<td>0.53 ± 0.16±0.15</td>
</tr>
</tbody>
</table>

Significances of all three states >5\( \sigma \)

Measurements of masses, widths, and relative production rates

N.B. \( B(\Lambda_b \rightarrow J/\psi p K^-) = (3.17±0.04±0.07±0.34^{+0.45}_{-0.28}) \times 10^{-4} \) Chin.Phys. C40 (2016) 011001

Main systematic uncertainties from background & signal modelling (e.g. interference effects)

No results on \( J^p \) or on properties of broad states!
Summary

• LHCb detector provides exceptional sensitivity for hadron spectroscopy
  - many spectacular discoveries, in particular the charmonium pentaquarks

• $\Lambda_b \rightarrow J/\psi p K^-$ is a true golden channel
  - studies of other channels require more statistics, but exciting prospects for results with full Run 1+2 sample
  - data sample will increase again with LHCb Upgrade in Run 3 (2021-4)
  - long-term prospects also excellent with LHCb Upgrade II

• Ongoing discussion on interpretation and best models with which to fit data
  - amplitude analyses of increasing complexity, pushing at many boundaries