Baryonic b decays at LHCb

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on behalf of the LHCb collaboration
LHCb experiment

- LHCb is a dedicated heavy flavour experiment at the LHC
- Very precise vertex detector (VELO)
- One tracking stations before and three after a vertical dipole magnet
- Two ring imaging Cherenkov detectors
- Three layers of calorimetry
- Five of muon detectors interspersed with iron shielding walls
LHCb data taking

Results are quoted on 3 fb$^{-1}$ of data taken during LHC Run I 2010 to 2012 with $\sqrt{s} = 7$ or 8 TeV
Determination of $|V_{ub}|$ with bayrons

While $|V_{ub}|$ has been well measured in mesons with the $b \rightarrow u l^- \bar{\nu}_l$ decays, the same can be done with baryons, here using:

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda^0_b \rightarrow p \mu^- \bar{\nu}_\mu)}{\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c \mu^- \bar{\nu}_\mu)} R_{FF}$$

However the branching fraction method and differential decay rate values for the B mesons are

$$|V_{ub}| = (3.28 \pm 0.29) \cdot 10^{-3} \text{ (HFAG average, inclusive) and}$$

$$|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \cdot 10^{-3} \text{ (PDG average, differential)}$$

So an alternate measurement with baryons may prefer one of the NP models suggested to explain the discrepancy of about $3\sigma$
Event reconstruction

- To account for the missing neutrino the corrected mass is used

\[ m_{\text{corr}} = \sqrt{m_{\Lambda_c\mu}^2 + p_{\perp}^2 + p_{\perp}^2} \]

  - \( m_{\Lambda_c\mu} \) is the visible mass of the \( \Lambda_c\mu \) pair
  - \( p_{\perp} \) is the momentum of \( \Lambda_c\mu \) perpendicular to the \( \Lambda_b \) flight direction

- The selection is biased to large \( q^2 \) (invariant mass of \( \mu\nu \)) as the LQCD uncertainties are smallest there

  - Missing \( \nu \) means there are two-fold ambiguous solutions with different mass resolutions, imaginary values of \( q^2 \) are rejected limiting \( m_{\text{corr}} \leq M(\Lambda_b^0) \)
Systematic errors

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$</td>
<td>$+4.7,-5.3$</td>
</tr>
<tr>
<td>Trigger</td>
<td>3.2</td>
</tr>
<tr>
<td>Tracking</td>
<td>3.0</td>
</tr>
<tr>
<td>$\Lambda^+_c$ selection efficiency</td>
<td>3.0</td>
</tr>
<tr>
<td>$\Lambda_b^0 \to N^*\mu^-\bar{\nu}_\mu$ shapes</td>
<td>2.3</td>
</tr>
<tr>
<td>$\Lambda_b^0$ lifetime</td>
<td>1.5</td>
</tr>
<tr>
<td>Isolation</td>
<td>1.4</td>
</tr>
<tr>
<td>Form factor</td>
<td>1.0</td>
</tr>
<tr>
<td>$\Lambda_b^0$ kinematics</td>
<td>0.5</td>
</tr>
<tr>
<td>$q^2$ migration</td>
<td>0.4</td>
</tr>
<tr>
<td>PID</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>$+7.8,-8.2$</td>
</tr>
</tbody>
</table>

\[
\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)_{q^2>15\text{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda^+_c\mu^-\bar{\nu}_\mu)_{q^2>7\text{GeV}/c^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}
\]

Ratio with $R_{FF} = 0.68 \pm 0.07$

\[
\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004
\]
Using PDG world average of $|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$

$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.05) \times 10^{-3}$

Errors are experimental, LQCD and uncertainty of $|V_{cb}|$

Using the new results the fraction of a right handed weak coupling ($\varepsilon_R$) is now compatible with zero
Mass of the $\Omega_b^-$ ($ssb$)

Heavy quark effective theory (HQET) makes predictions for heavy baryon lifetime ratios

$$\tau(\Omega_b^-) \approx \tau(\Xi_b^-) > \tau(\Xi_b^0) \approx \tau(\Lambda_b^0)$$

While the other three lifetimes are well measured (1-3%) the previous LHCb measurement of $\tau(\Omega_b^-)$ was $1.54^{+0.26}_{-0.21} \pm 0.05$ ps on 58 $\pm$ 8 events from the $\Omega_b^- \to J/\psi \Omega^- \to J/\psi \Lambda^0 K^- \to \mu^+ \mu^- p \pi^- K^-$ search.

Search for the decays

$\Omega_b^- \to \Omega_c^0 \pi^- \text{ then } \Omega_c^0 \to p K^- K^- \pi^+$ using

$\Xi_b^- \to \Xi_c^0 \pi^- \text{ then } \Xi_c^0 \to p K^- K^- \pi^+$ as the control channel.
\( \Omega_b^- \) reconstruction

\[ N(\Omega_b^-) = 62.9 \pm 9.0 \]

\[ N(\Xi_b^-) = 1384 \pm 39 \]

<table>
<thead>
<tr>
<th>Decay time bin (ps)</th>
<th>( \Omega_b^- ) yield</th>
<th>( \Xi_b^- ) yield</th>
<th>( \epsilon(\Xi_b^-)/\epsilon(\Omega_b^-) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0–1.5</td>
<td>20.8 ± 4.8</td>
<td>450 ± 21</td>
<td>1.10 ± 0.03</td>
</tr>
<tr>
<td>1.5–2.5</td>
<td>12.0 ± 3.7</td>
<td>427 ± 21</td>
<td>1.11 ± 0.04</td>
</tr>
<tr>
<td>2.5–4.0</td>
<td>17.7 ± 4.2</td>
<td>305 ± 17</td>
<td>1.02 ± 0.04</td>
</tr>
<tr>
<td>4.0–12.0</td>
<td>10.5 ± 3.3</td>
<td>201 ± 14</td>
<td>1.03 ± 0.05</td>
</tr>
</tbody>
</table>
The final results are for the mass:

\[ m_{\Omega^-} - m_{\Xi^-} = 247.3 \pm 3.2 \pm 0.5 \text{ MeV}/c^2, \]
\[ m_{\Omega^-} = 6045.1 \pm 3.2 \pm 0.5 \pm 0.6 \text{ MeV}/c^2 \]

(stat \ ± syst \ ± ctrl channel)

and lifetime:

\[ \frac{\tau_{\Omega^-}}{\tau_{\Xi^-}} = 1.11 \pm 0.16 \pm 0.03, \]
\[ \tau_{\Omega^-} = 1.78 \pm 0.26 \pm 0.05 \pm 0.06 \text{ ps} \]

After combination with the previous LHCb result gives:

\[ \tau_{\Omega^-} = 1.66^{+0.19}_{-0.18} \text{ ps} \]

So consistent with the HQET predictions
Properties of the $\Xi^{*0}_b$ ($d\bar{s}b$)

- First measured by CMS
- Measured properties needed to test the predictions of QCD and LQCD models as well as the interquark potential
- Use the decay to $\Xi_b^-\pi^+$ which is very close to the threshold

$$\frac{\sigma(pp \to \Xi^{*0}_b X)B(\Xi^{*0}_b \to \Xi^-_b\pi^+)}{\sigma(pp \to \Xi^-_b X)} = 0.27 \pm 0.03 \pm 0.01$$

- Reconstructed using the decay chain
  $\Xi^{*0}_b \to \Xi_b^- (\to \Xi^0_c\pi^-)\pi^+$ then $\Xi^0_c \to pK^-K^-\pi^+$
The improved mass measurement and first width measurements of the state are made.

\[
\delta(m) = m(\Xi_b^*0) - m(\Xi_b^-) - m(\pi^+) \\
\Xi_b^*0 \rightarrow \Xi_b^- \pi^+ 
\]
The spin and parity were confirmed to be $3/2^+$ which is the expected one for the quark model

$$m(\Xi^*_b) - m(\Xi_b^-) - m(\pi^+) = 15.727 \pm 0.068 \pm 0.023 \text{ MeV/c}^2, \quad \Gamma(\Xi^*_b) = 0.90 \pm 0.16 \pm 0.08 \text{ MeV}. \quad \text{(1)}$$

Which is compatible with the LCQD prediction of $\Gamma = 0.51 \pm 0.16 \text{ MeV}$ and also a $^3 P_0$ model which predicted $\Gamma = 0.85 \text{ MeV}$

The $\Xi'_b$ ($1/2^+$) was not observed suggesting it is below threshold for this decay mode
Looking for strangeness changing weak decays in $\Xi_b^-(\Xi_b^0) \to \Lambda_b^0\pi^-$

- HQEFT predicts that 1% of the decay width of the $\Xi_b$ would be from decays of the $s$ quark
  - This may be enhanced to 2-8% (1-4%) for $\Xi_b^- (\Xi_b^0)$ if the light diquarks system is in the $J^P = 0^+$ state
- Comparing lifetimes of the charged and neutral $\Xi_b$ would test these assumptions

$$r_s \equiv \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \mathcal{B}(\Xi_b^- \to \Lambda_b^0\pi^-) = \frac{N(\Xi_b^- \to \Lambda_b^0\pi^-)}{N(\Lambda_b^0)} \epsilon_{\text{rel}}$$

Where $f_X$ is the fragmentation fractions for $b \to X$, $N(X)$is the signal yield for $X$ and $\epsilon_{\text{rel}}$ is the relative efficiency of the signal and normalisation modes
Decay chain used is $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$ then $\Lambda_b^0 \rightarrow (\Lambda_c^+ \rightarrow pK^-\pi^+)\pi^-$

Use signal enriched and depleted regions as well as wrong sign combination ($\Lambda_b^0 \pi^+$) to estimate resonant and non-resonant backgrounds
Systematic errors on $r_s$

<table>
<thead>
<tr>
<th>Source</th>
<th>Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean $\delta m$</td>
<td>+4.9</td>
</tr>
<tr>
<td></td>
<td>-6.4</td>
</tr>
<tr>
<td>Signal resolution</td>
<td>3.0</td>
</tr>
<tr>
<td>Combinatorial background shape</td>
<td>12.6</td>
</tr>
<tr>
<td>$\epsilon(\text{high} S/B)/\epsilon(\text{low} S/B)$</td>
<td>2.0</td>
</tr>
<tr>
<td>Slow $\pi^-$ efficiency</td>
<td>2.3</td>
</tr>
<tr>
<td>$\Lambda^0_b$ normalization mode yield</td>
<td>1.0</td>
</tr>
<tr>
<td>Simulated sample size</td>
<td>2.1</td>
</tr>
<tr>
<td>Total for signal significance</td>
<td>+13.9</td>
</tr>
<tr>
<td></td>
<td>-14.5</td>
</tr>
<tr>
<td>Total for $r_s$</td>
<td>+14.4</td>
</tr>
<tr>
<td></td>
<td>-15.0</td>
</tr>
</tbody>
</table>

\[
\frac{f_{\Xi_b^-}}{f_{\Lambda^0_b}} B(\Xi_b^- \rightarrow \Lambda^0_b \pi^-) = (5.7 \pm 1.8_{-0.9}^{+0.8}) \times 10^{-4}
\]

Result

Giving $3.2\sigma$ evidence for the $\Xi_b^- \rightarrow \Lambda^0_b \pi^-$ decay, which is a weak $s$ quark transition.

The estimates of the $B(\Xi_b^- \rightarrow \Lambda^0_b \pi^-) = (0.57 \pm 0.21)\%$ to $(0.19 \pm 0.07)\%$ are based on reasonable assumptions for $\frac{f_{\Xi_b^-}}{f_{\Lambda^0_b}} = 0.1 - 0.3$

This is compatible with $0.19\% - 0.76\%$ from HQEFT and comparisons to $B$, $D$ and Kaon decays.

It disfavours the enhancements expected if the light diquark system were $0^+$
\[ \Lambda^0_b \rightarrow \psi(2s)pK^- \]

Search for heavier charmonium states to \( \mu^+\mu^- \) in decays of the \( \Lambda_b^0 \)

\[
\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2s)pK^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi pK^-)} = (20.70 \pm 0.76 \pm 0.46 \pm 0.37) \times 10^{-2}
\]

\[
\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \pi^+\pi^- pK^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi pK^-)} = (20.86 \pm 0.96 \pm 1.34) \times 10^{-2}
\]

Observation of \( \Lambda_b^0 \rightarrow \psi(2s)pK^- \) and \( \Lambda_b^0 \rightarrow J/\psi \pi^+\pi^- pK^- \) decays and a measurement of the \( \Lambda_b^0 \) baryon mass. 

arXiv:1603.06961v1
Mass of $\Lambda_b^0$ using $\Lambda_b^0 \rightarrow \mu^+ \mu^- pK^-$

Systematic errors on the mass fits

<table>
<thead>
<tr>
<th></th>
<th>J/$\psi$</th>
<th>$\psi(2S) \rightarrow \mu^+ \mu^-$</th>
<th>$\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$</th>
<th>$J/\psi \pi^+ \pi^-, \psi(2S)^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum scale</td>
<td>0.34</td>
<td>0.19</td>
<td>0.15</td>
<td>0.26</td>
</tr>
<tr>
<td>Energy loss correction</td>
<td>0.03</td>
<td>0.02</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>Fit model</td>
<td>0.04</td>
<td>0.03</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>Sum in quadrature</td>
<td>0.34</td>
<td>0.19</td>
<td>0.18</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Masses in four decay modes reconstructed (stat then syst errors)

<table>
<thead>
<tr>
<th>Channel</th>
<th>$M(\Lambda_b^0)$ [MeV/c$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0 \rightarrow J/\psi pK^-$</td>
<td>$5619.62 \pm 0.04 \pm 0.34$</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow \psi(2S)[\rightarrow \mu^+ \mu^-]pK^-$</td>
<td>$5619.84 \pm 0.18 \pm 0.19$</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow \psi(2S)[\rightarrow J/\psi \pi^+ \pi^-]pK^-$</td>
<td>$5619.38 \pm 0.33 \pm 0.18$</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow J/\psi \pi^+ \pi^- pK^-$ excluding $\psi(2S)$</td>
<td>$5619.08 \pm 0.30 \pm 0.27$</td>
</tr>
</tbody>
</table>

$M(\Lambda_b^0) = 5619.65 \pm 0.17 \pm 0.17$ MeV/c$^2$

This is the most precise measurement of any b-hadron mass reported to date
The decay of the $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ is a rare ($b \rightarrow s$) FCNC

- Requires penguin or $W$ box diagrams thus sensitive to new physics

The decay can be used to study the helicity structure of the Hamiltonian of the system

- The $\Lambda \rightarrow \rho \pi^-$ preserves the helicity of the $\Lambda$
$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$, reconstruction

The signal is evaluated using $\Lambda_b \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) \Lambda$ as a control channel where $q^2 = M(\mu^+ \mu^-)$

$$N_S(\Lambda \mu^+ \mu^-)_k = \left[ \frac{d\mathcal{B}(\Lambda \mu^+ \mu^-)/dq^2}{\mathcal{B}(J/\psi \Lambda)} \right] \cdot N_S(J/\psi \Lambda)_k \cdot \varepsilon_k^{\text{rel}} \cdot \frac{\Delta q^2}{\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)}$$

Long lived $\Lambda$ decays may decay after the VELO

$\Rightarrow$ two reconstruction categories with different reconstruction uncertainties on long and downstream decays ($k$)
Numbers of signal events

<table>
<thead>
<tr>
<th>Selection</th>
<th>$N_S$ (long)</th>
<th>$N_S$ (downstream)</th>
</tr>
</thead>
<tbody>
<tr>
<td>high-$q^2$</td>
<td>4313 ± 70</td>
<td>11 497 ± 123</td>
</tr>
<tr>
<td>low-$q^2$</td>
<td>3363 ± 59</td>
<td>7225 ± 89</td>
</tr>
</tbody>
</table>

High-$q^2$ is above the $\psi(2s)$ and low-$q^2$ is below

$q^2 = m(\mu^+\mu^-)$

LHCb

$J/\psi\Lambda$

$B_d \rightarrow J/\psi K_s$

$\Lambda_b \rightarrow \Lambda\mu^+\mu^-$,
$15 < q^2 < 20 \text{ GeV}^2/c^4$

Long and downstream combined
- Errors × 3 smaller than the previous LHCb measurement at high-\(q^2\)
- Significant discrepancies between SM predication and data at low-\(q^2\)
Forward/backward asymmetries

Not all bins had enough data to make a significant fit.

$A_{FB}^{p\pi^-}$ is compatible with SM, $A_{FB}^{\mu^+\mu^-}$ is consistently high.
Conclusion

• LHCb has used the Run I data set to make many detailed measurements of Baryonic b decays
  • Stringent limits on beyond the standard model processes have been set
  • LQCD and HQET have been tested and used to understand the behaviour of the quarks in the Baryons
• More to come: Run II is a year underway and more results will be coming soon
• I will also advertise the talk of Irina Nasteva who will present the results from three other $\Lambda_{b}^{0}$ decays papers
• In exotics Biplab Dey will speak about the pentaquarks found in $\Lambda_{b}^{0} \rightarrow J/\psi K^{-}p$ decays
Thank you for listening!

Any questions?