Recent results on b-baryon states and lifetimes

Steven Blusk
Syracuse University

On behalf of the LHCb collaboration
2011 + 2012 b-baryon results - a snapshot

- Pentaquarks ($\Lambda_b \rightarrow J/\psi pK$)
- Lifetimes
- New decays (charmless and charm+X and double-charm)
- Precision masses
- FCNC ($\Lambda_b \rightarrow \Lambda\phi, \Lambda\mu^+\mu^-$)
- CPV in $\Lambda_b \rightarrow p\phi^\pm$
- Excited $\Lambda_b, \Xi_b$ resonances
- Absolute $B(\Lambda_b \rightarrow \Lambda_c\pi)$
- Fragmentation ratio: $f(\Lambda_b)/f_d$
- Angular analysis/studies of $\Lambda_b \rightarrow (\psi/\psi')\Lambda$
- Spectator $b$-quark decays
But, today’s menu, focus on recent results..

- Lifetime of the $\Omega_{b^-}$ baryon
- Evidence of the strangeness-changing decay $\Xi_{b^-} \rightarrow \Lambda_{b} \pi^-$
- Precision measurements of the $\Xi_{b^*0}$ baryon

No new results on b-baryons from CMS or ATLAS... but stay tuned..
Introduction

- Systems with heavy quarks provide a unique laboratory to search for physics BSM.
- Because we measure decays of hadrons, we must also understand QCD, to the extent that it can alter BSM observables.
- A number of theoretical techniques used to quantify such effects:
  - Lattice QCD
  - HQET
  - Potential models
  - ...
- Measurements of the properties of these heavy quark systems provides valuable tests / input to theory.
  - Different helicity structure than mesons, so provide complementary information.
- Experimentally: b-baryons produced copiously at the LHC.
b-baryons

- For $m_b \gg m_q$, baryonic properties differentiated by dynamics of diquark system in color-field of static $b$-quark
- ‘Ground state’ baryons ($L = 0$), have $j^p = 0^+, 1^+ \rightarrow J^p = \frac{1}{2}^+, \frac{3}{2}^+$.

$J^p = \frac{1}{2}^+$

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$J^p = \frac{3}{2}^+$

Study of the properties of beauty baryons provide important tests of HQET, potential models, etc..
Additional motivations...

- Quark pairs with $\psi_{\text{color}} \psi_{\text{flavor}}$ and $\psi_{\text{spin}}$ anti-symmetric exhibit a “strong” attractive force within QCD through 1-gluon exchange.
  (e.g. $J^P=0^+$ are “good” scalar diquarks, see Jaffe hep-ph/0409065)

- The idea of such ‘di-quarks’ have been invoked & successfully used in the past to understand baryon production rates (e.g. $\Lambda$ vs $\Sigma$), as well as to explain existence of exotic hadrons (which were later debunked).

- With the emergence of many new (and experimentally robust) candidate tetra- and penta-quark states in the last decade, their understanding has led to a renewed interest in the notion of diquarks.

- Since diquarks are an antitriplet 3 of SU(3)$_C$, formation of tetraquarks, pentaquarks and dibaryons is quite natural (see talk by Jibo He on Thursday for experimental review on tetra & pentaquarks).
Lifetimes of \( b \) hadrons

- The HQE is a powerful theoretical tool to understand decay rates of heavy quark systems
  - Predictions for \( \Gamma_{sl}(X_b \to X\ell\nu) \) can be used to determine CKM matrix elements, \( V_{cb} \) and \( V_{ub} \).
  - Lifetimes, e.g. \( 1/\Gamma_{\text{tot}} \), provide a stringent test of the theory.
  - \( \Gamma_{\text{tot}} \sim m_b^5 \Rightarrow \) use lifetime ratios to reduce theory uncertainty.

- From HQET, expect:
  
  \[
  \left[ \tau(B^0) \approx \tau(B_S) \right] < \tau(B^-), \quad \left[ \tau(\Lambda_b^0) \approx \tau(\Xi_b^0) \right] < \left[ \tau(\Xi_b^-) \approx \tau(\Omega_b^-) \right]
  \]

- Largest differences arise due to
  - Weak annihilation/exchange and/or
  - Pauli interference at \( O(1/m_b^3) \)
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- Longstanding issue with $\tau(\Lambda_b)/\tau(B^0)$
  - Recently resolved, ratio much closer to unity, as expected.
Beyond $\Lambda_b$ ..

- In 2014, LHCb made the most precise measurements of the $\Xi_b$ lifetimes

$$\tau(\Xi_b^0) / \tau(\Lambda_b^0) = 1.006 \pm 0.018 \pm 0.010 \quad [\text{PRL113, 032001 (2014). Only } \tau(\Xi_b^0) \text{ moment}]$$

$$\tau(\Xi_b^-) / \tau(\Lambda_b^0) = 1.089 \pm 0.026 \pm 0.011 \quad [\text{PRL113, 242002 (2014)}]$$

- First statistically meaningful test of expected hierarchy from HQET.

$$\left[ \tau(\Lambda_b^0) \approx \tau(\Xi_b^0) \right] < \left[ \tau(\Xi_b^-) \approx \tau(\Omega_b^-) \right]$$

- What about $\Omega_b^-$?
  - Also, produced copiously at LHC, but lower production rate than $\Lambda_b$ by (roughly) two orders of magnitude.
  - Workhorse has been $\Omega_b \rightarrow J/\psi \Omega^-$, $\Omega^- \rightarrow \Lambda K^-$. Narrow resonances in final state, so PID not critical. However, two long-lived hyperons $\rightarrow$ lower acceptance

$$\tau(\Omega_b^-) = 1.66^{+0.53}_{-0.40} \pm 0.02 \quad [\text{CDF, PRD 89, 072014 (2014), 22 signal ev.}]$$

$$\tau(\Omega_b^-) = 1.54^{+0.26}_{-0.21} \pm 0.05 \quad [\text{LHCb, PLB 736, 154 (2014), 60 signal ev}]$$

- These data are not of sufficient precision to test the HQET expectation.
Measurement of the $\Omega_b^-$ lifetime
LHCb, Phys. Rev. D93 092007 (2016)

Idea: Try to find & exploit a decay mode with no hyperons.

• Search for mode: $\Omega_b^- \to \Omega_c^0 \pi^-$, $\Omega_c^0 \to pK^-\pi^+$.  
• This decay chain is yet to be observed.
• $\Omega_b^-$ decay is CF, $\Omega_c^0$ decay is CS.
• Excellent normalization mode: $\Xi_b^- \to \Xi_c^0 \pi^-$, $\Xi_c^0 \to pK^-\pi^+$, to make a relative lifetime measurement.
• Also get a **mass measurement** for free.
• Many systematics cancel, as modes are almost identical in all respects.

• **Reason for optimism going in...**
  
  • $\sim 3600 \, \Xi_b^0 \to \Xi_c^+ \pi^-$, $\Xi_c^+ \to pK^-\pi^+$ signal decays  
    ( $\Xi_c^+$ mode also CS )
  
  • Assume $f(\Omega_b)/f(\Xi_b) \sim 0.1$, factor of 0.5 for reco extra track  
    $\to$ might see $\sim 180$ such $\Omega_b$ decays.

  • This would be 3X larger yield than  
    $\Omega_b \to J/\psi \Omega^-$, $\Omega^- \to \Lambda K^-$ from LHCb (same $L_{int}$)
What do we find...

\[ \Omega_b^- \rightarrow \Omega_c^0 \pi^- \]

\[ 63 \pm 9 \]

\[ \Xi_b^- \rightarrow \Xi_c^0 \pi^- \]

\[ 1384 \pm 39 \]

Signal yield about the same as \( \Omega_b \rightarrow J/\psi \Omega^- \)

\[ \Omega_c^0 \] candidates

\[ \Xi_c^0 \] candidates
Bin data into four time bins to get the yields

Correct yields by relative efficiency from simulation

$$\frac{N_{\Omega_b^- \to \Omega_c^0 \pi^- (t)}}{N_{\Xi_b^- \to \Xi_c^0 \pi^- (t)}} = A \exp(\kappa t), \quad \kappa \equiv 1/\tau_{\Xi_b^-} - 1/\tau_{\Omega_b^-}.$$
Data fit to exponential function gives $\kappa$.

Use measured $\Xi_b^-$ lifetime, now precise enough, to get $\tau(\Omega_b^-)$.

This measurement

$\tau(\Omega_b^-)/\tau(\Xi_b^-) = 1.11 \pm 0.16 \pm 0.03$
$\tau(\Omega_b^-) = 1.78 \pm 0.26 \pm 0.05 \pm 0.06 \text{ ps}$

Consistent with previous m'ments, and as good sensitivity as $\Omega_b \rightarrow J/\psi \Omega^-$

Promising mode for further reduction of uncertainty.

Other measurements

$\tau(\Omega_b^-) = 1.66^{+0.53}_{-0.40} \pm 0.02$ [ CDF14 ]
$\tau(\Omega_b^-) = 1.54^{+0.26}_{-0.21} \pm 0.05$ [ LHCb14 ]

Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta m$ (MeV/$c^2$)</th>
<th>$\tau_{\Omega_b^-}/\tau_{\Xi_b^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal shape</td>
<td>$\pm 0.3$</td>
<td>$\pm 0.005$</td>
</tr>
<tr>
<td>Background shape</td>
<td>$\pm 0.1$</td>
<td>$\pm 0.009$</td>
</tr>
<tr>
<td>$\Omega_b^-$ shape</td>
<td>$\pm 0.1$</td>
<td>$\pm 0.003$</td>
</tr>
<tr>
<td>$X_b \rightarrow X_c K^-$ background</td>
<td>$\pm 0.2$</td>
<td>$\pm 0.002$</td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>$-3$</td>
<td>$\pm 0.018$</td>
</tr>
<tr>
<td>Average time in bin</td>
<td>$-3$</td>
<td>$\pm 0.002$</td>
</tr>
<tr>
<td>Lifetime fit</td>
<td>$-3$</td>
<td>$\pm 0.016 \pm 0.008$</td>
</tr>
<tr>
<td>Simulated sample size</td>
<td>$-3$</td>
<td>$\pm 0.017$</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>$\pm 0.1$</td>
<td>$\pm 0.004$</td>
</tr>
<tr>
<td>$\Xi_b^-$ lifetime</td>
<td>$-3$</td>
<td>$\pm 0.004$</td>
</tr>
<tr>
<td>Total systematic</td>
<td>$-0.4 \pm 0.5$</td>
<td>$\pm 0.016 \pm 0.029$</td>
</tr>
<tr>
<td>Total statistical</td>
<td>$\pm 3.2$</td>
<td>$\pm 0.16$</td>
</tr>
</tbody>
</table>

This measurement

$m(\Omega_b^-) - m(\Xi_b^-) = 247.4 \pm 3.2 \pm 0.5 \text{ MeV}$

$m(\Omega_b^-) = 6045.1 \pm 3.2 \pm 0.5 \pm 0.6 \text{ MeV}$

Consistent with previous CDF, LHCb; inconsistent with D0.

Better per-event mass resolution in $\Omega_b \rightarrow J/\psi \Omega^-$ due to low Q value.
Evidence of the strangeness-changing decay: $\Xi_b^- \rightarrow \Lambda_b \pi^-$

LHCb, PRL115, 241801 (2015)

- In the quark model, the $\Xi_b^-$ decay is dominated by the decay width of the $b$ quark.

- However, a small $O(1\%)$-ish contribution of the $\Xi_b^-$ decay width, should arise from the decay $\Xi_b^- \rightarrow \Lambda_b \pi^-$.

- It was argued by Li, Voloshin (PRD90, 033016, 2014), that, theoretically, with a scalar $(ds)$ diquark transition, the partial width could approach a level of 2-8% of the total width.
  - Such a large contribution could not be ignored in comparing measured $\Xi_b$ lifetimes with HQET!

- Such a (large) signal would be easily discernable from the background.
  - Narrow peak at $\delta m = m(\Xi_b^-) - m(\Lambda_b) - m(\pi^-) = 38.8\pm0.5$ MeV ... No LEE!
  - Two successive weak $b$-hadron decays, each with $\tau \sim 1.5$ ps $\rightarrow \Lambda_b$ decay is further from pp interaction vertex.
Search strategy

• Two samples
  • Inclusive $\Lambda_b \rightarrow \Lambda_c^+\pi^-$ sample.
  • $X \rightarrow \Lambda_b\pi^-$ sample (with $\Lambda_b \rightarrow \Lambda_c^+\pi^-$)

• Backgrounds (to $\Xi_b^- \rightarrow \Lambda_b\pi^-$)
  • Combinatorial: because of the low Q-value, the $\Lambda_b$ and $\pi^-$ are almost collinear.

• Only mild discrimination of prompt $\pi^-$ background. Use $\Lambda_b\pi^+$ combinations (WS) to help constrain this BG.

• $\Sigma_b^{(*)}\pi^\pm \rightarrow \Lambda_b\pi^\pm$: Broad peaks, include in full fit model to data using RBW x Gauss.

• BDT to provide discrimination between $\Xi_b^- \rightarrow \Lambda_b\pi^-$ and $\Lambda_b$+random $\pi^-$. 
  • Separate sample into a low S/B and a high S/B region (according to BDT output).
  • Perform simultaneous fit to 4 samples: RS & WS, low S/B and hi S/B.

• All selection requirements chosen/optimized prior to looking in the signal region.

N($\Lambda_b \rightarrow \Lambda_c^+\pi^-$) = 265,000
What is found...

Excess of events at the expected location in the high S/B RS bin.

LHCb, PRL 115, 241801 (2015)
Results

- The BF is related to the measured yields

\[ \frac{1}{\varepsilon_{rel}} \frac{N(\Xi^- \to \Lambda_b^0\pi^-)}{N(\Lambda_b^0)} = \frac{f_{\Xi^-_b}}{f_{\Lambda_b^0}} \cdot B(\Xi^- \to \Lambda_b^0\pi^-) \]

From simulation, we find: \( \varepsilon_{rel} = 1.47 \pm 0.03 \), mostly due to reconstructing the extra pion.

\[ \frac{f_{\Xi^-_b}}{f_{\Lambda_b^0}} \cdot B(\Xi^- \to \Lambda_b^0\pi^-) = (5.7 \pm 1.8^{+0.8}_{-0.9}) \times 10^{-4} \]

- \( f_{\Xi^-_b} / f_{\Lambda_b^0} \) is not known, but reasonable estimates would be in the range of 0.1 to 0.2. With this assumed range:

\[ f_{\Xi^-_b} / f_{\Lambda_b^0} = 0.1: \quad B(\Xi^- \to \Lambda_b^0\pi^-) = (0.57 \pm 0.18^{+0.08}_{-0.09})\% \]

\[ f_{\Xi^-_b} / f_{\Lambda_b^0} = 0.2: \quad B(\Xi^- \to \Lambda_b^0\pi^-) = (0.29 \pm 0.09^{+0.04}_{-0.05})\% \]

These data do not support the large enhancement that could arise, if the (us) system behaves as a diquark’ with enhanced correlations.
Resonances in the $\Xi_b\pi$ system

- In 2012, CMS reported 1\textsuperscript{st} observation of a single (neutral) resonance in the $\Xi_b^-\pi^+$ mass spectrum, using $\Xi_b^-\to J/\psi\Xi^-$ decays.
  - Consistent with the $J^P = 3/2^+$ $\Xi_b^*$

- Reported mass and width

\[
\delta m = 14.84 \pm 0.74 \pm 0.28 \text{ MeV} \\
\Gamma = 2.1 \pm 1.7\text{(stat)} \text{ MeV} \text{ (consistent with 0)}
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- In 2015, LHCb followed up with a search for narrow (charged) resonances in the $\Xi_b^0\pi^-$ mass spectrum, using $\Xi_b^0 \rightarrow \Xi_c^{±}\pi^-$, $\Xi_c^{±} \rightarrow pK^-\pi^+$.
  - Two states observed, consistent with the $\Xi_b^-^*$, $\Xi_b^*^-$

$$\delta m_1 = 3.653 \pm 0.018 \pm 0.006 \text{ MeV}, \quad \Gamma_1 < 0.08 \text{ MeV} \quad \text{at 95\% CL}$$
$$\delta m_2 = 23.96 \pm 0.12 \pm 0.06 \text{ MeV}, \quad \Gamma_2 = 1.65 \pm 0.31 \pm 0.10 \text{ MeV}$$

$$\frac{\sigma(pp \rightarrow \Xi_b^-X)B(\Xi_b^- \rightarrow \Xi_b^0\pi)}{\sigma(pp \rightarrow \Xi_b^0X)} = 0.118 \pm 0.017 \pm 0.007,$$
$$\frac{\sigma(pp \rightarrow \Xi_b^0X)B(\Xi_b^- \rightarrow \Xi_b^0\pi)}{\sigma(pp \rightarrow \Xi_b^0X)} = 0.207 \pm 0.032 \pm 0.015,$$
Precision measurements of the properties of $\Xi_b^{*0}$ baryon
LHCb, JHEP 1605, 161 (2016)

Goals:
- See if another state was possibly missed by CMS?
- Make precise measurement of mass
- First measurement of the width
- Measure the production rate (relative to $\Xi_b^-$)

Techniques/selections similar to $\Xi_b^{*0}$ analysis.
- Reconstruct $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$, $\Xi_c^0 \rightarrow pK^-K^+\pi^+$
- Add a $\pi^+$ consistent with pp interaction point.
- Form $\delta m = m_{\text{inv}}(\Xi_b^-\pi^+) - m_{\text{inv}}(\Xi_b^-) - m(\pi^+)$

Signal ($\delta m$) resolution obtained from simulation.
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- State seen by CMS confirmed.
- No second peak ($\Xi_b'0$) above threshold.
  - Depending on mass, should decay as $\Xi_b'0 \to \Xi_b^0\pi^0$ and/or $\Xi_b'0 \to \Xi_b^0\gamma$.
  - (Both difficult for LHCb, due to very low energy of neutral).
  \[ \delta m = 15.727 \pm 0.068 \pm 0.023 \text{ MeV} \]
  \[ \Gamma = 0.90 \pm 0.16 \pm 0.08 \text{ MeV} \]
- Consistent with CMS; $\delta m$ about 10X more precise (4X from stats, ~3X from per-event mass resolution)

- Production ratio:
  - Select subset of events that specifically pass the L0 hadron trigger.
  \[ \frac{\sigma(pp \to \Xi_b^{*0}X)B(\Xi_b^{*0} \to \Xi_b^{0}\pi^+)}{\sigma(pp \to \Xi_b^{0}X)} = 0.27 \pm 0.03 \text{ (stat)} \pm 0.01 \text{ (syst)} \]
- Similar ratio as for $\Xi_b^*/\Xi_b^0$
- Excited $\Xi_b$ states produced at a similar rate to direct production of the ground state baryons.
Summary and outlook

• LHC is a **beauty baryon factory**.
  - We’ve just ‘scratched the surface’ on beauty baryons.

• **Lifetimes:**
  - $\Lambda_b$: WA at 1% level, probably good enough for some time.
  - $\Xi_b$: currently $\sigma/\tau$~3% ... should be able to achieve ~1%-level precision in next couple of years.
  - $\Omega_b$: WA about 10% ... can be pushed down using modes presented here; possible explore $\Omega_b^- \rightarrow \Omega_c^0 \mu\nu$, $\Omega_c^0 \rightarrow \pi\bar{K}-\bar{K}+\pi$. Large stat gain (~10X) ... care needed with systematics (x-feed, form-factors, K-factors, etc).

• **Heavier baryons..**
  - Welcomed discoveries of $\Xi_b^{*,0}, \Xi_b^{'+}, \Xi_b^{*+}$
  - Many other states still to be discovered. Dipion transitions, modes with $\gamma$ and $\pi^0$ should be searched for (e.g. $\Sigma_b^0, \Sigma_b^{*,0}, \Xi_b^{'+}, \Xi_b^{*+}$, higher $\Lambda_b, \Sigma_b$ excitations, etc)
  - The $\Xi_{bc}$ baryon is awaiting discovery. Many $B_c$’s, so we must have plenty of $\Xi_{bc}$. (many modes will need to be combined)

• Exotics: See talk by Jibo He.

• CPV in baryons: See talk by Rafael Silva Coutinho

• Upgrade should greatly extend our reach on all fronts ... see talk by Laura Gavardi

• **There is much yet to be learned in the baryon sector. Expect more interesting results at FPCP 2017 in Prague!**