First steps towards the experimental observation of purely baryonic decay processes

Vladimír Macko¹
(LHCb Collaboration)

¹EPFL, Lausanne
SPS/CHIPP Annual meeting Lausanne 2018

29 August 2018
Purely baryonic decays of baryons

- Decays of baryons into final states containing *only* baryons
- Predicted by the Standard Model\(^1,^2\), examples:

Yet, *none of these modes has ever been experimentally observed*

- They constitute an unexplored class of decays...

- **Measurements of purely baryonic decays** represent valuable tests of theoretical predictions and can validate the factorization approach used.

\(^1\)Purely baryonic decay processes by C. Q. Geng, Y.K. Hsiao, E. Rodrigues [1806.00861]

\(^2\)Exploring the simplest purely baryonic decay processes by C. Q. Geng, Y.K. Hsiao, E. Rodrigues [1603.05602]
Objectives

- Study purely baryonic decays in modes:
  - $\Lambda_b^0 \rightarrow \Lambda p\bar{p}$
  - $\Xi_b^0 \rightarrow \Lambda p\bar{p}$
Objectives

- Study purely baryonic decays in modes:
  - $\Lambda^0_b \rightarrow \Lambda p\bar{p}$
  - $\Xi^0_b \rightarrow \Lambda p\bar{p}$

- Measure the branching fractions; Theoretical predictions$^1$:
  - $B(\Lambda^0_b \rightarrow \Lambda p\bar{p}) = (3.2^{+0.8}_{-0.3} \pm 0.4 \pm 0.7) \times 10^{-6}$
  - $B(\Xi^0_b \rightarrow \Lambda p\bar{p}) = (1.4 \pm 0.1 \pm 0.1 \pm 0.4) \times 10^{-7}$

  (uncertainties from non-factorisable effects, CKM matrix elements, and hadronic form factors)

- Depending on the successful observation and the available statistics:
  Carry out the first $CP$ violation measurement for these decay modes;
  Theoretical prediction of direct $CP$ violation:
  - $A_{CP}(\Lambda^0_b \rightarrow \Lambda p\bar{p}) = (3.4 \pm 0.1 \pm 0.1 \pm 0.1)\%$
  - $A_{CP}(\Xi^0_b \rightarrow \Lambda p\bar{p}) = (-13.0 \pm 0.5 \pm 1.5 \pm 1.1)\%$

---

$^1$ Purely baryonic decay processes by C. Q. Geng, Y.K. Hsiao, E. Rodrigues [1806.00861]
LHCb detector

- Single-arm forward spectrometer\textsuperscript{1}
- Covers the pseudorapidity range $2 < \eta < 5$
- Designed to study particles containing $b$ or $c$ quarks
- Measurements of rare decays and $CP$ violation

\textsuperscript{1} A. A. Alves Jr \textit{et al.} LHCb Collaboration, \textit{The LHCb Detector at the LHC}, 2008 JINST 3 S08005
Tracks at LHCb

Decays $\Lambda_b^0 \to \Lambda p\bar{p}$, $\Xi_b^0 \to \Lambda p\bar{p}$ contain $\Lambda$

In LHCb conditions $\Lambda$ can travel up to $\sim 2 \text{ m}$

- If $\Lambda$ decays in VELO $\to$ Two Long tracks
- If $\Lambda$ decays after traversing VELO $\to$ Two Downstream tracks

Figure taken from Jeroen van Hunen, NIKHEF B-physics meeting June 4, 2004
According to a Run 1 study:\(^1\)

\[ N_{\Lambda_b^0 \rightarrow \Lambda^0 p \bar{p}} = 27.5 \pm 9.6_{(\text{stat.})} \pm 3.0_{(\text{sys.})} \]

With Run 2 luminosity and improvements in reconstruction, trigger and event selection, \(\sim 100 \ \Lambda_b^0 \rightarrow \Lambda p \bar{p} \) signal events are expected.

---

\(^1\) R. Zillmer, Master Thesis, University of Rostock
Analysis steps:

- Trigger selection
- Event reconstruction
- Signal MC study
- Backgrounds
- Event Selection
- Hypothesis testing
- Systematic uncertainty studies

### LHCb Trigger

- **Level 0 (Hardware trigger):**
  A hadron from signal detected or triggered independently of signal

- **High Level Trigger 1 (Software trigger):**
  One or two good quality tracks of interest reconstructed

- **High Level Trigger 2 (Software trigger):**
  2-or-3-body decay of interest reconstructed

### Trigger $\varepsilon[\%]$

<table>
<thead>
<tr>
<th></th>
<th>2015 $LL$</th>
<th>2015 $DD$</th>
<th>2016 $LL$</th>
<th>2016 $DD$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda^0_b \to \Lambda p\bar{p}$</td>
<td>34.07 ± 0.66</td>
<td>29.22 ± 0.31</td>
<td>37.22 ± 0.40</td>
<td>33.05 ± 0.20</td>
</tr>
</tbody>
</table>
Analysis steps:

▶ Trigger selection
▶ **Event reconstruction**
▶ Signal MC study
▶ Backgrounds
▶ Event Selection
▶ *Hypothesis testing*
▶ *Systematic uncertainty studies*

▶ Look for events containing decay chain $\Lambda_b^0 \rightarrow \Lambda h\bar{h}$
\[
\rightarrow \Lambda \rightarrow p\pi^-
\]
with constraints on the decay product properties ($p_T$, angles,...)

▶ Apply proton mass ($h = p$) hypothesis and refit with constraints on $m_\Lambda$ and decay topology

<table>
<thead>
<tr>
<th>Combined trigger and reconstruction $\varepsilon[%]$</th>
<th>2015 $LL$</th>
<th>2015 $DD$</th>
<th>2016 $LL$</th>
<th>2016 $DD$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0 \rightarrow \Lambda p\bar{p}$</td>
<td>$\sim 0.16$</td>
<td>$\sim 0.50$</td>
<td>$\sim 0.19$</td>
<td>$\sim 0.56$</td>
</tr>
</tbody>
</table>
Analysis steps:

▶ Trigger selection
▶ Event reconstruction
▶ **Signal MC study**
▶ Backgrounds
▶ Event Selection
▶ *Hypothesis testing*
▶ *Systematic uncertainty studies*

Signal regions:

▶ $\Lambda_b^0 \rightarrow \Lambda p\bar{p} : m_{\Lambda_b} \pm 50\text{MeV}$
▶ $\Xi_b^0 \rightarrow \Lambda p\bar{p} : m_{\Xi_b} \pm 50\text{MeV}$
Analysis steps:

- Trigger selection
- Event reconstruction
- Signal MC study
- Backgrounds
- Event Selection
- Hypothesis testing
- Systematic uncertainty studies

Blind regions:

\[ m_{\Lambda^0_b} = 5619.60 \pm 0.17 \text{ MeV} \]

- \( \Lambda^0_b \): [5569, 5669] MeV

\[ m_{\Xi^0_b} = 5794.5 \pm 1.4 \text{ MeV} \]

- \( \Xi^0_b \): [5738, 5838] MeV

![Graph showing events vs. \( \Lambda^0_b \) mass]
Analysis steps:

- Trigger selection
- Event reconstruction
- Signal MC study
- Backgrounds
- Event Selection
- Hypothesis testing
- Systematic uncertainty studies

Backgrounds considered (1/2):

- Combinatorial
- Cross-feed: a double meson misidentification in $\Lambda_b^0 \rightarrow \Lambda hh'$
  - $h \in \{K, \pi\}$
- $K_s^0$ cross-feeds: proton-pion misidentification:
  - $B_{(s)}^0 \rightarrow K_s^0 hh'$
  - $B_{(s)}^0 \rightarrow K_s^0 p\bar{p}$
  - $\Lambda_b^0 \rightarrow K_s^0 ph$
- other (Relevant for LL tracks, unlike modes above):
  - $B^0 \rightarrow p\bar{p}hh' \ [B^0 \rightarrow p\bar{p}K\pi]$
Analysis steps:

- Trigger selection
- Event reconstruction
- Signal MC study
- Backgrounds
- Event Selection
- Hypothesis testing
- Systematic uncertainty studies

Backgrounds considered (2/2):

- Partially reconstructed (not observed) → toy simulation:
  - $\Lambda^0_b \rightarrow \Lambda p\bar{p}\pi^0$
  - $\Xi^0_b \rightarrow \Lambda p\bar{p}\pi^0$

- Modes like $\Lambda^0_b \rightarrow \Sigma^0 p\bar{p}$ (not observed) with a decay $\Sigma^0 \rightarrow \Lambda\gamma$ where the $\gamma$ is not reconstructed:
  - $\Delta m(\Sigma^0 - \Lambda) = (76.959 \pm 0.023)\text{MeV}$
  - $\mathcal{B}_{\Sigma^0 \rightarrow \Lambda\gamma} = 100\%$
Analysis steps:

- Trigger selection
- Event reconstruction
- Signal MC study
- Backgrounds
- **Event Selection**
- *Hypothesis testing*
- *Systematic uncertainty studies*

Selection optimization

- Multivariate approach utilizing machine learning tools to optimize signal event selection

Examples of input variables for optimization:

- $\Lambda_b^0$ transverse momentum
- $\Lambda_b^0$ pseudorapidity
- $\Lambda_b^0$ IP significance w.r.t PV
- $\Lambda_b^0$ pointing angle
- Daughter $\Lambda$ displacement
- ...

...
Purely baryonic decays of baryons are predicted by SM yet not observed, therefore constitute an unexplored class of decays.

Measurements of purely baryonic decays will test theoretical predictions and validate theoretical assumptions.

Selected signal channels $\Lambda^0_b \rightarrow \Lambda p\bar{p}$, $\Xi^0_b \rightarrow \Lambda p\bar{p}$ and associated backgrounds are analyzed.

Study aims at first observation of purely baryonic decays, branching fraction measurement and if the signal yield allows, $CP$ violation will be studied.