Abstract

I report the first observation of the decay of the $\Lambda_b^0$ baryon into a $D_s^+$ meson and a proton. The $D_s^+$ is detected via its $D_s^+ \rightarrow K^+K^-\pi^+$ decay channel and the $\Lambda_b^0 \rightarrow D_s^-p$ branching ratio is being measured with respect to the branching ratio of the $B_s^0 \rightarrow D_s^-\pi^+$ decay. The estimation of uncertainties is planned, but not part of this report.
1 Motivation

The $A^0_b \to D_s^- p$ decay is a possible background component in the LHCb analysis of the $B_s^0 \to D_s^\mp K^\pm$ decay \footnote{See Figure 1}. The final fit in this analysis assumes its presence and yields about 50 $A^0_b \to D_s^- p$ events on data corresponding to $1 \text{fb}^{-1}$. By treating it as signal rather than background, one would expect the significance to increase greatly, opening the possibility for a first observation of this new decay. The $A^0_b$ particle \footnote{See Figure 3} is a baryon with a mass of 5619 MeV and a lifetime of 1.5 ps. It is neutral and consists of a bottom-quark, a down-quark and an up-quark (or their charge conjugates). The decay of a $A^0_b$ into $D_s^+$ and $p$ is doubly Cabibbo suppressed (see Figure 3).

2 Detector

The LHCb detector \footnote{See Figure 4} is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. Different types of charged hadrons are distinguished by information from two ring-imaging Cherenkov (RICH) detectors. Photon,
electron and hadron candidates are identified by a system consisting of scintillating-pad
and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter.
Muons are identified by a system composed of alternating layers of iron and multiwire
proportional chambers. The trigger consists of a hardware stage, based on information
from the calorimeter and muon systems, followed by a software stage, which applies a full
event reconstruction.

3 Analysis

3.1 Preceding estimations

The analysis uses the combined data taken in 2011 and 2012, corresponding to an integrated
luminosity of about 3 fb$^{-1}$. The goal is to measure the $\Lambda_0^b \to D^- s p$ branching ratio,
normalized to the $B_0^s \to D_s^- \pi^+$ branching ratio, eliminating a variety of systematic
uncertainties:

$$\frac{B(\Lambda_0^b \to D^- s p)}{B(B_0^s \to D_s^- \pi^+)} \cdot \frac{f_{\Lambda_0^b}}{f_s} = \frac{N_{D_s^+ p}}{N_{D_s^+ \pi}} \cdot \frac{\varepsilon_{D_s^+ \pi}}{\varepsilon_{D_s^+ p}}.$$  (1)

In this equation, the leftmost term is the ratio of branching ratios, while $\frac{f_{\Lambda_0^b}}{f_s}$ represents
the number of $\Lambda_0^b$ being produced in the detector for each $B_0^s$. On the right side, $N_x$ stands
for the number of events $x$ observed at the end of the analysis and $\varepsilon_x$ is the corresponding
selection efficiency.

In the following, bachelor refers to the pion in the $B_0^s$ decay or the proton in the $\Lambda_0^b$
decay. As can be seen in the Feynman diagrams (Fig. 3) the decays are similar despite the
bachelor particle being a proton in the one and a pion in the other case. The only difference
Figure 3: Feynman diagrams for $\Lambda^0_b \rightarrow D^-_s p$ (a) and $B^0_s \rightarrow D^-_s \pi^+$ (b)

seems to be the ratio of relevant CKM matrix elements, which is roughly $\lambda \approx 0.23$. From this, it is possible to take a guess at the expected branching ratio of $\Lambda^0_b \rightarrow D^-_s p$:

$$B(\Lambda^0_b \rightarrow D^-_s p) = B(B^0_s \rightarrow D^-_s \pi^+) \cdot \left| \frac{V_{ub}}{V_{cb}} \right|^2 \cdot \frac{\tau_{\Lambda^0_b}}{\tau_{B^0_s}} = B(B^0_s \rightarrow D^-_s \pi^+) \cdot 0.0077 = 2.3 \times 10^{-5}. \quad (2)$$

With these numbers and the selection efficiencies taken from Monte Carlo simulated data, we expect an event yield ratio in data of about:

$$N_{D^+_s \pi} = N_{D^+_s \pi} \cdot \frac{B(\Lambda^0_b \rightarrow D^-_s p)}{B(B^0_s \rightarrow D^-_s \pi^+)} \cdot \frac{\epsilon_{D^+_s \pi}}{\epsilon_{D^+_s \pi}} \cdot \frac{f_{\Lambda^0_b}}{f_{B^0_s}} \cdot \frac{f_{D^+_s}}{f_{D^+_s}}$$

$$= N_{D^+_s \pi} \cdot 0.0077 \cdot 0.93 \cdot 1.2 = N_{D^+_s \pi} \cdot 0.085. \quad (4)$$

The $B^0_s$ efficiency is similar to the $\Lambda^0_b$ efficiency because some cuts are not applied on $B^0_s \rightarrow D^-_s \pi^+$.

3.2 Implementation

A multivariate classifier called Boosted Decision Tree (BDT) is used to select against combinatorial background. For training, it needs a signal sample for which we use Monte Carlo and a background sample which is obtained from signal-free data side band. The other cuts are single-dimensional.

The $\Lambda^0_b \rightarrow D^-_s p$ decays are initially reconstructed by the LHCb software as $B^0_{d,s} \rightarrow D^+ \rightarrow D^-_s K^+$. This is similar to the signal decay, but the assigned kaon mass differs from the proton mass. We replace the kaon mass assigned to the bachelor track with the mass of the proton and re-fit everything and store the affected variables. The same process is then repeated for the $B^0_s \rightarrow D^-_s \pi^+$ channel, where a Pion is taking the place of the bachelor particle. The $D^+_s$ is detected via its decay channel.

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This leads to non-trivial side effects. For example, the presence of a $B$ mass window in the initial reconstruction turns into a geometry-correlated cut after the proton refit. As can be seen in Figure 4, the shift towards bigger masses increases for lower values of $\text{lab1\_CosTheta}$. This takes a big effect on the BDT and through selective removal of some variables I could improve the BDT performance considerably.

We also discovered that some kinematic variables were not correctly simulated in the signal Monte Carlo samples. We mitigated this for those variables that entered the BDT by re-weighting the most affected ones via comparison with the $B_s^0 \rightarrow D^- \pi^+$ reference channel. I developed an algorithm that selected a very pure $B_s^0 \rightarrow D^- \pi^+$ signal sample in data and re-weighted the corresponding Monte Carlo distributions until both samples matched. The obtained weights were then applied to the $\Lambda_b^0 \rightarrow D^- p$ Monte Carlo. This approach relies on the fact that the Monte Carlo discrepancy is mostly a multiplicative factor common to both decays. Figure 5 shows the re-weighting process applied to the $B_s^0$ sample itself, providing a check for the algorithm. The Monte Carlo events (in red) are re-weighted to match the (black) data distribution. The result (in green) is a Monte Carlo distribution that much better matches the data.

Furthermore, I discovered discrepancies in the particle identification (PID) variables, which have a big influence on the estimated efficiencies and everything that depends on the latter. A data-driven estimation of the cut efficiency could solve this crucial problem. This is the next step in the further progress of the.

Most important for the offline analysis is the cut on $\text{lab1\_CosTheta}$, which currently is required to be greater zero. This removes most of the relevant background and most importantly, it constrains the $B_s^0 \rightarrow D^- \pi^+$ background to masses that are lower than 5600 MeV, isolating the true $\Lambda_b^0$ signal.
Figure 5: Re-weighting of MC variables, effect in $B_s^0 \rightarrow D_s^- \pi^+$ control channel. The red line stands for the original MC distribution. After re-weighting it to match the data signal distribution (black line), it is transformed into the green curve.

Figure 6: $A_0$ mass distribution after all selection cuts. The red dotted line is the scaled combinatorial background taken from the $D_s^+$ sideband.

4 Results and Discussion

The $A_0$ mass distribution after the final selection can be seen in Figure 6. A clear peak is observed at 5620 MeV. Its width is consistent with the detector resolution expected
Figure 7: $\Lambda^0_b$ lifetime distribution after all selection cuts. The red dotted line is the scaled combinatorial background taken from the $D_s^+$ sideband. The grey dotted line is the scaled Monte Carlo simulated $\Lambda^0_b$ signal.

from MC. On the left side, the remaining $B^0_s$ events are visible. It is possible to select pure combinatorial background by looking at the mass distribution in the $D_s^+$ sideband. The latter expression refers to a selection were the $D_s^+$ mass cut is shifted to exclude the actual $D_s^+$ mass. As can be seen, the combinatorial background is flat in the signal region. By selecting the peak region via a small mass window, the lifetime distribution shown in Figure 7 is obtained. The sample, which still contains a few background events, matches the Monte Carlo prediction quite well, while the lifetime distribution in the side band consists mostly of short-lived events. This gives strong confidence that the $\Lambda^0_b$ peak is genuine.

Figure 6 suggests that the observed yield ratio between the two considered decays does not match the expectations when comparing the $\Lambda^0_b$ peak to the lower-mass contribution below 5580 MeV stemming from $B^0_s \to D_s^- \pi^+$. To obtain a better estimate on the $B^0_s \to D_s^- \pi^+$ yield, we do not apply any proton-identification related cuts when counting the events in this channel. A fit by eye then gives about 60 events in $\Lambda^0_b \to D_s^- p$ and 26000 in $B^0_s \to D_s^- \pi^+$. The cuts on the bachelor PID are omitted for the latter, leading to a branching ratio of:

$$\mathcal{B}(\Lambda^0_b \to D_s^- p) = 6.6 \times 10^{-6}.$$  

The discrepancy to the expected branching ratio of Eq. 2 is likely due to the fact that the correction on the simulated distributions of the particle identification variables has not yet been applied. Also, not much is known about b-baryon dynamics, so that the simple estimate of Eq. 2 is perhaps not sufficient.
In summary, I observed a new decay mode of the \( \Lambda^0 \) baryon for the first time. After a limited number of improvements, such as the data-driven estimation of the PID efficiencies and a signal fit, it is planned to submit the results to a peer-reviewed journal.

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References

[1] LHCb collaboration, E. Rodrigues and A. Dziurda, Measurement of time-dependent \( CP \)-violation observables in \( B_s^0 \rightarrow D_s^{\mp} K^\pm \).
