Measurement of the lifetimes of the \( \Xi_b^- \) and \( \Omega_b^- \) baryons

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Abstract

We report on preliminary measurements of the \( \Xi_b^- \) and \( \Omega_b^- \) lifetimes. These strange \( b \)-baryons are fully reconstructed in the \( \Xi_b^- \rightarrow J/\psi \Xi^- \) and \( \Omega_b^- \rightarrow J/\psi \Omega^- \) decay modes using 1 fb\(^{-1} \) of data collected with the LHCb detector during the 2011 physics run of the Large Hadron Collider. We measure

\[
\tau(\Xi_b^-) = 2.20 \pm 0.32 \, \text{(stat)} \pm 0.08 \, \text{(syst)} \, \text{ps};
\]

\[
\tau(\Omega_b^-) = 1.23 \pm 0.42 \, \text{(stat)} \pm 0.16 \, \text{(syst)} \, \text{ps}.
\]
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1 Introduction

The aim of this master thesis is to measure the lifetimes of the $\Xi_b^-$ and $\Omega_b^-$ baryons which decay weakly. We use the data provided by the $pp$ collisions of the Large Hadron Collider (LHC) which can, due to the high energy of the collisions ($\sqrt{s} = 7$ TeV), create all the $b$-baryon species. The standard quark model predicts 16 different ground states, of which 13 should decay weakly.

First, we discuss briefly the LHCb detector, with focus on the detectors that we use to detect the $\Xi_b^-$ and $\Omega_b^-$ decay chains.

Then, we describe the topology of the decays that we are interested in, and discuss the selection applied to be able to observe the decays that truly correspond to our particles.

We also discuss the various acceptances (i.e., time-dependent efficiencies) that may affect the lifetime measurements such as the ones due to the HLT1 and HLT2 trigger and the offline reconstruction.

Moreover, we perform a two-dimensional fit on the offline selected candidate of the mass and the decay time to finally determine the lifetimes and secondarily the masses.

Finally, with all the above taken into consideration, we give our best estimate of the lifetimes of the two particles studied and evaluate the corresponding systematics.

2 Theoretical framework

2.1 Brief explanation of QCD implications in the $b$-hadron lifetime differences

In the spectator model the decay of $b$-flavored hadrons is governed entirely by the weak decay of the $b$ quark. For this reason, lifetimes of all $b$-flavored hadrons are the same in the spectator approximation regardless of the (spectator) quark content of the considered $b$-hadron.

In the early 1990s experiments became sophisticated enough to start seeing the differences between the lifetimes of the various $b$-hadron species. The first theoretical calculations of the spectator quark effects on the lifetime emerged only few years earlier [1].

Currently, most of such calculations are performed in the framework of the HQE (Heavy Quark Expansion). In the HQE, under certain assumptions, the decay rate of a $b$-hadron to a final state $f$ is expressed as the sum of a series of expectation values of operators of increasing dimension, multiplied by the correspondingly higher powers of $\frac{\Lambda_{QCD}}{m_b}$:

$$\Gamma_{H_b \rightarrow f} = |CKM|^2 \sum_n c_n^{(f)} \left( \frac{\Lambda_{QCD}}{m_b} \right)^n <H_b|O_n|H_b>$$

(1)

where $H_b$ is the $b$-flavored hadron , $|CKM|$ is the relevant combination of the CKM
matrix elements and $c_n^{(f)}$ the coefficients of this expansion that can be calculated perturbatively.

Hence, the HQE predicts $\Gamma_{H_b \to f}$ in the form of an expansion in both $\frac{\Lambda_{\text{QCD}}}{m_b}$ and $\alpha_s(m_b)$.

The precision of current experiments makes it mandatory to go to a higher order in QCD i.e. to include correction of the $\alpha_s(m_b)$ in the $c_n^{(f)}$ coefficients.

All non-perturbative physics is shifted into the expectation values $< H_b|O_n|H_b >$ of operators $O_n$.

These cannot be computed with small perturbative expansion and thus are calculated using numerical methods such as lattice QCD. One may reasonably expect that powers of $\frac{\Lambda_{\text{QCD}}}{m_b}$ provide enough suppression that only the first few terms of the sum in Eq. 1 matter [1].

2.2 Lifetime theoretical prediction

The sole reliable theoretical prediction that we were able to find is quoted in a paper by Alexander Lenz [2]. In this paper, there is a theoretical prediction of the lifetime ratio between the $\Xi_b^-$ and the $\Lambda_b$. It is important to note that this ratio is merely a prediction of the $\Xi_b^-$ lifetime since the $\Lambda_b$ is formed by the two quarks of the first generation and therefore its lifetime is known to a good accuracy (PDG value [3]: $\tau(\Lambda_b) = 1.425 \pm 0.023$ ps).

The ratio obtained by the numerical study of the QCD effects is

$$\frac{\tau(\Xi_b^-)}{\tau(\Lambda_b)} = 0.88 \pm 0.02 \pm ???,$$

where ??? stands for some unknown systematic errors.

The first approximation (without QCD corrections) and the second approximation Feynman diagrams of the $\Xi_b^-$ and $\Omega_b^-$ weak decay can be seen respectively on figures 1 and 2.

We can see the case without the gluons exchanged and the real case with the gluons that causes the differences in the lifetimes of the $b$-hadrons.

3 State of the art

A previous lifetime study of the two particles of interest was performed by the CDF experiment (Collider Detector at Fermilab), a proton anti-proton collider at a center-of-mass energy of 1.96 TeV [4].

They reported:

$$\tau(\Omega_b^-) = 1.13^{+0.53}_{-0.49} \text{ (stat)} \pm 0.02 \text{ (syst)} \text{ ps};$$

$$\tau(\Xi_b^-) = 1.56^{+0.27}_{-0.25} \text{ (stat)} \pm 0.02 \text{ (syst)} \text{ ps}.$$

The $\Omega_b^-$ was observed in the $\Omega_b^- \to J/\psi \Omega^-$ decay channel (the same as ours) with $16 \pm 6$ candidates and a significance of $5.5 \sigma$ from a combined mass-lifetime fit.
Figure 1: Feynman diagrams of the decay of the $\Xi_b^-$ into a $J/\psi (c\bar{c})$ and a $\Xi^-$. On the right we have gluons exchanged between the quarks which cause the QCD corrections.

Figure 2: Feynman diagrams of the decay of the $\Omega_b^-$ into a $J/\psi (c\bar{c})$ and a $\Omega^-$. On the right we have gluons exchanged between the quarks which cause the QCD corrections.

The $\Xi_b^-$ was observed in the $\Xi_b^- \rightarrow J/\psi \Xi^-$ decay channel (the same as ours) with $66 \pm 14$ candidates.
4 Brief description of the LHCb experiment

LHCb is one of the four main experiments at the Large Hadron Collider. It is a single-arm forward spectrometer. Its main purpose is to measure CP violation and rare decays in
the $b$-quark and $c$-quark sectors (such as the ones we are interested in).

4.1 The Vertex Locator

The VELO allows the primary and secondary (the desintegration one in case of $b$-decays) vertex reconstruction.

Due to the large boost of the produced bottom hadrons, their flight distance in the detector is long enough to be measured. A very good accuracy is required to separate the secondary vertices, i.e. where the $b$-hadron decays, from the primary vertices, i.e. the $pp$ interaction. The VELO has been designed for a decay time resolution for reconstructed $b$-hadrons of the order of 50 fs, which is a good resolution for our study since the particles that we study have a typical decay time of more than a picosecond.

The VELO plays a significant role in the High Level Trigger (HLT), because it allows the reconstruction of displaced vertices, which is a signature of a $b$-hadron decay.

4.2 The Cherenkov detectors

The Ring Imaging Cherenkov (RICH) detectors allow to distinguish between charged pions and kaons. This is important to increase the signal to background ratio in the selection of $b$-hadrons. There are two RICH detectors in LHCb, named RICH1 (upstream of the magnets) and RICH2 (downstream of the tracking stations). They allow the separation of pions from kaons in a momentum window from 1 to 150 GeV/c, which covers around 90% of the pions and kaons produced in a $b$-hadron decay.

4.3 The calorimeters

The LHCb calorimeter system consists of the Scintillator Pad Detector (SPD), a PreShower (PS), an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL).

The purpose of the calorimeter system is mainly to detect and measure the total energy and impact point of hadrons, photons and electrons for the Level 0 trigger and the offline analysis.

4.4 The tracking system

The main goal of the tracking system is to achieve a relative resolution on the track momenta of 0.4%, resulting in a typical resolution of 10 MeV/$c^2$ on the reconstructed $b$-hadron mass. The elements contributing to this are the magnet, the Vertex Locator, the Tracker Turicensis (TT) located in front of the magnet, and the three tracking stations downstream of the magnet.
4.5 The trigger system

We are particularly interested in the trigger because we use in our study some specific trigger lines for which we determine the acceptance in the Monte-Carlo simulation, and then we use this computed acceptance on the real data to adjust the lifetime measurement. Indeed, these trigger acceptances distort the shape of the lifetime distribution.

Firstly, there is the L0 trigger. The events accepted by this trigger are processed by the High Level Trigger (HLT), divided into HLT1 and HLT2.

The HLT is a software trigger, running on a large CPU farm. Both HLT1 and HLT2 contain some trigger lines causing a proper time bias (cuts on a parameter that will distort the lifetime measurement, like the impact parameter or the decay length significance for instance) and therefore the acceptance induced by these trigger lines will not be independent of the decay time.

The HLT1 lines must confirm the L0 decision, checking whether a track can be reconstructed from the hits in the tracking system, using the L0 object (which can be an electron, a muon or a hadron), then cuts are applied. A HLT1 accepted event is then fully reconstructed in HLT2, using algorithms as close as possible to the ones used during offline reconstruction, and a set of selections is applied.
5 Lifetime measurement method

5.1 Brief overview of the whole analysis

We search for \( \Xi_b^- \to J/\psi \Xi^- \) and \( \Omega_b^- \to J/\psi \Omega^- \) decays involving five charged tracks. The topology is the same in both cases. As the \( \Xi_b^- \) (\( \Omega_b^- \)) baryon decays weakly and has a lifetime of the same order as the other \( b \) hadrons, its decay vertex is expected to be separated from the primary \( pp \) interaction vertex: the two muons of the \( J/\psi \) originate from this secondary vertex. The long-lived \( \Xi^- \) (\( \Omega^- \)) decays into a \( \Lambda^0 \) and a charged pion (kaon) at a tertiary vertex, and the \( \Lambda^0 \) decay causes a quaternary vertex. The topology is summarized in figure 6.

The main idea in this analysis is on the one hand to study the event selection that has been applied on the data by using the Monte-Carlo as a test sample. On the other hand, we use the Monte-Carlo to determine the several effects that distort the distribution of the decay time.

With all this information, we finally perform a two-dimensional fit (mass-lifetime) to determine the lifetime of the two studied particles.

5.2 Definition of the lifetime

In our experiment this lifetime is determined indirectly by measuring the decay length i.e. the distance between the primary vertex and the secondary one in the Vertex Locator.

The true decay time is then given by :

\[
t_{\text{true}} = \frac{D}{P} \cdot M \tag{3}
\]

The reconstructed decay time is then given by :

\[
t_{\text{reconstructed}} = \frac{\vec{P} \cdot \vec{D}}{P^2} \cdot M \tag{4}
\]

Where \( \vec{D} \) correspond to the decay length, \( \vec{P} \) and \( M \) to the momentum and to the mass of the decaying particle.

Note that in reality it’s the DecayTreeFitter algorithm [5] that is used in LHCb (and thus in our study) for all the lifetimes studies.
5.3 PDF used to fit the lifetime

We assume that the $b$-hadron considered decay like standard weak decaying radioactive atoms which also decay due to the weak interaction. Consequently the number of $b$-hadrons present after a time $t_{\text{true}}$ must be simply:

$$N_{b-\text{hadrons}}(t_{\text{true}}) = N_{b-\text{hadrons}}(t_{\text{true}} = 0).e^{-\frac{t_{\text{true}}}{\tau}}$$  \hspace{1cm} (5)

where $\tau$ is precisely the lifetime of the $b$-hadron.

A priori we could have fitted the lifetime with the simple decreasing exponential, but the reality is much more complex due to the fact that the detector and the track reconstructions are not perfect.

One could think of many effect affecting the shape of the lifetime, but we decided to focus only on three most important corrections to the simple exponential.

Firstly, we take into account the resolution of the Vertex Locator which we measure using the Monte-Carlo sample by studying the distribution of the lifetime given by the detector (the reconstructed lifetime) minus the true lifetime for each decaying particle in the Monte-Carlo sample.

Secondly, we take into account the reconstruction effect, which is described by a linear decreasing efficiency. We also consider the efficiency induced by the lines of trigger that we use (see section 7).

Consequently, the (not normalized) PDF used to fit the lifetime signal is

$$N_{b-\text{hadrons}}(t_{\text{rec}}) = N_{b-\text{hadrons}}(t_{\text{rec}} = 0).e^{-\frac{t_{\text{true}}}{\tau}} \otimes res(t).(1 + \beta t_{\text{rec}}).Eff_{\text{Trig}}(t_{\text{rec}})$$  \hspace{1cm} (6)

where,
- $res(t)$ is the resolution function
- $\beta$ is the reconstruction factor (probably mainly due to the reconstruction in the Vertex locator)
- $Eff_{\text{Trig}}(t)$ is the efficiency of the trigger line which is multiplied numerically directly (see 7)

6 Dataset, stripping and selection strategy

6.1 Dataset

This analysis uses an integrated luminosity of about 1 fb$^{-1}$ of $pp$ collision data recorded with the LHCb detector at a center-of-mass energy of $\sqrt{s}=7$ TeV in 2011. All detector components were fully operational and in stable conditions. The dataset is the Stripping 17b. The sample contains data recorded with the two field polarities.
Table 1: Stripping level selection. The requirements are applied on the standard loose pions and kaons, standard loose $A^0$ candidates, and standard mass-constrained $J/\psi \rightarrow \mu^+\mu^-$ candidates, all associated with good tracks ($\chi^2/\text{ndf} < 4$). The mass windows are centered on the PDG mass values.

<table>
<thead>
<tr>
<th>$A^0$ selection requirements</th>
<th>$J/\psi$ selection requirements</th>
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<tbody>
<tr>
<td>$p[A^0]$ $p_T$</td>
<td>$\mu$ $p_T$</td>
</tr>
<tr>
<td>$\pi[A^0]$ $p_T$</td>
<td>$p_T$</td>
</tr>
<tr>
<td>$\pi[A^0]$ PIDK</td>
<td>PID$\mu$</td>
</tr>
<tr>
<td>$A^0$ vertex $\chi^2/\text{ndf}$</td>
<td>$J/\psi$ vertex $\chi^2/\text{ndf}$</td>
</tr>
<tr>
<td>$A^0$ mass window</td>
<td>$J/\psi$ mass window</td>
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<tr>
<th>$\Xi^-$ selection requirements</th>
<th>$\Omega^-$ selection requirements</th>
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<tr>
<td>$\pi[\Xi^-]$ $p_T$</td>
<td>$K[\Omega^-]$ $p_T$</td>
</tr>
<tr>
<td>$\pi[\Xi^-]$ IP $\chi^2/\text{ndf}$</td>
<td>$\Omega^- IP$ $\chi^2/\text{ndf}$</td>
</tr>
<tr>
<td>$\Xi^-$ vertex $\chi^2/\text{ndf}$</td>
<td>$\Omega^-$ vertex $\chi^2/\text{ndf}$</td>
</tr>
<tr>
<td>$\Xi^-$ flight significance</td>
<td>$\Omega^-$ flight significance</td>
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<tr>
<td>$\Xi^-$ mass window</td>
<td>$\Omega^-$ mass window</td>
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<th>$\Xi_b^-$ selection requirements</th>
<th>$\Omega_b^-$ selection requirements</th>
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<tr>
<td>$\Xi_b$ vertex $\chi^2/\text{ndf}$</td>
<td>$\Omega_b$ vertex $\chi^2/\text{ndf}$</td>
</tr>
<tr>
<td>$\Xi_b$ mass range</td>
<td>$\Omega_b$ mass range</td>
</tr>
</tbody>
</table>

6.2 Offline selection

The selection is the same that of a previous study of the mass of the two studied particles [6].

For the $\Omega_b^-$ it’s important to note that we have no $\Omega_b^-$ Monte Carlo sample, because of technical issues associated with PYTHIA and the low probability to generate a $bss$ baryon in the hadronization process. The lack of $\Omega_b^-$ Monte Carlo sample is not an issue in this analysis. Indeed, the strategy for selecting $\Omega_b^-$ candidates is simply to apply the $\Xi_b^-$ cuts, however with appropriate PID requirements for the kaon selection and mass windows for the $\Omega_b^-$ and $\Omega^-$ selection.

6.2.1 Stripping selection

For the stripping, we use the stripped sample Stripping 17b, very similar to the one that was used precedently to study the masses of the two studied particles [6]. The applied cuts can be seen on table 1. We have 1148412 candidates that pass the stripping for $\Omega_b^-$ and 147936 candidates that pass the stripping for $\Xi_b^-$. 
Table 2: Offline selection of $\Xi_b^- \rightarrow J/\psi \Xi^-$ candidates. The requirements are applied on candidates passing the stripping selection. The mass windows are centered on the PDG mass values.

<table>
<thead>
<tr>
<th>$\Lambda^0$ selection requirements</th>
<th>$J/\psi$ selection requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda^0$ $p_T$ $&gt;$ 700 MeV/c</td>
<td>$J/\psi$ vertex $\chi^2$/ndf $&lt;$ 10</td>
</tr>
<tr>
<td>$\Lambda^0$ proper time significance $&gt;$ 0</td>
<td>$J/\psi$ mass window $\pm 4.2 \times \sigma_M$</td>
</tr>
<tr>
<td>$\Lambda^0$ mass window $\pm 6$ MeV/c$^2$</td>
<td>$\Xi_b^-$ selection requirements</td>
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</tbody>
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<table>
<thead>
<tr>
<th>$\Xi^-$ selection requirements</th>
<th>$\Xi_b^-$ selection requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi^-$ $p_T$ $&gt;$ 900 MeV/c</td>
<td>$\Xi_b^-$ $\chi^2$/ndf $&lt;$ 10</td>
</tr>
<tr>
<td>$\Xi^-$ vertex $\chi^2$/ndf $&lt;$ 10</td>
<td>$\tau(\Xi_b^-)$ $&gt;$ 0.3 ps</td>
</tr>
<tr>
<td>$\Xi^-$ proper time significance $&gt;$ 5</td>
<td>$\Xi_b^-$ $\sigma(M)$ $&lt;$ 14 MeV/c$^2$</td>
</tr>
<tr>
<td>$\Xi^-$ mass window $\pm 11$ MeV/c$^2$</td>
<td></td>
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6.2.2 Final selection

The cuts to select $\Xi_b^-$ candidates are listed in Table 2. Moreover, we also request finally that the candidates pass the two trigger lines: Hlt1DiMuonHighMass and Hlt2DiMuonDetachedJPsi (the first one is unbiased, the second one is biased).

We plot the main variables on which we cut on the figures 18, 19, 20 and 21. After the selection on the data (but before the trigger) we have 320 candidates remaining for $\Xi^-$. Finally we have 221 candidates remaining for $\Xi^-$. We apply the same selection criteria to the $\Omega_b^-$ candidates as to the $\Xi_b^-$ candidates (see Table 2), but with the following two changes: firstly, the kaon from the $\Omega^-$ decay is selected by requiring the difference in log likelihood between the kaon and pion hypotheses to be larger than 5, and secondly the invariant mass of the $\Omega^-$ candidate is required to be within $\pm 11$ MeV/c$^2$ of the nominal $\Omega^-$ mass. The size of the $\Omega^-$ signal window is chosen to be same as that of the $\Xi^-$ signal window, on the assumption that the $\Omega^-$ and $\Xi^-$ mass resolutions are expected to be similar.

After the selection on the data (but before the trigger) we have 86 candidates remaining for $\Omega_b^-$. Finally we have 65 candidates remaining for $\Xi_b^-$. 7 Monte-Carlo studies

We use a Monte-Calo sample of $\Xi_b^- \rightarrow J/\psi \Xi^-$ events with a lifetime input of 1.42 ps to do the study. This sample contains 27850 events and approximately half of them have the MC truth.
7.1 Study of the types of the tracks produced in the final state

We have studied on the Monte-Carlo sample the different types of tracks (Long or Downstream) for the three particles produced in the final state of the decay of the $\Xi^{-}_b$: the two pions and the proton.

We talk about a Long track when the track is fully reconstructed from the VELO to the tracking stations.

The Downstream tracks are tracks that are only reconstructed in the tracking stations (TT and the T-stations). This can be seen on figure 7.

Since we have 3 particles in the final state we have different possible combinations of long and downstream tracks. The three main combination are listed in Table 3.

7.2 Resolution study

As said before, we first have to determine the resolution that we have on the measurement of the lifetime using the Monte-Carlo sample by comparing the true lifetime and the reconstructed lifetime for several tracks. The distribution of $t_{rec} - t_{true}$ is plotted on figure 8.

We now use this resolution function to convolve it with the lifetime function to see what we expect to obtain with the real data with a non-perfect (non-dirac) resolution. The result can be seen on Figure 9.
Figure 8: Distribution of the difference between the reconstructed decay time and the true decay time for Monte Carlo signal events passing the selection. It’s fitted with a double gaussian which have a mean value of \(-7 \pm 0.4 \) fs. In red we have the first gaussian \((\sigma = 142 \) fs\), in green the second one \((\sigma = 42 \) fs\) and in blue the sum of the two. (10% of the events in red and 90% of the events in green)

### 7.3 Efficiency Study

#### 7.3.1 Proportion of HLT1 and HLT2 accepted events on the Monte-Carlo Sample

We consider only the Hlt1DiMuonHighMass, Hlt2DiMuonDetachedJPsi and Hlt2DiMuonJPsi trigger lines. They trigger on a significant part of the events. Indeed, Hlt1DiMuonHighMass trigger 61.44 % of the events with MC truth, Hlt2DiMuonDetachedJPsi trigger 76.75 % of the events with MC truth and Hlt2DiMuonJPsi trigger 88.99 % of the events with MC truth.
7.3.2 Acceptance functions for the three lines of trigger considered on the Monte-Carlo Sample

We now want to see the shape of the acceptance induced by the three trigger lines considered. To do that we use bins of exponentially increasing size in decay time (since we have a lot less events for high decay time). The result can be seen in Figure 10.

As expected, the HLT1 and the HLT2 not detached (which must be unbiased for the lifetime) are quasi-flat, whereas the HLT2 detached cuts almost all the events for low lifetime.

7.3.3 Efficiency of the HLT2 line that we use

Since, we have seen before that the HLT1 line considered is flat, we can assume a constant efficiency and thus it will not affect the lifetime PDF.

Consequently, we must determine the effect of passing through the HLT2 line on the lifetime PDF.
This effect must be determined independently of the reconstruction effect. We could have done this in another way i.e. studying in the same time the trigger and the reconstruction efficiency, but we wanted to clearly separate the two effect in order to be able to study their systematics separately.

In order to do that, we divide the number of events that have passed the Hlt2DiMuonDetachedJPsi trigger line by the number of event that have passed the Hlt2DiMuonJPsi trigger line.

Since this two trigger lines are mainly the same after 0.3-0.4 ps we only have the effect of the small number of triggered events at low lifetime.

We compute this efficiency by requiring to pass HLT1 and to have the MC truth. Furthermore, we use variable-size bins because obviously we will have much less events in the high lifetime region.

This efficiency can be seen in Figure 11.

7.3.4 Efficiency induced by the reconstruction i.e. determination of the $\beta$

As seen in 5.3 we also have to determine the $\beta$ factor in the lifetime’s PDF.

In order to do that, we fix the lifetime at the value given to the MC sample (1.42 ps), and then we fit the signal PDF of the lifetime with only the $\beta$ as a free parameter to be
Figure 11: Efficiency of the passed trigger lines as a function of the decay time. This is done such that the reconstruction effect is eliminated.

Table 3: Summary of the tracks combination percentage and the corresponding $\beta$

<table>
<thead>
<tr>
<th>Type ($\pi, \pi$ (from $\Lambda_0$), $p$)</th>
<th>Percentage in the MC sample</th>
<th>Value of $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDD</td>
<td>41.2 %</td>
<td>$-0.024 \pm 0.0076 \text{ ps}^{-1}$</td>
</tr>
<tr>
<td>LLL</td>
<td>12.6 %</td>
<td>$-0.032 \pm 0.019 \text{ ps}^{-1}$</td>
</tr>
<tr>
<td>DDD</td>
<td>44.1 %</td>
<td>$-0.005 \pm 0.017 \text{ ps}^{-1}$</td>
</tr>
<tr>
<td>All</td>
<td>97.9 %</td>
<td>$-0.0324 \pm 0.0079 \text{ ps}^{-1}$</td>
</tr>
</tbody>
</table>

fitted.
We obtain $\beta = -0.0324 \pm 0.0079 \text{ ps}^{-1}$.
The value of $\beta$ differs slightly for each set of types of tracks (as indicated in table 3) of the final state, and therefore the whole study could have been done independently for each one.

8 Lifetime study on data

We now apply what we have learned from the Monte-Carlo sample to study correctly the selected data. In the following we use unbinned maximum likelihood fits.

It’s worth to mention that the whole study has been done with a blinding of the central lifetime value and therefore we were not influenced by the result when we decided if the work has been done correctly.
8.1 Description of the 2D fits

The total two-dimensional Probability Density Function is the sum, weighted by the coefficients which indicate the number of signal and background events, of the signal PDF and the background PDF.

Note that all the parameters are free (but a little bit constrained to help the fit to converge) except the lifetime resolution (the distribution of $t_{rec} - t_{true}$) and the efficiency which are fixed to their values from the Monte-Carlo study as explained before.

8.1.1 Description of the signal PDF

The joint PDF that describes the 2D signal is the product of the lifetime signal PDF as seen in section 5.3 and the mass signal PDF which is a double Gaussian function i.e. a weighted sum of two Gaussian functions having the same mean values but different standard deviations.

8.1.2 Description of the background PDF

The joint PDF that describes the 2D background is the product of the lifetime background PDF which is the weighted sum of two decaying exponential function and the mass background PDF which is a linear function.

8.2 2D fit results

8.2.1 For $\Xi_b^-$

We divide the mass range into three interval :
- Low mass range : from 5500 to 5720 MeV/$c^2$
- Signal mass range : from 5720 to 5870 MeV/$c^2$
- High mass range : from 5870 to 6100 MeV/$c^2$

We then plot on Figure 12 the projection of the lifetime for these different mass ranges. We do the two dimensional likelihood fit using the PDF on the full mass range (from 5500 to 6100 MeV and from 0.3 to 14 ps) and we obtain the results summarized in Table 4. After the trigger we have 221 candidates left (we had 320 in the sample).

8.2.2 For $\Omega_b^-$

We divide the mass range into three interval :
- Low mass range : from 5500 to 5970 MeV/$c^2$
- Signal mass range : from 5970 to 6120 MeV/$c^2$
- High mass range : from 6120 to 6500 MeV/$c^2$

We then plot on figure 14 the projection of the lifetime for these different mass ranges. We do the two dimensional fit on the full mass range (from 5500 to 6500 MeV/$c^2$ and from 0.3 to 14 ps) and we obtain the results summarized in Table 5. After the trigger we have 65 candidates left (we had 86 in the sample).
Figure 12: Projection on the lifetime axis of the 2D fit in different mass regions. We have in red the two decaying exponential which fit the background, in green the PDF of the signal, and in blue the sum i.e. the total PDF.

Figure 13: Left: the two-dimensional distribution of the 221 events in the data sample. Right: the projection on the mass axis of the 2D fit for all lifetime values. In red we have the background and in green the signal.

We can already be confident with the obtained results for the mass since the fitted mass is clearly similar to the one obtained in the mass study done on the same particles [6].
Table 4: Summary of the important results of the 2D fit for $\Xi_b^-$

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime</td>
<td>$2.20 \pm 0.32$ ps</td>
</tr>
<tr>
<td>Mass</td>
<td>$5.797 \pm 0.001$ GeV/$c^2$</td>
</tr>
<tr>
<td>Number of signal events</td>
<td>$67 \pm 9$</td>
</tr>
<tr>
<td>Number of background events</td>
<td>$154 \pm 13$</td>
</tr>
<tr>
<td>Lifetime (first background)</td>
<td>$0.29 \pm 0.05$ ps</td>
</tr>
<tr>
<td>Lifetime (second background)</td>
<td>$1.75 \pm 0.62$ ps</td>
</tr>
</tbody>
</table>

Figure 14: Projection on the lifetime axis of the 2D fit in different mass regions. We have in red the two decaying exponential which fit the background, in green the PDF of the signal, and in blue the sum i.e. the total PDF.

9 Systematics

The following sources of systematic uncertainty are considered:

- Background of the lifetime description
- Resolution ($t_{rec} - t_{true}$) of the lifetime description
Figure 15: Left : the two-dimensional distribution of the 65 events in the data sample. Right : the projection on the mass axis of the 2D fit for all lifetime’s values. In red we have the background and in green the signal.

Table 5: Summary of the important results of the 2D fit for $\Omega_b^-$

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime</td>
<td>$1.23 \pm 0.42$ ps</td>
</tr>
<tr>
<td>Mass</td>
<td>$6.0519 \pm 0.0275$ GeV/c^2</td>
</tr>
<tr>
<td>Number of signal events</td>
<td>$20 \pm 6$</td>
</tr>
<tr>
<td>Number of background events</td>
<td>$46 \pm 7$</td>
</tr>
<tr>
<td>Lifetime (first background)</td>
<td>$0.26 \pm 0.05$ ps</td>
</tr>
<tr>
<td>Lifetime (second background)</td>
<td>$5.10 \pm 2.45$ ps</td>
</tr>
</tbody>
</table>

- Trigger and reconstruction efficiency

- Momentum and decay-length scale

For the systematic error coming from the lifetime background description we use the value given for the lifetime by the $s$Plots. Indeed, the $s$Plots uses a complete different technique to describe these variables by attributing statistical weight to the events, and does not rely on a background model. The $s$Plot technique is a statistical tool which can extract the signal and the background from the data by attributing different weights to events considered as signal and background [7].

We use it to extract the signal which we fit with the same PDF as explained in 5.3. We see the result on figure 16 for $\Xi_b^-$ and figure 17 for $\Omega_b^-$. For the systematic error coming from the resolution description, we add 15% to the standard deviation of each of the two Gaussians function. This is justified by the fact that we see in [8] that the resolution is, in the worst case, underestimated by 15% on the Monte-Carlo sample relatively to the real data sample.
Figure 16: In green the signal fitted by the total PDF. In blue, the simple decaying exponential function convolved with the resolution. The result of the fit is $\tau = 2.25 \pm 0.48 \text{ps}$.

Figure 17: In green the signal fitted by the total PDF. In blue, the simple decaying exponential function convolved with the resolution. The result of the fit is $\tau = 1.08 \pm 0.26 \text{ps}$.

For the systematic error coming from the trigger acceptance, we compare with an acceptance measured with much more data on a real data sample of a similar decay (the decay of $B_0$ which is also due to the decay a $b$ quark).
Table 6: Summary of the systematics for $\Xi_b^-$

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Value (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background description</td>
<td>0.05</td>
</tr>
<tr>
<td>Time resolution</td>
<td>0.001</td>
</tr>
<tr>
<td>Trigger acceptance</td>
<td>0.01</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>0.06</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>0.001</td>
</tr>
<tr>
<td>Decay length scale</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 7: Summary of the systematics for $\Omega_b^-$

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Value (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background description</td>
<td>0.15</td>
</tr>
<tr>
<td>Time resolution</td>
<td>0.004</td>
</tr>
<tr>
<td>Trigger acceptance</td>
<td>0.01</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>0.01</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>0.001</td>
</tr>
<tr>
<td>Decay length scale</td>
<td>0.001</td>
</tr>
</tbody>
</table>

For the systematic error coming from the reconstruction efficiency i.e. the value of $\beta$, we simply vary the $\beta$ by 0.01 which correspond to a little more than the error on the $\beta$. We do that because we know that the value of $\beta$ vary by more that one standard deviation according to the track type considered as seen in table 3.

Finally, for the momentum scale and the decay length scale, since we assume that the systematic on these two quantity will be merely the same in all the experiments, we take the value given by a previous study [8].

9.1 Results for $\Xi_b^-$

Since we assume that all the uncertainties shown in Table 6 are independent, we take the quadratic sum to find the total systematic uncertainty on the lifetime measurement. The total systematic uncertainty of the $\Xi_b^-$ lifetime is then 0.08 ps.

9.2 Results for $\Omega_b^-$

Since we assume that all the uncertainties shown in Table 7 are independent, we take the quadratic sum to find the total systematic uncertainty on the lifetime measurement. The total systematic uncertainty of the $\Omega_b^-$ lifetime is then 0.16 ps.
10 Conclusion

In conclusion, the lifetime measured for the two particles is in agreement with the values measured previously (as seen in section 3).

Nevertheless, the $\Xi_b^-$ value is not in accordance with the theoretical prediction seen in section 2 (however this prediction is not very precise since it has unknown statistical uncertainty). Indeed, we find a ratio of $\frac{\tau(\Xi_b^-)}{\tau(\Lambda_b)} = 1.54 \pm 0.23$ using the PDG value for $\tau(\Lambda_b)$. 


References

[1] Heavy flavor averaging group (HFAG), ”Averages of b-hadron, c-hadron, and \(\tau\)-lepton Properties ”.


[3] Results for the PDG 2012 review


[5] W. Hulsbergen , ”Decay Chain Fitting with a Kalman Filter”.

[6] Y. Amhis et al., ”Measurement of the masses of the \(\Xi_b^-\) and \(\Omega_b^-\) “. LHCb-2011-075


[8] R. Aaij et al., ”Selections and lifetime measurements for exclusive \(b \to J/\Psi X\) decays with \(J/\Psi \to \mu\mu\) with 2010 data , LHCb-ANA-2011-001 “.

11 Appendix

We show in the following the Monte-Carlo distribution of the variable used in the selection after the stripping but before the cuts.
Figure 18: The Ξ’s variables on which we cut.
Figure 19: The Λ’s variables on which we cut.
Figure 20: The $\Xi_b$’s variables on which we cut.
Figure 21: The $J/\Psi$'s variables on which we cut.