Studies of $\Lambda_b^0 \rightarrow J/\psi \Lambda$ production in $pp$ collisions at $\sqrt{s} = 7$ TeV

The LHCb collaboration

Abstract

The $\Lambda_b^0 \rightarrow J/\psi \Lambda$ production cross-section is measured with the LHCb detector in inelastic $pp$ collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. Using 36.4 pb$^{-1}$ of data recorded in 2010, the cross-section for the region with rapidity $2.2 < y < 4.5$ and transverse momentum $p_T < 13.0$ GeV/c is found to be $\sigma(pp \rightarrow \Lambda_b^0 X)B(\Lambda_b^0 \rightarrow J/\psi \Lambda) = 4.19 \pm 0.61(\text{stat}) \pm 0.37(\text{syst})$ nb for the baryon and $\sigma(pp \rightarrow \Lambda_b^0 X)B(\Lambda_b^0 \rightarrow J/\psi \Lambda) = 2.63 \pm 0.48(\text{stat}) \pm 0.27(\text{syst})$ nb for the antibaryon decay.

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1 Introduction

The production of the $b$-baryons is a little explored territory, as they could not be produced at B factories and few results have been reported by the Tevatron experiments. The first measurement of the production cross-section of a $b$-baryon has been recently published by the CMS collaboration [1] from fully reconstructed $\Lambda^0_b \to J/\psi \Lambda$ decays\(^1\) in the transverse momentum and rapidity range $p_T > 10\text{ GeV}/c$ and $|y| < 2.0$. Few $b$-hadrons production studies exploiting $\sqrt{s} = 7\text{ TeV}$ data sample were published already by LHCb, the $b\bar{b}$ cross-section [2] being followed by the $b$-hadrons production fractions [3] and by the $B^{\pm}$ mesons [4] cross-section measurements. This note completes the landscape presenting a preliminary measurement of the $\Lambda^0_b$ cross-section using the decay channel, $\sigma(pp \to \Lambda^0_b X)\mathcal{B}(\Lambda^0_b \to J/\psi \Lambda)$ in the complementary region $p_T < 13.0\text{ GeV}/c$ and $2.2 < y < 4.5$, using $36.4 \pm 1.3\text{ pb}^{-1}$ of data recorded by the LHCb detector in 2010.

The LHCb detector [5] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of hadrons containing $b$ or $c$ quarks. The spectrometer includes a high precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about $4\text{ Tm}$, and three stations of silicon-strip detectors and straw drift-tubes placed downstream. The combined tracking system has a momentum resolution $\Delta p/p$ that varies from $0.4\%$ at $5\text{ GeV}/c$ to $0.6\%$ at $100\text{ GeV}/c$, and an impact parameter ($\text{IP}$) resolution of $20\ \mu\text{m}$ for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are identified by a calorimeter 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. An instrumental bias can be caused by the vertical magnetic field, which deflects oppositely-charged particles into different regions of the detector. This potential bias is experimentally reduced by regularly changing the polarity of the magnetic field during data taking. The data used in this analysis were recorded with both magnet polarities in almost equal amounts.

The trigger consists of a hardware stage, based on information from the calorimeter and muon systems, followed by software stages which apply a full event reconstruction. Events here analysed pass a hardware trigger which requires either one muon candidate with a $p_T$ larger than $1.4\text{ GeV}/c$, or two muons with $p_T$ larger than $0.56\text{ GeV}/c$ and $0.48\text{ GeV}/c$ respectively. For the purpose of this analysis the software trigger [6] selects high transverse momentum muons, $p_T > 1.8\text{ GeV}/c$, or softer ones, $p_T > 0.8\text{ GeV}/c$, accompanied by another track with which they can form a secondary vertex. In the latter case both the muon and the second accompanying track undergo further quality cuts which require a momentum $p > 8\text{ GeV}/c$ and an IP with respect to any primary $pp$ interactions larger than $110\ \mu\text{m}$. A successive stage of the software trigger accepts only events in which the muon and the track, also assumed to be a muon, have a combined invariant mass within $120\text{ MeV}/c^2$ of the nominal $J/\psi$ mass. In order to remove events that, in processing, would

\(^1\)Charge-conjugate states are implicitly included in this paper unless otherwise stated.
require too much CPU time a set of Global Event Cuts (GEC) based on sub-detector multiplicities, is applied at the beginning of each trigger stage.

The measurement presented here is based only on events in which the trigger selected muons originating from the $J/\psi$ produced in the $\Lambda^0_b$ decay, so called Trigger On Signal (TOS) events. It is however possible the trigger selects events independently of the $\Lambda^0_b$ daughters, Trigger Independent of Signal (TIS) events. TIS and TOS requirements are not mutually exclusive and are used to estimate the efficiency of the trigger.

Simulated events are used for the total efficiency estimation. The $pp$ collisions are generated using Pythia 6.4 [7] with a specific LHCb configuration [8]. Decays of hadronic particles are described by EvtGen [9] in which final state radiation is generated using Photos [10]. The interaction of the generated particles with the detector and its response are implemented using the Geant4 toolkit [11] as described in Ref. [12].

2 Cross-section measurement

Selection criteria, defined for the measurement of the $\Lambda^0_b$ lifetime with the LHCb detector [13], are applied to all final state particles identified as $p$, $\pi$, $\mu$ as well as to the reconstructed $J/\psi$, $\Lambda$, and $\Lambda^0_b$, a full list is shown in Table 1. Given the long lifetime of the $\Lambda$ final state, the pion and proton can be reconstructed either as a pair of tracks that leave a signal in the VELO, long tracks, or as one that is detected only in the subsequent tracking stations, downstream tracks. In order to maximize the statistical significance of the present measurement both $\Lambda$ reconstructed with long tracks and $\Lambda$ reconstructed with downstream tracks are used to measure $\Lambda^0_b$ production cross section. These two samples are analysed separately as they are subject to different experimental systematic effects. For similar reasons the data set is further split according to the $b$-quark content of the $\Lambda^0_b$ and to the polarity of the magnetic field. The number of signal $\Lambda^0_b$ candidates is estimated by means of an unbinned fit of the invariant mass distribution in each of the eight samples. The signal is assumed to be distributed as a Gaussian function while the background is described by a first order polynomial function. The $\Lambda^0_b$ and $\bar{\Lambda}^0_b$ samples are grouped in four pairs according to the track type and magnet polarity. These pairs are fitted simultaneously with the constraint that the mean value and the variance of the Gaussian function are the same. As an example Fig. 1 shows the results of the fits of the $\Lambda^0_b$ invariant mass distributions. The fits yield a total of $229 \pm 51$ signal events in the eight samples.

The sPlot technique [14] is used to estimate a statistical weight $w_{SP}$ for each candidate. This weight is related to the probability of the candidate to be a true signal candidate based on the fit model. The efficiency corrected number of $\Lambda^0_b \rightarrow J/\psi \Lambda$ decays is then calculated by weighting each candidate with

$$w_{TOT} = \frac{w_{SP}}{S \times \epsilon^{rec} \times \epsilon^{trig}}$$

where $S$ is a scale factor related to the GEC and to the differences between data and the simulation that are not taken into account in the efficiency determination, $\epsilon^{rec}$ combines
Table 1: Requirements used to select first the $J/\psi \rightarrow \mu^+\mu^-$ then the $A \rightarrow p\pi$ and finally the $A_0^0 \rightarrow J/\psi A$ candidates. $M$ and $m$ are used to indicate the measured invariant masses and the nominal masses respectively. As the $A$ can be reconstructed from a pair of long tracks (LL) or downstream tracks (DD) different values are indicated where applied, $\tau$ is the decay time of the particle and $IP_{\chi^2}$ the difference in the $\chi^2$ of the primary vertex measured with and without the respective track. The $K_S^0$ background is eliminated from the $A$ sample by applying a requirement on $|M_{\pi\pi} - m_{K_S^0}|$.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow \mu^+\mu^-$</td>
<td>$p_T(\mu^+), p_T(\mu^-)$</td>
<td>$&gt; 0.5$ GeV/c</td>
</tr>
<tr>
<td>$A \rightarrow p\pi$</td>
<td>$</td>
<td>M_{\mu^+\mu^-} - m_{J/\psi}</td>
</tr>
<tr>
<td>$A_0^0 \rightarrow J/\psi A$</td>
<td>$IP_{\chi^2}(p,\pi)$</td>
<td>$&gt; 9$(LL), $4$(DD)</td>
</tr>
<tr>
<td>$p_T(\pi)$</td>
<td>$&gt; 0.1$ GeV/c</td>
<td></td>
</tr>
<tr>
<td>$p_T(p)$</td>
<td>$&gt; 0.5$ GeV/c</td>
<td></td>
</tr>
<tr>
<td>$p(p,\pi)$</td>
<td>$&gt; 2$ GeV/c</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>M_{p\pi} - m_A</td>
<td>$, $</td>
</tr>
<tr>
<td>$p_T(A)$</td>
<td>$&gt; 1$ GeV/c</td>
<td></td>
</tr>
<tr>
<td>$M_{A_0^0}$, $IP_{\chi^2}$, $\tau(A_0^0)$</td>
<td>$\in (5120,6120)$ MeV/c$^2$, $&lt; 20$, $&gt; 0.25$ ps</td>
<td></td>
</tr>
</tbody>
</table>

The acceptance, detection, reconstruction and selection efficiencies while $\epsilon^{\text{trig}}$ is the trigger efficiency. The weighted yield obtained in this way is used to estimate the total number of $A_0^0 \rightarrow J/\psi A$ decays, $N_{A_0^0}^{\text{corr}}$.

The value of $\epsilon^{\text{rec}}$ is measured as a function of $p_T$ and $y$ for each of the eight categories of $A_0^0$ candidates using fully simulated samples of $A_0^0 \rightarrow J/\psi A$ signal decays. The simulated $p_T$ and $y$ distribution are reweighted event-by-event to account for the different track multiplicity and the distribution of the events over the phase-space observed in data.

The trigger efficiency has been determined from data by means of the procedure described in [15] and is defined as:

$$\epsilon^{\text{trig}} = \frac{1}{1 + \frac{N_{TIS}}{N_{TISTOS}}} \quad (2)$$

where $N_{J/\psi}^{\text{TIS}}$ is the number of $J/\psi$ candidates detected, reconstructed, and selected by the $J/\psi$ specific selection criteria, which pass the TIS but not the TOS criteria and $N_{J/\psi}^{\text{TISTOS}}$ is the number of corresponding $J/\psi$ candidates which pass both TIS and TOS criteria. A data-set enriched in $J/\psi$ mesons has been used to estimate these numbers of $J/\psi$ candidates as function of the $J/\psi$ rapidity and transverse momentum and magnet field polarity.
Figure 1: $\bar{\Lambda}^0_2 \rightarrow J/\psi \bar{\Lambda}$ mass fit. Top: $\bar{\Lambda}$ is reconstructed using long tracks. Bottom: using the downstream tracks. The plots on the left and on the right used data recorded with different magnet polarities.

The scale factor $S$ is equal to $0.984 \pm 0.006$ and it includes several factors. The first takes into account the loss in efficiency due to the global event cuts, $0.973 \pm 0.006$. The muon identification efficiency is found to be greater in data than in simulation, introducing a correction factor $1.024 \pm 0.012$. Analogously the vertex reconstruction efficiency is found to be smaller in data by $0.984 \pm 0.008$.

Two different techniques are applied to measure the integrated luminosity of the data sample. In addition to the Van der Meer scan method [16,17], LHCb also exploits the proximity to the beam and the high resolution of the VELO subdetector to measure beam parameters such as positions, angles and widths in beam-beam and beam-gas interactions [17]. Combining the results of both techniques it is possible to measure the integrated luminosity over the whole data taking period used in this analysis with an
Table 2: Systematic uncertainties for the cross-section measurements in percent. Where the uncertainty is different for the eight sub-samples in which the candidates are divided, the smallest and the largest estimated values are are shown. The total systematic uncertainty is obtained assuming total correlation among the correlated variables.

<table>
<thead>
<tr>
<th>Source of systematic uncertainties</th>
<th>Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEC</td>
<td>0.60</td>
</tr>
<tr>
<td>trigger efficiency</td>
<td>2.23 – 4.48</td>
</tr>
<tr>
<td>tracking efficiency</td>
<td>3.26 – 4.47</td>
</tr>
<tr>
<td>reconstruction efficiency</td>
<td>2.59 – 7.60</td>
</tr>
<tr>
<td>primary vertex efficiency</td>
<td>0.79</td>
</tr>
<tr>
<td>selection</td>
<td>0.13 – 1.94</td>
</tr>
<tr>
<td>muon particle identification</td>
<td>1.12</td>
</tr>
<tr>
<td>proton particle identification</td>
<td>0 – 0.56</td>
</tr>
<tr>
<td>fitting model</td>
<td>0.26 – 7.70</td>
</tr>
<tr>
<td>crossing angle</td>
<td>0.02 – 0.31</td>
</tr>
<tr>
<td>polarization</td>
<td>0.29 – 3.74</td>
</tr>
<tr>
<td>luminosity measurement</td>
<td>3.50</td>
</tr>
<tr>
<td>branching fractions</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>10.9 – 21.9</td>
</tr>
</tbody>
</table>

uncertainty of 3.5%, obtaining $36.4 \pm 1.3 \, \text{pb}^{-1}$.

The estimated $N_{\Lambda_0}^{\text{corr}}$ together with the information on luminosity and branching fractions provide eight measurements of the cross-section according to

$$\sigma(pp \rightarrow \Lambda_0^0 X)B(\Lambda_0^0 \rightarrow J/\psi \Lambda) = \frac{N_{\Lambda_0}^{\text{corr}}}{\mathcal{L} \cdot B(A \rightarrow p\pi^-)B(J/\psi \rightarrow \mu^+\mu^-)}$$  (3)

where $\mathcal{L}$ is the luminosity, $B(A \rightarrow p\pi^-)$ and $B(J/\psi \rightarrow \mu^+\mu^-)$ are the branching fractions of the $A \rightarrow p\pi^-$ and $J/\psi \rightarrow \mu^+\mu^-$ decays averaged by the PDG [18].

3 Systematic uncertainties

A number of systematic effects are studied, and their impact on the cross-section measurement is quantified.

A systematic uncertainty associated to the selection of the $\Lambda_0$ candidates is assigned varying the requirements listed in Table 1 by the error on the cut variable. To estimate the uncertainties introduced by the fit procedure, the $\Lambda_0$ samples are grouped in different ways and alternative constraints are imposed on the mean and variance of the Gaussian function used in the fit. A different model, where the background is described by an exponential, has also been tested.
Figure 2: The measured \(\sigma(pp \rightarrow \Lambda_b^0 X)B(\Lambda_b^0 \rightarrow J/\psi \Lambda)\) in nb for the eight samples. The black vertical bars represent the statistical error, the red limits represent the systematic uncertainty. The green horizontal band represents the average for the two species \(\Lambda_b^0\) and \(\bar{\Lambda}_b^0\). The red horizontal line represent the predictions from the LHCb simulated sample. (1)&(2) stand for the measurement using \(\Lambda_b^0\) reconstructed with \(\Lambda\) daughters as long tracks using data recorded with different polarity of the magnetic field, while (3)&(4) stand for the case in which the \(\Lambda\) daughters are reconstructed as downstream tracks.

Systematic uncertainties due to the errors on \(\epsilon^{\text{trig}}\), to the limited statistics of the simulated samples used to determine \(\epsilon^{\text{rec}}\), as well as to the differences between data and simulation are evaluated using a series of pseudo-experiments. The difference in the material description in data and simulation is treated separately and an additional systematic uncertainty is assigned to each track to account for it. Further contributions to the systematic uncertainties are introduced by the statistical error on the GEC efficiency determined from data, the difference between data and the simulated samples in the primary vertex reconstruction efficiency, muon and proton particle identification efficiencies and the beam collision geometry.

The uncertainty introduced in the production measurement by the lack of knowledge on the \(\Lambda_b^0\) polarization is estimated considering a transverse polarization \([19]\) and comparing the two extreme cases for the polarization, \(\pm 1\), with the nominal measurement where the \(\Lambda_b^0\) is assumed to be unpolarized.

The complete list of systematic uncertainties considered in this analysis, including the errors on the luminosity and on the theoretical values for the branching fractions of the decays considered, is shown in Table 2. All uncertainties are combined to provide a final systematic uncertainty. Where correlation is possible, maximum correlation is assumed.
Summary and results

Following Eq. (3), the results for the $\Lambda_0^b$ cross-section measurements for $2.2 < y < 4.5$ and $p_T < 13.0$ GeV/c for the eight data samples considered are shown in Fig. 2.

The $\Lambda_0^b$ and $\bar{\Lambda}_0^b$ production cross-sections are obtained as the weighted average of the individual samples assuming full correlation of the systematic uncertainties:

$$\sigma(pp \rightarrow \Lambda_0^b X)B(\Lambda_0^b \rightarrow J/\psi \Lambda) = 4.08 \pm 0.59\text{(stat)} \pm 0.36\text{(syst)} \text{nb},$$

$$\sigma(pp \rightarrow \bar{\Lambda}_0^b X)B(\bar{\Lambda}_0^b \rightarrow J/\psi \bar{\Lambda}) = 2.60 \pm 0.46\text{(stat)} \pm 0.26\text{(syst)} \text{nb}.$$

The values are in reasonable agreement with the LHCb Monte Carlo predictions, also shown in Fig. 2. They also agree qualitatively with the CMS measurement [1], however a quantitative comparison is difficult given the different $y$ and $p_T$ ranges covered by the two experiments.

References

[1] CMS Collaboration, S. Chatrchyan et al., Measurement of the $\Lambda_0^b$ cross section and the $\bar{\Lambda}_0^b$ to $\Lambda_0^b$ ratio with $\Lambda_0^b \rightarrow J/\psi \Lambda$ decays in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B714 (2012) 136, arXiv:1205.0594.


