PROCEEDINGS OF SCIENCE

b-hadron decays at ATLAS

Semen Turchikhin*, **on behalf of the ATLAS collaboration**
Joint Institute for Nuclear Research, Dubna, Russia
E-mail: Semen.Turchikhin@cern.ch

Recent results on Λ_b^0 baryon and B_c^+ meson decay studies from the ATLAS experiment at the LHC are presented. These include measurements of the parity-violating asymmetry parameter α_b and the helicity amplitudes for the $\Lambda_b^0 \to J/\psi\Lambda^0$ decay, the first observation of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay and a measurement of its rate relative to the $\Lambda_b^0 \to J/\psi\Lambda^0$ decay, and a study of the $B_c^+ \to J/\psi D_s^{(*)+}$ decay properties.

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*Speaker.

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1. Introduction

Although the Λ_b^0 baryon and B_c^+ meson were discovered many years ago, and their basic properties have been determined, the LHC allowed to increase precisions as well as to open an access to the measurements not done before. Three ATLAS [1] results on Λ_b^0 and B_c^+ decay properties, presented in this document, are measurements, that were first performed in LHC.

2. Measurement of the parity-violating asymmetry parameter α_b and the helicity amplitudes for the $\Lambda_b^0 \to J/\psi\Lambda^0$ decay

In weak decays of hadrons, parity violation depends on the hadron's constituents because of the presence of strongly bound spectator quarks. The strong interaction effects in the hadron decays are non-perturbative, which makes it difficult to predict the value of parity-violating decay asymmetry parameters. However, in heavy baryon decays, such as $\Lambda_b^0 \to J/\psi\Lambda^0$, the energy release in the decay of the *b*-quark is large enough, thus allowing to use the factorization theorem and perturbative QCD (pQCD). Theoretical predictions for the value of the asymmetry parameter α_b in this decay vary: pQCD calculations [2] predict it to be in a range between -0.17 and -0.14, while heavy quark effective theory (HQET) gives a value of 0.78 [3]. Experimental measurement of this parameter can thus serve as a test for those models.

The ATLAS analysis of the $\Lambda_b^0 \to J/\psi\Lambda^0$ decay [4] uses the data collected in 2011 at $\sqrt{s} =$ 7 TeV corresponding to an integrated luminosity of 4.6 fb^{-1}. The $J/\psi \to \mu^+\mu^-$ candidates are reconstructed by fitting two opposite-sign muons into a common vertex, and $\Lambda^0 \to p\pi^-$ candidates[1] are built from two inner detector tracks. The four tracks are then refitted using the Λ_b^0 decay hypothesis, in which a cascade of two vertices is built, and the masses of the J/ψ and Λ^0 candidates are constrained to their world averages. A good fit quality defined by $\chi^2/\text{n.d.f.} < 3$ is required. The Λ^0 candidate is required to have $p_\text{T} > 3.5$ GeV and a transverse decay length $L_{xy} > 10$ mm with respect to the dimuon vertex. Furthermore, the reconstructed Λ_b^0 candidate's proper decay time τ should be greater than 0.35 ps.

To suppress reflection from $B^0 \to J/\psi K_S^0$ decay, the four tracks are also fitted with this decay hypothesis, and the Λ_b^0 candidate is retained only if the cumulative probability for the Λ_b^0 hypothesis fit is higher than that for the B^0 hypothesis.

The reconstructed Λ_b^0 invariant mass distribution is shown in Fig. 1 (left). It is fitted with a sum of two templates extracted from Monte Carlo (MC) simulation describing the Λ_b^0 signal and B^0 reflection, and a linear function describing combinatorial background.

The decay $\Lambda_b^0 \to J/\psi\Lambda^0$ can be described by four helicity amplitudes $A(\lambda_\Lambda, \lambda_{J/\psi})$: $a_+ = A(1/2,0)$, $a_- = A(-1/2,0)$, $b_+ = A(-1/2,-1)$, $b_- = A(1/2,1)$, where λ_Λ and $\lambda_{J/\psi}$ are the helicities of the Λ^0 and J/ψ, respectively. The parity-violating asymmetry parameter is then $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$. The distribution of five decay angles $\Omega = (\theta, \theta_1, \phi_1, \theta_2, \phi_2)$ illustrated in Fig. 1 (right) can be written as [5]

$$w(\Omega, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega). \tag{2.1}$$

[1]Charge conjugate states are implied throughout the text.

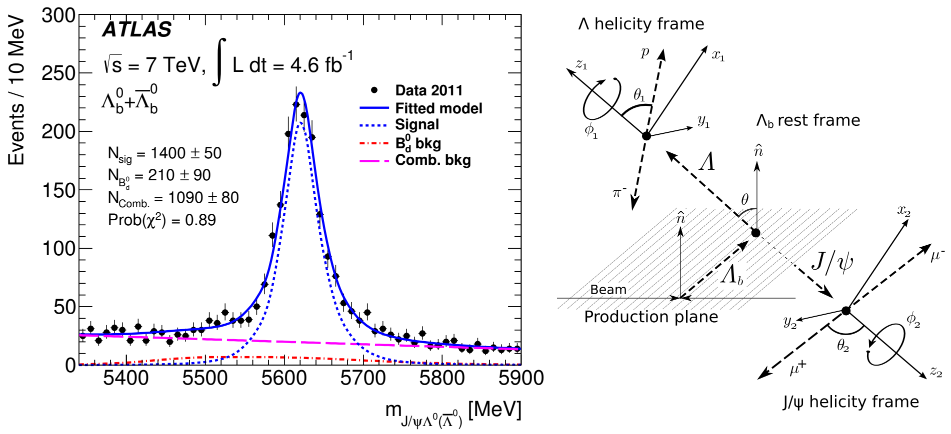

Figure 1: Left: distribution of the invariant mass of reconstructed Λ_b^0 candidates with the fit result overlaid. Right: definition of decay angles in $\Lambda_b^0 \to J/\psi\Lambda^0$ decay. Figures are taken from Ref. [4].

The average polarization P is taken to be zero due to the symmetry of the detector, and thus only six of twenty moments F_i remain non-zero.

The helicity amplitudes $\vec{A}$ are determined by minimization of the following function:

$$\chi^2 = \sum_i \sum_j (\langle F_i\rangle^{\text{expected}} - \langle F_i\rangle) V_{ij}^{-1} (\langle F_j\rangle^{\text{expected}} - \langle F_j\rangle), \tag{2.2}$$

where $\langle F_i\rangle^{\text{expected}}$ are the expected values of F_i predicted by the given helicity parameters, $\langle F_i\rangle$ are the measured average values, and V_{ij} are their covariance matrix elements. The expected values are calculated from the probability density function (2.1) and corrected for detector effects.

The magnitudes of the helicity amplitudes are measured to be

$$\begin{aligned}
|a_+| &= 0.17^{+0.12}_{-0.17}\,(\text{stat.}) \pm 0.09\,(\text{syst.}),\\
|a_-| &= 0.59^{+0.06}_{-0.07}\,(\text{stat.}) \pm 0.03\,(\text{syst.}),\\
|b_+| &= 0.79^{+0.04}_{-0.05}\,(\text{stat.}) \pm 0.02\,(\text{syst.}),\\
|b_-| &= 0.08^{+0.13}_{-0.08}\,(\text{stat.}) \pm 0.06\,(\text{syst.}).
\end{aligned}$$

The corresponding value of the parity-violating parameter is $\alpha_b = 0.30 \pm 0.16\,(\text{stat.}) \pm 0.06\,(\text{syst.})$. This result is consistent with the LHCb measurement [6]. It differs from both pQCD and HQET expectations by more than 2.5 standard deviations.

3. Measurement of the branching ratio $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0)$

The first observation of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay mode and measurement of the ratio $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0)$ was performed by ATLAS [7] using a dataset collected in 2012 at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 20.6 fb^{-1}.

The reconstruction and selection of the decay candidates for both decay modes are similar to those used in the analysis described in Section 2. Mass constraints corresponding to $\psi(2S)$ and J/ψ are used in the cascade fit of the corresponding decay candidates. In both channels, Λ_b^0 is reconstructed in a fiducial kinematic range $p_T > 10$ GeV, $|\eta| < 2.1$. Fits with $B^0 \to J/\psi K^0_S$ and $B^0 \to \psi(2S)K^0_S$ hypotheses are also applied to each candidate to control the B^0 reflections.

To extract the yields of the decay modes of interest, a simultaneous fit is applied to the Λ^0_b and B^0 mass distributions in both decay modes, where the signal and combinatorial background are described with analytical functions while MC templates are used for the mutual B^0 and Λ^0_b reflections. Figure 2 shows the fitted $\Lambda^0_b \to \psi(2S)\Lambda^0$ and $B^0 \to \psi(2S)K^0_S$ mass distributions.

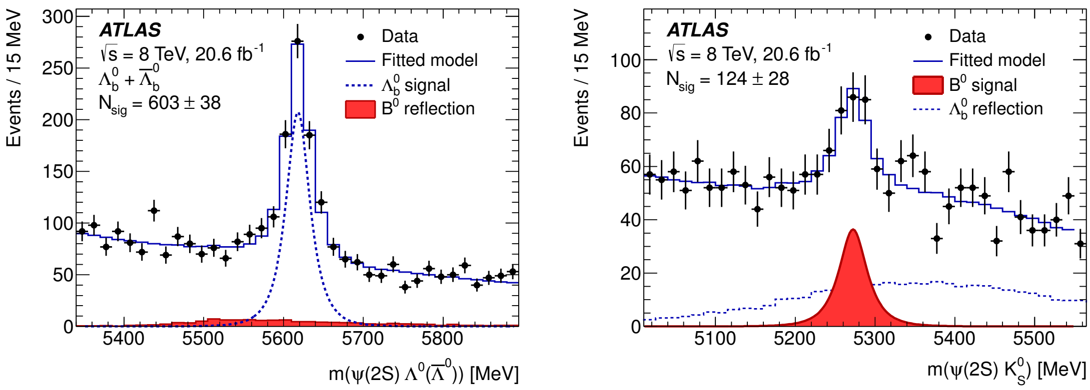

Figure 2: The invariant mass distributions for the selected Λ^0_b candidates obtained after their fits with the (left) $\Lambda^0_b \to J/\psi\Lambda^0$ and (right) $B^0 \to J/\psi K^0_S$ topologies. The solid histograms represent fit results. The Λ^0_b and B^0 signals and their mutual reflections are also shown. Figures are taken from Ref. [7].

Using the event yields extracted from the fits and corrected for the detector acceptance and efficiency, the ratio of the two Λ^0_b decay rates is measured to be $\Gamma(\Lambda^0_b \to \psi(2S)\Lambda^0)/\Gamma(\Lambda^0_b \to J/\psi\Lambda^0) = 0.501 \pm 0.033\ (\text{stat.}) \pm 0.016\ (\text{syst.}) \pm 0.011\ (\text{BF})$, where the last uncertainty corresponds to the uncertainties of charmonium branching fractions. The measured ratio lies in the range $0.5-0.8$ found for the analogous B meson decays to $\psi(2S)X$ and $J/\psi X$ [9]. The only available theoretical prediction [8] of this quantity (0.8 ± 0.1) exceeds the measured value.

4. Study of the $B^+_c \to J/\psi D^+_s$ and $B^+_c \to J/\psi D^{*+}_s$ decay properties

Measurements of the relative decay rates of $B^+_c \to J/\psi D^+_s$ and $B^+_c \to J/\psi D^{*+}_s$ decays as well as polarization in the latter decay were performed by ATLAS [10] using the full Run 1 dataset collected in 2011 and 2012 at $\sqrt{s} = 7$ and 8 TeV, corresponding to integrated luminosities of 4.9 and 20.6 fb^{-1}, respectively.

The signal candidates are identified through the $J/\psi \to \mu^+\mu^-$ and $D^+_s \to \phi(K^+K^-)\pi^+$ decay channels. They are reconstructed by fitting two muons and three inner detector tracks into two vertices, assuming a cascade decay topology of the B^+_c decay and applying mass constraints on the J/ψ and D^+_s candidates. In the case of the $B^+_c \to J/\psi D^{*+}_s$ mode, D^{*+}_s meson decays into $D^+_s\gamma/\pi^0$, where a neutral particle is not reconstructed.

The signal candidate selection mostly focuses on combinatorial background suppression. It uses kinematic properties of the candidates, mass windows for the intermediate resonances, cascade fit quality, vertices displacement, and angular properties.

The signal yields along with the transverse polarization fraction in $B_c^+ \to J/\psi D_s^{*+}$ decay are extracted using a two-dimensional maximum likelihood fit of the $J/\psi D_s^+$ reconstructed invariant mass and the angle $\theta'(\mu^+)$ between the μ^+ and D_s^+ candidate momenta in the J/ψ candidate rest frame. The fit probability density function is factorized into mass and angular parts. Mass shapes of $B_c^+ \to J/\psi D_s^+$ signal and combinatorial background are described with analytical functions, while for the transversely and longitudinally polarized components of $B_c^+ \to J/\psi D_s^{*+}$ mode, MC templates are used. Templates from MC simulation and from data sidebands are also used for the angular part of the PDF. Fit projections overlaid on the distributions are shown in Fig. 3.

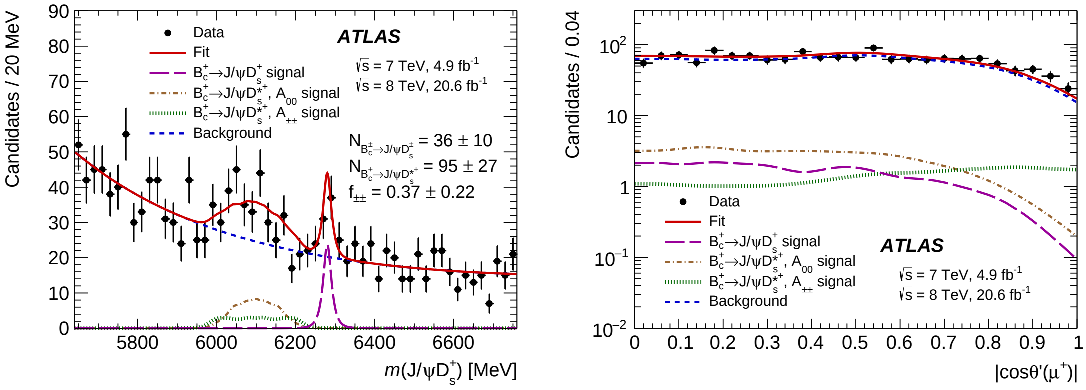

Figure 3: Distributions of (left) the invariant mass of reconstructed $J/\psi D_s^+$ candidates and (right) the variable $|\cos\theta'(\mu^+)|$. Projections of the likelihood fit on both variables are overlaid. Figures are taken from Ref. [10].

The $B_c^+ \to J/\psi\pi^+$ decay mode is used as a reference for the branching fraction measurement. The reference decay candidates are reconstructed by fitting two muons and another track to a common vertex. Selection criteria are chosen close to those used for the signal modes to reduce uncertainties of the measurement. The reference mode yield is obtained from the fit of the $J/\psi\pi^+$ mass distribution.

From the fitted yields, corrected for detector acceptance and efficiency, the following ratios of branching fractions are measured:

$$\mathscr{B}_{B_c^+ \to J/\psi D_s^+}/\mathscr{B}_{B_c^+ \to J/\psi\pi^+} = 3.8 \pm 1.1\,(\text{stat.}) \pm 0.4\,(\text{syst.}) \pm 0.2\,(\text{BF}),$$
$$\mathscr{B}_{B_c^+ \to J/\psi D_s^{*+}}/\mathscr{B}_{B_c^+ \to J/\psi\pi^+} = 10.4 \pm 3.1\,(\text{stat.}) \pm 1.5\,(\text{syst.}) \pm 0.6\,(\text{BF}),$$
$$\mathscr{B}_{B_c^+ \to J/\psi D_s^{*+}}/\mathscr{B}_{B_c^+ \to J/\psi D_s^+} = 2.8^{+1.2}_{-0.8}\,(\text{stat.}) \pm 0.3\,(\text{syst.}),$$

where (BF) uncertainty corresponds to uncertainty of the $D_s^+ \to \phi(K^+K^-)\pi^+$ decay branching fraction. The fraction of transversely polarized $B_c^+ \to J/\psi D_s^{*+}$ decays is measured to be $\Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23\,(\text{stat.}) \pm 0.07\,(\text{syst.})$. These results are in agreement with the earlier LHCb measurement [11]. They are generally described by available theoretical predictions. Figure 4 shows a detailed comparison.

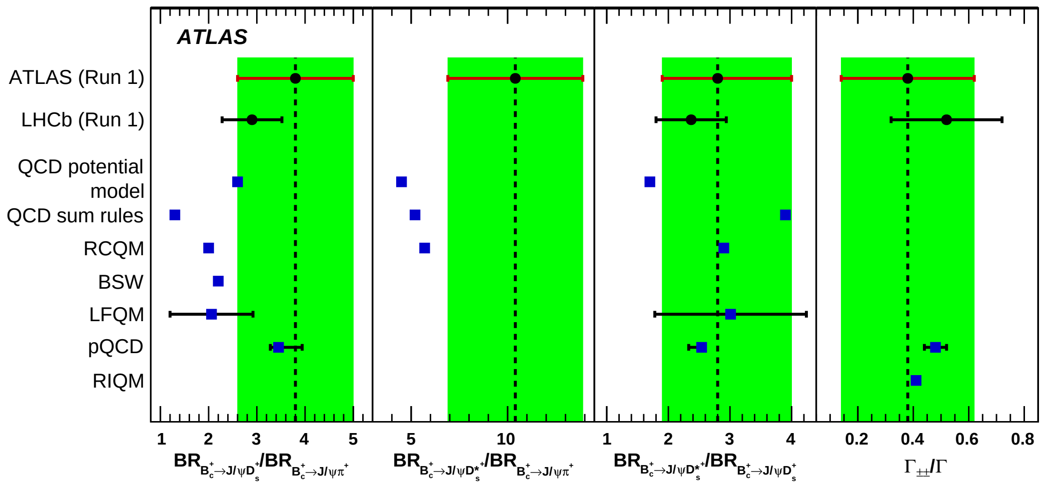

Figure 4: Comparison of the results of the $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decay properties measurement with those of LHCb [11] and various theoretical predictions (see references in Ref. [10]). Figure is taken from Ref. [10].

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