Decay properties of $b$-hadrons with the ATLAS experiment

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Abstract

Recent results of the ATLAS experiment at LHC on decay properties of $b$-hadrons are reviewed. The time-dependent $CP$ asymmetry parameters have been measured in $B^0 \rightarrow J/\psi \phi$ decays using flavour tagging. The parity-violating decay asymmetry parameter $\alpha_b$ and the helicity amplitudes have been measured for the decay $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$. The branching fraction $\mathcal{B}(B^+ \rightarrow \chi_c^0 K^+)$ has been measured with $\chi_c^1$ reconstruction in the decay $\chi_c^1 \rightarrow J/\psi \gamma$. An excited $B^+_{c}$ state has been observed through its decays to the ground $B^+_c$ state and two oppositely charged pions. The mass and decay of this state are consistent with expectations for the second $S$-wave state of the $B^+_c$ meson, $B^+_c(2S)$.

Keywords:
heavy quarks, $B$ physics, $CP$ violation, parity violation, ATLAS, LHC

1. Introduction

The ATLAS detector [1] at the Large Hadron Collider (LHC) consists of several subsystems including the inner detector (ID), the electromagnetic and hadronic calorimeters, and the muon spectrometer (MS). Muon reconstruction at ATLAS makes use of both the ID and the MS, and covers the pseudorapidity range $|\eta| < 2.5$. A there-level trigger system allows ATLAS to effectively select events containing single muons with large transverse momentum $p_T$ (above $\sim 20$ GeV), and events with two muons with the pair invariant mass between 2.5 GeV and 4.3 GeV. In such $J/\psi$ trigger, the minimal muon $p_T$ thresholds of $4 - 6$ GeV have been used in 2011-2012. During this period ATLAS has accumulated data samples of $pp$ collisions corresponding to luminosities of $\sim 5$ fb$^{-1}$ at $\sqrt{s} = 7$ GeV and $\sim 20$ fb$^{-1}$ at $\sqrt{s} = 8$ GeV.

In this note, recent ATLAS results on decay properties of $b$-hadrons are presented. The time-dependent $CP$ asymmetry parameters are measured in $B^0 \rightarrow J/\psi \phi$ decays using flavour tagging [2]. The parity-violating decay asymmetry parameter $\alpha_b$ and the helicity amplitudes are measured for the decay $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ [3]. The branching fraction $\mathcal{B}(B^+ \rightarrow \chi_c^0 K^+)$ is measured with $\chi_c^1$ reconstruction in the decay $\chi_c^1 \rightarrow J/\psi \gamma$ [4]. An excited $B^+_{c}$ state is observed through its decays to the ground $B^+_c$ state and two oppositely charged pions [5]. Corrections for detector effects are done with high-statistics Monte Carlo (MC) samples. Uncertainties due to uncertainties of simulation of physics processes and detector, MC statistic, luminosity measurement and assumptions of the analyses procedures are included into systematic errors. The measurements are compared to theoretical predictions and to the measurements by other experiments.

2. $CP$ violation for the $B^0_s \rightarrow J/\psi \phi$ decay

The decay $B^0_s \rightarrow J/\psi \phi$ is expected to be sensitive to new physics contributions. $CP$ violation in the decay occurs due to interference between direct decays and decays with $B^0_s \rightarrow B^0_{c}$ mixing. The $CP$ violating phase $\phi_s$ is defined as the weak phase difference between the $B^0_s - B^0_{c}$ mixing amplitude and the $b \rightarrow c\bar{c}s$ decay ampli-
The oscillation frequency of $B^0_s$ meson mixing is characterized by the mass difference of the heavy ($B_{H}$) and light ($B_L$) mass eigenstates. In the Standard Model (SM), the phase $\phi_s$ is small, $\phi_s \approx -0.037 \pm 0.002 \text{ rad}$ [6]. Another physical quantity involved in $B^0_s - \bar{B}^0_s$ mixing is the width difference $\Delta \Gamma = \Gamma_{L} - \Gamma_{H}$, which is predicted to be $\Delta \Gamma = 0.087 \pm 0.021 \text{ ps}^{-1}$ [7]. Although the $\Delta \Gamma$ value is not expected to be significantly affected by physics beyond the SM, its measurement allows theoretical predictions to be tested [8].

In this report, an update [2] to the previous ATLAS measurement [9] of the $B^0_s \rightarrow J/\psi \phi$ decay with the addition of flavour tagging, is presented. The analysis uses 4.9 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 7 \text{ TeV}$. The $CP$ states are separated statistically using an angular analysis of the final-state particles. Flavour tagging is used to reduce the uncertainty of the measured value of $\phi_s$. The determination of the initial flavour of neutral $B$-mesons is inferred using information from the $B$-meson that is typically produced from the other $b$-quark in the event. To study and calibrate the opposite-site tagging, events containing the decays of $B^\pm \rightarrow J/\psi K^\mp$ are used. Two methods are used to infer the flavour of the opposite-side $b$-quark, with varying efficiencies and discriminat-

![Figure 1: Left: The mass fit projection for the $B^0_s \rightarrow J/\psi \phi$. The red line shows the total fit, the dashed green line shows the signal component while the dotted blue line shows the contribution from $B^0_s \rightarrow J/\psi K^0$ events. Right: Proper decay time fit projection for the $B^0_s \rightarrow J/\psi \phi$. The red line shows the total fit while the green dashed line shows the total signal. The light and heavy components of the signal are shown in green as a dotted and a dash-dotted line, respectively. The total background is shown as a blue dashed line with a grey dotted line showing the prompt $J/\psi$ background. The pull distributions at the bottom show the difference between data and fit value normalized to the data statistical uncertainty.](image-url)

The measured charge of a muon from the semileptonic decay of the $B$ meson provides strong separation power. The separation power is enhanced by considering a weighted sum of the charge of the tracks in a cone around the muon. If no muon is present, a weighted sum of the charge of tracks associated with a $b$-tagged jet [10] provides some separation.

Candidates for $B^0_s \rightarrow J/\psi (\mu^+ \mu^-) K^+ K^-$ are reconstructed by fitting two oppositely-charged muon tracks and two additional oppositely-charged tracks, assumed to be kaons, to a common vertex. The fit is constrained by fixing the invariant mass calculated from the two muon tracks to the nominal $J/\psi$ mass [11]. The invariant mass of two kaon tracks is required to fall within the interval $1.0085 < m(K^+ K^-) < 1.0305 \text{ GeV}$. For each selected candidate the proper decay time $t$ is estimated as $t = \frac{L_{xy}}{\tau} (m(B^0_s)/p_T)$, where $p_T$ is the reconstructed transverse momentum of the $B^0_s$ meson candidate and $m(B^0_s)$ is the nominal $B^0_s$ mass [11]. The transverse decay length, $L_{xy}$, is the displacement in the transverse plane of the $B^0_s$ meson decay vertex with respect to the primary vertex, projected onto the direction of the $B^0_s$ transverse momentum.

An unbinned maximum likelihood fit is performed on
the selected candidates to extract the parameters of the $B^0_s \to J/\psi(\mu^+ \mu^-)\phi(K^+ K^-)$ decay. The fit uses information about the reconstructed $B^0_s$ mass and its uncertainty, the measured proper decay time $t$ and its uncertainty, the tag probability, and three transversity angles of each candidate. The transversity angles are defined in the $J/\psi$ and $\phi$ rest frames [2].

Figure 1 shows the mass and the proper decay time fit projections for the $B^0_s \to J/\psi \phi$. The number of signal $B^0_s$ mesons extracted from the fit is 22670±150. The signal contribution from $B^0_s \to J/\psi K^+ K^-$ and $B^0_s \to J/\psi f_0$ is measured to be consistent with zero. The results for $\phi_s$ and $\Delta \Gamma_s$, assuming $\Delta \Gamma_s$ is positive, are

$$\phi_s = 0.12 \pm 0.25(stat) \pm 0.05(syst) \, \text{rad},$$

$$\Delta \Gamma_s = 0.053 \pm 0.021(stat) \pm 0.010(syst) \, \text{ps}^{-1}.$$

Figure 2 shows the likelihood contours in the $\phi_s$–$\Delta \Gamma_s$ plane. The results are consistent with the values predicted in the Standard Model. The values measured for all physical parameters [2] are consistent with those obtained in the untagged analysis [9]. The overall uncertainty on $\phi_s$ is significantly reduced.

### 3. Parity violation for the $\Lambda_b^0 \to J/\psi \Lambda^0$ decay

The decay asymmetry parameter $\alpha$ enters into the angular distribution of a two-body spin 1/2 particle decay as

$$w(\cos \theta) = (1 + \alpha P \cos \theta)/2,$$

where $P$ is the polarization of the particle and $\theta$ is the angle between the polarization vector and the direction of the decay product in the particle’s rest frame. Parity violation is not maximal in hadrons weak decays due to the presence of strongly bound spectator quarks. The spectator quarks effects can be computed for decays of heavy baryons, where the factorization theorem and perturbative QCD (pQCD) are applicable. The decay $\Lambda_b^0 \to J/\psi \Lambda^0$ can be described by four helicity amplitudes: $a_s \equiv A(1/2, 0)$, $a_0 \equiv A(-1/2, 0)$, $b_s \equiv A(-1, 1/2, -1)$ and $b_0 \equiv A(1/2, 1)$, where first and second parameters represent the $J/\psi$ and $\Lambda^0$ helicities, respectively. A sum of the amplitudes squared is normalized to unity, and the parity-violating decay asymmetry parameter $\alpha_b$ is given by [12]

$$\alpha_b = |a_s|^2 - |a_0|^2 + |b_s|^2 - |b_0|^2.$$

The full angular probability density function (PDF) of the decay $\Lambda_b^0 \to J/\psi(\mu^+ \mu^-)\Lambda^0(p\pi^-)$ [12, 13, 14] connects the helicity amplitudes with functions of the angle $\theta$ and polar and azimuthal angles of the $J/\psi$ and $\Lambda^0$ decays with respect to their directions in the $\Lambda_b^0$ rest frame.

The analysis [3] uses 4.9 fb$^{-1}$ of $pp$ data at $\sqrt{s} = 7$ TeV. Candidates for $\Lambda_b^0 \to J/\psi(\mu^+ \mu^-)\Lambda^0(p\pi^-)$ are...
reconstructed by fitting two oppositely-charged muon tracks and two additional oppositely-charged tracks, assumed to be a proton and a pion, to their respective vertexes. The fit is constrained by fixing the invariant masses calculated from the two muon tracks and two additional tracks to the nominal \( J/\psi \) and \( \Lambda^0 \) masses [11], respectively. The combined momentum direction of the refitted \( \Lambda^0 \) track pair is constrained to point to the di-muon vertex.

Figure 3 shows the invariant mass distribution of events passing all selection cuts [3], fitted with a threecomponent probability density function consisting of signal, combinatorial background, and residual contribution of \( B^0 \rightarrow J/\psi(\mu^+\mu^-)K^0_s(\pi^+\pi^-) \) decays. The combinatorial background is non-resonant and assumed to be linear. The shapes of the \( \Lambda^0 \) signal component and the \( B^0 \) background are modeled using one-dimensional Gaussian-kernel estimation PDFs [15] of the MC events. The number of signal \( \Lambda^0 \) and \( \bar{\Lambda}^0 \) baryons extracted from the fit is 1400 ± 50.

The helicity amplitudes are obtained from the \( \chi^2 \) fit of the mean values of five angular distributions for \( \Lambda^0 \) and \( \bar{\Lambda}^0 \) candidates in the mass range 5560 < \( m(J/\psi\Lambda^0) \) < 5680 MeV to the mean values for MC with variable amplitudes values. The background is estimated by adding the left and right sidebands and scaling by 0.5. Figure 4(Left) shows one of the five angular distributions, \( F_2 = \cos\theta \), for data and a sum of the MC events, weighted to the measured values of \( \alpha_b \) and helicity amplitudes, and the background. The distribution for the sum with the unweighted MC events is also shown.

The measured values of \( \alpha_b \) and helicity amplitudes are

\[
\begin{aligned}
\alpha_b &= 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst}), \\
|\alpha_+| &= 0.17^{+0.12}_{-0.17}(\text{stat}) \pm 0.09(\text{syst}), \\
|\alpha_-| &= 0.59^{+0.06}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}), \\
|b_+| &= 0.79^{+0.04}_{-0.05}(\text{stat}) \pm 0.02(\text{syst}), \\
|b_-| &= 0.08^{+0.13}_{-0.08}(\text{stat}) \pm 0.06(\text{syst}).
\end{aligned}
\]

The statistical uncertainties are calculated by finding the range that satisfies \( \chi^2 - \chi^2_{\text{min}} < 1 \). Figure 4(right) shows \( \chi^2_{\text{min}} \) as a function of the assumed \( \alpha_b \) value with the condition that the \( \alpha_b \) parameter is fixed in the fit.

The large \( |\alpha_-| \) and \( |b_+| \) amplitudes correspond to the negative-helicity states of \( \Lambda^0 \). The measured \( \alpha_b \) value is consistent with the recent LHCb measurement [16]. The expectations from pQCD [17] (from −0.17 to −0.14) and heavy quark effective theory [18, 19] (0.78) disagree with the measured value at a level of ~ 2.5 standard deviations.

4. Branching fraction for the \( B^+ \rightarrow \chi_{c1}K^+ \) decay

The prompt and non-prompt (from \( B \)-hadron decays) production for the \( \chi_{c1} \) and \( \chi_{c2} \) charmonium states is measured [4] uses 4.5 fb\(^{-1}\) of LHC \( pp \) data at \( \sqrt{s} = 7 \) TeV. The \( \chi_{c} \) states are reconstructed through the radiative decay \( \chi_c \rightarrow J/\psi \gamma \) (with \( J/\psi \rightarrow \mu^+\mu^- \)) where photons are reconstructed from \( \gamma \rightarrow e^+e^- \) conversions. Candidate \( \chi_c \rightarrow J/\psi \gamma \) decays are selected by associating a reconstructed photon conversion with a candidate \( J/\psi \rightarrow \mu^+\mu^- \) decay. To reject combinations of \( J/\psi \rightarrow \mu^+\mu^- \) decays and photons not consistent with a
The measurement of the branching fraction \( \mathcal{B}(B^+ \to \chi^0_1 K^+) \) is compared to the measurements of other experiments and to the world average.

### 5. Observation of an excited \( B_c^+ \) meson state

Excited states of the \( B_c^+ \) meson have not previously been observed. The spectrum and properties of the \( B_c^+ \) family are predicted by non-relativistic potential models, perturbative QCD, and lattice calculations [22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38].

The second \( S \)-wave state, \( B_c^+(2S) \), is predicted to have a mass in the range 6835 \( \pm \) 6917 MeV. Both the \( 1S \) and \( 2S \) states have pseudoscalar \( B_c^+(0^-) \) and vector \( B_c^{*+}(1^-) \) spin states that are predicted to differ in mass by about 20 \( \pm \) 50 MeV. Transitions between the spin states occur through soft photon radiation. The dominant \( B_c^{+}\psi(2S) \) decay is expected to be \( B_c^{+}\psi(2S) \to B_c^{+}\psi(1S)\pi^+\pi^- \). The mass differences of \( 2S \) and \( 1S \) states for the pseudoscalar and vector \( B_c^+ \) mesons can be similar.

A search for excited \( B_c^+ \) states is performed using 4.9 fb\(^{-1}\) and 19.2 fb\(^{-1}\) of \( pp \) data at \( \sqrt{s} = 7 \) TeV and \( \sqrt{s} = 8 \) TeV, respectively. The \( B_c^+ \) mesons are reconstructed through their decays to \( J/\psi \pi^+ \) with \( J/\psi \to \mu^+\mu^- \). \( B_c^+ \) candidates are reconstructed by fitting two muon tracks from the \( J/\psi \) candidate together with a pion candidate track to a common vertex. The invariant mass of the two muons is constrained to the world average of \( J/\psi \) mass. The transverse momentum of the \( B_c^+ \) candidates is required to be above 15 GeV for 7 TeV data and above 18 GeV for 8 TeV data.

Figure 6 shows invariant mass distributions of the reconstructed \( B_c^+ \) candidates in 7 TeV and 8 TeV data. Both distributions are fitted separately using an extended unbinned maximum likelihood fit, with a Gaus-
Figure 6: Invariant mass distributions of the reconstructed $B_c^+ \to J/\psi \pi^+$ candidates in 7 TeV data (left) and in 8 TeV data (right). The data are represented by the points with error bars (statistical only). The solid line is the projection of the results of the unbinned maximum likelihood fit to all candidates in the mass range 5620 – 6820 MeV. The dashed line is the projection of the background component of the same fit.

The reconstruction of the excited state candidates uses the $B_c^+$ ground state candidates within $\pm 3\sigma$ of the fitted mass values. The excited state candidates are reconstructed in the decay to the $B_c^+$ meson and two oppositely charged tracks associated with the corresponding primary vertex and assumed to be pions. The transverse momentum threshold of the pion candidates is 400 MeV. The three tracks from the $B_c^+$ candidate vertex and the two additional tracks from the primary vertex are refitted simultaneously with the following constraints given by the decay topology: the refitted triplet of the $B_c^+$ tracks and the pair of additional tracks must intersect in two separate vertices. The invariant mass of the refitted muon tracks is constrained to the nominal $J/\psi$ mass, and the combined momentum of the refitted $B_c^+$ tracks must point to the vertex of the excited candidate.

Figure 7 shows the $m(B_c^+) - m(B^+) - 2m(\pi^+)$ distributions for the right-charge combinations and for the same (wrong) pion charge combinations in 7 TeV and 8 TeV data. A structure is observed in the mass difference distributions. In order to characterize it, an unbinned maximum likelihood fit to the right-charge combinations is performed. The fit includes a third-order polynomial to model the background and a Gaussian function for the structure. The fit finds the peak at a mass difference value of $288.2 \pm 5.1$ MeV in the 7 TeV data and $288.4 \pm 4.8$ MeV in the 8 TeV data. The fit yields $22 \pm 6$ and $35 \pm 13$ signal events in the 7 TeV and 8 TeV data, respectively. The peak mass difference values, combined as the error weighted mean, correspond to a mass of $6842 \pm 4(\text{stat}) \pm 5(\text{syst})$ MeV. Within the uncertainties, the mass of the resonance corresponding to the observed structure is consistent with the predicted mass of the $B_c^+(2S)$ state.

The significance of the new structure is evaluated with pseudo-experiments. For the combined 7 TeV and 8 TeV dataset the total significance of the observation is found to be $5.2\sigma$. The local significance of the observation, obtained by fixing the mean value of the signal component, is $5.4\sigma$.

6. Summary

A measurement of time-dependent $CP$ asymmetry parameters in $B_c^+ \to J/\psi (\mu^+ \mu^-) \phi (K^+ K^-)$ decays has been performed using flavour tagging. The results are consistent with those obtained in the previous untagged analysis and significantly reduce the overall uncertainty on the $CP$ violating phase $\phi_s$. The results are consistent with the values predicted in the Standard Model.

A measurement of the parity-violating decay asymmetry parameter $\alpha_b$ and the helicity amplitudes for the decay $\Lambda_b^0 \to J/\psi (\mu^+ \mu^-) \Lambda^0 (p\pi^-)$ has been performed. The measured $\alpha_b$ value is consistent with the recent measurement by LHCb, and does not support available theoretical predictions.

The branching fraction $\mathcal{B}(B^+ \to \Lambda_c^+ K^+) = (4.9 \pm 0.9(\text{stat}) \pm 0.6(\text{syst})) \times 10^{-4}$ has been measured. The measured value agrees well with the world average and is significantly better than previous measurements from hadron collider experiments.
An excited $B_s^+$ state has been observed through its hadronic transition to the ground state with a significance of 5.2 standard deviations. The mass of the observed state is $6842 \pm 5\text{(stat)} \pm 5\text{(syst)} \text{MeV}$. The mass and decay of this state are consistent with expectations for the second $S$-wave state of the $B_s^+$ meson, $B_s^+(2S)$.

References