B_c^+ physics at LHCb

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Abstract. We present recent LHCb results in B_c^+ physics with four topics. Using $3\,\mathrm{fb}^{-1}$ data collected in 2011 and 2012 produced in pp collisions, a baryonic decay mode, $B_c^+ \to J/\psi\, p\bar{p}\pi^+$, is observed for the first time. With $1\,\mathrm{fb}^{-1}$ data collected in 2011, the first measurement of the relative branching ratio $\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)$ is performed. With $2\,\mathrm{fb}^{-1}$ data collected in 2012, the lifetime of the B_c^+ meson is measured with the semileptonic decay $B_c^+ \to J/\psi\,\mu^+\nu_\mu$. Finally, evidence is presented for the decay $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$ using pp collision deta, corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$.

1. Introduction

In the Standard Model, B_c^+ meson is the only meson family composed of different heavy flavor quarks. Similar to quarkonia, B_c^+ has rich spectroscopy. At LHCb, the most precise mass measurement of the ground state of B_c^+ is given with the decay of $B_c^+ \to J/\psi\, D_s^+$ in Ref. [1]: $6276.3 \pm 1.4 \pm 0.4$. Recently ATLAS reported a search for excited state of the B_c^+ meson and new state is observed through its hadronic transition to the ground state, $B_c^+(2S) \to B_c^+\pi^+\pi^-$. The mass of that state is measured as $m(B_c^+(2S)) = 6842 \pm 4 \pm 5\,\mathrm{MeV}/c^2$ [2]. The B_c^+ meson provides a wide range of decay modes. Since b and c quarks are taking with the different flavors, the B_c^+ meson can only decay via the weak interaction, including the b quark decay, c quark decay and the annihilation modes [3]. At Tevatron, only two decay modes are observed, $B_c^+ \to J/\psi\,\pi^+$ and $B_c^+ \to J/\psi\,\mu^+\nu_\mu$ [4, 5]. Due to the large production rate at the LHC, more and more decays are observed at LHCb, such as $B_c^+ \to J/\psi\,\pi^+\pi^-\pi^+$ [6], $B_c^+ \to \psi(2S)\pi^+$ [7], $B_c^+ \to J/\psi\, D_s^{(*)+}$ [1], $B_c^+ \to J/\psi\, K^+$ [8], $B_c^+ \to J/\psi\, K^+K^-\pi^+$ [9] and the first c quark decay mode, $B_c^+ \to B_s^0\pi^+$ [10]. However, there are still many unclear issues about B_c^+ physics. The B_c^+ lifetime is measured with large uncertainty, many other decays are not observed jet, especially for the annihilation modes and so far there is no absolute branching ratio measurement for B_c^+ mesons. Therefore, more experimental studies on B_c^+ physics are still needed.

2. First observation of $B_c^+ \to J/\psi\, p\bar{p}\pi^+$

The baryonic decay modes of b hadrons are very important to understand baryon production mechanism and to search for new baryons and tera-quarks. Besides, in baryonic decays of B^+ and B^0, some special behaviors are observed, but they are not yet well understood [11, 12].

In this analysis, the pre-selection and multivariate selection based on boosted decision tree are used for the event selection. In order to select the well identified proton, the proton identification is also optimised. Figure 1 shows the fitting curves to invariant mass distributions of the

$B_c^+ \to J/\psi\, p\bar{p}\pi^+$ decay and the $B_c^+ \to J/\psi\, \pi^+$ decay, which is taken as the controlled channel. With the $3\,\mathrm{fb}^{-1}$ data collected by LHCb in 2011 and 2012, 23.9 ± 5.3 signals of $B_c^+ \to J/\psi\, p\bar{p}\pi^+$ are observed and the significance is 7.3σ. The branching fraction of the $B_c^+ \to J/\psi\, p\bar{p}\pi^+$ decay with respect to that of the $B_c^+ \to J/\psi\, \pi^+$ decay is measured as [13]:

$$\frac{\mathcal{B}(B_c^+ \to J/\psi\, p\bar{p}\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\, \pi^+)} = 0.143^{+0.039}_{-0.034}(\mathrm{stat}) \pm 0.013(\mathrm{syst}). \quad (1)$$

With the factorization assumption, this result is consistent with the B^0 baryonic decay, $\mathcal{B}(B^0 \to D^{\star-} p\bar{p}\pi^+)/\mathcal{B}(B^0 \to D^{\star-}\pi^+) = 0.17 \pm 0.02$ [14]. Because of the low Q-value in the decay $B_c^+ \to J/\psi\, p\bar{p}\pi^+$, it provides a precise measurement of the B_c^+ mass. The mass of B_c^+meson is measured, with corrections of the momentum scale and the final state radiation. Combining with LHCb previous measurements [1, 15], the result is $m(B_c^+) = 6274.7 \pm 0.9(\mathrm{stat}) \pm 0.8(\mathrm{syst})$ [13], which is the most precise B_c^+mass measurement up to date.

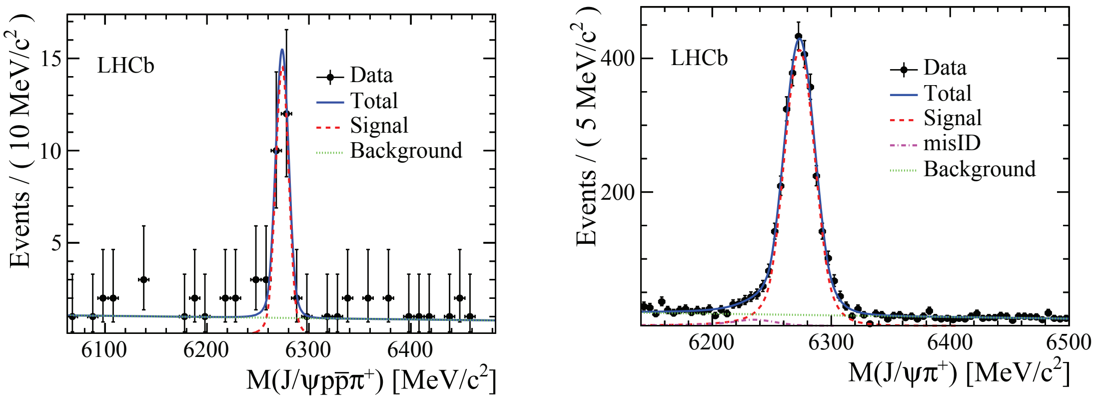

Figure 1. Fitting curves for invariant mass distributions of $B_c^+ \to J/\psi\, p\bar{p}\pi^+$ (left) and the controlled channel $B_c^+ \to J/\psi\, \pi^+$ (right), where the black dots represent the data, the blue lines stand for the fitting functions, with the components of signals (red dashed line), combinatorial background (green dotted line) and the misidentified background from $B_c^+ \to J/\psi\, K^+$ (pink dashed line)

3. Measurement of $\mathcal{B}(B_c^+ \to J/\psi\, \pi^+)/\mathcal{B}(B_c^+ \to J/\psi\, \mu^+\nu_\mu)$

The decays of $B_c^+ \to J/\psi\, \pi^+$ and $B_c^+ \to J/\psi\, \mu^+\nu_\mu$ are used in the studies of B_c^+properties, such as the measurements of B_c^+ lifetime and mass. However, there is no experimental determination of the relative size of these two decays, and the theoretical predictions have large spread among different models [16, 17, 18, 19, 20, 21]. Additionally, the decays of $B_c^+ \to J/\psi\, \pi^+$ and $B_c^+ \to J/\psi\, \mu^+\nu_\mu$ are used respectively as references for the measurement of the production cross section of B_c^+ by Tevatron [5] and LHCb [15] respectively. Therefore, the measurement of the relative branching ratio $\mathcal{B}(B_c^+ \to J/\psi\, \pi^+)/\mathcal{B}(B_c^+ \to J/\psi\, \mu^+\nu_\mu)$ will provide a comparison between the B_c^+ production cross sections measured at Tevatron and LHCb.

In the $B_c^+ \to J/\psi\, \mu^+\nu_\mu$ decay, the main challenge is caused by the undetected neutrino. According to the simulation study, most of the background events from $B \to J/\psi\, X$ will be suppressed with the requirement of $m(J/\psi\, \mu^+) > 5.3\,\mathrm{GeV}/c^2$. The signal-to-background likelihood-ratio method is used for further selection. The signal yields are determined from the fits to invariant mass distributions of the $B_c^+ \to J/\psi\, \mu^+\nu_\mu$ and $B_c^+ \to J/\psi\, \pi^+$ decays with $1\,\mathrm{fb}^{-1}$ data sample collected by LHCb in 2011, as shown in Figure 2. The relative branching ratio in the selected mass region $m(J/\psi\,\mu^+) > 5.3\,\mathrm{GeV}/c^2$ is measured [22]

$$R(m(J/\psi\,\mu^+) > 5.3\,\mathrm{GeV}/c^2) \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.271 \pm 0.016(\mathrm{stat}) \pm 0.016(\mathrm{syst}),$$

and the ratio is extrapolated to full mass region [22]

$$R \equiv f \times R(m(J/\psi\,\mu^+) > 5.3\,\mathrm{GeV}/c^2) = 0.0469 \pm 0.0028(\mathrm{stat}) \pm 0.0046(\mathrm{syst}),$$

where the ratio f is determined for theoretical prediction. This result is consistent with the predictions of the potential model [19], Bethe-Salpter equation [20] and light-front quark model [21], but lower than other predictions [16, 17, 18].

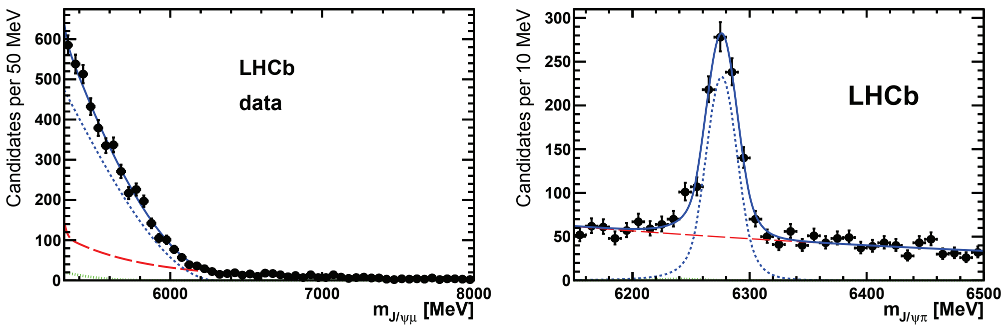

Figure 2. Fitting curves for invariant mass distributions of $B_c^+ \to J/\psi\,\mu^+\nu_\mu$ (left) and $B_c^+ \to J/\psi\,\pi^+$ (right), where the black dots represent the data, the blue lines stand for the fitting functions, with the components of signals (red dashed line), feed-down background or combinatorial background (green dotted line) and $B_{u,d,s} \to J/\psi\,X$ background or the misidentified background from $B_c^+ \to J/\psi\,K^+$ (pink dashed line) respectively

4. Measurement of the B_c^+ lifetime with $B_c^+ \to J/\psi\,\mu^+\nu_\mu$

It is predicted the decay mechanism of B_c^+ mesons is dominated by c-quark decay modes [3]. Therefore, the lifetime of B_c^+ mesons is less than other B mesons, but very close to that of charm mesons. The theoretical predictions of the B_c^+ lifetime have large spread and the world average value was $\tau(B_c^+) = 0.452 \pm 0.033$ ps [14], leading to the large uncertainty which dominates the systematic uncertainty in most of B_c^+ analyses.

In this analysis, the semileptonic decay $B_c^+ \to J/\psi\,\mu^+\nu_\mu$ is used. Comparing with the B_c^+ hadronic decay $B_c^+ \to J/\psi\,\pi^+$, the semileptonic decay has higher statistics and more clear signature with three muons. However, due to the undetected neutrino, the decay $B_c^+ \to J/\psi\,\mu^+\nu_\mu$ can only partially reconstructed at LHCb and the kinematics of this decay is model dependent. Therefore, the B_c^+ lifetime has to be determined by the 2D fit to the distributions of invariant mass $m(J/\psi\,\mu^+)$ and the pseudo-decay time t_{ps}, which is defined as $t_{ps} = m(J/\psi\,\mu^+) \times (\vec{p}\cdot\vec{L})/|\vec{p}|^2$, where, $\vec{p}$ represents the sum of the J/ψ and μ^+momenta, and $\vec{L}$ means the distance between the primary vertex and the B_c^+ decay vertex. With $2\,\mathrm{fb}^{-1}$ data sample collected by LHCb in 2012, the B_c^+ lifetime is measured as $\tau(B_c^+) = 509 \pm 8(\mathrm{stat}) \pm 12(\mathrm{syst})$ fs [23]. Comparing with the previous measurement by CDF and D0, the result of LHCb is the most precise measurement of $\tau(B_c^+)$ to date.

5. Evidence of $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$ decay

The $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$ decay is a new b-quark decay mode of B_c^+ meson and the study of this decay can provide the powerful tests to the form factors of $B_c^+ \to J/\psi$ transition and the spectral functions for virtual W^+ boson into light mesons. In this analysis, the $3\,\text{fb}^{-1}$ data are used for selecting the signals. With the fit to the invariant mass distributions of B_c^+ mesons, 32 ± 8 signals are observed and the significance is 4.5σ [24], which is the first evidence of this decay. Taking the $B_c^+ \to J/\psi\, \pi^+$ decay as the controlled channel, the branching fraction of $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$ with respect to that of $B_c^+ \to J/\psi\, \pi^+$ is measured [24]

$$\frac{\mathcal{B}(B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi\, \pi^+)} = 1.74 \pm 0.44(\text{stat}) \pm 0.24(\text{syst}). \tag{2}$$

The result is consistent with the theoretical prediction in Ref. [25], and with the factorization assumption, it is also in agreement with $B^0$and B^+meson decays [14]

$$\frac{\mathcal{B}(B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi\, \pi^+)} \approx \begin{cases} \dfrac{\mathcal{B}(B^0 \to D^{*-} 3\pi^+ 2\pi^-)}{\mathcal{B}(B^0 \to D^{*-} \pi^+)} = 1.70 \pm 0.34, \\ \dfrac{\mathcal{B}(B^+ \to \bar{D}^{*0} 3\pi^+ 2\pi^-)}{\mathcal{B}(B^0 \to \bar{D}^{*0} \pi^+)} = 1.10 \pm 0.24. \end{cases} \tag{3}$$

6. Summary

LHCb provides good opportunities for B_c^+ physics, many new B_c^+ decays are observed and its properties are measured. The first baryonic decay mode of $B_c^+$is observed and combining with LHCb previous measurements, the B_c^+ mass is measured most precisely up to date. For the first time, the relative ratio $\mathcal{B}(B_c^+ \to J/\psi\, \pi^+)/\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)$ is measured and is consistent with theoretical predictions. The most precise measurement of the B_c^+ lifetime is performed with the decay of $B_c^+ \to J/\psi\, \mu^+ \nu_\mu X$. The evidence of a new decay mode $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$ is reported.

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