Measurement of Bc± mass and lifetime at LHCb

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Measurement of $B_c^{\pm}$ Mass and Lifetime at LHCb

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The $B_c^{\pm}$ mass and lifetime measurements using the decay $B_c^{\pm} \to J/\psi\pi^{\pm}$ at the LHCb experiment were studied. About 310 signal events are expected for a data set which corresponds to an integrated luminosity of 1 fb^{-1}, with a B/S ratio equal to 2. Based on these data, the $B_c^{\pm}$ mass and lifetime can be measured with expected statistical errors below 2 MeV/c^2 and 30 fs, respectively.

1 Introduction

The $B_c^{+\,\text{a}}$ meson is the ground state of the meson family formed by two different heavy flavor quarks, the anti-b quark and the c quark. The mass of the B_c^+ meson has been estimated theoretically to be in a range of 6.2-6.4 GeV/c^2 [2]. Recently unquenched lattice QCD [3] gave the most accurate prediction of $M(B_c^+) = 6278(6)(4)$ MeV/c^2, where the first error is statistical, and the second is systematic. The $\bar{b}c$ mesons are open-flavored and the excited states below the BD threshold can decay only through the electromagnetic or hadronic interactions into the ground state, B_c^+, which can decay only weakly and has a relatively long lifetime. The estimated B_c^+ lifetime is in a range of 0.4-0.8 ps [2]. At present, the best prediction is given by QCD sum rules [4]: $\tau(B_c^+) = 0.48 \pm 0.05$ ps. Since the $\bar{b}c$ mesons carry two different heavy flavor quarks, their production [2] is more difficult than that of the heavy quarkonia. Including the contributions from the excited states, the cross section of the B_c^+ meson at LHC was estimated [5] to be at a level of 1 μb, and is one order higher than that at Tevatron. This means that O(10^9) B_c^+ mesons can be anticipated with 1 fb^{-1} of data at LHC, which is sufficient to study the $\bar{b}c$ meson family systematically.

The B_c^+ meson was observed in the semileptonic decay modes $B_c^+ \to J/\psi(\mu^+\mu^-)\ell^+ X$ ($\ell = e, \mu$) by CDF [6] at Tevatron. The measured mass and lifetime are consistent with the theoretical predictions. More precise measurements of the B_c^+ mass have been performed recently using the fully reconstructed decay $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+$ by CDF [7] and D0 [8], giving $M(B_c^+) = 6275.6 \pm 2.9(\text{stat.}) \pm 2.5(\text{syst.})$ MeV/c^2 and $M(B_c^+) = 6300 \pm 14(\text{stat.}) \pm 5(\text{syst.})$MeV/$c^2$ respectively. The B_c^+ lifetime measurements using the semileptonic decay were also updated with more data, giving $0.448^{+0.038}_{-0.036}(\text{stat.}) \pm 0.032(\text{sys.})$ ps by D0 [9] and $0.475^{+0.053}_{-0.049}(\text{stat.}) \pm 0.018(\text{sys.})$ ps by CDF [10].

In this paper, we report our performance study of the B_c^+ mass and lifetime measurements using the exclusive reconstruction of the decay $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+$ at LHCb. The LHCb detector is described elsewhere [11], hereafter is a summary of the LHCb detector performances which are relevant to this study. Based on Monte Carlo studies, the relative momentum resolution $\delta p/p$ was found to be 0.35%-0.55%, depending on the momentum. The primary vertex can be measured with a precision of about 10 μm in the plane transverse to the beam line, and of about 60 μm in the beam direction. The average resolution of the impact parameter respect to the primary vertex can be parameterized as $\sigma_{\text{IP}} = [14 + (35/p_{\text{T}})]$

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[a] Charge conjugate states are implied throughout this paper, if not specified differently.

μm where p_T is the transverse momentum respect to the beam direction expressed in GeV/c. The muon identification efficiency was measured to be $\varepsilon(\mu \to \mu)$ =94% with a misidentification probability $\varepsilon(\pi \to \mu)$ =3%.

2 Event selection

The simulation of the pp collision and the subsequent hadronization were performed with PYTHIA [12]. B_c^+ meson was generated with a dedicated B_c generator, BCVEGPY [13]. The decay of any b hadron produced was done by EvtGen [14]. The response of the detector was simulated by GEANT4 [15]. In this study, the specific $b \to J/\psi(\mu^+\mu^-)X$ (including $B_d \to J/\psi X$, $B_s \to J/\psi X$, $B_u \to J/\psi X$, $\Lambda_b \to J/\psi X$), the inclusive $J/\psi(\mu^+\mu^-)$ and inclusive $b\bar{b}$ MC data samples were simulated for the background study.

The event selection [16] began with selection of good tracks based on the χ^2 of the track fit, and requiring a p_T greater than 0.5 GeV/c. A pair of two tracks with opposite charges and identified as μ were used to reconstruct the J/ψ meson. J/ψ candidates were required to have an invariant mass in the range from 3.04 to 3.14 GeV/c^2 and a vertex fit quality of χ^2/ndf < 9. Then a track identified as pion from the rest of the event was combined with the J/ψ candidate to reconstruct the B_c^+ meson with a vertex fit cut of χ^2/ndf < 12. The impact parameter significance of the reconstructed B_c^+ track with respect to the production vertex must be less than 3. For events with more than one primary vertex, the production vertex is given by the primary vertex to which the B_c^+ candidate has the smallest impact parameter. To suppress combinatorial background further, $p_T(\mu)$ was required to be greater than 1.0 GeV/c, $p_T(\pi)$ and $p_T(B_c^+)$ were required to be greater than 1.6 GeV/c and 5.0 GeV/c respectively, and the impact parameter significance of the π and J/ψ mesons were required to be greater than 3.0 and 3.5 respectively.

The total reconstruction efficiency for the signal, including the trigger efficiency, was found to be (1.01 ± 0.02)%. In the M(B_c^+)$\pm$80 MeV/c^2 (about $\pm 3\sigma$) mass window, which was regarded as the signal region, the background to signal ratio B/S with 90% confidence level is 1 to 2. The upper limit of B/S was used in the following study. One can expect about 310 signal events with 1 fb^{-1} of data assuming the B_c^+ total production cross section $\sigma(B_c^+) = 0.4$ μb and BR($B_c^+ \to J/\psi\pi^+$)= 1.3×10^{-3}.

3 Mass measurement

To improve the B_c^+ mass resolution, the J/ψ mass constraint vertex fit was used in the mass measurement. M(B_c^+)$\pm$300 MeV/c^2 mass window was used in the following study. The un-binned maximum likelihood method was implemented to extract the B_c^+ mass. The invariant mass distribution of the signal was modeled by a single Gaussian, that of the background was parameterized as a first order polynomial.

For the fit the signal events were taken from the signal data sample with the full Monte Carlo simulation and the background events were generated by a standalone simulation using the invariant mass distribution obtained from the full Monte Carlo simulation. Both the signal and the background were normalized to 1 fb^{-1} of data. The fit gives the B_c^+ mass to be $M(B_c^\pm) = 6399.6 \pm 1.7$ (stat.) MeV/c^2, which is in good agreement with the input value of 6400 MeV/c^2. The result of the fit is shown in Figure 1.
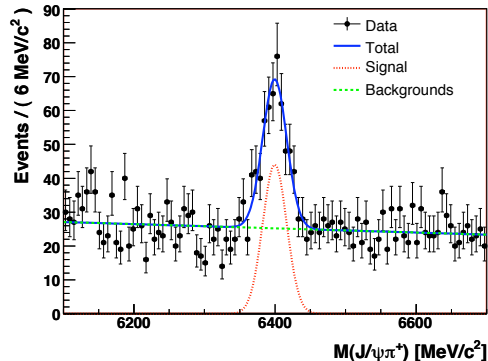
Figure 1: The B_c^+ candidate mass distribution together with the result of the fit described in the text.

4 Lifetime measurement

The J/ψ mass constraint vertex fit biases the B_c^+ decay vertex position because of the final state radiation in the J/ψ decay and the energy loss of particles. As a consequence, the J/ψ mass constraint vertex fit would bias the B_c^+ lifetime and was not used in the lifetime study.

A combined mass-lifetime fit was used to measure the B_c^+ lifetime. The invariant mass distributions for the signal and the background were obtained as in the mass measurement. The proper time (t) distribution of the signal was described by an exponential function smeared by resolution and multiplied by an acceptance function $\varepsilon(t)$ describing the distortion of t distribution caused by the trigger and offline event selection. The function form was derived from an independent Monte Carlo sample. The t distribution of the background was parameterized by the "KEYS" (Kernel Estimating Your Shapes) method [17]. The proper time resolution (σ_t) distributions of the signal and the background were also considered to avoid the potential bias caused by the so called Punzi effects [18]. The fitting framework was tested with a standalone simulation program. The pull of the B_c^+ lifetime was found to follow a Gaussian distribution with $\mu = 0.004 \pm 0.010$ and $\sigma = 1.0122 \pm 0.0072$, which is consistent with the Normal distribution.

As shown in Section 1, the resolution of the impact parameter depends on the transverse momentum. Therefore, the impact parameter significance and the proper time acceptance $\varepsilon(t)$ depend on the $p_T(B_c^+)$ distribution. In order to evaluate the systematics introduced by this, a fit to B_c^+, which was generated with the p_T distribution predicted for B^+ by PYTHIA, was made using the acceptance function obtained from the B_c^+ data generated by BCVEGPY. Note that the $p_T(B_c^+)$ spectrum predicted by BCVEGPY is harder than $p_T(B^+)$ spectrum predicted by PYTHIA. A standalone simulation study shows that in this case the B_c^+ lifetime would be biased by about 0.023 ps.

To reduce the dependence of the lifetime measurement on the $p_T(B_c^+)$ distribution, the $p_T(B_c^+)$ was divided into two intervals: 5-12 GeV/c and > 12 GeV/c. The event selection was re-optimized and for the data set with $p_T(B_c^+) > 12$ GeV/c, the impact parameter significance cuts are changed to > 2.0, > 2.5 and < 4.0 for pions, J/ψ and B_c^+ respectively. The event selection results of the two p_T intervals are summarized in Table 1. The combined

p_T intervals of B_c^+	5-12 GeV/c	≥ 12 GeV/c
Total efficiency ε_tot (including trigger)	(0.34 ± 0.01) %	(0.86 ± 0.02) %
Signal yield (1 fb^{-1} @ 14 TeV)	100	260
B/S @ 90% CL	3 to 6	0.6 to 1.2

Table 1: Summary of the event selection results in the two $p_\mathrm{T}(B_c^+)$ intervals. The total efficiency ε_tot in the two p_T intervals are both defined with respect to the total number of the events in the full p_T range.

mass-lifetime fit applied simultaneously for the two $p_\mathrm{T}(B_c^+)$ intervals reduces the bias in the lifetime measurement to about 0.004 ps.

The fit to the 1 fb^{-1} of data gives B_c^+ lifetime to be $\tau(B_c^+) = 0.438 \pm 0.027$ (stat.) ps, which is in good agreement with the input value of 0.46 ps. The results of the fit in the two $p_\mathrm{T}(B_c^+)$ intervals are shown in Figure 2.
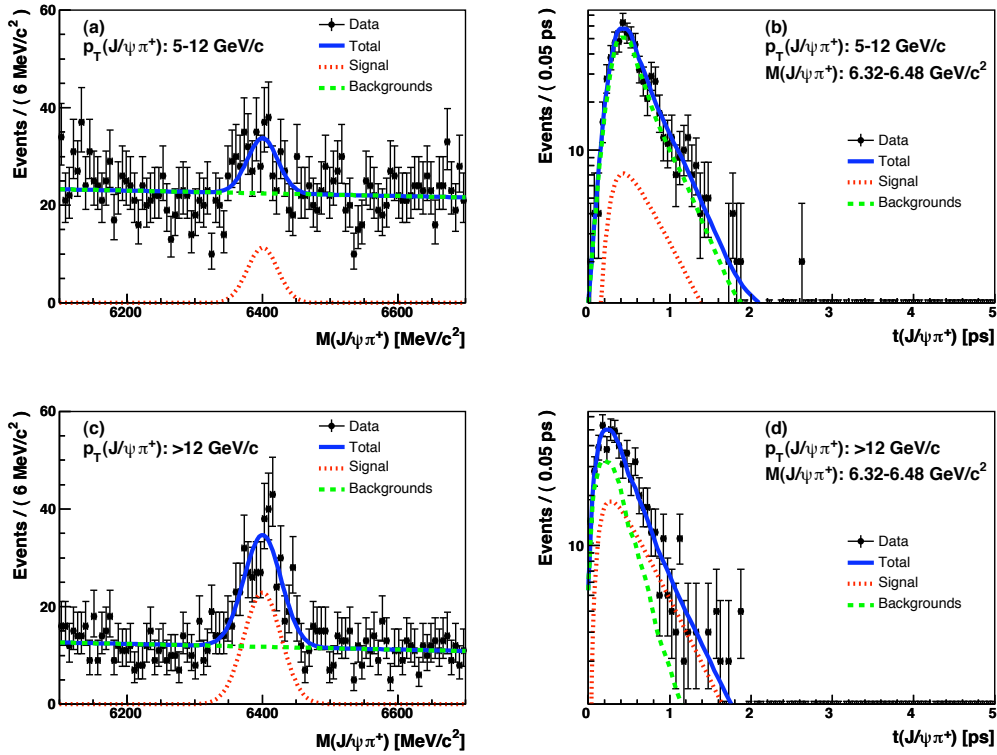

Figure 2: The results of the fit in the two $p_\mathrm{T}(B_c^+)$ intervals. The left column shows the invariant mass distributions, the right column shows the proper time distributions in the signal region.

5 Summary

In summary, the event selection of the decay $B_c^+ \to J/\psi(\mu^+\mu^-)\pi^+$ at LHCb was studied, about 310 signal events are expected from 1 fb^{-1} of data, with a B/S of 2. Based on the selected data sample, the B_c^+ mass can be measured with an expected statistical error to be below 2 MeV/c^2. For the B_c^+ lifetime measurement, to reduce a potential bias caused by the limited knowledge of the $p_{\mathrm{T}}(B_c^+)$ distribution, the data sample was divided into two $p_{\mathrm{T}}(B_c^+)$ intervals. The combined mass-lifetime fit performed in these two p_{T} intervals simultaneously gives a statistical uncertainty of the B_c^+ lifetime to be below 30 fs.

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