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Properties and decays of the B_c^+ meson

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The B_c^+ is the only ground-state meson in the Standard Model to be composed of two heavy quarks and decaying through weak interaction. LHCb has recently measured its lifetime and mass, and observed several decay channels, including the first B_c^+ decay due to charm quark decay.

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1. Introduction

The B_c^+ meson, and its charge-conjugation partner as always implied throughout this contribution, is the ground-state of the family of hadrons formed of a $\bar{b}$ and a c quark. It is an excellent laboratory to study both QCD, since its dynamics can be treated in a similar way to that of quarkonium states, and weak interaction because B_c^+ decays violate flavour quantum numbers and therefore they can only happen through weak interaction.

According to theoretical predictions, 70% of the total decay width is due to c-quark decays, 20% to b-quark decays and 10% to weak annihilation [1]. However, the experimental signature of of $b \to c$ transition is clearer having a substantial probability to produce a J/ψ in the final state, enhancing selection efficiency already at hardware trigger level. Indeed, the discovery of the B_c^+ meson at CDF was achieved by studying b-quark decay processes, namely the $B_c^+ \to J/\psi \mu^+ \nu_\mu X$ decays [2], and most of the observed decays are due to a $b \to c$ transition. The $B_c^+ \to B_s^0 \pi^+$ decay is the only observed decay due to a c-quark decay [3]. Recently reported by LHCb, it is discussed in Section 2.

Section 3 is devoted to the B_c^+ mass measurement using the low-Q decay $B_c^+ \to J/\psi D_s^+$ [4]. The lifetime measurement recently performed studying the abundant semileptonic decays $B_c^+ \to J/\psi \mu^+ \nu_\mu X$ is described in Section 4 [5].

The experimental characterization of the B_c^+ meson is nowadays lead by LHCb, described elsewhere [6], exploiting the unprecedented B_c^+ production rate achieved at the LHC.

2. Observation of the $B_c^+ \to B_s^0 \pi^+$ decay

LHCb reported [3] the first observation of $B_c^+ \to B_s^0 \pi^+$ (charge-conjugation implied throughout this contribution) decays analysing the pp-collision data collected in 2011 at a center-of-mass energy of 7 TeV, and in 2012 at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 1 fb^{-1} and 2 fb^{-1}, respectively.

Predictions for the branching fraction $\mathscr{B}(B_c^+ \to B_s^0 \pi^+)$ span a large range between 2.5% and 16.4% [7], and references therein. LHCb has performed a search starting from two samples of fully reconstructed B_s^0 mesons decaying to $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to J/\psi \phi$. The distributions of the invariant mass of the B_s^0 candidates, as reconstructed in the two final states, are shown in Figure 1.

$73\,700 \pm 500$ $B_s^0 \to D_s^- \pi^+$ and $103\,760 \pm 380$ $B_s^0 \to J/\psi \phi$ candidates are observed and combined to a charged pion to create B_c^+ candidates. The distributions of the invariant mass of such candidates are shown in Figure 2.

The fitted signal yield for $B_c^+ \to B_s^0 (\to D_s^- \pi^+) \pi^+$ decays is 64 ± 10 corresponding to a statistical significance of 7.7σ; for $B_c^+ \to B_s^0 (\to J/\psi \phi) \pi^+$, 35 ± 8 signal candidates are observed, corresponding to a statistical significance of 6.1σ.

The B_s^0 and B_c^+ yields are corrected for the relative detection efficiencies, to obtain the efficiency-corrected ratios of $B_c^+ \to B_s^0 \pi^+$ over B_s^0 yields,

$$\left(2.54 \pm 0.40(\text{stat})\ {}^{+0.23}_{-0.17}(\text{syst})\right) \times 10^{-3}, \quad \text{and} \quad (2.20 \pm 0.49(\text{stat}) \pm 0.23(\text{syst})) \times 10^{-3}. \tag{2.1}$$

for B_s^0 reconstructed as $D_s^- \pi^+$ and $J/\psi \phi$ respectively. The systematic uncertainty is dominated by the uncertainty on the lifetime of the B_c^+ meson which results into an uncertainty on the selection efficiency of criteria based on B_c^+ flight distance. Such contribution is correlated between the two B_s^0 reconstruction channels, and is therefore taken into account separately when combining the results above to give the ratio of production rates multiplied with the branching fraction

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathscr{B}(B_c^+ \to B_s^0\pi^+) = \left(2.37 \pm 0.31(\text{stat}) \pm 0.11(\text{syst})^{+0.17}_{-0.13}(\tau_{B_c^+})\right). \quad (2.2)$$

Assuming a value for $\sigma(B_c^+)/\sigma(B_s^0)$ of 0.2 [3], one would obtain a branching ratio $\mathscr{B}(B_c^+ \to B_s^0\pi^+)$ of about 10%, the highest branching fraction ever observed for a b-hadron weak decay.

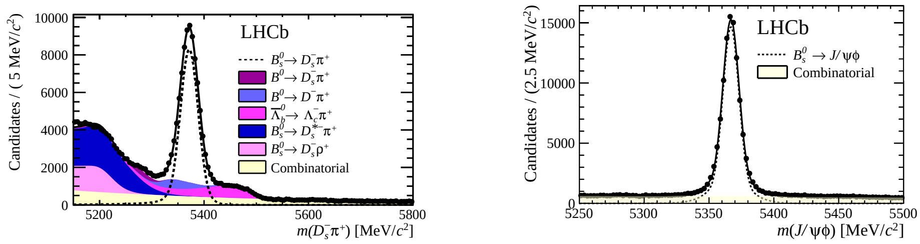

Figure 1: B_s^0 mass distribution for the candidates reconstructed as $B_s^0 \to D_s^-\pi^+$ (left) and $B_s^0 \to J/\psi\phi$ (right).

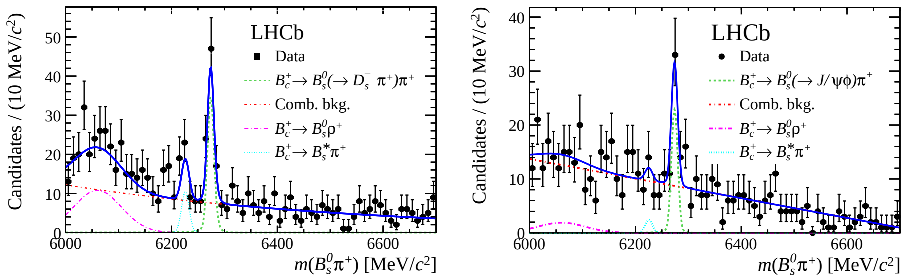

Figure 2: Invariant mass for the $B_s^0\pi^+$ combinations with the B_s^0 reconstructed as $B_s^0 \to D_s^-\pi^+$ (left) and $B_s^0 \to J/\psi\phi$ (right).

3. Mass measurement with the decay $B_c^+ \to J/\psi D_s^+$

Already with a first bunch of data collected in 2011 and corresponding to an integrated luminosity of 370 pb^{-1}, LHCb reported the world best measurement of the B_c^+ mass studying the channel $B_c^+ \to J/\psi\pi^+$: $M(B_c^+) = (6273.7 \pm 1.3(\text{stat}) \pm 1.6(\text{syst}))$ MeV$/c^2$ [8]. 162 ± 18 signal candidates were used to perform the mass measurement whose uncertainty was already dominated by systematic uncertainty on the momentum scale because of the large Q-value of the B_c^+ decay.

Better resolution and momentum scale calibration uncertainty have been obtained two years later studying the decay $B_c^+ \to J/\psi D_s^+$ [4]:

$$M(B_c^+) = (6276.28 \pm 1.44(\text{stat}) \pm 0.36(\text{syst})) \text{ MeV}/c^2. \quad (3.1)$$

Up to date, this is the world's most precise single measurement of the B_c^+ mass.

The signal yield of 28.9 ± 5.6 $B_c^+ \to J/\psi D_s^+$ is small compared to the size of the sample available for $B_c^+ \to J/\psi\pi$, but because of the low Q-value of the decay, the experimental resolution, as shown in Figure 3, is much better and therefore the statistical uncertainties are similar for the two channels. The systematic uncertainty is still dominated by momentum scale calibration (accounting for 0.30 MeV/c^2) on the B_c^+ meson mass, while other relevant contributions are the uncertainty on the D_s^+ mass (0.16 MeV/c^2), and signal modelling including simulation effects (0.11 MeV/c^2). The uncertainty on the D_s^+ meson mass and on the momentum scale largely cancels in the mass difference

$$m_{B_c^+} - m_{D_s^+} = 4607.97 \pm 1.44(\text{stat}) \pm 0.20(\text{syst})\ \text{MeV}/c^2. \tag{3.2}$$

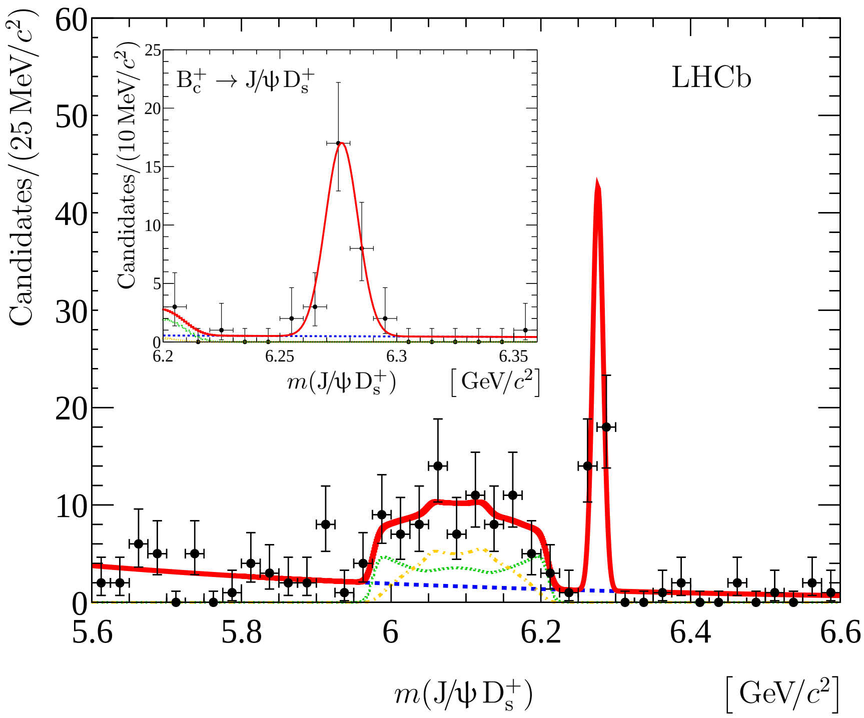

Figure 3: B_c^+ mass distribution for candidates reconstructed as $B_c^+ \to J/\psi D_s^+$ as used in the mass measurement. The broader structure at lower mass is due to partially reconstructed $B_c^+ \to J/\psi D_s^{*+}$ decays.

4. Lifetime measurement with the semileptonic decay channel $B_c^+ \to J/\psi\mu^+\nu_\mu X$

The lifetime of the B_c^+ meson is an important quantity for both theory and experiments. Many models developed describing heavy-quark properties can be used to predict the B_c^+ lifetime, the more precise is the knowledge of this quantity, the more theoretical models are constrained.

Experimentally, as already mentioned in Section 2, the uncertainty on the lifetime results in an uncertainty on the selection efficiency of criteria based on the B_c^+ flight distance. Since these criteria are very powerful in rejecting background, most of B_c^+ analyses rely on them and are affected by lifetime uncertainty.

LHCb has recently measured [5] the lifetime of the B_c^+ meson by studying the semileptonic decay channel $B_c^+ \to J/\psi\mu^+\nu_\mu X$, with the J/ψ reconstructed as a muon pair. The large branching fraction and the very clear experimental signature (a 3–muon vertex), allow this analysis to be performed with a cut-based decay-time-unbiased selection, avoiding the need to measure the acceptance as a function of the decay time, introducing the largest systematic uncertainty in most of the lifetime measurements.

On the other hand, when studying partially reconstructed decays background rejection is more difficult because the selection cannot rely on a mass peak. In the case of $B_c^+ \to J/\psi\mu^+\nu_\mu X$, the invariant mass of the $J/\psi\mu^+$ combination lies in a range between 3.2 and 6.25 GeV/c^2 and the shape of the distribution depends on the form-factors of the decay, for which no experimental measurement is available.

A correction, named k-factor, between the $J/\psi\mu^+$ combination rest frame and the B_c^+ rest frame, needed to calculate the *proper* decay-time and therefore the lifetime. The k-factor correction is applied on a statistical basis in bins of the mass reconstructed for the $J/\psi\mu^+$ combination. The shape of the k-factor distribution is determined using simulation and is affected by: (i) form-factor model of the B_c^+ decay; (ii) model of acceptance and efficiency as function of the kinematic variables; (iii) feed-down decays, where the final state $J/\psi\mu^+$ is reached through an intermediate state, *e.g.* $B_c^+ \to \psi(2S)(\to J/\psi\pi^+\pi^-)\mu^+\nu_\mu$.

Background is dominated by events in which a real J/ψ from a b-hadron decay is associated to a hadron misidentified as a muon. This background source, named for brevity *misidentification background*, is modeled with a data-driven technique requiring an accurate characterization of the PID performance of the LHCb detector.

Other non-negligible background sources are due to decay candidates with a fake J/ψ and candidates obtained combining a J/ψ with a muon, but not from the same vertex (combinatorial background).

The B_c^+ lifetime is obtained through a two-dimensional fit on the joint distribution of $M(J/\psi\mu^+)$ and $t_{\rm ps}$, the decay time reconstructed in the $J/\psi\mu^+$ rest-frame.

The result,

$$\tau_{B_c^+} = 509 \pm 8\ (\text{stat}) \pm 12\ (\text{syst})\ \text{fs}, \tag{4.1}$$

is the world's best measurement of the B_c^+ lifetime, with an uncertainty halved with respect to the world average. The systematic error is dominated by the uncertainties on the background (± 10 fs), and signal (± 5 fs) models, where the latter includes theoretical uncertainties on form-factors and branching fractions of the feed-down decays.

Further improvements on the precision of the lifetime measurement are expected studying the hadronic decay channel $B_c^+ \to J/\psi\pi^+$ where systematic uncertainties are largely uncorrelated with those affecting the measurement presented above.

5. Conclusion and outlook

The excellent performance of the LHC and of the detector has allowed LHCb to reach several achievements in the field of B_c^+ physics.

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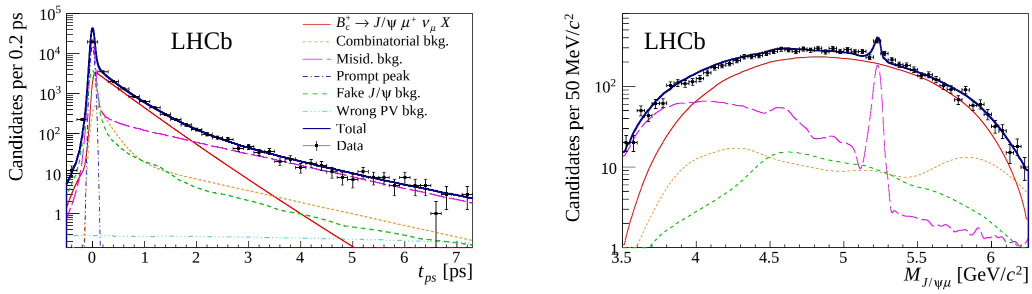

Figure 4: Data model for the $B_c^+ \to J/\psi\mu^+\nu_\mu X$ decays used in the B_c^+ lifetime measurement. On the left the model is projected on the reconstructed pseudo-proper decay time, on the right on the invariant mass of the $J/\psi\mu^+$ combination.

The world's best measurement of mass and lifetime were presented here together with the first observation of a $c \to s$ transition in a B_c^+ decay. Several other decay channels [9 – 13] have been observed for the first time and their relative decay branching fraction measured.

In 2015, LHCb will restart data-taking of the pp collisions at 13-14 TeV. Higher luminosity and larger B_c^+ production cross-section are expected and therefore many unobserved B_c^+ decay channels are expected to become accessible. Observed decays will be used as high-statistics control channels and studied for precision measurements.

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