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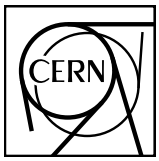

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Precision measurement of the B_c^+ meson mass

LHCb collaboration[†]

Abstract

A precision measurement of the B_c^+ meson mass is performed using proton-proton collision data collected with the LHCb experiment at centre-of-mass energies of 7, 8 and 13 TeV, corresponding to a total integrated luminosity of 9.0 fb^{-1}. The B_c^+ mesons are reconstructed via the decays $B_c^+ \to J/\psi\pi^+$, $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$, $B_c^+ \to J/\psi p\bar{p}\pi^+$, $B_c^+ \to J/\psi D_s^+$, $B_c^+ \to J/\psi D^0 K^+$ and $B_c^+ \to B_s^0\pi^+$. Combining the results of the individual decay channels, the B_c^+ mass is measured to be $6274.47 \pm 0.27\,(\text{stat}) \pm 0.17\,(\text{syst})\,\text{MeV}/c^2$. This is the most precise measurement of the B_c^+ mass to date. The difference between the B_c^+ and B_s^0 meson masses is measured to be $907.75 \pm 0.37\,(\text{stat}) \pm 0.27\,(\text{syst})\,\text{MeV}/c^2$.

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1 Introduction

The B_c meson family is unique in the Standard Model as its states contain two different heavy-flavour quarks, a $\bar{b}$ and a c quark. Quantum Chromodynamics (QCD) predicts that the $\bar{b}$ and c quarks are tightly bound in a compact system, with a rich spectroscopy of excited states. Studies of the B_c mass spectrum can reveal information on heavy-quark dynamics and improve our understanding of the strong interaction. Due to the presence of two heavy-flavour quarks the mass spectrum of the B_c states can be predicted with much better precision than many other hadronic systems. The mass spectrum of the B_c family has been calculated with nonrelativistic quark potential models [1–8], nonperturbative phenomenological models [9], perturbative QCD [10, 11], relativistic quark models [12–15], and lattice QCD [16–21]. The ground state of the B_c meson family, denoted hereafter as B_c^+, decays only through the weak interaction, with a relatively long lifetime. The most accurate prediction of the B_c^+ mass, $M(B_c^+) = 6278 \pm 6 \pm 4\,\mathrm{MeV}/c^2$ [20], is obtained with unquenched lattice QCD.

In 1998 the CDF collaboration discovered the B_c^+ meson via its semileptonic decay modes and measured its mass to be $6400 \pm 390 \pm 130\,\mathrm{MeV}/c^2$ [22]. At the LHCb experiment, considerable progress has been made on measurements of the B_c^+ production [23–27], spectroscopy [23, 28–31], lifetime [32, 33], and new decay modes [27, 30, 34–42]. The world average of the B_c^+ mass has an uncertainty of $0.8\,\mathrm{MeV}/c^2$ [43]. This is the dominant systematic uncertainty in the recent $B_c(2S)^{(*)+}$ mass measurements [31, 44].

This paper presents a precision measurement of the B_c^+ mass using the decay modes $B_c^+ \to J/\psi\,\pi^+$, $B_c^+ \to J/\psi\,\pi^+\pi^-\pi^+$, $B_c^+ \to J/\psi\,p\bar{p}\pi^+$, $B_c^+ \to J/\psi\,D_s^+$, $B_c^+ \to J/\psi\,D^0K^+$ and $B_c^+ \to B_s^0\pi^+$ [1]. The first two decays are chosen for their large signal yield, while the others have a low energy release. The data sample corresponds to an integrated luminosity of 9.0 fb^{-1}, collected with the LHCb experiment in pp collisions at centre-of-mass energies of 7, 8 and 13 TeV. This measurement supersedes results reported in Refs. [23, 28–30].

2 Detector and simulation

This LHCb detector [45, 46] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region [47], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes [48, 49] placed downstream of the magnet. The tracking system provides a measurement of the momentum, p, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at $200\,\mathrm{GeV}/c$. The momentum scale is calibrated using samples of $B^+ \to J/\psi\,K^+$ and $J/\psi \to \mu^+\mu^-$ decays collected concurrently with the data sample used for this analysis [50, 51]. The relative accuracy of this procedure is determined to be 3×10^{-4} using samples of other fully reconstructed B, Υ and K_S^0-meson decays. The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_{\mathrm{T}})\,\mu\mathrm{m}$, where p_{T} is the component of the momentum transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from

[1] The inclusion of charge-conjugate modes is implied throughout this paper.

two ring-imaging Cherenkov detectors [52]. Photons, electrons and hadrons are identified by a calorimeter system consisting of a scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [53]. The online event selection is performed by a trigger [54], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which performs a full event reconstruction.

Simulated samples are used to model the effects of the detector acceptance, optimise signal selection and validate the analysis technique. In simulation, pp collisions are generated using Pythia 8 [55] with an LHCb specific configuration [56]. The production of B_c^+ mesons is simulated using the dedicated generator BcVegPy [57]. Decays of hadrons are described by EvtGen [58], in which final-state radiation is generated using Photos 3 [59]. The interaction of the generated particles with the detector and its response are implemented using the Geant4 toolkit [60] as described in Ref. [61].

3 Event selection

The B_c^+ candidates are reconstructed in the following decay modes: $B_c^+ \to J/\psi\pi^+$, $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$, $B_c^+ \to J/\psi p\bar{p}\pi^+$, $B_c^+ \to J/\psi D_s^+$, $B_c^+ \to J/\psi D^0 K^+$ and $B_c^+ \to B_s^0\pi^+$. A pair of oppositely charged muons form J/ψ candidates. The D_s^+ candidates are reconstructed via the $D_s^+ \to K^+K^-\pi^+$ and $D_s^+ \to \pi^+\pi^-\pi^+$ decays, while the D^0 is reconstructed using the $D^0 \to K^-\pi^+$ decay. The B_s^0 candidates are reconstructed in the decay modes $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ and $B_s^0 \to D_s^-(\to K^+K^-\pi^-)\pi^+$, and a multivariate classifier as used in Ref. [24] is employed to separate signal from combinatorial background. Then the B_s^0 candidates are combined with an additional pion to reconstruct B_c^+ candidates. All of the intermediate-state particles are required to have an invariant mass within three times the expected mass resolution around their known masses [43]. Muons, kaons, pions and protons are required to have good track-fit quality and high transverse momentum. The J/ψ and B_c^+ candidates are required to have a good-quality vertex fit.

A boosted decision tree [62–64] implemented within the TMVA [65] package optimises separation of the signal from combinatorial background for each decay mode. The classifiers are trained with simulated signal samples and a background proxy obtained from the upper mass sideband of the data, in the range $[6.6, 7.0]\,\mathrm{GeV}/c^2$. Kinematic variables that generically separate b-hadron decays from background are used in the training of the classifiers. The variables include the decay time, transverse momenta, vertex-fit quality of the B_c^+ candidate, as well as variables related to the fact that the B_c^+ meson is produced at the PV. The requirement on the classifiers is determined by maximising the signal significance $S/\sqrt{S+B}$, where S is the expected signal yield estimated using simulation, and B is the expected background yield evaluated in the upper sideband in data and extrapolated to the signal region.

4 Mass measurement

The B_c^+ meson mass is determined in each decay mode by performing an unbinned maximum likelihood fit to the invariant mass distributions of the B_c^+ candidates. The signal

is described by a double-sided Crystal Ball (DSCB) function [66], while the background is described by an exponential function. The DSCB function comprises a Gaussian core with power-law tails to account for radiative effects. Parameters describing the radiative tails are determined from simulation.

The invariant mass of the B_c^+ candidates is calculated from a kinematic fit [67], in which the B_c^+ candidate is assumed to originate from its PV and the intermediate-state masses are constrained to their known values [43]. The PV of the B_c^+ candidate is that with respect to which it has the smallest $\chi^2_{\rm IP}$. The $\chi^2_{\rm IP}$ is defined as the difference in χ^2 of the PV fit with and without the particle in question. For $B_c^+ \to B_s^0\pi^+$ decays, the B_s^0 mass is constrained to the value of $5366.89 \pm 0.21\,{\rm MeV}/c^2$, which is an average of the measurements of the B_s^0 mass performed by the LHCb collaboration [68–71].

The difference between the B_c^+ and B_s^0 meson masses, $\Delta m = m(B_c^+) - m(B_s^0)$, is measured in the $B_c^+ \to B_s^0\pi^+$ decay mode, where $m(B_c^+)$ and $m(B_s^0)$ are the reconstructed masses of B_c^+ and B_s^0 candidates. The mass difference Δm is calculated with a kinematic fit [67], in which the B_c^+ candidate is assumed to originate from the PV with the smallest $\chi^2_{\rm IP}$ and the masses of the intermediate particles are constrained to their known values [43].

Figure 1 shows the invariant mass distributions and fit results for all B_c^+ decay modes. Figure 2 shows the distributions of Δm and fit results for the $B_c^+ \to B_s^0(D_s^-\pi^+)\pi^+$ and $B_c^+ \to B_s^0(J/\psi\,\phi)\pi^+$ decay modes. The signal yields, mass and resolution values as determined from fits to the individual mass distributions are given in Table 1. For the $B_c^+ \to B_s^0\pi^+$ decays, the results of the fits to the Δm distribution are reported in Table 2.

The reconstructed invariant-mass distribution is distorted due to the missing energy from unreconstructed photons (bremsstrahlung) emitted by final-state particles. The resulting bias in the extracted B_c^+ mass is studied with simulated samples for each decay channel, and is used to correct the mass obtained from the fit. Multiple scattering in detector material can decrease the observed opening angles among the B_c^+ decay products, affecting the reconstructed B_c^+ mass and decay length and thereby the selection efficiency. The corresponding bias of the B_c^+ mass measurement was studied with charmed hadrons ($D^+, D^0, D_s^+, \Lambda_c^+$), and was found to be well reproduced by simulation [72]. A bias associated with the selection from simulated samples is assigned as a corresponding correction. The measured masses (M) and mass difference (ΔM) are corrected for this bias (from -0.46 to $0.27\,{\rm MeV}/c^2$) due to final-state radiation and the selection, and summarised in Table 1 and 2.

5 Systematic uncertainties

To evaluate systematic uncertainties, the complete analysis is repeated varying assumed parameters, models and selection requirements. The observed differences in the B_c^+ mass central values between the nominal result and the alternative estimates are considered as one standard-deviation uncertainties.

The systematic uncertainty of the B_c^+ mass comprises uncertainties on the momentum-scale calibration, energy loss corrections, signal and background models, the mass of the intermediate states and the uncertainty on the bias caused by the final-state radiation and selection.

The dominant source of systematic uncertainty arises due to the limited precision of the momentum-scale calibration. For each decay, this uncertainty is propagated to the B_c^+

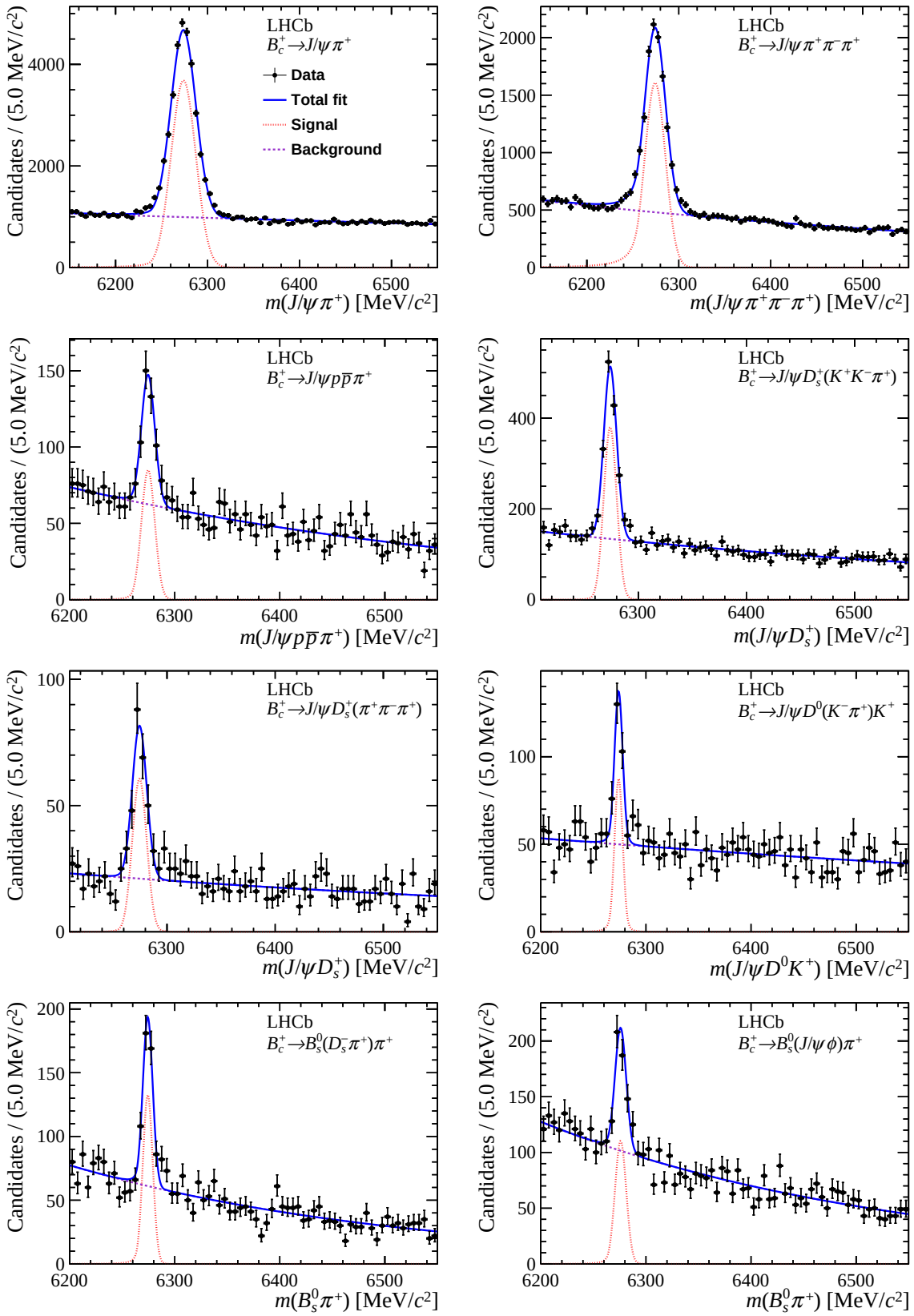

Figure 1: Distributions of invariant-mass m for B_c^+ candidates selected in the studied decay channels, where data are shown as the points with error bars; the total fits are shown as solid blue curves; the signal component are red dotted curves; the background components purple dotted curves.

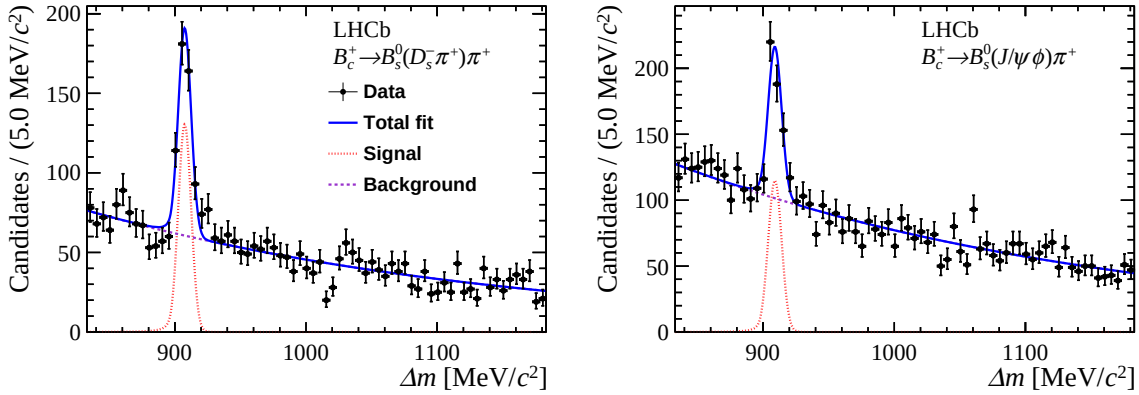

Figure 2: Distributions of mass difference Δm for the $B_c^+ \to B_s^0(D_s^-\pi^+)\pi^+$ and $B_c^+ \to B_s^0(J/\psi\,\phi)\pi^+$ decay modes, where data are shown as the points with error bars; the total fits are shown as solid blue curves; the signal component are red dotted curves; the background components purple dotted curves.

Table 1: Signal yields, mass values and mass resolutions as obtained from fits shown in Fig. 1, together with the mass corrected for the effects of final-state radiation and selection as described in the text. The uncertainties are statistical only.

Decay mode	Yield	Fitted mass [MeV/c^2]	Corrected mass [MeV/c^2]	Resolution [MeV/c^2]
$J/\psi\,\pi^+$	25181 ± 217	6273.71 ± 0.12	6273.78 ± 0.12	13.49 ± 0.11
$J/\psi\,\pi^+\pi^-\pi^+$	9497 ± 142	6274.26 ± 0.18	6274.38 ± 0.18	11.13 ± 0.18
$J/\psi\,p\bar{p}\pi^+$	273 ± 29	6274.66 ± 0.73	6274.61 ± 0.73	6.34 ± 0.76
$J/\psi\,D_s^+(K^+K^-\pi^+)$	1135 ± 49	6274.09 ± 0.27	6274.11 ± 0.27	5.93 ± 0.30
$J/\psi\,D_s^+(\pi^+\pi^-\pi^+)$	202 ± 20	6274.57 ± 0.71	6274.29 ± 0.71	6.63 ± 0.67
$J/\psi\,D^0(K^-\pi^+)K^+$	175 ± 21	6273.97 ± 0.53	6274.08 ± 0.53	3.87 ± 0.57
$B_s^0(D_s^-\pi^+)\pi^+$	316 ± 27	6274.36 ± 0.44	6274.08 ± 0.44	4.67 ± 0.48
$B_s^0(J/\psi\,\phi)\pi^+$	299 ± 37	6275.87 ± 0.66	6275.46 ± 0.66	5.32 ± 0.74

Table 2: Signal yields, mass difference (ΔM) and resolution as obtained from fits shown in Fig. 2, together with the values corrected for the effects of final-state radiation and selection as described in the text. The uncertainties are statistical only.

Decay mode	Yield	Fitted ΔM [MeV/c^2]	Corrected ΔM [MeV/c^2]	Resolution [MeV/c^2]
$B_s^0(D_s^-\pi^+)\pi^+$	325 ± 27	907.51 ± 0.46	907.24 ± 0.46	4.88 ± 0.47
$B_s^0(J/\psi\,\phi)\pi^+$	300 ± 32	908.98 ± 0.61	908.59 ± 0.61	5.12 ± 0.62

mass according to the energy release, which is the difference between the value of the B_c^+ mass and the sum of the masses of its intermediate states. Due to the limited knowledge of the energy loss in the material of the tracking system, the amount of material traversed by final-state particles is known to 10% accuracy. This translates into a measured mass uncertainty of $0.03\,\mathrm{MeV}/c^2$ for $D^0 \to K^+K^-\pi^+\pi^-$ decays [51]. The uncertainties on the B_c^+ mass are scaled from that of the D^0 decay by the number of final-state particles. The uncertainties due to the limited size of simulated samples are taken as systematic uncertainties from the selection-induced bias on the B_c^+ masses. The uncertainty on the masses of the intermediate states D_s^+, D^0, B_s^0 are propagated to the B_c^+ mass measurement.

The uncertainty related to the signal shape is estimated by using alternative signal models, including the sum of two Gaussian functions, a Hypatia function [73], the sum of a DSCB and a Gaussian function, and the sum of two DSCB functions. The differences of the fitted mass with final-state radiation corrections between the nominal and the alternative models are found to be smaller than $0.1\,\mathrm{MeV}/c^2$, which is taken as the corresponding systematic uncertainty. The uncertainty related to the background description is evaluated by using a first-order Chebyshev function instead of an exponential function.

The systematic uncertainties considered for the B_c^+ mass and mass difference measurements are summarised in Table 3 and 4, respectively.

6 Combination of the measurements

The combination of the B_c^+ mass measurements is performed using the Best Linear Unbiased Estimate (BLUE) method [74–76]. In the combination, uncertainties arising from the momentum-scale calibration, energy loss corrections, and final-state radiation are assumed to be 100% correlated, while all other sources of systematic uncertainty are assumed to be uncorrelated. The uncertainty on the momentum-scale calibration of the B_s^0 mass is assumed to be 100% correlated with that of the B_c^+ mass.

The individual mass measurements and the resulting combination are shown in Fig. 3. The individual measurements are consistent with each other. The breakdown of the combined systematic uncertainty is given in Table 5. The weights of individual measurements returned by the BLUE method are listed in Table 6. The weights are computed including all uncertainties. The measurement contributing most to the combination is obtained

Table 3: Summary of systematic uncertainties (in MeV/c^2) on the B_c^+ mass.

Decay mode	Momentum scale calibration	Energy loss correction	Signal model	Background model	Intermediate states	Selection	Total
$J/\psi\,\pi^+$	0.91	0.02	0.10	0.01	<0.01	0.01	0.92
$J/\psi\,\pi^+\pi^-\pi^+$	0.83	0.04	0.10	0.02	<0.01	0.05	0.84
$J/\psi\,p\bar{p}\pi^+$	0.35	0.04	0.10	0.01	<0.01	0.06	0.37
$J/\psi\,D_s^+(K^+K^-\pi^+)$	0.36	0.04	0.10	0.02	0.07	0.02	0.38
$J/\psi\,D_s^+(\pi^+\pi^-\pi^+)$	0.36	0.04	0.10	0.02	0.07	0.03	0.38
$J/\psi\,D^0(K^-\pi^+)K^+$	0.25	0.04	0.10	0.01	0.05	0.02	0.28
$B_s^0(D_s^-\pi^+)\pi^+$	0.23	0.04	0.10	<0.01	0.21	0.12	0.43
$B_s^0(J/\psi\,\phi)\pi^+$	0.23	0.04	0.10	0.01	0.21	0.02	0.41

Table 4: Summary of systematic uncertainties on the mass difference ΔM (in MeV/c^2) for the $B_s^0(D_s^-\pi^+)\pi^+$ and $B_s^0(J/\psi\phi)\pi^+$ decays.

Decay mode	Momentum scale calibration	Energy loss	Signal model	Background model	Intermediate states	Selection	Total
$B_s^0(D_s^-\pi^+)\pi^+$	0.23	0.04	0.10	0.01	<0.01	0.13	0.29
$B_s^0(J/\psi\phi)\pi^+$	0.23	0.04	0.10	<0.01	<0.01	0.02	0.25

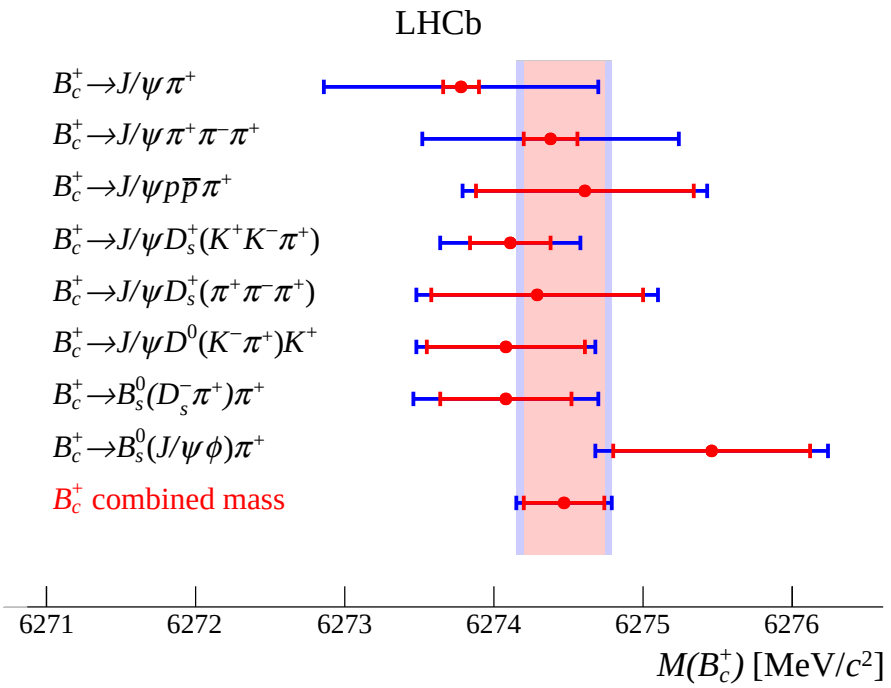

Figure 3: Individual B_c^+ mass measurements and their combination. The red (inner) cross-bars show the statistical uncertainties, and the blue (outer) cross-bars show the total uncertainties.

from the $B_c^+ \to J/\psi D_s^+(K^+K^-\pi^+)$ decay. The negative weight for the $B_c^+ \to J/\psi\pi^+$ channel arises from the 100% correlation between the systematic uncertainties due to the momentum-scale calibration. This results in a larger statistical and smaller systematic uncertainty relative to an uncorrelated average.

The combination for the mass difference ΔM is shown in Fig. 4. The breakdown of the combined systematic uncertainty is given in Table 5 and the weights of decay modes in the combination are listed in Table 6. The combined B_c^+ mass is determined to be $M(B_c^+) = 6274.47 \pm 0.27\,(\text{stat}) \pm 0.17\,(\text{syst})\,\text{MeV}/c^2$, while the mass difference between the B_c^+ and B_s^0 mesons, ΔM, is determined to be $\Delta M = 907.75 \pm 0.37\,(\text{stat}) \pm 0.27\,(\text{syst})\,\text{MeV}/c^2$.

Table 5: Breakdown of systematic uncertainties (in MeV/c^2) in the combination of the B_c^+ mass and the mass difference ΔM. The total uncertainty is the sum in quadrature of the uncertainty of different sources.

Source	Mass	Mass difference
Momentum-scale calibration	0.11	0.23
Energy loss	0.05	0.04
Signal line shape	0.10	0.10
Background line shape	0.01	0.01
Mass of intermediate state	0.06	<0.01
Selection bias correction	0.03	0.08
Total	0.17	0.27

Table 6: Weights of the decay modes in the combination of the B_c^+ mass and the mass difference ΔM.

Decay mode	Mass	Mass difference
$J/\psi\pi^+$	-0.446	-
$J/\psi\pi^+\pi^-\pi^+$	0.032	-
$J/\psi p\bar{p}\pi^+$	0.098	-
$J/\psi D_s^+(K^+K^-\pi^+)$	0.659	-
$J/\psi D_s^+(\pi^+\pi^-\pi^+)$	0.101	-
$J/\psi D^0(K^-\pi^+)K^+$	0.224	-
$B_s^0(D_s^-\pi^+)\pi^+$	0.220	0.620
$B_s^0(J/\psi\phi)\pi^+$	0.111	0.380

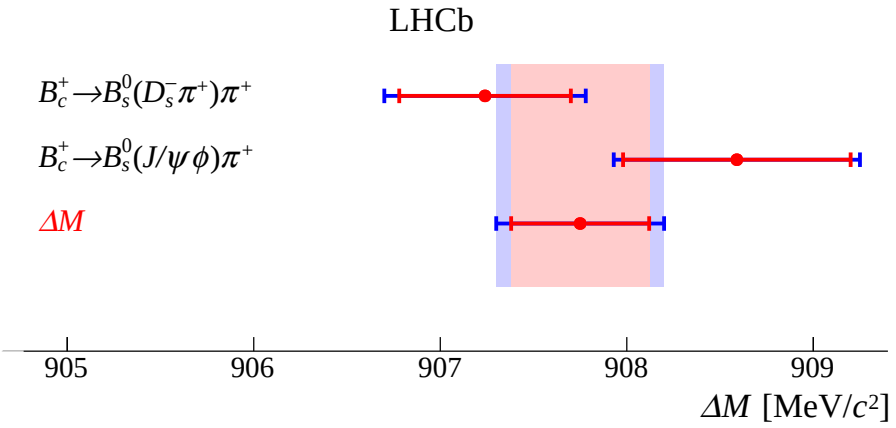

Figure 4: Individual mass difference measurements and their combination. The red (inner) cross-bars show the statistical uncertainties, and the blue (outer) cross-bars show the total uncertainties on the measurement.

7 Summary

In summary, a precise measurement of the B_c^+ mass is performed using data samples collected in pp collisions with the LHCb experiment at centre-of-mass energies of $\sqrt{s} = 7$, 8 and 13 TeV, corresponding to an integrated luminosity of 9 fb^{-1}. The B_c^+ candidates are reconstructed via the decays $B_c^+ \to J/\psi\pi^+$, $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$, $B_c^+ \to J/\psi p\bar{p}\pi^+$, $B_c^+ \to J/\psi D_s^+(K^+K^-\pi^+)$, $B_c^+ \to J/\psi D_s^+(\pi^+\pi^-\pi^+)$, $B_c^+ \to J/\psi D^0(K^-\pi^-)K^+$, $B_c^+ \to B_s^0(D_s^-\pi^+)\pi^+$ and $B_c^+ \to B_s^0(J/\psi\phi)\pi^+$. The B_c^+ mass is determined to be

$$6274.47 \pm 0.27\,(\text{stat}) \pm 0.17\,(\text{syst})\,\text{MeV}/c^2.$$

This result is consistent with theoretical predictions from perturbative and lattice QCD. The mass difference between the B_c^+ and B_s^0 mesons, ΔM, is determined to be

$$907.75 \pm 0.37\,(\text{stat}) \pm 0.27\,(\text{syst})\,\text{MeV}/c^2.$$

These results are the most accurate measurements of the B_c^+ mass to date. The precision compared to the world average [43] is improved by a factor of 2.

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