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# Precision measurement of the $B_c^+$ meson mass

LHCb collaboration<sup>†</sup>

## 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  $9.0 \text{ fb}^{-1}$ . The  $B_c^+$  mesons are reconstructed via the decays  $B_c^+ \rightarrow J/\psi \pi^+$ ,  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$ ,  $B_c^+ \rightarrow J/\psi p \bar{p} \pi^+$ ,  $B_c^+ \rightarrow J/\psi D_s^+$ ,  $B_c^+ \rightarrow J/\psi D^0 K^+$  and  $B_c^+ \rightarrow B_s^0 \pi^+$ . 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, 10], perturbative QCD [11, 12], relativistic quark models [13–17], and lattice QCD [18–23]. 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,  $M(B_c^+) = 6278 \pm 6 \pm 4 \text{ MeV}/c^2$  [22], 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  $6400 \pm 390 \pm 130 \text{ MeV}/c^2$  [24]. At the LHCb experiment, considerable progress has been made on measurements of the  $B_c^+$  production [25–29], spectroscopy [25, 30–33], lifetime [34, 35], and new decay modes [29, 32, 36–44]. The world average of the  $B_c^+$  mass has an uncertainty of  $0.8 \text{ MeV}/c^2$  [45]. This is the dominant systematic uncertainty in the recent  $B_c(2S)^{(*)+}$  mass measurements [33, 46].

This paper presents a precision measurement of the  $B_c^+$  mass using the decay modes  $B_c^+ \rightarrow J/\psi \pi^+$ ,  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$ ,  $B_c^+ \rightarrow J/\psi p \bar{p} \pi^+$ ,  $B_c^+ \rightarrow J/\psi D_s^+$ ,  $B_c^+ \rightarrow J/\psi D^0 K^+$  and  $B_c^+ \rightarrow B_s^0 \pi^+$ <sup>1</sup>. The first two decays are chosen for their large signal yield, while the others have a low energy release. As the  $B_s^0$  mass is known with limited precision, the difference between the  $B_c^+$  and  $B_s^0$  masses,  $\Delta M = M(B_c^+) - M(B_s^0)$ , is also measured, such that improvements in the  $B_s^+$  mass measurement allow for a more precise  $B_c^+$  mass determination. The data sample corresponds to an integrated luminosity of  $9.0 \text{ fb}^{-1}$ , collected with the LHCb experiment in  $pp$  collisions at centre-of-mass energies of 7, 8 and 13 TeV. The integrated luminosity used in this analysis is at least three times the one used in previous LHCb measurements [25, 30–32] and the results of this paper supersede those earlier  $B_c^+$  mass measurements.

## 2 Detector and simulation

This LHCb detector [47, 48] 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 [49], 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 [50, 51] 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 GeV/ $c$ . The momentum scale is calibrated using samples of  $B^+ \rightarrow J/\psi K^+$  and  $J/\psi \rightarrow \mu^+ \mu^-$  decays collected concurrently with the data sample used for this analysis [52, 53]. The

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<sup>1</sup>The inclusion of charge-conjugate modes is implied throughout this paper.

relative accuracy of this procedure is determined to be  $3 \times 10^{-4}$  using samples of other fully reconstructed  $B$ ,  $\Upsilon$  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  $(15 + 29/p_T) \mu\text{m}$ , where  $p_T$  is the component of the momentum transverse to the beam, in  $\text{GeV}/c$ . Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [54]. 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 [55]. The online event selection is performed by a trigger [56], 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 [57] with an LHCb specific configuration [58]. The production of  $B_c^+$  mesons is simulated using the dedicated generator BCVEGPy [59]. Decays of hadrons are described by EVTGEN [60], in which final-state radiation is generated using PHOTOS 3 [61]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [62] as described in Ref. [63].

### 3 Event selection

The  $B_c^+$  candidates are reconstructed in the following decay modes:  $B_c^+ \rightarrow J/\psi \pi^+$ ,  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$ ,  $B_c^+ \rightarrow J/\psi p \bar{p} \pi^+$ ,  $B_c^+ \rightarrow J/\psi D_s^+$ ,  $B_c^+ \rightarrow J/\psi D^0 K^+$  and  $B_c^+ \rightarrow B_s^0 \pi^+$ . A pair of oppositely charged muons form  $J/\psi$  candidates. The  $D_s^+$  candidates are reconstructed via the  $D_s^+ \rightarrow K^+ K^- \pi^+$  and  $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$  decays, while the  $D^0$  is reconstructed using the  $D^0 \rightarrow K^- \pi^+$  decay. The  $B_s^0$  candidates are reconstructed in the decay modes  $B_s^0 \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) \phi (\rightarrow K^+ K^-)$  and  $B_s^0 \rightarrow D_s^- (\rightarrow K^+ K^- \pi^-) \pi^+$ , and a multivariate classifier as used in Ref. [26] 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 [45]. Muons, kaons, pions and protons are required to have good track-fit quality and high transverse momentum. The  $J/\psi$  and  $B_c^+$  candidates are required to have a good-quality vertex fit.

A boosted decision tree [64–66] implemented within the TMVA [67] 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  $[6.6, 7.0] \text{ GeV}/c^2$ . 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 [68], 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 [69], in which the  $B_c^+$  candidate is assumed to originate from its PV and the intermediate-state masses are constrained to their known values [45]. The PV of the  $B_c^+$  candidate is that with respect to which it has the smallest  $\chi_{\text{IP}}^2$ . The  $\chi_{\text{IP}}^2$  is defined as the difference in  $\chi^2$  of the PV fit with and without the particle in question. For  $B_c^+ \rightarrow B_s^0 \pi^+$  decays, the  $B_s^0$  mass is constrained to the value of  $5366.89 \pm 0.21 \text{ MeV}/c^2$ , which is an average of the measurements of the  $B_s^0$  mass performed by the LHCb collaboration [70–73].

The difference between the  $B_c^+$  and  $B_s^0$  meson masses,  $\Delta m = m(B_c^+) - m(B_s^0)$ , is determined in the  $B_c^+ \rightarrow B_s^0 \pi^+$  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  $\Delta m$  is calculated with a kinematic fit [69], in which the  $B_c^+$  candidate is assumed to originate from the PV with the smallest  $\chi_{\text{IP}}^2$  and the masses of the intermediate particles are constrained to their known values [45]. The fitting procedure for the mass difference is the same as for the mass fit.

Figure 1 shows the invariant mass distributions and fit results for all  $B_c^+$  decay modes. Figure 2 shows the distributions of  $\Delta m$  and fit results for the  $B_c^+ \rightarrow B_s^0(D_s^- \pi^+) \pi^+$  and  $B_c^+ \rightarrow B_s^0(J/\psi \phi) \pi^+$  decay modes. The lower limit of the mass window is chosen to exclude the partially reconstructed background while keeping sufficient left mass sideband. The signal yields, mass and resolution values as determined from fits to the individual mass distributions are given in Table 1. For the  $B_c^+ \rightarrow B_s^0 \pi^+$  decays, the results of the fits to the  $\Delta m$  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. Such effect distorts the mass distribution after the event selection. 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 [74]. A bias associated with the selection from simulated samples is assigned as a corresponding correction. The measured masses ( $M$ ) and mass difference ( $\Delta M$ ) are corrected for this bias (from  $-0.46$  to  $0.27 \text{ MeV}/c^2$ ) 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

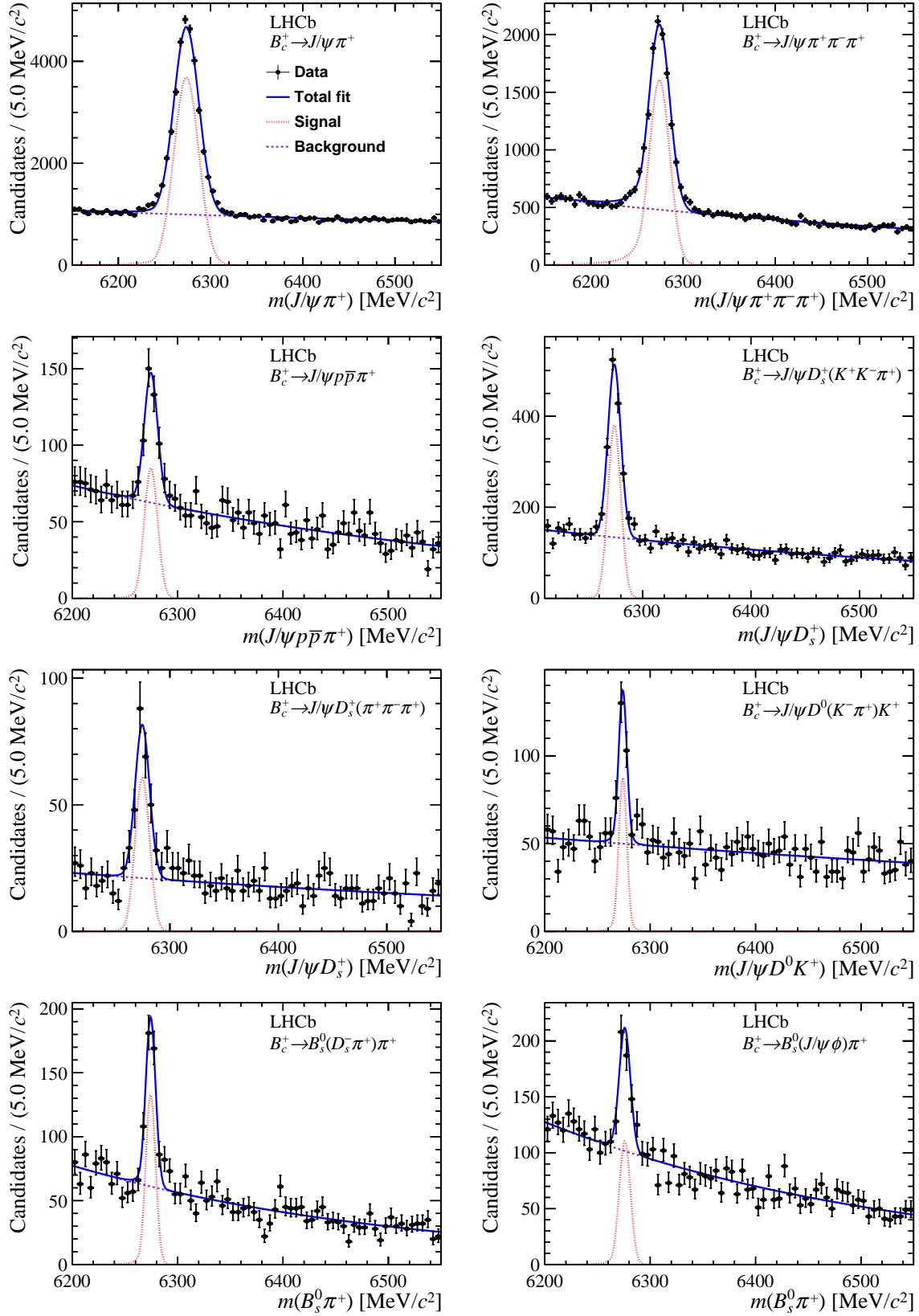


Figure 1: Distributions of invariant-mass  $m$  for  $B_c^+$  candidates selected in the studied decay channels, where data are shown as the points with error bars; the total fits are shown as solid blue curves; the signal component are red dotted curves; the background components purple dotted curves.

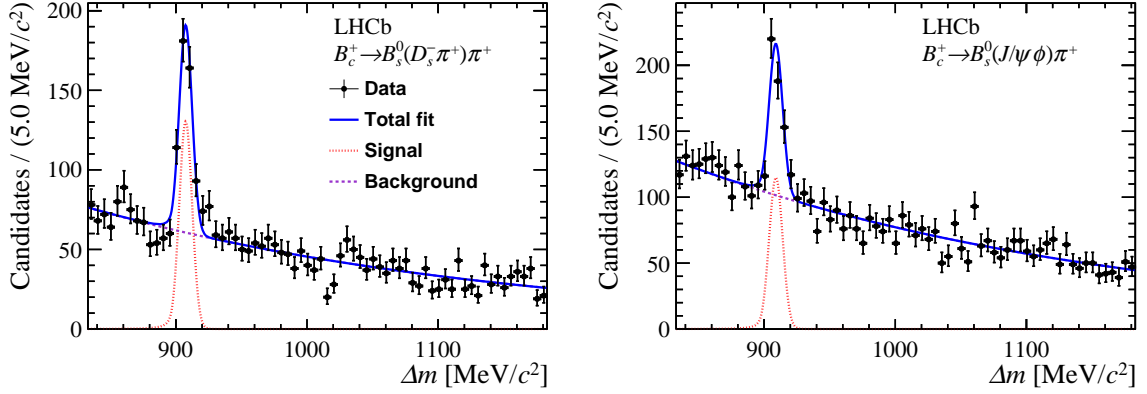


Figure 2: Distributions of mass difference  $\Delta m$  for the  $B_c^+ \rightarrow B_s^0(D_s^- \pi^+) \pi^+$  and  $B_c^+ \rightarrow B_s^0(J/\psi \phi) \pi^+$  decay modes, where data are shown as the points with error bars; the total fits are shown as solid blue curves; the signal component are red 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 <sup>2</sup> ]	Corrected mass [MeV/c <sup>2</sup> ]	Resolution [MeV/c <sup>2</sup> ]
$J/\psi \pi^+$	$25181 \pm 217$	$6273.71 \pm 0.12$	$6273.78 \pm 0.12$	$13.49 \pm 0.11$
$J/\psi \pi^+ \pi^- \pi^+$	$9497 \pm 142$	$6274.26 \pm 0.18$	$6274.38 \pm 0.18$	$11.13 \pm 0.18$
$J/\psi p \bar{p} \pi^+$	$273 \pm 29$	$6274.66 \pm 0.73$	$6274.61 \pm 0.73$	$6.34 \pm 0.76$
$J/\psi D_s^+(K^+ K^- \pi^+)$	$1135 \pm 49$	$6274.09 \pm 0.27$	$6274.11 \pm 0.27$	$5.93 \pm 0.30$
$J/\psi D_s^+(\pi^+ \pi^- \pi^+)$	$202 \pm 20$	$6274.57 \pm 0.71$	$6274.29 \pm 0.71$	$6.63 \pm 0.67$
$J/\psi D^0(K^- \pi^+) K^+$	$175 \pm 21$	$6273.97 \pm 0.53$	$6274.08 \pm 0.53$	$3.87 \pm 0.57$
$B_s^0(D_s^- \pi^+) \pi^+$	$316 \pm 27$	$6274.36 \pm 0.44$	$6274.08 \pm 0.44$	$4.67 \pm 0.48$
$B_s^0(J/\psi \phi) \pi^+$	$299 \pm 37$	$6275.87 \pm 0.66$	$6275.46 \pm 0.66$	$5.32 \pm 0.74$

Table 2: Signal yields, mass difference ( $\Delta M$ ) 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 $\Delta M$ [MeV/c <sup>2</sup> ]	Corrected $\Delta M$ [MeV/c <sup>2</sup> ]	Resolution [MeV/c <sup>2</sup> ]
$B_s^0(D_s^- \pi^+) \pi^+$	$325 \pm 27$	$907.51 \pm 0.46$	$907.24 \pm 0.46$	$4.88 \pm 0.47$
$B_s^0(J/\psi \phi) \pi^+$	$300 \pm 32$	$908.98 \pm 0.61$	$908.59 \pm 0.61$	$5.12 \pm 0.62$



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  $B_c^+$  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. The amount of material traversed in the tracking system by a particle is known to 10% accuracy, which leads to an uncertainty on the estimated energy loss. This translates into a measured mass uncertainty of  $0.03 \text{ MeV}/c^2$  for  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  decays [53]. 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 [75], 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  $0.1 \text{ MeV}/c^2$ , 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 non-resonant contribution, for example the contribution of  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$  decays to the  $B_c^+ \rightarrow J/\psi D_s^+(\pi^+ \pi^- \pi^+)$  candidates, is found to be highly suppressed and have negligible effects on the mass measurement. The systematic uncertainties considered for the  $B_c^+$  mass and mass difference measurements are summarised in Table 3 and 4, respectively.

Table 3: Summary of systematic uncertainties (in  $\text{MeV}/c^2$ ) 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  $\Delta M$  (in  $\text{MeV}/c^2$ ) 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

Table 5: Breakdown of systematic uncertainties (in  $\text{MeV}/c^2$ ) in the combination of the  $B_c^+$  mass and the mass difference  $\Delta M$ . 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

## 6 Combination of the measurements

The combination of the  $B_c^+$  mass measurements is performed using the Best Linear Unbiased Estimate (BLUE) method [76–78]. In the combination, uncertainties arising from the momentum-scale calibration, energy loss corrections, and signal model 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 ( $0.14 \text{ MeV}/c^2$ ) 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 from the  $B_c^+ \rightarrow J/\psi D_s^+(K^+ K^- \pi^+)$  decay. The negative weight for the  $B_c^+ \rightarrow J/\psi \pi^+$  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  $\Delta M$  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,  $\Delta M$ , is determined to be  $\Delta M = 907.75 \pm 0.37 \text{ (stat)} \pm 0.27 \text{ (syst)} \text{ MeV}/c^2$ .

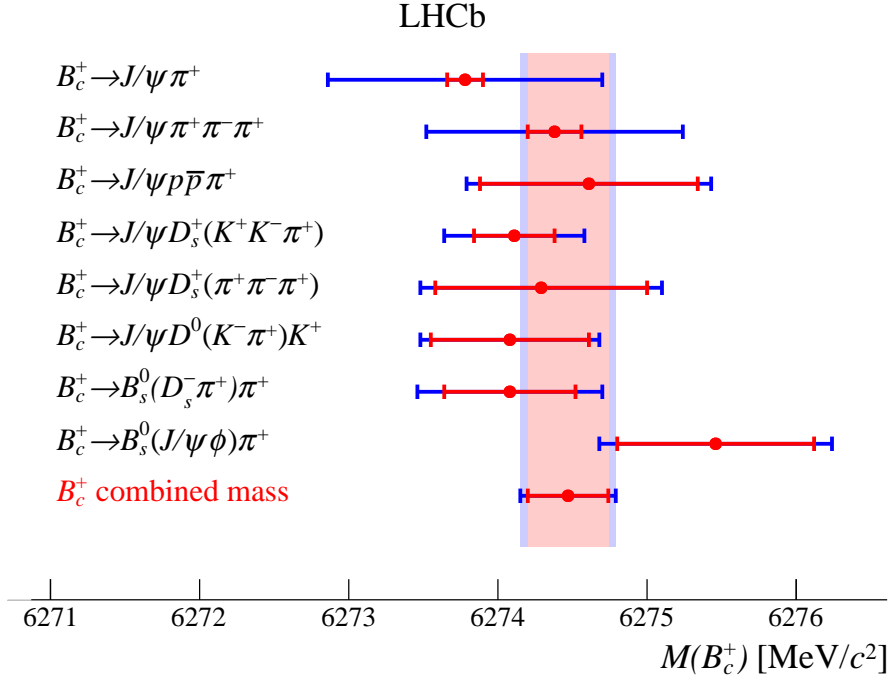


Figure 3: Individual  $B_c^+$  mass measurements and their combination. The red (inner) cross-bars show the statistical uncertainties, and the blue (outer) cross-bars show the total uncertainties.

Table 6: Weights of the decay modes in the combination of the  $B_c^+$  mass and the mass difference  $\Delta M$ .

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

## 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  $9 \text{ fb}^{-1}$ . The  $B_c^+$  candidates are reconstructed via the decays  $B_c^+ \rightarrow J/\psi \pi^+$ ,  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$ ,  $B_c^+ \rightarrow J/\psi p \bar{p} \pi^+$ ,  $B_c^+ \rightarrow J/\psi D_s^+(K^+ K^- \pi^+)$ ,  $B_c^+ \rightarrow J/\psi D_s^+(\pi^+ \pi^- \pi^+)$ ,  $B_c^+ \rightarrow J/\psi D^0(K^- \pi^+) K^+$ ,  $B_c^+ \rightarrow B_s^0(D_s^- \pi^+) \pi^+$  and  $B_c^+ \rightarrow B_s^0(J/\psi \phi) \pi^+$ . The  $B_c^+$  mass is determined to be

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

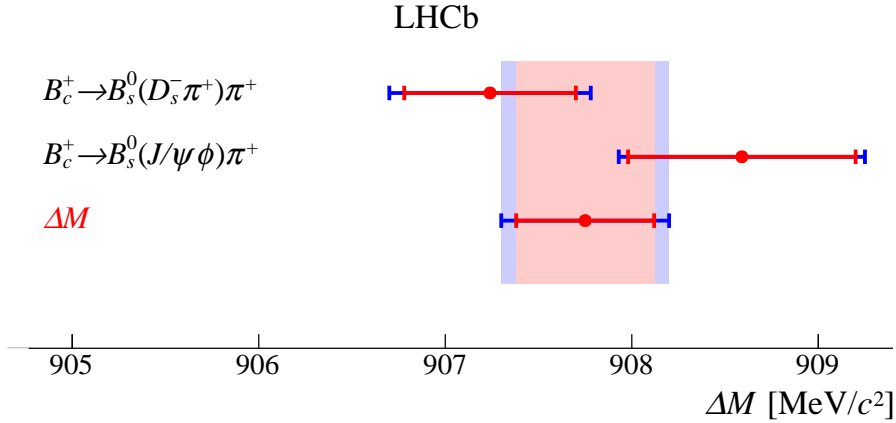


Figure 4: Individual mass difference measurements and their combination. The red (inner) cross-bars show the statistical uncertainties, and the blue (outer) cross-bars show the total uncertainties on the measurement.

This result is consistent with theoretical predictions from perturbative and lattice QCD. The mass difference between the  $B_c^+$  and  $B_s^0$  mesons,  $\Delta M$ , 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 [45] is improved by a factor of 2.

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## References

- [1] S. S. Gershtein *et al.*, *Production cross-section and spectroscopy of  $B_c$  mesons*, Sov. J. Nucl. Phys. **48** (1988) 327.
- [2] Y.-Q. Chen and Y.-P. Kuang, *Improved QCD motivated heavy quark potentials with explicit  $\Lambda_{\overline{\text{MS}}}$  dependence*, Phys. Rev. **D46** (1992) 1165.
- [3] E. J. Eichten and C. Quigg, *Mesons with beauty and charm: spectroscopy*, Phys. Rev. **D49** (1994) 5845, [arXiv:hep-ph/9402210](#).
- [4] V. V. Kiselev, A. K. Likhoded, and A. V. Tkabladze,  *$B_c$  spectroscopy*, Phys. Rev. **D51** (1995) 3613, [arXiv:hep-ph/9406339](#).
- [5] S. N. Gupta and J. M. Johnson,  *$B_c$  spectroscopy in a quantum-chromodynamic potential model*, Phys. Rev. **D53** (1996) 312, [arXiv:hep-ph/9511267](#).
- [6] L. P. Fulcher, *Phenomenological predictions of the properties of the  $B_c$  system*, Phys. Rev. **D60** (1999) 074006, [arXiv:hep-ph/9806444](#).
- [7] N. Devlani, V. Kher, and A. K. Rai, *Masses and electromagnetic transitions of the  $B_c$  mesons*, Eur. Phys. J. **A50** (2014) 154.
- [8] N. R. Soni *et al.*,  *$Q\bar{Q}$  ( $Q \in \{b, c\}$ ) spectroscopy using the Cornell potential*, Eur. Phys. J. **C78** (2018) 592, [arXiv:1707.07144](#).
- [9] K.-W. Wei and X.-H. Guo, *Mass spectra of doubly heavy mesons in Regge phenomenology*, Phys. Rev. **D81** (2010) 076005.
- [10] M. Chen, L. Chang, and Y.-x. Liu,  *$B_c$  meson spectrum via Dyson-Schwinger equation and Bethe-Salpeter equation approach*, Phys. Rev. D **101** (2020) 056002, [arXiv:2001.00161](#).
- [11] N. Brambilla and A. Vairo,  *$B_c$  mass up to order  $\alpha_s^4$* , Phys. Rev. **D62** (2000) 094019, [arXiv:hep-ph/0002075](#).
- [12] Z.-J. Xiao and X. Liu, *The two-body hadronic decays of  $B_c$  meson in the perturbative QCD approach: A short review*, Chin. Sci. Bull. **59** (2014) 3748, [arXiv:1401.0151](#).
- [13] D. Ebert, R. N. Faustov, and V. O. Galkin, *Properties of heavy quarkonia and  $B_c$  mesons in the relativistic quark model*, Phys. Rev. **D67** (2003) 014027, [arXiv:hep-ph/0210381](#).
- [14] S. Godfrey, *Spectroscopy of  $B_c$  mesons in the relativized quark model*, Phys. Rev. **D70** (2004) 054017, [arXiv:hep-ph/0406228](#).
- [15] D. Ebert, R. N. Faustov, and V. O. Galkin, *Spectroscopy and Regge trajectories of heavy quarkonia and  $B_c$  mesons*, Eur. Phys. J. C **71** (2011) 1825, [arXiv:1111.0454](#).
- [16] C. S. Fischer, S. Kubrak, and R. Williams, *Spectra of heavy mesons in the Bethe-Salpeter approach*, Eur. Phys. J. **A51** (2015) 10, [arXiv:1409.5076](#).

- [17] A. P. Monteiro, M. Bhat, and K. B. Vijaya Kumar,  *$c\bar{b}$  spectrum and decay properties with coupled channel effects*, Phys. Rev. **D95** (2017) 054016, arXiv:1608.05782.
- [18] C. T. H. Davies *et al.*,  *$B_c$  Spectroscopy from lattice QCD*, Phys. Lett. **B382** (1996) 131, arXiv:hep-lat/9602020.
- [19] UKQCD collaboration, H. P. Shanahan, P. Boyle, C. T. H. Davies, and H. Newton, *A non-perturbative calculation of the mass of the  $B_c$* , Phys. Lett. **B453** (1999) 289, arXiv:hep-lat/9902025.
- [20] HPQCD collaboration, I. F. Allison *et al.*, *A precise determination of the  $B_c$  mass from dynamical lattice QCD*, Nucl. Phys. Proc. Suppl. **140** (2005) 440, arXiv:hep-lat/0409090.
- [21] HPQCD collaboration, I. F. Allison *et al.*, *Mass of the  $B_c$  meson in three-flavor lattice QCD*, Phys. Rev. Lett. **94** (2005) 172001, arXiv:hep-lat/0411027.
- [22] TWQCD collaboration, T.-W. Chiu and T.-H. Hsieh,  *$B_s$  and  $B_c$  mesons in lattice QCD with exact chiral symmetry*, PoS **LAT2006** (2007) 180, arXiv:0704.3495.
- [23] R. J. Dowdall, C. T. H. Davies, T. C. Hammant, and R. R. Horgan, *Precise heavy-light meson masses and hyperfine splittings from lattice QCD including charm quarks in the sea*, Phys. Rev. **D86** (2012) 094510, arXiv:1207.5149.
- [24] CDF collaboration, F. Abe *et al.*, *Observation of the  $B_c$  meson in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV*, Phys. Rev. Lett. **81** (1998) 2432, arXiv:hep-ex/9805034; CDF collaboration, F. Abe *et al.*, *Observation of  $B_c$  mesons in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV*, Phys. Rev. **D58** (1998) 112004, arXiv:hep-ex/9804014.
- [25] LHCb collaboration, R. Aaij *et al.*, *Measurements of  $B_c^+$  production and mass with the  $B_c^+ \rightarrow J/\psi \pi^+$  decay*, Phys. Rev. Lett. **109** (2012) 232001, arXiv:1209.5634.
- [26] LHCb collaboration, R. Aaij *et al.*, *Observation of the decay  $B_c^+ \rightarrow B_s^0 \pi^+$* , Phys. Rev. Lett. **111** (2013) 181801, arXiv:1308.4544.
- [27] LHCb collaboration, R. Aaij *et al.*, *Measurement of the  $B_c^-$  production fraction and asymmetry in 7 and 13 TeV  $pp$  collisions*, Phys. Rev. **D100** (2019) 112006, arXiv:1910.13404.
- [28] LHCb collaboration, R. Aaij *et al.*, *Measurement of  $B_c^+$  production in proton-proton collisions at  $\sqrt{s} = 8$  TeV*, Phys. Rev. Lett. **114** (2015) 132001, arXiv:1411.2943.
- [29] LHCb collaboration, R. Aaij *et al.*, *Observation of  $B_c^+ \rightarrow D^0 K^+$  decays*, Phys. Rev. Lett. **118** (2017) 111803, arXiv:1701.01856.
- [30] LHCb collaboration, R. Aaij *et al.*, *Observation of  $B_c^+ \rightarrow J/\psi D_s^+$  and  $B_c^+ \rightarrow J/\psi D_s^{*+}$  decays*, Phys. Rev. **D87** (2013) 112012, arXiv:1304.4530.
- [31] LHCb collaboration, R. Aaij *et al.*, *First observation of a baryonic  $B_c^+$  decay*, Phys. Rev. Lett. **113** (2014) 152003, arXiv:1408.0971.

- [32] LHCb collaboration, R. Aaij *et al.*, *Observation of  $B_c^+ \rightarrow J/\psi D^{(*)} K^{(*)}$  decays*, Phys. Rev. **D95** (2017) 032005, [arXiv:1612.07421](#).
- [33] LHCb collaboration, R. Aaij *et al.*, *Observation of an excited  $B_c^+$  state*, Phys. Rev. Lett. **122** (2019) 232001, [arXiv:1904.00081](#).
- [34] LHCb collaboration, R. Aaij *et al.*, *Measurement of the  $B_c^+$  meson lifetime using  $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$  decays*, Eur. Phys. J. **C74** (2014) 2839, [arXiv:1401.6932](#).
- [35] LHCb collaboration, R. Aaij *et al.*, *Measurement of the lifetime of the  $B_c^+$  meson using the  $B_c^+ \rightarrow J/\psi \pi^+$  decay mode*, Phys. Lett. **B742** (2015) 29, [arXiv:1411.6899](#).
- [36] LHCb collaboration, R. Aaij *et al.*, *Observation of the decay  $B_c^+ \rightarrow \psi(2S)\pi^+$* , Phys. Rev. **D87** (2013) 071103(R), [arXiv:1303.1737](#).
- [37] LHCb collaboration, R. Aaij *et al.*, *First observation of the decay  $B_c^+ \rightarrow J/\psi K^+$* , JHEP **09** (2013) 075, [arXiv:1306.6723](#).
- [38] LHCb collaboration, R. Aaij *et al.*, *Observation of the decay  $B_c^+ \rightarrow J/\psi K^+ K^- \pi^+$* , JHEP **11** (2013) 094, [arXiv:1309.0587](#).
- [39] LHCb collaboration, R. Aaij *et al.*, *Measurement of the branching fraction ratio  $\mathcal{B}(B_c^+ \rightarrow \psi(2S)\pi^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$* , Phys. Rev. **D92** (2015) 057007, [arXiv:1507.03516](#).
- [40] LHCb collaboration, R. Aaij *et al.*, *Measurement of the ratio of branching fractions  $\mathcal{B}(B_c^+ \rightarrow J/\psi K^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$* , JHEP **09** (2016) 153, [arXiv:1607.06823](#).
- [41] LHCb collaboration, R. Aaij *et al.*, *Search for  $B_c^+$  decays to the  $p\bar{p}\pi^+$  final state*, Phys. Lett. **B759** (2016) 313, [arXiv:1603.07037](#).
- [42] LHCb collaboration, R. Aaij *et al.*, *Study of  $B_c^+$  decays to the  $K^+K^-\pi^+$  final state and evidence for the decay  $B_c^+ \rightarrow \chi_{c0}\pi^+$* , Phys. Rev. **D94** (2016) 091102(R), [arXiv:1607.06134](#).
- [43] LHCb collaboration, R. Aaij *et al.*, *Measurement of the ratio of branching fractions  $\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)/\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)$* , Phys. Rev. Lett. **120** (2018) 121801, [arXiv:1711.05623](#).
- [44] LHCb collaboration, R. Aaij *et al.*, *Search for  $B_c^+$  decays to two charm mesons*, Nucl. Phys. **B930** (2018) 563, [arXiv:1712.04702](#).
- [45] Particle Data Group, M. Tanabashi *et al.*, *Review of particle physics*, Phys. Rev. **D98** (2018) 030001.
- [46] CMS collaboration, A. M. Sirunyan *et al.*, *Observation of two excited  $B_c^+$  states and measurement of the  $B_c^+(2S)$  mass in  $pp$  collisions at  $\sqrt{s} = 13$  TeV*, Phys. Rev. Lett. **122** (2019) 132001, [arXiv:1902.00571](#).
- [47] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.

- [48] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, [arXiv:1412.6352](#).
- [49] R. Aaij *et al.*, *Performance of the LHCb Vertex Locator*, JINST **9** (2014) P09007, [arXiv:1405.7808](#).
- [50] R. Arink *et al.*, *Performance of the LHCb Outer Tracker*, JINST **9** (2014) P01002, [arXiv:1311.3893](#).
- [51] P. d'Argent *et al.*, *Improved performance of the LHCb Outer Tracker in LHC Run 2*, JINST **12** (2017) P11016, [arXiv:1708.00819](#).
- [52] LHCb collaboration, R. Aaij *et al.*, *Measurements of the  $\Lambda_b^0$ ,  $\Xi_b^-$ , and  $\Omega_b^-$  baryon masses*, Phys. Rev. Lett. **110** (2013) 182001, [arXiv:1302.1072](#).
- [53] LHCb collaboration, R. Aaij *et al.*, *Precision measurement of  $D$  meson mass differences*, JHEP **06** (2013) 065, [arXiv:1304.6865](#).
- [54] M. Adinolfi *et al.*, *Performance of the LHCb RICH detector at the LHC*, Eur. Phys. J. **C73** (2013) 2431, [arXiv:1211.6759](#).
- [55] A. A. Alves Jr. *et al.*, *Performance of the LHCb muon system*, JINST **8** (2013) P02022, [arXiv:1211.1346](#).
- [56] R. Aaij *et al.*, *The LHCb trigger and its performance in 2011*, JINST **8** (2013) P04022, [arXiv:1211.3055](#).
- [57] T. Sjöstrand, S. Mrenna, and P. Skands, *A brief introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852, [arXiv:0710.3820](#).
- [58] I. Belyaev *et al.*, *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, J. Phys. Conf. Ser. **331** (2011) 032047.
- [59] C.-H. Chang, J.-X. Wang, and X.-G. Wu, *BCVEGPY2.0: A upgrade version of the generator BCVEGPY with an addendum about hadroproduction of the  $P$ -wave  $B_c$  states*, Comput. Phys. Commun. **174** (2006) 241, [arXiv:hep-ph/0504017](#).
- [60] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. **A462** (2001) 152.
- [61] P. Golonka and Z. Was, *PHOTOS Monte Carlo: A precision tool for QED corrections in  $Z$  and  $W$  decays*, Eur. Phys. J. **C45** (2006) 97, [arXiv:hep-ph/0506026](#).
- [62] Geant4 collaboration, J. Allison *et al.*, *Geant4 developments and applications*, IEEE Trans. Nucl. Sci. **53** (2006) 270; Geant4 collaboration, S. Agostinelli *et al.*, *Geant4: A simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003) 250.
- [63] M. Clemencic *et al.*, *The LHCb simulation application, Gauss: Design, evolution and experience*, J. Phys. Conf. Ser. **331** (2011) 032023.
- [64] L. Breiman, J. Friedman, R. A. Olshen, and C. J. Stone, *Classification and regression trees*, Chapman and Hall/CRC, 1984.



- [65] Y. Freund and R. E. Schapire, *A decision-theoretic generalization of on-line learning and an application to boosting*, J. Comput. Syst. Sci. **55** (1997) 119.
- [66] J. H. Friedman, *Greedy function approximation: A gradient boosting machine.*, Ann. Statist. **29** (2001) 1189.
- [67] A. Hoecker *et al.*, *TMVA 4 — Toolkit for Multivariate Data Analysis with ROOT. Users Guide.*, arXiv:physics/0703039.
- [68] T. Skwarnicki, *A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances*, PhD thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02.
- [69] W. D. Hulsbergen, *Decay chain fitting with a Kalman filter*, Nucl. Instrum. Meth. **A552** (2005) 566, arXiv:physics/0503191.
- [70] LHCb collaboration, R. Aaij *et al.*, *Observation of  $B_{(s)}^0 \rightarrow J/\psi p\bar{p}$  decays and precision measurements of the  $B_{(s)}^0$  masses*, Phys. Rev. Lett. **122** (2019) 191804, arXiv:1902.05588.
- [71] LHCb collaboration, R. Aaij *et al.*, *Observation of the decay  $\bar{B}_s^0 \rightarrow \chi_{c2} K^+ K^-$* , JHEP **08** (2018) 191, arXiv:1806.10576.
- [72] LHCb collaboration, R. Aaij *et al.*, *Observation of the  $B_s^0 \rightarrow J/\psi \phi \phi$  decay*, JHEP **03** (2016) 040, arXiv:1601.05284.
- [73] LHCb collaboration, R. Aaij *et al.*, *Measurement of  $b$ -hadron masses*, Phys. Lett. **B708** (2012) 241, arXiv:1112.4896.
- [74] LHCb collaboration, R. Aaij *et al.*, *Observation of the doubly charmed baryon  $\Xi_{cc}^{++}$* , Phys. Rev. Lett. **119** (2017) 112001, arXiv:1707.01621.
- [75] D. Martínez Santos and F. Dupertuis, *Mass distributions marginalized over per-event errors*, Nucl. Instrum. Meth. **A764** (2014) 150, arXiv:1312.5000.
- [76] L. Lyons, D. Gibaut, and P. Clifford, *How to combine correlated estimates of a single physical quantity*, Nucl. Instrum. Meth. **A270** (1988) 110.
- [77] A. Valassi, *Combining correlated measurements of several different physical quantities*, Nucl. Instrum. Meth. **A500** (2003) 391.
- [78] R. Nisius, *BLUE: combining correlated estimates of physics observables within ROOT using the Best Linear Unbiased Estimate method*, SoftwareX **11** (2020) 100468, arXiv:2001.10310.

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 G. Graziani<sup>21</sup>, A. Grecu<sup>36</sup>, R. Greim<sup>31</sup>, P. Griffith<sup>20,g</sup>, L. Grillo<sup>61</sup>, L. Gruber<sup>47</sup>,  
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 L. Li<sup>62</sup>, X. Li<sup>66</sup>, Y. Li<sup>6</sup>, Z. Li<sup>67</sup>, X. Liang<sup>67</sup>, T. Lin<sup>60</sup>, R. Lindner<sup>47</sup>, V. Lisovskyi<sup>14</sup>, G. Liu<sup>71</sup>,  
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