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Observation of the $\Lambda_b^0 \to J/\psi\, p\pi^-$ decay

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Abstract: The first observation of the Cabibbo-suppressed decay $\Lambda_b^0 \to J/\psi\, p\pi^-$ is reported using a data sample of proton-proton collisions at 7 and 8 TeV, corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$. A prominent signal is observed and the branching fraction relative to the decay mode $\Lambda_b^0 \to J/\psi\, pK^-$ is determined to be

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p\pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, pK^-)} = 0.0824 \pm 0.0025\,(\text{stat}) \pm 0.0042\,(\text{syst}).$$

A search for direct *CP* violation is performed. The difference in the *CP* asymmetries between these two decays is found to be

$$\mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi\, p\pi^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi\, pK^-) = (+5.7 \pm 2.4\,(\text{stat}) \pm 1.2\,(\text{syst}))\%,$$

which is compatible with *CP* symmetry at the 2.2σ level.

Keywords: B physics, CP violation, Branching fraction, Flavor physics, Hadron-Hadron Scattering

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1 Introduction

The study of b-baryon decays is of considerable interest both to probe the dynamics of heavy flavour decay processes and to search for the effects of physics beyond the Standard Model. Owing to their non-zero spin, b baryons provide the potential to improve the limited understanding of the helicity structure of the underlying Hamiltonian [1, 2].

Beauty baryons are copiously produced at the LHC, where the Λ_b^0 baryon cross-section is about half of the size of the B^0 meson production in the forward region [3, 4]. The ATLAS, CMS and LHCb collaborations measured the Λ_b^0 lifetime [5–8], and the masses of the ground [8, 9] and first excited states [10]. The Λ_b^0 polarisation has been measured and found to be compatible with zero [11]. The LHCb collaboration has studied Λ_b^0 decays to charmonium [11, 12], open charm [13, 14], charmless states [15] and final states induced by electroweak penguins [16]. No evidence for *CP* violation has been reported in decays of baryons. Searches with b-baryon decays have been performed with the decay channels $\Lambda_b^0 \to p\pi^-$, pK^- [17] and $K_S^0 p\pi^-$ [15]. The corresponding theoretical literature is still limited compared to that on B meson decays.

The study of $b \to c\bar{c}q$ decays can be used to constrain penguin pollution in the determination of the *CP*-violating phases in B^0 and B_s^0 mixing [18, 19]. While decays originating from the $b \to c\bar{c}s$ transitions, such as $\Lambda_b^0 \to J/\psi\,\Lambda$ or $\Lambda_b^0 \to J/\psi\, pK^-$, are largely dominated by the tree amplitudes, penguins amplitudes are enhanced in Cabibbo-suppressed $b \to c\bar{c}d$ transitions, such as the $\Lambda_b^0 \to J/\psi\, p\pi^-$ decay.

This article reports the first observation of the $\Lambda_b^0 \to J/\psi\, p\pi^-$ decay and the determination of its branching fraction relative to the Cabibbo-favoured mode $\Lambda_b^0 \to J/\psi\, pK^-$. The latter, which was recently observed, has been used to obtain a precise measurement of the ratio of Λ_b^0 to B^0 lifetimes [5, 12]. Its absolute branching ratio is yet to be determined. A measurement of the *CP* asymmetry difference between the $\Lambda_b^0 \to J/\psi\, p\pi^-$ and $\Lambda_b^0 \to J/\psi\, pK^-$ decays is also reported. The analysis is based on a data sample of proton-proton collisions, corresponding to an integrated luminosity of $1\,\text{fb}^{-1}$ at a centre-of-mass energy of 7 TeV and $2\,\text{fb}^{-1}$ at 8 TeV, collected with the LHCb detector.

2 Detector and software

The LHCb detector [20] 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 proton-proton interaction region, 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 [21] placed downstream of the magnet. The combined tracking system provides a momentum measurement with a relative uncertainty that varies from 0.4% at low momentum to 0.6% at 100 GeV/c, and an impact parameter measurement with a resolution of 20 μm for charged particles with large transverse momentum, p_{T}. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov (RICH) detectors [22]. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [23]. The trigger [24] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

Candidate events are first required to pass the hardware trigger, which selects muons with $p_{\mathrm{T}} > 1.48$ GeV/c. In the subsequent software trigger, at least one of the candidate muons is required to be inconsistent with originating from any primary interaction. Finally, the muon pair is required to form a vertex that is significantly displaced from all primary vertices (PV) and to have a mass within 120 MeV/c^2 of the known J/ψ mass.

In the simulation, proton-proton collisions are generated using Pythia [25, 26] with a specific LHCb configuration [27]. Decays of hadronic particles are described by EvtGen [28], in which final state radiation is generated using Photos [29]. The interaction of the generated particles with the detector and its response are implemented using the Geant4 toolkit [30, 31] as described in ref. [32].

3 Event selection

The $\Lambda_b^0 \to J/\psi\, p\pi^-$ and $\Lambda_b^0 \to J/\psi\, pK^-$ decays are reconstructed with the J/ψ decaying to two muons. Charge conjugation is implied throughout except in the definition of the *CP* asymmetry.

Candidate $J/\psi \to \mu^+\mu^-$ decays are reconstructed from oppositely charged particles passing loose muon-identification requirements and with $p_{\mathrm{T}} > 500$ MeV/c. They are required

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to form a good quality vertex and have a mass in the range $[3030, 3150]\,\mathrm{MeV}/c^2$. This interval corresponds to about eight times the $\mu^+\mu^-$ mass resolution at the J/ψ mass and covers part of the J/ψ meson radiative tail.

Candidate Λ_b^0 baryons are selected from combinations of J/ψ candidates and two oppositely charged particles, one of which must be compatible with the proton hypothesis. The proton candidate is required to have a momentum, p, larger than $5\,\mathrm{GeV}/c$, while the second charged particle must have $p > 3\,\mathrm{GeV}/c$. Both particles must have $p_\mathrm{T} > 500\,\mathrm{MeV}/c$ and be inconsistent with coming from any PV. All four charged particles are required to be consistent with coming from a common vertex.

The reconstructed mass and decay time of the Λ_b^0 candidates are obtained from a kinematic fit [33] that constrains the mass of the $\mu^+\mu^-$ pairs to the known J/ψ mass and the Λ_b^0 candidate to originate from the PV. If the event has multiple PVs, all combinations are considered. Candidates are required to have a reconstructed decay time larger than 0.2 ps.

To remove backgrounds from $\Lambda_b^0 \to J/\psi\,\Lambda$ decays, candidates that have a $p\pi^-$ mass within $5\,\mathrm{MeV}/c^2$ of the Λ baryon mass are vetoed. To remove reflections from $B_s^0 \to J/\psi\,\phi$ decays, candidates are also vetoed if the hadron-pair mass is less than $1035\,\mathrm{MeV}/c^2$ when applying a K^+ mass hypothesis to both particles.

The remaining candidates are split into samples of $\Lambda_b^0 \to J/\psi\, p\pi^-$ and $\Lambda_b^0 \to J/\psi\, pK^-$ according to the estimated probabilities that the charged meson candidate is a kaon or a pion. These probabilities are determined using a neural network (NN) exploiting information from the RICH detectors, calorimeter and muon systems, as well as track quality. Particles with a larger pion probability are treated as $\Lambda_b^0 \to J/\psi\, p\pi^-$ candidates, otherwise they are treated as $\Lambda_b^0 \to J/\psi\, pK^-$ candidates. In addition, the larger of these two probabilities is required to be in excess of 5%. The Λ_b^0 candidates are required to be in the mass range $[4900, 6100]$ MeV/c^2. After this selection 4.3×10^5 $\Lambda_b^0 \to J/\psi\, p\pi^-$ and 1.9×10^5 $\Lambda_b^0 \to J/\psi\, pK^-$ candidates remain.

The selection described above is not sufficient to isolate the small $\Lambda_b^0 \to J/\psi\, p\pi^-$ signal from the combinatorial background. The initial selection is therefore followed by a multivariate analysis, based on another NN [34]. The NN classifier's output is used as the final selection variable.

The NN is trained entirely on data, using the $\Lambda_b^0 \to J/\psi\, pK^-$ signal as a proxy for the $\Lambda_b^0 \to J/\psi\, p\pi^-$ decay. The training is performed using half of the $\Lambda_b^0 \to J/\psi\, pK^-$ candidates chosen at random. The other half is used to define the normalisation sample, allowing an unbiased measurement of the $\Lambda_b^0 \to J/\psi\, pK^-$ yield. The training uses signal and background weights determined using the *sPlot* technique [35] and obtained by performing a maximum likelihood fit to the unbinned mass distribution of the candidates meeting the loose selection criteria.

The fit probability density function (PDF) is defined as the sum of the Λ_b^0 signal component and the combinatorial background components. The parameterisation of the individual components is described in the next section.

Several reflections from B^0, B_s^0 and Λ_b^0 decays, reconstructed using misidentified particles, must be accounted for in the mass spectrum. In order to avoid the training being biased by these reflections, all candidates that have a mass compatible with the B^0, B_s^0 or

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Λ_b^0 mass after swapping the p and K assignments with any of π, K, or p are removed from the training.

The NN classifier uses information about the candidate kinematic distributions, vertex and track quality, impact parameter and particle identification information on the proton. The most discriminating quantities are the proton particle identification probability, the kinematic fit quality and the kaon separation of the PV in this order. The variables that are used in the NN are chosen to avoid correlations with the reconstructed Λ_b^0 mass and to have identical distributions in $\Lambda_b^0 \to J/\psi p\pi^-$ and $\Lambda_b^0 \to J/\psi pK^-$ simulated data.

Final selection requirements of the NN classifier output are chosen to optimise the expected statistical precision on the $\Lambda_b^0 \to J/\psi p\pi^-$ signal yield. The expected signal and background yields entering the sensitivity estimation are obtained from the training sample by scaling the number of surviving $\Lambda_b^0 \to J/\psi pK^-$ candidates by the expected yield based on an assumed branching fraction ratio of 0.1. The expected background is extrapolated from the number of $\Lambda_b^0 \to J/\psi p\pi^-$ candidates in the mass range $[5770, 6100]\,\mathrm{MeV}/c^2$. After applying the final requirement on the NN classifier output, the multivariate selection rejects 99% of the background while keeping 75% of the $\Lambda_b^0 \to J/\psi pK^-$ signal, relative to the initial selection.

After applying the full selection, about 0.1% of the selected events have more than one candidate sharing at least one track, or more than one PV that can be used to determine the kinematic properties of the candidate. In these cases one of the candidates or PVs is used at random.

4 Signal and background description

For the candidates passing the NN requirements, the yields of $\Lambda_b^0 \to J/\psi p\pi^-$ and $\Lambda_b^0 \to J/\psi pK^-$ decays are determined from unbinned maximum likelihood fits to the mass distributions of reconstructed Λ_b^0 candidates. The PDF is defined as the sum of a Λ_b^0 signal component, a combinatorial background and the sum of several reflections.

The signal shape is parametrised by a Gaussian distribution with power-law tails on both sides, as indicated by simulation. The parameters describing the tails are taken from simulation, while the mean and width of the Gaussian are allowed to vary in the fit. The combinatorial background contribution is described by an exponential function, with yield and slope parameter allowed to vary freely.

Several peaking backgrounds due to decays of b hadrons to J/ψ mesons and two charged hadrons, where one or both hadrons are misidentified, survive the selection. In this fit they are not vetoed, unlike in the training of the NN, except for candidates consistent with the $B_s^0 \to J/\psi \phi$ hypothesis. Instead, their contribution is modelled by smoothed non-parametric functions determined from simulated data. The respective yields are determined by swapping the mass assignments of the p, π and K in turn and searching for peaks at the B^0, B_s^0 or Λ_b^0 masses. In the $\Lambda_b^0 \to J/\psi p\pi^-$ fit, significant backgrounds are found from the decays $\Lambda_b^0 \to J/\psi pK^-$ (with K^- identified as π^-), $B^0 \to J/\psi K^+\pi^-$ (with K^+ identified as p), and $B_s^0 \to J/\psi K^+K^-$ (with one K identified as p and the other as π). In the $\Lambda_b^0 \to J/\psi pK^-$ fit, the main contributions are from the decays $\overline{B}^0 \to J/\psi \pi^+K^-$ (with π^+ identified as p),

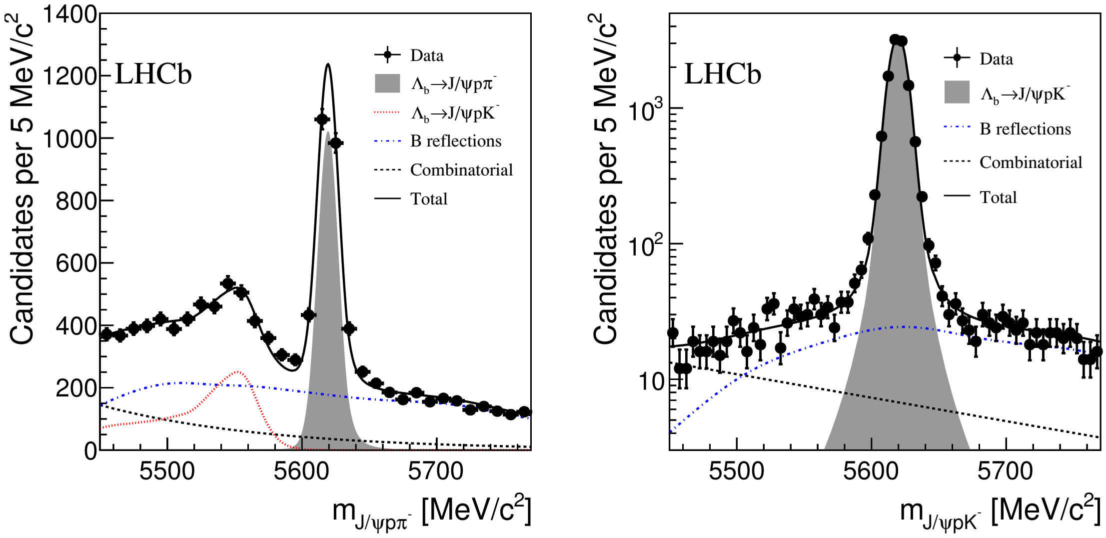

Figure 1. Distribution of (left) $J/\psi p\pi^-$ and (right) $J/\psi pK^-$ masses with fit projections overlaid. For $\Lambda_b^0 \to J/\psi pK^-$ candidates, only the normalisation sample is shown.

$B_s^0 \to J/\psi K^+K^-$ (with K^+ identified as p), and $\overline{\Lambda}_b^0 \to J/\psi \overline{p}K^+$ (with K^- and p swapped). These yields are then used as Gaussian constraints on the normalisation of the reflection background shapes. The results of the fits are shown in figure 1. The contributions of the reflections are summed, except for the large $\Lambda_b^0 \to J/\psi pK^-$ reflection in the $\Lambda_b^0 \to J/\psi p\pi^-$ fit, which is shown separately.

Low-mass contributions of partially reconstructed $\Lambda_b^0 \to J/\psi p\pi^-\pi^0$ and $\Lambda_b^0 \to J/\psi pK^-\pi^0$ decays, where the π^0 is not considered in the combination, are investigated. Adding such a component to the fit, with a mass shape taken from simulation, results in yields compatible with zero and does not change the signal yields.

In total $11\,179 \pm 109$ $\Lambda_b^0 \to J/\psi pK^-$ and 2102 ± 61 $\Lambda_b^0 \to J/\psi p\pi^-$ decays are obtained. The $\Lambda_b^0 \to J/\psi pK^-$ yield, having been determined on the half of the data not used in the training, is multiplied by two, resulting in a ratio of $\Lambda_b^0 \to J/\psi p\pi^-$ to $\Lambda_b^0 \to J/\psi pK^-$ yields of 0.0940 ± 0.0029.

The shapes used in the mass fit are varied to determine a systematic uncertainty related to the mass model. No significant differences are found when trying alternate signal parameterisation that still result in a good fit. Changing the peaking backgrounds PDF, or letting their yield free in the fit, change their relative fit fractions, as well as that of the combinatorial background, but does not affect the signal yields. The combinatorial background model is changed from an exponential to a second-order polynomial, which results in a $\Lambda_b^0 \to J/\psi p\pi^-$ ($\Lambda_b^0 \to J/\psi pK^-$) yield reduced by 2.1% (0.3%). These variations are added in quadrature and used to estimate a systematic uncertainty on the ratio of branching fractions.

5 *CP* asymmetry

The same fit procedure is repeated separately for baryon (tagged by a positively charged proton) and antibaryon candidates. All parameters of the fits are determined again separately, except for the signal shape and the combinatorial background slope, which are taken from the fit to all candidates. A total of 1131 ± 40 $\Lambda_b^0 \to J/\psi\, p\pi^-$, 964 ± 38 $\overline{\Lambda}_b^0 \to J/\psi\, \overline{p}\pi^+$, 5655 ± 77 $\Lambda_b^0 \to J/\psi\, pK^-$ and 5529 ± 76 $\overline{\Lambda}_b^0 \to J/\psi\, \overline{p}K^+$ decays are found, corresponding to the raw asymmetries

$$\begin{aligned} \mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi\, p\pi^-) &\equiv \frac{N(\Lambda_b^0 \to J/\psi\, p\pi^-) - N(\overline{\Lambda}_b^0 \to J/\psi\, \overline{p}\pi^+)}{N(\Lambda_b^0 \to J/\psi\, p\pi^-) + N(\overline{\Lambda}_b^0 \to J/\psi\, \overline{p}\pi^+)} \\ &= (+7.9 \pm 2.2)\%, \\ \mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi\, pK^-) &= (+1.1 \pm 0.9)\%. \end{aligned} \tag{5.1}$$

The procedure to assess the systematic uncertainties related to the shape of the mass distribution, described in section 4, is repeated to determine the sensitivity of the raw asymmetries. A total variation of 0.7% is obtained, which is dominated by a change in $\mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi\, p\pi^-)$ when using a second-order polynomial background model.

The raw decay-rate asymmetry can be decomposed as

$$\mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi\, ph^-) = \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi\, ph^-) + \mathcal{A}_{\rm prod}(\Lambda_b^0) - \mathcal{A}_{\rm reco}(h^+) + \mathcal{A}_{\rm reco}(p), \tag{5.2}$$

where the terms on the right hand side of the equation are the *CP*-violating, Λ_b^0 production and reconstruction asymmetries of the hadron $h^\pm = \pi^\pm, K^\pm$ and the proton, respectively. Reconstruction asymmetries are defined following the convention $\mathcal{A}_{\rm reco}(h^+) \equiv \frac{\epsilon(h^+)-\epsilon(h^-)}{\epsilon(h^+)+\epsilon(h^-)}$ throughout, where ϵ is the reconstruction efficiency. The production asymmetry $\mathcal{A}_{\rm prod}$ and the proton reconstruction asymmetry cancel in the difference of the two asymmetries

$$\begin{aligned} \Delta\mathcal{A}_{CP} &\equiv \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi\, p\pi^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi\, pK^-) \\ &= \mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi\, p\pi^-) - \mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi\, pK^-) + \mathcal{A}_{\rm reco}(\pi^+) - \mathcal{A}_{\rm reco}(K^+). \end{aligned} \tag{5.3}$$

The kaon and pion asymmetries can be determined from the raw asymmetry of the $\overline{B}^0 \to J/\psi\, \overline{K}^*(892)^0$ decay with $\overline{K}^*(892)^0 \to K^-\pi^+$. It has been measured [36] as

$$\mathcal{A}_{\rm raw}(\overline{B}^0 \to J/\psi\, \overline{K}^*(892)^0) \equiv \frac{N(\overline{B}^0) - N(B^0)}{N(\overline{B}^0) + N(B^0)} = (-1.10 \pm 0.32 \pm 0.06)\%, \tag{5.4}$$

where the first uncertainty is statistical and the second systematic. It can be decomposed as

$$\begin{aligned} \mathcal{A}_{\rm raw}(\overline{B}^0 \to J/\psi\, \overline{K}^*(892)^0) &= \mathcal{A}_{CP}(\overline{B}^0 \to J/\psi\, \overline{K}^*(892)^0) - \kappa\mathcal{A}_{\rm prod}(B^0) \qquad (5.5) \\ &\quad + \mathcal{A}_{\rm reco}(\pi^+) - \mathcal{A}_{\rm reco}(K^+) \\ &\approx \mathcal{A}_{\rm reco}(\pi^+) - \mathcal{A}_{\rm reco}(K^+), \qquad (5.6) \end{aligned}$$

where κ is a dilution factor due to B^0 mixing and $\mathcal{A}_{\rm prod}(B^0)$ is the B^0 production asymmetry, which is compatible with zero [37]. Under the assumption of no *CP* asymmetry in the

$\overline{B}^0 \to J/\psi\, \overline{K}^*(892)^0$ decay and negligible production asymmetry, this value can thus be taken as the combined kaon and pion reconstruction asymmetry, and is consistent with measurements in other decay modes to kaon and pions [37, 38].

The difference of *CP* asymmetries in the $\Lambda_b^0 \to J/\psi\, p\pi^-$ and $\Lambda_b^0 \to J/\psi\, pK^-$ decays can then be rewritten as

$$\begin{aligned}\Delta\mathcal{A}_{CP} &= \mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi\, p\pi^-) - \mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi\, pK^-) + \mathcal{A}_{\rm raw}(\overline{B}^0 \to J/\psi\, \overline{K}^*(892)^0) \\ &= (+5.7 \pm 2.4)\%,\end{aligned} \quad (5.7)$$

where the uncertainty is statistical only.

The kaon and pion momenta in Λ_b^0 decays are not identical to those in $\overline{B}^0 \to J/\psi\, \overline{K}^*(892)^0$ decays, which could induce different detector asymmetries in the Λ_b^0 and B^0 modes. This is investigated by weighting the $\Lambda_b^0 \to J/\psi\, p\pi^-$ and $\Lambda_b^0 \to J/\psi\, pK^-$ data to match the pion and kaon momentum distributions observed in $\overline{B}^0 \to J/\psi\, \overline{K}^*(892)^0$ decays. The value of $\Delta\mathcal{A}_{CP}$ changes by 0.8%, which is assigned as the systematic uncertainty related to reconstruction asymmetries.

Local *CP* asymmetries in the Dalitz plane are also searched for using the technique outlined in ref. [39, 40]. No significant local asymmetries are found.

6 Efficiency corrections and systematic uncertainties

The raw quantities need to be corrected to determine the physics quantities. The efficiency of the selection requirements is studied with simulation. Some quantities are known not to be well reproduced in simulation, namely the Λ_b^0 transverse momentum and lifetime, the particle multiplicity, and the $\Lambda_b^0 \to J/\psi\, p\pi^-$ and $\Lambda_b^0 \to J/\psi\, pK^-$ decay kinematic properties. For all these quantities the simulated data are weighted to match the observed distributions in data. They are obtained with the *sPlot* technique using the Λ_b^0 candidate mass as the control variable.

For three-body b-hadron decays, both the signal decays and the dominant combinatorial backgrounds populate regions close to the kinematic boundaries of the $J/\psi\, p\pi^-$ and $J/\psi\, pK^-$ Dalitz plot [41]. For more accurate modelling of these regions, it is convenient to transform the conventional Dalitz space to a rectangular space (hereafter referred to as the square Dalitz plot [42]). We follow the procedure described in ref. [15].

The $\Lambda_b^0 \to J/\psi\, p\pi^-$ and $\Lambda_b^0 \to J/\psi\, pK^-$ decays have different detector acceptance, reconstruction and selection efficiencies. They are determined from simulated data, which are weighted to match the experimental data. The main differences are induced by

i. the detector acceptance, as the efficiency of $\Lambda_b^0 \to J/\psi\, pK^-$ is 6% larger than that for the $\Lambda_b^0 \to J/\psi\, p\pi^-$ decays due to the lower kinetic energy release in the former, which causes smaller opening angles;

ii. the reconstruction and preselection efficiency, which is 4% larger in $\Lambda_b^0 \to J/\psi\, p\pi^-$ decays due to the average total and transverse momentum of the final state particles being larger than in $\Lambda_b^0 \to J/\psi\, pK^-$ decays;

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Source	BF	$\Delta\mathcal{A}_{CP}$
Simulation-based corrections	0.913 ± 0.040	-
PID	0.960 ± 0.010	-
Trigger	1.000 ± 0.010	-
Λ_b^0 lifetime	1.000 ± 0.001	-
Mass distribution model	1.000 ± 0.021	$0.0 \pm 0.7\%$
$\overline{B}^0 \to J/\psi \overline{K}^*(892)^0$	-	$-1.1 \pm 0.3\%$
Detection asymmetries	-	$0.0 \pm 0.8\%$
Total	0.876 ± 0.045	-1.1 ± 1.2 %

Table 1. Corrections and related systematic uncertainties on the ratio of $\Lambda_b^0 \to J/\psi p\pi^-$ to $\Lambda_b^0 \to J/\psi pK^-$ branching fractions (BF) and on the difference between the *CP* asymmetries $\Delta\mathcal{A}_{CP}$. The corrections are multiplicative on the branching fraction and additive for the asymmetry.

iii. the particle identification requirements on the π^- or K^-, which are more efficient on $\Lambda_b^0 \to J/\psi p\pi^-$ decays by 7%;

iv. the ϕ veto, which removes 7% (3%) of the $\Lambda_b^0 \to J/\psi pK^-$ ($J/\psi p\pi^-$) signal.

Overall, these effects result in a further correction on the ratio of branching fractions of $\Lambda_b^0 \to J/\psi p\pi^-$ to $\Lambda_b^0 \to J/\psi pK^-$ decays of 0.913 ± 0.040.

The efficiency of particle identification is not perfectly modelled in simulation. The kaon and pion identification efficiencies are further weighted after the kinematic weighting described above, using a large sample of D^*-tagged $D^0 \to K^-\pi^+$ decays. The uncertainties are determined by varying the weights of the simulated data within their uncertainties, yielding a correction of 0.960 ± 0.010. The kinematic properties of the proton in the $\Lambda_b^0 \to J/\psi p\pi^-$ and $\Lambda_b^0 \to J/\psi pK^-$ decays are found to be the same. The same applies to the muons. The efficiencies of proton and muon identification therefore cancel in the ratio of branching fractions, as well as in the *CP* asymmetries.

The trigger efficiency is determined using simulation, which is validated using $\Lambda_b^0 \to J/\psi pK^-$ decays from data. Differences between the $\Lambda_b^0 \to J/\psi p\pi^-$ and $\Lambda_b^0 \to J/\psi pK^-$ decays efficiencies are at the percent level and are assigned as systematic uncertainties.

The value of the Λ_b^0 lifetime used in simulation is taken from ref. [43], and is 3% lower than the current most precise measurement [5]. The simulated data is weighted to account for this and the difference is assigned as a systematic uncertainty.

The estimates of the systematic uncertainties described above are summarised in table 1, along with the total obtained by summing them in quadrature. The uncertainty on the ratio of branching fractions is dominated by the uncertainty on corrections obtained from simulation, mostly due to the unknown decay kinematic properties of the $\Lambda_b^0 \to J/\psi p\pi^-$ decay. For $\Delta\mathcal{A}_{CP}$, the mass model distribution and the detection asymmetries contribute about equally.

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7 Results and conclusions

A signal of the Cabibbo-suppressed $\Lambda_b^0 \to J/\psi\, p\pi^-$ decay is observed for the first time using a data sample of proton-proton collisions at 7 and 8 TeV, corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$. Applying the appropriate corrections detailed in table 1, the ratio of branching fractions is measured to be

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p\pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, pK^-)} = 0.0824 \pm 0.0025\,(\text{stat}) \pm 0.0042\,(\text{syst}).$$

Assuming these decays are dominated by tree $b \to c\bar{c}d$ and $b \to c\bar{c}s$ transitions, respectively, the ratio of Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{cd}|^2/|V_{cs}|^2$ times ratio of phase space factors is approximately 0.08, compatible with the measured value. This ratio can also be compared to that of the decays $\Lambda_b^0 \to \Lambda_c^+ D^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^+$, which involve the same quark lines as $\Lambda_b^0 \to J/\psi\, p\pi^-$ and $\Lambda_b^0 \to J/\psi\, pK^-$, respectively. The ratio of $\Lambda_b^0 \to \Lambda_c^+ D^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^+$ has been measured as $0.042 \pm 0.003\,(\text{stat}) \pm 0.003\,(\text{syst})$ [14], which is consistent with this measurement, when taking into account the D^- and D_s^+ meson decay constants [43] and the different ratio of phase space factors.

Background-subtracted and efficiency-corrected distributions of kinematic distributions determined in the $\Lambda_b^0 \to J/\psi\, p\pi^-$ decay are shown in figure 2. In this case the Λ_b^0 mass is fixed to its known value and the kinematic properties recomputed [33]. No attempt is made to fit the decay rate on the Dalitz plane. The $p\pi^-$ mass distribution shows a rich resonant structure, as expected from fits to fixed-target experiment data [44, 45], and suggests the presence of the narrow $N(1520)$ or $N(1535)$, the $N(1650)$, as well as the broad $N(1440)$ resonances. No signs of exotic structures in the $J/\psi\,\pi^-$ or $J/\psi\, p$ mass distributions are seen. More data and further studies will be needed to inverstigate the underlying dynamics of this decay.

The *CP* asymmetry difference between the $\Lambda_b^0 \to J/\psi\, p\pi^-$ and $\Lambda_b^0 \to J/\psi\, pK^-$ decays is measured to be

$$\Delta A_{CP} = A_{CP}(\Lambda_b^0 \to J/\psi\, p\pi^-) - A_{CP}(\Lambda_b^0 \to J/\psi\, pK^-) = (+5.7 \pm 2.4\,(\text{stat}) \pm 1.2\,(\text{syst}))\%,$$

corresponding to a 2.2σ deviation from zero. No indications of large local *CP* asymmetries in the Dalitz plane are observed. The precision of these measurements illustrate the potential of Cabibbo-suppressed Λ_b^0 decays in studies of direct *CP* violation.

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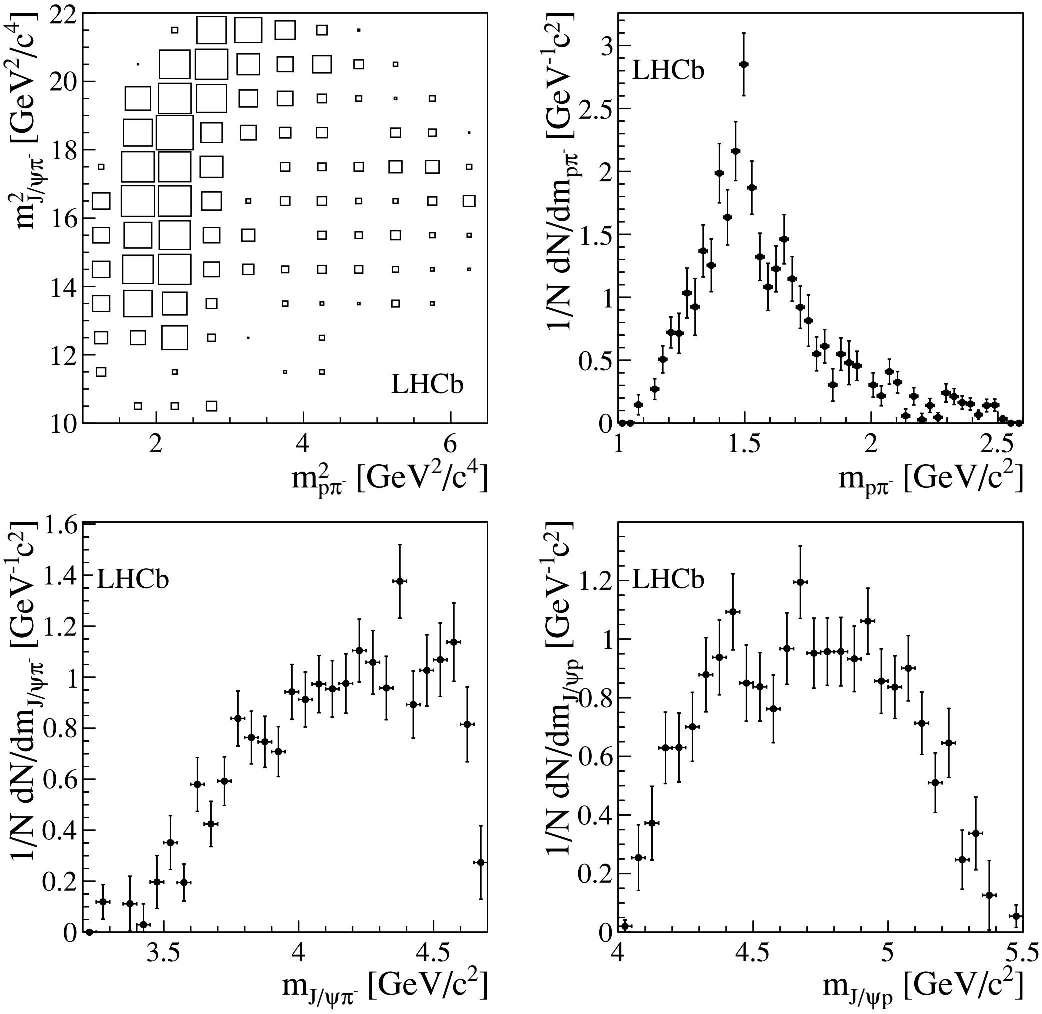

Figure 2. Efficiency-corrected and background-subtracted $\Lambda_b^0 \to J/\psi p \pi^-$ Dalitz plane and projections normalised to unit area on the $p\pi^-$, $J/\psi \pi^-$ and $J/\psi p$ axes.

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