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Branching fraction and *CP* asymmetry of the decays $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$ ☆

LHCb Collaboration

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ABSTRACT

An analysis of $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$ decays is performed with the LHCb experiment. The pp collision data used correspond to integrated luminosities of 1 fb^{-1} and 2 fb^{-1} collected at centre-of-mass energies of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively. The ratio of branching fractions and the direct *CP* asymmetries are measured to be $\mathcal{B}(B^+ \to K^0_S K^+)/\mathcal{B}(B^+ \to K^0_S\pi^+) = 0.064 \pm 0.009$ (stat.) $\pm$ 0.004 (syst.), $\mathcal{A}^{CP}(B^+ \to K^0_S\pi^+) = -0.022 \pm 0.025$ (stat.) $\pm$ 0.010 (syst.) and $\mathcal{A}^{CP}(B^+ \to K^0_S K^+) = -0.21 \pm 0.14$ (stat.) $\pm$ 0.01 (syst.). The data sample taken at $\sqrt{s} = 7$ TeV is used to search for $B_c^+ \to K^0_S K^+$ decays and results in the upper limit $(f_c \cdot \mathcal{B}(B_c^+ \to K^0_S K^+))/(f_u \cdot \mathcal{B}(B^+ \to K^0_S\pi^+)) < 5.8 \times 10^{-2}$ at 90% confidence level, where f_c and f_u denote the hadronisation fractions of a $\bar{b}$ quark into a B_c^+ or a B^+ meson, respectively.

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1. Introduction

Studies of charmless two-body B meson decays allow tests of the Cabibbo–Kobayashi–Maskawa picture of *CP* violation [1,2] in the Standard Model (SM). They include contributions from loop amplitudes, and are therefore particularly sensitive to processes beyond the SM [3–7]. However, due to the presence of poorly known hadronic parameters, predictions of *CP* violating asymmetries and branching fractions are imprecise. This limitation may be overcome by combining measurements from several charmless two-body B meson decays and using flavour symmetries [3]. More precise measurements of the branching fractions and *CP* violating asymmetries will improve the determination of the size of SU(3) breaking effects and the magnitudes of colour-suppressed and annihilation amplitudes [8,9].

In $B^+ \to K^0_S K^+$ and $B^+ \to K^0_S\pi^+$ decays,[1] gluonic loop, colour-suppressed electroweak loop and annihilation amplitudes contribute. Measurements of their branching fractions and *CP* asymmetries allow to check for the presence of sizeable contributions from the latter two [6]. Further flavour symmetry checks can also be performed by studying these decays [10]. First measurements have been performed by the BaBar and Belle experiments [11,12]. The world averages are $\mathcal{A}^{CP}(B^+ \to K^0_S\pi^+) = -0.015 \pm 0.019$, $\mathcal{A}^{CP}(B^+ \to K^0_S K^+) = 0.04 \pm 0.14$ and $\mathcal{B}(B^+ \to K^0_S K^+)/\mathcal{B}(B^+ \to K^0_S\pi^+) = 0.050 \pm 0.008$, where

$$\mathcal{A}^{CP}\big(B^+ \to K^0_S\pi^+\big) \equiv \frac{\Gamma(B^- \to K^0_S\pi^-) - \Gamma(B^+ \to K^0_S\pi^+)}{\Gamma(B^- \to K^0_S\pi^-) + \Gamma(B^+ \to K^0_S\pi^+)} \quad (1)$$

and $\mathcal{A}^{CP}(B^+ \to K^0_S K^+)$ is defined in an analogous way.

Since the annihilation amplitudes are expected to be small in the SM and are often accompanied by other topologies, they are difficult to determine unambiguously. These can however be measured cleanly in $B_c^+ \to K^0_S K^+$ decays, where other amplitudes do not contribute. Standard Model predictions for the branching fractions of pure annihilation B_c^+ decays range from 10^{-8} to 10^{-6} depending on the theoretical approach employed [13].

In this Letter, a measurement of the ratio of branching fractions of $B^+ \to K^0_S K^+$ and $B^+ \to K^0_S\pi^+$ decays with the LHCb detector is reported along with a determination of their *CP* asymmetries. The data sample corresponds to integrated luminosities of 1 and 2 fb^{-1}, recorded during 2011 and 2012 at centre-of-mass energies of 7 and 8 TeV, respectively. A search for the pure annihilation decay $B_c^+ \to K^0_S K^+$ based on the data collected at 7 TeV is also presented. The $B^+ \to K^0_S K^+$ and $B_c^+ \to K^0_S K^+$ signal regions, along with the raw *CP* asymmetries, were not examined until the event selection and the fit procedure were finalised.

2. Detector, data sample and event selection

The LHCb detector [14] 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 (VELO) surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a

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[1] The inclusion of charge conjugated decay modes is implied throughout this Letter unless otherwise stated.

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bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The magnetic field polarity is regularly flipped to reduce the effect of detection asymmetries. The pp collision data recorded with each of the two magnetic field polarities correspond to approximately half of the data sample. The combined tracking system provides a momentum measurement with relative uncertainty that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and an impact parameter resolution of 20 μm for tracks with high transverse momentum ($p_{\rm T}$). Charged hadrons are identified using two ring-imaging Cherenkov detectors [15]. 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.

Simulated samples are used to determine efficiencies and the probability density functions (PDFs) used in the fits. The pp collisions are generated using Pythia 6.4 [16] with a specific LHCb-configuration [17]. Decays of hadronic particles are described by EvtGen [18], in which final state radiation is generated using Photos [19]. The interaction of the generated particles with the detector and its response are implemented using the Geant4 toolkit [20] as described in Ref. [21].

The trigger [22] 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. The candidates used in this analysis are triggered at the hardware stage either directly by one of the particles from the B candidate decay depositing a transverse energy of at least 3.6 GeV in the calorimeters, or by other activity in the event (usually associated with the decay products of the other b-hadron decay produced in the $pp \to b\bar{b}X$ interaction). Inclusion of the latter category increases the acceptance of signal decays by approximately a factor two. The software trigger requires a two- or three-particle secondary vertex with a high scalar sum of the $p_{\rm T}$ of the particles and significant displacement from the primary pp interaction vertices (PVs). A multivariate algorithm [23] is used for the identification of secondary vertices consistent with the decay of a b hadron.

Candidate $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$ decays are formed by combining a $K^0_S \to \pi^+\pi^-$ candidate with a charged track that is identified as a pion or kaon, respectively. Only tracks in a fiducial volume with small detection asymmetries [24] are accepted in the analysis. Pions used to reconstruct the K^0_S decays are required to have momentum $p > 2$ GeV/c, $\chi^2_{\rm IP} > 9$, and track segments in the VELO and in the downstream tracking chambers. The $\chi^2_{\rm IP}$ is defined as the difference in χ^2 of a given PV reconstructed with and without the considered particle. The K^0_S candidates have $p > 8$ GeV/c, $p_{\rm T} > 0.8$ GeV/c, a good quality vertex fit, a mass within ± 15 MeV/c^2 of the known value [25], and are well-separated from all PVs in the event. It is also required that their momentum vectors do not point back to any of the PVs in the event.

Pion and kaon candidate identification is based on the information provided by the RICH detectors [15], combined in the difference in the logarithms of the likelihoods for the kaon and pion hypotheses ($\mathrm{DLL}_{K\pi}$). A track is identified as a pion (kaon) if $\mathrm{DLL}_{K\pi} \leqslant 3$ ($\mathrm{DLL}_{K\pi} > 3$), and $p < 110$ GeV/c, a momentum beyond which there is little separation between pions and kaons. The efficiencies of these requirements are 95% and 82% for signal pions and kaons, respectively. The misidentification probabilities of pions to kaons and kaons to pions are 5% and 18%. These figures are determined using a large sample of $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays reweighted by the kinematics of the simulated signal decays. Tracks that are consistent with particles leaving hits in the muon detectors are rejected. Pions and kaons are also required to have $p_{\rm T} > 1$ GeV/c and $\chi^2_{\rm IP} > 2$.

The B candidates are required to have the scalar $p_{\rm T}$ sum of the K^0_S and the π^+(or K^+) candidates that exceeds 4 GeV/c, to have $\chi^2_{\rm IP} < 10$ and $p > 25$ GeV/c and to form a good-quality vertex well separated from all the PVs in the event and displaced from the associated PV by at least 1 mm. The daughter (K^0_S or π^+/K^+) with the larger $p_{\rm T}$ is required to have an impact parameter above 50 μm. The angle $\theta_{\rm dir}$ between the B candidate's line of flight and its momentum is required to be less than 32 mrad. Background for K^0_S candidates is further reduced by requiring the K^0_S decay vertex to be significantly displaced from the reconstructed B decay vertex along the beam direction (z-axis), with $S_z \equiv (z_{K^0_S} - z_B)/\sqrt{\sigma^2_{z,K^0_S} + \sigma^2_{z,B}} > 2$, where σ^2_{z,K^0_S} and $\sigma^2_{z,B}$ are the uncertainties on the z positions of the K^0_S and B decay vertices $z_{K^0_S}$ and z_B, respectively.

Boosted decision trees (BDT) [26] are trained using the AdaBoost algorithm [27] to further separate signal from background. The discriminating variables used are the following: S_z; the $\chi^2_{\rm IP}$ of the K^0_S and π^+/K^+ candidates; $p_{\rm T}$, $\cos(\theta_{\rm dir})$, $\chi^2_{\rm VS}$ of the B candidates defined as the difference in χ^2 of fits in which the B^+ decay vertex is constrained to coincide with the PV or not; and the imbalance of $p_{\rm T}$, $A_{p_{\rm T}} \equiv (p_{\rm T}(B) - \sum p_{\rm T})/(p_{\rm T}(B) + \sum p_{\rm T})$ where the scalar $p_{\rm T}$ sum is for all the tracks not used to form the B candidate and which lie in a cone around the B momentum vector. This cone is defined by a circle of radius 1 unit in the pseudorapidity-azimuthal angle plane, where the azimuthal angle is measured in radians. Combinatorial background tends to be less isolated with smaller $p_{\rm T}$ imbalance than typical b-hadron decays. The background training samples are taken from the upper B invariant mass sideband region in data ($5450 < m_B < 5800$ MeV/c^2), while those of the signal are taken from simulated $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$ decays. Two discriminants are constructed to avoid biasing the background level in the upper B mass sideband while making maximal use of the available data for training the BDT. The $K^0_S\pi^+$ and $K^0_S K^+$ samples are merged to prepare the two BDTs. They are trained using two independent equal-sized subsamples, each corresponding to half of the whole data sample. Both BDT outputs are found to be in agreement with each other in all aspects and each of them is applied to the other sample. For each event not used to train the BDTs, one of the two BDT outputs is arbitrarily applied. In this way, both BDT discriminants are applied to equal-sized data samples and the number of events used to train the BDTs is maximised without bias of the sideband region and the simulated samples used for the efficiency determination. The choice of the requirement on the BDT output ($\mathcal{Q}$) is performed independently for the $K^0_S\pi^\pm$ and $K^0_S K^\pm$ samples by evaluating the signal significance $N_{\rm S}/\sqrt{N_{\rm S} + N_{\rm B}}$, where $N_{\rm S}$ ($N_{\rm B}$) denotes the expected number of signal (background) candidates. The predicted effective pollution from mis-identified $B^+ \to K^0_S\pi^+$ decays in the $B^+ \to K^0_S K^+$ signal mass region is taken into account in the calculation of $N_{\rm B}$. The expected signal significance is maximised by applying $\mathcal{Q} > 0.4$ (0.8) for $B^+ \to K^0_S\pi^+(B^+ \to K^0_S K^+)$ decays.

3. Asymmetries and signal yields

The CP-summed $B^+ \to K^0_S K^+$ and $B^+ \to K^0_S\pi^+$ yields are measured together with the raw charge asymmetries by means of a simultaneous unbinned extended maximum likelihood fit to the $B^\pm$ candidate mass distributions of the four possible final states ($B^\pm \to K^0_S\pi^\pm$ and $B^\pm \to K^0_S K^\pm$). Five components contribute to each of the mass distributions. The signal is described by the sum

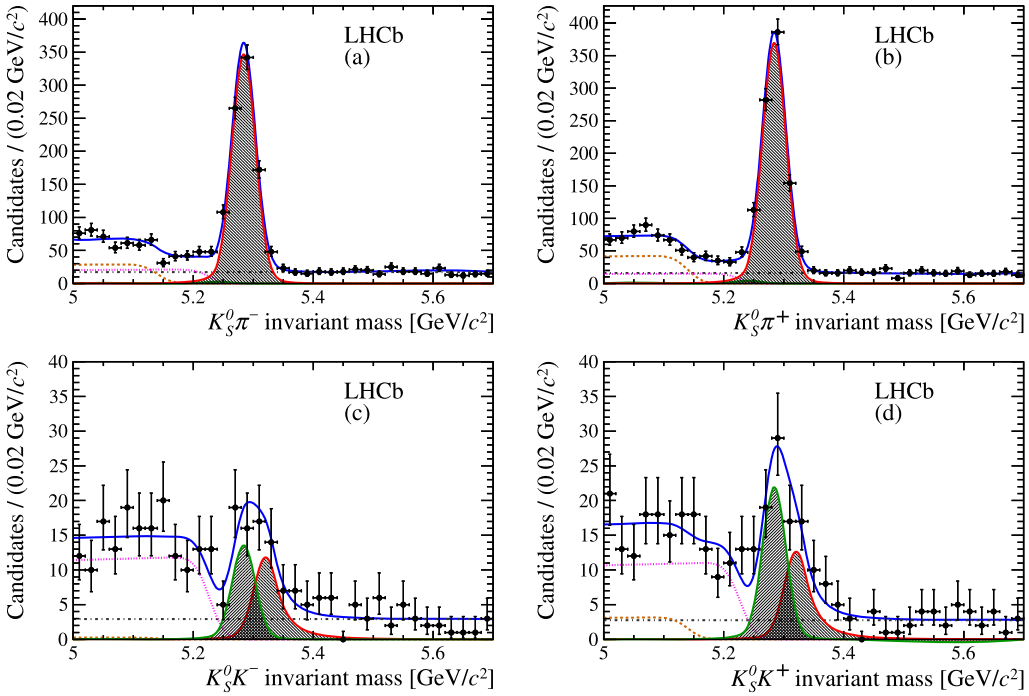

Fig. 1. Invariant mass distributions of selected (a) $B^- \to K^0_S\pi^-$, (b) $B^+ \to K^0_S\pi^+$, (c) $B^- \to K^0_SK^-$ and (d) $B^+ \to K^0_SK^+$ candidates. Data are points with error bars, the $B^+ \to K^0_S\pi^+(B^+ \to K^0_SK^+)$ components are shown as red falling hatched (green rising hatched) curves, combinatorial background is grey dash-dotted, partially reconstructed $B^0_s(B^0/B^+)$ backgrounds are dotted magenta (dashed orange). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

of a Gaussian distribution and a Crystal Ball function (CB) [28] with identical peak positions determined in the fit. The CB component models the radiative tail. The other parameters, which are determined from fits of simulated samples, are common for both decay modes. The width of the CB function is, according to the simulation, fixed to be 0.43 times that of the Gaussian distribution, which is left free in the fit.

Due to imperfect particle identification, $B^+ \to K^0_S\pi^+(B^+ \to K^0_SK^+)$ decays can be misidentified as $K^0_SK^+(K^0_S\pi^+)$ candidates. The corresponding PDFs are empirically modelled with the sum of two CB functions. For the $B^+ \to K^0_S\pi^+(B^+ \to K^0_SK^+)$ decay, the misidentification shape has a significant high (low) mass tail. The parameters of the two CB functions are determined from the simulation, and then fixed in fits to data.

Partially reconstructed decays, coming mainly from B^0 and B^+ (labelled B in this section), and B^0_s meson decays to open charm and to a lesser extent from three-body charmless B and B^0_s decays, are modelled with two PDFs. These PDFs are identical in the four possible final states. They are modelled by a step function with a threshold mass equal to $m_B - m_\pi$ ($m_{B^0_s} - m_\pi$) [25] for $B(B^0_s)$ decays, convolved with a Gaussian distribution of width 20 MeV/c^2 to account for detector resolution effects. Backgrounds from Λ^0_b decays are found to be negligible. The combinatorial background is assumed to have a flat distribution in all categories.

The signal and background yields are varied in the fit, apart from those of the cross-feed contributions, which are constrained using known ratios of selection efficiencies from the simulation and particle identification and misidentification probabilities. The ratio of $B^+ \to K^0_SK^+(B^+ \to K^0_S\pi^+)$ events reconstructed and selected as $K^0_S\pi^+(K^0_SK^+)$ with respect to $K^0_SK^+(K^0_S\pi^+)$ are 0.245 ± 0.018 (0.0418 ± 0.0067), where the uncertainties are dominated by the finite size of the simulated samples. These numbers appear in Gaussian terms inserted in the fit likelihood function. The charge asymmetries of the backgrounds vary independently in the fit, apart from those of the cross-feed contributions, which are identical to those of the properly reconstructed signal decay.

Fig. 1 shows the four invariant mass distributions along with the projections of the fit. The measured width of the Gaussian distribution used in the signal PDF is found to be approximately 20% larger than in the simulation, and is included as a systematic uncertainty. The *CP*-summed $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_SK^+$ signal yields are found to be $N(B^+ \to K^0_S\pi^+) = 1804 \pm 47$ and $N(B^+ \to K^0_SK^+) = 90 \pm 13$, with raw *CP* asymmetries $\mathcal{A}_{\rm raw}(B^+ \to K^0_S\pi^+) = -0.032 \pm 0.025$ and $\mathcal{A}_{\rm raw}(B^+ \to K^0_SK^+) = -0.23 \pm 0.14$. All background asymmetries are found to be consistent with zero within two standard deviations. By dividing the sample in terms of data taking periods and magnet polarity, no discrepancies of more than two statistical standard deviations are found in the raw *CP* asymmetries.

4. Corrections and systematic uncertainties

The ratio of branching fractions is determined as

$$\frac{\mathcal{B}(B^+ \to K^0_SK^+)}{\mathcal{B}(B^+ \to K^0_S\pi^+)} = \frac{N(B^+ \to K^0_SK^+)}{N(B^+ \to K^0_S\pi^+)} \cdot r_{\rm sel} \cdot r_{\rm PID}, \tag{2}$$

where the ratio of selection efficiencies is factorised into two terms representing the particle identification,

$$r_{\rm PID} \equiv \frac{\varepsilon_{\rm PID}(B^+ \to K^0_S\pi^+)}{\varepsilon_{\rm PID}(B^+ \to K^0_SK^+)}, \tag{3}$$

and the rest of the selection,

$$r_{\rm sel} \equiv \frac{\varepsilon_{\rm sel}(B^+ \to K^0_S\pi^+)}{\varepsilon_{\rm sel}(B^+ \to K^0_SK^+)}. \tag{4}$$

The raw *CP* asymmetries of the $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_SK^+$ decays are corrected for detection and production asymmetries

$\mathcal{A}_{\rm det+prod}$, as well as for a small contribution due to *CP* violation in the neutral kaon system ($\mathcal{A}_{K^0_S}$). The latter is assumed to be the same for both $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$ decays. At first order, the $B^+ \to K^0_S\pi^+$ *CP* asymmetry can be written as

$$\mathcal{A}^{CP}(B^+ \to K^0_S\pi^+) \approx \mathcal{A}_{\rm raw}(B^+ \to K^0_S\pi^+) - \mathcal{A}_{\rm det+prod}(B^+ \to K^0_S\pi^+) + \mathcal{A}_{K^0_S}$$

and similarly for $B^+ \to K^0_S K^+$, up to a sign flip in front of $\mathcal{A}_{K^0_S}$.

Selection efficiencies are determined from simulated samples generated at a centre-of-mass energy of 8 TeV. The ratio of selection efficiencies is found to be $r_{\rm sel} = 1.111 \pm 0.019$, where the uncertainty is from the limited sample sizes. To first order, effects from imperfect simulation should cancel in the ratio of efficiencies. In order to assign a systematic uncertainty for a potential deviation of the ratio of efficiencies in 7 TeV data with respect to 8 TeV, the $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$ simulated events are reweighted by a linear function of the B-meson momentum such that the average B momentum is 13% lower, corresponding to the ratio of beam energies. The 0.7% relative difference between the nominal and reweighted efficiency ratio is assigned as a systematic uncertainty. The distribution of the BDT output for simulated $B^+ \to K^0_S\pi^+$ events is found to be consistent with the observed distribution of signal candidates in the data using the *sPlot* technique [29], where the discriminating variable is taken to be the B invariant mass. The total systematic uncertainty related to the selection is 1.8%.

The determination of the trigger efficiencies is subject to variations in the data-taking conditions and, in particular, to the ageing of the calorimeter system. These effects are mitigated by regular changes in the gain of the calorimeter system. A large sample of $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays is used to measure the trigger efficiency in bins of $p_{\rm T}$ for pions and kaons from signal decays. These trigger efficiencies are averaged using the $p_{\rm T}$ distributions obtained from simulation. The hardware stage trigger efficiencies obtained by this procedure are in agreement with those obtained in the simulation within 1.1%, which is assigned as systematic uncertainty on the ratio of branching fractions. The same procedure is also applied to B^+ and B^- decays separately, and results in 0.5% systematic uncertainty on the determination of the *CP* asymmetries.

Particle identification efficiencies are determined using a large sample of $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays. The kaons and pions from this calibration sample are reweighted in 18 bins of momentum and 4 bins of pseudorapidity, according to the distribution of signal kaons and pions from simulated $B^+ \to K^0_S K^+$ and $B^+ \to K^0_S\pi^+$ decays. The ratio of efficiencies is $r_{\rm PID} = 1.154 \pm 0.025$, where the uncertainty is given by the limited size of the simulated samples. The systematic uncertainty associated with the binning scheme is determined by computing the deviation of the average efficiency calculated using the nominal binning from that obtained with a single bin in each kinematic variable. A variation of 0.7% (1.3%) is observed for pions (kaons). A systematic uncertainty of 0.5% is assigned due to variations of the efficiencies, determined by comparing results obtained with the 2011 and 2012 calibration samples. All these contributions are added in quadrature to obtain 2.7% relative systematic uncertainty on the particle identification efficiencies. Charge asymmetries due to the PID requirements are found to be negligible.

Uncertainties due to the modelling of the reconstructed invariant mass distributions are assigned by generating and fitting pseudo-experiments. Parameters of the signal and cross-feed distributions are varied according to results of independent fits to the $B^+ \to K^0_S K^+$ and $B^+ \to K^0_S\pi^+$ simulated samples. The relative uncertainty on the ratio of yields from mis-modelling of the signal (cross-feed) is 2.4% (2.7%) mostly affecting the small $B^+ \to K^0_S K^+$ yield. The width of the Gaussian resolution function used to model the partially reconstructed backgrounds is increased by 20%, while the other fixed parameters of the partially reconstructed and combinatorial backgrounds are left free in the fit, in turn, to obtain a relative uncertainty of 3.3%. The total contribution of the fit model to the systematic uncertainty is 4.9%. Their contribution to the systematic uncertainties on the *CP* asymmetries is found to be negligible.

Detection and production asymmetries are measured using approximately one million $B^\pm \to J/\psi K^\pm$ decays collected in 2011 and 2012. Using a kinematic and topological selection similar to that employed in this analysis, a high purity sample is obtained. The raw *CP* asymmetry is measured to be $\mathcal{A}(B^\pm \to J/\psi K^\pm) = (-1.4 \pm 0.1)\%$ within 20 MeV/c^2 of the B^+ meson mass. The same result is obtained by fitting the reconstructed invariant mass with a similar model to that used for the $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$ fits. This asymmetry is consistent between bins of momentum and pseudorapidity within 0.5%, which is assigned as the corresponding uncertainty. The *CP* asymmetry in $B^\pm \to J/\psi K^\pm$ decays is $\mathcal{A}^{CP}(B^\pm \to J/\psi K^\pm) = (+0.5 \pm 0.3)\%$, where the value is the weighted average of the values from Refs. [25] and [30]. This leads to a correction of $\mathcal{A}_{\rm det+prod}(B^+ \to K^0_S K^+) = (-1.9 \pm 0.6)\%$. The combined production and detection asymmetry for $B^+ \to K^0_S\pi^+$ decays is expressed as $\mathcal{A}_{\rm det+prod}(B^+ \to K^0_S\pi^+) = \mathcal{A}_{\rm det+prod}(B^+ \to K^0_S K^+) + \mathcal{A}_{K\pi}$, where the kaon-pion detection asymmetry is $\mathcal{A}_{K\pi} \approx \mathcal{A}_K - \mathcal{A}_\pi = (1.0 \pm 0.5)\%$ [31]. The assigned uncertainty takes into account a potential dependence of the difference of asymmetries as a function of the kinematics of the tracks. The total correction to $\mathcal{A}^{CP}(B^+ \to K^0_S\pi^+)$ is $\mathcal{A}_{\rm det+prod}(B^+ \to K^0_S\pi^+) = (-0.9 \pm 0.8)\%$.

Potential effects from *CP* violation in the neutral kaon system, either directly via *CP* violation in the neutral kaon system [32] or via regeneration of a K^0_S component through interactions of a K^0_L state with material in the detector [33], are also considered. The former is estimated [34] by fitting the background subtracted [29] decay time distribution of the observed $B^+ \to K^0_S\pi^+$ decays and contributes 0.1% to the observed asymmetry. The systematic uncertainty on this small effect is chosen to have the same magnitude as the correction itself. The latter has been studied [35] and is small for decays in the LHCb acceptance and thus no correction is applied. The systematic uncertainty assigned for this assumption is estimated by using the method outlined in Ref. [33]. Since the K^0_S decays reconstructed in this analysis are concentrated at low lifetimes, the two effects are of similar sizes and have the same sign. Thus an additional systematic uncertainty equal to the size of the correction applied for *CP* violation in the neutral kaon system and 100% correlated with it, is assigned. It results in $\mathcal{A}_{K^0_S} = (0.1 \pm 0.2)\%$. A summary of the sources of systematic uncertainty and corrections to the *CP* asymmetries are given in Table 1. Total systematic uncertainties are calculated as the sum in quadrature of the individual contributions.

5. Search for $B_c^+ \to K^0_S K^+$ decays

An exploratory search for $B_c^+ \to K^0_S K^+$ decays is performed with the data sample collected in 2011, corresponding to an integrated luminosity of 1 fb^{-1}. The same selection as for the $B^+ \to K^0_S K^+$ decays is used, only adding a proton veto $\mathrm{DLL}_{pK} < 10$ to the K^+ daughter, which is more than 99% efficient. This is implemented to reduce a significant background from baryons in the

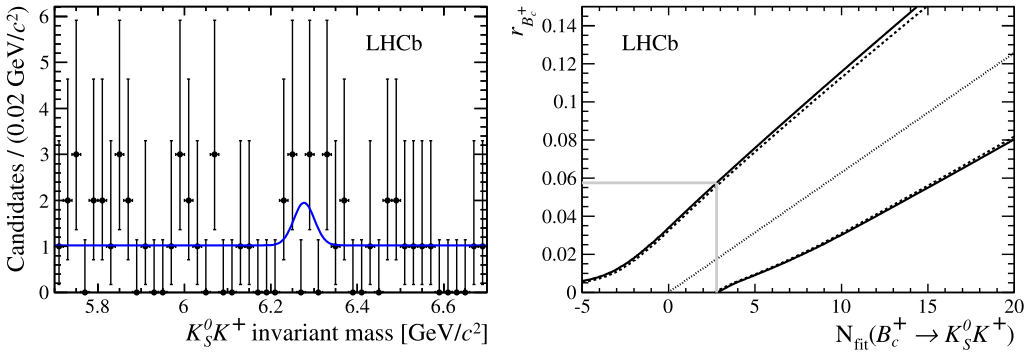

Fig. 2. (Left) Invariant mass distribution of selected $B_c^+ \to K_S^0 K^+$ candidates. Data are points with error bars and the curve represents the fitted function. (Right) The number of events and the corresponding value of $r_{B_c^+}$. The central value (dotted line) and the upper and lower 90% statistical confidence region bands are obtained using the Feldman and Cousins approach [36] (dashed lines). The solid lines includes systematic uncertainties. The gray outline of the box shows the obtained upper limit of $r_{B_c^+}$ for the observed number of 2.8 events.

Table 1
Corrections (above double line) and systematic uncertainties (below double line). The relative uncertainties on the ratio of branching fractions are given in the first column. The absolute corrections and related uncertainties on the *CP* asymmetries are given in the next two columns. The last column gathers the relative systematic uncertainties contributing to $r_{B_c^+}$. All values are given as percentages.

Source	$\mathcal{B}$ ratio	$\mathcal{A}^{CP} B^+ \to K_S^0 \pi^+$	$\mathcal{A}^{CP} B^+ \to K_S^0 K^+$	B_c^+
$\mathcal{A}_{\text{det+prod}}$	–	−0.9	−1.9	–
$\mathcal{A}_{K_S^0}$	–	0.1	0.1	–
Selection	1.8	–	–	6.1
Trigger	1.1	0.5	0.5	1.1
Particle identification	2.7	–	–	3.6
Fit model	4.9	–	–	2.0
$\mathcal{A}_{\text{det+prod}}$	–	0.8	0.6	–
$\mathcal{A}_{K_S^0}$	–	0.2	0.2	–
Total syst. uncertainty	6.0	1.0	0.8	7.4

invariant mass region considered for this search. The ratios of selection and particle identification efficiencies are $r_{\text{sel}} = 0.306 \pm 0.012$ and $r_{\text{PID}} = 0.819 \pm 0.027$, where the uncertainties are from the limited size of the simulated samples. The related systematic uncertainties are estimated in a similar way as for the measurement of $\mathcal{B}(B^+ \to K_S^0 K^+)/\mathcal{B}(B^+ \to K_S^0 \pi^+)$. The $B^+ \to K_S^0 \pi^+$ yield is also evaluated with the 2011 data only. The B_c^+ signal yield is determined by fitting a single Gaussian distribution with the mean fixed to the B_c^+ mass [25] and the width fixed to 1.2 times the value obtained from simulation to take into account the worse resolution in data. The combinatorial background is assumed to be flat. The invariant mass distribution and the superimposed fit are presented in Fig. 2 (left). Pseudo-experiments are used to evaluate the biases in the fit procedure and the systematic uncertainties are evaluated by assuming that the combinatorial background has an exponential slope. A similar procedure is used to take into account an uncertainty related to the assumed width of the signal distribution. The 20% correction applied to match the observed resolution in data, is assumed to estimate this uncertainty.

The Feldman and Cousins approach [36] is used to build 90% confidence region bands that relate the true value of $r_{B_c^+} = (f_c \cdot \mathcal{B}(B_c^+ \to K_S^0 K^+))/(f_u \cdot \mathcal{B}(B^+ \to K_S^0 \pi^+))$ to the measured number of signal events, and where f_c and f_u are the hadronisation fraction of a b into a B_c^+ and a B^+ meson, respectively. All of the systematic uncertainties are included in the construction of the confidence region bands by inflating the width of the Gaussian functions used to build the ranking variable of the Feldman and Cousins procedure. The result is shown in Fig. 2 (right) and gives the upper limit

$$r_{B_c^+} \equiv \frac{f_c}{f_u} \cdot \frac{\mathcal{B}(B_c^+ \to K_S^0 K^+)}{\mathcal{B}(B^+ \to K_S^0 \pi^+)} < 5.8 \times 10^{-2} \text{ at 90\% confidence level.}$$

This is the first upper limit on a B_c^+ meson decay into two light quarks.

6. Results and summary

The decays $B^+ \to K_S^0 K^+$ and $B^+ \to K_S^0 \pi^+$ have been studied using a data sample corresponding to an integrated luminosity of 3 fb^{-1}, collected in 2011 and 2012 by the LHCb detector and the ratio of branching fractions and *CP* asymmetries are found to be

$$\frac{\mathcal{B}(B^+ \to K_S^0 K^+)}{\mathcal{B}(B^+ \to K_S^0 \pi^+)} = 0.064 \pm 0.009\,(\text{stat.}) \pm 0.004\,(\text{syst.}),$$

$$\mathcal{A}^{CP}(B^+ \to K_S^0 \pi^+) = -0.022 \pm 0.025\,(\text{stat.}) \pm 0.010\,(\text{syst.}),$$

and

$$\mathcal{A}^{CP}(B^+ \to K_S^0 K^+) = -0.21 \pm 0.14\,(\text{stat.}) \pm 0.01\,(\text{syst.}).$$

These results are compatible with previous determinations [11,12]. The measurements of $\mathcal{A}^{CP}(B^+ \to K_S^0 K^+)$ and $\mathcal{B}(B^+ \to K_S^0 K^+)/\mathcal{B}(B^+ \to K_S^0 \pi^+)$ are the best single determinations to date. A search for $B_c^+ \to K_S^0 K^+$ decays is also performed with a data sample corresponding to an integrated luminosity of 1 fb^{-1}. The upper limit

$$\frac{f_c}{f_u} \cdot \frac{\mathcal{B}(B_c^+ \to K_S^0 K^+)}{\mathcal{B}(B^+ \to K_S^0 \pi^+)} < 5.8 \times 10^{-2} \text{ at 90\% confidence level}$$

is obtained. Assuming $f_c \simeq 0.001$ [13], $f_u = 0.33$ [25,37,38], and $\mathcal{B}(B^+ \to K^0 \pi^+) = (23.97 \pm 0.53\,(\text{stat.}) \pm 0.71\,(\text{syst.})) \times 10^{-6}$ [12], an upper limit $\mathcal{B}(B_c^+ \to \bar{K}^0 K^+) < 4.6 \times 10^{-4}$ at 90% confidence level is obtained. This is about two to four orders of magnitude higher than theoretical predictions, which range from 10^{-8} to 10^{-6} [13]. With the large data samples already collected by the LHCb experiment, other two-body B_c^+ decay modes to light quarks such as $B_c^+ \to \bar{K}^{*0} K^+$ and $B_c^+ \to \phi K^+$ may be searched for.

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