Abstract: An analysis of the decays $B^+\rightarrow K^0 S^{*+}$ and $B^+\rightarrow K^0 S K^+$ is performed with the LHCb experiment. The pp collision data used correspond to integrated luminosities of $1 \text{ fb}^{-1}$ and $2 \text{ fb}^{-1}$ collected at centre-of-mass energies of $7 \text{ TeV}$ and $8 \text{ TeV}$, respectively. The ratio of branching fractions and the direct CP asymmetries are measured to be $B(B^+\rightarrow K^0 S K^+)/B(B^+\rightarrow K^0 S^{*+})=0.064\pm0.009 \text{ (stat.)} \pm0.004 \text{ (syst.)}$, $A_{CP}(B^+\rightarrow K^0 S^{*+})=-0.022\pm0.025 \text{ (stat.)} \pm0.010 \text{ (syst.)}$ and $A_{CP}(B^+\rightarrow K^0 S K^+)= -0.21 \pm0.14 \text{ (stat.)} \pm0.01 \text{ (syst.)}$. The data sample taken at $7 \text{ TeV}$ is used to search for $B_{c^+}\rightarrow K^0 S K^+$ decays and results in the upper limit $\frac{f_{c^+} B(B_{c^+}\rightarrow K^0 S K^+)}{f_{u^+} B(B^+\rightarrow K^0 S^{*+})} < 5.8 \times 10^{-2}$ at 90\% confidence level, where $f_{c^+}$ and $f_{u^+}$ denote the hadronisation fractions of a $b^-$ quark into a $B_{c^+}$ or a $B^+$ meson, respectively.

DOI: https://doi.org/10.1016/j.physletb.2013.09.046

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-91547

Journal Article
Published Version

Originally published at:
LHCb Collaboration; Aaij, R; Adeva, B; Adinolfi, M; et al; Bernet, R; Müller, K; Steinkamp, O; Straumann, U; Vollhardt, A (2013). Branching fraction and CP asymmetry of the decays $B^+\rightarrow K^0 S$ and $B^+\rightarrow K^0 S K^+$. Physics Letters B, 726(4-5):646-655.

DOI: https://doi.org/10.1016/j.physletb.2013.09.046
Branching fraction and $CP$ asymmetry of the decays $B^+ \rightarrow K_S^0 \pi^+$ and $B^+ \rightarrow K^0_S K^+$

LHCb Collaboration

**Abstract**

An analysis of $B^+ \rightarrow K^0_S \pi^+$ and $B^+ \rightarrow K^0_S K^+$ 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 $B(B^+ \rightarrow K^0_S \pi^+)/B(B^+ \rightarrow K^0_S K^+) = 0.064 \pm 0.009$ (stat.) $\pm 0.004$ (syst.), $A^{CP}(B^+ \rightarrow K^0_S \pi^+) = -0.022 \pm 0.025$ (stat.) $\pm 0.010$ (syst.) and $A^{CP}(B^+ \rightarrow K^0_S K^+) = -0.21 \pm 0.14$ (stat.) $\pm 0.01$ (syst.). The data sample taken at $\sqrt{s} = 7$ TeV is used to search for $B^+_c \rightarrow K^0_S K^+$ decays and results in the upper limit $(f_c \cdot B(B^+_c \rightarrow K^0_S K^+))/(f_u \cdot B(B^+ \rightarrow K^0_S \pi^+)) < 5.8 \times 10^{-5}$ at 90% confidence level, where $f_c$ and $f_u$ denote the hadronisation fractions of a $b$ quark into a $B^+_c$ or a $B^+$ meson, respectively.

© 2013 CERN. Published by Elsevier B.V. All rights reserved.

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 $B^+ \rightarrow K^0_S K^+$ and $B^+ \rightarrow K^0_S \pi^+$ decays, $\gamma$ 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 $A^{CP}(B^+ \rightarrow K^0_S \pi^+) = -0.015 \pm 0.019$, $A^{CP}(B^+ \rightarrow K^0_S K^+) = 0.04 \pm 0.14$ and $B(B^+ \rightarrow K^0_S \pi^+)/B(B^+ \rightarrow K^0_S K^+) = 0.050 \pm 0.008$, where

$\frac{A^{CP}(B^+ \rightarrow K^0_S \pi^+)}{A^{CP}(B^+ \rightarrow K^0_S K^+)} = \frac{\Gamma(B^- \rightarrow K_S^0 \pi^-) - \Gamma(B^- \rightarrow K_S^0 K^-)}{\Gamma(B^- \rightarrow K_S^0 \pi^-) + \Gamma(B^- \rightarrow K_S^0 K^-)}$ (1)

and $A^{CP}(B^+ \rightarrow K^0_S K^+)$ 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 $B^+_c \rightarrow K^0_S K^+$ 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 $B^+ \rightarrow K^0_S K^+$ and $B^+ \rightarrow K^0_S \pi^+$ 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 $B^+_c \rightarrow K^0_S K^+$ based on the data collected at 7 TeV is also presented. The $B^+ \rightarrow K^0_S K^+$ and $B^+_c \rightarrow K^0_S K^+$ 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
hending 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 (pT). 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 PHOKOS [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 → bbX 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 pT 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 $B^+ \rightarrow K_S^0 \pi^+$ and $B^+ \rightarrow K_S^0 K^+$ decays are formed by combining a $K_S^0 \rightarrow \pi^+ \pi^-$ 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 $K_S^0$ decays are required to have momentum $p > 2$ GeV/c, $\chi^2_{pT} > 9$, and track segments in the VELO and in the downstream tracking chambers. The $\chi^2_{pT}$ is defined as the difference in $\chi^2$ of a given PV reconstructed with and without the considered particle. The $K_S^0$ candidates have $p > 8$ GeV/c, $p_T > 0.8$ GeV/c, a good quality vertex fit, a mass within ±15 MeV/c² 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 (DLLx,κ). A track is identified as a pion (kaon) if DLLx,π < DLLx,κ < 3, DLLx,π > 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 $D^+ \rightarrow D^0 K^−$ 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 $p_T > 1$ GeV/c and $\chi^2_{pT} > 2$.

The B candidates are required to have the scalar $p_T$ sum of the $K_S^0$ and the $\pi^+(or\ K^+)$ candidates that exceeds 4 GeV/c, to have $\chi^2_{pT} < 10$ 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 ($K_S^0$ or $\pi^+(or\ K^+)$) with the larger $p_T$ is required to have an impact parameter above 50 μm. The angle $\theta_{dir}$ between the B candidate’s line of flight and its momentum is required to be less than 32 mrad. Background for $K_S^0$ candidates is further reduced by requiring the $K_S^0$ decay vertex to be significantly displaced from the reconstructed B decay vertex along the beam direction (z-axis), with $S_z \equiv (z_k - z_B)/\sqrt{\sigma_{z_k}^2 + \sigma_{z_B}^2} > 2$, where $\sigma_{z_k}$ and $\sigma_{z_B}$ are the uncertainties on the z positions of the $K_S^0$ and B decay vertices $z_k$ 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 $\chi^2_{pT}$ of the $K_S^0$ and $\pi^+(or\ K^+)$ candidates; $p_T \cos(\theta_{dir})$. $\chi^2_{pT}$ of the B candidates is defined as the difference in $\chi^2$ of fits in which the $B^+$ decay vertex is constrained to coincide with the PV or not; and the imbalance of $p_T$, $A_{pT} \equiv ((p_T(B) - \sum p_T)/((p_T(B) + \sum p_T)$ where the scalar $p_T$ 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 $p_T$ imbalance than typical b-hadron decays. The background training samples are taken from the upper invariant mass sideband region in data (5450 < m_k < 5800 MeV/c²), while those of the signal are taken from simulated $B^+ \rightarrow K_S^0 \pi^+$ and $B^+ \rightarrow K_S^0 K^+$ 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 $K_S^0 \pi^+$ and $K_S^0 K^+$ candidates 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 (Q) is performed independently for the $K_S^0 \pi^+$ and $K_S^0 K^+$ samples by evaluating the signal significance $N_S/\sqrt{N_S + N_B}$, where $N_S$ (N_B) denotes the expected number of signal (background) candidates. The predicted effective pollution from mis-identified $B^+ \rightarrow K_S^0 \pi^+$ decays in the $B^+ \rightarrow K_S^0 K^+$ signal mass region is taken into account in the calculation of $N_B$. The expected signal significance is maximised by applying $Q > 0.4$ (0.8) for $B^+ \rightarrow K_S^0 \pi^+$ ($B^+ \rightarrow K_S^0 K^+$) decays.

3. Asymmetries and signal yields

The CP-summed $B^+ \rightarrow K_S^0 K^+$ and $B^+ \rightarrow K_S^0 \pi^+$ yields are measured together with the raw charge asymmetries by means of a simultaneous unbinned extended maximum likelihood fit to the B candidate mass distributions of the four possible final states ($B^+ \rightarrow K_S^0 \pi^+$ and $B^+ \rightarrow K_S^0 K^+$). Five components contribute to each of the mass distributions. The signal is described by the sum...
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 simula-
tion, fixed to be 0.43 times that of the Gaussian distribution, which
is left free in the fit.

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

Partially reconstructed decays, coming mainly from \( B^0 \) and \( B^+ \)
(labelled \( B \) in this section), and \( B_s^0 \) meson decays to open charm
and to a lesser extent from three-body charmless \( B \) and \( B_s^0 \) 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 \( m_B - m_\pi \) for \( B(B_s^0) \) decays,
convolved with a Gaussian distribution of width 20 MeV/c^2
to account for detector resolution effects. Backgrounds from \( A_s^0 \)
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 \( B^+ \to \bar{K}_S^0 K^+ (B^+ \to \bar{K}_S^0 \pi^+) \) events reconstructed and
selected as \( K_S^0 \pi^+ (K_S^0 \pi^+) \) with respect to \( K_S^0 \pi^+ (K_S^0 \pi^+) \) are \( 0.245 \pm 0.018 \) \((0.0418 \pm 0.0067)\), where the uncertainties are dominated
by the finite size of the simulated samples. These numbers ap-
pear 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 system-
atic uncertainty. The CP-summed \( B^+ \to \bar{K}_S^0 \pi^+ \) and \( B^+ \to \bar{K}_S^0 K^+ \)
signal yields are found to be \( N(B^+ \to \bar{K}_S^0 \pi^+) = 1804 \pm 47 \) and
\( N(B^+ \to \bar{K}_S^0 K^+) = 90 \pm 13 \), with raw CP asymmetries \( A_{\text{raw}}(B^+ \to \bar{K}_S^0 \pi^+) = -0.32 \pm 0.025 \) and \( A_{\text{raw}}(B^+ \to \bar{K}_S^0 K^+) = -0.23 \pm 0.14 \). 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
\[
\frac{\mathcal{B}(B^+ \to \bar{K}_S^0 K^+)}{\mathcal{B}(B^+ \to \bar{K}_S^0 \pi^+)} = \frac{N(B^+ \to \bar{K}_S^0 K^+)}{N(B^+ \to \bar{K}_S^0 \pi^+)} \cdot r_{\text{sel}} \cdot r_{\text{PID}},
\]
where the ratio of selection efficiencies is factorised into two terms
representing the particle identification,
\[
r_{\text{PID}} \equiv \frac{\varepsilon_{\text{PID}}(B^+ \to \bar{K}_S^0 \pi^+)}{\varepsilon_{\text{PID}}(B^+ \to \bar{K}_S^0 K^+)},
\]
and the rest of the selection,
\[
r_{\text{sel}} \equiv \frac{\varepsilon_{\text{sel}}(B^+ \to \bar{K}_S^0 \pi^+)}{\varepsilon_{\text{sel}}(B^+ \to \bar{K}_S^0 K^+)}. \tag{4}
\]
The raw CP asymmetries of the \( B^+ \to \bar{K}_S^0 \pi^+ \) and \( B^+ \to \bar{K}_S^0 K^+ \)
decays are corrected for detection and production asymmetries

![Figure 1](image-url)
\(A_{\text{det+prod}}\) as well as for a small contribution due to CP violation in the neutral kaon system \((A_{\text{K}^0_s})\). The latter is assumed to be the same for both \(B^+ \rightarrow K^0_s \pi^+\) and \(B^+ \rightarrow K^0_s \bar{K}^+\) decays. At first order, the \(B^+ \rightarrow K^0_S \pi^+ \) CP asymmetry can be written as

\[
A^{\text{CP}}(B^+ \rightarrow K^0_S \pi^+) \approx A_{\text{raw}}(B^+ \rightarrow K^0_S \pi^+ ) - A_{\text{det+prod}}(B^+ \rightarrow K^0_S \pi^+) + \Delta K^0_S,
\]

and similarly for \(B^+ \rightarrow K^0_S \bar{K}^+\), up to a sign flip in front of \(\Delta K^0_S\).

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 \(r_{\text{sel}} = 1.111 \pm 0.019\), 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 \(B^+ \rightarrow K^0_S \pi^+\) and \(B^+ \rightarrow K^0_S \bar{K}^+\) simulated events are Reweighted by a linear function of the \(\bar{B}\)-meson momentum such that the average \(\bar{B}\) 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 \(B^+ \rightarrow K^0_S \pi^+\) 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 \(D^{+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+\) decays is used to measure the trigger efficiency in bins of \(p_T\) for pions and kaons from signal decays. This trigger efficiency is averaged using the \(p_T\) 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 \(D^{+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+\) 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 \(B^+ \rightarrow K^0_S K^+\) and \(B^+ \rightarrow K^0_S \bar{K}^+\) decays. The ratio of efficiencies is \(r_{\text{PID}} = 1.154 \pm 0.025\), 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 \(B^+ \rightarrow K^0_S K^+\) and \(B^+ \rightarrow K^0_S \pi^+\) 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 \(B^+ \rightarrow K^0_S K^+\) 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 \(B^+ \rightarrow J/\psi K^+\) 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 \(A(B^+ \rightarrow J/\psi K^+) = (-1.4 \pm 0.1\%)\) within 20 MeV/c² 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 \(B^+ \rightarrow K^0_S \pi^+\) and \(B^+ \rightarrow K^0_S \bar{K}^+\) 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 \(B^+ \rightarrow J/\psi K^0\) decays is \(A^{\text{CP}}(B^+ \rightarrow J/\psi K^0) = (+0.5 \pm 0.3\%)\), where the value is the weighted average of the values from Refs. [25] and [30]. This leads to a correction of \(A_{\text{det+prod}}(B^+ \rightarrow K^0_S K^+) = (-1.9 \pm 0.6\%)\). The combined production and detection asymmetry for \(B^+ \rightarrow K^0_S \pi^+\) decays is expressed as \(A_{\text{det+prod}}(B^+ \rightarrow K^0_S \pi^+) = (-0.9 \pm 0.8\%)\).

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 \(K^0\) component through interactions of a \(K^0\) 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 \(B^+ \rightarrow K^0_S \pi^+\) 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 \(A_{K^0_S} = (0.1 \pm 0.2\%)\). A summary of the sources of systematic uncertainties and corrections to the CP asymmetries is given in Table 1. Total systematic uncertainties are calculated as the sum in quadrature of the individual contributions.

5. Search for \(B^+_c \rightarrow K^0_S K^+\) decays

An exploratory search for \(B^+_c \rightarrow K^0_S K^+\) decays is performed with the data sample collected in 2013, corresponding to an integrated luminosity of 1.0 fb⁻¹. The same selection as for the \(B^+ \rightarrow K^0_S K^+\) decays is used, only adding a proton veto DLL_{PR} < 10 to the \(K^+\) daughter, which is more than 99% efficient. This is implemented to reduce a significant background from baryons in the
The upper limit tainty.
The signal distribution. The 20% correction applied to match the ground has an exponential slope. A similar procedure is used to evaluate the biases in the fit procedure and the systematic uncertainties are presented in Fig. 2 (left). Pseudo-experiments are used to evaluate flat. The invariant mass distribution and the superimposed fit resolution in data. The combinatorial background is assumed to value obtained from simulation to take into account the worse systematic uncertainties are included in the construction of the 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 \( B^+ \to K^0_S K^+ \) yield is also evaluated with the 2011 data only. The \( B^+ \) signal yield is determined by fitting a single Gaussian distribution with the mean fixed to the \( B^+ \) 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 \( r_{B^+} = (f_c \cdot \mathcal{B}(B^+ \to K^0_S K^+) / (f_u \cdot \mathcal{B}(B^+ \to K^0_S \pi^+)) \) to the measured number of signal events, and where \( f_c \) and \( f_u \) are the hadronisation fraction of a b into \( B^+ \) and \( B^+ \) 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

![Fig. 2](left) Invariant mass distribution of selected \( B_c^+ \to K^0_S K^+ \) candidates. Data are points with error bars and the curve represents the fitted function. (Right) The number of events and the corresponding value of \( r_{B^+} \). 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 \( r_{B^+} \) for the observed number of 2.8 events.

| Source                   | \( B \) ratio | \( \mathcal{A}^{CP} B^+ \to K^0_S K^+ \) | \( \mathcal{A}^{CP} B^+ \to K^0_S \pi^+ \) | \( B^+ \) |
|-------------------------|---------------|----------------------------------|----------------------------------|----------|
| \( A_{\text{det}, \text{prod}} \) | -             | -0.9                             | -1.9                             | -        |
| \( A_{\text{K}} \)      | -             | 0.1                              | 0.1                              | -        |
| Selection               | 1.8           | -                                | -                                | 6.1      |
| Trigger                 | 0.1           | 0.5                              | 0.5                              | 1.1      |
| Particle identification | 2.7           | -                                | -                                | 3.6      |
| Fit model               | 4.9           | -                                | -                                | 2.0      |
| \( A_{\text{det}, \text{prod}} \) | -             | 0.8                              | 0.6                              | -        |
| \( A_{\text{K}} \)      | -             | 0.2                              | 0.2                              | -        |
| Total syst. uncertainty | 6.0           | 1.0                              | 0.8                              | 7.4      |

This is the first upper limit on a \( B^+_c \) meson decay into two light quarks.

### 6. Results and summary

The decays \( B^+ \to K^0_S K^+ \) and \( B^+ \to K^0_S \pi^+ \) 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

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

\[
\mathcal{A}^{CP}(B^+ \to K^0_S K^+) = -0.022 \pm 0.025 \text{ (stat.)} \pm 0.010 \text{ (syst.)},
\]

and

\[
\mathcal{A}^{CP}(B^+ \to K^0_S \pi^+) = -0.21 \pm 0.14 \text{ (stat.)} \pm 0.01 \text{ (syst.)}.
\]

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

\[
f_c \cdot \frac{\mathcal{B}(B^+_c \to K^0_S K^+)}{\mathcal{B}(B^+ \to K^0_S \pi^+)} < 5.8 \times 10^{-2} \text{ at 90% confidence level}
\]

is obtained. Assuming \( f_c \simeq 0.001 \) [13], \( f_u = 0.33 \) [25,37,38], and \( B(\bar{B}^+ \to \bar{K}^0 \pi^+) = (23.97 \pm 0.53 \text{ (stat.)} \pm 0.71 \text{ (syst.)}) \times 10^{-6} \) [12], an upper limit \( B(\bar{B}^+_c \to \bar{K}^0 K^+) < 4.6 \times 10^{-4} \) 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.

### Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national
agencies: CAPES, CNPq, FAPERJ and FINENP (Brazil); NSFC (China); CNRS/IN2P3 and Region Auvergne (France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); SCSR (Poland); MEN/IFA (Romania); MiniEoS, Rosatom, RFBR and NRC “Kurchatov Institute” (Russia); MinECo, XuntaGal and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (United Kingdom); NSF (USA). We also acknowledge the support received from the EKC under FP7. The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom). We are thankful for the computing resources put at our disposal by Yandex LLC (Russia), as well as to the communities behind the multiple open source software packages that we depend on.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References

[1] N. Cabibbo, Unitary symmetry and lepton decays, Phys. Rev. Lett. 10 (1963) 53.
[2] M. Kobayashi, T. Maskawa, CP-violation in the renormalizable theory of weak interaction, Prog. Theor. Phys. 49 (1973) 652.
[3] R. Fleischer, New strategies to extract $\beta$ and $\gamma$ from $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$, Phys. Lett. B 459 (1999) 306, arXiv:hep-ph/9903436.
[4] M. Gronau, J.L. Rosner, The role of $B_s \to K\gamma$ in determining the weak phase $\gamma$, Phys. Lett. B 482 (2000) 71, arXiv:hep-ph/0003119.
[5] H.J. Lipkin, Is observed direct CP violation in $B_s \to K^+\pi^-$ due to new physics? Check Standard Model prediction of equal violation in $B_s \to K^+\pi^-$, Phys. Lett. B 621 (2005) 126, arXiv:hep-ph/0503022.
[6] R. Fleischer, $B_{s,d} \to \pi\pi, K^0K^0$: status and prospects, Eur. Phys. J. C 52 (2007) 267, arXiv:0705.1121.
[7] R. Fleischer, R. Kneijens, In pursuit of new physics with $B^0 \to K^+K^-$, Eur. Phys. J. C 71 (2011) 1532, arXiv:1011.096.
[8] A.J. Buras, R. Fleischer, S. Recksiegel, New physics in $B \to \pi K$ and implications for rare $K$ and $B$ decays, Phys. Lett. B 52 (2004) 101804, hep-ph/0312259.
[9] S. Hayakawa, Y. Hidaka, S. Ito, Is there still a puzzle?, Phys. Lett. B 653 (2007) 249, arXiv:hep-ph/0701181.
[10] T. Sjostrand, M. Asttrup, P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 7 (2009) 101804, arXiv:0801.0546.
[11] T. Sjostrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 7 (2011) 1011805, arXiv:1002.2240.
[12] L. Breiman, J.H. Friedman, Classification and regression trees, Wadsworth international group, Belmont, California, USA, 1984.

LHCb Collaboration

R. Aaij 40, B. Adeeva 36, M. Adinolfi 45, C. Adrover 6, A. Affolder 51, Z. Ajaltouni 5, J. Albrecht 9, F. Alessio 37, M. Alexander 50, S. Ali 40, G. Alkhazov 29, P. Alvarez Cartelle 36, A.A. Alves Jr 24,37, S. Amato 2, S. Amerio 21, Y. Amhis 7, L. Anderlini 17,18, J. Anderson 39, R. Andreassen 56, J.E. Andrews 57, R.B. Appleby 43, O. Aquines Gutierrez 10, F. Archilli 18, A. Artamonov 34, M. Artuso 58, E. Aslanides 6, G. Auriemma 24,31, M. Baalouch 5, S. Bachmann 11, J.J. Back 47, C. Baesso 59, V. Balagora 30, W. Baldini 16, R.J. Barlow 53, C. Barschel 37, S. Barsuk 7, W. Barter 46, Th. Bauer 40, A. Bay 38, J. Beddow 50, F. Bedeschi 22, I. Bediaga 1, S. Belogurov 30, K. Belous 14, I. Belyaev 40, E. Ben-Haim 19, G. Bencivenni 18, S. Benson 49, J. Benton 45, A. Berezhnoy 31, R. Bernet 39, M.-O. Bettler 46, M. van Beuzekom 40, A. Bien 11, S. Bifani 44, T. Bird 53, A. Bizzeti 17, P.M. Bjørnstad 53.
