Flavor-untagged angular analysis of $B^0_d \to J/\psi K^*$ and $B^0_s \to J/\psi \phi$ decays

The LHCb Collaboration

Abstract

Using the data sample recorded with the LHCb detector in 2010 we perform a combined angular and decay time analysis of the two decays $B^0_d \to J/\psi K^*$ and $B^0_s \to J/\psi \phi$ where, in the analysis, we do not distinguish between the different flavour states of the initial $B$ meson. The data correspond to an integrated luminosity of about 36 pb$^{-1}$ and was taken at the LHC at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. A total of $(2631 \pm 66)$ $B^0_d \to J/\psi K^*$ signal candidates and $(571 \pm 25)$ $B^0_s \to J/\psi \phi$ signal candidates are used to extract the polarisation amplitudes and the corresponding strong phases for both decays. For the decay $B^0_s \to J/\psi \phi$ also the $B^0_s$ decay width $\Gamma_s$ and the decay width difference $\Delta \Gamma_s$ have been determined, $\Gamma_s = (0.680 \pm 0.034_{\text{stat}} \pm 0.027_{\text{syst}})$ ps$^{-1}$ and $\Delta \Gamma_s = (0.084 \pm 0.112_{\text{stat}} \pm 0.021_{\text{syst}})$ ps$^{-1}$. The latter results have been obtained constraining the mixing phase $\phi_s$ to zero.

\footnote{Conference report prepared for LaThuile 2011, LaThuile, Aosta Valley, Italy. Contact authors: M. Needham and U. Uwer.}
1 Introduction

Neutral B mesons ($B^0_d$, $B^0_s$) exhibit the phenomenon of particle-antiparticle mixing, that is, transitions between the two flavour eigenstates $B^0_q$ and $\bar{B}^0_q$. As a consequence, the flavour eigenstates $B^0_q$ and $\bar{B}^0_q$ are not equal to the mass eigenstates, which are usually denoted by $B^H$ and $B^L$. In the Standard Model, CP violation in mixing is small and the two mass eigenstates of the $B^0_q$ mesons are to a good approximation pure CP eigenstates.

For the $B^0_s$ meson, the light mass eigenstate is expected to be the CP-even state with a larger decay width and a shorter lifetime than the heavy mass state. By measuring decays with known CP content it is possible to disentangle the two decay widths $\Gamma_L$ and $\Gamma_H$, and to determine the decay width difference $\Delta\Gamma_q = \Gamma_L - \Gamma_H$, which for the $B^0_s$ meson is found to be several percent of the mean decay rate $[1, 2, 3, 4]$. The decay width difference is negligible for the $B^0_d$ meson.

The decays $B^0_s \to J/\psi \phi$ and $B^0_d \to J/\psi K^*$ which are discussed in this document are both pseudo-scalar to vector-vector transitions. Both decays are described by three decay time dependent decay amplitudes corresponding to transitions in which the $J/\psi$ and $\phi$ (or $K^{*0}$) have a relative orbital momentum $L$ of 0, 1, or 2. In the transversity formalism $[5]$, the initial amplitudes at time $t = 0$, $A_0(0)$ and $A_\parallel(0)$ describe the decays with $L = 0, 2$ while $A_\perp(0)$ describes the $L = 1$ final states. The arguments of these complex amplitudes are strong phases denoted $\delta_0$, $\delta_\parallel$ and $\delta_\perp$. Only two amplitudes and two strong phases are independent. We choose the convention:

- $\delta_0 = 0$, $\delta_\parallel = \arg(A_\parallel(0)A_0^*(0))$ and $\delta_\perp = \arg(A_\perp(0)A_0^*(0))$,
- $|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2 = 1$.

For the decays $B^0_s \to J/\psi \phi$ and $B^0_d \to J/\psi K^*$ an analysis of the decay products is required to disentangle, statistically, the three angular distributions. The three final state decay angles are given by $\Omega = \{\cos \theta, \phi, \cos \psi\}$ as shown in Figure 1. In the coordinate system of the $J/\psi$ rest frame the transversity polar and azimuthal angles ($\theta, \phi$) describe the direction of the $\mu^+$. In the rest frame of the $\phi$ meson ($K^*$ meson respectively), $\psi$ is the angle between the two momentum vectors $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$.

For the analysis discussed here, the fully reconstructed decays $B^0_d \to J/\psi K^*$ (with $J/\psi \to \mu^+\mu^-$ and $K^{*0} \to K^+\pi^-$) and $B^0_s \to J/\psi \phi$ (with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$) and their charge conjugates are used to measure the polarisation amplitudes. In both cases only the final state is analysed and we do not determine the flavour of the initial B meson (untagged analysis).

In the decay $B^0_s \to J/\psi \phi$ the observed final state has a definite CP-value depending on the relative orbital angular momentum of the two vector mesons. The decay widths and thus the decay width difference $\Delta\Gamma_s$ of the $B^0_s$ mass eigenstates can be determined by measuring the three angular distributions as a function of the $B^0_s$ proper time. Ignoring

\footnote{Where the $\phi$ or the $K^*$ and B meson move in the x direction, the z axis is perpendicular to the decay plane of $\phi \to K^+K^-$ ($K^* \to K^+\pi^-$), and $p_y(K^+) > 0$.}
Figure 1: Angle definition for the decay $B^0_s \rightarrow J/\psi\phi$ and $B^0_d \rightarrow J/\psi K^*$: $\theta$ is the angle formed by the positive lepton ($\ell^+$) and the $z$ axis in the $J/\psi$ rest frame. The angle $\varphi$ is the azimuthal angle of $\ell^+$ in the same frame. In the $\phi \rightarrow K^+ K^-$ meson rest frame ($K^* \rightarrow K^+ \pi^-$ meson rest frame respectively) $\psi$ is the angle between $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$.

Both direct CP violation and CP violation in mixing, the summed differential decay distributions of produced $B^0_s$ and $\bar{B}^0_s$ mesons are described by the time and angular dependent differential decay width:

$$\frac{d^4\Gamma}{dtd\Omega} \propto |A_0(t)|^2 \cdot f_1(\Omega) + |A_\parallel(t)|^2 \cdot f_2(\Omega) + |A_\perp(t)|^2 \cdot f_3(\Omega) + \Re(A_0(t)A_\parallel(t)) \cdot f_5(\Omega) + \Im(A_0(t)A_\parallel(t)) \cdot f_6(\Omega).$$  \hspace{1cm} (1)

The bilinear combinations of the time-dependent amplitudes $A_i(t)$ are functions of the total decay width $\Gamma_s$, the decay width difference $\Delta\Gamma_s$ and the mixing phase $\phi_s$. They are given in the appendix together with the angular dependent functions $f_i(\Omega)$. For a vanishing mixing phase $\phi_s$ the differential decay rate for $B^0_s \rightarrow J/\psi\phi$ simplifies to

$$\frac{d^4\Gamma}{dtd\Omega} = e^{-\Gamma_s t}[|A_0(0)|^2 f_1(\Omega)e^{-\frac{\Delta\Gamma_s}{2} t} + |A_\parallel(0)|^2 f_2(\Omega)e^{-\frac{\Delta\Gamma_s}{2} t} + |A_\perp(0)|^2 f_3(\Omega)e^{\frac{\Delta\Gamma_s}{2} t} + \cos \delta_\parallel |A_0(0)||A_\parallel(0)|f_5(\Omega)e^{-\frac{\Delta\Gamma_s}{2} t}].$$  \hspace{1cm} (2)

For the decay $B^0_d \rightarrow J/\psi K^*$ the final state is flavour specific, with the kaon charge identifying the flavour of the decaying neutral B meson. This decay channel provides a valuable control sample since it occurs via similar (parity-odd and parity-even) decay amplitudes which are already well measured \[3, 6, 7, 8\]. Summing over the initially produced $B^0_d$ and $\bar{B}^0_d$ mesons and assuming $\Delta\Gamma_d = 0$ yields the following differential decay...
rate:

\[
\frac{d^4 \Gamma}{d t d \Omega} = e^{-\Gamma_d t} \left[ f_1(\Omega)|A_0(0)|^2 + f_2(\Omega)|A_(0)|^2 + f_3(\Omega)|A_{\perp}(0)|^2 \\
\pm f_4(\Omega) \sin (\delta_{\perp} - \delta_{\parallel}) |A_0(0)||A_{\perp}(0)| \\
+ f_5(\Omega) \cos \delta_{||} |A_0(0)||A_{||}(0)| \\
\pm f_6(\Omega) \sin \delta_{\perp} |A_0(0)||A_{\parallel}(0)| \right].
\]

(3)

Here the upper (lower) sign is used for \( K^+\pi^- (K^-\pi^+) \) in the final state and \( \Gamma_d \equiv 1/\tau_{B_0^d} \) is the total decay width of the \( B_0^d \) meson. In contrast to the \( B^0_s \) decays the flavour specific \( B_0^d \) decays provide access to both strong phases, \( \delta_{\parallel} \) and \( \delta_{\perp} \).

This note presents the measurement of the polarisation amplitudes \( A_{\parallel}(0), A_{\perp}(0) \) and the related strong phases \( \delta_{\parallel} \) and \( \delta_{\perp} \) for the decay \( B_0^d \rightarrow J/\psi K^* \). For the decay \( B^0_s \rightarrow J/\psi \phi \) the measurement of the \( B^0_s \) average decay width \( \Gamma_s \), the decay width difference \( \Delta \Gamma_s \), and polarisation amplitudes \( A_{\parallel}(0) \) and \( A_{\perp}(0) \) together with the strong phase \( \delta_{\parallel} \) is presented. The measurements exploit a data sample corresponding to an integrated luminosity of 36 pb⁻¹ collected with the LHCb detector in the course of the year 2010 at a centre-of-mass energy of \( \sqrt{s} = 7 \) TeV. In this article we use the convention \( \hbar = c = 1 \).

2 LHCb Detector, data sample and event selection

2.1 LHCb detector and trigger

The LHCb detector is a forward spectrometer described in detail in Ref. [9]. For the data included in this analysis all detector components were fully operational and in stable operation conditions.

The data were collected using two different lines of the Level-0 (L0) hardware trigger: the single-muon line which requires one muon candidate with a transverse momentum \( p_T > 1.4 \) GeV, and the dimuon line, which requires two muon candidates with \( p_T > 0.56 \) GeV and \( p_T > 0.48 \) GeV, respectively. The L0 trigger output is further processed by a two stage software trigger (HLT). The first stage, HLT1, performs a partial event reconstruction and confirms or discards the L0 trigger decision. The second stage, HLT2, performs a full event reconstruction with a subsequent event selection.

The HLT1 and HLT2 trigger lines can be separated into two categories. The first set of trigger lines, \textit{decay time unbiased}, are designed to be fully efficient for all B meson decay times. The second set of trigger lines, referred to as \textit{decay time biased} lines, use decay time dependent track properties, such as the track impact parameter, and are not fully efficient for small B meson decay times. In this analysis only events collected with the \textit{decay time unbiased} HLT lines are used.

2.2 Event selection

The event selection for the two decay channels, \( B_0^d \rightarrow J/\psi K^* \) and \( B^0_s \rightarrow J/\psi \phi \), is kept as similar as possible. It was developed to keep the distortions of the proper decay time and
angular acceptances small. The event selection follows closely the selection developed in Ref. [5].

\( J/\psi \to \mu^+\mu^- \) selection. For both decay channels the \( J/\psi \to \mu^+\mu^- \) meson decay is selected in a common way. Two muon candidates with a minimum \( p_T > 0.5 \) GeV are required to form a common vertex with a \( \chi^2 \)-value of the vertex fit \( \chi^2/n_{DOF} < 11 \). The significance of the invariant dimuon mass\(^3\) was required to be less than 4.2. For the subsequent calculation of the reconstructed B mass a constraint of the reconstructed \( J/\psi \) mass to the nominal value is used.

\( K^{*0} \to K^+\pi^- \) and \( B^0_d \to J/\psi K^* \) selection. The \( K^{*0} \to K^+\pi^- \) selection requires two well reconstructed tracks one of which is positively identified as a charged kaon. The two tracks should form a common vertex (\( \chi^2_{vtx}/n_{DOF} < 16 \)) and the reconstructed invariant (\( K,\pi \)) mass should be within \( \pm 70 \) MeV of the nominal \( K^{*0} \) mass. The transverse momentum of the reconstructed \( K^{*0} \) should be larger than 1 GeV. The \( K^{*0} \) is combined with the \( J/\psi \) candidate. The combination is accepted as a \( B^0_d \) candidate if the \( \chi^2 \) of the vertex fit is less than five and if the transverse momentum of the \( B^0_d \) candidate is larger than 2 GeV. Only events with a reconstructed mass of the \( B^0_d \) candidate \( m_B \in [5100,5450] \) MeV are considered.

\( \phi \to K^+K^- \) and \( B^0_s \to J/\psi \phi \) selection. The \( \phi \to K^+K^- \) selection requires two well reconstructed tracks, both positively identified as a charged kaon. The two tracks should form a common vertex (\( \chi^2_{vtx}/n_{DOF} < 16 \)) and the reconstructed invariant (\( K^+,K^- \)) mass should be within \( [1008,1032] \) MeV. The transverse momentum of the reconstructed \( \phi \) should be larger than 1 GeV. The \( \phi \) is combined with the \( J/\psi \) candidate. The combination is accepted as a \( B^0_s \) candidate if the \( \chi^2 \) of the vertex fit is less than 5. No cut is applied on the \( B^0_s \) transverse momentum. Only events with a reconstructed mass of the \( B^0_s \) candidate \( m_B \in [5200,5550] \) MeV are considered.

Primary vertex association. Due to the high pile-up conditions in the 2010 data-taking events contain, on average, 2.1 reconstructed primary vertices. Each B candidate is associated to the primary vertex for which the impact parameter \( \chi^2 \) is minimised. To reduce the fraction of wrongly associated primary vertices it is required that the impact parameter \( \chi^2 \) of the B to the second best matching primary vertex be greater than 50\(^4\). This requirement removes the majority of the events in the tail of the proper time distribution but keeps the signal events with correctly associated primary vertex with an efficiency of 94%.

\(^3\) Defined as \( |m_{J/\psi}(\text{reco}) - m_{J/\psi}(\text{PDG})|/\sigma_{m_{J/\psi}} \), with \( \sigma_{m_{J/\psi}} \) being the mass resolution.

\(^4\)
Multiple B candidates. In the case there are multiple B candidates per event only the candidate with the smallest vertex $\chi^2_{vtx}/n_{DoF}$ is kept. It has been checked that candidates removed by this criteria are either duplicates of the selected candidate or are consistent with combinatorial background.

Selected events. After applying the above selection criteria a large combinatorial background remains at low reconstructed B proper decay time $t$. To remove these events a selection cut $t > 0.3$ ps is applied. For the $B^0_d \rightarrow J/\psi K^*$ sample 3909 (7526) candidates with proper times above $t > 0.3$ ps are found in the B mass window $[5234, 5324]$ MeV, $([5100, 5450]$ MeV), resulting in a signal-over-background ratio (S/B) of 3.4 in a $\pm 3\sigma$ mass window. The $B^0_s \rightarrow J/\psi \phi$ sample is cleaner. In the considered mass window $([5200, 5550]$ MeV) we select in total 578 candidates with a S/B of 12.5 in a $3\sigma$ mass window. Figures 2 and 3 show the reconstructed B mass distribution and the distribution of the reconstructed $J/\psi$ masss versus the reconstructed B mass of the selected $B^0_d \rightarrow J/\psi K^*$ and $B^0_s \rightarrow J/\psi \phi$ candidates respectively.

![Figure 2: Reconstructed B mass distribution (left) and reconstructed J/ψ mass versus reconstructed B mass (right) for the selected B^0_d → J/ψK^* candidates. A cut on the reconstructed proper time of the candidates t > 0.3 ps is applied. The plot on the right shows the signal window used to fit the physics parameters and the mass sidebands used for the determination of the background shape (red). The green boxes indicate the area used for the study of the non-J/ψ background.](image)

2.3 Monte Carlo samples

The Monte Carlo samples used for this analysis are based on the PYTHIA 6.4 generator [11]. The EvtGen [12] package was used to generate hadron decays, in particular $J/\psi$ and $b$-hadrons, and the GEANT4 package [13] is used to simulate the detector response.

In the $B^0$ ($B^0_s$) case there are 1.5 (1.1) candidates per event in the full time range and the mass range $5100$ MeV < $m_B$ < $5450$ MeV ($5200$ MeV < $m_{B^*}$ < $5550$ MeV).
Figure 3: Reconstructed $B_s^0$ mass distribution (left) and reconstructed $J/\psi$ mass versus reconstructed $B_s^0$ mass (right) for the selected $B_s^0 \to J/\psi\phi$ candidates. A cut on the reconstructed proper time of the candidates $t > 0.3$ ps is applied. The plot on the right shows in addition the mass sidebands (red) used for the determination of the background shape.

3 Extraction of the physics parameters

The physics parameters of interest are extracted from the data by performing an unbinned maximum likelihood fit of the probability density function (PDF) based on the theoretical prediction to the measured $B$ mass $m$, the proper time $t$ and the transversity angles $\Omega = \{\cos \theta, \varphi, \cos \psi\}$.

The theory prediction depends on a set of physics parameters $\lambda_{\text{Phys}}$ which differ slightly for the two decay modes discussed in this document. For a comparison with data, detector resolution effects described by the parameter set $\lambda_{\text{Det}}$, the time and angular acceptance $\epsilon(t, \Omega)$ of the detector, and backgrounds (parameterised by $\lambda_{\text{Bkg}}$) need to be taken into account.

The likelihood function for $N$ events can be written as:

$$\mathcal{L} = \prod_{e}^{N} \mathcal{P}(\{m, t, \Omega\}_e; \epsilon, \lambda_{\text{Phys}}, \lambda_{\text{Det}}, \lambda_{\text{Bkg}})$$

(4)

where the probability density function (PDF) $\mathcal{P}$ consists of a signal part $\mathcal{S}$ and a background component $\mathcal{B}$:

$$\mathcal{P} = f_{\text{sig}} \mathcal{S} + (1 - f_{\text{sig}}) \mathcal{B}$$

(5)

The parameter $f_{\text{sig}}$ denotes the signal fraction. Assuming a factorisation of the mass dependent PDF components and the components depending on the proper time and the transversity angles one can rewrite the PDF as:

$$\mathcal{P} = f_{\text{sig}} \mathcal{S}(m; \lambda_{\text{Phys}}, \lambda_{\text{Det}}) \epsilon(t, \Omega) + (1 - f_{\text{sig}}) \mathcal{B}(m; \lambda_{\text{Bkg}}) \epsilon(t, \Omega)$$

(6)
3.1 Signal PDF

The expected theoretical distributions of the events as functions of the proper decay time \( t \) and the transversity angles \( \Omega \) are given by the differential decay widths of Eq. (2) and Eq. (3) for the decays \( B_s^0 \to J/\psi \phi \) and \( B_d^0 \to J/\psi K^* \) respectively. The physics parameters determined in the fit are:

\[
\begin{align*}
B_s^0 \to J/\psi \phi : & \quad \lambda_{\text{Phys}} = (\Gamma_s, \Delta \Gamma_s, |A_0(0)|^2, |A_{||}(0)|^2, |A_{\perp}(0)|^2, \cos \delta_{||}) \\
B_d^0 \to J/\psi K^* : & \quad \lambda_{\text{Phys}} = (\Gamma_d, |A_0(0)|^2, |A_{||}(0)|^2, |A_{\perp}(0)|^2, \delta_{||}; \delta_{\perp})
\end{align*}
\]

The mass dependence of the signal PDF \( S \) is modeled as a single Gaussian with width \( \sigma_m \) and mean \( m_B \):

\[
S(m; \lambda_{\text{Phys}}, \lambda_{\text{Det}}) = \frac{1}{\sqrt{2\pi}\sigma_m} e^{-\left(m-m_B\right)^2/(2\sigma_m^2)}.
\] (7)

The mass distribution is used to separate the signal and background contributions.

**Time and angular resolution.** To correctly take into account the finite proper time resolution of the detector the time dependent exponential terms in Eq. (2) and (3) are convolved with an empirical resolution model chosen to be the sum of three Gaussians [10].

The effect of the angular resolution on the transversity angle distributions has been studied with fully simulated events with similar resolutions to those seen in the data and has been found to be small [5]. The finite angular resolution is therefore ignored in the signal modeling.

**Angular and proper time acceptances** The geometrical acceptance of the LHCb detector and, to a lesser extent, the trigger and signal selection lead to non-uniform angular and proper time acceptance functions that have to be accounted for. We assume that proper time and angular acceptance corrections factorise. For the decay \( B_s^0 \to J/\psi \phi \) the possible effect of a non-flat proper time acceptance on the decay angle distributions is treated by the fit.

Simulation studies for the selected events show a non-flat proper time acceptance which can be parameterised [10] as:

\[
\epsilon(t) = 1 + \beta t
\] (8)

with \( \beta = -0.015 \text{ps}^{-1} (\beta = -0.025 \text{ps}^{-1}) \) for \( B_d^0 \to J/\psi K^* (B_s^0 \to J/\psi \phi) \). This non-flat proper time acceptance is accounted for in the fit procedure.

---

5 Eq (2) for \( B_s^0 \to J/\psi \phi \) explicitly assumes \( \phi_s = 0 \). As can be seen from Eq. (1), the untagged analysis provides some sensitivity to determine \( \phi_s \). For the default untagged analysis performed in this document \( \phi_s \) is fixed to zero in the fits. The possibility of floating \( \phi_s \) is discussed in Section 5.4.

For the \( B_d^0 \to J/\psi K^* \) a possible S-wave contribution is also considered when fitting the data. More details are given in Section 4.1.
Angular acceptance effects however are large \cite{14}. The acceptance correction $\epsilon(\Omega)$ is
determined using fully simulated Monte Carlo signal events. Two different approaches
are applied to implement the acceptance corrections into the fitting procedure:

1. The angular acceptance is described by a three-dimensional histogram
   $\mathcal{H}(\cos \theta, \varphi, \cos \psi)$

2. The angular acceptance is described by an analytical parametrisation.

Both approaches have been tested in different implementations of the fitting programs
and were found to give consistent results for the physics parameters.

The normalised 1-dimensional projection of the 3-dimensional acceptance corrections
as determined with fully simulated events are shown in Figure 4 for $B^0_d \rightarrow J/\psi K^*$ (left) and
for $B^0_s \rightarrow J/\psi \phi$ (right). For $B^0_s \rightarrow J/\psi \phi$ also the projections of the analytical description
using Legendre polynomials is shown.

### 3.2 Background description

Several different sources contribute to the observed background: Random combinations of
four tracks; Background from prompt $J/\psi$ events which are combined with random tracks;
Background due to long lived true $J/\psi$ decays from other $B \rightarrow J/\psi X$ decays; Long lived
combinatorial background where the two reconstructed muons do not originate from a
true $J/\psi$ decay.

The cut on the proper time at $t > 0.3$ ps removes most of the prompt background peak.
Therefore, detailed modeling of this component is not necessary. The two remaining long
lived components are modeled empirically by analysing the mass sidebands in data.

The PDF describing the background contribution factorises in a mass dependent, a
time dependent and an angular dependent part

$$B(m, t, \theta, \varphi, \psi; \lambda_{Bkg}) = B(m; \lambda_{Bkg}) B(t; \lambda_{Bkg}) B(\Omega).$$ (9)

The mass distribution of the background is described by an exponential function with
parameter $\alpha_{bkg}$,

$$B(m; \lambda_{Bkg}) = N_m e^{-\alpha_{bkg} m},$$ (10)

with $N_m$ denoting the factor needed for proper normalisation of the PDF component.

Two exponentials with lifetimes $\tau_{bkg,1}$ and $\tau_{bkg,2}$ describe the proper time distribution of
the long lived background events.

$$B(t; \lambda_{Bkg}) = f_{bkg}^1 \tau_{bkg,1} e^{-t/\tau_{bkg,1}} + (1 - f_{bkg}^1) \tau_{bkg,2} e^{-t/\tau_{bkg,2}}$$ (11)

The relative fraction of the two components with different proper times is given by the
parameter $f_{bkg}^1$.

The background events are correlated in the transversity angles and the angular de-
pendent background part $B(\Omega)$ therefore does not factorise for the three angles. Several
different approaches to describe the angular dependence have been studied:
• The analysis of the $B^0 \rightarrow J/\psi K^{*0}$ events uses a three-dimensional histogram which is is filled with background events from the $B^0_d$ mass sidebands.

• For the $B^0_s \rightarrow J/\psi \phi$ analysis an approach where the angular distribution of the background events from the sidebands is described with a set of Legendre polynomials.

• For $B^0_s \rightarrow J/\psi \phi$ also a flat background distribution has been studied.

• Parameterisations based on an s-weight technique [15] have been tested for the channel $B^0_s \rightarrow J/\psi \phi$. 
Figure 4: Normalised 1-dimensional projections of the 3D angular acceptance corrections for $B^0 \to J/\psi K^{*0}$ decays (left) and $B^0_s \to J/\psi \phi$ decays (right) as obtained from fully simulated Monte Carlo events. For the $B^0_s \to J/\psi \phi$ decays also the projection of the analytical description using Legendre polynomials is shown. Note that the vertical scales are zero suppressed.
4 Analysis of $B^0 \rightarrow J/\psi K^{*0}$ events

In this section the measurement of the polarisation amplitudes and strong phases of the decay $B^0_d \rightarrow J/\psi K^*$ is discussed. A 5-dimensional maximum likelihood fit as described in section 3 is performed for candidates in the mass window of $\pm 45$ MeV around the nominal B mass and is used to extract the physics parameters $\Gamma_d$, $|A_{\parallel}|^2$, $|A_{\perp}|^2$, $\delta_{\parallel}$ and $\delta_{\perp}$. The mass window contains in total 3909 candidates.

4.1 S-Wave contribution

For the channel $B^0_d \rightarrow J/\psi K^*$ it has been shown [7, 8, 16, 17] that a significant $(K, \pi)$ S-wave contribution is needed to describe the transversity angle distribution of the data. In particular the cos $\psi$ distribution is strongly affected by the interference between the S-wave amplitude and the P-wave components describing the vector resonance. In general the S-wave amplitude is dependent on $m_{K\pi}$, the invariant mass of the $(K, \pi)$ system. As the analysis in performed in the relatively narrow mass window of $\pm 70$ MeV around the nominal $K^*$ mass, we ignore the explicit mass dependence.

The implementation of the S-wave amplitude follows the prescription of the BABAR collaboration [17]. When an $(K\pi)$ S-wave in the B decay amplitude is included in addition to the $(K\pi)$ P-wave the differential decay rate, given in Eq. 3 and abbreviated here by $g(\Omega, A)$, becomes:

$$\frac{d\Gamma}{d\Omega} = \left[ g(\Omega, A) + |A_S|^2 f_7(\Omega) + f_8(\Omega) \Re(A_{\parallel}A^*_S) + f_9(\Omega) \Im(A_{\parallel}A^*_S) + f_{10}(\Omega) \Re(A_0A^*_S) \right],$$

(12)

where $A_S = |A_S| e^{i\phi_S}$ is the complex S-wave amplitude. The additional angular functions $f_7$ - $f_{10}(\Omega)$ are given in the appendix. P and S-wave component should sum to one, i.e. $|A_0|^2 + |A_{\perp}|^2 + |A_{\parallel}|^2 + |A_S|^2 = 1$. Note that for the S-wave contribution in the absence of direct CP violation $A_S = +A_S$.

4.2 Background shape determination

As the $K^*$ resonance is relatively broad the background contribution to the selected $B^0_d \rightarrow J/\psi K^*$ events is significant. In the $\pm 45$ MeV signal mass window used for the determination of the polarisation amplitudes (indicated in Fig. 2 by the inner red lines), the background fraction is about 33% of the events and is composed mainly from events with a correctly reconstructed long-lived $J/\psi$ (98.6%) mostly from other B decay channels. The remaining background fraction of 1.4% are from events without a correct $J/\psi$ (non-$J/\psi$). For the extraction of the physics parameters the two background categories are described by as a single background PDF. The angular and lifetime shape of the background PDF is determined using events from the B mass sidebands which are are

---

6 A study of fully simulated and selected background events from other B decay channels showed within the available event statistic a smooth background shape.
defined as \([m_B - 170; m_B - 45]\) MeV (lower sideband) and \([m_B + 45; m_B + 100]\) MeV (upper sideband) and indicated in Figure 2. The reduced upper sideband is chosen to exclude background from \(B \rightarrow J/\psi K^+\) decays which are not explicitly rejected and which have reconstructed B masses above the upper sideband boundary. The angular and lifetime distributions of the background events in the lower and upper sidebands are compatible within their statistical errors. This justifies the usage of the sideband events to describe the background PDF.

4.3 Physics parameter extraction

The 5-dimensional fit to extract the polarisation amplitudes and strong phases of the selected \(B_0^d \rightarrow J/\psi K^*(K\pi)\) events also accounts for a possible S-wave contribution to the selected events. Angular and lifetime acceptance corrections, see section 3.1, and the description of the background (\(J/\psi\) and non-\(J/\psi\)) which is obtained from the sidebands are included into the PDF.

When analysing simulated \(B_0^d \rightarrow J/\psi K^*\) events it was found that a fraction of the selected candidates are not correctly reconstructed. While the \(J/\psi\) and K candidates can be assigned to the corresponding particle at the generator level the assigned pion differ from the true particle. A part of these events have a B mass distribution similar to the signal but differs significantly in the transversity angles. The events, in the following referred as \(wrong-signal\), are treated in the fit as an additional background component with a floating fraction. The mass and transversity angle distribution of theses events are taken from the simulation.

<table>
<thead>
<tr>
<th>parameter</th>
<th>results S-wave</th>
<th>results no S-wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>A_\parallel</td>
<td>^2</td>
</tr>
<tr>
<td>(</td>
<td>A_\perp</td>
<td>^2</td>
</tr>
<tr>
<td>(\delta_\parallel</td>
<td>\quad -2.87 \pm 0.11 \quad -2.82 \pm 0.12</td>
<td></td>
</tr>
<tr>
<td>(\delta_\perp</td>
<td>\quad 3.02 \pm 0.10 \quad 3.07 \pm 0.09</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>A_s</td>
<td>^2</td>
</tr>
<tr>
<td>(\delta_s</td>
<td>\quad 2.16 \pm 0.15 \quad -</td>
<td></td>
</tr>
<tr>
<td>(\Gamma_d \ [\text{ps}^{-1}]</td>
<td>\quad 0.659 \pm 0.015 \quad 0.661 \pm 0.015</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Results of the fit to the selected \(B_0^d \rightarrow J/\psi K^*\) events with and without an S-wave component included. Only statistical errors are shown.

The fit determines a total of \((2630.8 \pm 66.0)\) signal events. Table I lists the results of the fit for the physics parameters together with their statistical errors. An S-wave component of \(5 \pm 2\%\) is found. The 1-dimensional projections of the 5-dimensional fit function arex compared to the measured data in Figure 5.

As the PDF is invariant under the simultaneous transformation \((\delta_\parallel \rightarrow -\delta_\parallel)\) and
(\delta_\perp \to \pi - \delta_\perp) the strong phases exhibit an ambiguity. The choice in Table 1 follows the conventions of earlier measurements.

**Fit without S-wave component.** As a cross-check a fit ignoring the S-wave component is performed. The results for the physics parameters and their statistical errors are also given in Table 1. The projections of the fitted PDFs compared to the data are shown in Figure 6.

While the extracted physics parameters agree well with values obtained in the fit with S-wave component, the cos \psi distribution is no longer well described by the fitted PDF. The missing S-wave interference terms in the signal description leads to a clear deviation between data and the fitted prediction.

### 4.4 Systematic uncertainties

The systematic uncertainties assigned to the polarisation amplitudes and their strong phases are summarised in Table 2. The total systematic uncertainty, listed in the last line, is the quadratic sum of the individual contributions which have been determined as follows.

| Systematic effect                  | \|A||^2 | \|A_\perp||^2 | \|\delta|| | \|\delta_\perp|| |
|-----------------------------------|-------|---------------|----------|-----------|
| proper time acceptance            | -     | -             | -        | -         |
| data/MC differences               | 0.008 | 0.006         | 0.07     | 0.05      |
| statistical error of acceptance   | 0.002 | 0.001         | -        | 0.01      |
| wrong-signal fraction             | 0.004 | 0.001         | -        | 0.01      |
| background treatment              | 0.002 | 0.008         | 0.04     | 0.01      |
| statistical error of background   | 0.008 | 0.005         | 0.02     | 0.01      |
| mass model                        | 0.010 | 0.002         | 0.01     | 0.01      |
| s-wave treatment                  | 0.001 | 0.013         | 0.05     | 0.05      |
| total (quadratic sum)             | 0.016 | 0.017         | 0.10     | 0.07      |

Table 2: Summary of the systematic uncertainties assigned to the polarisation amplitudes and strong phases of the $B^0 \to J/\psi K^{*0}$ decay.

**Proper time resolution.** To assess the influence of the proper time resolution model the nominal results are compared to fit results in which the assumed time resolution is increased by 50 %.

**Proper time acceptance.** The systematic effect of the lifetime acceptance correction ($\beta = -0.015$) was estimated by using the full size of the correction as uncertainty, i.e. fits are performed with $\beta = 0.000$ and $\beta = -0.030$. Differences are only observed for the value of $\Gamma$. All other physics parameters are unchanged.
Angular acceptance correction. The angular acceptance correction is determined from the simulation. To estimate possible systematic effects from an imperfect description of detector acceptance by the simulation on the extracted physics parameters, the fit was performed using acceptance corrections obtained with “reweighted” MC events. The reweighting is done for all kinematical variables which do not show a perfect agreement between data and MC and which have an influence on the angular acceptance. The difference between the physics parameters extracted with the “nominal acceptance corrections” and the “reweighted acceptance corrections” is assigned as systematic error associated with the reweighted variable. The total uncertainty of the acceptance related to data/MC differences is calculated as quadratic sum of the single components and is also listed in Table 2.

To check possible systematic effects due to the statistical uncertainty of the acceptance corrections, each bin of the acceptance histogram is smeared independently with a Gaussian function with an width corresponding to the statistical error of the corresponding bin. The fit result using this “smeared” acceptance are compared to the nominal results. The difference is assigned as systematic error.

Background description and modeling. For the estimation of the wrong-signal background we entirely rely on the fit and the Monte Carlo description. To estimate the uncertainties related to this background component we change the fraction of the wrong-signal background when extracting the physics parameters. The effect on the physics parameters is shown in Table 2.

The systematic uncertainty related to the background description has been estimated by replacing the background histogram by a description using Legendre polynomials.

Similar to the statistical uncertainty of the acceptance calculation due to limited MC statistic there is also an statistical uncertainty of the background shape determination. This uncertainty is studied by varying the background histogram according to the statistical error in each bin and extracting the physics parameters.

Mass model. The mass description in the PDF of the fit is changed from a single to a double Gaussian and the parameter extraction repeated. The differences to the nominal fit are treated as systematic error.

S-wave treatment. The systematics of the S-wave extraction has not been studied in detail. We assign a preliminary uncertainty to the physics parameters which is estimated by the full difference between the parameters extracted with and without using an S-wave component in the fit.

$B_d^0$-$\bar{B}_d^0$-Production asymmetry. In pp-collisions at the LHC, $B_d^0$ and $\bar{B}_d^0$ are not necessarily produced in equal quantities. Small production asymmetries ($\mathcal{O}(1\%)$) are expected. The effect of a production asymmetry of 1% has been studied and found to be negligible compared to the other systematic effects.
Figure 5: Fitted PDF with S-wave included projected on the reconstructed $B$ mass, the lifetime and the transversity angles compared to the data distributions for the selected $B^0 \rightarrow J/\psi K^{*0}$ candidates. Shown are the total PDF, the PDFs for signal (blue), S-wave (green), total background (red) and wrong-signal (purple).
Figure 6: Fitted PDF without S-wave component included projected on the reconstructed B mass, the lifetime and the transversity angles compared to the data distributions for the selected $B^0 \to J/\psi K^{*0}$ candidates. Shown are the total PDF, the PDFs for signal (blue), S-wave (green), total background (red) and wrong-signal (purple).
5 Untagged Analysis of $B_s^0 \rightarrow J/\psi \phi$

This section discusses the determination of the $B_s^0$ decay width $\Gamma_s$, the decay width difference $\Delta \Gamma_s$ and the polarisation amplitudes together with the strong phase $\delta_\parallel$ for the decay $B_s^0 \rightarrow J/\psi \phi$. No distinction between the two initial flavour states of the produced $B_s^0$ mesons is done which is referred as untagged analysis.

The unbinned maximum likelihood fit to extract the physics parameters is described in section 3. All selected 778 $B_s^0 \rightarrow J/\psi \phi$ candidates with a reconstructed B mass in the range $5200 \text{ MeV} < M_{B_s^0} < 5550 \text{ MeV}$ are used in the fit.

The dependence of the differential decay width according to Eq. (1) on the $B_s^0$ mixing phase $\phi_s$ provides in principle sensitivity to the mixing phase $\phi_s$ also for the untagged $B_s^0 \rightarrow J/\psi \phi$ measurement. In particular there is sensitivity for New Physics for the case of large values of $\sin \phi_s$. However, with the present data set this sensitivity does not provide useful constraints on the mixing phase.

As the physics parameters which are extracted in the fit depend upon the value of $\phi_s$ this is constrained to zero (close to the Standard Model prediction of -0.036) when performing point estimates of the physics parameters in section 5.2. Two-dimensional probability contours in the $(\Delta \Gamma_s, \phi_s)$-plane are provided for the case that the mixing phase $\phi_s$ is left free in the fit in section 5.4.

5.1 Background shape determination

The background fraction in the selected $B_s^0 \rightarrow J/\psi \phi$ candidates is much smaller than for the $B_d^0 \rightarrow J/\psi K^*$ channel. In a mass window of ±22 MeV (±3σ of the mass resolution) the signal-to-background ratio is about 12.5. The small background is due to the usage of particle identification for both kaons and the narrow width of the $\phi$ resonance.

Figure 3 shows the 2-dimensional distribution of the reconstructed $B_s^0$ and $J/\psi$ masses for the selected candidates. The background consists mainly of events with a correctly reconstructed $J/\psi$, mostly from other B decay channels and an additional small non-$J/\psi$ background. As in the case of the $B_d^0 \rightarrow J/\psi K^*$ the background is described in the fit by a single background PDF. The lifetime and transversity angle shape of the background PDF is determined using events in the B mass sidebands given by $[5200 \text{ MeV}, m_{B_s^0} - 45 \text{ MeV}]$ and $[m_{B_s^0} + 45 \text{ MeV}, 5500 \text{ MeV}]$ and described analytically by a series of Legendre polynomials. The angular and lifetime distributions of the background events from lower and upper sidebands are compatible within their statistical errors which justifies the usage of the sideband events to determine the background PDF. Assuming a flat angular background dependence gives compatible results for the physics parameters.

7 A study of fully simulated selected background events from other B decay channels gave, within the available statistics, a smooth background shape.
5.2 Physics parameter extraction with $\phi_s$ constrained to zero

In the 5-dimensional fit to extract $\Gamma_s$, $\Delta\Gamma_s$ and the polarisation amplitudes the mixing phase $\phi_s$ is fixed to zero. The PDF includes the angular and lifetime acceptance corrections of section 3.1 and the background description obtained from the events in the B mass sidebands. The fit uses all $B^0_s \rightarrow J/\psi\phi$ candidates in the mass window $5200\text{ MeV} < M_{B^0_s} < 5550\text{ MeV}$. A total of $(571.2 \pm 24.5)$ signal events are found.

Table 3 lists the results of the fit for the physics parameters and their statistical errors. The 1-dimensional projections of the 5-dimensional fit function are compared to the measured data in Figure 7.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_s \ [\text{ps}^{-1}]$</td>
<td>$0.680 \pm 0.034$</td>
</tr>
<tr>
<td>$\Delta\Gamma_s \ [\text{ps}^{-1}]$</td>
<td>$0.084 \pm 0.112$</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\cos \delta_\parallel$</td>
<td>$-1.24 \pm 0.27$</td>
</tr>
</tbody>
</table>

Table 3: Results from the fit (untagged analysis) to the $B^0_s \rightarrow J/\psi\phi$ data set. Only statistical errors are shown.

Two-dimensional likelihood contour: The two-dimensional likelihood contour plot for the parameters $(\Gamma_s, \Delta\Gamma_s)$ is shown in Figure 8. The contour is obtained using the “profile likelihood method”. For every grid point a likelihood fit is performed in which $(\Gamma_s, \Delta\Gamma_s)$ are fixed to the grid point and all other parameters are floating. The log-likelihood difference $(\Delta \ln L)$ to the nominal fit is assigned to the grid point. The regions corresponding to confidence levels of 68.3, 90, 95 and 99% are given by the grid points for which $2\Delta \ln L \leq 2.30, 4.61, 5.99$ and 9.21 respectively.

5.3 Systematic uncertainties

The systematic uncertainties assigned to the extracted physics parameters are summarised in Table 4. The total systematic uncertainty, listed in the last line, is the quadratic sum of the individual contributions which have been determined as follows.

Proper time resolution. To assess the influence of the proper time resolution model the nominal results are compared to a fit where the assumed time resolution was increased by 50%. The resulting systematic deviation is given in Table 4.

Angular acceptance. As in the $B^0 \rightarrow J/\psi K^{*0}$ analysis to account for a possible imperfect modeling of the detector acceptance by the simulation, the fit was performed
Table 4: Systematic uncertainties assigned to the extracted physics parameters of the decay \( B_0^s \rightarrow J/\psi \phi \).

| Systematic effect               | \( \Gamma_s \) [ps\(^{-1}\)] | \( \Delta \Gamma_s \) [ps\(^{-1}\)] | \( |A_\perp(0)|^2 \) | \( |A_\parallel(0)|^2 \) | \( \cos \delta \) |
|---------------------------------|-------------------------------|-------------------------------|-----------------|-----------------|----------------|
| Proper time resolution          | 0.0001                        | -                             | -                | -                | -               |
| Angular acceptance              | -                             | -                             | -                | 0.0007           | -               |
| Acceptance parametrisation      | 0.0002                        | 0.001                         | 0.0017           | 0.0013           | -               |
| Proper time acceptance          | 0.0272                        | 0.001                         | 0.0003           | 0.0002           | -               |
| S-wave treatment                | 0.003                         | 0.003                         | 0.013            | 0.028            | 0.09            |
| Background treatment            | 0.0002                        | 0.02                           | 0.0016           | 0.0012           | -               |
| Mass model                      | 0.0004                        | 0.004                         | 0.0032           | 0.0006           | -               |
| Total (quadratic sum)           | 0.0274                        | 0.0206                        | 0.0136           | 0.0281           | 0.09            |

using acceptance corrections obtained with “reweighted” Monte Carlo events as described in section 4.4. The only variable for which this procedure is applied in case of the \( B_0^s \rightarrow J/\psi \phi \) channel is the muon momentum as it is the only distribution which exhibits a possible data/MC discrepancy. The absolute deviations between the two fits is taken as systematic uncertainty.

Additionally, we studied the effect of a statistical variation of the Monte Carlo simulated data from which we derive our acceptance description. All bins are varied within their statistical uncertainty and the analytic parametrisation is determined afterwards. We take the absolute deviation of every physics parameter as systematic uncertainty.

**Proper time acceptance.** The systematic effect of the lifetime acceptance correction \( (\beta = -0.025) \) is estimated by using the full size of the correction as uncertainty, i.e. a fit is performed with \( \beta = 0.000 \) and the full differences of the physics parameters are taken as systematic uncertainty.

**Effect of S-wave component.** The influence of an possible S-wave component on the extraction of physics parameters in the \( B_0^s \rightarrow J/\psi \phi \) mode is discussed in [18] and [19]. With the present data set it is not possible to fit for an S-wave component. Instead a conservative systematic uncertainty determined from a simulation study is assigned. In this study 1000 data sets each containing 6000 events which are generated assuming a S-wave component of 6.7\% and a relative phase of \( \pi/2 \) with respect to \( \delta_0 \) [2, 20] are simulated and fitted using the signal PDF which ignores the S-wave. The deviation of the parameters determined in these fits with respect to the values used in the generation are taken as estimate of the effect of ignoring the S-wave component.

**Background modeling.** To determine the influence of the background model the fit was repeated with the assumption of a flat angular background distribution. The devia-
tions of the parameters with respect to the fit results obtained when using the background description from the sidebands described by Legendre polynomials are taken as systematic uncertainties.

**Mass model.** The influence of the signal mass model is checked by performing a fit modeling the signal contribution as a double Gaussian. The deviations to the fit using the nominal single Gaussian mass model are taken as systematic uncertainties due to modeling of the signal mass distribution.

**B\(_s^0\)-\(\bar{B}\(_s^0\)-Production asymmetry.** From the study which was performed for the \(B\(_d\rightarrow J/\psi K^*\) we conclude that the effect of the \(B\(_s^0\)-\(\bar{B}\(_s^0\)-production asymmetry on the extracted physics parameters is negligible with respect to other systematic uncertainties.

### 5.4 Fit results with \(\phi_s\) unconstrained

In Figure 9 (top) we show the 2-dimensional Likelihood scan in the \((\Delta \Gamma_s, \phi_s)\)-plane where a 4-fold ambiguity is visible. Whilst it is clear that there is no constraint on \(\phi_s\) from the untagged analysis presented here, one can limit \(\Delta \Gamma_s\) in the case that \(\phi_s\) is left free in the fit.

For low statistics the likelihood projection method can lead to a significant under-coverage. Therefore we also provide confidence contours using the Feldman-Cousins method \[21\] which provides correct coverage by construction. This method determines the confidence contours in the \((\phi_s, \Delta \Gamma_s)\) plane by repeatedly generating and fitting simplified simulation data sets for every grid point. For every generated data sample two fits are performed, one with \(\phi_s\) and \(\Delta \Gamma_s\) fixed to the values at the grid point given by \(\phi'_s\) and \(\Delta \Gamma'_s\) and one fit which leaves these two parameters free. Each simulated data set therefore results in a likelihood ratio \(LR_{\text{toy}} = -2 \ln \left( \frac{L_{\text{toy}}(\phi'_s, \Delta \Gamma'_s, \lambda^*)}{L_{\text{toy}}(\hat{\phi}_s, \hat{\Delta \Gamma}_s, \hat{\lambda})} \right)\), where \(\lambda\) denotes the remaining physics parameters which are varied in the fit. At every grid point the \(p\)-value is given by the fraction of simulated data sets which have a larger \(LR_{\text{toy}}\) value than the data sample at this point (LR\(_{\text{Data}}\)). A given confidence contour is defined by C.L. = 1 − \(p\). Confidence contours obtained from a Feldman-Cousins study performed using 1000 generated Monte Carlo data sets at every grid point are shown in Figure 9 (bottom).}

---

8 A change of \(\phi_s\) by \(\pi\) leads to the interchange of \(\Gamma_L \leftrightarrow \Gamma_H\) which is equivalent to a change of sign of \(\Delta \Gamma_s\).

9 Since the systematic uncertainties (nuisance parameters) are small compared to the statistical ones, only statistical uncertainties are included in the coverage adjustment of the confidence region \[22\].
Figure 7: Fitted PDF projected on the reconstructed B mass, the lifetime and the transversity angles compared to the data distributions for the selected $B^0 \rightarrow J/\psi \phi$ candidates. Shown are the total PDF, the PDFs for signal, the PDFs for the CP-even and CP-odd signal components and the total background PDF.
Figure 8: Likelihood contours for the parameters \((\Gamma_s, \Delta\Gamma_s)\) with \(\phi_s = 0\) fixed. The 68.3, 90, 95 and 99% confidence level contours are shown.
Figure 9: **Top:** Likelihood confidence contours for parameters \((\Delta \Gamma_s, \phi_s)\) with \(\phi_s\) as free fit parameter. The 68, 90, 95 and 99% confidence level contours are shown. **Bottom:** Confidence contours in the \((\Delta \Gamma_s, \phi_s)\)-plane derived using the Feldman-Cousins method. For each grid point 1000 toy studies have been performed to determine the probability. The 68, 90 and 95% confidence level contours are shown.
6 Summary and conclusion

The data used in this analysis were recorded with the LHCb detector at the LHC in the year 2010 at a centre-of-mass energy $\sqrt{s} = 7$ TeV. The data sample corresponds to an integrated luminosity of $36 \text{ pb}^{-1}$ of $pp$ collisions.

The polarisation amplitudes and their respective strong phases have been measured for the decay $B_0^d \rightarrow J/\psi K^*$. Using $(2631 \pm 66)$ signal events we find the following results for the transversity amplitudes and strong phases,

$$ |A_\parallel(0)|^2 = 0.252 \pm 0.020 \pm 0.016, $$

$$ |A_\perp(0)|^2 = 0.178 \pm 0.022 \pm 0.017, $$

$$ \delta_\parallel = -2.87 \pm 0.11 \pm 0.10, $$

$$ \delta_\perp = 3.02 \pm 0.10 \pm 0.07, $$

where the first error is the statistical error from the 5-dimensional fit and the second error is the systematic uncertainty according to Table 2.

Within errors the LHCb results agree with earlier measurements [3, 6, 7, 8] though with uncertainties that are a factor of 2 larger.

By using $(571 \pm 25)$ signal events for the decay $B_s^0 \rightarrow J/\psi \phi$ the $B_s^0$ decay width $\Gamma_s$ and the decay width difference $\Delta \Gamma_s$ as well as the transversity amplitudes have been measured. The following results are obtained:

$$ \Gamma_s = 0.680 \pm 0.034 \pm 0.027 \text{ ps}^{-1}, $$

$$ \Delta \Gamma_s = 0.084 \pm 0.112 \pm 0.021 \text{ ps}^{-1}, $$

$$ |A_\perp(0)|^2 = 0.279 \pm 0.057 \pm 0.014, $$

$$ |A_0(0)|^2 = 0.532 \pm 0.040 \pm 0.028, $$

$$ \cos \delta_\parallel = -1.24 \pm 0.27 \pm 0.09, $$

where the first error is the statistical error from the fit and the second error is the systematic uncertainty according to Table 4.

Within their errors the results agree with earlier measurements [1, 2, 3, 4].

Although the LHCb results are not yet competitive with the best measurements, the presented results show that the analysis procedures are well established and ready to analyse a larger data sample. A significant improvement of the LHCb statistical and systematic uncertainties is expected in 2011.
References


[2] The CDF Collaboration. An Updated Measurement of the CP Violating Phase $\beta_s^{J/\psi\phi}$ in Decays $B_s^0 \rightarrow J/\psi \phi$ using 5.2 fb$^1$ of Integrated Luminosity. CDF public note 10206.


[4] The D0 Collaboration. Updated combined D0 results on $\Delta \Gamma_s$ versus CP-violating phase $\phi_s^{J/\psi\phi}$. D0 Conference Note 6093.


[6] CDF Collaboration. Angular Analysis of $B_s \rightarrow J/\psi \phi$ and $B^0 \rightarrow J/\psi K^{*0}$ Decays and Measurement of $\Delta \Gamma_s$ and $\phi_s$. CDF public note 8950.


[9] A.A. Alves Jr. et. al. (The LHCb collaboration). The LHCb detector at the LHC. JINST, 3(S08005), 2008.


Appendix

Definition of amplitudes and angular functions

The bilinear combinations of the time-dependent amplitudes $A_i(t)$ in Eq. [1] are functions of the total decay width $\Gamma_s$, the decay width difference $\Delta \Gamma_s$ and the mixing phase $\phi_s$. They are defined (see Ref. [5]) as:

$$|A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma_s}{2} t \right) \right]$$

$$|A_\parallel(t)|^2 = |A_\parallel(0)|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma_s}{2} t \right) \right]$$

$$|A_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s}{2} t \right) + \cos \phi_s \sinh \left( \frac{\Delta \Gamma_s}{2} t \right) \right]$$

$$\Im \left( A_\parallel^*(t) A_\perp(t) \right) = |A_\parallel(0)| |A_\perp(0)| e^{-\Gamma_s t} \left[ -\cos (\delta_\perp - \delta_\parallel) \sin \phi_s \sinh \left( \frac{\Delta \Gamma_s}{2} t \right) \right]$$

$$\Re \left( A_0^*(t) A_\parallel(t) \right) = |A_0(0)| |A_\parallel(0)| e^{-\Gamma_s t} \cos \delta_\parallel \left[ \cosh \left( \frac{\Delta \Gamma_s}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma_s}{2} t \right) \right]$$

$$\Im \left( A_0^*(t) A_\perp(t) \right) = |A_0(0)| |A_\perp(0)| e^{-\Gamma_s t} \left[ -\cos \delta_\perp \sin \phi_s \sinh \left( \frac{\Delta \Gamma_s}{2} t \right) \right]$$

The angular dependent functions $f_i(\Omega)$ in the partial decay rates are given by:

$$f_1(\Omega) = \frac{9}{32 \pi} 2 \cos^2 \psi \left( 1 - \sin^2 \theta \cos^2 \varphi \right)$$

$$f_2(\Omega) = \frac{9}{32 \pi} \sin^2 \psi \left( 1 - \sin^2 \theta \sin^2 \varphi \right)$$

$$f_3(\Omega) = \frac{9}{32 \pi} \sin^2 \psi \sin^2 \theta$$

$$f_4(\Omega) = -\frac{9}{32 \pi} \sin^2 \psi \sin 2\theta \sin \varphi$$

$$f_5(\Omega) = \frac{9}{32 \pi \sqrt{2}} \sin 2\psi \sin^2 \theta \sin 2\varphi$$

$$f_6(\Omega) = \frac{9}{32 \pi \sqrt{2}} \sin 2\psi \sin 2\theta \cos \varphi$$

For the description of S-wave contribution considered in the analysis of the $B^0_d \to J/\psi K^*(K\pi)$ events the definition of the additional angular functions $f_{7,8,9,10}(\Omega)$ follows the prescription of the BABAR experiment [17]:

27
\[ f_7(\Omega) = \frac{3}{32\pi} 2 \left[ 1 - \sin^2 \theta \cos^2 \phi \right] \]
\[ f_8(\Omega) = \frac{3}{32\pi} \sqrt{6} \sin \psi \sin^2 \theta \sin 2\phi \]
\[ f_9(\Omega) = \frac{3}{32\pi} \sqrt{6} \sin \psi \sin 2\theta \cos \phi \]
\[ f_{10}(\Omega) = \frac{3}{32\pi} 4\sqrt{3} \cos \psi \left[ 1 - \sin^2 \theta \cos^2 \phi \right] \]

As LHCb uses a different x-axis convention the sign of \( f_8(\Omega) \) is opposite to the BABAR definition.