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Time-dependent angular analysis of the decay $B_s^0 \to J/\psi\phi$ and extraction of $\Delta\Gamma_s$ and the CP-violating weak phase ϕ_s by ATLAS

The ATLAS Collaboration

Abstract

A measurement of $B_s^0 \to J/\psi\phi$ decay parameters, including the CP-violating weak phase ϕ_s and the decay width difference $\Delta\Gamma_s$ is reported, using $4.9\,\mathrm{fb}^{-1}$ of integrated luminosity collected in 2011 by the ATLAS detector from LHC pp collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV. The mean decay width Γ_s and the transversity amplitudes $|A_0(0)|^2$ and $|A_{\parallel}(0)|^2$ are also measured. The values reported for these parameters are:

$$
\begin{aligned}
\phi_s &= 0.22 \pm 0.41 \ (\mathrm{stat.}) \pm 0.10 \ (\mathrm{syst.})\ \mathrm{rad} \\
\Delta\Gamma_s &= 0.053 \pm 0.021 \ (\mathrm{stat.}) \pm 0.010 \ (\mathrm{syst.})\ \mathrm{ps}^{-1} \\
\Gamma_s &= 0.677 \pm 0.007 \ (\mathrm{stat.}) \pm 0.004 \ (\mathrm{syst.})\ \mathrm{ps}^{-1} \\
|A_0(0)|^2 &= 0.528 \pm 0.006 \ (\mathrm{stat.}) \pm 0.009 \ (\mathrm{syst.}) \\
|A_{\parallel}(0)|^2 &= 0.220 \pm 0.008 \ (\mathrm{stat.}) \pm 0.007 \ (\mathrm{syst.})
\end{aligned}
$$

where the values quoted for ϕ_s and $\Delta\Gamma_s$ correspond to the solution compatible with the external measurements to which the strong phase $\delta_{\perp}$ is constrained and where $\Delta\Gamma_s$ is constrained to be positive. The fraction of S-wave KK or f_0 contamination through the decays $B_s^0 \to J/\psi K^+K^-(f_0)$ is measured as well and is found to be consistent with zero. Results for ϕ_s and $\Delta\Gamma_s$ are also presented as 68%, 90% and 95% likelihood contours, which show agreement with Standard Model expectations.

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1 Introduction

New phenomena beyond the predictions of the Standard Model (SM) may alter CP violation in B-decays. A channel that is expected to be sensitive to new physics contributions is the decay $B_s^0 \to J/\psi\phi$. CP violation in the $B_s^0 \to J/\psi\phi$ decay occurs due to interference between direct decays and decays occurring through $B_s^0 - \overline{B_s^0}$ mixing. The oscillation frequency of B_s^0 meson mixing is characterized by the mass difference Δm_s of the heavy (B_H) and light (B_L) mass eigenstates. The CP-violating phase ϕ_s is defined as the weak phase difference between the $B_s^0 - \overline{B_s^0}$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude. In the absence of CP violation, the B_H state would correspond exactly to the CP-odd state and the B_L to the CP-even state. In the SM the phase ϕ_s is small and can be related to CKM quark mixing matrix elements via the relation $\phi_s \simeq -2\beta_s$, with $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$; a value of $\phi_s \simeq -2\beta_s = -0.0368 \pm 0.0018$ rad [1] is predicted in the SM. Many new physics models predict large ϕ_s values whilst satisfying all existing constraints, including the precisely measured value of Δm_s [2, 3].

Another physical quantity involved in $B_s^0 - \overline{B_s^0}$ mixing is the width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ of B_L and B_H. Physics beyond the SM is not expected to affect $\Delta\Gamma_s$ as significantly as ϕ_s [4]. Extracting $\Delta\Gamma_s$ from data is nevertheless useful as it allows theoretical predictions to be tested [4].

The decay of the pseudoscalar B_s^0 to the vector-vector final-state $J/\psi\phi$ results in an admixture of CP-odd and CP-even states, with orbital angular momentum $L = 0$, 1 or 2. The final states with orbital angular momentum $L = 0$ or 2 are CP-even while the state with $L = 1$ is CP-odd. No flavour tagging to distinguish between the initial B_s^0 and $\overline{B_s^0}$ states is used in this analysis; the CP states are separated statistically through the time-dependence of the decay and angular correlations amongst the final-state particles.

In this paper, measurements of ϕ_s, the average decay width $\Gamma_s = (\Gamma_L + \Gamma_H)/2$ and the value of $\Delta\Gamma_s$, using the fully reconstructed decay $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ are presented. Previous measurements of these quantities have been reported by the CDF and DØ collaborations [5, 6] and recently by the LHCb collaboration [7]. The analysis presented here uses data collected by the ATLAS detector from LHC pp collisions running at $\sqrt{s} = 7$ TeV in 2011, corresponding to an integrated luminosity of approximately 4.9 fb^{-1}.

2 ATLAS detector and Monte Carlo simulation

The ATLAS experiment [8] is a multipurpose particle physics detector with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic calorimeter. An iron/scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward regions are instrumented with LAr calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids with eight coils each, a system of tracking chambers, and detectors for triggering.

The muon and tracking systems are of particular importance in the reconstruction of B meson candidates. Only data where both systems were operating correctly and where the LHC beams were declared to be stable are used. The data were collected during a period of rising instantaneous luminosity at the LHC, and the trigger conditions varied over this time.

The triggers used to select events for this analysis are based on identification of a $J/\psi \to \mu^+\mu^-$ decay, with either a 4 GeV transverse momentum* (p_{T}) threshold for each muon or an asymmetric configuration that applies a higher p_{T} threshold $(4 - 10$ GeV$)$ to one of the muons and a looser muon-identification requirement (p_{T} threshold below 4 GeV) to the second one.

Monte Carlo (MC) simulation is used to study the detector response, estimate backgrounds and model systematic effects. For this study, 12 million MC-simulated $B_s^0 \to J/\psi\phi$

*The ATLAS coordinate system and the definition of transverse momentum are described in reference [8] events were generated using PYTHIA [9] tuned with recent ATLAS data [10]. No p_{T} cuts were applied at the generator level. Detector responses for these events were simulated using an ATLAS simulation package based on GEANT4 [11, 12]. In order to take into account the varying trigger configurations during data-taking, the MC events were weighted to have the same trigger composition as the collected collision data. Additional samples of the background decay $B^0 \to J/\psi K^{0*}$ as well as the more general $bb \to J/\psi X$ and $pp \to J/\psi X$ backgrounds were also simulated using PYTHIA.

3 Reconstruction and candidate selection

Events passing the trigger and the data quality selections described in section 2 are required to pass the following additional criteria: the event must contain at least one reconstructed primary vertex built from at least four ID tracks in order to be considered in the subsequent analysis; the event must contain at least one pair of oppositely charged muon candidates that are reconstructed using two algorithms that combine the information from the MS and the ID [13]. In this analysis the muon track parameters are taken from the ID measurement alone, since the precision of the measured track parameters for muons in the p_{T} range of interest for this analysis is dominated by the ID track reconstruction. The pairs of muon tracks are refitted to a common vertex and accepted for further consideration if the fit results in χ^2/d.o.f. < 10. The invariant mass of the muon pair is calculated from the refitted track parameters. To account for varying mass resolution, the J/ψ candidates are divided into three subsets according to the pseudorapidity η of the muons. A maximum likelihood fit is used to extract the J/ψ mass and the corresponding resolution for these three subsets. When both muons have $|\eta| < 1.05$, the di-muon invariant mass must fall in the range $(2.959 - 3.229)$ GeV to be accepted as a J/ψ candidate. When one muon has $1.05 < |\eta| < 2.5$ and the other muon $|\eta| < 1.05$, the corresponding signal region is $(2.913 - 3.273)$ GeV. For the third subset, where both muons have $1.05 < |\eta| < 2.5$, the signal region is $(2.852 - 3.332)$ GeV. In each case the signal region is defined so as to retain 99.8% of the J/ψ candidates identified in the fits.

The candidates for $\phi \to K^+K^-$ are reconstructed from all pairs of oppositely charged tracks with $p_{\mathrm{T}} > 0.5$ GeV and $|\eta| < 2.5$ that are not identified as muons. Candidates for $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ are sought by fitting the tracks for each combination of $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ to a common vertex. All four tracks are required to have at least one hit in the pixel detector and at least four hits in the silicon strip detector. The fit is further constrained by fixing the invariant mass calculated from the two muon tracks to the world average J/ψ mass [14]. These quadruplets of tracks are accepted for further analysis if the vertex fit has a χ^2/d.o.f. < 3, the fitted p_{T} of each track from $\phi \to K^+K^-$ is greater than 1 GeV and the invariant mass of the track pairs (under the assumption that they are kaons) falls within the interval 1.0085 GeV $< m(K^+K^-) <$ 1.0305 GeV. In total 131k B_s^0 candidates are collected within a mass range of $5.15 < m(B_s^0) < 5.65$ GeV used in the fit.

For each B_s^0 meson candidate the proper decay time t is determined by the expression:

$$t = \frac{L_{xy}\ M_B}{c\ p_{\mathrm{T}_B}},$$

where p_{T_B} is the reconstructed transverse momentum of the B_s^0 meson candidate and M_B denotes the world average mass value [14] of the B_s^0 meson (5.3663 GeV). The transverse decay length L_{xy} is the displacement in the transverse plane of the B_s^0 meson decay vertex with respect to the primary vertex, projected onto the direction of B_s^0 transverse momentum. The position of the primary vertex used to calculate this quantity is [14] refitted following the removal of the tracks used to reconstruct the B_s^0 meson candidate.

For the selected events the average number of pileup interactions is 5.6, necessitating a choice of the best candidate for the primary vertex at which the B_s^0 meson is produced. The variable used is a three-dimensional impact parameter d_0, which is calculated as the distance between the line extrapolated from the reconstructed B_s^0 meson vertex in the direction of the B_s^0 momentum, and each primary vertex candidate. The chosen primary vertex is the one with the smallest d_0. Using MC simulation it is shown that the fraction of B_s^0 candidates which are assigned the wrong primary vertex is less than 1% and that the corresponding effect on the final results is negligible. No B_s^0 meson lifetime cut is applied in the analysis.

4 Maximum likelihood fit

An unbinned maximum likelihood fit is performed on the selected events to extract the parameters of the $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay. The fit uses information about the reconstructed mass m, the measured proper decay time t, the measured mass and proper decay time uncertainties σ_m and σ_t, and the transversity angles Ω of each $B_s^0 \to J/\psi\phi$ decay candidate. There are three transversity angles; $\Omega = (\theta_T, \psi_T, \varphi_T)$ and these are defined in section 4.1.

The likelihood function is defined as a combination of the signal and background probability density functions as follows:

$$\begin{aligned}\ln\ \mathcal{L} = \sum_{i=1}^{N}\{w_i \cdot \ln(f_{\mathrm{s}} \cdot \mathcal{F}_{\mathrm{s}}(m_i, t_i, \Omega_i) + f_{\mathrm{s}} \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \Omega_i) \\ +(1 - f_{\mathrm{s}} \cdot (1 + f_{B^0}))\mathcal{F}_{\mathrm{bkg}}(m_i, t_i, \Omega_i))\} + \ln P(\delta_\perp)\end{aligned} \tag{4.1}$$

where N is the number of selected candidates, w_i is a weighting factor to account for the trigger efficiency (described in section 4.5), f_{s} is the fraction of signal candidates, f_{B^0} is the fraction of peaking B^0 meson background events (described in section 4.2) calculated relative to the number of signal events; this parameter is fixed in the likelihood fit. The mass m_i, the proper decay time t_i and the decay angles Ω_i are the values measured from the data for each event i. $\mathcal{F}_{\mathrm{s}}$, $\mathcal{F}_{B^0}$ and $\mathcal{F}_{\mathrm{bkg}}$ are the probability density functions (PDF) modelling the signal, the specific B^0 background and the other background distributions, respectively. $P(\delta_\perp)$ is a constraint on the strong phase $\delta_\perp$. A detailed description of the PDF functions and other terms in the equation 4.1 is given in sections 4.1 − 4.5.

4.1 Signal PDF

The PDF describing the signal events, $\mathcal{F}_s$, has the form of a product of PDFs for each quantity measured from the data:

$$\mathcal{F}_{\mathrm{s}}(m_i, t_i, \Omega_i) = P_{\mathrm{s}}(m_i|\sigma_{m_i}) \cdot P_{\mathrm{s}}(\sigma_{m_i}) \cdot P_{\mathrm{s}}(\Omega_i, t_i|\sigma_{t_i}) \cdot P_{\mathrm{s}}(\sigma_{t_i}) \cdot A(\Omega_i, p_{\mathrm{T}i}) \cdot P_{\mathrm{s}}(p_{\mathrm{T}i}) \tag{4.2}$$

The terms $P_{\mathrm{s}}(m_i|\sigma_{m_i})$, $P_{\mathrm{s}}(\Omega_i, t_i|\sigma_{t_i})$ and $A(\Omega_i, p_{\mathrm{T}i})$ are explained in the current section, and the remaining per-candidate uncertainty terms $P_{\mathrm{s}}(\sigma_{m_i})$, $P_{\mathrm{s}}(\sigma_{t_i})$ and $P_{\mathrm{s}}(p_{\mathrm{T}i})$ are described in section 4.4. Ignoring detector effects, the joint distribution for the decay time t and the transversity angles Ω for the $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay is given by the differential decay rate [15]:

$$\frac{d^4\Gamma}{dt\ d\Omega} = \sum_{k=1}^{10} \mathcal{O}^{(k)}(t) g^{(k)}(\theta_T, \psi_T, \varphi_T), \tag{4.3}$$

where $\mathcal{O}^{(k)}(t)$ are the time-dependent amplitudes and $g^{(k)}(\theta_T, \psi_T, \varphi_T)$ are the angular functions, given in table 1. The time-dependent amplitudes are slightly different for decays of mesons that were initially $\overline{B_s^0}$. As an untagged analysis is performed here, all B_s^0 meson candidates are assumed to have had an equal chance of initially being either a particle or anti-particle. This leads to a significant simplification of the time-dependent amplitudes as any terms involving the mass splitting Δm_s cancel out. These simplified time-dependent amplitudes are given in table 1. $A_\perp(t)$ describes a CP-odd final-state configuration while both $A_0(t)$ and $A_\parallel(t)$ correspond to CP-even final-state configurations. A_S describes the contribution of CP-odd $B_s \to J/\psi K^+K^-(f_0)$, where the non-resonant KK or f_0 meson is an S-wave state. The corresponding amplitudes are given in the last four lines of table 1 (k=7-10) and follow the convention used in previous analysis [7]. The likelihood is independent of the invariant KK mass distribution.

The equations are normalised such that the squares of the amplitudes sum to unity; three of the four amplitudes are fit parameters and $|A_\perp(0)|^2$ is determined according to this constraint.

The angles $(\theta_T, \psi_T, \varphi_T)$, are defined in the rest frames of the final-state particles. The x-axis is determined by the direction of the ϕ meson in the J/ψ rest frame, the K^+K^- system defines the xy plane, where $p_y(K^+) > 0$. The three angles are defined:

- θ, the angle between $p(\mu^+)$ and the xy plane, in the J/ψ meson rest frame
- φ, the angle between the x-axis and $p_{xy}(\mu^+)$, the projection of the μ^+ momentum in the xy plane, in the J/ψ meson rest frame
- ψ, the angle between $p(K^+)$ and $-p(J/\psi)$ in the ϕ meson rest frame

k	$\mathcal{O}^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \varphi_T)$
1	$\frac{1}{2}\|A_0(0)\|^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t}\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$
2	$\frac{1}{2}\|A_\parallel(0)\|^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t}\right]$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\varphi_T)$
3	$\frac{1}{2}\|A_\perp(0)\|^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t}\right]$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}\|A_0(0)\|\|A_\parallel(0)\|\cos\delta_{\|\|}$ $\left[(1+\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t}\right]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\varphi_T$
5	$\frac{1}{2}\|A_\parallel(0)\|\|A_\perp(0)\| \left(e^{-\Gamma_{\rm H}^{(s)}t} - e^{-\Gamma_{\rm L}^{(s)}t}\right)\cos(\delta_\perp - \delta_{\|\|})\sin\phi_s$	$\sin^2\psi_T\sin 2\theta_T\sin\varphi_T$
6	$-\frac{1}{2}\|A_0(0)\|\|A_\perp(0)\| \left(e^{-\Gamma_{\rm H}^{(s)}t} - e^{-\Gamma_{\rm L}^{(s)}t}\right)\cos\delta_\perp\sin\phi_s$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\varphi_T$
7	$\frac{1}{2}\|A_S(0)\|^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t}\right]$	$\frac{2}{3}\left(1-\sin^2\theta_T\cos^2\varphi_T\right)$
8	$-\frac{1}{2}\|A_S(0)\|\|A_\parallel(0)\| \left(e^{-\Gamma_{\rm H}^{(s)}t} - e^{-\Gamma_{\rm L}^{(s)}t}\right)\sin(\delta_\parallel - \delta_S)\sin\phi_s$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\varphi_T$
9	$\frac{1}{2}\|A_S(0)\|\|A_\perp(0)\|$ $\left[(1-\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t}\right]\sin(\delta_\perp - \delta_S)$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\varphi_T$
10	$-\frac{1}{2}\|A_0(0)\|\|A_S(0)\|\sin(-\delta_S)\left(e^{-\Gamma_{\rm H}^{(s)}t} - e^{-\Gamma_{\rm L}^{(s)}t}\right)\sin\phi_s$	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\varphi_T\right)$

Table 1. Table showing the ten time-dependent amplitudes, $\mathcal{O}^{(k)}(t)$ and the functions of the transversity angles $g^{(k)}(\theta_T, \psi_T, \varphi_T)$. The amplitudes $|A_0(0)|^2$ and $|A_\parallel(0)|^2$ are for the CP-even components of the $B_s^0 \to J/\psi\phi$ decay. $|A(0)_\perp|^2$ is the CP-odd amplitude. They have corresponding strong phases δ_0, $\delta_\parallel$ and $\delta_\perp$; by convention δ_0 is set to be zero. The S-wave amplitude $|A_S(0)|^2$ gives the fraction of $B_s^0 \to J/\psi K^+K^-(f_0)$ and has a related strong phase δ_S.

It can be seen from table 1, that in the untagged analysis used in this study the time-dependent amplitudes depending on $\delta_\perp$ ($\mathcal{O}^{(k)}(t), k = 5, 6$) are multiplied by $\sin\phi_s$. Previous measurement by LHCb ref. [7] showed that ϕ_s is close to zero $(0.15 \pm 0.18 \pm 0.06)$ rad. For such a small value of ϕ_s the untagged analysis is not sensitive to $\delta_\perp$. A Gaussian constraint to the best measured value, $\delta_\perp = (2.95 \pm 0.39)$ rad [7], is therefore applied by adding a Gaussian function term $P(\delta_\perp)$ into the likelihood fit.

The signal PDF, $P_{\rm s}(\Omega_i, t_i|\sigma_{t_i})$ must take into account the time resolution and thus each time-dependent element in table 1 is convoluted with a Gaussian function. This convolution is performed numerically on an event-by-event basis where the width of the Gaussian is the proper decay time uncertainty σ_{t_i}, multiplied by an overall scale factor to account for any mis-measurements.

The angular sculpting of the detector and kinematic cuts on the angular distributions is included in the likelihood function through $A(\Omega_i, p_{{\rm T}i})$. This is calculated using a four-dimensional binned acceptance method, applying an event-by-event efficiency according to the transversity angles $(\theta_T, \psi_T, \varphi_T)$ and the $p_{\rm T}$ of the B_s^0. The acceptance was calculated from the $B_s^0 \to J/\psi\phi$ MC events. In the likelihood function, the acceptance is treated as an angular sculpting PDF, which is multiplied by the time- and angular-dependent PDF describing the $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays. Consequently, the complete angular function must be normalised as a whole as both the acceptance and the time-angular decay PDFs depend on the transversity angles. This normalisation is performed numerically in the likelihood fit.

The signal mass PDF, $P_{\rm s}(m_i)$, is modelled as a single Gaussian function smeared with an event-by-event mass resolution σ_{m_i}, see figure 1, which is scaled using a factor to account for mis-estimation of the mass errors. The PDF is normalised over the range $5.15 < m(B_s^0) < 5.65$ GeV.

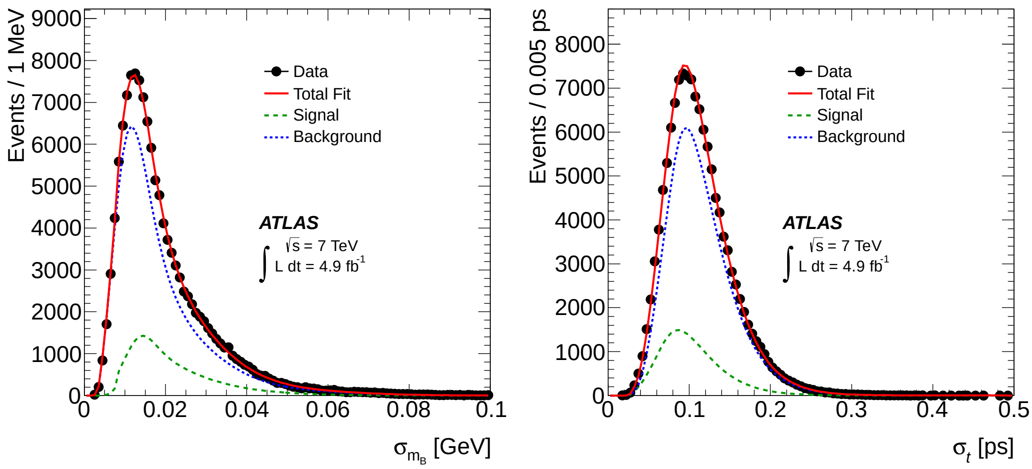

Figure 1. Left: mass uncertainty distribution for data, the fits to the background and the signal fractions and the sum of the two fits. Right: proper decay time uncertainty distribution for data, the fits to the background and the signal fractions and the sum of the two fits.

4.2 Specific B^0 background

The $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ sample is contaminated with mis-reconstructed $B^0 \to J/\psi K^*$ and $B^0 \to J/\psi K^+\pi^-$ (non-resonant) decays, where the final-state pion is misidentified as a kaon. The two components of the background are referred to as B^0 reflections, since the B^0 is reconstructed as a B_s^0 meson and therefore lies within the B_s^0 meson mass window rather than in the usual B^0 mass range. The fractions of these components are fixed in the likelihood fit to values $(6.5\pm2.4)\%$ and $(4.5\pm2.8)\%$ respectively. These values are calculated from the relative production fractions of the B_s^0 and B^0 mesons and their decay probabilities taken from the PDG values [14] and from their selection efficiencies, which are determined from MC events. The corresponding uncertainties are dominated by uncertainties in the decay probabilities.

Mis-reconstructed B^0 decays are treated as part of the background and are described by a dedicated PDF:

$$\begin{aligned} \mathcal{F}_{B^0}(m_i, t_i, \Omega_i) &= P_{B^0}(m_i) \cdot P_{\rm s}(\sigma_{m_i}) \cdot P_{B^0}(t_i|\sigma_{t_i}) \\ &\cdot\; P_{B^0}(\theta_T) \cdot P_{B^0}(\varphi_T) \cdot P_{B^0}(\psi_T) \cdot P_{\rm s}(\sigma_{t_i}) \cdot P_{\rm s}(p_{{\rm T}i}) \end{aligned} \tag{4.4}$$

The mass is described by the $P_{B^0}(m_i)$ term in the form of a Landau function due to the distortion caused by the incorrect mass assignment. The decay time is described in the term $P_{B^0}(t_i|\sigma_{t_i})$ by an exponential smeared with event-by-event Gaussian errors. The transversity angles are described using the same functions as the other backgrounds but with different values for the parameters obtained from the fit to MC data. The terms $P_{\rm s}(\sigma_{m_i})$, $P_{\rm s}(\sigma_{t_i})$ and $P_{\rm s}(p_{{\rm T}i})$ are described in section 4.4. All the PDFs describing these B^0 reflections have fixed shapes determined from the MC studies.

4.3 Background PDF

The background PDF has the following composition:

$$\begin{aligned}\mathcal{F}_{\rm bkg}(m_i, t_i, \Omega_i) &= P_{\rm b}(m_i)\cdot P_{\rm b}(\sigma_{m_i})\cdot P_{\rm b}(t_i|\sigma_{t_i}) \\ &\quad\cdot\; P_{\rm b}(\theta_T)\cdot P_{\rm b}(\varphi_T)\cdot P_{\rm b}(\psi_T)\cdot P_{\rm b}(\sigma_{t_i})\cdot P_{\rm b}(p_{{\rm T}i}) \end{aligned} \tag{4.5}$$

The proper decay time function $P_{\rm b}(t_i|\sigma_{t_i})$ is parameterised as a prompt peak modelled by a Gaussian distribution, two positive exponentials and a negative exponential. This function is smeared with the same resolution function as the signal decay time-dependence. The prompt peak models the combinatorial background events, which are expected to have reconstructed lifetime distributed around zero. The two positive exponentials represent a fraction of longer-lived backgrounds with non-prompt J/ψ, combined with hadrons from the primary vertex or from a B/D hadron in the same event. The negative exponential takes into account events with poor vertex resolution.

The shape of the background angular distributions, $P_{\rm b}(\theta_T)$, $P_{\rm b}(\varphi_T)$, and $P_{\rm b}(\psi_T)$ arise primarily from detector and kinematic sculpting. These are described by the following empirically determined functions:

$$\begin{aligned} f(\cos\theta_T) &= \frac{a_0 - a_1\cos^2(\theta_T) + a_2\cos^4(\theta_T)}{2a_0 - 2a_1/3 + 2a_2/5} \\ f(\varphi_T) &= \frac{1 + b_1\cos(2\varphi_T + b_0)}{2\pi} \\ f(\cos\psi_T) &= \frac{c_0 + c_1\cos^2(\psi_T)}{2c_0 + 2c_1/3} \end{aligned}$$

They are initially fitted to data from the B_s^0 mass sidebands only, to find reasonable starting values for $a_{0,1,2}$, $b_{0,1}$ and $c_{0,1}$, then allowed to float freely in the full likelihood fit. The B_s^0 mass sidebands, $(5.150-5.317)$ GeV and $(5.417-5.650)$ GeV, are defined to retain 0.02% of signal events identified in the fit. The correlations between the background angular shapes are neglected, but a systematic error arising from this simplification is evaluated in section 5. The background mass model, $P_{\rm b}(m)$ is a linear function.

4.4 Time and mass uncertainties of signal and background

The event-by-event proper decay time and mass uncertainty distributions differ significantly for signal and background, as shown in figure 1. The background PDFs cannot be factorized and it is necessary to include extra PDF terms describing the error distributions in the likelihood function to avoid significant biases [16].

The signal and background time and mass error distributions are described with Gamma functions:

$$P_{\mathrm{s,b}}(\sigma_{t(m)_i}) = \frac{(\sigma_{t(m)_i} - c)^{a_{\mathrm{s,b}}} e^{-(\sigma_{t(m)_i} - c)/b_{\mathrm{s,b}}}}{b_{\mathrm{s,b}}^{a_{\mathrm{s,b}}+1}\Gamma(a_{\mathrm{s,b}}+1)} \tag{4.6}$$

where $a_{\mathrm{s,b}}$ and $b_{\mathrm{s,b}}$ are constants fitted from (b) sideband and (s) sideband-subtracted signal and fixed in the likelihood fit. Since $P_{\mathrm{s,b}}(\sigma_{t(m)_i})$ depend on transverse momentum of the B_s^0 meson, they were determined in six selected p_{T} bins, the choice of which is reflecting the natural p_{T} dependence of the detector resolution.

The same treatment is used for B_s^0 p_{T} signal and background, by introducing additional terms $P_{\mathrm{s}}(p_{\mathrm{T}i})$ and $P_{\mathrm{b}}(p_{\mathrm{T}i})$ into the PDF. These are described using the same functions as $P_{\mathrm{s,b}}(\sigma_{t(m)_i})$ but with different values for the parameters obtained from the fit to sideband and sideband-subtracted signal p_{T} distributions.

4.5 Muon trigger time-dependent efficiency

It has been observed that the muon trigger biases the transverse impact parameter of muons toward smaller values. The trigger selection efficiency was measured in data and MC simulation using a tag-and-probe method [17]. To account for this efficiency in the fit, the events are re-weighted by a factor w:

$$w = e^{-|t|/(\tau_{\mathrm{sing}}+\epsilon)}/e^{-|t|/\tau_{\mathrm{sing}}} \tag{4.7}$$

where the τ_{sing} is a single B_s^0 lifetime measured before the correction, using unbinned mass-lifetime maximum likelihood fit. The weight form and the factor $\epsilon = 0.013 \pm 0.004$ ps are determined using MC events by comparing the B_s^0 lifetime distribution of an unbiased sample with the lifetime distribution obtained after including the dependence of the trigger efficiency on the muon transverse impact parameter as measured from the data. The value of ϵ is determined as the difference of exponential fits to the two distributions. The uncertainty 0.004 ps, which reflects the precision of the tag-and-probe method, is used to assign a systematic error due to this time efficiency correction.

5 Systematic uncertainties

Systematic uncertainties are assigned by considering several effects that are not accounted for in the likelihood fit. These are described below.

- **Inner Detector Alignment:** Residual misalignments of the ID affect the impact parameter distribution with respect to the primary vertex. The effect of this residual misalignment on the measurement is estimated using events simulated with perfect and distorted ID geometries. The distorted geometry is produced by moving detector components to match the observed small shifts in data. The observable of interest is the impact parameter distribution with respect to the primary vertex as a function of η and ϕ. The mean value of this impact parameter distribution for a perfectly aligned detector is expected to be zero and in data a maximum deviation of less than 10 μm is observed. The difference between the measurement using simulated events reconstructed with a perfect geometry compared to the distorted geometry is used to assess the systematic uncertainty.

- **Angular acceptance method:** The angular acceptance is calculated from a binned fit to MC data. In the kinematical region used in this analysis, the angular acceptance varies with the transversity angles by about ±10%. The statistical error in the acceptance is smaller than 1% in any bin, and data driven analyses show that systematic uncertainties in modelling detector and reconstruction are also at the level of 1% [18, 19]. Possible dependences of the results on the choice of the binning are tested by varying bin widths and central values. Taking all these arguments into consideration, the systematic uncertainties due to detector acceptance are found to be negligible.

- **Trigger efficiency:** To correct for the trigger lifetime bias the events are re-weighted according to equation 4.7. The uncertainty in the parameter ϵ is used to estimate the systematic uncertainty due to the time efficiency correction.

- **Fit model:** Pseudo-experiments are used to estimate systematic uncertainties. In a first test, the results of 1000 pseudo-experiments are compared to the generated values, and the average of the differences are taken as systematic uncertainties. Additional sets of 1000 pseudo-experiments are generated with variations in the signal and background mass model, resolution model, background lifetime and background angles models, as discussed below. These sets are analysed with the default model, and average deviations in the results of the fit are taken as additional systematic errors. The following variations are considered:

  - The signal mass distribution is generated using a sum of two Gaussian functions. Their relative fractions and widths are determined from a likelihood fit to data. In the PDF for this fit, the mass of each event is modelled by two different Gaussians with widths equal to products of the scale factors multiplied by a per-candidate mass error.
  - The background mass is generated from an exponential function. The default fit uses a linear model for the mass of background events.
  - Two different scale factors instead of one are used to generate the lifetime uncertainty.
  - The values used for the background lifetime are generated by sampling data from the mass sidebands. The default fit uses a set of functions to describe the background lifetime.
  - Pseudo-experiments are performed using two methods of generating the background angles. The default method uses a set of functions describing the background angles of data without taking correlations between the angles into ac-

count. In the alternative fit the background angles are generated using a three dimensional histogram of the sideband-data angles.

- **B^0 contribution:** Contamination from $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K\pi$ events mis-reconstructed as $B_s^0 \to J/\psi\phi$ are accounted for in the default fit; the fractions of these contributions are fixed to values estimated from selection efficiencies in MC simulation and decay probabilities from ref. [14]. To estimate the systematic uncertainty arising from the precision of the fraction estimates, the data are fitted with these fractions increased and decreased by 1σ. The largest shift in the fitted values from the default case is taken as the systematic uncertainty for each parameter of interest.

The systematic uncertainties are summarised in table 4. In general, pseudo-experiments generated with the default model produce pull-distributions that show a negligible bias, and confirm that the uncertainties are correctly estimated by the fit. The largest average deviation in a residual divided by its fit uncertainty (or pull) is 0.32; the second largest is 0.26, while the remainder where much smaller. These two largest deviations were added in quadrature to those obtained by varying the model assumptions, resulting for each variable in a total systematic uncertainty shown in table 4.

6 Results

The full maximum likelihood fit contains 26 free parameters. This includes the eight physics parameters: $\Delta\Gamma_s$, ϕ_s, Γ_s, $|A_0(0)|^2$, $|A_\parallel(0)|^2$, $\delta_{||}$, $|A_S(0)|^2$ and δ_S, and strong phase $\delta_\perp$ constrained by external data. The other free parameters in the likelihood function are the B_s^0 signal fraction $f_{\rm s}$, the parameters describing the $J/\psi\phi$ mass distribution, the parameters describing the decay time and the angular distributions of the background, the parameters used to describe the estimated decay time uncertainty distributions for signal and background events, and the scale factors between the estimated decay-time and mass uncertainties and their true uncertainties, see equation 4.6.

As discussed in section 4.1, the strong phase $\delta_\perp$ is constrained to the value measured in ref. [7], as the fit in the absence of flavour tagging is not sufficiently sensitive to this value. The second strong phase, $\delta_{||}$, is fitted very close to its symmetry point at π. Pull studies, based on pseudo-experiments using input values determined from the fit to data, return a non-Gaussian pull distribution for this parameter. For this reason the result for the strong phase $\delta_{||}$ is given in the form of a 1σ confidence interval $[3.04, 3.24]$ rad. The strong phase of the S-wave component is fitted relative to $\delta_\perp$, as $\delta_\perp - \delta_S = (0.03 \pm 0.13)$ rad.

The number of signal B_s^0 meson candidates extracted from the fit is 22690 ± 160. The results and correlations for the measured physics parameters of the unbinned maximum likelihood fit are given in tables 2 and 3. Fit projections of the mass, proper decay time and angles are given in figures 2, 3 and 4 respectively.

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s(rad)	0.22	0.41	0.10
$\Delta\Gamma_s$(ps^{-1})	0.053	0.021	0.010
Γ_s(ps^{-1})	0.677	0.007	0.004
$\|A_0(0)\|^2$	0.528	0.006	0.009
$\|A_\parallel(0)\|^2$	0.220	0.008	0.007
$\|A_S(0)\|^2$	0.02	0.02	0.02

Table 2. Fitted values for the physics parameters along with their statistical and systematic uncertainties.

	ϕ_s	$\Delta\Gamma_s$	Γ_s	$\|A_0(0)\|^2$	$\|A_\parallel(0)\|^2$	$\|A_S(0)\|^2$
ϕ_s	1.00	−0.13	0.38	−0.03	−0.04	0.02
$\Delta\Gamma_s$		1.00	−0.60	0.12	0.11	0.10
Γ_s			1.00	−0.06	−0.10	0.04
$\|A_0(0)\|^2$				1.00	−0.30	0.35
$\|A_\parallel(0)\|^2$					1.00	0.09
$\|A_S(0)\|^2$						1.00

Table 3. Correlations between the physics parameters.

Systematic Uncertainty	ϕ_s(rad)	$\Delta\Gamma_s$(ps^{-1})	Γ_s(ps^{-1})	$\|A_\parallel(0)\|^2$	$\|A_0(0)\|^2$	$\|A_S(0)\|^2$
Inner Detector alignment	0.04	< 0.001	0.001	< 0.001	< 0.001	< 0.01
Trigger efficiency	< 0.01	< 0.001	0.002	< 0.001	< 0.001	< 0.01
Default fit model	< 0.001	0.006	< 0.001	< 0.001	0.001	< 0.01
Signal mass model	0.02	0.002	< 0.001	< 0.001	< 0.001	< 0.01
Background mass model	0.03	0.001	< 0.001	0.001	< 0.001	< 0.01
Resolution model	0.05	< 0.001	0.001	< 0.001	< 0.001	< 0.01
Background lifetime model	0.02	0.002	< 0.001	< 0.001	< 0.001	< 0.01
Background angles model	0.05	0.007	0.003	0.007	0.008	0.02
B^0 contribution	0.05	< 0.001	< 0.001	< 0.001	0.005	< 0.01
Total	0.10	0.010	0.004	0.007	0.009	0.02

Table 4. Summary of systematic uncertainties assigned to parameters of interest.

7 Symmetries of the likelihood function and two-dimensional likelihood contours

The PDF describing the $B_s^0 \to J/\psi\phi$ decay is invariant under the following simultaneous transformations:

$$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \to \{\pi - \phi_s, -\Delta\Gamma_s, \pi - \delta_\perp, -\delta_\parallel, -\delta_S\}.$$

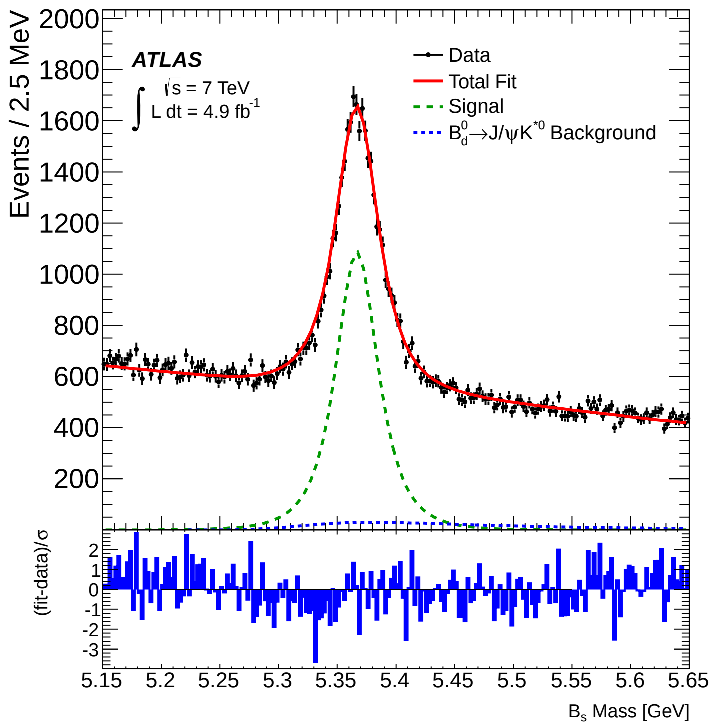

Figure 2. Mass fit projection for the B_s^0. The pull distribution at the bottom shows the difference between the data and fit value normalised to the data uncertainty.

In the absence of initial state flavour tagging the PDF is also invariant under

$$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \rightarrow \{-\phi_s, \Delta\Gamma_s, \pi - \delta_\perp, -\delta_\parallel, -\delta_S\} \tag{7.1}$$

leading to a fourfold ambiguity.

The two-dimensional likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane are calculated allowing all parameters to vary within their physical ranges. As discussed in section 6, the value for the Gaussian constraint on $\delta_\perp$ is taken from the LHCb measurement [7]. That paper quotes only two solutions with a positive ϕ_s and two $\Delta\Gamma_s$ values symmetric around zero, by using initial state flavour tagging to eliminate the symmetry defined in equation 7.1. Due to the accurate local determination of ϕ_s and $\Delta\Gamma_s$ in both this measurement and in the LHCb measurement [7], the other two solutions seen in the ATLAS analysis are not compatible with the observations of the two experiments. As such, two of the four minima fitted in the present non-flavour tagged analysis are excluded from the results presented here. Additionally a solution with negative $\Delta\Gamma_s$ is excluded following the LHCb measurement [20] which determines the $\Delta\Gamma_s$ to be positive. Therefore, the two-dimensional contour plot for ϕ_s and $\Delta\Gamma_s$ has been computed only for the solution consistent with the

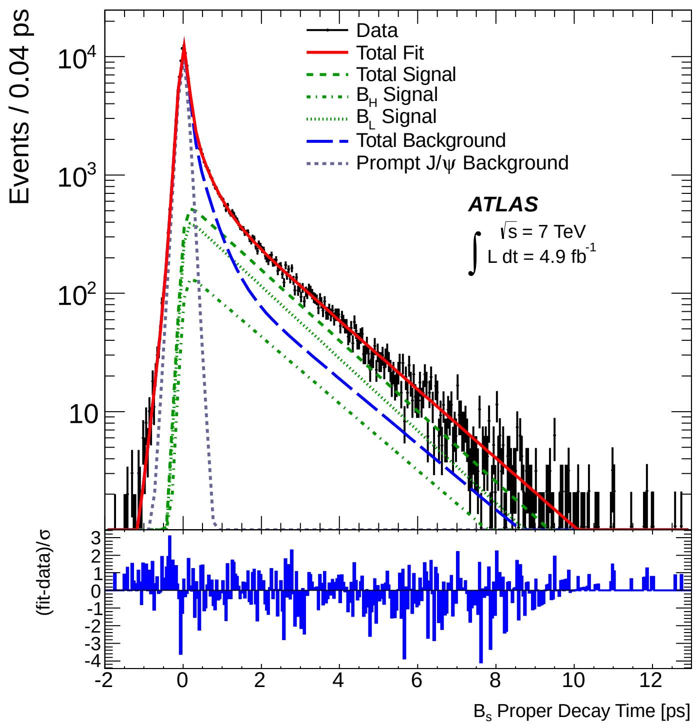

Figure 3. Proper decay time fit projection for the B_s^0. The pull distribution at the bottom shows the difference between the data and fit value normalised to the data uncertainty.

previous measurements. The resulting contours for the 68%, 90% and 95% confidence intervals are produced using a profile likelihood method and are shown in figure 5.

The systematic errors are not included in figure 5 but as seen from table 2 they are small compared to the statistical errors. The confidence levels are obtained using the corresponding $\Delta \ln \mathcal{L}$ intervals. Pseudo-experiments are used to study the coverage of the likelihood contours. This test suggests that the statistical uncertainty of our result is overestimated by about 5%. No correction to compensate for this overestimation is applied.

8 Conclusion

A measurement of CP violation in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays from a 4.9 fb^{-1} data sample of pp collisions collected with the ATLAS detector during the 2011 $\sqrt{s} = 7$ TeV run was presented. Several parameters describing the B_s^0 meson system are measured. These include the mean B_s^0 lifetime, the decay width difference $\Delta\Gamma_s$ between the heavy and light mass eigenstates, the transversity amplitudes $|A_0(0)|$ and $|A_{\|}(0)|$ and the CP-violating week phase ϕ_s. They are consistent with the world average values.

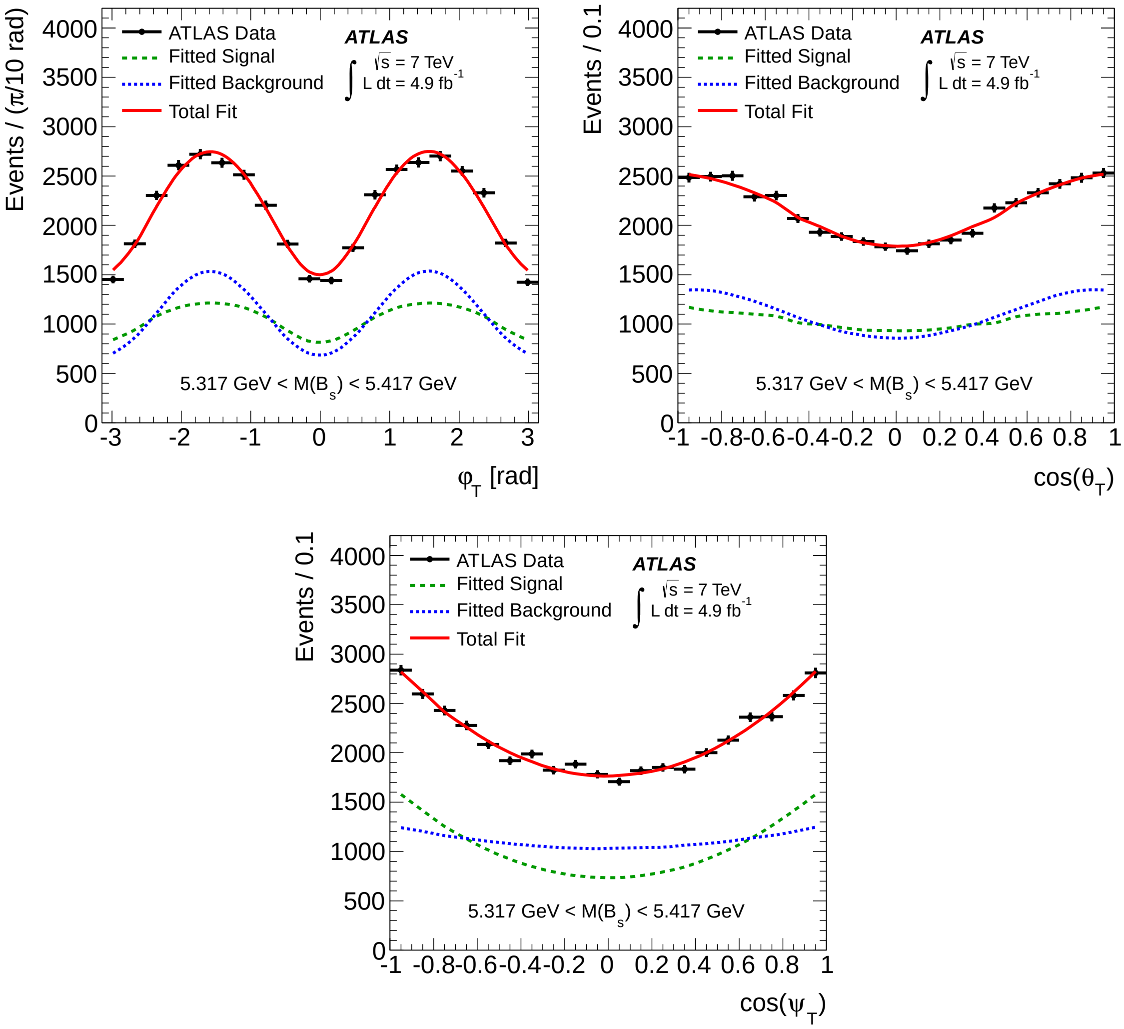

Figure 4. Fit projections for transversity angles. (Left): φ_T, (Right): $\cos\theta_T$, (Bottom): $\cos\psi_T$ for the events with B_s^0 mass from signal region (5.317 - 5.417) GeV.

The measured values, for the minimum resulting from $\delta_\perp$ constrained to the LHCb value of 2.95 ± 0.39 rad [7] and $\Delta\Gamma_s$ being constrained to be positive following LHCb measurement [20], are:

$$\begin{aligned}
\phi_s &= 0.22 \quad \pm 0.41 \quad (\text{stat.}) \pm \; 0.10 \quad (\text{syst.}) \text{ rad} \\
\Delta\Gamma_s &= 0.053 \pm 0.021 \; (\text{stat.}) \pm \; 0.010 \; (\text{syst.}) \text{ ps}^{-1} \\
\Gamma_s &= 0.677 \pm 0.007 \; (\text{stat.}) \pm \; 0.004 \; (\text{syst.}) \text{ ps}^{-1} \\
|A_0(0)|^2 &= 0.528 \pm 0.006 \; (\text{stat.}) \pm \; 0.009 \; (\text{syst.}) \\
|A_{||}(0)|^2 &= 0.220 \pm 0.008 \; (\text{stat.}) \pm \; 0.007 \; (\text{syst.})
\end{aligned}$$

These values are consistent with theoretical expectations, in particular ϕ_s is within 1σ of

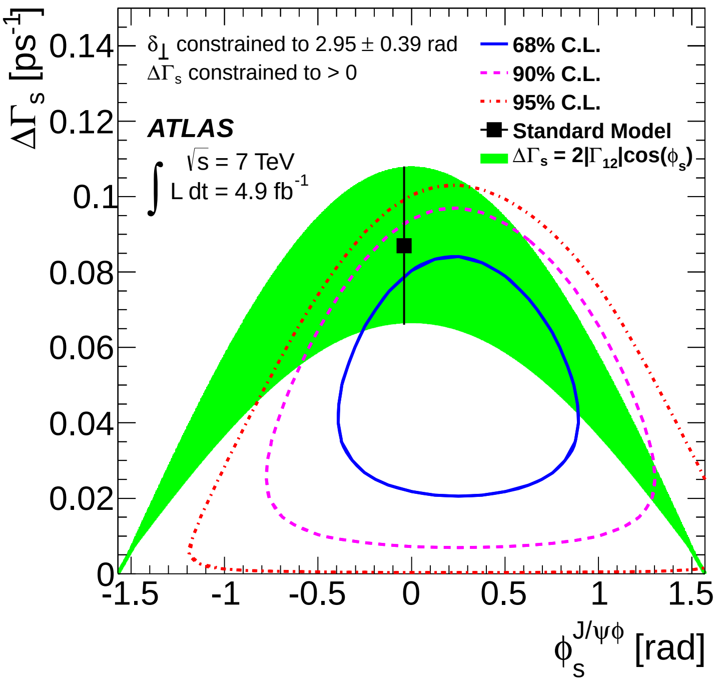

Figure 5. Likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane. Three contours show the 68%, 90% and 95% confidence intervals (statistical errors only). The green band is the theoretical prediction of mixing- induced CP violation. The PDF contains a fourfold ambiguity. Three minima are excluded by applying the constraints from the LHCb measurements [7, 20].

the expected value in the Standard Model. A likelihood contour in the $\phi_s - \Delta\Gamma_s$ plane is also provided for the minimum compatible with the LHCb measurements [7, 20]. The fraction of S-wave KK or f_0 contamination is measured to be consistent with zero, at $|A_S(0)|^2 = 0.02 \pm 0.02$.

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G. Aad[48], T. Abajyan[21], B. Abbott[111], J. Abdallah[12], S. Abdel Khalek[115], A.A. Abdelalim[49], O. Abdinov[11], R. Aben[105], B. Abi[112], M. Abolins[88], O.S. AbouZeid[158], H. Abramowicz[153], H. Abreu[136], E. Acerbi[89a,89b], B.S. Acharya[164a,164b], L. Adamczyk[38], D.L. Adams[25], T.N. Addy[56], J. Adelman[176], S. Adomeit[98], P. Adragna[75], T. Adye[129], S. Aefsky[23], J.A. Aguilar-Saavedra[124b,a], M. Agustoni[17], M. Aharrouche[81], S.P. Ahlen[22], F. Ahles[48], A. Ahmad[148], M. Ahsan[41], G. Aielli[133a,133b], T. Akdogan[19a], T.P.A. Åkesson[79], G. Akimoto[155], A.V. Akimov[94], M.S. Alam[2], M.A. Alam[76], J. Albert[169], S. Albrand[55], M. Aleksa[30], I.N. Aleksandrov[64], F. Alessandria[89a], C. Alexa[26a], G. Alexander[153], G. Alexandre[49], T. Alexopoulos[10], M. Alhroob[164a,164c], M. Aliev[16], G. Alimonti[89a], J. Alison[120], B.M.M. Allbrooke[18], P.P. Allport[73], S.E. Allwood-Spiers[53], J. Almond[82], A. Aloisio[102a,102b], R. Alon[172], A. Alonso[79], F. Alonso[70], B. Alvarez Gonzalez[88], M.G. Alviggi[102a,102b], K. Amako[65], C. Amelung[23], V.V. Ammosov[128,*], A. Amorim[124a,b], N. Amram[153], C. Anastopoulos[30], L.S. Ancu[17], N. Andari[115], T. Andeen[35], C.F. Anders[58b], G. Anders[58a], K.J. Anderson[31], A. Andreazza[89a,89b], V. Andrei[58a], X.S. Anduaga[70], P. Anger[44], A. Angerami[35], F. Anghinolfi[30], A. Anisenkov[107], N. Anjos[124a], A. Annovi[47], A. Antonaki[9], M. Antonelli[47], A. Antonov[96], J. Antos[144b], F. Anulli[132a], M. Aoki[101], S. Aoun[83], L. Aperio Bella[5], R. Apolle[118,c], G. Arabidze[88], I. Aracena[143], Y. Arai[65], A.T.H. Arce[45], S. Arfaoui[148], J-F. Arguin[15], E. Arik[19a,*], M. Arik[19a], A.J. Armbruster[87], O. Arnaez[81], V. Arnal[80], C. Arnault[115], A. Artamonov[95], G. Artoni[132a,132b], D. Arutinov[21], S. Asai[155], R. Asfandiyarov[173], S. Ask[28], B. Åsman[146a,146b], L. Asquith[6], K. Assamagan[25], A. Astbury[169], M. Atkinson[165], B. Aubert[5], E. Auge[115], K. Augsten[127], M. Aurousseau[145a], G. Avolio[163], R. Avramidou[10], D. Axen[168], G. Azuelos[93,d], Y. Azuma[155], M.A. Baak[30], G. Baccaglioni[89a], C. Bacci[134a,134b], A.M. Bach[15], H. Bachacou[136], K. Bachas[30], M. Backes[49], M. Backhaus[21], E. Badescu[26a], P. Bagnaia[132a,132b], S. Bahinipati[3], Y. Bai[33a], D.C. Bailey[158], T. Bain[158], J.T. Baines[129], O.K. Baker[176], M.D. Baker[25], S. Baker[77], E. Banas[39], P. Banerjee[93], Sw. Banerjee[173], D. Banfi[30], A. Bangert[150], V. Bansal[169], H.S. Bansil[18], L. Barak[172], S.P. Baranov[94], A. Barbaro Galtieri[15], T. Barber[48], E.L. Barberio[86], D. Barberis[50a,50b], M. Barbero[21], D.Y. Bardin[64], T. Barillari[99], M. Barisonzi[175], T. Barklow[143], N. Barlow[28], B.M. Barnett[129], R.M. Barnett[15], A. Baroncelli[134a], G. Barone[49], A.J. Barr[118], F. Barreiro[80], J. Barreiro Guimarães da Costa[57], P. Barrillon[115], R. Bartoldus[143], A.E. Barton[71], V. Bartsch[149], A. Basye[165], R.L. Bates[53], L. Batkova[144a], J.R. Batley[28], A. Battaglia[17], M. Battistin[30], F. Bauer[136], H.S. Bawa[143,e], S. Beale[98], T. Beau[78], P.H. Beauchemin[161], R. Beccherle[50a], P. Bechtle[21], H.P. Beck[17], A.K. Becker[175], S. Becker[98], M. Beckingham[138], K.H. Becks[175], A.J. Beddall[19c], A. Beddall[19c], S. Bedikian[176], V.A. Bednyakov[64], C.P. Bee[83], L.J. Beemster[105], M. Begel[25], S. Behar Harpaz[152], M. Beimforde[99], C. Belanger-Champagne[85], P.J. Bell[49], W.H. Bell[49], G. Bella[153], L. Bellagamba[20a], F. Bellina[30], M. Bellomo[30], A. Belloni[57], O. Beloborodova[107,f], K. Belotskiy[96], O. Beltramello[30], O. Benary[153], D. Benchekroun[135a], K. Bendtz[146a,146b], N. Benekos[165], Y. Benhammou[153],

E. Benhar Noccioli[49], J.A. Benitez Garcia[159b], D.P. Benjamin[45], M. Benoit[115], J.R. Bensinger[23], K. Benslama[130], S. Bentvelsen[105], D. Berge[30], E. Bergeaas Kuutmann[42], N. Berger[5], F. Berghaus[169], E. Berglund[105], J. Beringer[15], P. Bernat[77], R. Bernhard[48], C. Bernius[25], T. Berry[76], C. Bertella[83], A. Bertin[20a,20b], F. Bertolucci[122a,122b], M.I. Besana[89a,89b], G.J. Besjes[104], N. Besson[136], S. Bethke[99], W. Bhimji[46], R.M. Bianchi[30], M. Bianco[72a,72b], O. Biebel[98], S.P. Bieniek[77], K. Bierwagen[54], J. Biesiada[15], M. Biglietti[134a], H. Bilokon[47], M. Bindi[20a,20b], S. Binet[115], A. Bingul[19c], C. Bini[132a,132b], C. Biscarat[178], B. Bittner[99], K.M. Black[22], R.E. Blair[6], J.-B. Blanchard[136], G. Blanchot[30], T. Blazek[144a], C. Blocker[23], J. Blocki[39], A. Blondel[49], W. Blum[81], U. Blumenschein[54], G.J. Bobbink[105], V.B. Bobrovnikov[107], S.S. Bocchetta[79], A. Bocci[45], C.R. Boddy[118], M. Boehler[48], J. Boek[175], N. Boelaert[36], J.A. Bogaerts[30], A. Bogdanchikov[107], A. Bogouch[90,*], C. Bohm[146a], J. Bohm[125], V. Boisvert[76], T. Bold[38], V. Boldea[26a], N.M. Bolnet[136], M. Bomben[78], M. Bona[75], M. Boonekamp[136], C.N. Booth[139], S. Bordoni[78], C. Borer[17], A. Borisov[128], G. Borissov[71], I. Borjanovic[13a], M. Borri[82], S. Borroni[87], V. Bortolotto[134a,134b], K. Bos[105], D. Boscherini[20a], M. Bosman[12], H. Boterenbrood[105], J. Bouchami[93], J. Boudreau[123], E.V. Bouhova-Thacker[71], D. Boumediene[34], C. Bourdarios[115], N. Bousson[83], A. Boveia[31], J. Boyd[30], I.R. Boyko[64], I. Bozovic-Jelisavcic[13b], J. Bracinik[18], P. Branchini[134a], A. Brandt[8], G. Brandt[118], O. Brandt[54], U. Bratzler[156], B. Brau[84], J.E. Brau[114], H.M. Braun[175,*], S.F. Brazzale[164a,164c], B. Brelier[158], J. Bremer[30], K. Brendlinger[120], R. Brenner[166], S. Bressler[172], D. Britton[53], F.M. Brochu[28], I. Brock[21], R. Brock[88], F. Broggi[89a], C. Bromberg[88], J. Bronner[99], G. Brooijmans[35], T. Brooks[76], W.K. Brooks[32b], G. Brown[82], H. Brown[8], P.A. Bruckman de Renstrom[39], D. Bruncko[144b], R. Bruneliere[48], S. Brunet[60], A. Bruni[20a], G. Bruni[20a], M. Bruschi[20a], T. Buanes[14], Q. Buat[55], F. Bucci[49], J. Buchanan[118], P. Buchholz[141], R.M. Buckingham[118], A.G. Buckley[46], S.I. Buda[26a], I.A. Budagov[64], B. Budick[108], V. Büscher[81], L. Bugge[117], O. Bulekov[96], A.C. Bundock[73], M. Bunse[43], T. Buran[117], H. Burckhart[30], S. Burdin[73], T. Burgess[14], S. Burke[129], E. Busato[34], P. Bussey[53], C.P. Buszello[166], B. Butler[143], J.M. Butler[22], C.M. Buttar[53], J.M. Butterworth[77], W. Buttinger[28], M. Byszewski[30], S. Cabrera Urbán[167], D. Caforio[20a,20b], O. Cakir[4a], P. Calafiura[15], G. Calderini[78], P. Calfayan[98], R. Calkins[106], L.P. Caloba[24a], R. Caloi[132a,132b], D. Calvet[34], S. Calvet[34], R. Camacho Toro[34], P. Camarri[133a,133b], D. Cameron[117], L.M. Caminada[15], R. Caminal Armadans[12], S. Campana[30], M. Campanelli[77], V. Canale[102a,102b], F. Canelli[31,g], A. Canepa[159a], J. Cantero[80], R. Cantrill[76], L. Capasso[102a,102b], M.D.M. Capeans Garrido[30], I. Caprini[26a], M. Caprini[26a], D. Capriotti[99], M. Capua[37a,37b], R. Caputo[81], R. Cardarelli[133a], T. Carli[30], G. Carlino[102a], L. Carminati[89a,89b], B. Caron[85], S. Caron[104], E. Carquin[32b], G.D. Carrillo Montoya[173], A.A. Carter[75], J.R. Carter[28], J. Carvalho[124a,h], D. Casadei[108], M.P. Casado[12], M. Cascella[122a,122b], C. Caso[50a,50b,*], A.M. Castaneda Hernandez[173,i], E. Castaneda-Miranda[173], V. Castillo Gimenez[167], N.F. Castro[124a], G. Cataldi[72a], P. Catastini[57], A. Catinaccio[30], J.R. Catmore[30], A. Cattai[30], G. Cattani[133a,133b], S. Caughron[88], V. Cavaliere[165], P. Cavalleri[78], D. Cavalli[89a], M. Cavalli-Sforza[12], V. Cavasinni[122a,122b], F. Ceradini[134a,134b], A.S. Cerqueira[24b], A. Cerri[30], L. Cerrito[75],

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I. Vukotic[31], W. Wagner[175], P. Wagner[120], H. Wahlen[175], S. Wahrmund[44], J. Wakabayashi[101], S. Walch[87], J. Walder[71], R. Walker[98], W. Walkowiak[141], R. Wall[176], P. Waller[73], B. Walsh[176], C. Wang[45], H. Wang[173], H. Wang[33b,ak], J. Wang[151], J. Wang[55], R. Wang[103], S.M. Wang[151], T. Wang[21], A. Warburton[85], C.P. Ward[28], M. Warsinsky[48], A. Washbrook[46], C. Wasicki[42], I. Watanabe[66], P.M. Watkins[18], A.T. Watson[18], I.J. Watson[150], M.F. Watson[18], G. Watts[138], S. Watts[82], A.T. Waugh[150], B.M. Waugh[77], M.S. Weber[17], P. Weber[54], A.R. Weidberg[118], P. Weigell[99], J. Weingarten[54], C. Weiser[48], H. Wellenstein[23], P.S. Wells[30], T. Wenaus[25], D. Wendland[16], Z. Weng[151,w], T. Wengler[30], S. Wenig[30], N. Wermes[21], M. Werner[48], P. Werner[30], M. Werth[163], M. Wessels[58a], J. Wetter[161], C. Weydert[55], K. Whalen[29], S.J. Wheeler-Ellis[163], A. White[8], M.J. White[86], S. White[122a,122b], S.R. Whitehead[118], D. Whiteson[163], D. Whittington[60], F. Wicek[115], D. Wicke[175], F.J. Wickens[129], W. Wiedenmann[173], M. Wielers[129], P. Wienemann[21], C. Wiglesworth[75], L.A.M. Wiik-Fuchs[48], P.A. Wijeratne[77], A. Wildauer[99], M.A. Wildt[42,s], I. Wilhelm[126], H.G. Wilkens[30], J.Z. Will[98], E. Williams[35], H.H. Williams[120], W. Willis[35], S. Willocq[84], J.A. Wilson[18], M.G. Wilson[143], A. Wilson[87], I. Wingerter-Seez[5], S. Winkelmann[48], F. Winklmeier[30], M. Wittgen[143], S.J. Wollstadt[81], M.W. Wolter[39], H. Wolters[124a,h], W.C. Wong[41], G. Wooden[87], B.K. Wosiek[39], J. Wotschack[30], M.J. Woudstra[82], K.W. Wozniak[39], K. Wraight[53], M. Wright[53], B. Wrona[73], S.L. Wu[173], X. Wu[49], Y. Wu[33b,al], E. Wulf[35], B.M. Wynne[46], S. Xella[36], M. Xiao[136], S. Xie[48], C. Xu[33b,z], D. Xu[139], B. Yabsley[150], S. Yacoob[145a,am], M. Yamada[65], H. Yamaguchi[155], A. Yamamoto[65], K. Yamamoto[63], S. Yamamoto[155], T. Yamamura[155], T. Yamanaka[155], J. Yamaoka[45], T. Yamazaki[155], Y. Yamazaki[66], Z. Yan[22], H. Yang[87], U.K. Yang[82], Y. Yang[60], Z. Yang[146a,146b], S. Yanush[91], L. Yao[33a], Y. Yao[15], Y. Yasu[65], G.V. Ybeles Smit[130], J. Ye[40], S. Ye[25], M. Yilmaz[4c], R. Yoosoofmiya[123], K. Yorita[171], R. Yoshida[6], C. Young[143], C.J. Young[118], S. Youssef[22], D. Yu[25], J. Yu[8], J. Yu[112], L. Yuan[66], A. Yurkewicz[106], B. Zabinski[39], R. Zaidan[62], A.M. Zaitsev[128], Z. Zajacova[30], L. Zanello[132a,132b], D. Zanzi[99], A. Zaytsev[25], C. Zeitnitz[175], M. Zeman[125], A. Zemla[39], C. Zendler[21], O. Zenin[128], T. Ženiš[144a], Z. Zinonos[122a,122b], S. Zenz[15], D. Zerwas[115], G. Zevi della Porta[57], Z. Zhan[33d], D. Zhang[33b,ak], H. Zhang[88], J. Zhang[6], X. Zhang[33d], Z. Zhang[115], L. Zhao[108], T. Zhao[138], Z. Zhao[33b], A. Zhemchugov[64], J. Zhong[118], B. Zhou[87], N. Zhou[163], Y. Zhou[151], C.G. Zhu[33d], H. Zhu[42], J. Zhu[87], Y. Zhu[33b], X. Zhuang[98], V. Zhuravlov[99], D. Zieminska[60], N.I. Zimin[64], R. Zimmermann[21], S. Zimmermann[21], S. Zimmermann[48], M. Ziolkowski[141], R. Zitoun[5], L. Živković[35], V.V. Zmouchko[128,*], G. Zobernig[173], A. Zoccoli[20a,20b], M. zur Nedden[16], V. Zutshi[106], L. Zwalinski[30].

[1] School of Chemistry and Physics, University of Adelaide, North Terrace Campus, 5000, SA, Australia

[2] Physics Department, SUNY Albany, Albany NY, United States of America

[3] Department of Physics, University of Alberta, Edmonton AB, Canada

[4] [(a)]Department of Physics, Ankara University, Ankara; [(b)]Department of Physics, Dumlupinar University, Kutahya; [(c)]Department of Physics, Gazi University, Ankara; [(d)]Division of Physics, TOBB University of Economics and Technology, Ankara;

[e]Turkish Atomic Energy Authority, Ankara, Turkey
[5] LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
[6] High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
[7] Department of Physics, University of Arizona, Tucson AZ, United States of America
[8] Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
[9] Physics Department, University of Athens, Athens, Greece
[10] Physics Department, National Technical University of Athens, Zografou, Greece
[11] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[12] Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
[13] [a]Institute of Physics, University of Belgrade, Belgrade; [b]Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[14] Department for Physics and Technology, University of Bergen, Bergen, Norway
[15] Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
[16] Department of Physics, Humboldt University, Berlin, Germany
[17] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[18] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[19] [a]Department of Physics, Bogazici University, Istanbul; [b]Division of Physics, Dogus University, Istanbul; [c]Department of Physics Engineering, Gaziantep University, Gaziantep; [d]Department of Physics, Istanbul Technical University, Istanbul, Turkey
[20] [a]INFN Sezione di Bologna; [b]Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[21] Physikalisches Institut, University of Bonn, Bonn, Germany
[22] Department of Physics, Boston University, Boston MA, United States of America
[23] Department of Physics, Brandeis University, Waltham MA, United States of America
[24] [a]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [b]Federal University of Juiz de Fora (UFJF), Juiz de Fora; [c]Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; [d]Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
[25] Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
[26] [a]National Institute of Physics and Nuclear Engineering, Bucharest; [b]University Politehnica Bucharest, Bucharest; [c]West University in Timisoara, Timisoara, Romania
[27] Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[28] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[29] Department of Physics, Carleton University, Ottawa ON, Canada
[30] CERN, Geneva, Switzerland
[31] Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

[32] [(a)]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[33] [(a)]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)]Department of Modern Physics, University of Science and Technology of China, Anhui; [(c)]Department of Physics, Nanjing University, Jiangsu; [(d)]School of Physics, Shandong University, Shandong, China
[34] Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
[35] Nevis Laboratory, Columbia University, Irvington NY, United States of America
[36] Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[37] [(a)]INFN Gruppo Collegato di Cosenza; [(b)]Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
[38] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
[39] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[40] Physics Department, Southern Methodist University, Dallas TX, United States of America
[41] Physics Department, University of Texas at Dallas, Richardson TX, United States of America
[42] DESY, Hamburg and Zeuthen, Germany
[43] Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[44] Institut für Kern-und Teilchenphysik, Technical University Dresden, Dresden, Germany
[45] Department of Physics, Duke University, Durham NC, United States of America
[46] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[47] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[48] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
[49] Section de Physique, Université de Genève, Geneva, Switzerland
[50] [(a)]INFN Sezione di Genova; [(b)]Dipartimento di Fisica, Università di Genova, Genova, Italy
[51] [(a)]E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; [(b)]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[52] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[53] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[54] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[55] Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
[56] Department of Physics, Hampton University, Hampton VA, United States of America
[57] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America

[58] [(a)]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(c)]ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[59] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[60] Department of Physics, Indiana University, Bloomington IN, United States of America
[61] Institut für Astro-und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[62] University of Iowa, Iowa City IA, United States of America
[63] Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
[64] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[65] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[66] Graduate School of Science, Kobe University, Kobe, Japan
[67] Faculty of Science, Kyoto University, Kyoto, Japan
[68] Kyoto University of Education, Kyoto, Japan
[69] Department of Physics, Kyushu University, Fukuoka, Japan
[70] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[71] Physics Department, Lancaster University, Lancaster, United Kingdom
[72] [(a)]INFN Sezione di Lecce; [(b)]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[73] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[74] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[75] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[76] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[77] Department of Physics and Astronomy, University College London, London, United Kingdom
[78] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[79] Fysiska institutionen, Lunds universitet, Lund, Sweden
[80] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[81] Institut für Physik, Universität Mainz, Mainz, Germany
[82] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[83] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[84] Department of Physics, University of Massachusetts, Amherst MA, United States of America
[85] Department of Physics, McGill University, Montreal QC, Canada

[86] School of Physics, University of Melbourne, Victoria, Australia
[87] Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
[88] Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
[89] [(a)]INFN Sezione di Milano; [(b)]Dipartimento di Fisica, Università di Milano, Milano, Italy
[90] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[91] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[92] Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
[93] Group of Particle Physics, University of Montreal, Montreal QC, Canada
[94] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[95] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[96] Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[97] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[98] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[99] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[100] Nagasaki Institute of Applied Science, Nagasaki, Japan
[101] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[102] [(a)]INFN Sezione di Napoli; [(b)]Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
[103] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
[104] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[105] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[106] Department of Physics, Northern Illinois University, DeKalb IL, United States of America
[107] Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[108] Department of Physics, New York University, New York NY, United States of America
[109] Ohio State University, Columbus OH, United States of America
[110] Faculty of Science, Okayama University, Okayama, Japan
[111] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
[112] Department of Physics, Oklahoma State University, Stillwater OK, United States of America
[113] Palacký University, RCPTM, Olomouc, Czech Republic

[114] Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
[115] LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[116] Graduate School of Science, Osaka University, Osaka, Japan
[117] Department of Physics, University of Oslo, Oslo, Norway
[118] Department of Physics, Oxford University, Oxford, United Kingdom
[119] [(a)]INFN Sezione di Pavia; [(b)]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[120] Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
[121] Petersburg Nuclear Physics Institute, Gatchina, Russia
[122] [(a)]INFN Sezione di Pisa; [(b)]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[123] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
[124] [(a)]Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; [(b)]Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
[125] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[126] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[127] Czech Technical University in Prague, Praha, Czech Republic
[128] State Research Center Institute for High Energy Physics, Protvino, Russia
[129] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[130] Physics Department, University of Regina, Regina SK, Canada
[131] Ritsumeikan University, Kusatsu, Shiga, Japan
[132] [(a)]INFN Sezione di Roma I; [(b)]Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[133] [(a)]INFN Sezione di Roma Tor Vergata; [(b)]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[134] [(a)]INFN Sezione di Roma Tre; [(b)]Dipartimento di Fisica, Università Roma Tre, Roma, Italy
[135] [(a)]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; [(b)]Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; [(c)]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; [(d)]Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; [(e)]Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
[136] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
[137] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
[138] Department of Physics, University of Washington, Seattle WA, United States of

America
[139] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[140] Department of Physics, Shinshu University, Nagano, Japan
[141] Fachbereich Physik, Universität Siegen, Siegen, Germany
[142] Department of Physics, Simon Fraser University, Burnaby BC, Canada
[143] SLAC National Accelerator Laboratory, Stanford CA, United States of America
[144] [(a)]Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; [(b)]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[145] [(a)]Department of Physics, University of Johannesburg, Johannesburg; [(b)]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[146] [(a)]Department of Physics, Stockholm University; [(b)]The Oskar Klein Centre, Stockholm, Sweden
[147] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[148] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
[149] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[150] School of Physics, University of Sydney, Sydney, Australia
[151] Institute of Physics, Academia Sinica, Taipei, Taiwan
[152] Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
[153] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[154] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[155] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[156] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[157] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[158] Department of Physics, University of Toronto, Toronto ON, Canada
[159] [(a)]TRIUMF, Vancouver BC; [(b)]Department of Physics and Astronomy, York University, Toronto ON, Canada
[160] Institute of Pure and Applied Sciences, University of Tsukuba,1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
[161] Science and Technology Center, Tufts University, Medford MA, United States of America
[162] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[163] Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
[164] [(a)]INFN Gruppo Collegato di Udine; [(b)]ICTP, Trieste; [(c)]Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[165] Department of Physics, University of Illinois, Urbana IL, United States of America

[166] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[167] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[168] Department of Physics, University of British Columbia, Vancouver BC, Canada
[169] Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
[170] Department of Physics, University of Warwick, Coventry, United Kingdom
[171] Waseda University, Tokyo, Japan
[172] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[173] Department of Physics, University of Wisconsin, Madison WI, United States of America
[174] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[175] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[176] Department of Physics, Yale University, New Haven CT, United States of America
[177] Yerevan Physics Institute, Yerevan, Armenia
[178] Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
[a] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
[b] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
[c] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[d] Also at TRIUMF, Vancouver BC, Canada
[e] Also at Department of Physics, California State University, Fresno CA, United States of America
[f] Also at Novosibirsk State University, Novosibirsk, Russia
[g] Also at Fermilab, Batavia IL, United States of America
[h] Also at Department of Physics, University of Coimbra, Coimbra, Portugal
[i] Also at Department of Physics, UASLP, San Luis Potosi, Mexico
[j] Also at Università di Napoli Parthenope, Napoli, Italy
[k] Also at Institute of Particle Physics (IPP), Canada
[l] Also at Department of Physics, Middle East Technical University, Ankara, Turkey
[m] Also at Louisiana Tech University, Ruston LA, United States of America
[n] Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[o] Also at Department of Physics and Astronomy, University College London, London, United Kingdom
[p] Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
[q] Also at Department of Physics, University of Cape Town, Cape Town, South Africa
[r] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[s] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

[t] Also at Manhattan College, New York NY, United States of America
[u] Also at School of Physics, Shandong University, Shandong, China
[v] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[w] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
[x] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
[y] Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[z] Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
[aa] Also at Section de Physique, Université de Genève, Geneva, Switzerland
[ab] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
[ac] Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
[ad] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
[ae] Also at California Institute of Technology, Pasadena CA, United States of America
[af] Also at Institute of Physics, Jagiellonian University, Krakow, Poland
[ag] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[ah] Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America
[ai] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[aj] Also at Department of Physics, Oxford University, Oxford, United Kingdom
[ak] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
[al] Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
[am] Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
* Deceased

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