

Measurement of the CP-violating phase ϕ_s and the B_s^0 meson decay width difference with $B_s^0 \rightarrow J/\psi\phi$ decays in ATLAS (Postprint)

Authors: Aad, Georges and others

Date: 2016-08-15T00:00:00+00:00

Abstract

A measurement of the B_s^0 decay parameters in the $B_s^0 \rightarrow J/\psi\phi$ channel using an integrated luminosity of 14.3 fb^{-1} collected by the ATLAS detector from 8 TeV pp collisions at the LHC is presented. The measured parameters include the CP-violating phase ϕ_s , the decay width Γ_s and the width difference between the mass eigenstates $\Delta\Gamma_s$. The values measured for the physical parameters are statistically combined with those from 4.9 fb^{-1} of 7 TeV data, leading to the following:

Full Text

Preamble

Measurement of the CP-violating phase ϕ_s and the B_s^0 decay width difference with $B_s^0 \rightarrow J/\psi\phi$ decays in ATLAS

The ATLAS Collaboration

Abstract

A measurement of the $B_s^0 \rightarrow J/\psi\phi$ decay parameters is presented using an integrated luminosity of 14.3 fb^{-1} collected by the ATLAS detector from 8 TeV pp collisions at the LHC. The measured parameters include the CP-violating phase ϕ_s , the decay width Γ_s , and the width difference between the mass eigenstates $\Delta\Gamma_s$. The values measured for the physical parameters are statistically combined with those from 4.9 fb^{-1} of 7 TeV data, leading to the following results:

$$\begin{aligned}\phi_s &= -0.098 \pm 0.084 \text{ (stat.)} \pm 0.040 \text{ (syst.) rad} \\ \Delta\Gamma_s &= 0.083 \pm 0.011 \text{ (stat.)} \pm 0.007 \text{ (syst.) ps}^{-1} \\ \Gamma_s &= 0.677 \pm 0.003 \text{ (stat.)} \pm 0.003 \text{ (syst.) ps}^{-1}\end{aligned}$$

In the analysis, the parameter $\Delta\Gamma_s$ is constrained to be positive. Results for ϕ_s and $\Delta\Gamma_s$ are also presented as 68% and 95% likelihood contours in the ϕ_s - $\Delta\Gamma_s$ plane. Also measured in this decay channel are the transversity amplitudes and corresponding strong phases. All measurements are in agreement with the Standard Model predictions.

1 Introduction

New phenomena beyond the predictions of the Standard Model (SM) may alter CP violation in b-hadron decays. A channel that is expected to be sensitive to new physics contributions is the decay $B_0 \rightarrow J/\psi \phi$. CP violation in the $B_0 \rightarrow J/\psi \phi$ decay occurs due to interference between direct decays and decays with B_0 - \bar{B}_0 mixing. The oscillation frequency of B_0 - \bar{B}_0 mixing is characterized by the mass difference Δm_s of the heavy (BH) and light (BL) mass eigenstates. The CP-violating phase ϕ_s is defined as the weak phase difference between the B_0 mixing amplitude and the $b \rightarrow ccs$ decay amplitude. In the absence of CP violation, the BH state would correspond to the CP-odd state and the BL to the CP-even state.

In the SM, the phase ϕ_s is small and can be related to Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix elements via the relation $\phi_s = -2\beta_s$, with $\beta_s = \arg[-(V_{ts}V_{tb})/(V_{cs}V_{cb})]$. Assuming no physics beyond the SM contributions to B_0 mixing and decays, a value of $-2\beta_s = -0.0363^{+0.0016}_{-0.0015}$ rad can be predicted by combining beauty and kaon physics observables [1]. Other physical quantities involved in B_0 - \bar{B}_0 mixing are the decay width $\Gamma_s = (\Gamma_L + \Gamma_H)/2$ and the width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, where Γ_L and Γ_H are the decay widths of the different eigenstates. The width difference is predicted to be $\Delta\Gamma_s = 0.087 \pm 0.021 \text{ ps}^{-1}$ [2]. Physics beyond the SM is not expected to affect $\Delta\Gamma_s$ as significantly as ϕ_s [3]. However, extracting $\Delta\Gamma_s$ from data is interesting as it allows theoretical predictions to be tested [3].

Previous measurements of these quantities have been reported by the DØ, CDF, LHCb, ATLAS, and CMS collaborations [4, 5, 6, 7, 8, 9]. The decay of the pseudoscalar B_0 to the vector-vector $J/\psi (\psi^+ \psi^-) \phi (K^+ K^-)$ final state 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. The same final state can also be produced with $K^+ K^-$ pairs in an S-wave configuration [10]. This S-wave final state is CP-odd. The CP states are separated statistically using an angular analysis of the final-state particles. Flavour tagging is used to distinguish between the initial B_0 and \bar{B}_0 states.

The analysis presented here provides a measurement of the $B_0 \rightarrow J/\psi \phi$ decay parameters using 14.3 fb^{-1} of LHC pp data collected by the ATLAS detector during 2012 at a centre-of-mass energy of 8 TeV. This is an update of the previous flavour-tagged time-dependent angular analysis of $B_0 \rightarrow J/\psi \phi$ [8] that was performed using 4.9 fb^{-1} of data collected at 7 TeV. Electrons are now

included, in addition to final-state muons, for the flavour tagging using leptons.

2 ATLAS Detector and Monte Carlo Simulation

The ATLAS detector [11] is a multi-purpose particle physics detector with a forward-backward symmetric cylindrical geometry and nearly 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 a high-granularity liquid-argon (LAr) sampling electromagnetic calorimeter. A steel/scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward regions are instrumented with LAr calorimeters for 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 collected when both these systems were operating correctly and when the LHC beams were declared to be stable are used in the analysis. The data were collected during a period of rising instantaneous luminosity, and the trigger conditions varied over this time. The triggers used to select events for this analysis are based on identification of a $J/\psi \rightarrow e^+e^-$ decay, with transverse momentum (pT) thresholds of either 4 GeV or 6 GeV for the muons. The measurement uses 14.3 fb^{-1} of pp collision data collected with the ATLAS detector at a centre-of-mass energy of 8 TeV. Data collected at the beginning of the 8 TeV data-taking period are not included in the analysis due to a problem with the trigger tracking algorithm. The trigger was subsequently changed to use a different tracking algorithm that did not have this problem.

To study the detector response, estimate backgrounds, and model systematic effects, 12 million Monte Carlo (MC) simulated $B_0 \rightarrow J/\psi \phi$ events were generated using Pythia 8 [12, 13] tuned with ATLAS data [14]. No pT cuts were applied at the generator level. The detector response was simulated using the ATLAS simulation framework based on GEANT4 [15, 16]. In order to take into account the varying number of proton-proton interactions per bunch crossing (pile-up) and trigger configurations during data-taking, the MC events were weighted to reproduce the same pile-up and trigger conditions in data. Additional samples of the background decay $B_0 \rightarrow J/\psi K_0^*$, as well as the more general $b\bar{b} \rightarrow J/\psi X$ and $pp \rightarrow J/\psi X$ backgrounds, were also simulated using Pythia 8.

3 Reconstruction and Candidate Selection

Events must pass the trigger and the data-quality selections described in Section 2. In addition, each event must contain at least one reconstructed primary vertex, formed from at least four ID tracks, and at least one pair of oppositely charged muon candidates that are reconstructed using information from the MS

and the ID [17]. A muon identified using a combination of MS and ID track parameters is referred to as a combined-muon. A muon formed from a MS track segment that is not associated with a MS track but is matched to an ID track extrapolated to the MS is referred to as a segment-tagged muon.

The muon track parameters are determined from the ID measurement alone, since the precision of the measured track parameters is dominated by the ID track reconstruction in the pT range of interest for this analysis. Pairs of oppositely charged muon tracks are refitted to a common vertex and the pair is accepted for further consideration if the quality of the fit meets the requirement $\chi^2/\text{d.o.f.} < 10$. The invariant mass of the muon pair is calculated from the refitted track parameters. In order to account for varying mass resolution in different parts of the detector, the J/ψ candidates are divided into three subsets according to the pseudorapidity of the muons. A maximum-likelihood fit is used to extract the J/ψ mass and the corresponding mass resolution for these three subsets. When both muons have $|\eta| < 1.05$, the dimuon 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 the decay $\phi \rightarrow K^+K^-$ are reconstructed from all pairs of oppositely charged particles with $pT > 1$ GeV and $|\eta| < 2.5$ that are not identified as muons. Candidate events for $B_0 \rightarrow J/\psi (\pi^+\pi^-)\phi(K^+K^-)$ decays are selected by fitting the tracks for each combination of $J/\psi \rightarrow \pi^+\pi^-$ and $\phi \rightarrow K^+K^-$ to a common vertex. Each of the four tracks is required to have at least one hit in the pixel detector and at least four hits in the silicon microstrip detector. The fit is further constrained by fixing the invariant mass calculated from the two muon tracks to the J/ψ mass [18]. A quadruplet of tracks is accepted for further analysis if the vertex fit has a $\chi^2/\text{d.o.f.} < 3$, the fitted pT of each track from $\phi \rightarrow K^+K^-$ is greater than 1 GeV, and the invariant mass of the track pairs (assuming that they are kaons) falls within the interval $1.0085 \text{ GeV} < m(K^+K^-) < 1.0305 \text{ GeV}$. If there is more than one accepted candidate in the event, the candidate with the lowest $\chi^2/\text{d.o.f.}$ is selected. In total, 375,987 B_0 s candidates are collected within a mass range of 5.150–5.650 GeV.

For each B_0 s meson candidate the proper decay time t is estimated using the expression:

$$t = (L_{xy} \cdot m_B) / p_{TB}$$

where p_{TB} is the reconstructed transverse momentum of the B_0 s meson candidate and m_B denotes the mass of the B_0 s meson, taken from [18]. The transverse decay length, L_{xy} , is the displacement in the transverse plane of the B_0 s meson decay vertex with respect to the primary vertex, projected onto the direction of the B_0 s transverse momentum. The position of the primary vertex used to calculate this quantity is determined from a refit following the removal of the

tracks used to reconstruct the B_0 s meson candidate.

For the selected events the average number of pile-up proton-proton interactions is 21, necessitating a choice of the best candidate for the primary vertex at which the B_0 s meson is produced. The variable used is the three-dimensional impact parameter d_0 , which is calculated as the distance between the line extrapolated from the reconstructed B_0 s momentum and each primary vertex candidate. The chosen primary vertex is the one with the smallest d_0 . A study [19] made using a MC simulated dataset has shown that the precision of the reconstructed B_0 s proper decay time remains stable over the range of pile-up encountered during 2012 data-taking. No B_0 s meson decay-time cut is applied in this analysis.

4 Flavour Tagging

The initial flavour of a neutral B meson can be inferred using information from the opposite-side B meson that contains the other pair-produced b-quark in the event [20, 21]. This is referred to as opposite-side tagging (OST).

To study and calibrate the OST methods, events containing $B_{\pm} \rightarrow J/\psi K_{\pm}$ decays are used, where the flavour of the B_{\pm} -meson is provided by the kaon charge. A sample of $B_{\pm} \rightarrow J/\psi K_{\pm}$ candidates is selected from the entire 2012 dataset satisfying the data-quality selection described in Section 2. Since the OST calibration is not affected by the trigger problem at the start of the 8 TeV data-taking period, the tagging measurement uses 19.5 fb^{-1} of integrated luminosity of pp collision data.

[Figure 1: see original paper]

4.1 $B_{\pm} \rightarrow J/\psi K_{\pm}$ Event Selection

In order to select candidate $B_{\pm} \rightarrow J/\psi K_{\pm}$ decays, firstly J/ψ candidates are selected from pairs of oppositely charged combined-muons forming a good vertex, following the criteria described in Section 3. Each muon is required to have a transverse momentum of at least 4 GeV and pseudorapidity within $|\eta| < 2.5$. The invariant mass of the dimuon candidate is required to satisfy $2.8 < m(\mu^+\mu^-) < 3.4 \text{ GeV}$.

To form the B candidate, an additional track, satisfying the same quality requirements described for tracks in Section 3, is combined with the dimuon candidate using the charged kaon mass hypothesis, and a vertex fit is performed with the mass of the dimuon pair constrained to the known value of the J/ψ mass. To reduce the prompt component of the combinatorial background, a requirement is applied to the transverse decay length of the B candidate of $L_{xy} > 0.1 \text{ mm}$.

A sideband subtraction method is used in order to study parameter distributions corresponding to the B_{\pm} signal processes with the background component subtracted. Events are divided into subsets into five intervals in the pseudorapidity of the B candidate and three mass regions. The mass regions are defined as a signal region around the fitted peak signal mass position $\pm 2\sigma$ and the

sideband regions are defined as $[-5\sigma, -3\sigma]$ and $[+3\sigma, +5\sigma]$, where μ and σ are the mean and width of the Gaussian function describing the B signal mass. Separate binned extended maximum-likelihood fits are performed to the invariant mass distribution in each region of pseudorapidity. An exponential function is used to model the combinatorial background and a hyperbolic tangent function to parameterize the low-mass contribution from incorrectly or partially reconstructed B decays. A Gaussian function is used to model the $B_{\pm} \rightarrow J/\psi \pi_{\pm}$ contribution. The contribution from non-combinatorial background is found to have a negligible effect on the tagging procedure. Figure 1 shows the invariant mass distribution of B candidates for all rapidity regions overlaid with the fit result for the combined data.

[Figure 2: see original paper]

4.2 Flavour Tagging Methods

Several methods that differ in efficiency and discriminating power are available to infer the flavour of the opposite-side b-quark. The measured charge of a muon or electron from a semileptonic decay of the B meson provides strong separation power; however, the $b \rightarrow c$ transitions are diluted through neutral B meson oscillations, as well as by cascade decays $b \rightarrow c \rightarrow s$, which can alter the charge of the lepton relative to those from direct $b \rightarrow c$ decays. The separation power of lepton tagging is enhanced by considering a weighted sum of the charge of the tracks in a cone around the lepton, where the weighting function is determined separately for each tagging method by optimizing the tagging performance. If no lepton is present, a weighted sum of the charge of tracks in a jet associated with the opposite-side B meson decay provides some separation. The flavour tagging methods are described in detail below.

For muon-based tagging, an additional muon is required in the event, with $p_T > 2.5$ GeV, $|\eta| < 2.5$, and with $|\Delta z| < 5$ mm from the primary vertex. Muons are classified according to their reconstruction class, combined or segment-tagged, and subsequently treated as distinct flavour tagging methods. In the case of multiple muons, the muon with the highest transverse momentum is selected.

A muon cone charge variable is constructed, defined as:

$$Q = \left(\sum_i q_i \cdot (p_{Ti})^{\alpha} \right) / \left(\sum_i (p_{Ti})^{\alpha} \right)$$

where q is the charge of the track, $\alpha = 1.1$, and the sum is performed over the reconstructed ID tracks within a cone, $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.5$, around the muon direction. The reconstructed ID tracks must have $p_T > 0.5$ GeV and $|\eta| < 2.5$. Tracks associated with the B_{\pm} signal decay are excluded from the sum. In Figure 2 the opposite-side muon cone charge distributions are shown for candidates from B_{\pm} signal decays.

For electron-based tagging, an electron is identified using information from the inner detector and calorimeter and is required to satisfy the tight electron quality criteria [22]. The inner detector track associated with the electron is required

to have $p_T > 0.5$ GeV and $|\eta| < 2.5$. It is required to pass within $|\Delta z| < 5$ mm of the primary vertex to remove electrons from non-signal interactions. To exclude electrons associated with the signal-side of the decay, electrons are rejected that have momenta within a cone of size $\Delta R = 0.4$ around the signal B candidate direction in the laboratory frame and opening angle between the B candidate and electron momenta, θ , of $\cos(\theta) > 0.98$. In the case of more than one electron passing the selection, the electron with the highest transverse momentum is chosen. As in the case of muon tagging, additional tracks within a cone of size $\Delta R = 0.5$ are used to form the electron cone charge Q_e with $\eta = 1.0$. If there are no additional tracks within the cone, the charge of the electron is used. The resulting opposite-side electron cone charge distribution is shown in Figure 3 for B^+ and B^- signal events.

[Figure 3: see original paper]

In the absence of a muon or electron, b-tagged jets (i.e., jets that are the product of a b-quark) are identified using a multivariate tagging algorithm [23], which is a combination of several b-tagging algorithms using an artificial neural network and outputs a b-tag weight classifier. Jets are selected that exceed a b-tag weight of 0.7. This value is optimized to maximize the tagging power of the calibration sample. Jets are reconstructed from track information using the anti-kt algorithm [24] with a radius parameter $R = 0.8$. In the case of multiple jets, the jet with the highest value of the b-tag weight is used.

The jet charge is defined as:

$$Q_{\text{jet}} = \left(\sum_i q_i \cdot (p_{Ti})^\eta \right) / \left(\sum_i (p_{Ti})^\eta \right)$$

where $\eta = 1.1$ and the sum is over the tracks associated with the jet, excluding those tracks associated with a primary vertex other than that of the signal decay and tracks from the signal candidate. Figure 4 shows the distribution of the opposite-side jet-charge for B_{\pm} signal candidates.

The efficiency, ϵ , of an individual tagging method is defined as the ratio of the number of events tagged by that method to the total number of candidates. A probability $P(B|Q)$ ($P(B|Q)$) that a specific event has a signal decay containing a \bar{b} -quark (b-quark) given the value of the discriminating variable is constructed from the calibration samples for each of the B^+ and B^- samples, which defines $P(Q|B^+)$ and $P(Q|B^-)$, respectively. The probability to tag a signal event as containing a \bar{b} -quark is therefore $P(B|Q) = P(Q|B^+) / (P(Q|B^+) + P(Q|B^-))$, and correspondingly $P(B|Q) = 1 - P(B|Q)$. It is possible to define a quantity called the dilution $D = P(B|Q) - P(\bar{B}|Q) = 2P(B|Q) - 1$, which represents the strength of a particular flavour tagging method. The tagging power of a particular tagging method is defined as $T = D^2 = \sum_i \epsilon_i \cdot (2P_i(B|Q_i) - 1)^2$, where the sum is over the bins of the probability distribution as a function of the charge variable. An effective dilution, $D = \sqrt{T/\epsilon}$, is calculated from the measured tagging power and efficiency.

The flavour tagging method applied to each B_0 s candidate event is taken from

the information contained in a given event. By definition there is no overlap between lepton-tagged and jet-charge-tagged events. The overlap between muon- and electron-tagged events, corresponding to 0.4% of all tagged events, is negligibly small. In the case of doubly tagged events, the tagger with the highest tagging power is selected; however, the choice of hierarchy between muon- and electron-tagged events is shown to have negligible impact on the final fit results. If it is not possible to provide a tagging response for the event, then a probability of 0.5 is assigned. A summary of the tagging performance is given in Table 1.

4.3 Using Tag Information in the B0s Fit

The tag-probability for each B0s candidate is determined from calibrations derived from a sample of $B_{\pm} \rightarrow J/K_{\pm}$ candidates, as described in Section 4.2. The distributions of tag-probabilities for the signal and background are different and since the background cannot be factorized out, additional probability terms, $P_s(P(B|Q))$ and $P_b(P(B|Q))$ for signal and background, respectively, are included in the fit. The distributions of tag-probabilities for the B0s candidates consist of continuous and discrete parts (events with a tag charge of ± 1); these are treated separately as described below.

To describe the continuous part, a fit is first performed to the sideband data, i.e., $5.150 < m(B0s) < 5.317$ GeV or $5.417 < m(B0s) < 5.650$ GeV, where $m(B0s)$ is the mass of the B0s candidate. Different functions are used for the different tagging methods. For the combined-muon tagging method, the function has the form of the sum of a fourth-order polynomial and two exponential functions. A second-order polynomial and two exponential functions are applied for the electron tagging algorithm. A sum of three Gaussian functions is used for the segment-tagged muons. For the jet-charge tagging algorithm an eighth-order polynomial is used. In all four cases unbinned maximum-likelihood fits to data are used. In the next step, the same function as applied to the sidebands is used to describe the distributions for events in the signal region: the background parameters are fixed to the values obtained from the fits to the sidebands while the signal parameters are free in this step. The ratio of background to signal (obtained from a simultaneous mass-lifetime fit) is fixed as well. The results of the fits projected onto histograms of B0s tag-probability for the different tagging methods are shown in Figure 5.

To account for possible deviations between data and the selected fit models, a number of alternative fit functions are used to determine systematic uncertainties in the B0s fit. These fit variations are described in Section 7.

The discrete components of the tag-probability distribution originate from cases where the tag is derived from a single track, giving a tag charge of exactly +1 or -1. The fractions of events f_{+1} and f_{-1} with charges +1 and -1, respectively, are determined separately for signal and background using events from the same B0s mass signal and sideband regions. Positive and negative charges are equally

probable for background candidates formed from a random combination of a J/ψ and a pair of tracks, but this is not the case for background candidates formed from a partially reconstructed b-hadron. For signal and background contributions, similar fractions of events that are tagged with +1 or -1 tagging charge are observed for each of the tagging methods. The remaining fraction of events, $1 - f_1 - \bar{f}_1$, constitute the continuous part of the distributions. Table 2 summarizes the fractions f_1 and \bar{f}_1 obtained for signal and background events and for the different tag methods.

To estimate the fractions of signal and background events which have tagging, a similar sideband-subtraction method is used to determine the relative fraction of signal and background events tagged using the different methods. These fractions are also included in the maximum-likelihood fit, described in Section 5. The results are summarized in Table 3.

[Figure 5: see original paper]

5 Maximum Likelihood Fit

An unbinned maximum-likelihood fit is performed on the selected events to extract the parameter values of the $B^0 \rightarrow J/\psi(K^+K^-)$ decay. The fit uses information about the reconstructed mass values of the B^0 meson m , the measured proper decay time t , the measured proper decay time uncertainty σ_t , the tagging probability, and the transversity angles Ω of each $B^0 \rightarrow J/\psi$ decay candidate. The measured proper decay time uncertainty σ_t is calculated from the covariance matrix associated with the vertex fit of each candidate event. The transversity angles $\Omega = (\theta, \phi, \phi_T)$ are defined in Section 5.1. The likelihood is independent of the K^+K^- mass distribution. The likelihood function is defined as a combination of the signal and background probability density functions as follows:

$$\ln L = \sum_{i=1}^N \{ w_i \cdot \ln(f_i \cdot F(m_i, t_i, \sigma_{t_i}, \Omega_i, P(B|Q), pT_i) + f_{B0} \cdot FB0(m_i, t_i, \sigma_{t_i}, \Omega_i, P(B|Q), pT_i) + (1 - f_i - f_{B0}) F_{bkg}(m_i, t_i, \sigma_{t_i}, \Omega_i, P(B|Q), pT_i)) \}$$

where N is the number of selected candidates, w_i is a weighting factor to account for the trigger efficiency (described in Section 5.3), f_i is the fraction of signal candidates, and f_{B0} is the fraction of B^0 mesons mis-identified as B^0 candidates calculated relative to the number of signal events; this parameter is fixed to its MC value and varied as part of the systematic uncertainties. The mass m , the proper decay time t , and the decay angles Ω are the values measured from the data for each event i . F , $FB0$, and F_{bkg} are the probability density functions (PDF) modelling the signal, the specific B^0 background, and the other background distributions, respectively. A detailed description of the signal PDF terms in Equation (1) is given in Section 5.1. The two background functions are described in Section 5.2.

5.1 Signal PDF

The PDF used to describe the signal events, F , has the following composition:

$$F(m, t, \sigma t, \Omega, P(B|Q), pT) = P(m) \cdot P(\Omega, t, P(B|Q), \sigma t) \cdot P(\sigma t) \cdot P(P(B|Q)) \cdot A(\Omega, pT) \cdot P(pT)$$

The mass function $P(m)$ is modelled by a sum of three Gaussian distributions. The probability terms $P(\sigma t)$ and $P(pT)$ are described by gamma functions and are unchanged from the analysis described in Ref. [25]. The tagging probability term for signal $P(P(B|Q))$ is described in Section 4.3.

The term $P(\Omega, t, P(B|Q), \sigma t)$ is a joint PDF for the decay time t and the transversity angles Ω for the $B_0s \rightarrow J/\psi(\psi')\phi(K^+K^-)$ decay. Ignoring detector effects, the distribution for the time t and the angles Ω is given by the differential decay rate [26]:

$$d^2N/(dt d\Omega) = \sum_i^{10} O^{(i)}(t) g^{(i)}(\theta, \phi, \psi)$$

where $O^{(i)}(t)$ are the time-dependent functions corresponding to the contributions of the four different amplitudes ($A_0, A_+, A_-,$ and AS) and their interference terms, and $g^{(i)}(\theta, \phi, \psi)$ are the angular functions. Table 4 shows these time-dependent functions and the angular functions of the transversity angles. The formulae for the time-dependent functions have the same structure for B_0 s but with a sign reversal in the terms containing Δm_s . In Table 4, the parameter $A(t)$ is the time-dependent amplitude for the CP-odd final-state configuration while $A_0(t)$ and $A_+(t)$ correspond to CP-even final-state configurations. The amplitude $AS(t)$ gives the contribution from the CP-odd non-resonant $B_0s \rightarrow J/\psi K^+K^-$ S-wave state (which includes the f_0). The corresponding functions are given in the last four lines of Table 4 ($k = 7-10$). The amplitudes are parameterized by $|A_i|e^{i\delta_i}$, where $i = \{0, +, -, S\}$, with $\delta_0 = 0$ and are normalized such that $|A_0(0)|^2 + |A_+(0)|^2 + |A_-(0)|^2 = 1$. $|A_-(0)|$ is determined according to this condition, while the remaining three amplitudes are parameters of the fit. The formalism used throughout this analysis assumes no direct CP violation.

The angles (θ, ϕ, ψ) 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, and the K^+K^- system defines the x-y plane, where $p_y(K^+) > 0$. The three angles are defined as: θ - θ , the angle between $p(\psi')$ and the normal to the x-y plane, in the J/ψ meson rest frame - ϕ , the angle between the x-axis and $p_{xy}(\psi')$, the projection of the ψ' momentum in the x-y plane, in the J/ψ meson rest frame - ψ , the angle between $p(K^+)$ and $-p(J/\psi)$ in the ϕ meson rest frame

The PDF term $P(\Omega, t, P(B|Q), \sigma t)$ takes into account the lifetime resolution, so each time element in Table 4 is smeared with a Gaussian function. This smearing is performed numerically on an event-by-event basis where the width of the Gaussian function is the proper decay time uncertainty, measured for each event, multiplied by a scale factor to account for any mis-measurements.

The angular sculpting of the detector and kinematic cuts on the angular distri-

butions are included in the likelihood function through $A(\Omega, p_T)$. This is calculated from the $B_0s \rightarrow J/\psi \phi$ MC events using a 4D binned acceptance method, applying an event-by-event efficiency according to the transversity angles ($T, T, \phi T$) and the p_T of the candidate. The p_T binning is necessary because the angular sculpting is influenced by the p_T of the B_0s candidate. Taking the small discrepancies between data and MC events into account has negligible effect on the fit results. In the likelihood function, the acceptance is treated as an angular sculpting PDF, which is multiplied with the time- and angle-dependent PDF describing the $B_0s \rightarrow J/\psi(K^+K^-)$ decays. As both the acceptance and time- and angle-dependent decay PDFs depend on the transversity angles they must be normalized together. This normalization is done numerically during the likelihood fit. The PDF is normalized over the entire B_0s mass range 5.150–5.650 GeV.

5.2 Background PDF

The background PDF has the following composition:

$$F_{\text{bkg}}(m, t, \sigma t, \Omega, P(B|Q), p_T) = P_b(m) \cdot P_b(t|\sigma t) \cdot P_b(P(B|Q)) \cdot P_b(\Omega) \cdot P_b(\sigma t) \cdot P_b(p_T)$$

The proper decay time function $P_b(t|\sigma t)$ is parameterized as a prompt peak modelled by a Gaussian distribution, two positive exponential functions, and a negative exponential function. These functions are 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 lifetimes distributed around zero. The two positive exponential functions represent a fraction of longer-lived backgrounds with non-prompt J/ψ , combined with hadrons from the primary vertex or from a B/D meson in the same event. The negative exponential function takes into account events with poor vertex resolution. The probability terms $P_b(\sigma t)$ and $P_b(p_T)$ are described by gamma functions. They are unchanged from the analysis described in Ref. [25] and explained in detail there. The tagging probability term for background $P_b(P(B|Q))$ is described in Section 4.3.

The shape of the background angular distribution, $P_b(\Omega)$, arises primarily from detector and kinematic sculpting effects. These are described by Legendre polynomial functions:

$$P_b(T, T, \phi T) = \sum_{m=0}^6 a_m \cdot \sqrt{((1-|m|)!/(1+|m|)!)} \cdot P^{|m|}(\cos T) \cdot P(\cos T) \cdot \begin{cases} \cos(m\phi T) & \text{if } m > 0; \\ \sin(|m|\phi T) & \text{if } m < 0; \\ 1 & \text{if } m = 0 \end{cases}$$

where the coefficients a_m , are adjusted to give the best fit to the angular distributions for events in the B_0s mass sidebands. These parameters are then fixed in the main fit. The B_0s mass interval used for the background fit is between 5.150 and 5.650 GeV excluding the signal mass region $|m(B_0s) - 5.366 \text{ GeV}| < 0.110 \text{ GeV}$. The background mass model, $P_b(m)$, is an exponential function with a constant term added.

Contamination from $B_d \rightarrow J/\psi K^*0$ events mis-reconstructed as $B^0s \rightarrow J/\psi \phi$ are accounted for in the fit through the FB0 term in the PDF function described in Equation (1). The fraction of this contribution, $f_{B0} = (3.3 \pm 0.5)\%$, is evaluated from MC simulation using production and branching fractions from Refs. [18, 27, 28]. MC simulated events are also used to determine the shape of the mass and transversity angle distributions of $B_d \rightarrow J/\psi K^*0$ and its conjugate decay. These shapes are modelled using input from Ref. [29] and are described by Legendre polynomial functions, Equation (4), as in the case of the background described by formula (3). These shapes are fixed in the fit. The B_d lifetime is accounted for in the fit by adding an additional exponential term, scaled by the ratio of B_d/B^0s masses, where the B_d lifetime and mass are taken from Ref. [18].

Systematic uncertainties due to the background from $B_d \rightarrow J/\psi K^*0$ decays are described in Section 7. The contribution of $B_d \rightarrow J/\psi K\pi$ events as well as their interference with $B_d \rightarrow J/\psi K^*0$ events is not included in the fit and is instead assigned as a systematic uncertainty.

To account for possible deviations between data and the selected fit models, a number of alternative fit functions and mass selection criteria are used to determine systematic uncertainties in the B^0s fit. These fit variations are described in Section 7.

5.3 Muon Trigger Proper Time-Dependent Efficiency

It was observed that the muon trigger biases the transverse impact parameter of muons, resulting in a minor inefficiency at large values of the proper decay time. This inefficiency is measured using MC simulated events, by comparing the B^0s proper decay time distribution of an unbiased sample with the distribution obtained including the trigger. To account for this inefficiency in the fit, the events are re-weighted by a factor w :

$$w = p_0 \cdot [1 - p_1 \cdot (\text{Erf}((t - p_3)/p_2) + 1)]$$

where p_0 , p_1 , p_2 , and p_3 are parameters determined in the fit to MC events.

6 Results

The full simultaneous unbinned maximum-likelihood fit contains nine physical parameters: $\Delta\Gamma_s$, ϕ_s , Γ_s , $|A_0(0)|^2$, $|A(0)|^2$, δ , δ , $|AS(0)|^2$, and δS . The other parameters in the likelihood function are the B^0s signal fraction f_s , parameters describing the $J/\psi \phi$ mass distribution, parameters describing the decay time plus angular distributions of background events, parameters used to describe the estimated decay time uncertainty distributions for signal and background events, and scale factors between the estimated decay time uncertainties and their true uncertainties. In addition, there are also 353 nuisance parameters describing the background and acceptance functions that are fixed at the time of the fit.

Multiplying the total number of events supplied to the fit with the extracted signal fraction and its statistical uncertainty provides an estimate for the total number of B_0 s meson candidates of 74900 ± 400 . The results and correlations of the physics parameters obtained from the fit are given in Tables 5 and 6. Fit projections of the mass, proper decay time, and angles are given in Figures 6 and 7, respectively.

[Figure 6: see original paper] [Figure 7: see original paper]

7 Systematic Uncertainties

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

- **Flavour tagging:** There are two contributions to the uncertainties in the fit parameters due to the flavour tagging procedure, the statistical and systematic components. The statistical uncertainty due to the size of the sample of $B_{\pm} \rightarrow J/K_{\pm}$ decays is included in the overall statistical error. The systematic uncertainty arising from the precision of the tagging calibration is estimated by changing the model used to parameterize the probability distribution, $P(B|Q)$, as a function of tag charge from the third-order polynomial function used by default to one of several alternative functions. The alternatives used are: a linear function; a fifth-order polynomial; or two third-order polynomials describing the positive and negative regions that share the constant and linear terms but have independent quadratic and cubic terms. For the combined-muon tagging, an additional model consisting of two third-order polynomials sharing the constant term but with independent linear, quadratic, and cubic terms is also used. The B_0 s fit is repeated using the alternative models and the largest difference is assigned as the systematic uncertainty.
- **Angular acceptance method:** The angular acceptance (from the angular sculpting mentioned in Section 5.1) is calculated from a binned fit to MC simulated data. In order to estimate the size of the systematic uncertainty introduced from the choice of binning, different acceptance functions are calculated using different bin widths and central values. These effects are found to be negligible.
- **Inner detector alignment:** Residual misalignments of the ID affect the impact parameter, d_0 , distribution with respect to the primary vertex. The effect of a radial expansion on the measured d_0 is determined from data collected at 8 TeV, with a trigger requirement of at least one muon with a transverse momentum greater than or equal to 4 GeV. The radial expansion uncertainties determined in this way are 0.14% for $|\eta| < 1.5$ and 0.55% for $1.5 < |\eta| < 2.5$. These values are used to estimate the effect on the fitted B_0 s parameter values. Small deviations are seen in some parameters, and these are included as systematic uncertainties.

- **Trigger efficiency:** To correct for the trigger lifetime bias the events are re-weighted according to Equation (5). The uncertainty of the parameters p_0 , p_1 , p_2 , and p_3 are used to estimate the systematic uncertainty due to the time efficiency correction. These uncertainties originate from the following sources: the limited size of the MC simulated dataset, the choice of bin-size for the proper decay time distributions, and variations between different triggers. The systematic effects are found to be negligible.
- **Background angles model, choice of pT bins:** The shape of the background angular distribution, $P_b(\theta, \phi, p_T)$, is described by the Legendre polynomial functions given in Equation (4). The shapes arise primarily from detector and kinematic sculpting effects and are sensitive to the p_T of the B_0 s meson candidate. For this reason, the parameterization using the Legendre polynomial functions is performed in four p_T intervals: 0–13 GeV, 13–18 GeV, 18–25 GeV, and >25 GeV. The systematic uncertainties due to the choice of p_T intervals are estimated by repeating the fit, varying these intervals. The biggest deviations observed in the fit results were taken to represent the systematic uncertainties.
- **Background angles model, choice of mass sidebands:** The parameters of the Legendre polynomial functions given in Equation (4) are adjusted to give the best fit to the angular distributions for events in the B_0 s mass sidebands. To test the sensitivity of the fit results to the choice of sideband regions, the fit is repeated with alternative choices for the excluded signal mass regions: $|m(B_0s) - 5.366| > 0.085$ GeV and $|m(B_0s) - 5.366| > 0.160$ GeV (instead of $|m(B_0s) - 5.366| > 0.110$ GeV). The differences in the fit results are assigned as systematic uncertainties.
- **Bd contribution:** The contamination from $B_d \rightarrow J/\psi K_0^*$ events misreconstructed as $B_0s \rightarrow J/\psi \phi$ is accounted for in the final fit. Studies are performed to evaluate the effect of the uncertainties in the $B_d \rightarrow J/\psi K_0^*$ fraction, and the shapes of the mass and transversity angles distribution. In the MC events the angular distribution of the $B_d \rightarrow J/\psi K_0^*$ decay is modelled using parameters taken from Ref. [29]. The uncertainties of these parameters are taken into account in the estimation of systematic uncertainty. After applying the B_0 s signal selection cuts, the angular distributions are fitted using Legendre polynomial functions. The uncertainties of this fit are included in the systematic tests. The impact of all these uncertainties is found to have a negligible effect on the B_0 s fit results. The contribution of $B_d \rightarrow J/\psi K\pi$ events as well as their interference with $B_d \rightarrow J/\psi K_0^*$ events is not included in the fit and is instead assigned as a systematic uncertainty. To evaluate this uncertainty, the MC background events are modelled using both the P-wave $B_d \rightarrow J/\psi K_0^*$ and S-wave $B_d \rightarrow J/\psi K\pi$ decays and their interference, using the input parameters taken from Ref. [29]. The B_0 s fit using this input was compared to the default fit, and differences are included in Table 7.
- **Fit model variations:** To estimate the systematic uncertainties due to

the fit model, variations of the model are tested in pseudo-experiments. A set of 2500 pseudo-experiments is generated for each variation considered, and fitted with the default model. The systematic error quoted for each effect is the difference between the mean shift of the fitted value of each parameter from its input value for the pseudo-experiments altered for each source of systematic uncertainty.

In the first variation tested, the signal mass is generated using the fitted B_0 s mass convolved with a Gaussian function using the measured per-candidate mass errors. In another test, the background mass is generated from an exponential function with the addition of a first-degree polynomial function instead of an exponential function plus a constant term. The time resolution model was varied by using two different scale factors to generate the lifetime uncertainty, instead of the single scale factor used in the default model. The non-negligible uncertainties derived from these tests are included in the systematic uncertainties shown in Table 7. To determine the possible systematic effects of mis-modelling of the background events by the fitted background model, as seen in the low mass side-band region (5.150–5.210 GeV) of Figure 6 (left), alternative mass selection cuts are used with the default fit model. The effect of these changes on the fit results are found to be negligible.

- **Default fit model:** Due to its complexity, the fit model is less sensitive to some nuisance parameters. This limited sensitivity could potentially lead to a bias in the measured physics parameters, even when the model perfectly describes the fitted data. To estimate the systematic uncertainty due to the choice of default fit model, a set of pseudo-experiments were conducted using the default model in both the generation and fit. The systematic uncertainties are determined from the variations in the measured physics parameters in the same way as for the previous cases.

The systematic uncertainties are listed in Table 7. For each parameter, the total systematic error is obtained by adding all of the contributions in quadrature.

8 Discussion

The PDF describing the B_0 s $\rightarrow J/\psi \phi$ decay is invariant under the following simultaneous transformations:

$$\{\phi_s, \Delta\Gamma_s, \delta, \delta\} \rightarrow \{\pi - \phi_s, -\Delta\Gamma_s, \pi - \delta, 2\pi - \delta\}$$

Since $\Delta\Gamma_s$ was determined to be positive [30], there is a unique solution. Figure 8 shows the 1D log-likelihood scans of ϕ_s , $\Delta\Gamma_s$, and of the three measured strong phases δ , δ , and $\delta - \delta_S$. The variable on the vertical axis, $2\Delta\ln(L) = 2(\ln(L_G) - \ln(L_i))$, is a difference between the likelihood values of a default fit (LG) and of the fit in which the physical parameter is fixed to a value shown on the horizontal axis (Li). $2\Delta\ln(L) = 1$ corresponds to the estimated 1σ confidence level. There are small asymmetries in the likelihood curves; however, at the level of one statistical σ these are small compared to the corresponding

statistical uncertainties of the physical variables, for which the scan is done. Therefore, symmetric statistical uncertainties are quoted. Figure 9 shows the likelihood contours in the ϕ_s - $\Delta\Gamma_s$ plane. The region predicted by the Standard Model is also shown.

[Figure 8: see original paper] [Figure 9: see original paper]

9 Combination of 7 TeV and 8 TeV Results

The measured values are consistent with those obtained in a previous analysis [8], using ATLAS data collected in 2011 at a centre-of-mass energy of 7 TeV. This consistency is also clear from a comparison of the likelihood contours in the ϕ_s - $\Delta\Gamma_s$ projection shown in Figure 10. A Best Linear Unbiased Estimate (BLUE) combination [31] is used to combine the 7 TeV and 8 TeV measurements to give an overall result for Run 1. In Ref. [8] the strong phases δ and $\delta - \delta_S$ were given as 1σ confidence intervals. These are not considered in the combination and the 8 TeV result is taken as the Run 1 result.

The BLUE combination requires the measured values and uncertainties of the parameters in question as well as the correlations between them. These are provided by the fits separately in the 7 TeV and 8 TeV measurements. The statistical correlation between these two measurements is zero as the events are different. The correlations of the systematic uncertainties between the two measurements are estimated by splitting the uncertainty into several categories.

The trigger efficiency was included as systematic uncertainties only in the 7 TeV measurement, so there is no correlation with the 8 TeV measurement. Similarly, the systematic uncertainties arising from the choice of pT bins and the choice of mass sidebands in the modelling of background angles are included as systematic uncertainties only in the 8 TeV measurement, so there is no correlation with the 7 TeV measurement. In both the 7 TeV and 8 TeV results, a systematic uncertainty is assigned to the inner detector alignment and Bd contribution. The inner detector alignment systematic uncertainties are highly correlated and small. The assumed correlation between these systematics made no difference to the final combined result and was set to 100%. For the Bd contribution, while the systematic uncertainty tests are different, they are both performed to account for an imprecise knowledge of the Bd contribution and are therefore assumed to be 100% correlated.

The tagging, acceptance, and fit model uncertainties are quoted for both 7 TeV and 8 TeV. For the fit model, there are several different model variations each with their own uncertainty. For each year, these are summed in quadrature to produce a single fit model systematic uncertainty. The tagging, acceptance, and fit model systematic uncertainties are each assigned a variable ρ_i , where $i = \text{tag, acc, mod}$ corresponding to the correlation between the 7 TeV and 8 TeV results. Several different combinations were tried with different values of $\rho_i = 0, 0.25, 0.5, 0.75, 1.0$. The acceptance systematic uncertainty is small and therefore regardless of what value of ρ_{acc} is chosen the combination stays

the same. For the 8 TeV measurement, electron tagging is added; therefore the systematic uncertainty is not 100% correlated. For $\text{tag} = 0.25, 0.5, 0.75$ there is negligible difference between the results. The fit model was changed between the 7 TeV and 8 TeV measurement; the most significant change is that the mass uncertainty modelling was removed and the event-by-event Gaussian error distribution was replaced with a sum of three Gaussian distributions. It would be incorrect to estimate the correlation as 100% and there is negligible difference between the results for $\text{mod} = 0.25, 0.5, 0.75$.

The combined results for the fit parameters and their uncertainties for Run 1 are given in Table 8. The Run 1 likelihood contours in the ϕ s- $\Delta\Gamma$ s plane are shown in Figure 10. They agree with the Standard Model predictions.

[Figure 10: see original paper]

10 Summary

A measurement of the time-dependent CP asymmetry parameters in B_0 s $\rightarrow J/\psi(K^+K^-)$ decays from a 14.3 fb^{-1} data sample of pp collisions collected with the ATLAS detector during the 8 TeV LHC run is presented. The values from the 8 TeV analysis are consistent with those obtained in the previous analysis using 7 TeV ATLAS data [8]. The two measurements are statistically combined, leading to the following results:

$$\begin{aligned} \phi_s &= -0.098 \pm 0.084 \text{ (stat.)} \pm 0.040 \text{ (syst.) rad} \\ \Delta\Gamma_s &= 0.083 \pm 0.011 \text{ (stat.)} \pm 0.007 \text{ (syst.) ps}^{-1} \\ \Gamma_s &= 0.677 \pm 0.003 \text{ (stat.)} \pm 0.003 \text{ (syst.) ps}^{-1} \\ |A(0)|^2 &= 0.227 \pm 0.004 \text{ (stat.)} \pm 0.006 \text{ (syst.)} \\ |A_0(0)|^2 &= 0.514 \pm 0.004 \text{ (stat.)} \pm 0.003 \text{ (syst.)} \\ |AS(0)|^2 &= 0.071 \pm 0.007 \text{ (stat.)} \pm 0.017 \text{ (syst.)} \\ \delta &= 4.13 \pm 0.33 \text{ (stat.)} \pm 0.16 \text{ (syst.) rad} \\ \delta &= 3.15 \pm 0.13 \text{ (stat.)} \pm 0.05 \text{ (syst.) rad} \\ \delta - \delta_S &= -0.08 \pm 0.04 \text{ (stat.)} \pm 0.01 \text{ (syst.) rad} \end{aligned}$$

The ATLAS Run 1 results for the B_0 s $\rightarrow J/\psi$ decay are consistent with the SM.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and

Lundbeck Foundation, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America.

In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d' Avenir Labex and Idex, ANR, Region Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

References

- [1] J. Charles et al., Predictions of selected flavor observables within the standard model, *Phys. Rev. D* 84 (2011) 033005.
- [2] A. Lenz and U. Nierste, Numerical Updates of Lifetimes and Mixing Parameters of B Mesons, arXiv:1102.4274 [hep-ph].
- [3] A. Lenz and U. Nierste, Theoretical update of B_0 s- B_0 s mixing, *JHEP* 0706 (2007) 072, arXiv:hep-ph/0612167 [hep-ph].
- [4] D0 Collaboration, V. M. Abazov et al., Measurement of the CP-violating phase ϕ_J/ϕ using the flavor-tagged decay B_0 s $\rightarrow J/\phi$ in 8 fb^{-1} of $\bar{p}p$ collisions, *Phys. Rev. D* 85 (2012) 032006, arXiv:1109.3166 [hep-ex].
- [5] CDF Collaboration, T. Aaltonen et al., Measurement of the Bottom-Strange Meson Mixing Phase in the Full CDF Data Set, *Phys. Rev. Lett.* 109 (2012) 171802, arXiv:1208.2967 [hep-ex].
- [6] LHCb Collaboration, R. Aaij et al., Measurement of CP violation and the B_0 s meson decay width difference with B_0 s $\rightarrow J/\psi K^+K^-$ and B_0 s $\rightarrow J/\psi \pi^+\pi^-$ decays, *Phys. Rev. D* 87, 112010 (2013), arXiv:1304.2600 [hep-ex].
- [7] LHCb Collaboration, R. Aaij et al., Precision measurement of CP violation in B_0 s $\rightarrow J/\psi K^+K^-$ decays, *Phys. Rev. Lett.* 114 (2015) 041801, arXiv:1411.3104

- [hep-ex].
- [8] ATLAS Collaboration, Flavour tagged time dependent angular analysis of the $B_s \rightarrow J/\psi \phi$ decay and extraction of $\Delta\Gamma$ and the weak phase ϕ_s in ATLAS, Phys. Rev. D90 (2014) 052007, arXiv:1407.1796 [hep-ex].
- [9] CMS Collaboration, Measurement of the CP-violating weak phase ϕ_s and the decay width difference $\Delta\Gamma_s$ using the $B_0 \rightarrow J/\psi(1020)$ decay channel at $\sqrt{s} = 8$ TeV, Submitted to Phys. Lett. B (2015), arXiv:1507.07527v1 [hep-ex].
- [10] S. Stone and L. Zhang, S-waves and the measurement of CP violating phases in Bs decays, Phys. Rev. D 79 (2009) 074024.
- [11] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.
- [12] T. Sjöstrand, S. Mrenna, and P. Z. Skands, PYTHIA 6.4 Physics and Manual, JHEP 0605 (2006) 026, arXiv:hep-ph/0603175 [hep-ph].
- [13] T. Sjöstrand, S. Mrenna, and P. Z. Skands, A Brief Introduction to PYTHIA 8.1, Comput. Phys. Commun. 178 (2008) 852–867, arXiv:0710.3820 [hep-ph].
- [14] ATLAS Collaboration, ATLAS tunes of PYTHIA 6 and Pythia 8 for MC11, Tech. Rep. ATL-PHYS-PUB-2011-009, CERN, Geneva, Jul, 2011.
- [15] ATLAS Collaboration, The ATLAS Simulation Infrastructure, Eur. Phys. J. C70 (2010) 823–874, arXiv:1005.4568 [physics.ins-det].
- [16] GEANT4 Collaboration, S. Agostinelli et al., GEANT4: A Simulation toolkit, Nucl. Instrum. Meth. A506 (2003) 250–303.
- [17] ATLAS Collaboration, Measurement of the differential cross-sections of inclusive, prompt and non-prompt J/ψ production in proton-proton collisions at $\sqrt{s} = 7$ TeV, Nucl. Phys. B850 (2011) 387–444, arXiv:1104.3038 [hep-ex].
- [18] Particle Data Group Collaboration, K. A. Olive et al., Review of Particle Physics, Chin. Phys. C38 (2014) 090001.
- [19] ATLAS Collaboration, ATLAS B-physics studies at increased LHC luminosity, potential for CP-violation measurement in the $B_0 \rightarrow J/\psi \phi$ decay, Tech. Rep. ATL-PHYS-PUB-2013-010, CERN, Geneva, Sep, 2013.
- [20] R. Field and R. Feynman, A Parametrization of the Properties of Quark Jets, Nucl. Phys. B136 (1978) 1.
- [21] ATLAS Collaboration, Jet charge studies with the ATLAS detector using 8 TeV pp collisions data, Tech. Rep. ATLAS-CONF-2013-086, CERN, Geneva, August, 2013.
- [22] ATLAS Collaboration, Electron performance measurements with the ATLAS detector using the 2010 LHC proton-proton collision data, Eur. Phys. J. C72 (2012) 1909, arXiv:1110.3174 [hep-ex].
- [23] ATLAS Collaboration, Calibration of the performance of b-tagging for c and light-flavour jets in the 2012 ATLAS data, Tech. Rep. ATLAS-CONF-2014-046, CERN, Geneva, Jul, 2014.
- [24] M. Cacciari, G. P. Salam, and G. Soyez, The Anti-k(t) jet clustering algorithm, JHEP 0804 (2008) 063, arXiv:0802.1189 [hep-ph].
- [25] ATLAS Collaboration, Time-dependent angular analysis of the decay $B_0 \rightarrow J/\psi \phi$ and extraction of $\Delta\Gamma_s$ and the CP-violating weak phase ϕ_s by ATLAS, JHEP 1212 (2012) 072, arXiv:1208.0572 [hep-ex].

- [26] A. S. Dighe, I. Dunietz, and R. Fleischer, Extracting CKM phases and B0s mixing parameters from angular distributions of nonleptonic B decays, Eur. Phys. J. C6 (1999) 647–662, arXiv:hep-ph/9804253 [hep-ph].
- [27] LHCb Collaboration, R. Aaij et al., Updated average fs/fd b-hadron production fraction ratio for 7 TeV pp collisions.
- [28] BABAR Collaboration, B. Aubert et al., Search for the $Z(4430)^-$ at BABAR, Phys. Rev. 79 (2009) 112001, arXiv:0811.0564 [hep-ex].
- [29] LHCb Collaboration, R. Aaij et al., Measurement of the polarization amplitudes in $B^0 \rightarrow J/K^*(892)^0$ decays, Phys. Rev. D 88 (2013) 052002, arXiv:1307.2782 [hep-ex].
- [30] LHCb Collaboration, R. Aaij et al., Determination of the sign of the decay width difference in the B0s system, Phys. Rev. Lett. 108 (2012) 241801, arXiv:1202.4717 [hep-ex].
- [31] R. Nisius, On the combination of correlated estimates of a physics observable, Eur. Phys. J. C 74 (2014) 1–20.

The ATLAS Collaboration

G. Aad et al.

Affiliations are listed at the end of the paper

Note: The author list and affiliations have been truncated for brevity. The complete list is available in the original publication.

Affiliations

34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

37 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy

38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

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, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

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 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

72 Physics Department, Lancaster University, Lancaster, United Kingdom

73 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy

80 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

90 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

91 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy

92 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

93 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

94 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

99 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia

103 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

104 (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy

105 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America

106 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

107 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America

120 Department of Physics, Oxford University, Oxford, United Kingdom

121 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy

123 National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia

124 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America

126 (a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

132 (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, 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 Matematica e 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 à l' Energie Atomique et aux Energies Alternatives),

Gif-sur-Yvette, France

137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

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 Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden

148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, 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

163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

164 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

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

178 Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

a Also at Department of Physics, King' s College London, London, United Kingdom

b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

c Also at Novosibirsk State University, Novosibirsk, Russia

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 Department of Physics, University of Fribourg, Fribourg, Switzerland

g Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal

h Also at Tomsk State University, Tomsk, Russia

i Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

j Also at Università di Napoli Parthenope, Napoli, Italy

k Also at Institute of Particle Physics (IPP), Canada

l Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

m Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia

n Also at Louisiana Tech University, Ruston LA, United States of America

o Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain

p Also at Graduate School of Science, Osaka University, Osaka, Japan

q Also at Department of Physics, National Tsing Hua University, Taiwan

r Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America

s Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia

t Also at CERN, Geneva, Switzerland

u Also at Georgian Technical University (GTU), Tbilisi, Georgia

v Also at Manhattan College, New York NY, United States of America

w Also at Hellenic Open University, Patras, Greece

x Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

y Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France

z Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

aa Also at School of Physics, Shandong University, Shandong, China

ab Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia

ac Also at Section de Physique, Université de Genève, Geneva, Switzerland

ad Also at International School for Advanced Studies (SISSA), Trieste, Italy

ae Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

af Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China

ag Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia

ah Also at National Research Nuclear University MEPhI, Moscow, Russia

ai Also at Department of Physics, Stanford University, Stanford CA, United States of America

aj Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

ak Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

al Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

- Deceased

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.