Mixing and CP Violation in the $B_d$ and $B_s$ Systems at ATLAS

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Abstract. This note includes a measurement of the $B^0_s$ decay parameters in the $B_s \to J/\psi \phi$ channel and a measurement of the $B^0_s$ meson proper decay time and decay width using the statistics collected by the ATLAS experiment in Run I of the LHC. The first result presents the measurement of the CP-violating phase $\phi_s$, the decay width $\Gamma_s$ and the width difference between the mass eigenstates $\Delta \Gamma_s$. The second result presents the measurement of the width difference $\Delta \Gamma_d$, which is extracted from the measurement of the lifetime dependence of $B^0 \to J/\psi K_S$ and $B^0 \to J/\psi K^*0$ decays. The obtained results are $\phi_s = 0.098 \pm 0.084 \text{(stat.)} \pm 0.040 \text{(syst.)} \text{ rad.}$ and $\Delta \Gamma_d / \Gamma_d = (-0.1 \pm 1.1 \text{(stat.)} \pm 0.9 \text{(syst.)}) \times 10^{-2}$.

1. Introduction
ATLAS [1] is a general purpose detector that measures heavy flavour properties using its inner detectors, muon spectrometers and electromagnetic calorimeters (for tagging). Measuring the properties of heavy-flavour particles has been part of the B physics program of the ATLAS experiment since the start of the proton-proton collisions at LHC in 2010. This note presents an overview of recent results obtained using data collected at $\sqrt{s} = 7 \text{ TeV}$ during 2011 and $\sqrt{s} = 8 \text{ TeV}$ during 2012. The analysis of CP violation and mixing can still access physics beyond the standard model; precise measurements may constrain new physics scenarios such as supersymmetry or advance b and c hadron spectroscopy and test QCD.

2. The $B^0_q$ system
The time evolution of the neutral $B^0_q - \bar{B}^0_q$ system is described by:

$$\frac{d}{dt} \left( \begin{array}{c} B^0_q(t) \\ \bar{B}^0_q(t) \end{array} \right) = M_q \left( \begin{array}{c} B^0_q(t) \\ \bar{B}^0_q(t) \end{array} \right),$$

$$M_q = \left( \begin{array}{cc} m_q & m_{12}^q \\ \langle m_{12}^q \rangle^* & m_q \end{array} \right) - \frac{i}{2} \left( \begin{array}{cc} \Gamma_q & \Gamma_{12}^q \\ \Gamma_{12}^q & \Gamma_q \end{array} \right).$$ (1)

The time dependence of the decay rate $B^0_q \to f$ is sensitive to $f$. The time-dependent decay rate is given by:

$$\Gamma(B^0_q(t) \to f) \propto e^{-\Gamma_q t} \left[ \cosh \frac{\Delta \Gamma_q t}{2} + A_{\text{dir}}^{\text{CP}} \cos(\Delta m_q t) + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma_q t}{2} + A_{\text{mix}}^{\text{CP}} \sin(\Delta m_q t) \right].$$ (2)
Here $t$ is the proper decay time of the $B^0_q$ meson.

The parameters $A_{\text{dir}}^\text{CP}$, $A_{\Delta \Gamma}$ and $A_{\text{mix}}^\text{CP}$ depend on the final state $f$. The abbreviations “dir” and “mix” stand for “direct” and “mixing”. By definition:

$$|A_{\text{dir}}^\text{CP}|^2 + |A_{\Delta \Gamma}|^2 + |A_{\text{mix}}^\text{CP}|^2 = 1. \quad (3)$$

Assuming that the CP-violating phase $\phi_{q}^{12}$ is small, which is experimentally confirmed for both the $B^0$ and $B_s$ mesons [2]:

$$\Gamma(B^0_q(t) \to f) \propto e^{-\Gamma_q t} \left[ \cosh \frac{\Delta \Gamma_q t}{2} - A_{\text{dir}}^\text{CP} \cos(\Delta m_q t) + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma_q t}{2} - A_{\text{mix}}^\text{CP} \sin(\Delta m_q t) \right]. \quad (4)$$

The parameters $A_{\text{dir}}^\text{CP}$, $A_{\Delta \Gamma}$ and $A_{\text{mix}}^\text{CP}$ are theoretically well defined for flavour-specific final states and CP eigenstates [3]. For a flavour-specific final state $f_{fs}$, such that only the decay $B^0_q \to f_{fs}$ is allowed while $\bar{A}_f = \langle f_{fs}|\bar{B}^0_q |0\rangle = 0$, the parameters are:

$$A_{\text{dir}}^\text{CP} = 1, \quad A_{\Delta \Gamma} = 0, \quad A_{\text{mix}}^\text{CP} = 0. \quad (5)$$

For a flavour-specific final state $\bar{f}_{fs}$, such that $A_f = \langle \bar{f}_{fs}|B^0_q \rangle = 0$, i.e. only the decay $\bar{B}^0_q \to \bar{f}_{fs}$ is allowed, the parameters are:

$$A_{\text{dir}}^\text{CP} = -1, \quad A_{\Delta \Gamma} = 0, \quad A_{\text{mix}}^\text{CP} = 0. \quad (6)$$

For the $B^0$ decay to the CP eigenstate $J/\psi K_s$ the parameters are:

$$A_{\text{dir}}^\text{CP} = 0, \quad A_{\Delta \Gamma} = \cos(2\beta), \quad A_{\text{mix}}^\text{CP} = -\sin(2\beta), \quad (7)$$

$$\beta = \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right). \quad (8)$$

If the initial flavour of the $B^0_q$ meson is not tagged and the mixture of the states is equal and unbiased, the decay rates given by equations (2) and (4) are added together. In this case, the production asymmetry $A_P$ of the $B^0_q$ meson in $pp$ collisions should be taken into account. This asymmetry is defined as:

$$A_P = \frac{\sigma(B^0_q) - \sigma(\bar{B}^0_q)}{\sigma(B^0_q) + \sigma(\bar{B}^0_q)}. \quad (9)$$

The oscillation rates $\Delta m_d$ and $\Delta m_s$ have not been measured at ATLAS so the world averages [4] are used in our analyses.

$$\Delta m_d = 0.510 \pm 0.003 \times 10^{12}s^{-1} \quad (10)$$

$$\Delta m_s = 17.757 \pm 0.021 \times 10^{12}s^{-1} \quad (11)$$

3. CP Violation

ATLAS has performed a measurement of the CP-violating phase $\phi_s$ using the 2012 proton-proton dataset [5]. This is done using the exclusive decay $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$, which is a mixture of CP-even and CP-odd eigenstates. CP violation arises from interference between the direct decay and the mixing. From existing measurements, the standard model constrains this to be $\phi_s \approx -0.04$ rad.
Table 1: Summary of tagging performance for the different flavour tagging methods described in the text. Uncertainties shown are statistical only. The efficiency and tagging power are each determined by summing over the individual bins of the charge distribution. The effective dilution is obtained from the measured efficiency and tagging power. For the efficiency, dilution and tagging power, the corresponding uncertainty is determined by combining the appropriate uncertainties in the individual bins of each charge distribution. [5]

| Tagger                  | Efficiency [%] | Dilution [%] | Tagging Power [%] |
|-------------------------|----------------|--------------|-------------------|
| Combined $\mu$          | 4.12 ± 0.02    | 47.4 ± 0.2   | 0.92 ± 0.02       |
| Electron $\mu$          | 1.19 ± 0.01    | 49.2 ± 0.3   | 0.29 ± 0.01       |
| Segment-tagged $\mu$    | 1.20 ± 0.01    | 28.6 ± 0.2   | 0.10 ± 0.01       |
| Jet-charge $\mu$        | 13.15 ± 0.03   | 11.85 ± 0.03 | 0.19 ± 0.01       |
| Total                   | 19.66 ± 0.04   | 27.56 ± 0.06 | 1.49 ± 0.02       |

The analysis measures the mass, lifetime, three transversity angles and tagging information. These are placed in an unbinned maximum likelihood fit function:

$$\ln L = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_s(F_s + f_{B_d}^0 \cdot F_{B_d}^0) + (1 - f_s \cdot (1 + f_{B_d}^0)) F_{bkg}) \}$$  (12)

where $w_i$ is a per-candidate weight for trigger lifetime efficiency.

The fitted PDF has four components:

- $F_s = \text{Mass} \cdot \text{Lifetime+Angles+Tagging} \cdot \text{Acceptance}$
- $F_{B_d}^0 = \text{Mass} \cdot \text{Lifetime} \cdot \text{Angles}$
- $F_{bkg} = \text{Mass} \cdot \text{Lifetime} \cdot \text{Angles}$

The probability density function contains a number of symmetries. As the sign of the $\Delta \Gamma_S$ is not resolved by the data, it is assumed to be $> 0$ and a measurement from LHCb confirms this [6]. A second ambiguity exists in $\phi_s$ and the strong phases, this can be resolved by the flavour tagging information.

3.1. Tagging
The analysis uses opposite-side tagging which was calibrated from the $B^\pm$ self-tagging channels. A combination of four tagging methods are used and they can be seen along with their efficiency $\epsilon$, dilution $D = (1 - \omega)$ and power $P = \epsilon D^2$ in the table 1.

3.2. Results
The results from the 2012 data set demonstrate compatibility with the standard model and the 2011 dataset previously published [7]. The combined parameters are calculated using the Best Linear- unbiased Estimate (BLUE) taking into account parameter correlations. The results can be seen in table 2, with figures 1 and 2 showing the likelihood contours for the result. Comparisons with other experiments can be seen in figure 3, it shows the ATLAS result is in agreement with the other measurements.

3.3. Future performance of detector
ATLAS has released a note which gives estimates of the detector performance after the planned upgrades in the coming years [8]. This includes the IBL (insertable-B-layer) that has been
Table 2: Current measurements using data from 8 TeV pp collisions, the previous measurement using data taken at centre of mass energy of 7 TeV and the values for the parameters of the two measurements, statistically combined. [5]

| Par          | 8 TeV data Value | Stat | Syst | 7 TeV data Value | Stat | Syst | Run1 combined Value | Stat | Syst |
|--------------|------------------|------|------|------------------|------|------|---------------------|------|------|
| $\phi_s$ [rad] | -0.109           | 0.082| 0.042| 0.12             | 0.25 | 0.05 | -0.098              | 0.084| 0.040|
| $\Delta \Gamma_s$ [ps$^{-1}$] | 0.101           | 0.013| 0.007| 0.053            | 0.021| 0.010| 0.083               | 0.011| 0.007|
| $\Gamma_s$ [ps$^{-1}$] | 0.676           | 0.004| 0.004| 0.677            | 0.007| 0.004| 0.677               | 0.003| 0.003|
| $|A_1(0)|^2$ | 0.229           | 0.005| 0.006| 0.220            | 0.008| 0.009| 0.227               | 0.004| 0.006|
| $|A_0(0)|^2$ | 0.521           | 0.004| 0.007| 0.529            | 0.006| 0.012| 0.514               | 0.004| 0.003|
| $|A_S|^2$ | 0.098           | 0.008| 0.022| 0.024            | 0.014| 0.028| 0.071               | 0.007| 0.017|
| $\delta_\perp$ [rad] | 4.50          | 0.45 | 0.30 | 3.89             | 0.47 | 0.11 | 4.13               | 0.33  | 0.16  |
| $\delta_\parallel$ [rad] | 3.15          | 0.13 | 0.05 | [3.04, 3.23]     | 0.09 | 3.15 | 0.13               | 0.05  | 0.05  |
| $\delta_\perp - \delta_S$ [rad] | -0.08         | 0.04 | 0.01 | [3.02, 3.25]     | 0.04 | -0.08 | 0.04               | 0.01  | 0.01  |

![Figure 1](image1.png) ![Figure 2](image2.png)

Figure 1. Likelihood contours for the 2011 and 2012 datasets. [5] Figure 2. Likelihood contours for the combined result [5]

installed for 2015 and the planned ITK detector that will be installed alongside the High-Luminosity LHC upgrade. Figure 4 shows the proper decay time uncertainty vs the $p_T$ of the decaying $B_s$ meson for the tested detector layouts. Table 3 includes information on the estimated signal yields and the estimated precision of the $\phi_s$ measurements.

4. Measurement of the relative width difference of the $B_0-\bar{B}_0$ system with the ATLAS detector

$\Delta \Gamma_d$ is one of the least measured parameters in the B mass system. The standard model makes a precise prediction of a small value for $\Delta \Gamma_d^{SM} = 0.1 \pm 1.0 \times 10^{-2}$. The eigenstate information outlined in section 2 indicates we can measure this using a ratio of events from the decays $B_d^0 \rightarrow J/\psi K^*$ and $B_d^0 \rightarrow J/\psi K_S^0$. This is measured with the 2011 and 2012 datasets recorded by the ATLAS experiment [10].

$A_p$ is the particle/anti-particle production asymmetry. The observed asymmetry $A_{obs}$ is calculated in bins of proper decay length, the asymmetry $A_P$ is then obtained from a $\chi^2$
Table 3: Estimated ATLAS statistical precisions $\phi_s$ for considered LHC periods. Values for 2011 and 2012 in this table are derived using the same method as for future periods. [8]

| Detector          | 2011   | 2012   | 2015-17 | 2019-21 | 2023-30+ |
|-------------------|--------|--------|---------|---------|----------|
| Average interaction per BX $<\mu>$ | 6-12   | 21     | IBL     | IBL     | ITK      |
| Luminosity, fb$^{-1}$ | 4.9    | 20     | 100     | 250     | 3 000    |
| Di-$\mu$ trigger $p_T$ thresholds, GeV | 4-4(6) | 4-6    | 6-6     | 11-11   | 11-11    |
| Signal events per fb$^{-1}$ | 4 400  | 4 320  | 3 280   | 460     | 460      |
| Total events in analysis | 130 000 | 550 000 | 1 874 000 | 284 000 | 758 000  |
| MC $\sigma(\phi_s)((\text{stat.}))$, rad | 0.25   | 0.10   | 0.045   | 0.083   | 0.053    |

minimisation where $A_{det}$ is the detector reconstruction asymmetry:

$$A_{i,\text{obs}} = \frac{N_i(J/\psi K^{*0}) - N_i(J/\psi K^{*0})}{N_i(J/\psi K^{*0}) + N_i(J/\psi K^{*0})},$$

(13)

$$\chi^2[A_{det}, A_p] = \sum_{i=2}^{10} \frac{(A_{i,\text{obs}} - A_{i,\text{exp}})^2}{\sigma_i^2}. $$

(14)

The detector asymmetry $A_{det}$ and $A_p$ are fit to obtain values of $A_{det} = (+1.33 \pm 0.24 \pm 0.22) \times 10^{-2}$ and $A_p = (+0.25 \pm 0.48 \pm 0.05) \times 10^{-2}$ The $A_p$ is found to be consistent with LHCb, although since ATLAS is observing a different region it does not need to be equivalent.

The mass spectra are fitted in each proper decay length bin to extract the yields. Examples of the fits can be seen in figures 5 and 6. Each bin has an efficiency correction ratio applied; this ratio is determined using Monte Carlo data.

The final results are $\Delta \Gamma_d/\Gamma_d = (-2.8 \pm 2.2(\text{stat.}) \pm 1.5(\text{MC stat.})) \times 10^{-2}$ for the 2011 dataset and $\Delta \Gamma_d/\Gamma_d = (+0.8 \pm 1.3(\text{stat.}) \pm 0.5(\text{MC stat.})) \times 10^{-2}$ for the 2012 dataset. These results are combined using the $\chi^2$ method. Correlations between sources of systematics common to the two datasets are taken into account. The systematic uncertainty due to the background description and the MC are considered to be uncorrelated. This combined result is
\[ \Delta \Gamma_d/\Gamma_d = (-0.1 \pm 1.1 \text{(stat.)} \pm 0.9 \text{(syst.)}) \times 10^{-2}. \]

This combined result is currently the most precise single measurement of this quantity; it agrees well with the standard model prediction and the indirect measurement by D0 [9].

The fact the asymmetry is a ratio cancels out most biases from the trigger, time resolution or B production properties. However, differences between the channels and simulation inaccuracies could remain. The systematics uncertainties are thus estimated and shown in table 4.

Table 4: Sources of systematic uncertainty in the \( \Delta \Gamma_d/\Gamma_d \) measurement and their values for the 2011 and 2012 data sets. [10]

| Source                  | \( \delta(\Delta \Gamma_d/\Gamma_d), 2011 \) | \( \delta(\Delta \Gamma_d/\Gamma_d), 2012 \) |
|-------------------------|---------------------------------------------|---------------------------------------------|
| \( K_S \) decay length  | \( 0.21 \times 10^{-2} \)                   | \( 0.16 \times 10^{-2} \)                   |
| \( K_S \) pseudorapidity| \( 0.14 \times 10^{-2} \)                   | \( 0.01 \times 10^{-2} \)                   |
| \( B^0 \rightarrow J/\psi K_s \) mass range | \( 0.47 \times 10^{-2} \)                   | \( 0.59 \times 10^{-2} \)                   |
| \( B^0 \rightarrow J/\psi K^{*0} \) mass range | \( 0.30 \times 10^{-2} \)                   | \( 0.15 \times 10^{-2} \)                   |
| Background description  | \( 0.16 \times 10^{-2} \)                   | \( 0.09 \times 10^{-2} \)                   |
| \( B_s \rightarrow J/\psi K_S \) contribution | \( 0.11 \times 10^{-2} \)                   | \( 0.08 \times 10^{-2} \)                   |
| \( L_B^{\text{prop}} \) resolution | \( 0.29 \times 10^{-2} \)                   | \( 0.29 \times 10^{-2} \)                   |
| Fit bias (Toy MC)        | \( 0.07 \times 10^{-2} \)                   | \( 0.07 \times 10^{-2} \)                   |
| \( B^0 \) production asymmetry | \( 0.01 \times 10^{-2} \)                   | \( 0.01 \times 10^{-2} \)                   |
| MC sample               | \( 1.54 \times 10^{-2} \)                   | \( 0.45 \times 10^{-2} \)                   |
| Total uncertainty       | \( 1.69 \times 10^{-2} \)                   | \( 0.84 \times 10^{-2} \)                   |

Figure 5. The \( J/\psi K_S \) mass fit [10]

Figure 6. The \( J/\psi K^{*0} \) mass fit [10]

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