The latest results measured by the ATLAS experiment on lifetime, mixing and CP violation in the $B^0$ and $B^0_s$ systems are presented. First, the measurement of the $B^0_s \rightarrow J/\psi \phi$ decay parameters using 4.9 fb$^{-1}$ and 14.3 fb$^{-1}$ of integrated luminosity collected by the ATLAS detector at the LHC in $pp$ collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV respectively is given. The measured values include the CP-violating phase $\phi_s$ and the width difference of the mass eigenstates $\Delta \Gamma_s$. The measurements for the 7 and 8 TeV data samples are combined, giving values of $\phi_s = -0.098 \pm 0.084\text{(stat.)} \pm 0.040\text{(syst.)}\text{ rad}$ and $\Delta \Gamma_s = 0.083 \pm 0.011\text{(stat.)} \pm 0.007\text{(syst.)}\text{ ps}^{-1}$. The measured values agree with the Standard Model predictions. Second, the measurement of the relative width difference $\Delta \Gamma_d / \Gamma_d$ of the $B^0$–$\bar{B}^0$ system at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 25.2 fb$^{-1}$ is presented. The measured value is $\Delta \Gamma_d / \Gamma_d = (-0.1 \pm 1.1 \text{ (stat.)} \pm 0.9 \text{ (syst.)}) \times 10^{-2}$. Currently, this is the most precise single measurement of $\Delta \Gamma_d / \Gamma_d$. It agrees with the Standard Model prediction and measurements by other experiments.
1. The ATLAS detector

ATLAS is a general purpose detector that consists of an inner tracker, a calorimeter and a muon spectrometer [1]. Analyses of $B$-physics in ATLAS mainly use information from the inner detector and the muon spectrometer. The inner detector provides momentum resolution in the pseudorapidity range $|\eta| < 2.5$. The muon spectrometer provides muon identification and triggers. The ATLAS trigger system employs a Level-1 hardware trigger and two high-level software triggers. Heavy flavour analyses in ATLAS mostly use trigger selections based on a di-muon signature. These triggers have muon transverse momentum ($p_T$) thresholds of 4 or 6 GeV and pseudorapidity coverage of $|\eta| < 2.4$. Di-muon vertex reconstruction is also utilized.

2. CP violation in the $B^0_s \rightarrow J/\psi \phi$ decay

The occurrence of CP violation in the $B^0_s$ system is due to interference between direct decays and decays with $B^0_s - \bar{B}^0_s$ mixing to a final state accessible to both $B^0_s$ and $\bar{B}^0_s$, such as $J/\psi \phi$. The CP asymmetry is represented by the weak phase difference $\phi_s$ between the $B^0_s - \bar{B}^0_s$ mixing amplitude and the $b \rightarrow c \bar{c} s$ decay amplitude. In the Standard Model, $\phi_s$ is predicted to be small and is related to elements of the CKM matrix [2]:

$$\phi_s \approx -2\beta_s = 2\arg \left( \frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right) = -0.0363^{+0.0016}_{-0.0015} \text{ rad.} \quad (2.1)$$

The keen interest in $B^0_s \rightarrow J/\psi \phi$ is because of the possible new physics contribution that may exist within $\phi_s$, which can therefore be expressed as the sum of its SM and NP components:

$$\phi_s = \phi_s^{SM} + \phi_s^{NP}. \quad (2.2)$$

Precise measurements of $\phi_s$ performed by LHC experiments have already constrained this new physics contribution, but more precision is still needed to test the SM and evaluate $\phi_s^{NP}$.

The results of the $B^0_s \rightarrow J/\psi \phi$ analysis using 4.9 fb$^{-1}$ of integrated luminosity collected by ATLAS in 2011 at $\sqrt{s} = 7$ TeV were published in 2014 [3]. The measured values of $\phi_s$ and the width difference $\Delta \Gamma_s$ were:

$$\phi_s = 0.12 \pm 0.25 \text{ (stat.)} \pm 0.05 \text{ (syst.) \ rad.} \quad (2.3)$$

$$\Delta \Gamma_s = 0.053 \pm 0.21 \text{ (stat.)} \pm 0.010 \text{ (syst.) \ ps}^{-1}. \quad (2.4)$$

The more recent analysis of the 14.3 fb$^{-1}$ of integrated luminosity collected in 2012 at $\sqrt{s} = 8$ TeV was released by the ATLAS collaboration in January 2016 [4]. In addition to the increased data sample, this analysis included a number of improvements over the 2011 analysis.

The $B^0_s \rightarrow J/\psi \phi$ candidates were selected by fitting the four track combinations (two muon tracks and two hadronic tracks) to a common vertex. The muon tracks were required to pass the trigger thresholds of $p_T > 4$ or 6 GeV and $\eta < 2.4$. The hadronic tracks were required to be oppositely charged and have $p_T > 1$ GeV and $\eta < 2.5$. All selection criteria are independent of the $B^0_s$ lifetime. A total of 375987 $B^0_s$ candidates were selected with $5.15 < m(J/\psi \phi) < 5.65$. The
number of signal candidates was estimated to be $74900 \pm 400$, which is approximately 3.5 times that of the sample used in the 2011 analysis.

Since the measured effect in the $B_s^0 \rightarrow J/\psi\phi$ analysis is due to $B_s^0 - \bar{B}_s^0$ mixing, it is important to tag the initial flavour of the $B_s^0$ or $\bar{B}_s^0$ meson. Opposite side flavour tagging is used in ATLAS. The flavour tagging algorithm is calibrated using $B^+ \rightarrow J/\psi K^+$ events. Three flavour tagging methods are used: opposite side muon tagging, opposite side electron tagging and jet charge tagging. The jet charge tag uses the jet with largest value of $b$-tagging in the event, excluding the $B^0_s$ decay. The tagging variable is given by:

$$Q = \frac{\sum_i q_i (p_i^T)^k}{\sum_i (p_i^T)^k},$$

(2.5)

where $q_i$ and $p_i^T$ are, respectively, the charge and transverse momentum of track $i$. For muon (electron) tagging, $k = 1.1$ (1.0) and the sum is over tracks within a cone of $\Delta R < 0.5$ around the muon (electron). For jet charge tagging, $k = 1.1$ and the sum is over all tracks in the jet.

An unbinned maximum likelihood fit is used to extract the values of the physical parameters of the $B^0_s \rightarrow J/\psi\phi$ decay. The information used by the fit includes several variables describing the $B^0_s \rightarrow J/\psi\phi$ candidates including the reconstructed mass, transverse momentum, proper decay time, the measured proper decay time uncertainty, transversity angles and flavour tagging value. The maximum likelihood fit of the 8 TeV data sample gives the following results for $\phi_s$ and $\Delta \Gamma_s$:

$$\phi_s = -0.123 \pm 0.089 \text{ (stat.)} \pm 0.041 \text{ (syst.) rad.}$$

(2.6)

$$\Delta \Gamma_s = 0.096 \pm 0.013 \text{ (stat.)} \pm 0.007 \text{ (syst.) ps}^{-1}.$$  

(2.7)

The results from the 7 TeV and 8 TeV data samples are consistent and are combined:

$$\phi_s = -0.098 \pm 0.084 \text{ (stat.)} \pm 0.040 \text{ (syst.) rad.}$$

(2.8)

$$\Delta \Gamma_s = 0.083 \pm 0.011 \text{ (stat.)} \pm 0.007 \text{ (syst.) ps}^{-1}.$$  

(2.9)

Figure 1 shows the likelihood contours in the $\phi_s - \Delta \Gamma_s$ plane for the 7 TeV and 8 TeV analyses separately and combined.

3. Measurement of the relative width difference of the $B^0 - \bar{B}^0$ system

The relative value of the $B^0 - \bar{B}^0$ width difference $\Delta \Gamma_d/\Gamma_d$ is reliably predicted in the Standard Model [5]:

$$\Delta \Gamma_d/\Gamma_d = (0.42 \pm 0.08) \times 10^{-2}$$

(3.1)

It has been shown [6] that a relatively large variation of $\Delta \Gamma_d/\Gamma_d$ due to a possible new physics contribution would not contradict other existing SM results. A precise measurement of $\Delta \Gamma_d/\Gamma_d$ would therefore provide a stringent test of the underlying theory, complementary to other searches.

The current experimental uncertainty of $\Delta \Gamma_d/\Gamma_d$ is much larger than the SM central value, which prevents a meaningful test of the SM prediction. Furthermore, the measurements of $\Delta \Gamma_d/\Gamma_d$ made by Belle [7] and LHCb [8] differ by more than 1.5 standard deviations. Therefore, more precise measurements of $\Delta \Gamma_d/\Gamma_d$ are needed to establish its value and perform an important test of the SM. The measurement of $\Delta \Gamma_d/\Gamma_d$ was performed by the ATLAS collaboration using the methods described below. The full details of this analysis are given in the corresponding paper [9].
Lifetime, mixing and CPV in ATLAS

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Figure 1: Likelihood contours in the $\phi_s - \Delta \Gamma_s$ plane for (a) the separate results and (b) the combined results from the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV analyses [4]. The blue line shows the 68% likelihood contour, while the red dotted line shows the 95% likelihood contour (statistical errors only).

The untagged time-dependent decay rate of $B^0$ meson into a final state $f$ is given by:

$$\Gamma(f,t) \propto e^{-\Gamma_d t} \left[ \cosh \frac{\Delta \Gamma_d t}{2} + A_p A_{CP}^{\text{dir}} \cos(\Delta m_d t) + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma_d t}{2} + A_p A_{CP}^{\text{mix}} \sin(\Delta m_d t) \right]. \tag{3.2}$$

In this expression, $\Gamma_d$ and $\Delta m_d$ are respectively the mean width and mass difference of the $B^0 - \bar{B}^0$ system. The parameters $A_{CP}^{\text{dir}}$, $A_{\Delta \Gamma}$ and $A_{CP}^{\text{mix}}$ depend on the final state $f$. The abbreviations “dir” and “mix” stand for “direct” and “mixing”. By definition, $|A_{CP}^{\text{dir}}|^2 + |A_{\Delta \Gamma}|^2 + |A_{CP}^{\text{mix}}|^2 = 1$. The final states considered in this analysis were $J/\psi K_S$ and $J/\psi K^*_{0}$. The $J/\psi$ is reconstructed using the decay $J/\psi \rightarrow \mu^+ \mu^-$. The $K_S$ and $K^*_{0}$ are reconstructed using the $K_S \rightarrow \pi^+ \pi^-$ and $K^*_{0} \rightarrow K^+ \pi^-$ decay modes. For the $J/\psi K^*_{0}$ ($\bar{K}^*_{0}$) final state, $A_{CP}^{\text{dir}} = +1 (-1)$, $A_{\Delta \Gamma} = 0$, $A_{CP}^{\text{mix}} = 0$. For the $J/\psi K_S$ channel, $A_{CP}^{\text{dir}} = 0$, $A_{\Delta \Gamma} = \cos 2\beta$, $A_{CP}^{\text{mix}} = -\sin 2\beta$, where $\beta$ is the Unitarity Triangle angle measured as $\sin 2\beta = 0.679 \pm 0.020$ [10]. $A_p$ is the production asymmetry of $B^0$ and $\bar{B}^0$ in ATLAS.

The value of $\Delta \Gamma_d/\Gamma_d$ is determined by measuring the experimental ratio of the proper decay length ($L^B_{\text{prop}}$) distributions of the two decay modes. The sensitivity to $\Delta \Gamma_d/\Gamma_d$ comes from $\Gamma(J/\psi K_S, L^B_{\text{prop}})$ while $\Gamma(J/\psi K^*_{0}, L^B_{\text{prop}})$ provides the normalization, which cancels the factor of $e^{-\Gamma_d t}$, increasing the sensitivity to $\Delta \Gamma_d/\Gamma_d$. This method also helps to reduce some of the systematic uncertainties.

The proper decay length distribution is obtained by first dividing the range of $L^B_{\text{prop}}$ between $-0.3$ and $6.0$ mm into ten bins. In each bin, distributions of the invariant mass of the $J/\psi K_S$ and $J/\psi K^*_{0}$ candidates are produced and the number of signal $B^0 \rightarrow J/\psi K_S$ and $\bar{B}^0 \rightarrow J/\psi K^*_{0}$ candidates in each bin is determined by a fit to these distributions. The total number of $B^0 \rightarrow J/\psi K_S$ decays is $28170 \pm 250$ in the 7 TeV data sample and $110830 \pm 520$ in the 8 TeV data sample.
The total number of $B^0 \rightarrow J/\psi K^{*0}$ candidates is 129 200 ± 900 in the 7 TeV data sample and 555 800 ± 1900 in the 8 TeV sample.

The ratio of the number of $B^0$ candidates in the two channels in each $L^B_{\text{prop}}$ bin gives the experimental ratio of proper decay lengths $R_{\text{uncor}}(L^B_{\text{prop}})$. This ratio must be corrected to account for the difference in reconstruction efficiencies of the $B^0 \rightarrow J/\psi K_S$ and $B^0 \rightarrow J/\psi K^{*0}$ channels. This difference exists because the hadronic tracks in the $B^0 \rightarrow J/\psi K_S$ decay come from a displaced $K_S \rightarrow \pi\pi$ vertex, while all four tracks from the $B^0 \rightarrow J/\psi K^{*0}$ decay come from a single vertex. This difference is the largest source of experimental bias in $R_{\text{uncor}}(L^B_{\text{prop}})$ and it can be assessed only with Monte Carlo simulation. The ratio of reconstruction efficiencies in MC in each $L^B_{\text{prop}}$ bin is determined:

$$R_{\text{un}} = \frac{\epsilon_i(J/\psi K_S, L^B_{\text{prop}})}{\epsilon_i(J/\psi K^{*0}, L^B_{\text{prop}})}.$$

The ratio $R_{\text{un}}$ is divided by $R_{\text{eff}}$ to obtain the corrected ratio $R_{\text{cor}}$:

$$R_{\text{cor}}(L^B_{\text{prop}}) = \frac{R_{\text{un}}(L^B_{\text{prop}})}{R_{\text{eff}}(L^B_{\text{prop}})}.$$

The $B^0 \rightarrow \bar{B}^0$ production asymmetry is measured from the charge asymmetry of the $B^0 \rightarrow J/\psi K^{*0}$ decay, which is measured as a function of $L^B_{\text{prop}}$. The charge asymmetry has two contributions: the detector asymmetry $A_{\text{det}}$ and the production asymmetry $A_P$ which should oscillate with $L^B_{\text{prop}}$. The values of $A_{\text{det}}$ and $A_P$ measured by the ATLAS experiment using data obtained at 7 and 8 TeV are:

$$A_{\text{det}} = (+1.33 \pm 0.24 \pm 0.30) \times 10^{-2}.$$  \hspace{1cm} (3.4)

$$A_P = (+0.25 \pm 0.48 \pm 0.05) \times 10^{-2}.$$  \hspace{1cm} (3.5)

The first uncertainty is statistical and the second is due to uncertainties in the mistag fraction of $K^{*0}$ and $\bar{K}^{*0}$ and in the value of $|q/p|$.

The corrected ratio of proper decay lengths $R_{\text{cor}}(L^B_{\text{prop}})$ is fitted by the expected number of events in each channel, in each bin. The fitted distributions of $R_{\text{cor}}(L^B_{\text{prop}})$ for the 7 and 8 TeV data samples are shown in Fig. 2. The values of $\Delta \Gamma_d/\Gamma_d$ at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV are obtained separately:

$$\Delta \Gamma_d/\Gamma_d = (-2.8 \pm 2.2 \text{ (stat.)} \pm 1.7 \text{ (syst.)}) \times 10^{-2} \quad [\sqrt{s} = 7 \text{ TeV}].$$  \hspace{1cm} (3.6)

$$\Delta \Gamma_d/\Gamma_d = (+0.8 \pm 1.3 \text{ (stat.)} \pm 0.8 \text{ (syst.)}) \times 10^{-2} \quad [\sqrt{s} = 8 \text{ TeV}].$$  \hspace{1cm} (3.7)

The results from the two data samples are consistent and are combined:

$$\Delta \Gamma_d/\Gamma_d = (-0.1 \pm 1.1 \text{ (stat.)} \pm 0.9 \text{ (syst.)}) \times 10^{-2}$$  \hspace{1cm} (3.8)

4. Conclusions

The measurement of $CP$ violation in the $B^0 \rightarrow J/\psi \phi$ using data collected by the ATLAS experiment during Run 1 of the LHC is consistent with measurements by other experiments. It also agrees with the SM prediction. There is, however, still room for new physics in $CP$ violation in this channel.

The value of $\Delta \Gamma_d/\Gamma_d$ obtained by ATLAS during LHC Run 1 is currently the most precise measurement of this quantity. The result agrees with the SM prediction. It is also consistent with measurements performed by other experiments.
Figure 2: Efficiency-corrected ratio of the observed decay length distributions, $R_{\text{cor}}(L_{\text{prop}}^B)$ for the (a) $\sqrt{s} = 7$ TeV and (b) $\sqrt{s} = 8$ TeV data samples [9]. The normalisation of the two data sets is arbitrary. The full line shows the fit of $R_{\text{cor}}(L_{\text{prop}}^B)$. The error bands correspond to uncertainties in $\Delta\Gamma_d/\Gamma_d$ determined by the fit.

References


[4] ATLAS Collaboration, Measurement of the CP-violating phase $\phi_s$ and the $B_s^0$ meson decay width difference with $B_s^0 \rightarrow J/\psi\phi$ decays in ATLAS, arXiv:1601.03297 [hep-ex].


