PROCEEDINGS OF SCIENCE

Lifetime, mixing and CPV in ATLAS

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The latest results measured by the ATLAS experiment on lifetime, mixing and *CP* violation in the B^0 and B_s^0 systems are presented. First, the measurement of the $B_s^0 \to J/\psi\phi$ decay parameters using 4.9 fb^{-1} and 14.3^{-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 ϕ_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
$\phi_s = -0.098 \pm 0.084(\text{stat.}) \pm 0.040(\text{syst.})$ rad and $\Delta\Gamma_s = 0.083 \pm 0.011(\text{stat.}) \pm 0.007(\text{syst.})$ 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.

16th International Conference on B-Physics at Frontier Machines
2-6 May 2016
Marseille, France

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1. The ATLAS detector

ATLAS is a general purpose detector that conists 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 $B_s^0 \to J/\psi\phi$ decay

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

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

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

$$\phi_s = \phi_s^{SM} + \phi_s^{NP}. \tag{2.2}$$

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

The results of the $B_s^0 \to J/\psi\phi$ 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 ϕ_s and the width difference $\Delta\Gamma_s$ were:

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

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

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 $B_s^0 \to J/\psi\phi$ 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 selectrion criteria are independent of the B_s^0 lifetime. A total of 375 987 B_s^0 candidates were selected with $5.15 < m(J/\psi\phi) < 5.65$. The number of signal candidates was estimated to be $74\,900 \pm 400$, which is approximately 3.5 times that of the sample used in the 2011 analysis.

Since the measured effect in the $B_s^0 \to J/\psi\phi$ 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 $B^+ \to J/\psi K^{\pm}$ 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_s^0 decay. The tagging variable is given by:

$$Q = \frac{\sum_i q^i (p_T^i)^k}{\sum_i (p_T^i)^k}. \tag{2.5}$$

where q^i and p_T^i 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 $B_s^0 \to J/\psi\phi$ decay. The information used by the fit includes several variables describing the $B_s^0 \to J/\psi\phi$ 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 ϕ_s and $\Delta\Gamma_s$:

$$\phi_s = -0.123 \pm 0.089 \text{ (stat.)} \pm 0.041 \text{ (syst.) rad.} \tag{2.6}$$

$$\Delta\Gamma_s = 0.096 \pm 0.013 \text{ (stat.)} \pm 0.007 \text{ (syst.) ps}^{-1}. \tag{2.7}$$

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

$$\phi_s = -0.098 \pm 0.084 \text{ (stat.)} \pm 0.040 \text{ (syst.) rad.} \tag{2.8}$$

$$\Delta\Gamma_s = 0.083 \pm 0.011 \text{ (stat.)} \pm 0.007 \text{ (syst.) ps}^{-1}. \tag{2.9}$$

Figure 1 shows the likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane for the 7 TeV and 8 TeV analyses seperately 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]:

$$\Delta\Gamma_d/\Gamma_d = (0.42 \pm 0.08) \times 10^{-2} \tag{3.1}$$

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, complementery 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 he methods described below. The full details of this analysis are given in the corresponding paper [9].

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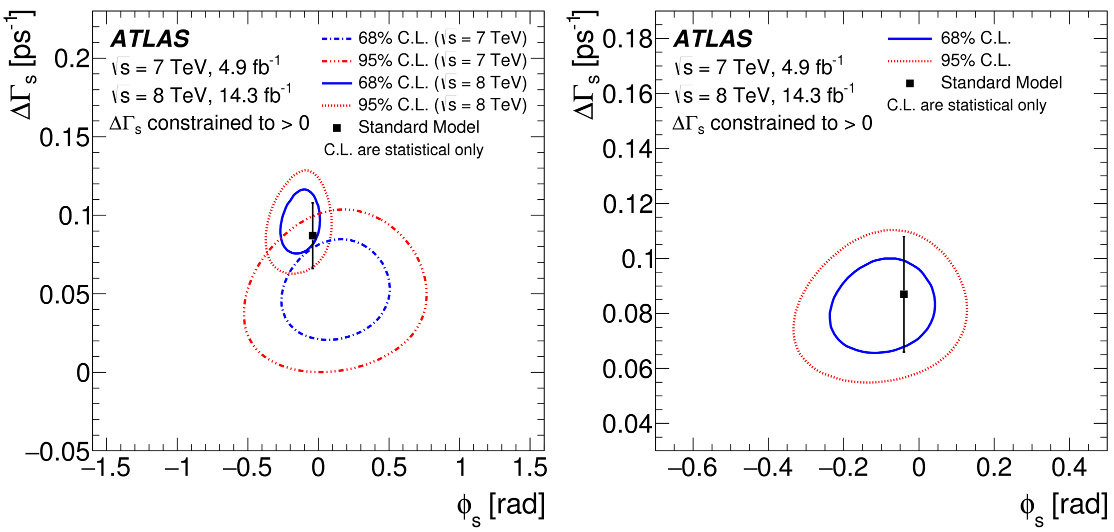

(a) (b)

Figure 1: Likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane for (a) the seperate 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:

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

In this expression, Γ_d and Δm_d are respectively the mean width and mass difference of the $B^0 - \bar{B}^0$ system. The parameters $A_{\mathrm{CP}}^{\mathrm{dir}}$, $A_{\Delta\Gamma}$ and $A_{\mathrm{CP}}^{\mathrm{mix}}$ depend on the final state f. The abbreviations "dir" and "mix" stand for "direct" and "mixing". By definition, $|A_{\mathrm{CP}}^{\mathrm{dir}}|^2 + |A_{\Delta\Gamma}|^2 + |A_{\mathrm{CP}}^{\mathrm{mix}}|^2 \equiv 1$. The final states considered in this analysis were $J/\psi K_S$ and $J/\psi K^{*0}$. The J/ψ is reconstructed using the decay $J/\psi \to \mu^+\mu^-$. The K_S and K^{*0} are reconstructed using the $K_S \to \pi^+\pi^-$ and $K^{*0} \to K^+\pi^-$ decay modes. For the $J/\psi K^{*0}(\bar{K}^{*0})$ final state, $A_{\mathrm{CP}}^{\mathrm{dir}} = +1(-1)$, $A_{\Delta\Gamma} = 0$, $A_{\mathrm{CP}}^{\mathrm{mix}} = 0$. For the $J/\psi K_S$ channel, $A_{\mathrm{CP}}^{\mathrm{dir}} = 0$, $A_{\Delta\Gamma} = \cos 2\beta$, $A_{\mathrm{CP}}^{\mathrm{mix}} = -\sin 2\beta$, where β 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_{prop}^B) distributions of the two decay modes. The sensitivity to $\Delta\Gamma_d/\Gamma_d$ comes from $\Gamma(J/\psi K_S, L_{\mathrm{prop}}^B)$ while $\Gamma(J/\psi K^{*0}, L_{\mathrm{prop}}^B)$ provides the normalization, which cancels the factor of $\mathrm{e}^{-\Gamma_d t}$, increasing the sensitivity to $\Delta\Gamma_d/\Gamma_d$. This method also helps to reduce come of the systematic uncertainties.

The proper decay length distribution is obtained by first dividing the range of L_{prop}^B 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 $B^0 \to J/\psi K_S$ and $B^0 \to J/\psi K^{*0}$ candidates in each bin is determined by a fit to these distributions. The total number of $B^0 \to J/\psi K_S$ decays is $28\,170 \pm 250$ in the 7 TeV data sample and $110\,830 \pm 520$ in the 8 TeV data sample.

The total number of $B^0 \to J/\psi K^{*0}$ candidates is $129\,200 \pm 900$ in the 7 TeV data sample and $555\,800 \pm 1\,900$ in the 8 TeV sample.

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

$$R_{i,\text{eff}}(L^B_{\text{prop}}) = \frac{\varepsilon_i(J/\psi K_S, L^B_{\text{prop}})}{\varepsilon_i(J/\psi K^{*0}, L^B_{\text{prop}})}. \tag{3.3}$$

The ratio $R_{i,\text{uncor}}(L^B_{\text{prop}})$ is divided by $R_{i,\text{eff}}(L^B_{\text{prop}})$ to obtain the corrected ratio $R_{i,\text{cor}}(L^B_{\text{prop}})$.

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

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

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

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 $R_{i,\text{cor}}(L^B_{\text{prop}})$ is fitted by the expected number of events in each channel, in each bin. The fitted distributions of $R_{i,\text{cor}}(L^B_{\text{prop}})$ 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 seperately:

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

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

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

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

4. Conclusions

The measurement of *CP* violation in the $B^0_s \to J/\psi\phi$ 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 agress with the SM prediction. It is also consistent measurements performed by other experiments.

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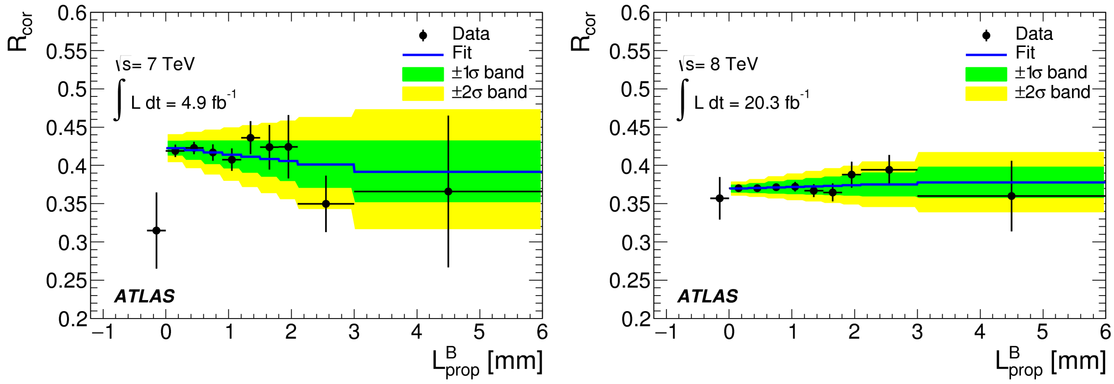

Figure 2: Efficiency-corrected ratio of the observed decay length distributions, $R_{\rm cor}(L^B_{\rm prop})$ for the (a) $\sqrt{s}=7$ TeV and (b) $\sqrt{s}=8$ TeV data samples [9]. The normalisation of the two data sets is arbitrary. The full line shows the fit of $R_{\rm cor}(L^B_{\rm prop})$. The error bands correspond to uncertainties in $\Delta\Gamma_d/\Gamma_d$ determined by the fit.

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