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CP violation measurements with the ATLAS detector

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Abstract

The ATLAS experiment at the Large Hadron Collider measures *CP* violation in the neutral B_s^0 meson system through the exclusive decay $B_s^0 \to J/\psi(\mu^+\mu^-)\,\phi(K^+K^-)$ by analysing time dependent angular correlations of the final state. With $4.9\,\text{fb}^{-1}$ of integrated luminosity recorded in 2011 in pp collisions at the LHC at a centre of mass energy of $\sqrt{s} = 7$ TeV first ATLAS results on the values of the *CP*-violating phase ϕ_s, the decay width difference $\Delta\Gamma_s$ as well as other physics parameters of the B_s^0 meson decay have been obtained and will be presented here.

Keywords: ATLAS, CP violation, weak mixing phase

1. Introduction

CP-violation has been established in the *b*-quark sector in 2001 [1]. Presently at the LHC precision measurements are being carried out in order to check if there are deviations from the expected size of *CP*-violating effects. For example, the Standard Model predicts $\phi_s = -0.0368 \pm 0.0018$ rad [2], where the *CP*-violating phase ϕ_s is related to the angle $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$ of one of the unitarity triangles through the relation $\phi_s \simeq -2\beta_s$. The phase ϕ_s is sensitive to physics beyond the Standard Model via non-Standard Model contributions to the B_s^0 mixing box diagram. Thus it can be parameterised as $\phi_s = \phi_s^{SM} + \phi_s^{\Delta}$, where ϕ_s^{SM} stands for the value within the Standard Model quoted above and ϕ_s^{Δ} accounts for possible additional phase contributions due to new physics.

The ATLAS experiment measures ϕ_s through the decays of the B_s^0 and $\overline{B_s^0}$ mesons into the final state $J/\psi(\mu^+\mu^-)\,\phi(K^+K^-)$, where *CP*-violation occurs due to interference between the direct decay and the decay via $B_s^0 - \overline{B_s^0}$ mixing. The oscillation frequency of this B_s^0 meson mixing is characterized by the mass difference Δm_s between the heavy (B_H) and light (B_L) mass eigenstates. In the absence of *CP* violation the mass eigenstates would correspond exactly to the *CP* eigenstates,

B_H being *CP*-odd ($|B_s^0\rangle - |\overline{B_s^0}\rangle$) and B_L being *CP*-even ($|B_s^0\rangle + |\overline{B_s^0}\rangle$). In general one has $|B_{L,H}\rangle = p|B_s^0\rangle \pm q|\overline{B_s^0}\rangle$, where p and q are complex numbers.

In the decay of the pseudoscalar B_s^0 meson to the vector-vector final-state $J/\psi\phi$ the allowed orbital angular momenta are $L = 0$, 1 and 2. Since the $L = 0$ and $L = 2$ states are *CP*-even whereas the $L = 1$ state is *CP*-odd, the final state is an admixture of *CP*-odd and *CP*-even states. These *CP* states can be separated statistically by using the time-dependence of the decay and angular correlations between the final-state particles. For describing the angular distributions of the four final state particles ($K^+K^-\mu^+\mu^-$) the so-called transversity angles θ_T, ψ_T and φ_T are used [3].

Besides ϕ_s also the following parameters of the B_s^0 system are measured: the average decay width $\Gamma_s = (\Gamma_L + \Gamma_H)/2$ and the width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ of B_L and B_H.

An untagged analysis is presented, meaning that the initial state flavour of the B_s^0 meson is not determined. Also in this text charge conjugate processes are always implicitly assumed.

The outline of this report, which is mainly based on [4], is as follows: in the next section some relevant information about the ATLAS experiment and the event reconstruction is given. After explaining the maximum

likelihood fit in section 3 the results are presented and discussed in section 4 and summarized in section 5.

2. The ATLAS detector, the trigger, event reconstruction and Monte Carlo events

ATLAS is a general purpose particle physics detector described in detail in [5]. For this analysis the most important components are the inner detector (consisting of a pixel detector, a silicon microstrip detector and a transition radiation tracker) and the muon spectrometer (consisting of tracking chambers and trigger chambers). Only data where these two detectors have been working well are used.

The trigger used to select the events for this analysis is primarily based on identifying the $J/\psi \rightarrow \mu^+\mu^-$ decay where the transverse momentum threshold is either 4 GeV for both muons, or higher (up to 10 GeV) for one muon and lower than 4 GeV for the other muon. The ϕ meson candidates are constructed assuming the decay $\phi \rightarrow K^+K^-$ by combining oppositely charged tracks that are not identified as muons. They are then combined with the J/ψ in a four track secondary vertex fit to build the B_s^0 candidates. Details of the event reconstruction and the candidate selection are given in [4] and not repeated here because more emphasis is put on discussing the results.

To study the detector response, calculate background contributions and estimate systematic effects, 12 million signal Monte Carlo events $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ as well as various background samples, like the specific decay $B^0 \rightarrow J/\psi K^{0*}$ and the inclusive decays $bb \rightarrow J/\psi X$ and $pp \rightarrow J/\psi X$ have been simulated using PYTHIA [7] and the ATLAS detector simulation package based on GEANT4 [8].

3. Maximum likelihood fit

The measured physics variables of the sample of selected B_s^0 candidates are used to do an unbinned maximum likelihood fit in order to determine the physics parameters we are interested in. The full fit contains 26 free parameters, 8 of them are the physics parameters we are mainly interested in, namely the three parameters of the B_s^0 system (ϕ_s, Γ_s and $\Delta\Gamma_s$), and five parameters related to the amplitudes describing the proper time distribution of the B_s^0 decay.

Altogether there are four amplitudes, three of them describing the different polarization states of the vector mesons J/ψ and ϕ. They are also called transversity amplitudes and the parameters in the fit are the absolute values of the amplitudes at zero proper time: $|A_0(0)|$ for longitudinal polarization, for polarization transverse to the direction of motion the amplitudes are $|A_\parallel(0)|$ for the case where the polarizations are parallel to each other and $|A_\perp(0)|$ when they are perpendicular. In terms of CP eigenvalues $|A_\parallel(0)|$ and $|A_0(0)|$ are CP-even while $|A_\perp(0)|$ is CP-odd. The fourth amplitude $|A_S(0)|$ accounts for possible contamination by $B_s^0 \rightarrow J/\psi K^+K^-(f_0)$, where the non-resonant K^+K^- system or the f_0 meson is an S-wave state. Because of the normalization $|A_0(0)|^2 + |A_\parallel(0)|^2 + |A_\perp(0)|^2 + |A_S(0)|^2 = 1$ we are left with three free parameters.

The four amplitudes A_i come with their associated strong phases δ_i. Since these phases can only be measured relative to each other, one phase is arbitrary. We use the convention $\delta_0 = 0$, which leaves us with three free phase parameters for the fit. It turns out that due to the absence of flavour tagging the analysis is not sensitive to the phase $\delta_\perp$. Therefore this parameter is fixed in the fit (using a Gaussian constraint) to the value as measured by the LHCb experiment [11]: $\delta_\perp = 2.95 \pm 0.39$ rad. The two strong phases determined by the fit therefore are $\delta_\parallel$ and δ_S.

Another important parameter is the signal fraction parameter f_s which allows to calculate the number of $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ events contained in the data.

Finally there are parameters describing various distributions of signal and background since for the likelihood function one has to model these distributions for all the measured variables. Besides describing the combinatorial background, terms modeling the B^0 reflections are explicitly included in the fit. These contributions come from the decays $B^0 \rightarrow J/\psi K^*$ and non-resonant $B^0 \rightarrow J/\psi K^+\pi^-$, where the pion is misidentified as a kaon.

Having a closer look at the likelihood function (see [4]) reveals that the probability density function (PDF) describing the proper time distribution of the $B_s^0 \rightarrow J/\psi\phi$ decay exhibits a fourfold symmetry. This PDF is invariant under the transformation $\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \rightarrow \{\pi - \phi_s, -\Delta\Gamma_s, \pi - \delta_\perp, -\delta_\parallel, -\delta_S\}$ as well as under the transformation $\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \rightarrow \{-\phi_s, \Delta\Gamma_s, \pi - \delta_\perp, -\delta_\parallel, -\delta_S\}$. These ambiguities are resolved by using the results of this ATLAS analysis in combination with previous measurements by LHCb [11, 12]. This will be explained in more detail in subsection 4.2.

4. Results

Maximizing the likelihood function yields the best fit parameters where the most interesting physics param-

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

Table 1: Fitted values for the physics parameters along with their statistical and systematic uncertainties. Table taken from [4].

eters are shown in table 1. The best fit value for $\delta_\parallel$ is close to π, but due to non-Gaussian errors (as indicated by Monte Carlo studies) the result is given in the form of the 1σ confidence interval [3.04, 3.24] rad. The phase δ_S of the S-wave component, which can only be fitted relative to $\delta_\perp$, is found to be $\delta_\perp - \delta_S = (0.03 \pm 0.13)$ rad.

Systematic uncertainties of the physics parameters cannot be obtained through the maximum likelihood fit, they are determined using other techniques, such as making changes to the detector simulation, doing data based studies, generating Monte Carlo pseudo experiments and slightly varying the analysis method. Overall the largest systematic effect comes from varying the model that is used to describe the angular distributions of the background events.

4.1. Fit projections

In addition to quoting the best fit parameters it is instructive to plot the fit projections to compare data agreement with the fit functions. Figure 1 shows the fit projection for the B_s^0 mass variable. One can see a clear mass peak of 22700 B_s^0 signal events on top of a relatively large background, which is due to the fact that the analysis does not contain a lifetime cut. This can be seen in figure 2 which shows the proper decay time fit projection. The large background peak centered at $t \sim 0$ is mainly due to prompt J/ψ's which are produced in pp collisions and not in B_s^0 meson decays. The signal dominates for $t > 1$ ps and the tail is extending almost up to 10 ps. The plot clearly shows the two components of the signal, namely the B_L and the B_H parts. B_L dominates by a factor of about 2 over the whole range. Looking closely one can see that the slopes of the two components are different, meaning that $\Delta\Gamma_s$ is different from 0.

The reason for not doing a cut on the proper decay time (*e.g.* $t > 0.3$ ps) is two-fold. First, the analysis very well profits from the fact that there is not much background for large proper decay times. Second, keeping
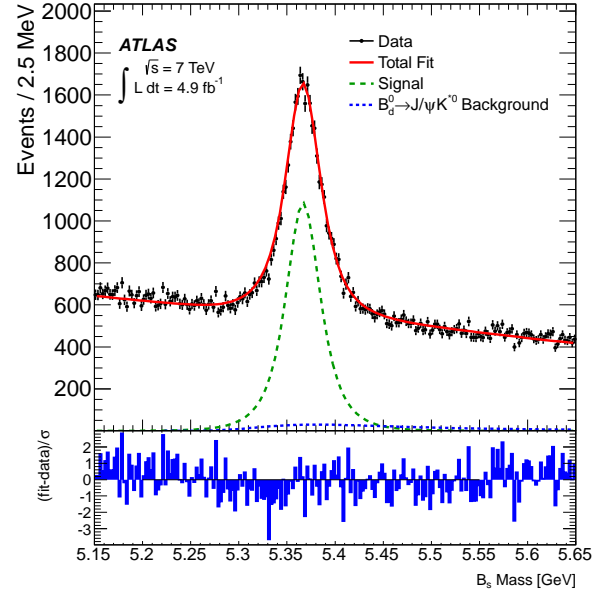

Figure 1: Mass fit projection for the B_s^0. The pull distribution at the bottom shows the difference between the data and fit value normalised to the data uncertainty. Figure taken from [4].
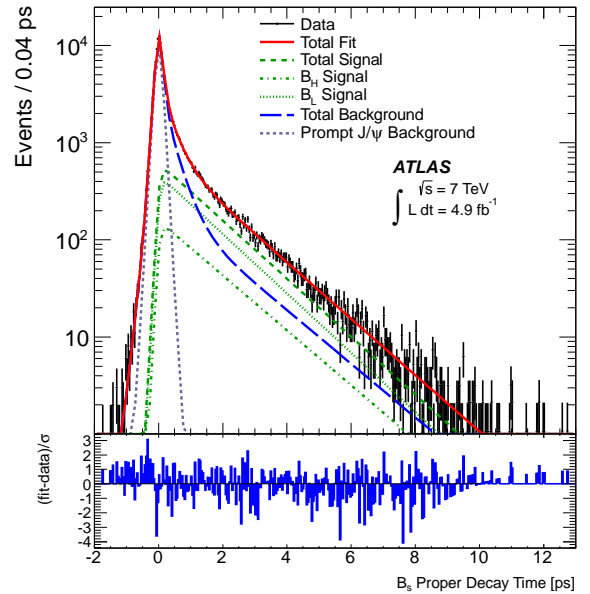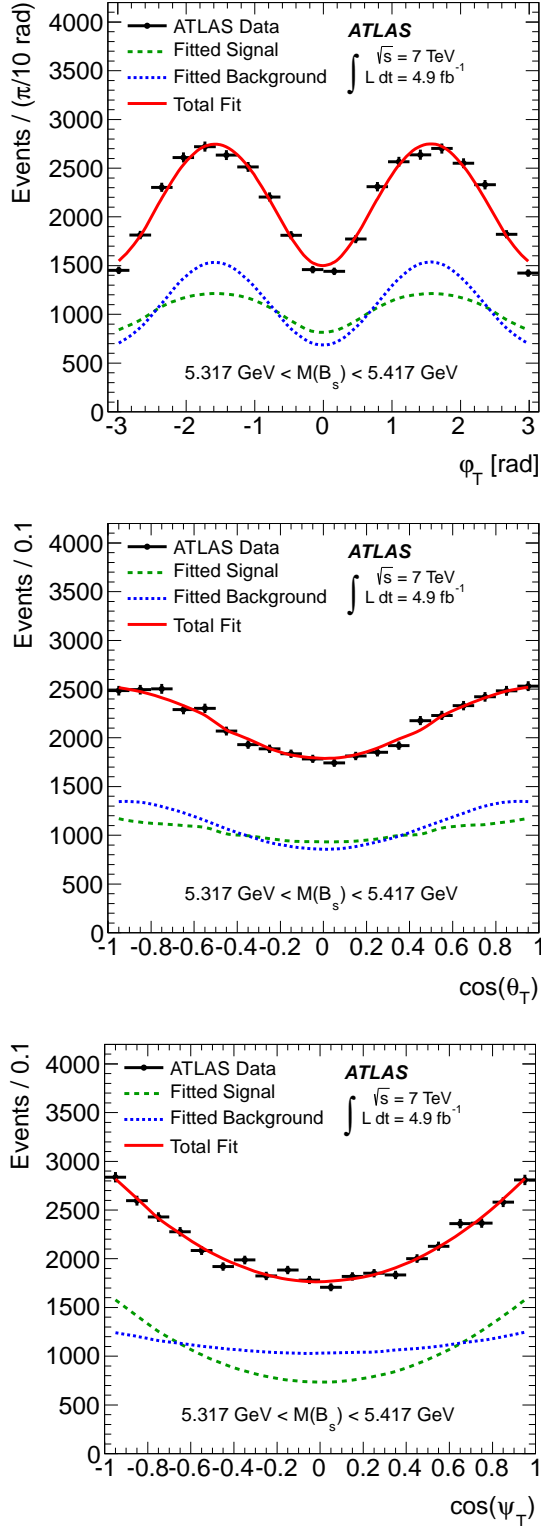

Figure 2: Proper decay time fit projection for the B_s^0. The pull distribution at the bottom shows the difference between the data and fit value normalised to the data uncertainty. Figure taken from [4].

Figure 3: Fit projections for the three transversity angles. Top: φ_T, Middle: $\cos\theta_T$, Bottom: $\cos\psi_T$ for events with a B_s^0 mass in the signal region (5.317 - 5.417) GeV. Figures taken from [4].

the events around $t \sim 0$ allows to measure important properties of background events (like the angular distributions), and therefore helps to better distinguish the different CP states – which is needed to measure the transversity amplitudes.

The fit projections of the transversity angles are shown in figure 3. The distributions are plotted for events in a mass region of 100 MeV/c^2 around the nominal B_s^0 mass. This yields roughly the same number of signal and background events and thus allows to more easily compare the shapes of the signal and background components.

4.2. $\phi_s - \Delta\Gamma_s$ plane and comparison with results from other experiments

Figure 4 shows the parameters most sensitive to new physics as a two-dimensional contour plot. It can be seen that the ATLAS result is in good agreement with the Standard Model prediction. As indicated on the plot this analysis uses the LHCb measurements from [11] and [12] to contrain the phase $\delta_\perp$ (Gaussian constraint in the fit) and the width difference $\Delta\Gamma_s$. Due to the symmetries mentioned at the end of section 3 the fit leads to four different solutions in the $\phi_s - \Delta\Gamma_s$ plane, but only one of them is compatible with the above mentioned constraints, which is the one shown in figure 4.

To see the relevance of the ATLAS measurement, figure 5 shows a comparison with the results from other experiments (DØ, CDF and LHCb). All the results are consistent. Comparing the precision of $\Delta\Gamma_s$ on the vertical axis one can see that ATLAS is competitive with the other experiments (slightly smaller error than the Tevatron experiments, but slightly larger error compared to the LHCb result). Since flavour tagging in not applied in this analysis the sensitivity to ϕ_s is limited. Looking along the horizontal axis on can seen that the ATLAS uncertainty in measuring the CP-violating mixing phase is as large as the one of the Tevatron experiments, but significantly larger than the one of the LHCb result.

5. Summary and Outlook

From 4.9 fb^{-1} of data collected by ATLAS in the year 2011 decay time and angular distributions have been studied in a sample of about 22700 $B_s^0/\overline{B_s^0} \rightarrow J/\psi\phi$ decays. Without flavour tagging, and assuming $\delta_\perp = 2.95 \pm 0.39$ rad we obtain a value of $\phi_s = 0.22 \pm 0.41(\text{stat.}) \pm 0.10(\text{syst.})$ rad for the CP-violating weak mixing phase and $\Delta\Gamma_s = 0.053 \pm 0.021(\text{stat.}) \pm 0.008(\text{syst.})$ ps^{-1} for the decay width difference.
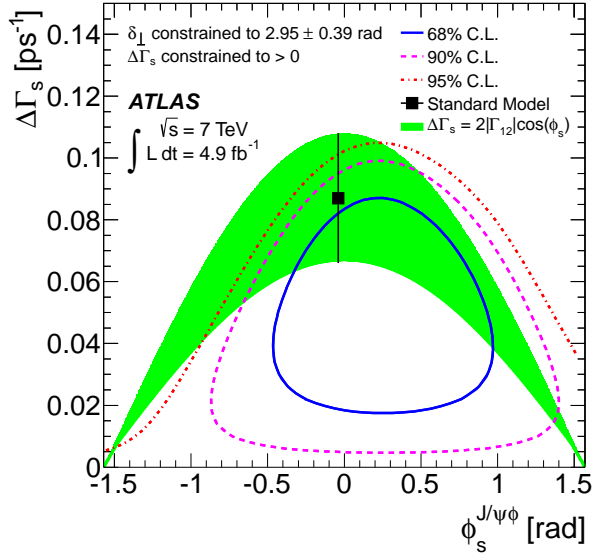
Figure 4: Likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane. The three contour lines show the 68%, 90% and 95% confidence intervals (statistical errors only). The grey (green) band is the theoretical prediction of mixing induced *CP* violation. The PDF contains a fourfold ambiguity. Three fit minima are excluded by applying the constraints from the LHCb measurements [11, 12]. The ATLAS measurement is in good agreement with the Standard Model theory value [14], which is represented by the single black point. The Standard Model error of ϕ_s is too small to be visible on this plot. Figure taken from [4].
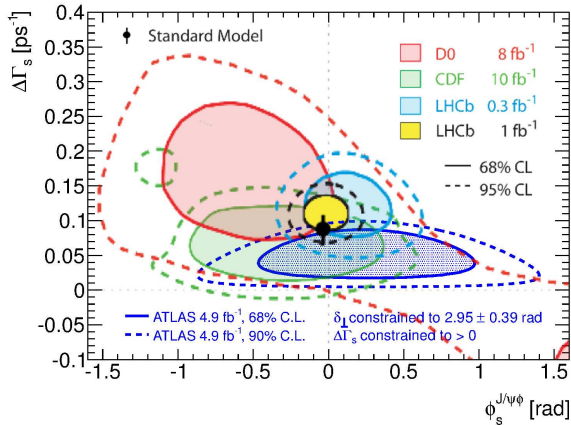

Figure 5: Likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane. The ATLAS result is the same as shown in figure 4. As can be seen, it is consistent with the measurements from other experiments. Details about the contour plots of the other experiments can be found in [10] for DØ in [9] for CDF and in [11, 13] for LHCb.

In 2012 ATLAS uses trigger setups that apply higher transverse momentum cuts. This means fewer signal events per fb^{-1}, but they will have a better proper-decay-time resolution. In order to be more sensitive to ϕ_s in a future analysis ATLAS also plans to distinguish between the initial B_s^0 and $\overline{B_s^0}$ states by using flavour tagging.

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