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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 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} is the value within the Standard Model 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: section 2 describes the relevant information about the ATLAS experiment and the event reconstruction. After explaining the maximum likelihood fit in section 3, the results are presented and discussed

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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 $J/\psi \to \mu^+\mu^-$ 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 $\phi \to K^+K^-$ 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].

To study the detector response, calculate background contributions and estimate systematic effects, 12 million signal Monte Carlo events $B_s^0 \to J/\psi(\mu^+\mu^-)\,\phi(K^+K^-)$ as well as various background samples, such as the specific decay $B^0 \to J/\psi K^{0*}$ and the inclusive decays $bb \to J/\psi X$ and $pp \to J/\psi X$ 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 of interest. 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 eigenstates, $|A_\parallel(0)|$ 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 $B_s^0 \to J/\psi K^+K^-(f_0)$, 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 us to calculate the number of $B_s^0 \to J/\psi(\mu^+\mu^-)\,\phi(K^+K^-)$ 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 $B^0 \to J/\psi K^*$ and non-resonant $B^0 \to J/\psi K^+\pi^-$, 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 $B_s^0 \to J/\psi\phi$ decay exhibits a fourfold symmetry. This PDF is invariant under the transformation $\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \to \{\pi-\phi_s, -\Delta\Gamma_s, \pi-\delta_\perp, -\delta_\parallel, -\delta_S\}$ as well as under the transformation $\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \to \{-\phi_s, \Delta\Gamma_s, \pi-\delta_\perp, -\delta_\parallel, -\delta_S\}$. 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 parameters 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