Measurement of CP violation and mixing in $B^{0}_{s} \rightarrow J/\psi\phi$ in ATLAS

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Abstract

An overview of a measurement of time-dependent CP asymmetry parameters in $B^{0}_{s} \rightarrow J/\psi(\mu^{+}\mu^{-})\phi(K^{+}K^{-})$ decays using 80.5 fb$^{-1}$ of integrated luminosity collected with the ATLAS detector from 13 TeV $pp$ collisions at the LHC is presented. A manifestation of the CP violation is an interference between direct and mixing-mediated $B^{0}_{s}$ decays, producing a common final state. In the Standard Model, it is characterized by a phase shift $\phi_{s}$ related to the CKM matrix. In the case of $B^{0}_{s} \rightarrow J/\psi\phi$, this shift is predicted to be small, $\phi_{s} = -0.0363^{+0.0016}_{-0.0015}$ rad. New physics can enhance $\phi_{s}$ whilst satisfying all existing constraints. Results presented in this talk are compatible with those obtained from 19.2 fb$^{-1}$ of 7 TeV and 8 TeV data as well as with the Standard Model predictions and other LHC measurements.

Keywords: CP Violation, Bs J/psi Phi, ATLAS, CERN, B Physics, Flavour Physics

1. Introduction

The $B^{0}_{s} \rightarrow J/\psi\phi$ decay channel is expected to be sensitive to new physics contributions in the CP violation. In this channel, CP violation occurs due to interference between direct decays and decays occurring through $B^{0}_{s}-\bar{B}^{0}_{s}$ mixing. The frequency of this mixing is characterized by the mass difference $\Delta M_{s}$ between light ($B_{L}$) and heavy ($B_{H}$) mass eigenstates. The CP violation is described by the weak phase difference $\phi_{s}$ between the $B^{0}_{s}-\bar{B}^{0}_{s}$ mixing amplitude and the $b \rightarrow ccs$ decay amplitude, the decay width $\Gamma_{s} = (\Gamma_{L}^{s} + \Gamma_{H}^{s})/2$, and the width difference $\Delta \Gamma_{s} = \Gamma_{L}^{s} - \Gamma_{H}^{s}$, where $\Gamma_{L}^{s}$ and $\Gamma_{H}^{s}$ are decay widths of $B_{L}$ and $B_{H}$ states, respectively. In the Standard Model (SM), the phase $\phi_{s}$ is related to CKM quark mixing matrix via the relation

$$\phi_{s} \simeq -2 \arg \left( \frac{V_{ts}V_{cb}^{*}}{V_{ub}V_{cd}^{*}} \right).$$

Assuming no beyond the SM physics contributions to the $B^{0}_{s}$ mixing and decays, a value of $\phi_{s} = -0.0363^{+0.0016}_{-0.0015}$ rad is predicted [1]. Many New Physics (NP) models allow a larger value of $\phi_{s}$ whilst satisfying all existing constraints, including the precisely measured value of $\Delta M_{s}$.

The analysis presented here introduces a measurement of parameters describing the CP violation in the $B^{0}_{s} \rightarrow J/\psi\phi$ decay using 80.5 fb$^{-1}$ of LHC $pp$ 13 TeV data collected by the ATLAS detector during 2015-2017 [2]. The results are combined with those obtained from the analysis of 19.2 fb$^{-1}$ of data collected at 7 TeV and 8 TeV [3].

2. The ATLAS detector

The ATLAS experiment [4] is a multipurpose particle detector at the LHC. It consists of three main parts: the Inner Detector (ID) immersed in a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a Muon Spectrometer (MS), all located within the magnetic field produced by three large superconducting air-core toroid systems.
The ID subsystem covers the pseudorapidity region of $|\eta| < 2.5$ and is used for a precise tracking. The ID consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. A new Insertable B-Layer was added to the present ID during the Long Shutdown 1. This fourth layer with a radius of 33 mm was placed between a new beam pipe and the current inner pixel layer.

3. Data, reconstruction, and candidate selection

The data were collected using triggers based on the identification of a $J/\psi \rightarrow \mu \mu$ decay, with transverse momentum ($p_T$) thresholds of either 4 GeV or 6 GeV for the muons.

Events must contain at least one reconstructed primary vertex, formed from at least four ID tracks, to pass the selection. Also at least one pair of oppositely charged muons reconstructed using information from both the MS and the ID must be present in the event. Pairs of oppositely charged muon tracks are refitted to a common vertex and the pair is accepted if $\chi^2/\text{ndf} < 10$. Varying mass resolution in different parts of the detector is accounted for by the $|p_T|\mu|\eta|$ dependent $J/\psi$ mass cuts. Decays $\phi \rightarrow K^+K^-$ are reconstructed from all pairs of oppositely charged particles with $p_T > 1$ GeV and $|\eta| < 2.5$ that are not identified as muons. Candidates for $B_{s}^{0}$ are selected by fitting the four tracks to a common vertex with $J/\psi$ mass constraint [5]. A candidate is accepted if the vertex fit has $\chi^2/\text{ndf} < 3$ and $|m(K^+K^-) - m_\text{PDG}(\phi)| < 11$ MeV. In the case of more than one $B_{s}^{0}$ candidate in the event, the one with the lowest $\chi^2/\text{ndf}$ is selected.

For each $B_{s}^{0}$ candidate the proper decay time $t$ is calculated:

$$t = \frac{L_{xy} \ m(B_{s}^{0})}{p_T(B_{s}^{0})},$$

where $p_T(B_{s}^{0})$ is the transverse momentum of the $B_{s}^{0}$ meson and $m(B_{s}^{0})$ is the mass of the $B_{s}^{0}$ meson, taken from [5]. The transverse decay length $L_{xy}$ is the displacement in the transverse plane of the $B_{s}^{0}$ meson decay vertex with respect to the primary vertex, projected onto the direction of the $B_{s}^{0}$ transverse momentum.

4. Flavour tagging

Initial flavour of (neutral) $B_{s}^{0}$ is inferred using the other $B$-meson typically produced in the event. Discrimination is provided by measuring the cone charge from the semileptonic decay of this meson, which is defined as a $p_T$-weighted sum of charge of tracks in the cone $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} < 0.5$, i.e.,

$$Q_x = \frac{\sum_{i}^{N \text{ tracks}} q_i \cdot (p_T)^x}{\sum_{i}^{N \text{ tracks}} (p_T)^x},$$

where $x = [\mu, e, \text{jet}]$ refers to muon, electron, or jet charge tagging method, respectively. Jet charge is used if no lepton is present in the event. The constant $\kappa$ is found empirically for each tagging method to achieve the best performance. To study and calibrate used tagging methods, events containing the decays of “self-calibrated” channel $B^{0} \rightarrow J/\psi K^{*}$ were used (flavour of the $B$-meson at production is provided by the kaon charge). Using this sample, a cone charge is mapped to a probability $P(B(Q_x))$ that a $B$ meson is produced in a state containing a $\bar{b}$-quark. This information is then used in a fit on a per-candidate basis. If there is no information available for a given $B_{s}^{0}$ meson, a probability of 0.5 is assigned to that candidate.

A strength of a particular flavour tagging method is represented by a dilution $D_x(Q_x) = 2P(B(Q_x)) - 1$. An efficiency $\epsilon_i$ is defined as the fraction of signal events tagged by the method compared to the total number of signal events in the sample. A tagging power is then defined as $T_x = \sum \epsilon_i \cdot (2P(B(Q_i)) - 1)^2$, where the sum is over the probability distribution in intervals of the cone charge variable. An effective dilution, $D_x = \sqrt{T_x/\epsilon_i}$, is calculated from the measured tagging power and efficiency. A summary of the tagging performance for each method is given in Table [7].

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Table 1: Tagging performance for the methods used in the analysis, determined by using the sample of $B^{0}$ signal candidates. Uncertainties shown are statistical only. Taken from [5].

<table>
<thead>
<tr>
<th>Tag method</th>
<th>Efficiency [%]</th>
<th>Effective Dilution [%]</th>
<th>Tagging Power [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight muon</td>
<td>4.50 ± 0.01</td>
<td>43.8 ± 0.2</td>
<td>0.862 ± 0.009</td>
</tr>
<tr>
<td>Electron</td>
<td>1.57 ± 0.01</td>
<td>41.8 ± 0.2</td>
<td>0.274 ± 0.004</td>
</tr>
<tr>
<td>Low-$p_T$ muon</td>
<td>3.12 ± 0.01</td>
<td>29.9 ± 0.2</td>
<td>0.278 ± 0.006</td>
</tr>
<tr>
<td>Jet</td>
<td>5.54 ± 0.01</td>
<td>20.4 ± 0.1</td>
<td>0.231 ± 0.005</td>
</tr>
<tr>
<td>Total</td>
<td>14.74 ± 0.02</td>
<td>33.4 ± 0.1</td>
<td>1.65 ± 0.01</td>
</tr>
</tbody>
</table>
Table 2: Fit results for the selected physical parameters with their statistical and systematic uncertainties, both for the 13 TeV measurement and for the combination with the results obtained from 7 TeV and 8 TeV data. Taken from [2].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>13 TeV Data</th>
<th>13 TeV and Run 1 combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_1$ [rad]</td>
<td>$-0.068$</td>
<td>0.038</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$]</td>
<td>0.067</td>
<td>0.005</td>
</tr>
<tr>
<td>$\Gamma_s$ [ps$^{-1}$]</td>
<td>0.669</td>
<td>0.001</td>
</tr>
</tbody>
</table>

5. Maximum likelihood fit

To extract the parameters characterising the decay, an unbinned maximum likelihood fit is performed on 3210429 $B^0_s$ candidates passing the selection and collected within a mass range of 5.15 GeV < $m(B^0_s) < 5.65$ GeV. The fit uses information about the reconstructed mass $m$, the measured proper decay time $t$, the measured proper decay time uncertainty $\sigma_t$, the tagging probability $P(B|Q_\ell)$, and the transversity angles (\(\theta_T, \psi_T, \phi_T\)) of each $B^0_s$ candidate. The likelihood function is defined as a combination of the Probability Density Functions (PDF) describing the signal (including a non-resonant S-wave state $B^0_s \rightarrow J/\psi K^+ K^-$), backgrounds from $B^0_s$ mesons and $\Lambda_b$ baryons misidentified as $B^0_s$ candidates, and the combinatorial background distributions.

Systematic uncertainties are evaluated for effects that are not accounted for in the likelihood fit. Following sources were identified and are described in detail in [2]: flavour tagging, angular acceptance method, ID alignment, fit model used, trigger efficiency, $B^0_s$ and $\Lambda_b$ contributions, and limitation of the data modelling. For each parameter, the total systematic uncertainty is obtained by adding these contributions in quadrature.

6. Results

The fit results are compatible with those obtained from 19.2 fb$^{-1}$ of 7 TeV and 8 TeV data analysis. A Best Linear Unbiased Estimator (BLUE) method [6] is used to perform a combination of the current measurements with the previous analysis. Selected parameters of the fit results and the obtained combined results together with their uncertainties are given in Table [2].
projections of mass, lifetime, and transversity angles between final state particles are shown in Figure 3 and 4 respectively. The two dimensional likelihood contours in the $\phi_s - \Delta \Gamma_s$ plane for the both measurements and the combined results are shown in Figure 4.

7. Summary

A measurement of the time-dependent CP asymmetry parameters in $B^0_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays using 80.5 fb$^{-1}$ of integrated luminosity collected with the ATLAS detector from 13 TeV $pp$ collisions at the LHC is presented. Results are compatible with those obtained from 19.2 fb$^{-1}$ of 7 TeV and 8 TeV data analysis and both measurements are statistically combined to the following results:

$$\phi_s = -0.076 \pm 0.03(\text{stat.}) \pm 0.019(\text{syst.}) \text{ rad}$$

$$\Delta \Gamma_s = 0.068 \pm 0.004(\text{stat.}) \pm 0.003(\text{syst.}) \text{ ps}^{-1}$$

$$\Gamma_s = 0.669 \pm 0.001(\text{stat.}) \pm 0.001(\text{syst.}) \text{ ps}^{-1}$$

Both the new measurement and the combination are still consistent with the Standard Model predictions as well as with the other LHC measurements.

Acknowledgements

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References


[3] ATLAS Collaboration, Measurement of the CP-violating phase $\phi_s$ and the $B^0_s$ meson decay width difference with $B^0_s \to J/\psi K^0_{SD}$ decays in ATLAS, JHEP 1608 (2016) 147.

