Mixing and CP violation in the $B_s$ system with ATLAS

Pavol Bartoš\textsuperscript{1, a}
On behalf of the ATLAS Collaboration.

\textsuperscript{1}Department of nuclear physics and biophysics, Faculty of Mathematics, Physics and Informatics, Comenius University, Mlynská Dolina F1, 842 48 Bratislava, Slovakia

Abstract. The different amplitudes contributing to the decay of $B_s$ into $J/\psi\phi(\mu^+\mu^- K^+ K^-)$ can be studied with a combined analysis of the decay time and angular correlations. An analysis based on the LHC data collected by the ATLAS detector in 2011 and with initial $B$-meson flavour tagging is presented, improving the accuracy in the CP-violating phase $\phi_s$ compared to the untagged analysis.

1 Introduction

New phenomena beyond the Standard Model (SM) may alter CP violation in $B$–meson decays. The $B^0 \rightarrow J/\psi \phi(\mu^+\mu^- K^+ K^-)$ decay channel is expected to be sensitive to a new physics contribution. The CP violation in this channel occurs due to interference between direct $B^0_s$ decays and decays following the $B^0_s - \bar{B}^0_s$ mixing. The oscillation frequency of $B^0_s$ mixing is characterized by the mass difference $\Delta m_s$ of the heavy ($B_H$) and light ($B_L$) mass eigenstates.

There are several quantities involved in $B^0_s - \bar{B}^0_s$ mixing. The CP-violating phase $\phi_s$ is defined as the weak phase difference between amplitudes of $B^0_s - \bar{B}^0_s$ mixing and direct decay. In the SM, the phase $\phi_s$ is small ($\phi_s = -0.0368 \pm 0.0018$ rad [1]) and can be related to CKM quark mixing matrix elements. Some new physics models predicts large values of $\phi_s$ while satisfying all existing constrains [2, 3]. The width difference $\Delta \Gamma_s = \Gamma_L - \Gamma_H$ of $B_L$ and $B_H$ is predicted to be $\Delta \Gamma_s = 0.087 \pm 0.021$ ps\textsuperscript{-1} [4]. Physics beyond the SM is not expected to affect $\Delta \Gamma_s$ as significantly as $\phi_s$ [5]. Nevertheless, it is useful to extract $\Delta \Gamma_s$ from data as it allows testing the theoretical predictions [5]. One can also define average decay width $\Gamma_s = (\Gamma_L + \Gamma_H)/2$. Among important parameters are also the amplitudes $A_0(0)$ and $A_\parallel(0)$ for the CP-even components of the $B^0_s$ decay, and $A_{\perp}(0)$ for the CP-odd component. The amplitudes have corresponding strong phases $\delta_0$, $\delta_{\parallel}$ and $\delta_{\perp}$ (by convention, $\delta_0$ is set to zero). The $S$-wave amplitude $A_s$ describes the contribution of CP-odd $B_s \rightarrow J/\psi K^+ K^-(f_0)$, where the non-resonant $KK$ or $f_0$ meson is an $S$-wave state. The strong phase $\delta_s$ corresponds to the $A_s$.

The previous measurements of these quantities have been reported by the CDF [6], DØ [7], and LHCb [3] collaborations. In this paper, an update to the previous ATLAS measurement [8], using flavour tagging, is presented [9]. The analysis uses LHC pp data at $\sqrt{s} = 7$ TeV collected by the ATLAS detector [10] in 2011.

\textsuperscript{a} e-mail: Pavol.Bartos@cern.ch

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2 Event selection

The candidate events have to pass trigger based on $J/\psi \to \mu^+\mu^-$ decay identification. In addition to that, events are required to contain at least one reconstructed primary vertex built from at least four Inner-detector tracks and at least one pair of oppositely charged muons. The pairs of muon tracks are refitted to a common vertex and accepted as a $J/\psi$ candidate if the fit results in $\chi^2$/d.o.f. $< 10$ and the invariant mass of the pair falls in a signal region. Taking into account varying mass resolution, the signal region is a mass range around $J/\psi$ mass, which depends on the pseudorapidity of the muons. The mass range is defined so as to retain 99.8% of the $J/\psi$ candidates identified in the fit.

The $\phi \to K^+K^-$ candidates are reconstructed from all pairs of oppositely charged tracks with transverse momentum $p_T > 0.5$ GeV and pseudorapidity $|\eta| < 2.5$, which are not identified as muons. The final selection is done by fitting the tracks for each combination of $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ to a common vertex. The fit is further constrained by fixing the calculated invariant mass from the two muon tracks to the world average $J/\psi$ mass [11]. The quadruples of tracks are accepted as $B^0_s$ candidates if the fit results in $\chi^2$/d.o.f. $< 3$, the fitted transverse momentum $p_T$ of the tracks from $\phi \to K^+K^-$ is greater than 1 GeV and the invariant mass of the track pair (under assumption that they are kaons) falls within interval $1.0085$ GeV $< m(K^+K^-) < 1.0305$ GeV. In total, 131k $B^0_s$ candidates are collected within a mass range of $5.15 < m(B^0_s) < 5.65$ GeV.

In the selected events, there are 5.6 interactions per event in average. The primary vertex at which the $B^0_s$ meson is produced, is selected by requiring the smallest three-dimensional impact parameter [12]. Using the Monte Carlo simulation it is shown that the wrong assignment of $B^0_s$ to primary vertex occurs in less than 1% of cases.

3 Flavour tagging

To increase the sensitivity of the measurement, the opposite side flavour tagging is used. The initial flavour of neutral $B$-mesons is inferred from the other $B$-meson which is coming from the other $b$ quark in the event. The method is studied and calibrated using $B^+ \to J/\psi K^+$ events, where the charge of the $B$-meson at production is extracted from the kaon charge.

There are two possibilities to obtain the charge of the other $B$-meson in the event. In case of presence of an additional muon, which originates near the interaction point, one can define muon cone charge as a weighted sum of the charges of the tracks (with $p_T > 0.5$ GeV and $|\eta| < 2.5$), which are reconstructed within a cone of $\Delta R < 0.5$ around the muon momentum axis. In case of multiple muons, the one with the highest transverse momentum is selected. In the absence of an additional muon, a $b$-tagged jet [13] is required in the event, with tracks associated to the same primary vertex as the signal decay. The jet is reconstructed using the anti-$k_t$ algorithm with a cone size of 0.6. In this case, a jet charge is defined as a weighted sum of the charges of the tracks associated to the jet. In case of multiple jets, the jet with the highest value of $b$-tag weight is used.

Using the calculated muon-cone charge or jet charge (in the absence of an additional muon), one can define per-$B_s$ candidate probability that the $B_s$ was born as $B^0_s$ and not as $\bar{B}^0_s$. If it is not possible to provide tagging response for the event, the probability of 0.5 is assigned.

4 Likelihood fit

An unbinned likelihood fit is used to extract the $B^0_s$-decay parameters mentioned in section 1. The fit uses the information about reconstructed mass, the measured proper decay time together with their uncertainties, tag probability, and the transversity angles. The likelihood function is defined as a combination of the signal and background probability density functions as follows:
\[ \ln L = \sum_{i=1}^{N} \left[ w_i \cdot \ln(f_s \cdot F_s(m_i, t_i, \Omega_i)) + f_{B^0} \cdot F_{B^0}(m_i, t_i, \Omega_i) \right] + (1 - f_s \cdot (1 + f_{B^0})) F_{\text{bkg}}(m_i, t_i, \Omega_i) , \]

where \( N \) is the number of selected candidates, \( w_i \) is a weighting factor to account for the trigger efficiency, \( f_s \) is the fraction of signal candidates, \( f_{B^0} \) is the fraction of peaking \( B^0 \)-meson background events calculated relative to the number of signal events (this parameter is fixed in the likelihood fit). The mass \( m_i \), the proper decay time \( t_i \), and the decay angles \( \Omega_i \) are the values measured from the data for each event \( i \). \( F_s \), \( F_{B^0} \), and \( F_{\text{bkg}} \) are the probability density functions (PDF) modeling signal, the specific \( B^0 \) background and the other background distributions, respectively. A detailed description of the likelihood terms can be found in [9].

5 Results and conclusions

The PDF describing the \( B^0_s \to J/\psi \phi \) decay is invariant under the following simultaneous transformations:

\[ \{ \phi_s, \Delta \Gamma_s, \delta_\perp, \delta_\parallel \} \to (\pi - \phi_s, -\Delta \Gamma_s, \pi - \delta_\perp, 2\pi - \delta_\parallel) . \]

\( \Delta \Gamma_s \) has been defined to be positive [14]. Therefore, there is a unique solution.

Table 1. Fitted values for the physical parameters along with their statistical and systematic uncertainties [9].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_s ) (rad)</td>
<td>0.12</td>
<td>0.25</td>
<td>0.05</td>
</tr>
<tr>
<td>( \Delta \Gamma_s ) (ps(^{-1}))</td>
<td>0.053</td>
<td>0.021</td>
<td>0.010</td>
</tr>
<tr>
<td>( \Gamma_s ) (ps(^{-1}))</td>
<td>0.677</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td>(</td>
<td>A_\parallel(0)</td>
<td>^2 )</td>
<td>0.220</td>
</tr>
<tr>
<td>(</td>
<td>A_0(0)</td>
<td>^2 )</td>
<td>0.529</td>
</tr>
<tr>
<td>(</td>
<td>A_S</td>
<td>^2 )</td>
<td>0.024</td>
</tr>
<tr>
<td>( \delta_\perp )</td>
<td>3.89</td>
<td>0.47</td>
<td>0.11</td>
</tr>
<tr>
<td>( \delta_\parallel )</td>
<td>[3.04 – 3.23]</td>
<td></td>
<td>0.09</td>
</tr>
<tr>
<td>( \delta_\perp - \delta_S )</td>
<td>[3.02 – 3.25]</td>
<td></td>
<td>0.04</td>
</tr>
</tbody>
</table>

The results of the measurement are summarized in table 1. The values are consistent with those obtained in the untagged analysis [8], while the overall uncertainty of \( \phi_s \) is significantly improved. The results are consistent with theoretical expectations, in particular \( \phi_s \) and \( \Delta \Gamma_s \) are in good agreement with the values predicted by the Standard Model. Figure 1 shows the likelihood contour in \( \phi_s - \Delta \Gamma_s \) plane. The fraction of \( S \)-wave \( KK \) of \( f_0 \) contamination is measured to be consistent with zero. The results of \( \delta_\parallel \) and \( \delta_\perp - \delta_S \) are given in the form of a 1\( \sigma \) confidence interval. The \( |A_\perp(0)|^2 \) can be determined from a constrain that the squares of the amplitudes sum to unity.

For all of the measured parameters except \( \phi_s \), the main source of the systematics uncertainty comes from assumptions made for the transversity angles in case of background events. The main source of the systematics uncertainty for the \( \phi_s \) is flavour tagging.
Figure 1. Likelihood contours in $\phi_s - \Delta \Gamma_s$ plane. The blue line shows the 68% likelihood contour, the dashed pink line shows the 90% likelihood contour, and the red dotted line shows the 95% likelihood contour (statistical errors only). The green band is the theoretical prediction of mixing-induced CP violation [9].

Acknowledgements

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References

[12] Three-dimensional impact parameter is defined as the distance between the line extrapolated from the reconstructed $B^0_s$ meson vertex in the direction of the $B^0_s$ momentum and a primary vertex.