CP VIOLATION RESULTS AND PROSPECTS WITH LHCb

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The LHCb experiment at the Large Hadron Collider searches for New Physics by performing precision measurements of CP-violating processes in the B sector. A key measurement of the LHCb programme is the extraction of the CP-violating phase \( \phi_s \) via a time-dependent angular analysis of the decay \( B^0 \to J/\psi \phi \). In the Standard Model the phase \( \phi_s \) which arises in the interference between \( B^0 \) mixing and decay is predicted to be small, \( \phi_s = -0.0363 \pm 0.0017 \). \(^1\) Possible deviations from this prediction can be attributed to New Physics. Key results on the way to a measurement of \( \phi_s \) are presented. The decay amplitudes in the \( P \to \pi \pi \) decays \( B \to J/\psi K^* \) and \( B^0 \to J/\psi \phi \) are extracted via an angular analysis. The decay \( B^0 \to J/\psi \phi \) additionally gives access to \( \phi_s \) which is determined to be \( \Delta \Gamma_s = (0.077 \pm 0.11 \text{stat} \pm 0.021 \text{syst}.) \text{ps}^{-1} \) assuming \( \phi_s = 0 \). \(^2\) A crucial ingredient for the extraction of \( \phi_s \) is the determination of the \( B^0 \) production flavor (flavor tagging). The flavor tagging procedure is verified by the determination of the mixing frequency in the \( B^0 \) and \( B^0 \) systems giving \( \Delta m_s = (0.499 \pm 0.032 \text{stat} \pm 0.003 \text{syst}.) \text{ps}^{-1} \) and \( \Delta m_s = (17.63 \pm 0.11 \text{stat} \pm 0.04 \text{syst}.) \text{ps}^{-1} \) respectively. \(^3,4\) The data used were taken with the LHCb detector in 2010 and correspond to an integrated luminosity of 36 pb\(^{-1} \).

1 Introduction

\( B^0_s \) mixing as shown in Figure 1b gives rise to transitions between the flavor eigenstates \( B^0 \) and \( B^0_s \). As a result the flavor eigenstates differ from the mass eigenstates \( B_L \) and \( B_H \) with masses \( m_L \) and \( m_H \). Their mass difference determines the \( B^0_s \) mixing frequency \( \Delta m_s = m_H - m_L \). The mass eigenstates also exhibit different total decay widths \( \Gamma_L \) and \( \Gamma_H \) respectively. The Standard Model predicts the decay width difference \( \Delta \Gamma_s = \Gamma_L - \Gamma_H \) to be sizeable, \( \Delta \Gamma_s = (0.087 \pm 0.021) \text{ps}^{-1} \).\(^5\)

The CP-violating phase \( \phi_s \) arises due to interference between the tree level decay shown in Figure 1a and mixing via box diagrams as given in Figure 1b followed by decay. Neglecting penguin contributions the phase \( \phi_s \) is in the Standard Model given by \( \phi_s = -2\beta_s \) where \( \beta_s = \arg \left(-V_{ub} V_{ub}^\dagger/N_{cb} V_{cb}^\dagger \right) \) is the smallest angle of the \( b-s \) unitarity triangle. Contributions from New Physics can lead to a deviation from this prediction \( \phi_s = \phi_s^{\text{SM}} \to \phi_s = \phi_s^{\text{SM}} + \phi_s^{\text{NP}} \).

The Tevatron has measured the \( B^0_s \) mixing frequency \( \Delta m_s = (17.77 \pm 0.10 \text{stat} \pm 0.07 \text{syst}) \text{ps}^{-1} \) with high precision,\(^6\) however the limits on \( \Delta \Gamma_s \) and \( \phi_s \) are much less stringent.\(^7\) LHCb aims to improve these measurements using the large number of \( B \)-mesons produced at the Large Hadron Collider. The LHCb experiment, as a dedicated \( B \) physics experiment, is particularly well suited for this task. LHCb exhibits an efficient low \( \pT \) trigger system, excellent mass and proper time resolution as well as good particle identification over the full relevant momentum range. In the following the main steps towards a measurement of \( \phi_s \) at LHCb will be discussed.
The signal decay $B_d^0 \rightarrow J/\psi K^+$ can occur via direct decay (1a) or via mixing (1b) followed by decay.

Table 1: Lifetimes determined from $b$-hadron $\rightarrow J/\psi X$ decays.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Yield</th>
<th>LHCb result $\tau [\text{ps}]$</th>
<th>PDG $\tau [\text{ps}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \rightarrow J/\psi K^\pm$</td>
<td>6741 ± 85</td>
<td>$1.689 \pm 0.022_{\text{stat.}} \pm 0.047_{\text{syst.}}$</td>
<td>$1.638 \pm 0.011$</td>
</tr>
<tr>
<td>$B^0_d \rightarrow J/\psi K^*$</td>
<td>2668 ± 58</td>
<td>$1.512 \pm 0.032_{\text{stat.}} \pm 0.042_{\text{syst.}}$</td>
<td>$1.525 \pm 0.009$</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K_{S}^0$</td>
<td>838 ± 31</td>
<td>$1.558 \pm 0.056_{\text{stat.}} \pm 0.022_{\text{syst.}}$</td>
<td>$1.525 \pm 0.009$</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi \phi$</td>
<td>570 ± 24</td>
<td>$1.447 \pm 0.064_{\text{stat.}} \pm 0.056_{\text{syst.}}$</td>
<td>$1.477 \pm 0.046$</td>
</tr>
<tr>
<td>$A_b \rightarrow J/\psi \Lambda$</td>
<td>187 ± 16</td>
<td>$1.353 \pm 0.108_{\text{stat.}} \pm 0.035_{\text{syst.}}$</td>
<td>$1.391 + 0.034 - 0.037$</td>
</tr>
</tbody>
</table>

2 Determination of lifetimes in $b$-hadron $\rightarrow J/\psi X$ decays

B-hadron lifetimes are studied using the decays $B^0_d \rightarrow J/\psi K^*$, $B^0 \rightarrow J/\psi K_{S}^0$, $B^+ \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi \phi$ and $A_b \rightarrow J/\psi \Lambda$. Signal yields and lifetimes resulting from the fit of a single exponential to the reconstructed proper time distributions are given in Table 1. While the results are compatible with the current world average the measurements have not yet reached a competitive error. The study however gives valuable input to the analysis of $B^0_s \rightarrow J/\psi \phi$ by providing proper time resolutions and acceptances.  

3 Angular analysis of the $P \rightarrow VV$ decay $B_d^0 \rightarrow J/\psi K^*$

The decay $B_d^0 \rightarrow J/\psi K^*$ is a decay of a pseudo-scalar meson to two vector mesons. Since the vector mesons in the final state can have different relative angular momenta an angular analysis is required to statistically separate the decay amplitudes. The three decay amplitudes $A_0$, $A_\perp$ and $A_{||}$ correspond to the three possible relative angular momenta $L = 0, 1$ and 2. $\delta_\perp$ and $\delta_{||}$ denote the strong phases of $A_\perp$ and $A_{||}$ relative to $A_0$. The extracted amplitudes and phases are given in Table 2a and agree with previous measurements within their errors. This result constitutes a valuable cross-check for the correct implementation of angular dependent acceptance effects caused by detector geometry and selection. The possible presence of a non-resonant S-wave component was accounted for in the fit. Other systematic uncertainties that have been evaluated include the background shape, acceptance effects and the signal mass model.

4 Extraction of $\Delta \Gamma_s$ from an untagged angular analysis

The decay $B_d^0 \rightarrow J/\psi \phi$ has a structure which is very similar to the decay $B \rightarrow J/\psi K^*$ discussed in the previous section since both decays are $P \rightarrow VV$ transitions. The decay width difference $\Delta \Gamma_s$ can be extracted by performing an untagged (i.e. without using information on the initial $B_d^0$ flavor) angular analysis of $B_d^0 \rightarrow J/\psi \phi$ decays. For this study $\phi_s = 0$ is assumed which is close to the Standard Model prediction. The results are given in Table 2b. The extracted
Table 2: Results from untagged angular fits of the two $P \rightarrow VV$ decays $B_d^0 \rightarrow J/\psi K^*$ (Table 2a) and $B_s^0 \rightarrow J/\psi \phi$ (Table 2b). $\phi_s = 0$, which is close to the Standard Model prediction, is assumed for the untagged fit of the signal channel $B_s^0 \rightarrow J/\psi \phi$.

(a) Untagged fit of $B_d^0 \rightarrow J/\psi K^*$ events

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHCb result</th>
<th>± stat.</th>
<th>± syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>A_1</td>
<td>^2$</td>
<td>0.252 ± 0.020 ± 0.016</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
<td>^2$</td>
<td>0.178 ± 0.022 ± 0.017</td>
</tr>
<tr>
<td>$\delta_1 [\text{rad}]$</td>
<td>$-2.87 \pm 0.11 \pm 0.10$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta_0 [\text{rad}]$</td>
<td>$3.02 \pm 0.10 \pm 0.07$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b) Untagged fit of $B_s^0 \rightarrow J/\psi \phi$ events

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHCb result</th>
<th>± stat.</th>
<th>± syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_s$ [ps$^{-1}$]</td>
<td>0.679 ± 0.036 ± 0.027</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$]</td>
<td>0.077 ± 0.119 ± 0.021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>A_0(0)</td>
<td>^2$</td>
<td>0.528 ± 0.040 ± 0.028</td>
</tr>
<tr>
<td>$</td>
<td>A_0(0)</td>
<td>^2$</td>
<td>0.263 ± 0.056 ± 0.014</td>
</tr>
</tbody>
</table>

value, $\Delta \Gamma_s = (0.077 \pm 0.119_{\text{stat}} \pm 0.021_{\text{syst}}) \text{ps}^{-1}$, is well in agreement with the current best measurement $\Delta \Gamma_s = (0.075 \pm 0.035_{\text{stat}} \pm 0.01_{\text{syst}}) \text{ps}^{-1}$. However the measurement is limited by the small statistics of the 2010 data sample and therefore not competitive yet. The signal yield amounts to only 571 ± 24 events. Systematic uncertainties that have been studied include the background shape, the angular acceptance description and a possible S-wave contribution. To estimate the sensitivity of the untagged fit to $\phi_s$, a Feldman-Cousins study is performed in the two-dimensional $\phi_s-\Gamma_s$ plane. The resulting confidence-contours are given in Figure 2. They show that with the current statistics $\phi_s$ can not be constrained when performing the untagged analysis. For the extraction of $\phi_s$ information about the initial $B_d^0$ flavor is needed.

Figure 2: $\phi_s-\Delta \Gamma_s$ confidence contours of the untagged analysis of $B_d^0 \rightarrow J/\psi \phi$ events. The contours are determined by performing a Feldman-Cousins study with 1000 toys for each grid point. The untagged analysis provides no constraints on $\phi_s$.

5 Determination of the $B_{d,s}^0$ mixing frequency

The mixing frequency in the $B_d^0$ system is determined from the time dependent mixing asymmetry in the decay $B_d^0 \rightarrow D \pi$, defined as

$$A(t) = \frac{(N_{\text{unmixed}}(t) - N_{\text{mixed}}(t))/(N_{\text{unmixed}}(t) + N_{\text{mixed}}(t))}{(N_{\text{unmixed}}(t) - N_{\text{mixed}}(t))/(N_{\text{unmixed}}(t) + N_{\text{mixed}}(t))}$$

Figure 3a shows the mixing asymmetry extracted from 5999 ± 8 signal events. The mixing frequency in the $B_d^0$ system is determined to be $\Delta m_d = (0.499 \pm 0.032_{\text{stat}} \pm 0.003_{\text{syst}}) \text{ps}^{-1}$ which is in agreement with the world average $\Delta m_d = (0.507 \pm 0.005) \text{ps}^{-1}$.

The mixing frequency in the $B_s^0$ system is determined using $B_s^0 \rightarrow D_s \pi, D_s \pi \pi \pi$ decays. Figure 3b shows the likelihood scan over the mixing frequency $\Delta m_s$. Mixing is observed with a statistical significance of 4.6$\sigma$ and the mixing frequency $\Delta m_s$ is determined to be $\Delta m_s = (17.63 \pm 0.11_{\text{stat}} \pm 0.04_{\text{syst}}) \text{ps}^{-1}$. This measurement, performed with the 2010 data, is competitive with the measurement published previously by the CDF collaboration, $\Delta m_s = (17.77 \pm 0.10_{\text{stat}} \pm 0.07_{\text{syst}}) \text{ps}^{-1}$. Since the $B_s^0$ oscillation is much faster than the oscillation in
the $B_d^0$ system LHCb profits from its excellent proper time resolution and is able to overcome
the statistical limitation.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{Fig3.png}
\caption{(a) The mixing frequency in the $B_d^0$ system is determined via the time dependent mixing asymmetry. (b) The results of the likelihood scan over the mixing frequency $\Delta m_s$ in the $B_d^0$ system. A minimum is observed for $\Delta m_s = (17.63 \pm 0.11_{\text{stat.}} \pm 0.04_{\text{syst.}})$ ps$^{-1}$.}
\end{figure}

6 Summary

The main steps on the way to a measurement of $\phi_s$ at LHCb have been presented. Using the data taken by the LHCb detector in 2010 the polarization amplitudes and strong phases for the $P \rightarrow VV$ decay $B_d^0 \rightarrow J/\psi K^*$ have been extracted. An untagged analysis was performed to determine the decay width difference in the $B_d^0$ system giving $\Delta \Gamma_s = (0.077 \pm 0.11_{\text{stat.}} \pm 0.02_{\text{syst.}})$ ps$^{-1}$. Additionally the mixing frequencies in both the $B_d^0$ and $B_s^0$ systems have been extracted. The measurement of $\Delta m_s = (17.63 \pm 0.11_{\text{stat.}} \pm 0.04_{\text{syst.}})$ ps$^{-1}$ is competitive with the world average.

References

2. The LHCb Collaboration, “Untagged angular analysis of $B^0_s \rightarrow J/\psi \phi$ and $B^0 \rightarrow J/\psi K^*$ with the 2010 data”, LHCb-CONF-2011-002.
3. The LHCb Collaboration, “Measurement of $\Delta m_d$ in $B^0 \rightarrow D\pi$”, LHCb-CONF-2011-010.
4. The LHCb Collaboration, “Measurement of $\Delta m_s$ and calibration and tuning of the Same-Side Tagging algorithm with $B_d^0 \rightarrow D_s \pi$ decays using the 2010 data sample”, LHCb-CONF-2011-005.
6. CDF Collaboration (A. Abulencia et al.), “Observation of $B_0(s)$ - anti-$B_0(s)$ Oscillations”, Phys.Rev.Lett.97:242003,2006., hep-ex/0609040
7. CDF Collaboration (A. Abulencia et al.), “An Updated Measurement of the CP Violating Phase $\beta_s$ with $L = 5.2$ fb$^{-1}$”, Public Note 10206