Prospects for $B_{d,s} \rightarrow h^+h^-$ measurements at LHCb

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LHCb will collect large samples of $B_d$ and $B_s$ decays. Combining the CP-violating observables of the decays $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ it is possible to extract the $\gamma$ angle of the unitarity triangle. The selection of these decays within the current LHCb simulation framework is outlined and the expected annual event yields and background-to-signal ratios are quoted. Then, the results of a study on the sensitivity that LHCb can achieve for the corresponding CP-violating observables are presented.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Monte Carlo Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \rightarrow \pi^+\pi^-$</td>
<td>60000</td>
</tr>
<tr>
<td>$B_s \rightarrow K^+K^-$</td>
<td>65000</td>
</tr>
<tr>
<td>$B_d \rightarrow K^+\pi^-$</td>
<td>62000</td>
</tr>
<tr>
<td>$B_s \rightarrow K^-\pi^+$</td>
<td>24000</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow pK^-$</td>
<td>20000</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow p\pi^-$</td>
<td>21000</td>
</tr>
<tr>
<td>$b\bar{b} \rightarrow X$</td>
<td>1144000</td>
</tr>
</tbody>
</table>

Table 1. Monte Carlo event samples used to study the selection of $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decays. The other channels are studied as potential sources of background.

1 Introduction

LHCb is a dedicated experiment on b-quark physics, currently under construction at the Large Hadron Collider (LHC). It will profit from the 500 $\mu$b b-hadron production cross section in the 14 TeV proton-proton collisions at LHC (i.e. about 1% of the total visible cross section) to make precise measurements of CP-violation and rare decays of the B-mesons [1]. By over-constraining the Cabibbo-Kobayashi-Maskawa matrix elements, LHCb will hopefully be able to observe subtle inconsistencies with the Standard Model, therefore providing indications of new physics. A sketch of the LHCb detector is shown in Fig. 1.

Figure 1. Schematic drawing of the LHCb detector.

Profitting from the large $b\bar{b}$ cross section, LHCb will collect large samples of $B_d$ and $B_s$ decays. Combining the CP-violating observables of the decays $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ it is possible, by means of a method proposed by R. Fleischer [2], to extract the $\gamma$ angle of the unitarity triangle.

In section 2 the selection strategy, implemented to identify the $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decays within the current LHCb Monte Carlo simulation framework, is described and the estimated annual event yields and background levels are quoted.

By using the results shown in section 2, the sensitivities achievable on the CP-violating observables can be determined. This is described in section 3.

2 Event reconstruction

To evaluate the performance of LHCb in the reconstruction of $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decays, a full GEANT Monte Carlo simulation has been performed, followed by realistic pattern recognition algorithms for the track reconstruction and particle identification. The Monte Carlo event samples used for this analysis are shown in Tab. 1.

Two sources of background have been considered: two charged body decays of B mesons and baryons, which can fake the signal in case of particle mis-identification, and combinatorial background. The dominant source of combinatorial background is believed to come from beauty events.

To select the interesting decays and reject the backgrounds, a set of kinematical and topological cuts has been used. For each pair of tracks with opposite charge identified as pions or kaons by the RICH detectors, cuts are applied on:

- momentum;
- smallest and largest transverse momentum;
Figure 2. Invariant mass distribution for $B_d \rightarrow \pi^+\pi^-$ reconstructed events, together with the mass spectrum due to other two body B-decays background. The mass resolution is about 18 MeV/$c^2$.

- smallest and largest impact parameter significance;
- $\chi^2$ of common vertex fit.

Each pair surviving to these cuts is used to form a $B$-meson candidate, and further cuts are applied on it:

- transverse momentum;
- impact parameter significance;
- distance of flight significance;
- invariant mass.

With these set of cuts, with values specifically optimized for each of the two decays under study, all the combinatorial $bb$ background events, in the limited Monte Carlo statistics available at the moment of this analysis, are rejected. At the same time the two body $B$ decays studied as specific backgrounds, thanks to the particle identification performance relying on the two RICH detectors [B], are maintained under control.

Fig. 2 shows the invariant mass distribution for the reconstructed $B_d \rightarrow \pi^+\pi^-$ events surviving the selection, together with the two body $B$-decay background. The estimated annual event yields and background-to-signal ratios can be read in Tab. 2.

### 3 CP sensitivity

The time dependent CP asymmetry takes the usual form:

$$A_{\text{CP}}(\tau) = \mathcal{A}_{\text{dir}}\cos(x \cdot \tau) + \mathcal{A}_{\text{mix}}\sin(x \cdot \tau)$$

<table>
<thead>
<tr>
<th>Channel</th>
<th>B/S</th>
<th>Untagged annual yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \rightarrow \pi^+\pi^-$</td>
<td>&lt; 0.8</td>
<td>27000</td>
</tr>
<tr>
<td>$B_s \rightarrow K^+K^-$</td>
<td>&lt; 0.55</td>
<td>35000</td>
</tr>
</tbody>
</table>

Table 2. Estimated number of offline-selected events per year and background-to-signal ratios for the $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decays at LHCb.

which is valid assuming the decay width difference of the $B$ mass eigenstates $\Delta \Gamma$ to be negligible.

In order to generate the requested samples of tagged $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decays to perform a study on the sensitivity that LHCb can achieve on the measurements of $\mathcal{A}_{\text{dir}}$ and $\mathcal{A}_{\text{mix}}$, a standalone toy Monte Carlo program has been used. The program takes as input the number of reconstructed events per year and the background levels shown in Tab. 2. It reproduces the acceptance as a function of the proper time and the proper time resolution as studied in detail by using the full GEANT simulation and simulates the effect of CP violation using given values of $\mathcal{A}_{\text{dir}}$ and $\mathcal{A}_{\text{mix}}$, then simulates the tagging procedure, finally giving as output a sample of proper times of tagged $B$ and $\bar{B}$ decays.

To “measure” from this sample of proper times the values of $\mathcal{A}_{\text{dir}}$ and $\mathcal{A}_{\text{mix}}$, with their uncertainties and correlation, an unbinned maximum likelihood method has been used. The log-likelihood function to be maximised with respect to $\mathcal{A}_{\text{dir}}$ and $\mathcal{A}_{\text{mix}}$ is:

$$\log \mathcal{L} = \log \left[ \prod_i n(\tau_i) \cdot \prod_j \tilde{n}(\tau_j) \right]$$

where $\{\tau_i\}$ and $\{\tau_j\}$ are the sets of decay proper times for the tagged $B$ and $\bar{B}$ respectively, and

$$n(\tau_i) = \left[ e^{-t_i/\tau_B} \cdot \left( 1 + \frac{1 - 2\omega}{1 + B/S} \cdot \mathcal{A}_{\text{CP}}(t) \right) \cdot e(t) \right] \otimes R(\tau_i - t)$$

$$\tilde{n}(\tau_j) = \left[ e^{-t_j/\tau_B} \cdot \left( 1 + \frac{1 - 2\omega}{1 + B/S} \cdot \mathcal{A}_{\text{CP}}(t) \right) \cdot e(t) \right] \otimes R(\tau_j - t)$$

being $\tau_B$ the B-meson lifetime, B/S the background-to-signal ratio, $\omega$ the wrong tagging fraction, $e(t)$ the acceptance as function of the proper time, $R(\tau - t)$ a function accounting for the proper time resolution of the LHCb spectrometer (normal distribution with a width of 40 $f$s) and where the symbol $\otimes$ stands for convolution product.

As an example, Fig. 3 shows the dependence of $\log \mathcal{L}$ on $\mathcal{A}_{\text{dir}}$ and $\mathcal{A}_{\text{mix}}$ for a sample of $B_d \rightarrow \pi^+\pi^-$ and a sample of $B_s \rightarrow K^+K^-$ events generated by the toy Monte Carlo program, corresponding to one year of LHCb data.
Table 3. Resolutions on the measurements of $A_{\text{CP}}^{\text{dir}}$ and $A_{\text{CP}}^{\text{mis}}$ for the $B_d \to \pi^+\pi^-$ decay and the $B_s \to K^+K^-$ decay (lower plot).

Table 3. Resolutions on the measurements of $A_{\text{CP}}^{\text{dir}}$ and $A_{\text{CP}}^{\text{mis}}$ for the $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays expected at LHCb after one year of data taking. The last column reports the correlation between the measured values of the asymmetries.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma(A_{CP}^{dir})$</th>
<th>$\sigma(A_{CP}^{mis})$</th>
<th>Corr($A_{CP}^{dir}$, $A_{CP}^{mis}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \to \pi^+\pi^-$</td>
<td>0.054</td>
<td>0.054</td>
<td>-0.53</td>
</tr>
<tr>
<td>$B_s \to K^+K^-$</td>
<td>0.043</td>
<td>0.043</td>
<td>0</td>
</tr>
</tbody>
</table>

taking, where the following input values for the CP asymmetries have been used: $A_{CP}^{\text{dir}}(B_d \to \pi^+\pi^-) = -0.3$, $A_{CP}^{\text{mis}}(B_d \to \pi^+\pi^-) = 0.58$, $A_{CP}^{\text{dir}}(B_s \to K^+K^-) = 0.16$ and $A_{CP}^{\text{mis}}(B_s \to K^+K^-) = -0.17$. Fig. 4 shows the corresponding confidence regions determined for $A_{CP}^{\text{dir}}$ and $A_{CP}^{\text{mis}}$, while Fig. 5 shows the binned asymmetry for the $B_d \to \pi^+\pi^-$ decay with the result of the likelihood fit superimposed.

The obtained resolutions and correlations for $A_{CP}^{\text{dir}}$ and $A_{CP}^{\text{mis}}$, corresponding to one year of LHCb data taking, are shown in Tab. 3. The measurements of $A_{CP}^{\text{dir}}$ and $A_{CP}^{\text{mis}}$ are strongly correlated in the case of the $B_d \to \pi^+\pi^-$ channel, while the correlation for the $B_s \to K^+K^-$ channel is negligible, as it can easily be argued by looking at the contour plots of Fig. 4.
The previous results for the $B_s \to K^+K^-$ channel are obtained for a value of the mixing parameter $x_s = 20$. Due to the finite proper time resolution of the spectrometer (about 40 $f_s$), higher values of $x_s$, i.e. faster $B_s - \bar{B}_s$ oscillations, lead to larger errors for the measurements of $\mathcal{R}^{dir}_{CP}$ and $\mathcal{R}^{mix}_{CP}$. Thus, a study of the dependence of the resolution of $\mathcal{R}^{dir}_{CP}$ and $\mathcal{R}^{mix}_{CP}$ on $x_s$, up to $x_s = 40$, has been performed. The results of this study for $\mathcal{R}^{dir}_{CP}$ are shown in Fig. 6 (the dependence for $\mathcal{R}^{mix}_{CP}$ is identical and is omitted here). As it can be seen the error on the asymmetries increases by about a factor 1.6 at $x_s = 40$ with respect to $x_s = 20$.

4 Conclusions

The results presented in this paper show the potential of LHCb in collecting large samples of $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays. They are obtained by using a full and realistic Monte Carlo simulation of the detector response.

The number of $B_d \to \pi^+\pi^-$ offline-selected decays are 27000/year, while for $B_s \to K^+K^-$ it is 35000/year, with background-to-signal ratios respectively of about 0.8 and 0.55.

The sensitivity on the CP-violating observables achievable by LHCb for these channels has been studied in detail, yielding very encouraging results. The estimated precision on $\mathcal{R}^{dir}_{CP}$ and $\mathcal{R}^{mix}_{CP}$ after one year of data taking, assuming $x_s$ to be equal to 20, is 0.054 for the $B_d \to \pi^+\pi^-$ channel and 0.043 for the $B_s \to K^+K^-$ channel.

By means of these observables it is possible to extract the $\gamma$ angle of the unitarity triangle. In fact, $\mathcal{R}^{dir}_{CP}$ and $\mathcal{R}^{mix}_{CP}$, related to the $B_d \to \pi^+\pi^-$ decay, can be expressed in the framework of the Standard Model as:

$$\mathcal{R}^{dir}_{CP}(B_d) = -\frac{2d \sin \theta \sin \gamma}{1 - 2d \cos \theta \cos \gamma + d^2}$$

$$\mathcal{R}^{mix}_{CP}(B_d) = \frac{\sin(\phi_d + 2\gamma) - 2d \cos \theta \sin(\phi_d + \gamma) + d^2 \sin \phi_d}{1 - 2d \cos \theta \cos \gamma + d^2}$$

where $\phi_d = 2\beta$ is the $B_d - \bar{B}_d$ mixing phase, while $d$ and $\theta$ parametrize - sloppily speaking - the penguin over tree amplitude ratio of the decay transition $[2]$. Analogously, $\mathcal{R}^{dir}_{CP}$ and $\mathcal{R}^{mix}_{CP}$, related to the $B_s \to K^+K^-$ decay, can be written as

$$\mathcal{R}^{dir}_{CP}(B_s) = \frac{2\tilde{d} \sin \theta' \sin \gamma}{1 + 2\tilde{d} \cos \theta' \cos \gamma + \tilde{d}^2}$$

$$\mathcal{R}^{mix}_{CP}(B_s) = \frac{\sin(\phi_s + 2\gamma) + 2\tilde{d} \cos \theta' \sin(\phi_s + \gamma) + \tilde{d}^2 \sin \phi_s}{1 + 2\tilde{d} \cos \theta' \cos \gamma + \tilde{d}^2}$$

where $\phi_s = 2\delta \gamma$ is the $B_s - \bar{B}_s$ mixing phase, $\tilde{d} = \frac{1-|V_{us}|^2}{|V_{ud}|^2} d'$, and the $d'$ and $\theta'$ parameters are analogous to $d$ and $\theta$ for the $B_s \to K^+K^-$ transition.

In the limit of exact U-spin symmetry of the strong interactions the relations $d = d'$ and $\theta = \theta'$ hold, and the measurements of the four asymmetry coefficients allow to determine $\phi_d$ and $\gamma$ simultaneously, provided that $\phi_s$ is determined elsewhere (e.g. through the $B_s \to J/\psi\phi$ transition) or considered negligibly small, as it is expected in the Standard Model. Moreover $\phi_d$ will be accurately known at the time of LHCb, thus allowing a more precise determination of $\gamma$.

The resolution on $\gamma$ achievable at LHCb by using this method, in case of negligible U-spin breaking effects, is of the order of few degrees.

Acknowledgements

The author is grateful to T. Nakada and O. Schneider for their encouragement and suggestions. Special thanks to U. Marconi for his help and practical support.

References