Studies of Hadronic B Decays with Early LHCb Data

Eduardo Rodrigues¹ (on behalf of the LHCb Collaboration)

¹ SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK
E-mail: eduardo.rodrigues@glasgow.ac.uk

Abstract. Hadronic B decays offer rich opportunities for CP-violation studies. Decays of the type \( B \to DX \), where \( D \) represents a charmed meson (\( D^0 \), \( D^{(*)} \) or \( D_s \)), allow for a theoretically clean determination of the CKM triangle angle \( \gamma \) which will provide a Standard Model benchmark of this quantity, robust against new physics effects. Decays into charmless final states, on the other hand, in general receive significant contributions from loop diagrams and are susceptible to the effects of new heavy particles. The trigger schemes of LHCb, and the particle identification provided by its RICH system, give the experiment high sensitivity to these decays. Signals will be shown from the present LHC run, and the measurement programme with the 2010-11 data set will be discussed.

1. Introduction

The investigation of hadronic \( B \) decays offers both a test-bed for the understanding of the (decay) dynamics of heavy flavoured particles and for the study of mixing and CP violation. Hadronic \( B \) decays encompass a large range of decays, from two- to multi-body modes, from final states with charged mesons (typically pions and kaons) or baryons (typically protons and \( \Lambda \) resonances) to modes of the form \( B \to DX \), where \( D \) represents a charmed meson such as \( D^0 \), \( D^{(*)} \) or \( D_s \). From an experimental point of view one has at hand a large variety of measurable quantities: lifetimes, branching ratios, time-dependent and time-independent CP asymmetries.

We here focus on decay modes sensitive to the CKM angle \( \gamma \) = \( \arg (-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*) \), the relative weak phase between \( b \to u \) and \( b \to c \) transitions. The \( \gamma \) angle plays a unique role, being the only CP violating parameter that can be cleanly measured via tree-level decays\(^1\), which are to a large extent insensitive to New Physics (NP). As such, it stands out as a benchmark Standard Model (SM) reference measurement. \( \gamma \) can also be determined with decays involving loop diagrams, potentially providing sensitivity to CP violating effects beyond the SM. A comparison of several independent \( \gamma \) measurements is thus a very powerful tool to probe the SM and search for NP. It is one of the goals of the LHCb experiment to measure \( \gamma \) accurately in tree-level and loop-dominated \( B \) decays [1], in particular to improve significantly its present poor knowledge – \( \sigma_\gamma \approx 11\text{−}20^\circ \) – from direct measurements [2, 3].

In Sec. 2 the aspects of the LHCb experiment most relevant to the physics studies at hand are briefly presented. The following two sections, Secs. 3 and 4, discuss measurements of \( \gamma \) that are insensitive or sensitive to NP, respectively. We conclude with an outlook of the prospects for the near future.

\(^1\) This statement is valid to an excellent approximation, though not strictly true due to (negligible) higher-order effects.
2. The LHCb experiment
The LHCb experiment [4] at CERN’s Large Hadron Collider (LHC) is dedicated to (1) the search for NP probing the flavour structure of weak interactions and (2) the study of CP violation and rare b- and c-flavoured hadron decays. The physics goals of LHCb demand excellent tracking and identification of secondary vertices from long-lived particles, and a highly efficient particle identification system capable of separating for example pions from kaons and protons over a large momentum range.

The LHCb detector is a forward spectrometer located around interaction point 8 (IP8) at the LHC. Particles originating from a collision first encounter the vertex locator (VELO), a movable silicon vertex detector designed to measure precisely the production and decay vertices of long-lived particles, thereby separating primary from secondary vertices. It is retracted by 29 mm during LHC beam injection and ramping in energy. The nominal closed position – with the detector at 8 mm from the proton beams – is only achieved once the LHC declares stable beams, i.e. when conditions are met for physics data taking.

Downstream of the VELO are two tracking devices and the 4 Tm warm dipole magnet. They provide an accurate determination of the track parameters and an excellent momentum resolution $\delta p/p \approx 0.5\%$.

LHCb comprises a variety of particle identification systems: two Ring Imaging Cherenkov (RICH) detectors for pions, kaons and protons, a set of calorimeters for the identification of photons, electrons and hadrons, and a muon system for triggering on and measuring muons.

2.1. Trigger requirements
Heavy flavour production has a large cross-section at the LHC. But due to an even larger rate of inelastic processes, LHCb requires a fast, flexible and efficient trigger scheme. This is particularly true for triggering on hadronic $B$ decays, which are more challenging than decay modes with muons in their final states.

LHCb opted for a two-level trigger. In the first-level (custom) hardware trigger, high transverse energy $E_T$ and momentum $p_T$ particles are selected based on partial information from the detector thereby providing a fast decision. The highest $E_T$ hadron, electron and photon clusters are selected by the calorimeter system whereas the two highest $p_T$ muons are selected by the muon chambers. The collision rate is brought down to a rate of about 1 MHz. The High Level software Trigger (HLT) runs on a PC farm of several thousand CPU nodes and comprises several steps of increasing complexity in event reconstruction and selection. It has access to the whole detector information for the search of interesting physics signatures. A nominal event rate of 2 kHz is stored for subsequent data analysis.

2.2. The 2010 LHC and LHCb run
The LHC delivered just over 42 $\text{pb}^{-1}$ at IP8 during the first $\sqrt{s} = 7$ TeV proton-proton collision run of 2010. The LHCb experiment performed very well in this first data taking period, running stably and at an efficiency around 90%. It recorded close to 38 $\text{pb}^{-1}$ of data in spite of the LHC running conditions at times well above nominal design at the LHCb interaction point (the average number of visible proton-proton collisions per LHC bunch crossing attained a value as high as 2.7, to compare with the nominal specification of $\approx 0.4$).
3. Measurements of $\gamma$ from tree-level diagrams

As mentioned in Sec. 1, tree-level decays of the type $B \to DX$ provide a clean determination of $\gamma$ insensitive to NP. LHCb is at present considering the following modes:

- $B^0 \to D^-\pi^+, DK^{*0}$;
- $B^- \to D(\ast)K^{(\ast)-}$;
- $B^0_s \to D_s^- K^+, D \phi$

where the charm meson $D(\ast)$ can either decay via 2-, 3- or 4-body modes\(^2\).

The physics case for this set of modes is rather broad, ranging from the study of branching ratios to mixing and CP violation measurements. The modes $B^- \to DK^-$ are particularly interesting when the final state can be “reached” by both $b \to u$ and $b \to c$ transitions: the quantum interference of the amplitudes gives sensitivity to $\gamma$. Several time-independent methods have been developed, exploiting different final states to which both $D^0$ and $D^0$ can decay. Among those methods one can distinguish (1) the GLW method where the $D$ decays to CP eigenstates (e.g. $K^+K^-$) [5, 6], (2) the ADS method where the $D$ decays to the double Cabibbo-suppressed final state $K^+\pi^-$ [7, 8], and (3) the GGSZ method focusing on the Dalitz plot analysis of three-body $D$ decays (e.g. $D \to K_S h^+ h^-$, $h$ denoting a pion or a kaon) [9]. The analysis of $B_s \to D_s^- K^+$ provides yet another clean and promising way of determining $\gamma$ via time-dependent measurements of all decay combinations involved [10].

![Figure 1. Reconstructed $B^- \to D^0(\to K^-\pi^+)K^-$ signal obtained in $\approx 34$ pb\(^{-1}\) of the 2010 data taking sample.](image)

Figure 1 shows the $B^- \to D^0K^-$ signal obtained during the LHCb 2010 data run for the Cabibbo-favoured $D^0 \to K^-\pi^+$ mode. Clean signals with large signal-over-background ratios have also been seen in $B^- \to D^0\pi^-$ with $D^0 \to K^-\pi^+, K^+K^-$ and $\pi^+\pi^-$. Dalitz plot analyses with the 3-body final states $D^0 \to K_S h^+ h^-$ are being prepared. Clean signals for $B^- \to D^0\pi^-$ have been seen in the 2010 data sample with $D^0 \to K_S \pi^+\pi^-$ and $K_S K^+K^-$, see Figs. 2 and 3.

Time-dependent CP measurements are foreseen with the $B_s \to D_s^- h^+$ modes. Indeed large CP violation is expected in $B_s \to D_s^+K^\mp$. A fair signal for $B_s \to D_s^-\pi^+$ has been found in the 2010 sample. An example, with $D_s^- \to \phi\pi^-$, is displayed in Fig. 4 (the $D_s^-$ decay is also reconstructed in the modes $K^{*0}K^-$ and non-resonant $K^+K^-\pi^-$).

\(^2\) In the remainder the inclusion of charge conjugate modes will always be implicit.
Figure 2. Reconstructed $B^- \rightarrow D^0(\rightarrow K_S\pi^+\pi^-)\pi^-$ signal obtained in $\approx 34$ pb$^{-1}$ of the 2010 data taking sample.

Figure 3. Reconstructed $B^- \rightarrow D^0(\rightarrow K_SK^+K^-)\pi^-$ signal obtained in $\approx 34$ pb$^{-1}$ of the 2010 data taking sample.

Figure 4. Reconstructed $B_s \rightarrow D_s^-(\rightarrow \phi\pi^-)\pi^+$ signal obtained in $\approx 34$ pb$^{-1}$ of the 2010 data taking sample.

Figure 5. Tree level diagram for the decay $B^0 \rightarrow \pi^+\pi^-$.  

Figure 6. Penguin diagram for the decay $B^0 \rightarrow \pi^+\pi^-$.  

4. Measurements of $\gamma$ from loop-level diagrams

LHCb has the possibility to exploit various families of charmless $B$ decays in view of a NP sensitive determination of $\gamma$. The families $H_b^0 \rightarrow h^+h^-$ ($H_b^0$ stands for a $B^0$, $B_s$ or $\Lambda_b$) and $B^+ \rightarrow h^+h'^+h''^-$ have been the focus of attentions; in the present paper we will not further discuss the 3-body family.

The $H_b \rightarrow h^+h'^-$ family allows for a rich list of important measurements such as time-integrated direct CP asymmetries, time-dependent asymmetries, and the determination of the angle $\gamma$ using U-spin symmetry to relate the $K^+K^-$ and $\pi^+\pi^-$ final states. The U-spin method of extracting $\gamma$ [11] is sensitive to NP and originates from the interference between the tree-level $b \rightarrow u$ transition and the so-called Penguin diagrams ($b \rightarrow d, s$ transitions); examples of such diagrams are given in Figs. 5 and 6. In practice the method requires a combined analysis of all $H_b \rightarrow h^+h'^-$ modes, to better take into account backgrounds and cross-feed from similar final states.

![Figure 7](image_url)

**Figure 7.** Reconstructed $H_b \rightarrow h^+h'^-$ signal obtained in $\approx 35 \text{ pb}^{-1}$ of the 2010 data taking sample. About $2 \times 100$ candidates were selected.

Figure 7 shows the $H_b \rightarrow h^+h'^-$ spectrum obtained with the LHCb 2010 data sample for all modes combined, assuming the $\pi$ mass for all daughters; a total of around $2 \times 100$ candidates were selected. The various decay modes — e.g. $B^0 \rightarrow \pi^+\pi^-$, $B_s \rightarrow K^+K^-$ — are distinguished after applying particle identification requirements, see Figs. 8 and 9.

The first LHCb (time-integrated) CP analysis with $H_b \rightarrow h^+h'^-$ is under way. As can be seen comparing Fig. 10 with Fig. 11, the 2010 data already exhibits an expected direct CP asymmetry in both the $B^0$ and $B_s$ modes decaying into $K\pi$. It is important to note that the visible asymmetry is raw and should not be quantitatively interpreted, given that it is not corrected for production and detector asymmetries, which are known to be non-negligible. At present one obtains for the raw uncorrected $B_s$ CP asymmetry the value $A_{CP}(B_s \rightarrow K\pi) = 0.43 \pm 0.17$ (stat.), see Fig. 12. Being the raw asymmetry, only the magnitude of the statistical error can be compared with the sensitivity obtained in previous measurements. The CDF analysis obtained $A_{CP}(B_s \rightarrow K\pi) = 0.39 \pm 0.15$ (stat.) $\pm 0.08$ (syst.) with $1 \text{ fb}^{-1}$ of proton-antiproton collisions at the TeVatron [12]. A world-best measurement of the $B^0, B_s \rightarrow K\pi$ direct CP asymmetries should be achieved with the data to be collected in 2011-12.

Clean signals for the two $\Lambda_b \rightarrow ph^-$ modes have also been obtained, see Figs. 13 and 14.
Figure 8. Reconstructed $B^0 \to \pi^+\pi^-$ signal obtained in $\approx 35 \text{ pb}^{-1}$ of the 2010 data taking sample.

Figure 9. Reconstructed $B_s \to K^+K^-$ signal obtained in $\approx 35 \text{ pb}^{-1}$ of the 2010 data taking sample.

Figure 10. Reconstructed $K^+\pi^-$ invariant mass spectrum obtained with a tight selection in $\approx 35 \text{ pb}^{-1}$ of the 2010 data taking sample. Both the $B^0$ (larger peak) and the $B_s$ (smaller peak, right-hand side) resonances are clearly seen.

Figure 11. Reconstructed $K^-\pi^+$ invariant mass spectrum obtained with a tight selection in $\approx 35 \text{ pb}^{-1}$ of the 2010 data taking sample. Both the $B^0$ (larger peak) and the $B_s$ (smaller peak, right-hand side) resonances are clearly seen.

Figure 12. Reconstructed $K\pi$ invariant mass spectrum obtained with a tight selection in $\approx 35 \text{ pb}^{-1}$ of the 2010 data taking sample. Both the $B^0$ (larger peak) and the $B_s$ (smaller peak, right-hand side) resonances are clearly seen.
5. Prospects for the 2011-12 data run

In this first data taking period LHCb has proved its capability as a heavy flavour experiment at a hadron machine. Several (exclusive) $B$ decays have been selected and reconstructed with high efficiency and high signal-to-background significance. Many promising results are to be expected in the near future, with some of them being competitive with previous TeVatron publications or even world-best measurements. In particular, various complementary methods promise a plethora of measurements of the CKM angle $\gamma$. Statistical errors on $\gamma$ of $\sigma_\gamma \approx 7^\circ$ are expected with $1 \text{ fb}^{-1}$ of data.

References

[1] The LHCb Collaboration, Roadmap for selected key measurements of LHCb, arXiv:0912.4179.
[2] J. Charles et al. (CKMfitter Group), Eur. Phys. J. C 41 (2005), 1.
Updated results and plots at http://ckmfitter.in2p3.fr/.
[3] M. Bona et al. (UTfit Collaboration), JHEP 0507 (2005) 028.
Updated results and plots at http://www.utfit.org/.
[4] The LHCb Collaboration, The LHCb Detector at the LHC, JINST 3 (2008) S08005.
[5] M. Gronau, D. London, How to determine all the angles of the unitarity triangle from $B_0 \to DK_S$ and $B_0 \to D\phi$,
Phys. Lett. B 253 (1991) 483.
[6] M. Gronau, D. Wyler, On determining a weak phase from charged $B$ decay asymmetries,
Phys. Lett. B 265 (1991) 172.
[7] D. Atwood, I. Dunietz, A. Soni, Enhanced CP Violation with $B \to KD^0(\bar{D}^0)$ Modes and Extraction of the Cabibbo-Kobayashi-Maskawa Angle $\gamma$, Phys. Rev. Lett. 78 (1997) 3257.
[8] D. Atwood, I. Dunietz, A. Soni, Improved methods for observing CP violation in $B^\pm \to KD$ and measuring the CKM phase $\gamma$, Phys. Rev. D 65 (2001) 036005.
[9] A. Giri et al., Determining $\gamma$ using $B^\pm \to DK^\pm$ with multibody $D$ decays, Phys. Rev. D 68 (2003) 054018.
[10] R. Fleischer, New strategies to obtain insights into CP violation through $B_\pm \to D_s^\pm K^\mp, D^\pm K^\mp, \ldots$ and $B_d \to D^\pm \pi^\mp, D^{\ast\pm} \pi^\mp, \ldots$ decays, Nucl. Phys. B 671 (2003) 459.
[11] R. Fleischer, New strategies to extract $\beta$ and $\gamma$ from $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$,
Phys. Lett. B 459 (1999) 306.
[12] A. Abulencia et al. (CDF Collaboration), Observation of $B^0 \to K^+K^-$ and Measurements of Branching Fractions of Charmless Two-body Decays of $B^0$ and $B^0_s$ Mesons in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV,
Phys. Rev. Lett. 97 (2006) 211802.