PROCEEDINGS OF SCIENCE

Studies of b-hadron decays to charmless final states at LHCb

Vincenzo Vagnoni[*†]
INFN Bologna
E-mail: Vincenzo.Vagnoni@bo.infn.it

The study of charmless B decays provides valuable information for testing the Cabibbo-Kobayashi-Maskawa paradigm of *CP* violation in the Standard Model. In addition, as the amplitudes of these decays receive contributions from loop diagrams, measurements of *CP* violation are sensitive to physics beyond the Standard Model. The latest results obtained by the LHCb collaboration in this sector are presented.

XV International Conference on Hadron Spectroscopy-Hadron 2013
4-8 November 2013
Nara, Japan

[*]Speaker.
[†]On behalf of the LHCb collaboration

 http://pos.sissa.it/

PoS(Hadron 2013)043

1. Introduction

Charmless B decays have been extensively studied in the past both at e^+e^- colliders and at the Tevatron, looking for the presence of physics beyond the Standard Model (SM). As there are contributions of penguin topologies to the decay amplitudes, new virtual particles may appear in the loops. However, precise calculations of physical quantities with these decays are challenging, because of theoretical uncertainties affecting the hadronic factors in the decay amplitudes. For this reason it is crucial to perform measurements of several charmless B decays, in order to aid theory in constraining the values of the unknown hadronic parameters. Here we present the latest results on charmless B decays obtained by the LHCb collaboration [1], analyzing the pp collisions recorded during 2011 and 2012.

2. Two-body B decays

2.1 First observation of CP violation in the decays of B_s^0 mesons

The measurement of the direct CP asymmetries $A_{CP}\left(B^0 \to K^+\pi^-\right)$ and $A_{CP}\left(B_s^0 \to \pi^+K^-\right)$ is performed on a data sample corresponding to $1.0\,\mathrm{fb}^{-1}$ of pp collisions collected during the 2011 LHC run. Raw asymmetries are determined from data performing a simultaneous unbinned maximum likelihood fit to the invariant mass spectrum. The raw asymmetries need to be corrected for spurious effects related to the asymmetry in detecting $K^+\pi^-$ and $K^-\pi^+$ final states and to the presence of asymmetries in the production of B and $\overline{B}$ mesons in pp collisions. The main sources of systematic uncertainty come from the determination of the detection asymmetry in the case of the $B^0 \to K^+\pi^-$ decay and from the modelling of the invariant mass shape in the case of $B_s^0 \to K^-\pi^+$ decays. The final results are [2]

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\mathrm{stat}) \pm 0.003\,(\mathrm{syst}),$$
$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst}).$$

The former is the most precise measurement of $A_{CP}(B^0 \to K^+\pi^-)$ to date, whereas the latter represents the first observation of CP violation in decays of B_s^0 mesons, with a significance of 6.5σ.

2.2 First measurement of time-dependent CP violation in $B_s^0 \to K^+K^-$ decays

The time-dependent CP asymmetry of a generic neutral B meson decay, $B \to f$, can be written as

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)} = \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right) - A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma}{2}t\right)},$$

where $\Gamma(t)$ represents the time dependent decay rate of the initial B or $\bar{B}$ meson to the final state f, Δm and $\Delta\Gamma$ are the B meson oscillation frequency and decay width difference respectively, and where the relation $(C_f)^2 + (S_f)^2 + (A_f^{\Delta\Gamma})^2 = 1$ holds. With this parameterization, C_f and S_f account for direct and mixing-induced CP violation, respectively. Using a data sample corresponding to $1.0\,\mathrm{fb}^{-1}$ of pp collisions collected during 2011, LHCb measures the C and S coefficients for the $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays. Crucial aspects of the analysis are the flavour tagging, *i.e.* the capability of identifying the initial flavour of the decaying B meson, and the determination

PoS(Hadron 2013)043

of the decay time resolution, as both effects dilute the observed amplitude of the time-dependent asymmetry. The response of the flavour tagging algorithm is calibrated by measuring the oscillation of the flavour specific decay $B^0 \to K^+\pi^-$, in which the amplitude is related to the effective mistag rate. The decay time resolution of the B meson is studied by means of charmonium and bottomonium states decaying into $\mu^+\mu^-$ pairs. The values for $C_{\pi^+\pi^-}$, $S_{\pi^+\pi^-}$, $C_{K^+K^-}$ and $S_{K^+K^-}$ are determined from a two dimensional (invariant mass and tagged decay time) maximum likelihood fit to the $\pi^+\pi^-$ and K^+K^- spectra. The measured values for the direct and mixing-induced *CP* violation terms are [3]

$$\begin{aligned} C_{KK} &= 0.14 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst}), \\ S_{KK} &= 0.30 \pm 0.12\,(\text{stat}) \pm 0.04\,(\text{syst}), \end{aligned}$$

with a statistical correlation coefficient of 0.02, and

$$\begin{aligned} C_{\pi\pi} &= -0.38 \pm 0.15\,(\text{stat}) \pm 0.02\,(\text{syst}), \\ S_{\pi\pi} &= -0.71 \pm 0.13\,(\text{stat}) \pm 0.02\,(\text{syst}), \end{aligned}$$

with a statistical correlation coefficient of 0.38. In the case of the $B_s^0 \to K^+K^-$ decay, the correlation coefficient is very small due to the fast B_s^0 oscillations. The significances for (C_{KK}, S_{KK}) and $(C_{\pi\pi}, S_{\pi\pi})$ to differ from $(0, 0)$ are determined to be 2.7σ and 5.6σ, respectively. The parameters C_{KK} and S_{KK} are measured for the first time.

2.3 First evidence for the two-body charmless baryonic decay $B^0 \to p\bar{p}$

The $B^0_{(s)} \to p\bar{p}$ decays are still unobserved. The theoretical predictions of the branching ratio of the $B^0 \to p\bar{p}$ decay vary within a wide range ($10^{-7}-10^{-6}$), and depend on the method used for the calculation. Up to now, no theoretical predictions have been published for the branching ratio of the $B_s^0 \to p\bar{p}$ decay mode.

The branching ratios of the two decay modes are determined using the $B^0 \to K^+\pi^-$ decay as a normalization channel. Yields are extracted from unbinned maximum likelihood fits to the $p\bar{p}$ and $K\pi$ invariant mass spectra.

Using the Feldman-Cousins frequentist method [4] the 68.3% and 90% confidence level (CL) intervals on the branching ratios of signal modes are determined to be [5]

$$\begin{aligned} \mathscr{B}\left(B^0 \to p\bar{p}\right) &= (1.47\,^{+0.62}_{-0.51}\,^{+0.35}_{-0.14}) \times 10^{-8} \text{ at } 68.3\% \text{ CL}, \\ \mathscr{B}\left(B^0 \to p\bar{p}\right) &= (1.47\,^{+1.09}_{-0.81}\,^{+0.69}_{-0.18}) \times 10^{-8} \text{ at } 90\% \text{ CL}, \\ \mathscr{B}\left(B_s^0 \to p\bar{p}\right) &= (2.84\,^{+2.03}_{-1.68}\,^{+0.85}_{-0.18}) \times 10^{-8} \text{ at } 68.3\% \text{ CL}, \\ \mathscr{B}\left(B_s^0 \to p\bar{p}\right) &= (2.84\,^{+3.57}_{-2.12}\,^{+2.00}_{-0.21}) \times 10^{-8} \text{ at } 90\% \text{ CL}, \end{aligned}$$

where the first uncertainties are statistical and the second systematic. The statistical significances of the $B^0_{(s)} \to p\bar{p}$ signals are $3.3\,\sigma$ and $1.9\,\sigma$ for the $B^0 \to p\bar{p}$ and $B_s^0 \to p\bar{p}$ decays, respectively. The $B^0 \to p\bar{p}$ measurement represents the first evidence for a two-body charmless baryonic B^0 decay. Main contributions to the systematic uncertainties come from the particle identification (PID) calibration and from the modelling of invariant mass shapes that affect the determination of signal yields. In the case of the $B_s^0 \to p\bar{p}$ decay a relevant role is played by the uncertainty on the ratio of hadronisation fractions of the b quark to B_s^0 and B^0 mesons [6].

PoS(Hadron 2013)043

2.4 Branching ratio and *CP* asymmetry of the decays $B^+ \to K_S^0 \pi^+$ and $B^+ \to K_S^0 K^+$

Candidates of $B^+ \to K_S^0 K^+$ and $B^+ \to K_S^0 \pi^+$ decays are selected from a data sample corresponding to $3.0\,\text{fb}^{-1}$ of pp collisions collected during 2011 and 2012. The $B^+ \to K_S^0 \pi^+$ and $B^+ \to K_S^0 K^+$ yields are measured together with the raw charge asymmetries by means of a simultaneous unbinned extended maximum likelihood fit to the $B^\pm$ candidate mass distributions. The ratio of branching ratios is determined from the fitted yields using relative efficiencies that include trigger, reconstruction, selection and PID effects.

The main systematic uncertainties on the *CP* asymmetry measurements are the determination of detection and production asymmetries. The final results are [7]

$$\begin{aligned}
\frac{\mathscr{B}(B^+ \to K_S^0 K^+)}{\mathscr{B}(B^+ \to K_S^0 \pi^+)} &= 0.064 \pm 0.009\,(\text{stat.}) \pm 0.004\,(\text{syst.}), \\
A_{CP}(B^+ \to K_S^0 \pi^+) &= -0.022 \pm 0.025\,(\text{stat.}) \pm 0.010\,(\text{syst.}), \\
A_{CP}(B^+ \to K_S^0 K^+) &= -0.21 \pm 0.14\,(\text{stat.}) \pm 0.01\,(\text{syst.}).
\end{aligned}$$

The measurements of $A_{CP}(B^+ \to K_S^0 K^+)$ and $\mathscr{B}(B^+ \to K_S^0 K^+)/\mathscr{B}(B^+ \to K_S^0 \pi^+)$ are the best single determinations to date.

3. Three-body B decays

3.1 Direct *CP* violation in $B^+ \to h^+ h^+ h^-$ decays

In recent analyses of $B^+ \to h^+ h^+ h^-$ decays, where $h = K$ and π, LHCb measures the global *CP* asymmetry as well as the local asymmetries in regions of the Dalitz plane. The analyses use $1.0\,\text{fb}^{-1}$ of pp collision data collected during 2011 [8, 9]. The raw asymmetries are determined from simultaneous fits to the samples of B^+ and B^- candidates. The raw asymmetries must be corrected for both production and detection asymmetries which are determined from the control channel $B^+ \to J/\psi K^+$, where the J/ψ meson decays to $\mu^+\mu^-$. The values of the *CP* asymmetries are found to be

$$\begin{aligned}
A_{CP}(B^+ \to K^+\pi^+\pi^-) &= 0.032 \pm 0.008\,(\text{stat}) \pm 0.004\,(\text{syst}) \pm 0.007(J/\psi K^+)\,, \\
A_{CP}(B^+ \to K^+K^+K^-) &= -0.043 \pm 0.009\,(\text{stat}) \pm 0.003\,(\text{syst}) \pm 0.007(J/\psi K^+)\,, \\
A_{CP}(B^+ \to \pi^+\pi^+\pi^-) &= 0.117 \pm 0.021\,(\text{stat}) \pm 0.009\,(\text{syst}) \pm 0.007(J/\psi K^+)\,, \\
A_{CP}(B^+ \to \pi^+K^+K^-) &= -0.141 \pm 0.040\,(\text{stat}) \pm 0.018\,(\text{syst}) \pm 0.007(J/\psi K^+)\,,
\end{aligned}$$

where the last uncertainty is due to the knowledge of direct *CP* violation in $B^+ \to J/\psi K^+$ decays. The significances of *CP* violation to differ from zero in each decay mode are $2.8\,\sigma$, $3.7\,\sigma$, $4.9\,\sigma$ and $3.2\,\sigma$, respectively.

The variation of the raw asymmetries over the Dalitz plane are also studied. Some regions of the Dalitz plane are characterized by very large values of *CP* asymmetries that are not clearly associated with the presence of an intermediate resonance. There are indications that $\pi^+\pi^- \leftrightarrow K^+K^-$ rescattering is playing a role in the generation of the strong phase difference with these decays. Amplitude analyses of these modes using the larger dataset now available at LHCb will soon help in clarifying the picture.

The closely related decays $B^+ \to p\bar{p}h^+$ can shed some light on this issue since it is expected that $h^+h^- \leftrightarrow p\bar{p}$ rescattering should be much smaller. The analysis, which uses the LHCb 1.0 fb^{-1} data sample collected during 2011, studies the dynamics of the decays as well as the *CP* asymmetries [10].

The *CP* asymmetries for $B^+ \to p\bar{p}K^+$ are determined by repeating the fits to the *B*-candidate invariant mass in bins of both the $p\bar{p}$ and $K^+\bar{p}$ invariant masses and distinguishing the charge of the *B* candidate. The results are consistent with no *CP* violation in all bins.

3.2 Studies of $B^0_{(s)} \to K^0_S h^+h^-$ decays

The analysis uses 1.0 fb^{-1} of data collected during 2011 [11]. The decay $B^0_s \to K^0_S K^\pm\pi^\mp$ is unambiguously observed and the BaBar result [12] is confirmed. This is the first observation with a significance of 5.9 σ, while no significant evidence is obtained for the decay $B^0_s \to K^0_S K^+K^-$.

The branching ratios of all the modes are measured with respect to that of the $B^0 \to K^0_S\pi^+\pi^-$ decay. The results are

$$\frac{\mathcal{B}\left(B^0 \to K^0_S K^\pm\pi^\mp\right)}{\mathcal{B}\left(B^0 \to K^0_S\pi^+\pi^-\right)} = 0.128 \pm 0.017\ (\text{stat.})\ \pm 0.009\ (\text{syst.}),$$

$$\frac{\mathcal{B}\left(B^0 \to K^0_S K^+K^-\right)}{\mathcal{B}\left(B^0 \to K^0_S\pi^+\pi^-\right)} = 0.385 \pm 0.031\ (\text{stat.})\ \pm 0.023\ (\text{syst.}),$$

$$\frac{\mathcal{B}\left(B^0_s \to K^0_S\pi^+\pi^-\right)}{\mathcal{B}\left(B^0 \to K^0_S\pi^+\pi^-\right)} = 0.29\ \pm 0.06\ (\text{stat.})\ \pm 0.03\ (\text{syst.})\ \pm 0.02\ (f_s/f_d),$$

$$\frac{\mathcal{B}\left(B^0_s \to K^0_S K^\pm\pi^\mp\right)}{\mathcal{B}\left(B^0 \to K^0_S\pi^+\pi^-\right)} = 1.48\ \pm 0.12\ (\text{stat.})\ \pm 0.08\ (\text{syst.})\ \pm 0.12\ (f_s/f_d),$$

$$\frac{\mathcal{B}\left(B^0_s \to K^0_S K^+K^-\right)}{\mathcal{B}\left(B^0 \to K^0_S\pi^+\pi^-\right)} \in [0.004; 0.068]\ \text{at}\ 90\%\ \text{CL},$$

where f_s/f_d refers to the uncertainty on the ratio of hadronisation fractions of the *b* quark to B^0_s and B^0 mesons [6].

4. Summary

An overview of the latest LHCb results on charmless two-body and three-body decays of *B* mesons has been given. With LHCb starting to analyse the 2012 data sample, corresponding to an integrated luminosity of 2.0 fb^{-1}, more interesting results will come, both in the sector of *B* meson decays and in the new land of Λ^0_b and other *b*-baryon decays.

References

[1] A. A. Alves Jr. et al. The LHCb detector at the LHC. *JINST*, 3:S08005, 2008.

[2] R. Aaij et al. First observation of *CP* violation in the decays of B^0_s strange mesons. *Phys. Rev. Lett.*, 110:221601, 2013.

[3] R Aaij et al. First measurement of time-dependent *CP* violation in $B^0_s \to K^+K^-$ decays. *JHEP*, 10:183, 2013.

[4] Gary J. Feldman and Robert D. Cousins. Unified approach to the classical statistical analysis of small signals. *Phys. Rev.*, D57:3873, 1998.

[5] R Aaij et al. First evidence for the two-body charmless baryonic decay $B^0 \to p\bar{p}$. *JHEP*, 10:005, 2013.

[6] R Aaij et al. Measurement of the fragmentation fraction ratio f_s/f_d and its dependence on B meson kinematics. *JHEP*, 04:001, 2013.

[7] R Aaij et al. Branching fraction and CP asymmetry of the decays $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$. *Phys. Lett.*, B726:646, 2013.

[8] R Aaij et al. Measurement of CP violation in the phase space of $B^\pm \to K^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+ K^-$ decays. *Phys. Rev. Lett.*, 111:101801, 2013.

[9] Roel Aaij et al. Measurement of CP violation in the phase space of $B^\pm \to K^+K^-\pi^\pm$ and $B^\pm \to \pi^+\pi^-\pi^\pm$ decays. *Phys. Rev. Lett.*, 112:011801, 2014.

[10] R Aaij et al. Studies of the decays $B^+ \to p\bar{p}h^+$ and observation of $B^+ \to \bar{\Lambda}(1520)p$. *Phys. Rev.*, D88:052015, 2013.

[11] R Aaij et al. Study of $B^0_{(s)} \to K^0_S h^+ h'^-$ decays with first observation of $B^0_s \to K^0_S K^\pm\pi^\mp$ and $B^0_s \to K^0_S\pi^+\pi^-$. *JHEP*, 10:143, 2013.

[12] P. del Amo Sanchez et al. Observation of the rare decay $B^0 \to K^0_S K^\pm\pi^\mp$. *Phys. Rev.*, D82:031101, 2010.