Measuring direct CP violation in four body baryonic B decay modes at LHCb

Internal Note

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Abstract

Baryonic B decays may allow direct measurements of CP violation at LHCb. Direct CP violation in the decay mode $B^{\pm} \to p\bar{p}K^{*\pm}$ has been predicted to be 22% in the Standard Model, while it is predicted to be only 1% in $B^0 \to p\bar{p}K^{*0}$. Both modes are believed to proceed through penguin diagrams, making them sensitive to new physics effects which could significantly alter the observed level of CP violation. LHCb's potential to observe CP violation in these decay modes is discussed. The decay mode $B^{\pm} \to p\bar{p}K^{*\pm}$ is expected to yield ~ 400 and $B^0 \to p\bar{p}K^{*0} \sim 1600$ signal events with 2 fb^{-1} of data taking. LHCb can expect to measure CP violating asymmetries with a precision of $\sim 7\%$ in $B^{\pm} \to p\bar{p}K^{*\pm}$ and $\sim 3.5\%$ in $B^0 \to p\bar{p}K^{*0}$ with 2 fb^{-1} of data taking, and these measurements are not expected to be systematics limited.

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1 Motivation

LHCb[1] is a dedicated B physics detector at the LHC[2]. It will collect data at a luminosity of $2 \cdot 10^{32}\ cm^{-2}s^{-1}$, and a centre of mass energy of 14 TeV, giving access to large statistics samples across the full range of B hadron flavours. In particular, LHCb will be sensitive to new physics effects arising through penguin loop diagrams, and will therefore be able to constrain a wide range of theoretical predictions beyond the standard model.

The four body baryonic B decays $B^{\pm} \to p\bar{p}K^{*\pm}$ and $B^0 \to p\bar{p}K^{*0}$ have been observed at the B factories[3, 4], and are believed to proceed through $b \to s$ penguin loop diagrams. Recently, the level of CP violation in the Standard Model for these decay modes has been computed[5, 6] to be 1% for $B^0 \to p\bar{p}K^{*0}$ and 22% for $B^{\pm} \to p\bar{p}K^{*\pm}$. This can be compared with the current measurements of this CP violation at the B factories, shown in Table 1. Neither B factory has yet measured CP violation in these modes at the 3σ level (the results are statistically limited). However, LHCb can realistically aim to do so in $B^{\pm} \to p\bar{p}K^{*\pm}$ with 2 fb^{-1} of data taking, corresponding to one year of running at its nominal luminosity. In addition, if new physics were to significantly enhance CP violation in $B^0 \to p\bar{p}K^{*0}$, LHCb could make a 3σ observation with 2 fb^{-1} of data taking.

Table 1 The standard model predictions and B factory measurements of CPV in the modes $B^{\pm} \to p\bar{p}K^{*\pm}$ and $B^0 \to p\bar{p}K^{*0}$.

	$A_{CP}\,(K^{*\pm})$	$A_{CP}\,(K^{*0})$
Standard Model prediction[5, 6]	$0.22^{+0.04}_{-0.03} \pm 0.01 \pm 0.01$	0.01
BELLE[3]	-0.01 ± 0.019	-0.08 ± 0.20
BaBar[4]	0.32 ± 0.14	0.11 ± 0.14

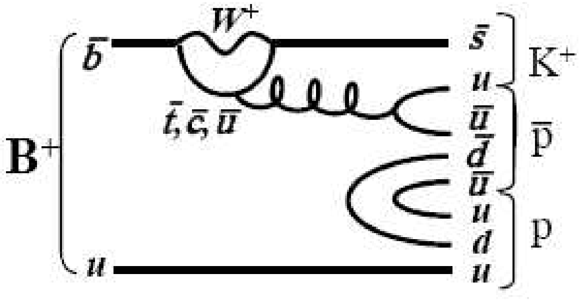

Figure 1 The penguin diagram for the decay $B^{\pm} \to p\bar{p}K^{*\pm}$, from (8).

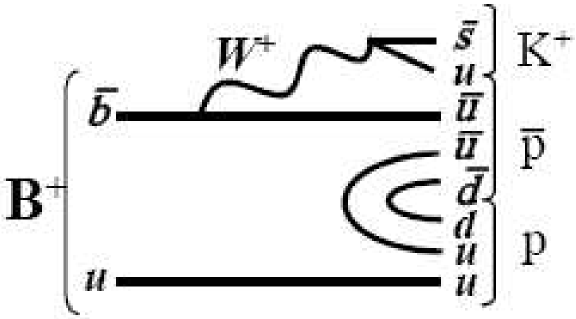

Figure 2 The tree-level diagram for the decay $B^{\pm} \to p\bar{p}K^{*\pm}$, from (8).

In addition to the measurement of CP violation, other interesting physics exists in these channels, notably the threshold production of the $p\bar{p}$ pair, the helicity of the K^{*0} and $K^{*\pm}$, and angular distributions[7] of the $p\bar{p}$ pair. In particular, there is currently disagreement between BaBar and BELLE as to whether threshold enhancement exists for the mode $B^0 \to p\bar{p}K^{*0}$, and no consistent theoretical explanation for the angular distributions of the $p\bar{p}$ pair [8]. Both the threshold production of the $p\bar{p}$ pair and its angular distribution give information about the decay mechanisms for this channel.

Although $b \to s$ penguin diagrams are believed to dominate, these decays can also proceed through a tree level diagram, and intermediate baryonium resonances have been postulated to account for the threshold $p\bar{p}$ production. Figure 1 shows the penguin diagram for $B^{\pm} \to p\bar{p}K^{*\pm}$, while Figure 2 shows the tree level diagram for the same decay. Any new physics present at the LHC could alter these distributions, for example by introducing a hitherto unseen intermediate resonance into the decay diagrams. It will therefore be important to compare the angular and mass distributions of the $p\bar{p}$ pair at LHCb with existing measurement made by BaBar and BELLE.

The helicity of the K^{*0} and $K^{*\pm}$ is related to the size of the penguin contributions in these decays, with the helicity zero amplitude expected to dominate in $b \to s$ transitions due to helicity conservation in the strong interaction[9]. Measuring the helicity composition of these states is therefore a valuable guide to the size of expected new physics effects. Indeed such a measurement has already been made by BELLE, who find that the K^{*0} has a fraction of $(101 \pm 13 \pm 3\%)$ in the helicity zero state, while the $K^{*\pm}$ has a fracion of $(32 \pm 17 \pm 9\%)$ in the helicity zero state. Therefore one might expect any new physics effects to be largest in $B^0 \to p\bar{p}K^{*0}$, and any deviation from the small CP violation predicted for this channel in the Standard Model would be a sign of new physics.

Although these measurements will not be explored further here, they will form an essential part of any final study of these channels. The remainder of this note will concentrate on LHCb's potential to measure CP violation in the decays $B^0 \to p\bar{p}K^{*0}$ and $B^{\pm} \to p\bar{p}K^{*\pm}$.

2 The LHCb trigger

In order to estimate the yields which can be expected for these channels at LHCb, it is important to understand the way in which the LHCb trigger selects events. As currently designed, the LHCb trigger consists of three stages: the L0, HLT1, and HLT2 triggers. The L0 is a hardware trigger which selects events with a single high transverse energy muon, charged hadron, or neutral particle. Typically such a particle requires a transverse energy of ~ 4 GeV to pass the trigger. HLT1 and HLT2 are software triggers which perform a partial reconstruction of data from all the LHCb subdetectors. The HLT1 trigger's purpose is to reconfirm the decision made by the L0 trigger: it searches for the candidate which fired the L0 trigger and applies cuts depending on which kind of particle this candidate is (muon, hadron, or neutral). Finally, the HLT2 trigger exclusively reconstructs specific decay modes.

3 Signal yields and purities

No Monte Carlo samples currently exist for these decay channels, hence their yields must be estimated by comparison to related decay channels which have been studied with the full LHCb Monte Carlo simulation. LHCb will observe 10^{12} $b\bar{b}$ decays in 2 fb^{-1} of data taking, and the B^+ production fraction is 40%.

Throughout this section, the phrase overall selection efficiency will be taken to mean the fraction of signal events created at the LHC which will actually be observed by LHCb. It includes the geometric acceptance of the detector, reconstruction efficiencies of the subdetectors, the efficiency of the full trigger chain, and the efficiency of the final offline selection.

3.1 $B^\pm \to p\bar{p}K^{*\pm}$

The most challenging aspect of this channel's selection is passing the LHCb L0 trigger. It is a four body decay, which makes it less likely that any of the final state particles will have enough momentum to pass this trigger compared to two and three body B decays. Moreover, the $K^{*\pm}$ can decay into either $K_S\pi^\pm$ (with a branching fraction of 2/3) or into $K^\pm\pi^0$ (with a branching fraction of 1/3). Despite the known inefficiencies associated with LHCb's calorimeter system, the latter mode may have an advantage at the trigger level. It can fire the L0 trigger through either the hadron or electron calorimeters, and does not require the K_S to be reconstructed in the HLT1/2 triggers. It also makes background rejection easier, because the signal vertex no longer contains any charged pions. For these reasons, we will only consider the decay mode $K^{*\pm} \to K^\pm\pi^0$ for now. The inclusion of the $K^{*\pm} \to K_S\pi^\pm$ decay mode will eventually improve the yields computed below, which should therefore be treated as conservative.

The nearest comparable decay which has been studied in the full LHCb Monte Carlo framework is $B^\pm \to \rho^\pm\left(\pi^\pm\pi^0\right)\rho^0\left(\pi^+\pi^-\right)$. It will [10] have an overall selection efficiency of 0.045% and yield 2000 events per annum with a $B/S \sim 1$.

The branching ratio of $B^\pm \to p\bar{p}K^{*\pm}$ has been measured by both BaBar and BELLE

$$Br(B^\pm \to p\bar{p}K^{*\pm} = 4.94 \pm 1.66 \pm 1.00 \cdot 10^{-6}\,(\text{BaBar})\,; \tag{1}$$

$$Br(B^\pm \to p\bar{p}K^{*\pm} = 3.38^{+0.78}_{-0.60} \pm 0.39 \cdot 10^{-6}\,(\text{BELLE})\,. \tag{2}$$

The HFAG [11] average

$$Br(B^\pm \to p\bar{p}K^{*\pm} = 3.64^{+0.79}_{-0.70} \cdot 10^{-6}\,(\text{HFAG})\,, \tag{3}$$

will be assumed here. The branching ratio of $K^{*\pm} \to K^\pm\pi^0$ is $\sim 1/3$. The expected signal yield in 2 fb^{-1} of data taking at LHCb is:

$$N_S = N_{b\bar{b}} \cdot 0.80 \cdot B.R. \cdot \frac{1}{3} \cdot \epsilon_{\text{eff}}, \tag{4}$$

where $N_{b\bar{b}} = 10^{12}$ is the expected number of $b\bar{b}$ events expected in 2 fb^{-1} of data taking at LHCb, 0.8 is the fraction of $B^{\pm}$ mesons produced in these events, $B.R.$ is the channel branching ratio, the factor of $\frac{1}{3}$ accounts for the choice of $K^{\pm}\pi^{0}$ decays for the $K^{*\pm}$, and ϵ_{eff} is the overall selection efficiency for this channel at LHCb. Therefore

$$N_S = 10^{12} * 0.8 * (3.64 \pm 0.8) \cdot 10^{-6} * \frac{1}{3} * 4.5 \cdot 10^{-4} = 420 \pm 90. \tag{5}$$

The quoted uncertainty comes from the uncertainty on the HFAG average of the branching ratio.

The presence of two protons and a kaon in the $B^{\pm} \to p\bar{p}K^{*\pm}$ final state will result in the selection of fewer background events as compared with $B^{\pm} \to \rho^{\pm}\rho^{0}$, owing to LHCb's particle identification[12]. On the other hand, the signal yield will be five times smaller, so fewer background events must be selected in order to reach the same B/S level. It is interesting to note that the decay channel $B_s \to \phi\phi$, which contains four kaons in the final state, has an expected [13] $B/S \sim 0.8$ for a signal yield of 3100 events and a selection efficiency of $4.4 \cdot 10^{-3}$. The selection efficiency for $B_s \to \phi\phi$ is a factor ten greater than for $B^{\pm} \to \rho^{\pm}\rho^{0}$, because of the need to cleanly reconstruct the π^{0}. This inefficiency will also affect the background events though! Therefore, a $B/S = 1$ might be reasonably expected for $B^{\pm} \to p\bar{p}K^{*\pm}$.

3.2 $B^{0} \to p\bar{p}K^{*0}$

Like $B^{\pm} \to p\bar{p}K^{*\pm}$, $B^{0} \to p\bar{p}K^{*0}$ is also a four body decay. The nearest comparable decay which has been studied in the full LHCb Monte Carlo framework is $B^{0} \to \rho^{0}\,(\pi^{+}\pi^{-})\,\rho^{0}\,(\pi^{+}\pi^{-})$, which will [10] have an overall selection efficiency of 0.16% and is expected to yield 1200 events per annum with a $B/S < 5$.

The branching ratio of $B^{0} \to p\bar{p}K^{*0}$ has been measured by both BaBar and BELLE

$$Br(B^{\pm} \to p\bar{p}K^{*\pm} = 1.28^{+0.18}_{-0.17} \pm 0.56 \cdot 10^{-6}\,(\text{BaBar})\,; \tag{6}$$

$$Br(B^{\pm} \to p\bar{p}K^{*\pm} = 1.18^{+0.29}_{-0.25} \pm 0.11 \cdot 10^{-6}\,(\text{BELLE})\,. \tag{7}$$

The HFAG [11] average

$$Br(B^{\pm} \to p\bar{p}K^{*\pm} = 1.24^{+0.28}_{-0.25} \cdot 10^{-6}\,(\text{HFAG})\,, \tag{8}$$

will be assumed here. The expected signal yield in 2 fb^{-1} of data taking is:

$$N_S = 10^{12} * 0.8 * (1.24 \pm 0.25) \cdot 10^{-6} * 1.6 \cdot 10^{-3} = 1580 \pm 320. \tag{9}$$

The quoted uncertainty comes from the uncertainty on the HFAG average of the branching ratio.

Using similar arguments as for $B^{\pm} \to p\bar{p}K^{*\pm}$, we might expect a $B/S = 1$ for $B^{0} \to p\bar{p}K^{*0}$.

4 Sensitivity to CP violation

4.1 $B^{\pm} \to p\bar{p}K^{*\pm}$

In order to measure the direct CP violation in $B^{\pm} \to p\bar{p}K^{*\pm}$, one has to first determine the number of signal events in the mass peak by performing a background subtraction, where the background is typically estimated from the sidebands. The error on the measured CP violation is then given by the statistical error on the observed number of events and an extra uncertainty due to the background subtraction method. For example, BELLE observed

$$N_S = 54.2^{+10.9}_{-10.1}, \tag{10}$$

in $B^{\pm} \to p\bar{p}K^{*\pm}$. Since BELLE's background subtraction increases the statistical error on the number of signal events by $\sim 40\%$ compared to a naive $\sqrt{(N)}$ estimate, such an increase will be assumed here as well. Figure 3 shows the expected uncertainty on the asymmetry as a function of the integrated luminosity. Assuming a CP violation of 22%, as per the theoretical predictions, LHCb can hope to see 3σ evidence with around 2 fb^{-1} of data taking, corresponding to a nominal year of LHCb running.

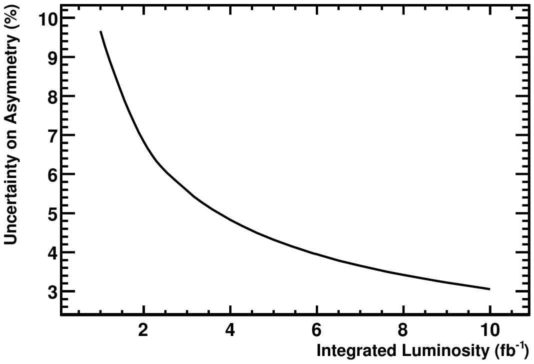

Figure 3 The expected uncertainty on the asymmetry as a function of the integrated luminosity in the channel $B^{\pm} \rightarrow p\bar{p}K^{*\pm}$.

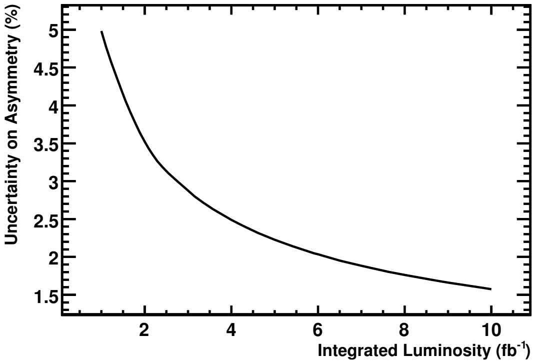

Figure 4 The expected uncertainty on the asymmetry as a function of the integrated luminosity in the channel $B^{0} \rightarrow p\bar{p}K^{*0}$.

4.2 $B^0 \rightarrow p\bar{p}K^{*0}$

Although the current Standard Model prediction for CP violation in $B^0 \rightarrow p\bar{p}K^{*0}$ is only 1%, it is believed to proceed through penguin loop diagrams, which would make it sensitive to new physics, and could lead to an enhancement of this asymmetry at LHCb. It is interesting to explore a scenario in which such effects enhance the CP asymmetry to 10%, which is the central value of the BaBar measurements. Using similar arguments as for $B^{\pm} \rightarrow p\bar{p}K^{*\pm}$, Figure 4 shows the expected uncertainty on the asymmetry as a function of the integrated luminosity. Assuming a CP asymmetry of 10%, LHCb will make a 3σ observation of new physics in this decay channel with little more than one year of data taking at its design luminosity. If the asymmetry is smaller, LHCb will help to constrain it.

5 Measurement uncertainties

An attempt has already been made in the above discussion to include realism, by assuming an additional 40% error due to background subtraction in CP violation estimates. In addition, there will be systematic errors associated with detector efficiencies. However, as long as LHCb is only measuring CP asymmetries, it can be hoped that many such systematics will cancel out. In particular, any systematics associated with selection efficiencies and trigger biases can be expected to cancel out in the asymmetry ratio.

Two kinds of systematic errors will not cancel out: production asymmetries between B^+ and B^- mesons, and an asymmetry in detecting positively vs. negatively charged tracks. LHCb will control any such asymmetries by regularly reversing the polarity of its magnet[14], as well as from control channels such as $B_s \rightarrow D_s \mu \nu$ [15] or $B_d^0 \rightarrow D^{\pm *} \mu^{\pm} X^0$ [16].

6 Conclusion

LHCb's potential to measure the CP violation in four body baryonic decay modes has been discussed. The decay mode $B^{\pm} \rightarrow p\bar{p}K^{*\pm}$ is expected to yield ~ 400 signal events in 2 fb^{-1} of data taking, while $B^0 \rightarrow p\bar{p}K^{*0}$ is expected to yield ~ 1600 signal events with the same integrated luminosity. It is estimated that both will have a $B/S \sim 1$. LHCb can expect to measure CP violation with a precision of $\sim 7\%$ in $B^{\pm} \rightarrow p\bar{p}K^{*\pm}$ and $\sim 3.5\%$ in $B^0 \rightarrow p\bar{p}K^{*0}$ with 2 fb^{-1} of data taking, and these measurements are not expected to be systematics limited. The further study of these decay modes is encouraged. A study using the full LHCb Monte Carlo simulation is required in order to obtain a better estimate of signal yields and purities, while work is also encouraged on the measurement of $p\bar{p}$ threshold production, $K^{*0,\pm}$ helicity, and the angular distribution of the $p\bar{p}$ pair.

7 References

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