LHCb prospects in flavour physics and CP violation

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Abstract. A selection of key measurements of the LHCb physics programme is reviewed where competitive results can be expected from the first year of data taking. The LHCb experiment will search for New Physics in $B_s$ mixing, notably through the measurement of the $B_s$ mixing phase $\phi_s$ from the time-dependent CP asymmetry in exclusive $B_s$ decays governed by the $b \rightarrow c\bar{c}s$ quark-level transition. The LHCb experiment will exploit a number of methods to measure the CKM angle $\gamma$ from $B \rightarrow D K$ tree decays, with the goal of reaching a precision comparable to the indirect determinations of $\gamma$ within the CKM model. The LHCb experiment will search for New Physics in $B_0^0 \rightarrow \mu^+\mu^-$ and $B_0^0 \rightarrow K^*\mu^+\mu^-$ decays, for the former decay with a 90% CL exclusion sensitivity down to the Standard Model prediction.

1. Introduction

This paper will summarise a selection of key measurements of the LHCb physics programme where interesting results from the first year of data taking can be expected. All presented results were obtained with Monte-Carlo studies with fully simulated events and a complete model of the LHCb detector. Most presented results refer to an accumulated luminosity of $2^{\text{fb}^{-1}}$ which corresponds to one nominal year of data taking with LHCb.

2. New Physics in $B_s$ from channels with a $b \rightarrow c\bar{c}s$ quark-level transition

The $B_s$ mixing phase $\phi_s$ can be determined from the decay $B_s^0 \rightarrow J/\Psi \phi$. In the Standard Model (SM) $\phi_s$ is predicted to be very small, $\phi_s = -0.037 \pm 0.002$ rad [1], and to be straightly related to the Unitarity angle $\chi$, $\phi_s = -2\chi$. This phase has not yet been precisely measured and could turn out to be much larger if New Physics (NP) would add to the $B_s - B_s$ mixing. Both, $B_s$ and $\overline{B}_s$, can decay into the same final state, $J/\Psi \phi$. To find CP-violation the time-dependent asymmetry of the decay-rates into a CP eigenstate is measured:

$$A_{CP}(t) = \frac{\Gamma(B_s^0(t) \rightarrow f) - \Gamma(B_s^0(t) \rightarrow \bar{f})}{\Gamma(B_s^0(t) \rightarrow f) + \Gamma(B_s^0(t) \rightarrow \bar{f})} = \frac{\eta_f \sin \phi_s \sin(\Delta m_s t)}{\cosh(\Delta \Gamma_s t/2) - \eta_f \cos \phi_s \sinh(\Delta \Gamma_s t/2)}$$

The asymmetry can be parameterised in terms of the mixing phase, $\phi_s$, the relative decay width, $\Delta \Gamma_s$, and the mass difference, $\Delta m_s$, with $\eta_f = \pm 1$ depending on the CP eigenstate and $t$ is the proper time. To perform this measurement one needs efficient flavour tagging, a very good proper time resolution to resolve the $B_s - \overline{B}_s$ oscillations. An angular analysis is needed to separate out the CP-even and CP-odd contributions to the vector-vector final state.

The tagging efficiency, $\epsilon_{\text{tag}}$, quantifies how often the tagging gives an answer. The wrong tag fraction, $\omega_{\text{tag}}$, gives the probability of the answer being wrong. The dilution, $D = 1 - 2\omega_{\text{tag}}$. 

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transversity angle, $\Theta_{\text{tr}}$ expected to be $131_{-12}^{+32}\sigma$. LHCb data will be the rates measured at LHCb if the mixing phase $\phi_s$ is five times larger than predicted by the SM.

The proper-time resolution of the decay channel $B_s^0 \to J/\Psi(\mu^+\mu^-)\phi$. The proper-time resolution of the decay channel $B_s^0 \to J/\Psi(\mu^+\mu^-)$ was determined to be $\sigma(t)_{\text{eff}} = 3.6 \text{ fs}$. Fig. 1 shows the simulated time dependence of the $B_s$ and $\bar{B}_s$ decay rates measured at LHCb if the mixing phase $\phi_s$ is five times larger than predicted by the SM.

The decay channel $B_s^0 \to J/\Psi(l^+l^-)\phi(K^+K^-)$ is the golden channel. It is theoretically clean. Experimentally it can be efficiently triggered by the di-muon and just has four charged tracks and a secondary vertex which can be reconstructed efficiently. The event yield in $2 \text{ fb}^{-1}$ is expected to be $131 \, k$ events with a background-over-signal ratio $B/S = 0.12$.

The $1$-angle analysis measures the differential decay widths depending on the polar transversity angle, $\Theta_{\text{tr}}$, which measures the direction of the positive lepton with respect to the plane of the kaons:

$$\frac{d\Gamma(t)}{d\cos \Theta_{\text{tr}}} \propto \left[ |A_0(t)|^2 + |A_\perp(t)|^2 \right] (1 + \cos^2 \Theta_{\text{tr}}) + 2 |A_\parallel(t)|^2 (1 - \cos^2 \Theta_{\text{tr}})$$

Equation (2)

CP-odd states, $A_\perp : \eta_f = +1$, emit the leptons perpendicular to the kaon plane, CP-even states, $A_0, A_\parallel : \eta_f = -1$, emit them within that plane while the background distribution is uniform. The method can be improved by using all three decay angles simultaneously. For the additional complexity a better separation power is gained. Regarding only statistical errors the sensitivity for the mixing phase and the difference in decay widths using the 1-angle method and 2 $\text{ fb}^{-1}$ of LHCb data will be $\sigma(\phi_s) = 0.023 \, \text{ rad}$ and $\sigma(\Delta \Gamma_s/\Gamma_s) = 0.0092$. Other $c\tau s$ states can be added.

The measurement of the $B_s$ mixing phase can be used to efficiently constrain NP. The ratio of the full Hamiltonian over that of the SM can be parameterised as:

$$\langle B^0_s | H_{\text{eff}}^{(1)} | B^0_s \rangle / \langle B^0_s | H_{\text{eff}}^{(0)} | B^0_s \rangle = 1 + (A^\text{NP}_s/A^\text{SM}_s) e^{2i\phi^\text{NP}_s}$$

with $A^\text{NP}_s/A^\text{SM}_s$ the ratio of the mixing amplitudes and $\phi^\text{NP}_s$ the mixing phase of NP. Figure 2 demonstrates by how much the phase space gets restricted using $0.2 \text{ fb}^{-1}$ of LHCb data, worth about two months of LHCb data taking, by which a sensitivity of $\sigma(\phi_s) = 0.1 \, \text{ rad}$ can be reached.

3. Measurement of $\gamma$ from $B \to DK$ tree decays

The Unitarity angle $\gamma$ is determined in a theoretically clean way using the ADS method[2] in the decays $B^+ \to D^0(D^0)K^\pm$. The amplitude ratio between the colour-favoured and colour-suppressed decay mode is $r_B = 7.5\pm3.0\%$. The subsequent decays of $D^0(D^0) \to K^\mp \pi^\pm$ provide a

![Figure 1. Time dependence of the $B_s$ and $\bar{B}_s^0$ decay rates simulated at LHCb for $\phi_s = 0.2$.](image1.png)

![Figure 2. LHCb sensitivity to New Physics with $0.2 \text{ fb}^{-1}$ of data. The contours give 95%, 32% and 5% confidence limits.](image2.png)
doubly Cabibbo-suppressed path with an amplitude of \( r_D = 6.0 \pm 0.3 \% \).

The four decay rates \( B^\pm \to K^+K^-\pi^\pm(\pi^\pm) \) are simply counted. No flavour tagging or proper time analysis are needed. The effects of NP will be small as they only would enter through \( D^0 \) mixing. The ratio \( r_B \), the strong phase \( \delta_B \) and \( \gamma \) can be determined with the external input of the ratio \( r_D \) and the strong phase \( \delta_D \).

This limitation is overcome by adding the three observables of the decay \( D^0 \to K\pi\pi\pi \), the unknown strong phase, \( \delta_K^{3\pi} \), and the well measured relative decay rate, \( r_D^{3\pi} \). Further addition of another observable of the decay modes into CP eigenstates \( D^0 \to KK/\pi\pi \) adds no further unknown parameters (GLW method\(^3\)[4]). With a simultaneous fit to all \( B^\pm \to D^0K^\pm \) decays all parameters can be determined independent of external inputs.

Table 1 displays the expected annual yields of selected charged \( B \) meson decays at LHCb and the corresponding background-over-signal ratios, \( B/S \). Derived from that the sensitivity to \( \gamma \) with \( 2 \) fb\(^{-1} \) of LHCb data will be \( \sigma(\gamma) \sim 5^\circ -15^\circ \), depending on the strong phase \( \delta_D \). The same method can be applied to the decays \( B^0(\bar{B}^0) \to D^0(\bar{D}^0)K\pi \) with the yields shown in Table 1 as well. The expected sensitivity to \( \gamma \) from this decay is \( \sigma(\gamma) \sim 7^\circ -10^\circ \) for \( 2 \) fb\(^{-1} \).

A different method to measure \( \gamma \) uses many decays of \( B^\pm \to D^0K^\pm \) into CP eigenmodes with three or four particles in the final state (GGSZ method\(^5\)). From that a \( D \) decay model is built by measuring across the phase space the magnitudes, \( r_D \), and the phases, \( \delta_D \). The \( D \) decay model is used to parameterise the Dalitz amplitudes of the chosen decay \( D^0 \to K^0_0\pi^+\pi^- \) or \( D^0 \to K^0_0\pi^+\pi^- \) and \( D^0 \to K^0_0\pi^+\pi^- \). The \( B \) decays to a common final state depend on the model, the decay ratio, \( r_B \), the strong phase, \( \delta_B \), and on \( \gamma \) which can be extracted from a simultaneous fit. With \( 2 \) fb\(^{-1} \) of data LHCb expects \( 5k \) events in the \( B^\pm \to (K_0^0\pi^+\pi^-)_D K^\pm \) mode. The background-over-signal ratio is expected to be \( B/S \sim 0.2 - 1.0 \) and the sensitivity to \( \gamma \) will be \( \sigma(\gamma) \sim 8^\circ \).

### 4. New Physics in \( B_s^0 \to \mu^+\mu^- \) and \( B^0 \to K^{*0}\mu^+\mu^- \) decays

Due to the tiny Branching Ratio (BR) the rare loop decay \( B_s^0 \to \mu^+\mu^- \) can be very sensitive to NP which can also add to the decay rates via additional decay processes. The SM predicts \( BR(B_s^0 \to \mu^+\mu^-) = (3.4 \pm 0.4) \times 10^{-9} \). The current limit from CDF and D0 using \( 1 \) fb\(^{-1} \) of data is \( BR(B_s^0 \to \mu^+\mu^-) < 75 \times 10^{-9} \) (90% CL). Predictions for this decay by the constraint MSSM fill the range from just above the SM prediction up to the current limit. Recent measurements of the anomalous magnetic moment of the muon hint for a BR just in this range \([6]\).

The main issue about this decay mode is the rejection of background which seems to be dominated by muons from separate B decays, \( B_{Q\beta} \). Figure 3 displays the results of the LHCb sensitivity study for the BR of \( B_s^0 \to \mu^+\mu^- \). With \( 0.5 \) fb\(^{-1} \) LHCb will be able to exclude BR values down to the SM prediction. With \( 2 \) fb\(^{-1} \) LHCb expects to see a 3\( \sigma \) evidence of the SM signal. With \( 10 \) fb\(^{-1} \) LHCb will exceed the 5\( \sigma \) significance of the SM signal.

The decay of \( B^0 \to K^{*0}\mu^+\mu^- \) is a suppressed loop decay with an expected BR of \( 1.2 \times 10^{-6} \). The forward-backward asymmetry, \( A_{FB}(s) \), depending on the invariant mass of the muon system, \( s = m_{\mu\mu}^2 \), is a sensitive probe to NP. Its zero-point, \( S_0 = S(A_{FB}(s) = 0) \), can be
used to distinguish between different models. LHCb expects 7.7k signal events in 2 fb\(^{-1}\), with a background-to-signal ratio of \(B_{bb}/S = 0.4 \pm 0.1\). Using a fast Monte-Carlo LHCb estimates to restrict the error on the zero-point to \(\sigma(S_0) = 0.52\) GeV\(^2\). With that the ratio of the electroweak Wilson coefficients in the SM can be limited to a statistical error \(\sigma_{\text{stat}}(C^{\ell f f}_{7}/C^{\ell f f}_{9}) = 13\%\). In addition LHCb will look at the transversity amplitudes of this decay. Figure 4 shows that the transversal asymmetry, \(A_T^{(2)}(q^2)\), provides a good separation power between the SM and some SUSY models [7] for 2 fb\(^{-1}\).

5. Conclusions
With the decay \(B_s^0 \rightarrow J/\Psi\phi\) LHCb will reach in the first year of data taking a sensitivity on the mixing phase and on the difference in the decay widths of \(\sigma(\phi_s) = 0.023 \text{ rad} \) and \(\sigma(\Delta\Gamma_s/\Gamma_s) = 0.0092\), respectively. For the clean decays of \(B^\pm \rightarrow D^0 K^\pm\) different methods have been explored to extract \(\gamma\). LHCb expects a sensitivity of \(\sigma(\gamma) \sim 5^{\circ} - 15^{\circ}\) with 2 fb\(^{-1}\). The study of rare decays will open a big potential for search for NP. The decay \(B_s^0 \rightarrow \mu^+\mu^-\) is expected to provide a 3\(\sigma\) evidence for the SM signal with 2 fb\(^{-1}\). The decay \(B^0 \rightarrow K^{*0}\mu^+\mu^-\) will limit the zero-point of the forward-backward asymmetry to \(\sigma(S_0) = 0.52\) GeV\(^2\).

LHCb is waiting for collisions in summer 2008 and expects many new and exciting results in flavour physics and possible signs of NP.

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