Prospects for New Physics in rare decays, mixing and related CP violation at LHCb

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The LHCb experiment currently constructed at CERN has been designed to perform precision measurements on CP asymmetries and to measure rare decays of B mesons. We discuss some selected key measurements to demonstrate the potential of LHCb to find New Physics beyond the Standard Model.

1. The LHCb Experiment

CP asymmetries and rare decays of B mesons are sensitive to contributions from New Physics scenarios introducing flavor changing neutral currents (FCNC) in the transition of a b quark to a d or an s quark. In the standard model (SM) these processes are GIM suppresed, i.e. they occur only via loop and box diagrams. Taking into account current experimental constraints physics beyond the SM may have contributions to the amplitudes and phases for many of these processes of the same or even higher order of magnitude as the SM contributions [1]. The main goal of the LHCb experiment is to disentangle these New Physics contributions by precise measurements of these phenomena.
The LHCb detector [2] is designed as forward spectrometer with excellent vertex resolution, momentum resolution, particle identification and proper time resolution. The performance has been studied by Monte Carlo simulations. The resulting proper time resolution is shown in figure 1 for $B_s \to D_s^-(K^+K^-\pi^-)\pi^+$. The trigger has a high bandwidth and allows to apply moderate p_t cuts. It also includes exclusive fully hadronic triggers important to reconstruct e.g. the decay $B_s \to \Phi\Phi$. The flavor tagging power is $\approx 9\%$ for B_s and $\approx 5\%$ for B_d events [3].

2. Mixing and CP asymmetries

$B - \overline{B}$ mixing is described by the Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} |B(t)\rangle \\ |\overline{B}(t)\rangle \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} |B(t)\rangle \\ |\overline{B}(t)\rangle \end{pmatrix} \quad (1)$$

where M and Γ are the mass and decay matrices. The eigenstates $|B_H(t)\rangle$ and $|B_L(t)\rangle$ have defined masses M_H, M_L and decay rates Γ_H and Γ_L. Up to corrections of order m_b^2/M_W^2 the mass and decay rate difference are given within the SM by $\Delta M = M_H - M_L = 2\,|M_{12}|$ and $\Delta\Gamma = \Delta\Gamma_H - \Delta\Gamma_L = 2\,|\Gamma_{12}|\cos\zeta$. Here ζ denotes the phase $\arg(M_{12}/\Gamma_{12})$. Measurements of the CP asymmetry in flavour specific decays allow to extract $\frac{\Delta\Gamma}{\Delta M}\tan\zeta$. Examples are semileptonic decays, like $B_s \to D_s^-\mu^+\nu_\mu$. Their selection in the LHCb experiment is described in [4].
The decay of a neutral B meson into a final state f_{CP} that is a CP eigenstate can occur as a direct decay or by an oscillation of the meson into a $\overline{B}$ subsequently decaying into f_{CP}. The interference between the two decay modes to f_{CP} may induce a CP violating asymmetry. Assuming there is no direct CP violation in the decay it is given by

$$A_{CP} = \frac{\Gamma(\overline{B}\to f_{CP})-\Gamma(B\to f_{CP})}{\Gamma(\overline{B}\to f_{CP})+\Gamma(B\to f_{CP})} \quad (2)$$

$$= -\eta_f\frac{\sin(\phi-2\omega)\sin(\Delta m t)}{\cosh(\frac{\Delta\Gamma t}{2})-\eta_f\cos(\Phi)\cos(\Delta\Gamma t)} \quad (3)$$

The phase Φ is given by $\arg(M_{12})$ and ω is the weak decay phase. Using current experimental constraints in [1] the mixing parameters are calculated within the SM for the B_s system to

$$\Delta\Gamma_s = (0.096 \pm 0.039)\mathrm{ps}^{-1}, \quad \frac{\Delta\Gamma_s}{\Gamma_s} = 0.147 \pm 0.060,$$
$$\frac{\Delta\Gamma_s}{\Delta M_s} = (49.7 \pm 9.4)10^{-4}, \quad \zeta = 0.0041 \pm 0.0008.$$

Contributions to New Physics are expected to affect $M_{12,s}$, but not $\Gamma_{12,s}$. Parametrizing these contributions as $M_{12,s} = M_{12,s}^{SM} \cdot |\Delta_s| \cdot \exp i\zeta_s^{NP}$ results in

$$\begin{aligned}\Delta M_s &= 2\left|M_{12}^{SM}\right| \cdot |\Delta_s| \\ \Delta\Gamma_s &= 2\left|\Gamma_{12}^{SM}\right| \cdot \cos\left(\zeta^{SM} + \zeta_s^{NP}\right) \\ \frac{\Delta\Gamma_s}{\Delta M_s} &= \frac{\left|M_{12}^{SM}\right|}{\left|M_{12}^{SM}\right|} \frac{\cos(\zeta_s^{SM}+\zeta_s^{NP})}{|\Delta_s|}\end{aligned}$$

A precise measurement of these observables allows a seperation of New Physics contribution to M_{12}. From A_{CP} the phase difference $\phi - 2\omega$ can be determined according to equation 3. The quantity $\frac{\Delta\Gamma_s}{\Delta M_s}$ is specially interresting. Contrary to ΔM_s or $\Delta\gamma_s$ it can be calculated without hadronic uncertainities[1]. The phase $\Phi = \arg M_{12}$ stems from the mixing and is given by $(V_{tb}V_{ts}^*)^2$. ω depends on the decay channel. Consider the decay channels $B_s \to J/\Psi\Phi$ and $B_s \to \Phi\Phi$ shown in figure 2. For the former decay mode the inteference of the transitions $b \to c\bar{c}s$ and $\bar{b} \to \bar{c}c\bar{s}$ gives a phase $(V_{cb}V_{cs}^*)^2$. Therefore $\Phi - 2\omega$ is equal to $\arg[(V_{tb}V_{ts}^*)^2/(V_{cb}V_{cs}^*)^2] =: -2\beta_s$. To a very good approximation $2\beta_s$ is equal to $-\arg[(V_{tb}V_{ts}^*)^2] \sim -\arg[V_{ts}^*]^2$. As seen in figure 2 the decay $B_s \to J/\Psi\Phi$ is a tree level decay and therefore not expected to be altered by New Physics. Contrary the decay $B_s \to \Phi\Phi$ is a penguin decay. New Physics may contribute therefore e.g. by a charged Higgs boson running in the loop. Within the SM the graph shown in figure 2 is dominant. It yields a phase $(V_{tb}^*V_{ts})^2$ that cancels the contribution from the mixing. Therefore a vanishing CP asymmetry is expected if contributions from u and c quarks to M_{12} are neglected, which is an reasonable assumption.

2.1. $B_s \to J/\Psi\Phi$ and $B_s \to \Phi\Phi$

Both decays are of type $B_s \to VV$, i.e. the final state is composed of two vector mesons. Therefore values between 0 and 2 are possible for the

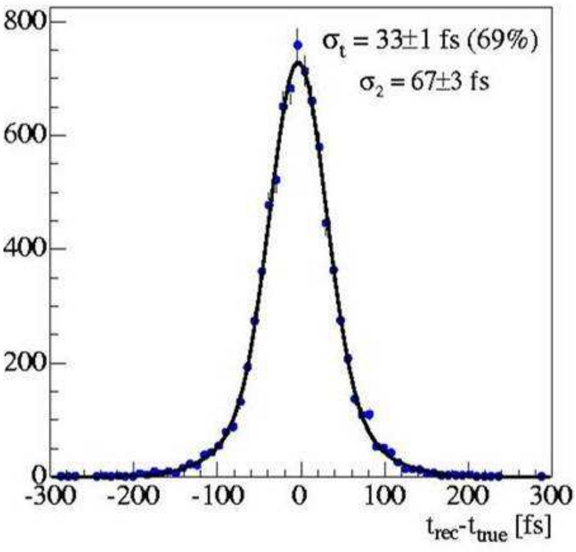

Figure 1. Propertime resolution for the decay mode $B_s \to D_s^-(K^+K^-\pi^-)\pi^+$.

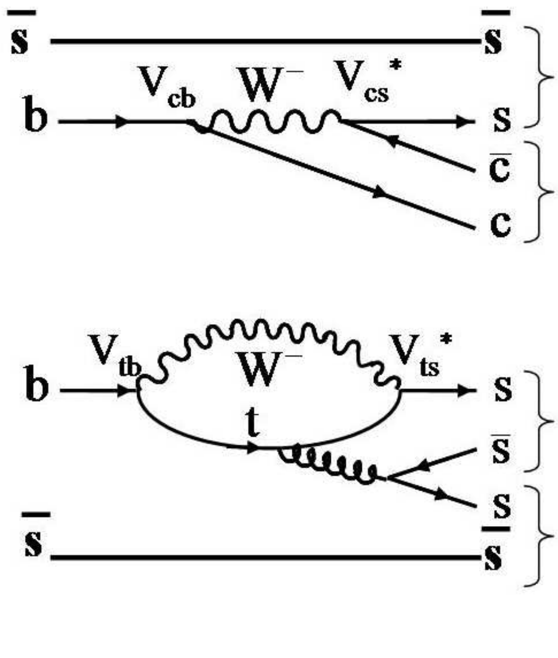

Figure 2. The dominant feynman graphs contributing to the decays $B_s \to J/\Psi\Phi$ and $B_s \to \Phi\Phi$.

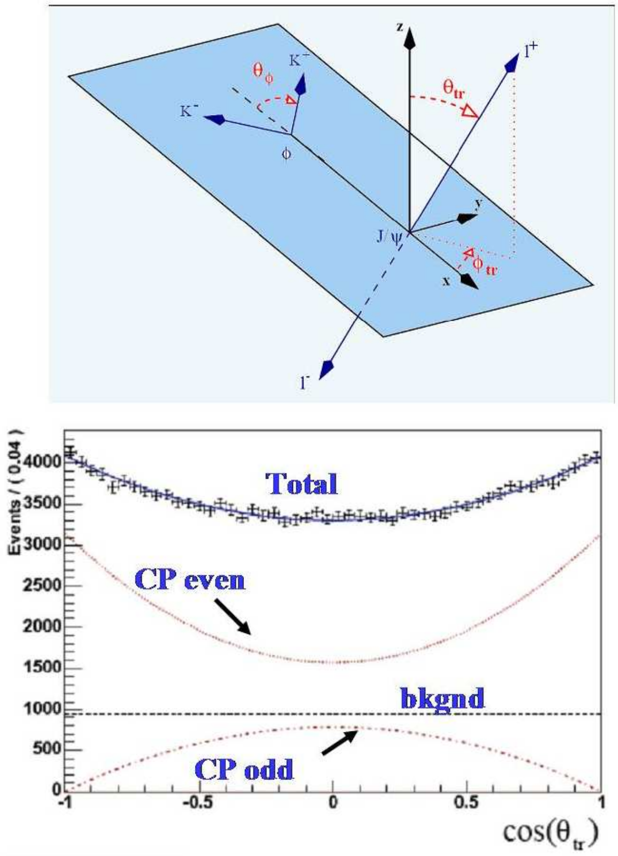

Figure 3. Definition of the angle $\cos\Theta_{tr}$ in the traversity base and the differential decay width distribution $d\Gamma/d\cos\Theta_{tr}$.

angular momentum. The CP eigenvalue of the final state is given by $CP(V_1V_2) = CP(V_1)\cdot CP(V_2)\cdot(-1)^L$. Consequently the final state is a mixture of CP odd and CP even states. To measure the CP asymmetries of that decay the fraction of both components contributing to the final state has to be known. It can be extracted from the data by an angular analysis. For that we define the angle Θ_{tr} in the traversity base as shown in figure 3. The differential decay width as a function of $\cos\Theta_{tr}$ is given by [5]

$$\frac{d\Gamma}{d\cos\Theta_{tr}} \propto \left(|A_0(t)|^2 + |A_2(t)|^2\right)\tfrac{3}{8}\left(1+\cos^2\Theta_{tr}\right) + |A_1(t)|^2\,\tfrac{3}{4}\sin^2\Theta_{tr}$$

where

$$|A_{0,2}(t)|^2 = |A_{0,2}(0)|^2\left(e^{\Gamma_L t} - e^{\bar\Gamma t}\sin\Phi_s\sin\Delta m_s t\right),$$

$$|A_1(t)|^2 = |A_1(0)|^2\left(e^{\Gamma_L t} + e^{\bar\Gamma t}\sin\Phi_s\sin\Delta m_s t\right).$$

$|A_0(t)|^2 + |A_2(0)|^2$ ($|A_1(0)|^2$) are the portions of the CP even (CP odd) contributions to the final state at decay time. From the measurement of $\frac{d\Gamma}{d\cos\Theta_{tr}}$ the fraction of the CP even and CP odd contribution to the final state can be estimated as shown in figure 3.

The selection efficiency and the quality of the event reconstruction has been studied using Monte Carlo events generated by the PYTHIA event generator. The detector response has been simulated using the GEANT4 program. The annual event yields are estimated based on an integrated luminosity of 2fb^{-1}. It corresponds to a nominal year of LHCb data taking at a nominal luminosity of $10^{32}\text{cm}^{-2}\text{s}^{-1}$ for 10^7s. The sensitivity to the mixing parameters can be enhanced for $b \to c\bar{c}s$ transitions by adding the decay modes $B_s \to J/\Psi\eta$, $B_s \to J/\Psi\eta\prime$, $B_s \to \eta_c\Phi$ and $B_s \to D_sD_s$. The advantage of these decay modes is the pure CP eigenstate of the decay, but they suffer from lower branching fractions and a more difficult reconstruction of the final state. The decay mode $B_s \to D_s\pi$ is used as a control channels to estimate the B_s mass difference and wrong tagging fraction. The results from this Monte Carlo study are summarized in table 1 for the mentioned decay modes.

To study the sensitivity to the parameters Φ and $\Delta\Gamma/\Gamma$, a fast Monte Carlo simulation has been performed. As input the signal yield, B/S, proper time acceptance function and the resolutions taken from the full simulation are used.

The sensitivity to the mixing parameters is summarized in table 2. They demonstrate that the SM prediction can be tested already with data from one year of nominal data taking at LHCb and evidence for contribution from New Physics might be obtained.

Table 1
Summary of the annual yields and parameters to describe the reconstruction quality for decay modes used to extract mixing parameters for the $B_s - \bar{B}_s$ system. Limits are given at 90%CL.

Decay	annual yield	B/S	tagging power	$\sigma_{M_{B_s}}$ [MeV/c^2]
$B_s \to J/\Psi\Phi$	$\sim$ 131k	0.12	6.6%	14
$B_s \to J/\Psi\eta(\gamma\gamma)$	$\sim$ 8.5k	2.0	6%	34
$B_s \to J/\Psi\eta(\pi^+\pi^-\pi^0)$	$\sim$ 3k	< 3.0	10%	20
$B_s \to J/\Psi\eta\prime(\rho^0(\pi^+\pi^-))$	$\sim$ 4k	< 0.47	9.2%	14
$B_s \to J/\Psi\eta\prime(\rho^0(\pi^+\pi^-))$	$\sim$ 4k	< 0.47	9.2%	14
$B_s \to \eta_c\phi$	$\sim$ 3k	< 1.17	9.6%	12
$B_s \to D_s D_s$	$\sim$ 4k	< 0.3	6%	6
$B_s \to D_s\pi$	$\sim$ 120k	0.4	6.9%	14
$B_s \to \Phi\Phi$	$\sim$ 3.1k	< 0.8	9.7%	12

Table 2
Sensitivity to the mixing parameters of the $B_s - \bar{B}_s$ system expected for LHCb obtained from data corresponding to one year of nominal data taking. The errors given are only statistical errors.

Parameter	Error	Channel	Ref.
$\Phi_s - 2\omega(b \to c\bar{c}s)$	0.023 rad 0.022 rad	$B_s \to J/\Psi\Phi$ $B_s \to J/\Psi\eta$, $B_s \to \eta_c\Phi$ $B_s \to D_s D_s$	[6] [6]
	0.08 rad	$B_s \to J/\Psi\eta\prime$	[7]
$\Phi_s - 2\omega(b \to s\bar{s}s)$	0.1 rad	$B_s \to J/\Psi\phi$	[8]
$\Delta\Gamma/\Gamma$	0.092	$B_s \to J/\Psi\Phi$	[6]
ΔM_s	0.007 ps^{-1}	$B_s \to D_s^-(D^+D^-\pi^-)\pi^+$	[6]
w_{tag}	0.36%	$B_s \to D_s^-(D^+D^-\pi^-)\pi^+$	[6]

3. Rare decays

Rare decays are a powerful tool to establish New Physics contributions to these decays. The most prominent example for this is the decay $B_s \to \mu^+\mu^-$. In the SM this decay is mediated by the diagram shown in figure 4a. The branching ratio is predicted to $(3.4 \pm 0.4) \cdot 10^{-9}$. Even at this very low value LHCb expects to observe evidence for this decay on a 3σ level after one year of nominal data taking. An observation on the 5σ level is expected after a few years of data taking [10]. The measurement of an enhanced branching ratio compared to the SM prediction would be a clear sign for New Physics.
Beside the establishment of New Physics rare decays allow to extract valuable information about the nature of New Physics [9]. In supersymmetric models the above mentioned decay gets additional contribution from penguin decays as shown in figure 4b. Due to the strong dependence of that diagram on $\tan\beta$ the measurement of the branching ratio BR $(B_s \to \mu^+\mu^-)$ is sensitive to this parameter especially for high values.
Another example is the decay $B \to K^{*0}\mu^+\mu^-$. For this decay a set of observables exists sensitive to right handed currents. The capability of the LHCb experiment to measure these observables

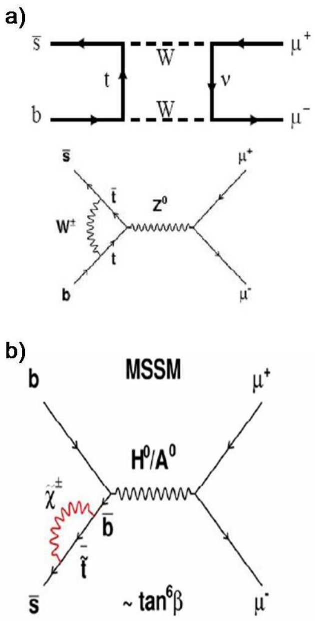

Figure 4. a) Example for SM feynman diagrams contributing to the rare decay $B_s \to \mu^+\mu^-$. b) Example for a contribution in supersymmetric models.

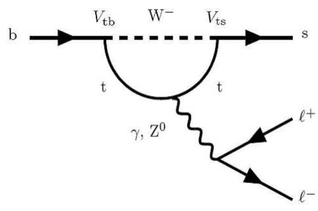

Figure 5. Feynman diagram for the transition $b \to sll$ taking place in the decay $B_u^- \to K^- ll$.

has been discussed in [11].

Here we show how sensitivity to non-SM (pseudo)scalar couplings is obtained by a combination of informations for the decays $B_s \to \mu^+\mu^-$, $B_u \to K^+e^+e^-$ and $B_u \to K^+\mu^+\mu^-$, see figure 5. The observables used are the branching ratio of the decay of the B_s into two muons and the ratio

$$R_k = \frac{\int_{4m_\mu^2}^{q^2_{max}} ds \frac{d\Gamma(B\to K\mu^+\mu^-)}{ds}}{\int_{4m_e^2}^{q^2_{max}} ds \frac{d\Gamma(B\to Ke^+e^-)}{ds}}. \quad (4)$$

Due to lepton universality the value for this ratio is very close to one in the SM [12]. The existence e.g. by additional non-SM Higgs might enhance both observables. In [12] minimum flavour violating models (MFV) are investigated that have

- (pseudo)scalar couplings beyond the SM,
- negligible right handed charged currents,
- minimum flavour violation, i.e. there is no new CP phase beyond the SM.

For this class of models the following relation between these two observables is predicted

$$R_k - 1 \propto BR(B_s \to \mu\mu) \quad (5)$$

LHCb is capable to measure both parameters and therefore it will be possible to test these modules using this relation. For the measurement of R_k the selection efficiencies for the decays $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ have been studied in [13]. The resulting B^+ mass

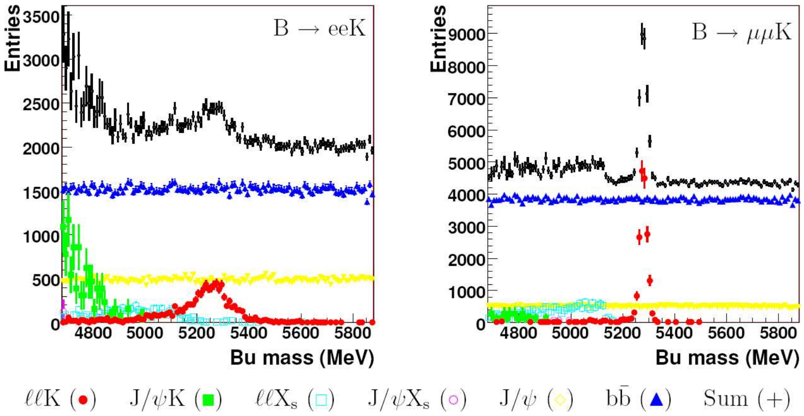

Figure 6. B^+ mass spectra for the decay modes $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$. The contribution coming from different background channels to the measured mass spectrum is also shown.

spectrum for both decay modes is shown in figure 6. The efficiency of the inclusive di-lepton trigger of LHCb has been taken into account and Bremsstrahlungs corrections have been applied to the electron mode. The background contributions to the measured spectrum are indicated in the figure. The annual yield and the resolution for the reconstructed B^+ mass for these decays is estimated to

	Signal	σ_{B+}
eeK :	349 ± 34	74MeV
$\mu\mu K$:	1550 ± 50	15MeV

From this result it is estimated, that the parameter R_k can be measured with an error of $\sim 10\%$ at an integrated luminosity of 2fb^{-1} corresponding to one year of nominal data taking at LHCb. For an integrated luminosity of 10fb^{-1} the error reduces to $\sim 4-6\%$.

In figure 7 the current experimental situation is shown in the $R_k - \text{BR}(B_s \to \mu\mu)$ plane together with the projection for the LHCb experiment using data of 10fb^{-1}.

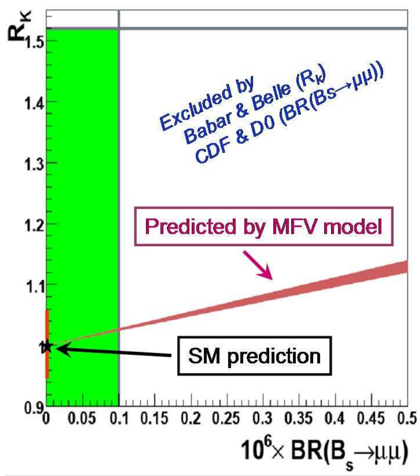

Figure 7. Current experimental situation in the $R_k - \text{BR}(B_s \to \mu\mu)$ plane. Shown are also the SM prediction and the prediction for MFV models as described in the text.

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