Looking for New Physics: Prospects for B Physics at LHCb

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With the startup of LHCb, the dedicated heavy flavor experiment at the LHC, the next round of precision B-experiments will be launched. LHCb has access to about 10^{12} B meson decays per year, allowing significant measurements of even very rare B decays and, in particular, the precision study of the B_s system. With the measurement of rates, angular distributions and CP asymmetries of loop suppressed B decays, LHCb will probe the quantum corrections predicted by the Standard Model. Many observables show a large sensitivity to New Physics contributions. In the following the expected LHCb physics performance and the potential to search for New Physics is discussed for a set of key measurements.

1 Introduction

The LHCb experiment [1] is a dedicated beauty and charm-physics experiment at the proton-proton collider LHC at CERN. The experiment exploits the copious production of heavy quarks in proton-proton collisions. For a centre-of-mass energy of 14 TeV a $b\bar{b}$ production cross section of more than 500 μb is expected. At LHC, all b-hadron species (B_d, B_u, B_s, B_c, Λ_b, ...) will be produced.

To unambigiously assign long-lived particles to an interaction point (primary vertex) and to facilitate the event reconstruction, single interactions per beam crossing are prefered. It is therefore planned, to adjust the beam luminosity at the LHCb interaction point to a value of 2×10^{32} cm^{-2}s^{-1}. At this luminosity, the number of bunch crossings with a single interaction is maximized.

With the measurement of rates, angular distributions and CP asymmetries of loop suppressed B decays LHCb will probe the quantum corrections predicted by the Standard Model. Many of the observables show large sensitivities to New Physics contributions. The unprecedented quantity of b hadrons will allow LHCb to perform significant measurements of rare B decays down to branching fractions of 10^{-9}. One of the early LHCb key measurements will be the determination of the B_s mixing phase, Φ_s, in the decay $B_s \rightarrow J/\psi\phi$. Data of a few months of LHC running will allow to cross-check the deviation from the Standard Model prediction currently observed by the two TEVATRON experiments CDF and D0 [2]. The measurement of the direct CP asymmetry in $B \rightarrow DK$ tree-level decays will result in a determination of the CKM angle γ with an expected final precision better than 3°. The comparison with results from loop-suppressed decays and with the result of the indirect determination of γ from the CKM fits will probe possible new physics contributions. Flavor changing neutral current (FCNC) decays such as $B_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow K^*\mu^+\mu^-$ are very sensitive to different extensions of the Stadard Model and might be the first place to observe effects of New Physics at the LHC.

The LHCb detector construction was completed in summer 2008. The commissioning of the detector is well advanced. A large sample of cosmic muon events was taken and was used to perform a first time and and space alignment of the large area tracking detectors and the calorimeters. Data taken during injection tests, where the LHC beam was dumped before reaching the LHC main ring upstream of the LHCb detector, showed to be very useful for the understanding of the silicon detectors. The events with muon fluxes of several particles/cm^2 were successfully used to align the silicon detectors.

In the following the expected physics performance of the LHCb experiment is discussed for four key measurements.

2 Measurement of the B_s mixing phase

The interference between $B_s \rightarrow J/\psi\phi$ decays with or without $B_s - \bar{B}_s$ oscillation gives rise to an observable CP violating phase Φ_s. In the Standard Model, this phase is predicted to be $\Phi_s = -2\beta_s = -0.0368 \pm 0.0017$, where $\beta_s = arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$ is the smaller angle of the bs unitary triangle of the CKM matrix.

The value of Φ_s can be extracted from the mesurement of the time dependent CP asymmetry $A_{CP}(t)$,

$$A_{CP}(t) = \frac{\eta_f \sin\Phi_s \sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) - \eta_f \cos\Phi_s \sinh(\Delta\Gamma_s t/2)},$$

where Δm_s and $\Delta\Gamma_s$ are the differences in mass and width of the two B_s mass eigenstates, and $\eta_f = \pm 1$ is the CP eigenvalue of the final state.

The measurement of the phase Φ_s is a sensitive test of the Standard Model as Φ_s is one of the CP observables with the smallest theoretical uncertainty. New Physics could significantly modify this prediction, if, for example, new particles contribute to the $B_s - \bar{B}_s$ mixing diagram.

As the final state $J/\psi\phi$ contains two vector mesons its CP value depends on the relative angular momentum of both vector mesons. The relative contribution of the two CP states has to be determined on a statistical basis using an angular analyis of the three decay product angles $\Omega = \{\theta, \phi, \psi\}$ as depicted in Figure 1.

Both TEVATRON collaborations, CDF and D0, have recently presented measurements of the time dependent CP asymmetrie for the channel $B_s \rightarrow J/\psi\phi$ and the phase Φ_s [2]. A combination by HFAG [3] results in the following experimentally prefered 90% CL intervalls for Φ_s,

$$\Phi_s \in [-1.47; -0.29] \cup [-2.85; -1.65] \quad \text{at 90\% CL},$$

These experimental constraints deviate from the Standard Model prediction. An update by CDF [4] using 2.8 fb^{-1} further degrades the consistency with the Standard Model value.

For the decay $B_s \rightarrow J/\psi\phi$ the LHCb experiment expects a proper time resolution of about 38 ps, a B_s mass resolution of 16 MeV and an effective tagging power (ϵD^2) of 6.2 %. With a total efficiency of 2.6% (including the trigger) the simulation predicts a yield of 117k selected

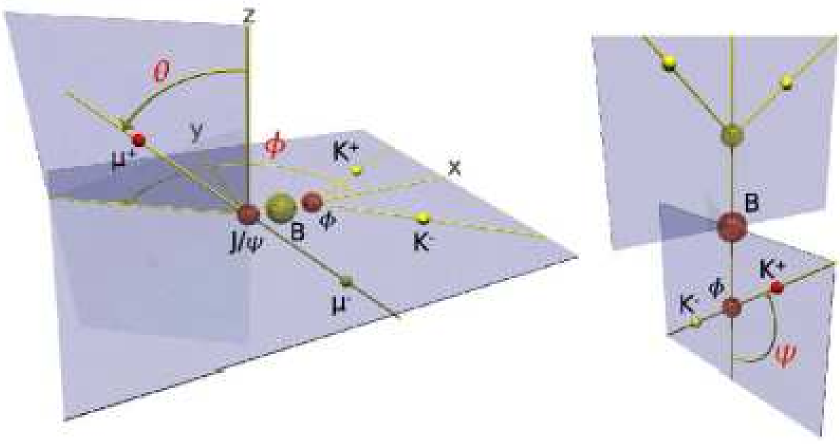

Figure 1: Definition of the angles $\Omega = \{\theta, \phi, \psi\}$ in the transversity basis.

signal events per 2 fb^{-1} with a background to signal ratio of long-lived backgrounds of about 0.5. The signal events will allow a determination of the phase $\Phi_s = -2\beta_s$ with a statistical precision $\sigma(\Phi_s) \sim 0.03$. Systematic effects due to proper time and angular resolutions, angular acceptance and flavour tagging have been studied and found to be smaller than the statistical uncertainty expected for 2 fb^{-1}.

Figure 2 shows the expected statistical uncertainty for $\Phi_s = -2\beta_s$ versus the integrated luminosity $\mathcal{L}_{int}$. The sensitivity has been estimated for 0.5 and 2 fb^{-1}, the values are 0.060 ± 0.005 and 0.030 ± 0.002 respectively. The red line is an extrapolation from these two values. The blue lines show the uncertainties related to the $b\bar{b}$ cross-section and the visible branching ratio of $B_s \to J/\psi(\mu\mu)\phi(KK)$. The line labelled "CDF+D0" is the combined CDF/D0 uncertainty in 2008 scaled to an integrated luminosity of 2×9 fb^{-1}, as expected for the TEVATRON by 2010. It should be noted that LHCb is able to perform a competitive measurement of Φ_s already with the very first data.

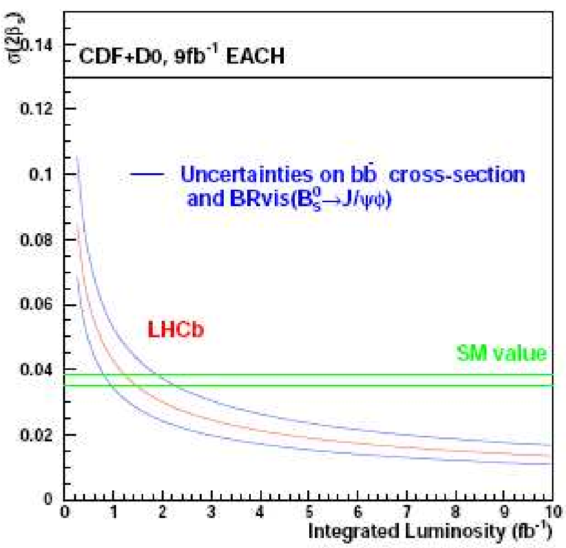

Figure 2: Expected statistical uncertainty on $\Phi_s = -2\beta_s$ as function of the integrated luminosity.

3 Measurement of the CKM angle γ

Several methods to directly measure the CKM angle γ in $B \to DK$ tree decays have been pioneered by the BABAR and BELLE experiment. The achieved precision so far is limited by statistics and is still much worse than the precision of γ determined indirectly from the CKM fits [5].

In all cases, the measurement of γ in $B \to DK$ tree decays exploits the interference between the two decay amplitudes, $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$, depicted in Figure 3, which appears in the case that the D and $\bar{D}$ are observed in the same final state. The interference allows the observation of the phase difference between the two amplitudes,

$$\frac{\mathcal{A}(B^- \to D^0K^-)}{\mathcal{A}(B^- \to \bar{D}^0K^-)} = r_B e^{\delta_B} e^{-i\gamma} \,,$$

where r_B is the relative magnitude of the two amplitudes and δ_B is an additional strong phase difference.

LHCb has investigated the expected sensitivity to γ for the ADS [6] the GLW [7] and the GGSZ [8] method. The different methods result into a similar sensitivity (between 10 and 13 degrees for a data-sample corresponding to 2 fb^{-1}). For the combination, a sensitivity, depending on the strong phase δ_B, between 4.3° ($\delta_B = 180°$) and 6.1° ($\delta_B = 45°$) is expected [9].

An alternative way to determine γ, unique to LHCb, is the determination of the sum of the two phases $\gamma + \Phi_s$ from the observation of the time dependent CP asymmetry of the decays $B_s \to D_s^{\mp}K^{\pm}$. As the B_s and the $\bar{B}_s$ can both decay to $D_s^{\pm}K^{\mp}$, there exists an intereference between amplitudes with and without a preceding oscillation. The main issue of this analysis is to separate the decay $B_s \to D_s^{\mp}K^{\pm}$ from the very similar decay $B_s \to D_s^{\mp}\pi^{\pm}$ with a $\sim$15 times larger branching fraction. Here, the excellent LHCb particle identification based on the two RICH counters allows a significant reduction of the background contamination. For a data-sample equivalent to 2 fb^{-1}, a signal yield of $6.2{\times}10^3$ $B_s \to D_s^{\mp}K^{\pm}$ events with a background-to-signal ratio of $\sim$0.7 is expected. The resulting sensitivity to $\gamma + \Phi_s$ depends on the strong phase and varies between 9° and 12°.

Combining all tree-level measurements of γ ($B^{\pm} \to DK^{\pm}$, $B^0 \to DK^*$ and $B_s \to D_s^{\mp}K^{\pm}$) one obtains the expected sensitivities listed in Table 1 [9]. As can be seen, data corresponding to about 0.5 fb^{-1} would already allow a determination of γ with an error better than 10°.

4 Search for New Physics in flavor changing neutral current processes

4.1 $B \to K^*\mu^+\mu^-$

In the Standard Model, the flavor changing neutral current decay $b \to s\ell^+\ell^-$ cannot occur at tree level but only through electroweak penguin amplitudes with small branching fractions, e.g.

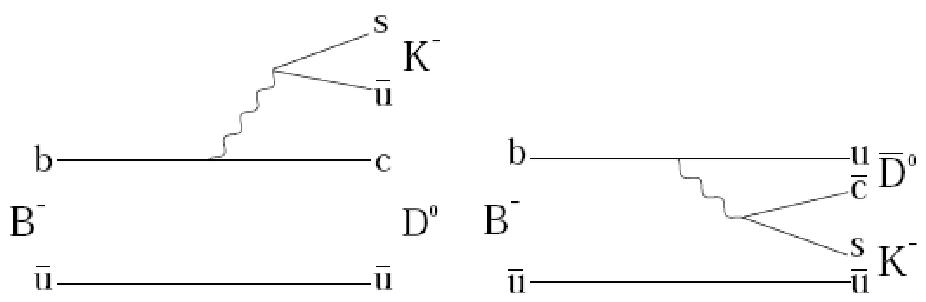

Figure 3: Feynman diagrams for the decays $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$.

Table 1: The expected combined sensitivity to γ from $B \to DK$ and time-dependent measurements [9] for data sets corresponding to integrated luminosities of 0.5, 2 and 10 fb^{-1}.

$\delta_B(^\circ)$	0	45	90	135	180
σ_γ for 0.5 $\text{fb}^{-1}(^\circ)$	8.1	10.1	9.3	9.5	7.8
σ_γ for 2 $\text{fb}^{-1}(^\circ)$	4.1	5.1	4.8	5.1	3.9
σ_γ for 0.5 $\text{fb}^{-1}(^\circ)$	2.0	2.7	2.4	2.6	1.9

$BR(B \to K^*\mu^+\mu^-) \sim 1.2 \times 10^{-6}$. An angular analysis of the decay $B \to K^*\mu^+\mu^-$ is well suited to search for New Physics: most New Physics scenarios make definite predictions, for the forward-backward asymmetry, A_{FB}, of the μ^+ relative to the B direction in the $\mu^+\mu^-$ rest frame. In particular, the value s_0 of the $\mu^+\mu^-$ invariant mass, q^2, for which the asymmetry becomes zero, is predicted with small theoretical uncertainties and may provide a stringent test of the Standard Model and New Physics scenarios.

Because of the clear di-muon signature and the good K/π separation provided by the RICH detectors, the exclusive decay $B \to K^*\mu^+\mu^-$ can be triggered and reconstructed in LHCb with high efficiency [10]. The selection including trigger has an efficiency of $\sim$1% resulting in an expectation of $\sim$7.2k signal events for an integrated luminosity of 2 fb^{-1}. A simple counting of forward and backward events together with a linear fit results in a precision on s_0 of 0.5 GeV^2. In addition to measuring A_{FB}, LHCb is able to extract other angular observables, such as the longuitudinal $K^\star$ polarization $F_L(q^2)$ or the transverse asymmetry $A_T^{(2)}(q^2)$ [11]. These quantities show a high sensitivity to minimal flavor violating MSSM models with small $\tan\beta$. In the theoretically favored region away from the photon pole and below the charm resonances ($1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$) the sensitivity of F_L and $A_T^{(2)}$ is 0.016 and 0.42 respectively, for the above mentionned data sample.

4.2 $B_s \to \mu^+\mu^-$

The purely leptonic decays $B^0_{d,s} \to \mu^+\mu^-$ are FCNC processes. In the Standard Model, these decays can only proceed at a very low rate through higher order diagrams (Z/Higgs-penguins and W-box diagram - the latter is suppressed). Moreover, the decays are helicity suppressed by a factor $(m_\mu/M_B)^2$. The decays are therefore very sensitive to any New Physics model with new scalar or pseudo-scalar interactions, in particular, they are sensitive to models with an extended Higgs sector. In the MSSM the branching fractions are known to increase with $\tan^6\beta$.

The Standard Model branching fraction for $B_s \to \mu^+\mu^-$ is computed [12] to be $BR(B_s \to \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^9$. The branching fraction for $B^0_d \to \mu^+\mu^-$ is further suppressed by the CKM ratio $|V_{td}/V_{ts}|^2$ leading to a predicted Standard Model branching fraction of $\sim 1 \times 10^{-10}$. The current upper limit of the $B_s \to \mu^+\mu^-$ branching fraction from the TEVATRON experiments [3,13] is 4.7×10^{-8}.

At LHCb, the background expected in the search for the decay $B_s \to \mu^+\mu^-$ is dominated by random combinations of two muons originating from two distinct B decays. This background can be kept under control by exploiting the excellent tracking and vertexing capabilities of the detector. Due to a very low muon misidentification rate, two-body hadronic decays, $B \to h^+h^-$, where the hadrons are misindentified as muons, do not contribute to a significant level compared to the combinatorial background. The LHCb experiment has the sensitivity to observe a branching fraction of 1×10^{-8} with a 3σ significance already with 0.1 fb^{-1} of data. A data-set of 2(6) fb^{-1}will allow the observation of the Standard Model branching fraction with a $3(5)\sigma$ signficance.

5 Summary and Outlook

The large $b\bar{b}$ production cross section at the LHC provides a unique opportunity to measure rates, angular distributions, and CP asymmetries of even very rare, loop suppressed b decays. Many of the observables show large sensitivities to New Physics contributions. In particular, the production of B_s mesons could play a crucial role to identify new CP violating effects originating from New Physics. Already with a data-set of 0.5 fb^{-1} LHCb expects to perform sensitive tests of the Standard Model and New Physics scenarios: The B_s mixing phase Φ_s can be measured with a precision of ± 0.06; the reachable precision of the CKM phase γ is estimated to be between 8° and 10°; a $B_s \to \mu^+\mu^-$ branching fraction of 5×10^{-9} can be observed.

The LHCb measurements will either limit New Physics contributions to B decays or, more optimistically, uncover them. The measurements will complement the direct searches of New Physics performed by ATLAS and CMS. If New Physics phenomena will be observed first by the high-p_t experiments, the LHCb measurements will help to understand the flavor structure of the new phenomena.

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