Search for new physics in the B-sector at the LHC

Johannes Albrecht

Physikalisches Institut
Philosophenweg 12, 69120 Heidelberg
Germany

A set of key measurements of B decays which have the potential to uncover New Physics at the LHC is discussed. Together with the general purpose detectors ATLAS and CMS, the LHCb detector, which is devoted to B physics, can study these effects precisely. Due to the large $b\bar{b}$ cross section at 14 TeV, LHCb has access to 10^{12} B meson decays per year. This allows significant measurements of even very rare B decays and, in particular, the precision study of the B_s system.

1 Introduction

The Large Hadron Collider (LHC) at CERN is a proton-proton collider which will operate at a center of mass energy of 14 TeV. Three of the LHC experiments search for New Physics signatures in the flavor sector: The ATLAS and CMS experiments study B meson decays in parallel to their main focus on direct searches for New Physics and the Higgs boson. In contrast to that, the LHCb experiment is designed and optimized to measure precisely the B meson properties. Therefore, this article puts the main focus on the expected LHCb measurements and, where available, compare them with the predictions from ATLAS and CMS.

To unambiguously assign long lived particles to their primary vertex, events with a single proton-proton interaction are preferred. LHCb therefore plans to adjust the beam luminosity to an average value of $2 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$. In contrast to that, the ATLAS and CMS experiments plan to run at the maximal LHC luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$.

The unprecedented quantity of b -hadrons that will be produced at the LHC allow stringent tests of the Standard Model and of possible New Physics scenarios. Indirect effects studied in b hadron decays provide complementary information to that from direct searches and allow to probe the flavor structure of possible New Physics. One of the early measurements of major interest will be the determination of the B_s mixing phase Φ_s from the decay $B_s \rightarrow J/\psi\phi$. Data with a few months of LHC running will allow to cross check the deviation from the Standard Model prediction currently indicated by the two Tevatron experiments [2]. Flavor changing neutral current decays such as $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow K^*\mu^+\mu^-$ are very sensitive to different extensions of the Standard Model. In case no signatures of New Physics would be observed, possible New Physics scenarios will be significantly constrained. The measurement of the direct CP asymmetry in $B \rightarrow DK$ tree-level decays will result in a precise determination of the CKM angle γ , which in combination with indirect measurements can probe possible New Physics contributions.

2 Measurement of the B_s mixing phase

The interference between $B_s \rightarrow J/\psi\phi$ decays with and without a $B_s - \bar{B}_s$ oscillation gives rise to the CP violating asymmetry proportional to $\sin \Phi_s$. In the Standard Model, when

DIS 2009

penguin contributions to the decay amplitude are neglected, this phase is predicted to be

$$\Phi_s = -2\beta_s = (-0.0368 \pm 0.0017) \text{ rad}, \quad (1)$$

where $\beta_s = \arg((V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*))$. New Physics could significantly modify this by contributing to the $B_s - \bar{B}_s$ mixing diagram.

The final state $J/\psi\phi$ consists of two vector mesons, hence its CP -eigenvalue depends on the relative angular momentum of the two mesons. An angular analysis allows to disentangle on a statistical basis the CP -odd and CP -even components. The time dependent CP asymmetry $A_{CP}(t)$ is given by

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

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.

CDF and DØ recently published measurements of the time dependent CP asymmetry for the channel $B_s \rightarrow J/\psi\phi$, which use 1.3 and 2.8 fb^{-1} of data respectively [2]. The HFAG combination [3] results in the following value of the weak mixing phase Φ_s ,

$$\Phi_s = [(-0.77^{+0.29}_{-0.37}) \text{ or } (-2.36^{+0.37}_{-0.29})] \text{ rad}. \quad (3)$$

This result shows a possible deviation from the Standard Model prediction. An update by CDF [4] using 2.8 fb^{-1} further degrades the consistency with the SM.

For the decay $B_s \rightarrow J/\psi\phi$, the LHCb experiment expects a proper time resolution of 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 trigger, the simulation predicts a yield of 117 000 selected signal events per 2 fb^{-1} with a background-to-signal ratio of about 0.5 [5]. The Φ_s sensitivity has been estimated to be

$$\mathcal{L} = 0.5 \text{ fb}^{-1} : \sigma(\Phi_s) = 0.060 \pm 0.005,$$

$$\mathcal{L} = 2 \text{ fb}^{-1} : \sigma(\Phi_s) = 0.030 \pm 0.002,$$

where only statistical errors are given. Systematic effects due to proper time and angular resolutions, angular acceptance and flavor tagging have been studied and found to be smaller than the statistical uncertainty expected for 2 fb^{-1} . Figure 1 shows the expected LHCb statistical uncertainty for $\Phi_s = -2\beta_s$ versus the integrated luminosity $\mathcal{L}_{int}$. The red line is an extrapolation from the above two values. The blue lines show the uncertainties related to the $b\bar{b}$ cross-section and the visible branching ratio of $B_s \rightarrow J/\psi(\mu\mu)\phi(KK)$. The black vertical line is the combined CDF/DØ uncertainty in 2008 scaled to an integrated luminosity of $2 \times 9 \text{ fb}^{-1}$, as expected for the two Tevatron experiments 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 1: Expected LHCb sensitivity on $\Phi_s = -2\beta_s$ as a function of the integrated luminosity. The Standard Model prediction and the Tevatron expectation for 2010 are indicated.

3 Search for New Physics in flavor changing neutral current processes

3.1 $B_s \rightarrow \mu^+\mu^-$

The very rare decays $B_{d,s}^0 \rightarrow \mu^+\mu^-$ proceed via CKM suppressed Z-penguin or W-box diagrams. Additionally, the decays are helicity suppressed by a factor $(m_\mu/M_B)^2$. The Standard Model branching fraction is computed to be $BR(B_s^0 \rightarrow \mu^+\mu^-) \sim 3.3 \times 10^{-9}$ [6]. The branching fraction for $B_d^0 \rightarrow \mu^+\mu^-$ is further suppressed by the CKM ratio $|V_{td}/V_{ts}|^2$ leading to a predicted Standard Model branching fraction of $\sim 1 \times 10^{-10}$. These rare decays are very sensitive to any New Physics model with new scalar or pseudo-scalar interactions, in particular to models with an extended Higgs sector. In the MSSM the branching fractions are proportional to $\tan^6 \beta$. The current upper limit of the $B_s^0 \rightarrow \mu^+\mu^-$ branching fraction from the CDF and DØ experiments is 4.7×10^{-8} [3, 7].

Experimentally, the search for the $B_s \rightarrow \mu^+\mu^-$ decay has to deal with the problem of an enormous level of background, dominated by random combinations of two muons originating from two distinct B decays. It can be kept under control by exploiting the excellent tracking and vertexing capabilities of the LHCb detector. Due to a very low muon misidentification rate (0.5 %), two-body hadronic decays, $B \rightarrow h^+h^-$, where the hadrons are misidentified as muons, do not contribute to a significant level. The LHCb experiment estimates the total efficiency to select $B_s \rightarrow \mu^+\mu^-$ events to 10 %, including trigger efficiency. As shown in Figure 2, this yields to a sensitivity to exclude a branching ratio down to 7×10^{-9} with a confidence level of 90 %, with 0.5 fb^{-1} of data. A data-set of 2 fb^{-1} (6 fb^{-1}) will allow the observation of the Standard Model branching fraction with a 3σ (5σ) significance.

The ATLAS and CMS collaborations estimate their sensitivity to be able to exclude a branching ratio down to 10^{-8} at 90 % CL with a dataset of 2 fb^{-1} [8].

Figure 2: Expected upper limit for the branching ratio of the $B_s \rightarrow \mu^+\mu^-$ decay at 90 % CL for LHCb as a function of the integrated luminosity. A prediction of the Standard Model is also indicated.

3.2 $b \rightarrow s\ell^+\ell^-$

In the Standard Model, the electroweak penguin decays $b \rightarrow s\ell^+\ell^-$ are only induced at loop level which leads to small branching fractions and thus a high sensitivity to contributions from physics beyond the Standard Model. The decay $B_d \rightarrow K^*\mu^+\mu^-$ ($\mathcal{BR} \sim 1.2 \times 10^{-6}$) is experimentally best accessible due to the clear dimuon signature. An angular analysis of this decay is well suited to search for New Physics as most scenarios make definite predictions for the forward-backward asymmetry (A_{FB}) of the μ^+ relative to the B direction in the dimuon rest frame as a function of the dimuon mass. In particular s_0 , the zero crossing point of A_{FB} , is predicted with small theoretical uncertainties and will provide a stringent test of the Standard Model and New Physics scenarios.

The decay $B_d \rightarrow K^* \mu^+ \mu^-$ can be triggered and reconstructed in LHCb with a total efficiency of $\sim 1\%$ [9]. This results in an expectation of $\sim 7\,200$ signal events for an integrated luminosity of $2\,fb^{-1}$ with a background-to-signal ratio of about 0.5. A simple counting analysis results in a precision of $0.5\,GeV^2$ on the zero crossing point s_0 . In addition to measuring A_{FB} , LHCb is able to extract other angular observables, such as the longitudinal K^* polarization $F_L(q^2)$ or the transverse asymmetry $A_T^{(2)}(q^2)$ [10].

4 Measurement of the CKM angle γ

The BABAR and BELLE experiments have performed first direct measurements of the CKM angle γ using $B \rightarrow DK$ tree decays. Limited by statistics, the precision is still much below the indirect determination from CKM fits [11]. The measurement exploits the interference between the two tree decay amplitudes $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow \bar{D}^0 K^-$, as shown in Figure 3. The interference of the D^0 and $\bar{D}^0$ decays into the same final state allows the observation of the phase difference between the two amplitudes,

$$\frac{\mathcal{A}(B^- \rightarrow D^0 K^-)}{\mathcal{A}(B^- \rightarrow \bar{D}^0 K^-)} = r_B e^{\delta_B} e^{-i\gamma}, \quad (4)$$

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

LHCb has investigated the expected sensitivity for γ using the ADS, GLW and the GGSZ method for the time integrated decay rates [12]. The different methods result into a similar sensitivity. For a data-sample corresponding to $2\,fb^{-1}$, it is $10 - 13^\circ$, depending on the strong phase δ_B , which can be simultaneously determined.

An alternative way to determine γ is the measurement of the time dependent CP asymmetry of the decays $B_s \rightarrow D_s^\mp K^\pm$. As the B_s and the $\bar{B}_s$ can both decay to $D_s^\pm K^\mp$, there exists an interference between amplitudes with and without a preceding oscillation which gives access to sum of $\gamma + \Phi_s$. The main issue of this analysis is to separate the decay $B_s \rightarrow D_s^\mp K^\pm$ from the very similar but ~ 15 times more frequent decay $B_s \rightarrow D_s^\mp \pi^\pm$. Here, the excellent LHCb particle identification based on the two RICH counters allows a significant reduction of the background contamination. For a data-sample of $2\,fb^{-1}$, a signal yield of $6\,200\,B_s \rightarrow D_s^\mp K^\pm$ events with a background-to-signal ratio of ~ 0.7 is expected.

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

The resulting sensitivity to $\gamma + \Phi_s$ varies between 9° and 12° , dependent on δ_B , the strong phase difference which can be determined from the data.

Table 1 summarizes the expected LHCb sensitivity, combining all tree-level measurements of γ [13]. A dataset corresponding to 0.5 fb^{-1} would already allow the determination of γ with an error below 10° .

$\mathcal{L}_{int}$	σ_γ
0.5 fb^{-1}	$7.8 - 10.1^\circ$
2 fb^{-1}	$3.9 - 5.1^\circ$
10 fb^{-1}	$1.9 - 2.7^\circ$

Table 1: Expected combined LHCb sensitivity to measure γ , covering all values of δ_B .

5 Summary and outlook

The large $b\bar{b}$ production cross section at the LHC provides a unique opportunity for the precision study of very rare B decays. In particular the B_s system could play a crucial role to identify new CP violating effects originating from New Physics. Many of the observables constructed from rates, angular distributions, and CP asymmetries for the loop suppressed B decays show large sensitivities to New Physics contributions.

Already with a data-set of 0.5 fb^{-1} LHCb expects to perform sensitive tests of the Standard Model and New Physics scenarios beyond the current experiments: 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 $B_s \rightarrow \mu^+ \mu^-$ branching fraction of 5×10^{-9} can be observed. These measurements, complemented by ATLAS and CMS, will either limit New Physics contributions to B decays or, more optimistically, uncover them.

References

- [1] Slides: <http://indico.cern.ch/contributionDisplay.py?contribId=81&sessionId=2&confId=53294>
- [2] The CDF collaboration, *Phys. Rev. Lett.* **100**, 16802 (2008),
The D0 collaboration, *hep-ex*, arXiv:0802.2255v1, (2008).
- [3] Heavy Flavor Averaging Group, <http://www.slac.stanford.edu/xorg/hfag/>
- [4] The CDF collaboration, CDF/ANAL/BOTTOM/PUBLIC/9458 (2008).
- [5] M. Calvi *et al.*, *CERN-LHCb-2009-025* (2009)
- [6] M. Blanke, A.J. Buras, D. Guadagnoli and C. Tarantino *JHEP***0610**, 003 (2006).
- [7] The D0 Collaboration, <http://wwwd0.fnal.gov/Run2Physics/WWW/results/bhtm> (2006),
The CDF Collaboration, CDF/ANAL/BOTTOM/PUBLIC/8176 (2006).
- [8] G. Buchalla *et al.* *B, D and K decays*, arXiv:0801.1833v1 [hep-ph] (2008)
- [9] J. Dickens *et al.*, *CERN-LHCb-2007-038* (2007).
- [10] U. Egede, *CERN-LHCb-2007-057* (2007).
- [11] CKM fitter: <http://ckmfitter.in2p3.fr>
- [12] ADS: D. Atwood, I. Dunietz and A. Soni, *Phys. Rev. Lett.* **78**, 3257 (1997),
GLW: M. Gronau and D. London, *Phys. Lett. B* **253**, 483 (1991),
GGSZ: A. Giri, Yu. Grossman, A. Soffer and J. Zupan, *Phys. Rev. D* **68**, 054018 (2003).
- [13] K. Akiba *et al.*, *CERN-LHCb-2008-038* (2008).