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Search for New Physics with Rare Heavy Flavour Decays at LHCb

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The LHCb experiment has the potential to observe, or improve significantly the exclusion bounds on New Physics, during the 2010-2011 data-taking period at the LHC. High sensitivity to New Physics contributions is achieved by searching for the rare decay $B_s^0 \to \mu^+\mu^-$, measuring direct CP violation in $B^0 \to K^*\gamma$, performing a time dependent analysis of $B_s^0 \to \phi\gamma$, and making an angular study of the decay $B^0 \to K^*\mu^+\mu^-$. Preparations for these analyses are presented, and studies are shown of how existing data, for example prompt $J\psi$ events, can be used to validate the analysis strategy.

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1. Introduction

The LHCb experiment aims at measuring CP violation and rare B-decays [1]. In the first data-taking period of the LHC in 2010 the LHCb experiment accumulated a data set that corresponds to a luminosity of about 38 pb^{-1}. Thanks to the large b production cross section at the LHC of about 300 μb [2], approximately 10^{10} B-mesons have been produced in 2010 at LHCb.

The study of Flavour Changing Neutral Currents (FCNC) is particularly powerful to scrutinize the Standard Model (SM). B-decays that only occur through FCNC are suppressed in the SM, since they are forbidden at tree level. New Physics (NP) can potentially affect these so-called rare decays at the same level as the SM. Prime examples of rare decays at LHCb are the radiative decays $B^0 \to K^*\gamma$ and $B_s^0 \to \phi\gamma$ and the muonic decays $B^0 \to K^*\mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$.

Usually an effective theory is constructed to describe these B-decays at low energy scales [3, 4]. The Operator Product Expansion (OPE) allows to separate the perturbative short distance effects from the non-perturbative long distance effects and the effective Hamiltonian can be expressed as

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^i C_i(\mu) \mathscr{O}_i. \tag{1.1}$$

The Wilson coefficients $C_i(\mu)$ can be calculated perturbatively, whereas the long distance effects are contained in $\mathscr{O}_i$. A classification of these operators can be found in Ref. [5].

The important operator for the radiative decays is the magnetic penguin operator $\mathscr{O}_{7\gamma}$. The decay $B^0 \to K^*\mu^+\mu^-$ is mainly affected by $\mathscr{O}_{7\gamma}$ and the semi-leptonic operator $\mathscr{O}_{9V}$, whereas the decay $B_s^0 \to \mu^+\mu^-$ is particularly sensitive to NP contributions from potential scalar or pseudo-scalar currents, $\mathscr{O}_S$ and $\mathscr{O}_P$ originating from Higgs couplings.

In Section 2 the LHCb detector and its performance is described. In Section 3 the prospects for the measurements of radiative decays is discussed together with signals from early data that are important to understand the LHCb detector towards the final analysis. Similarly, the status and prospects of the $B^0 \to K^*\mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ decays are discussed in Section 4 and 5, respectively.

2. The LHCb Detector

The LHCb experiment is a single arm spectrometer, designed to study B-decays at the LHC, covering the range $1.8 < \eta < 4.9$ in rapidity, corresponding to an acceptance in the polar angle of 10 mrad < θ < 250 mrad. This covers a large fraction of the range where B-mesons are produced. The LHCb detector is optimized to select and accurately measure b-hadrons that fly on average 7 mm with a (transverse) momentum of about (5) 100 GeV.

The trigger system allows to select events with B-decay products at the lowest trigger level (L0) with low transverse momentum, $p_T > 1.2(3.6)$ GeV for muons (hadrons). This reduces the LHC bunch crossing rate of 40 MHz down to 1 MHz. Subsequently, the full event information is shipped to a dedicated CPU farm, where the high level trigger reduces the rate to 2 kHz.

A good tracking system is essential to determine the proper lifetime of the B-mesons and to accurately determine the momentum of its decay products. The tracking system is divided in a silicon detector close to the interaction region (the vertex locator, VELO), a dipole magnet, and a tracking system behind the magnet. The tracking system behind the magnet is divided in two parts: a silicon detector at high rapidity in the highest particle flux region, the Inner Tracker (IT), and a gaseous straw tube detector, the Outer Tracker (OT). In addition a silicon detector, the Trigger Tracker (TT), is placed in the fringe field before the dipole magnet.

In order to take advantage of the large number of B-decay modes and to distinguish its final states (such as $D_s^+\pi^-$ and $D_s^+K^-$) accurately, LHCb is equipped with two Ring Imaging Cherenkov (RICH) detectors, before and after the dipole magnet. The calorimeter system enables the selection of hadronic B-decays at the lowest trigger level, and in addition provides particle identification for γ's, electrons and π^0's. Finally, the muon spectrometer identifies and selects muons both in the trigger and offline.

3. Radiative Decays

The first measurement of the decay $B^0 \to K^*\gamma$ showed that the SM model is the dominant contribution to the decay amplitude. Theoretically, the prediction of the inclusive decay $b \to s\gamma$ is more accurate, because in the inclusive amplitude the hadronic ingredients for the $B \to K^*$ transition can be omitted.

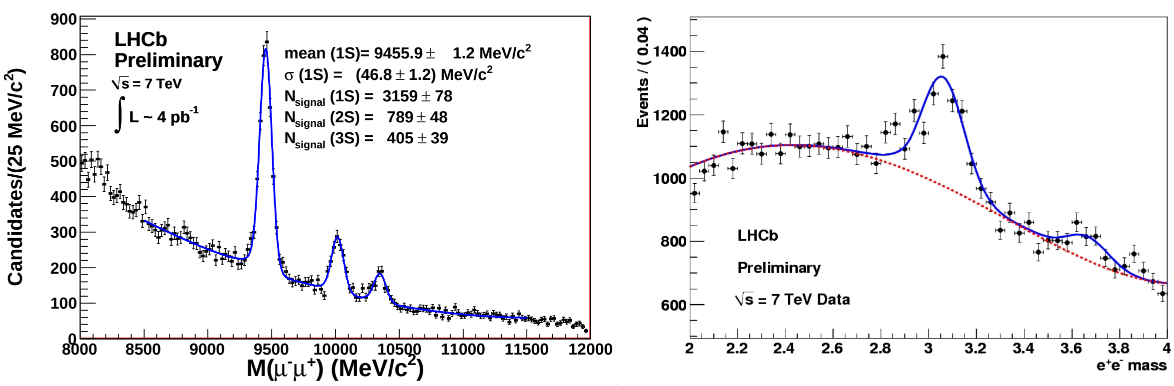
The comparison between the measured and predicted inclusive branching ratio is impressive:

$$\mathrm{BR}(B^0 \to X_s\gamma)_{\mathrm{exp}} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}, \quad [6] \tag{3.1}$$

$$\mathrm{BR}(B^0 \to X_s\gamma)_{\mathrm{th}} = (3.15 \pm 0.23) \times 10^{-4}. \quad [7] \tag{3.2}$$

Nevertheless, measurements on the polarization of the photon can still reveal NP effects. Contributions from right-handed couplings are quantified by the right-handed operator $C'_{7\gamma}$ and is at present still poorly constrained.

The polarization of the photon is experimentally accessible in LHCb through the decay $B_s^0 \to \phi\gamma$, taking advantage of the lifetime difference in the B_s^0 system. At closer inspection the decay $B_s^0 \to \phi\gamma$ is not a CP eigenstate, because $\bar{B}_s^0 \to \phi\gamma_L$ and $B_s^0 \to \phi\gamma_R$. A deviation from the SM of the admixture left-handed and right-handed photons will result in a modified time-dependence of



(a) (b)

Figure 1: *The di-lepton invariant mass distributions for (a) $\mu^+\mu^-$ and (b) e^+e^- showing the $\Upsilon, \Upsilon(2S), \Upsilon(3S)$ and J/ψ, $\psi(2S)$ resonances, respectively.*

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the decay $B_s^0 \to \phi\gamma$ [8]. A possibility to assess the photon polarization in the decay $B^0 \to K^*\gamma$ is by inspecting the angular distribution of the e^+e^- pair in $B^0 \to K^*e^+e^-$ in decays at low invariant mass of the di-lepton pair.

LHCb is well underway to understand the calorimeter performance, which is crucial for the radiative decays. The calorimeter calibration and the calorimeter performance in terms of photon/electron separation is illustrated by the clear signals from $J/\psi \to e^+e^-$ and $\psi(2S) \to e^+e^-$ in Fig. 1(b). Both the central values and the widths are close to the expectation from simulation.

A first signal of 49 ± 17(stat) $B^0 \to K^*\gamma$ events have been observed with a data set corresponding to 26 pb^{-1} (Fig. 2(a)). A competitive measurement of direct CP violation in $B^0 \to K^*\gamma$ is expected with a subset of the upcoming data set in 2011.

4. $B^0 \to K^*\mu^+\mu^-$

The decay $B^0 \to K^*\mu^+\mu^-$ is a particularly interesting decay to distinguish the large variety of NP models and parameters, as presented for example in Refs [9, 10]. Even models that involve extra dimensions can affect decay distributions of the $B^0 \to K^*\mu^+\mu^-$ decay [11].

The SM predicts a clear asymmetry between the number of forward and backward going muons with respect to the K^* flight direction in the di-muon rest frame. The size of this forward-backward asymmetry A_{FB} depends on the di-muon centre-of-mass, and in fact vanishes at a well defined value, s_0, of the di-muon invariant mass. The hadronic uncertainties cancel at this zero-crossing point s_0 , and the value of s_0 is predicted in the SM at [10]:

$$s_0 = (3.90 \pm 0.12)\ \mathrm{GeV}^2. \tag{4.1}$$

Interestingly, all three presently available measurements of A_{FB}, (from Belle [12], Babar [13] and CDF [14, 15]) show an opposite sign of the asymmetry at values of the di-muon invariant mass below the J/ψ resonance. The LHCb experiment is well suited to study the angular asymmetries in $B^0 \to K^*\mu^+\mu^-$ [16, 17].

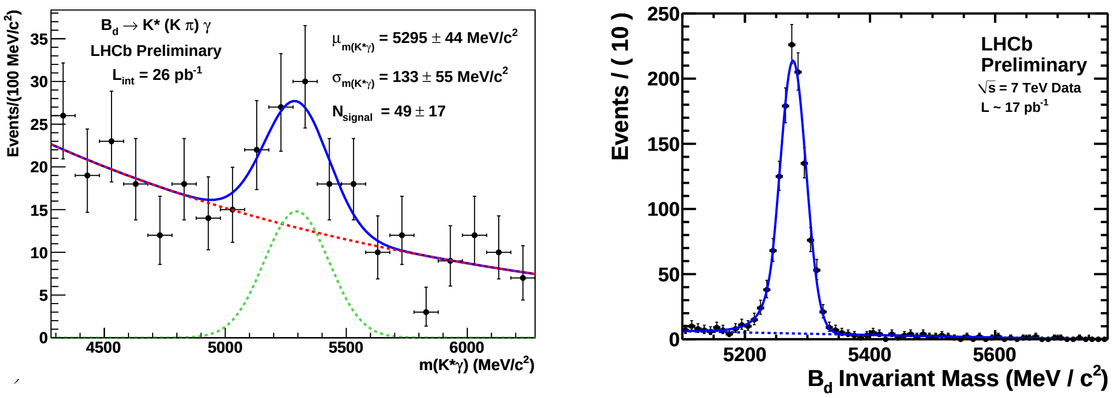


Figure 2: *Invariant mass distributions for (a) $B^0 \to K^*\gamma$ and (b) $B^0 \to K^*J/\psi(\mu^+\mu^-)$. The $B^0 \to K^*J/\psi(\mu^+\mu^-)$ decays have been selected with the event selection algorithm designed for the $B^0 \to K^*\mu^+\mu^-$ decays*

By using the resonances $\phi \to K^+K^-$ and $J/\psi \to \mu^+\mu^-$ from early data, the particle identification efficiency for kaons and muons could be accurately measured using the tag-and-probe method. Both the RICH and muon detectors perform as expected from simulation. The effect of trigger and event selection on the angular distributions has been checked both on simulation, and on data using a large $D^0 \to K^+\pi^-\pi^+\pi^-$ sample. This has been found to be negligible with respect to the statistical uncertainty.

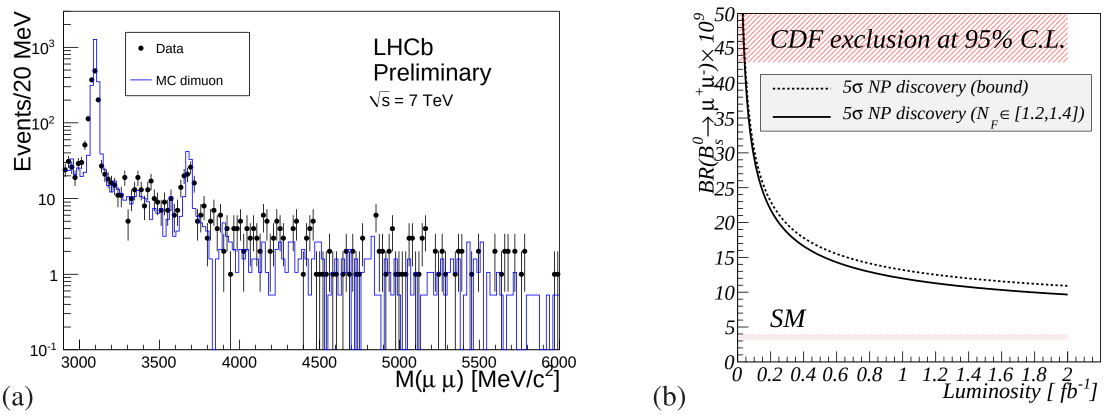
The LHCb analysis of the decay $B^0 \to K^*\mu^+\mu^-$ has not yet been fully unblinded, but based on simulation about 50 events are expected to be finally selected from the 2010 data sample. Based on a data set corresponding to 17 pb^{-1} a clear $B^0 \to K^*J/\psi(\mu^+\mu^-)$ sample has been selected (Fig. 2(b)), showing that the event selection rejects background, and potentially selects the $B^0 \to K^*\mu^+\mu^-$ events efficiently. With a data set corresponding to a luminosity of 200 pb^{-1}, we expect a similar sample of $B^0 \to K^*\mu^+\mu^-$ events compared to the published Belle result, which will allow LHCb to measure A_{FB} in the range $1 < q^2 < 6$ GeV^2.

5. $B_s^0 \to \mu^+\mu^-$

One of the most promising channels for detecting signals of NP is the rare decay $B_s^0 \to \mu^+\mu^-$, which as for the decay $B^0 \to K^*\mu^+\mu^-$ originates in the SM from "penguin" and box topologies, i.e. quantum loop processes. The corresponding branching ratio is predicted as follows [3]:

$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-)|_{\mathrm{SM}} = (3.6 \pm 0.4) \times 10^{-9}, \qquad [10] \qquad (5.1)$$

where the error is fully dominated by a non-perturbative "bag parameter" coming from lattice QCD. As is well known, this observable may be significantly enhanced through NP [18]. The present upper bounds from the CDF and DØ collaborations are still about 1 order of magnitude away from (5.1) and read as 4.3×10^{-8} [19] and 5.3×10^{-8} (95% C.L.) [20], respectively.



(a) (b)

Figure 3: *(a) The di-muon invariant mass distribution as measured with the early data set of 0.2 pb^{-1}. The Monte Carlo describes the background in reasonably well. (b) The smallest value of BR($B_s^0 \to \mu^+\mu^-$) that allows the detection of a 5σ deviation from the SM as a function of the luminosity at LHCb at the nominal beam energy of 14 TeV [24]. The corresponding curve for the 2011 running with twice lower $b\bar{b}$-cross section can be obtained by scaling the luminosity with a factor 2.*

Interestingly, a large part of the m_A-$\tan\beta$ parameter space allowed by experiment (in supersymmetric models with non-universal Higgs masses (NUHM) or in the constrained MSSM), is accessible through the measurement of the $B_s^0 \to \mu^+\mu^-$ branching ratio [21]. Also, the limits on m_A-$\tan\beta$ from limits on the $B_s^0 \to \mu^+\mu^-$ branching ratio will be very competitive with respect to the direct searches by the general purpose experiments at the LHC [22].

At LHCb, the search for $B_s^0 \to \mu^+\mu^-$ will be done using three main variables, that are largely independent, namely the invariant mass, the muon identification likelihood and the geometrical likelihood. The last variable includes information on the B-lifetime, impact parameters, vertexing and isolation. Information on the shape of the invariant mass and and on the distribution of the geometrical likelihood will be obtained from the data using $B^0 \to h^+h^-$ decays, where $h = \pi^{\pm}, K^{\pm}$. Using simulation, the geometrical likelihood of $B^0 \to \pi^+\pi^-$ decays is shown to behave the same as $B_s^0 \to \mu^+\mu^-$ decays. The resolution of the invariant mass for a two-prong B-decay is measured with $B^0 \to K^{\pm}\pi^{\mp}$ decays to be approximately 23 MeV, close to the 22 MeV as expected from simulation. This superb mass resolution (see also Fig. 1(a)) will allow to significantly reduce the background in the search for $B_s^0 \to \mu^+\mu^-$. The background is well simulated as is indicated in Fig. 3(a). Subsequently, the extraction of $\mathrm{BR}(B_s^0 \to \mu^+\mu^-)$ will rely on normalization channels such as $B_u^+ \to J/\psi K^+$, $B_d^0 \to K^+\pi^-$ and/or $B_d^0 \to J/\psi K^{*0}$ in the following way:

$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathrm{BR}(B_q \to X)\frac{f_q}{f_s}\frac{\varepsilon_X}{\varepsilon_{\mu\mu}}\frac{N_{\mu\mu}}{N_X}, \tag{5.2}$$

where the ε factors are total detector efficiencies and the N factors denote the observed numbers of events. The f_q are fragmentation functions, which describe the probability that a b quark will fragment in a $\bar{B}_q$ meson ($q \in \{u,d,s\}$). At present, f_q/f_s is actually the major source of the systematic uncertainty. Two ways are at present being pursuit to determine the B fragmentation fractions at LHCb, using semi-leptonic decays and using the hadronic decays $B^0 \to D^-K^+$, $B^0 \to D^-\pi^+$ and $B_s^0 \to D_s^-\pi^+$ [24, 25]. A first sample of $65 \pm 11(\mathrm{stat})$ $B_s^0 \to D_s^-\pi^+$ decays has been selected in the first data set corresponding to 0.75 pb^{-1}.

With the data set collected in 2010 LHCb expects to exclude a value for $\mathrm{BR}(B_s^0 \to \mu^+\mu^-)$ larger than approximately 5×10^{-8} at 90% CL, close to the present bounds from the Tevatron. With the 2011 data set corresponding to 1 fb^{-1} LHCb can discover a 5σ deviation from the SM if $\mathrm{BR}(B_s^0 \to \mu^+\mu^-)$ is larger than approximately 1.7×10^{-8}, see Fig. 3.

6. Conclusions

The LHCb experiment has the potential to observe, or improve significantly the exclusion bounds on New Physics, during the 2010-2011 data-taking period at the LHC.

High sensitivity to New Physics contributions is achieved by searching for the rare decay $B_s^0 \to \mu^+\mu^-$, measuring direct CP violation in $B^0 \to K^*\gamma$, performing a time dependent analysis of $B_s^0 \to \phi\gamma$, and making an angular study of the decay $B^0 \to K^*\mu^+\mu^-$.

With the 2010 data set a clear $B^0 \to K^*\gamma$ signal has been observed, and 60 events are expected to be selected for the $B^0 \to K^*\mu^+\mu^-$ decay, allowing for an interesting measurement of the forward-backward asymmetry with a precision that corresponds to a 1.5σ deviation from the Standard Model if the Belle central value is assumed. In addition, a value for $\mathrm{BR}(B_s^0 \to \mu^+\mu^-)$ larger approximately 5×10^{-8} at 90% CL could be excluded with the 2010 data set, whereas with the 2011 data set a branching fraction as low as 1.7×10^{-8} would be detected with a 5σ deviation from the Standard Model.

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