Search for New Physics in Heavy Quark Decays at LHCb

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LHCb is an experiment designed to search for evidence of new physics effects through precise measurements of decays of B and D mesons. Already with the early data from the first LHC running it is possible to assess the performance of the detector and to understand better the potential of the LHCb flavour programme. Highlights of these early data are presented and the physics reach of LHCb in certain key CP-violation and rare decay measurements is discussed. Emphasis is given to those topics where results with particular sensitivity to new physics are expected during the present 2010–11 run.

1. INTRODUCTION

Both indirect and direct searches for new physics are pursued at the LHC. New physics predicts the existence of new particles, which are likely to appear at the TeV scale [1]. In the case of indirect measurements, these new particles appear as virtual particles in loop and penguin diagrams. An advantage of indirect searches is that they can have a higher sensitivity to effects from new particles. This means in practice that it is possible that we would observe new particles in loop and penguin diagrams before we would find them in direct searches. It also means that indirect measurements can access higher scales, beyond the reach of direct searches. Another advantage of indirect measurements is that it is possible to measure the phases of the new couplings, thereby giving access to the flavour structure of physics beyond the Standard Model (SM).

Roughly two approaches for new physics searches in heavy flavour physics can be distinguished. In the first approach we are looking in transitions involving flavour-changing, neutral currents (FCNC). These transitions are forbidden at tree level in the SM. Some models beyond the SM predict large deviations in these FCNC transitions. In heavy flavour decays the SM prediction can often be calculated with high precision. That is why it is interesting to explore rare B and D decays which are suppressed in the SM, but can be significantly enhanced in models beyond the SM. Especially in $b \to s$ transitions, which are not so much constrained by current data, large effects might be observed.

In contrast to the large possible effects in rare decays, it is equally important to continue to improve the precision of the currents constraints of the CKM matrix. Although the current data are consistent with the SM, it is still open to corrections of the order 10%–20% [2]. Hence, a measurement with an uncertainty below this level is required. New physics can emerge by looking for inconsistencies when comparing many different measurements, which may or may not have contributions from unknown virtual particles. In this light it is worthwhile to point out that the unitarity triangle is currently not so much constrained from tree decays (see e.g. Ref. [3]). These decays are insensitive to new physics. For instance, a precise measurement of the CKM angle γ could establish a reference point against which other measurements sensitive to new physics can be compared.

The LHCb detector [4] provides an ideal place for these indirect searches. The key features of this detector are the excellent vertex resolution, particle identification and momentum resolution. All of these features are especially important for heavy flavour physics in the harsh hadronic environment of the LHC. With only $0.014\,\mathrm{pb}^{-1}$ of data LHCb has recorded clear signs of B decays, including some exclusive candidate decay modes. Towards the end of the 2010-2011 run it is expected to record $1000\,\mathrm{pb}^{-1}$ ($1\,\mathrm{fb}^{-1}$) of data. Note that this is close to the nominal design luminosity of $2\,\mathrm{fb}^{-1}$ per year. The status of the detector and performance on the early data is presented in more detail in Ref. [5] and [6].

2. KEY MEASUREMENTS

In the following we present some of the key measurements that are planned for this run. More detailed information about the analysis in LHCb of these decays is given in the road map document [7].

2.1. B_s mixing phase with $B_s^0 \to J/\psi\,\phi$

The decay $B_s^0 \to J/\psi\,\phi$ is a $b \to c\bar{c}s$ decay which is sensitive to the B_s mixing phase ϕ_s through the interference between the mixing amplitudes and decay amplitudes. This decay is the B_s counterpart of the decay $B_d^0 \to J/\psi\,K^0$ which measures the B_d mixing phase. The contribution from penguin diagrams is small and, unlike the B_d counterpart, the mixing phase is estimated to be small, with a precisely predicted SM value of $\phi_s = (-36.0^{+1.6}_{-2.0})$mrad [3]. New particles in box diagrams can easily modify the measured phase making it a promising measurement to search for new physics. The current CDF sensitivity is $\sigma(\phi_s) = 0.5$ for $5.2\,\mathrm{fb}^{-1}$ [8].

Experimentally, this decay requires measuring the time-dependent decay rates of the B_s^0 and $\overline{B}{}_s^0$. Hence, the initial flavour of the B_s needs to be tagged. From Monte Carlo simulations a mistag rate of 33% is obtained and a total effective tagging efficiency of about 6%. In addition, an accurate measurement of the decay time is required to resolve the fast B_s oscillations. From the simulations a proper time resolution for the $B_s^0 \to J/\psi\,\phi$ decay of about 40 fs is expected. Finally, since the B_s decays into two vector mesons, an angular analysis needs to be carried out (statistically) to disentangle contributions from the CP-even and CP-odd final states. In order to check the angular acceptance it is foreseen to use control channels as $B^+ \to J/\psi\,K^+$ and $B_d^0 \to J/\psi\,K^*$. On top of that similar decays to pure CP eigenmodes (e.g. $B_s^0 \to J/\psi\,f_0$ and $B_s^0 \to J/\psi\,\eta^{(\prime)}$) will be studied as well. Although the rate for these decays is expected to be lower, they do not require an angular analysis. About 58,500 untagged decays are expected to be triggered and offline-selected for $1.0\,\mathrm{fb}^{-1}$. The corresponding error on ϕ_s is $\sigma(\phi_s) = 0.07$.

2.2. Search for $B_s^0 \to \mu^+\mu^-$

The decay $B_s^0 \to \mu^+\mu^-$ is a very rare decay. The SM prediction of the branching fraction is very low at $\mathcal{B} = (3.35 \pm 0.32) \times 10^{-9}$ [9]. In many models beyond the SM the branching fraction is affected. In the Minimal Supersymmetric Standard Model (MSSM) the branching fraction is enhanced by the sixth power of $\tan\beta$. This makes this decay channel a very sensitive probe for new physics. The present limit from CDF (using a data sample of $3.7\,\mathrm{fb}^{-1}$) is $\mathcal{B} < 3.6 \times 10^{-8}$ (90% CL) [10].

The selection of events is designed such that the branching ratio is obtained from data using control channels, without relying on the simulation. The selection parameters are divided into three uncorrelated groups, which are invariant mass, muon likelihood and geometrical likelihood. This procedure allows the calibration of the selection parameters with different control samples.

Two-body invariant mass spectra have been studied already in data using decays of $K_S^0 \to \pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$. The obtained mass resolutions are given in Table 1. The data agrees well with the simulations for K_S^0's and to a lesser extent for J/ψ's. This is because the K_S^0 mass resolution is dominated by the error on the opening angle, while the J/ψ mass resolution is, just as for the $B_s^0 \to \mu^+\mu^-$ decays, dominated by the

Table 1
Invariant mass resolution in data (preliminary) and Monte Carlo simulation (MC).

	$K_S^0 \to \pi^+\pi^-$	$J/\psi \to \mu^+\mu^-$
Data	$3.47 \pm 0.13\,\mathrm{MeV}$	$15.4 \pm 0.4\,\mathrm{MeV}$
MC	$3.31 \pm 0.12\,\mathrm{MeV}$	$13.12 \pm 0.05\,\mathrm{MeV}$

momentum of the muons. Although the effect is small, one can conclude that the momentum resolution is not yet optimal, possibly due to unresolved misalignments in the tracking stations. Ultimately, it is planned to use the kinematically similar decays $B_s^0 \to K^+K^-$ to extract the mass resolution from data. The simulation indicates a B_s mass resolution of about 20 MeV.

Normalisation channels, such as $B_d^0 \to K\pi$ and $B^+ \to J/\psi K^+$, will be used to determine the branching ratio. The main contribution to the systematic uncertainty comes from the production ratio of B_s over $B_{u,d}$, which is only known to $\sim$ 13% [7]. It is planned to measure this ratio from data using $B_s^0 \to D_s^-\pi^+$ and $B_d^0 \to D^-K^+$ [11]. With 0.2 fb^{-1} the 90% CL upper limit for branching ratio is expected to be 16×10^{-9}, which is slightly better than the expected Tevatron limit for 8 fb^{-1} (see Fig. 1). Furthermore, with 1.0 fb^{-1} we could exclude branching ratios down to 7×10^{-9}, or observe a signal in case the branching ratio is 3.5 times the one in the SM.

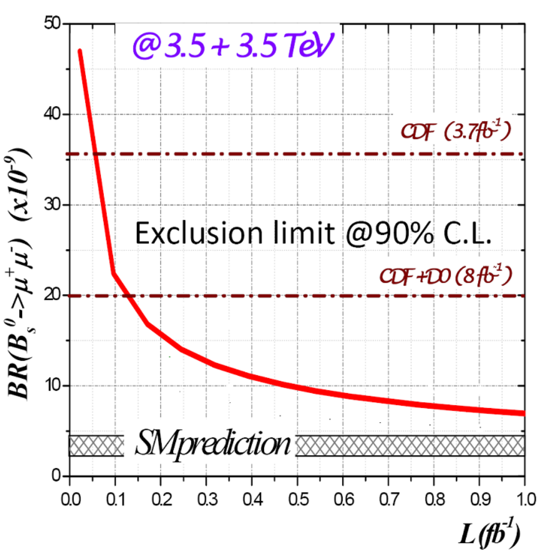

Figure 1. Exclusion limits at 90% CL for the $B_s^0 \to \mu^+\mu^-$ branching fraction versus integrated luminosity at LHCb. The current limit from CDF [10] and the expected Tevatron limit for 8 fb^{-1} are indicated as well.

2.3. Asymmetries in $B_d^0 \to \mu^+\mu^-K^*$ decays

Another interesting decay is $B_d^0 \to \mu^+\mu^-K^*$. It has a branching ratio of $\mathcal{B} \sim 1.0 \times 10^{-6}$ in the SM. In this decay the angular distributions contain a lot of information about the underlying physics, giving many observables that are sensitive to new physics. For the first data, LHCb will focus on measuring the the forward-backward asymmetry as a function of the q^2 of the two muons, $A_{FB}(q^2)$. The zero-crossing point of A_{FB} is well predicted in SM, since the hadronic uncertainties are minimized here. LHCb expects to have about 1400 events selected after 1.0 fb^{-1}. In the most sensitive bin (1–6 GeV^2) this gives an estimated error on A_{FB} of $\sigma(A_{FB}) = 0.07$.

2.4. CKM angle γ from tree-level B decays

Tree decays with $b \to c$ and $b \to u$ transitions allow for a clean extraction of γ. Currently, γ is the least well-known CKM angle. The present experimental knowledge on γ from indirect measurements shows that $\gamma = (67.7^{+4.5}_{-3.7})^\circ$ [3]. On the other hand from direct measurements with $B \to DK$ tree decays it is found that $\gamma = (73^{+22}_{-25})^\circ$ [3]. Clearly, γ is not so much constrained from direct measurements and the sensitivity to new physics can be greatly improved with a clean and direct measurement of γ.

There are two strategies that are experimentally well-suited for a measurement of γ at LHCb. The first strategy uses the charged $B^+ \to D^0K^+$ and neutral $B_d^0 \to D^0K^*$ decays. These modes measure γ directly through the interference between the B and the subsequent D^0 decay. Two methods of extracting γ can be highlighted: the ADS+GLW method which requires a measurement of the relative decay rates for two-body D^0 decays into $K\pi$, KK, $\pi\pi$, and the GGSZ method which requires a measurement of the differences in the Dalitz distributions for three- or more body D^0 decays as for instance $D^0 \to K_S^0\pi\pi$. The second strategy involves the $B_s^0 \to D_s^\mp K^\pm$ decay which measures the weak phase $\gamma + \phi_s$ through the interference between the B_s mixing and the decay. Note that the mixing phase ϕ_s is also measured directly in the $B_s^0 \to J/\psi\,\phi$ decay. This approach is probably unique to LHCb and therefore of special interest. However, the analysis requires flavour tagging and a time-dependent analysis. The combined sensitivity on γ for these decays is $\sigma_\gamma \sim 7^\circ$ for $1.0\,\mathrm{fb}^{-1}$.

2.5. Charm Physics

Not only is the LHC is copious source of B hadrons, there are many more charm hadrons produced. As discussed in Ref. [6], LHCb has an excellent potential for charm physics. There is a dedicated HLT trigger line for $D^{*+} \to D^0(\to hh')\pi^+$, which has the advantage that the flavour of the initial D^0 is tagged by the charge of the slow pion. A total yield of the order of 10^8 events is expected in $1.0\,\mathrm{fb}^{-1}$. Some of the most promising charm measurements are detailed below.

CP violation in the D system is very small in the SM. This means effectively that any significant measurement of CP violation would indicate new physics. Several measurements are foreseen to probe the amount of CP violation in the D system. With only $0.1\,\mathrm{fb}^{-1}$ a very large sample of 17 million tagged $D^0 \to K\pi$ decays and 1.3 million tagged $D^0 \to KK$ decays is expected. Such two-body decays can be used to probe for CP violation in the mixing. In addition, direct CP violation can be measured with a Dalitz analysis of single-Cabibbo suppressed decays $D^+ \to K^+K^-\pi^+$. Several million events are expected in $0.1\,\mathrm{fb}^{-1}$.

The decay $D^0 \to \mu^+\mu^-$ is highly suppressed in the SM with a branching fraction of $\mathcal{B} \sim 3 \times 10^{-13}$, which can be significantly enhanced by new physics. The Belle collaboration has measured an upper limit of $\mathcal{B} < 1.4 \times 10^{-7}$ at 90% CL [12]. The analysis of this decay is very similar to the one of $B_s^0 \to \mu^+\mu^-$. With $0.1\,\mathrm{fb}^{-1}$ LHCb expects to set an upper limit of $\mathcal{B} < 4 \times 10^{-8}$ at 90% CL.

3. CONCLUSIONS

We have demonstrated that the LHCb experiment is well on track for its heavy flavour programme. As the first B decays have already been recorded, the performance parameters for the key measurements are being verified and the results agree well with Monte Carlo expectations. Already with $0.2\,\mathrm{fb}^{-1}$ we expect to improve on the current constraints on new physics and with $1.0\,\mathrm{fb}^{-1}$ it is possible to find physics beyond the SM or at least to narrow down the allowed parameter space dramatically. The data are now starting to accumulate, and there are exciting times ahead.

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