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Rare leptonic and semileptonic b-hadron decays and tests of lepton flavour universality at LHCb

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Rare decays of heavy-flavoured particles provide an ideal laboratory to look for deviations from the Standard Model, and explore energy regimes beyond the LHC reach. Decays proceeding via electroweak penguin diagrams are excellent probes to search for New Physics, and $b \to s\ell^+\ell^-$ processes are particularly interesting since they give access to many observables such as branching fractions, asymmetries and angular observables. Recent results from the LHCb experiment are reviewed.

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1. Introduction

Flavour Changing Neutral Current (FCNC) processes, where a quark changes its flavour without altering its electric charge, are forbidden at tree level in the Standard Model (SM) and can only occur via loop diagrams. This makes such transitions rare and, due to the lack of a dominant tree-level SM contribution, sensitive to new unobserved particles that can show up either as a sizeable increase or decrease in the rate of particular decays, or as a change in the angular distribution of the particles in the detector. A good laboratory to study FCNC are decays of a b quark into an s quark and two leptons, $b \to s\ell^+\ell^-$, which are described by the electroweak penguin diagram shown in Fig. 1 (left).

The LHCb detector [1, 2] is a single arm spectrometer fully instrumented in the forward region and designed to study heavy-flavoured hadrons. During Run-1, LHCb collected about 1 and 2 fb^{-1} of pp collisions at centre-of-mass energies of 7 and 8 TeV, respectively. Due to the large production cross-section in the forward direction these data provide unprecedentedly large numbers of B and Λ_b^0 hadron decays. A flexible trigger system, excellent momentum and impact parameter resolutions, and the most performant vertexing and particle identification capabilities at the LHC, make LHCb the ideal place to look for New Physics (NP) through precise studies of rare b-quark processes. Recent measurements of semileptonic b-hadron decays are discussed.

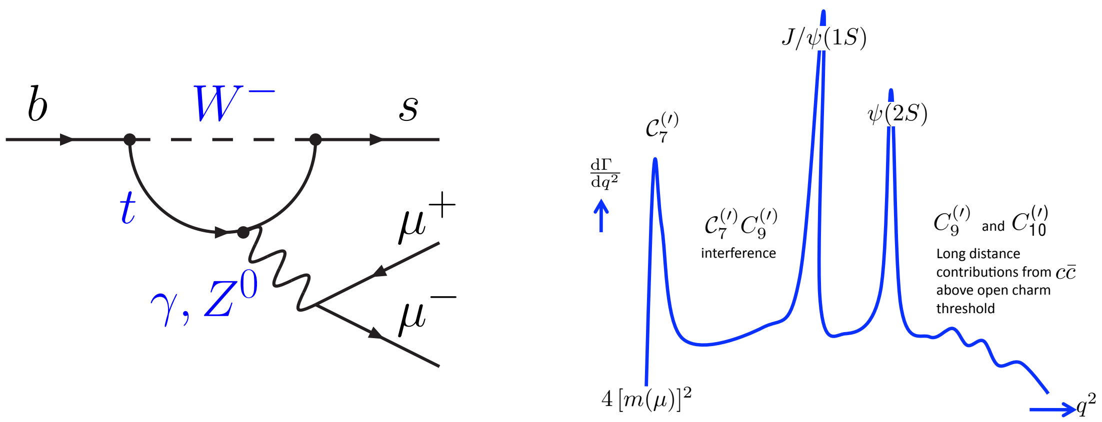

Figure 1: (left) Electroweak penguin diagram describing the transition of a b quark into an s quark and two leptons. (right) Sketch of the differential branching fraction as a function of the dilepton invariant mass squared, q^2, for $b \to s\ell^+\ell^-$ processes. Different Wilson coefficients can be probed in different q^2 regions.

2. Branching fractions

The most basic observable that physics beyond the SM can affect is the rate at which a particular decay occurs, which motivated the LHCb collaboration to perform the measurement of the branching fraction of a series of FCNC processes. All measurements are performed as a function of the dilepton invariant mass squared, q^2, and compared against the SM prediction. Final states with muons are considered as being experimentally easier to reconstruct. The dependence of the differential branching fraction as a function of q^2 is shown in Fig. 1 (right). Figure 2 shows the differential branching fraction of a collection of $b \to s\ell^+\ell^-$ decays of B and Λ_b^0 hadrons, as well as partner transitions such as $b \to d\ell^+\ell^-$. In all cases, the experimental uncertainty is dominated by the limited statistics of the samples available in the Run-1 data set.

In the region below $\sim 6\ \mathrm{GeV}^2/c^4$ in q^2, the SM predictions consistently overshoot the data, a common trend that is observed both in the mesonic and in the baryonic sectors. The largest deviation is found in the decay $B_s^0 \to \phi\mu^+\mu^-$ in the region $1 < q^2 < 6\ \mathrm{GeV}^2/c^4$, where the data are 3.3σ below the prediction [3]. Decays of Λ_b^0 hadrons are also overestimated in the SM, however predictions are currently much less precise than for B mesons [4]. Finally, although the $B^+ \to \pi^+\mu^+\mu^-$ branching fraction is generally compatible with the prediction, agreement in the lowest-q^2 bin is only achieved when contributions from ρ and ω resonances are taken into account [5].

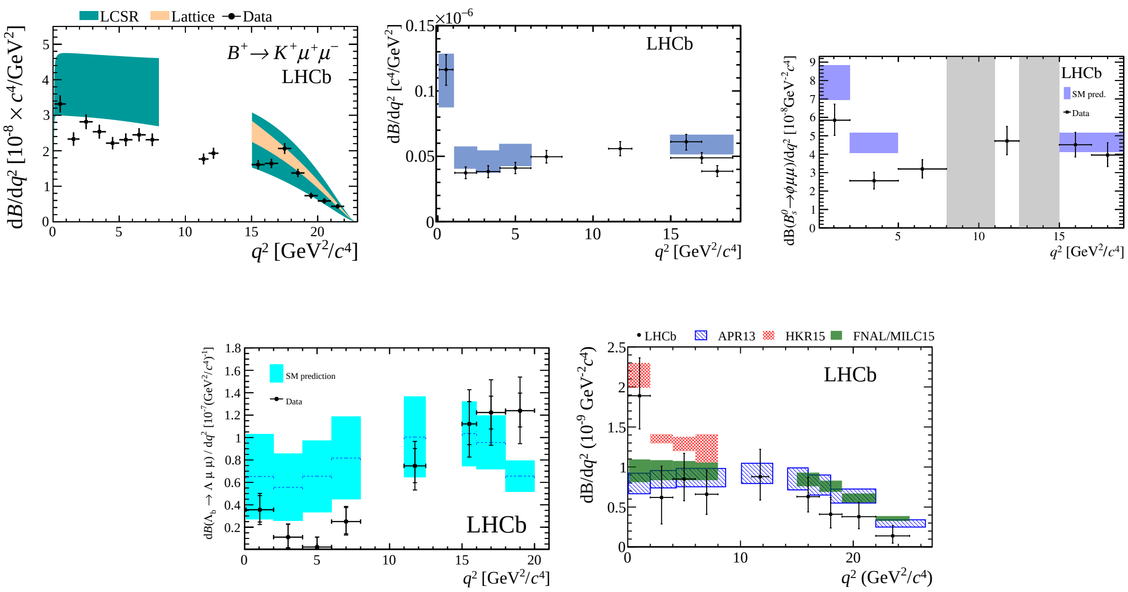

Figure 2: Differential branching fraction of the decay (top) $B^+ \to K^+\mu^+\mu^-$ [6], $B^0 \to K^{*0}\mu^+\mu^-$ [7], $B_s^0 \to \phi\mu^+\mu^-$ [3] and (bottom) $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [4], $B^+ \to \pi^+\mu^+\mu^-$ [5], compared to SM predictions.

3. Angular analyses

Besides using branching fractions, much stronger constraints to possible extensions of the SM can be set by studying the angular distribution of the final state particles of FCNC decays. Depending on the decay mode and on the size of the available data sample, full or simplified angular analyses have been performed.

The decay $B^0 \to K^{*0}\mu^+\mu^-$ has a complex angular structure that can be fully described by three angles and q^2, and that provides many observables sensitive to different types of NP. The LHCb collaboration has performed the first full angular analysis of this mode, and measured the full set of CP-averaged angular terms, their correlations, as well as the full set of CP-asymmetries [7]. The forward-backward asymmetry of the dimuon system, A_{FB}, and the longitudinal polarisation fraction of the K^{*0}, F_L, compared to the SM prediction are presented in Fig. 3 (top). There is general consistency, but similarly to the branching fraction large uncertainties due to the hadronic-matrix elements affect the predictions. However, it is possible to construct form-factor independent ratios of observables that can be theoretically better determined [8]. Figure 3 (top right) shows the observable P_5', defined as $P_5' = S_5/\sqrt{F_L(1-F_L)}$, which manifests a local deviation from the SM in the region between 4 and 8 GeV^2/c^4 in q^2 of about 3σ. An angular analysis of the decay $B^0 \to K^{*0}e^+e^-$ in the q^2 range between 0.002 and 1.120 GeV^2/c^4 has also been performed by LHCb [9], where all the measured observables are found to be consistent with the predictions.

Although the decay $B_s^0 \to \phi\mu^+\mu^-$ has a reduced number of angular observables that can be accessed compared to $B^0 \to K^{*0}\ell^+\ell^-$ modes, a full angular analysis has also been performed [3]. Figure 3 (bottom left) shows F_L, which is found to be in good agreement with the SM prediction. Finally, because baryonic transitions allow to extract complementary information to that available in decays of B mesons, LHCb has performed the first angular analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [4]. Two forward-backward asymmetries, one in the hadronic and one in the leptonic system, have been measured. While the former is in good agreement with the SM, the latter is consistently above the prediction, as reported in Fig. 3 (bottom left).

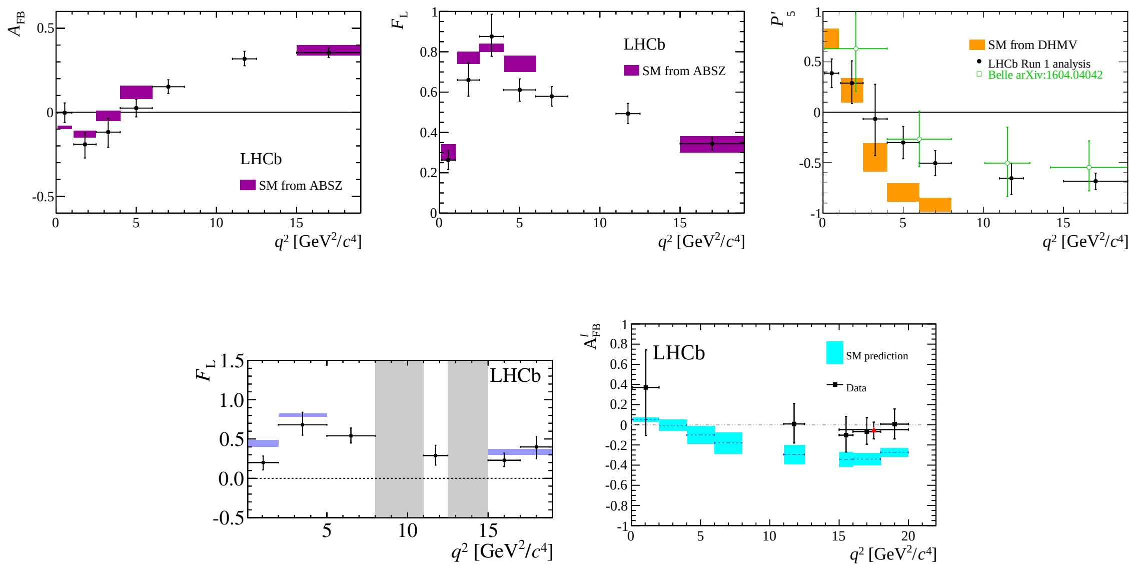

Figure 3: Angular observables of the decay (top) $B^0 \to K^{*0}\mu^+\mu^-$ [7] and (bottom) $B_s^0 \to \phi\mu^+\mu^-$ [3], $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [4], compared to SM predictions.

4. Tests of lepton universality

Due to the equality of the electroweak couplings of electrons and muons, the decay rate of processes whose final states only differ by the flavour of the participating leptons are expected to be the same in the SM, except from very small Higgs penguin contributions and difference in phase space due to the lepton mass. In particular, ratios of branching fractions represent a powerful null test of the SM as theoretical uncertainties largely cancel in the predictions, and experimental systematics are much reduced.

The LHCb collaboration has performed the most precise test of lepton universality using $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ decay modes to date [10]. In the SM the value of R_K, defined as $R_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)}$, in the range $1 < q^2 < 6$ GeV$^2/c^4$ is precisely predicted to be $1 \pm \mathcal{O}(10^{-3})$ [11]. The experimental result, displayed in Fig. 4, is $R_K = 0.745^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$, in tension with the SM prediction at 2.6σ.

Furthermore, a test involving semileptonic B decays with tau leptons in the final state has been carried out for the first time at a hadron collider [12]. The ratio of branching fractions $R_{D^*} = \frac{\mathcal{B}(\bar{B}^0\to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0\to D^{*+}\mu^-\bar{\nu}_\mu)}$ is measured to be $R_{D^*} = 0.336 \pm 0.027(stat) \pm 0.030(syst)$, which is 2.1σ larger than the value expected in the SM.

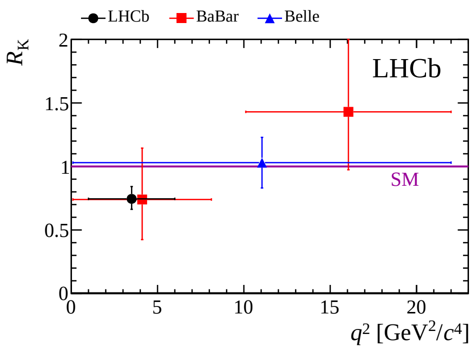

Figure 4: Measurement of $R_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)}$ [10], compared to previous experiments and to the SM prediction.

5. Summary and conclusions

Recent rare decays of B and Λ_b^0 hadrons performed by the LHCb collaboration have been presented. While most of the observables are in good agreement with the SM predictions, some intriguing tensions have been observed, most notably in branching fractions of $b \to s\ell^+\ell^-$ processes in the low region of q^2, in the P_5' angular observable in $B^0 \to K^{*0}\mu^+\mu^-$, and in R_K and R_{D^*}.

Several attempts to interpret these anomalies have been made by performing global fits to the $b \to s$ data from different experiments and including various observables [13, 14, 15]. All these fits point to a tension between the data and the SM with a significance of around 3–4σ. Various models have been proposed to account for such effects, for example as an indication of a new vector current that would couple more strongly to muons and interfere destructively with the SM vector current [16, 17], but a definitive explanation has yet to be found.

The current status strongly motivates further work both in the theory as well as in the experimental side to clarify the present observations. With the upcoming Run-2 data LHCb will continue to perform analyses of rare b-quark decays, including additional tests of lepton universality such as $R_{K^{*0}}$ and R_ϕ.

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