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Searching for new physics in rare B meson decays

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Summary. — The $b \to sl^+l^-$ transitions are flavour-changing neutral currents, where new physics can enter in competing loop diagrams with respect to the Standard Model contributions. In these decays several observables sensitive to new physics and where theoretical uncertainties are under control can be built. Particularly interesting are the angular asymmetries in the decay $B_d \to K^*\mu^+\mu^-$ and the measurement of the branching ratio of the decays $B_{s,d} \to \mu^+\mu^-$. Recent measurements of these observables and implications for the search of physics beyond the Standard Model will be discussed. Measurements of the isospin asymmetry in the decays $B \to K^{(*)}l^+l^-$ and the measurement of the branching ratio of the decay $B^+ \to \pi^+\mu^+\mu^-$ will also be discussed.

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1. – Introduction

Rare decays which proceed via Flavour-Changing Neutral Currents (FCNC) are induced by one-loop diagrams in the Standard Model (SM) and are excellent probes for New Physics (NP). New particles can enter in competing loop order diagrams, resulting in large deviations from SM predictions. In general, an effective Hamiltonian formalism is used to describe the amplitudes of FCNC processes, according to the formula

$$H_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) Q_i, \tag{1}$$

where V^i_{CKM} are the relevant factors of the CKM matrix; Q_i are local operators; C_i are the corresponding couplings (Wilson coefficients); and μ is the QCD renormalization scale. The correlation of different channels, where different combinations of Wilson coefficients contribute, is a powerful tool for searching and understanding the structure of NP. This approach is complementary to the direct search for NP. At current experiments, precision measurements of flavour physics are sensitive to new particles contributing to quantum loops up to a scale of 200 TeV [1], which exceed the reach for direct production

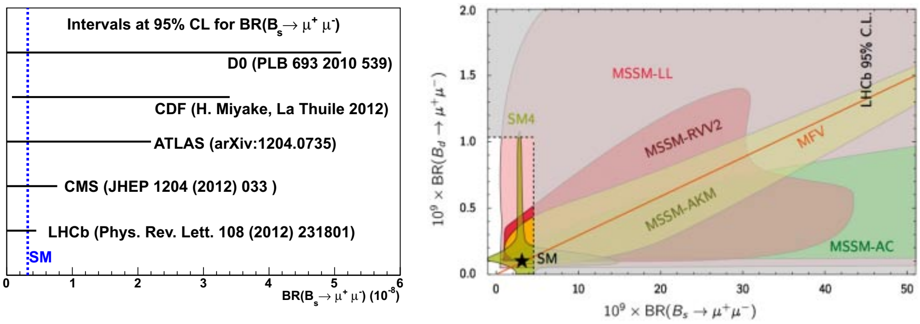

Fig. 1. – Left: Present limits on $\mathcal{B}(B_s \to \mu^+\mu^-)$ at 95% CL set by the experiments D0 [9] CDF [10], ATLAS [11] CMS [12] and LHCb [13]. The SM prediction is indicated by the blue-dashed line. Right: Correlation for the branching fractions of the decays $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ for several models of physics beyond the SM. Details on the models can be found in [8]. The impact of the recent upper limits set by LHCb are shown as the shaded region. Reproduced from [14].

by about two orders of magnitudes. Here, some of the recent rare-decay measurements and their implications for the search of NP will be discussed.

2. – $B_{d,s} \to \mu^+\mu^-$ decays

The decays $B_{d,s} \to \mu^+\mu^-$ are suppressed in the SM, being FCNC and helicity suppressed. Their branching ratios are predicted to be: $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ and $\mathcal{B}(B_d \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$ in the SM [2, 3]. In general these branching ratios are given by the following formula:

$$BR(B_q \to \mu^+\mu^-) \propto \left(\sqrt{1 - \frac{4m_\mu^2}{m_{B_q}}} \left| \frac{m_{B_q}^2}{2}(C_s - C_s') \right|^2 \right) + \left(\left| \frac{m_{B_q}^2}{2}(C_P - C_P') + m_\mu (C_{10} - C_{10}') \right|^2 \right), \tag{2}$$

where the Wilson coefficients $C_s^{(\prime)}$ and $C_P^{(\prime)}$ are scalar and pseudo-scalar effective operators. In the SM these operators are negligibly small, but this is not generally the case in NP models, as for instance in models with an extended Higgs sector [4]. Constraints on these branching ratios have been set by the experiments D0 [9], CDF [10], ATLAS [11], CMS [12] and LHCb [13]. The strongest of these being set by LHCb: $BR(B_s \to \mu^+\mu^-) < 4.5 \cdot 10^{-9}$ and $BR(B_d \to \mu^+\mu^-) < 1.0 \cdot 10^{-9}$ at 95% CL. Present constraints for the decay $B_s \to \mu^+\mu^-$ are shown in fig. 1.

When comparing theoretical predictions with experimental measurements, it is worth emphasising that while the theory predictions refer to branching ratios at $t = 0$, experiments measure time-integrated branching ratios. This imply that the effective measured branching ratio for $B_s \to \mu^+\mu^-$ is about 10% larger than predictions [15, 16].

At hadron colliders relative measurements of branching ratios are performed, to minimize systematic uncertainties. For the normalization of the $B_s \to \mu^+\mu^-$ decay, knowledge

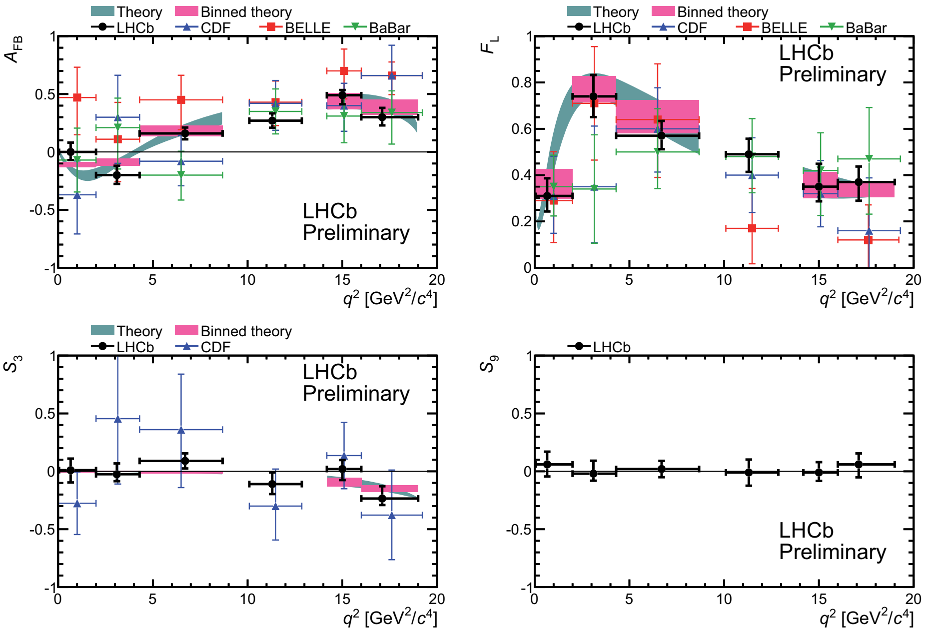

Fig. 2. – The A_{FB}, F_L, S_3 and S_9 measured by the experiments BaBar [22], Belle [24], CDF [25] and LHCb [23]. The comparison with the SM prediction, taken from [20] is also shown. Reproduced from [23].

of the fraction of B_s and B_d mesons produced by the primary interaction (*i.e.* f_s/f_d) is needed([1]). This quantity was measured at LHCb by combining measurements with semi-leptonic and hadronic decays [5]: $f_s/f_d = 0.267^{+0.021}_{-0.020}$ [6, 7]. The uncertainty on this parameter is, in the long run, a limiting systematic uncertainty to discriminating between SM and NP contributions in the $B_s \to \mu^+\mu^-$ decay.

The correlation between the branching fractions of the decays $B_{s,d} \to \mu^+\mu^-$ is shown in fig. 1 for several scenarios of physics beyond SM. It is remarkable the big impact of the recent upper limits on $B_{s,d} \to \mu^+\mu^-$ set by LHCb. Large part of the NP parameter space is currently ruled out. However, it is also possible that NP and SM contributions interfere destructively, decreasing these branching ratios. Therefore, precise measurements of the decays $B_{s,d} \to \mu^+\mu^-$ remain key observables for the search of NP.

3. – $B \to H\mu^+\mu^-$ decays

In the decay $B_d \to K^*\mu^+\mu^-$ several angular observables, which are sensitive to physics beyond the SM, can be built. For some of these observables theoretical uncertainties are under control or cancel out (see [17, 18] and references therein). These observables include the forward-backward asymmetry of the dimuon system, A_{FB}, the fraction of K^* longitudinal polarization, F_L, the transverse asymmetry, S_3 [18] (often referred to as $\frac{1}{2}(1-F_L)A_T^2$ in the literature [19]), and the CP-averaged A_{Im}, S_9 [20].

([1]) Isospin symmetry, *i.e.* $f_u = f_d$, has been assumed.

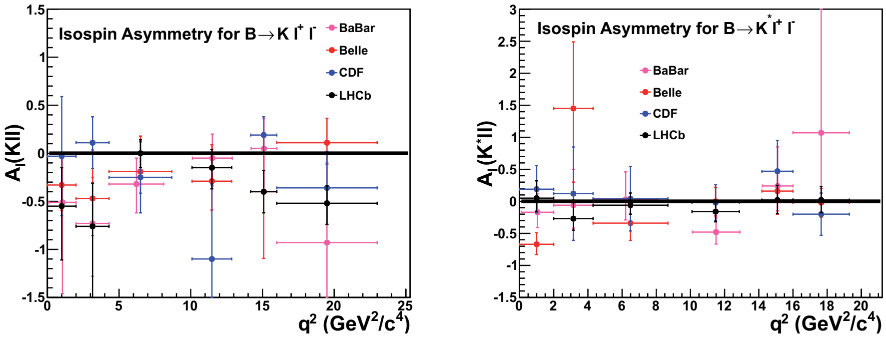

Fig. 3. – Isospin asymmetry for the decays $B \to K^{(*)} l^+ l^-$, measured by the experiments BaBar [22], Belle [24] (with electrons and muons), CDF [25] and LHCb [26] (with muons).

They can be extracted by performing an angular analysis as a function of the dimuon invariant mass squared, q^2, with respect to the following angles: the angle θ_l between the μ^+ (μ^-) and the B^0 ($\overline{B}^0$) in the dimuon rest frame; the angle θ_K between the kaon and B^0 in the K^* rest frame; and the angle ϕ between the planes of the dimuon system and the plane of the K^*. A formal definition of these angles can be found in [21]. It should be noticed that the definition of the angles varies in the literature. In particular, the sign of the ϕ angle in LHCb is opposite to that of CDF for the $\overline{B}^0$ decay. Consequently in place of A_{Im} in the angular distribution LHCb is sensitive to the CP-average S_9, whereas CDF is sensitive to the asymmetry A_9. Recent measurements of these observables are shown in fig. 2. These measurements are dominated by LHCb results [23].

The point in q^2 where A_{FB} changes sign is a sensitive probe for NP and it is theoretically clean, since form factor uncertainties cancel out at first order. The LHCb Collaboration reported the world's first measurement of this observables, shown in fig. 2. The measurement of the zero-crossing point is $q_0^2 = 4.9^{+1.1}_{-1.3}\,\mathrm{GeV}^2/c^4$, which is in agreement with SM predictions. This measurement strongly disfavours scenarios with flipped C_7 sign with respect to the SM, which early measurements of A_{FB} seemed to be hinting to. The isospin asymmetry of the decays $B \to K^{(*)} l^+ l^-$ is defined as

$$(3) \qquad A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0} l^+ l^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm} l^+ l^-)}{\mathcal{B}(B^0 \to K^{(*)0} l^+ l^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm} l^+ l^-)},$$

where τ is the lifetime. In the SM this quantity is expected to be at percent level, slightly larger and positive at very low q^2. Measurements of this quantity have been performed by the BaBar [22] and Belle [24] experiments, using electrons and muons and by CDF [25] and LHCb [26], using muons. These results are shown in fig. 3. All the measurements are consistent with each other and they are consistent with SM predictions for the $B \to K^* l^+ l^-$ decays. For the $B \to K l^+ l^-$ decays the measurements are in agreement with each other but they show a tension with respect to predictions. In particular the LHCb Collaboration reported a deviation from zero at the level of 4 sigmas.

Recently the LHCb Collaboration reported the world's first observation of a $b \to dll$ transition, measuring the branching ratio of the decay $B^+ \to \pi^+ \mu^+ \mu^-$ to be $(2.4 \pm 0.6 \pm 0.2) \times 10^{-8}$ [27], which is in good agreement with the SM predictions. This observation is the rarest B meson decay ever observed.

4. – Conclusions

Precise measurements of rare B-meson decays are sensitive probe for new physics. The most recent measurements of the decays $B_{s,d} \to \mu^+\mu^-$ and the decay $B_d \to K^*\mu^+\mu^-$ are in good agreement with SM predictions and set strong constraints for several NP models. The isospin asymmetry in the decays $B \to K^{(*)}l^+l^-$ has been measured by several experiments. These measurements agree with each other and with SM predictions for the decays with a K^*, while there is a significant tension with predictions for the decays with a K. Recently, the LHCb experiment reported the first observation of a $b \to dll$ transition, by measuring the branching fraction of the decay $B^+ \to \pi^+\mu^+\mu^-$, found to be in agreement with SM expectations. While no significant sign of NP has been found yet in rare decays, these measurements are at the moment statistically limited and there is still large room for NP. Future and more precise measurements will be important to test SM predictions and establish the flavour structure of NP.

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