RARE B-MESON DECAYS

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Abstract. Rare decays of the B-meson that arise due to loop-mediated FCNC transitions are known to provide important constraints on beyond-SM theories. Basic properties of several such decays are reviewed here.

1 Introduction

Flavour Changing Neutral Current (FCNC) phenomena arise at the one-loop level in the Standard Model (SM). They may receive similar loop contributions from beyond-SM particles. Many rare decays of B mesons belong to this class of processes. I will begin with discussing $B_s \to \mu^+ \mu^-$ that receives particular attention this year. Next, I will pass to other decay modes that are generated by the quark-level $b \to s \gamma$ and $b \to sl^+l^-$ transitions.

2 $B_s \to \mu^+ \mu^-$ — the 2011 highlight

The decay of $B_s$ to two muons has a very clean experimental signature – a sharp peak in the dimuon invariant mass. However, its branching ratio in the SM is extremely small (see Sec. 4):

$$B(B_s \to \mu^+ \mu^-)_{\text{SM}} = (3.34 \pm 0.21) \times 10^{-9}. \quad (1)$$

It is known to be very sensitive to new physics even in models with Minimal Flavour Violation [1]. Enhancements by orders of magnitude are possible even when constraints from all the other available observables are taken into account. In July 2011, a new bound on the branching ratio was announced by the CDF Collaboration [2]:

$$B(B_s \to \mu^+ \mu^-)_{\text{CDF}} < 40 \times 10^{-9} \text{ at 95\% C.L.} \quad (2)$$

Since an excess of signal events remained after cuts, their measurement could have also been interpreted as an observation:

$$B(B_s \to \mu^+ \mu^-)_{\text{CDF}} = (18^{+11}_{-9}) \times 10^{-9}. \quad (3)$$

An excitement about its large central value ended two weeks later at the EPS 2011 conference where the LHCb and CMS collaborations announced results of their searches. They observed no signal excess and presented upper bounds only, whose combination reads [3]

$$B(B_s \to \mu^+ \mu^-)_{\text{LHC}} < 10.8 \times 10^{-9} \text{ at 95\% C.L.} \quad (4)$$

At present (November 2011), the LHC experiments have accumulated data samples that are several times larger than those used for EPS 2011. Updates of their analyses are eagerly awaited.

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3 The low-energy effective Lagrangian

Before continuing, let me recall the basic framework that is used for calculations of flavour-changing observables at scales much below the electroweak one. We pass from the full theory of electroweak interactions to an effective one by removing the high-energy degrees of freedom, i.e. integrating out the $W$-boson and all the other particles with masses of order $M_W$ or heavier. The resulting Lagrangian takes the form

$$L_{\text{eff}} = L_{\text{QCD} \times \text{QED}}(\text{leptons, quarks } \neq t) + N \sum_n C_n Q_n,$$  

where $Q_n$ are higher-dimensional interaction terms (operators), $C_n$ are the corresponding coupling constants (Wilson coefficients), and $N$ is a normalization constant. Information on electroweak-scale physics is encoded in the values of $C_i(\mu)$. Such an effective theory is a modern version of the Fermi theory for weak interactions. It is “non-renormalizable” in the traditional sense, but actually renormalizable because an infinite set of operators of arbitrarily high dimensions is included. It is also predictive, because all the $C_i$ are calculable, and only a finite number of them is necessary at each given order in the $(\text{external momenta})/M_W$ expansion. The main advantages of using the effective theory language are easier account for symmetries and the possibility of resumming large logarithms like $(\alpha_s \ln m^2/W^2)^n$ from all orders of the perturbation series using renormalization group techniques.

4 More on $B_s \to \mu^+\mu^-$ and $B^0 \to l^+l^-$

There are three dimension-six operators in $L_{\text{eff}}$ that matter for $B_s \to \mu^+\mu^-$ in the SM and beyond. They read

$$Q_A = \bar{b} \gamma_\mu [\gamma^\nu \gamma_\mu], \quad Q_S = \bar{b} \gamma_\mu \mu, \quad Q_P = \bar{b} \gamma_\mu \mu.$$  

Setting $N = V_{tb}^* V_{ts} G_F^2 M_W^2/\pi^2$ in Eq. (3), one obtains

$$B(B_s \to \mu^+\mu^-) = \frac{|N|^2 M_{B_s}^3 f_{B_s}^2}{4\pi \Gamma_{B_s}} \sqrt{1-r^2} \left[ |rC_A - uC_P|^2 + |uC_S|^2 (1-r^2) \right],$$  

where $r = 2m_\mu/M_{B_s}$ and $u = M_{B_s}/(m_b + m_\mu)$. The decay constant $f_{B_s}$ parametrizes the matrix element $\langle 0 | \bar{b} \gamma^\nu \gamma_\mu | B_s(p) \rangle = ip^\nu f_{B_s}$. Only the coefficient $C_A$ matters in the SM because $C_{S,P} \sim m_\mu/M_W$, and their effects on the r.h.s. of Eq. (5) are thus suppressed by $M_{B_s}^2/M_W^2$ with respect to those of $C_A$.

At the leading order, $C_A^{\text{SM,LO}} = 3 x^2 - 1$ for $x = m_T^2/M_{B_s}^2$. When the $\overline{\text{MS}}$ mass $m_t(\overline{m}_t) \approx 165(1)$ GeV is used in $x$, the $O(\alpha_s)$ corrections [4] enhance the branching ratio by around +2.2%, while the electroweak
corrections to $C_{A}^{SM}$ that have been calculated in Refs. [5, 6] act in the opposite way, and suppress the branching ratio by around $-1.7\%$. The central value in Eq. (1) has been obtained for $|V_{cb}| = 0.04185(73)$ [7], $\tau_{B_{s}} = 1.472(26)\, ps$ [8], and $f_{B_{s}} = 225(4)\, MeV$ [9]. If $f_{B_{s}} = 242.0(9.5)\, MeV$ [10] was used instead, the SM result in Eq. (1) would become $(3.86 \pm 0.36) \times 10^{-9}$.

Useful phenomenological expressions for all the $B_{s} \rightarrow l^{+}l^{-}$ and $B^{0} \rightarrow l^{+}l^{-}$ branching ratios in the SM can be found in Eqs. (127)–(132) of Ref. [11].b The quoted uncertainties there should be understood to include around 3\% ones due to the unknown $O(\alpha_{s}^{2})$ and subleading electroweak corrections. For the $B_{s} \rightarrow l^{+}l^{-}$ decays, the current experimental bounds are above the SM predictions by factors $O(10^{6})$, 3.3, $O(10^{5})$, for $l = e, \mu, \tau$, respectively. The corresponding numbers for $B^{0} \rightarrow l^{+}l^{-}$ are $O(10^{7})$, 35, $O(10^{5})$. Thus, the muonic decay of $B_{s}$ is definitely the most restrictive at present.

Constraints on the Two-Higgs-Doublet Model II from Fig. 3 of Ref. [12] can easily be updated to include the new upper bound on $B_{s} \rightarrow \mu^{+}\mu^{-}$ (2) and the lower bound $M_{H^{\pm}} > 295\, GeV$ that comes from $B \rightarrow X_{s}\gamma$ [13]. It follows that $\tan \beta < 50$ remains allowed for the charged Higgs boson mass values that survive the $B \rightarrow X_{s}\gamma$ constraint.

As far as the Minimal Supersymmetric Standard Model (MSSM) is concerned, the first analysis [14] performed after the EPS 2011 conference implies that $\tan \beta$ larger than 50 is hard to accommodate in the CMSSM given the current $B_{s} \rightarrow \mu^{+}\mu^{-}$ bounds. Assuming SM-like measurement with $\pm 10\%$ accuracy, the authors find that $\tan \beta$ must be smaller than around 40 for stop $\tilde{t}_{1}$ masses up to 2 TeV.

5 What other rare $B$ decays are interesting?

There are two basic scenarios for flavour physics beyond the SM. The scenario "A" (Attractive or Arbitrary) is characterized by Generic Flavour Violation in interactions of new particles with the SM ones. Its properties are as follows:

(i) Large deviations from the SM in the Wilson coefficients are possible.

(ii) Observable new physics effects may arise despite QCD-induced theory uncertainties in many FCNC decays of the $B$ meson, like penguin-induced exclusive hadronic decays, $B \rightarrow K^{*}\gamma$, $B \rightarrow K(\ast)l^{+}l^{-}$, etc.

(iii) Interesting constraints can be obtained from branching ratios, angular distributions and various asymmetries.

The scenario "B" (Boring or Beautiful) corresponds to quite heavy new particles and Minimal Flavour Violation. In such a case:

(i) Only mild beyond-SM effects in most of the Wilson coefficients are expected.

(ii) CP-asymmetries are unaffected.

(iii) Precise measurements are needed. Consequently, small rates

\[b\] Note different normalization conventions for the operators and their Wilson coefficients there.
are not welcome, i.e. $b \to s$ transitions are preferred over $b \to d$ ones. (iv) Precise theory predictions in the SM case are needed, which implies that inclusive rather than exclusive hadronic final states are preferred. (v) Suppression in the SM due to parameters other than CKM angles is a positive property of any considered observable because it increases sensitivity to new physics. (vi) Apart from $B \to l^+l^-$, the inclusive decay $\bar{B} \to X_s\gamma$ is of main interest. Other inclusive decays like $\bar{B} \to X_s\nu\bar{\nu}$ or $\bar{B} \to X_s l^+l^-$ undergo no chiral suppression in the SM but still deserve consideration. (vii) Exclusive observables (like asymmetries) may still be useful to resolve discrete ambiguities.

In the following, I shall comment on several observables that remain relevant in the case "B".

6 $\bar{B} \to X_s\gamma$

The inclusive decay rate $\Gamma(\bar{B} \to X_s\gamma)$ with $\bar{B} = \bar{B}^0$ or $B^-$ and the lower cut on the photon energy $E > E_0$ is well approximated by the corresponding perturbative partonic rate $\Gamma(b \to X_p\gamma)$, provided $E_0$ is neither too large, nor too small. For a conventional choice $E_0 = 1.6 \text{ GeV} \simeq m_b/3$, unknown non-perturbative corrections to this approximation have been analyzed in detail in Ref. [15], and estimated to remain at around $\pm 5\%$ level. The goal of the ongoing perturbative calculations (see Ref. [16] for a review) is to make the $O(\alpha'^2)$ uncertainties negligible with respect to the non-perturbative ones. At present, the SM prediction $B(\bar{B} \to X_s\gamma)^{\text{SM}} = (3.15 \pm 0.23) \times 10^{-4}$ [13] agrees with the world average $B(\bar{B} \to X_s\gamma)^{\text{exp}} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$ [7] within $1.2\sigma$. This fact has been used to derive constraints on various new physics models, like the bound on $M_{H^\pm}$ that has been mentioned in Sec. 4, or effects in the recent MSSM parameter space fits [17].

7 Processes generated by the quark-level $b \to sl^+l^-$ decay

Contrary to $B \to X_s\gamma$ and $B_{(s)} \to l^+l^-$, the quark-level $b \to sl^+l^-$ decay undergoes no chiral suppression in the SM, which makes it less sensitive to new physics. It is also more complicated due to partial screening of beyond-SM effects by $J/\psi$ and higher $c\bar{c}$ resonances in the dilepton spectrum. A very recent model-independent analysis of observables that are available in processes generated by this decay has been presented in Ref. [18]. The authors consider inclusive $\bar{B} \to X_sl^+l^-$ in various regions of the dilepton invariant mass, asymmetries of angular distributions in $B \to K^*l^+l^-$, as well as the branching ratio and CP asymmetry in the radiative mode. No significant (larger than 2$\sigma$) deviations from the SM are found. However, allowed regions in the Wilson coefficient space remain large, so there is no clear indication which scenario (“A” or “B”) is preferred.
8 Summary

Rare $B$ decays provide improving constraints on beyond-SM physics, with a prominent role played by $B_s \rightarrow \mu^+\mu^-$ this year. New results are awaited soon.

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