SLAC-PUB-8551
August 2000

$b \to s\ell^+\ell^-$ decays in and beyond the Standard Model [1]

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Abstract. We briefly review the status of rare radiative and semileptonic $b \to s(\gamma, \ell^+\ell^-)$, $(\ell = e, \mu)$ decays. We discuss possible signatures of new physics in these modes and emphazise the role of the exclusive channels. In particular, measurements of the Forward-Backward asymmetry in $B \to K^*\ell^+\ell^-$ decays and its zero provide a clean test of the Standard Model, complementary to studies in $b \to s\gamma$ decays. Further, the Forward-Backward CP asymmetry in $B \to K^*\ell^+\ell^-$ decays is sensitive to possible non-standard sources of CP violation mediated by flavor changing neutral current Z-penguins.

INTRODUCTION

Flavor changing neutral current (FCNC) b decays do not occur at tree level in the Standard Model (SM). Being loop induced, they feel scales of order $\mathcal{O}(m_W, m_t)$ and in principle much higher ones, making them important probes of the flavor sector of the SM and beyond.

Rare radiative $b \to s\gamma$ decays proceed via so-called electromagnetic penguins. They have been measured in exclusive $B \to K^*\gamma$ [1] and inclusive $B \to X_s\gamma$ [2,3] decays. In dilepton channels $b \to s\ell^+\ell^-$ $(\ell = e, \mu)$, we identify two additional structures in the Feynman diagrams: boxes and Z-penguins. None of the dilepton modes has been detected to date, but we expect large data samples from operating B-factories (CLEO,BaBar,Belle), dedicated B-physics programmes at colliders (Tevatron Run II,Hera-B) and LHC-B in the long term. Corresponding $b \to d$ transition amplitudes are CKM suppressed $V_{td}^*/V_{ts}^* \propto \lambda \sim 0.22$.

The existing best bound in the dimuon channels for inclusive decays is $\mathcal{B}(B \to X_s\mu^+\mu^-) < 5.8 \cdot 10^{-5}$ at 90% C.L. [4], which is one order of magnitude above the NLO SM expectation $\mathcal{B}(B \to X_s\mu^+\mu^-)_{SM} = 5.7 \pm 1.1 \cdot 10^{-6}$ [5]. Note that

1) Work supported by the Department of Energy, Contract DE-AC03-76SF00515
2) Invited Talk at 7th Conference on the Intersections of Particle and Nuclear Physics, Quebec City, Quebec, Canada, May 22-28, 2000

the NNLO calculation in $b \to s\ell^+\ell^-$ is only partially available [6]. Corresponding bounds for the exclusive channels are $\mathcal{B}(B^+ \to K^+\mu^+\mu^-) < 5.2 \cdot 10^{-6}$, $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) < 4.0 \cdot 10^{-6}$ at 90% C.L. [7] and their respective SM predictions are $\mathcal{B}(B \to K\mu^+\mu^-)_{SM} = 5.9 \pm 2.1 \cdot 10^{-7}$, $\mathcal{B}(B \to K^*\mu^+\mu^-)_{SM} = 2.0 \pm 0.7 \cdot 10^{-6}$ with the dominant theoretical uncertainty resulting from hadronic matrix elements, which are estimated here using Light cone sum rules [8]. Currently, the exclusive $B \to K^*\mu^+\mu^-$ decay has the most interesting bound, which is only a factor of 2 away from the SM prediction. Despite larger theoretical uncertainty than in the inclusive cases, rare exclusive decays are more accessible experimentally in the near future and have observables (e.g. existence and position of the zero of the Forward-Backward asymmetry discussed below), which are as clean as the respective ones in the inclusive modes.

MODEL INDEPENDENT ANALYSIS PHOTON AND Z PENGUINS

The calculational tool for the description of $b \to s(\gamma, \ell^+\ell^-)$ decays is the low energy effective Hamiltonian $\mathcal{H}_{eff} \sim G_F V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$ [9]. This enables the analysis of relevant observables in a model independent way, with the goal being to extract the Wilson coefficients C_i from data [10]. The major player is the $bs\gamma$ vertex $O_7 \sim m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$. Its effective coupling strength C_7^{eff} is related to the branching ratio $\mathcal{B}(B \to X_s\gamma) \sim |C_7^{eff}|^2$ thus $0.25 \leq |C_7^{eff}| \leq 0.37$ [2,8] which is in good agreement with the SM value $C_7^{eff}|_{SM} = -0.31$ at $\mu = m_b$ at leading log. We see that the $b \to s\gamma$ data fix the modulus of C_7^{eff}, but not its sign (phase).

In $b \to s\ell^+\ell^-$ decays, in addition to O_7, also 4-Fermi operators involving dileptons contribute, given by $O_9 \sim \bar{s}_L \gamma^\mu b_L \bar{\ell}\gamma_\mu \ell$, $O_{10} \sim \bar{s}_L \gamma^\mu b_L \bar{\ell}\gamma_\mu \gamma_5 \ell$. Due to the charge assignments of lepton-Z couplings the Z-penguin contribution to C_9 is suppressed with respect to C_{10} by $(\bar{\ell}\ell Z|_V)/(\bar{\ell}\ell Z|_A) = -1 + 4\sin^2\theta_W \sim -0.08$. We thus identify C_{10} as a measure of the sZb coupling modulo the box contribution [11].

Decomposition of the $B \to K^*\mu^+\mu^-$ branching ratio yields $\mathcal{B} = a|C_7^{eff}|^2 + b|C_9|^2 + c|C_{10}|^2 + dC_7^{eff}C_9 + eC_7^{eff} + fC_9 + g$ [8]. Using the CDF bound [7] on this mode and allowing C_7^{eff} to have both SM-like and SM-opposite signs gives the present best bound on the strength of generic FCNC Z-penguins of $|C_{10}| \leq 10$, which is a factor of 2-3 larger than the SM value $C_{10}|_{SM} = -4.7$ [11]. Scenarios with non-standard Z-penguins arise in many extensions of the SM like such as supersymmetry, 4th generation and Z' [11]. Another interesting possibility to test the sZb vertex arises in $b \to s\nu\bar{\nu}$ decays, since here no photon penguins contribute.

EXCLUSIVE $B \to K, K^*\ell^+\ell^-$ DECAYS

Supersymmetric effects in inclusive $b \to s\ell^+\ell^-$ decays have been studied in [12,13]. The reach of a new physics search in the dilepton invariant mass distribution in $B \to K^* \mu^+ \mu^-$ decays is exemplified in Fig. 1 [8]. Supergravity (SUGRA) (dotted) and a supersymmetric scenario with non-minimal sources of flavor violation in the mass insertion approximation (dashed), can be well discriminated from the SM (solid) and its hadronic uncertainties (shaded area); the upper curves contain resonant $c\bar{c}$ background via $B \to K^* \Psi^i \to K^* \mu^+ \mu^-$, lower ones are pure short-distance contributions [14]. Note that the dashed curve saturates the experimental bound in this channel. Similar findings are valid for $B \to K \mu^+ \mu^-$ decays, which however show less sensitivity to C_7^{eff} as the photon pole at $s = 0$ is absent. In either case $C_7^{eff} > 0$ (opposite-to-SM sign) enhances the rates through constructive interference of C_7^{eff} with C_9.

Forward-Backward Asymmetry

The Forward-Backward asymmetry in $B \to K^* \ell^+ \ell^-$ decays results from V/A interference in the lepton pair $A(s) \sim C_{10}(C_7^{eff} + \beta(s) Re(C_9^{eff}))$, shown in Fig. 2 [8]; see [11] for a discussion of the sign of A, which is opposite to the Forward-Backward asymmetry $\bar{A}$ of the CP conjugate channel in the CP conserving limit. In the SM ($C_7^{eff} < 0$, solid curve), A has a zero around $s_0 \sim 3\text{GeV}^2$, which would disappear if C_7^{eff} would have the opposite sign (long-short-dashed curve). The existence of a zero in the Forward-Backward asymmetry in $B \to K^* \ell^+ \ell^-$ decays below the J/Ψ resonance is an important test of the SM and is independent of

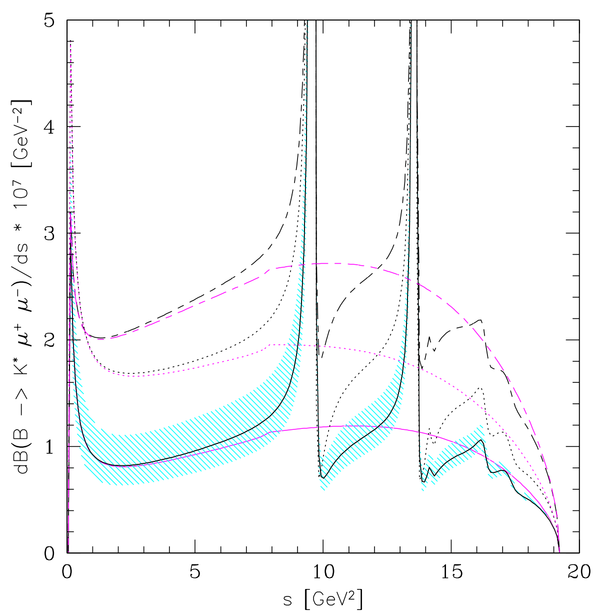

FIGURE 1. Dilepton invariant mass spectrum in $B \to K^* \mu^+ \mu^-$ decays. Figure taken from [8].

hadronic matrix elements [8]. Positive C_7^{eff} occurs generically in supersymmetric theories [12], but only for large $tan\beta$ in relaxed and/or minimal SUGRA [13].

Further, the position of the zero s_0 has very small hadronic uncertainties [15]. In the limit where the final hadron has large energy, i.e., small dilepton mass, the Large Energy Effective Theory [16] is applicable and here all form factors cancel out in the ratios which determines s_0 [8].

A recently proposed observable, the Forward-Backward CP asymmetry FB_{CP} in $B \to K^* \ell^+ \ell^-$ decays probes the phase of C_{10} or of the sZb vertex [11], respectively. Defined as $FB_{CP} \equiv (A + \bar{A})/(A - \bar{A}) = ImC_{10}/ReC_{10} ImC_9^{eff}/ReC_9^{eff}(1 + \ldots)$, its magnitude scales with $ImC_9^{eff} = ImY$, where $Y(s)$ contains contributions from resonant and non-resonant $c\bar{c}$ states [14]; $ImY = 0$ below threshold, so it is sizeable only in the high dilepton mass region. Integration over $m_{\Psi'}^2 < s \leq (m_B - m_{K*})^2$ yields $\Delta FB_{CP} = (3 \pm 1)\% ImC_{10}/ReC_{10}$, which can be large in the case of $\mathcal{O}(1)$ phases. Hadronic uncertainties are not small, but the SM background is below 10^{-3} and any effect above this would be due to a non-SM source of CP violation [11].

RADIATIVE RARE B-DECAYS

The SM branching ratio in $B \to X_s \gamma$ decays is known at NLO with 10 % accuracy $\mathcal{B}(B \to X_s \gamma) = (3.32 \pm^{0.00}_{0.11} \pm^{0.00}_{0.08} \pm^{0.26}_{0.25}) \cdot 10^{-4}$ [17]. This is in good agreement with data from LEP $\mathcal{B}(B \to X_s \gamma) = (3.11 \pm 0.80 \pm 0.72) \cdot 10^{-4}$ [3], and CLEO,

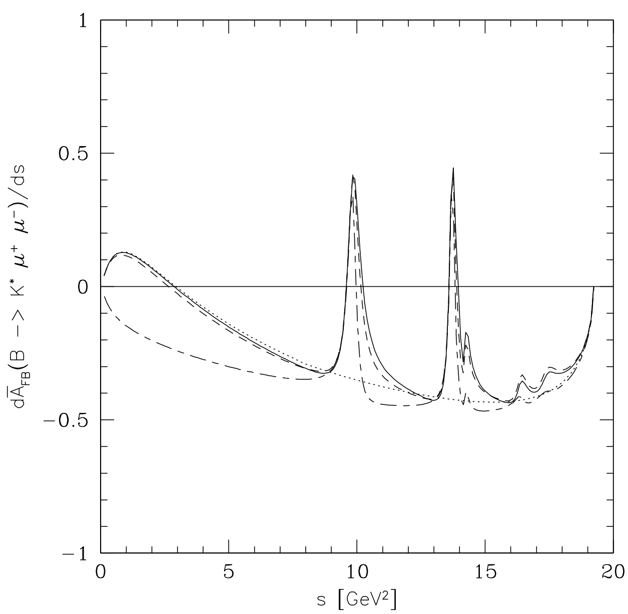

FIGURE 2. Forward-backward asymmetry for $B \to K^* \mu^+ \mu^-$. Figure taken from [8].

$\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \cdot 10^{-4}$ [2].

A promising observable in $b \to s\gamma$ decays where dramatic signals of possible physics beyond the SM could show up is the CP asymmetry in the rate $a_{CP} \equiv (, (\bar{B} \to X_s\gamma) - , (B \to X_{\bar{s}}\gamma))/(, (\bar{B} \to X_s\gamma) + , (B \to X_{\bar{s}}\gamma))$ [18]. It is very tiny in the SM since $a_{CP} \propto \alpha_s(m_b)\eta\lambda^2$, η, λ are Wolfenstein parameters, thus $a_{CP} \leq 1\%$ [18]. However, large effects of (10-50) % are possible in scenarios with an enhanced chromo-magnetic dipole operator C_8 in the bsg vertex. CP asymmetry in exclusive $B \to K^*\gamma$ decays has a less clean prediction due to strong phases, however, in the SM, $a_{CP}^{B \to K^*\gamma} \leq \mathcal{O}(1\%)$ holds [19]. Any significant deviation from this would signal new physics. In both inclusive $-0.09 < a_{CP}^{B \to X_s\gamma} < 0.42$ [2] and exclusive cases $a_{CP}^{B \to K^*\gamma} = (8 \pm 13 \pm 3)\%$ [1], the measurements are not conclusive yet.

SUMMARY

Theoretically clear signatures of possible new physics can be experimentally isolated in $b \to s\gamma$ and $b \to s\ell^+\ell^-$ decays in the near future via the observables $(A(s_0), FB_{CP}, a_{CP})$. It is exciting to see whether the SM passes this next round of FCNC tests.

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