Z PENGUINS AND RARE B DECAYS

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Rare B decays of the type \( b \to s \ell^+ \ell^- (\bar{\nu} \nu) \) are analyzed in a generic scenario where New Physics effects enter predominantly via Z penguin contributions. We show that this possibility is both phenomenologically allowed and well motivated on theoretical grounds. The important role played in this context by the lepton forward-backward asymmetry in \( B \to K^* \ell^+ \ell^- \) is emphasized.

1 Introduction

Flavour-changing neutral-current (FCNC) processes provide a powerful tool in searching for clues about non-standard flavour dynamics. Being generated only at the quantum level and being additionally suppressed, within the Standard Model (SM), by the smallness of the off-diagonal entries of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, their observation is very challenging. This suppression, however, ensures a large sensitivity to possible non-standard effects, even if these occur at very high energy scales, rendering their experimental search highly valuable.

In the present talk we focus on a specific class of non-standard \( \Delta B = 1 \) FCNC transitions: those mediated by the Z-boson exchange and contributing to rare B decays of the type \( b \to s \ell^+ \ell^- (\bar{\nu} \nu) \). As we shall show, these are particularly interesting for two main reasons: i) there are no stringent experimental bounds on these transitions yet; ii) it is quite natural to conceive extensions of the SM where the Z-mediated FCNC amplitudes are substantially modified, even taking into account the present constraints on \( \Delta B = 2 \) and \( b \to s \gamma \) processes.

In a generic extension of the Standard Model where new particles appear only above some high scale \( M_X > M_Z \), we can integrate out the new degrees of freedom and generate a series of local FCNC operators already at the electroweak scale. Those relevant for \( b \to s \ell^+ \ell^- (\bar{\nu} \nu) \) transitions can be divided into three wide classes: generic dimension-six operators, magnetic penguins and FCNC couplings of the Z boson. The latter are dimension-four operators of the type \( \bar{b}_{L(R)} \gamma^\mu s_{L(R)} Z_{\mu} \), that we are allowed to consider due to the spontaneous breaking of \( SU(2)_L \times U(1)_Y \). Their coefficients must be proportional to some symmetry-breaking term but do not need to contain any explicit \( 1/M_X \) suppression for dimensional reasons, contrary to the case of dimension-six operators and magnetic penguins. This naive argument seems to suggest that FCNC couplings of the Z boson are particularly interesting and worth to be studied independently of the other effects. It should be noticed that the requirement of naturalness in the size of the \( SU(2)_L \times U(1)_Y \) breaking terms implies that also the adimensional couplings of the non-standard Z-mediated FCNC amplitudes must vanish in the limit \( M_X/M_Z \to \infty \). Nonetheless, as we will illustrate below with an explicit example, the above naive dimensional argument remains a strong indication of an independent behaviour of these couplings with respect to the other FCNC amplitudes.

2 FCNC Z penguins in generic SUSY models

An explicit example where the largest deviations from the SM, in the sector of FCNC, are generated by the Z boson exchange can be
realized within supersymmetric models with generic flavour couplings. Within this context, assuming $R$ parity conservation and minimal particle content, FCNC amplitudes involving external quark fields turn out to be generated only at the quantum level. Moreover, assuming the natural link between trilinear soft-breaking terms and Yukawa couplings, sizable $SU(2)_{L}$- and flavour-breaking effects can be expected in the up sector due to the large Yukawa coupling of the third generation. Thus the potentially dominant non-SM effects in the effective $Zbs$ vertex turn out to be generated by chargino-up-squarks loops and have a pure left-handed structure, like in the SM.

Similarly to the $Zsd$ case,[4] the first non-vanishing contribution appears to the second order in a simultaneous expansion of chargino and squark mass matrices in the basis of electroweak eigenstates. The potentially largest effect arises when the necessary $SU(2)_{L}$ breaking ($\Delta I_{W} = 1$) is equally shared by the $\tilde{t}_{R} - \tilde{u}_{L}^{s}$ mixing and by the chargino-higgsino mixing, carrying both $\Delta I_{W} = 1/2$. For a numerical evaluation, normalizing the SUSY result to the SM one (evaluated in the ’t Hooft-Feynman gauge) and varying the parameters in the allowed ranges, leads to

$$
\frac{Z_{sb}^{SUSY}}{Z_{sb}^{SM}} \leq 0.1 \left| \frac{M_{2}^{2}}{M_{2}^{2}} \right| \left( \frac{M_{W}}{M_{2}} \right) \leq 2.5 \left( \delta^{U}_{RL} \right)_{32} \left( \frac{M_{W}}{M_{2}} \right).
$$

The coupling $(\delta^{U}_{RL})_{32}$, which represents the analog of the CKM factor $V_{ts}$ in the SM case, is not very constrained at present and can be of $O(1)$ with an arbitrary $CP$-violating phase. Note, however, that vacuum stability bounds[4] imply $|\delta^{U}_{RL}| \lesssim (3m_{t}/M_{S})$, where $M_{S}$ denotes the generic scale of sparticle masses. Therefore the SUSY contribution to the $Z$ penguin decouples as $(M_{Z}/M_{S})^{2}$ in the limit $M_{S}/M_{Z} \rightarrow \infty$.

As it can be checked by the detailed analysis of Lunghi et al.,[3] in the interesting scenario where the left-right mixing of up-type squarks is the only non-standard source of flavour mixing, $Z$ penguins are largely dominant with respect to other supersymmetric contributions to $b \rightarrow s \ell^{+}\ell^{-}$. Indeed, due to the different $SU(2)_{L}$ structure, the $\tilde{t}_{R} - \tilde{u}_{L}^{s}$ mixing contributes to magnetic penguins only to the third order in the mass expansion discussed above. Therefore in this scenario the magnetic-penguin contribution to $b \rightarrow s \ell^{+}\ell^{-}$ is additionally suppressed by $M_{Z}/M_{S}$ with respect to the $Z$-penguin one. Similarly, in the case of box diagrams the $\tilde{t}_{R} - \tilde{u}_{L}^{s}$ mixing alone leads to a contribution that decouples like $M_{Z}^{4}/M_{S}^{4}$.

3 Experimental bounds on the $Zbs$ vertex

An extended discussion of other non-standard scenarios where large deviations form the SM occur in the $Zbs$ vertex can be found elsewhere.[4] We proceed here analyzing the experimental information on this FCNC amplitude in a model-independent way.

The dimension-four effective FCNC couplings of the $Z$ boson relevant for $b \rightarrow s$ transitions can be described by means of the following effective Lagrangian

$$
\mathcal{L}_{FC}^{Z} = G_{F} \frac{\alpha}{\sqrt{2} \pi} M_{Z}^{2} \cos \theta_{W} \frac{Z_{u}}{\sin \theta_{W}} \times \left( Z_{sb}^{L} \bar{b}_{L} \gamma_{\mu} s_{L} + Z_{sb}^{R} \bar{b}_{R} \gamma_{\mu} s_{R} \right) + \text{h.c.,}
$$

where $Z_{sb}^{L,R}$ are complex couplings. Evaluated in the ’t Hooft-Feynman gauge, the SM contribution to $Z_{sb}^{L,R}$ is given by

$$
Z_{sb}^{L,R}|_{SM} = 0, \quad Z_{sb}^{L,R} = V_{tb}^{*} V_{ts} C_{0}(x_{t}) \text{,}
$$

where $x_{t} = m_{t}^{2}/m_{W}^{2}$ and $C_{0}(x)$ is a loop function of $O(1)$. Although $Z_{sb}^{L,R}|_{SM}$ is not gauge invariant, we recall that the leading contribution to both $b \rightarrow s \ell^{+}\ell^{-}$ and $b \rightarrow s \nu \bar{\nu}$ amplitudes in the limit $x_{t} \rightarrow \infty$ is gauge independent and is generated by the large $x_{t}$ limit of $Z_{sb}^{L,R}|_{SM} (C_{0}(x_{t}) \rightarrow x_{t}/8 \text{ for } x_{t} \rightarrow \infty)$. 


Constraints on $|Z_{sb}^{L,R}|$ can be obtained from the experimental upper bounds on exclusive and inclusive $b \to s \ell^+\ell^-(\nu\bar{\nu})$ transitions. The latter are certainly more clean form the theoretical point of view (especially the $b \to s \nu\bar{\nu}$ one) although their experimental determination is quite difficult. At present the most significant information from exclusive decays is given by $\mathcal{B}(B \to X_s \ell^+\ell^-) < 4.2 \times 10^{-5}$ and leads to

$$\left( |Z_{sb}^L|^2 + |Z_{sb}^R|^2 \right)^{1/2} \lesssim 0.15.$$  

Within exclusive channels the most stringent information can be extracted from $B \to K^* \mu^+\mu^-$, where the experimental upper bound on the non-resonant branching ratio ($B^{n.r.} < 4.0 \times 10^{-6}$) lies only about a factor two above the SM expectation. Taking into account the uncertainties on the hadronic form factors, this implies

$$|Z_{bs}^{L,R}| \lesssim 0.13.$$  

Additional constraints on the $Z_{bs}^{L,R}$ couplings could in principle be obtained by the direct limits on $\mathcal{B}(Z \to bs)$ and by $B_s - \bar{B}_s$ mixing, but in both cases these are not very significant.

Interestingly the bounds leave open the possibility of large deviations from the SM expectation. In the optimistic case where $Z_{bs}^L$ or $Z_{bs}^R$ were close to saturate these bound, we would be able to detect the presence of non-standard dynamics already by observing sizable rate enhancements in the exclusive modes. In processes like $B \to K^* \ell^+\ell^-$ and $B \to K \ell^+\ell^-$, where the standard photon-penguin diagrams provide a large contribution, the enhancement could be at most of a factor 2-3. On the other hand, in processes like $B \to K^*\nu\bar{\nu}$, $B \to K\nu\bar{\nu}$ and $B_s \to \ell^+\ell^-$, where the photon-exchange amplitude is forbidden, the maximal enhancement could reach a factor 10.

### 4 Forward-backward asymmetry in $B \to K^* \mu^+\mu^-$

If the new physics effects do not produce sizable deviations in the magnitude of the $b \to Z's$ transition, it will be hard to detect them from rate measurements, especially in exclusive channels. A much more interesting observable in this respect is provided by the forward-backward (FB) asymmetry of the emitted leptons, also within exclusive modes.

In the $\bar{B} \to \bar{K}^* \mu^+\mu^-$ case this is defined as

$$A_{FB}(\bar{s}) = \frac{1}{\mathcal{B}(\bar{B} \to \bar{K}^* \mu^+\mu^-)/ds} \int_{-1}^1 d\cos\theta\frac{d^2\Gamma(\bar{B} \to \bar{K}^* \mu^+\mu^-)}{ds\,d\cos\theta} \text{sgn}(\cos\theta),$$

where $s = m_{\mu^+\mu^-}^2/m_B^2$ and $\theta$ is the angle between the momenta of $\mu^+$ and $\bar{B}$ in the dilepton center-of-mass frame. Assuming that the leptonic current has only a vector ($V$) or axial-vector ($A$) structure, then the FB asymmetry provides a direct measure of the $A-V$ interference. Since the vector current is largely dominated by the photon-exchange amplitude and the axial one is very sensitive to the $Z$ exchange, $A_{FB}^{(V)}$ and $A_{FB}^{(A)}$ provide an excellent tool to probe the $Z\bar{b}s$ vertex.

Employing the usual notations for the Wilson coefficients of the SM effective Hamiltonian relevant to $b \to s \ell^+\ell^-$ transitions, $A_{FB}^{(B)}$ turns out to be proportional to

$$\text{Re} \left\{ C_{10}^{*} \left[ s \, C_9^{\text{eff}}(s) + \alpha_+(s) \frac{m_b^2 C_7}{m_B} \right] \right\},$$

where $\alpha_+(s)$ is an appropriate ratio of hadronic form factors. The overall factor ruling the magnitude of $A_{FB}^{(B)}(s)$ is affected by sizable theoretical uncertainties. Nonetheless there are at least three features of this observable that provide a clear short-distance information:

- i) Within the SM $A_{FB}^{(B)}(s)$ has a zero in the low $s$ region ($s_0|_{\text{SM}} \sim 0.1$). The exact

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$^a$ To simplify the notations we have introduced the parameter $C_9^{\text{eff}}(s)$ that is not a Wilson coefficient but can be identified with $C_9$ at the leading-log level.
position of \( s_0 \) is not free from hadronic uncertainties at the 10\% level, nonetheless the existence of the zero itself is a clear test of the relative sign between \( C_7 \) and \( C_9 \). The position of \( s_0 \) is essentially unaffected by possible new physics effects in the \( Z\bar{b}s \) vertex.

ii) The sign of \( A_{FB}(\bar{B} \rightarrow \bar{K}^*\mu^+\mu^-) \) around the zero is fixed unambiguously in terms of the relative sign of \( C_{10} \) and \( C_9 \) within the SM one expects \( A_{FB}^{(B)}(s) > 0 \) for \( s > s_0 \), as in Fig. 1. This prediction is based on a model-independent relation among the form factors that has been overlooked in most of the recent literature. Interestingly, the sign of \( C_{10} \) could change in presence of a non-standard \( Z\bar{b}s \) vertex leading to a striking signal of new physics in \( A_{FB}^{(B)}(s) \), even if the rate of \( \bar{B} \rightarrow \bar{K}^*\ell^+\ell^- \) was close to its SM value.

iii) In the limit of \( CP \) conservation one expects \( A_{FB}^{(B)}(s) = -A_{FB}^{(B)}(s) \). This holds at the per-mille level within the SM, where \( C_{10} \) has a negligible \( CP \)-violating phase, but again it could be different in presence of new physics in the \( Z\bar{b}s \) vertex. In this case the ratio \( [A_{FB}^{(B)}(s) + A_{FB}^{(B)}(s)]/[A_{FB}^{(B)}(s) - A_{FB}^{(B)}(s)] \) could be different from zero, for \( s \) above the charm threshold, reaching the 10\% level in realistic models.

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