Flavor violation in meson decays

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Abstract

Some extended models predict the existence of a new neutral massive gauge boson, identified as the Z' boson, together with flavor-changing neutral currents. In this theoretical framework, we estimate the intensity of couplings regarding the interaction between the Z' boson with the bottom and the strange quarks through the $B_s^0 \to \mu^+\mu^-$ transition, which allow us to study the $B_s^0 \to \tau\mu, \tau e, \mu e$ decays. We present preliminary results, where the corresponding branching ratios are estimated; our predictions are contrasted with similar ones coming from several extended models. In particular, our estimates for the branching ratios range between 10^{-9} and 10^{-6}.

1 The extension model

- Many extensions of the Standard Model (SM) predict the existence of an extra $U'(1)$ gauge symmetry group and its associated Z' boson, which has been an object of extensive phenomenological studies [1]. In particular, the $SU_C(3) \times SU_L(2) \times U_Y(1) \times U'(1)$ extended electroweak gauge group is the simplest extended model that predicts an extra neutral gauge boson, known as Z' boson. This boson can induce flavor-changing neutral currents (FCNC) at the tree level through the $Z' f_i f_j$ couplings, where f_i and f_j are always fermions of different flavor. Thus, we consider the more general renormalizable Lagrangian that includes FCNC, mediated by this new massive neutral gauge boson, coming from several extended model [2, 3]. This Lagrangian is

$$\mathcal{L}_{NC} = \sum_{i,j} \left[\bar{f}_i \gamma^\alpha (\Omega_{Lf_if_j} P_L + \Omega_{Rf_if_j} P_R) f_j + \bar{f}_j \gamma^\alpha (\Omega^*_{Lf_jf_i} P_L + \Omega^*_{Rf_jf_i} P_R) f_i\right] Z'_\alpha, \tag{1}$$

where $P_{L,R}$ are the chiral projectors and Z'_α represents the new neutral massive gauge boson. The $\Omega_{Lf_if_j}$, $\Omega_{Rf_if_j}$ parameters symbolizes the strength of the $Z' f_i f_j$ coupling. For our purpose, we will assume that $\Omega_{Lf_if_j} = \Omega_{Lf_jf_i}$ and $\Omega_{Rf_if_j} = \Omega_{Rf_jf_i}$. Notice that the Lagrangian in equation (1) includes both flavor-conserving and flavor-violating couplings. The flavor-conserving couplings, $Q^{f_i}_{L,R}$ [4], are related to the Ω couplings as $\Omega_{Lf_if_i} = -g_2 Q^{f_i}_L$ and $\Omega_{Rf_if_i} = -g_2 Q^{f_i}_R$, where g_2 is the gauge coupling for the Z' boson. Here, we only consider the following Z' bosons: the Z_S of the sequential Z model, the $Z_{L,R}$ of the left-right symmetric model, the Z_χ arising from the breaking of $SO(10) \to SU(5) \times U(1)$, the Z_ψ resulting from $E_6 \to SO(10) \times U(1)$, and the Z_η that would appear in many superstring-inspired models. The extended models we are interested in here are distinguished by their gauge couplings with the Z's boson

$$g_2 = \sqrt{5/3}\, \sin\theta_W\, g_1 \lambda_g,$$

where $g_1 = g/\cos\theta_W$ and λ_g is a parameter that depends of the symmetry breaking pattern, which is commonly assumed as $\mathcal{O}(1)$ [5]. In the sequential Z_S model, the gauge coupling $g_2 = g_1$.

- By making use of the above presented details, the effective Hamiltonian that describes the $B_s^0 \to l_i l_j$ process (see Fig. 1(a)) can be expressed as follows

$$\mathcal{H}_{eff} = \frac{C_{\text{eff}}(m_b)}{m^2_{B^0_s} - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}} \{[\bar{s}(p_2)\gamma^\mu(\Omega_{Lbs}P_L + \Omega_{Rbs}P_R)b(p_1)] \times [\bar{l}_i(p_3)\gamma^\mu(\Omega_{Ll_il_j}P_L + \Omega_{Rl_il_j}P_R)l_j(p_4)] + [\bar{s}(p_2)\gamma^\mu(\Omega_{Lbs}P_L + \Omega_{Rbs}P_R)b(p_1)][\bar{l}_j(p_4)\gamma^\mu(\Omega^*_{Ll_jl_i}P_L + \Omega^*_{Rl_jl_i}P_R)l_i(p_3)]\}, \tag{2}$$

where $\Gamma_{Z'}$ is the total decay width of the Z' boson, $m_{B^0_s}$ is the B^0_s meson mass, and $C_{\text{eff}}(m_b)$ is the respective Wilson coefficient. To calculate the transition amplitude $\langle 0|\mathcal{H}^s_{eff}|B^0_s\rangle$, one can generally adopt the vacuum insertion method for the evaluation of the matrix elements in Eq. (2), which are given in general [6] as

$$\langle 0|\bar{s}\gamma^\mu\gamma_5 b|B^0_s\rangle = i f_{B^0_s} P^\mu, \quad \langle 0|\bar{q}\gamma^\mu b|B^0_q\rangle = 0, \tag{3}$$

where P is the momentum of the B^0_s meson.

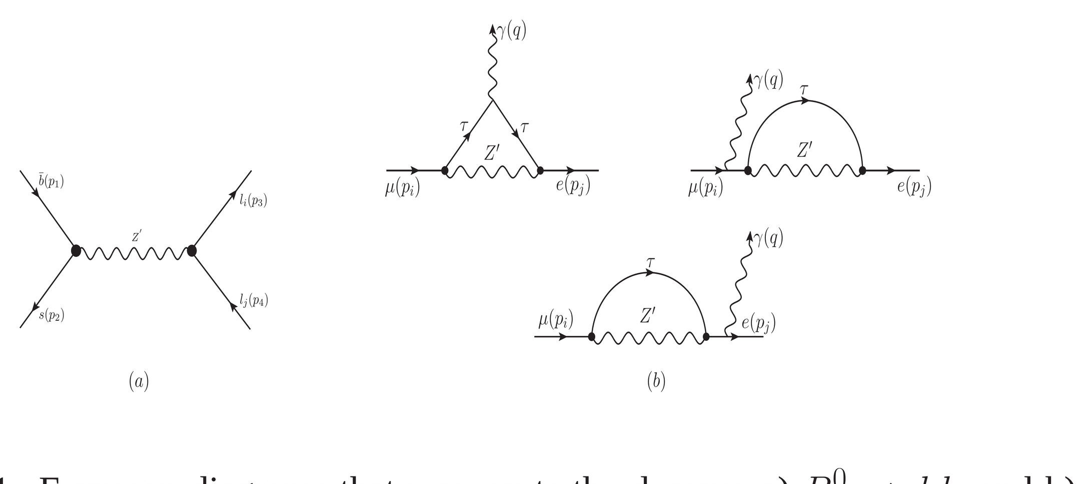


Figure 1: Feynman diagrams that represents the decays: a) $B^0_s \to l_i l_j$ and b) $\mu \to e\gamma$. Both processes are mediated by a Z' gauge boson.

By using Eq. (3) and assuming that $\Omega_{Rbs} - \Omega_{Lbs} \equiv \Omega_{bs}$, we find that the amplitudes for the $B^0_s \to l_i l_j$ decay are

$$\mathcal{M}(B^0_s \to \bar{l}_i l_j) = \frac{i}{2} \frac{f_{B^0_s} C_{\text{eff}}(m_b)\,\Omega_{bs}}{m^2_{B^0_s} - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}} \bar{l}_i(p_4)\left[(m_{l_i}\Omega_{Rl_il_j} - m_{l_j}\Omega_{Ll_il_j})P_R + (m_{l_i}\Omega_{Ll_il_j} - m_{l_j}\Omega_{Rl_il_j})P_L\right] l_j(p_3), \tag{4}$$

$$\mathcal{M}(B^0_s \to l_i \bar{l}_j)) = \frac{i}{2} \frac{f_{B^0_s} C_{\text{eff}}(m_b)\,\Omega_{bs}}{m^2_{B^0_s} - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}} \overline{l_j}(p_3)\left[(m_{l_j}\Omega^*_{Rl_il_j} - m_{l_i}\Omega^*_{Ll_jl_i})P_R + (m_{l_j}\Omega^*_{Ll_il_j} - m_{l_i}\Omega^*_{Rl_jl_i})P_L\right] l_i(p_4). \tag{5}$$

The decay width of the $B^0_s \to l_i l_j$ process is

$$\Gamma(B^0_s \to l_i l_j) = \frac{C^2_{\text{eff}}(m_b)|\Omega_{bs}|^2 m^3_{B^0_s} f^2_{B^0_s}}{32\pi\left[(m^2_{B^0_s} - m^2_{Z'})^2 + m^2_{Z'}\Gamma^2_{Z'}\right]} \left\{(|\Omega_{Ll_il_j}|^2 + |\Omega_{Rl_il_j}|^2) \times \left[\frac{(m^2_{li} + m^2_{lj})}{m^2_{B^0_s}} - \frac{(m^2_{li} - m^2_{lj})^2}{m^4_{B^0_s}}\right] - \frac{4 m_{li} m_{lj}}{m^2_{B^0_s}} \text{Re}(\Omega_{Rl_il_j}\Omega^*_{Rl_il_j})\right\} \times \sqrt{\left[1 - \frac{(m_{l_j} + m_{l_i})^2}{m^2_{B^0_s}}\right]\left[1 - \frac{(m_{l_i} - m_{l_j})^2}{m^2_{B^0_s}}\right]}. \tag{6}$$

At this stage, it will be supposed that $\Omega_{Ll_il_j} = \Omega_{Rl_il_j} = \Omega_{l_il_j}$. When confronting the theoretical prediction with the experimental conditions one needs to account for the sizable effect of the $B^0_s - \overline{B^0_s}$ mixing, in which the decay-width difference between the B^0_s−mass eigenstates is crucial [7]. In this way,

$$\text{Br}(B^0_s \to l_i l_j) = \tau_{B^0_s}\Gamma(B^0_s \to l_i l_j) \simeq (1 - y_s)\text{Br}(B^0_s \to l_i l_j)_{\text{Exp}}, \tag{7}$$

where $\tau_{B^0_s}$ is the mean life of the B^0_s meson, $y_s = \Delta\Gamma_{B^0_s}/(2\Gamma_{B^0_s})$ is the correction factor, being $\Gamma_{B^0_s}$ the average decay width of B^0_s, and $\Delta\Gamma_{B^0_s}$ the width difference between the B^0_s-mass eigenstates.

Estimation the $Z'bs$ coupling coming from the $B^0_s \to \mu^+\mu^-$ decay

In the following, we are going to derive the expression for the Ω_{bs}, which represents the $Z'bs$ coupling, through the $B^0_s \to \mu^+\mu^-$ process. To achieve this purpose, is it resorted to Eq. (6). Since the $B^0_s \to \mu^+\mu^-$ decay was experimentally measured, we will assume that within the experimental uncertainty the new physics effects could be found. Thereby,

$$\Delta\Gamma(B^0_s \to \mu\bar{\mu})_{\text{Exp}} = \frac{g_2^2 C^2_{eff}(m_b)|\Omega_{bs}|^2 m_{B^0_s} f^2_{B^0_s} m^2_\mu}{32\pi\left[(m^2_{B^0_s} - m^2_{Z'})^2 + m^2_{Z'}\Gamma^2_{Z'}\right]} |Q^\mu_L - Q^\mu_R|^2 \sqrt{1 - \frac{4m^2_\mu}{m^2_{B^0_s}}}, \tag{8}$$

where $\Omega_{L,R_{\mu\mu}} = -g_2 Q^\mu_{L,R}$. Finally, when inserting Eq. (8) in Eq. (7), we obtain that

$$|\Omega_{bs}|^2 = \frac{32\pi(1 - y_s)\left[(m^2_{B^0_s} - m^2_{Z'})^2 + m^2_{Z'}\Gamma^2_{Z'}\right]\Delta\text{Br}(B^0_s \to \mu\bar{\mu})_{\text{Exp}}}{\tau_{B^0_s} g_2^2 C^2_{\text{eff}}(m_b) m_{B^0_s} f^2_{B^0_s} m^2_\mu |Q^\mu_L - Q^\mu_R|^2 \sqrt{1 - \frac{4m^2_\mu}{m^2_{B^0_s}}}}. \tag{9}$$

Constraining the $Z'\mu e$ coupling from $\mu - e$ conversion

We will estimate the $\Omega_{\mu e}$ parameter through the $\mu \to e\gamma$ process resorting to the $\mu - e$ conversion. Thus, the contributions of the flavor-violating vertex, $Z'\mu e$, to the $\mu \to e\gamma$ decay are given by the Feynman diagrams shown in Fig. 1(b). By considering this together with the definition of the decay width we can write the branching ratio $\mu \to e\gamma$ in the following manner

$$Br(\mu \to e\gamma) = \frac{\alpha}{2}(1 - x^2)^3 \left[|\Omega_{\mu\tau}\Omega_{e\tau}|^2 |y_1 + y_2 + y_3 + y_4|^2\right] \frac{m_\mu}{\Gamma_\mu}, \tag{10}$$

where $x = \frac{m_e}{m_\mu}$ and Γ_μ is the total decay width of the muon. Here, y_1, y_2, y_3 and y_4 are given in Ref. [8]. We will estimate the $\Omega_{\mu e}$ parameter using Eq. (10) together with the relation $CR(\mu Ti \to eTi) \cong \frac{1}{200}\text{Br}(\mu \to e\gamma)$ [9], where the form factors represent dipolar transitions. Here, the $CR(\mu Ti \to eTi)$ is the decay fraction of the $\mu - e$ conversion on Titanium. Particularly, we propose two scenarios: (a) First case. By supposing that $\Omega_{\mu\tau}\Omega_{e\tau} = \Omega_{\mu e}$, it is found that $|\Omega_{\mu e}|^2$ can be expressed

$$|\Omega_{\mu e}|^2 < 400 \frac{\Gamma_\mu}{m_\mu} \frac{CR(\mu Ti \to eTi)}{\alpha(1 - x^2)^3 |y_1 + y_2 + y_3 + y_4|^2}. \tag{11}$$

(b) Second case. By considering that $\Omega_{\mu\tau}\Omega_{e\tau} = \Omega_{\tau\tau}\Omega_{\mu e}$, it is found that

$$|\Omega_{\mu e}|^2 < 400 \frac{\Gamma_\mu}{m_\mu} \frac{CR(\mu Ti \to eTi)}{\alpha(1 - x^2)^3 |\Omega_{\tau\tau}|^2 |y_1 + y_2 + y_3 + y_4|^2}. \tag{12}$$

2 Results and conclusions

To estimate values for the Ω_{bs} parameter and branching ratios for the $B^0_s \to \tau\mu, \tau e, \mu e$ processes, we use the following input data: $m_\mu = 0.105$ GeV, $m_e = 0.00051099$ GeV, $m_\tau = 1.77686$ GeV, $m_{B^0_s} = 5.3668$ GeV, $f_{B^0_s} = 0.230$ GeV, $\tau_{B^0_s} = 2.2876 \times 10^{12}$ GeV^{-1}, Br$(B^0_s \to \mu\bar{\mu})_{\text{Exp}} = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ [10], $\Delta\text{Br}(B^0_s \to \mu\bar{\mu})_{\text{Exp}} = 0.6 \times 10^{-9}$, $y_s = 0.065$, $CR(\mu Ti \to eTi) < 4.3 \times 10^{-12}$ [11, 12]. The Fig. 2 shows the behavior of $|\Omega_{bs}|^2$ as a function of the Z' boson mass for the different models considered here. The mass range considered for the Z' gauge boson is the interval $m_{Z'} = [2, 6]$ TeV, which is in strict accordance with current experimental restrictions. From the graph it can be seen that the Z_η boson is the responsible for the highest signal, while for the same mass interval, the Z_χ provides the lowest signal.

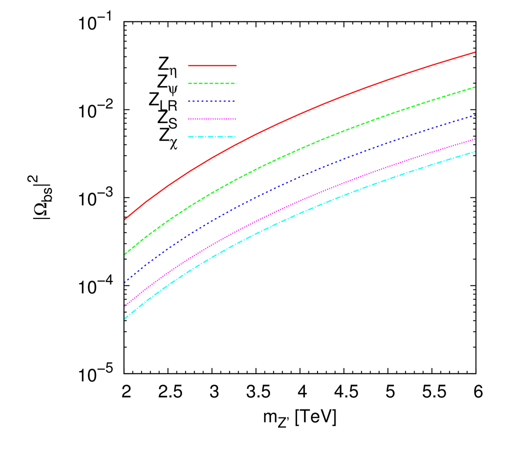
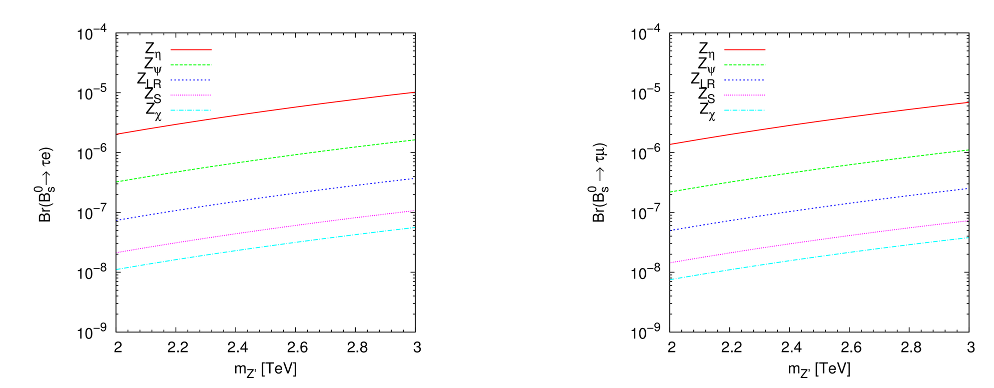


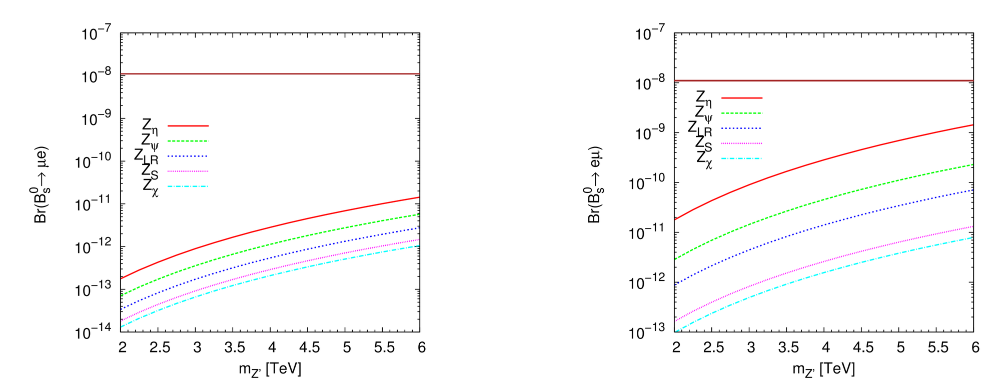
Figure 2: The parameter $|\Omega_{bs}|^2$ as a function of the Z' boson mass.

Finally, by using Eqs. (7) and (9), we can make the predictions for the $B^0_s \to \tau\mu, \tau e, \mu e$ processes. Regarding the $B^0_s \to \tau\mu, \tau e$ decays, we use the $\Omega_{\tau\mu}$ and $\Omega_{\tau e}$ parameters, which were calculated just as in Ref. [13]; by using the experimental upper limits on the $\tau \to ee\bar{e}$ and $\tau \to \mu\mu\bar{\mu}$ decays [11]. In Fig. 3(a), for the $B^0_s \to \tau e$ decay, it can be observed that the Z_η boson provides the highest signal, which is estimated to be Br$(B^0_s \to \tau e) \sim 10^{-6}$, for the mass interval $m_{Z'} = [2, 3]$ TeV; while that for the $B^0_s \to \tau\mu$ decay (Fig. 3(b)), once again, the Z_η boson offers the most intense signal, being of the order of 10^{-6} for the same mass range.



(a) (b)

Figure 3: (a) Br$(B^0_s \to \tau e)$ as a function of $m_{Z'}$. (b) Br$(B^0_s \to \tau\mu)$ as a function of $m_{Z'}$.



(a) (b)

Figure 4: (a) Br$(B^0_s \to e\mu)$ for the scenario $\Omega_{\mu\tau}\Omega_{\tau e} = \Omega_{\mu e}$ and (b) Br$(B^0_s \to e\mu)$ for the scenario $\Omega_{\mu\tau}\Omega_{\tau e} = \Omega_{\tau\tau}\Omega_{\mu e}$. The horizontal line represents the experimental limit Br$(B^0_s \to e\mu)_{\text{Exp}} < 1.1 \times 10^{-8}$.

For the $B^0_s \to e\mu$ process, we are going to consider two scenarios: (a) $\Omega_{\mu\tau}\Omega_{\tau e} = \Omega_{\mu e}$ and (b) $\Omega_{\mu\tau}\Omega_{\tau e} = \Omega_{\tau\tau}\Omega_{\mu e}$, both derived from the $\mu - e$ conversion rate in titanium nuclei. The Fig. 4 shows that the Z_η is responsible for the main signal, while the lowest signal corresponds to the Z_χ boson. In particular, for scenario (a), the Z_η boson offers a signal for Br$(B^0_s \to \mu e) \sim 10^{-13}$ in $m_{Z'} = [2, 3]$ TeV, Br$(B^0_s \to \mu e) \sim 10^{-12}$ in $m_{Z'} = [3.1, 5.4]$ TeV, and Br$(B^0_s \to \mu e) \sim 10^{-11}$ in $m_{Z'} = [5.5, 6]$ TeV; whereas that for (b), Br$(B^0_s \to \mu e) \sim 10^{-11}$ in $m_{Z'} = [2, 2.3]$ TeV, Br$(B^0_s \to \mu e) \sim 10^{-10}$ in $m_{Z'} = [2.4, 4.1]$ TeV, and Br$(B^0_s \to \mu e) \sim 10^{-9}$ in $m_{Z'} = [4.2, 6]$ TeV, being approximately one order of magnitude lower than the experimental limit [11].

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