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Flavor violation in meson decays

J. I. Aranda[a], E. Cruz-Albaro*[a], D. Espinosa-Gómez†[a], J. Montaño[a,b], F. Ramírez-Zavaleta[a], E. S. Tututi[a]
[a] *Facultad de Ciencias Físico Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Avenida Francisco J. Mújica S/N, 58060, Morelia, Michoacán, México*
[b] *CONACYT, México*
E-mail: `feramirez@umich.mx`

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}.

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*Speaker.
†Speaker.

PoS(LHCP2019)023

1. The 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. We consider the more general renormalizable Lagrangian that includes FCNC, mediated by this new massive neutral gauge boson, which is predicted in several extended models [2, 3]:

$$\mathscr{L}_{NC}=\sum_{i,j}\left[\bar{f}_i\gamma^{\alpha}(\Omega_{Lfifj}P_L+\Omega_{Rfifj}P_R)f_j+\bar{f}_j\gamma^{\alpha}(\Omega^*_{Lfjfi}P_L+\Omega^*_{Rfjfi}P_R)f_i\right]Z'_{\alpha}, \tag{1.1}$$

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 represent the strength of the $Z' f_i f_j$ couplings. For simplicity, we assume that $\Omega_{Lf_if_j}=\Omega_{Lf_jf_i}$ and $\Omega_{Rf_if_j}=\Omega_{Rf_jf_i}$. The Lagrangian in Eq. (1.1) contains both flavor-conserving and flavor-violating couplings. The flavor-conserving couplings, $Q^{f_i}_{L,R}$ [4], are related to the Ω couplings as $\Omega_{Lf_if_i}=-g_2Q^{f_i}_L$ and $\Omega_{Rf_if_i}=-g_2Q^{f_i}_R$, where g_2 is the gauge coupling of 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 arising in many superstring-inspired models. The different models are distinguished by their gauge coupling 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 $\mathscr{O}(1)$ [5]. In the sequential Z_S model, the gauge coupling $g_2=g_1$.

2. The decay

The effective Hamiltonian that describes the $B^0_s\to l_il_j$ process (see Fig. 1(a)) can be expressed as follows [6]

$$\begin{aligned}\mathscr{H}_{eff} &= \frac{C_{\rm eff}(m_b)}{m^2_{B^0_s}-m^2_{Z'}+im_{Z'}\Gamma_{Z'}}\{[\bar{s}(p_2)\gamma^{\mu}(\Omega_{Lbs}P_L+\Omega_{Rbs}P_R)b(p_1)]\\ &\times[\bar{l}_i(p_3)\gamma^{\mu}(\Omega_{Ll_il_j}P_L+\Omega_{Rl_il_j}P_R)l_j(p_4)]+[\bar{s}(p_2)\gamma^{\mu}(\Omega_{Lbs}P_L\\ &+\Omega_{Rbs}P_R)b(p_1)][\bar{l}_j(p_4)\gamma^{\mu}(\Omega^*_{Ll_jl_i}P_L+\Omega^*_{Rl_jl_i}P_R)l_i(p_3)]\Big\},\end{aligned} \tag{2.1}$$

where $\Gamma_{Z'}$ is the total decay width of the Z' boson, $m_{B^0_s}$ is the B^0_s meson mass, and $C_{\rm eff}(m_b)$ is the respective Wilson coefficient. To calculate the transition amplitude $\langle 0|\mathscr{H}_{eff}|B^0_s\rangle$, one can generally adopt the vacuum insertion method for the evaluation of the matrix elements in Eq. (2.1), which are given in general as

$$\langle 0|\bar{s}\gamma^{\mu}\gamma_5 b|B^0_s\rangle = i f_{B^0_s}P^{\mu},\ \ \langle 0|\bar{q}\gamma^{\mu}b|B^0_q\rangle=0, \tag{2.2}$$

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

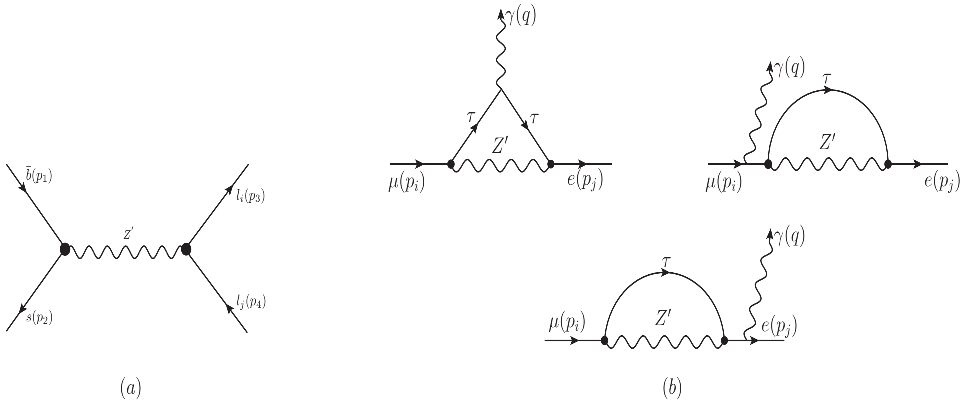


Figure 1: Feynman diagrams that represent the decays: a) $B_s^0 \to l_i l_j$ and b) $\mu \to e\gamma$. Both processes are mediated by a Z' gauge boson.

By using Eq. (2.2) and assuming that $\Omega_{Rbs} - \Omega_{Lbs} \equiv \Omega_{bs}$, the amplitudes for the $B_s^0 \to l_i l_j$ decays can be written as

$$\begin{aligned}\mathscr{M}(B_s^0 \to \overline{l_i} l_j) \;=\; & \frac{i}{2}\frac{f_{B_s^0} C_{\rm eff}(m_b)\,\Omega_{bs}}{m_{B_s^0}^2 - m_{Z'}^2 + i m_{Z'}\Gamma_{Z'}} \overline{l_i}(p_4)\left[(m_{l_i}\Omega_{Rl_il_j} - m_{l_j}\Omega_{Ll_il_j})P_R\right.\\ & + \left.(m_{l_i}\Omega_{Ll_il_j} - m_{l_j}\Omega_{Rl_il_j})P_L\right] l_j(p_3),\end{aligned} \tag{2.3}$$

$$\begin{aligned}\mathscr{M}(B_s^0 \to l_i \overline{l_j}) \;=\; & \frac{i}{2}\frac{f_{B_s^0} C_{\rm eff}(m_b)\,\Omega_{bs}}{m_{B_s^0}^2 - m_{Z'}^2 + i m_{Z'}\Gamma_{Z'}} \overline{l_j}(p_3)\left[(m_{l_j}\Omega^*_{Rl_il_j}\right.\\ & - \left. m_{l_i}\Omega^*_{Ll_jl_i})P_R + (m_{l_j}\Omega^*_{Ll_il_j} - m_{l_i}\Omega^*_{Rl_jl_i})P_L\right] l_i(p_4).\end{aligned} \tag{2.4}$$

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

$$\begin{aligned}\Gamma(B_s^0 \;\to\; l_i l_j) = & \frac{C_{\rm eff}^2(m_b)|\Omega_{bs}|^2 m_{B_s^0}^3 f_{B_s^0}^2}{32\pi\left[(m_{B_s^0}^2 - m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2\right]}\left\{(|\Omega_{Ll_il_j}|^2 + |\Omega_{Rl_il_j}|^2)\right.\\ & \times \left[\frac{(m_{li}^2 + m_{lj}^2)}{m_{B_s^0}^2} - \frac{(m_{li}^2 - m_{lj}^2)^2}{m_{B_s^0}^4}\right] - \left.\frac{4 m_{li} m_{lj}}{m_{B_s^0}^2}{\rm Re}(\Omega_{Rl_il_j}\Omega^*_{Rl_il_j})\right\}\\ & \times \sqrt{\left[1 - \frac{(m_{l_j} + m_{l_i})^2}{m_{B_s^0}^2}\right]\left[1 - \frac{(m_{l_i} - m_{l_j})^2}{m_{B_s^0}^2}\right]}.\end{aligned} \tag{2.5}$$

In the following, we suppose that $\Omega_{Ll_il_j} = \Omega_{Rl_il_j} = \Omega_{l_il_j}$.

In accordance with experimental conditions we need to account for the sizable effect of the $B_s^0 - \overline{B_s^0}$ mixing, in which the decay width difference between the B_s^0-mass eigenstates is crucial [7]. In this sense,

$${\rm Br}(B_s^0 \to l_i l_j) = \tau_{B_s^0}\Gamma(B_s^0 \to l_i l_j) \simeq (1 - y_s){\rm Br}(B_s^0 \to l_i l_j)_{\rm Exp}, \tag{2.6}$$

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

3. Estimation of the $Z'bs$ coupling from the $B_s^0 \to \mu^+\mu^-$ decay

In the following, we are going to derive the expression for the Ω_{bs}, which represents the intensity of th $Z'bs$ coupling, by using the $B_s^0 \to \mu^+\mu^-$ process, to this purpose, it is resorted to Eq. (2.5). Since the $B_s^0 \to \mu^+\mu^-$ decay was already measured [8], we will assume that within the experimental uncertainty the new physics effects could be found. Thereby,

$$\Delta\Gamma(B_s^0 \to \mu\bar{\mu})_{\rm Exp} = \frac{g_2^2 C_{eff}^2(m_b)|\Omega_{bs}|^2 m_{B_s^0} f_{B_s^0}^2 m_\mu^2}{32\pi\left[(m_{B_s^0}^2 - m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2\right]}|Q_L^\mu - Q_R^\mu|^2 \sqrt{1-\frac{4m_\mu^2}{m_{B_s^0}^2}}, \tag{3.1}$$

where $\Omega_{L,R_{\mu\mu}} = -g_2 Q_{L,R}^\mu$. Finally, when inserting Eq. (3.1) into Eq. (2.6) we obtain

$$|\Omega_{bs}|^2 = \frac{32\pi(1-y_s)\left[(m_{B_s^0}^2 - m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2\right]\Delta{\rm Br}(B_s^0 \to \mu\bar{\mu})_{\rm Exp}}{\tau_{B_s^0} g_2^2 C_{\rm eff}^2(m_b) m_{B_s^0} f_{B_s^0}^2 m_\mu^2 |Q_L^\mu - Q_R^\mu|^2 \sqrt{1-\frac{4m_\mu^2}{m_{B_s^0}^2}}}. \tag{3.2}$$

It should be recalled that the last equation represents a bound over the strength of the $Z'bs$ coupling.

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

We will estimate the $\Omega_{\mu e}$ parameter through the $\mu \to e\gamma$ decay resorting to the $\mu - e$ conversion, where the contributions of the flavor-violating vertex, $Z'\mu e$, to the $\mu \to e\gamma$ process are given by the Feynman diagrams shown in Fig. 1(b). Therefore, we can write the associated branching ratio as follows

$$Br(\mu \to e\gamma) = \frac{\alpha}{2}(1-x^2)^3\left[|\Omega_{\mu\tau}\Omega_{e\tau}|^2|y_1+y_2+y_3+y_4|^2\right]\frac{m_\mu}{\Gamma_\mu}, \tag{4.1}$$

where $x = \frac{m_e}{m_\mu}$ and Γ_μ is the total decay width of the muon. The y_1, y_2, y_3 and y_4 variables contain the loop contributions and are explicitly given in Ref. [9]. The $\Omega_{\mu e}$ parameter can be extracted by using Eq. (4.1) along with the conversion rate in titanium nuclei, $CR(\mu Ti \to eTi) \cong \frac{1}{200}{\rm Br}(\mu \to e\gamma)$ [10]. In order to bound $\Omega_{\mu e}$, 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

$$|\Omega_{\mu e}|^2 < 400\frac{\Gamma_\mu}{m_\mu}\frac{CR(\mu Ti \to eTi)}{\alpha(1-x^2)^3|y_1+y_2+y_3+y_4|^2}. \tag{4.2}$$

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

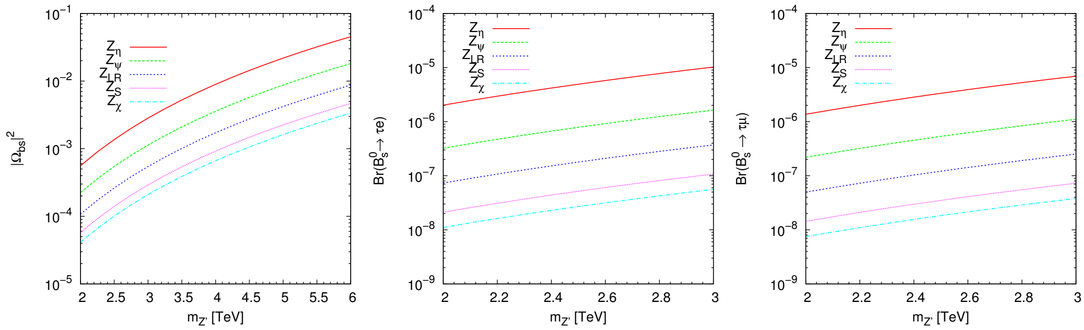
$$|\Omega_{\mu e}|^2 < 400\frac{\Gamma_\mu}{m_\mu}\frac{CR(\mu Ti \to eTi)}{\alpha(1-x^2)^3|\Omega_{\tau\tau}|^2|y_1+y_2+y_3+y_4|^2}. \tag{4.3}$$

The former scenarios can be justified by thinking that there is an effective coupling between four charged leptons $\mu e\tau\tau$, for example, through a dispersion $\mu e \to \tau\tau$ mediated by a Z' gauge boson.

PoS(LHCP2019)023

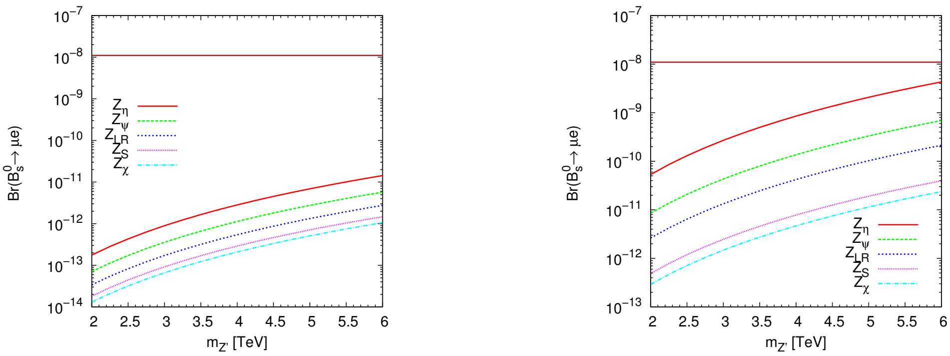
5. Results and conclusions

In order to estimate values for the Ω_{bs} parameter and branching ratios for the $B_s^0 \to \tau\mu, \tau e, \mu e$ processes, we use the following input data: $m_\mu = 0.105$ GeV, $m_e = 0.00051099$ GeV, $m_\tau = 1.77686$ GeV, $m_{B_s^0} = 5.3668$ GeV, $f_{B_s^0} = 0.230$ GeV, $\tau_{B_s^0} = 2.2876 \times 10^{12}$ GeV^{-1}, $\mathrm{Br}(B_s^0 \to \mu\bar{\mu})_{\mathrm{Exp}} = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ [8], $\Delta\mathrm{Br}(B_s^0 \to \mu\bar{\mu})_{\mathrm{Exp}} = 0.6 \times 10^{-9}$, $y_s = 0.065$ and $CR(\mu Ti \to eTi) < 4.3 \times 10^{-12}$ [11, 12]. The Fig. 2(a) shows the behavior of $|\Omega_{bs}|^2$ as a function of the Z' boson mass for the different models considered. The mass range corresponds to the interval $m_{Z'} = [2,6]$ TeV, which is in strict accordance with current experimental restrictions. From Fig. 2, it can be appreciated that the Z_η boson is the responsible for the highest value, while for the same mass interval, the Z_χ provides the lowest one. Regarding the $B_s^0 \to \tau\mu, \tau e$ decays, we estimate the $\Omega_{\tau\mu}$ and $\Omega_{\tau e}$ parameters just as in Ref. [13], by using experimental upper limits on the $\tau \to ee\bar{e}$ and $\tau \to \mu\mu\bar{\mu}$ decays [11]. In Fig. 2(b), it can be observed that the Z_η boson contribution is $\mathrm{Br}(B_s^0 \to \tau e) \sim 10^{-6}$, for the mass interval $m_{Z'} = [2,3]$ TeV; while that for the $B_s^0 \to \tau\mu$ decay (Fig. 2(c)), once again, the Z_η boson offers the most intense contribution, being of the order of 10^{-6} for the same $m_{Z'}$ range.



(a) (b) (c)

Figure 2: (a) The parameter $|\Omega_{bs}|^2$ as a function of the Z' boson mass. (b) $\mathrm{Br}(B_s^0 \to \tau e)$ as a function of $m_{Z'}$. (c) $\mathrm{Br}(B_s^0 \to \tau\mu)$ as a function of $m_{Z'}$.



(a) (b)

Figure 3: (a) $\mathrm{Br}(B_s^0 \to \mu e)$ for the scenario $\Omega_{\mu\tau}\Omega_{\tau e} = \Omega_{\mu e}$ and (b) $\mathrm{Br}(B_s^0 \to \mu e)$ for the scenario $\Omega_{\mu\tau}\Omega_{\tau e} = \Omega_{\tau\tau}\Omega_{\mu e}$. The horizontal line represents the experimental bound for $\mathrm{Br}(B_s^0 \to \mu e)_{\mathrm{Exp}} < 1.1 \times 10^{-8}$.

In Fig. 3 the numerical results for the $\mathrm{Br}(B_s^0 \to \mu e)$ are presented. From this figure we observe that the Z_η is responsible for the main contribution, while the lowest one corresponds to the Z_χ boson. In particular, for scenario (a), the Z_η boson offers a $\mathrm{Br}(B_s^0 \to \mu e) \sim 10^{-13}$ in $m_{Z'} = [2,3]$ TeV, $\mathrm{Br}(B_s^0 \to \mu e) \sim 10^{-12}$ in $m_{Z'} = [3.1, 5.4]$ TeV and $\mathrm{Br}(B_s^0 \to \mu e) \sim 10^{-11}$ in $m_{Z'} = [5.5, 6]$ TeV; whereas for scenario (b), $\mathrm{Br}(B_s^0 \to \mu e) \sim 10^{-11}$ in $m_{Z'} = [2, 2.3]$ TeV, $\mathrm{Br}(B_s^0 \to \mu e) \sim 10^{-10}$ in $m_{Z'} = [2.4, 4.1]$ TeV and $\mathrm{Br}(B_s^0 \to \mu e) \sim 10^{-9}$ in $m_{Z'} = [4.2, 6]$ TeV, being approximately one order of magnitude lower than the experimental bound [11].

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PoS(LHCP2019)023