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Heavy Majorana Neutrinos and Delta L=2 B and top decays in B factories

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Majorana neutrinos can induced Lepton number violation (LNV)in four-body decays of the neutral B meson and the top quark. We study the effects of Majorana neutrinos in these $|\Delta L| = 2$ decays in an scenario where a single heavy neutrino can enhance the amplitude via the resonant mechanism. Using current bounds on heavy neutrino mixings, the most optimistic branching ratios turn out to be at the level of 10^{-6} for $\bar{B}^0 \to D^+ e^- e^- \pi^+$ and $t \to b l^+ l^+ W^-$ decays. Searches for these LNV decays at future facilities can provide complementary constraints on masses and mixings of Majorana neutrinos.

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1. Introduction

The possibility to observe the effects of heavier Majorana neutrinos, accessible in the kinematical range of current experiments, is very exciting as they can induce large rates for $\Delta L = 2$ decays through the mechanism of resonant enhancement [1]. Indeed, the appearance of sterile neutrinos with masses in the range of hundreds of MeV's to a few GeV's is possible in scenarios of dynamical electroweak symmetry breaking as shown for instance in [2, 3, 4]. By means of the resonant mechanism, neutrinos with these intermediate mass scales can produce an enhancement in the three-body $\Delta L = 2$ decays of pseudoscalar mesons $M_1^+ \to l^+ l^+ M_2^-$ and the tau lepton $\tau^- \to l^+ M_1^- M_2^-$ [1, 5, 6, 7, 8, 9]. So far, some experimental uppers bounds have been reported in refs. [10, 11, 12, 13]; very recently, by using 36 pb-1 of integrated luminosity, the LHCb collaboration has been able to derive upper limits for LNV charged B meson decays $B(B^+ \to K^-(\pi^-)\mu^+\mu^+) < 5.8(5.4) \times 10^{-8}$ [14]. These studies are expected to be extended by the LHCB experiment by including the $B^+ \to D^-_{(s)}\mu^+\mu^+,\ \bar{D}^0\mu^+\mu^+\pi^-$ decay modes [14], which toghether with similar analyses that can be performed at the SuperB Flavor Factories [15] makes very attractive the studies of LNV B meson decays. Similarly, like-sign dileptons may be produced via the resonance enhancement mechanism in four-body decays of top quarks and W gauge bosons, as it has been investigated for instance in Refs. [17, 18, 19, 16].

In the present talk we consider the four-body decays of neutral B mesons, $\bar{B}^0 \to D^+ l^- l^- \pi^+$ with $l = e,\ \mu$, in the favored scenario of resonant neutrino enhancement. The dynamics of this four-body decay involves the transition $B \to D$ form factors and is different from the one driving the three-body decays of mesons and tau leptons which involve the meson decay constants. These $\Delta L = 2$ decays of neutral B mesons and $t \to b l^+ l^+ W^-$ decays ($l = e,\ \mu,\ \tau$) decays have been investigated in ref. [16]. In this talk we shall present a summary of these results.

2. Four-body $\Delta L = 2$ decays of heavy flavors

The Feynman diagrams that describe the LNV decays of the neutral B meson are shown in Figures 1. Contributions containing the properly antisymmetrized contributions due to the exchange of identical leptons in the final state must be added to these diagrams.

Following previous studies [17, 1], we consider a model with three left-handed SU(2) lepton doublets $L_{aL}^T = (\nu_a,\ l_a)_L$, $(a = 1,2,3)$, and n right-handed singlets N_{bR} $(b = 1,2,\cdots n)$. In the basis

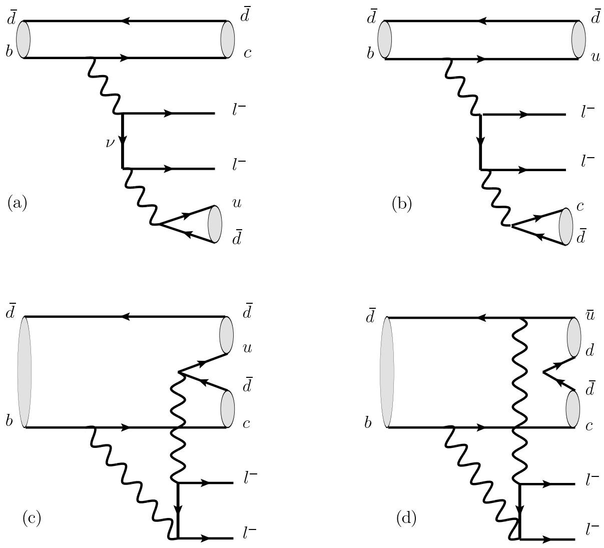

Figure 1: Feynman graph for the $\Delta L = 2$ neutral $\bar{B}$ meson decay.

of mass eigenstates, the charged current interactions of leptons are given by [1]:

$$\mathscr{L}_l^{\rm ch} = -\frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{l=e}^{\tau} \sum_{m=1}^{3} V_{lm} \bar{\nu}_m \gamma^\mu P_L l + \sum_{l=e}^{\tau} \sum_{m=1}^{n} U_{lm} \overline{N_m^c} \gamma^\mu P_L l \right) + \text{h. c.} \tag{2.1}$$

where $P_L = (1-\gamma_5)/2$ is the left-handed chirality operator, g is the $SU(2)_L$ gauge coupling, $\psi^c \equiv C\bar{\psi}^T$ is the charge conjugated spinor, and V_{lm} (U_{lm}) denotes the light (heavy) neutrino mixings; the subscript m refers to the mass eigenstate basis entering the diagonalized Majorana mass term for neutrinos [1]:

$$\mathscr{L}_m^\nu = -\frac{1}{2} \left(\sum_{m=1}^{3} m_m^\nu \overline{\nu_{mL}} \nu_{mR}^c + \sum_{m=4}^{n} m_m^N \overline{N_{mL}^c} N_{mR} \right) + \text{h. c.} \, . \tag{2.2}$$

For simplicity,we will assume that only one heavy neutrino with mass m_N and charged current couplings U_{lN} to leptons, dominates the decay amplitudes via the resonant enhancement mechanism.

2.1 $B \to Dll\pi$ decays

Let us first consider the $\bar{B}^0(p) \to D^+(p_1) l^-(p_2) l^-(p_3) \pi^+(p_4)$ decays (see Figure 2), where p_i denote the four-momenta of final state particles. In the range of neutrino masses m_N where the resonance effects dominate the decay amplitude, the diagrams of Figure 2(c) and 2(d) will give very small contributions. In addition, we note that diagram 2(b) is suppressed with respect to 2(a) due to smaller Cabibbo-Kobayashi-Maskawa (CKM) factors ($|V_{ub}V_{cd}/(V_{cb}V_{ud})| \sim 0.02$). Therefore, we keep the diagram shown in 2(a) as the dominant contribution. The properly antisymmetrized decay amplitude is given by:

$$\mathscr{M} = G_F^2 V_{cb} V_{ud} \langle D(p_1)|\bar{c}\gamma^\mu b|B(p)\rangle \cdot \bar{u}(p_2)\left[\mathscr{P}_N(p_2)\gamma_\mu\gamma_\nu + \mathscr{P}_N(p_3)\gamma_\nu\gamma_\mu\right] u^c(p_3)\,(i f_\pi p_4^\nu) \quad (2.3)$$

where V_{ij} denotes the ij entry of the CKM quark mixing matrix, G_F is the Fermi constant and $f_\pi = 130.4$ MeV is the π^+ decay constant.

In the above expression we have defined the factor

$$\mathscr{P}_N(p_i) = \frac{U_{lN}^2 m_N}{(Q-p_i)^2 - m_N^2 + i m_N \Gamma_N}\ , \quad (2.4)$$

where $Q = p - p_1 = p_2 + p_3 + p_4$ is the momentum transfer and U_{lN} denotes the heavy neutrino mixing. Γ_N represents the decay width of the heavy neutrino which depends on the decay channels that can be opened at the mass m_N.The mixings of the heavy neutrino with the three charged leptons will be taken as the currently most restrictive bounds as reported in Ref. [21]

$$\mathrm{SetI}: \ \ |U_{eN}|^2 < 3\times 10^{-3},\ \ |U_{\mu N}|^2 < 3\times 10^{-3},\ \ |U_{\tau N}|^2 < 6\times 10^{-3}\ . \quad (2.5)$$

The hadronic matrix element in Eq. (4) is given by:

$$\langle D^+(p_1)|\bar{c}\gamma_\mu b|\bar{B}^0(p)\rangle = \left((p+p_1)_\mu - \frac{m_B^2 - m_D^2}{t} Q_\mu\right) F_1(t) + \frac{m_B^2 - m_D^2}{t} Q_\mu F_0(t)\ , \quad (2.6)$$

where $t = Q^2$. For the purposes of a numerical evaluation, we will use two common parametrizations of the form factors $F_{1,0}(t)$, namely the one provided by the Wirbel-Stech-Bauer (WSB) model [22]:

$$F_1^{\mathrm{WSB}}(t) = \frac{F_1^{\mathrm{WSB}}(0)}{1 - t/m_{1^-}^2},\quad F_0^{\mathrm{WSB}}(t) = \frac{F_0^{\mathrm{WSB}}(0)}{1 - t/m_{0^+}^2}\ , \quad (2.7)$$

where $F_1^{\mathrm{WSB}}(0) = F_0^{\mathrm{WSB}}(0) = 0.69$, $m_{1^-} = 6.34$ GeV and $m_{0^+} = 6.8$ GeV [22] and, just for comparison, we will use also the parametrization provided by the covariant light front (CLF) model [23]:

$$F_1^{\mathrm{CLF}}(t) = \frac{F_1^{\mathrm{CLF}}(0)}{1 - a_1(t/m_B^2) + b_1(t/m_B^2)^2},\quad F_0^{\mathrm{CLF}}(t) = \frac{F_0^{\mathrm{CLF}}(0)}{1 - a_0(t/m_B^2) + b_0(t/m_B^2)^2}\ , \quad (2.8)$$

where $F_1^{\mathrm{CLF}}(0) = F_0^{\mathrm{CLF}}(0) = 0.67$, $a_1 = 1.25$, $b_1 = 0.39$, $a_0 = 0.65$ and $b_0 = 0.0$ [23]. The dominant decay modes of the neutrino in the range of masses relevant for resonant B meson decays are the following: $l^\mp P^\pm$, $\nu_l P^0$, $l^\mp V^\pm$, $\nu_l V^0$, $l_1^\mp l_2^\pm \nu_{l_2}$, $\nu_{l_1} l_2^- l_2^+$, and $\nu_{l_1}\nu\bar{\nu}$, where $l,\ l_1,\ l_2 = e,\ \mu,\ \tau$, and P (V) denotes a pseudoscalar (vector) meson state. The expressions for the partial decay rates of

$\bar{B}^0 \to D^+e^-e^-\pi^+$			$\bar{B}^0 \to D^+\mu^-\mu^-\pi^+$		
m_N (MeV)	WSB	CLF	m_N (MeV)	WSB	CLF
170	2.6×10^{-6}	3.4×10^{-6}	250	3.0×10^{-7}	3.9×10^{-7}
190	2.8×10^{-6}	3.6×10^{-6}	270	4.1×10^{-7}	5.4×10^{-7}
200	2.6×10^{-6}	3.4×10^{-6}	300	3.4×10^{-7}	4.3×10^{-7}
220	1.5×10^{-6}	2.0×10^{-6}	400	1.4×10^{-7}	1.9×10^{-7}
250	7.3×10^{-7}	9.7×10^{-7}	500	7.0×10^{-8}	1.0×10^{-7}
300	2.5×10^{-7}	3.3×10^{-7}	600	4.0×10^{-8}	6.0×10^{-8}

Table 1: Branching ratios for $\bar{B}^0 \to D^+\ell^-\ell^-\pi^+$ decays using the Set I of the heavy neutrino mixings. WSB [22] and CLF [23] refer to the form factor models for the $B \to D$ transition.

these channels can be found in Appendix C of Ref. [1].The decay width Γ_N is so tiny that the Narrow Width Approximation (NWA) of Eq. (5),

$$\lim_{\Gamma_N\to 0} \mathscr{P}_N(p_i) = -i\pi m_N U_{lN}^2 \delta\left((Q-p_i)^2 - m_N^2\right) \tag{2.9}$$

is required to perform the numerical integrations to compute the decay rates from Eq. (3).

In Table I we show the largest possible values of the branching ratios of $\bar{B}^0 \to D^+l^-l^-\pi^+$ decays ($l = e,\ \mu$), which correspond to the lower range of neutrino masses. We have evaluated these results for the two different form factor models previously mentioned.

2.2 LNV top quark decay

LNV transitions with $\Delta L = 2$ has been studied also at higher energies. The $t \to b l_i^+ l_j^+ W^-$ decay (and its crossed $W^+ \to l_i^+ l_j^+ + 2$ jets channel) has been considered previously in Ref. [17]; similar top quark decays that also include the final W gauge boson decay into two jets were studied in [18]. The top decay can be resonantly enhanced if the heavy neutrino mass lies in the range $m_W + m_l \leq m_N \leq m_t - m_b - m_l$. In addition (see Figure 1) we can expect an enhancement of the top quark decay amplitude due to the virtual W boson emitted from the top quark vertex which can be produced also in a resonant way. As it was emphasized in ref. [17], the final state W boson in this $\Delta L = 2$ top quark decay has the 'wrong' charge signature when compared to the dominant $t \to bW^+$ decay. The total decay width of the neutrino for the range of neutrino masses giving rise to the resonance enhancement, is determined from the following set of two-body final states: $N \to l^\pm W^\mp,\ \nu_l Z^0$ and $\nu_l H$. The expressions for the total width by neglecting the charged lepton masses is given in ref. [17, 1]: The branching ratios of $t \to bl^+l^+W^-$ $(l = e,\ \mu,\ \tau)$ decays turn out to be of order $10^{-6} \sim 10^{-7}$ for these values of Majorana masses.

3. LNV in heavy quarks decays and Super B factories

We close this section with an estimate of the expected sensitivities to the signals of our $\Delta L = 2$ decays. Using as a (conservative) reference the $\sim 450 \times 10^6$ $B\bar{B}$ pairs accumulated by the BABAR collaboration at the $\Upsilon(4S)$, we can provide an estimate of the sensitivity to the branching ratio of $\bar{B}^0 \to D^+l^-l^-\pi^+$ decay at the B factories by using the $K^-\pi^+\pi^+$ mode to reconstruct the charged D meson. By assuming a 70% efficiency for the identification and reconstruction of each of the six charged tracks in the final state one can reach a sensitivity of $\sim 2.0 \times 10^{-7}$ which can test some range of our upper limits for the di-leptonic channels. Of course, this optimistic estimate does not include the combinatorial background for this detection channel, although it can motivate a more detailed study of backgrounds and efficiencies (note also that, under similar assumptions, slightly better sensitivities can be reached using Belle data which is about the double of B meson pairs produced by BABAR). Improved sensitivities can be obtained at the Super Flavor Factories [15] which are expected to accumulate a larger data set by a factor of 50 to 75 with respect to B factories. Also, as it was mentioned in the Introduction, there are good perspectives at the LHCb Experiment which can provide sensitive improvements on these LNV decays in the dimuon channel based on the analysis already done in the case of LNV searches in B^+ meson decays [14]. Regarding the top quark $\Delta L = 2$ decays, the sensitivities that can be reached at the Large Hadron Collider (LHC) are not sufficient to test our predictions, as it has been discussed in Ref. [17]. Only in the eventual case of an upgraded Super-LHC Experiment, which should increase the LHC luminosity by a factor of 10 [25], one can expect that branching ratios of 10^{-6} for $t \to bl^+l^+W^-$ decays could be accessible.

4. Conclusions

In this talk, we have studied the potential of heavy flavor four-body $\Delta L = 2$ decays to shed some light on the masses and couplings of heavier Majorana neutrinos. If the masses of such neutrinos produce a resonance enhancement of these heavy flavor decays, the corresponding branching ratios turns out to be, in the most optimistic cases, at the level of 10^{-6} for neutral B meson and top quarks decays. These branching fractions of four-body neutral B meson decays are at the level of the upper bounds obtained in experimental studies of $B^{\pm}$ three-body decays. Thus, their searches at current and future experimental facilities can be helpful to provide complementary constrains to the ones derived from three-body decays of τ leptons and charged B and D mesons.

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