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Study Majorana neutrino contribution to B-meson semi-leptonic rare decays

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ABSTRACT

B-meson semi-leptonic rare decays are sensitive to new physics beyond standard model. We study the $B^- \to \pi^-\mu^+\mu^-$ process and investigate the Majorana neutrino contribution besides the standard model contribution to its decay width. The standard model predictions are estimated with Heavy Quark Symmetry and Lattice QCD, perturbative QCD and QCD Light Cone Sum Rule. The constraints on the Majorana neutrino mass and mixing parameter are obtained from this decay channel with the latest LHCb data. Utilizing the best fits for the parameters, we study the lepton number violating decay $B^- \to \pi^+\mu^-\mu^-$, and find its branching ratio is roughly consistent with the LHCb data reported recently.

1. Introduction

In standard model (SM), neutrinos only take part in the weak interaction and are massless particles. However, the neutrino oscillations discovered in neutrino experiments indicate that neutrinos have non-zero mass [1–5]. The 10^{12} order hierarchy in m_t/m_ν and the large mixing in neutrino sector suggest a possible new mechanism for neutrino mass generation which is different from the fermion mass generated in SM such as seesaw mechanisms [6]. In type I seesaw mechanism, the neutrino mass is generated by introducing heavy right-handed Majorana neutrino. The Majorana nature of massive neutrinos typically manifests itself in some processes where the lepton number can be violated by two units. In order to disentangle the neutrino mass generation mechanism, many efforts have been made to study such lepton number violating (LNV) processes [7–11].

It is well known that neutrinoless nuclear double beta ($0\nu\beta\beta$) decays can be induced by Majorana neutrino. For the exchange of a light Majorana neutrino, $0\nu\beta\beta$ decay rate is proportional to the square of the effective Majorana mass, and many strong constraints have been obtained under this assumption [13,12,14]. For the heavy Majorana neutrino, the heavy meson LNV decays have been studied extensively both in theory and at experiment. Many LNV processes from pseudoscalar meson and τ lepton decays are studied, and the existing limits on the mass and mixing of the heavy Majorana neutrino are extracted from the experimental data in [15]. The rare decays of heavy mesons to a vector or pseudoscalar meson are investigated in [16,17]. The four-body LNV decays of heavy pseudoscalar B and D mesons are studied in [18,19]. The upper limits for the branching ratios of the B-meson LNV decays have been obtained. $B^+ \to D^-e^+e^+(e^+\mu^+, \mu^+\mu^+)$ are measured by Belle Collaboration [20], $B^+ \to \pi^-(K^-)e^+e^+(\mu^+\mu^+)$ by BaBar Collaboration [22], and $B^- \to D^+(D^{*+}, \pi^+, D_s^+, D^0\pi^+)\mu^-\mu^-$ by LHCb Collaboration [21,23]. According to LHCb results, the upper limit for the branch ratio of $B^- \to \pi^+\mu^-\mu^-$ is 4.0×10^{-9} at 95% confidence level (C.L.) which is applicable for the heavy Majorana neutrino lifetime $\tau_N \lesssim 1$ ps, and a model dependent upper limit on the coupling between muon and a possible Majorana neutrino as a function of m_N ($250\text{ MeV} < m_N < 5000\text{ MeV}$) is also given for τ_N up to 1000 ps at 95% C.L.

Recently, $B^- \to \pi^-\mu^+\mu^-$ has been observed with high statistics at the LHCb experiment, with its branching ratio measured at $(2.3 \pm 0.6\ (stat.) \pm 0.1\ (syst.)) \times 10^{-8}$ (5.2σ significance) [24]. This rare decay is induced by flavor changing neutral current $b \to d\ell^+\ell^-$ and suppressed in SM. This kind of process can be used to probe the new physics beyond SM. Many theoretical studies on

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this channel within SM have been performed [25–29], and new physics contributions cannot be ruled out. In this paper, we investigate the Majorana neutrino contribution to $B^- \to \pi^-\mu^+\mu^-$, and obtain constraints on the mixing parameter between muon and the Majorana neutrino. Furthermore, we study the LNV decay $B^- \to \pi^+\mu^-\mu^-$ with the obtained mixing parameter, and our predictions for the $B^- \to \pi^+\mu^-\mu^-$ branching ratio are roughly consistent with LHCb data.

This paper is organized as follows. In Section 2, we briefly review the theoretical framework related to Majorana neutrino. In Section 3, the numerical results and discussion are given. Finally, we give a short summary.

2. Theoretical framework

In one of the simplest extensions of the SM, Majorana neutrino mass term is generated by introducing n right-handed $SU(2)_L \times U(1)_Y$ singlet neutrinos N_R in addition to the three generations of left-handed $SU(2)_L$ doublet leptons L_L and right-handed charged leptons ℓ_R,

$$L_L = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L, \quad \ell_R, \quad N_R. \tag{1}$$

The Dirac mass terms are generated with the Yukawa couplings to the Higgs doublet in the SM, and the corresponding gauge invariance allows the right-handed neutrino singlets to have Majorana mass terms. The gauge-invariant Lagrangian relevant to lepton masses is expressed as

$$-\mathcal{L}_Y = Y_\ell \overline{L_L} H \ell_R + Y_\nu \overline{L_L}\tilde{H} N_R + \overline{N_R^c} M_R N_R + \text{h.c.} \tag{2}$$

where H denotes the Higgs doublet, and $\tilde{H} = i\sigma_2 H^*$. M_R is the right-handed Majorana neutrino mass matrix. After the spontaneous gauge symmetry breaking, the mass matrix of charged leptons $M_\ell = Y_\ell v/\sqrt{2}$ and the Dirac neutrino mass matrix $M_D = Y_\nu v/\sqrt{2}$ are obtained, with the vacuum expectation value $\langle H\rangle = v/\sqrt{2}$. The complete neutrino mass sector is composed of both Dirac and Majorana mass term

$$-\mathcal{L}_M = \left(\overline{\nu_L}, \overline{N_R^c}\right) \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix} + \text{h.c.} \tag{3}$$

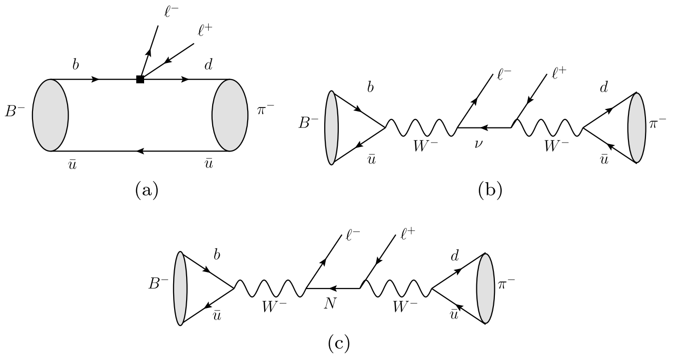
At the leading-order in M_R^{-1}, mass matrix for the three light neutrinos can be written as

$$M_\nu \sim -M_D M_R^{-1} M_D^T. \tag{4}$$

This is the type I seesaw mechanism which connects the small neutrino masses to the heavy Majorana neutrino masses. Seesaw mechanism provides a natural explanation for the tiny neutrino mass. The gauge interaction Lagrangian for the charged current in terms of the neutrino mass eigenstates has the following form

$$-\mathcal{L} = \frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U_{\ell m}^* \overline{\nu_m} \gamma^\mu P_L \ell + \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \overline{N_{m'}^c} \gamma^\mu P_L \ell \right) + \text{h.c.} \tag{5}$$

where $P_L = (1-\gamma_5)/2$, ν_m $(m = 1, 2, 3)$ and $N_{m'}$ $(m' = 4, \cdots, 3+n)$ are the mass eigenstates, $U_{\ell m}$ $(V_{\ell m'})$ is the mixing matrix element between the lepton flavor and light (heavy) neutrinos. In this paper, we simply assume that there is only one heavy Majorana neutrino N, with its mass $m_\pi < m_N < m_B$ where $m_{B(\pi)}$ is the mass of the $B(\pi)$ meson.



(a) (b) (c)

Fig. 1. Feynman diagrams for the decay process $B^- \to \pi^-\ell^+\ell^-$.

First, we study the process $B^-(p) \to \ell^-(p_1)\ell^+(p_2)\pi^-(p_3)$, where p, p_1, p_2 and p_3 denote the four-momentum of the corresponding particle. The dominated Feynman diagram in SM is displayed in Fig. 1(a), where the black square denotes the effective vertex of the leading-order $b \to d\ell^+\ell^-$ transition [30]. The corresponding amplitude can be written as

$$\begin{aligned}\mathcal{M}_a = \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{td}^* \Big[& C_9^{eff}\langle\pi(p_3)|\bar{d}\gamma_\mu P_L b|B(p)\rangle \bar{u}(p_1)\gamma^\mu v(p_2) \\ & + C_{10}^{eff}\langle\pi(p_3)|\bar{d}\gamma_\mu P_L b|B(p)\rangle \bar{u}(p_1)\gamma^\mu\gamma_5 v(p_2) \\ & - 2C_7^{eff}\frac{1}{q^2}\langle\pi(p_3)|\bar{d} i\sigma_{\mu\nu}q^\nu(m_b P_R + m_d P_L)b|B(p)\rangle \\ & \times \bar{u}(p_1)\gamma^\mu v(p_2)\Big],\end{aligned} \tag{6}$$

with $P_{L,R} = (1 \mp \gamma_5)/2$ and $s = q^2 = (p_1+p_2)^2 = (p-p_3)^2$. $m_{b(d)}$ denotes the mass of the b (d) quark. G_F is the Fermi coupling constant, α is the fine-structure constant and $V_{q_1q_2}$ is the CKM matrix element. The analytic expressions for all Wilson coefficients C_i, except C_9^{eff}, are the same as that used to study the $b \to s$ transition, and can be founded in [31]. The next-to-leading approximation for Wilson coefficient C_9^{eff} can be written as [32]

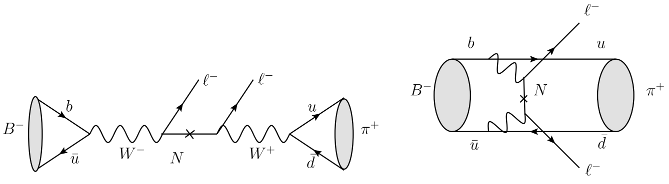
$$\begin{aligned}C_9^{eff} = C_9\left[1 + \frac{\alpha_s(\mu)}{\pi}\omega(\hat{s})\right] & + g(\hat{m}_c, \hat{s})(3C_1 + C_2 + 3C_3 + C_4 + 3C_5 + C_6) \\ & - \frac{1}{2}g(\hat{m}_d, \hat{s})(C_3 + 3C_4) \\ & - \frac{1}{2}g(\hat{m}_b, \hat{s})(4C_3 + 4C_4 + 3C_5 + C_6) \\ & + \frac{2}{9}(3C_3 + C_4 + 3C_5 + C_6) \\ & + \lambda_u\big[g(\hat{m}_c, \hat{s}) - g(\hat{m}_u, \hat{s})\big](3C_1 + C_2),\end{aligned} \tag{7}$$

where $\lambda_u = (V_{ub}V_{ud}^*)/(V_{tb}V_{td}^*)$, $\hat{m}_j = m_j/m_B$ with $j = u, d, c, b$ and $\hat{s} = s/m_B^2$. The values of Wilson coefficients C_i $(i = 1, 2, \cdots, 10)$ used in this work are listed in Table 1. The relevant expressions of $\omega(\hat{s})$ and $g(\hat{m}_j, \hat{s})$ can be found in [32,33]. The hadronic matrix elements in the decay amplitude can be parameterized in terms of $B \to \pi$ form factors $f_+^{B\pi}(q^2)$, $f_0^{B\pi}(q^2)$ and $f_T^{B\pi}(q^2)$,

$$\langle\pi(p_3)|\bar{d}\gamma_\mu b|B(p)\rangle = (p+p_3)_\mu f_+^{B\pi}(q^2) + \frac{m_B^2 - m_\pi^2}{q^2} q_\mu\left(f_0^{B\pi}(q^2) - f_+^{B\pi}(q^2)\right),$$

Table 1
The values of Wilson coefficients $C_i(\mu)$ in SM at the scale $\mu = m_b$ at the leading logarithmic approximation, with $m_W = 80.4$ GeV, $m_t = 173.5$ GeV, $m_b = 4.8$ GeV.

C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
−0.246	1.106	0.011	−0.025	0.007	−0.031	−0.312	−0.187	4.211	−4.501



(a) (b)

Fig. 2. Feynman diagrams for $B^- \to \pi^+ \ell^- \ell^-$ via Majorana neutrino exchange.

$$\langle \pi(p_3) \big| \bar{d}\sigma_{\mu\nu} q^\nu b \big| B(p) \rangle = i\big[(p+p_3)_\mu q^2 - \big(m_B^2 - m_\pi^2\big) q_\mu\big] \frac{f_T^{B\pi}(q^2)}{m_B + m_\pi}. \tag{8}$$

Fig. 1(c) can have an enhanced contribution when the intermediate Majorana neutrino is on-shell. The amplitudes corresponding to Fig. 1(b) and 1(c) are as follows

$$\mathcal{M}_b = 8G_F^2 V_{ub} V_{ud}^* \frac{\bar{u}(p_1)\gamma_\mu \not{p}_\nu \gamma^\rho P_L v(p_2)}{p_\nu^2} \times \langle \pi(p_3) \big| \bar{d}\gamma_\rho P_L u|0\rangle \langle 0|\bar{u}\gamma^\mu P_L b \big| B(p) \rangle, \tag{9}$$

$$\mathcal{M}_c = 8G_F^2 V_{ub} V_{ud}^* V_{\ell_1 N} V_{\ell_2 N} \frac{\bar{u}(p_1)\gamma_\mu \not{p}_N \gamma^\rho P_L v(p_2)}{p_N^2 - m_N^2 + i m_N \Gamma_N} \times \langle \pi(p_3) \big| \bar{d}\gamma_\rho P_L u|0\rangle \langle 0|\bar{u}\gamma^\mu P_L b \big| B(p) \rangle, \tag{10}$$

where $p_{\nu(N)}$ represents the four-momentum of the light (heavy) neutrino $\nu(N)$. $V_{\ell N}$ is the mixing matrix element between the lepton flavor ℓ and heavy neutrino N. The hadronic matrix elements in Eqs. (9) and (10) are expressed as

$$\langle 0|\bar{u}\gamma^\mu(1-\gamma_5)b \big| B(p) \rangle = -i f_B p^\mu,$$
$$\langle \pi(p_3) \big| \bar{d}\gamma^\mu(1-\gamma_5)u|0\rangle = i f_\pi p_3^\mu, \tag{11}$$

where $f_{B(\pi)}$ is the decay constant of the $B(\pi)$ meson. Γ_N is the total decay width of the Majorana neutrino, and can be estimated by [34]

$$\Gamma_N \approx 2 \sum_\ell |V_{\ell N}|^2 \left(\frac{m_N}{m_\tau}\right)^5 \times \Gamma_\tau, \tag{12}$$

where m_τ and Γ_τ denote the mass and total decay width of the τ lepton, respectively. The decay branching ratio of $B^- \to \pi^- \ell^+ \ell^-$ is given by

$$\mathcal{B} = \frac{\tau_B}{2m_B(2\pi)^5} \int |\mathcal{M}_a + \mathcal{M}_b + \mathcal{M}_c|^2 \times \frac{|\vec{p}_1^{\,B}|}{4m_B} \frac{|\vec{p}_2^{\,*}|}{4\sqrt{s_{23}}} d\Omega_1^B d\Omega_2^* ds_{23}, \tag{13}$$

where $\vec{p}_1^{\,B}$ ($\vec{p}_2^{\,*}$) and $d\Omega_1^B$ ($d\Omega_2^*$) denote the 3-momentum and solid angle of charged lepton ℓ^- (ℓ^+) in the rest frame of B-meson ($\ell^+\pi$ system), respectively. It is found that the contributions from Fig. 1(b) and from the interferences can be neglected.

Next, we study the LNV process $B^-(p) \to \ell^-(p_1)\ell^-(p_2)\pi^+(p_3)$. Such $\Delta L = 2$ process may occur via Majorana neutrino exchange. In this case, this process is dominated by the annihilation diagram shown in Fig. 2(a) as the intermediate neutrino can be on-shell and has a resonantly enhanced effect, while the contribution from the emission diagram in Fig. 2(b) is small enough and can be neglected [17]. Omitting the light charged lepton mass, one can obtain the corresponding decay branching ratio as follows

Table 2
The form factors obtained by LCSR and the fitted parameters for z-series parameterization [35]. $f_T^{B\pi}(0)$ is at the renormalization scale $\mu = m_b$.

$f_+^{B\pi}(0)$	b_1^+	$f_T^{B\pi}(0)$	b_1^T
0.275	−2.037	0.293	−1.780

Table 3
Parameters used in our numerical calculation and the values taken from PDG [37].

α	1/137	m_u	2.3 MeV
G_F	1.16637×10^{-5} GeV^{-2}	m_d	4.8 MeV
τ_B	1.641 ps	m_c	1.275 GeV
Γ_τ	2.3×10^{-12} GeV	m_τ	1.777 GeV
f_π	130.4 MeV	m_π	0.13957 GeV
f_B	194 MeV	m_B	5.279 GeV

$$\mathcal{B}\big(B^- \to \pi^+ \ell^- \ell^-\big) = \frac{\tau_B G_F^4 f_B^2 f_\pi^2}{128\pi^2} \big|V_{ub} V_{ud}^*\big|^2 |V_{\ell N}|^4 \frac{m_B m_\tau^5}{2\Gamma_\tau} \times \left(1 - \frac{m_\pi^2}{m_N^2}\right)^2 \left(1 - \frac{m_N^2}{m_B^2}\right)^2. \tag{14}$$

3. Numerical analysis

We neglect the mass of muon in the branching ratio calculation of $B^- \to \pi^- \mu^+ \mu^-$, so that the term containing the scalar form factor $f_0^{B\pi}(q^2)$ vanishes. In order to estimate the SM contribution as precisely as possible, we adopt the following simplified Boyd–Grinstein–Lebed version [36] of z-series parameterization forms,

$$f_{+(T)}^{B\pi}(q^2) = \frac{f_{+(T)}^{B\pi}(0)}{1 - q^2/m_{B^*}^2} \left\{1 + b_1^{+(T)} \left[z(q^2, t_0) - z(0, t_0) + \frac{1}{2}\big(z(q^2, t_0)^2 - z(0, t_0)^2\big)\right]\right\}, \tag{15}$$

where $m_{B^*} = 5.325$ GeV denotes the mass of the vector meson B^*. $f_+^{B\pi}(0)$ and $f_T^{B\pi}(0)$ are $B \to \pi$ form factors at $q^2 = 0$. These form factors can be obtained by the QCD Light Cone Sum Rules (LCSR). The corresponding values are listed in Table 2. The function $z(q^2, t_0)$ has the following form,

$$z(q^2, t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \tag{16}$$

with the auxiliary parameters $t_0 = t_+ - \sqrt{(t_+ - t_-)(t_+ - q_{min}^2)}$ and $t_\pm = (m_B \pm m_\pi)^2$. In our numerical calculations, the CKM matrix elements are obtained by the Wolfenstein parameterization with $\lambda = 0.22535 \pm 0.00065$, $A = 0.817 \pm 0.015$, $\bar{\rho} = 0.136 \pm 0.018$ and $\bar{\eta} = 0.348 \pm 0.014$ [37]. The uncertainty induced by the scale μ is obtained by varying μ between $m_b/2$ and $2m_b$. The other parameters used in this paper are collected in Table 3.

The SM prediction for the branching ratio of $B^- \to \pi^- \mu^+ \mu^-$ obtained by the above LCSR method is given in Table 4. The dominate uncertainty is from the CKM matrix elements and the renormalization scale variation. This branching ratio has been also

Table 4
SM results and experimental value for the $\mathcal{B}(B^- \to \pi^-\mu^+\mu^-)$ (in 10^{-8}).

Decay channel	LCSR	HQS + LQCD [27]	pQCD [26]	LHCb [24]
$B^- \to \pi^-\mu^+\mu^-$	$2.23^{+0.22}_{-0.21}$	$1.88^{+0.32}_{-0.21}$	$1.95^{+0.61}_{-0.48}$	2.3 ± 0.6

studied by Heavy Quark Symmetry and the Lattice QCD (HQS + LQCD) [27] and also by perturbative QCD (pQCD) [26]. The corresponding results are also listed in Table 4. Obviously, the theoretical results for the branching ratio obtained by these three methods agree with the LHCb data within error.

We analyze the contribution from the Majorana neutrino to the $B^- \to \pi^-\mu^+\mu^-$ process together with the SM contributions. The SM contributions are respectively obtained with HQS + LQCD, pQCD and LCSR in this paper. By comparing the numerical results with LHCb data, we obtain the contour plots for the Majorana neutrino mass m_N and the $V_{\mu N}$ which is the mixing parameter between μ and the Majorana neutrino N. The results are displayed in Fig. 3(a), (b) and (c). The region above (below) the dashed line is excluded (allowed) by LHCb with $B \to \pi\mu^+\mu^-$ at 95% C.L. The solid line denotes the best fit for $|V_{\mu N}|^2$ and m_N. One can notice from the solid line that at $m_N = 3$ GeV, $|V_{\mu N}|^2 \approx 1.6 \times 10^{-3}$, 1.4×10^{-3} and 2.5×10^{-4} corresponding to HQS + LQCD, pQCD and LCSR in this paper respectively. Using the best fits for $|V_{\mu N}|^2$ and m_N, we have the branching ratios for the LNV decay $B^- \to \pi^+\mu^-\mu^-$ presented in Table 5. These results roughly agree with LHCb data [23]

$$\mathcal{B}_{exp}\left(B^- \to \pi^+\mu^-\mu^-\right) < 4.0 \times 10^{-9} \quad \text{at 95\% C.L.} \tag{17}$$

The CP violation effect is too small to be observed, so that $\mathcal{B}(B^+ \to \pi^-\mu^+\mu^+) = \mathcal{B}(B^- \to \pi^+\mu^-\mu^-)$.

Table 5
Branching ratios with the best fits for $|V_{\mu N}|^2$ and m_N shown in Fig. 3(a)–(c).

Decay channel	Fig. 3(a)	Fig. 3(b)	Fig. 3(c)	LHCb [23]
$B^- \to \pi^+\mu^-\mu^-$	4.2×10^{-9}	3.5×10^{-9}	6.5×10^{-10}	$<4.0 \times 10^{-9}$

4. Summary

The type I seesaw mechanism is one of the natural schemes to describe the tiny neutrino mass. In this paper, we study the contribution from Majorana neutrino to the semi-leptonic B-meson rare decays within type I seesaw mechanism. The constraints for the Majorana neutrino parameters are obtained by analyzing $B^- \to \pi^-\mu^+\mu^-$ process from the latest LHCb data. The SM contributions are estimated with HQS + LQCD, pQCD and LCSR. It is found that new physics effects from Majorana neutrino cannot be eliminated. Then we adopt these parameters to investigate the LNV B-meson decay $B^- \to \pi^+\mu^-\mu^-$. Our results for its branching ratio is roughly consistent with the upper limit given by LHCb experiment. The B-meson rare decays can be measured with high precision at LHCb in the near future. As a result, it is possible to search for new physics by studying the B-meson rare decays. In particular, studying the LNV B-meson decays will be important to explore the neutrino mass mechanism.

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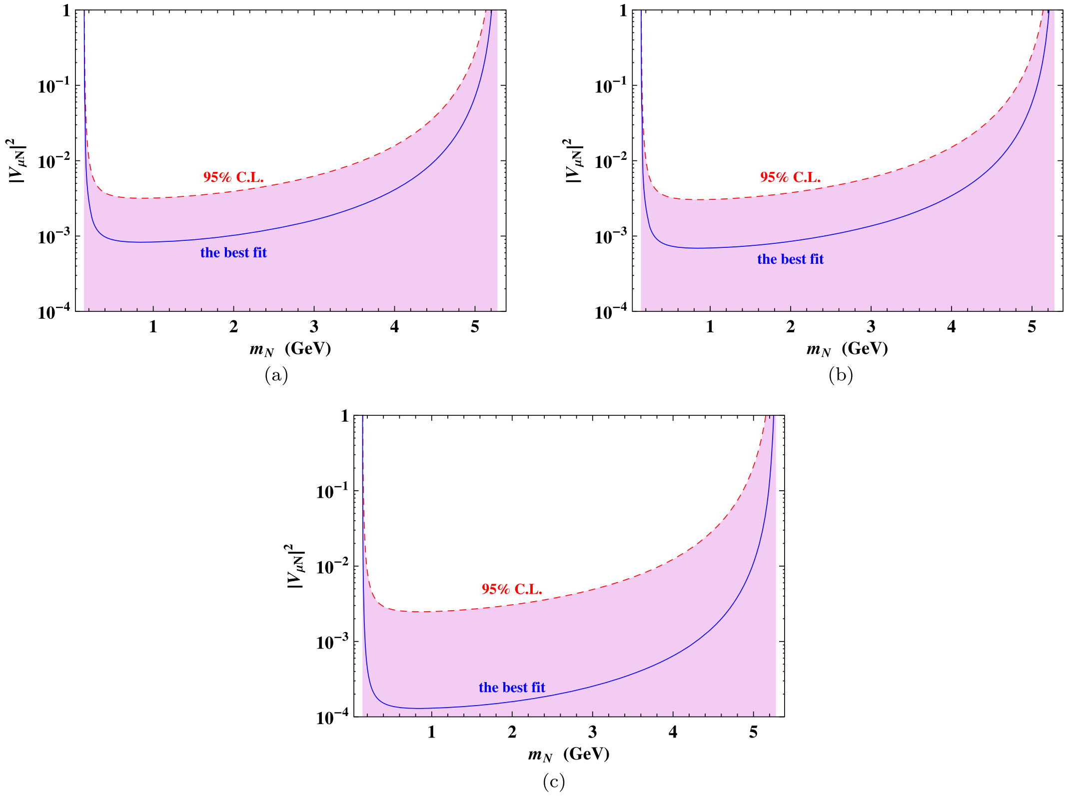

(a)

(b)

(c)

Fig. 3. Contour plots obtained from $B^- \to \pi^-\mu^+\mu^-$ for the Majorana Neutrino mass and the mixing parameter between the light flavor μ and the Majorana neutrino N. The contribution from SM is estimated with a) HQS + LQCD, b) pQCD and c) LCSR.

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