

# Heavy quark production via supersymmetric interaction at a neutrino factory

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## Abstract

We investigate b-quark production in both charged and neutral current channels through  $\nu_\mu - N$  scattering at a neutrino factory, mediated by the lepton flavour violating interactions present in a supersymmetric theory with broken R-parity. Using values of the effective interaction strengths well below the current and projected experimental bounds, we are still able to predict markedly enhanced event rates, especially for the neutral current events which are not allowed at the lowest order in the standard model (SM). Data from neutrino factories can therefore be used to probe strengths of such interactions to considerably higher precision than what can be envisioned in other experiments.

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It is being frequently suggested nowadays that a neutrino factory, cashing on the intense and well-calibrated supply of  $\nu_\mu$ 's and  $\nu_e$ 's coming out of a muon storage ring [1,2], can go a long way in investigating the world of neutrinos where numerous puzzles are still in store for us. In addition to its usefulness in probing neutrino oscillations, such high precision neutrino experiments can have several other interesting physics goals [2,3]. One of these is the possible investigation of physics beyond the standard model, something which becomes a necessity once one accepts the existence of neutrino mass and mixing. It is thus natural to ask whether there are observables, rising above the threshold of detectability in a neutrino factory, which will unequivocally imply the existence of such new physics interactions involving the neutrino sector. In this paper we suggest heavy flavour production, particularly in neutral current events, as such a demonstration of new physics. We illustrate our point in the context of an R-parity violating supersymmetric theory, emphasizing, however, that the conclusions drawn therefrom can be of a rather general nature.

We assume a design for muon production, capture, cooling, acceleration and storage as given in ref. [1,2]. The muons decaying along a straight section of the storage ring will give rise to a collimated neutrino beam that is of interest to us. It has been argued that one can thus have an yearly supply of a few times  $10^{20}$  neutrinos (or antineutrinos) of either flavour. The feasibility studies carried out so far agree that the muons in the storage ring can easily

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have energies upto 50 GeV. In order to observe new physics effects in the deep inelastic scattering (DIS) of these neutrinos, it is preferable to have a near-site detector rather than a long-baseline one, so that oscillation effects do not dominate.

The interaction taking place at the detector (which is the fixed target for the scattering phenomena under study) is basically between the neutrinos and the partons present in nucleons. In the Standard Model (SM), heavy quark production in such scattering can take place at the tree-level via the charged current channels,  $\nu_\mu \bar{u} \rightarrow \mu^- \bar{b}$ ,  $\nu_\mu \bar{c} \rightarrow \mu^- \bar{b}$ ,  $\nu_\mu d \rightarrow \mu^- c$  and  $\nu_\mu s \rightarrow \mu^- c$ . The SM charged current cross-section depends on two factors, the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements and the quark distributions in a nucleon. All the processes mentioned above, excepting the third one, occur through the interaction of muon-neutrino with the sea quarks in nucleons and are thus depend on the parton distributions relevant in the energy range under consideration. As far as charm production is concerned, the rates undergo suppression by either the strange quark distribution or the CKM element  $V_{cd}$ . For b-production, however, there is no CKM-diagonal channel, and the decidedly small element  $V_{ub}$  [4] severely suppresses the predicted rates. In addition, neutral current processes (whose measurements are also projected goals of a neutrino factory) where a b-quark can be tagged among the DIS products can come only at the one-loop level at the SM, and therefore such processes are unlikely to be detected, given any realistic muon luminosity.

One can conclude from above that if there is any observation of an excess in charged current b-production over the standard model rate, or if neutral current events are observed with a b in the final state, it will clearly signal some kind of new physics. The question is, given other kinds of constraints (especially those from b-decays) on the same operators that give rise to such events, is it possible at a neutrino factory to have any observable excess of events, or to use the absence of such excess to impose useful bounds on the new interactions?

The conservation of both baryon and lepton number in the SM is a consequence of its gauge current structure and renormalizability. In the supersymmetric (SUSY) extension of the SM [5], the existence of scalar quarks and leptons make it possible to violate baryon and lepton numbers, without leading to any theoretical problems. This entails the possibility of the violating R-parity in SUSY [6], defined by  $R = (-1)^{3B+L+2S}$ , where  $B$  is the baryon number,  $L$ , the lepton number and  $S$ , the spin of the particle. Clearly, all SM particles have  $R = +1$  while their superpartners have  $R = -1$ . While there is no fundamental principle dictating the conservation of R-parity, the need to avoid fast proton decay leads to the conjecture that out of  $B$  and  $L$ , only *one* can be violated. Here we consider the situation where  $L$ -violation occurs, since that is the scenario which can affect the observed events at a neutrino factory. The resulting interactions can in general fake the signals of neutrino oscillation, as discussed in an earlier work [7].

In terms of the superfields, the  $\Delta L = 1$  part of the  $R$ -violating superpotential is given by [8],

$$\mathcal{L}_R = \epsilon_{ab} \left[ \epsilon_i \hat{L}_i^a \hat{H}_u^b + \lambda_{ijk} (\hat{L}_i^a \hat{L}_j^b) \hat{E}_k^c + \lambda'_{ijk} (\hat{L}_i^a \hat{Q}_j^b) \hat{D}_k^c \right] \quad (1)$$

where  $\hat{L}_i$  and  $\hat{Q}_i$  are  $SU(2)$  doublet leptons and quarks,  $\hat{E}_i^c$  and  $\hat{D}_i^c$  are  $SU(2)$  singlet charged lepton and down quarks, and  $\hat{H}_u$  is the Higgs superfield responsible for the generation of the up-type quark masses.  $i, j$  and  $k$  are generation indices, while colour indices are not explicitly shown above. The corresponding interaction terms can then be written in terms of the component fields as [8]

$$\mathcal{L}_R = \lambda'_{ijk} \left[ \tilde{d}_L^j \tilde{d}_R^k \nu_L^i + (\tilde{d}_R^k)^* (\bar{\nu}_L^i)^c d_L^j + \tilde{\nu}_L^i \tilde{d}_R^k d_L^j \right]$$

$$\begin{aligned}
& -\tilde{e}_L^i \tilde{d}_R^k u_L^j - \tilde{u}_L^j \tilde{d}_R^k e_L^i - (\tilde{d}_R^k)^* (\tilde{e}_L^i)^c u_L^j] + h.c. \\
& + \lambda_{ijk} [\tilde{e}_L^j \tilde{e}_R^k \nu_L^i + (\tilde{e}_R^k)^* (\tilde{\nu}_L^i)^c e_L^j + \tilde{\nu}_L^i \tilde{e}_R^k e_L^j - (i \leftrightarrow j)] + h.c.
\end{aligned} \tag{2}$$

The most important thing to note among the terms shown above is that not only lepton number but also *lepton flavour* can be violated through them. Thus it is possible to have  $\Delta L = 0$  processes with flavour violation by taking suitable products of the  $\Delta L = 1$  couplings. One of the consequences of this is the production of the b-quark through both charged and flavour changing neutral currents (FCNC), represented by diagrams shown in figure 1. Although 9  $\lambda$ -type and 27  $\lambda'$ -type couplings are allowed altogether, we demonstrate our argument by assuming non-zero values of only the  $\lambda'$ -interactions with indices conforming to the requirements of b-production in  $\nu_\mu$  scattering.

As has been already mentioned, we shall confine ourselves to near-site experiments in which one places the neutrino detectors at a short distance (40 m) from the straight section of the storage ring [2]. Under such circumstances, the incoherent scattering effects (only of  $\nu_\mu$ 's here, by virtue of our choice of non-vanishing new physics interactions) dominate over oscillation effects. The number of b-production events per year, via either charged-current or neutral current interactions, can be obtained by folding the relevant cross-section by a survival probability and the neutrino flux,

$$N_Q = \frac{N_N}{\pi R_d^2} \int d\sigma(\nu_\mu + N \rightarrow \mu^- + Q) \frac{d^2 N_\nu}{dE_{\nu_\mu} dE_\theta} (1 - \mathcal{P}_{\nu_\mu \rightarrow \nu_{e,\tau}}) dE_{\nu_\mu} d\theta \tag{3}$$

where P is the total probability of oscillation of a muon neutrino to any other flavour. Here we use the  $\nu_\mu \rightarrow \nu_\tau$  oscillation probability corresponding to the solution space for the atmospheric  $\nu_\mu$  deficit [9], and the  $\nu_\mu \rightarrow \nu_e$  oscillation probability for the Mikheyev-Smirnov-Wolfenstein (MSW) solution to the solar neutrino problem [10]. In any case, for a near-site detector, the predictions on b-production have no perceptible dependence on the precise values of the oscillation parameters. In our calculation, we have assumed a target of mass 100 T containing  $N_N = 6.023 \times 10^{31}$  nucleons. The cross-sectional area of the target ( $\pi R_d^2$ ) and the distance (L) from the muon decay point to the target define a cone with the semi-vertical angle  $\theta_d$ , related through the relation  $R_d = L\theta_d$ . While the available energy range of the the neutrino (together with the energy distribution) is specified by the energy of the decaying muon, the  $\theta$ -integration has an upper limit  $\theta_d$ . This brings in not only the detector size but also the length of the straight section of the storage ring and the probability of the muon decaying at any given point along the straight section. This has been taken into account in our calculation, where we have assumed a straight section of length 100 m and that  $2 \times 10^{20}$  muons decay within this section per year. Our numerical results correspond to a target cross-section of 1 m<sup>2</sup>. Also, CTEQ4LQ [11] parton distributions have been used here.

The contributions to the b quark production from the Feynman diagrams shown in figure 1 are obtained from the following Fierz-rearranged amplitudes:

$$\begin{aligned}
\mathcal{M}_R(\nu_\mu + \bar{u} \rightarrow \mu^- + \bar{b}) &= \frac{\lambda'_{213} \lambda'_{233}}{2(t - m_{b_R}^2)} [\bar{u}_\mu \gamma_\mu P_L u_{\nu_\mu}] [\bar{\nu}_u \gamma^\mu P_L v_b] \\
\mathcal{M}_R(\nu_\mu + d \rightarrow \nu_\mu + b) &= \frac{\lambda'_{231} \lambda'_{233}}{2(t - m_{b_L}^2)} [\bar{u}_{\nu_\mu} \gamma_\mu P_L u_{\nu_\mu}] [\bar{u}_b \gamma^\mu P_R u_d]
\end{aligned} \tag{4}$$

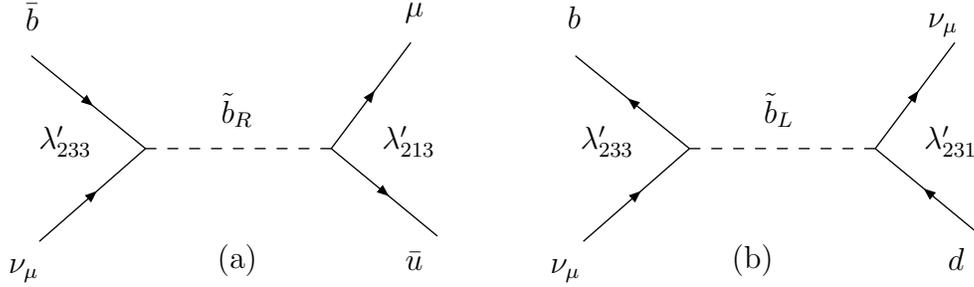


Figure 1: *Feynman diagrams for processes producing a  $b$  quark or a  $\bar{b}$  antiquark in  $R$ -parity violating SUSY.*

where,  $t = (p_{\nu_\mu}^i - p_b)^2$  in each case.

As can be seen from above,  $b$ -production via charged current is driven by the product  $\lambda'_{213}\lambda'_{233}$ , while  $\lambda'_{231}\lambda'_{233}$  controls the neutral current event rate. We take  $b$ -squark mass to be  $300 \text{ GeV}$ . With this choice, a not-so-stringent constraint ( $\sim 0.048$ ) exists on the first one of these products [12], which is not appreciably different from the product ( $\sim 0.046$ ) of the upper limits on the individual couplings taken in isolation [13]. To be conservative, we have used the value corresponding to this latter limit. As for the second pair of couplings which controls the neutral current rate, the product of the individual limits is approximately 0.14 for a  $b$ -squark of mass  $300 \text{ GeV}$ . A somewhat weaker limit for the same  $m_{\tilde{b}}$  ( $\sim 0.225$ ) is derived from the  $\nu_\mu N \rightarrow \nu_\mu b + X$  scattering data from Fermilab NuTeV Experiment [17]. On the other hand, searches for the FCNC decay  $B^0 \rightarrow \mu^+\mu^-$  at CDF [14] and CLEO [15] set upper limits on the branching ratio of the above decay at  $8.6 \times 10^{-7}$  and  $6.1 \times 10^{-7}$  respectively. The BaBar B-factory experiment, too, has a projected upper limit of  $5.0 \times 10^{-7}$  that can be obtained on the branching ratio for  $B^0 \rightarrow \mu^+\mu^-$  [16]. Using the last one of these, one may be able to set a limit of about 0.018 on  $\lambda'_{231}\lambda'_{233}$  for the above squark mass.

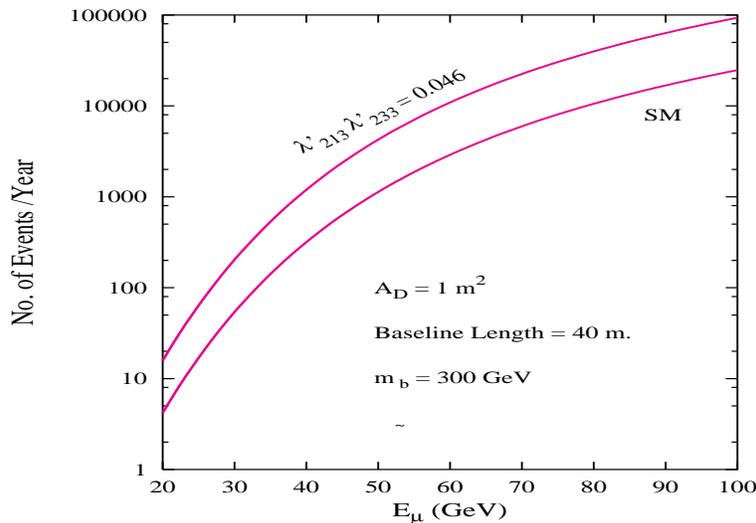


Figure 2: *Number of events coming from  $\nu_\mu$ - $N$  DIS at a muon storage ring in charged current interaction with  $100 \text{ T}$  of target material.*

The other process which can be of useful in this context is the rare decay  $B \rightarrow X_d \mu^+ \mu^-$ . However, here the measurement of the decay rate depends crucially on the end-point analysis of the  $\mu^+ \mu^-$  invariant mass spectrum. The uncertainties coming from the onset of resonant peaks as well as those in heavy-to-light transition form-factors make the prospect less bright for strengthening the limit on the new physics effective interaction to any substantial extent. Results coming from, say, the LHC-B experiment (via the channel  $B \rightarrow \rho \mu^+ \mu^-$ ) may throw some further light on this issue [18]. Here we present our numerical results in terms of the current limit on  $\lambda'_{231} \lambda'_{233}$  as well as the projected limit from B-factories.

In figure 2, we have plotted the number of charged current b-production events expected per year against the muon energy, for a 100 T target of cross-section  $1 m^2$ . The SM (using  $V_{ub} = 0.004$  [4]) rates as well as those from R parity violating SUSY have been shown for comparison. It is clear from the graph that, with values of the non-standard couplings satisfying the existing constraints, an excess of 3 to 4 times over the standard model event rate can be expected, with, say  $E_\mu = 50 GeV$ .

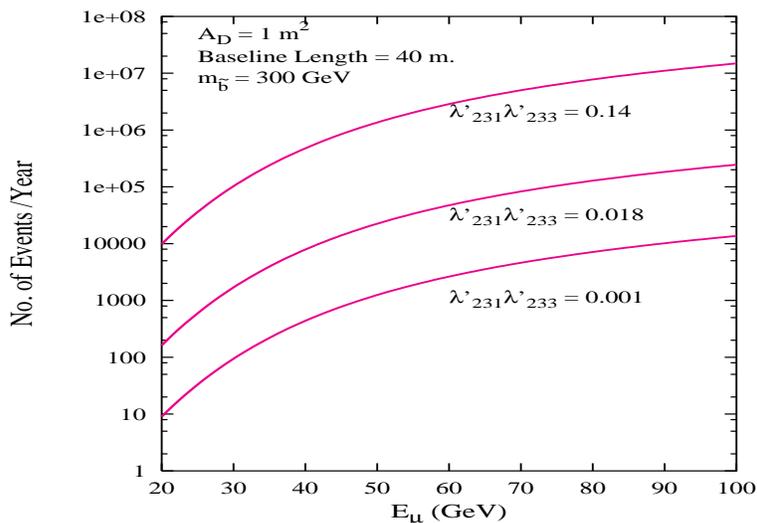


Figure 3: *Number of events coming from  $\nu_\mu$ -N DIS at a muon storage ring in neutral current interaction with 100 T of target material.*

The new physics effects are even more spectacular for neutral current where the SM contributions are negligibly small. As figure 3 shows, a very large number of neutral current events with a b in the final state is predicted. This is true not only with  $\lambda'_{231} \lambda'_{233}$  at the current experimental upper bound, but also using the limit envisioned at B-factories, and even with a value one order lower. Even with in the last, rather conservative, choice, one expects an event rate of about a thousand per year with  $E_\mu = 50 GeV$ , so that a b-tagging efficiency even as low as 25% will still make the events detectable. It can thus be argued that the observation (or otherwise) of b-production in neutral current events at a neutrino factory will enable one to probe flavour-violating coupling of the relevant types (in models including R-parity violating SUSY) to a higher degree of precision than in the currently operative B-factories.

For charm production, on the other hand, although the SUSY contributions can give rise to event rates of observable order of magnitude with the effective new coupling fixed at the experimental limit, the SM contributions are larger, since the CKM element  $V_{cd}$  is involved in the process. Consequently, It may be somewhat more difficult to discern the

additional contributions. In addition, the structure of the R-violating couplings implies that at least one charge  $-\frac{1}{3}$  quark superfield must be involved at each  $\lambda'$ -type interaction vertex. Consequently, charm production in neutral current events is not possible at the tree level.

Although we have discussed the above effects in the light of an R-parity violating SUSY scenario, the general features of our results are true for any non-standard theory which allows flavour violating couplings involving a b-quark. It is possible to make predictions for such models by suitably replacing  $\lambda'\lambda'/2m_b^2$  by the coefficient of the new effective four-fermion interaction term, on which all the limits discussed by us will be still applicable.

In summary, we have demonstrated that the production of the b-quark with substantial rate at a neutrino factory is a clear signal of non-standard interactions for neutrinos. In particular, we have considered an R-parity violating supersymmetric theory to predict markedly enhanced b-production rates, particularly in neutral current events, with values of the relevant couplings well below the existing and projected limits.

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