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Can R-parity violating supersymmetry be seen in long baseline beta-beam experiments?

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ABSTRACT

Long baseline oscillation experiments may well emerge as test beds for neutrino interactions as are present in R-parity violating supersymmetry. We show that flavour diagonal (FDNC) and flavour changing (FCNC) neutral currents arising therefrom prominently impact a neutrino β-beam experiment with the source at CERN and the detector at the proposed India-based Neutrino Observatory. These interactions may preclude any improvement of the present limit on θ_{13} and cloud the hierarchy determination unless the upper bounds on $\not{R}$ couplings, particularly λ', become significantly tighter. If $\not{R}$ interactions are independently established then from the event rate a lower bound on θ_{13} may be set. We show that there is scope to see a clear signal of non-standard FCNC and FDNC interactions, particularly in the inverted hierarchy scenario and also sometimes for the normal hierarchy. In favourable cases, it may be possible to set lower and upper bounds on λ' couplings. FCNC and FDNC interactions due to λ type $\not{R}$ couplings are unimportant.

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I Introduction

Neutrino physics, a bit player on the physics stage in yesteryears, has now donned a central role. Various experiments on atmospheric [1], solar [2], reactor [3], and long baseline neutrinos [4] not only indicate oscillation but also pin down most neutrino mass and mixing parameters – two mass-square differences and two mixing angles. The best-fit [5] values with 3σ error from atmospheric neutrinos are $|\Delta m^2_{23}| \simeq 2.12^{+1.09}_{-0.81} \times 10^{-3}$ eV^2, $\theta_{23} \simeq 45.0^{\circ}{}^{+10.55^{\circ}}_{-9.33^{\circ}}$ and from solar neutrinos $\Delta m^2_{12} \simeq 7.9^{+1.0}_{-0.8} \times 10^{-5}$ eV^2, $\theta_{12} \simeq 33.21^{\circ}{}^{+4.85^{\circ}}_{-4.55^{\circ}}$. Here $\Delta m^2_{ij} = m^2_j - m^2_i$. The sign of Δm^2_{23} is yet unknown and the neutrino mass spectrum will be referred here as normal (inverted) hierarchical if it is positive (negative). Using reactor antineutrinos [5, 3, 6], an upper bound has been set on the third mixing angle at 3σ level as $\sin^2\theta_{13} < 0.044$ resulting in $\theta_{13} < 12.1^{\circ}$. The phase δ in the neutrino mixing matrix is not known.

Research in this area is now poised to move into the precision regime. Can we use upcoming neutrino experiments to probe non-standard interactions like $\not{R}$ supersymmetry? If present, can they become spoilers in attempts to further sharpen the neutrino properties? We attempt to address these issues with a specific experiment as our laboratory.

Long baseline neutrino oscillation experiments using neutrino factories [7] and β-beams [8, 9, 10, 11] hold promise of refining our knowledge of θ_{13}, δ, and the sign of Δm^2_{23}. A possible experiment in this category would use neutrinos from a β-beam from CERN to the proposed India-based Neutrino Observatory [12] (INO), a baseline of $\sim$ 7152 Km. This is the set-up which we consider here. For such an experiment the β-beam is required to be boosted to high γ.

Interaction of neutrinos with matter affect long baseline experiments and this becomes more prominent at higher values of θ_{13}. Various authors [13] have considered this effect for atmospheric neutrinos.

Apart from the electroweak effects, there may well be non-standard interactions leading to flavour changing as well as flavour diagonal neutral currents (FCNC and FDNC). R-parity violating supersymmetric models (RPVSM) [14], which have such interactions already built-in, will be the main focus of our work. Very recently a model in which couplings associated with FCNC and FDNC can be quite a bit higher than permitted in RPVSM has also been considered [15, 16]. Naturally, here the matter effect will be further enhanced. However, as RPVSM is a well-studied, renormalizable model which can satisfy all phenomenological constraints currently available, we shall restrict our main analysis only to it and shall make qualitative remarks about the other model, for which our results can be easily extended.

Consequences of FCNC and FDNC for solar and atmospheric neutrinos [17, 18], and neutrino factory experiments [19] have been looked into. Our focus is on β-beam experiments, particularly over a long distance (7152 Km) baseline. Our analysis encompasses both normal and inverted hierarchies and we also incorporate all relevant trilinear R-parity violating couplings leading to FCNC and FDNC. Huber *et al* [20] have a somewhat similar analysis using neutrino beams obtained from muon decays.

The very long baseline from CERN to INO will capture a significant matter effect and offers a scope to signal non-standard interactions. We examine whether the presence of $\not{R}$ interactions will come in the way of constraining the mixing angle θ_{13} or unraveling the neutrino mass hierarchy. The possiblity to obtain bounds on some R-parity violating couplings is also probed.

II β-beams

A beta-beam [8], is a pure, intense, collimated beam of electron neutrinos or their antiparticles produced *via* the beta decay of completely ionized, accelerated radioactive ions circulating in a storage ring [21]. It has been proposed to produce ν_e beams through the decay of highly accelerated ^{18}Ne ions and $\bar{\nu}_e$ from ^{6}He [21]. More recently, ^{8}B and ^{8}Li [22] with much larger end-point energy have been suggested as alternate sources since these ions can yield higher energy ν_e and $\bar{\nu}_e$ respectively, with lower values of the Lorentz boost γ. It may be possible to have both beams in the same ring, an arrangement which will result in a ν_e as well as a $\bar{\nu}_e$ beam pointing towards a distant target. In such a set-up the ratio between the boost factors of the two ions is fixed by the e/m ratios of the ions. Here, we will present our results with the ^{8}B ion ($Q = 13.92$ MeV and $t_{1/2} = 0.77s$) taking $\gamma = 350$. As we show, $\gamma \sim 350$ may permit a distinction between matter effects due to Standard Model interactions and those from R-parity violating supersymmetry (SUSY). Details of the neutrino flux from such a β-beam can be found in [11].

Using the CERN-SPS at its maximum power, it will be possible to access $\gamma \sim 250$[1] [23]. For a medium $\gamma \sim 500$, a refurbished SPS with super-conducting magnets or an acceleration technique utilizing the LHC [23, 24, 25] would be required. In the low-γ configuration, 1.1×10^{18} useful decays per year can be obtained with ^{18}Ne ions [26, 27]. We have used this same luminosity for ^{8}B and higher γ [28]. This issue is being examined in an on-going dedicated machine study at CERN.

III R-parity violating Supersymmetry

In supersymmetric theories [14], gauge invariance does not imply baryon number (B) and lepton number (L) conservation and, in general, R-parity (defined as $\mathrm{R} = (-1)^{3B+L+2S}$ where S is the spin) is violated. To maintain consistency with non-observation of fast proton decay etc, in the R-parity violating Minimal Supersymmetric Standard Model (imposing baryon number conservation) one may consider the following superpotential

$$W_{\not{L}} = \sum_{i,j,k} \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \mu_i L_i H_u, \tag{1}$$

(suppressing colour and $SU(2)$ indices) where $i,\ j,\ k$ are generation indices. Here L_i and Q_i are $SU(2)$-doublet lepton and quark superfields respectively; E_i, D_i denote the right-handed $SU(2)$-singlet charged lepton and down-type quark superfields respectively; H_u is the Higgs superfield which gives masses to up-type quarks. Particularly, λ_{ijk} is antisymmetric under the interchange of the first two generation indices. We assume that the bilinear terms have been rotated away with appropriate redefinition of superfields and focus on the two trilinear L-violating terms with λ and λ' couplings. Expanding those in standard four-component Dirac notation, the quark-neutrino interaction lagrangian can be written as:

$$\mathcal{L}_{\lambda'} = \lambda'_{ijk}\ [\ \tilde{d}^j_L\ \bar{d}^k_R \nu^i_L + (\tilde{d}^k_R)^* (\bar{\nu}^i_L)^c d^j_L] + h.c. \tag{2}$$

Above, the sfermion fields are characterized by the tilde sign. The charged lepton interacts with the neutrino *via*

$$\mathcal{L}_{\lambda} \ = \ \frac{1}{2}\lambda_{ijk}\ [\ \tilde{e}^j_L\ \bar{e}^k_R \nu^i_L + (\tilde{e}^k_R)^* (\bar{\nu}^i_L)^c e^j_L - (i \leftrightarrow j)] + h.c, \tag{3}$$

[1] $\gamma = 250$ yields too few events in this experiment for the extraction of interesting physics.

In what follows we shall consider these couplings as real but will entertain both positive and negative values. The interactions of neutrinos with electrons and d-quarks in matter induce transitions (i) $\nu_i + d \to \nu_j + d$ and (ii) $\nu_i + e \to \nu_j + e$. (i) is possible through λ' couplings *via* squark exchange for all i, j and through Z exchange for $i = j$ while (ii) can proceed *via* W and Z exchange for $i = j$, as well as through λ couplings *via* slepton exchange for all i, j.

IV Neutrino oscillation probabilities & matter effect

In a three neutrino framework, the neutrino flavour states $|\nu_\alpha\rangle$, $\alpha = e, \mu, \tau$, are related to the neutrino mass eigenstates $|\nu_i\rangle$, $i = 1, 2, 3$, with masses m_i:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \ , \tag{4}$$

where U is a 3×3 unitary matrix which can be expressed as:

$$U = V_{23} V_{13} V_{12}, \tag{5}$$

where

$$V_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} ; \ V_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} ; \ V_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} . \tag{6}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and δ denotes the CP violating (Dirac) phase. There may be a diagonal phase matrix on the right containing two more Majorana phases. These are not considered below. Apart from some qualitative remarks, we present our result considering $\delta = 0$ corresponding to the CP conserving case. In the mass basis of neutrinos

$$M^2 = \text{diag}(m_1^2, m_2^2, m_3^2) = U^\dagger M_\nu^+ M_\nu U, \tag{7}$$

where M_ν is the neutrino mass matrix in the flavour basis and m_1, m_2, and m_3 correspond to masses of three neutrinos in the ascending order of magnitudes respectively for the normal hierarchy. If $m_2 > m_3$, we have an inverted hierarchy.

The neutrino flavour eigenstates evolve in time as:

$$i\frac{d}{dt} \begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \\ \nu_\tau(t) \end{pmatrix} = H \begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \\ \nu_\tau(t) \end{pmatrix} , \tag{8}$$

where

$$H = E \times \mathbf{1}_{3\times3} + U \left(\frac{M^2}{2E}\right) U^\dagger + R. \tag{9}$$

Here E is the neutrino energy while $\mathbf{1}_{3\times3}$ is the identity matrix. R is a 3×3 matrix reflecting the matter effect, absent for propagation in vacuum.

$$R_{ij} = R_{ij}(SM) + R_{ij}(\lambda') + R_{ij}(\lambda). \tag{10}$$

Specifically,

$$R_{ij}(SM) = \sqrt{2}G_F n_e \delta_{ij}(i,j=1) + \frac{G_F n_n}{\sqrt{2}}\delta_{ij}, \tag{11}$$

$$R_{ij}(\lambda') = \sum_m \left(\frac{\lambda'_{im1}\lambda'_{jm1}}{4m^2(\tilde{d}_m)} n_d + \frac{\lambda'_{i1m}\lambda'_{j1m}}{4m^2(\tilde{d}_m)} n_d \right), \tag{12}$$

$$R_{ij}(\lambda) = \sum_{k\neq i,j} \frac{\lambda_{ik1}\lambda_{jk1}}{4m^2(\tilde{l}^\pm_k)} n_e + \sum_n \frac{\lambda_{i1n}\lambda_{j1n}}{4m^2(\tilde{l}^\pm_n)} n_e, \tag{13}$$

where G_F is the Fermi constant, n_e, n_n, and n_d, respectively, are the electron, neutron, and down-quark densities in earth matter. Note that R is a symmetric matrix and also that antineutrinos will have an overall opposite sign for R_{ij}. Assuming earth matter to be isoscalar, $n_e = n_p = n_n$ and $n_d = 3n_e$. The current bounds on the $\not{R}$ couplings [14] imply that the λ' induced contributions to R_{11}, R_{12} and R_{13} are several orders less than $\sqrt{2}G_F n_e$. We neglect those terms in our analysis. The upper bounds on all couplings in $R_{ij}(\lambda)$ are also very tight [14] in comparison to $\sqrt{2}G_F n_e$ and their effect will be discussed later. So, first we consider, in addition to the Standard Model contribution, only

$$\begin{aligned} R_{23} &= R_{32} = \frac{n_d}{4m^2(\tilde{d}_m)} \left(\lambda'_{2m1}\lambda'_{3m1} + \lambda'_{21m}\lambda'_{31m}\right), \\ R_{22} &= \frac{n_d}{4m^2(\tilde{d}_m)} \left(\lambda'^2_{2m1} + \lambda'^2_{21m}\right), \quad R_{33} = \frac{n_d}{4m^2(\tilde{d}_m)} \left(\lambda'^2_{3m1} + \lambda'^2_{31m}\right), \end{aligned} \tag{14}$$

which are comparable to $\sqrt{2}G_F n_e$. One can see from eq. (14) that $R_{23} \neq 0$ implies both R_{22} and R_{33} are non-zero[2].

The current bounds on the relevant couplings are as follows [14]:

$$|\lambda'_{2m1}| < 0.18;\ |\lambda'_{21m}| < 0.06;\ |\lambda'_{331}| < 0.58;\ |\lambda'_{321}| < 0.52;\ |\lambda'_{31m}| < 0.12, \tag{15}$$

for down squark mass $m_{\tilde{d}} = 100$ GeV. We have checked that the chosen limits on λ'_{21m} and λ'_{31m} do not conflict with the ratio $R_{\tau\pi} = \Gamma(\tau \to \pi\nu_\tau)/\Gamma(\pi \to \mu\bar{\nu}_\mu)$ [14].

In general, it is cumbersome to write an analytical form of the probability of neutrino oscillation in the three-flavour scenario with matter effects. However, under certain reasonable approximations it is somewhat tractable. Firstly, a constant matrix can be extracted from M^2 in eqs. (7) and (9). Also for the energies and baselines under consideration, $\Delta m^2_{12} L/E << 1$. Under this approximation, the V_{12} part of U drops out from eq. (9). With these modifications, the effective mass squared matrix is:

$$\frac{\tilde{M}^2}{2E} = H - (E + \frac{G_F n_n}{\sqrt{2}})\mathbf{1}_{3\times 3}. \tag{16}$$

In the special case where $R_{22} = R_{33}$, if one uses the best-fit value of the vacuum mixing angle $\theta_{23} = \pi/4$ then the neutrino mass squared eigenvalues are:

$$\left(\frac{\tilde{M}^2_2}{2E}\right) = R_{22} - R_{23}, \quad \left(\frac{\tilde{M}^2_{1,3}}{2E}\right) = \frac{1}{2}\left(\frac{\Delta m^2_{13}}{2E} + R_{11} + R_{22} + R_{23} \mp A\right), \tag{17}$$

[2]However, in other models [15] this may not be the case.

where

$$A = \left[\left(\frac{\Delta m_{13}^2}{2E}\right)^2 + (-R_{11} + R_{22} + R_{23})^2 - 2\frac{\Delta m_{13}^2}{2E}\cos 2\theta_{13}\,(R_{11} - R_{22} - R_{23})\right]^{1/2} . \tag{18}$$

The matter induced neutrino mixing matrix is given by

$$U^m = \begin{pmatrix} U_{11}^m & 0 & U_{13}^m \\ N_1 & -\frac{1}{\sqrt{2}} & N_3 \\ N_1 & \frac{1}{\sqrt{2}} & N_3 \end{pmatrix} . \tag{19}$$

Here

$$N_{1,3} = \left[\frac{2\left(-R_{11} + R_{22} + R_{23} + \frac{\Delta m_{13}^2}{2E}\cos 2\theta_{13} \pm A\right)^2}{\left(\frac{\Delta m_{13}^2}{2E}\right)^2 \sin^2 2\theta_{13}} + 2\right]^{-1/2} , \tag{20}$$

where N_1 (N_3) corresponds to $+(-)$ sign in the above expression. Neglecting the CP phase in the standard parametrization of U^m, one may write $U_{13}^m = \sin\theta_{13}^m$ and $U_{23}^m = \sin\theta_{23}^m \cos\theta_{13}^m$. From eq. (19) it follows that $\theta_{23}^m = \theta_{23}$, the vacuum mixing angle. θ_{13}^m, on the other hand, changes from its vacuum value and it is $\pi/4$ for

$$R_{11} - R_{22} - R_{23} = \frac{\Delta m_{13}^2}{2E}\cos 2\theta_{13}. \tag{21}$$

In the absence of non-standard interactions, $R_{22} = R_{23} = R_{33} = 0$ and $R_{11} = \sqrt{2}G_F n_e$, this is the well-known condition for matter induced maximal mixing. Since in eq. (19) $U_{12}^m = 0$, in the ν_e to ν_μ oscillation probability the terms involving $(\tilde{M}_2^2 - \tilde{M}_1^2)$ and $(\tilde{M}_3^2 - \tilde{M}_2^2)$ will not survive and we get:

$$P_{\nu_e \to \nu_\mu} = 4\ (U_{13}^m)^2\ (U_{23}^m)^2\ \sin^2(1.27\ A\ L)\,, \tag{22}$$

where E, Δm_{13}^2 and L are expressed in GeV, eV^2, and Km, respectively. This expression is also valid for antineutrinos. Using eqs. (17) and (19) one can easily obtain the oscillation probabilities for other channels.

We use the above analytical formulation as a cross-check on our numerical results. For example, Fig. 1, which shows the variation of $P_{\nu_e \to \nu_\mu}$ as a function of the energy, is obtained using the full matter-induced three-flavour neutrino propagation including non-standard interactions. The range of energy is chosen in line with the discussions in the rest of the paper. The probability falls with decreasing θ_{13} and, for illustration, we have chosen a value in the middle of its permitted range. The purpose of Fig. 1 is twofold: (a) to show how the distinguishability between the normal and inverted hierarchies may get blurred by the RPVSM interactions, and (b) how irrespective of the hierarchy chosen by Nature the results may be completely altered by the presence of these interactions. Each panel of Fig. 1 has three curves: the solid line (only electroweak interactions), dot-dashed line (in addition, R_{33} gets a non-zero RPVSM contribution), and dashed line ($R_{22} = R_{33}$, R_{23} are all nonzero in addition to the electroweak contribution). Only in the last case is the analytical formula we have presented above applicable. We find excellent agreement. Two aspects of the results are worth pointing out.

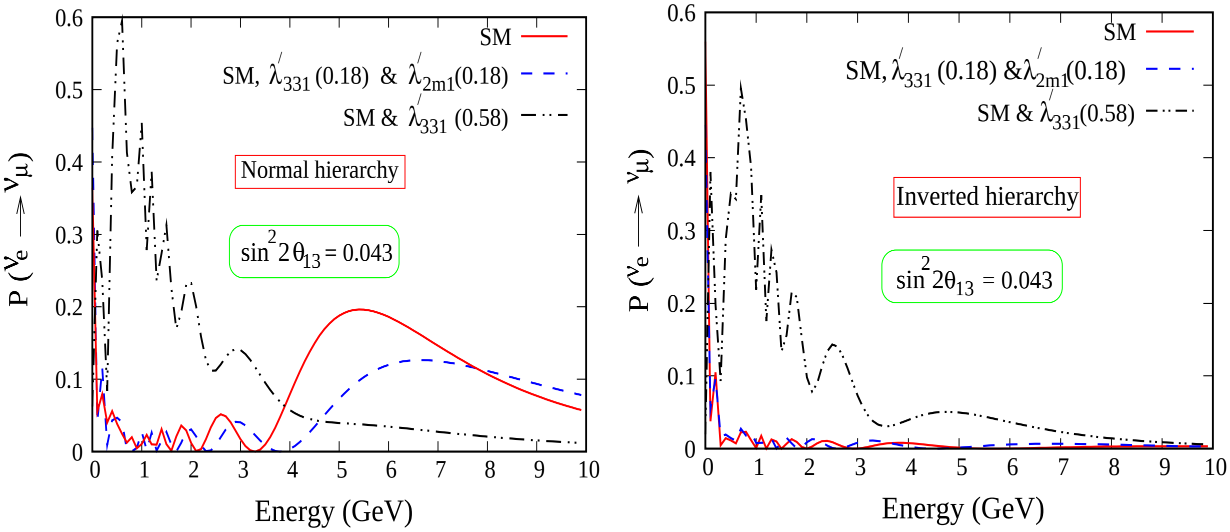

Figure 1: $P_{\nu_e \to \nu_\mu}$ for the normal and inverted mass hierarchies. SM corresponds to only standard electroweak interactions. The values of λ' are given in parantheses.

First, in the absence of non-Standard interactions, for an inverted hierarchy the resonance condition eq. (21) is not satisfied and the oscillation probability is negligible (right panel solid line). This could be altered prominently by the RPVSM interactions (dot-dashed curve) so that the distinguishability between the two hierarchy scenarios may well get marred by $\not{R}$ SUSY.

Secondly, for the normal hierarchy, it is seen that the peak in the probability shifts to a higher energy in the presence of the RPVSM interactions. This is because the condition for maximal mixing in eq. (21) is affected by the $\not{R}$ interactions. For the inverted hierarchy, the oscillation probability is considerably enhanced for some energies. Thus, physics expectations for both hierarchies will get affected by RPVSM.

In the following section we dwell on the full impact of this physics on a long baseline β-beam experiment.

V Results

We consider a long baseline experiment with a ν_e β-beam source. β-beams producing $\bar{\nu}_e$ are also very much under consideration. Broadly speaking, the results obtained for a ν_e beam with a normal (inverted) hierarchy are similar to that with a $\bar{\nu}_e$ beam for an inverted (normal) hierarchy but details do differ.

The average energy of the ν_e beam in the lab frame is $\langle E \rangle = 2\gamma E_{cms}$, where E_{cms} is the mean center-of-mass neutrino energy. With $\gamma = 350$ and $Q = 13.92$ MeV for an ^{8}B source, $\langle E \rangle \simeq 5$ GeV. The proposed ICAL detector at INO [12] consists of magnetized iron slabs with glass resistive plate chambers as interleaved active detector elements. We present results for a 50 Kt iron detector with energy threshold 2 GeV. As signature of $\nu_e \to \nu_\mu$ oscillation, prompt muons will appear. Their track reconstruction will give the direction and energy of the incoming neutrino. ICAL has good charge identification efficiency ($\sim 95\%$) and a good energy resolution $\sim 10\%$ above 2 GeV. Details about the detector and neutrino nucleon cross sections may be found in [11]. For the cross section we include contributions from quasi-elastic, single pion, and deep inelastic channels. For our chosen high threshold (2 GeV), the contribution from the deep inelastic channel is relatively large. For the CERN-INO baseline, the averaged matter density is 4.21 g cm^{-3}. We use best-fit values of vacuum neutrino mixing parameters as mentioned in the Introduction. All the presented results are based on a five year ICAL data sample[3]. At the production and detection levels FCNC and FDNC effects are small; but they may significantly affect the propagation of neutrinos through matter.

V.1 Extraction of θ_{13} and determination of hierarchy

If neutrinos have only Standard Model interactions then the expected number of muon events is fixed for a particular value of θ_{13} with either normal or inverted hierarchy[4] as may be seen from the solid lines in Fig. 2. The vast difference for the alternate hierarchies picks out such long baseline experiments as good laboratories for addressing this open question of the neutrino mass spectrum.

If non-standard interactions are present then, depending on their coupling strength, the picture can change dramatically. In Fig. 2, the shaded region corresponds to the allowed values when SUSY FCNC and FDNC interactions are at play. It is obtained by letting the λ' couplings[5] vary over their entire allowed range – both positive and negative – given in eq. (15).

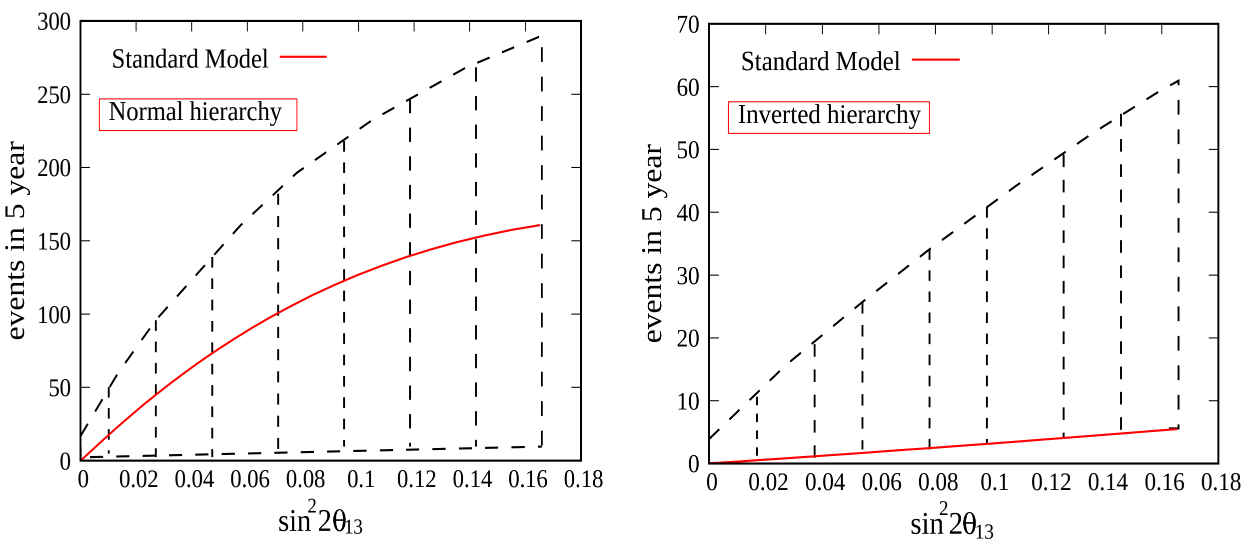

Figure 2: Number of muon events for normal and inverted mass hierarchies as a function of $\sin^2 2\theta_{13}$ for a five-year ICAL run. The solid lines correspond to the absence of any non-Standard neutrino interaction. The shaded area is covered if the λ' couplings are varied over their entire allowed range.

It is seen that to a significant extent the distinguishability of the two hierarchies is obstructed by the $\not{R}$ interactions unless the number of events is more than about 60. Also, the one-to-one correspondence is lost between θ_{13} and the number of events and, at best, a

[3]Backgrounds can be eliminated by imposing directionality cuts. The detector is assumed to be of perfect efficiency.

[4]Recall we assume that, but for θ_{13} and the mass hierarchy, the other neutrino mass and mixing parameters are known.

[5]In fact, we have chosen the subscript m in the λ' couplings in eq. (14) to be any one of 1,2, or 3.

lower bound can now be placed on θ_{13} from the observed number. Of course, if the neutrino mass hierarchy is known from other experiments, then this lower bound can be strengthened, especially for the inverted hierarchy.

It is also noteworthy that for some values of λ'-couplings there may be more events than can be expected from the Standard Model interactions, no matter what the value of θ_{13}. Thus, observation of more than 161 (5) events for the normal (inverted) hierarchy would be a clear signal of new physics.

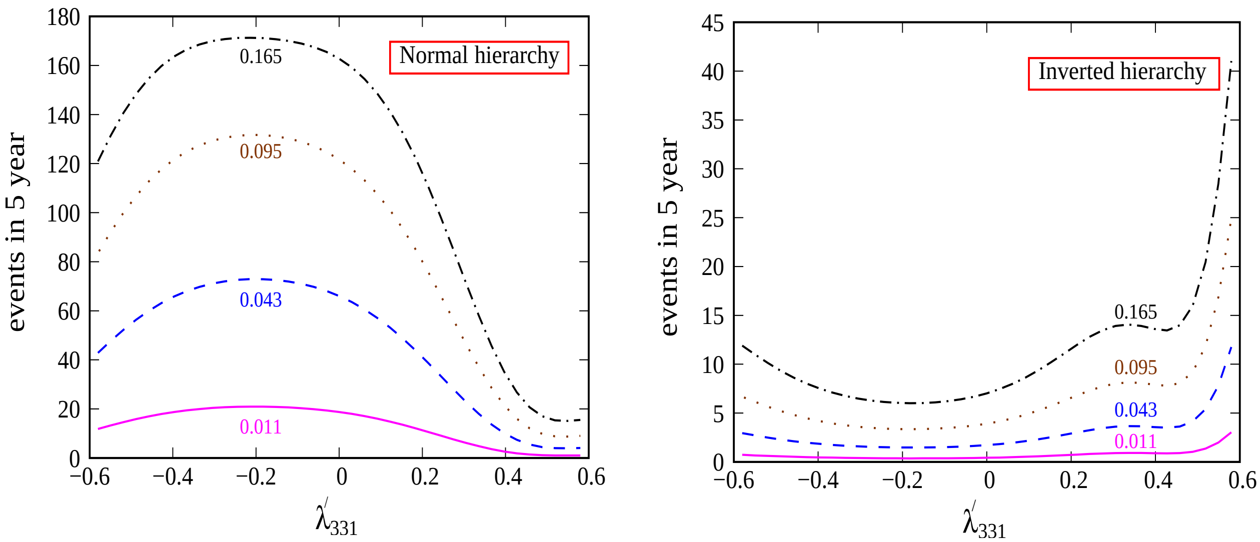

Figure 3: The number of events as a function of λ'_{331} when λ'_{231} is fixed at its currently allowed maximum (0.18) for normal (left panel) and inverted (right panel) hierarchies. The chosen $\sin^2 2\theta_{13}$ are indicated next to the curves.

V.2 Constraining λ'

If θ_{13} is determined from other experiments, then one can tighten the constraints on the λ' couplings from the results of this β-beam experiment. Fig. 2 reflects the overall sensitivity of the event rate to the $\not{R}$ interactions obtained by letting all RPVSM couplings vary over their entire allowed ranges. In this subsection, we want to be more specific and ask how the event rate depends on any chosen λ' coupling.

At the outset, it may be worth recalling that λ'_{2m1} and λ'_{3m1}, if simultaneously present, contribute to R_{22}, R_{33}, and R_{23} in the effective neutrino mass matrix[6] eq. (9). In contrast, if only λ'_{2m1} (λ'_{3m1}) is non-zero, then R_{22} (R_{33}) alone receives an RPVSM contribution. First, we take up the former situation.

When λ'_{231} and λ'_{331} are both present[7], individually they contribute to R_{22} and R_{33}, respectively while R_{23} is fixed through their product. Setting bounds in the most general situation is not very illuminating. Instead, we exhibit the dependence of the number of events on one of these couplings when the other is held fixed at its maximum allowed value.

[6] λ'_{21m} and λ'_{31m} would also do so, but their bounds are tighter.

[7] For the purpose of illustration, we present results for λ'_{2m1}, λ'_{3m1} for $m = 3$. Needless to say, the analysis can be done just as well for $m = 1,2$.

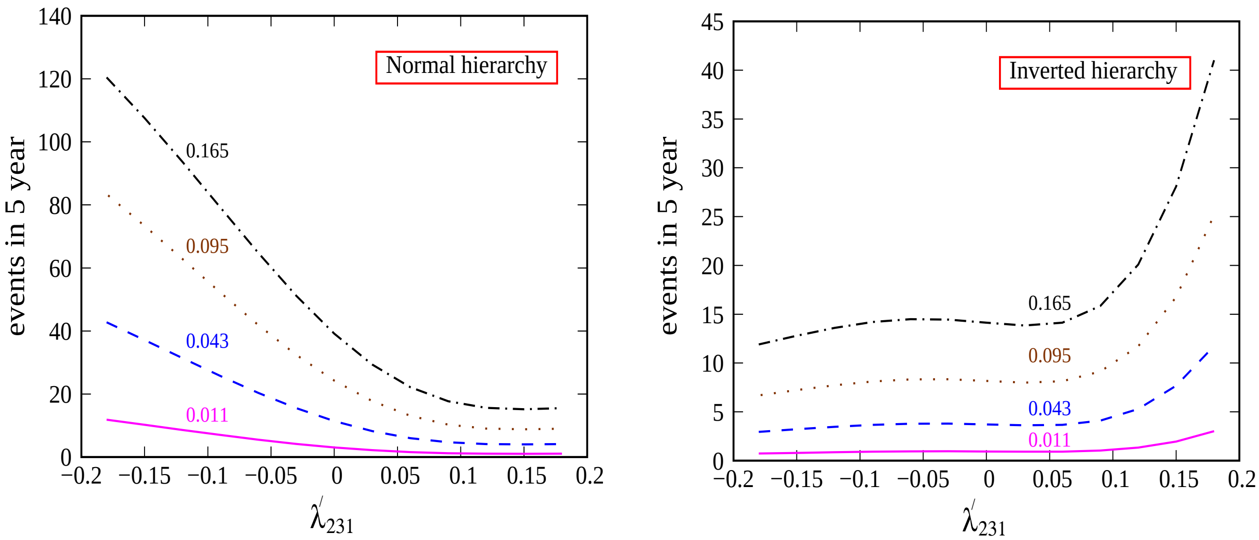

Figure 4: The number of events as a function of λ'_{231} when λ'_{331} is fixed at its currently allowed maximum (0.58) for normal (left panel) and inverted (right panel) hierarchies. The chosen $\sin^2 2\theta_{13}$ are indicated next to the curves.

For example, in Fig. 3 we show, for various values of $\sin^2 2\theta_{13}$, the dependence of the number of events on λ'_{331} when λ'_{231} is held fixed at its maximum (= 0.18). We let λ'_{331} run over both positive and negative values. It is readily seen that if the signs of both λ'_{331} and λ'_{231} are reversed then the results are unaffected. Therefore taking the positive value of λ'_{231} does not amount to any loss of generality.

A bound is set on the coupling from the consideration that the true number of events cannot be less than the observed number. For example, for the normal hierarchy case, the number of events along with the value of $\sin^2 2\theta_{13}$ will determine an upper as well as a lower bound on λ'_{331}. In the inverted hierarchy spectrum, the number of events is smaller and most often only a lower bound can be set on λ'_{331}.

Fig. 4 is a similar analysis where λ'_{331} has been fixed at its maximum allowed limit of 0.58 and the number of events is shown as a function of λ'_{231}. The nature of the curves in both panels are somewhat different from those in Fig. 3. Both figures indicate that for the normal hierarchy, the number of events is more if λ'_{231} and λ'_{331} have opposite sign, *i.e.*, R_{23} is negative. The opposite is true for the inverted hierarchy. This may provide a handle to determine the relative sign of the two λ' couplings. From Fig. 4, for the normal hierarchy one can set an upper bound on λ'_{231} while for the inverted case a lower bound may be obtained.

Finally, we consider the situation where only one $\not{R}$ coupling is non-zero. In such an event, $R_{23} = 0$ and only one of R_{22}, R_{33} is non-zero. The dependence of the number of events on a non-zero λ'_{331} or λ'_{2m1}, for a chosen $\sin^2 2\theta_{13}$, can be seen from Fig. 5. In this figure, we use the fact that if only one of these $\not{R}$ couplings is non-zero, it appears in the results through $|\lambda'|$. For the normal hierarchy, the curves for λ'_{2m1} are terminated at the maximum allowed value of 0.18. Fig. 5 can also be used for λ'_{321}, λ'_{31m} and λ'_{21m}, bearing in mind their different upper bounds. For the inverted hierarchy, the number of events is small for λ'_{2m1} and λ'_{21m} and insensitive to the magnitude of the coupling. These are not shown. It is seen that for the normal hierarchy there is a good chance to determine the $\not{R}$ couplings

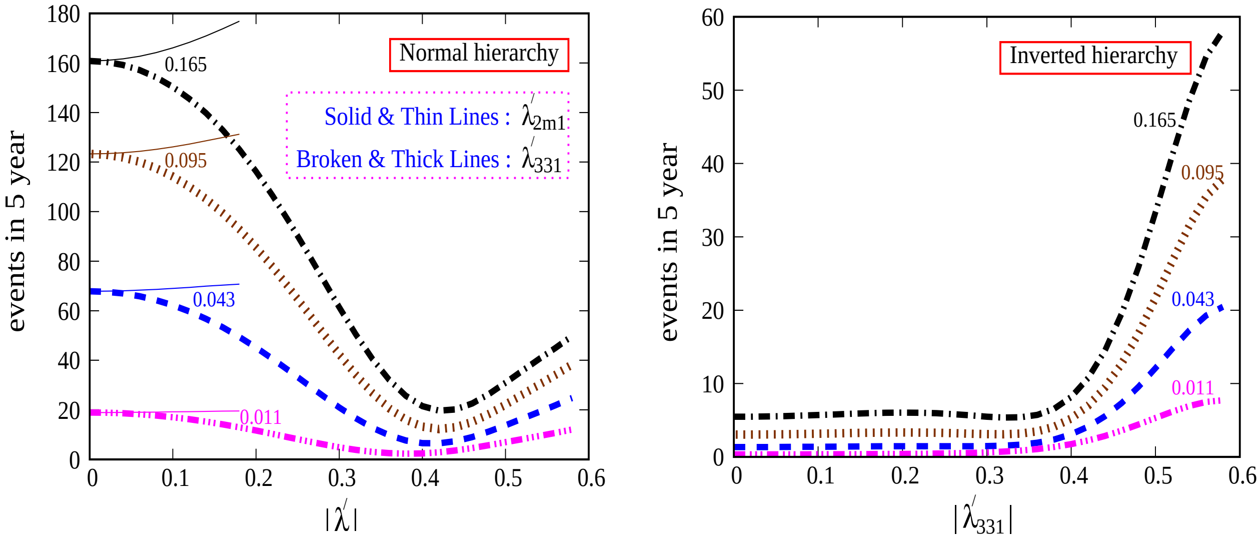

Figure 5: The number of events as a function of a coupling $|\lambda'|$, present singly, for the normal (left panel) and inverted (right panel) hierarchies. The chosen $\sin^2 2\theta_{13}$ are indicated next to the curves.

from the number of events. In fact, if the number of events is less than about 50 there is a disallowed region for $|\lambda'|$, while for larger numbers there is only an upper bound. For the inverted hierarchy, more than about five events will set a lower bound on the coupling.

V.3 Effect of λ

The λ couplings which can contribute in eq. (13) have strong existing bounds [14] and their contribution to R is rather small in comparison to $\sqrt{2}G_F n_e$. Among them, the bounds $\lambda_{121} < 0.05$ and $\lambda_{321} < 0.07$ for $m_{\tilde{l}} = 100$ GeV are relatively less stringent [14]. We show their very modest impact in Fig. 6. It is clear from this figure that (a) the λ-type couplings cannot seriously deter the extraction of θ_{13} or the determination of the neutrino mass hierarchy, and (b) when θ_{13} is known in future it will still not be possible to constrain these couplings through long baseline experiments.

VI Conclusion

R-parity violating supersymmetry is among several extensions of the Standard Model crying out for experimental verification. The model has flavour diagonal and flavour changing neutral currents which can affect neutrino masses and mixing and can leave their imprints in long baseline experiments. This is the focus of this work.

We consider a β-beam experiment with the source at CERN and the detector at INO. We find that the $\not{R}$ interactions may obstruct a clean extraction of the mixing angle θ_{13} or determination of the mass hierarchy unless the bounds on the λ' couplings are tightened. On the other hand, one might be able to see a clean signal of new physics. Here, the long baseline comes as a boon over experiments like MINOS which cover shorter distances.

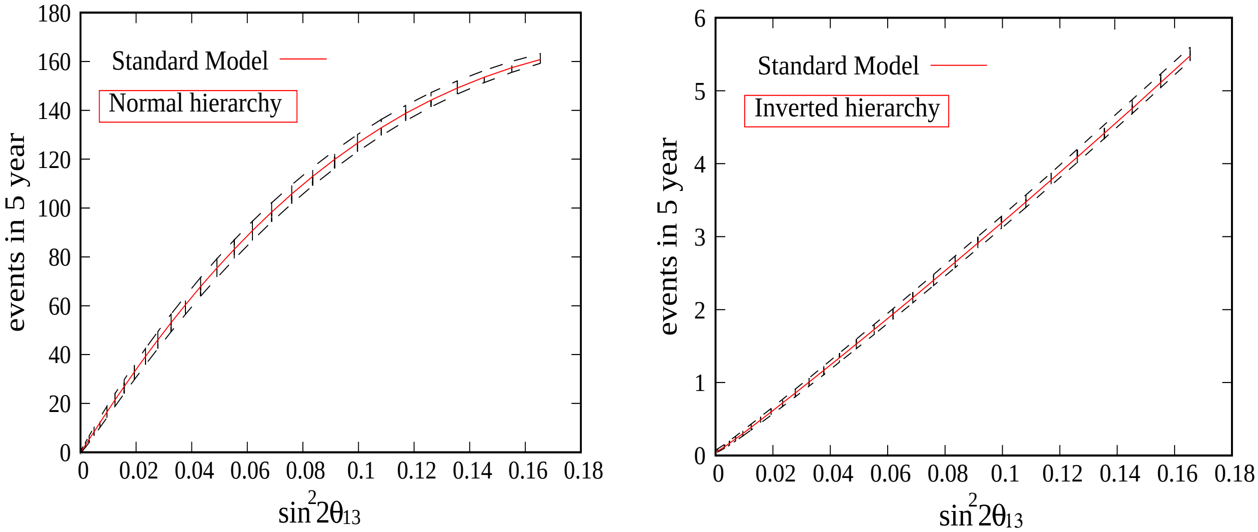

Figure 6: Number of muon events for normal and inverted mass hierarchies as a function of $\sin^2 2\theta_{13}$ for a five-year ICAL run. The solid lines correspond to the absence of any non-Standard neutrino interaction. The shaded area is covered if the λ couplings are varied over their entire allowed range.

Two experiments of these contrasting types, taken together, can expose the presence of a non-standard interaction like RPVSM.

There are other non-standard models [15] where four-fermion neutrino couplings with greater strength have been invoked. The signals we consider will be much enhanced in such cases.

Our results are presented for the CP conserving case. As θ_{13} is small, the CP violating effect is expected to be suppressed. We have checked this for the Standard Model, where the 'magic' nature of the baseline [29] also plays a role.

Finally, in this paper we have restricted ourselves to a β-beam neutrino source. Much the same could be done for antineutrinos as well; then the signs of all terms in R – see eq. (9) – will be reversed. It follows from eq. (21) that θ_{13}^m can then be maximal only for the inverted hierarchy and as such more events are expected here than in the normal hierarchy. Broadly, results similar to the ones presented here with neutrinos can be obtained with antineutrinos if normal hierarchy is replaced by inverted hierarchy and *vice-versa*.

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