A general analysis with trilinear and bilinear R-parity violating couplings in the light of recent SNO data

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Abstract

We analyse an extension of the minimal supersymmetric standard model including the dominant trilinear and bilinear R-parity violating contributions. We take the trilinear terms from the superpotential and the bilinear terms from the superpotential as well as the scalar potential. We compute the neutrino masses induced by those couplings and determine the allowed ranges of the R-parity violating parameters that are consistent with the latest SNO results, atmospheric data and the Chooz constraint. We also estimate the effective mass for neutrinoless double beta decay in such scenarios.

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I. INTRODUCTION

It is firmly established that non-zero neutrino masses can provide a solution to the observed solar and atmospheric neutrino deficits. This requires two large mixing angles (very recent SNO data favour the large mixing angle solution, LMA, for the solar anomaly) and two hierarchical neutrino mass squared differences ($\Delta m_{\text{atm}}^2 \ll \Delta m_{\text{solar}}^2$). We assume that the three mass eigenstates are given by $m_i$ ($i = 1, 2, 3$) and we parametrise the rotation matrix from neutrino flavour $(f)$ to mass $(i)$ eigenstates as: $V_{ji} = R_{\nu 23}(\theta_{23})R_{\nu 13}(\theta_{13})R_{\nu 12}(\theta_{12})$. The MNS matrix (analogous to the CKM mixing matrix for the quark sector) neglecting CP phases is given by

$$V_{fi} = \begin{pmatrix}
    c_{12}c_{13} & c_{12}s_{13}s_{23} & s_{13} \\
    -c_{12}s_{13} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\
    s_{23}s_{12} - c_{23}s_{12}s_{13} & -c_{23}s_{23} - c_{23}s_{12}s_{13} & c_{13}c_{23}
\end{pmatrix},$$

where $c_{ij} \equiv \cos \theta_{ij}$ and $s_{ij} \equiv \sin \theta_{ij}$. For the solar anomaly, which we take to be a consequence of $\nu_e - \nu_\mu$ oscillation, the relevant mass squared difference is $\Delta m_{12}^2 = \Delta m_{\text{solar}}^2$, while for the atmospheric case, the oscillation being between $\nu_\mu$ and $\nu_\tau$, the relevant mass squared difference is $\Delta m_{32}^2 \approx \Delta m_{\text{atm}}^2$. After the inclusion of the SNO data, the MSW-LMA oscillation is the most favoured solution with $\Delta m_{\text{atm}}^2 = (2.5 - 19.0) \times 10^{-5} \text{ eV}^2$ and $\sin^2 2\theta_{23} = 0.61 - 0.95$. The SuperK atmospheric neutrino data suggest $\Delta m_{\text{atm}}^2 = (2 - 5) \times 10^{-3} \text{ eV}^2$ with $\sin^2 2\theta_{23} = 0.88 - 1.0$. The Chooz \cite{chooz} and Palo Verde \cite{palo_vene} long baseline reactor experiments bound $\sin^2 \theta_{13} \lesssim 0.04$. Concerning the absolute masses, the recent claim for the evidence of neutrinoless double beta decay ($0\beta \beta$) by the Moscow-Heidelberg Collaboration \cite{0beta}, although not yet firmly established, constrains the $(ee)$-element of the neutrino mass matrix in the flavour basis to lie between 0.1 and 0.5 eV. Tritium $\beta$-decay requires $m_\nu \lesssim 2.2 \text{ eV}$ \cite{tbf}. Cosmological analysis from the recent 2dF Galaxy Redshift Survey constrains $\sum m_i \lesssim 2.2 \text{ eV}$ \cite{cosmo}.

Neutrino masses can be generated in the R-parity violating ($R_p$) Supersymmetric Standard Model, where $R_p$ is defined as $(-1)^{3B + L + 2S}$. Here $B, L$ and $S$ are the baryon number, lepton number and spin of a particle, respectively. Strict phenomenological bounds on $B$ and/or $L$ violation exist in the literature \cite{bounds}.

In this paper we assume that $B$ violating couplings are absent and generate neutrino Majorana masses via superpotential bilinear and trilinear ($\lambda, \lambda'$) interactions in the superpotential as well as the bilinear soft terms ($B_i$) \cite{soft}.

$$W = \mu^J H_u L_J + \frac{1}{2} \lambda^{JK\ell} L_J L_K E_\ell^c + \lambda'^{jps} L_J Q_p D_s^c + h_u^m H_u Q_p U_q^c,$$

where the vector $L_J = (H_d, L_i)$ with $J : 4,1$, and the soft supersymmetry-breaking potential is

$$V_{\text{soft}} = \frac{\tilde{m}_u^2}{2} H_u^* H_u + \frac{1}{2} L^I |\tilde{m}_L^I|_J L_K + B^I H_u L_J + A^{uqs} H_u Q_p U_q^c + A^{jps} L_J Q_p D_s^c + \frac{1}{2} A^{JK\ell} L_J L_K E_\ell^c + \text{h.c.}$$

As has been extensively discussed in refs \cite{refs} (and references therein), field redefinitions of the $H_d, L_i$ fields correspond to basis changes in $L_J$ space and consequently the Lagrangian parameters will be altered. We use the basis-independent parameters constructed in \cite{basis} and write the neutrino mass matrix in terms of $\delta^i_\mu, \delta^i_\nu, \delta^i_{\lambda'}, \delta^i_{\lambda''}$, which in the basis in which the neutrino vevs are zero correspond to $\mu^f/|\mu|, B^f/|B|, \lambda_{ijk}, \lambda'_{ipq}$, respectively.

Calculations of neutrino masses in the context of $R_p$ theories have focused on tree-level contributions from the bilinear $\mu$-parameter or loop contributions from the trilinear $\lambda$ and $\lambda'$ couplings \cite{loop}. Recently a detailed phenomenological analysis has been done for a model including both $\lambda$, $\lambda'$ and the superpotential bilinear parameter $\mu_\nu$ \cite{recent}. In the basis-independent approach, a phenomenological analysis has been done including only the purely bilinear contributions, $\delta^i_\mu$ from the superpotential and $\delta^i_\nu$ from the soft Lagrangian \cite{basis}. The possibility that loops involving $\delta^i_\nu$ were important was also discussed in \cite{loop}.

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1We follow closely the conventions given in \cite{conventions} and we refer the reader to these papers for more details. The symbols used in Eqs. \cite{symbols} and \cite{symbols} have their usual significance.
Our purpose in this paper is to perform for the first time an analysis in a model which includes both the superpotential and soft bilinear parameters \( \delta^i_{\mu} \) and \( \delta^j_{\mu} \) along with the superpotential trilinear couplings \( \delta^{ijk}_\lambda \), in the mass insertion approximation. A similar analysis can be performed including the trilinears \( \delta^{ipq}_{\lambda'} \).

In our analysis we take all \( \mathcal{R}_p \) parameters to be real. Thus we update the analysis in [17] by including the trilinear loop contributions alongside the bilinear tree and loop terms. We interface the neutrino mass matrix constructed out of the \( \mathcal{R}_p \) parameters with the constraints on the solar and atmospheric mass squared splittings, the corresponding mixing angles, and the Chooz constraint on \( \theta_{13} \). We then examine the nature of the mass spectrum and we check the consistency with cosmological data. We also obtain the effective mass for neutrinoless double beta decay in our scenario. Furthermore, we observe the impact of adding the trilinear contributions to the numerical results obtained in [17].

II. PARAMETRIZATION OF THE MASS MATRIX

The \( \mathcal{R}_p \) model we are considering generates a single neutrino mass at tree level proportional to \( \delta^i_{\mu} \delta^j_{\nu} \). There are additional loop corrections to the mass matrix when non-vanishing \( \delta^i_{B} \), \( \delta^{ijk}_\lambda \) (and \( \delta^{ipq}_{\lambda'} \)) are included, leading to more than one non-zero mass eigenvalue. This enables us to fit the data on mass squared splittings and mixing angles. The relevant types of loops we consider in the mass insertion approximation are:

- the well-known loops involving the trilinear \( \mathcal{R}_p \) couplings \( \lambda \) or \( \lambda' \) at the neutrino vertices I and II in Fig. 1 (with lepton/slepton or quark/squark as propagators), which give contributions proportional to \( \delta_{\lambda}\delta_{\lambda'} \) (or \( \delta_{\lambda'}\delta_{\lambda} \));

- the Grossman-Haber diagrams [14], in which there are gauge couplings at the neutrino vertices while there are two types of \( \mathcal{R}_p \) interactions contributing to the \( \Delta L = 2 \) Majorana mass in the diagram of Fig. 1. The first kind have \( \mathcal{R}_p \) couplings located at positions III + IV (slepton-Higgs mixing) with contributions proportional to \( \delta_{B}\delta_{B} \). In the second type, the \( \mathcal{R}_p \) interactions are located at positions V + IV (neutrino-neutralino and slepton-Higgs mixing) with contributions proportional to \( \delta_{\mu}\delta_{B} \);

- the diagram of Fig. 2, where two units of \( L \) violation come from positions V (neutrino-neutralino mixing) and II (\( \lambda \) or \( \lambda' \) vertex). The contribution to the neutrino mass is proportional to \( \delta_{\mu}\delta_{\lambda} \) (or \( \delta_{\mu}\delta_{\lambda'} \)).

The last two types of loops have frequently been overlooked in analytic estimates of neutrino masses. Exact formulae for these diagrams can be found in [16]. Our formulae are robust (see later) and good enough for an order-of-magnitude estimate.

Setting all unknown sparticle masses equal to \( M_S = 100 \text{ GeV} \), and neglecting the mixing angles among the sparticles, we have a neutrino mass matrix of the form

\[
\begin{pmatrix}
\nu_i & \cdots & \nu_j
\end{pmatrix}
\begin{pmatrix}
\delta^i_{\mu} & \cdots & \delta^j_{\nu}
\end{pmatrix}
\]
Thus, the neutrino mass matrix elements will be given by,

\[
[m_{\nu}]_{ij} = M_S \left[ \frac{\delta^i}{\cos \beta} \right]_{\mu} \left( \delta^j_{\lambda} \right)_{\mu} + \frac{\kappa_1}{\cos \beta} \left( \delta^i_{\mu} \delta^j_{\lambda} + \delta^j_{\mu} \delta^i_{\lambda} \right) + \frac{\kappa_1}{\cos^2 \beta} \delta^i_{\mu} \delta^j_{\lambda} \\
+ \kappa_2 \sum_{k,n} m_e \delta^i_{\lambda} \delta^{nk}_{\lambda} \delta^{kn}_{\lambda} + 3 \sum_{k,n} m_d \delta^i_{\lambda} \delta^{nk}_{\lambda} \delta^{kn}_{\lambda} \\
+ \kappa_3 \sum_{k} m_e \left( \delta^i_{\mu} \delta^{jk}_{\lambda} + \delta^j_{\mu} \delta^{ik}_{\lambda} \right) + 3 \sum_{k} m_d \left( \delta^i_{\mu} \delta^{jk}_{\lambda} + \delta^j_{\mu} \delta^{ik}_{\lambda} \right),
\]

where

\[
\kappa_1 = \frac{g^2}{64\pi^2}, \quad \kappa_2 = \frac{1}{8\pi^2 M_S}, \quad \kappa_3 = \frac{g}{16\pi^2 \sqrt{2}}.
\]

We have included for completeness the contributions arising from the \(\delta_{\lambda'}\) terms which we put to zero in our numerical analysis. The simplest case to consider with a common \(\delta_{\lambda'}^i \equiv \delta_{\mu}, \delta_{\lambda}^i \equiv \delta_B\) and \(\delta_{\lambda'}^{nk} \equiv \delta_{\lambda}\) does not work as it gives only two non-zero masses and an eigenvector of the form \((1/\sqrt{2}, -1/\sqrt{2}, 0)\) which cannot accommodate two large mixing angles for \(\theta_{12}\) and \(\theta_{23}\).

In our numerical analysis we take : \(\delta_{\lambda}^i, \delta_B, \delta_{\lambda_{\lambda'}}^i \equiv \delta_{\lambda}, \delta_{\lambda_{\lambda'}}^{nk} \equiv 0\), for \(i = 1, 2, 3\), i.e., seven independent parameters. Thus, the neutrino mass matrix elements will be given by,

\[
\begin{align*}
 m_{11} &= M_S \left[ (\delta^1_{\mu})^2 + \frac{\kappa_1}{\cos \beta} (\delta^1_{\lambda})^2 + 2 \frac{\kappa_1}{\cos \beta} \delta^1_{\mu} \delta^1_{\lambda} \right] + 2 \kappa_3 \tau^1_{\mu} \delta^1_{\lambda} + \kappa_2 m^2 \delta^3_{\lambda}, \\
 m_{12} &= M_S \left[ \frac{\delta^1_{\mu}}{\cos \beta} (\delta^2_{\lambda})^2 + \frac{\kappa_1}{\cos \beta} (\delta^2_{\mu} \delta^1_{\lambda} + \delta^2_{\mu} \delta^2_{\lambda}) \right] + \kappa_3 \tau^1_{\mu} (\delta^2_{\mu} \delta^1_{\lambda} + \delta^2_{\mu} \delta^2_{\lambda}) + \kappa_2 m^2 \delta^3_{\lambda}, \\
 m_{22} &= M_S \left[ (\delta^2_{\mu})^2 + \frac{\kappa_1}{\cos \beta} (\delta^2_{\lambda})^2 + 2 \frac{\kappa_1}{\cos \beta} \delta^2_{\mu} \delta^2_{\lambda} \right] + 2 \kappa_3 \tau^2_{\mu} \delta^2_{\lambda} + \kappa_2 m^2 \delta^3_{\lambda}, \\
 m_{13} &= M_S \left[ \frac{\delta^1_{\mu}}{\cos \beta} (\delta^3_{\lambda})^2 + \frac{\kappa_1}{\cos \beta} (\delta^3_{\mu} \delta^1_{\lambda} + \delta^3_{\mu} \delta^3_{\lambda}) \right] + \kappa_3 \tau^1_{\mu} (\delta^3_{\mu} \delta^1_{\lambda} + \delta^3_{\mu} \delta^3_{\lambda}), \\
 m_{23} &= M_S \left[ \frac{\delta^2_{\mu}}{\cos \beta} (\delta^3_{\lambda})^2 + \frac{\kappa_1}{\cos \beta} (\delta^3_{\mu} \delta^2_{\lambda} + \delta^3_{\mu} \delta^3_{\lambda}) \right] + \kappa_3 \tau^2_{\mu} \delta^3_{\lambda}, \\
 m_{33} &= M_S \left[ (\delta^3_{\mu})^2 + \frac{\kappa_1}{\cos \beta} (\delta^3_{\lambda})^2 + 2 \frac{\kappa_1}{\cos \beta} \delta^3_{\mu} \delta^3_{\lambda} \right],
\end{align*}
\]

where we have employed the hierarchy of the charged fermion masses to keep only the dominant terms.
III. RESULTS AND CONCLUSIONS

We have performed a general scan of parameter space made up by the seven parameters that appear in the mass matrix allowing tree-level contributions to either dominate over the loop corrections, to be on the same order as these, or to be much smaller than the loop terms. The fitted values of the couplings, obtained by using the atmospheric and Chooz data together with the preferred solar MSW-LMA solution from SNO, are presented in table I. Here we have taken $\cos \beta = 1$ primarily to ensure a comparison with results in [17], which too employed the same value of $\cos \beta$, on the same footing. We stress that although this choice of $\cos \beta$ leads to an unacceptably low $\tan \beta$, we still use this value for illustration and effective comparison with previous results, noting at the same time that an order-of-magnitude estimate of the couplings is not sensitive to this choice. We also show in table I the allowed ranges of $\sum_i m_i$, and $m_{\text{eff}} \equiv \sum_i V_{ei}^2 m_i = \sum_i |V_{ei}|^2 m_i$ (since we have assumed the $V$ matrix to be real). This last quantity is the effective mass relevant for neutrinoless double beta decay (the neutrino masses induced by $\mathcal{R}_p$ interactions are Majorana type).

| Couplings | Min | Max |
|-----------|-----|-----|
| $\delta_\lambda$ | $-2.0 \times 10^{-5}$ | $2.0 \times 10^{-4}$ |
| $\delta_\mu$ | $-6.8 \times 10^{-3}$ | $6.8 \times 10^{-3}$ |
| $\delta_0^L$ | $-8.4 \times 10^{-2}$ | $8.4 \times 10^{-2}$ |
| $\delta_0^R$ | $-8.4 \times 10^{-2}$ | $8.4 \times 10^{-2}$ |
| $\delta_B$ | $-2.7 \times 10^{-3}$ | $2.7 \times 10^{-3}$ |
| $\delta_\beta$ | $0.3 \times 10^{-3}$ | $3.0 \times 10^{-3}$ |
| $\delta_\beta$ | $0.3 \times 10^{-3}$ | $3.0 \times 10^{-3}$ |
| $m_{\text{eff}}$ (eV) | $1.9 \times 10^{-3}$ | $6.7 \times 10^{-2}$ |
| $\sum_i m_i$ (eV) | $4.9 \times 10^{-2}$ | $0.2$ |

TABLE I. Fitted range of the couplings satisfying MSW-LMA, SuperK and Chooz simultaneously. The fit is performed taking $\cos \beta = 1$.

In Fig. 3 we present the allowed region in the $|\delta_B| = \sqrt{\sum_i (\delta_i^B)^2}$ versus $|\delta_\mu| = \sqrt{\sum_i (\delta_i^\mu)^2}$ plane for the combined fit taking $\cos \beta = 1$. We present our results for both $\delta_\lambda \neq 0$ and $\delta_\lambda = 0$. It can be clearly seen that the allowed region increases when we admit non-zero values of $\delta_\lambda$. This is mainly due to the presence of the $\delta_\mu \delta_\lambda$ terms in the mass matrix (originating from Fig. 2) which can take either sign and thus can accommodate a larger region of parameter space.

The resulting fit strongly prefers a hierarchical mass pattern in our scenario, although our analysis cannot make a distinction between the inverted and the normal hierarchy. The inclusion of a non-zero $\delta_\lambda$ to the set of non-vanishing $\delta_\mu$ and $\delta_B$ allows us to have all three non-vanishing neutrino masses while if only the latter two vectors are non-zero there are only two non-zero eigenvalues [17]. The maximum value of $m_{\text{eff}}$ we predict can be tested in the next generation of neutrinoless double beta decay experiments. We have also checked that the cosmological bound restricting the sum of eigenvalues to be at most $\sim 2$ eV is fulfilled.

To conclude, we outline the novel features of our analysis: (i) the trilinear $\mathcal{R}_p$ interactions along with both types (originating from superpotential and soft terms) of bilinear $\mathcal{R}_p$ terms have been employed for the first time to analyse the neutrino mass matrix; (ii) the seven parameter neutrino mass matrix has been interfaced with the latest SNO results favouring MSW-LMA solution along with the SuperK atmospheric and Chooz data; (iii) by including a non-vanishing $\delta_\lambda$ we have updated the analysis in [17] and the numerical impact of adding this term has been highlighted in Fig. 3; (iv) the mass spectrum in this kind of scenario implies a hierarchical pattern, although a distinction between the normal and inverted pictures cannot be made; (v) our prediction of $m_{\text{eff}}$ can be tested in the next generation of neutrinoless double beta decay experiments (GENIUS, Majorana, MOON, EXO) [24]. We finally make a remark that allowing a non-vanishing $\delta_\lambda$ will not qualitatively change the pattern of our fit.

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[1] Q.R. Ahmed et al., (SNO Collaboration), Phys. Rev. Lett. 89 (2002) 011301; ibid. 89 (2002) 011302.
[2] S. Fukuda et al., (SuperKamiokande Collaboration), Phys. Rev. Lett. 86 (2001) 5656.
[3] SuperKamiokande Collaboration (T. Toshito for the collaboration), hep-ex/0105023 (to appear in the proceedings of 36th Rencontres de Moriond on Electroweak Interactions and Unified Theories, Les Arcs, France, 10-17 Mar 2001).
[4] Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. 28 (1962) 870.
[5] P.C. de Holanda and A. Yu. Smirnov, hep-ph/0205241; G.L. Fogli, E. Lisi, D. Montanino, A. Palazzo, Phys. Rev. D 64 (2001) 093007; J.N. Bahcall, M.C. Gonzalez-Garcia, C. Peña-Garay, JHEP 0108 (2001) 014; A. Bandopadhyay, S. Choubey, S. Goswami, K. Kar, Phys. Lett. B 519 (2001) 83; P.I. Krastev, A. Yu. Smirnov, Phys. Rev. D 63 (2002) 073022.
[6] M. Apollonio et al., Chooz Collaboration, Phys. Lett. B 466 (1999) 415.
[7] F. Boehm et al., Palo Verde Collaboration, Phys. Rev. D 64 (2001) 112001.
[8] H.V. Klapdor-Kleingrothaus et al., Mod. Phys. Lett. A 16 (2001) 2409.
[9] J. Bonn et al., Nucl. Phys. Proc. Suppl. 91 (2001) 273.
[10] O. Elgaroy et al., astro-ph/0204152.
[11] H.P. Nilles and N. Polonsky, Nucl. Phys. B 499 (1997) 33; T. Banks, Y. Grossman, E. Nardi and Y. Nir, Phys. Rev. D 52 (1995) 5319; F.M. Borzumati, Y. Grossman, E. Nardi and Y. Nir, Phys. Lett. B 384 (1996) 123; E. Nardi, Phys. Rev. D 55 (1997) 5772; L. Hall and M. Suzuki, Nucl. Phys. B 231 (1984) 419.
[12] G. Farrar and P. Fayet, Phys. Lett. B 76 (1978) 575; S. Weinberg, Phys. Rev. D 26 (1982) 287; N. Sakai and T. Yanagida, Nucl. Phys. B 197 (1982) 533; C. Aulakh and R. Mohapatra, Phys. Lett. B 119 (1982) 136.
[13] G. Bhattacharyya, Nucl. Phys. Proc. Suppl. 52A (1997) 83; hep-ph/9703393; H. Dreiner, hep-ph/9707433; B. Allanach, A. Dedes and H. Dreiner, Phys. Rev. D 60 (1999) 075014.
[14] Y. Grossman and H. Haber, Phys. Rev. Lett. 78 (1997) 3438; Phys. Rev. D 59 (1999) 093008; Phys. Rev. D 63 (2001) 075011.
[15] S. Davidson and M. Losada, JHEP 0005 (2000) 021.
[16] S. Davidson and M. Losada, Phys. Rev. D 65 (2002) 075025.
[17] A. Abada, S. Davidson, M. Losada, Phys. Rev. D 65 (2002) 075010.
[18] A partial list includes:
A.Y. Smirnov, F. Vissani, Nucl. Phys. B 460 (1996) 37; C. Liu, Mod. Phys. Lett. A 12 (1997) 329; B. Mukhopadhyaya, S. Roy, F. Vissani, Phys. Lett. B 443 (1998) 191; D.E. Kaplan, A. Nelson, JHEP 0001 (2000) 033; J. Valle, hep-ph/9712277; A.S. Joshipura, S. Vempati, Phys. Rev. D 60 (1999) 111303; A. Datta, B. Mukhopadhyaya, S. Roy, Phys. Rev. D 61 (2000) 055006; D.A.R. Quintero, hep-ph/0111198; S. Dimopoulos, L. Hall, Phys. Lett. B 207 (1988) 210; R. Godbole, P. Roy, X. Tata, Nucl. Phys. B 401 (1993) 67; S. Rakshit, G. Bhattacharyya, A. Raychaudhuri, Phys. Rev. D 59 (1999) 091701; R. Adhikari, G. Omanovic, Phys. Rev. D 59 (1999) 073003; G. Bhattacharyya, H.V. Klapdor-Kleingrothaus, H. Päs, Phys. Lett. B 463 (1999) 77; M. Drees, S. Pakvasa, X. Tata, T. ter Veldhuis, Phys. Rev. D 57 (1998) 5335; E.J. Chun, S.K. Kang, C.W. Kim, U.W. Lee, Nucl. Phys. B 544 (1999) 89; S.Y. Choi, E. J. Chun, S. K. Kang, J. S. Lee, Phys. Rev. D 60 (1999) 075002; Y. Koide, A. Ghosal, hep-ph/0203113; I. Gogoladze, A. Perez-Lorenzana, Phys. Rev. D 65 (2002) 095011; T.-F. Feng, X.-Q. Li, Phys. Rev. D 63 (2001) 073006; A. de Gouvea, S. Lola, K. Tobe, Phys. Rev. D 63 (2001) 035004; F. Borzumati, J.S. Lee, hep-ph/0207184.
[19] A. Abada and M. Losada, Nucl. Phys. B 585 (2000) 45.
[20] A. Abada and M. Losada, Phys. Lett. B 492 (2000) 310.
[21] S.R. Elliot and P. Vogel, hep-ph/0202264.
FIG. 3. We present the available region in the $\delta_B \equiv |\delta_B|$ versus $\delta_\mu \equiv |\delta_\mu|$ plane for a combined fit using Chooz, SuperK and the SNO results for the MSW-LMA solar oscillation solution, with $\cos \beta = 1$. The circles are solutions for $\delta_\lambda \neq 0$, the crosses are for $\delta_\lambda = 0$. This figure should be compared with Fig. 5 of ref. [17].