Sensitivity to SUSY Seesaw Parameters and Lepton Flavour Violation

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We address the constraints on the SUSY seesaw parameters arising from Lepton Flavour Violation observables. Working in the Constrained Minimal Super-symmetric Standard Model extended by three right-handed (s)neutrinos, we study the predictions for the branching ratios of $l_i \rightarrow l_j + 3 \ell_k$ channels. We impose compatibility with neutrino data, electric dipole moments, and further require a successful baryon asymmetry of the Universe (via them all leptogenesis). We emphasize the interesting interplay between the current and future experimental bounds on the latter ratios, $m$, and may lead to a better knowledge of the heavy neutrino mass parameters.

1. Introduction

Supersymmetric (SUSY) extensions of the Standard Model (SM), including three right-handed neutrino super partners, are well motivated models which can accommodate a seesaw mechanism, and at the same time establish the hierarchy between the scale of new physics and the electroweak (EW) scale. One of the most striking phenomena in the context of SUSY seesaw models is the prediction of sizable rates for lepton number violating (LFV) processes, any orders of magnitude larger than those expected from the SM seesaw. In this sense, the $l_i \rightarrow l_j + 3 \ell_k$ lepton decay channels, as well as the electroweak sphaleron processes, are the most interesting processes. Experimentally, the most prominent decay is the $\mu \rightarrow e$ process, which exhibits the most stringent present bounds, and our analysis is performed modulo the future sensitivity.

Given the fact that both light and heavy neutrinos enter in the determination of the LFV rates (via the Yukawa interactions), a powerful link between the low- and high-energy neutrino parameter spaces can be obtained from these LFV processes. From the requirement of compatibility with LFV bounds and low-energy data, one can then extract information on the heavy neutrino sector, thus providing an indirect access to the heavy neutrino parameter spaces.

In Ref. [1], we have systematically explored the sensitivity of LFV processes to the seesaw parameters in a broad class of SUSY seesaw scenarios, with different possibilities for the mixing in the neutrino sector. We have also incorporated in this analysis the requirement of generating a successful baryon asymmetry of the Universe (BAU) via them all leptogenesis [2]. In particular, we have shown that, subject to the condition that $m_\ell \not\subset \{m_D, m_{H^\pm}\}$, channels indeed offer interesting expectations regarding the sensitivity to the seesaw parameter spaces. This sensitivity to the seesaw parameter spaces has been previously pointed out in Refs. [3,4], for some specific seesaw cases.

2. LFV within the SUSY Seesaw

The lepton superpotential containing the relevant terms to describe a type-I SUSY seesaw is given by $W = \sum_i \ell_i^c Y_1 H_1^2 + E^c Y_2 H_2^2 + \sum_i \delta_i^c m_i H_N^c$; where $N^c$ is the additional super partner of the right-handed neutrinos and their scalar partners, $Y_i$ are the lepton Yukawa couplings and $m_i$ is a mass parameter. Henceforth, we will assume that we are in a basis where $Y_1$ and $m_N$ are diagonal in flavour space. After EW symmetry breaking, the full 6 x 6 neutrino mass matrix is given in terms of the three Majorana mass matrices, $m_D = Y v_2$, where $Y$ denotes the neutrino Yukawa couplings and $v_2$ are the vacuum expectation values of the neutral Higgs scalars, with $v_2 = 174 \text{GeV}$. In the seesaw limit, $v_2 \gg m$, we obtain the seesaw equation for the light neutrino masses, $m = m_D^T m_N^{-1} m_D$. The diagonalization of the full neutrino mass matrix leads to the six physical Majorana states: three light $\nu$ and three heavy states $\nu$. Their masses are given by $m_{\nu}^O = \sum_i U^O_{\nu i} m_i$, where $m_i = \delta_i^c m_i H_N^c$ and $U_{\nu i} = \sum_i \sum_j U^O_{\nu i} U^O_{\nu j}$, and $v_2$. We use the standard parametrization proposed in Ref. [5], the solution to the seesaw equation can be written as

$$m_D = U^O_{\nu i} m_i H_N^c$$

and

$$m_D = U^O_{\nu i} m_i H_N^c$$

for some specific seesaw cases.
where $R$ is a generic complex orthogonal 3 × 3 matrix, defined by three complex angles $i$. This parameterisation allows to accommodate the experimental data, while leaving room for extra neutrino masses, in addition to those in $\nu_{\mu,\tau}$. It further shows how large Yukawa couplings $Y_{ij}$ (1) can be obtained by choosing large entries in $m_{\nu}^{\text{diag}}$.

In our analysis, we have considered scenarios of hierarchical heavy and light neutrinos, $m_{\nu_1}, m_{\nu_2}, m_{\nu_3}$, and $m^{\nu_1}_1 m^{\nu_2}_2 m^{\nu_3}_3$, with $m_1 = m_2 = m_3 = m_{\nu_1}^{2}$ and $m_3 = m_{\nu_2}^{2} + m_{\nu_3}^{2}$. Regarding the numerical values, we have used $m_{\nu_1}^{2} = 8 \times 10^5$ eV$^2$, $m_{\nu_2}^{2} = 2 \times 10^3$ eV$^2$, $\mu_2 = 30$, $\mu_3 = 45 < 10$. For simplicity, we have further set $m_1 = m_2 = 0$.

Within the context of the Constrained Minimal Supersymmetric Standard Model (CMSSM), universality of the soft SUSY breaking parameters is imposed at a high-energy scale $M_X$, which we choose to be the SU(2) × U(1) gauge coupling unification scale ($M_X \approx 10^6$ GeV). Instead of scanning over the full CMSSM parameter space (generated by $M_{1/2} ; M_0 ; A_0 ; \tan \beta ; \text{sign} \mu$), we considered specific choices for the latter parameters, given some of the "Snowmass Points and Slopes" (SPS) [1] cases defined in Table I.

### Table I Values of $M_{1/2}, M_0, A_0, \tan \beta$, and sign $\mu$ for the SPS points considered in the analysis.

| SPS | $M_{1/2}$ (GeV) | $M_0$ (GeV) | $A_0$ (GeV) | $\tan \beta$ |
|-----|----------------|-------------|-------------|-------------|
| 1a  | 250            | 100         | -100        | 10 < 0      |
| 1b  | 400            | 200         | 0           | 30 < 0      |
| 2   | 300            | 1450        | 0           | 10 < 0      |
| 3   | 400            | 90          | 0           | 10 < 0      |
| 4   | 300            | 400         | 0           | 50 < 0      |
| 5   | 300            | 150         | -1000       | 5 > 0       |

Regarding our computation of the LFV observables [2], it is in order to stress the following points:

- It is a full one-loop computation of the branching ratios (BRs), i.e., we include all contributing one-loop diagrams with the SUSY particles oiving in the loops. For the case of $l_1 \to l_2$, the analytical formulae can be found in [6,13].
- Regarding the $l_1 \to 3l$ decays, the complete set of diagrams (including photon-penguin, $Z-$penguin, $H-$penguin, and box diagrams) and form factors are given in [6].

The computation is performed in the physical basis for all SUSY particles entering in the loops. In other words, we do not use the Masse Insertion Approximation (MIA).

To obtain the low-energy parameters of the model, the full renormalisation group equations (RGEs), including relevant terms and equations for the neutrinos and sneutrinos, are run down from $M_X$ to $m_{\nu}$, at the seesaw scale (in particular at $m_{\nu}$), we impose the boundary condition of Eq. (1). After the decoupling of the heavy neutrinos and sneutrinos, the new RGEs are then run down from $m_{\nu}$, to the EW scale, at which the observables are computed. We therefore, do not use the Leading Log Approximation (LLog), but rather numerically solve the full one-loop RGEs.

The numerical implementation of the above procedure is achieved by means of the public Fortran code SPheno2.2.2 [13], which has been adapted in order to fully incorporate the right-handed neutrino (and sneutrino) sectors, as well as the full lepton flavour structure [5].

The SPheno code has been further enlarged by additional subroutines that compute the LFV branching ratios for all the $l_i \to l_j$ and $l_i \to 3l$ channels [5]. We have also included subroutines [5] to implement the requirement of successful baryogenesis (which we define as having $n_b = 2 \times 10^{11} ; 10^9$) via the leptonic baryogenesis in the presence of upper bounds on the reheating temperature, and to ensure compatibility with present bounds on lepton electric dipole moments (EDMs) $\sigma_{e \mu} < 6.9 \times 10^{-24} ; 3.7 \times 10^{-19} ; 4.5 \times 10^{-17}$ [12].

In what follows we present our main results for the case of hierarchical heavy neutrinos. We also include a comparison with present bounds on LFV rates [12,13,14,15,16,17] and their future sensitivities [18,19,20,21] collected in Table II.

### Table II Present bounds and future sensitivities for the LFV processes.

| LFV process | Present bound | Future sensitivity |
|-------------|---------------|--------------------|
| BR (l ! e ) | $1 \times 10^{-11}$ | $1 \times 10^{-11}$ |
| BR (l ! e ) | $1 \times 10^{-7}$ | $1 \times 10^{-7}$ |
| BR (l ! e ) | $6 \times 10^{-8}$ | $6 \times 10^{-8}$ |
| BR (l ! e ) | $1 \times 10^{-12}$ | $1 \times 10^{-12}$ |
| BR (l ! e ) | $2 \times 10^{-7}$ | $2 \times 10^{-7}$ |
| BR (l ! e ) | $1 \times 10^{-7}$ | $1 \times 10^{-7}$ |

3. Results and Discussion

Here we focus on the sensitivity of the BRs to $\tan \beta$, and on the dependence on other relevant parameters, which, for the case of hierarchical heavy neutrinos, are the heaviest mass $m_{\nu_3}$, $\tan \beta$, and $\mu$ (using...
the R parameterization of $\theta$). The other input see-
seesaw paramaters $m_{11}, m_{22}$ and $m_{33}$ play a secondary role since the BRs do not strongly depend on them. Finally, we consider effects on the hints on the SUSY see-
seesaw paramaters that can be derived from a measurement of the BRs and $\theta_{13}$.

For $R = 1$, the predictions of the BRs as functions of $\theta_{13}$ in the experimentally allowed range of $0 \leq \theta_{13} \leq 10$ are illustrated in Fig. 1. In this case we also include the present and future experimental sensitivities for the channels. We see clearly that the BRs of $\mu \to e$ and $\mu \to 3e$ are extremely sensitive to $\theta_{13}$, with their predicted rates varying by many orders of magnitude along the explored $\theta_{13}$ interval. The BRs of $\mu \to e$ and $\mu \to 3e$ channels are also sensitive to $\theta_{13}$, but experimentally less challenging. The other LFV channels, $\tau \to e$ and $\tau \to 3e$, are nearly insensitive to this parameter (see Ref. 3). In the case of $\mu \to e$ this strong sensitivity was previously pointed out in Ref. 3. In Ref. 3, working within a full RGE approach, it was noticed that $\mu \to e$ and $\mu \to 3e$ were the channels that, in addition to manifesting a clear $\theta_{13}$ dependency, were the most promising from the experimental viewpoint.

The most important conclusion from Fig. 1 is that, for this choice of parameters, the predicted BRs for both muon decay channels, $\mu \to e$ and $\mu \to 3e$, are clearly within the present experimental reach for several of the studied SPS points. The most stringent channel is manifestly $\mu \to e$ where the predicted BRs for all the SPS points are clearly above the present experimental bound for $\theta_{13} > 5$. With the expected improvement in future experiments, the $\mu \to e$ channel is clearly within the present experimental sensitivity to this channel, this would happen for $\theta_{13} > 1$.

In addition to the small neutrino mass generation, the seesaw mechanism offers the interesting possibility of baryogenesis via leptogenesis [3]. The most successful baryogenesis is an attractive and minimal mechanism to produce a successful BAU, even compatible with present data, $n_B = 6.10^{10} 0.21$ $10^{10}$ [22]. In the supersymmetric version of the seesaw mechanism, it can be successfully implemented provided that the following conditions can be satisfied. Firstly, Big Bang Nucleosynthesis gravitino problem should be avoided, which is possible, for instance, for sufficiently heavy gravitinos. Since we consider the gravitino mass as a free parameter, this condition can be easily achieved.

In any case, further bounds on the reheating temperature, $T_{RH}$, similar to decays of gravitinos into the lightest supersymmetric particle (LSP). The case of gravitinos and neutralino LSP masses in the range 100-150 GeV (which is the case of our work), one obtains $T_{RH} < 2 \times 10^{10}$ GeV. In the presence of these constraints on $T_{RH}$, the favoured region by them all leptogenesis corresponds to small (but non-vanishing) complex $R$ matrix angles. For vanishing $U_{H_S 13}$ CP phases the constraints on $R$ are basically $|j_2 j_3| \leq 1$ rad (mod ). Their all leptogenesis also constrains $m_{S_2}$ to be roughly in the range $10^{10}$ GeV $\approx T_{RH}$ (see also Ref. 23, 24).

In Ref. 2 we have explicitly calculated the produced BAU in the presence of upper bounds on the reheating temperature $T_{RH}$. We have further one set as favoured BAU values those that are within the interval $\{10^{10}, 10^{9}\}$, which contains the WMAP value, and chosen the value of $m_{S_2} = 10^{10}$ GeV in most of our analysis. Similar studies of the constraints from leptogenesis on LFV rates have been done in Ref. 23.

For very small values of $m_{S_2}$ ($m_{S_2} \approx 10^{5}$ GeV) a baryon asymmetry in the range $10^{10}$ to $10^{9}$ can be obtained for a considerable region of the $j_2 j_3$ parameter space, with the BRs exhibiting a clear sensitivity to the value of $\theta_{13}$ in Ref. 3. On the other hand, the situation changes dramatically for larger values of $m_{S_2}$.

Figure 1: BR ( $\mu \to e$ ) and BR ( $\mu \to 3e$ ) as a function of $\theta_{13}$ (in degrees), for SPS 1a (dots), 1b (crosses), 2 (asterisks), 3 (triangles), 4 (circles) and 5 (tines). A dashed (dotted) horizontal line denotes the present experimental bound (future sensitivity).
In Fig. 2, we display the dependence of the most sensitive BR to $j_{2j}$ for $2 = f = 6$ for $j_{2j} = -8$ (dots, thin, diamond, respectively) and $3 = 0, 5$ (blue/darker, green/lighter lines). We take $m_1 = 10^3$ eV. In all cases black dots represent points associated with a disfavoured BAU scenario and a dashed (dotted) horizontal line denotes the present experimental bound (future sensitivity).

We now consider the dependence of BR (e $\rightarrow$ e) on $m_{N_3}$. As displayed in Fig. 3, there is a strong sensitivity of the BRs to $m_{N_3}$. In fact, the BRs vary by as much as six orders of magnitude in the explored range of $5 \times 10^3$ GeV $m_{N_3} = 5 \times 10^6$ GeV. Notice also that for the largest values of $m_{N_3}$ considered, the predicted rates for e $\rightarrow$ e enter into the present experimental reach. Although not shown here, it is also worth mentioning that by comparing our full results with the LLLog predictions, we found that the LLLog approximation dramatically fails in some cases. Similar effects were also noticed in [24, 25].

Regarding the tan$^2$ dependence of the BRs we obtained that the BR grow as tan$^2$. In fact, the hierarchy of the BR predictions for the several SPS points (as already manifest in Fig. 1) is dictated by the corresponding tan value, with a secondary role being played by the given SUSY spectra. We found the following generic hierarchy: $BR_{SPS4} > BR_{SPS1} > BR_{SPS2} > BR_{SPS3} > BR_{SPS5}$.

Let us now address the question of whether a joint measurement of the BRs and $\tan \beta$ can shed some light on experimentally unreachable parameters, like $m_{N_3}$. The expected joint measurement in the experimental sensitivity to the LFV rates supports the possibility that a BR could be measured in the future, thus providing the first experimental evidence for new physics, even before its discovery at the LHC. The prospects are especially encouraging regarding the $e \rightarrow e$ where the experimental sensitivity will in prove by at least two orders of magnitude. Moreover, and given the impressive e ort on experiment neutrino physics, a measurement of $\tan \beta$ will likely also occur in the future [26].

Given that, as previously emphasized, e $\rightarrow$ e is very sensitive to $m_{N_3}$, whereas this is not the case for BR (e $\rightarrow$ e), and that both BRs display the same approximate behaviour with $m_{N_3}$ and tan $\beta$, we have studied the correlation between these two observables. This optimizes the impact of a $m_{N_3}$ measurement, since it allows to m in imise the uncertainty introduced from
Figure 4: Correlation between BR(\(\tau \rightarrow \mu \gamma\)) and BR(\(\tau \rightarrow e\gamma\)) as a function of \(m_{N_3}\), for SPS 1a. The areas displayed represent the scan over \(\theta_3\), as given in Eq. (2). From bottom to top, the coloured regions correspond to \(\theta_3 = 1, 3, 5, 10\) (red, green, blue and pink, respectively). Horizontal and vertical dashed (dotted) lines denote the experimental bounds (future sensitivities).

We consider the following values, \(\theta_3 = 1, 3, 5, 10\) and only included in the plot the BR predictions which allow for a favourable BAU. Other SPS points have also been considered but they are not shown here for brevity (see 3). We clearly observe in Fig. 4 that for a fixed value of \(m_{N_3}\), and for a given value of \(\theta_3\), the dispersion arising from a 1 and 2 variation produces a small area rather than a point in the BR(\(\tau \rightarrow e\gamma\)) plane.

The dispersion along the BR(\(\tau \rightarrow e\gamma\)) axis is of approximately one order of magnitude for all \(\theta_3\). In contrast, the dispersion along the BR(\(\tau \rightarrow \mu\gamma\)) axis increases with decreasing \(\theta_3\), ranging from an order of magnitude for \(\theta_3 = 10\), to over three orders of magnitude for the case of small \(\theta_3\). From Fig. 4 we can also infer that other choices of \(m_{N_3}\) (for \(\theta_3 = 2 [1, 10]\)) would lead to BR predictions which would roughly lie within the diagonal lines depicted in the plot. Comparing these predictions for the shaded areas along the expected diagonal "corridor", with the allowed experimental region, allows to conclude about the impact of a \(\theta_3\) measurement on the allowed/excluded \(m_{N_3}\) values.

The most important conclusion from Fig. 4 is that for SPS 1a, and for the parameter space defined in Eq. (2), an hypothetical \(\theta_3\) measurement larger than 1, together with the present experimental bound on the BR(\(\tau \rightarrow e\gamma\)), will have the impact of excluding values of \(m_{N_3} > 10^{14}\) GeV. Moreover, with the planned MEG sensitivity, the same \(\theta_3\) measurement can further constrain \(m_{N_3} < 3 \times 10^{12}\) GeV. The impact of any other \(\theta_3\) measurement can be analogously extracted from Fig. 4.

As a final comment let us add that, remarkably, within a particular SUSY scenario and scanning over specific 1 and 2 BAU-enabling ranges for various values of \(\theta_3\), the comparison of the BR predictions for BR(\(\tau \rightarrow e\gamma\)) and BR(\(\tau \rightarrow \mu\gamma\)) with the present experimental bounds allows to set \(\theta_3\)-dependent upper bounds on \(m_{N_3}\). Together with the indirect lower bound arising from leptogenesis considerations, this clearly provides interesting hints on the value of the seesaw parameter \(m_{N_3}\). With the planned future sensitivities, these bounds would further improve by approximately one order of magnitude.

Ultimately, a joint measurement of the LFV branching ratios, \(\theta_3\), and the particle spectrum would be a powerful tool for shedding some light on otherwise unreachable SUSY seesaw parameters. It is clear from all this study that the interplay between LFV processes and future in proven ent in neutrino data is challenging for the searches of new physics.
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References

[1] S. Antusch, E. Arganda, M. J. Herrero and A. M. Tekebea, JHEP 0611 (2006) 090 [arXiv:hep-ph/0607263].
[2] F. Minkowski, Phys. Lett. B 67 (1977) 421; M. Gelmini, F. Ramond and R. Slansky, in: Complex Spinsors and Unified Theories, eds. P. Van. Nieuwenhuizen and D. Z. Freedman, Supergravity (North-Holland, Amsterdam, 1979), p.315 [Print-80-0576 (CERN)]; T. Yanagida, in: Proceedings of the Workshop on the Unified Theory and the Baryon Number in the Universe, eds. O. Sawada and A. Sugamoto (KEK, Tsukuba, 1979), p.95; S.L. Glashow, in Quarks and Leptons, eds. M. Levy et al. (Plenum Press, New York, 1980), p.687; R.N. Mandel, G. Senjanovic, Phys. Rev. Lett. 44 (1980) 912.

[3] F. Bozumati and A. M. Tekebea, Phys. Rev. Lett. 57 (1986) 961.
[4] M. Folkvand and T. Yanagida, Phys. Lett. B 174 (1986) 45.
[5] A. M. Askero, S. K. Vempati and O. Vives, New J. Phys. 6 (2004) 202 [arXiv:hep-ph/0407325].
[6] E. Arganda and M. J. Herrero, Phys. Rev. D 73 (2006) 055003 [arXiv:hep-ph/0510405].
[7] Z. Maaki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. 28 (1962) 870; B. Pontecorvo, Sov. Phys. JETP 6 (1957) 429 [Zh. Eksp. Teor. Fiz. 33 (1957) 549]; Sov. Phys. JETP 7 (1958) 172 [Zh. Eksp. Teor. Fiz. 34 (1957) 247].
[8] A. J. Casas and A. Ibarra, Nucl. Phys. B 618 (2001) 171 [arXiv:hep-ph/0103065].
[9] B. C. Allanach et al., in Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001) ed. N. Graf, Eur. Phys. J. C 25 (2002) 113 [arXiv:hep-ph/0202233].
[10] J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Rev. D 53 (1996) 2442 [arXiv:hep-ph/9510309].
[11] W. Porod, Comput. Phys. Commun. 153 (2003) 275 [arXiv:hep-ph/0301101].
[12] W. M. Yao et al. [Particle Data Group], J. Phys. G 33 (2006) 1.
[13] M. L. Brooks et al. [MEGA Collaboration], Phys. Rev. Lett. 83 (1999) 1521 [arXiv:hep-ex/9905013].

[14] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 96 (2006) 041801 [arXiv:hep-ex/0508012].
[15] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 95 (2005) 041802 [arXiv:hep-ex/0502032].
[16] U. Bellgardt et al. [SINDRUM Collaboration], Nucl. Phys. B 299 (1988) 1.
[17] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 92 (2004) 121801 [arXiv:hep-ex/0312027].
[18] S. Ritt [MEGA Collaboration] on the web page http://meg.web.psi.ch/docs/talks/sritt/0606.novosibirsk/sritt.ppt.
[19] A. A. Kenty et al. [SuperKEKB Physics Working Group], arXiv:hep-ph/0406071.
[20] T. Iijima, A. Overview of Physics at Super B-Facility”, talk given at the 6th Workshop on a Higher luminosity B Factory, KEK, Tsukuba, Japan, November 2004.
[21] J. Ayrove et al., arXiv:hep-ph/0109217.
[22] D. N. Spergel et al., arXiv:astro-ph/0603449.
[23] G. F. Giudice, A. Notari, M. Raidal, A. Riotto and A. Strumia, Nucl. Phys. B 685 (2004) 89 [arXiv:hep-ph/0310123].
[24] S. Antusch and A. M. Tekebea, JCAP 0702 (2007) 024 [arXiv:hep-ph/0611232].
[25] S. T. Petcov, W. Rodephann, T. Shindou and Y. Takahashi, Nucl. Phys. B 739 (2006) 208 [arXiv:hep-ph/0510040].
[26] S. T. Petcov, S. Profumo, O. Takanishi and C. E. Yaguna, Nucl. Phys. B 676 (2004) 453 [arXiv:hep-ph/0306195].
[27] P. H. Chankowski, J. R. Ellis, S. Pokorski, M. Raidal and K. Turzynski, Nucl. Phys. B 690 (2004) 279 [arXiv:hep-ph/0403180].
[28] E. Ables et al. [MINOS Collaboration], Fermilab-proposal-0875; G. S. Tzanakos [MINOS Collaboration], AIP Conf. Proc. 721 (2004) 179; M. Komatsu, P. M. Igbozi and F. Terranova, J. Phys. G 29 (2003) 443 [arXiv:hep-ph/0210043]; P. M. Igbozi and F. Terranova, Phys. Lett. B 563 (2003) 73 [arXiv:hep-ph/0302274]; P. Huber, J. Kopp, M. Lindner, M. Rolhe and W. Winter, JHEP 0605 (2006) 072 [arXiv:hep-ph/0601266]; Y. Hnon et al., arXiv:hep-ex/0601019; A. Bondel, A. Cervera-Villanueva, A. Donini, P. Huber, M. Mazzetto and P. Strolin, arXiv:hep-ph/0606111; P. Huber, M. Lindner, M. Rolhe and W. Winter, arXiv:hep-ph/0606119; J. Burguet-Castell, D. Casper, E. Coce, J. Gom ez-Cadenas and P. Hernandez, Nucl. Phys. B 725 (2005) 306 [arXiv:hep-ph/0503021]; J. E. Campane, M. Maltoni, M. Mazzetto and T. Schwetz, arXiv:hep-ph/0603172.