Beyond the Standard Model in the Lepton Sector

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Abstract

I review some of the physics motivations and potential of various extensions of the standard model that pertain to the lepton sector. These include extensions of the lepton multiplet content, closely related to the properties of neutrinos, extensions of the electroweak breaking sector, such as supersymmetry, as well as possible extensions of the gauge sector. They may all lead to new signatures at levels accessible to experiment.

1. Introduction.

Our present standard model leaves open many of the fundamental issues in particle physics, such as the mechanism of mass generation and the properties of neutrinos. Extensions of the basic picture that seek to address these issues, such as higher unification and supersymmetry, may lead to extensions of the lepton multiplet and/or Higgs boson content, and thereby affect the physics of the lepton sector in an important way that fortunately can be probed in a variety of present and future experiments.

2. Neutral Heavy Leptons.

There are many motivations to extend the lepton sector of the electroweak theory. Extra heavy leptons may arise in models with a higher unification, for example those with left-right symmetry [1] or superstrings [2]. These models contain isosinglet neutral heavy leptons and typically, also neutrino masses [3].

They may induce lepton flavour violating (LFV) decays such as $\mu \rightarrow e\gamma$, which are exactly forbidden in the standard model. Although these are a generic feature of models with massive neutrinos, in some cases, they may proceed in models where neutrinos are strictly massless [3-5].

In the simplest models of seesaw type [6] the NHLs are superheavy so that the expected rate for LFV processes is expected to be low, due to limits on neutrino masses. However, in other variants [2] this is not the case [4, 5] and this suppression need not be present. Indeed, present constraints on weak universality violation allow for decay branching ratios larger than the present experimental limits [7] so that these already are probing the masses and admixtures of the NHLs with considerable sensitivity. Similar estimates can be done for the corresponding tau decays [7, 8]. The results are summarized in table 1. See also figures 5 and 6 given in ref. [8]. Clearly these branching ratios lie within the sensitivities of the planned tau and B factories, as shown in ref. [9].

The physics of rare $Z$ decays nicely complements what can be learned from the study of rare LFV muon and tau decays. The stringent limits on $\mu \rightarrow e\gamma$ preclude any possible detectability at LEP of the corresponding $Z \rightarrow e\mu$ decay. While experimentally closer, under realistic luminosity and experimental resolution assumptions, it is still unlikely that one will be able to see even the $e\tau$ or $\mu\tau$ decays of the $Z$ at LEP [10]. In any case, there have been dedicated searches...
Table 1. Allowed $\tau$ decay branching ratios

| channel       | strength     |
|---------------|--------------|
| $\tau \to e\gamma, \mu\gamma$ | $\lesssim 10^{-6}$ |
| $\tau \to e\pi^0, \mu\pi^0$ | $\lesssim 10^{-6}$ |
| $\tau \to e\nu, \mu\nu$       | $\lesssim 10^{-6} - 10^{-7}$ |
| $\tau \to 3e, 3\mu, \mu\mu e$, etc. | $\lesssim 10^{-6} - 10^{-7}$ |

Table 2. Allowed branching ratios for rare $Z$ decays.

| channel       | strength     |
|---------------|--------------|
| $Z \to N\tau, \nu\tau$ | $\lesssim 10^{-3}$ |
| $Z \to e\tau$     | $\lesssim 10^{-6} - 10^{-7}$ |
| $Z \to \mu\tau$   | $\lesssim 10^{-7}$ |

which have set good limits

If lighter than the $Z$, NHLS may also be produced in $Z$ decays such as

$$Z \to N\tau + \nu\tau$$  \hspace{1cm} (1)

Note that the isosinglet neutral heavy lepton $N\tau$ is singly produced, through the off-diagonal neutral currents characteristic of models containing doublet and singlet leptons. Subsequent $N\tau$ decays would then give rise to large missing energy events, called zen-events. As seen in Table 2 this branching ratio can be as large as $\lesssim 10^{-3}$ a value that is already superseded by the good limits on such decays from the searches for acoplanar jets and lepton pairs from $Z$ decays at LEP, although some inconclusive hints have been recently reported by ALEPH

Finally we note that there can also be large rates for lepton flavour violating decays in models with radiative mass generation. For example, this is the case in the models proposed to reconcile present hints for neutrino masses. The expected decay rates may easily lie within the present experimental sensitivities and the situation should improve at PSI or at the proposed tau-charm factories.

3. Supersymmetry.

If supersymmetry exists at the TeV scale it helps to stabilize the gauge hierarchy problem, one of the central issues in particle theory today. The most conventional realization of the idea of supersymmetry postulates the conservation of R parity. As a result of this ad hoc selection rule, in the so-called minimal supersymmetric standard model SUSY particles are only produced in pairs, with the lightest of them (LSP) being stable.

Nobody knows the origin of this R parity symmetry and why it is there. There are many ways to break it, either explicitly or spontaneously (RPSUSY models). If R parity is broken spontaneously it shows up primarily in the couplings of the $W$ and the $Z$, leading to rare $Z$ decays such as the single production of the charginos and neutralinos, for example,

$$Z \to \chi^\pm \tau^\mp$$  \hspace{1cm} (2)

where the lightest chargino mass is assumed to be smaller than the $Z$ mass. In the simplest models, the magnitude of R parity violation is correlated with the nonzero value of the $\nu\tau$ mass and is restricted by a variety of experiments. Nevertheless the R parity violating $Z$ decay branching ratios, as an example, can easily exceed $10^{-5}$, well within present LEP sensitivities. Similarly, the lightest neutralino (LSP) could also be singly-produced as $Z \to \chi^0 \nu\tau$. Being unstable due to R parity violation, $\chi^0$ is not necessarily an origin of events with missing energy, since some of its decays are into charged particles. Thus the decay $Z \to \chi^0 \nu\tau$ would give rise to zenith events, similar to those of the MSSM but where the missing energy is carried by the $\nu\tau$. Another possibility for zen events in RPSUSY is the usual pair neutralino production process, where one $\chi^0$ decays visibly and the other invisibly. The corresponding zen-event rates can be larger than in the MSSM.

Although the $\nu\tau$ can be quite massive in these models, it is perfectly consistent with cosmology including primordial nucleosynthesis, since it decays sufficiently fast by majoron emission. On the other hand, the $\nu_e$ and $\nu_\mu$ have a tiny mass difference in the model of ref. Due to this peculiar hierarchical pattern, one can go even further, and regard the rare R parity violating processes as a tool to probe the physics underlying the solar neutrino conversions in this model. Indeed, the rates for such rare decays can be used in order to discriminate between large and small mixing angle MSW solutions to the solar neutrino problem. Typically, in the nonadiabatic region of small mixing one can have larger rare decay branching ratios, as seen in Fig. 5 of ref.
Table 3. Allowed branching ratios for rare decays in the RPSUSY model. χ denotes the lightest electrically charged SUSY fermion (chargino) and χ^0 is the lightest neutralino.

| channel       | strength     |
|---------------|--------------|
| Z → χτ        | $\lesssim 6 \times 10^{-5}$ |
| Z → χ^0ντ     | $\lesssim 10^{-4}$ |
| τ → μ + J     | $\lesssim 10^{-3}$ |
| τ → e + J     | $\lesssim 10^{-4}$ |

It is also possible to find manifestations of R parity violation at the superhigh energies available at hadron supercolliders such as LHC. Either SUSY particles, such as gluinos, are pair produced and in their cascade decays the LSP decays or, alternatively, one violates R parity by singly producing the SUSY states. An example of this situation has been discussed in ref. [25]. In this reference one has studied the single production of weakly interacting supersymmetric fermions (charginos and neutralinos) via the Drell Yan mechanism, leading to possibly detectable signatures. More work on this will be desirable.

Another possible signal of the RPSUSY models based on the simplest $SU(2) \otimes U(1)$ gauge group is rare decays of muons and taus. In this model the spontaneous violation of R parity generates a physical Goldstone boson, called majoron. Its existence is consistent with the measurements of the invisible $Z$ decay width at LEP if the majoron is (mostly) a singlet under the $SU(2) \otimes U(1)$ gauge symmetry.

Although the original majoron proposal was made in the framework of the minimal seesaw model, and required the introduction of a relatively high energy scale associated to the mass of the right-handed neutrinos [24], there are many attractive theoretical alternatives where lepton number is violated spontaneously at the weak scale or lower. In this case although the majoron has very tiny couplings to matter and the gauge bosons, it can have significant couplings to the Higgs bosons. As a result one has the possibility that the Higgs boson may decay with a substantial branching ratio into the invisible mode

$$h \rightarrow J + J$$

where $J$ denotes the majoron. The presence of this invisible decay channel can affect the corresponding Higgs mass bounds in an important way.

The production and subsequent decay of a Higgs boson which may decay visibly or invisibly involves three independent parameters: its mass $M_H$, its coupling strength to the $Z$, normalized by that of the standard model, $\epsilon^2$, and its invisible decay branching ratio. The LEP searches for various exotic channels can be used in order to determine the regions in parameter space that are already ruled out, as described in ref. [28]. The exclusion contour in the plane $\epsilon^2$ vs. $M_H$, was shown in Fig. 2 of ref. [24].

Another mode of production of invisibly decaying Higgs bosons is that in which a CP even Higgs boson is produced at LEP in association with a massive CP odd scalar [30]. This production mode is present in all but the simplest majoron model containing just one complex scalar singlet in addition to the standard model Higgs doublet. Present limits on the relevant parameters are given in ref. [30].

Finally, the invisible decay of the Higgs boson may also affect the strategies for searches at higher energies. For example, the ranges of parameters that can be covered by LEP2 searches for a total integrated luminosity of 500 pb^-1 and various centre-of-mass energies have been given in Fig. 2 of the first paper in ref. [23]. Similar analysis were made for the case of a high energy linear $e^+e^-$ collider (NLC) [31], as well as for the LHC [32].
5. New Gauge Bosons.

Superstring extensions of the standard model suggest the existence of additional gauge bosons at the TeV scale and this may affect the lepton sector and the interactions of neutrinos. For example, an additional $Z'$ at low energies would modify the couplings of leptons to the $Z$ and be thereby restricted by low energy neutral current data \[3\], as well as by the LEP precision data on $Z$ decays \[34\]. In string models the Higgs sector is constrained in such a way that these limits are strongly correlated with the top quark mass $m_t$. The recent data from the CDF collaboration leads to constraints around a TeV on the $Z'$ mass for various models of the string type that fit in the $E_6$ gauge group. The limits are much weaker in the case of unconstrained models.

Acknowledgements

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References

[1] R.N. Mohapatra and G. Senjanovic, *Phys. Rev.* D23 (1981) 165 and references therein.
[2] R. Mohapatra, J. W. F. Valle, *Phys. Rev.* D34 (1986) 1642; J. W. F. Valle, *Nucl. Phys. B* (Proc. Suppl.) B11 (1989) 118
[3] For a review see J. W. F. Valle, *Gauge Theories and the Physics of Neutrino Mass, Prog. Part. Nucl. Phys.* 26 (1991) 91-171 and references therein.
[4] J. Bernabeu, A. Santamaria, J. Vidal, A. Mendez, J. W. F. Valle, *Phys. Lett.* B187 (1987) 303; J. G. Korner, A. Pillafstis, K. Schilcher, *Phys. Lett.* B300 (1993) 381; A. Barroso, J. P. Silva, *Phys. Rev.* D50 (1994) 4581
[5] G. C. Branco, M. N. Rebelo, J. W. F. Valle, *Phys. Lett.* B225 (1989) 385; N. Rius, J. W. F. Valle, *Phys. Lett.* B246 (1990) 249
[6] M. Gell-Mann, P. Ramond, R. Slansky, in *Supergravity*, ed. D. Freedman et al. (1979); T. Yanagida, in KEK lectures, ed. O. Sawada et al. (1979)
[7] M. C. Gonzalez-Garcia, J. W. F. Valle, *Mod. Phys. Lett.* A7 (1992) 477
[8] A. Ilakovac, A. Pillafstis, RAL preprint RAL/94-032
[9] R. Alemany et al., in *ECFA/93-151*, ed. R. Aleksan, A. Ali, p. 191-211
[10] M. Dittmar, J. W. F. Valle, contribution to the High Luminosity at LEP working group, yellow report CERN-91/02, p. 98-103, Fig. 3.22 and 3.23
[11] See, e.g., OPAL collaboration, *Phys. Lett.* B247 (1990) 448, *ibid.* B254 (1991) 293, L3 collaboration, *Phys. Rep.* 236 (1993) 1-146; *Phys. Lett.* B316 (1993) 427, *ibid.* B295 (1992) 371, ALEPH collaboration, CERN-PPE 94-93
[12] M. Dittmar, M. C. Gonzalez-Garcia, A. Santamaria, J. W. F. Valle, *Nucl. Phys.* B332 (1990) 1; M. C. Gonzalez-Garcia, A. Santamaria, J. W. F. Valle, *ibid.* B342 (1990) 108.
[13] J. Schechter and J. W. F. Valle, *Phys. Rev.* D22 (1980) 2227
[14] A. Zee, *Phys. Lett.* B93 (1980) 389; K. S. Babu, *Phys. Lett.* B203 (1988) 132
[15] J. T. Peltoniemi, D. Tommasini, and J W F Valle, *Phys. Lett.* B298 (1993) 383 J. T. Peltoniemi, and J W F Valle, *Nucl. Phys.* B406 (1993) 409; for another scheme, see E. Akhmedov, Z. Berezhiani, G. Senjanovic and Z. Tao, *Phys. Rev.* D47 (1993) 3245.
[16] P. Nogueira, J. C. Romão, J. W. F. Valle, *Phys. Lett.* B251 (1990) 142; R. Barbieri, L. Hall, *Phys. Lett.* B238 (1990) 86, M. C. Gonzalez-Garcia, J. W. F. Valle, *Nucl. Phys.* B355 (1991) 330
[17] E. Kolb, M. Turner, *The Early Universe*, Addison-Wesley, 1990.
[18] L. Krauss, P. Kerman, CWRU preprint-P9-94; For a review see G. Steigman; proceedings of the International School on Cosmological Dark Matter, (World Scientific, 1994), ed. J. W. F. Valle and A. Perez, p. 55
[19] J. W. F. Valle, *Phys. Lett.* B131 (1983) 87; G. Gelmini, J. W. F. Valle, *Phys. Lett.* B142 (1984) 181; M. C. Gonzalez-Garcia, J. W. F. Valle, *Phys. Lett.* B216 (1989) 360. A. Joshipura, S. Rindani, PRL-T/H-92-10; for an early discussion see J. Schechter and J. W. F. Valle, *Phys. Rev.* D25 (1982) 774
[20] M. C. Gonzalez-Garcia, J. W. F. Valle, *Phys. Rev.* Lett. B251 (1990) 273; J. C. Romao, C. A. Santos, and J. W. F. Valle, *Phys. Lett.* B288 (1992) 311; G. Giudice, A. Masiero, M. Pietroni, A. Riotto, *Nucl. Phys.* B396 (1993) 243; M. Shiraishi, I. Umemura, K. Yamamoto, *Phys. Lett.* B313 (1993) 89
[21] M. Mikheyev, A. Smirnov, *Sov. J. Nucl. Phys.* 42 (1986) 913; L. Wolfenstein, *Phys. Rev.* D17 (1978) 2369; *ibid.* D20 (1979) 2634.
[22] J. C. Romao and J. W. F. Valle, *Phys. Rev.* Lett. B272 (1991) 436; *Nucl. Phys.* B381 (1992) 87.
[23] M. C. Gonzalez-Garcia, J. C. Romário, J. W. F. Valle, *Nucl. Phys.* B399 (1993) 100
[24] J. C. Romão, N. Rius, J. W. F. Valle, *Nucl. Phys.* B363 (1991) 369.
[25] Particle Data Group, *Phys. Rev.* D50 (1994) 1173
[26] Y. Chikashige, R. Mohapatra, R. Peccei, *Phys. Rev. Lett.* 45 (1980) 1926
[27] A. Joshipura and J. W. F. Valle, *Nucl. Phys.* B397 (1993) 105; J. C. Romao, F. de Campos, and J. W. F. Valle, *Phys. Lett.* B292 (1992) 329; A. S. Joshipura, S. Rindani, *Phys. Rev.* Lett. 69 (1992) 3269; R. Barbieri, and L. Hall, *Nucl. Phys.* B364, 27 (1991). G. Jungman and M. Luty, *Nucl. Phys.* B361, 24 (1991). E. D. Carlson and L. B. Hall, *Phys. Rev.* D40, 3187 (1989)
[28] A. Lopez-Fernandez, J. Romao, F. de Campos and J. W. F. Valle, *Phys. Lett.* B312 (1993) 240; B. Brahmachari, A. Joshipura, S. Rindani, D. P. Roy, K. Sridhar, *Phys. Rev.* D48 (1993) 4224.
[29] F. de Campos et al., talk at Moriond94, FTUV/94-28, *Phys. Lett.* B336 (1994) 446-456
[30] O. Eboli, et al. *Nucl. Phys.* B421 (1994) 65
[31] J. W. F. Valle, *Nucl. Phys. B* (Proc. Suppl.) 31 (1993) 221-232; J. C. Romao, F. de Campos, L. Díaz-Cruz, and J. W. F. Valle, *Mod. Phys. Lett.* A9 (1994) 817; L. Jungion, *Phys. Rev. Lett.* 72 (1994) 199; D. Choudhary, D. F. Roy, *Phys. Lett.* B322 (1994) 368
[32] CHARM collaboration these proceedings
[33] D. Schalle, these proceedings and references therein.
[34] M. C. Gonzalez-Garcia, J. W. F. Valle, *Phys. Lett.* B259 (1991) 365 and references therein.