Probing the Origin of Neutrino Mass: from GUT to LHC

Goran Senjanović
ICTP, Trieste, Italy

Abstract

Ever since the Majorana classic work, the nature of neutrino has been one of the central questions of the weak interaction physics. If neutrino is its own antiparticle, the immediate consequence is lepton number violation through the neutrinoless double beta decay. However, colliders such as the LHC offer a hope of seeing directly the same phenomenon, and moreover the Majorana nature of new particles needed to complete the Standard Model. I review here the salient features of these phenomena, and then turn to grand unification as a way of probing the scale of the relevant new physics. The minimal supersymmetric SO(10) theory basically eliminates the LHC physics, but leads naturally to the large atmospheric mixing angle and furthermore predicts $\theta_{13} \simeq 10^\circ$ without any additional symmetries, in agreement with new T2K and MINOS data. It also assures that the R-parity is exact and thus leads to the stable LSP as a natural Dark Matter candidate. The minimal realistic SU(5) theory, on the other hand, predicts the light fermion triplet, below TeV, as a source of neutrino Majorana mass.

Contents

1 Introduction: from Majorana to see-saw  
2 Large scale see-saw: GUT  
  2.1 SO(10)  
  2.2 SU(5)  
3 Low scale seesaw: LHC  
  3.1 Left-Right Symmetry  
  3.2 More SU(5)  
4 Summary and Outlook  
5 Acknowledgements

1 Introduction: from Majorana to see-saw

We know that neutrinos are massive but light [1]. We can account for tiny neutrino masses with only the Standard Model (SM) degrees of freedom via the effective [2]

§Based on the talk for the Neutrino Roadmap 2012, Paris, May 2011.
\[ \mathcal{L} = Y_{ij} \frac{L_i H H L_j}{M}, \]  

(1)

where \( L_i \) stands for left-handed leptonic doublets and \( H \) for the usual Higgs doublet (with a vev \( v \)). This in turn produces neutrino Majorana mass matrix

\[ m_\nu = Y \frac{v^2}{M}. \]  

(2)

The non-renormalizable nature of the above operator signals the appearance of new physics through the mass scale \( M \). The main consequence is \( \Delta L = 2 \) violation of lepton number, which can be observed through:

- neutrinoless double beta decay \((0\nu 2\beta)\) \([3]\). The canonical contribution due to neutrino Majorana mass is measured by the 1-1 element of the matrix \( m_\nu \) in (2). The left-hand side of Fig.1 shows the process, while in the right panel one can see the \( |m_{ee}\nu| \) element as a function of the lightest neutrino mass;

- same sign charged lepton pairs in colliders \([4]\). This was the first proposal to search for lepton number violation at colliders, and is complementary to the neutrinoless double beta decay. This has only recently received wide attention, but it may be our best bet in probing directly the origin of neutrino mass.

If the scale \( M \) is huge, there is no hope of direct observation of the relative new physics. It is often said that large \( M \) is more natural, for then Yukawas do not have to be small. For example, \( M = 10^{13}\text{GeV} - 10^{14}\text{GeV} \) corresponds to \( Y \) of order one. However, small Yukawas are natural in a sense of being protected by chiral symmetries.

In order to get a window to new physics, we need a renormalizable theory of the above effective operator. In the minimal scenario there are three ways of producing it, through \([5]\):

- fermion singlets, so-called right-handed neutrinos (seesaw, or type I seesaw) \([6]\);

- bosonic weak triplet (type II seesaw) \([7]\);

- fermion weak triplet (type III seesaw) \([8]\);

2 \textbf{Large scale see-saw: GUT}

Large scale seesaw allows for Yukawas of order one. This happens naturally in grand unified theories (GUT). Let us see the situation in the most popular candidates, SO(10) and SU(5) GUTs.
lightest neutrino mass in eV

normal
inverted

| \text{m}_{\nu} | in eV
\begin{tabular}{c|c|c|c|c|c}
$10^{-4}$ & 0.001 & 0.01 & 0.1 & 1 & $10^{-4}$
\end{tabular}

$10^{-3}$

$0.01$

$0.1$

$1$

Figure 1: Neutrinoless double beta decay through the neutrino Majorana mass (left), and canonical contribution from light neutrino mass (right). The mixing angles are fixed at $\{\theta_{12}, \theta_{23}, \theta_{13}\} = \{35^\circ, 45^\circ, 7^\circ\}$, while the Dirac and Majorana phases vary in the interval $\{0, 2\pi\}$.

2.1 SO(10)

There are some features that make SO(10) special [9].

1. A family of fermions is unified in a 16-dimensional spinorial representation $(16_F)$, together with a right-handed neutrino. The seesaw mechanism emerges naturally.

2. In the supersymmetric version, R-parity is exact [10]. The LSP is then stable, a natural candidate for the dark matter.

3. The unification of gauge couplings can be achieved even without supersymmetry, with heavy right-handed neutrino and the seesaw.

4. The minimal supersymmetric version gives naturally a large atmospheric mixing angle in the context of the type II see-saw [11].

From

$$16 \times 16 = 10 + 120 + \overline{126},$$

the most general Yukawa sector in general contains $10_H$, $120_H$ and $\overline{126}_H$.

The see-saw mechanism, whether type I or II, requires $\overline{126}$ [9], which can be a fundamental field, or a composite of two $16_H$ fields. Consider for simplicity only the former, more predictive possibility. The minimal version contains a $10_H$ light Higgs and $\overline{126}_H$.

**Minimal supersymmetric version.** It is based on the following Higgs multiplets [12]: $10_H$, $\overline{126}_H$ and $210_H$. It has a plethora interesting predictions, such as naturally large leptonic and small quark mixings [11], without any additional symmetries. It predicts $\theta_{13} \simeq 10^\circ$, which is in accord with the recent T2K [14]
and MINOS [15]. These are remarkable results for they follow from the pure SO(10) structure, without any ad-hoc flavor symmetries assumed. This shows that small quark and large lepton mixing angles are nothing special, but simply a consequence of a strongly broken Pati-Salam quark-lepton symmetry.

Missing: predictions for proton decay branching ratios, but see a version with heavy sfermions [16].

**Minimal non-supersymmetric version.** Needs to be worked out [17].

### 2.2 SU(5)

**Minimal non-supersymmetric version.** The minimal SU(5) theory fails for two reasons:

- gauge couplings do not unify
- neutrinos as massless as in the SM.

A simple extension cures both problems: add an extra fermionic $24_F$ [18]. Under $SU(3)_C \times SU(2)_W \times U(1)_Y$: $24_F = (1,1)_0 + (1,3)_0 + (8,1)_0 + (3,2)_{-5/6} + (\bar{3},2)_{5/6}$. The unification forces the triplet fermion to lie below TeV, with the color octet around $10^7$ GeV. The singlet mass is not determined, and the rest must be at the GUT scale.

With the notation $S = (1,1)_0$ (singlet), $T = (1,3)_0$ (triplet), it is evident that we have hybrid Type-I and Type-III seesaw,

$$(M_\nu)^{ij} = v^2 \left( \frac{y_i^j y_T^j}{m_T} + \frac{y_i^j y_S^j}{m_S} \right).$$

An immediate consequence is one massless neutrino, with a hierarchical spectrum.

**Minimal supersymmetric version.** Perfectly consistent theory [19], including proton decay and unification constraints. It can even include supersymmetry breaking without a hidden sector [20], however it cannot say much about charged fermion masses due to the plethora of needed higher dimensional terms. Neutrino masses and mixings can follow from bilinear R-parity violating terms [21].

### 3 Low scale seesaw: LHC

In the case of low scale seesaw, one can look for collider signatures. However, this is not motivated very strongly since it requires taking ad-hoc some states that can serve as a source of neutrino mass, and keeping them light. Instead, it is preferable to study theories of neutrino masses and mixings. A natural candidate is provided by the left-right symmetric theories. These theories were prophetic regarding neutrino mass, and the curse of its apparent largeness turned into the blessing with the advent of the seesaw mechanism. After going through their collider signatures, I discuss briefly the resulting situation in the simplifying cases of the three types of seesaw.
3.1 Left-Right Symmetry

$L – R$ symmetric theories [9] are based on the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge group augmented by parity or charge conjugation. Then:

- $W_L$ implies $W_R$,
- $\nu_L$ implies $\nu_R$, with $m_{\nu_R}$ of order $M_R$ through the breaking of $L – R$ symmetry,
- Type-I seesaw: connects neutrino mass to the scale of parity restoration.

These facts lead immediately to the new contribution [22] to the neutrino-less double beta decay mentioned above, see Fig. 2. With $W_R$ in the TeV region and the right-handed neutrino mass $m_N$ in the 100 GeV -TeV region, this contribution can easily dominate over the left-handed one. Neutrino mass can even go to zero (vanishing Dirac Yukawa) while keeping the $W_R$ contribution finite. This was revisited and studied carefully in the context of the Type-II seesaw [23].

The new physics source of the neutrinoless double beta decay, may not be just an amusing possibility but even a must. The point is that cosmology keeps pushing down the sum of neutrino masses. The recent study [24] concludes $\Sigma m_\nu \lesssim 0.44$ eV(@ 95 % CL), while [25] finds an even stronger limit $\Sigma m_\nu \lesssim 0.17$ eV(@ 95 % CL).

The observation of neutrinoless double beta decay in the present and near future experiments, such as GERDA and CUORE [3], may thus require new physics, especially if the sum of neutrino masses is to go down even more. As it is, there is already a mild tension between cosmological limits and the claimed positive result [26].

The discrete $L – R$ symmetry can be P or C. From $K_L - K_S$ mass difference one gets the limit $M_{W_R} \gtrsim 4$ TeV in the case of P, whereas for C, $M_{W_R} \gtrsim 2.5$ TeV [27].

Colliders. Produce $W_R$ through Drell-Yan as in Fig. 3. The right-handed gauge boson decays into a right-handed neutrino and a charged lepton. The right-handed

![Diagram of neutrinoless double beta decay](image)

Figure 2: Neutrinoless double beta decay induced by the right-handed gauge boson and right-handed neutrino (left) and new physics contribution, taken from [23] (right). $M_{\nu e}^{ee}$ is the LR analogue of $m_{\nu e}^{ee}$, as explained in [23].
Figure 3: The production of $W_R$ and the subsequent decay into same sign leptons and two jets through the Majorana character of the right-handed neutrino (left) and number of events (right) as a function of energy (GeV) for $L = 10 fb^{-1}$ (courtesy of F. Nesti) where $M_R$ (TeV) is taken to be: 1.8; 2.0; 2.4; 2.6; 3.0; 3.4.

neutrino, being a Majorana particle, decays equally often into charged leptons or anti-leptons [4] and jets. This offers the only possible way of probing directly the Majorana nature of any particle.

In turn one has exciting events of same sign lepton pairs and two jets, as a clear signature of lepton number violation. This is the collider analog of neutrino-less double beta decay, and it allows for the determination of $W_R$ mass as shown in the right side of Fig. 3 offering

- direct test of parity restoration through a discovery of $W_R$,
- direct test of lepton number violation through a Majorana nature of $\nu_R$,
- determination of $W_R$ and $N$ masses.

A detailed study [28] concludes a possible probe at the LHC of $W_R$ up to 4 TeV and $\nu_R$ between 100 – 1000 GeV for integrated luminosity of 30 fb$^{-1}$, and $W_R$ up to 5.5 TeV for a luminosity of 300 fb$^{-1}$. The flavor structure of this process would help determine (at least partially) the right-handed lepton mixing matrix, which in turn would allow to make predictions for flavor violating processes (LFV) and the neutrinoless double beta decay [23]. It is impressive that the early LHC data already established a limit $M_{W_R} \gtrsim 1.4$ TeV [29] for a wide range of right-handed neutrino mass.

It is worth noting that the same signatures can be studied in the SM with $\nu_R$ [5], but it requires miraculous cancellations of large Dirac Yukawa couplings in order to keep neutrino masses small. When a protection symmetry is called for, one ends up effectively with lepton number conservation and the phenomenon disappears [30].

The $L - R$ theory possesses naturally [22] also Type-II seesaw. The Type-II offers another potentially interesting signature: pair production of doubly charged scalars which decay into same sign lepton (anti lepton) pairs. This can serve as a determination of the neutrino mass matrix in the case when Type-I is not present or very small [31].
3.2 More SU(5)

We saw that unification predicts the mass of the fermion triplet below TeV, and thus it becomes accessible to the colliders such as Tevatron and LHC. It can be produced through gauge interactions (Drell-Yan)

\[
pp \rightarrow W^\pm + X \rightarrow T^\pm T^0 + X \\
pp \rightarrow (Z \text{ or } \gamma) + X \rightarrow T^+ T^- + X.
\]

The best channel is like-sign dileptons + jets

\[
BR(T^\pm T^0 \rightarrow l_i^\pm l_j^\pm + 4\text{jets}) \approx \frac{1}{20} \times \frac{|y^i_T|^2 |y^j_T|^2}{(\sum_k |y^k_T|^2)^2}
\]

Same couplings \(y^i_T\) contribute to \(\nu\) mass matrix and \(T\) decays, so that \(T\) decays can serve to probe the neutrino mass matrix \[18\];\[32\].

With an integrated luminosity of 10 (100) fb\(^{-1}\) one could find the fermionic triplet \(T\) at 14 TeV LHC for \(M_T\) up to about 450 (700) GeV \[32\].

4 Summary and Outlook

I discussed here an experimental probe of Majorana neutrino mass origin, both at colliders and through the neutrinoless double beta decay. It is shown that a TeV scale \(L-R\) symmetry would have spectacular signatures at LHC, with a possible discovery of \(W_R\) and \(\nu_R\). Moreover, if neutrinoless double beta decay were to be established, and neutrino masses were to be pushed down by cosmology, the TeV L-R scale could be a must. It is gratifying that these fundamental experiments are going on at the same time.

A case is made for a predictive grand unified theory: minimal \(SU(5)\) with extra fermionic adjoint. A weak fermionic triplet must lie in the TeV range, with good chances for discovery at LHC. Its decays probe directly the masses and mixings.

I also discussed the \(SO(10)\) grand unified theory of neutrino masses and mixings. The minimal supersymmetric version succeeds in connecting large leptonic and small quark mixing angles, and predicts the 13 leptonic mixing in accordance with the new T2K and MINOS results. It is worth considering the implications of this results. It is often argued that the quark and lepton mixing angles ought to be similar and that their disparity is a deep question. However, this question makes sense only in a theory with quark-lepton symmetry such as \(SO(10)\), and yet, a minimal such theory gives automatically this dichotomy once the quark-lepton symmetry is broken at the large GUT scale. Moreover, it also seem to happen in the \(SO(10)\) theory with the radiative seesaw mechanism \[33\]. This theory also gives naturally a dark matter candidate in the form of the LSP since it predicts exact R-parity, otherwise assumed ad-hoc in the MSSM. This too happens automatically, without any ad-hoc discrete symmetries. Simply, matter parity, equivalent to R-parity is a gauge symmetry, and it has to remain exact or otherwise there would a light pseudo-majoron coupled to the Z-boson and thus ruled out.
5 Acknowledgements

I am grateful to Alejandra Melfo and Fabrizio Nesti for their help in preparing this report, and Miha Nemevšek for a careful reading of the manuscript. I wish to thank Silvia Pascoli, Vittorio Paladino and other organizers of the Neutrino Roadmap 2012 for the invitation to present an overview of the origin of neutrino mass.

References

[1] For a review and references on neutrino masses and mixings, see A. Strumia and F. Vissani, arXiv:hep-ph/0606054.

[2] S. Weinberg, Phys. Rev. Lett. 43, 1566 (1979).

[3] For recent reviews and references, see e.g., Course CLXX of the International School of Physics "Enrico Fermi", Varenna, 2008. Published in Measurements of Neutrino Mass, Volume 170. Edited by F. Ferroni, F. Vissani and C. Brofferio.

[4] W. Y. Keung and G. Senjanović, Phys. Rev. Lett. 50, 1427 (1983).

[5] For a recent review and references, see e.g. G. Senjanović, [arXiv:0911.0029 [hep-ph]].

[6] P. Minkowski, Phys. Lett. B 67 (1977) 421.

R. Mohapatra, G. Senjanović, Phys.Rev.Lett. 44 (1980) 912

T. Yanagida, proceedings of the Workshop on Unified Theories and Baryon Number in the Universe, Tsukuba, 1979, eds. A. Sawada, A. Sugamoto, KEK Report No. 79-18, Tsukuba.

S. Glashow, in Quarks and Leptons, Cargèse 1979, eds. M. Lévy. et al., (Plenum, 1980, New York).

M. Gell-Mann, P. Ramond, R. Slansky, proceedings of the Supergravity Stony Brook Workshop, New York, 1979, eds. P. Van Niewenhuizen, D. Freeman (North-Holland, Amsterdam).

[7] M. Magg and C. Wetterich, Phys. Lett. B 94 (1980) 61.

G. Lazarides, Q. Shafi and C. Wetterich, Nucl. Phys. B 181 (1981) 287.

R. N. Mohapatra and G. Senjanović, Phys. Rev. D 23 (1981) 165.

[8] R. Foot, H. Lew, X. G. He and G. C. Joshi, Z. Phys. C 44, 441 (1989).

[9] For a review, see G. Senjanović, Riv. Nuovo Cim. 034, 1-68 (2011).

[10] C. S. Aulakh, B. Bajc, A. Melfo, A. Rašin, G. Senjanović, Nucl. Phys. B597, 89-109 (2001). [hep-ph/0004031]. See also,

C. S. Aulakh, A. Melfo, A. Rašin, G. Senjanović, Phys. Lett. B459, 557-562 (1999). [hep-ph/9902409].
[11] B. Bajc, G. Senjanović, F. Vissani, Phys. Rev. Lett. 90, 051802 (2003). [hep-ph/0210207].
    B. Bajc, G. Senjanović, F. Vissani, [hep-ph/0110310].

[12] C. S. Aulakh, R. N. Mohapatra, Phys. Rev. D28, 217 (1983).
    T. E. Clark, T. -K. Kuo, N. Nakagawa, Phys. Lett. B115, 26 (1982).
    C. S. Aulakh, B. Bajc, A. Melfo, G. Senjanović, F. Vissani, Phys. Lett. B588 (2004) 196-202. [hep-ph/0306242].

[13] H. S. Goh, R. N. Mohapatra, S. -P. Ng, Phys. Lett. B570, 215-221 (2003).
    [hep-ph/0303055].

[14] K. Abe et al. [ T2K Collaboration ], [arXiv:1106.2822 [hep-ex]].

[15] http://www-numi.fnal.gov/PublicInfo/plots/nuecontour2011.png

[16] B. Bajc, I. Doršner, M. Nemevšek, JHEP 0811, 007 (2008). [arXiv:0809.1069 [hep-ph]].

[17] For a recent attempt regarding fermion masses, see B. Bajc, A. Melfo, G. Senjanović, F. Vissani, Phys. Rev. D73, 055001 (2006). [hep-ph/0510139].
    For a recent study of symmetry breaking, see S. Bertolini, L. Di Luzio, M. Malinsky, Phys. Rev. D81, 035015 (2010). [arXiv:0912.1796 [hep-ph]].

[18] B. Bajc and G. Senjanović, JHEP 0708, 014 (2007) [arXiv:hep-ph/0612029].
    B. Bajc, M. Nemevšek and G. Senjanović, Phys. Rev. D 76, 055011 (2007) [arXiv:hep-ph/0703080].

[19] B. Bajc, P. Fileviez Perez, G. Senjanović, [hep-ph/0210374].
    B. Bajc, P. Fileviez Perez, G. Senjanović, Phys. Rev. D66, 075005 (2002). [hep-ph/0204311].

[20] B. Bajc, G. Senjanović, Phys. Lett. B648, 365-373 (2007). [hep-ph/0611308].

[21] See e.g., D. E. Kaplan, A. E. Nelson, JHEP 0001, 033 (2000). [hep-ph/9901254].

[22] R. N. Mohapatra and G. Senjanović, Phys. Rev. D 23 (1981) 165.

[23] V. Tello, M. Nemevšek, F. Nesti, G. Senjanović, F. Vissani, Phys. Rev. Lett. 106, 151801 (2011). [arXiv:1011.3522 [hep-ph]].

[24] S. Hannestad, A. Mirizzi, G. G. Raffelt, Y. Y. Y. Wong, JCAP 1008, 001 (2010).
    [arXiv:1004.0695 [astro-ph.CO]].

[25] U. Seljak, A. Slosar, P. McDonald,
    JCAP 0610, 014 (2006). [astro-ph/0604335].
[26] H. V. Klapdor-Kleingrothaus, I. V. Krivosheina, A. Dietz, O. Chkvorets, Phys. Lett. B586, 198-212 (2004). [hep-ph/0404088].

[27] For a recent complete study and references therein, see A. Maiezza, M. Nemevšek, F. Nesti and G. Senjanović, Phys. Rev. D82 (2010) 055022 arXiv:1005.5160 [hep-ph].
Y. Zhang, H. An, X. Ji, R. N. Mohapatra, Nucl. Phys. B802, 247-279 (2008). [arXiv:0712.4218 [hep-ph]].

[28] A. Ferrari et al., Phys. Rev. D 62, 013001 (2000). S. N. Gninenko, M. M. Kirsanov, N. V. Krasnikov and V. A. Matveev, Phys. Atom. Nucl. 70, 441 (2007).

[29] M. Nemevšek, F. Nesti, G. Senjanović, Y. Zhang, Phys. Rev. D83 (2011) 115014. [arXiv:1103.1627 [hep-ph]].

[30] J. Kersten and A. Y. Smirnov, Phys. Rev. D 76, 073005 (2007) [arXiv:0705.3221 [hep-ph]].

[31] J. Garayoa and T. Schwetz, JHEP 0803 (2008) 009 [arXiv:0712.1453 [hep-ph]].
M. Kastrati, M. Raidal and L. Rebane, Phys. Rev. D 77, 115023 (2008) [arXiv:0712.3912 [hep-ph]].
P. Fileviez Pérez, T. Han, G. Y. Huang, T. Li and K. Wang, Phys. Rev. D 78, 071301 (2008)
[arXiv:0803.3450 [hep-ph]].

[32] A. Arhrib, B. Bajc, D. K. Ghosh, T. Han, G. -Y. Huang, I. Puljak, G. Senjanović, Phys. Rev. D82, 053004 (2010). [arXiv:0904.2390 [hep-ph]].

[33] B. Bajc, G. Senjanović, Phys. Rev. Lett. 95, 261804 (2005). [hep-ph/0507169].
B. Bajc, G. Senjanović, Phys. Lett. B610, 80-86 (2005). [hep-ph/0411193].