INTRODUCTION

The existence of massive neutrinos is one of the main motivations for physics beyond the Standard Model. There are many possible theoretical frameworks where one could understand the origin of neutrino masses. In my opinion, the simplest way to classify these scenarios is using the $B-L$ symmetry, where $B$ and $L$ stand for Baryon and Lepton number, respectively. Now, one can have scenarios where $B-L$ is a local symmetry or scenarios where $B-L$ is not a local symmetry at the low-scale. At the same time there are several appealing ideas for physics beyond the Standard Model (SM) such as Supersymmetry and Grand Unification which deserve our attention. Then, it is important to understand the origin of neutrino masses in theories where SUSY is present or not, and in the context of grand unified theories, where one can understand the origin of the SM interactions and the correlation between fermion masses. It is easy to understand that combining all these ideas one finds different interesting theoretical frameworks and we should investigate the possible predictions that one could test at future neutrino experiments, at the LHC, or in the context of a grand unified theory, one should investigate the predictions for proton decay.

The SM fermionic spectrum is very peculiar. We do not understand why the electron mass is much smaller than the top mass, and in general it is difficult to explain the hierarchies between the charged fermion masses. Now, the neutrino is the only neutral fermion in the SM and today thanks to the effort of many experimental collaborations we know that they are massive. We believe that the explanation of the fermion hierarchies demands the existence of physics beyond the SM, and in particular since the neutrino masses are so tiny, $m_{\nu} \sim 1$ eV, perhaps they are special and the mechanism needed to explain their masses is different.

In the neutrino sector one defines the so-called PMNS mixing matrix, $V_{PMNS} = U(\theta_{12}, \theta_{13}, \delta_{23}, \delta)$, where $\theta_{ij}$ and $\delta$ are the different mixing angles and the Dirac phase, respectively. In general there are two more free phases in the case of Majorana neutrinos. Thanks to all experimental collaborations one has very good constraints on the mixing angles and the mass squared difference, $\Delta m^2_{21} = (7.2 \pm 0.9) \times 10^{-5}$ eV$^2$, $\Delta m^2_{32} = (2.4 \pm 0.4 \pm 0.7) \times 10^{-3}$ eV$^2$, $0 < \theta_{12} < 38$, $36 < \theta_{23} < 54$, and $\theta_{13} < 10$. Unfortunately, still we do not know if the spectrum for neutrinos has a Normal Hierarchy (NH), Inverted Hierarchy (IH) or is Quasi-Degenerate (QD).

Now, let us start with the properties of the neutrinos in the Standard Model. As it is well-known the neutrinos are massless in the SM due to the conservation of the lepton number in each family, i.e. $U(1)_{L}$, with $L_{\nu} = L_{e} + L_{\mu} + L_{\tau}$, are accidental global symmetries. In general the neutrinos can be a Dirac or Majorana fermions. In the Dirac case one has to introduce a SM singlet, $\nu^{C} \sim (1; 1; \beta)$, and the relevant interaction is given by

$$\mathcal{L}_{\nu}^D = Y_{\nu} \bar{L} \nu^{C} + h.c. ;$$

where $l^T = (\nu, e \mu, \tau)$ and $H^T = (H^+, H^0)$ are the leptonic doublet and the Higgs, respectively. Then, in this case after electroweak symmetry breaking (EWSB) the neutrino mass matrix reads as: $M_{\nu}^D = Y_{\nu} \nu_0 \overline{\tau}$, with $\nu_0 \equiv \tau$ the vacuum expectation value (vev) of the SM Higgs. Then, $Y_{\nu}$ should be around 10$^{-11}$ in order to reproduce the correct neutrino mass “scale”, $m_{\nu} \sim 1$ eV. This scenario is possible, however one has to impose by hand the conservation of the total lepton number. Now, if higher-dimensional operators in the SM are allowed one expects that the neutrinos are naturally Majorana fermions since one finds the dimension five operator $\mathcal{M}$:

$$\mathcal{L}_{\nu}^M = \epsilon_{\nu} \ell H \overline{\ell} = \lambda \nu + h.c. ;$$

where $\epsilon_{\nu} \overline{\ell} H \ell = \lambda \nu$ + h.c. ;
where $\Lambda_\nu$, typically called as the seesaw scale, corresponds to the scale where $L$ is broken. After EWSB one finds that $M_\nu=M_3=v_0^2/2\Lambda_\nu$. Now, if one assumes that the unknown coefficient $c_\nu$ is of order one the scale $\Lambda_\nu \sim 10^{14}$ GeV in order to reproduce the neutrino scale. Then, one could think that physics needed to explain neutrino masses is connected to the idea of grand unification since the unification scale is $M_{GUT} \sim 10^{16}$ GeV. However, since in general the coefficient $c_\nu$ is a free parameter one could have the case where the scale $\Lambda_\nu$ is close to the electroweak scale. It is important to say that this possibility is appealing since one can hope to test directly this idea at the LHC or at future collider experiments. Now, what is the origin of the operator in Eq. (2)?

There are many possible scenarios where one could understand the origin of this operator and those will be discussed in the next section.

### MECHANISMS FOR NEUTRINO MASSES

Let us discuss the simplest mechanisms for generating neutrino masses at tree level and one-loop level. The simplest mechanisms at tree level are the following:

**Type I Seesaw** [2]: This is perhaps the simplest mechanism for generating neutrino masses. In this case one adds a SM singlet, $\nu^C$ $(1; 1; \beta)$, and using the interactions:

$$ \mathcal{L}_I = Y_\nu^I H \nu^C + \frac{1}{2} M \nu^C \nu^C + \text{h.c.}; \quad (3) $$

in the limit $M \gg Y_\nu v_0$ one finds

$$ \mathcal{M}^{I}_\nu = \frac{1}{2} Y_\nu^I M \nu^C \nu^C \nu_0^2; \quad (4) $$

where $M$ is typically defined by the $B-L$ breaking scale. Then, one understands the smallness of the neutrino masses due to the existence of a mass scale, $M \gg Y_\nu v_0 \gg m_\nu$. Here, again if we assume $Y_\nu \sim 1$ the scale $M \sim 10^{14}$ GeV. Now, in general it is not possible to make predictions for the neutrino masses and mixing in this framework since we do not know the matrices $Y_\nu$ and $M$. Then, one should look for a theory where one could predict these quantities.

**Type II Seesaw** [3]: In this scenario one introduces a new Higgs boson, $\Delta$ $(1; \beta; 1)$, which couples to the leptonic doublets and the SM Higgs boson:

$$ \mathcal{L}_II = Y_\nu^I H \nu^C + \mu H \Delta^* H + \text{h.c.}; \quad (5) $$

and when the neutral component in $\Delta = (\delta^0 \rho^0 \rho^+ \rho^+)$ gets a vev, $v_\Delta$, one finds:

$$ \mathcal{M}^{II}_\nu = \frac{\mu}{2} Y_\nu^I v_\Delta = \mu Y_\nu v_0^2 = M_\Delta^2; \quad (6) $$

Notice that if $\mu = M_\rho$ and $M_\Delta \sim 10^{14}$ GeV the vev $v_\Delta$ should be of order 1 eV. However, in general the triplet mass can be around the TeV scale and $\mu$ can be small. Now, one should know the matrix $Y_\nu$, $\mu$ and $M_\Delta$ in order to make predictions for neutrino mixing and masses. Then, as in the previous case, one should look for a theory where one can predict these quantities.

Here I cannot discuss the testability of seesaw mechanisms at the LHC since this topic is beyond the scope of this talk but I would like to mention an interesting scenario. Suppose that $M_\Delta \sim 1$ TeV and $v_\Delta < 10^4$ GeV. In this case one could produce at the LHC the doubly and singly charged Higgses present in the model and through the dominant decays, $H^{++} \rightarrow e^+ e^+ e^+ \nu$, $H^{+} \rightarrow e^+ \nu \nu$, we could learn about the neutrino spectrum. In Fig. 1 one can see the predictions for the branching ratios of $H^{++}$ versus the lightest neutrino mass [4]. Notice that using the properties of the doubly charged Higgs decays in each spectrum one can distinguish between NH, IH or QD. Now, in the case when the Majorana phases play an important role the predictions in Fig. 1 can change dramatically, and in order to learn about the neutrino spectrum it is better to use the singly charged Higgs decays [4].

Then, as it has been proposed in Ref. [4], the associated production $H^{++}$, is crucial for the test of the mechanism and to learn about the spectrum for neutrinos. For other studies see Ref. [5].

**Type III Seesaw** [6, 7, 8, 9, 10, 11]: In the case of Type III seesaw one adds new fermions, $\rho$ $(1; \beta; 1)$, and the neutrino masses are generated using the following interactions:

$$ \mathcal{L}_III = Y_\nu^I H \rho + M_\rho \text{Tr} \rho^2 + \text{h.c.}; \quad (7) $$

where $\rho = (\rho^0 \rho^+ \rho^- \rho^+ \rho^-)$. Integrating out the neutral component of the fermionic triplet one finds

$$ \mathcal{M}^{III}_\nu = \frac{1}{2} Y_\nu^I M_\rho \nu^C \nu^C \nu_0^2; \quad (8) $$

Here, as in the case of Type I seesaw, if $Y_\nu \sim 1$ one needs $M_\rho \sim 10^{14}$ GeV. Here one faces the same problem, if we want to make predictions for neutrinos masses and mixings, a theory where $Y_\nu$, $M_\rho$ can be predicted is needed. In the next section we will discuss this issue in the context of grand unified theories.

We have mentioned the simplest mechanisms at tree level. Now, if Supersymmetry is realized in nature one has the extra possibility to generate neutrino masses through the R-parity violating couplings. R-parity is defined as $R = (1 \frac{1}{3} B L)_{\text{sym}}$, and the R-parity violating interactions are given by

$$ \mathcal{L}^W_{RPV} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{L}_k + \lambda_{ijk} \hat{U}_i^C \hat{D}_j \hat{D}_k^C + \lambda_{ijk} \hat{U}_i^C \hat{D}_j \hat{D}_k^C + \lambda_{ijk} \hat{U}_i^C \hat{D}_j \hat{D}_k^C; \quad (9) $$
where the last term violates B and the others break L. The problem with this possibility is that in general one has too many free parameters. Then, it is also important to understand the origin of these interactions in a theory where R-parity is spontaneously broken. Recently, this issue has been investigated in Ref. [12] in the context of different theories where $B = L$ is a local symmetry.

There are several mechanisms for generating neutrino masses at one-loop level. In this case one assumes that the mechanisms discussed above are absent and only through quantum corrections one generates neutrino masses. This possibility is very appealing since the neutrino masses are very tiny and the seesaw "scale" can be low.

**Zee Model** [13]: In the so-called Zee model one introduces two extra Higgs bosons, $h$ $(1, 1, 1)$ and $H$ $(1, 2, 1)$. In this case the relevant interactions are

$$L_{\text{Zee}} = Y_l h l + \mu H H^0 h^\dagger + \sum_{i=1}^2 Y_i e^C H^i l + \text{h.c.};$$

(10)

where in general both Higgs doublets couple to the matter fields. Using these interactions one can generate neutrino masses at one-loop level. See Ref. [13] for details. Now, it is important to mention that in the simple case where only one Higgs doublet couples to the leptons [14] it is not possible to generate neutrino masses in agreement with neutrino data. See for example Ref. [15] for details.

**A New Mechanism at One-Loop Level** [16]: Now, suppose that one looks for the simplest mechanism for neutrino masses at one-loop level where we add only two types of representations, a fermionic and a scalar one, and with no extra symmetry. All the possibilities were considered in Ref. [16] where we found that only two cases are allowed by cosmology. In this case one has two possible cases: 1) The extra fields are a fermionic $\rho_1 (8, 1, 0)$ and the scalar $S (8, 2, 1)$. 2) One adds $\rho_2 (8, 3, 0)$ and $S (8, 2, 1)$. In both cases one generates neutrinos masses through the loop in Fig. 2.

![Fig. 2. New mechanism at one-loop level.](image)

The relevant interactions in this case are given by

$$\mathcal{L} = \frac{\lambda_1}{2} S \rho_1 + M_{\rho_1} \text{Tr} \rho_1^2 + \lambda_2 \text{Tr} S^2 H^2 + \text{h.c.};$$

(11)

Using as input parameters, $M_{\rho_1} = 200 \text{ GeV}$, $v_0 = 246 \text{ GeV}$ and $M_S = 2 \text{ TeV}$ we find that in order to get the neutrino "scale", $1 \text{ eV}$, the combination of the couplings, $Y_1^2 \lambda_2 \approx 10^{-8}$. This mechanism could be tested at the LHC through the channels $pp \rightarrow \rho \rho \rightarrow e_e e_j \overline{\tau} \overline{b} b$, [16]. See Ref. [17] for the study of leptogenesis in this context.
GRAND UNIFICATION AND MASSIVE NEUTRINOS

The so-called grand unified theories are one of the most appealing extensions of the SM where one can understand the origin of SM interactions. Here we will discuss the implementation of the different mechanisms for neutrino masses in the context of renormalizable SU(5) and SO(10) theories.

**SU(5) and Neutrino Masses:** The original model proposed by Georgi and Glashow [18] in 1974 has been considered as the simple grand unified theory. This model is based on SU(5), the SM matter fields live in the $\overline{5}$ = $(d^{C} \tau^{C})$ and $10$ = $(u^{C} \nu^{C})$ representations, and the minimal Higgs sector is composed of $5_{H}$ and $24_{H}$. As is well-known this model is ruled out by unification. At the same time one has $M_{D} = M_{L}^{2}$ which is in disagreement with the experiment and there are no neutrino masses. In order to have a consistent relation between the masses of down quarks and charged leptons one has two possibilities: a) one introduces a $45_{H}$ [19], b) one includes higher-dimensional operators [20]. In the case of neutrino masses one can have the mechanisms at tree level mentioned above: i) we can introduce at least two singlets and use the Type I seesaw, ii) in the case of Type II seesaw one introduces a new Higgs $15_{H}$ ($15_{H}$ and $1\overline{5}_{H}$ in the SUSY case), iii) a new fermionic $24$ representation is needed to realize the Type III seesaw mechanism. Since the simplest SU(5) model with Type I seesaw is ruled out by unification I would like to focus on the models with Type II or Type III seesaw.

**Type II-SU(5) [21]:** One can realize a simple realistic SU(5) theory when the neutrino masses are generated through the Type II seesaw mechanism. In this case the Higgs sector is composed of $5_{H}$, $15_{H}$ and $24_{H}$ [21] and one can have unification in agreement with proton decay lifetime bounds and all experimental constraints. See Refs. [22] and [23] for details. Now, the $15_{H} = (\Phi_{q}, \Phi_{l}, \Phi_{\nu}) = (1; \beta; 1) - (3; 2; 1 = 6) - (\overline{6}; 1; 2 = 3)$ contains the field needed for seesaw $\Phi_{a} = i\sigma_{2}\Delta$ and relevant interactions are

$$V_{\nu} = Y_{\nu} \overline{\overline{5}} \; 15_{H} + \mu \; 5_{H} \; 15_{H} + \text{h.c.} : (12)$$

In this case the mass matrix for neutrinos is given by Eq. (6). It is clear from Eq. (6) one cannot predict the neutrino masses and mixing. However, let us discuss the possible constraints on the seesaw scale in this case. In Fig. 2 we show the full parameter space allowed by unification. Now, one can make two observations: a) the mass of the seesaw triplet, $\Phi_{q} = i\sigma_{2}\Delta$, has to be in the range 100 GeV $M_{A}$ $9 \times 10^{8}$ GeV. Then, one can say that the seesaw scale in this context can be very low in a consistent way. Maybe, this is a good way to justify the studies in Ref. [4]. b) If one studies results shown in Fig. [2] it is easy to see that the leptoquark, $\Phi_{q} = (3; 2; 1 = 6)$, is very light in a large region of the parameter space. Then, this is perhaps a way to test this theory at colliders. See Ref. [24] for the study of this leptoquark signatures at the LHC.

**Adjoint SU(5):** The implementation of the Type III seesaw mechanism in the context of grand unified theories have been studied by several groups [7, 8, 9, 10]. Here we will focus on the first realization of the mechanism in a renormalizable GUT model [9, 10]. In this theory the matter fields live in $\overline{5}$, $10$ and $24$, while the Higgs sector is composed of $5_{H}$, $24_{H}$ and $45_{H}$. Once one has the decomposition of $24 = (p_{3}, p_{1}, p_{(3, 2)}, p_{(\overline{3}, 2)}, p_{0}) = (8; 1) - (1; 3) - (3; 2) - (3; 2) - (1; 1)$ it is easy to realize that the mechanism for neutrino masses is a combination of Type I and Type III seesaw. The relevant interactions for our discussion are:

$$V_{\nu} = c_{\alpha} \overline{\overline{5}}_{\alpha} 24_{5_{H}} + p_{\alpha} \overline{\overline{5}}_{\alpha} 24_{45_{H}} + M_{\nu} Tr 24^{2} + \lambda_{\nu} Tr 24^{2} 24_{H} + \text{h.c.} : (13)$$

Now, integrating out the singlet, $\rho_{0}$, and the neutral component of the triplet, $\rho_{3}$, one finds that the mass matrix for neutrinos is given by

$$M_{\nu} = \frac{h_{u1} h_{p1}}{M_{\rho_{0}}} \overline{v}_{0}^{2} + \frac{h_{u2} h_{p2}}{M_{\rho_{3}}} \overline{v}_{3}^{2} : (14)$$

Then, we have as prediction one massless neutrino and the spectrum can be: $m_{1} = 0$, $m_{2} = \Delta m_{sol}^{2}$ and $m_{3} = \Delta m_{atm}^{2}$ in the case of NH or $m_{3} = 0$, $m_{2} = \Delta m_{atm}^{2}$ and $m_{1} = \Delta m_{sol}^{2}$ in the case of IH. Here $\Delta m_{sol}^{2} 8 \times 10^{5} eV^{2}$ and $\Delta m_{atm}^{2} 2 \times 10^{3} eV^{2}$ are the solar and atmospheric mass squared differences. In order to prove that in this model one can satisfy all constraints coming from proton decay searches we show in Fig. 3 the possible predictions coming from the unification of gauge couplings. It is important to make several observations in this case: a) In this model the seesaw triplet can be light only if we have a fine-tuning between the last two terms in Eq. (13), b) In order to have gauge unification in agreement with proton decay bounds one should have a light color octet. See Ref. [26] for the study of color octets at the LHC. c) This model could be tested at future proton decay experiments since the upper bounds on the lifetimes are: $\tau(p \rightarrow K^{+} \nu \nu) 10^{37}$ years and $\tau(p \rightarrow \pi^{+} \nu \nu) 3 \times 10^{8}$ years. For the study of the leptonogenesis mechanism in this context see Ref. [27]. In our opinion these are the simplest models based on SU(5) where one could understand the origin of neutrino masses. Of course, one can add in those models a flavour symmetry and study the predictions for
neutrino mixings but this issue is beyond the scope of this letter.

**Renormalizable SO(10) and Neutrino Masses:** Now, let us study the neutrino mass mechanisms in grand unified theories based on \( \text{SO}(10) \) [28]. For a review on \( \text{SO}(10) \) see Ref. [29]. Here, I will focus on the study of renormalizable theories since we would like to know the possible predictions for neutrinos in the case when we stick only to the idea of grand unified theories. In \( \text{SO}(10) \) one has the possibility to unify all matter fields of one family in the spinor representation \( 16 = (Q u^C, d^C, L e^C, \nu^C) \). Now, since one can have the right-handed neutrino in 16 one expects from the beginning that the neutrino masses will be generated at least through the Type I seesaw mechanism. In naive \( \text{SO}(10) \) one can generate fermion masses using the interactions

\[
\mathcal{L} = Y_{10} 16 16 10_H + \text{h.c.};
\]

and one finds the following relations

\[
M_U = M_V^D = v_{10}^u Y_{10} \quad \text{(wrong)}; \quad (16)
\]

\[
M_D = M_E = v_{10}^d Y_{10} \quad \text{(wrong)}; \quad (17)
\]

\[
Y_{10} = Y_{10}^T. \quad (18)
\]

As one can see the minimal \( \text{SO}(10) \) model fails badly since one cannot have a consistent relation for fermion masses. Unfortunately, in order to realize a realistic SUSY model at the renormalizable level one needs to introduce a new large Higgs representation, \( 126_H \) and \( \overline{126}_H \). In this case the relevant Yukawa interactions are

\[
\mathcal{L}^R_{\text{SO}(10)} = Y_{10} 16 16 10_H + Y_{126} 16 16 \overline{126}_H + \text{h.c.}; \quad (19)
\]

and one finds the relations

\[
\mathcal{M}_U = v_{10}^u Y_{10} + v_{126}^u Y_{126}; \quad (20)
\]

\[
\mathcal{M}_V^D = v_{10}^u Y_{10} + 3 v_{126}^u Y_{126}; \quad (21)
\]

\[
\mathcal{M}_D = v_{10}^d Y_{10} + v_{126}^d Y_{126}; \quad (22)
\]

\[
\mathcal{M}_E = v_{10}^d Y_{10} + 3 v_{126}^d Y_{126}; \quad (23)
\]

\[
\mathcal{M}_{\nu_R} = Y_{126} \nu_R; \quad (24)
\]

\[
\mathcal{M}_{\nu_L} = \mathcal{M}_V^D \mathcal{M}_{\nu_R} \mathcal{M}_V^D + Y_{126} \nu_L. \quad (25)
\]

Now, as one can appreciate in this context the neutrino masses are generated through the Type I and Type II seesaw mechanisms and taking as input parameters all experimental values for charged fermion masses and mixings one can make predictions in the neutrino sector. See Refs. [30, 31] for the study of fermion masses in this context. In order to illustrate the possible predictions in this context we will take as an example the results shown in Ref. [31]. In Fig. 4 we show possible predictions for the neutrino mixing angles. In this case only when one assumes a particular scenario for the seesaw mechanism we can talk about a prediction for the mixing angles. For example, in the case of \( \theta_{13} \) one can have a better fit in the mixed scenario, where one has the type I and Type II contributions, and the preferred value for \( \sin^2 \theta_{13} \) is around \( 10^{-2} \). There are many aspects of these models that we cannot cover here and we refer the reader to Ref. [30, 31]. For the possible predictions in models with additional flavour symmetries see Ref. [32].
We have discussed the simplest models for the generation of neutrinos masses at tree level and one-loop level. The realization of the different seesaw mechanisms in the context of renormalizable SU(5) and SO(10) theories and possible predictions for neutrino masses and mixing have been briefly reviewed. A new mechanism for the generation of neutrino masses at one-loop level was presented. We discussed the first realization of the Type III seesaw mechanism in the context of renormalizable SU(5) theory, called “Adjoint SU(5)”.

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FIGURE 4. Predictions for the neutrino mixings in SO(10) models where the Higgs sector is composed of 10_H, 126_H, and 126_H. For details see Ref. [31].