Neutrino Physics

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Abstract

In this talk I will review our present knowledge on neutrino masses and mixing trying to emphasize the most direct implications and challenges of these results.

1. Introduction: The New Minimal Standard Model

The SM is a gauge theory based on the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ spontaneously broken to $SU(3)_C \times U(1)_{EM}$ by the the vacuum expectation value of a Higgs doublet field $\phi$. As I will explain in Sec.3 with the matter contents required for describing the observed particle interactions, the SM predicts that neutrinos are strictly massless and there is neither mixing nor CP violation in the leptonic sector.

We now know that this picture cannot be correct. Over several years we have accumulated important experimental evidence that neutrinos are massive particles and there is mixing in the leptonic sector. In particular we have learned that:
- Solar $\nu_e’$s convert to $\nu_\mu$ or $\nu_\tau$ with confidence level (CL) of more than $7 \sigma$ [1].
- KamLAND find that reactor $\nu_e$ disappear over distances of about 180 km and they observe a distortion of their energy spectrum. Altogether their evidence has more than $3 \sigma$ CL [2].
- The evidence of atmospheric (ATM) $\nu_\mu$ disappearing is now at $> 15 \sigma$, most likely converting to $\nu_\tau$ [3].
- K2K observe the disappearance of accelerator $\nu_\mu$’s at distance of 250 km and find a distortion of their energy spectrum with a CL of 2.5–4 $\sigma$ [4].
- MINOS observes the disappearance of accelerator $\nu_\mu$’s at distance of 735 km and find a distortion of their energy spectrum with a CL of $\sim 5 \sigma$ [5].
- LSND found evidence for $\nu_\mu \rightarrow \nu_e$. This evidence has not been confirmed by any other experiment so far and it is being tested by MiniBooNE [6].
These results imply that neutrinos are massive and the Standard Model has to be extended at least to include neutrino masses. This minimal extension is what I call The New Minimal Standard Model.

In the New Minimal Standard Model flavour is mixed in the CC interactions of the leptons, and a leptonic mixing matrix appears analogous to the CKM matrix for the quarks. However, the discussion of leptonic mixing is complicated by two factors. First the number of massive neutrinos ($n$) is unknown, since there are no constraints on the number of right-handed, SM-singlet, neutrinos. Second, since neutrinos carry neither color nor electromagnetic charge, they could be Majorana fermions. As a consequence the number of new parameters in the model depends on the number of massive neutrino states and on whether they are Dirac or Majorana particles.

In general, if we denote the neutrino mass eigenstates by $\nu_i$, $i = 1, 2, \ldots, n$, and the charged lepton mass eigenstates by $l_i = (e, \mu, \tau)$, in the mass basis, leptonic CC interactions are given by

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} l_{iL} \gamma^\mu U_{ij} \nu_j W^\mu_{\mu} + \text{h.c.}$$

Here $U$ is a $3 \times n$ matrix $U_{ij} = P_{\ell,ii} V^\dagger_{\ell,ij} V^\nu_{\nu,ij}$ where $V^\ell$ ($3 \times 3$) and $V^\nu$ ($n \times n$) are the diagonalizing matrix of the charged leptons and neutrino mass matrix respectively $V^\ell = \text{diag}(m_1^2, m_2^2, m_3^2)$ and $V^\nu = \text{diag}(m_1^2, m_2^2, m_3^2, \ldots, m_n^2)$.

$P_\ell$ is a diagonal $3 \times 3$ phase matrix, that is conventionally used to reduce by three the number of phases in $U$. $P_\nu$ is a diagonal matrix with additional arbitrary phases (chosen to reduce the number of phases in $U$) only for Dirac states. For Majorana neutrinos, this matrix is simply a unit matrix, the reason being that if one rotates a Majorana neutrino by a phase, this phase will appear in its mass term which will no longer be real. Thus, the number of phases that can be absorbed by redefining the mass eigenstates depends on whether the neutrinos are Dirac or Majorana particles. In particular, if there are only three Majorana (Dirac) neutrinos, $U$ is a $3 \times 3$ matrix analogous to the CKM matrix for the quarks but due to the Majorana (Dirac) nature of the neutrinos it depends on six (four) independent parameters: three mixing angles and three (one) phases.

A consequence of the presence of the leptonic mixing is the possibility of flavour oscillations of the neutrinos. Neutrino oscillations appear because of the misalignment between the interaction neutrino eigenstates and the propagation eigenstates (which for propagation in vacuum are the mass eigenstates). Thus a neutrino of energy $E$ produced in a CC interaction with a charged lepton $l_\alpha$ can be detected via a CC interaction with a charged lepton $l_\beta$ with a probability which presents an oscillatory behaviour, with oscillation lengths given by the phase difference between the different propagation eigenstates – which in the ultrarelativistic limit is $L_{\text{osc}}^{\alpha\beta} = \frac{4\pi E}{\Delta m^2_{\alpha\beta}}$ – and amplitude that is proportional to elements in the mixing matrix.

It follows that neutrino oscillations are only sensitive to mass squared differences and do not give us information on the absolute value of the masses. Also the Majorana phases do not affect oscillations because total lepton number is conserved in the process. Experimental information on absolute neutrino masses can be obtained from Tritium $\beta$ decay experiments and from its effect on the cosmic microwave background radiation and large structure formation data. If neutrinos are Majorana particles their mass and also additional phases can be determined in $\nu$-less $\beta\beta$ decay experiments.

Besides the flavour vacuum oscillations, described above, further flavour dependent
effects occur when neutrinos travel through regions of dense matter. This is so, because they can undergo forward scattering with the particles in the medium and these interactions are, in general, flavour dependent and as a consequence the oscillation pattern is modified. However the flavour transition probability still depends only on the mass squared differences and it is independent of the Majorana phases.

The neutrino experiments described above have measured some non-vanishing $P_{\alpha\beta}$ and from these measurements we have inferred all the positive evidence that we have on the non-vanishing values of neutrino masses and mixing as described below.

2. The Parameters of the NMSM: 3$\nu$ Analysis

I describe here the present determination of the parameters of the model from the analysis of the data from solar, KamLAND, ATM and K2K experiments and ignore the LSND evidence as it was not confirmed by MiniBoone.

In Fig. 1 I show the results from a recent analysis [7] of KamLAND $\bar{\nu}_e$ disappearance data and solar $\nu_e$ data. The main features of these results are:

- In the analysis of solar data, only the formerly called large mixing angle solution (LMA) is allowed with maximal mixing rejected at more than 5$\sigma$. This is so since the release of the SNO salt-data (SNOII) in Sep 2003.

Fig. 1. Allowed regions for 2-$\nu$ oscillations of solar $\nu_e$ (left) and KamLAND $\bar{\nu}_e$ (right). The different contours correspond to the allowed regions at 90%, 95%, 99% and 3$\sigma$ CL.

Fig. 2. Allowed regions from the analysis of ATM data (left), K2K (central) and MINOS (right). The different contours correspond to at 90%, 95%, 99% and 3$\sigma$ CL.
The analysis of the KamLAND data determines more precisely $\Delta m^2_{\odot}$ and it already makes an impact on the lower bound of the corresponding mixing angle, whereas the upper bound is dominated by solar data, most importantly by the CC/NC solar neutrino rates measured by SNO.

There is a mismatch between the best fit mixing angle and $\Delta m^2$ from solar and KamLAND at the $\sim 1.5\sigma$ level.

In Fig. 2 I show the results of an updated analysis of the ATM, K2K and MINOS data (updated from [7]). As seen in the figure, the determination of the corresponding $\Delta m^2_{\text{atm}}$ is dominated by the data from the MINOS experiment. The measurement of the mixing angle is still largely dominated by atmospheric neutrino data from Super-Kamiokande with a best fit point close to maximal mixing.

From the previous partial analysis, it is clear that the minimum joint description of ATM, LBL, solar and reactor data requires that all the three known neutrinos take part in the oscillations. The mixing parameters are encoded in the $3 \times 3$ lepton mixing matrix which can be conveniently parametrized in the standard form

$$U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{-i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{21} & s_{21} & 0 \\
-s_{21} & c_{21} & 0 \\
0 & 0 & 1
\end{pmatrix} \tag{2}
$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. The angles $\theta_{ij}$ can be taken without loss of generality to lie in the first quadrant, $\theta_{ij} \in [0, \pi/2]$.

There are two possible mass orderings, which we denote as Normal and Inverted. In the normal scheme $m_1 < m_2 < m_3$ while in the inverted one $m_3 < m_1 < m_2$.

In total the $3\nu$ oscillation analysis involves six parameters: 2 mass differences (one of which can be positive or negative), 3 mixing angles, and the CP phase. Generic $3\nu$ oscillation effects include: (i) coupled oscillations with two different wavelengths; (ii) CP violating effects; (iii) difference between Normal and Inverted schemes. The strength of these effects is controlled by the values of the ratio of mass differences $\Delta m^2_{21}/|\Delta m^2_{31}|$, by the mixing angle $\theta_{13}$ and by the CP phase $\delta$.

From the previous $2\nu$ analysis we see that $\Delta m^2_{\odot} = \Delta m^2_{21} \ll |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| = \Delta m^2_{\text{atm}}$. As a consequence the dominant oscillations in the joint $3\nu$ analysis behave as follows:

- for solar and KamLAND neutrinos, the oscillations with the $\Delta m^2_{31}$-driven oscillation length are completely averaged and the survival probability takes the form:

$$P^\text{atm}_{ee} = \sin^4 \theta_{13} + \cos^4 \theta_{13} P^{2\nu}_{ee} \tag{3}$$

where in the Sun $P^{2\nu}_{ee}$ is obtained with the modified sun density $N_e \rightarrow \cos^2 \theta_{13} N_e$. So the analyses of solar data constrain three of the six parameters: $\Delta m^2_{31}$, $\theta_{12}$ and $\theta_{13}$.

- For ATM and LBL neutrinos, the $\Delta m^2_{31}$-driven wavelength is very long and the corresponding oscillating phase is almost negligible. As a consequence, the ATM and LBL data analysis mostly restricts $\Delta m^2_{31} \simeq \Delta m^2_{32}$, $\theta_{23}$ and $\theta_{13}$, the latter being the most relevant parameter common to both solar+KamLAND and ATM+LBL neutrino oscillations and which may potentially allow for some mutual influence. The effect of $\theta_{13}$ is to add a $\nu_{\mu} \rightarrow \nu_{\tau}$ contribution to the ATM and LBL oscillations.

- In reactor experiments at short and intermediate baselines, in particular at CHOOZ, the $\Delta m^2_{31}$-driven wavelength is unobservable and the relevant oscillation wavelength is determined by $\Delta m^2_{31}$ and its amplitude by $\theta_{13}$. 

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The CP phase is basically unobservable although there is some marginal sensitivity in the present ATM neutrino analysis [7]. Normal versus Inverted orderings could be discriminated due to matter effects in the Earth for ATM neutrinos. However, this effect is controlled by the mixing angle $\theta_{13}$. Presently all data favour small $\theta_{13}$. Consequently, the difference between Normal and Inverted orderings is too small to be statistically meaningful in the present analysis.

The previously mentioned mismatch between the best fit angle $\theta_{12}$ as determined by solar versus KamLAND experiments, can be resolved by a non vanishing $\theta_{13}$ [8,9,10]. The exact CL for the non-zero value depends on the details of the analysis. A careful comparison of the results can be found in Ref.[10] in which the best fit $\theta_{13}$ is finally found to be compatible with zero at the $0.9\sigma$ level.

Altogether the derived ranges for the $\Delta m^2$s at $1\sigma$ ($3\sigma$) are:

$$\Delta m^2_{21} = 7.67^{+0.22}_{-0.21} \left( ^{+0.67}_{-0.61} \right) \times 10^{-5} \text{ eV}^2,$$

$$\Delta m^2_{31} = \begin{cases} -2.39 \pm 0.12 \left( ^{+0.37}_{-0.40} \right) \times 10^{-3} \text{ eV}^2 & \text{(inverted hierarchy),} \\ +2.49 \pm 0.12 \left( ^{+0.39}_{-0.36} \right) \times 10^{-3} \text{ eV}^2 & \text{(normal hierarchy),} \end{cases}$$

while our present knowledge of the moduli of the mixing matrix $U$ yields:

$$|U|_{3\sigma} = \begin{pmatrix} 0.77 \rightarrow 0.86 & 0.50 \rightarrow 0.63 & 0.00 \rightarrow 0.22 \\ 0.22 \rightarrow 0.56 & 0.44 \rightarrow 0.73 & 0.57 \rightarrow 0.80 \\ 0.21 \rightarrow 0.55 & 0.40 \rightarrow 0.71 & 0.59 \rightarrow 0.82 \end{pmatrix}.$$ (5)

3. Implications

3.1. The Need of New Physics

The SM is based on the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ spontaneously broken to $SU(3)_C \times U(1)_{EM}$ by the the vacuum expectations value (VEV), $v$, of the a Higgs doublet field $\phi$. The SM contains three fermion generations which reside in chiral representations of the gauge group. Right-handed fields are included for charged fermions as they are needed to build the electromagnetic and strong currents. As a consequence no right-handed neutrino is included in the model since neutrinos are neutral and colorless.

In the SM, fermion masses arise from the Yukawa interactions which couple the right-handed fermion singlets to the left-handed fermion doublets and the Higgs doublet. After spontaneous electroweak symmetry breaking (EWSB) these interactions lead to charged fermion masses but leave the neutrinos massless. No Yukawa interaction can be written that would give a tree level mass to the neutrino because no right-handed neutrino field exists in the model.

Furthermore, within the SM $G_{\text{SM}}^{\text{global}} = U(1)_B \times U(1)_C \times U(1)_\mu \times U(1)_e$ is an accidental global symmetry. Here $U(1)_B$ is the baryon number symmetry, and $U(1)_{\mu,e}$ are the three lepton flavor symmetries. In principle one can think of a neutrino mass term built with the particle content of the SM $\frac{Y_{\nu}}{v} \left( \bar{L}_i \phi \right) \left( \phi^* L^C_i \right) + \text{h.c.}$, where $L_i$ are the lepton doublets – as induced perturbatively at higher order or by non-perturbative effects. However such term would violate the $U(1)_L$ subgroup of $G_{\text{SM}}^{\text{global}}$ and therefore cannot be induced by
loop corrections. Also, it cannot be induced by non-perturbative corrections because the $U(1)_{B-L}$ subgroup of $G_{\text{SM}}^{\text{global}}$ is non-anomalous.

It follows that the SM predicts that neutrinos are precisely massless. Consequently, there is neither mixing nor CP violation in the leptonic sector. Thus the simplest and most straightforward lesson of the evidence for neutrino masses is also the most striking one: there is New Physics (NP) beyond the SM. This is the first experimental result that is inconsistent with the SM.

3.2. The Scale of New Physics

There are many good reasons to think that the SM is not a complete picture of Nature and some new physics (NP) is expected to appear at higher energies. In this case the SM is an effective low energy theory valid up to the scale $\Lambda_{\text{NP}}$ which characterizes the NP. In this approach, the gauge group, the fermionic spectrum, and the pattern of spontaneous symmetry breaking are still valid ingredients to describe Nature at energies $E \ll \Lambda_{\text{NP}}$. The difference between the SM as a complete description of Nature and as a low energy effective theory is that in the latter case we must consider also non-renormalizable (dim $> 4$) terms whose effect will be suppressed by powers $1/\Lambda_{\text{NP}}^{\text{dim}-4}$. In this approach the largest effects at low energy are expected to come from dim= 5 operators.

There is a single set of dimension-five terms that is made of SM fields and is consistent with the gauge symmetry given by

$$O_5 = \frac{Z_{ij}^{\nu}}{\Lambda_{\text{NP}}} \left( \bar{L}_{Li} \tilde{\phi} \right) \left( \phi^+ L_{Lj}^C \right) + \text{h.c.},$$

which violates total lepton number by two units and leads, upon EWSB, to neutrino masses:

$$(M_\nu)_{ij} = Z_{ij}^{\nu} \frac{v^2}{\Lambda_{\text{NP}}}.$$  \hfill (6)

This is a Majorana mass term.

Eq. (6) arises in a generic extension of the SM which means that neutrino masses are very likely to appear if there is NP. Furthermore from Eq. (7) we find that the scale of neutrino masses is suppressed by $v/\Lambda_{\text{NP}}$ when compared to the scale of charged fermion masses providing an explanation not only for the existence of neutrino masses but also for their smallness. Finally, Eq. (7) breaks not only total lepton number but also the lepton flavor symmetry. Thus we should expect lepton mixing and CP violation.

Given the relation (7), $m_\nu \sim v^2/\Lambda_{\text{NP}}$, it is straightforward to use measured neutrino masses to estimate the scale of NP that is relevant to their generation. In particular, if there is no quasi-degeneracy in the neutrino masses, the heaviest of the active neutrino masses can be estimated, $m_h = m_3 \sim \sqrt{\Delta m^2_{31}} \approx 0.05$ eV (in the case of inverted hierarchy the implied scale is $m_h = m_2 \sim \sqrt{\Delta m^2_{21}} \approx 0.05$ eV). It follows that the scale in the non-renormalizable term (6) is given by

$$\Lambda_{\text{NP}} \sim v^2/m_h \approx 10^{15} \text{ GeV}.$$ \hfill (8)

We should clarify two points regarding Eq. (8):

1. There could be some level of degeneracy between the neutrino masses that are relevant to the atmospheric neutrino oscillations. In such a case Eq. (8) becomes an upper bound on the scale of NP.
2. It could be that the $Z_{ij}$ couplings of Eq. (6) are much smaller than one. In such a case, again, Eq. (8) becomes an upper bound on the scale of NP. On the other hand, in models of approximate flavor symmetries, there are relations between the structures of the charged lepton and neutrino mass matrices that give quite generically $Z_{33} \geq m_\tau^2/v^2 \sim 10^{-4}$. We conclude that the likely range of $\Lambda_{NP}$ that is implied by the atmospheric neutrino results is given by

$$10^{11} \text{ GeV} \leq \Lambda_{NP} \leq 10^{15} \text{ GeV}. \quad (9)$$

The estimates (8) and (9) are very exciting. First, the upper bound on the scale of NP is well below the Planck scale. This means that there is a new scale in Nature which is intermediate between the two known scales, the Planck scale $m_{Pl} \sim 10^{19}$ GeV and the electroweak breaking scale, $v \sim 10^2$ GeV. Second, the scale $\Lambda_{NP} \sim 10^{15}$ GeV is intriguingly close to the scale of gauge coupling unification.

Of course, neutrinos could be conventional Dirac particles. In the minimum realization of this possibility, one must still extend the SM to add right-handed neutrinos and impose the conservation of total lepton number (since in the presence of right-handed neutrinos total lepton number is not an accidental symmetry) to prevent the right-handed neutrinos from acquiring a singlet Majorana mass term. In this scenario, neutrinos could acquire a mass like any other fermion of the Standard Model and no NP scale would be implied. We would be left in the darkness on the reason of the smallness of the neutrino mass.

3.3. The Challenge of Reconstructing the New Physics

In order to illustrate what I mean with this title I will focus on the what is probably the best known scenario that leads to (6): the see-saw mechanism.

In what it is also called Type-I see-saw, one assumes the existence of heavy sterile neutrinos $N_i$. Such fermions have SM gauge invariant bare mass terms and Yukawa interactions:

$$- \mathcal{L}_{NP} = \frac{1}{2} M_{Nij} \overline{N_i} N_j + Y_{\nu ij} \overline{L_i} \phi N_j + \text{h.c.} \quad (10)$$

The resulting mass matrix in the basis $(\nu_{Li}, N_j)^T$ has the following form:

$$M_\nu = \begin{pmatrix} 0 & Y_\nu \frac{v}{\sqrt{2}} \\ Y_\nu^T \frac{v}{\sqrt{2}} & M_N \end{pmatrix} \quad (11)$$

If the eigenvalues of $M_N$ are all well above the electroweak breaking scale $v$, then the diagonalization of $M_\nu$ leads to three light mass eigenstates and an effective low energy interaction of the form (6). In particular, the scale $\Lambda_{NP}$ is identified with the mass scale of the heavy sterile neutrinos, that is the typical scale of the eigenvalues of $M_N$. Two well-known examples of extensions of the SM that lead to a see-saw mechanism for neutrino masses are SO(10) GUTs and left-right symmetry.

Another form of new physics which also leads to a see-saw mechanism is the Type-II see-saw\cite{14}. In this case, no additional neutrino states are included in the theory but in order to construct a gauge invariant neutrino mass term involving only left-handed neutrinos the Higgs sector of the Standard Model is extended to include besides the doublet $\phi$, an $SU(2)_L$ scalar triplet $\Delta \sim (1, 3, 1)$. We can write the triplet in the matrix representation as
\[ \Delta = \begin{pmatrix} \Delta^0 & -\Delta^+ / \sqrt{2} \\ -\Delta^+ / \sqrt{2} & -\Delta^{++} \end{pmatrix} . \]  

(12)

The neutrino mass term arises from the Lagrangian:

\[ \mathcal{L}_{NP} = -f_{\nu} \bar{L}_{L,i} C L,_{L,j} \Delta L,_{L,j} - V(\phi, \Delta) \]  

(13)

where the scalar potential, besides the usual mass and self-coupling terms for the doublet contains additional pieces such as a triple mass term \( M_\Delta \) and a double-triple mixing term \( \mu \) (which breaks \( L \) explicitly)

\[ V(\phi, \Delta)_{NP} = M_\Delta^2 \text{Tr}(\Delta^0 \Delta) + \left( \mu \tilde{\phi}^T \Delta \tilde{\phi} + \text{h.c.} \right) . \]

The potential minimization leads to a vev for the triplet

\[ v_\Delta = \frac{\mu v^2}{\sqrt{2} M_\Delta^2} . \]

(14)

which induces a Majorana mass for the three neutrinos

\[ M_\nu = \sqrt{2} f_{\nu} v_\Delta . \]

(15)

So if \( M_\Delta^2 \gg \mu v \), then \( v_\Delta \ll v \) which gives an explanation to the smallness of the neutrino mass. In this case the scale \( \Lambda_{NP} = M_\Delta^2 / \mu \), and a characteristic setting would be for \( f_{\nu} \approx 1 \) and \( \mu \sim M_\Delta \approx 10^{14-15} \) GeV.

One may notice that even in these particularly simple forms of NP, \( \mathcal{L}_{NP} \) contains very different high-energy particle contents as well as 18 parameters for Type-I and > 12 for Type-II which we would need to know in order to fully determine the dynamics of the NP. However the effective low energy operator \( O_5 \) contains only 9 parameters which is everything we can measure at the low energy experiments. This simple example illustrates the limitation of the “bottom-up” approach in deriving model independent implications of the presently observed neutrino masses and mixing. This is the challenge.

Alternatively one can go “top-down” by studying the low energy effective neutrino masses and mixing induced by specific high energy models. Unfortunately the number of possible models is overwhelming and impossible to review in this talk.

The bottom line of this discussion is that in order to advance further in the understanding of the dynamics underlying neutrino masses, we need more (and more precise) data. Furthermore synergy among different types of observations are probably going to be fundamental in this advance. In this respect I will finish by discussing two possible consequences of neutrino mass models which have deserved special attention in the last years.

3.4. Signatures at LHC

Ideally in order to directly test the dynamics underlying the neutrino mass generation one needs to observe the associated new states. For instance, in the examples above we would like to produce and study the new heavy states responsible for the see-saw mechanism, either the heavy neutral leptons or the triplet scalars. As discussed above, most generically the characteristic mass scales of the new states are very large, rendering the new states experimentally inaccessible in the foreseeable future. However, one can envision scenarios in which this may not be necessarily the case.
As an example let’s take the Type II see-saw introduced in the previous section. The key ingredient that makes this model testable at LHC is to assume a very small doublet-triplet mixing

$$\mu \ll M_\Delta$$

(16)

so the Higgs triplet is heavy, typically $$M_\Delta^2 > v^2/2$$, but not much heavier than this bound. Once the neutral component in the triplet gets the vev, $$v_\Delta$$ as in Eq. (14), the neutrinos acquire a Majorana mass as described above, but because of the smallness of $$\mu$$ one can have small neutrino masses even with $$M_\Delta$$ as light as

$$M_\Delta \sim 110 \text{ GeV}$$

(17)

without conflicting with any existing data.

After EWSB, there are 7 physical massive Higgs bosons left in the spectrum. One is a SM-like doublet while the other 6 are triplet-like: two neutral ($$H_2$$ and $$A$$), two single charged $$H^\pm$$ and two double charged $$H^{\pm\pm}$$ with $$M_{H_2} \simeq M_A \simeq M_{H^\pm} \simeq M_{H^{\pm\pm}} = M_\Delta$$. Thus all these states are within reach of the LHC.

In the physical basis for the fermions the Yukawa interactions of the single and double charged scalars can be written as

$$- \mathcal{L} = Y_{ij}^+ \bar{\nu}_L^C i e_L H^+ + \bar{Y}_{ij}^{++} \bar{\nu}_L e_L H^{++},$$

(18)

where

$$Y^+ = \cos \theta_+ \frac{m^\text{diag}_\nu}{v_\Delta} U^\dagger_{\text{LEP}}, \quad Y^{++} = U^*_{\text{LEP}} \frac{m^\text{diag}_\nu}{\sqrt{2} v_\Delta} U^\dagger_{\text{LEP}} = f_\nu. \quad (19)$$

Thus in this scenario the values of the couplings $$Y^+$$ and $$Y^{++}$$ are determined by the spectrum and mixing angles for the active neutrinos. Therefore, by observing lepton-number violating decays of the Higgs bosons, $$H^{++} \rightarrow e_i^+ e_j^+$$ and $$H^+ \rightarrow e_i^+ \bar{\nu}$$ ($$e_i = e, \mu, \tau$$) one can obtain information about neutrino masses and mixings and in particular it is possible to determine the neutrino mass spectrum.

3.5. Leptogenesis

Even if its characteristic NP scale is as high as estimated in Eq.(9), neutrino mass models can lead to important visible consequences. In particular they may help us to explain the origin of the cosmic matter-antimatter asymmetry, via leptogenesis [15].

From the detail cosmological data from CMB and BBN we know that there is only a tiny asymmetry in the baryon number, $$n_B/n_\gamma \approx 5 \times 10^{-10}$$. Leptogenesis [15] is the possible origin of such a small asymmetry related to neutrino physics. In a possible realization of leptogenesis, $$L \neq 0$$ is generated in the Early Universe by the decay of one of the heavy right-handed neutrinos of the the see-saw mechanism, with a direct CP violation. Due to the interference between the tree-level and one-loop diagrams shown in Fig. 3 the decay rates of the right-handed neutrino into leptons and anti-leptons are different. In order to generate a lepton asymmetry the decay must be out of equilibrium ($$\Gamma_{\nu_R} \ll \text{Universe expansion rate}$$. Sphaleron processes transform the lepton asymmetry in baryon asymmetry and below the electroweak phase transition a net baryon asymmetry is generated $$\Delta B \simeq -\frac{\Delta L}{2}$$ (the exact coefficient relating $$\Delta B$$ to $$\Delta L$$ is model dependent.)
Fig. 3. The tree-level and one-loop diagrams of right-handed neutrino decay into leptons and Higgs.

In general, the details are model dependent and much work has been done to explain the observed asymmetry in realizations which are able to accommodate the neutrino oscillation data. In its minimal implementation a right-handed neutrino of about $10^{10}$ GeV can account for the cosmic baryon asymmetry from its out-of-equilibrium decay [16].

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