Universidad de los Andes

Phenomenological Study of Search of Heavy Neutrinos, with Displaced Vertices and Vector Boson Fusion

This dissertation is submitted for the degree of

Physicist

by

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State of the Art

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As it was mentioned earlier the SM does not explain the reason why the mass of neutrinos is smaller than the mass of the other fermions by a factor of almost 10^{-6}. Moreover, it does not provide an explanation to the fact that only left handed netrinos had been observed in nature. In this section we are going to work on possible solutions to these problems. [1]

2.2.1 Dirac Mass

The lagrangian of a free fermion is:

$$L = \overline{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi \tag{2.1}$$

Where ψ is the Dirac Spinor. The mass is included in the SM through the second term in the former equation, it is called "Dirac mass term":

$$m\overline{\psi}\psi \tag{2.2}$$

[1] The detailed calculation is explain in A

We can write the Dirac Spinor as a sum of it's left- and right- chiral states:

$$m\overline{\psi}\psi = m\left(\overline{\psi_L + \psi_R}\right)(\psi_L + \psi_R) = m\overline{\psi_L}\psi_R + m\overline{\psi_R}\psi_L \tag{2.3}$$

Previously we have used the fact that: $\overline{\psi_L}\psi_L = \overline{\psi_R}\psi_R = 0$ which is proved in A. It can be seen from the lastest equation that a massive particle must have both quiral states: left and right. Thus, the Dirac Mass can be interpreted as the coupling constant between the two chiral states. Since right-handed neutrinos had never been observed in nature, it is expected that neutrinos have zero mass. Although the experiments of neutrino oscillations indicate that neutrinos have a small mass of the order of meV. The former implies either the existence of a right-handed neutrino which is responsable for the mass of the neutrino or there other sort of mass term.

2.2.2 Majorana Mass

The Majorana mechanism is based in the reasoning of writing the mass term in the Lagrangian only in term of the left-handed chiral state. We start by decomposing the wavefunction into its left and right chiral states in the Dirac Lagrangian:

$$\begin{aligned} L &= \overline{\psi}\left(i\gamma^\mu\partial_\mu - m\right)\psi \\ &= (\overline{\psi_L} + \overline{\psi_R})(i\gamma^\mu\partial_\mu - m)(\psi_L + \psi_R) \\ &= i\overline{\psi_L}\gamma^\mu\partial_\mu\psi_L - \overline{\psi_L}m\psi_R + i\overline{\psi_R}\gamma^\mu\partial_\mu\psi_R - \overline{\psi_R}m\psi_L \end{aligned} \tag{2.4}$$

Since $\overline{\psi_L}\psi_L = \overline{\psi_R}\psi_R = 0$ and $\overline{\psi_R}\gamma^\mu\partial_\mu\psi_L = \overline{\psi_L}\gamma^\mu\partial_\mu\psi_R = 0$ as it is explained in the Apendix A. Now we can find two independent equations of motion using the Euler Langrange equation:

$$\frac{\partial L}{\partial(\partial\phi)} - \frac{\partial L}{\partial\phi} = 0 \tag{2.5}$$

We obtain two coupled Dirac equations for the right- and left- handed fields:

$$i\gamma^{\mu}\partial_{\mu}\psi_L = m\psi_R \tag{2.6}$$

$$i\gamma^{\mu}\partial_{\mu}\psi_R = m\psi_L \tag{2.7}$$

The formulation of the SM takes assumes that the mass of the neutrino is zero, in this case we obtain two equations which are called "Weyl equations":

$$i\gamma^{\mu}\partial_{\mu}\psi_L = 0 \tag{2.8}$$

$$i\gamma^{\mu}\partial_{\mu}\psi_R = 0 \tag{2.9}$$

The former means that neutrino can be described using two two-component spinors that are helicity eigenstates which represents two states with definite and opposite helicity which correspond to the left- and right-handed neutrinos. However, since we have not observed a right-handed neutrino we just represent the neutrino as a single left-handed massless field.

Majorana work out in a way to describe a massive neutrino just in terms of it's left-handed field. This calculation is perform in the apendix A. The objetive of Majorana was to write the equation 2.7 as 2.6 by finding an expression for ψ_R in terms of ψ_L. By manipulating the equation 2.7 we find that it can be written as:

$$i\gamma^{\mu}\partial_{\mu}C\overline{\psi}_R^{\intercal} = mC\overline{\psi}_L^{\intercal} \tag{2.10}$$

Where C is the operator Charge Conjugation Operator. This operator and its properties are explained in Apendix (...). Now, the lastest equation would have the same structure as equation 2.6 if impose the right handed term to be:

$$\psi_R = C\overline{\psi}_L^{\intercal} \tag{2.11}$$

The former assumption requires $C\overline{\psi}_L^{\intercal}$ to be right-handed, this is proved in the apendix A. Thus, the complete Majorana field can be written as:

$$\psi = \psi_L + \psi_R = \psi_L + C\overline{\psi}_L^{\intercal} \tag{2.12}$$

Defining the charge-conjugate field: $\psi_L^C = C\overline{\psi}_L^{\intercal}$. We get for the expression of the complete Majorana field:

$$\psi = \psi_L + \psi_L^C \tag{2.13}$$

The implications of requiring the right handed component of ψ to have that certain expresion are studied by taking the charge conjugate of the complete Majorana field.

$$\psi^C = (\psi_L + \psi_L^C)^C = \psi_L^C + \psi_L = \psi \tag{2.14}$$

Having in mind that the charge conjugation operator turns a particle state into an antiparticle state, it can be deduced that a Majorana particle is it's own antiparticle. Since the charge conjugation operator flips the sign of electric charge, a Majorana particle must be neutral. Thus, the neutrino is the only fermion that could be a Majorana particle.

Majorana Mass Term

Previously, we saw that the mass term in the Lagrangian couples the left and right chiral states of the neutrino (equation 2.3). Replacing the expression we found for the right-handed component of the neutrino field in the mass term of the Lagrangian, we get (having in mind that its hermitian conjugate is identical):

$$L_{Maj}^L = m\overline{\nu_L}\nu_L^C + m\overline{\nu_L^C}\nu_L = \frac{1}{2}m\overline{\nu_L^C}\nu_L \tag{2.15}$$

2.3 Seesaw Mechanism

As it was mentioned before, in the case that the right-handed chiral field does not exist there can be no Dirac mass term, but we can have a Majarona mass term in the Lagrangian so neutrino would be a Majorana particle:

$$L_{Maj}^L = \frac{1}{2}m_L\overline{\nu^C}_L\nu_L \tag{2.16}$$

But due to ... (Higgs) such a term can not exist. In order to let the neutrino have mass there must exist that interacts only with gravity and the Higgs mechanism because it has not been observed. If we consider that a right-handed chiral neutrino can exist, we would have to add different terms to the Lagrangian. First, if we assume that it is possible to write a left-handed Majorana field, we have for the first term:

$$L_L^M = m_L \overline{\nu_L} \nu_L^C + m_L \overline{\nu_L^C} \nu_L \tag{2.17}$$

Additionally, we have to include a similar term which is the right-handed Majorana field:

$$L_L^M = m_R \overline{\nu_R^C} \nu_R + m_R \overline{\nu_R} \nu_R^C \tag{2.18}$$

We also have to add to Dirac mass terms: the first Dirac mass term we mentioned on this section (equation 2.19)and another one that comes from the charge-conjugate fields (equation 2.20):

$$L = m_D \overline{\nu_L} \nu_R + m_D \overline{\nu_R} \nu_L \tag{2.19}$$

$$L = m_D \overline{\nu_R^C} \nu_L^C + m_D \overline{\nu_L^C} \nu_R^C \tag{2.20}$$

Since the hermitian conjugate of each equation is identical, we can write the most general mass term as:

$$L = \frac{1}{2} \left(m_L \overline{\nu_L^C} \nu_L + m_R \overline{\nu_R^C} \nu_R + m_D \overline{\nu_R} \nu_L + m_D \overline{\nu_L^C} \nu_R^C \right) \tag{2.21}$$

The former equation can be written as a matrix equation:

$$L_{mass} \propto \begin{pmatrix} \overline{\nu_L^C} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^C \end{pmatrix} \tag{2.22}$$

The former matrix express the Lagrangian in term of the left and right chiral states. These states do not have a definite mass because the matrix is not diagonal. Thus, the left and right chiral states do not correspond to the physical particles (which have a definite mass), instead the real particles are a superposition of the mass eigenstates. In order to find the mass eigenvalues we need to diagonalize the M matrix (the one in the middle of equation 2.22). This calculation is explained is Appendix A. We find the mass eigenstates are given by the expression:

$$m_{1,2} = \frac{1}{2} \left((m_L + m_R) \sqrt{(\mathrm{m_L} - \mathrm{m_R})^2 + 4\mathrm{m_D^2}} \right) \tag{2.23}$$

The fact that the SM does not allow a Majorana left-chiral mass term implies $m_L = 0$. We are going to study the expression of the mass eigenstates m_1 and m_2. When we choose $m_R >> m_D$, we get for the masses:

$$m_1 = \frac{m_D^2}{m_R} \tag{2.24}$$

$$m_2 = m_R \left(1 + \frac{m_D^2}{m_R^2}\right) \approx m_R \tag{2.25}$$

From the both equations above we can deduce that if there exist a neutrino with mass m_2 very large, then the other neutrino must have a small mass. Now, the neutrino mass eigenstates are given by the following expresions:

$$\nu_1 \propto \left(\nu_L + \nu_L^C\right) - \frac{m_D}{m_R^2} \left(\nu_R + \nu_R^C\right) \tag{2.26}$$

$$\nu_2 \propto \left(\nu_R + \nu_R^C\right) + \frac{m_D}{m_R^2} \left(\nu_L + \nu_L^C\right) \tag{2.27}$$

The former equations show that ν_1 is mostly the left-handed light Majorana neutrino while ν_2 is the heavy sterile right-handed neutrino. This is the explanation that the Seesaw Mechanism gives to the fact that the neutrino is much lighter than the other fermions.

Chapter 3

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Appendix A

Neutrinos and Seesaw Mechanism

A.0.1 Dirac Mass

In this Appendix we are going to perform with detail the calculations for neutrino physics which where described in the State of the Art chapter. We start here by studying the Dirac Mass wich was a term of the form:

$$m\overline{\psi}\psi = m\overline{(\psi_L + \psi_R)}(\psi_L + \psi_R) = m(\overline{\psi_L}\psi_L + \overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L + \overline{\psi_R}\psi_R) \tag{A.1}$$

Lets study the term $\overline{\psi_L}\psi_L$ and using $P_R P_L = 0$:

$$\overline{\psi_L}\psi_L = \overline{\psi} P_L^\dagger P_L \psi = \overline{\psi} P_R P_L \psi = 0 \tag{A.2}$$

Using an analogous reasoning we can find $\overline{\psi_R}\psi_R = 0$, too. Finally, we obtain the expresion:

$$m\overline{\psi}\psi = m(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L) \tag{A.3}$$

A.0.2 Majorana Mass

The expresion we had for the Dirac Lagrangian was:

$$
\begin{aligned}
L &= \overline{\psi}\left(i\gamma^\mu\partial_\mu - m\right)\psi \\
&= (\overline{\psi_L} + \overline{\psi_R})(i\gamma^\mu\partial_\mu - m)(\psi_L + \psi_R) \\
&= i\overline{\psi_L}\gamma^\mu\partial_\mu\psi_L + i\overline{\psi_L}\gamma^\mu\partial_\mu\psi_R - m\overline{\psi_L}\psi_L - m\overline{\psi_L}\psi_R \\
&\qquad + i\overline{\psi_R}\gamma^\mu\partial_\mu\psi_L + i\overline{\psi_R}\gamma^\mu\partial_\mu\psi_R - m\overline{\psi_R}\psi_L - m\overline{\psi_R}\psi_R
\end{aligned} \tag{A.4}
$$

$$\tag{A.5}$$

We already proved that $\overline{\psi_L}\psi_L = \overline{\psi_R}\psi_R = 0$. Now we study the second term in the latest equation, which has a term of the form:

$$
\begin{aligned}
P_R\gamma^\mu &= \frac{1}{2}(1+\gamma^5)\gamma^\mu = \frac{1}{2}(\gamma^\mu + \gamma^5\gamma^\mu) \\
&= \frac{1}{2}(\gamma^\mu - \gamma^\mu\gamma^5) && \text{Since } \{\gamma^5, \gamma^\mu\} = \gamma^5\gamma^\mu + \gamma^\mu\gamma^5 = 0 \\
&= \frac{1}{2}\gamma^\mu(1-\gamma^5) = \gamma^\mu P_L
\end{aligned} \tag{A.6}
$$

Using what we have found in the last expression, we get for the second term:

$$
\begin{aligned}
i\overline{\psi_L}\gamma^\mu\partial_\mu\psi_R &= i\overline{\psi}P_R\gamma^\mu\partial_\mu P_R\psi \\
&= i\overline{\psi}\gamma^\mu P_L\partial_\mu P_R\psi \\
&= i\overline{\psi}\gamma^\mu\partial_\mu P_L P_R\psi \quad \text{Since } P_L \text{ is a constant operator} \\
&= 0
\end{aligned} \tag{A.7}
$$

Following a similar calculus we get: $i\overline{\psi_R}\gamma^\mu\partial_\mu\psi_L = 0$. Our next step is to find the two coupled Dirac equations using the Euler-Lagrange equation. We obtained for the Lagrangian:

$$L = i\overline{\psi_R}\gamma^\mu\partial_\mu\psi_R + i\overline{\psi_L}\gamma^\mu\psi_L - m\overline{\psi_R}\psi_L - m\psi_L\psi_R \tag{A.8}$$

Replacing in the Euler-Lagrange equation we get for both states:

$$\begin{aligned}
\frac{\partial L}{\partial(\partial\overline{\psi_R})} &= \frac{\partial L}{\partial\overline{\psi_R}} \quad \rightarrow \quad 0 = i\gamma^\mu\partial_\mu\psi_L - m\psi_R \\
\frac{\partial L}{\partial(\partial\overline{\psi_L})} &= \frac{\partial L}{\partial\overline{\psi_L}} \quad \rightarrow \quad 0 = i\gamma^\mu\partial_\mu\psi_R - m\psi_L
\end{aligned} \tag{A.9}$$

Now, we are going to find an expression for ψ_R in terms of ψ_L. First, we take the hermitian conjugate of the bottom equation in A.9:

$$\begin{aligned}
i\gamma^\mu\partial_\mu\psi_R &= m\psi_L \\
(i\gamma^\mu\partial_\mu\psi_R)^\dagger &= m\psi_L^\dagger && \text{Taking the hermitian conjugate} \\
-i\partial_\mu\psi_R^\dagger\gamma^{\mu\dagger} &= m\psi_L^\dagger \\
-i\partial_\mu\psi_R^\dagger\gamma^{\mu\dagger}\gamma^0 &= m\psi_L^\dagger\gamma^0 && \text{Multiplying on the right by } \gamma^0 \\
-i\partial_\mu\psi_R^\dagger\gamma^0\gamma^\mu &= m\psi_L^\dagger\gamma^0 && \text{Using } \gamma^{\mu\dagger}\gamma^0 = \gamma^0\gamma^\mu \\
-i\partial_\mu\overline{\psi_R}\gamma^\mu &= m\overline{\psi_L} && \text{We have } \overline{\psi} = \psi^\dagger\gamma^0 \\
-i(\partial_\mu\overline{\psi_R}\gamma^\mu)^\intercal &= m\overline{\psi_L}^\intercal && \text{Taking the transpose} \\
-i\gamma^{\mu\intercal}\partial_\mu\overline{\psi_R}^\intercal &= m\overline{\psi_L}^\intercal \\
-i(-C^{-1}\gamma^\mu C)\partial_\mu\overline{\psi_R}^\intercal &= m\overline{\psi_L}^\intercal && \text{Using } \gamma^{\mu\intercal} = -C^{-1}\gamma^\mu C \\
i\gamma^\mu\partial_\mu C\overline{\psi_R}^\intercal &= mC\overline{\psi_L}^\intercal && \text{Multiplying on the left by C}
\end{aligned} \tag{A.10}$$

As we saw previosly, for the lastest equation to have a similar structure to the top equation of A.9, the right handed component of ψ must be:

$$\psi_R = C\overline{\psi_L}^\intercal \tag{A.11}$$

Now, we need to prove that $C\overline{\psi_L}^\intercal$ is actually right-handed. To do this we apply the right-handed chiral projection operator P_L on this state and the result must be zero.

$$
\begin{aligned}
P_L \left(C\overline{\psi_L}^{\intercal} \right) &= C P_L^{\intercal} \overline{\psi_L}^{\intercal} \qquad \text{Property of C: } P_L C = C P_L^{\intercal} \\
&= C \left(\overline{\psi_L} P_L \right)^{\intercal}
\end{aligned}
\tag{A.12}
$$

Now, lets examine the term $\overline{\psi_L} P_L$: