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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Bogotá, D.C. 2017

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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]

2.3.1 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.

2.3.2 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:

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

The intermediate steps are 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. Here we will briefly follow his calculation (which is explained with detail in A). His objetive was to work out the equation 2.3.2 to made it look like the equation 2.3.2 by finding an expression for ψ_R in terms of ψ_L. First, we take the hermitian conjugate of the equation 2.3.2 and multiplying on the right by γ^0:

$$-i\partial_\mu \psi_R^\dagger \gamma^{\mu\dagger}\gamma^0 = m\psi_L^\dagger \gamma^0 \tag{2.10}$$

Using the property $\gamma^{\mu\dagger}\gamma^0 = \gamma^0\gamma^\mu$ (also explain in the apendix A) we get:

$$-i\partial_\mu \psi_R^\dagger \gamma^0 \gamma^\mu = m\psi_L^\dagger \gamma_0 \quad \rightarrow \quad -i\partial_\mu \overline{\psi}\gamma^\mu = m\overline{\psi_L} \tag{2.11}$$

Taking the transpose of the last equation and using the property $C\gamma^{\mu\intercal} = -\gamma^\mu C$ involving the charge conjugation matrix C (the operator charge conjugation and its properties are described in the apendix A), we obtain:

$$i\gamma^\mu \partial_\mu C\overline{\psi}_R^\intercal = mC\overline{\psi}_L^\intercal \tag{2.12}$$

Now, the lastest equation would have the same structure as equation 2.3.2 if impose the right handed term to be:

$$\psi_R = C\overline{\psi}_L^\intercal \tag{2.13}$$

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:

$$\psi = \psi_L + \psi_R = \psi_L + C\overline{\psi}_L^{\intercal} \tag{2.14}$$

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

$$\psi = \psi_L + \psi_L^C \tag{2.15}$$

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.

$$\psi^C = (\psi_L + \psi_L^C)^C = \psi_L^C + \psi_L = \psi \tag{2.16}$$

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 2.3.1). Using the expression we found for the right-handed component in terms of the left one in the mass term of the Lagrangian we get:

$$m\overline{\psi}\psi = m\overline{\psi_L}\psi_R + m\overline{\psi_R}\psi_L = \tag{2.17}$$

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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:

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

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

$$\overline{\psi_L}\psi_L = \overline{\psi}P_L^{\dagger}P_L\psi = \overline{\psi}P_R P_L\psi = 0 \quad \text{(A.2)}$$

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

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

A.0.2 Majorana Mass

The expresion we had for the Dirac Lagrangian was:

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

$$\tag{A.5}$$

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:

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

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

$$
\begin{aligned}
i\overline{\psi_L}\gamma^{\mu}\partial_{\mu}\psi_R &= i\overline{\psi}P_R\gamma^{\mu}P_R\psi \\
&= && \text{Since} \\
&= \\
&=
\end{aligned}
$$