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A New Mechanism for Neutrino Mass

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Abstract

A mechanism for generating massive but naturally light Dirac neutrinos is proposed. It involves composite Higgs within the standard model as well as some new interaction beyond the standard model. According to this scenario, a neutrino mass of 0.1 eV or higher, signals new physics at energies of 10–100 TeV or lower.

The recent announcement of a depletion in the expected number on the earth's surface of $\nu_\mu' s$ originating from cosmic ray interactions in the atmosphere [1] has once again focussed attention on the fundamental properties of neutrinos. The favoured explanation for this effect is that a ν_μ oscillates into a neutrino of another family, most likely a ν_τ, implying that at least one neutrino has a nonzero mass. From the reported value of $\delta m^2 \approx 10^{-3}$ to $10^{-2} eV^2$, we can conclude that the average mass of the two neutrinos involved is bounded approximately by $m > \frac{1}{2}\sqrt{\delta m^2} \approx 10^{-1} eV$.

Massive but light neutrinos have intrigued model-makers for quite some time now. The most widely discussed possibility is to assume that neutrinos are Majorana particles, in which case they can be driven to a small mass by the see-saw mechanism [2]. If, however, neutrinos turn out to be Dirac particles, we would require an alternative scenario. In this brief note, we propose such an alternative. We suggest a simple, qualitative, model-independent line of reasoning that naturally accommodates light, massive, Dirac neutrinos and draw from it information regarding the scale at which new physics beyond the standard model can be expected to come into play.

Neutrinos are unique in the standard model. They are the only fermions, a part of which, namely the right-handed part ν_R, has zero quantum numbers under $SU(3) \times SU(2) \times U(1)$ and as a consequence has no gauge interaction. Thus, if there are no elementary Higgs bosons and if the W,Z, the charged leptons and the quarks get their masses by dynamical breaking of symmetry induced by the $SU(3) \times SU(2) \times U(1)$ gauge interactions alone, then neutrinos will remain massless. In such a case, new interactions going beyond the standard model will be required for giving mass to the neutrino. If the mass scale of the new physics beyond the standard model is large enough, the mass of the neutrino will remain small. This would provide a natural mechanism for small neutrino masses. In contrast, totally arbitrary neutrino masses would result from the introduction of elementary Higgs boson, which we discard.

To make our suggestion a little more concrete, let us envisage a picture in which the Higgs boson H is a composite of fermions and antifermions bound by the $SU(3) \times SU(2) \times U(1)$ gauge forces through some nonperturbative mechanism [3]. In principle, H can be a combination of $\bar{t}_L t_R, \bar{b}_L b_R \ldots \bar{d}_L d_R, \bar{\tau}_L \tau_R \ldots \bar{e}_L e_R$, but it cannot contain $\bar{\nu}_L \nu_R$ of any family, since ν_R does not have any gauge interaction. *In other words, the effective Yukawa coupling $H\bar{\nu}_L \nu_R$ vanishes exactly, to all orders in the $SU(3) \times SU(2) \times U(1)$ gauge coupling constants.* On the other hand, the effective Yukawa vertex $H\bar{e}_L e_R$ for the electron (or for any other charged fermion) exists and it has a form factor characterized by a momentum scale Λ_H

which we take to be the electroweak scale ≈ 100 GeV as that is the only relevant scale. We may call the standard model interactions as "allowed" interactions. In this sense, masses of the charged fermions are allowed, via the Yukawa interaction, if H has a nonvanishing vaccuum expectation value, while neutrino masses are forbidden in the regime of validity of the standard model - the only way to make neutrinos massive is to invoke forces beyond the standard model.

We next go to the "first-forbidden" approximation, i.e. we include the nonstandard effects in the lowest nontrivial order. Without being committed to a specific model, we parametrize the required new physics beyond the standard model by effective four-fermion couplings with a Fermi-type couping constant generically denoted as G_X. The corresponding mass scale $G_X^{-1/2}$ must be substantially higher than the mass scale (≈ 100 GeV) of the standard model. This will generate the first-forbidden coupling $H\bar{\nu}_L\nu_R$ through the graphs shown in Fig.1, where the shaded vertex is the "allowed" Yukawa vertex with form factor, for a charged fermion which we may take to be a charged lepton ℓ, so as not to violate B and L at the X vertex. The corresponding effective Yukawa coupling constant f_ν for ν can be estimated :

$$f_\nu \approx f_\ell G_X \int^{\Lambda_H} \frac{d^4p}{\not{p}\ \not{p}} \ \approx\ f_\ell G_X \Lambda_H^2 \tag{1}$$

where f_ℓ is the Yukawa coupling constant for ℓ and the integral is cut off at Λ_H because of the form factor of the composite Higgs. If the Higgs has a nonvanishing vacuum expectation value, then we get for the neutrino mass

$$m_\nu \approx m_\ell G_X \Lambda_H^2 \tag{2}$$

where m_ℓ is the mass of the charged lepton. For $\Lambda_H \approx 100 GeV$, we arrive at

$$G_X^{-1/2} \approx 100\sqrt{m_\ell/m_\nu}\ GeV\,. \tag{3}$$

A lower bround on m_ν thus results in an upper bound on the scale of new physics $G_X^{-1/2}$. Also, the lower the mass of ℓ to which ν couples at the $\bar{\ell}_R\nu_R X$ vertex, the lower is the bound on $G_X^{-1/2}$ and the best bound is obtained for the charged lepton of lowest mass ℓ to which the neutrino of mass m_ν couples.

If the dominant mixing of the atmospheric ν_μ is with ν_τ, the best bound on $G_X^{-1/2}$ is realised for $\ell = \mu$ in the above formula :

$$G_X^{-1/2} \leq 10^5 - 10^6 GeV. \tag{4}$$

If the massive neutrino couples also to e_R (for which there is no clear evidence), this bound will be reduced by a factor of about 10. In contrast to the see-saw mechanism where m_ν

depends linearly on the mass of the heavy right-handed Majorana neutrino, in our formula (2), m_ν depends on the square of the mass-scale of new physics. As a result, in the scenario envisaged here, new physics would occur at much lower energies than with the see-saw mechanism and so our proposal can be confronted with experiment much earlier and either confirmed or ruled out.

We discuss briefly two illustrative possibilities of new physics beyond the standard model (SM), that would lead to the two types of effective four-fermion couplings introduced in Fig.1. We must note that the type (a) coupling (Fig.1(a)) is consistent with SM symmetry, but type (b) coupling (Fig.1(b)) violates $SU(2) \times U(1)$. Type (a) can be obtained by the exchange of a charged or neutral scalar boson S (as shown in Fig.(2)), with coupling constant h and mass $m_S \gg 100$ GeV. In this case, G_X can be replaced by

$$G_X \approx \frac{h^2}{m_S^2}\,, \tag{5}$$

and hence the upper bound on m_S would be smaller than $10^5 - 10^6$ GeV, if h is less than unity. If all elementary scalars are forbidden (which is not necessary for our argument on the neutrino mass), these S bosons also could be composite, but formed by forces beyond the standard model. (For obvious reasons S^o must have zero vacuum expectation value).

The SM-symmetry violating four-fermion coupling (type (b)) occurs in a large class of models in which the W boson of the SM mixes with a heavier W boson that couples to righthanded fermions. The best model of this kind is the one in which $SU(2)_L \times U(1)$ of the SM is extended [4] to $SU(2)_L \times SU(2)_R \times U(1)$. This has two pairs of charged W bosons, $W_L^\pm$ and $W_R^\pm$. The mass eigenstates $W_1^\pm$ and $W_2^\pm$ can be expressed through the mixing angle ζ :

$$W_1 = W_L \cos\zeta + W_R \sin\zeta \tag{6}$$

$$W_2 = -W_L \sin\zeta + W_R \cos\zeta\,. \tag{7}$$

One identifies W_1 with the known W boson and W_2 is presumed to be heavy. The current experimental limits are [5]

$$|\zeta| < 10^{-2} - 10^{-3} \tag{8}$$

$$\beta \equiv \frac{m_{W_1}^2}{m_{W_2}^2} < 0.02. \tag{9}$$

We also have a theoretical bound [6]

$$|\zeta| < \beta\,. \tag{10}$$

Fig.3 shows the W-exchange graphs that generate the required coupling of Fig.1b. The effective Fermi-coupling constant arising from the sum of these two graphs can be estimated to be

$$G_X \approx g^2 \cos\zeta \sin\zeta \left(\tfrac{1}{m_{W_1}^2} - \tfrac{1}{m_{W_2}^2} \right) \tag{10}$$

$$\approx \left(\frac{\zeta}{\beta}\right) \frac{g^2}{m_{W_2}^2} \ \leq \ \frac{g^2}{m_{W_2}^2} \, . \tag{11}$$

Combining (4) and (11) and using the value of the $SU(2)_L$ gauge coupling constant g, we get the bound

$$m_{W_2} \leq 10^4 - 10^5 GeV. \tag{12}$$

Our conclusions are : (i) The physics of a composite Higgs or, more generally, dynamical symmetry breaking within the standard model followed by new interactions beyond the standard model provides a natural mechanism for generating very small neutrino masses. (ii) Within this scenario, a finite but small Dirac mass for neutrinos may be regarded as a signal that interesting new physics can be expected at an energy scale of 10–100 TeV or lower.

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References and Footnotes

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Figure Captions

Fig.1. Generation of the Yukawa coupling of the neutrino, from that of the charged lepton with form factor denoted by the shaded vertex, through new physics represented by the four-fermion coupling of two types (a) and (b). (To each diagram, one must add a corresponding diagram with *all* fermion lines reversed).

Fig.2. Type (a) coupling illustrated by scalar boson exchanges.

Fig.3. Type (b) coupling illustrated by exchanges of W_1 and W_2 gauge bosons which are mixtures of W_L and W_R.

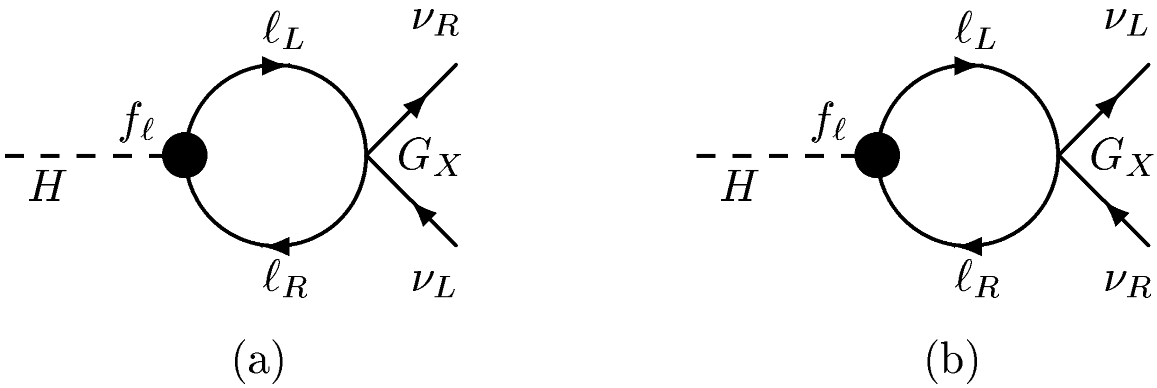
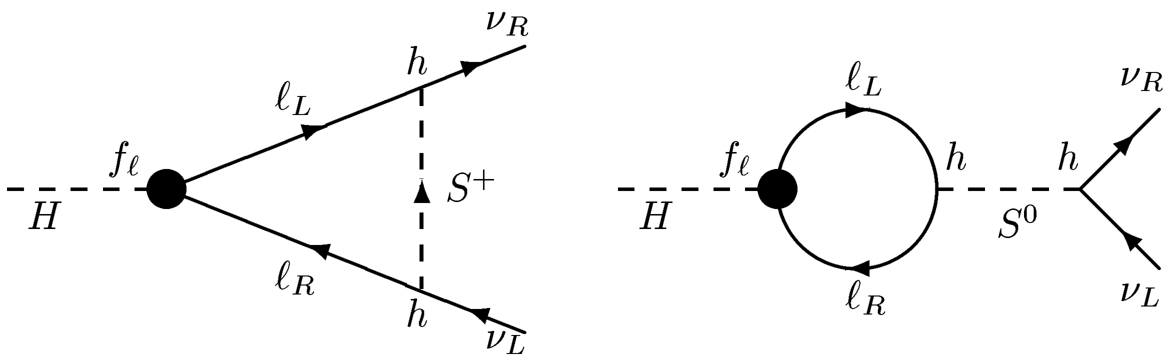


Figure 1:



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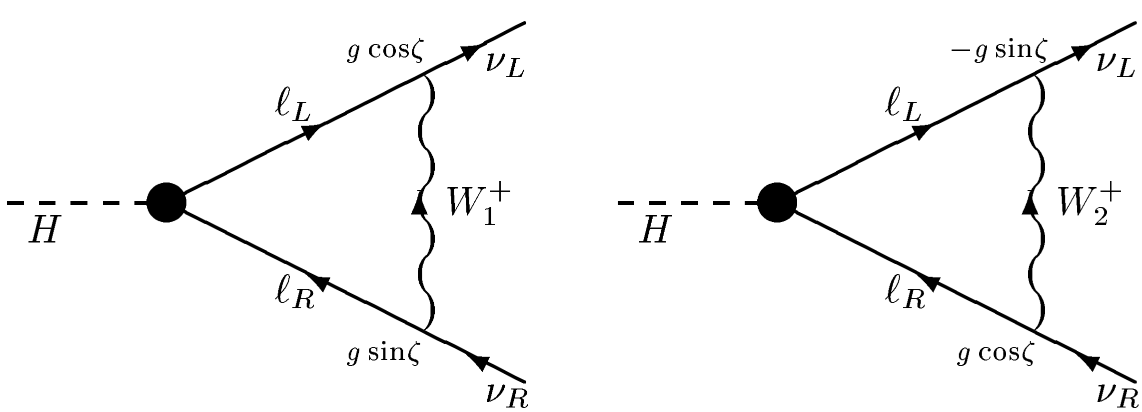

Figure 3: