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Seesaw at LHC

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Abstract: We study the implementation of the type III seesaw in the ordinary nonsupersymmetric SU(5) grand unified theory. This allows for an alternative definition of the minimal SU(5) model, with the inclusion of the adjoint fermionic multiplet. The main prediction of the theory is the light fermionic SU(2) triplet with mass at the electroweak scale. Due to their gauge couplings, these triplets can be produced pair-wise via Drell-Yan, and due to the Majorana nature of the neutral component their decays leave a clear signature of same sign di-leptons and four jets. This allows for their possible discovery at LHC and provides an example of directly measurable seesaw parameters.

Keywords: GUT, Neutrino Physics.

Contents

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1. Introduction

We know today that neutrinos are massive (at least two of them). This implies that the minimal standard model cannot be the whole story. If one is not to change its low energy structure, one is led to a higher dimensional operator [1] simbolically

$$Y_{ij}\frac{l_i l_j H H}{M} \, , \tag{1.1}$$

where l_i is the usual lefthanded leptonic doublet and H the Higgs doublet of the SM. Demanding perturbativity, i.e. $Y_{ij} \lesssim 1$ implies $M \lesssim 10^{14}$ GeV, much below the Planck scale. In other words, gravity does not suffice and one must introduce new heavy states to be integrated out. This is called the seesaw mechanism. There are only three possible ways [2] of implementing the seesaw:

(i) one introduces right-handed neutrinos (at least two) [3];

(ii) one utilizes a heavy SU(2) triplet with an appropriate hypercharge and a small vev [4];

(iii) one introduces heavy triplet fermions with zero hypercharge (at least two of them) [5, 2].

The first two possibilities, called type I and type II are being pursued daily, whereas the third one, called type III, has been very little discussed. The reason could be the necessity of having a number of such triplets, but even that may be weakened, if one accepts a combination of seesaw mechanisms. For example, a triplet and a singlet of fermions suffice to give two massive light neutrinos. Still, at first glance, it seems raher ad-hoc to use such a strange combination.

By itself, the seesaw mechanism sheds no light on neutrino mass, for it is equivalent to the effective operator written above. It is indispensable to have a theory beyond the standard model that predicts at least the scale M, if not the couplings themselves. The natural framework for such a theory is grand unification and the minimal grand unified group, as well known, is based on SU(5). Suppose that one wants to study the minimal such theory without introducing supersymmetry, i.e. the original theory [6] with 24_H and 5_H and the three generations of 10_F and $\overline{5}_F$. This theory is ruled out since the couplings of the standard model do not unify and furthermore neutrinos are massless. Adding I) righthanded neutrinos does not help, unification still fails. When defining the minimal nonsupersymmetric SU(5) one normally resorts thus to the case II), i.e. one adds the 15_H dimensional Higgs. This has been studied recently at length [7].

The third possibility was not studied at all and this is the scope of our work. It amounts to adding a new set of fermions, 24_F, and can be considered as an alternative minimal nonsupersymmetric SU(5) theory. This cures both the unification problem and accounts for a realistic neutrino spectrum. The reason for the latter is that 24_F contains both triplet and singlet fermions, and thus utilizing type III seesaw gives also type I as a bonus.

Although the theory will require substantial fine-tuning, it turns out to be remarkably predictive. The combination of proton decay and unification constraints predicts the mass of the triplet fermion in 24_F and the mass of the triplet scalar in 24_H below TeV, likely to be found at LHC. This is the main and the most interesting prediction of the theory. The stability of the proton prefers these particles to lie as close as possible to M_Z.

The masses of the other particles are also restricted. The colour octets are some 3 to 6 orders of magnitude heavier than the triplets, while the fermionic leptoquarks turn out to lie at the intermediate scale 10^{11-13} GeV.

The low-energy supersymmetric version of this theory would not be as predictive, the reason being that TeV spartners already fix the unification constraints, so that extra intermediate scale multiplets would only spoil it. This is the main reason why we are considering here the non supersymmetric SU(5) model. We will however comment later on the possibility of having a nontypical split supersymmetric scenario.

In short, this theory provides an interesting example of seesaw particles predicted to be detectable at LHC and their Yukawa couplings directly accessible.

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2. The model

The minimal implementation of the type III seesaw in nonsupersymmetric SU(5) requires a fermionic adjoint 24_F in addition to the usual field content 24_H, 5_H and three generations of fermionic 10_F and $\overline{5}_F$. The consistency of the charged fermion masses requires higher dimensional operators in the usual Yukawa sector [8]. One must add the new Yukawa interactions

$$\mathcal{L}_{Y\nu} = y_0^i \left(\bar{5}_F^i\right) \left(24_F\right) 5_H + \frac{1}{M_{Pl}} \left(\bar{5}_F^i\right) \left[y_1^i 24_F 24_H + y_2^i 24_H 24_F + y_3^i Tr\left(24_F 24_H\right)\right] 5_H \ . \quad (2.1)$$

After the SU(5) breaking (for later use $\langle 24_H \rangle = diag\,(2,2,2,-3,-3)\, v/\sqrt{30}$) one obtains the following physical relevant Yukawa interactions for neutrino with the triplet

$\sigma_3^F \equiv \vec{\sigma}_3^F \vec{\tau}$ (type III) and singlet σ_0^F (type I) fermions:

$$\mathcal{L}_{Y\nu} = L_i \left(y_\nu^{(3)i} \sigma_3^F + y_\nu^{(0)i} \sigma_0^F \right) H \ , \tag{2.2}$$

where $y_\nu^{(3)i}$, $y_\nu^{(0)i}$ are two different linear combinations of y_0^i and $y_a^i v/M_{Pl}$ $(a = 1, 2, 3)$. It is clear from the above formula that besides the new appearence of the triplet fermion, the singlet fermion in 24_F acts precisely as the righthanded neutrino; it should not come out as a surprise, as it has the right SM quantum numbers.

Even before we discuss the physical consequences in detail, one important prediction emerges: only two light neutrinos get mass, while the third one remains massless.

In order to discuss the masses of the new fermions, we need the new Yukawa couplings between 24_F and 24_H

$$\begin{aligned} \mathcal{L}_F = {} & m_F Tr\left(24_F^2\right) + \lambda_F Tr\left(24_F^2 24_H\right) \\ & + \frac{1}{M_{Pl}} \Big[a_1 Tr\left(24_F^2\right) Tr\left(24_H^2\right) + a_2 \left(Tr\left(24_F 24_H\right)\right)^2 \\ & \qquad + a_3 Tr\left(24_F^2 24_H^2\right) + a_4 Tr\left(24_F 24_H 24_F 24_H\right) \Big] \ , \end{aligned} \tag{2.3}$$

where we include the higher dimensional terms for the sake of consistency. The masses of the new fermions are

$$m_0^F = m_F - \frac{\lambda_F v}{\sqrt{30}} + \frac{v^2}{M_{Pl}} \left[a_1 + a_2 + \frac{7}{30}\left(a_3 + a_4\right) \right] \ , \tag{2.4}$$

$$m_3^F = m_F - \frac{3\lambda_F v}{\sqrt{30}} + \frac{v^2}{M_{Pl}} \left[a_1 + \frac{3}{10}\left(a_3 + a_4\right) \right] \ , \tag{2.5}$$

$$m_8^F = m_F + \frac{2\lambda_F v}{\sqrt{30}} + \frac{v^2}{M_{Pl}} \left[a_1 + \frac{2}{15}\left(a_3 + a_4\right) \right] \ , \tag{2.6}$$

$$m_{(3,2)}^F = m_F - \frac{\lambda_F v}{2\sqrt{30}} + \frac{v^2}{M_{Pl}} \left[a_1 + \frac{\left(13 a_3 - 12 a_4\right)}{60} \right] \ . \tag{2.7}$$

Next we turn to the bosonic sector of the theory. We will need the potential for the heavy field 24_H

$$V_{24_H} = m_{24}^2 Tr\left(24_H^2\right) + \mu_{24} Tr\left(24_H^3\right) + \lambda_{24}^{(1)} Tr\left(24_H^4\right) + \lambda_{24}^{(2)} \left(Tr\left(24_H^2\right)\right)^2 \ , \tag{2.8}$$

and its interaction with the light fields

$$V_{5_H} = m_H^2 5_H^\dagger 5_H + \lambda_H \left(5_H^\dagger 5_H\right)^2 + \mu_H 5_H^\dagger 24_H 5_H + \alpha \left(5_H^\dagger 5_H\right) Tr\left(24_H^2\right) + \beta 5_H^\dagger 24_H^2 5_H \ . \tag{2.9}$$

It is a straightforward exercise to show that the masses of the bosonic triplet and octet are arbitrary and that one can perform the doublet-triplet splitting through the usual fine-tuning.

We are now fully armed to study the constraints on the particle spectrum by performing the renormalization group analysis.

3. Proton decay and unification constraints

Before getting lost in the numerics, it is useful to recall the failure of the SM unification [9]. The weak and strong couplings actually unify at the scale around 10^{16} GeV, just as in the supersymmetric version of the theory. This is ideal for the proton decay point of view, but the trouble is that the U(1) coupling hits the weak coupling too soon, at the scale of about 10^{12-13} GeV. This indicates that the weak triplets are expected to be light in order to slow down the decrease of the weak coupling. It is easy to see that the fermionic leptoquark makes things worse and, as we show carefully below, they should be as heavy as possible. However splitting its mass from the triplet and the octet fermion masses require the inclusion of higher dimensional terms, which in turn gives an upper bound to the mass of the leptoquark

$$m^F_{(3,2)} \lesssim \frac{M^2_{\rm GUT}}{M_{Pl}} \, . \tag{3.1}$$

For the sake of illustration we present first the one-loop analysis. The renormalization group equations at this level are

$$2\pi\left(\alpha_1^{-1}(M_Z)-\alpha_U^{-1}\right) = \frac{41}{10}\ln\frac{M_{\rm GUT}}{M_Z}+\frac{10}{3}\ln\frac{M_{\rm GUT}}{m^F_{(3,2)}}+\frac{1}{15}\ln\frac{M_{\rm GUT}}{m_T}\, , \tag{3.2}$$

$$2\pi\left(\alpha_2^{-1}(M_Z)-\alpha_U^{-1}\right) = -\frac{3}{2}\ln\frac{M_{\rm GUT}}{M_Z}-\frac{4}{3}\ln\frac{m^F_3}{M_Z}-\frac{1}{3}\ln\frac{m^B_3}{M_Z}+2\ln\frac{M_{\rm GUT}}{m^F_{(3,2)}}\, , \tag{3.3}$$

$$2\pi\left(\alpha_3^{-1}(M_Z)-\alpha_U^{-1}\right) = -\frac{9}{2}\ln\frac{M_{\rm GUT}}{M_Z}-2\ln\frac{m^F_8}{M_Z}-\frac{1}{2}\ln\frac{m^B_8}{M_Z}+\frac{4}{3}\ln\frac{M_{\rm GUT}}{m^F_{(3,2)}}+\frac{1}{6}\ln\frac{M_{\rm GUT}}{m_T}\, , \tag{3.4}$$

where $m^{F,B}_3$, $m^{F,B}_8$, $m^F_{(3,2)}$ and m_T are the masses of weak triplets, colour octets, (only fermionic) leptoquarks and (only bosonic) colour triplets respectively.

From the above a straightforward computation gives

$$\exp\left[30\pi\left(\alpha_1^{-1}-\alpha_2^{-1}\right)(M_Z)\right] = \left(\frac{M_{\rm GUT}}{M_Z}\right)^{84}\left(\frac{\left(m^F_3\right)^4 m^B_3}{M^5_Z}\right)^5\left(\frac{M_{\rm GUT}}{m^F_{(3,2)}}\right)^{20}\left(\frac{M_{\rm GUT}}{m_T}\right) \tag{3.5}$$

$$\exp\left[20\pi\left(\alpha_1^{-1}-\alpha_3^{-1}\right)(M_Z)\right] = \left(\frac{M_{\rm GUT}}{M_Z}\right)^{86}\left(\frac{\left(m^F_8\right)^4 m^B_8}{M^5_Z}\right)^5\left(\frac{M_{\rm GUT}}{m^F_{(3,2)}}\right)^{20}\left(\frac{M_{\rm GUT}}{m_T}\right)^{-1} \tag{3.6}$$

where we still keep all the masses generic, including the one of the leptoquark. As we argued before, its mass must be at most of order $M^2_{\rm GUT}/M_{Pl}$, which simplifies the analysis. From the well known problem in the standard model of the low meeting scale of α_1 and α_2, it is clear that the SU(2) triplet should be as light as possible and the colour triplet as heavy as possible. In order to illustrate the point, take $m^F_3 = m^B_3 = M_Z$ and $m_T = M_{\rm GUT}$. This gives ($\alpha_1^{-1}(M_Z) = 59$, $\alpha_2^{-1}(M_Z) = 29.57$, $\alpha_3^{-1}(M_Z) = 8.55$) $M_{\rm GUT} \approx 10^{15.5}$ GeV. Increasing the triplet masses $m^{F,B}_3$ reduces $M_{\rm GUT}$ dangerously, making at the same time proton decay too fast and higher dimensional operators (needed to correct the second generation charged fermion masses) too small.

The two loop effects [10] relax this somewhat and for the above example of the GUT scale the triplet mass increases to about 500 GeV. Even if one allows $M_{\rm GUT}$ as low as

10^{15} GeV, one gets the triplet mass about few TeV. In this extreme case this particle would not be produced at LHC, but would make leptogenesis easier to function. We should stress though that one is really stretching the parameters in order to avoid this triplet be discovered at LHC.

We can safely conclude that the SU(2) triplets, especially the fermionic one responsible for the type III seesaw, should lie close to M_Z and possibly be detectable at LHC. This is the main result of our work. Simultaneously proton lifetime is predicted to be close to the experimental limit, since the GUT scale must lie below 10^{16} GeV. This makes a strong case for the new generation of proton decay experiments.

From eq. (3.6) one finds the fermion colour octet mass in the range $10^5 - 10^8$ GeV, beyond experimental reach. The bosonic equivalent is actually not constrained by RGE at all and can be as light as M_Z. The solution we described here reminds the so called split supersymmetry [11] in the limit of very large higgsino masses. Due to their absence here the colour octet (the gluino in split supersymmetry) is much heavier that the weak triplet (the wino in split susy).

4. Phenomenological implications

The simplicity of the theory is reflected in the neutrino sector too. As we remarked, one neutrino is massless. This is true up to possible effects of gravity [12], but gravity can only give a mass of about $10^{-5} - 10^{-6}$ eV, effectively zero for all practical purposes. The six complex parameters in (2.2) ($y_\nu^{(3)i}$, $y_\nu^{(0)i}$) become only nine real parameters after the redefinition of the leptonic phases. The model is thus similar to an often imagined situation of two righthanded neutrinos, only here it is predicted by the structure of the theory.

Since the triplet σ_3^F is at the weak scale, the couplings $y_\nu^{(3)i}$ are generically of the order of $10^{-6} - 10^{-7}$ (barring accidental cancellations) , whereas the couplings $y_\nu^{(0)i}$ depend on the mass of the singlet σ_0^F. This mass cannot be determined by the unification constraints, because σ_0^F is a SM gauge singlet. In any case, since one of the masses vanishes, the spectrum of light neutrinos corresponds either to the normal or inverse hierarchy.

The most interesting predictions of the theory regards LHC. The fact that seesaw is achieved through a triplet has a remarkable impact. Since its mass is close to M_Z, its Yukawa couplings are very small and thus if it were a standard model singlet, it would be basically invisible. However, as an SU(2) triplet, it can be easily produced (if $m_3 \lesssim 500\,\mathrm{GeV}$ [13]) through the gauge interactions, and in this sense it behaves very much as a wino without higgsinos. These leptons would be produced in pairs through a Drell-Yan process. The production cross section for the sum of all three possible final states, T^+T^-, T^+T^0 and T^-T^0, can be read from figure2 of ref. [14]: it is approximately 20 pb for 100 GeV triplet mass, and around 50 fb for 500 GeV triplets. The triplets then decay through the same Yukawa couplings (2.2) that enter into the seesaw. More precisely, after the SU(2) breaking the heavy triplet mixes with leptons and thus its main decays become

$$\left(\sigma_3^F\right)^- \to Zl^- \ , \ W^-\nu \tag{4.1}$$

$$\left(\sigma_3^F\right)^0 \to W^+l^- \ , \ Z\nu \ . \tag{4.2}$$

One can estimate

$$\Gamma\left(\sigma_3^F\right) \approx |y_\nu^{(3)}|^2 m_3^F \, , \tag{4.3}$$

which gives $\tau\left(\sigma_3^F\right) \approx 10^{-13} - 10^{-16}$ sec. This leaves a clear signature at LHC, providing an important example of the seesaw mechanism being testable at TeV energies. The clearest signature is the three charged lepton decay of the charged triplet, but it has only a 3% branching ratio. A more promising situation is the decay into two jets with heavy gauge boson invariant mass plus a charged lepton: this happens in approximately 23% of all decays. The main point here is that the neutral component of the triplet decays as often into a charged lepton as into an antilepton due to its Majorana nature (just like right handed neutrinos).

The signatures in this case would be two same charge leptons plus two pairs of jets having the W or Z mass and peaks in the lepton-dijet mass. From the above estimates the cross section for such events is around 2pb (5fb) for 100 (500) GeV triplet mass. Such signatures were suggested originally in the case of the type I seesaw in L-R symmetric theories [15], but are quite generic of the seesaw mechanism. The only difference in the type I case is that the dileptons are accompanied by two jets instead of four for the type III.

The colour octet fermions and bosons must decay before nucleosynthesis. It is easy to see that the bosonic octet decays through $1/M_{Pl}$ Yukawa couplings, which sets a limit $m_8^B \gtrsim 10^5$ GeV. If the fermionic octet is heavier than the bosonic one and the fermionic singlet together, then it can decay into them through the couplings in (2.3). If the opposite is true, the fermionic octet can decay through the exchange of the heavy colour triplet in 5_H, which requires $m_T \lesssim 10^{13}$ GeV. This would be yet another hope for an observable proton decay in the future.

Although somewhat less firmly, the theory also predicts a light scalar triplet σ_3^B from 24_H. If stable, this would provide a classical example of an ideal dark matter candidate (wimp). Can it be stable? The answer is no due to the unavoidable presence of higher dimensional operators that correct the bad SU(5) fermion mass relations [10].

5. Summary and outlook

In this letter we have constructed the minimal predictive SU(5) theory. It is based on the addition of an adjoint fermionic multiplet to the already existing bosonic adjoint and fundamental Higgses. Through the existence of the standard model fermion singlet and weak triplet, one obtains a combination of the type I and type III seesaw and thus one massless neutrino. The scale is too low for thermal leptogenesis [16] to work (for a generic discussion of leptogenesis with type III seesaw see [17]) unless the singlet and triplet fermions are almost degenerate (resonant leptogenesis) as explicitly shown for the case of right-handed neutrinos in [18].

The crucial prediction of the theory are the light weak fermionic and bosonic SU(2) triplets with masses around M_Z.

Probably the most exciting aspect of this theory is that the decays of possibly observable seesaw particles will probe directly the Yukawa Dirac couplings of neutrinos. Thus the neutrino masses are correlated with observable phenomena at the TeV energies. Last but not least, this is simultaneously tied to the prediction of proton decay being observable in the next generation of experiments. We postpone the detailed phenomenological and cosmological analysis of all these issues for the future.

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