Seesaw at LHC

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JSI

Motivation & Outline

- GUT theory with *firm* predictions
- constrained due to small number of parameters
- *testable* at colliders and proton decay experiments

Constraints and predictions

Running

- unification
- proton decay
- split-susy like

ν masses

- type I & III seesaw
- one neutrino massless
- related to decays

Non-Susy $SU(5)$ Revival

Remember the minimal renormalizable Georgi-Glashow $SU(5)$

$$5_H + 24_H + 3 \times (\overline{5}_F + 10_F)$$

ruled out due to:

- lack of gauge coupling unification,
- a wrong mass relation $M_d = M_e$ and
- massless neutrinos.

Cure the theory by:

- adding a single fermionic adjoint representation,
- no ad-hoc family symmetries, no singlets, no XD
- including non-renormalizable terms.

Neutrino masses

Low energy ($d = 5$) Weinberg operator

$$\frac{1}{\Lambda_\nu} LH\, LH$$

Three possible $SU(2)_L \times U(1)_Y$ invariant *tree-level* realizations - seesaw.

$$\boxed{2 \otimes 2 = 3 \oplus 1}$$

I	$L_i H S$	S a fermionic $Y = 0$ weak singlet
II	$L_i \Delta L_j$	Δ bosonic $Y = 1$ triplet
III	$L_i H T$	T a fermionic $Y = 0$ weak triplet

At least two ν's are massive. Need *two* (S,T) or one Δ.

Type I and Type III

Adding a single fermionic 24_f:

$$24_f = (8,1)_0 + \underbrace{(3,1)_0}_{T} + \underbrace{(1,1)_0}_{S} + (3,2)_{5/6} + (\overline{3},2)_{-5/6}$$

under $SU(3)_C \times SU(2)_L \times U(1)_Y$, the two terms

$$\mathcal{L}_{Y_\nu} = L_i (y_T^i T + y_S^i S) H$$

give a mixed type I + III seesaw (rank 2):

$$m_\nu^{ij} = v^2 \left(\frac{y_T^i y_T^j}{m_T} + \frac{y_S^i y_S^j}{m_S} \right)$$

1^{st} prediction: one neutrino is *massless* at tree level

break L due to Majorana nature of the triplets

Yukawas and Neutrino masses

- type I & III seesaw similar to a 2RHN case
- useful parametrization due to Casas & Ibarra
- controlled by a single complex parameter z and U_{PMNS}

Normal hierarchy:

$$\frac{v y_T^{i*}}{\sqrt{2}} = i\sqrt{m_T}\left(U_{i2}\sqrt{m_2^\nu}\cos z \pm U_{i3}\sqrt{m_3^\nu}\sin z\right)$$

Inverse hierarchy:

$$\frac{v y_T^{i*}}{\sqrt{2}} = i\sqrt{m_T}\left(U_{i1}\sqrt{m_1^\nu}\cos z \pm U_{i2}\sqrt{m_2^\nu}\sin z\right)$$

Introducing a Cutoff

When $\Lambda \simeq 100 M_{GUT}$ is introduced, one has additional terms

$$\mathcal{L}_{Yuk} = y_5 5_H^* 10_F \overline{5}_F + y_{10} 10_F 10_F 5_H^* + y_{24} \overline{5}_F 24_F 5_H + \frac{1}{\Lambda}\left[h_5 5_H^* 10_F 24_H \overline{5}_F + \overline{5}_F (y_1 24_F 24_H + \ldots) 5_H + \ldots \right]$$

- Correct for $m_b = m_\tau$ at M_{GUT}
- Obtain light states with almost arbitrary spectrum

$$m_3, m_8, m_{(3,2)} \lesssim M_{GUT}/\Lambda^2$$

Gauge Coupling Unification

New light particles *alter the running*! At one loop, new equations are

$$\exp\left[30\pi\left(\alpha_1^{-1}-\alpha_2^{-1}\right)(M_Z)\right]=\left(\frac{M_{GUT}}{M_Z}\right)^{84}\left(\frac{m_3}{M_Z}\right)^{25}\left(\frac{M_{GUT}}{m_{(3,2)}}\right)^{20}$$

$$\exp\left[20\pi\left(\alpha_1^{-1}-\alpha_3^{-1}\right)(M_Z)\right]=\left(\frac{M_{GUT}}{M_Z}\right)^{86}\left(\frac{m_8}{M_Z}\right)^{25}\left(\frac{M_{GUT}}{m_{(3,2)}}\right)^{20}$$

With a limit from proton decay

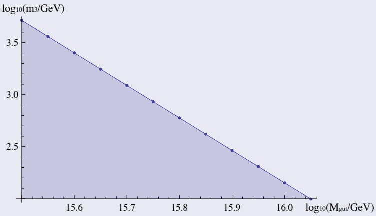
$$M_{GUT}>10^{15.5}\text{GeV},$$

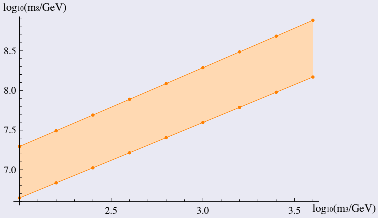
the *only* possible mass pattern is split-susy like:

$$m_3 \ll m_8 \ll m_{(3,2)} \sim M_{GUT}^2/\Lambda$$

A Light Triplet

A two loop calculation gives an upper bound on the triplet mass





$$M_{GUT} = 10^{16}\text{GeV}$$
$$m_3 = 10^2\text{GeV}$$
$$m_8 = 10^7\text{GeV}$$
$$m_{(3,2)} = M_{GUT}^2/\Lambda$$

We predict a

Light $SU(2)$ Triplet!

Light Triplet Phenomenology

Fastest decay channels are electroweak (small Δm_T):

$$T^\pm \to Z\ell^\pm \qquad T^0 \to W^\pm \ell^\mp$$
$$T^\pm \to W^\pm \nu_k \qquad T^0 \to Z\nu_k$$

and controlled by Yukawa couplings (i.e. z parameter). Typically:

$$\Gamma_T \sim m_T |y_T|^2 \Rightarrow \tau_T \lesssim 10^{-12}\text{sec}$$

Possible Direct Detection!

Limits also from tree level FCNC's and flavor violation e.g.: $\mu \to 3e$ and $\mu \to e\gamma$.

Best Decay Channels

No missing energy in the final state. Purely leptonic

$$T^{\pm} \to Z\ell^{\pm} \to \ell^{\pm}\ell'^{+}\ell'^{-}$$

or semi-leptonic

$$T^{\pm} \to Z\ell^{\pm} \to \ell^{\pm} + 2 \text{ jets}$$

$$T^{0} \to W^{\mp}\ell^{\pm} \to \ell^{\pm} + 2 \text{ jets}$$

Usually, $T^{\pm}$ and T^{0} will be produced together

$$T^{\pm}T^{0} \to \ell^{\pm}\ell'^{\pm} + 4 \text{ jets}$$

Same sign dileptons with very low SM background.

Conclusions

- Minimal $SU(5)$ non-susy GUT with a single adjoint
- type I & type III seesaw, one massless neutrino
- predict a light fermionic triplet around TeV
- testable in near future (*LHC*, proton decay searches)
- constrained model (T decays, FCNC)
- (resonant) leptogenesis possible

Mass Spectrum

$$\mathcal{L}_F = m_F \text{tr}\left(24_F^2\right) + \lambda_F \text{tr}\left(24_F^2 24_H\right)$$
$$+\frac{1}{\Lambda}\left[a_1 \text{tr}\left(24_F^2\right)\text{tr}\left(24_H^2\right) + a_2\left(\text{tr}\left(24_F 24_H\right)\right)^2 + a_3 \text{tr}\left(24_F^2 24_H^2\right) + a_4 \text{tr}\left(24_F 24_H 24_F 24_H\right)\right]$$

after $SU(5)$ breaking one has

$$m_3 = m_F - \frac{3\lambda_F M_{GUT}}{\sqrt{30}} + \frac{M_{GUT}^2}{\Lambda}\left[a_1 + \frac{3}{10}\left(a_3 + a_4\right)\right]$$
$$m_8 = m_F + \frac{2\lambda_F M_{GUT}}{\sqrt{30}} + \frac{M_{GUT}^2}{\Lambda}\left[a_1 + \frac{2}{15}\left(a_3 + a_4\right)\right]$$
$$m_{(3,2)} = m_F - \frac{\lambda_F M_{GUT}}{2\sqrt{30}} + \frac{M_{GUT}^2}{\Lambda}\left[a_1 + \frac{(13a_3 - 12a_4)}{60}\right]$$

$$a_i \neq 0 \Rightarrow m_3, m_8, m_{(3,2)} \lesssim M_{gut}/\Lambda^2$$

Production and SM background

Production mechanism of $T^{\pm}T^{0}$ by Drell-Yan:

$$pp \to W^{\pm} + X \to T^{\pm}T^{0} + X$$
$$pp \to (Z, \gamma) + X \to T^{+}T^{-} + X$$

$\mathcal{O}(10^3)$ like-sign dimuons for $\int \mathcal{L}dt = 100\text{fb}^{-1}$ SM background

$$pp \to \left(W^{\pm}Z, W^{\pm}W\pm, t\bar{t}\right) + jets$$

Example

for $m_T = 100(500)$ GeV, LHC will produce

$$1.5 \times 10^{6}(4 \times 10^{3})\, T^{\pm}T^{0} \text{ pairs!}$$

Mass Matrices

Charged:

$$\left(e^c, \mu^c, \tau^c, T^+\right) \cdot \begin{pmatrix} m_e & & & 0 \\ & m_\mu & & 0 \\ & & m_\tau & 0 \\ v y_T^e & v y_T^\mu & v y_T^\tau & m_T \end{pmatrix} \cdot \begin{pmatrix} e \\ \mu \\ \tau \\ T^- \end{pmatrix} + \text{h.c.}$$

Neutral:

$$\frac{1}{2}\left(\nu_i, T^0, S\right) \cdot \begin{pmatrix} 0 & v y_T^i/\sqrt{2} & v y_S^i/\sqrt{2} \\ v y_T^j/\sqrt{2} & m_T & 0 \\ v y_T^j/\sqrt{2} & 0 & m_S \end{pmatrix} \cdot \begin{pmatrix} \nu_j \\ T^0 \\ S \end{pmatrix} + \text{h.c.}$$

- FCNC at tree level
- no GIM