Phenomenology of a light Higgs triplet in $SU(5)$

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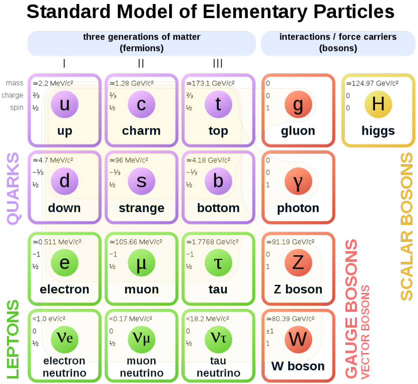
Standard Model of Particle Physics



Source: https://en.wikipedia.org/wiki/Standard_Model

- Gauge Group
  $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Electroweak Sector
  $SU(2)_L \times U(1)_Y \xrightarrow{\langle H\rangle \neq 0} U(1)_{EM}$
  Unification of Electromagnetic and Weak Interaction

Yukawa interactions

$$\mathcal{L}_Y = -Y_e \overline{L} e_R H - Y_d \overline{Q} d_R H - Y_u \overline{Q} u_R \tilde{H} + h.c.$$

Grand Unification $SU(5)$

- Unify all three forces of the Standard Model at $\sim 10^{16}$ GeV
  $\Rightarrow$ explain charge quantization
- $SU(5)$ is simplest choice [Georgi Glashow, 1974]
- Fermions in 5_F and 10_F
- Scalars:

$$5_H = \begin{pmatrix} T^r \\ T^g \\ T^b \\ H^+ \\ H^0 \end{pmatrix} \quad \text{and} \quad \langle 24_H \rangle = v \cdot \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -\frac{3}{2} & 0 \\ 0 & 0 & 0 & 0 & -\frac{3}{2} \end{pmatrix}$$

- SSB:

$$SU(5) \xrightarrow{\langle 24_H \rangle \neq 0} SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{\langle 5_H \rangle \neq 0} SU(3)_C \times U(1)_{EM}$$

Yukawa couplings

$$\mathcal{L}_Y = Y_d 5_H \overline{10}_F 5_F + Y_u 10_F^T C 10_F 5_H + h.c. \tag{1}$$

or in terms of the particles in the SM

$$\begin{aligned}\mathcal{L}_Y = &\frac{Y_d}{\sqrt{2}} \left[\epsilon^{ijk} (\bar{u}_L^C)^k d_R^j - (\bar{u}_L)^i e_R^C + (\bar{d}_L)^i \nu_R^C\right] T^i \\ &+ 4 Y_u \left[\epsilon^{ijk} d_L^{jT} C u_L^k + (e_L^C)^T C (u_L^C)^i\right] T^i \\ &+ \frac{Y_d}{\sqrt{2}} \left[\bar{Q}_L^{\alpha i} d_R^i - \bar{e}_L^C (L_R^C)^\alpha\right] H^\alpha + 4 Y_u \left[Q_L^{\beta i T} \epsilon_{\beta\alpha} C u_L^i\right] H^\alpha\end{aligned}$$

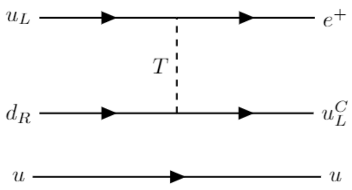
- $B - L$ conservation
- $Y_u, Y_d \sim 10^{-5}$ (from SM)

Phenomenology of the Higgs Triplet

- From proton decay, usually expect triplet to be heavy
- Amplitude for proton decay $\mathcal{M} \sim \frac{Y^2}{m_T^2}$

  $\Rightarrow$ Lifetime of proton $\tau_p \sim \frac{m_T^4}{Y^4 \text{GeV}^5}$
- Experimental lifetime of proton ($p \rightarrow \pi^0 e^+$)

$$\tau_p > 10^{34} yr \approx 10^{65} \frac{1}{\text{GeV}} \text{ [PDG]}$$



- Using $Y \sim 10^{-5} \Rightarrow$ limit for the triplet mass $m_T > 10^{11}$GeV

Idea: If we tune down the triplet-fermion coupling, we can have a much lighter triplet with mass $m_T \sim 1$ TeV!

Effective 5-dimensional Operators

5-dimensional Operators with two fermions and two scalars:

$$\begin{aligned}\mathcal{L}_{\text{5-dim}} \supset & \frac{g_1}{\Lambda} 5_H \overline{10}_F 24_H 5_F + \frac{g_2}{\Lambda} 5_H 24_H \overline{10}_F 5_F \\ & + \frac{g_3}{\Lambda} 10_F^T C 10_F 24_H 5_H + \frac{g_4}{\Lambda} 24_H 10_F^T C 10_F 5_H \\ & + \frac{g_5}{\Lambda} 5_H^\dagger 5_F^T C 5_F 5_H^\dagger\end{aligned}$$

$\Rightarrow$ Split up the couplings with $\langle 24_H \rangle$!

Effective 5-dimensional Operators

All Yukawa couplings in $SU(5)$ together with 5-dimensional Yukawas:

$$
\begin{aligned}
\mathcal{L} \supset & \frac{1}{\sqrt{2}}\left(Y_d + \frac{vg_1}{\Lambda} + \frac{vg_2}{\Lambda}\right)[\epsilon^{ijk}(\bar{u}_L^C)^k d_R^j]\; T^i \\
& - \frac{1}{\sqrt{2}}\left(Y_d - \frac{3vg_1}{2\Lambda} + \frac{vg_2}{\Lambda}\right)[(\bar{u}_L)^i e_R^C - (\bar{d}_L)^i \nu_R^C]\; T^i \\
& + \frac{1}{\sqrt{2}}\left(Y_d + \frac{vg_1}{\Lambda} - \frac{3vg_2}{2\Lambda}\right)[\bar{Q}_L^{\alpha i} d_R^i]\; H^\alpha \\
& - \frac{1}{\sqrt{2}}\left(Y_d - \frac{3vg_1}{2\Lambda} - \frac{3vg_2}{2\Lambda}\right)[\bar{e}_L^C (L_R^C)^\alpha]\; H^\alpha \\
& + \left(4Y_u + \frac{4vg_3}{\Lambda} - \frac{vg_4}{\Lambda}\right) T^i\, [(u_L^C)^{iT} C e_L^+ - (u_L)^{jT} C d_L^k \epsilon^{ijk}] \\
& + \left(4Y_u - \frac{6vg_3}{\Lambda} + \frac{3vg_4}{2\Lambda}\right) H^\alpha [(u_L^C)^{iT} C(\epsilon^{\alpha\beta} Q^{i\beta})]
\end{aligned}
$$

Effective 5-dimensional Operators

$$\mathcal{L} \supset \underbrace{\boxed{\frac{1}{\sqrt{2}}\left(Y_d + \frac{vg_1}{\Lambda} + \frac{vg_2}{\Lambda}\right)}}_{g_{Tqq}} [\epsilon^{ijk}(\bar{u}_L^C)^k d_R^j]\, T^i$$

$$- \underbrace{\boxed{\frac{1}{\sqrt{2}}\left(Y_d - \frac{3vg_1}{2\Lambda} + \frac{vg_2}{\Lambda}\right)}}_{g_{Tql} \text{ and } g'_{Tql}} [(\bar{u}_L)^i e_R^C - (\bar{d}_L)^i \nu_R^C]\, T^i$$

$$+ \underbrace{\boxed{\frac{1}{\sqrt{2}}\left(Y_d + \frac{vg_1}{\Lambda} - \frac{3vg_2}{2\Lambda}\right)}}_{Y'_d} [\bar{Q}_L^{\alpha i} d_R^i]\, H^\alpha$$

$$- \underbrace{\boxed{\frac{1}{\sqrt{2}}\left(Y_d - \frac{3vg_1}{2\Lambda} - \frac{3vg_2}{2\Lambda}\right)}}_{Y'_e} [\bar{e}_L^C (L_R^C)^\alpha]\, H^\alpha$$

$$+ \underbrace{\boxed{\left(4Y_u + \frac{4vg_3}{\Lambda} - \frac{vg_4}{\Lambda}\right)}}_{g_{Tqq} \text{ and } g_{Tql}} T^i\, [(u_L^C)^{iT} C e_L^+ - (u_L)^{jT} C d_L^k \epsilon^{ijk}]$$

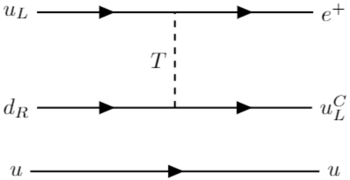
$$+ \underbrace{\boxed{\left(4Y_u - \frac{6vg_3}{\Lambda} + \frac{3vg_4}{2\Lambda}\right)}}_{Y'_u} H^\alpha [(u_L^C)^{iT} C(\epsilon^{\alpha\beta} Q^{i\beta})]$$

There is one relation between the couplings:
$\Rightarrow$ Tune down g_{Tql} arbitrarily, but $g_{Tqq} \sim 10^{-5}$!

Proton Decay in Effective Theory

- New proton decay amplitude

$$\mathcal{M} \sim \frac{g_{Tqq} g_{Tql}}{m_T^2}$$



- With $m_T \sim 1$ TeV, how small do the couplings have to be such that we find a proton lifetime of $10^{34}\text{yr} \approx 10^{65}\text{GeV}^{-1}$?

$$\tau_p \sim \frac{m_T^4 \text{GeV}^{-5}}{g_{Tqq}^2 g_{Tql}^2} \sim \frac{10^{12}\text{GeV}^{-1}}{g_{Tqq}^2 g_{Tql}^2} > 10^{65}\text{GeV}^{-1} \quad (2)$$

$\Rightarrow$ limit for couplings $g_{Tqq} g_{Tql} < 10^{-26}$

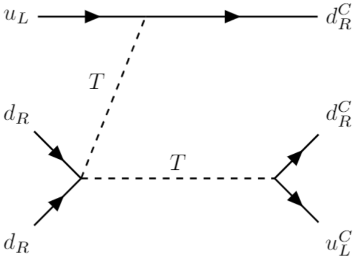
- We can slow down proton decay while keeping a light triplet!
- What about other processes like neutron-antineutron oscillations?

Neutron Oscillations in Effective Theory

- Need a $B-L$ violating operator: $\frac{g_5}{\Lambda} 5_H^\dagger \, 5_F^T C 5_F \, 5_H^\dagger$ Weinberg operator
- Amplitude for neutron oscillations $\mathcal{M} \sim \frac{g_{Tqq}^2 g_5}{\Lambda m_T^4}$
- Oscillation time $\tau_{n\to\bar{n}} \sim \frac{1}{\mathcal{M}}$ estimation

$$\tau_{n\to\bar{n}}^{-1} \sim \frac{10^{-10} g_5}{10^{16}\text{GeV TeV}^4} \text{GeV}^6 \sim g_5 10^{-38}\text{GeV} \sim g_5(10^{14}s)^{-1} \qquad (3)$$

- Compared to experimental value $\tau_{n\to\bar{n}} > 10^8 s$ [PDG] too big!
- Expected neutrino mass $m_\nu < 10^{-3}$ eV

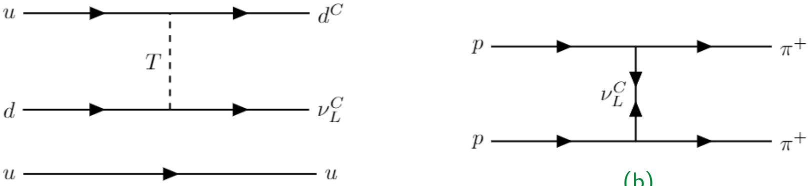


Introducing a Right-handed Neutrino

- New particle ν_R, singlet under $SU(5)$
- New fermion couplings

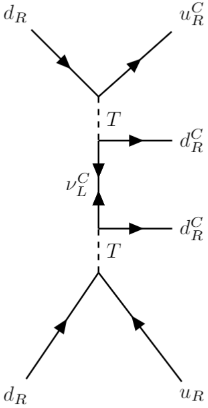
$$\mathcal{L} \supset g^{\nu}\, 5_H \bar{5}_F \nu_L^C + \frac{g}{\Lambda}\, 5_H 24_H \bar{5}_F \nu_L^C + m_R\, \nu_R^T C \nu_R + \text{h.c.}.$$

- New triplet interaction $g_T^{\nu} \bar{d}_R \nu_L^C T$
- New mass term from doublet interaction $g_D^{\nu} \langle H \rangle \bar{\nu}_R \nu_L$
- Seesaw mechanism gives neutrino a mass
- New proton decay channels:



(a) (b)

Neutron Oscillations



- Neutron oscillation time

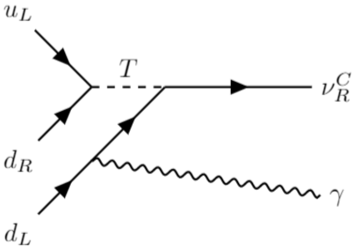
$$\tau_{n-\bar{n}} \sim \frac{m_T^4 m_R}{g_{Tqq}^2 (g_T^\nu)^2} \text{ GeV}^{-6}$$

- For $pp \to \pi^+\pi^+$,

$$\tau_{n-\bar{n}} \sim \frac{m_T^4 m_R}{g_{Tqq}^2 (g_T^\nu)^2} \text{ GeV}^{-6} > 10^7 s \qquad (4)$$

- Neutron-sterile neutrino oscillations if their masses are close enough

Neutron Decay



Summary

1. We can split the coupling of the doublet and triplet with effective operators.
2. Tuning down the triplet couplings, we can slow down proton decay.
3. We can have a Higgs triplet with mass $m_T \sim 1$ TeV.
4. This can also give predictions for neutron oscillations close to the experimental limit.

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