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

Anja Stuhlfauth

IMPRS Young Scientist Workshop

anjast@mpp.mpg.de

with Prof. Dr. Gia Dvali, Otari Sakhelashvili

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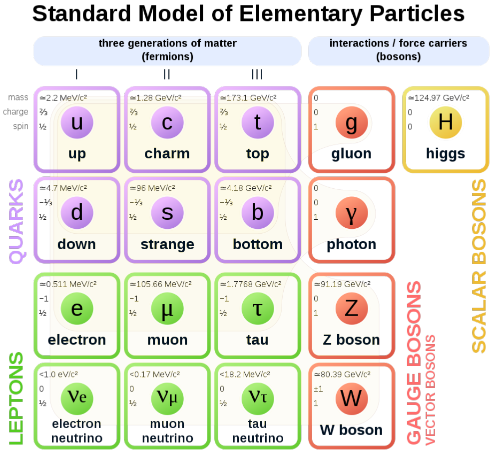
Standard Model of Particle Physics

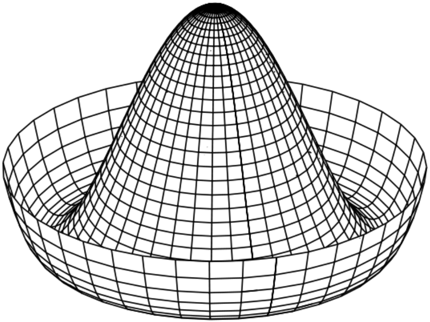
Gauge Group: $SU(3)_C \times SU(2)_L \times U(1)_Y$



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

Higgs-Mechanism

Higgs-Potential (Mexican-Hat):



$\Rightarrow$ Spontaneous Symmetry Breaking in Electroweak Sector:

$$SU(2)_L \times U(1)_Y \xrightarrow{\langle H \rangle \neq 0} U(1)_{EM}$$

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

Higgs-Mechanism

- Higgs doublet VEV: $\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$
- VEV responsible for masses of fermions
- Yukawa interactions

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

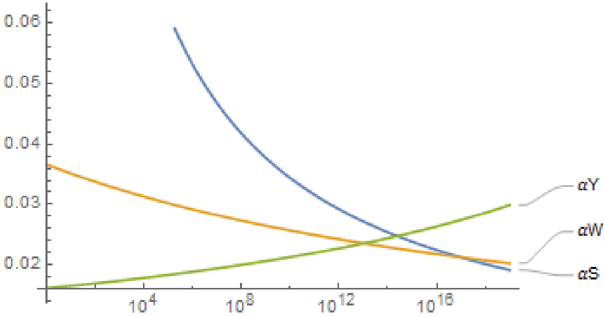
$$\Rightarrow \mathcal{L}_Y \supset -\frac{Y_e v}{\sqrt{2}} \bar{e}_L e_R - \frac{Y_d v}{\sqrt{2}} \bar{d}_L d_R - \frac{Y_u v}{\sqrt{2}} \bar{u}_L u_R$$

- Unification of Electromagnetic and Weak Interaction

Can we unify the strong force with the electroweak?

Running of the Couplings in SM

$\alpha = \frac{g^2}{2\pi}$ depends on Energy Scale via Renormalization Group Equations



$\Rightarrow$ Unification of all three forces at $\sim 10^{16}$ GeV?

$\Rightarrow$ Unification into which group?

Why GUT? Why $SU(5)$?

Standard Model:

- 19 free parameters
- charges fixed only by anomaly cancellation

GUT:

- mass relations for fermions
- explains charges

$SU(5)$:

- $SU(5)$ is simplest choice [Georgi Glashow, 1974]
- $SU(3)_C \times SU(2)_L \times U(1)_Y \subset SU(5)$

Grand Unification $SU(5)$

- SSB:

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

- Structure 5×5 matrix

$$\left[\begin{array}{c|c} SU(3) & \\ \hline & SU(2) \end{array}\right]$$

- $SU(5)$ contains "Leptoquarks": 12 new gauge bosons X,Y and new scalar colour triplet

Grand Unification $SU(5)$

Scalars:

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

Fermions:

$$u_L^i, u_R^i, d_L^i, d_R^i, e_L, e_R, \nu_L \quad \rightarrow \quad 5_F, 10_F$$

Yukawa couplings in $SU(5)$

Yukawa couplings

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

or in terms of the particles in the SM

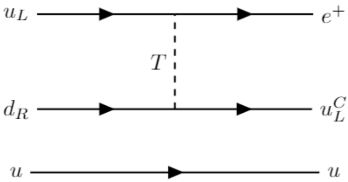
$$\begin{aligned}\mathcal{L}_Y = &\frac{Y_d}{\sqrt{2}} \left[\epsilon^{ijk} (\bar{u}_R^C)^k d_R^j - (\bar{u}_L)^i e_L^C + (\bar{d}_L)^i \nu_L^C\right] T^i \\ &+ 4Y_u \left[\epsilon^{ijk} d_L^{jT} C u_L^k + (e_R^C)^T C (u_R^C)^i\right] T^i \\ &+ \frac{Y_d}{\sqrt{2}} \left[\bar{Q}_L^{\alpha i} d_R^i -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

- $B - L$ conservation
- $Y_u, Y_d \sim 10^{-5}$ (from SM)
- Wrong mass relation down quark and electron
  $\Rightarrow$ Fix with higher-dimensional operators [Ellis, Gaillard]

Phenomenology of the Higgs Triplet

- Amplitude for proton decay $\mathcal{M} \sim \frac{Y^2}{m_T^2}$
- Experimental lifetime of proton $(p \to \pi^0 e^+)$

$$\tau_p > 10^{34} yr \text{ [PDG]}$$



- 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!

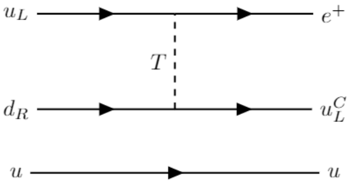
Effective 5-dimensional Operators

- Add 24_H in Yukawa couplings
- $\langle 24_H \rangle$ gives different coefficients for triplet and doublet

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

$$\mathcal{L} \supset g_{Tqq}[\epsilon^{ijk}(\bar{u}_R^C)^k d_R^j]\, T^i - g_{Tql}\,[(\bar{u}_L)^i e_L^C]\, T^i + g'_{Tql}[(\bar{d}_L)^i \nu_L^C]\, T^i$$
$$+ Y'_d[\bar{Q}_L^{\alpha i} d_R^i]\, H^\alpha - Y'_e[\bar{e}_R^C(L_L^C)^\alpha]\, H^\alpha + Y'_u H^\alpha[(u_R^C)^{iT} C(\epsilon^{\alpha\beta} Q_L^{i\beta})]$$

Proton Decay in Effective Theory



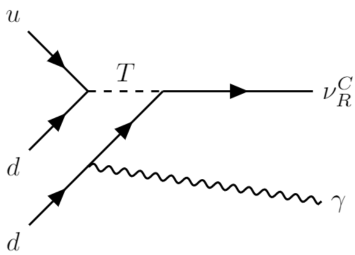
- New proton decay amplitude

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

- With $m_T \sim 1$ TeV, how small do the couplings have to be such that we find a proton lifetime of 10^{34}yr?
  $\Rightarrow$ limit for couplings $g_{Tqq} g_{Tql} < 10^{-26}$
- We can slow down proton decay while keeping a light triplet!
- What else can we predict with this setup?

Outlook

- Neutron-antineutron oscillations
- Introducing a RH neutrino
- Neutron-RH neutrino oscillations
- Neutron Decay $n \to \nu_R^C \gamma$



Summary

1. $SU(5)$ is a beautiful theory
2. Predicts a partner of the Higgs doublet, the triplet
3. Higgs triplet mediates proton decay
4. Instead of heavy triplet tune down the triplet couplings
5. Split the coupling of the doublet and triplet with effective operators

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