On the Origin of a Two-Loop Neutrino Mass Model from $SU(5)$ GUT

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Based on: Saad (to appear)

Outline of the talk

- The Shortcomings of the Standard Model (SM)
- Why $SU(5)$ Grand Unified Theory (GUT)?
- The minimal $SU(5)$ GUT
- Toward a realistic $SU(5)$ GUT
- Possibilities of neutrino mass generation in $SU(5)$ GUT
- Two-loop neutrino mass generation in $SU(5)$ GUT

SM: Beautiful but Flawed Theory

- ν is massless (Experimentally existence of ν mass has been discovered)
- Charged fermion masses and mixings are not predicted by the theory; completely arbitrary free parameters
- Charge quantization is not realized
- No Dark Matter candidate ($\sim$ 4% visible matter, $\sim$ 23% DM)
- No explanation of matter-antimatter asymmetry of the universe
- Many scattered fermions multiples
- No relations between quarks and lepton is realized
- Three different force strengths, not predicted by the theory
- Baryon and Lepton numbers are global symmetries, why?

Why $SU(5)$ GUT?

- GUTs are attractive candidates for physics beyond the SM.
- The simplest choice is the $SU(5)$ GUT (rank 4).
- Unification of the three SM gauge couplings can be achieved.
- Quarks and Leptons of each family are unified into two irreducible representations.
- Electric charge quantization is understood due to non-Abelian nature of the gauge group.
- Anomaly is canceled between the two fermionic multiplets.
- Baryon and Lepton numbers are not conserved, as a consequence proton decays.
- Like other GUT models, in $SU(5)$ there is no uncertainty in breaking pattern, more predictive.

The minimal $SU(5)$ GUT

H. Georgi, Glashow (1979)

- Fermions belong to $\overline{5}_F + 10_F$ dimensional presentation

$$\overline{5}_F = \begin{pmatrix} \nu^0 \\ e^- \\ \overline{d}^{1/3} \\ \overline{d}^{1/3} \\ \overline{d}^{1/3} \end{pmatrix}_L \qquad 10_F = \begin{pmatrix} 0 & e^+ & d^{-1/3} & d^{-1/3} & d^{-1/3} \\ & 0 & u^{+2/3} & u^{+2/3} & u^{+2/3} \\ & & 0 & \overline{u}^{-2/3} & \overline{u}^{-2/3} \\ & & & 0 & \overline{u}^{-2/3} \\ & & & & 0 \end{pmatrix}_L$$

- Symmetry is broken by adjoint representation, 24_H

$$SU(5) \xrightarrow{24_H} SU(3)_C \times SU(2)_L \times U(1)_Y$$

- EW symmetry is broken by fundamental representation, 5_H

$$SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{5_H} SU(3)_C \times U(1)_{em}$$

The minimal $SU(5)$ GUT: Not realistic

- Gauge coupling unification is not realized
- Wrong mass relation at the GUT scale

$$\mathcal{L}_Y = y_1\, \overline{5}_F\, 10_F\, 5^*_H + y_2\, 10_F\, 10_F\, 5_H$$
$$\Rightarrow m_e = m_d,\ m_\mu = m_s,\ m_\tau = m_b$$

- Neutrino is massless
- Proton decay is too rapid, $\tau_p^{SM} \sim 10^{31}$ yrs

Toward a realistic $SU(5)$ GUT

- Non-renormalizable models:

→ Higher dimensional operators

◇ to correct wrong mass relations

* Not enough

→ Particle content needs to be extended as well

◇ for gauge coupling unification

◇ to avoid rapid proton decay

- Renormalizable models:

→ Extended particle content to

◇ correct wrong mass relations

◇ avoid rapid proton decay

* Complete model. Elegant and More natural?

My focus: non-SUSY framework

Non-renormalizable models

- Non-renormalizable models : J.R. Ellis, M.K. Gaillard (1979)

→ Correcting wrong mass relations

$$\mathcal{L} = \mathcal{L}^{ren}_{d\leqslant 4} + \sum_{d=5}^{\infty} \left(\frac{1}{M_P}\right)^{d-4} \mathcal{L}^{unren}_{d}$$

$$\mathcal{L}_5 = \frac{1}{M_P}\, \overline{5}\; 10\; 24_H\; 5^*_H$$

◇ provides correct order correction

→ Additional particles needs to be added to solve the other problems

Renormalizable models: Minimal Extension

- Minimality : number of required additional fields
- $\overline{5} \times 10 = 5 + 45$
- Extended Higgs sector: $5_H + 24_H + 45_H$ H. Georgi, C. Jarlskog (1979)

→ Corrects the bad mass relationship of charged fermions

$$\mathcal{L}_Y = y_1\, \overline{5}\; 10\; 5_H^* + y_2\; 10\; 10\; 5_H + y_3\, \overline{5}\; 10\; 45_H^* + y_4\; 10\; 10\; 45_H$$

→ Unification is realized

→ Proton decay rate can be raised beyond the experimental bound

I. Dorsner, P. F. Perez (2006)

What about Neutrino Mass in $SU(5)$ GUT?

- Still not realistic: Neutrino is massless
- Possibilities:

→ Tree-level

◇ Type I seesaw ✓

◇ Type II seesaw✓

◇ Type III seesaw✓

◇ other Vector-like fermions✓

→ Quantum level

◇ One-loop ✓

◇ Two-loop: ×

Neutrino Mass: Tree-level models

- ◇ Type I seesaw: $1_{F,i} + 45_H$, $(i = 1 - 2)$ (singlets ⇒ uninteresting)
- ◇ Type II seesaw: $15_H + \mathcal{L}_5$ or $15_H + 45_H$ I. Dorsner, P. F. Perez (2006)
- ◇ Type III seesaw: $24_F + \mathcal{L}_5$ or $24_F + 45_H$ B. Bajc, G. Senjanovic (2006)

- ◇ other Vector-like fermions:

→ scalars + fermions : $1_{F,i} + 5'_F + \overline{5}'_F + 50_H$, $(i = 1 - 2)$

Dorsner, Fajfer, Mustac (2014)

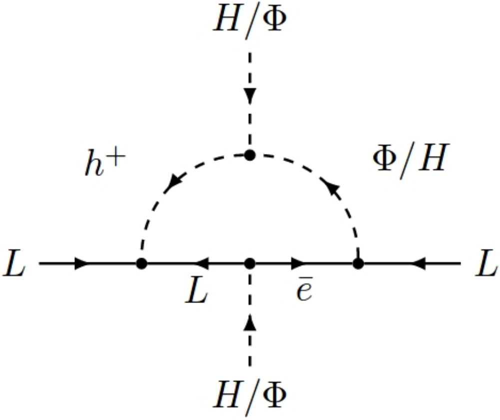
→ fermions : $5'_F + \overline{5}'_F + 24_{F,i}$, $(i = 1 - 2)$ Dorsner, Fajfer, Mustac (2014)

→ fermions : $5'_{F,i} + \overline{5}'_{F,i} + 24_F$, $(i = 1 - 3)$ Perez, Gross, Murgui (2018)

Neutrino Mass: Quantum correction

- One-loop: $10_H + 45_H$ Perez, Murgui (2016)

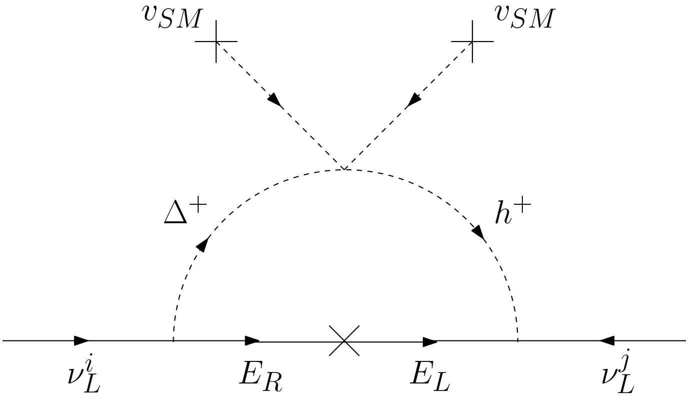
$$V_{SU(5)} \supset \lambda\, \overline{5}_F \overline{5}_F 10_H + \overline{5}_F 10_F \left(Y_1 5_H^* + Y_2 45_H^* \right) - \mu\, 5_H 45_H 10_H^*$$



Neutrino Mass: Quantum correction

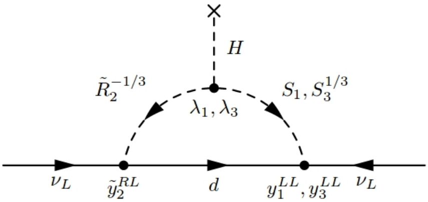
- One-loop: $3 \times \overline{5}'_F + 45_H + 10_H$ or $3 \times \overline{5}'_F + 70_H + 10_H$

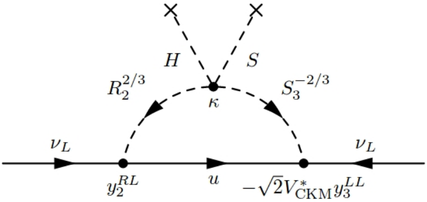
Kumericki, Mede, Picek (2017)



Neutrino Mass: Quantum correction

→ One-loop: $45_H + 10_H$ or $45_H + 15_H$ Dorsner, Fajfer, Kosnik (2017)





LEPTOQUARK	$(SU(3), SU(2), U(1))$	$SU(5)$
S_3	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	$\overline{\mathbf{45}}$
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$	$\overline{\mathbf{45}}$,
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	$\mathbf{10}$, $\mathbf{15}$
$\tilde{S}_1$	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	$\mathbf{45}$
S_1	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	$\overline{\mathbf{5}}$, $\overline{\mathbf{45}}$,

Two-loop Neutrino Mass in $SU(5)$?

- Two-loop origin?

- Model building requirement:

→ What is the minimal realistic model?

◇ Renormalizable Model : $\mathbf{45}_H + ???$

- All possible Yukawa interactions:

○ $\overline{\mathbf{5}} \times \mathbf{10} = \mathbf{5} + \mathbf{45}$

○ $\mathbf{10} \times \mathbf{10} = \mathbf{5} + \mathbf{45} + \mathbf{50}$

Minimal Model: Two-loop Origin for Neutrino Mass

- Extending the minimal model with: $40_H + 50_H$

$$40_H = \eta_1(1,2,-\tfrac{3}{2}) \oplus \eta_2(\overline{3},1,-\frac{2}{3}) \oplus \eta_3(3,2,\frac{1}{6}) \oplus \eta_4(\overline{3},3,-\frac{2}{3}) \oplus \eta_5(\overline{6},2,\frac{1}{6}) \oplus \eta_6(8,1,1)$$

$$50_H = \chi_1(1,1,-2) \oplus \chi_2(3,1,-\frac{1}{3}) \oplus \chi_3(\overline{3},2,-\frac{7}{6}) \oplus \chi_4(6,1,\frac{4}{3}) \oplus \chi_5(\overline{6},3,-\frac{1}{3}) \oplus \chi_6(8,2,\frac{1}{2})$$

- Relevant for generating neutrino mass:

$$\phi^- \subset \phi_1 \; (1,2,-\tfrac{1}{2}) \subset 5^*_H/45^*_H$$

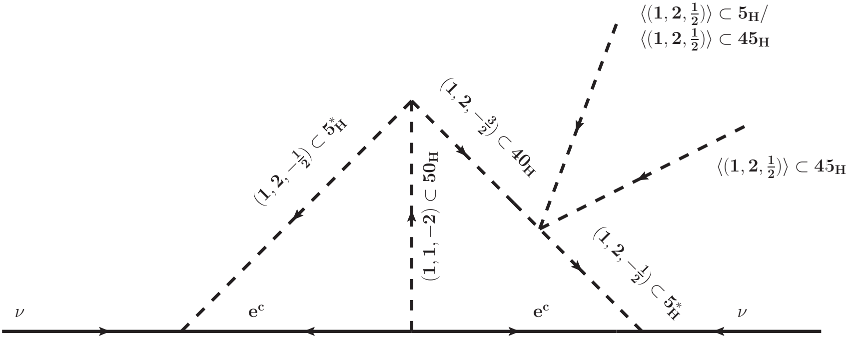
$$\eta^- \subset \eta_1 \; (1,2,-\tfrac{3}{2}) \subset 40_H$$

$$\chi^{--} \subset \chi_1 \; (1,1,-2) \subset 50_H$$

Two-loop Diagram

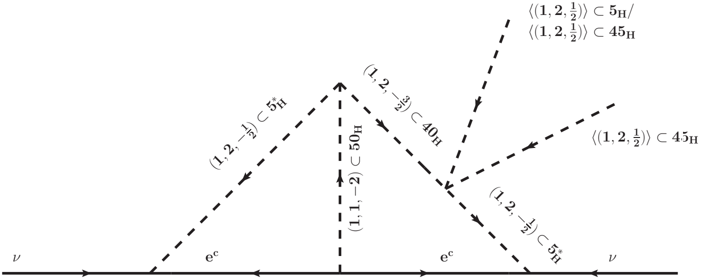
- Relevant part of the Lagrangian:

$$\mathcal{L}_{SU(5)} \supset y\, \overline{5}_F\, 10_F\, 5^*_H + f\, 10_F\, 10_F\, 50_H$$
$$\mathcal{V}_{SU(5)} \supset \mu\, 5_H\, 40^*_H\, 50_H + \lambda\, 5_H\, 5_H\, 40_H\, 45_H$$



Two-loop Neutrino Mass

$$m_\nu \sim \frac{1}{(16\pi^2)^2}\frac{v_{SM}^2\,\lambda\,\mu}{m_{max}^2}y^2 f$$

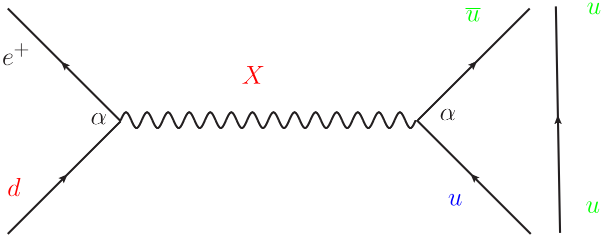


$v_{SM} \sim 174\,GeV, \lambda \sim 1$

$y \sim 10^{-2}, f \sim 1$ $\quad\Rightarrow m_\nu \sim 0.1eV$

$\mu, m_{max} \sim 10^6\,GeV$

Proton Life Time



$$\text{life time}, \tau \sim \frac{M_X^4}{\alpha^4 \, m_p^5}$$

- Gauge bosons: $(3, 2, -\frac{5}{6}) + (\overline{3}, 2, \frac{5}{6})$
- Experimentally bounds:
  $\Rightarrow \tau > 1.6 \times 10^{34}$ years
  $\Rightarrow M_X \gtrsim 5 \times 10^{15}$ GeV

Proton Decay by Scalars

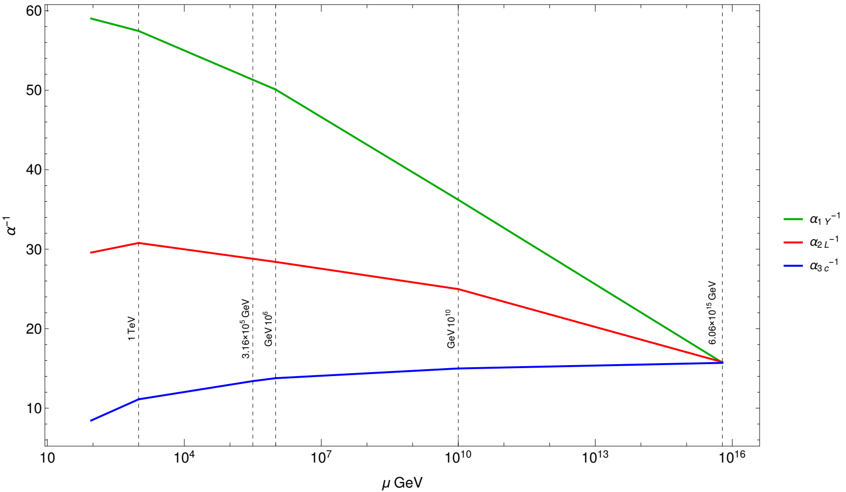
- If condition like $M_{GUT} \gtrsim 5 \times 10^{15}$ GeV can be achieved, then proton decay is mainly caused by the scalars, if they are light.
- Note, light scalars must be present in these theories for gauge coupling unification constraints.
- The scalars that mediate proton decay in our theory are:

$$\phi_2(3,1,-\frac{1}{3}) \subset \mathbf{5}_H$$

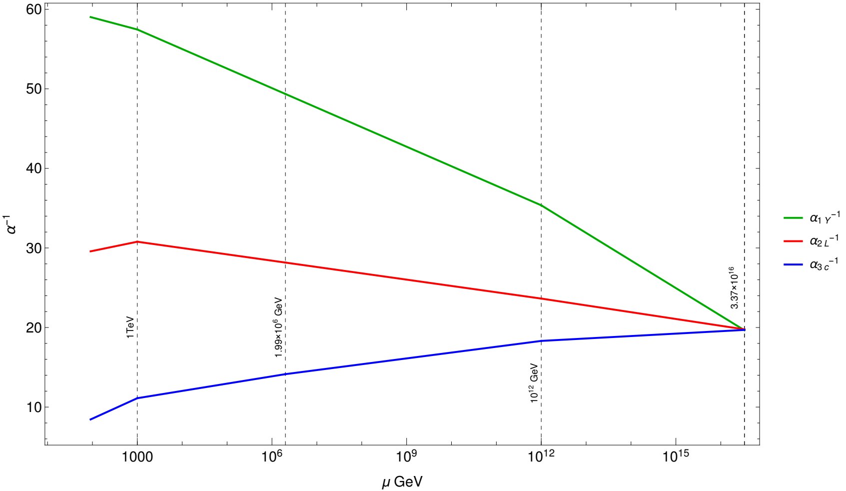
$$\Sigma_2(3,1,-\frac{1}{3}),\ \Sigma_3(\overline{3},1,\frac{4}{3}),\ \Sigma_5(3,3,-\frac{1}{3}) \subset \mathbf{45}_H$$

$$\chi_2(3,1,-\frac{1}{3}) \subset \mathbf{50}_H$$

- To suppress proton decay one would expect these fields to have mass of the order of the GUT scale or somewhat lower.



scale	fields
1 TeV	$\Sigma_{1,7},\ \Phi_2,\ \eta_{3,4,5},\ \chi_1$
3.16×10^5 GeV	Φ_3
10^6 GeV	$\eta_{1,2,6}$
$\{\alpha_{GUT}^{-1},\ M_{GUT}\}$	$\{15.8,\ 6.0 \times 10^{15}\, GeV\}$



scale	fields
1 TeV	$\Sigma_{1,7},\ \Phi_2,\ \eta_{3,4,5},\ \chi_1$
1.99×10^6 GeV	Φ_3
10^{12} GeV	$\eta_{1,2,6}$
$\{\alpha_{GUT}^{-1},\ M_{GUT}\}$	$\{19.8,\ 3.4\times10^{16}\,GeV\}$

Proposed Model: Summary

- Two-loop neutrino mass in the context of $SU(5)$ GUT
- Renormalizable model
- 45_H is needed to correct the wrong charged fermion mass relationships
- 45_H also plays important role in neutrino mass generation
- Additional required Higgs fields are: $40_H + 50_H$
- Fields responsible for neutrino mass generation play important role in unification and to avoid too rapid proton decay
- Proton decay can be observed in near future (consistent with unification)

THANK YOU!