Minimal SU(5) GUTs with vectorlike fermions

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Based on: - arXiv:2307.xxxxx (Stefan Antusch, Kevin Hinze, Shaikh Saad)

Georgi-Glashow model

- Fermions

$$\overline{\mathbf{5}}_{\mathbf{F}} = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix} , \quad \mathbf{10}_{\mathbf{F}} = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix} .$$

- Scalars

$$\mathbf{24}_{\mathbf{H}} : \quad \mathrm{SU}(5) \xrightarrow{\langle \mathbf{24}_{\mathbf{H}} \rangle} \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

$$\mathbf{5}_{\mathbf{H}} : \quad \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \xrightarrow{\langle \mathbf{5}_{\mathbf{H}} \rangle} \mathrm{SU}(3)_C \times \mathrm{U}(1)_{em}$$

Georgi, Glashow (1974)

Georgi-Glashow model

- No gauge coupling unification
  - Introduce intermediate-scale particles
- Massless neutrinos
  - $n \times \mathbf{1_F}$: type I seesaw
  - $1 \times \mathbf{15_H}$: type II seesaw
    Doršner, Perez (2005)
  - $1 \times \mathbf{24_F}$: hybrid type III + I seesaw
    Bajc, Senjanović (2007); Perez (2007)
  - Loop-level
    Perez, Murgui (2016); Saad (2019); Doršner, Saad (2019)
- "Bad-mass-relation":

$$\mathbf{Y_e} = \mathbf{Y_d}^T \quad \Rightarrow \quad \boxed{y_\tau/y_b = 1\,, \;\; y_\mu/y_s = 1\,, \;\; y_e/y_d = 1}$$

Solutions to "bad-mass-relation"

- Higher dimensional operators
  Ellis, Gaillard (1979)

- Second electroweak Higgs doublet embedded in $\mathbf{45_H}$
  Georgi, Jarlskog (1979)

$$\mathbf{M_d} = \mathbf{Y_5}\langle \mathbf{5_H}\rangle + \mathbf{Y_{45}}\langle \mathbf{45_H}\rangle, \qquad \mathbf{M_e} = \mathbf{Y_5^T}\langle \mathbf{5_H}\rangle - 3\mathbf{Y_{45}^T}\langle \mathbf{45_H}\rangle$$

- Vectorlike fermions

$\mathbf{5_F} + \overline{\mathbf{5}}_\mathbf{F}$

- GG model + $\mathbf{5_F} + \overline{\mathbf{5}}_\mathbf{F}$

- $\mathcal{L} \supset \mathbf{Y^u_{ij}}\, \mathbf{10_{F\,i} 10_{F\,j} 5_H} + \mathbf{Y^d_{ia}}\, \mathbf{10_{F\,i}} \overline{\mathbf{5}}_{\mathbf{F\,a}} \mathbf{5^*_H} + \overline{\mathbf{5}}_{\mathbf{F\,a}} (\mu_\mathbf{a} + \eta_\mathbf{a} \mathbf{24_H}) \mathbf{5_{F\,4}}$

- $\mathbf{M_D} = \begin{pmatrix} \langle \mathbf{5_H} \rangle \mathbf{Y^d} & \mathbf{M^D_i} \\ 0 & \mathbf{M^D_4} \end{pmatrix}, \qquad \mathbf{M_E} = \begin{pmatrix} \langle \mathbf{5_H} \rangle \mathbf{Y^d}^\mathbf{T} & 0 \\ \mathbf{M^E_i} & \mathbf{M^E_4} \end{pmatrix},$

  where $\mathbf{M^D_a} = \mu_\mathbf{a} - 2\eta_\mathbf{a} \langle \mathbf{24_H} \rangle, \qquad \mathbf{M^D_a} = \mu_\mathbf{a} + 3\eta_\mathbf{a} \langle \mathbf{24_H} \rangle$

Babu, Bajc, Tavartkiladze (2012)

Doršner, Fajfer, Mustać (2012)

$\mathbf{10_F} + \overline{\mathbf{10}}_\mathbf{F}$ / $\mathbf{15_F} + \overline{\mathbf{15}}_\mathbf{F}$

- Similar solution to "bad-mass-relation"
- $\mathbf{10_F}(\mathbf{15_F}) \supset \Sigma_3(\mathbf{3}, \mathbf{2}, 1/6)$
- $\mathbf{24_H} \supset \phi_1(\mathbf{1}, \mathbf{3}, 0) + \phi_8(\mathbf{8}, \mathbf{1}, 0)$
- $\Sigma_3 + \phi_1 + \phi_8$ suffice to achieve high GUT scale

  $M_{\mathrm{GUT}} > 10^{16}$ GeV $\Rightarrow \tau_p \sim \frac{M_{\mathrm{GUT}}^4}{\alpha_{\mathrm{GUT}}^2 m_p^5} \sim 10^{36} - 10^{37}$ years

$\mathbf{5_F} + \overline{\mathbf{5}}_\mathbf{F}$

- GG model + $\mathbf{5_F} + \overline{\mathbf{5}}_\mathbf{F}$

Case	Neutrino mass	Leptogenesis	Proton lifetime (years)
$2 \times \mathbf{1_F}$	✓	✓	10^{28}
$2 \times \mathbf{24_F}$	✓	✓/✗	$10^{33}/10^{39}$
$1 \times \mathbf{15_H}$	✓	✗	10^{31}
$2 \times \mathbf{15_H}$	✓	✓	10^{35}

$\mathbf{5_F} + \overline{\mathbf{5}}_\mathbf{F}$

- GG model + $\mathbf{5_F} + \overline{\mathbf{5}}_\mathbf{F}$

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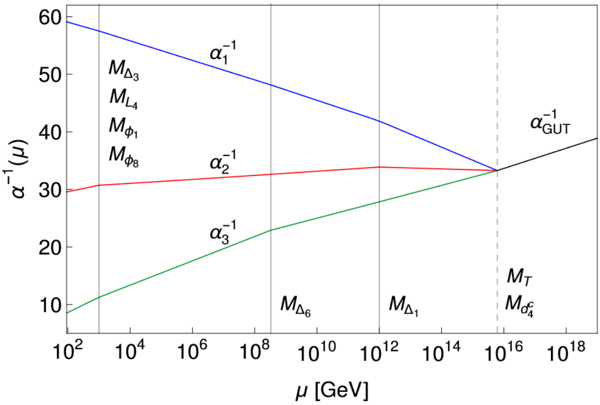
$1 \times \mathbf{15_H}$	✓	✗	10^{31}
$2 \times \mathbf{15_H}$	✓	✓	10^{35}

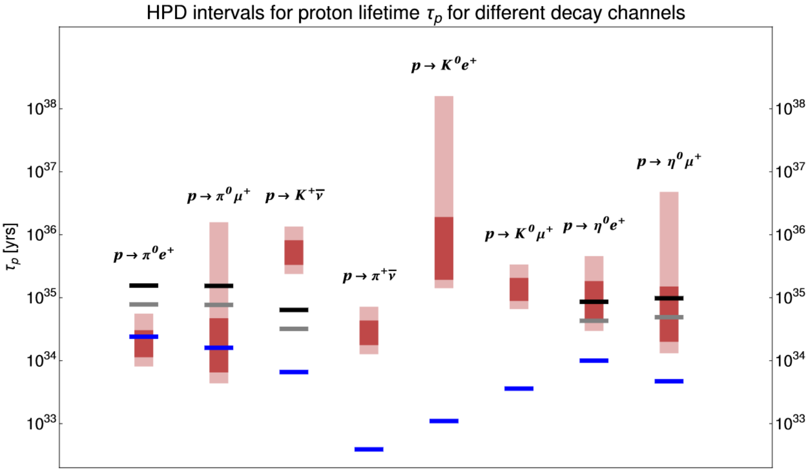
Testable model

- GG model $+ \mathbf{5_F} + \mathbf{\overline{5}_F} + 2 \times \mathbf{15_H}$

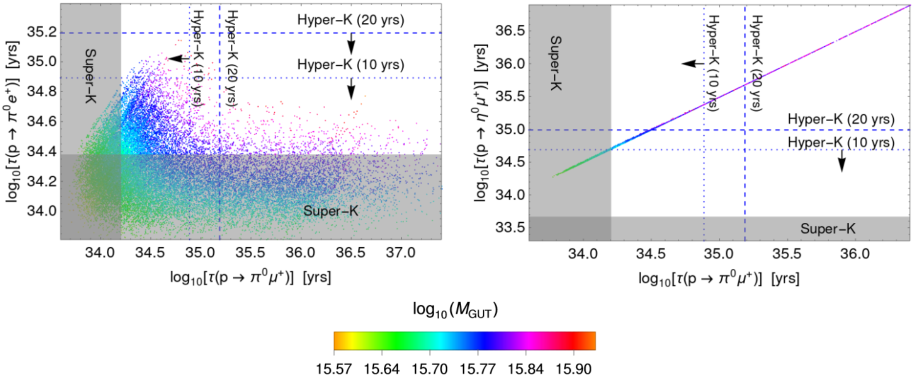
- $M_{\mathrm{GUT}} < 7 \times 10^{15}$ GeV $\Rightarrow$ $\tau_p \lesssim 10^{35}$ years



Proton decay channels



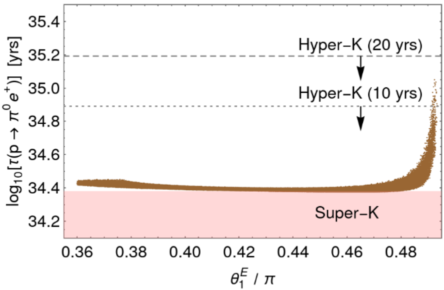
Relations between proton decay channels

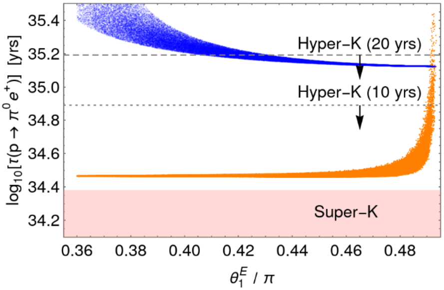


Can proton decay be rotated away?

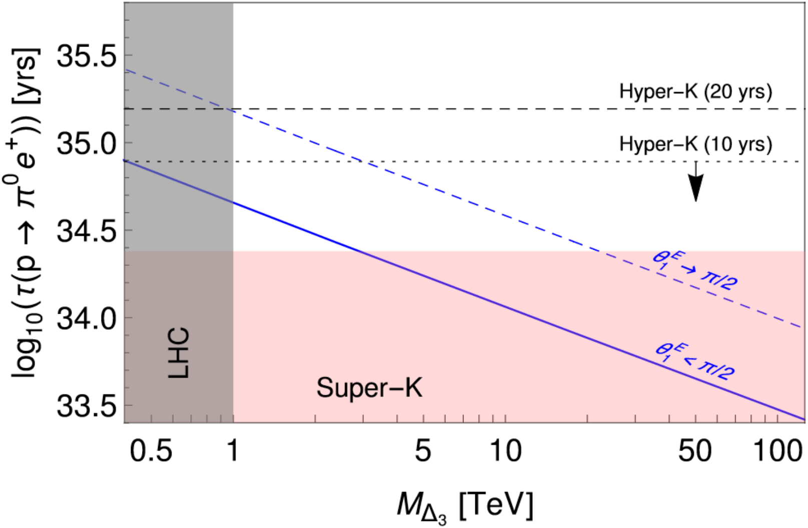
$$\mathbf{M_D} = \begin{pmatrix} m_1 & 0 & 0 & M_1^D \\ 0 & m_2 & 0 & M_2^D \\ 0 & 0 & m_3 & M_3^D \\ 0 & 0 & 0 & M_4^D \end{pmatrix}, \quad \mathbf{M_E} = \begin{pmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ M_1^E & M_2^E & M_3^E & M_4^E \end{pmatrix}$$

Define $\tan(\theta_i^{D/E}) \equiv M_i^{D/E}/M_4^{D/E}$

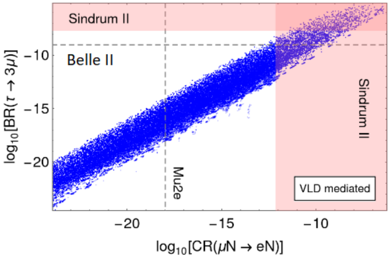


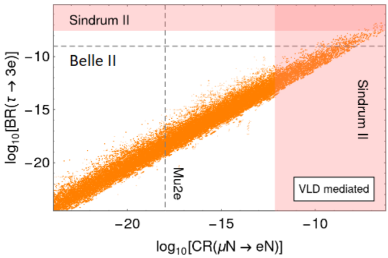


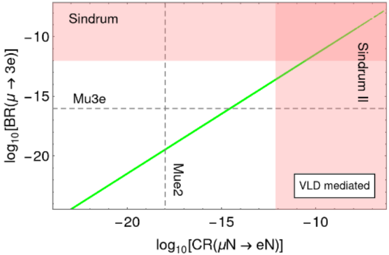
LQ mass vs proton decay



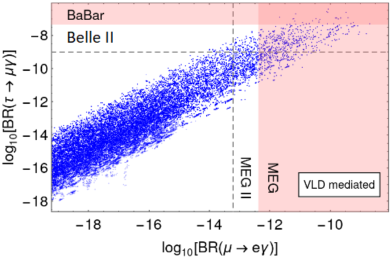
Flavor violation

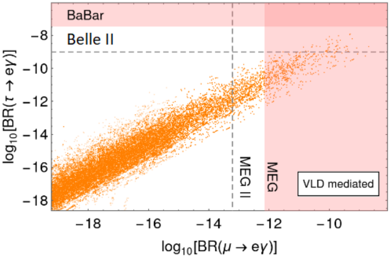




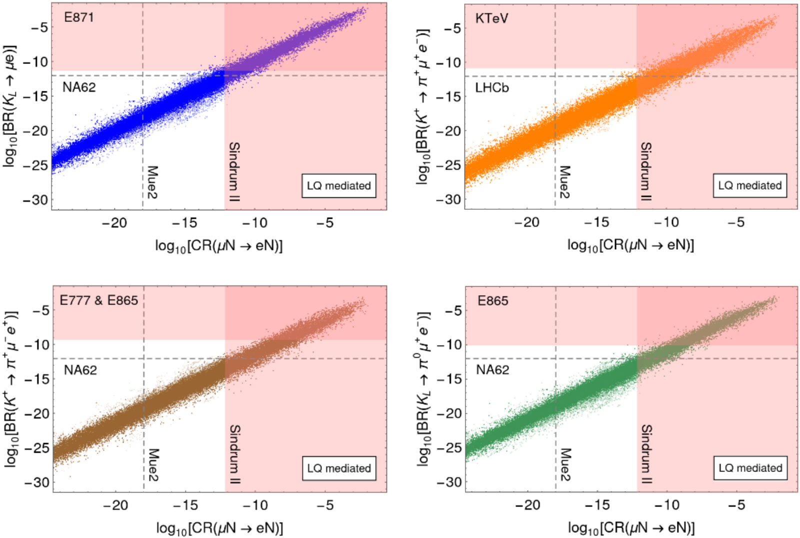


Flavor violation





Flavor violation



Conclusion

- VLFs provide an interesting solution to the the "bad-mass-relation" of the GG model.

- The addition of $\mathbf{10_F} + \overline{\mathbf{10}}_\mathbf{F}$ or $\mathbf{15_F} + \overline{\mathbf{15}}_\mathbf{F}$ allows to build viable models which are however not fully testable by planed experiments.

- The addition of $\mathbf{5_F} + \overline{\mathbf{5}}_\mathbf{F}$ in combination with $2 \times \mathbf{15_H}$ gives a highly predictive model which will be fully tested by upcoming proton decay experiments. Moreover, future flavor violation experiments provide additional possibilities to test this model.

$\mathbf{10_F} + \overline{\mathbf{10}}_\mathbf{F}$

- GG model + $\mathbf{10_F} + \overline{\mathbf{10}}_\mathbf{F}$

- $\mathcal{L} \supset \mathbf{Y^u_{ab}}\, \mathbf{10_{F\,a}} \mathbf{10_{F\,b}} \mathbf{5_H} + \mathbf{Y^d_{ai}}\, \mathbf{10_{F\,a}} \overline{\mathbf{5}}_{\mathbf{F\,i}} \mathbf{5^*_H}$
  $+ \overline{\mathbf{10}}_{\mathbf{F\,4}} (\mu_\mathbf{a} + \eta_\mathbf{a} \mathbf{24_H}) \mathbf{10_{F\,a}}$

- $$\mathbf{M_D} = \Big(\underbrace{\langle \mathbf{5_H} \rangle \mathbf{Y^d}}_{4\times3} \quad \underbrace{\mathbf{M^D_a}}_{4\times1} \Big), \qquad \mathbf{M_E} = \begin{pmatrix} \langle \mathbf{5_H} \rangle \mathbf{Y^d}^\mathbf{T} \big\}_{3\times4} \\ \mathbf{M^E_a} \big\}_{1\times4} \end{pmatrix},$$
  where $\mathbf{M^D_a} = \mu_a + \frac{1}{4}\eta_a \langle \mathbf{24_H} \rangle$, $\quad \mathbf{M^E_a} = \mu_a + \frac{3}{2}\eta_a \langle \mathbf{24_H} \rangle$

$\mathbf{15_F} + \overline{\mathbf{15}}_\mathbf{F}$

- GG model + $\mathbf{15_F} + \overline{\mathbf{15}}_\mathbf{F}$

- $\mathbf{15_F} = \Sigma_1(\mathbf{1}, \mathbf{3}, 1) + \Sigma_3(\mathbf{3}, \mathbf{2}, \frac{1}{6}) + \Sigma_6(\mathbf{6}, \mathbf{1}, -\frac{2}{3})$

- $\mathcal{L} \supset \mathbf{Y^u_{ij}}\, \mathbf{10_{F\,i}} \mathbf{10_{F\,j}} \mathbf{5_H} + \mathbf{Y^d_{ij}}\, \mathbf{10_{F\,i}} \overline{\mathbf{5}}_{\mathbf{F\,j}} \mathbf{5^*_H} + \mathbf{Y^a_i}\, \mathbf{15_F} \overline{\mathbf{5}}_{\mathbf{F\,i}} \mathbf{5^*_H}$
  $+ \mathbf{Y^c_i}\, \mathbf{10_{F\,i}} \overline{\mathbf{15}}_\mathbf{F} \mathbf{24_H} + (\mathbf{m_{15}} + \mathbf{y}\, \mathbf{24_H})\, \overline{\mathbf{15}}_\mathbf{F} \mathbf{15_F} + \mathrm{h.c.}$

- $\mathbf{M_D} = \begin{pmatrix} \langle \mathbf{5_H} \rangle \mathbf{Y^d} & \langle \mathbf{24_H} \rangle \mathbf{Y^c} \\ \langle \mathbf{5_H} \rangle \mathbf{Y^a} & \mathbf{M_{\Sigma_3}} \end{pmatrix}, \qquad \mathbf{M_e} = \langle \mathbf{5_H} \rangle \mathbf{Y^d}^T$

$\Rightarrow \mathbf{M_d} \approx \langle \mathbf{5_H} \rangle \left(\mathbf{Y^d} + \delta\, \mathbf{Y^c Y^a} \right), \qquad \mathbf{M_e} = \langle \mathbf{5_H} \rangle \mathbf{Y^d}^T$

Doršner, Saad (2019)

Proton decay

$$\Gamma(p \to \pi^0 e^+_\beta) = \frac{m_p \pi}{2}\left(1 - \frac{m_\pi^2}{m_p^2}\right)^2 \frac{\alpha^2_{\rm GUT}}{M^4_{\rm GUT}} A_L^2$$
$$\times\left(A_{SL}^2 |c(e^c_\alpha, d)\langle\pi^0|(ud)_L u_L|p\rangle|^2 + A_{SR}^2 |c(e_\alpha, d^c)\langle\pi^0|(ud)_R u_L|p\rangle|^2\right),$$

$$c(e^c_\alpha, d_\beta) = (E^*_R)_{i\alpha}(D^*_L)_{i\beta} + (E^*_R)_{i\alpha}(U^*_L)_{i1}(U_L)_{i1}(D^*_L)_{i\beta} + (E^*_R)_{4\alpha}(D^*_L)_{4\beta},$$
$$c(e_\alpha, d^c_\beta) = (E^*_L)_{a\alpha}(D^*_R)_{a\beta},$$

$$\mathbf{M_U} = U\,\mathbf{M_U^{\rm diag}}\,U^T, \qquad \mathbf{M_D} = D_L\,\mathbf{M_D^{\rm diag}}\,D_R^\dagger,$$
$$\mathbf{M_E} = E_L\,\mathbf{M_E^{\rm diag}}\,E_R^\dagger, \qquad \mathbf{M_N} = N^*\,\mathbf{M_N^{\rm diag}}\,N^\dagger.$$

Particle masses