

Minimal SU(5) GUTs with vectorlike fermions

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Joint annual meeting of SPS and ÖPG 2023
September 5, 2023

Based on: - [arXiv:2308.08585](https://arxiv.org/abs/2308.08585) (Stefan Antusch, Kevin Hinze, Shaikh Saad)

Unification

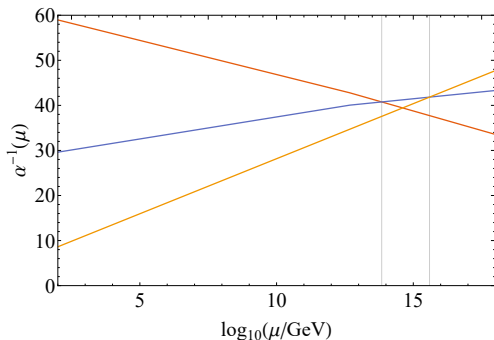
- ❑ 17th century: Unification of celestial and terrestrial gravity
- ❑ 19th century: Unification of electricity and magnetism
- ❑ 20th century: Unification of space and time as well as mass and energy
- ❑ 20th century: Unification of QED and the weak nuclear force

Grand Unified Theory?

Unification of the electroweak
and strong nuclear force

Motivation

- Unification of gauge couplings
- 5 different matter field representations
- Electromagnetic charge quantization
- Cancellation of gauge anomalies



Predictions

- Proton decay
- Cosmological consequences (topological defects, gravitational waves, baryogenesis, ...)
- Low energy phenomenology (neutrino properties, light relics, flavor violation, ...)

Georgi-Glashow model

□ $G_{\text{SM}} = \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y \subset \text{SU}(5)$

□ Fermions

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

□ Scalars

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

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

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”:

$$\mathbf{Y}_e = \mathbf{Y}_d^T \Rightarrow \boxed{y_\tau/y_b = 1, \quad y_\mu/y_s = 1, \quad y_e/y_d = 1}$$

Solutions to “bad-mass-relation”

- Higher dimensional operators

Ellis, Gaillard (1979)

- Second electroweak Higgs doublet embedded in $\mathbf{45}_H$

Georgi, Jarlskog (1979)

$$\mathbf{M}_d = \mathbf{Y}_5 \langle \mathbf{5}_H \rangle + \mathbf{Y}_{45} \langle \mathbf{45}_H \rangle, \quad \mathbf{M}_e = \mathbf{Y}_5^T \langle \mathbf{5}_H \rangle - 3\mathbf{Y}_{45}^T \langle \mathbf{45}_H \rangle$$

- Vectorlike fermions

$5_F + \bar{5}_F$

□ GG model + $5_F + \bar{5}_F$

□ $\mathcal{L} \supset \mathbf{Y}_{ij}^u \mathbf{10}_{Fi} \mathbf{10}_{Fj} \mathbf{5}_H + \mathbf{Y}_{ia}^d \mathbf{10}_{Fi} \bar{\mathbf{5}}_{Fa} \mathbf{5}_H^* + \bar{\mathbf{5}}_{Fa} (\mu_a + \eta_a \mathbf{24}_H) \mathbf{5}_{F4}$

□ $\mathbf{M}_D = \begin{pmatrix} \langle \mathbf{5}_H \rangle \mathbf{Y}_{ij}^d & \mathbf{M}_i^D \\ \langle \mathbf{5}_H \rangle \mathbf{Y}_{i4}^d & \mathbf{M}_4^D \end{pmatrix}, \quad \mathbf{M}_E = \begin{pmatrix} \langle \mathbf{5}_H \rangle (\mathbf{Y}_{ij}^d)^T & \langle \mathbf{5}_H \rangle (\mathbf{Y}_{i4}^d)^T \\ \mathbf{M}_i^E & \mathbf{M}_4^E \end{pmatrix},$

$\mathbf{M}_a^D = \mu_a - 2\eta_a \langle \mathbf{24}_H \rangle, \quad \mathbf{M}_a^E = \mu_a + 3\eta_a \langle \mathbf{24}_H \rangle$

Babu, Bajc, Tavartkiladze (2012)

Doršner, Fajfer, Mustać (2014)

$$10_F + \overline{10}_F / 15_F + \overline{15}_F$$

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

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

- Current bound $t_p > 2.4 \times 10^{34}$ years,
Future sensitivity $t_p \gtrsim 10^{35}$ years

$5_F + \bar{5}_F$

□ GG model + $5_F + \bar{5}_F$

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

□ Current bound $t_p > 2.4 \times 10^{34}$ years

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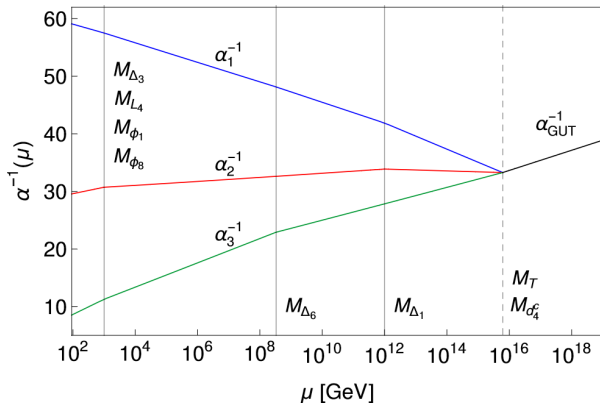
□ Current bound $t_p > 2.4 \times 10^{34}$ years

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Testable model

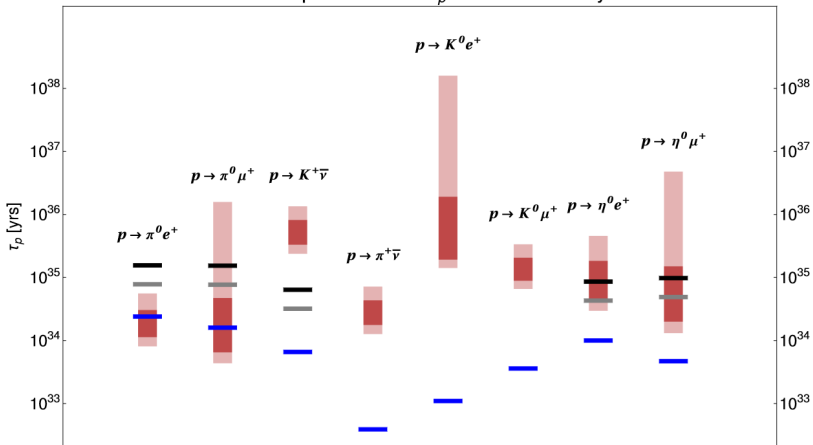
□ GG model + $\mathbf{5}_F + \bar{\mathbf{5}}_F + 2 \times \mathbf{15}_H$

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

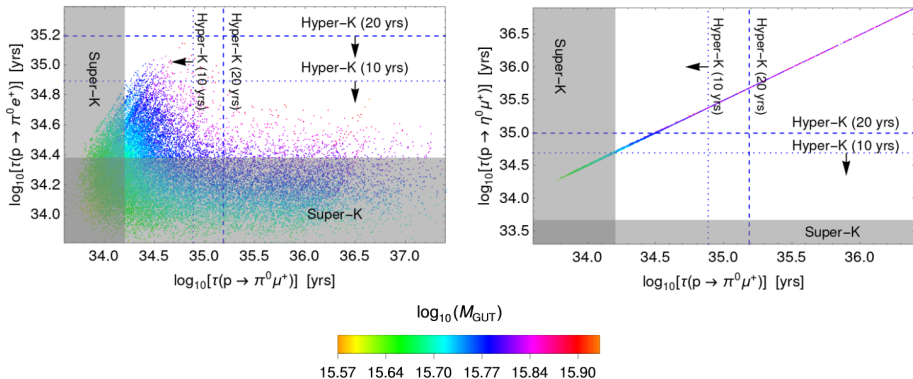


Proton decay channels

HPD intervals for proton lifetime τ_p for different decay channels



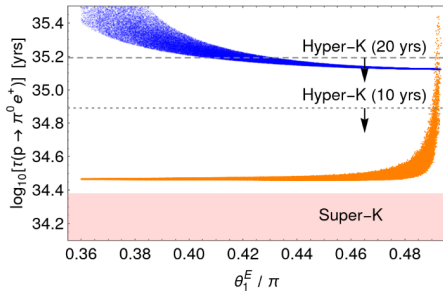
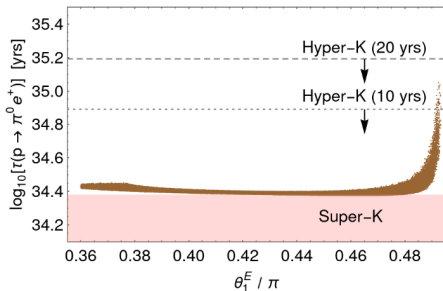
Relations between proton decay channels



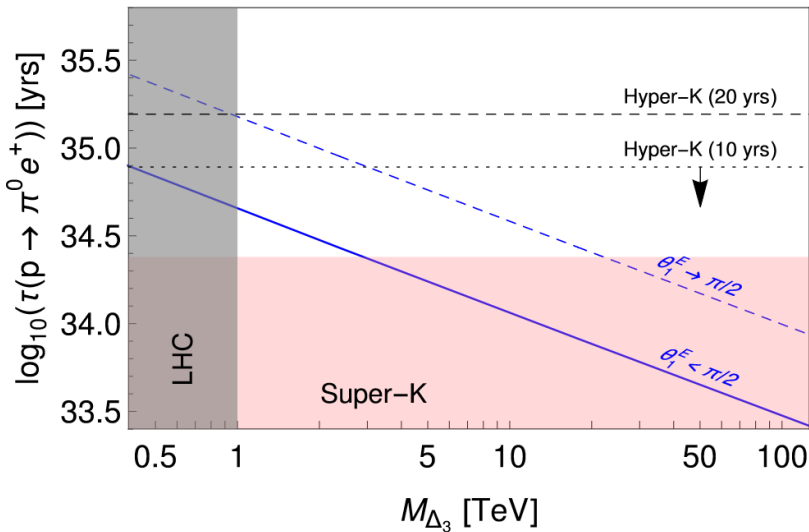
Can proton decay be rotated away?

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

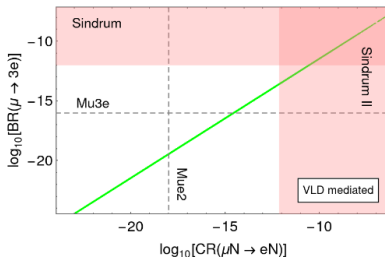
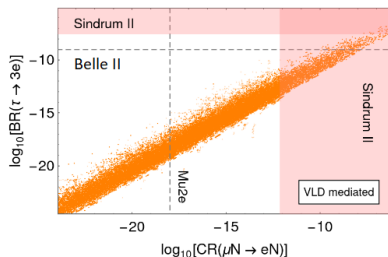
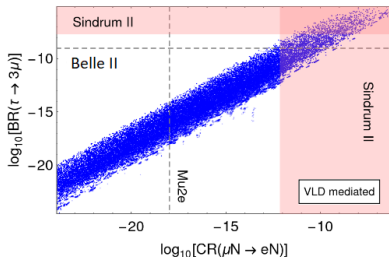
Define $\tan(\theta_i^{D/E}) \equiv M_i^{D/E} / M_4^{D/E}$



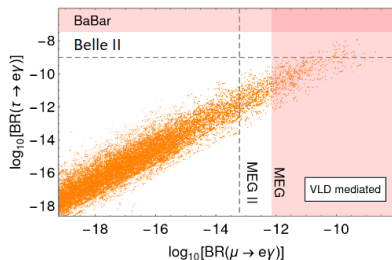
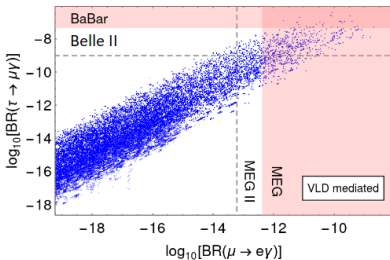
LQ mass vs proton decay



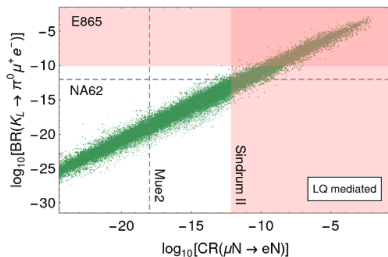
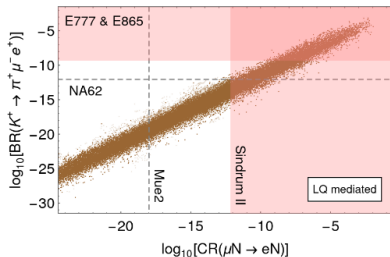
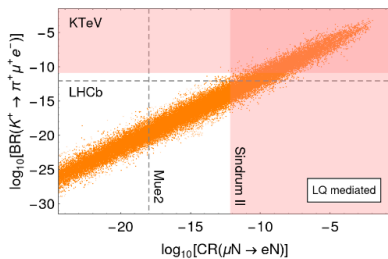
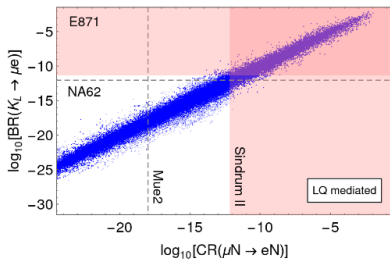
Flavor violation



Flavor violation



Flavor violation



Conclusion

- ❑ VLFs provide an interesting solution to the the “bad-mass-relation” of the GG model.
- ❑ The addition of $\mathbf{10}_F + \overline{\mathbf{10}}_F$ or $\mathbf{15}_F + \overline{\mathbf{15}}_F$ allows to build viable models which are however not fully testable by planned experiments.
- ❑ The addition of $\mathbf{5}_F + \overline{\mathbf{5}}_F$ 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.

$10_F + \overline{10}_F$

□ GG model + $10_F + \overline{10}_F$

□ $\mathcal{L} \supset \mathbf{Y}_{ab}^u 10_{Fa} 10_{Fb} 5_H + \mathbf{Y}_{ai}^d 10_{Fa} \overline{5}_{Fi} 5_H^*$
 + $\overline{10}_{F4} (\mu_a + \eta_a 24_H) 10_{Fa}$

□ $\mathbf{M}_D = \left(\underbrace{\langle 5_H \rangle \mathbf{Y}^d}_{4 \times 3} \quad \underbrace{\mathbf{M}_a^D}_{4 \times 1} \right), \quad \mathbf{M}_E = \left(\begin{array}{c} \langle 5_H \rangle \mathbf{Y}^{dT} \\ \mathbf{M}_a^E \end{array} \right) \begin{array}{l} \left. \vphantom{\langle 5_H \rangle \mathbf{Y}^{dT}} \right\} 3 \times 4 \\ \left. \vphantom{\mathbf{M}_a^E} \right\} 1 \times 4 \end{array},$

where $\mathbf{M}_a^D = \mu_a + \frac{1}{4} \eta_a \langle 24_H \rangle, \quad \mathbf{M}_a^E = \mu_a + \frac{3}{2} \eta_a \langle 24_H \rangle$

$15_F + \overline{15}_F$

□ GG model + $15_F + \overline{15}_F$

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

□ $\mathcal{L} \supset \mathbf{Y}_{ij}^u 10_{Fi} 10_{Fj} \mathbf{5}_H + \mathbf{Y}_{ij}^d 10_{Fi} \overline{\mathbf{5}}_{Fj} \mathbf{5}_H^* + \mathbf{Y}_i^a 15_F \overline{\mathbf{5}}_{Fi} \mathbf{5}_H^* + \mathbf{Y}_i^c 10_{Fi} \overline{15}_F 24_H + (m_{15} + y 24_H) \overline{15}_F 15_F + \text{h.c.}$

□ $\mathbf{M}_D = \begin{pmatrix} \langle \mathbf{5}_H \rangle \mathbf{Y}^d & \langle 24_H \rangle \mathbf{Y}^c \\ \langle \mathbf{5}_H \rangle \mathbf{Y}^a & \mathbf{M}_{\Sigma_3} \end{pmatrix}, \quad \mathbf{M}_e = \langle \mathbf{5}_H \rangle \mathbf{Y}^{dT}$

$\Rightarrow \mathbf{M}_d \approx \langle \mathbf{5}_H \rangle (\mathbf{Y}^d + \delta \mathbf{Y}^c \mathbf{Y}^a), \quad \mathbf{M}_e = \langle \mathbf{5}_H \rangle \mathbf{Y}^{dT}$

Doršner, Saad (2019)

Proton decay

$$\Gamma(p \rightarrow \pi^0 e_\beta^+) = \frac{m_p \pi}{2} \left(1 - \frac{m_\pi^2}{m_p^2}\right)^2 \frac{\alpha_{\text{GUT}}^2}{M_{\text{GUT}}^4} A_L^2 \times \left(A_{SL}^2 |c(e_\alpha^c, d)\langle \pi^0 | (ud)_{LU_L} | p \rangle|^2 + A_{SR}^2 |c(e_\alpha, d^c)\langle \pi^0 | (ud)_{RU_L} | p \rangle|^2 \right),$$

$$c(e_\alpha^c, d_\beta) = (E_R^*)_{i\alpha} (D_L^*)_{i\beta} + (E_R^*)_{i\alpha} (U_L^*)_{i1} (U_L)_{i1} (D_L^*)_{i\beta} + (E_R^*)_{4\alpha} (D_L^*)_{4\beta},$$

$$c(e_\alpha, d_\beta^c) = (E_L^*)_{a\alpha} (D_R^*)_{a\beta},$$

$$\mathbf{M}_U = U \mathbf{M}_U^{\text{diag}} U^T, \quad \mathbf{M}_D = D_L \mathbf{M}_D^{\text{diag}} D_R^\dagger,$$

$$\mathbf{M}_E = E_L \mathbf{M}_E^{\text{diag}} E_R^\dagger, \quad \mathbf{M}_N = N^* \mathbf{M}_N^{\text{diag}} N^\dagger.$$

Particle masses

HPD intervals for masses of added fields

