Minimal SO(10)-based GUT

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Based on:
Boucenna, Ohlsson, MP
1812.10548

Ohlsson, MP 1903.08241

Motivation

Open questions in the Standard Model

- Neutrino masses
- Dark matter
- Baryon asymmetry of the universe
- Higgs vacuum stability

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Open questions in the Standard Model

- Neutrino masses
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- Why three gauge groups?
- Near unification of gauge couplings
- Fermion charge assignment
- Anomaly cancellation

SO(10) Grand Unified Theory

Fritzsch, Minkowski 1975

$SO(10) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$

- Three gauge groups unified
- Gauge coupling unification
- Anomalies vanish identically

Fermionic representation

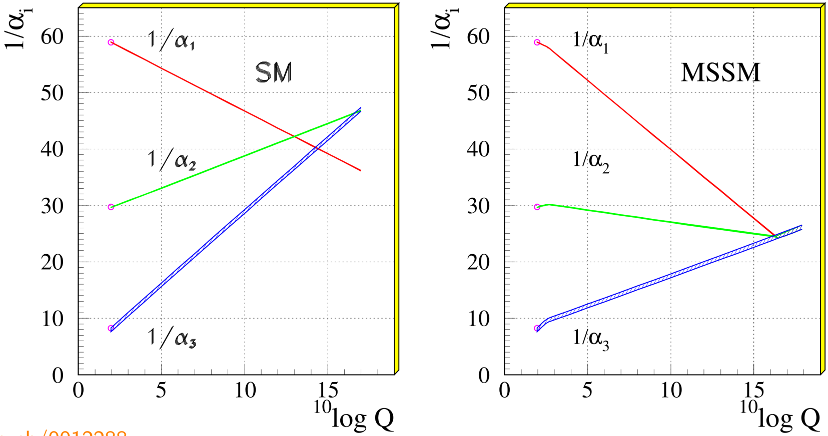
$$\mathbf{16}_F \to \underset{Q_L}{(\mathbf{3},\mathbf{2})_{1/6}} \oplus \underset{u_R^c}{(\overline{\mathbf{3}},\mathbf{1})_{1/3}} \oplus \underset{d_R^c}{(\overline{\mathbf{3}},\mathbf{1})_{-2/3}} \oplus \underset{\ell_L}{(\mathbf{1},\mathbf{2})_{-1/2}} \oplus \underset{e_R^c}{(\mathbf{1},\mathbf{1})_{1}} \oplus \underset{N_R^c}{(\mathbf{1},\mathbf{1})_{0}}$$

$$Q_L + u_R^c + d_R^c + \ell_L + e_R^c + N_R^c$$

- One fermionic representation
- Right-handed neutrinos
- Relation between hypercharges

Gauge Coupling Unification

How do we unify the coupling constants without SUSY...?

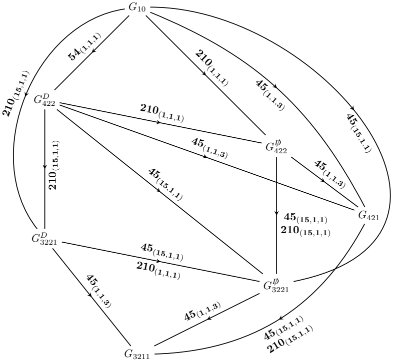


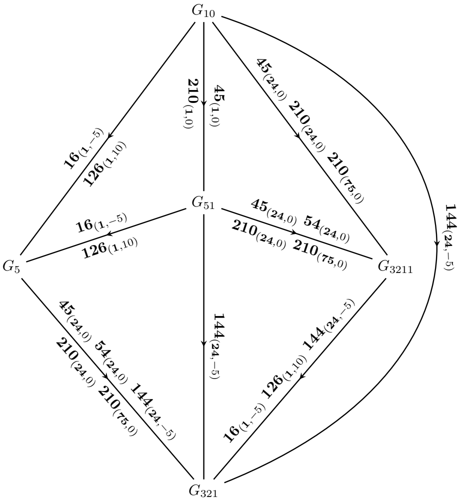
hep-ph/0012288

Gauge Coupling Unification

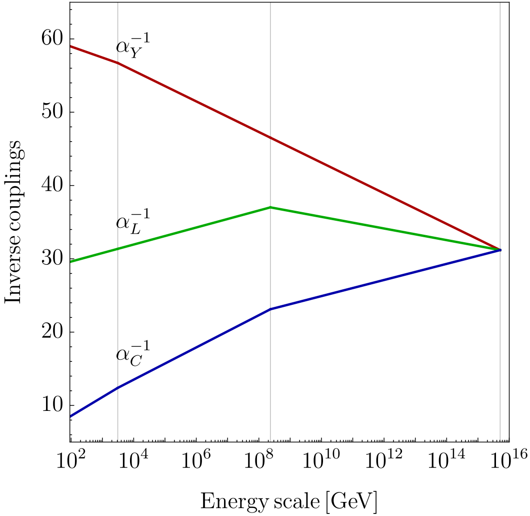
... And without introducing multiple steps?

Ferrari et al. 1811.07910
Chang et al. 1985
Deshpande et al. 1993





Split $\mathbf{210} \supset S_1(\mathbf{8},\mathbf{1})_1 \oplus S_2(\mathbf{8},\mathbf{3})_0$



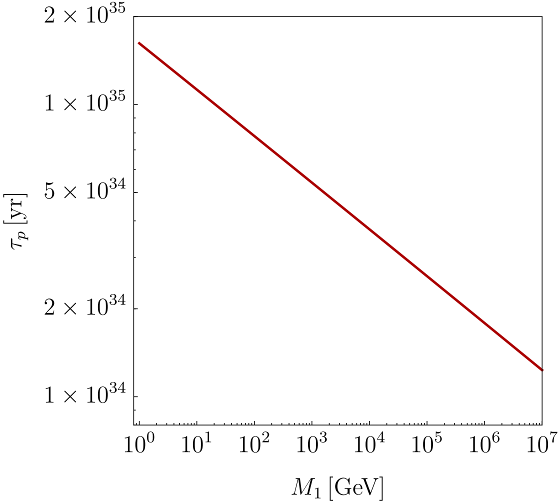
$M_1 = 3.1$ TeV
$M_2 = 2.34 \times 10^8$ GeV
$M_{\mathrm{GUT}} = 4.51 \times 10^{15}$ GeV

M_2 and M_{GUT} determined uniquely by M_1 and requirement of gauge coupling unification

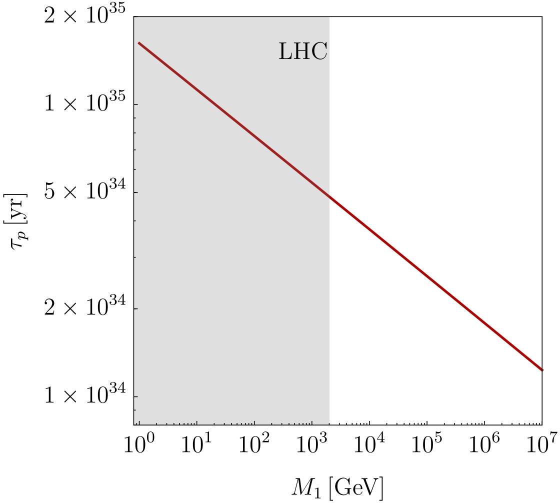
Similar constructions in:
Frigerio, Hambye 0912.1545
Parida et al. 1608.03956

Babu et al. hep-ph/0506312

Proton Lifetime and LHC

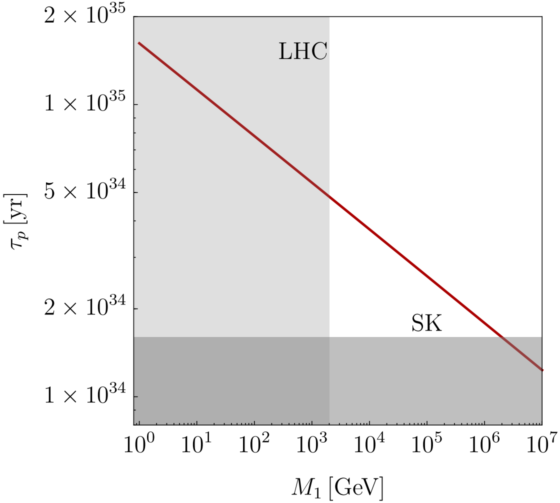


Proton Lifetime and LHC



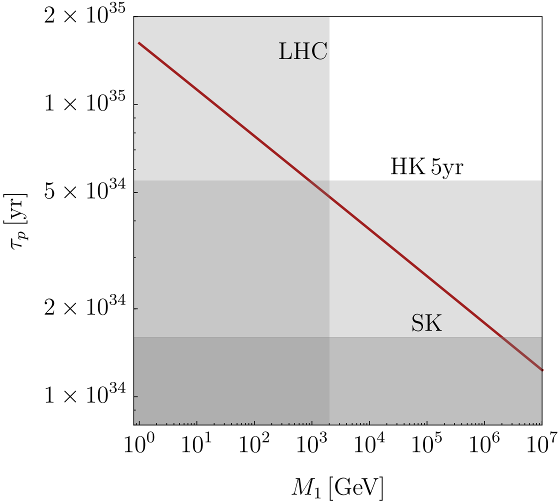
- $M_1 > 3.1$ TeV

  CMS 1512.01224



- $M_1 > 3.1$ TeV
  CMS 1512.01224
- $\tau_p > 1.6 \times 10^{34}$ yr ($p \to e^+\pi^0$)
  SK 1610.03597

Proton Lifetime and LHC



- $M_1 > 3.1$ TeV
  CMS 1512.01224
- $\tau_p > 1.6 \times 10^{34}$ yr ($p \to e^+\pi^0$)
  SK 1610.03597
- $\tau_p > 5.5 \times 10^{34}$ yr ($p \to e^+\pi^0$)
  HK 1805.04163

Fermion Masses

Higgs

- Higgs $H_u = (\mathbf{1}, \mathbf{2})_{1/2}$ and $H_d = (\mathbf{1}, \mathbf{2})_{-1/2}$ reside in $\mathbf{10}_H$ and $\overline{\mathbf{126}}_H$
- SM Higgs doublet is a combination of these
- Yukawa Lagrangian $\mathbf{16}_F(Y_{10}\mathbf{10}_H + Y_{126}\overline{\mathbf{126}}_H)\mathbf{16}_F$

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Neutrino Masses

- Neutrino Dirac mass through $\overline{\ell_L} H_u N_R$
- $\sigma \equiv (\mathbf{1}, \mathbf{1})_0 \subset \overline{\mathbf{126}}_H$ gives Majorana mass through $\sigma \overline{N_R^c} N_R$
- Type-I seesaw
- (Type-II seesaw also possible using $\Delta_L \equiv (\mathbf{1}, \mathbf{3})_{-1} \subset \overline{\mathbf{126}}_H$)

Accommodating the SM parameters

Bajc et al. hep-ph/0510139
Altarelli, Meloni 1305.1001
Babu, Khan 1507.06712

Babu et al. 1612.04329

- $\mathbf{10}_H$ is a real representation $\implies v_{10}^u = v_{10}^d$.
  Not enough freedom to fit
- Solution: Complexify it as $\mathbf{10}_H \equiv \mathbf{10}_{H,1} + \mathrm{i}\mathbf{10}_{H,2}$
- But then have extra Yukawa couplings

$$Y_{10}\mathbf{16}_F\mathbf{10}_H\mathbf{16}_F + \tilde{Y}_{10}\mathbf{16}_F\mathbf{10}_H^*\mathbf{16}_F$$

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$$Y_{10}\mathbf{16}_F\mathbf{10}_H\mathbf{16}_F + \tilde{Y}_{10}\mathbf{16}_F\mathbf{10}_H^*\mathbf{16}_F$$

- Introduce $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry with charges

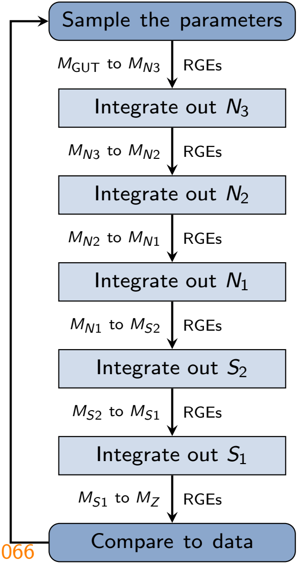
$$\mathbf{16}_F \to \mathrm{e}^{\mathrm{i}\alpha}\mathbf{16}_F,\ \mathbf{10}_H \to \mathrm{e}^{-2\mathrm{i}\alpha}\mathbf{10}_H,\ \overline{\mathbf{126}}_H \to \mathrm{e}^{-2\mathrm{i}\alpha}\overline{\mathbf{126}}_H$$

- Axions: Strong CP problem and DM. $f_a = M_{\mathrm{GUT}} = 4.51 \times 10^{15}$ GeV

Fitting to the Standard Model

$$v_{SM} Y_u = v_{10}^u Y_{10} + v_{126}^u Y_{126} ,$$
$$v_{SM} Y_d = v_{10}^d Y_{10} + v_{126}^d Y_{126} ,$$
$$v_{SM} Y_\nu = v_{10}^u Y_{10} - 3 v_{126}^u Y_{126} ,$$
$$v_{SM} Y_\ell = v_{10}^d Y_{10} - 3 v_{126}^d Y_{126} ,$$
$$M_R = v^\sigma Y_{126} .$$

- 19 free parameters and 19 data
- Integrate out RH neutrinos: $\kappa \to \kappa + \frac{2}{M_{Ni}} (Y_\nu^i)^T (Y_\nu^i)$ at each RH neutrino threshold
- Find acceptable fit ($\chi^2 \simeq 21$)
- Simple leptogenesis not successfully fit



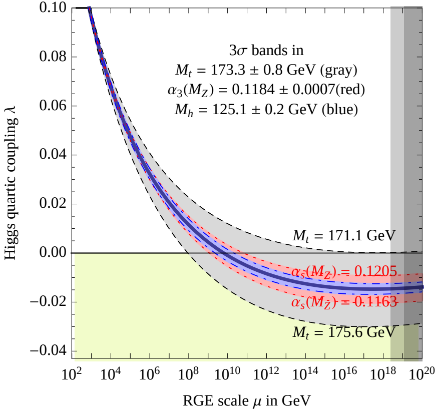
Babu, Mohapatra hep-ph/9209215, Fukuyama, Okada hep-ph/0205066
Bertolini et al. hep-ph/0605006, Joshipura, Patel 1102.5148

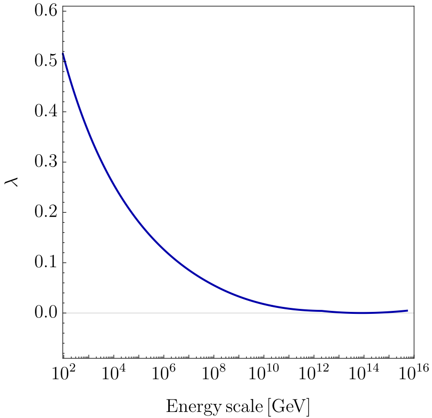
Dueck, Rodejohann 1306.4468, Antusch et al. hep-ph/0203233, arXiv:hep-ph/0501272

Vacuum Stability

$$16\pi^2 \frac{d\lambda}{d\ln\mu} = \cdots - 3\lambda\left(3g_2^2 + \tfrac{3}{5}g_1^2\right) + 3g_2^4 + \tfrac{3}{2}\left(\tfrac{3}{5}g_1^2 + g_2^2\right)^2 + 4\lambda \mathrm{Tr}\left[Y_\nu^\dagger Y_\nu\right] - 8\mathrm{Tr}\left[Y_\nu^\dagger Y_\nu Y_\nu^\dagger Y_\nu\right] + \ldots$$

Machacek, Vaughn 1985





Buttazzo et al. 1307.3536

Towards More General Fits

Dueck, Rodejohann 1306.4468

Let us relax some model specifications:

- Do not specify the extra scalars
- Do not know exact M_{GUT}
- Both Type-I and Type-II seesaw

Towards More General Fits

Dueck, Rodejohann 1306.4468

Let us relax some model specifications:

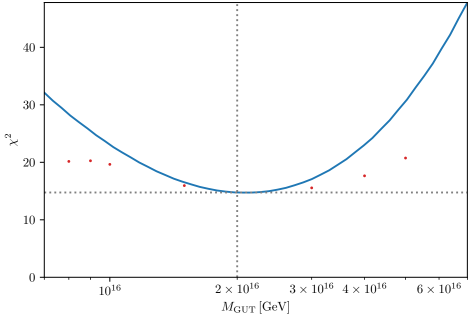
- Do not specify the extra scalars
- Do not know exact M_{GUT}
- Both Type-I and Type-II seesaw

- Remove the colored octet scalars
- Set $M_{\mathrm{GUT}} = 2 \times 10^{16}$ GeV, but check sensitivity to M_{GUT}
- Introduce another scale: Mass of $\Delta_L \equiv (\mathbf{1}, \mathbf{3})_{-1}$

Neglects some model details, but indicative

Fit Results

- Acceptable fits to normal neutrino mass ordering ($\chi^2 \simeq 14.7$), but not inverted
- Type-II seesaw is sub-dominant: $M_\Delta \sim M_{\mathrm{GUT}}$, $v_\Delta \sim 10^{-6}$ GeV
- Largest contribution to χ^2 is $\sin^2\theta^\ell_{23}$: fit favours value in first octant (0.474), but actual value is in second octant (0.547)



Conclusion

Minimal SO(10) model with $U(1)_{PQ}$ symmetry

- Neutrino masses ✓
- Dark matter ✓
- Baryon asymmetry of the universe (More detailed analysis needed)
- Higgs vacuum stability ✓
- Fit the Yukawa sector to SM ✓

BACKUP SLIDES

$$
\begin{aligned}
M_1 &\lesssim 5.92 \times 10^{10}\,\mathrm{GeV}\,, \\
M_2 &\approx \left(\frac{M_1}{\mathrm{GeV}}\right)^{0.330} \times 1.65 \times 10^{7}\,\mathrm{GeV}\,, \\
M_{\mathrm{GUT}} &\approx \left(\frac{M_1}{\mathrm{GeV}}\right)^{-0.0447} \times 7.34 \times 10^{15}\,\mathrm{GeV}\,.
\end{aligned}
$$

$$
\tau_p \equiv \tau(p \to e^+\pi^0) \simeq \frac{4}{\pi}\,\frac{f_\pi^2}{m_p}\,\frac{1}{\alpha_H^2 A_R^2}\,\frac{1}{F_q}\,\frac{M_{\mathrm{GUT}}^4}{\alpha(M_{\mathrm{GUT}})^2}\,,
$$

where $f_\pi \approx 139\,\mathrm{MeV}$ is the pion decay constant, $m_p \approx 938.3\,\mathrm{MeV}$ is the proton mass, $\alpha_H \approx 0.012\,\mathrm{GeV}^3$ is the hadronic matrix element, $A_R \approx 2.726$ is a renormalisation factor, and $F_q \approx 7.6$ is a quark-mixing factor.

$$
\tau_p \approx 3.22 \times \frac{M_{\mathrm{GUT}}^4}{\alpha(M_{\mathrm{GUT}})^2}\,.
$$

$$H \equiv \frac{v_{10}^d}{v_{\text{SM}}} Y_{10}, \quad F \equiv \frac{v_{126}^d}{v_{\text{SM}}} Y_{126}, \quad r \equiv \frac{v_{10}^u}{v_{10}^d},$$

$$s \equiv \frac{1}{r} \frac{v_{126}^u}{v_{126}^d} = \frac{v_{10}^d}{v_{10}^u} \frac{v_{126}^u}{v_{126}^d}, \quad r_R \equiv v_{126}^R \frac{v_{\text{SM}}}{v_{126}^d}, \quad r_L \equiv \frac{v_{\text{SM}}}{v_{126}^d}.$$

$$Y_u = r(H + sF), \quad Y_d = H + F,$$
$$Y_\nu = r(H - 3sF), \quad Y_\ell = H - 3F,$$
$$M_R = r_R F, \quad Y_\Delta = r_L F.$$

Observable	Value	Error
m_u (MeV)	1.36	0.15
m_c (MeV)	635	32
m_t (GeV)	172	8.7
m_d (MeV)	2.90	0.15
m_s (MeV)	54.1	2.8
m_b (GeV)	2.87	0.15
m_e (MeV)	0.487	0.025
m_μ (MeV)	103	5.2
m_τ (GeV)	1.75	0.088
Δm^2_{21} ($10^{-5}\mathrm{eV}^2$)	7.55	0.38
Δm^2_{31} ($10^{-3}\mathrm{eV}^2$) (NO)	2.50	0.13
Δm^2_{32} ($10^{-3}\mathrm{eV}^2$) (IO)	-2.42	0.13
$\sin\theta^q_{12}$	0.225	0.012
$\sin\theta^q_{13}$	0.00372	0.00019
$\sin\theta^q_{23}$	0.0418	0.0021
δ_{CKM}	1.14	0.058
$\sin^2\theta^\ell_{12}$	0.320	0.020
$\sin^2\theta^\ell_{13}$ (NO)	0.0216	0.0011
$\sin^2\theta^\ell_{13}$ (IO)	0.0222	0.0012
$\sin^2\theta^\ell_{23}$ (NO)	0.547	0.030
$\sin^2\theta^\ell_{23}$ (IO)	0.551	0.030
λ	0.516	0.026

Parameter	Value
m_1	$3.70 \times 10^{-3}\,\mathrm{eV}$
m_2	$9.55 \times 10^{-3}\,\mathrm{eV}$
m_3	$4.93 \times 10^{-2}\,\mathrm{eV}$
M_1	$1.87 \times 10^{10}\,\mathrm{GeV}$
M_2	$4.46 \times 10^{11}\,\mathrm{GeV}$
M_3	$2.34 \times 10^{12}\,\mathrm{GeV}$
m_{ee}	$1.56 \times 10^{-3}\,\mathrm{eV}$
δ_{CP}	0.441