Flavor structure in $\mathrm{SO}(10)$ SUSY GUT from effective operators

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work in progress

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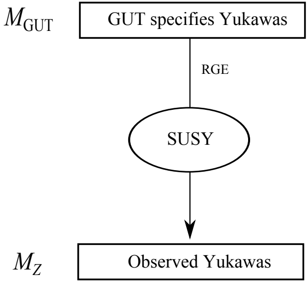
Outline

- Introduction
  - Flavor GUT models.
  - Usual $\mathrm{SO}(10)$ Yukawa operators.
- A class of non-renormalizable Yukawa operators.
- A simple predictive setup using these opeartors.
- Conclusions

Flavor GUT models

- GUT models: relate Yukawas in different sectors at M_{GUT}.
- Connecting Yukawas at low and high scale:



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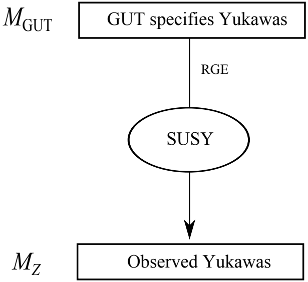

- Examples of ratios in $\mathrm{SU}(5)$:
  - $m_b = m_\tau$: "b-τ unification"
  - Georgi-Jarlskog: $m_e = m_d/3$, $m_\mu = 3m_s$.
  - $y_\tau = \pm\frac{3}{2}y_b$, $y_\mu = 6y_s$, $y_\mu = \frac{9}{2}y_s$.

Reminder on $\mathrm{SO}(10)$ group

Dimension: 45

Maximal subgroups:

$\mathrm{SU}(5) \times \mathrm{U}(1)$
$\mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$

Fermions:
spinorial 16
All sectors join: u, d, e, ν

Irreducible representations:
126, $\overline{126}$, 45, 210
10, 120
16, $\overline{16}$

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MSSM fields	SU(5)	SO(10)
$Q \sim (3, 2, +1/6)$	10	16
$u^c \sim (\overline{3}, 1, -4/6)$		
$e^c \sim (1, 1, +6/6)$		
$d^c \sim (\overline{3}, 1, +2/6)$	$\overline{5}$	
$L \sim (1, 2, -3/6)$		
$\nu^c \sim (1, 1, +0/6)$	1	

$H_u \sim (1, 2, +3/6)$

$H_d \sim (1, 2, -3/6)$

Masses in renormalizable SUSY $\mathrm{SO}(10)$

- Fermions: $3 \times 16_F$
- Yukawa terms:

$$W = 16 \cdot 16 \cdot \; (\mathbf{Y}_{10}\, 10 + \mathbf{Y}_{\overline{126}}\, \overline{126} + \mathbf{Y}_{120}\, 120). \qquad (1)$$

- 3 Independent matrices: 2 symmetric, 1 antisymmetric
- Sectors u, d, e, ν: differ in CG coefficients $\forall\, \mathbf{Y}$

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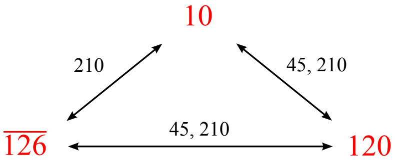
- Sectors u, d, e, ν: differ in CG coefficients $\forall\, \mathbf{Y}$
- MSSM H_u and H_d have presence in all reps 10,120,$\overline{126}$:



- No a priori definite ratios Y_d/Y_e etc. at GUT scale.

Effective operators 1

- Non-renormalizable Yukawa operators (partly in hep-ph/9308333):

$$c_{ijnm}\,\frac{1}{\Lambda^{n+m}}\,16_i\cdot 16_j\cdot 10\cdot 45^n\cdot 210^m \tag{2}$$

$$c_{ijnm}\,\frac{1}{\Lambda^{n+m}}\,16_i\cdot 16_j\cdot \overline{126}\cdot 45^n\cdot 210^m \tag{3}$$

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VEVs $\langle 45\rangle$ and $\langle 210\rangle$:

45: 2 SM singlets,
210: 3 SM singlets

32×32 matrices, diagonal with "charges"

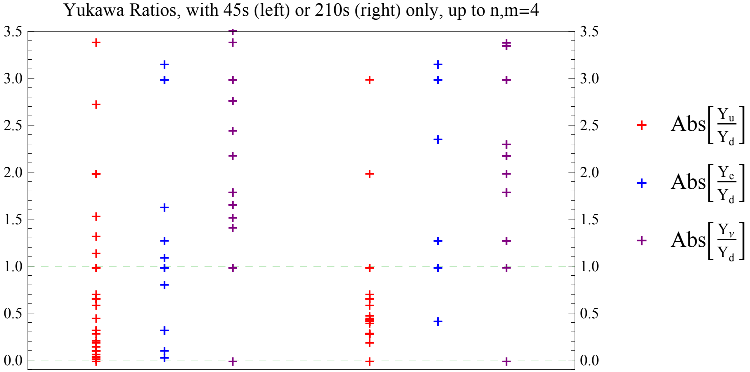
$\rightarrow$ Yukawa terms:
$Y \propto \Pi_{n,m}[\phi] + \Pi_{n,m}[\phi^c]$

45:	$\langle 1\rangle$	$\langle 24\rangle$	T^3_R	$B-L$
Q	1	1	0	1
u^c	1	−4	1	−1
d^c	−3	2	−1	−1
L	−3	−3	0	−3
e^c	1	6	−1	3
ν^c	5	0	1	3

210:	$\langle 1\rangle$	$\langle 24\rangle$	$\langle 75\rangle$	$(1,1,1)$	$(1,1,15)$	$(1,3,15)$
Q	1	1	1	1	1	0
u^c	1	−4	−1	−1	1	1
d^c	−1	−6	0	−1	1	−1
L	−1	9	0	1	−3	0
e^c	1	6	−3	−1	−3	3
ν^c	−5	0	0	−1	−3	−3

Discrete directions and new ratios for model building

- If SU(5) or PS discrete VEV alignment of each 45 or 210: new possible Yukawa ratio predictions at M_{GUT}



Effective operators — arbitrary directions

- Operators $16 \cdot 16 \cdot H \cdot 45^n \cdot 210^m$ with continuous VEVs:

$$Y_x = c\; p_x^{n,m}(\kappa, \kappa_1, \kappa_2), \tag{4}$$

$$\kappa \equiv \frac{\langle 24_{45} \rangle}{\langle 1_{45} \rangle},\; \kappa_1 \equiv \frac{\langle 24_{210} \rangle}{\langle 1_{210} \rangle},\; \kappa_2 \equiv \frac{\langle 75_{210} \rangle}{\langle 1_{210} \rangle} \tag{5}$$

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$$\begin{aligned} p_u &= \quad \Big((1+\kappa)^n(1+\kappa_1+\kappa_2)^m + (1-4\kappa)^n(1-4\kappa_1-\kappa_2)^m\Big), \\ p_d &= \quad \Big((1+\kappa)^n(1+\kappa_1+\kappa_2)^m + (2\kappa-3)^n(-1-6\kappa_1)^m\Big), \\ p_e &= \alpha_H\Big((-3)^n(1+\kappa)^n(-1+9\kappa_1)^m + (1+6\kappa)^n(1+6\kappa_1-3\kappa_2)^m\Big), \\ p_\nu &= \alpha_H\Big((-3)^n(1+\kappa)^n(-1+9\kappa_1)^m + 5^{m+n}(-1)^m\Big), \end{aligned} \tag{6}$$

- $\alpha_{10} = 1$, $\alpha_{\overline{126}} = -3$.
- We assume: κ, κ_1, κ_2 can take any $\mathbb{C}$ value.

Simple model — the setup

- We assume operators only of type $16^2 \cdot 10 \cdot 45^n$:
  - We use only the 10 for H_u and H_d.
    only $\tan\beta$ needed
  - No 210, only one 45 with arbitrary direction κ.
- Only 3rd and 2nd family, neglect mixing, no neutrino masses:

$$\begin{pmatrix} \times & \times & \times \\ \times & c_{22}\, O_{22} & \times \\ \times & \times & c_{33}\, O_{33} \end{pmatrix} \tag{7}$$

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- Single operator dominance:
  just O_{22} and O_{33}, no linear combinations.
  - 3rd family: t-b-τ unification ($n_{33} = 0$)

$$O_{33} = 16_3 \cdot 16_3 \cdot 10, \tag{8}$$

  - 2nd family: assume $n_{22} \in \{2, 3, 4\}$

$$O_{22} = 16_2 \cdot 16_2 \cdot 10 \cdot 45^{n_{22}} \tag{9}$$

Quick analysis

- Threshold parameters: $\tan\beta$, η_b, η_q (assuming $\eta_l = 0$):

$$Y_u^{\mathsf{SM}} \simeq Y_u^{\mathsf{MSSM}} \sin\beta, \tag{10}$$

$$Y_d^{\mathsf{SM}} \simeq (\mathbf{1} + \mathrm{diag}[\eta_q, \eta_q, \eta_b])\, Y_d^{\mathsf{MSSM}} \cos\beta, \tag{11}$$

$$Y_e^{\mathsf{SM}} \simeq Y_e^{\mathsf{MSSM}} \cos\beta. \tag{12}$$

- Quick fit to high-energy data:[1]

$$Y_t, Y_b, Y_\tau, Y_c, Y_\mu\ (\tan\beta, \eta_b), \qquad Y_s\ (\tan\beta\eta_b, \eta_q) \tag{13}$$

[1] arXiv 1306.6879

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- Procedure:
  1. Determine $\tan\beta, \eta_b$ from $Y_t/Y_b = Y_\tau/Y_b = 1$.
  2. Determine $\kappa \in \mathbb{C}$ from $Y_\mu/Y_c(\tan\beta, \eta_b)_{\mathrm{data}} = Y_\mu/Y_c(\kappa)_{\mathrm{model}}$.
  3. Determine η_q from the ratio Y_s/Y_c.

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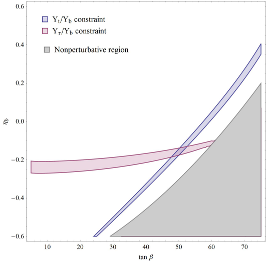
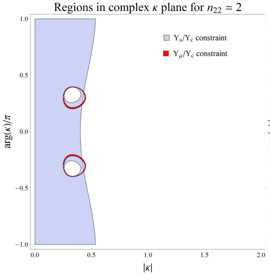
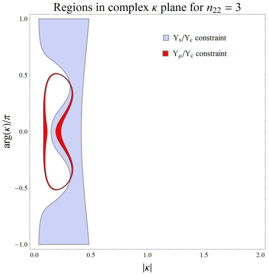
Quick analysis 2

$\tan\beta \approx 50$, $\eta_b \approx -0.16$

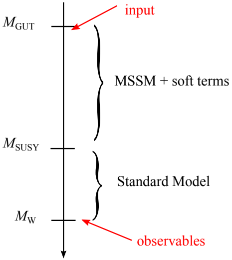






More thorough analysis — SUSY soft terms

- Use *SusyTC 1.2*[2] (REAP extension) to compute the SUSY spectrum:



- Use constrained MSSM parameters: m_0, $M_{1/2}$, A_0.

[2]SUSYTC, arXiv:1512.06727 + FeynHiggs 2.13.0 hep-ph/9812320

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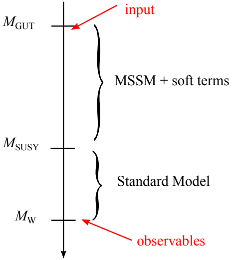

- Use constrained MSSM parameters: m_0, $M_{1/2}$, A_0.
- Input parameters [7 real+1 phase]:
  $\tan\beta$, m_0, $M_{1/2}$, A_0, c_{22}, c_{33}, $|\kappa| e^{i \arg \kappa}$
- Compute χ^2 for 7 observables: relative errors $\geq 1\%$
  m_t, m_b, m_τ, m_c, m_s, m_μ, $m_{\rm Higgs}$
- Find: best fit point, then MCMC (goal: 10^6 points)

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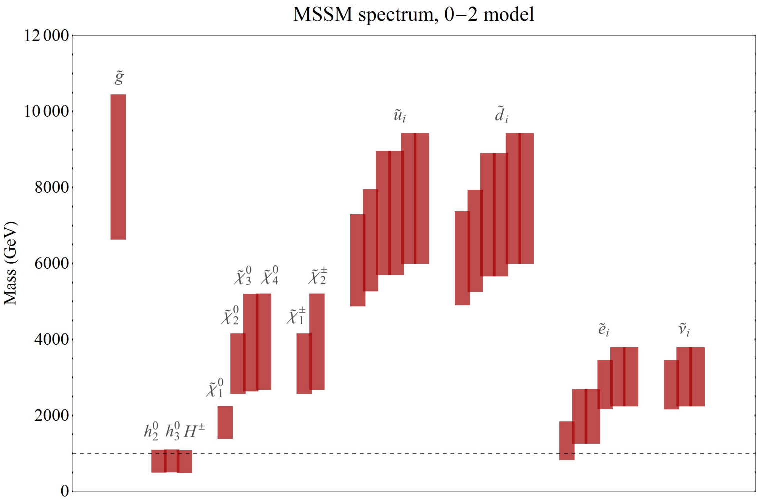
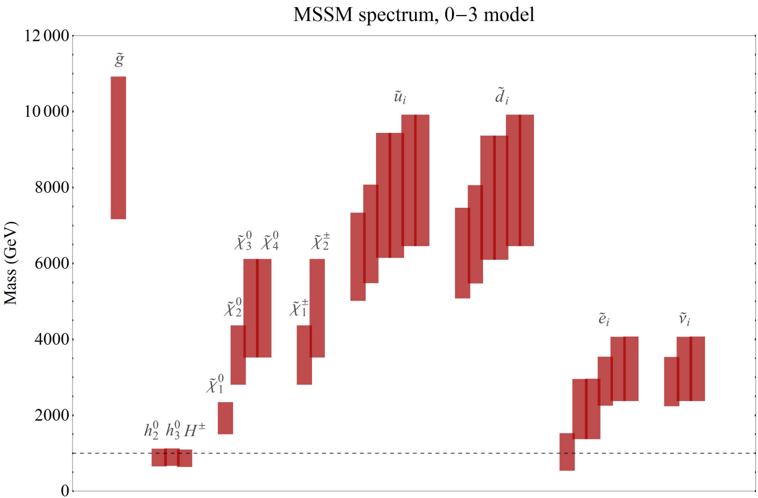
SUSY spectrum of 0 − 2 model (preliminary)



Best point: $\chi^2 < 10^{-6}$

$\tan\beta = 50.99$, $m_0 = 1393\,\mathrm{GeV}$, $M_{1/2} = 3783\,\mathrm{GeV}$, $A_0 = -2307\,\mathrm{GeV}$.

SUSY spectrum of 0 − 3 model (preliminary)

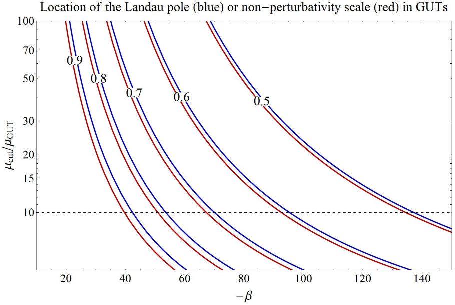


Best point: $\chi^2 = 1.36$.

$\tan\beta = 48.57$, $m_0 = 2797\,\mathrm{GeV}$, $M_{1/2} = 5403\,\mathrm{GeV}$, $A = -10010\,\mathrm{GeV}$.

Specific model with Higgs sector

- Landau pole: $dg/dt = -\frac{\beta}{16\pi^2} g^3$, $\beta = 3C_2(V) - D_2(C)$.



R	$D_2(R)$
10	1
16	2
45	8
54	12
120	28
126	35
210	56

- Avoided if we choose small representations: avoid 126, 210
- Breaking $\mathrm{SO}(10)$ to SM, $\langle 45 \rangle$ arbitrary direction, DT splitting by fine-tuning:

$$3 \times 16_F + 45 + 16 + \overline{16} + 10 \;\; [+\text{discrete symmetries}]. \quad (14)$$

- Above model $\beta = +5$: asymtotically free $\to \Lambda$ can be M_{Pl}

Conclusions

- Alternative class of operators for $\mathrm{SO}(10)$ Yukawa sector:

$$16 \cdot 16 \cdot 10 \cdot 45^n \cdot 210^m \tag{15}$$

- Discrete or continuous directions of 45 or 210:
  new ratios for flavor GUT model building

- A simple model:
  using 45 only, arbitrary direction,
  single operator dominance, Y_{22} and Y_{33} entries,
  predicts the super-partner spectrum.