Testing Flavor Symmetries with Flavored Gauge Mediation

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The SM Flavor Puzzle

A popular idea to address the SM Flavor Puzzle is in terms of flavor symmetries

Even very simple symmetries like U(1) can account for all hierarchies in fermion masses and mixings

For large flavor scale testable only if new physics at TeV scale, as suggested by hierarchy problem

The SUSY Flavor Problem

Generic SUSY flavor-violating effects
are already strongly constrained

e.g. $K - \overline{K}$ mixing:

$$\sqrt{\delta_{12}^{D,LL}\delta_{12}^{D,RR}} < 2.6 \times 10^{-4} \left(\frac{\tilde{m}}{\text{TeV}}\right)$$

For SUSY around TeV scale need to explain
strong suppression of sfermion flavor structure

Relating Sflavor and Flavor

Suggestive that sfermion masses controlled by same dynamics that render Yukawas small

Flavor Symmetry

$(\tilde{m}^2_U)_{ij}$ $\quad\quad$ y^U_{ij}

Realization depends on relation of messenger scales

$\Lambda_S \longleftrightarrow \Lambda_F$

scale SUSY messengers $\quad\quad$ scale flavor messengers

High-scale SUSY breaking

$\Lambda_S \gtrsim \Lambda_F$ e.g. Gravity Mediation

Sfermion masses are directly sensitive to flavor sector: most general invariants

Strongly constrained, simplest flavor models are in big trouble

e.g. single U(1): $\tilde{m} > 750$ TeV

Low-scale SUSY breaking

$\Lambda_S < \Lambda_F$ e.g. Gauge Mediation

Allows to decouple sfermion masses from flavor sector

Sfermion masses sensitive only to SM Yukawas: MFV

Solves SUSY Flavor Problem but no way to test flavor sector

Flavored Gauge Mediation

Shadmi, Szabo '11
Calibbi, Paradisi, RZ, '13

Simple modification of minimal gauge mediation that reintroduces sensitivity of low-energy physics to flavor sector in a controlled way

- General framework: applicable to any flavor model
- Built-in suppression of FV: even U(1) perfectly viable
- Highly predictive SUSY spectrum
- Natural solution of $\mu - B_\mu$ in NMSSM

Main Idea

Take minimal GM with messengers in $\mathbf{5}, \bar{\mathbf{5}}$
with positive R-parity

Same quantum number as MSSM Higgs:
motivates existence coupling matter-messengers
(in MGM forbidden by hand)

Assume that couplings are controlled by same
underlying flavor symmetry as Yukawas

Have same parametric suppression if messenger
and Higgs have same flavor quantum numbers

Example

Calibbi, Paradisi, RZ, '13

$$\Delta W = (\lambda_U)_{ij} Q_i U_j \Phi_{H_u}$$

New coupling has same parametric suppression of up-Yukawa: $\lambda^U_{ij} \sim y^U_{ij}$

Controls new contributions to soft masses

$$A_U \sim \lambda_U \lambda_U^\dagger y_U + y_U \lambda_U^\dagger \lambda_U \qquad A_D \sim \lambda_U \lambda_U^\dagger y_D$$

$$\Delta\tilde{m}^2_Q \sim \lambda_U \lambda_U^\dagger \qquad \Delta\tilde{m}^2_U \sim \lambda_U^\dagger \lambda_U \qquad \Delta\tilde{m}^2_D \sim y_D^\dagger \lambda_U \lambda_U^\dagger y_D$$

No flavor-blind phases at LO:
additional 3-rd generation Yukawa suppression !

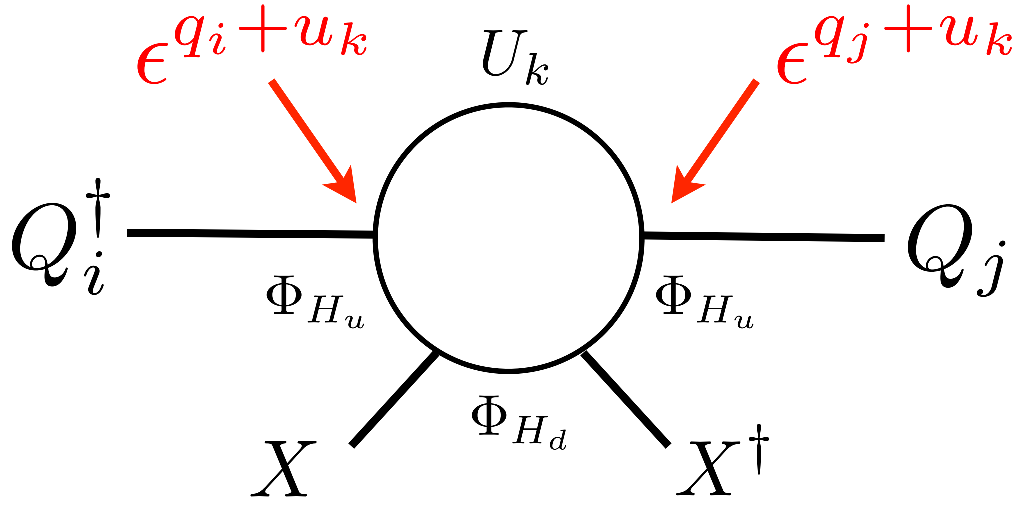
Sflavor Structure in U(1) Model

In U(1) model can estimate couplings in terms of masses and mixing through charges

$$(\lambda_U)_{ij} \sim \epsilon^{q_i+u_j}$$

Loop origin gives strong suppression

$$(\delta^u_{LL})_{ij} \sim (\lambda_U)_{ik}(\lambda_U)^*_{jk} \sim \epsilon^{q_i+q_j+2u_k} \sim V_{i3}V_{j3}y_t^2$$



Gravity Mediation: $\sim V_{i3}/V_{j3}$

Comparison

	MFV	PC	$U(1)$	$\text{FGM}_{U,D} + U(1)$	$\text{FGM}_U + U(1)$
$(\delta^u_{LL})_{ij}$	$V_{i3}V^*_{j3}y_b^2$	$(\epsilon_3^q)^2 V_{i3}V^*_{j3}$	$\frac{V_{i3}}{V_{j3}}\|_{i\leq j}$	$V_{i3}V^*_{j3}y_t^2$	$V_{i3}V^*_{j3}y_t^2$
$(\delta^d_{LL})_{ij}$	$V^*_{3i}V_{3j}y_t^2$	$(\epsilon_3^q)^2 V_{i3}V^*_{j3}$	$\frac{V_{i3}}{V_{j3}}\|_{i\leq j}$	$V^*_{3i}V_{3j}y_t^2$	$V^*_{3i}V_{3j}y_t^2$
$(\delta^u_{RR})_{ij}$	$y_i^U y_j^U V_{i3}V^*_{j3}y_b^2$	$\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}} \frac{(\epsilon_3^u)^2}{y_t^2}$	$\frac{y_i^U V_{j3}}{y_j^U V_{i3}}\|_{i\leq j}$	$\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$	$\frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$
$(\delta^d_{RR})_{ij}$	$y_i^D y_j^D V^*_{3i}V_{3j}y_t^2$	$\frac{y_i^D y_j^D}{V_{i3}V^*_{j3}} \frac{(\epsilon_3^u)^2}{y_t^2}$	$\frac{y_i^D V_{j3}}{y_j^D V_{i3}}\|_{i\leq j}$	$\frac{y_i^D y_j^D}{V_{i3}V^*_{j3}}$	$y_i^D y_j^D V^*_{3i}V_{3j}y_t^2$
$(\delta^u_{LR})_{ij}$	$y_j^U V_{i3}V^*_{j3}y_b^2$	$y_j^U \frac{V_{i3}}{V^*_{j3}}$	$y_j^U \frac{V_{i3}}{V^*_{j3}}$	$y_j^U V_{i3}V^*_{j3}y_t^2 + y_i^U \frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$ $y_j^U \frac{V_{i3}}{V^*_{j3}} y_t^6$	$y_j^U V_{i3}V^*_{j3}y_t^2 + y_i^U \frac{y_i^U y_j^U}{V_{i3}V^*_{j3}}$ $y_j^U \frac{V_{i3}}{V^*_{j3}} y_t^6$
$(\delta^d_{LR})_{ij}$	$y_j^D V^*_{3i}V_{3j}y_t^2$	$y_j^D \frac{V_{i3}}{V^*_{j3}}$	$y_j^D \frac{V_{i3}}{V^*_{j3}}$	$y_j^D V^*_{3i}V_{3j}y_t^2 + y_i^D \frac{y_i^D y_j^D}{V_{i3}V^*_{j3}}$ $y_j^D \frac{V^*_{3i}}{V_{3j}} y_t^4 y_b^2$	$y_j^D V^*_{3i}V_{3j}y_t^2$

Sizable flavor violation only in LR up-sector

LFV Models

Calibbi, Paradisi, RZ, in progress

Reconcile U(1) models for lepton masses with muon g-2 vs. LFV and eEDM

- Yukawa-like

$$\Delta W = (\lambda_e)_{ij} L_i E_j \Phi_{H_d} \qquad (\lambda_e)_{ij} \sim (y_e)_{ij}$$

- Type-I Seesaw

$$\Delta W = (y_\nu)_{ij} L_i N_j H_u + (\lambda_\nu)_{ij} L_i N_j \Phi_{H_u}$$

$(\lambda_\nu)_{ij} \sim (y_\nu)_{ij}$ or mixing $(\lambda_\nu)_{ij} = \tan\theta \, (y_\nu)_{ij}$

Neutrino U(1) Models

Large lepton mixing angles suggest
anarchical structure of neutrino mass matrix

In U(1) models achieved by small
charge differences of LH leptons

e.g. Altarelli & al '12

"Anarchy"

$$L_i = (0,0,0) + L_3 \qquad E_i = (3,2,0) \qquad \epsilon_A \approx 0.2 \div 0.3$$

$$\vdots$$

"Hierarchy"

$$L_i = (2,1,0) + L_3 \qquad E_i = (5,3,0) \qquad \epsilon_H \approx 0.4 \div 0.5$$

Predictions in FGM

Yukawa-like: $(\lambda_e)_{ij} \sim \epsilon^{L_i+E_j}$ Type-I: $(\lambda_\nu)_{ij} \sim \epsilon^{L_i+N_j}$

	$U(1)$	PC	Yukawa-like FGM	Type-I FGM
$\frac{\tilde{m}}{m_e}\mathrm{Im}(\delta_{LR})_{11}$	1	1	y_τ^4 (D)	0
$\frac{\tilde{m}}{m_\mu}(\delta_{LR})_{12}$	$\epsilon^{L_{13}-L_{23}}$	$\epsilon^{L_{13}-L_{23}}$	$y_\tau^2\epsilon^{L_{13}+L_{23}}$ (S)	$y_\tau^2\epsilon^{L_{13}+L_{23}+2N_3}$
$(\delta_{LL})_{12}$	$\epsilon^{L_{13}-L_{23}}$	$y_\tau^2\epsilon^{L_{13}+L_{23}}$	$y_\tau^2\epsilon^{L_{13}+L_{23}}$	$y_\tau^2\epsilon^{L_{13}+L_{23}+2N_3}$
$(\delta_{RR})_{12}$	$\epsilon^{E_1-E_2}$	$\epsilon^{E_1+E_2}$	$y_\tau^2\epsilon^{E_1+E_2}$	$y_\tau^4\epsilon^{E_1+E_2}\epsilon^{2(L_{13}+L_{23}+N_3)}$

$$A_e \sim \lambda_e\lambda_e^\dagger y_e^{diag} + y_e^{diag}\lambda_e^\dagger\lambda_e$$

$$\tilde{m}_L^2 \sim \mathbf{1} + \lambda_e\lambda_e^\dagger \qquad \tilde{m}_E^2 \sim \mathbf{1} + \lambda_e^\dagger\lambda_e$$

$$A_e \sim \lambda_\nu\lambda_\nu^\dagger y_e^{diag}$$

$$\tilde{m}_L^2 \sim \mathbf{1} + \lambda_\nu\lambda_\nu^\dagger \qquad \tilde{m}_E^2 \sim \mathbf{1} + y_e^{diag}\lambda_\nu\lambda_\nu^\dagger y_e^{diag}$$

LFV Constraints

$\mu \to e\gamma$ dominated by LL, same in FGM models

$$(\delta_{LL})_{12} \sim k\, y_\tau^2 \epsilon^{L_{13}+L_{23}}$$

k: $\mathcal{O}(1)$

Estimate for common "weak" SUSY scale

$$\frac{\tilde{m}}{100\,\mathrm{GeV}} \gtrsim 1.0\,\sqrt{k}\,\sqrt{\epsilon^{L_{13}+L_{23}}}\,\tan^{3/2}\beta$$

$\sqrt{\epsilon^{L_{13}+L_{23}}}$: Anarchy: 1, Hierarchy: 1/4

For very low tanβ well compatible
with ~100 GeV sleptons

eEDM Constraints

Bound recently increased by factor 12

$$|d_e| < 8.7 \times 10^{-29} e \text{ cm}$$ (ACME coll.)

$$\frac{\tilde{m}}{100\,\text{GeV}} \gtrsim 27 \sqrt{\frac{\tilde{m}}{m_e} \text{Im}(\delta_{LR})_{11}}$$

SUSY Partial Compositeness	~ 1
Yukawa-like FGM	$\sim y_\tau^2$
Type-I Seesaw FGM	0

Much weaker than LFV constraints

Towards a complete model

Issues to address:

- Split sleptons from squarks & gluinos → RG
- Higgs mass
- $\mu - B_\mu$

} → NMSSM

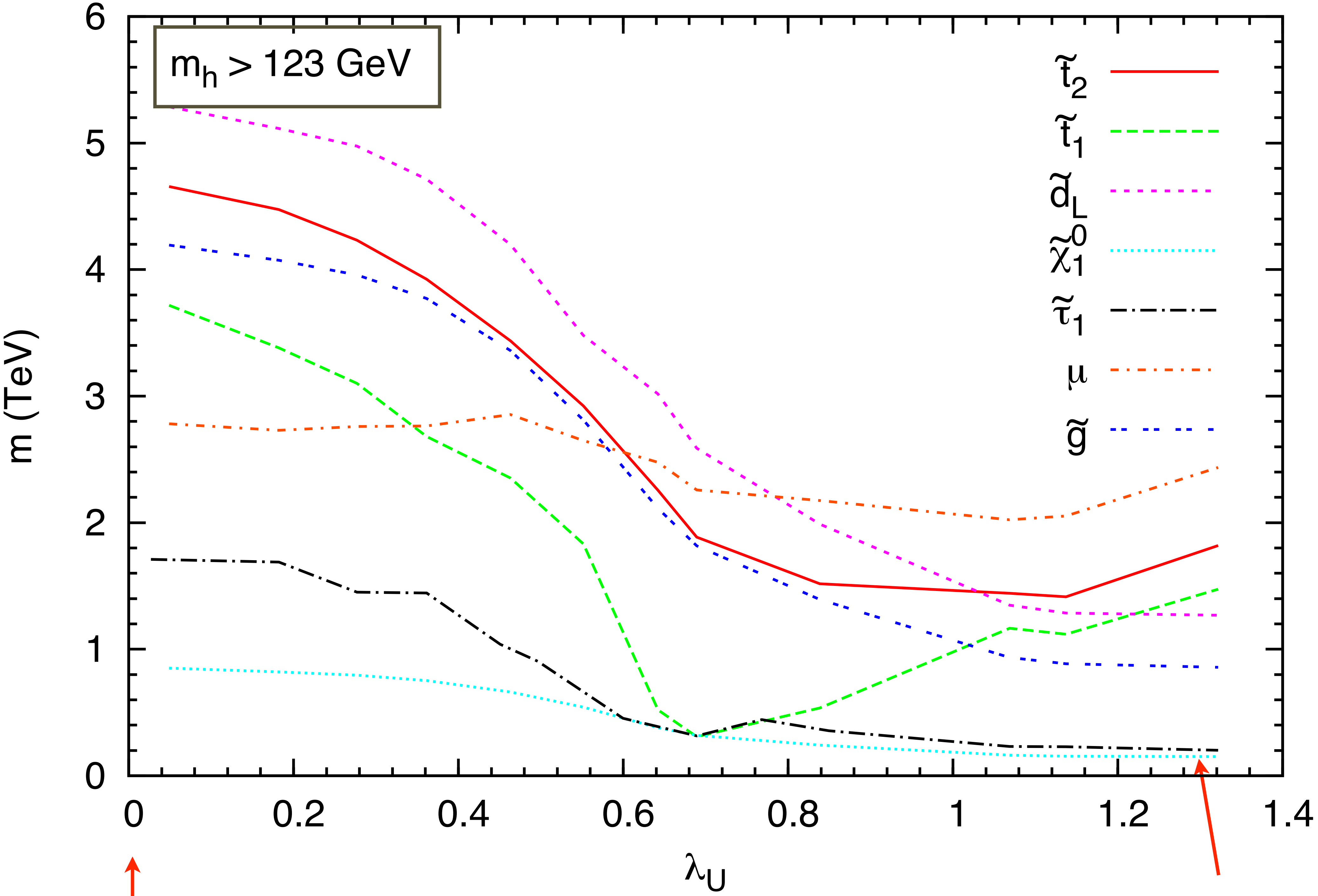
E.g. Type-I Seesaw Model in NMSSM:

$$\Delta W = \lambda S H_u H_d + k S^3 + (y_u)_{ij} Q_i U_j H_u + \lambda' S \Phi_{H_u} H_d + (\lambda_u)_{ij} Q_i U_j \Phi_{H_u}$$

↑ λ': helps to get negative m_S^2

↑ $(\lambda_u)_{ij}$: gives large A_t and drives LH sleptons light

Low-energy Spectrum FGM_U



minimal GM

light LH smuon
from induced FI

Summary

- FGM models are simple modifications of MGM that allow to test flavor models due to non-trivial sfermion flavor structure
- They have a built-in suppression of FV and flavor-blind phases that allows the implementation of U(1) flavor models compatible with ~100 GeV sleptons
- Explicit realization in NMSSM leads to complete model with very predictive SUSY spectrum

Anomalous muon magnetic moment

$$\delta a_\mu \approx 1.7 \times 10^{-9} \tan\beta \left(\frac{100\,\mathrm{GeV}}{\tilde{m}}\right)^2$$

⬇

$$\frac{\tilde{m}}{100\,\mathrm{GeV}} \lesssim \sqrt{\tan\beta} \begin{cases} 0.9 & 1\sigma \\ 1.2 & 2\sigma \end{cases}$$

Easy to reconcile with LFV constraint:

$$\sqrt{k}\underbrace{\sqrt{\epsilon^{L_{13}+L_{23}}}}\tan\beta \lesssim \begin{cases} 0.9 & 1\sigma \\ 1.2 & 2\sigma \end{cases}$$

Anarchy: 1, Hierarchy: 1/4

SU(5) invariant charge assignment

	Φ_{H_u}	Φ_T	$\overline{\Phi}_{H_d}$	$\overline{\Phi}_T$	H_u	H_d	X	Q, U, D, E, L
$U(1)$	1	~~0~~ 1	-1	~~0~~ -1	1	1	0	$-1/2$

$$\Delta W = (\lambda_{QQ})_{ij} Q_i Q_j \Phi_T + (\lambda_{UE})_{ij} U_i E_j \Phi_T$$

with $\quad \lambda_{QQ} \sim \lambda_{UE} \sim \lambda_U \sim y_U$

no dim 5 proton decay operators

$$K_{eff} \sim \underbrace{\frac{(\lambda_{QQ})_{11}(\lambda_{UE})_{11}}{M^2}}_{1/M_{eff}^2} Q_1^\dagger Q_1^\dagger U_1 E_1$$

$$M_{eff} \gtrsim 10^{15}\mathrm{GeV}$$

$$\Rightarrow \quad M \gtrsim 10^{10}\mathrm{GeV}$$

SU(5) invariant charge assignment