New physics scales and local family symmetry in a quartification SUSY GUT

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July 23rd, 2018

26th International Conference on Supersymmetry and Unification of Fundamental Interactions – Barcelona

Follow up of 1711.05199 and 1610.03642

Outline

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Motivation

Large mass and mixing hierarchies found in Nature

- $m_t\ ,\ m_h\ , m_z\ , m_w \sim 10^2$ GeV (EW scale)
- $m_t \gtrsim 10^{11} m_\nu$
- $m_e \gtrsim 10^5 m_\nu$
- $m_\tau \sim 10^{1.2} m_\mu \sim 10^{3.5} m_e$
- $m_t \sim 10^2 m_c \sim 10^{4.6} m_u$
- $m_t \sim 10^{1.6} m_b \sim 10^{3.2} m_s \sim 10^{4.8} m_d$
-

$$V_{\mathrm{CKM}} \sim \begin{pmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{pmatrix} + \text{Perturbations}\ .$$

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$$V_{\rm CKM} \sim \begin{pmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{pmatrix} + \text{Perturbations}\ .$$

IDEA

- Framework based on unification principles with a family symmetry and:
  - > hierarchial scales/VEVs,
  - > large parameters **tree-level generated**,
  - > small parameters and splitting **radiatively generated** (RGEs, threshold corrections).

The Quartification model (Q-GUT)

Our proposal: **Extend the SUSY trinification model (Georgi, Glashow and De Rujula 1984) with a local family $\mathrm{SU}(3)_\mathrm{F}$ symmetry**

$$[\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R}] \rtimes \mathbb{Z}_3 \times \mathrm{SU}(3)_\mathrm{F}$$

- Use the minimal field content:

$$(1,\mathbf{3},\overline{\mathbf{3}},\mathbf{3}) = (L^i)^l{}_r = \begin{pmatrix} H_u^0 & H_d^- & e_L \\ H_u^+ & H_d^0 & \nu_L \\ e_R & \nu_R & \phi \end{pmatrix}^i, \quad \begin{array}{l} (\mathbf{3},\overline{\mathbf{3}},1,\mathbf{3}) = (Q_L^i)^x{}_l = \begin{pmatrix} u_L^x & d_L^x & D_L^x \end{pmatrix}^i, \\ (\overline{\mathbf{3}},1,\mathbf{3},\mathbf{3}) = (Q_R^i)^r{}_x = \begin{pmatrix} u_{Rx}^c & d_{Rx}^c & D_{Rx}^c \end{pmatrix}^{\top\, i}. \end{array}$$

- Higgs and leptons unified in L due to SUSY
- $W_1 = \lambda_{27}\varepsilon_{ijk}\,(Q_L^i)^x{}_l\,(Q_R^j)^r{}_x\,(L^k)^l{}_r$
  - > **One** family of quarks and **all** leptons massless at tree-level $\rightarrow$ **radiatively generated**,
  - > Exact Yukawa unification for all three families.

So far no mass scale and due to SUSY protection there is no minimum in the scalar potential consistent with SSB.

- Solution is to introduce adjoint superfields inspired by the embedding of $[\mathrm{SU}(3)]^4$ into E_8.

$$(\mathbf{8},1,1,1) = \boldsymbol{\Delta}^a_C\,, \quad (1,\mathbf{8},1,1) = \boldsymbol{\Delta}^a_L\,, \quad (1,1,\mathbf{8},1) = \boldsymbol{\Delta}^a_R\,, \quad (1,1,1,\mathbf{8}) = \boldsymbol{\Delta}^a_F$$

-

$$W_2 = \sum_{A=\mathrm{L,R,C}} \left(\lambda_{\mathbf{78}} d_{abc} \Delta^a_A \Delta^b_A \Delta^c_A + \mu_{\mathbf{78}} \delta_{ab} \Delta^a_A \Delta^b_A\right) + \left(\lambda_{\mathbf{1}} d_{abc} \Delta^a_{\mathrm{F}} \Delta^b_{\mathrm{F}} \Delta^c_{\mathrm{F}} + \mu_{\mathbf{1}} \delta_{ab} \Delta^a_{\mathrm{F}} \Delta^b_{\mathrm{F}}\right)$$

- $\mu_{78} \sim \mu_1 \sim M_{\mathrm{GUT}}$
- No μ-like problem as Higgs sits in fundamental sector.

- Embedding of $[\mathrm{SU}(3)]^4$ into $\mathrm{E}_8 \Rightarrow$ **No gauge anomalies.**

$$[\mathrm{SU}(3)]^3 \times \mathrm{SU}(3)_\mathrm{F} \subset \mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{F} \subset \mathrm{E}_8$$

- We motivate our field content in the Katsuki et. al. $\mathbb{Z}_3$-orbifold for the breaking $\mathrm{E}_8 \to \mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{F}$ (Prog.Theor.Phys. 82 (1989) 171)
  - > massless physical $(\mathbf{27}, \mathbf{3})$,
  - > massive adjoint $(\mathbf{78}, 1) \oplus (1, \mathbf{8})$,
  - > $(\overline{\mathbf{27}}, \overline{\mathbf{3}})$ removed by orbifolding.
  - > No dangerous $(\mathbf{27}, \mathbf{3}) \cdot (\overline{\mathbf{27}}, \overline{\mathbf{3}})$ terms and low energy limit is chiral.

Outline

Q-GUT:
$[\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R}] \times \mathrm{SU}(3)_\mathrm{F}$

Region - I $\left\langle \widetilde{\Delta}^8_{\mathrm{L,R,F}} \right\rangle \sim M_\mathrm{GUT}$

SUSY-LRF:
$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{SU}(2)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{F}$

Region - II $\left\langle \widetilde{\phi}^3 \right\rangle \sim M^{(1)}_\mathrm{soft} \ll M_\mathrm{GUT}$ $\qquad T_{\mathrm{L+R}} = T^8_\mathrm{L} + T^8_\mathrm{R}\,, \quad T_\mathrm{S} = T^8_\mathrm{L} - T^8_\mathrm{R} - 2T_\mathrm{F}$

non-SUSY-LRF:
$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{SU}(2)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{L+R} \times \mathrm{U}(1)_\mathrm{S}$

Region - III $\left\langle \widetilde{\phi}^2 \right\rangle \sim M^{(2)}_\mathrm{soft} \lesssim M^{(1)}_\mathrm{soft}$ $\qquad T_\mathrm{V} = T^3_\mathrm{F} - \frac{1}{2\sqrt{2}} T_\mathrm{S}$

non-SUSY-LR:
$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{L+R} \times \mathrm{U}(1)_\mathrm{V}$

Region - IV $\langle \widetilde{\nu}^1_\mathrm{R} \rangle \sim M^{(3)}_\mathrm{soft} \lesssim M^{(2)}_\mathrm{soft}$ $\qquad T_\mathrm{Y} = \sqrt{3} T^3_\mathrm{R} + T_\mathrm{L+R}\,, \quad T_\mathrm{T} = T_\mathrm{V} - \frac{3}{2} T^3_\mathrm{R}$

3HDM EFTs:
$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y} \times \mathrm{U}(1)_\mathrm{T}$

Region - V $\langle S \rangle \sim m_{z'} \lesssim M^{(3)}_\mathrm{soft}$

3HDM EFTs:
$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$

- $\mathrm{U}(1)_{\mathrm{T}}$ is a family symmetry at low-energy scales.
- After $\left\langle \widetilde{\Delta}^{8}_{\mathrm{L,R,F}} \right\rangle$ VEVs, the components of adjoint superfieds remain heavy and are integrated out.
  - Neutral components still relevant for neutrino sector (See-Saw mechanism)
- After Q-GUT breaking the SUSY-LRF theory reads

$$W = \varepsilon_{ijk} \left\{ y_{1-3} \boldsymbol{\phi}^i \boldsymbol{D}_{\mathrm{L}}{}^j \boldsymbol{D}_{\mathrm{R}}{}^k + y_{4-6} (\boldsymbol{H}^i)^L{}_R (\boldsymbol{q}_{\mathrm{L}}{}^j)_L (\boldsymbol{q}_{\mathrm{R}}{}^k)^R \right.$$
$$\left. + y_{7-9} (\boldsymbol{E}_{\mathrm{L}}{}^i)^L (\boldsymbol{q}_{\mathrm{L}}{}^j)_L \boldsymbol{D}_{\mathrm{R}}{}^k + y_{10-12} (\boldsymbol{E}_{\mathrm{R}}{}^i)_R \boldsymbol{D}_{\mathrm{L}}{}^j (\boldsymbol{q}_{\mathrm{R}}{}^k)^R \right\} \,.$$

- Mass scale in the fundamental sector emerges solely from soft-SUSY breaking interactions.
- SUSY stabilizes the $M_{\mathrm{GUT}} \gg M^{(1)}_{\mathrm{soft}}$ hierarchy.

Why 3HDM EFTs?

The simplest scenario that automatically provides CKM mixing with Cabibbo form.

$$\langle L^1\rangle \sim \tfrac{1}{\sqrt{2}}\begin{pmatrix} v_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \omega & 0 \end{pmatrix} \qquad \langle L^2\rangle \sim \tfrac{1}{\sqrt{2}}\begin{pmatrix} v_2 & 0 & 0 \\ 0 & v_3 & 0 \\ 0 & 0 & f \end{pmatrix} \qquad \langle L^3\rangle \sim \tfrac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & p \end{pmatrix}.$$

$$M_{\mathrm{EW}} \sim v_{1,2,3} \ll \omega \lesssim f \lesssim p \lll M_{\mathrm{GUT}}, \qquad (p, f, \omega) \sim M_{\mathrm{soft}}^{(1,2,3)}$$

Classical approach: $(y_{1-12} \to \lambda_{27})$

$$m_{\mathrm{c,t}}^2 = \frac{1}{2}\lambda_{27}^2({v_1}^2 + {v_2}^2), \quad m_{\mathrm{b}}^2 = 3m_{\mathrm{s}}^2 = \frac{1}{2}\lambda_{27}^2 v_3^2, \quad m_{\mathrm{u,d}}^2 = 0, \quad \tan\theta_{\mathrm{C}} = \frac{v_1}{v_2}$$

$$m_{\mathrm{B}}^2 = \frac{1}{2}\lambda_{27}^2(2p^2 + f^2 + \omega^2), \quad m_{\mathrm{S}}^2 = \frac{1}{2}\lambda_{27}^2(p^2 + f^2), \quad m_{\mathrm{D}}^2 = \frac{1}{2}\lambda_{27}^2\omega^2.$$

Quantum effects - a schematic view:

$$\frac{m_t^2}{m_c^2} = \frac{{y'}_u^{(1)\,2} {v_1}^2 + {y'}_u^{(2)\,2} {v_2}^2}{y_u^{(1)\,2} {v_1}^2 + y_u^{(2)\,2} {v_2}^2}, \qquad \frac{m_b^2}{m_s^2} = \frac{{y'}_d^{(2)\,2}}{a_{11}^2 {y_d}^{(2)\,2}}, \qquad m_{u,d}^2 = \text{loop-suppressed.}$$

Full CKM mixing radiatively generated

$$\tan\theta_C = \frac{y_u^{(1)} v_1}{y_u^{(2)} v_2},$$

$$y_u^{(2)} \sim \frac{1}{16\pi^2} \frac{p^3 f A_{soft} M_{gau}}{\Lambda^6} y' y \lambda' \lambda$$

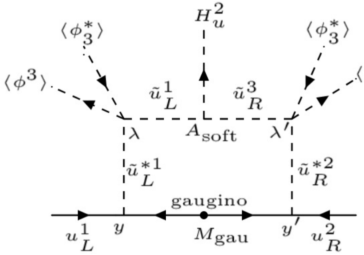


Figure: Example of radiative generation of Yukawa interactions: $y_u^{(2)} H_u^2 u_L^1 u_R^2$

- It is possible to get one generation of VLQ close to TeV scale $m_D \propto y_D \omega$
- Charged lepton masses all loop-generated: 3 chiral, $m_{chi} \propto v_{1,2,3}$, and 3 vector-like, $m_{vec} \propto \omega, f, p$.
- Neutrino masses contain both loop and See-Saw effects.

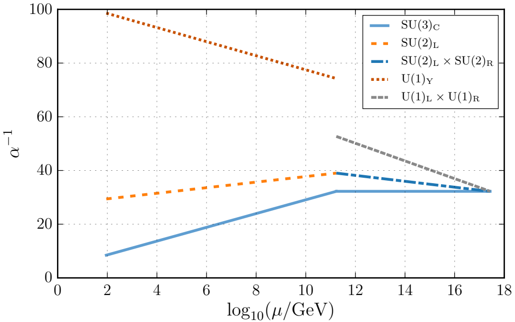
Outline

Estimation of $\omega = \langle \tilde{\nu}^1_R \rangle$, $f = \langle \tilde{\phi}^2 \rangle$, $p = \langle \tilde{\phi}^3 \rangle$ scales

Use 1-loop running and three-level matching to **estimate** scale hierarchies.

- Consider for simplicity $\omega \simeq f \simeq p = M_{\rm soft}$
- Unification condition: $\alpha^{-1}_{\tilde{g}_{L,R}}(M_{\rm GUT}) = \alpha^{-1}_{g_{L,R,C}}(M_{\rm GUT}) = \alpha^{-1}_{\rm U}$

$$\alpha_i^{-1}(\mu_2) = \alpha_i^{-1}(\mu_1) - \frac{b_i}{2\pi} \ln\left(\frac{\mu_2}{\mu_1}\right)$$



- Threshold conditions:

$$\alpha^{-1}_{\tilde{g}_{L+R}}(p) = \alpha^{-1}_{\tilde{g}_L}(p) + \alpha^{-1}_{\tilde{g}_R}(p)$$
$$\alpha^{-1}_{\tilde{g}_Y}(\omega) = \alpha^{-1}_{g_R}(\omega) + \frac{1}{3}\alpha^{-1}_{\tilde{g}_{L+R}}(\omega)$$
$$\alpha^{-1}_{\tilde{g}_Y}(m_z) = \cos^2\theta_W \alpha^{-1}_{\rm EM}$$
$$\alpha^{-1}_{\tilde{g}_L}(m_z) = \sin^2\theta_W \alpha^{-1}_{\rm EM},$$

- Solution:

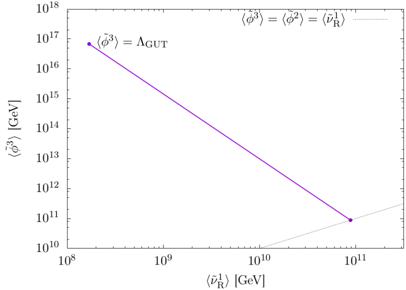
$$M_{\rm soft} \sim 8.8 \cdot 10^{10}\ \mathrm{GeV},$$
$$M_{\rm GUT} \sim 4.9 \cdot 10^{17}\ \mathrm{GeV},$$
$$\alpha^{-1}_{\rm U} \sim 31.5,$$

Effect of decoupling scales

- **Solve RGEs for** ω

$$\omega = m_Z \exp\left\{20.69 - \frac{1}{19}\ln\left(\frac{p}{f}\right)\left[4b^{\rm II}_{g_C} - 9b^{\rm II}_{g_L} + 3b^{\rm II}_{g_R} + b^{\rm II}_{\tilde{g}_{L+R}}\right] - \frac{1}{19}\ln\left(\frac{p}{f}\right)\left[4b^{\rm III}_{g_C} - 9b^{\rm III}_{g_L} + 3b^{\rm III}_{g_R} + b^{\rm III}_{\tilde{g}_{L+R}}\right]\right\}.$$

- To minimize ω need to maximise $b^{\rm II,III}_{g_C}$, $b^{\rm II,III}_{g_R}$, $b^{\rm II,III}_{\tilde{g}_{L+R}}$ and minimise $b^{\rm II,III}_{g_L}$.
  - > Scalar content in regions II and III without $(\tilde{u}_L, \tilde{d}_L)^{1,2,3}$, $(\tilde{e}_L, \tilde{\nu}_L)^{1,2,3}$ and $H^3_{u,d}$
  - > $b^{\rm II,III}_{g_C} = -\frac{13}{3}$, $b^{\rm II,III}_{g_L} = -\frac{2}{3}$, $b^{\rm II,III}_{g_R} = \frac{4}{3}$, $b^{\rm II,III}_{\tilde{g}_{L+R}} = \frac{40}{3}$.



- purple line: run to measured values
- ω decreases with increasing p
- **Optimal scenario when $p = f = \omega$**

How to lower the ω, f and p scales?

- Consider unification at E_6 level relaxing $\mathbb{Z}_3$ in the original $[\mathrm{SU}(3)]^3 \rtimes \mathbb{Z}_3$ unification.
- Consider correction to gauge-kinetic terms from dim-5 operators (Chakrabortty, Raychaudhuri 0812.2783 [hep-ph])

$$\mathcal{L}_{d5} = -\frac{\eta}{M_{\mathrm{Pl}}}\left[\frac{1}{4c} Tr\left(F_{\mu\nu}\Phi_{\boldsymbol{R}} F^{\mu\nu}\right)\right]$$

  - $\Phi_{\boldsymbol{R}}$ sits in $(\mathbf{78}\otimes\mathbf{78})_{\mathrm{sym}} = \mathbf{1}\oplus\mathbf{650}\oplus\mathbf{2430}$
  - $\mathbf{650}$ contains two $[\mathrm{SU}(3)]^3$ singlets which provide linearly independent contributions whose VEVs break $\mathrm{E}_6 \to [\mathrm{SU}(3)]^3$.
  - In general we consider $\Phi_{\boldsymbol{R}} = \kappa_1\Phi_{\mathbf{1}} + \kappa_{650}\Phi_{\mathbf{650}} + \kappa_{650'}\Phi_{\mathbf{650'}} + \kappa_{2430}\Phi_{\mathbf{2430}}$ with $\kappa_1^2 + \kappa_{650}^2 + \kappa_{650'}^2 + \kappa_{2430}^2 = 1$
- Unification condition modified

$$\alpha_{\mathrm{C}}^{-1}\left(1+\epsilon\delta_{\mathrm{C}}\right)^{-1} = \alpha_{\mathrm{L}}^{-1}\left(1+\epsilon\delta_{\mathrm{L}}\right)^{-1} = \alpha_{\mathrm{R}}^{-1}\left(1+\epsilon\delta_{\mathrm{R}}\right)^{-1} \qquad \epsilon \sim \frac{M_{\mathrm{E}_6}}{M_{\mathrm{Pl}}}$$

$$\delta_{\mathrm{C}} = -\tfrac{1}{\sqrt{2}}\kappa_{650} - \tfrac{1}{\sqrt{26}}\kappa_{2430}$$

$$\delta_{\mathrm{L,R}} = \tfrac{1}{2\sqrt{2}}\kappa_{650} \pm \tfrac{3}{2\sqrt{2}}\kappa_{650'} - \tfrac{1}{\sqrt{26}}\kappa_{2430}$$

A possible solution: (not unique)

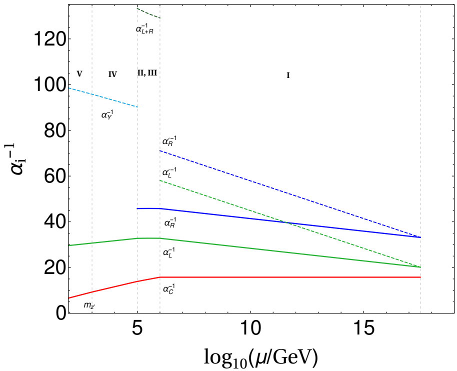
$$\epsilon = 0.66 \qquad M_{3333} = 10^{17.5}\ \text{GeV} \qquad p = 10^{6}\ \text{GeV}$$

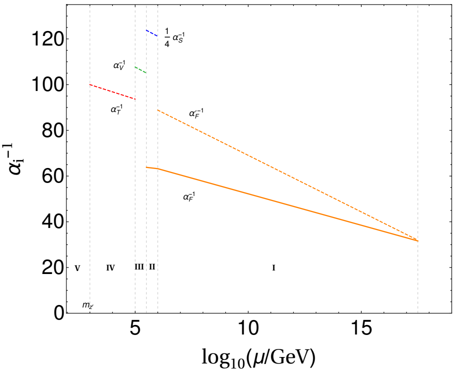
$$f = 10^{5.5}\ \text{GeV} \qquad \omega = 10^{5}\ \text{GeV} \qquad m_{z'} = 10^{3}\ \text{GeV}$$

$$\Phi_{R} = -0.61\Phi_{\mathbf{650}} + 0.75\Phi_{\mathbf{650'}} + 0.27\Phi_{\mathbf{2430}}$$

$$\alpha_{C}^{-1} = 1.15\alpha_{L}^{-1} = 1.89\alpha_{R}^{-1} \qquad \alpha_{L+R}^{-1} = \alpha_{L}^{\prime -1} + \alpha_{R}^{\prime -1} \qquad \alpha_{S}^{-1} = \alpha_{L}^{\prime -1} + \alpha_{R}^{\prime -1} + 4\alpha_{F}^{\prime -1}$$

$$\alpha_{V}^{-1} = \alpha_{F}^{-1} + \frac{1}{12}\alpha_{S}^{-1} \qquad \alpha_{T}^{-1} = \frac{4}{9}\alpha_{V}^{-1} + \alpha_{R}^{-1} \qquad \alpha_{Y}^{-1} = \frac{1}{3}\alpha_{L+R}^{-1} + \alpha_{R}^{-1}$$





This example considers:

- **Region I:** Keep all states in $\mathbf{27} = (\boldsymbol{L}, \boldsymbol{Q}_{\mathrm{L}}, \boldsymbol{Q}_{\mathrm{R}})$
- **Region II:** Keep all fermions in $\mathbf{27}$ and remove all squarks and $\tilde{\phi}^3$
- **Region III:** Keep all fermions in $\mathbf{27}$, all Higgs doublets and the $\mathrm{SU}(2)_{\mathrm{R}}$ doublet $\begin{pmatrix} e^1_{\mathrm{R}} & \nu^1_{\mathrm{R}} \end{pmatrix}$
- **Regions IV and V contain:** (low-scale phenomenology)
  - All chiral (SM-like) quarks and leptons,
  - One generation of VLQs,
  - Three generations of VLLs,
  - Three Higgs doublets
  - One $\mathrm{U}(1)_{\mathrm{T}}$-charged complex singlet $\rightarrow$ new Z' after $\mathrm{U}(1)_{\mathrm{T}}$-breaking

Full classification of low-energy scale 3HDMs

3HDM	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_T$
q_{Li}	**3**	**2**	$1/3$	$(3,-1,-1)$
u_{Ri}	**3**	**1**	$4/3$	$(0,4,4)$
d_{Ri}	**3**	**1**	$-2/3$	$(-6,2,-2)$
ℓ_{Li}	**1**	**2**	-1	$(3,-1,-1)$
e_{Li}	**1**	**1**	-2	$(-6,-2,-2)$
H_i	**1**	**2**	1	(x_1,x_2,x_3)

extra	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_T$
$D_{L,R}$	**3**	**1**	$-2/3$	-2
E_{Li}	**1**	**2**	-1	$(-1,-5,-5)$
E_{Ri}	**1**	**2**	-1	$(-5,-1,-1)$
ν_{Rk}	**1**	**1**	0	$(\underbrace{0,\cdots,0}_{17\text{ entries}}\vert\underbrace{4,\cdots,4}_{6\text{ entries}}\vert\underbrace{-4,\cdots,-4}_{9\text{ entries}})$
T_l	**1**	**3**	0	$(0,0)$
S	**1**	**1**	0	-4

$$(x_1,x_2,x_3) = \begin{cases} (5,1,5) & \text{Model I-A} \\ (1,5,1) & \text{Model I-B} \\ (5,1,-3) & \text{Model II} \end{cases}$$

- $U(1)_T$ must be broken by $\langle S \rangle$ providing a TeV scale Z' boson.
- **New exotic states offer rich phenomenology/cosmology:** EW-precision, flavour, collider, neutrino, dark-matter, baryogenesis, primordial GW.
  - > see my talk on Wed 25/07, Cosmology and GW section 1 (simplified to a THDSM inspired by Q-GUT).

Outline

Conclusions and outlook

- Constructed a framework based on the quartification group
- Discussed how to achieve a consistent low-energy, spectrum/mixing via hierarchial VEVs and quantum effects.

Direction 1

- Phenomenology and cosmology studies on Models I-(A and B) and II (standalone)
  - Search for all viable regions (flavour, EW-precision),
  - New physics: exotic states (VLF, flavour non-universal Z', scalars), DM, GW, EWBG.

Direction 2

- Linking Models I-(A and B) and II to the high scale Q-GUT
  - Matching and RG running analysis