E_6-extended SUSY trinification

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- Postulate a supersymmetric (SUSY) grand unified theory GUT valid at high energy scales
- Large degree of symmetry ⇒ Very few parameters
- Study to what degree the Standard Model (SM) can emerge in the low energy limit
- Hope to explain seemingly arbitrary features of the SM such as the number of families, fermion mass hierarchies, the almost Cabibbo form of the CKM matrix etc.
- The model was recently introduced in **Camargo-Molina, J.E., Morais, A.P., Ordell, A., Pasechnik, R., Sampaio, M., JW, Phys. Rev. D 95, 075031**
- We are currently finalizing a more detailed paper that will soon appear on arXiv
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- The trinification gauge group (Glashow, '84)

$$[\mathrm{SU}(3)_{\mathrm{L}} \times \mathrm{SU}(3)_{\mathrm{R}} \times \mathrm{SU}(3)_{\mathrm{C}}] \rtimes \mathbb{Z}_3^{(\mathrm{LRC})}$$
$$\downarrow$$
$$\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}} \times \mathrm{U}(1)_{\mathrm{L+R}}$$
$$\downarrow$$
$$\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}}$$

- Subgroup of $\mathrm{E}_6 \supset [\mathrm{SU}(3)]^3$
- SM fields sit in chiral superfields that are bi-fundamental representations of the gauge group: $\mathbf{L} \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1})$, $\mathbf{Q}_{\mathrm{L}} \sim (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{3})$, and $\mathbf{Q}_{\mathrm{R}} \sim (\mathbf{1}, \mathbf{3}, \bar{\mathbf{3}})$:

$$(\mathbf{L}^i)^l{}_r = \begin{pmatrix} \mathbf{H}_{11} & \mathbf{H}_{12} & \nu_{\mathrm{L}} \\ \mathbf{H}_{21} & \mathbf{H}_{22} & \mathbf{e}_{\mathrm{L}} \\ \nu^c_{\mathrm{R}} & \mathbf{e}^c_{\mathrm{R}} & \phi \end{pmatrix}^i, \quad \begin{aligned} (\mathbf{Q}^i_{\mathrm{L}})^x{}_l &= \begin{pmatrix} \mathbf{u}^x_{\mathrm{L}} & \mathbf{d}^x_{\mathrm{L}} & \mathbf{D}^x_{\mathrm{L}} \end{pmatrix}^i, \\ (\mathbf{Q}^i_{\mathrm{R}})^r{}_x &= \begin{pmatrix} \mathbf{u}^c_{\mathrm{R}x} & \mathbf{d}^c_{\mathrm{R}x} & \mathbf{D}^c_{\mathrm{R}x} \end{pmatrix}^{\top\ i}, \end{aligned}$$

- Each family can be arranged into an E_6 **27**-plet:

$$\mathbf{27}^i = (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1})^i \otimes (\mathbf{1}, \mathbf{3}, \bar{\mathbf{3}})^i \otimes (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{3})^i$$

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- The model can accomodate any quark and lepton masses and mixing angles **(Sayre et al. 2006)**
- Naturally light neutrinos via radiative see-saw with split-SUSY **(Cauet et al. 2011)**
- Gauge symmetry preserves baryon number $\Rightarrow$ No gauge-mediated proton decay **(Achiman and Stech, 1978) (Glashow and Kang 1984)**
- Well motivated as low energy versions of $E_8 \times E_8$ heterotic string theory **(Gross et al. 1985)**, E_6 orbifold **(Braam et al. 2010)** or $N = 8$ supergravity **(Cremmer et al. 1979)**.

- The most general superpotential contains a large number of free parameters $\Rightarrow$ Calculations become messy beyond tree-level!
- We introduce global $\mathrm{SU}(3)_\mathrm{F}$ symmetry
- With $\mathbf{L}^i$, $\mathbf{Q}^i_\mathrm{L}$ and $\mathbf{Q}^i_\mathrm{R}$ being $\mathrm{SU}(3)_\mathrm{F}$ triplets, the superpotential becomes extraordinarily simple:

$$W_{27} = \lambda_{27}\epsilon_{ijk}\mathbf{L}^i\mathbf{Q}^j_\mathrm{L}\mathbf{Q}^k_\mathrm{R}$$

- Only two free parameters in total: λ_{27} and the unified gauge coupling g_U.
- $\mathrm{SU}(3)_\mathrm{F}$ also fits neatly into an $\mathrm{E}_8 \subset \mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{F}$ embedding.

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A set of accidental symmetries follow from $\mathrm{SU}(3)_{\mathrm{F}}$:

- $\mathrm{U}(1)_{\mathrm{A}} \times \mathrm{U}(1)_{\mathrm{B}}$, where $\mathrm{U}(1)_{\mathrm{B}}$ gives a conserved baryon number.
- Left-Right parity! I.e. spatial inversion + swapping $\mathrm{SU}(3)_{\mathrm{L}} \leftrightarrow \mathrm{SU}(3)_{\mathrm{R}}$ representations:

$$(t,\vec{x}) \xrightarrow{\mathbb{P}} (t,-\vec{x}), \quad \theta^{\alpha} \xrightarrow{\mathbb{P}} -\mathrm{i}\theta^{\dagger}_{\dot{\alpha}}$$

$$(\mathbf{L}^i)^a{}_b \xrightarrow{\mathbb{P}} -(\mathbf{L}^*_i)_b{}^a, \quad (\mathbf{Q}^i_{\mathrm{L}})^c{}_a \overset{\mathbb{P}}{\leftrightarrow} (\mathbf{Q}^*_{\mathrm{R}\,i})_a{}^c \quad \text{(chiral superfields)}$$

$$\mathbf{V}_{\mathrm{L,R,C}} \xrightarrow{\mathbb{P}} -\mathbf{V}_{\mathrm{R,L,C}} \quad \text{(vector superfields)}$$

- ($\theta\theta \overset{\mathbb{P}}{\leftrightarrow} \theta^{\dagger}\theta^{\dagger}$ means that $W \overset{\mathbb{P}}{\leftrightarrow} W^*$ for $\theta^{\dagger}\theta^{\dagger}W + \theta\theta W^*$ to be parity invariant)
- Parity exists at the $\mathrm{SU}(3)$ level, contrary to common LR-symmetric constructions in which parity means $\mathrm{SU}(2)_{\mathrm{L}} \overset{\mathbb{P}}{\leftrightarrow} \mathrm{SU}(2)_{\mathrm{R}}$
- There are also Colour-Left and Right-Colour parity transformations (due to $\mathbb{Z}_3^{(\mathrm{LRC})}$)

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- This is all nice... but does it look anything like the SM at lower energies? No!
- W has $\mathrm{SU(3)_C}$ breaking flat directions, and no $[\mathrm{SU(3)}]^3 \to \mathrm{SU(3)_C} \times \mathrm{SU(2)_L} \times \mathrm{SU(2)_R} \times \mathrm{U(1)_{L+R}}$ VEV in $\tilde{L}$ is possible.
- Our solution: Add gauge adjoint chiral superfields $\mathbf{\Delta}_{\mathrm{L,R,C}}$ (transforming as the **8** under $\mathrm{SU(3)_{L,R,C}}$ respectively)
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Gauge Global

$$[\mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R} \times \mathrm{SU}(3)_\mathrm{C}] \rtimes \mathbb{Z}_3 \times \{\mathrm{SU}(3)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{A} \times \mathrm{U}(1)_\mathrm{B}\}$$

$$\downarrow \quad \langle \tilde{\Delta}^{8}_{\mathrm{L,R}} \rangle, \text{ GUT scale}$$

$$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{R} \times \{\mathrm{SU}(3)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{A} \times \mathrm{U}(1)_\mathrm{B}\}$$

- All components of $\boldsymbol{\Delta}_{\mathrm{L,R,C}}$ receive $\mathcal{O}$(GUT scale) masses and are integrated out.

- We can break SUSY softly by adding soft SUSY breaking (SSB) terms
- The SSB terms induce VEVs $\langle (\tilde{L}^3)^3{}_3 \rangle \equiv \langle \tilde{\phi}^3 \rangle$ and $\langle (\tilde{L}^i)^3{}_1 \rangle \equiv \langle \tilde{\nu}_{\mathrm{R}}^{\mathrm{c}\,i} \rangle$ that further breaks the symmetry (including parity).
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$$\downarrow \quad \langle \tilde{\phi}^3 \rangle, \text{ SSB scale}$$

$$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{L+R} \times \{\mathrm{SU}(2)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{X} \times \mathrm{U}(1)_\mathrm{Z} \times \mathrm{U}(1)_\mathrm{B}\}$$

$$\downarrow \quad \langle \tilde{\nu}^{\mathrm{c}\,i}_\mathrm{R} \rangle, \text{ SSB scale (tree-level / radiative?)}$$

$$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y} \times \{(\,?\,) \times \mathrm{U}(1)_\mathrm{B}\}$$

$$\downarrow \quad \text{(radiative?)}$$

$$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{U}(1)_\mathrm{E.M.} \times \{(\,?\,) \times \mathrm{U}(1)_\mathrm{B}\}$$

All symmetry breaking scales (including the elecro-weak) except v_GUT are controlled by SSB parameters $\Rightarrow$ No μ-problem!

Conclusions and outlook

- SUSY trinification GUT with global $\mathrm{SU}(3)_\mathrm{F}$ family symmetry.
- Few free parameters, full unification of Yukawa couplings in the fundamental sector
- Also enjoys baryon number conservation and symmetry under parity at the $\mathrm{SU}(3)$ level.
- Gauge adjoints $\boldsymbol{\Delta}_{\mathrm{L,R,C}}$ are needed to initiate the first symmetry breaking
- All other scales are controlled by SSB parameters $\Rightarrow$ naturally a hierarchy between the electro-weak scale and the GUT scale
- Future work: Run the parameters of the effective Left-Right symmetric theory towards lower energies using the renormalization group, to see if radiative symmetry breaking occur (i.e. if $m^2_{\tilde{\nu}_\mathrm{R}}, m^2_{H_i}$ turn negative at lower energies)

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