Phenomenology of Flavoured Trinification

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The SM is a tremendously successful theory that explains "boringly" well all its predictions!

However, it fails to...

- Explain neutrino masses
- Explain dark matter
- Explain CP violation and matter/anti-matter assymetry
- Explain the observed flavour structure

What Grand Unification can teach us about these problems?

Top-down approach: the story of Trinification

- The trinification gauge group (Glashow, '84)

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

- Subgroup of $\mathrm{E}_6 \supset [\mathrm{SU}(3)]^3$

- SM fields sit in chiral superfields that are bi-fundamental representatic 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 $\mathbf{Q}_{\mathrm{R}} \sim (\mathbf{1}, \mathbf{3}, \bar{\mathbf{3}})$:

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

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

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

Why Trinification

Positives:

- The model accommodates any quark and lepton masses and mixings (Sayre et al 2016)
- Naturally light neutrinos via radiative see-saw with split-SUSY (Cauet et al 2011)
- Gauge symmetry preserve baryon number, i.e. no gauge-mediated proton decay (Achiman&Stech'78; Glashow&Kang'84)
- Motivated as a low-energy version of E8xE8 heterotic string theory (Gross et al 1985)

- GUT scale fermion masses through $L \cdot L' \cdot L''$ type operators
  - Higher dimensional operators needed **(Cauet et al. 2011)**

Negatives:

- Considerable amount of particles and many couplings involved
  - Realistic calculations cumbersome
- Unmotivated Hierarchy between the trinification and the EW breaking scales (common to most GUTs)

Trinification-based models were left as the least developed GUT scenarios

"Flavoured" T-GUT approach

Build a SUSY GUT-scale framework in the top-down approach that:

> Features all **the basic advantages of the trinification GUTs** and resolves their major issues;

> Addresses **the μ-problem** of conventional MSSM-based approaches;

> Generates **larger masses** and **Cabibbo mixing** at **tree-level**;

> **Full CKM and light fermion masses** to be **radiatively generated**;

> **Adopts a seesaw mechanism** for **light active neutrinos, with no strong PMNS hierarchies**;

> **Unifies gauge interactions** and reduces parametric freedom in the Yukawa sector **(Yukawa unification)**.

References:

2004.114550,

2001.06383, 2001.04804,

1711.05199, 1610.03642,

1606.03492

"Flavoured" T-GUT with gauged family symmetry

Consider embedding Trinification into E6:

$$\mathcal{G} \xrightarrow{M_{\rm GUT}} \mathrm{E}_6 \times \mathrm{SU}(2)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{F} \xrightarrow{M_6} [\mathrm{SU}(3)]^3 \times \mathrm{SU}(2)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{F}$$
$$\xrightarrow{M_3} \mathrm{SU}(3)_\mathrm{C} \times [\mathrm{SU}(2) \times \mathrm{U}(1)]^2 \times \mathrm{SU}(2)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{F} \xrightarrow{M_\mathrm{S}} \ldots .$$

Scale hierarchy:

$$M_{\rm GUT} \gtrsim M_6 \gtrsim M_3 \qquad M_\mathrm{S} \ll M_3$$

Anomaly-free content:

$\mathbb{Z}_2$-even	$\mathbb{Z}_2$-odd
$\psi^{\mu i} = (\mathbf{27},\mathbf{2})_{(1)}$, $\psi^{\mu 3} = (\mathbf{27},\mathbf{1})_{(-2)}$	
$\mathcal{H}_\mathcal{U} = (\mathbf{1},\mathbf{2})_{(-1)}$, $\mathcal{H}_\mathcal{D} = (\mathbf{1},\mathbf{2})_{(+1)}$	$\mathcal{L}_k = (\mathbf{1},\mathbf{2})_{(-1)}$
$\mathcal{A} = (\mathbf{78},\mathbf{1})_{(0)}$	$\mathcal{E}_k = (\mathbf{1},\mathbf{1})_{(+2)}$
$\Sigma, \Sigma' = (\mathbf{650},\mathbf{1})_{(0)}$	$\mathcal{N}_k = (\mathbf{1},\mathbf{1})_{(0)}$
$\Psi = (\mathbf{2430},\mathbf{1})_{(0)}$	

possible source for Dark Matter

Massless sector dim-3 superpotential with universal Yukawa coupling:

$$W_{27} = \frac{1}{2}\lambda_{27} d_{\mu\nu\lambda}\, \varepsilon_{ij} \psi^{\mu i}\psi^{\nu j}\psi^{\lambda 3} = 0$$

$d_{\mu\nu\lambda}$ — completely symmetric $\qquad$ ε_{ij} — totally anti-symmetric

$$(\mathbf{27},\mathbf{2})_{(1)} \equiv \psi^{\mu i}, \qquad (\mathbf{27},\mathbf{1})_{(-2)} \equiv \psi^{\mu 3} \qquad \mu = 1, , \ldots , 27 \qquad i = 1, 2$$

Effects from higher dimensional operators become dominant!

$$W_\psi = \frac{\varepsilon_{ij}\psi^{\mu i}\psi^{\nu j}\psi^{\lambda 3}}{2M_{\rm GUT}}\left[\tilde{\lambda}_1 \Sigma^\alpha_\mu d_{\alpha\nu\lambda} + \tilde{\lambda}_2 \Sigma^\alpha_\nu d_{\alpha\mu\lambda} + \tilde{\lambda}_4 \Sigma'^\alpha_\mu d_{\alpha\nu\lambda} + \tilde{\lambda}_5 \Sigma'^\alpha_\nu d_{\alpha\mu\lambda}\right]$$

E6 and Trinification breaking

$$\mathcal{L}_{5D} = -\frac{\xi}{M_{\rm GUT}}\left[\frac{1}{4C}\,{\rm Tr}\left(\boldsymbol{F}_{\mu\nu}\cdot\tilde{\Phi}_{E_6}\cdot\boldsymbol{F}^{\mu\nu}\right)\right] \qquad \tilde{\Phi}_{E_6} \in \left(\mathbf{78}\otimes\mathbf{78}\right)_{\rm sym} = \mathbf{1}\oplus\mathbf{650}\oplus\mathbf{2430}$$

$\boldsymbol{\Sigma}$, $\boldsymbol{\Sigma}'$ and Ψ allow quadratic and cubic superpotential interactions

$$W_{E_6} \supset M_\Sigma {\rm Tr}\Sigma^2 + M_{\Sigma'}{\rm Tr}\Sigma'^2 + M_\Psi {\rm Tr}\Psi^2 + \lambda_\Sigma {\rm Tr}\Sigma^3 + \lambda_{\Sigma'}{\rm Tr}\Sigma'^3 + \lambda_\Psi {\rm Tr}\Psi^3$$
$$+ \text{ crossed terms}$$

and can develop VEVs obeying the relation

$$v_{E_6}^2 = v_\Sigma^2 + v_{\Sigma'}^2 + v_\Psi^2 \equiv \left(k_\Sigma^2 + k_{\Sigma'}^2 + k_\Psi^2\right) v_{E_6}^2\,, \qquad k_\Sigma^2 + k_{\Sigma'}^2 + k_\Psi^2 = 1$$

$$k_\Psi \propto \frac{\langle\mathbf{2430}\rangle}{M_6}\,, \qquad k_\Sigma \propto \frac{\langle\mathbf{650}\rangle}{M_6}\,, \qquad k_{\Sigma'} \propto \frac{\langle\mathbf{650}'\rangle}{M_6}$$

$$\alpha_{3C}^{-1}(1+\zeta\delta_C)^{-1} = \alpha_{3L}^{-1}(1+\zeta\delta_L)^{-1} = \alpha_{3R}^{-1}(1+\zeta\delta_R)^{-1}\,, \qquad \zeta\sim 1$$

$$\alpha_{3A}^{-1} = \frac{4\pi}{g_A^2}\,, \qquad \delta_C = -\frac{1}{\sqrt{2}}k_\Sigma - \frac{1}{\sqrt{26}}k_\Psi\,, \qquad \delta_{L,R} = \frac{1}{2\sqrt{2}}k_\Sigma \pm \frac{3}{2\sqrt{2}}k_{\Sigma'} - \frac{1}{\sqrt{26}}k_\Psi$$

Chakrabortty, Raychaudhuri Phys.Lett. B673 (2009) 57-62

Below E6 breaking scale:

$$W_{78} = \sum_{A=L,R,C}\left[\frac{1}{2}\mu_{78}{\rm Tr}\boldsymbol{\Delta}_A^2 + \frac{1}{3!}\mathcal{Y}_{78}{\rm Tr}\boldsymbol{\Delta}_A^3\right] + \mu_{78}{\rm Tr}(\boldsymbol{\Xi}\boldsymbol{\Xi}') + \sum_{A=L,R,C}\mathcal{Y}_{78}{\rm Tr}(\boldsymbol{\Xi}\boldsymbol{\Xi}'\boldsymbol{\Delta}_A)$$

	$\mathrm{SU(3)_L}$	$\mathrm{SU(3)_R}$	$\mathrm{SU(3)_C}$	$\mathrm{SU(2)_F}$	$\mathrm{U(1)_F}$
$\boldsymbol{\Delta}_L$	$\mathbf{8}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0
$\boldsymbol{\Delta}_R$	$\mathbf{1}$	$\mathbf{8}$	$\mathbf{1}$	$\mathbf{1}$	0
$\boldsymbol{\Delta}_C$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{8}$	$\mathbf{1}$	0
$\boldsymbol{\Xi}$	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{1}$	0
$\boldsymbol{\Xi}'$	$\overline{\mathbf{3}}$	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	0

$$\mathrm{SU(3)_L\times SU(3)_R \overset{v_{L,R}}{\to} SU(2)_L\times SU(2)_R\times U(1)_L\times U(1)_R} \qquad v_L = v_R \equiv M_3$$

Trinification EFT: Yukawa sector

E$_6$ **27**-plet contains three trinification $\mathrm{SU}(3)_\mathrm{L}\times\mathrm{SU}(3)_\mathrm{R}\times\mathrm{SU}(3)_\mathrm{C}$ bi-triplets:

$$\mathbf{27}\supset(\mathbf{3},\bar{\mathbf{3}},\mathbf{1})\oplus(\bar{\mathbf{3}},\mathbf{1},\mathbf{3})\oplus(\mathbf{1},\mathbf{3},\bar{\mathbf{3}})\equiv \boldsymbol{L}\oplus\boldsymbol{Q}_\mathrm{L}\oplus\boldsymbol{Q}_\mathrm{R}$$

After $\langle\boldsymbol{\Sigma}\rangle$ and $\langle\boldsymbol{\Sigma}'\rangle$ VEVs the massless superpotential reduces to

Accidental symmetries

	$\mathrm{U}(1)_\mathrm{W}$	$\mathrm{U}(1)_\mathrm{B}$
$\boldsymbol{L}$	$+1$	0
$\boldsymbol{Q}_\mathrm{L}$	$-1/2$	$+1/3$
$\boldsymbol{Q}_\mathrm{R}$	$-1/2$	$-1/3$

$$\boxed{W_\mathrm{eff}=\varepsilon_{ij}(\mathcal{Y}_1\boldsymbol{L}^i\cdot\boldsymbol{Q}^3_\mathrm{L}\cdot\boldsymbol{Q}^j_\mathrm{R}-\mathcal{Y}_2\boldsymbol{L}^i\cdot\boldsymbol{Q}^j_\mathrm{L}\cdot\boldsymbol{Q}^3_\mathrm{R}+\mathcal{Y}_2\boldsymbol{L}^3\cdot\boldsymbol{Q}^i_\mathrm{L}\cdot\boldsymbol{Q}^j_\mathrm{R})}$$

$$\mathcal{Y}_1=\zeta\frac{k_{\Sigma'}}{\sqrt{6}}\tilde{\lambda}_{45},\quad \mathcal{Y}_2=\zeta\frac{k_{\Sigma}}{2\sqrt{2}}(\tilde{\lambda}_{21}-\tilde{\lambda}_{45})$$

$$\tilde{\lambda}_{ij}\equiv\tilde{\lambda}_i-\tilde{\lambda}_j \qquad \zeta\simeq M_6/M_{3\mathrm{F}}$$

$$\zeta\sim 1 \qquad k_\Sigma\simeq -k_{\Sigma'} \qquad \tilde{\lambda}_{21}\simeq\tilde{\lambda}_{45}$$

Compressed hierarchy + steep E6 RG evolution suggest:

$$\boxed{\mathcal{Y}_2\ll\mathcal{Y}_1\sim 1}$$

tree-level quark hierarchies are secured!

$$\boxed{\frac{\mathcal{Y}_1}{\mathcal{Y}_2}=\frac{m_\mathrm{t}}{m_\mathrm{c}}\approx\frac{m_\mathrm{b}}{m_\mathrm{s}}\approx\frac{m_\mathrm{B}}{m_\mathrm{D,S}}\sim\mathcal{O}(100)}$$

- SUSY unifies Higgs and Leptons in $\boldsymbol{L}$
- Only two universal Yukawa couplings at trinification scale
- Only two quark generations acquire tree-level masses

Quark spectrum: more details

The most generic VeV setting:

$$\left\langle \tilde{L}^1 \right\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u_1 & 0 & 0 \\ 0 & d_1 & e_1 \\ 0 & \omega & s_1 \end{pmatrix}, \quad \left\langle \tilde{L}^2 \right\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u_2 & 0 & 0 \\ 0 & d_2 & e_2 \\ 0 & s_2 & f \end{pmatrix}, \quad \left\langle \tilde{L}^3 \right\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u_3 & 0 & 0 \\ 0 & d_3 & e_3 \\ 0 & s_3 & p \end{pmatrix}$$

Up-quark sector:

light up-type quarks!

$$M_{\rm u} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3\mathcal{Y}_2 & u_2\mathcal{Y}_2 \\ -u_3\mathcal{Y}_2 & 0 & -u_1\mathcal{Y}_2 \\ -u_2\mathcal{Y}_1 & u_1\mathcal{Y}_1 & 0 \end{pmatrix} \qquad m_{\rm u} = 0 \qquad m_{\rm c}^2 = \tfrac{1}{2}\mathcal{Y}_2^2\left(u_1^2 + u_2^2 + u_3^2\right) \qquad m_{\rm t}^2 = \tfrac{1}{2}\left[\mathcal{Y}_1^2\left(u_1^2 + u_2^2\right) + \mathcal{Y}_2^2 u_3^2\right]$$

vector-like quarks!

Down-quark sector (before EWSB):

$$\left(d_{\rm L}^i \quad D_{\rm L}^i\right)^\top M_d \left(d_{\rm R}^i \quad D_{\rm R}^i\right)$$

$$M_{\rm d}^{6\times 6} \simeq \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & p\mathcal{Y}_2 & f\mathcal{Y}_2 \\ 0 & 0 & -\omega\mathcal{Y}_2 & -p\mathcal{Y}_2 & 0 & 0 \\ 0 & w\mathcal{Y}_1 & 0 & -f\mathcal{Y}_1 & 0 & 0 \end{pmatrix}$$

$$m_{\rm D/S}^2 \simeq \frac{1}{2}(f^2 + p^2)\mathcal{Y}_2^2 \,, \quad m_{\rm S/D}^2 \simeq \frac{\omega^2(f^2 + p^2 + \omega^2)}{2(f^2 + \omega^2)}\mathcal{Y}_2^2 \,,$$

$$m_{\rm B}^2 \simeq \frac{1}{2}(f^2 + \omega^2)\mathcal{Y}_1^2 + \frac{f^2 p^2}{2(f^2 + \omega^2)}\mathcal{Y}_2^2 \,.$$

Scenarios	ω [TeV]	f [TeV]	p [TeV]	$m_{\rm D}$ [TeV]	$m_{\rm S}$ [TeV]	$m_{\rm B}$ [TeV]
$\omega \sim f \sim p$	$100-1000$	$100-1000$	$100-1000$	$1-10$	$1-10$	$100-1000$
$\omega \sim f \ll p$	$10-100$	$10-100$	$100-1000$	$1-10$	$1-10$	$10-100$
$\omega \ll f \sim p$	100	1000	1000	1	10	1000

Down-quark sector (after EWSB):

$$M_{\rm d}^{6\times 6} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & d_3\mathcal{Y}_2 & d_2\mathcal{Y}_2 & 0 & 0 & 0 \\ -d_3\mathcal{Y}_2 & 0 & -d_1\mathcal{Y}_2 & 0 & 0 & 0 \\ -d_2\mathcal{Y}_1 & d_1\mathcal{Y}_2 & 0 & 0 & 0 & 0 \\ 0 & s_3\mathcal{Y}_2 & s_2\mathcal{Y}_2 & 0 & p\mathcal{Y}_2 & f\mathcal{Y}_2 \\ -s_3\mathcal{Y}_2 & 0 & -\omega\mathcal{Y}_2 & -p\mathcal{Y}_2 & 0 & -s_1\mathcal{Y}_2 \\ -s_2\mathcal{Y}_1 & w\mathcal{Y}_1 & 0 & -f\mathcal{Y}_1 & s_1\mathcal{Y}_1 & 0 \end{pmatrix}$$

$$M_{\rm d} \approx \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & \mathcal{Y}_2\frac{d_3 f - d_2 p}{\sqrt{f^2+p^2+\omega^2}} \\ -d_3\mathcal{Y}_2 & 0 & d_1\mathcal{Y}_2\frac{p}{\sqrt{f^2+p^2+\omega^2}} \\ -d_2\mathcal{Y}_1 & 0 & d_1\mathcal{Y}_1\frac{f}{\sqrt{f^2+p^2+\omega^2}} \end{pmatrix}$$

light down-type quarks!

$$m_{\rm d} = 0 \,, \qquad m_{\rm s}^2 = \frac{(d_3 f - d_2 p)^2}{2(f^2 + p^2 + \omega^2)}\mathcal{Y}_2^2 \,, \qquad m_{\rm b}^2 = \frac{1}{2}(d_2^2\mathcal{Y}_1^2 + d_3^2\mathcal{Y}_2^2)$$

Quark mixing

$$d_1 = 0$$

CKM mixing:

$$V_{\rm CKM} \equiv L_{\rm u} L_{\rm d}^{\dagger} = \begin{pmatrix} \frac{d_2 u_2 \mathcal{Y}_1^2 + d_3 u_3 \mathcal{Y}_2^2}{\sqrt{\mathcal{A}\mathcal{B}}} & -\frac{u_1 \mathcal{Y}_1}{\sqrt{\mathcal{A}}} & \frac{(d_2 u_3 - d_3 u_2)\mathcal{Y}_1 \mathcal{Y}_2}{\sqrt{\mathcal{A}\mathcal{B}}} \\ -\frac{d_2 u_1 \mathcal{Y}_1}{\sqrt{\mathcal{B}\mathcal{C}}} & -\frac{u_2}{\sqrt{\mathcal{C}}} & \frac{d_3 u_1 \mathcal{Y}_2}{\sqrt{\mathcal{B}\mathcal{C}}} \\ \frac{(\mathcal{C} d_3 - d_2 u_2 u_3)\mathcal{Y}_1 \mathcal{Y}_2}{\sqrt{\mathcal{A}\mathcal{B}\mathcal{C}}} & \frac{u_1 u_3 \mathcal{Y}_2}{\sqrt{\mathcal{A}\mathcal{C}}} & \frac{\mathcal{C} d_2 \mathcal{Y}_1^2 + d_3 u_2 u_3 \mathcal{Y}_2^2}{\sqrt{\mathcal{A}\mathcal{B}\mathcal{C}}} \end{pmatrix}$$

$$\mathcal{A} = \mathcal{C}\mathcal{Y}_1^2 + u_3^2 \mathcal{Y}_2^2 \,, \qquad \mathcal{B} = d_2^2 \mathcal{Y}_1^2 + d_3^2 \mathcal{Y}_2^2 \,, \qquad \mathcal{C} = u_1^2 + u_2^2 \,.$$

For consistency with the up-quark spectrum, we require $\mathcal{Y}_2 \ll \mathcal{Y}_1$

$$V_{tb} \simeq 1 - \left(\frac{\mathcal{Y}_2}{\mathcal{Y}_1}\right)^2 \frac{d_3^2 \mathcal{C} + d_2 u_3 (d_2 u_3 - 2 d_3 u_2)}{2 d_2^2 \mathcal{C}}$$

Minimal 3HDM limit:

$$u_3 \to 0 \qquad d_3 \to 0 \qquad |V_{\rm CKM}| = \begin{pmatrix} \cos\theta_C & \sin\theta_C & 0 \\ \sin\theta_C & \cos\theta_C & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \theta_C = \arctan\left(\frac{u_1}{u_2}\right)$$

Fully compressed $\omega \sim f \sim p$ scenario

$$p = 220 \text{ TeV}\,, \quad f = 210 \text{ TeV}\,, \quad \omega = 200 \text{ TeV}$$

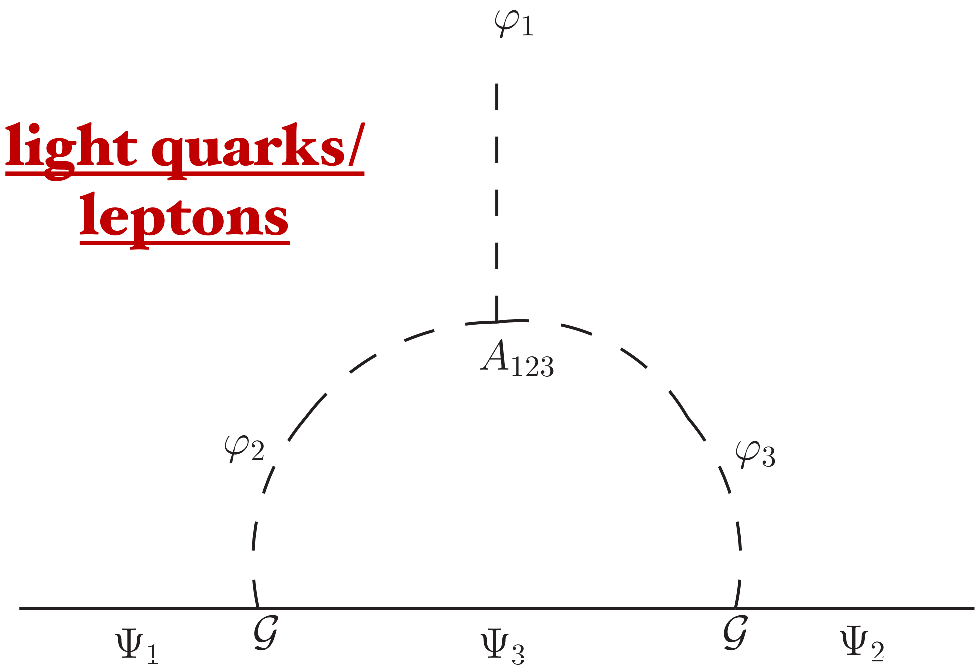
$$m_{\rm s} = 0.017 \text{ GeV}\,, \ m_{\rm b} = 4.15 \text{ GeV}\,, \ m_{\rm D} = 1.3 \text{ TeV}\,, \ m_{\rm S} = 1.5 \text{ TeV}\,, \ m_{\rm B} = 211.0 \text{ TeV}$$

$$|V_{\rm CKM}| \simeq \left(\begin{array}{ccc|ccc} 0.97 & 0.24 & 2.31\times10^{-5} & 4.36\times10^{-6} & 7.29\times10^{-7} & \sim 0 \\ 0.24 & 0.97 & 9.23\times10^{-5} & 1.74\times10^{-5} & 2.92\times10^{-6} & \sim 0 \\ 0 & 9.51\times10^{-5} & 1 & 5.55\times10^{-5} & 1.15\times10^{-5} & 6.47\times10^{-7} \end{array}\right)$$

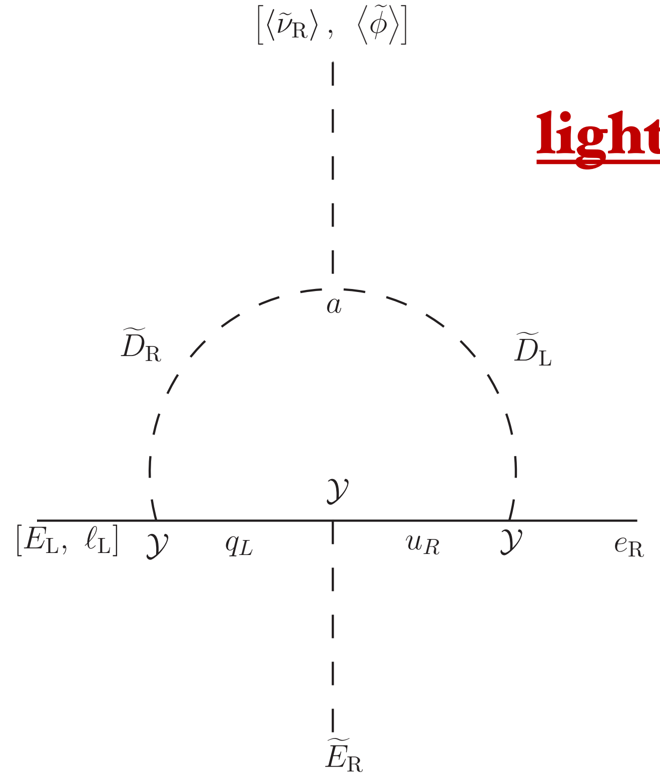
Good opportunity to probe the model at the LHC or future colliders

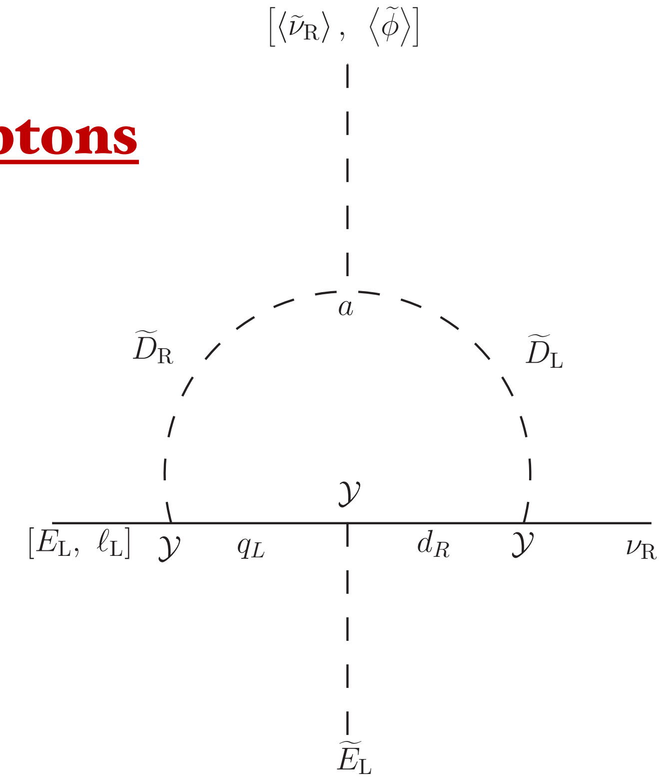
Radiative generation of charge lepton spectra

light quarks/ leptons



light leptons

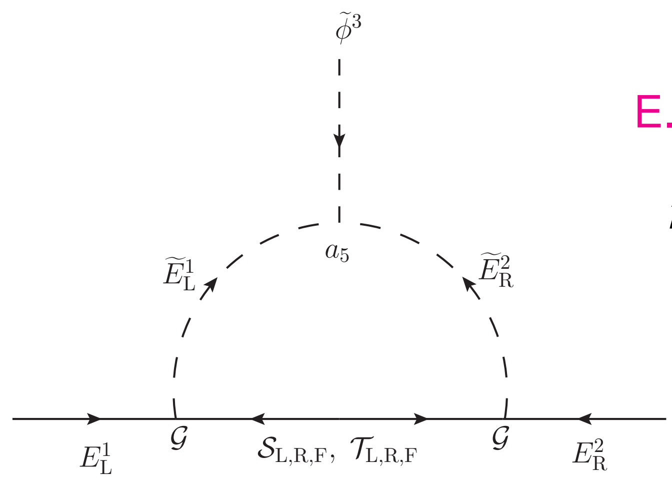


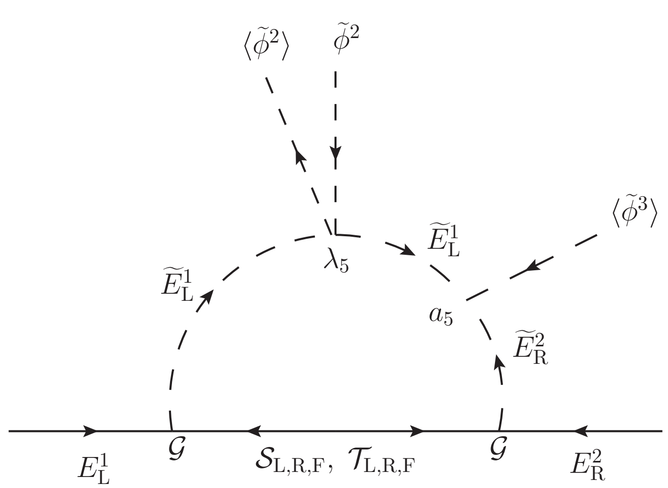


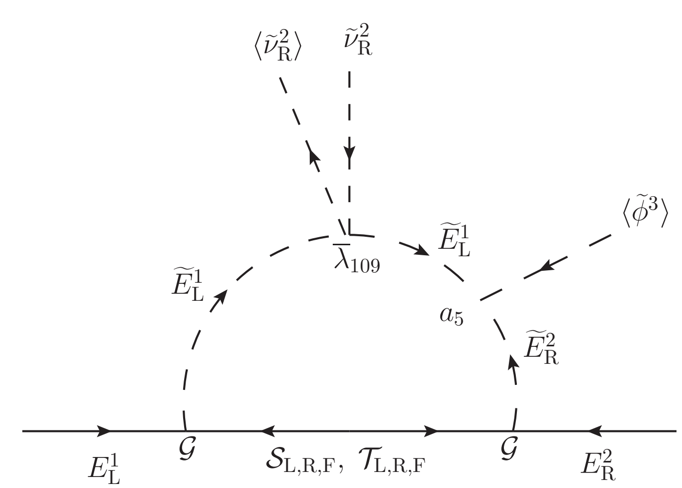
E.g.: $p \sim 10^3$ TeV, $\omega \sim 100$ TeV and $\kappa_i \sim 10^{-3}$ to 10^{-2}:

$m_{T,M} \sim 1$ to 10 TeV $\qquad m_E \sim 0.1$ to 1 TeV

heavy vector-like leptons (VLLs)







Emergence of SM-like EFT

$\mathrm{E}_6 \times \mathrm{SU}(2)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{F}$

$\downarrow \; \langle \Phi_{\mathrm{E}_6} \rangle \equiv M_6$

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

$\downarrow \; \left\langle \widetilde{\Delta}^8_{\mathrm{L,R}} \right\rangle \equiv M_3$

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

$\downarrow \; \left\langle \widetilde{\phi}^3 \right\rangle \equiv p \sim M_\mathrm{Soft}$

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

$\downarrow \; \left\langle \widetilde{\phi}^2 \right\rangle \equiv f$

$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{L+R} \times \mathrm{U}(1)_\mathrm{V}$

$\downarrow \; \langle \widetilde{\nu}^1_\mathrm{R} \rangle \equiv \omega$

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

$\downarrow \; \langle \widetilde{\nu}^{2,3}_\mathrm{R} \rangle, \left\langle \widetilde{\phi}^1 \right\rangle \equiv s_{1,2,3}$

$G_\mathrm{SM} = \mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$

No proton decay below E6 scale!

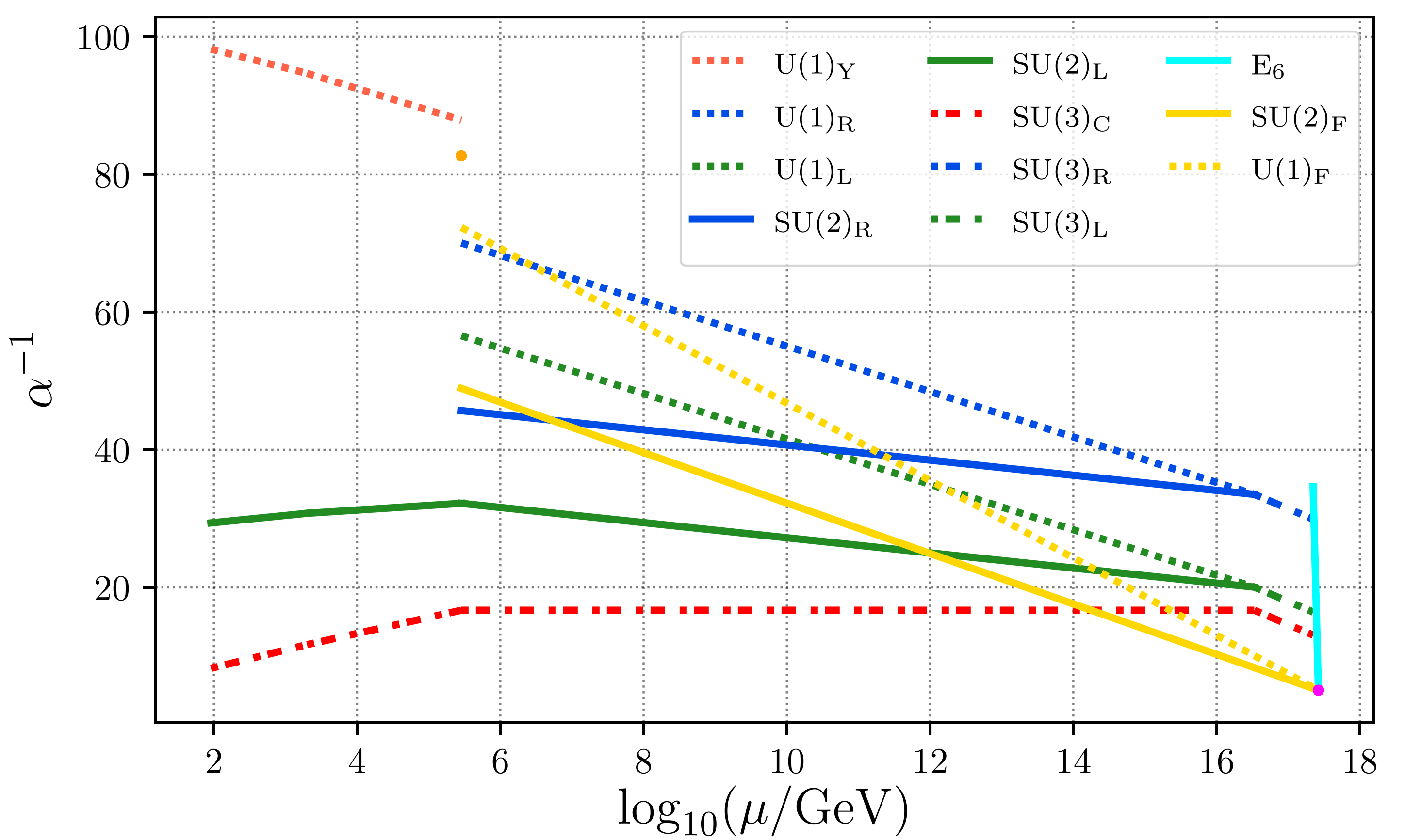
$\mathbb{P}_\mathrm{B}$-parity $\quad \mathbb{P}_\mathrm{B} = (-1)^{2W+2S} = (-1)^{3B+2S}$

- SUSY theory, broken SUSY, broken flavour
- Between M_6 and M_3: **Steep running** due to $\boldsymbol{\Psi}$, $\boldsymbol{\Sigma}$, $\boldsymbol{\Sigma'}$
- Between M_3 and M_Soft: Trinification running including $\boldsymbol{L}$, $\boldsymbol{Q}_\mathrm{L}$, $\boldsymbol{Q}_\mathrm{R}$, $\boldsymbol{\Delta}_\mathrm{L,R,C}$
- **Soft scales compressed** $s = \omega = f = p$

Low scale G_SM theory

1. Three Higgs doublets - 3HDM
2. Two generations of VLQ below the soft scale
3. Three generations of VLL below the soft scale

$M_\mathrm{S} \lesssim 10^3$ TeV, $\quad M_\mathrm{GUT} = 10^{16} - 10^{18}$ GeV $\quad M_\mathrm{EW} \ll M_\mathrm{S}$



Concluding remarks

- We developed a novel Flavoured Trinification GUT framework giving rise to a SM-like EFT, with a realistic flavour structure in charged fermion and neutrino sectors

- The framework offers interesting implications for flavour and collider physics, primarily through vector-like fermions and scalar leptoquarks (LQs)