Sculpting the Standard Model from low-scale Gauge-Higgs-Matter Grand Unification

António P. Morais[1]

Co-authors: Alfredo Aranda, Francisco J. de Anda and Roman Pasechnick

[1] **Departamento de Física da Universidade de Aveiro and Center for Research and Development in Mathematics and Applications (CIDMA)**

September 1st, 2021

Workshop on the Standard Model and Beyond – Corfu Summer Institute

2107.05495, 2107.05421

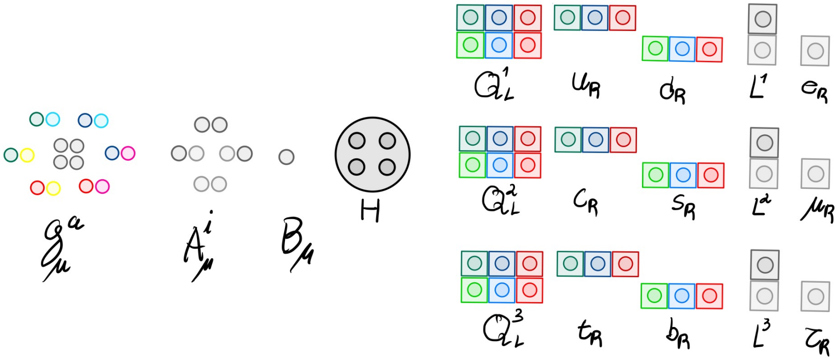
PTDC/FIS-PAR/31000/2017

FCT Fundação para a Ciência e a Tecnologia CENTRO 2020 PORTUGAL 2020 UNIÃO EUROPEIA Fundos Europeus Estruturais e de Investimento universidade de aveiro

The Standard Model

Gauge: $SU(3)_C \times SU(2)_L \times U(1)_Y$

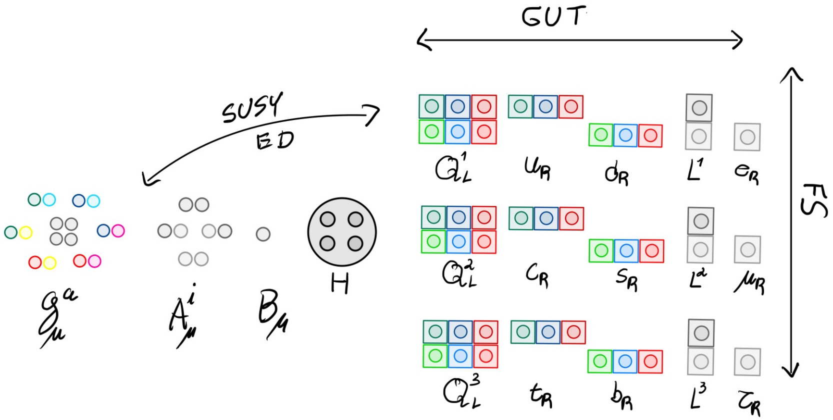
Poincarè: $T^4 \ltimes SO(3,1)$



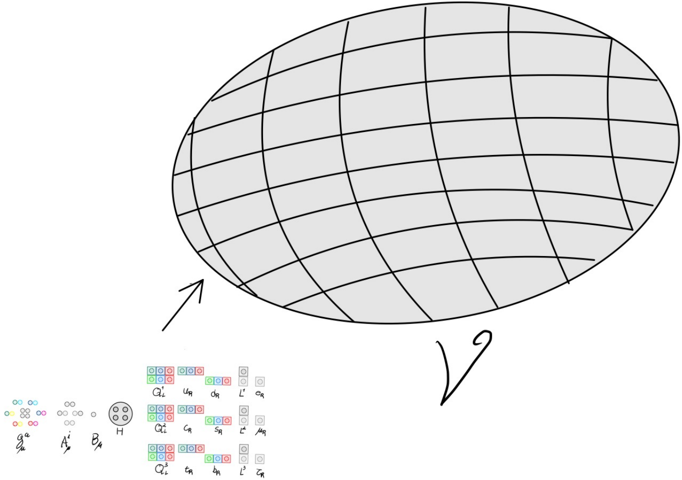
Beyond the Standard Model

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

Poincarè: $T^4 \ltimes \mathrm{SO}(3,1)$

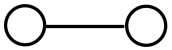


Full Unification



The Exceptional chain - SM

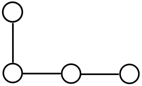
Buchmuller, Napoly, Phys. Lett. B 163 (1985); Koca, Lect. Notes Phys. 180 (2005); Nilles, Eur.Phys.J.C 74 (2014) 2712



$T^4 \ltimes SO(3,1)$	$SU(3)_C \times SU(2)_L \times U(1)_Y \sim E_3$
$(\mathbf{1})$	$(\mathbf{1},\mathbf{2},3)$
$(\mathbf{2})$	$3\times(\mathbf{1},\mathbf{2},-3)+3\times(\mathbf{1},\mathbf{1},6)+3\times(\bar{\mathbf{3}},\mathbf{1},-4)+3\times(\bar{\mathbf{3}},\mathbf{1},2)+3\times(\mathbf{3},\mathbf{2},1)$
$(\mathbf{4})$	$(\mathbf{8},\mathbf{1},0)+(\mathbf{1},\mathbf{3},0)+(\mathbf{1},\mathbf{1},0)$

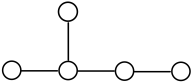
The Standard Model

[Georgi, Glashow, Phys.Rev.Lett. 32 (1974) 438-441]



$T^4 \ltimes SO(3,1)$	$SU(5) \sim E_4$
$(\mathbf{1})$	$(\bar{\mathbf{5}})$
$(\mathbf{2})$	$3 \times (\bar{\mathbf{5}}) + 3 \times (\mathbf{10})$
$(\mathbf{4})$	$(\mathbf{24})$

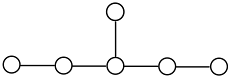
Gauge Field Unification



$T^4 \ltimes SO(3,1)$	$SO(10) \sim E_5$
$(\mathbf{1})$	$(\mathbf{10})$
$(\mathbf{2})$	$3 \times (\mathbf{16})$
$(\mathbf{4})$	$(\mathbf{45})$

+ Matter Unification

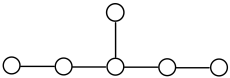
E_6



$T^4 \ltimes SO(3,1)$	E_6
$(\mathbf{1})$	$(\mathbf{27})$
$(\mathbf{2})$	$3 \times (\mathbf{27})$
$(\mathbf{4})$	$(\mathbf{78})$

$(\mathbf{27}) + 3 \times (\mathbf{27})$ **suggests SUSY**

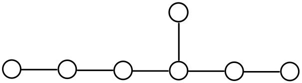
SUSY E_6



$S^1 \ltimes \left[T^4 \ltimes SO(3,1)\right]$	E_6
$(2\times\mathbf{1}+\mathbf{2})$	$3\times(\mathbf{27})$
$(\mathbf{4}+\mathbf{2})$	$(\mathbf{78})$

+ Higgs-Matter Unification

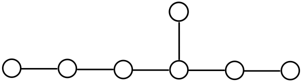
SUSY E_7



$S^1 \ltimes \left[T^4 \ltimes SO(3,1)\right]$	E_7
$(2 \times \mathbf{1} + \mathbf{2})$	$(\mathbf{912})$
$(\mathbf{4} + \mathbf{2})$	$(\mathbf{133})$

Only real representations: suggests orbifolding

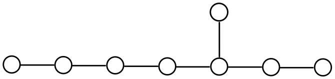
SUSY 6d E_7



$S^1 \ltimes \left[T^6 \ltimes SO(5,1)\right]$	E_7
$(2 \times \mathbf{1} + \mathbf{4})$	$(\mathbf{912})$
$(\mathbf{6} + \mathbf{4})$	$(\mathbf{133})$

+ Family Unification

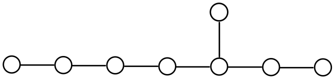
SUSY 6d E_8



$S^1 \ltimes \left[\mathrm{T}^6 \ltimes \mathrm{SO}(5,1)\right]$	E_8
$(2 \times \mathbf{1} + \mathbf{4})$	$(\mathbf{248})$
$(\mathbf{6} + \mathbf{4})$	$(\mathbf{248})$

Suggests $N = 1$ SUSY in 10d or $N = 4$ SUSY in 4d

SUSY 10d E_8



$S^1 \ltimes \left[\mathrm{T}^{10} \ltimes \mathrm{SO}(9,1)\right]$	E_8
$(\mathbf{10}+\mathbf{8})$	$(\mathbf{248})$

FULL UNIFICATION

10d QFT

N=1 Super Yang-Mills Theory based on E_8

A 10d vector and a 10d Weyl fermion in the adjoint/fundamental representation $(\mathbf{248})$.

10d QFT

N=1 Super Yang-Mills Theory based on E_8

A 10d vector and a 10d Weyl fermion in the adjoint/fundamental representation $(\mathbf{248})$.

Note: This **is not** a String Theory

Extra Dimensions

$$S^1 \ltimes \left[\mathrm{T}^{10} \ltimes \mathrm{SO}(9,1)\right] \times \mathrm{E}_8$$

- T^{10}: Open EDs not observed
- E_8: No 4d chiral matter

Orbifolded Extra Dimensions

$$S^1 \ltimes \left[T^4 \times T^6/\Gamma \ltimes SO(9,1)/F\right] \ltimes E_8$$

- Γ: Lattice group compactification (Wilson lines)
- F: Orbifold group
- $[E_8, \Gamma \ltimes F] \neq 0 \Rightarrow$ gauge and Super-Poincarè simultaneous breaking Aranda, Anda, King, Nucl.Phys.B 960 (2020) 115209, 2005.03048 [hep-ph]

Abelian Orbifolding

$$S^1 \ltimes \left[\mathrm{T}^4 \times \mathrm{T}^6/\Gamma \ltimes \mathrm{SO}(9,1)/\mathrm{F}\right] \ltimes \mathrm{E}_8$$

$\Gamma = \mathbb{Z}^6 \rightarrow$ compactification into Tori $\mathbb{T}^6 \simeq \mathbb{R}^6/\mathbb{Z}^6$

$\mathrm{F} = \mathbb{Z}_M \times \mathbb{Z}_N \rightarrow$ Generic abelian orbifold preserving $N = 1$ SUSY

Fischer, Ratz, Torrado and Vaudrevange, JHEP01(2013),1209.3906 [hep-th]

The Full Model

10d QFT

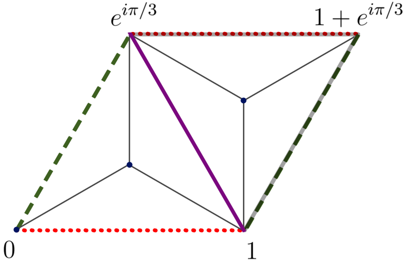
N=1 Super Yang-Mills Theory based on E_8

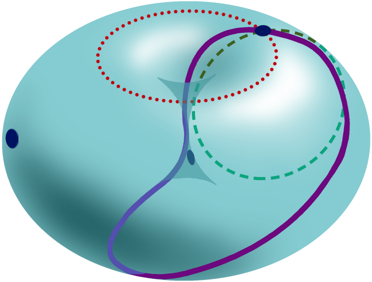
A 10d **vector** **and a 10d** **Weyl fermion** **in the adjoint/fundamental representation $(\mathbf{248})$.**

Extra dimensions compactified as

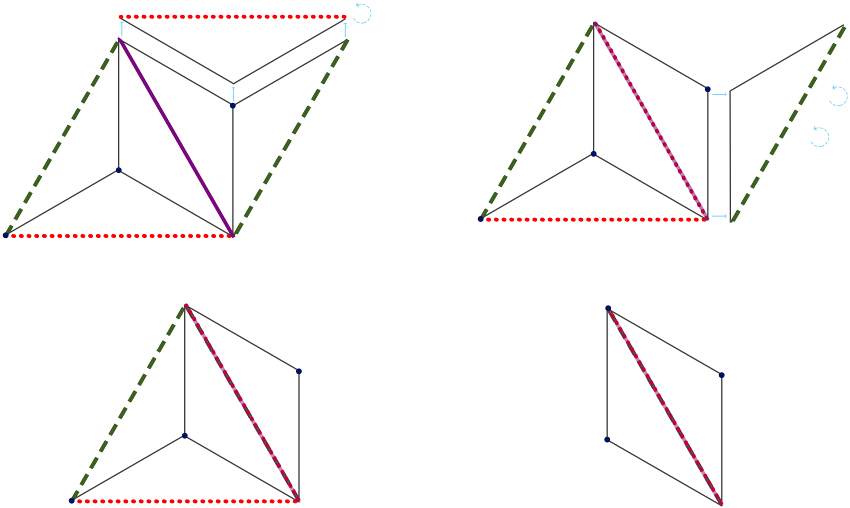
$$\mathbb{T}^6/\left(\mathbb{Z}_3 \times \mathbb{Z}_3\right)$$

$\mathbb{T}^2/\mathbb{Z}_3$ orbifold visualization for one z_i

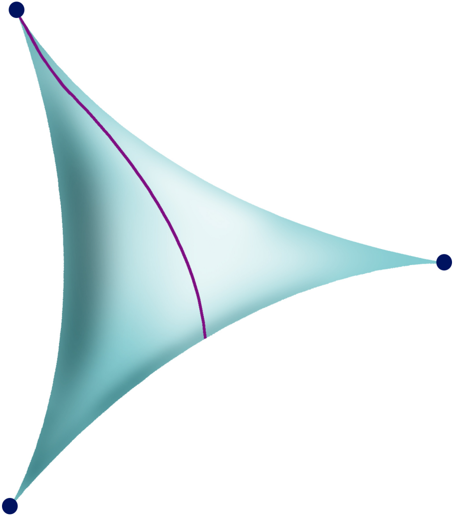




$\mathbb{T}^2/\mathbb{Z}_3$ orbifold folding for one z_i



$\mathbb{T}^2/\mathbb{Z}_3$ orbifold



Symmetry breaking by orbifolding

$$\mathbb{Z}_3 : \mathcal{V}_{(\mathbf{248})} \to e^{2i\pi q_8^F/3}\, \mathcal{V}_{(\mathbf{248})} \Longrightarrow \quad \text{preserves} \quad \mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{F}$$

$$\mathbb{Z}_3 : \mathcal{V}_{(\mathbf{248})} \to e^{2i\pi q_8^C/3}\, \mathcal{V}_{(\mathbf{248})} \Longrightarrow \quad \text{preserves} \quad \mathrm{E}_6' \times \mathrm{SU}(3)_\mathrm{C}$$

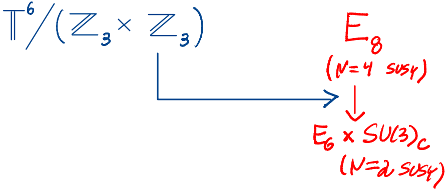
$\mathbb{T}^6/(\mathbb{Z}_3 \times \mathbb{Z}_3)$

E_8
($N=4$ susy)

Symmetry breaking by orbifolding

$$\mathbb{Z}_3 : \mathcal{V}_{(\mathbf{248})} \to e^{2i\pi q_8^F/3}\, \mathcal{V}_{(\mathbf{248})} \Longrightarrow \quad \text{preserves} \quad \mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{F}$$

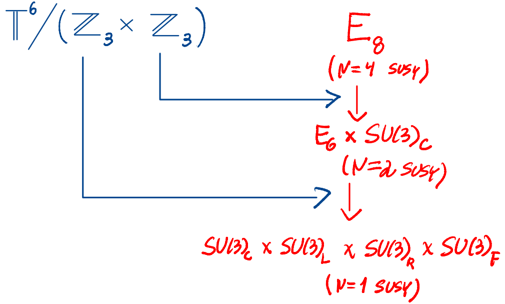
$$\mathbb{Z}_3 : \mathcal{V}_{(\mathbf{248})} \to e^{2i\pi q_8^C/3}\, \mathcal{V}_{(\mathbf{248})} \Longrightarrow \quad \text{preserves} \quad \mathrm{E}_6' \times \mathrm{SU}(3)_\mathrm{C}$$



Symmetry breaking by orbifolding

$$\mathbb{Z}_3 : \mathcal{V}_{(\mathbf{248})} \to e^{2i\pi q_8^F/3}\, \mathcal{V}_{(\mathbf{248})} \implies \text{preserves} \quad \mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{F}$$

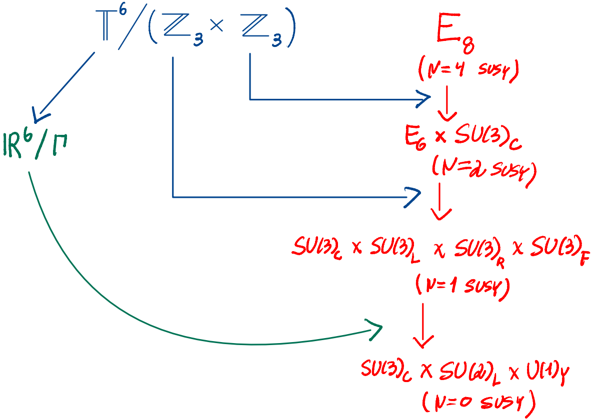
$$\mathbb{Z}_3 : \mathcal{V}_{(\mathbf{248})} \to e^{2i\pi q_8^C/3}\, \mathcal{V}_{(\mathbf{248})} \implies \text{preserves} \quad \mathrm{E}_6' \times \mathrm{SU}(3)_\mathrm{C}$$



Symmetry breaking by orbifolding

$$\mathbb{Z}_3 : \mathcal{V}_{(\mathbf{248})} \to e^{2i\pi q_8^F/3}\, \mathcal{V}_{(\mathbf{248})} \implies \text{preserves} \quad \mathrm{E}_6 \times \mathrm{SU}(3)_{\mathrm{F}}$$

$$\mathbb{Z}_3 : \mathcal{V}_{(\mathbf{248})} \to e^{2i\pi q_8^C/3}\, \mathcal{V}_{(\mathbf{248})} \implies \text{preserves} \quad \mathrm{E}_6' \times \mathrm{SU}(3)_{\mathrm{C}}$$



Compressed orbifolding and Wilson-line scales

Model's freedom completely defined with:

1. 3 complex R_i (scales)
2. 6 complex arbitrary Wilson line dimensionless parameters $\rightarrow$ SM aligned
3. 1 single gauge coupling from E_8

$$\mathbb{T}^6/\left(\mathbb{Z}_3 \times \mathbb{Z}_3\right) : \mathrm{E}_8 \rightarrow \mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$$

- E_8 in the bulk $\rightarrow$ anomaly free ✓
- $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ **at the fixed points $\rightarrow$ anomaly free** ✓

Field Content

$\mathbb{Z}_3 \times \mathbb{Z}_3 : E_8 \to \mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R} \times \mathrm{SU}(3)_\mathrm{F}$

$\mathbb{Z}_3 \times \mathbb{Z}_3 : \mathcal{V}(x_\mu, z_1, z_2, z_3) \to V(x_\mu) + \Phi_1(x_\mu) + \Phi_2(x_\mu) + \Phi_3(x_\mu)$

	V	ϕ_1	ϕ_2	ϕ_3
$\mathcal{V}_{(\mathbf{8},\mathbf{1},\mathbf{1},\mathbf{1})}$	$1, 1$	$\omega^2, 1$	ω^2, ω	ω^2, ω^2
$\mathcal{V}_{(\mathbf{1},\mathbf{8},\mathbf{1},\mathbf{1})}$	$1, 1$	$\omega^2, 1$	ω^2, ω	ω^2, ω^2
$\mathcal{V}_{(\mathbf{1},\mathbf{1},\mathbf{8},\mathbf{1})}$	$1, 1$	$\omega^2, 1$	ω^2, ω	ω^2, ω^2
$\mathcal{V}_{(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{8})}$	$1, 1$	$\omega^2, 1$	ω^2, ω	ω^2, ω^2
$\mathcal{V}_{(\bar{\mathbf{3}},\mathbf{3},\mathbf{3},\mathbf{1})}$	$1, \omega^2$	ω^2, ω^2	$\omega^2, 1$	ω^2, ω
$\mathcal{V}_{(\mathbf{3},\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1})}$	$1, \omega$	ω^2, ω	ω^2, ω^2	$\omega^2, 1$

	V	ϕ_1	ϕ_2	ϕ_3
$\mathcal{V}_{(\mathbf{1},\bar{\mathbf{3}},\mathbf{3},\mathbf{3})}$	$\omega, 1$	$1, 1$	$1, \omega$	$1, \omega^2$
$\mathcal{V}_{(\mathbf{3},\mathbf{3},\mathbf{1},\mathbf{3})}$	ω, ω	$1, \omega$	$1, \omega^2$	$1, 1$
$\mathcal{V}_{(\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}},\mathbf{3})}$	ω, ω^2	$1, \omega^2$	$1, 1$	$1, \omega$
$\mathcal{V}_{(\mathbf{1},\mathbf{3},\bar{\mathbf{3}},\bar{\mathbf{3}})}$	$\omega^2, 1$	$\omega, 1$	ω, ω	ω, ω^2
$\mathcal{V}_{(\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}})}$	ω^2, ω^2	ω, ω^2	$\omega, 1$	ω, ω
$\mathcal{V}_{(\mathbf{3},\mathbf{1},\mathbf{3},\bar{\mathbf{3}})}$	ω^2, ω	ω, ω	ω, ω^2	$\omega, 1$

Table: Decomposition of $\mathcal{V}_{248}$: adjoint fields, Higgs and leptons, quarks, mirror Higgs and mirror fermions, mirror quarks, and exotics.

> **Zero/massless modes obtained from orbifolding**

> **Choose, without loss of generality, generic $\langle \phi_1 \rangle$ while $\langle \phi_{2,3} \rangle = 0$**

> **always preserves one $\mathrm{SU}(3)$ → identify with colour**

$$V_\mu : \Delta_C + \Delta_L + \Delta_R + \Delta_F, \quad \phi_1 : \mathbf{L}, \quad \phi_2 : \mathbf{Q}_R, \quad \phi_3 : \mathbf{Q}_L.$$

Align $\langle\phi_1\rangle$ to preserve $\mathrm{SU}(2)\times\mathrm{U}(1)$ $\rightarrow$ 9 zero and 6 non-zero parameters

$$V_\mu : G_\mu + W_\mu + B_\mu ,$$

$$\phi_1 + \langle\phi_1\rangle : \mathbf{L} + \langle\mathbf{L}\rangle = \begin{pmatrix} h_{ui} & h_{di} & L_i \\ e_i^c & \nu_i^c & \varphi_i \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & \langle\nu_i^c\rangle & \langle\varphi_i\rangle \end{pmatrix} ,$$

$$\phi_2 : \mathbf{Q}_R = \begin{pmatrix} u_i^c & d_i^c & D_i^c \end{pmatrix}^\top ,$$

$$\phi_3 : \mathbf{Q}_L = \begin{pmatrix} Q_i & D_i \end{pmatrix} ,$$

$$i = 1, 2, 3$$

Wilson line effective VEVs in $\langle \mathbf{L} \rangle \sim \langle \varphi_i \rangle$, $\langle \nu_i^c \rangle$ yield $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$

$$\begin{aligned}\mathcal{W} =& g\varepsilon^{ijk}\Big(h_{ui}u_j^c Q_k + h_{di}d_j^c Q_k \\ &+ [\varphi_i + \langle \varphi_i \rangle] D_j^c D_k + [\nu_i^c + \langle \nu_i^c \rangle] d_j^c D_k \\ &+ e_i^c u_j^c D_k + L_i Q_j D_k^c\Big),\end{aligned}$$

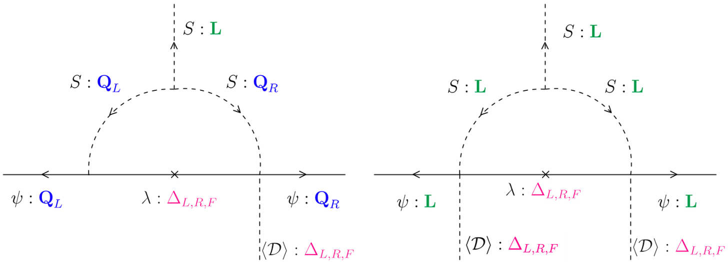
- First line: 2nd and 3rd generation quark masses
- **u and d quarks massless at tree-level**

Wilson lines induce D-term SUSY breaking

$$\langle \mathcal{D}_A \rangle = \sum_{ij} \langle \nu_i^c \rangle^\dagger t_A \langle \nu_j^c \rangle + \langle \varphi_i \rangle^\dagger t_A \langle \varphi_j \rangle + \langle \varphi_i \rangle^\dagger t_A \langle \nu_j^c \rangle + \langle \nu_i^c \rangle^\dagger t_A \langle \varphi_j \rangle \neq 0,$$

- $\langle \mathcal{D}_A \rangle$ **further induces radiative masses for leptons, u and d quarks**

Chiral fermions



- **Quark and lepton masses are of SUSY-breaking origin and of radiative nature** ($l_i \to$ loop factor)

$$m_{t,c} \propto \left(g + l_{1,2}\frac{\langle \mathcal{D} \rangle}{\Lambda^2}\right)\langle h_{ui}\rangle \quad m_{b,s} \propto \left(g + l_{3,4}\frac{\langle \mathcal{D} \rangle}{\Lambda^2}\right)\langle h_{di}\rangle \quad m_{u,d} \propto l_{5,6}\frac{\langle \mathcal{D} \rangle}{\Lambda^2}\langle h_{(u,d)i}\rangle$$

$$m_{e,\mu,\tau} \propto l^2_{7,8,9}\frac{\langle \mathcal{D} \rangle^2}{\Lambda^4}\langle h_{di}\rangle \qquad m_{\nu_i} \propto l^2_{10,11,12}\frac{\langle \mathcal{D} \rangle^2}{\Lambda^4}\frac{\langle h_{ui}\rangle^2}{\langle \nu^c\rangle} \to \textbf{Seesaw}$$

[Morais, Pasechnik, Porod, Eur.Phys.J.C 80 (2020) 12, 1162]

- **Hierarchical quarks $\Rightarrow$ small mixing**
- **Less-hierarchical leptons $\Rightarrow$ large mixing**

Conceptually viable SM ✓

without specifying parameters

Several KK modes contribute to the RG-running of the theory parameters

Power law running for a given parameter $\mathcal{P}$:

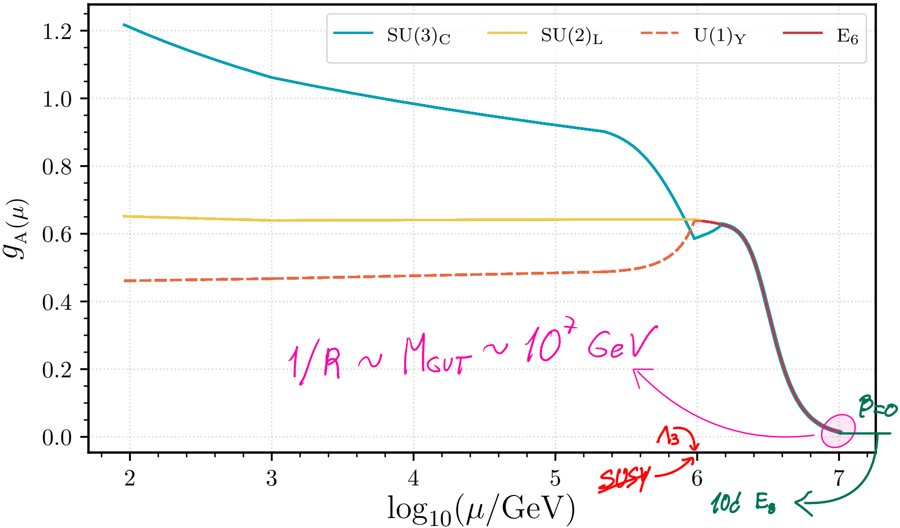
$$\beta_{\mathcal{P}}^{(1)} \to \beta_{\mathcal{P}}^{(1)} + [S(\mu, \delta) - 1]\, \tilde{\beta}_{\mathcal{P}}^{(1)} \qquad S(\mu, \delta) = X_\delta \left(\frac{\mu}{\mu_{\mathrm{KK}}} \right)^\delta \text{ for } \mu \geqslant \mu_{\mathrm{KK}}$$

$X_\delta = \frac{2\pi^{\delta/2}}{\delta \Gamma(\delta/2)}$ comes from an integral regulator [Dienes et al. Phys. Lett. B436(1998), 55-65]

$\delta \to$ number of extra dimensions

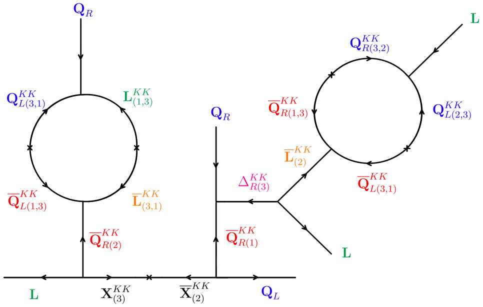
$\mu_{\mathrm{KK}} \to$ the KK modes scale

Gauge coupling unification



Proton decay

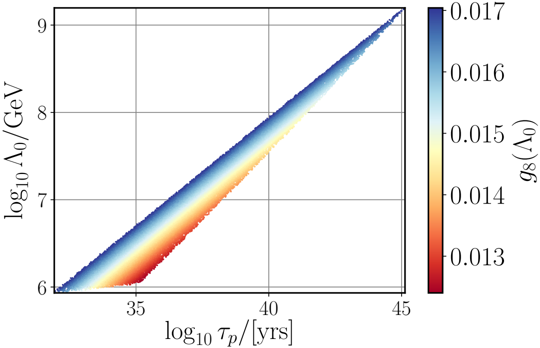
Leading order contribution that generates $L_i Q_k u_f^{c\dagger} d_l^{c\dagger} (\delta_f^i \delta_l^k - \delta_l^i \delta_f^k)$ operators



1. Highly suppressed by two loops and internal KK propagators
2. Involves two different generations thus the decay is to Kaons
3. With the flipped embedding proton decay only takes place at E_8 level

Decay width to Kaons and leptons

$$\Gamma_{p\to K+L} \sim g^{18} l^4 \left\langle \tilde{\nu}^{c\dagger s} \tilde{\nu}^c_s \right\rangle^2 \frac{m_p^5}{\Lambda_0^8},$$



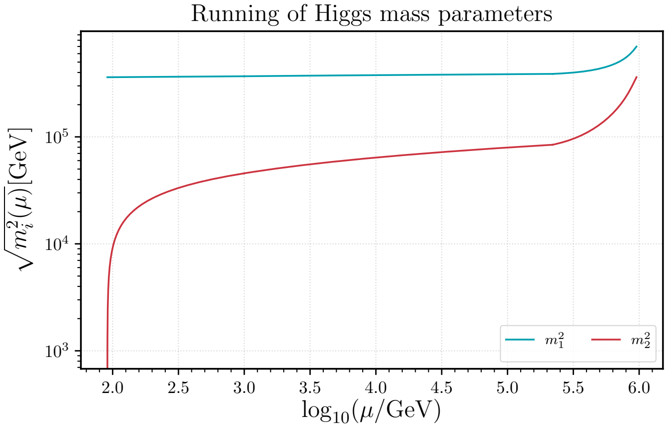
All points satisfy $\tau_{p\to K+L} > 1.1 \times 10^{32}$ yrs ($l = 0.08,\ \Lambda_3 \in [10^4, 10^{15}]$ GeV)

$$\boxed{\mathrm{O}(10^{32}) \lesssim \tau_{p\to K+L}/\mathrm{yrs} \lesssim \mathrm{O}(10^{45})}$$

Model consistent with low-scale Grand Unification and PeV-scale SUSY

Within reach of near future experiments

Generating the electroweak scale



$\sqrt{-m_{H_u}^2} = 161$ GeV, $m_{H_d} = 361$ TeV, $m_2 = 362$ TeV, $m_1 = 700$ TeV.

- The model features a light Higgs boson mostly aligned with H_{u1} while the remaining are of order Λ_3

- The third-lightest Higgs can induce FCNCs **if lighter than 150 TeV**

  [Branco, Ferreira, Lavoura, Rebelo, Sher, Silva, Phys. Rept.516(2012), 1-102]

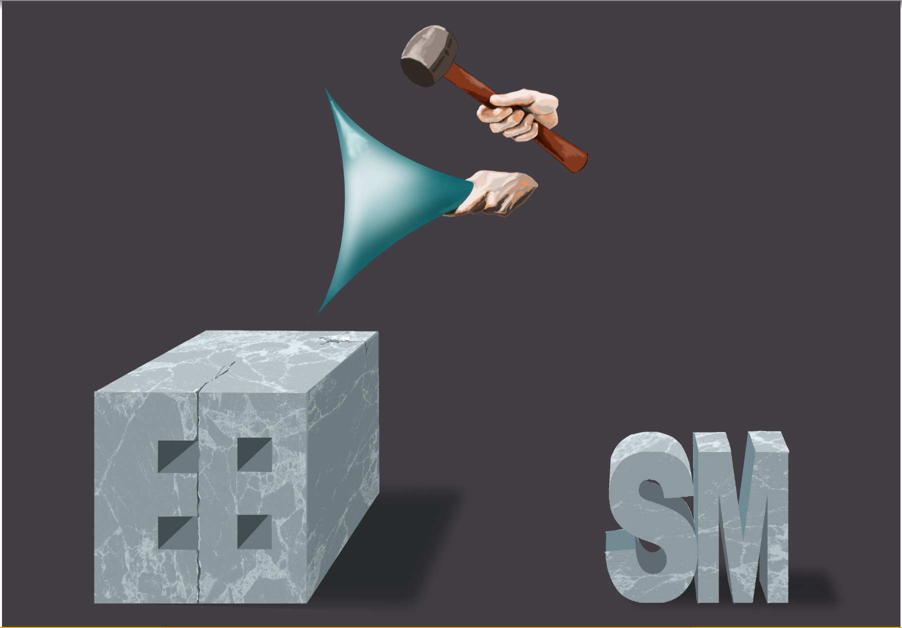
- **FCNC condition conceptually valid**

- Radiative stability of the Higgs mass may point towards $\Lambda_0 \sim \mathcal{O}(10^6 - 10^7 \text{ GeV})$

- **Gravity can be emergent at 4d from the model's d.o.f.**

  [De Anda, Class.Quant.Grav. 37 (2020) 19, 195012]

Conclusion



Backup

Abelian Orbifolding

$$S^1 \ltimes \left[\mathrm{T}^4 \times \mathrm{T}^6/\Gamma \ltimes \mathrm{SO}(9,1)/\mathrm{F}\right] \ltimes \mathrm{E}_8$$

$\Gamma = \mathbb{Z}^6 \to$ compactification into Tori $\mathbb{T}^6 \simeq \mathbb{R}^6/\mathbb{Z}^6$

$\mathrm{F} = \mathbb{Z}_M \times \mathbb{Z}_N \times \mathbb{Z}_L \to$ Generic abelian orbifold

Fischer, Ratz, Torrado and Vaudrevange, JHEP01(2013),1209.3906 [hep-th]

Abelian Orbifolding

$$S^1 \ltimes \left[\mathrm{T}^4 \times \mathrm{T}^6/\Gamma \ltimes \mathrm{SO}(9,1)/\mathrm{F}\right] \ltimes \mathrm{E}_8$$

$\Gamma = \mathbb{Z}^6 \rightarrow$ compactification into Tori $\mathbb{T}^6 \simeq \mathbb{R}^6/\mathbb{Z}^6$

$\mathrm{F} = \cancel{\mathbb{Z}_M \times \mathbb{Z}_N \times \mathbb{Z}_L} \rightarrow N = 4$ SUSY preserved

Fischer, Ratz, Torrado and Vaudrevange, JHEP01(2013),1209.3906 [hep-th]

Abelian Orbifolding

$$S^1 \ltimes \left[\mathrm{T}^4 \times \mathrm{T}^6/\Gamma \ltimes \mathrm{SO}(9,1)/\mathrm{F}\right] \ltimes \mathrm{E}_8$$

$\Gamma = \mathbb{Z}^6 \rightarrow$ compactification into Tori $\mathbb{T}^6 \simeq \mathbb{R}^6/\mathbb{Z}^6$

$\mathrm{F} = \mathbb{Z}_M$ ~~$\times \mathbb{Z}_N \times \mathbb{Z}_L$~~ $\rightarrow N = 2$ SUSY preserved

Fischer, Ratz, Torrado and Vaudrevange, JHEP01(2013),1209.3906 [hep-th]

Abelian Orbifolding

$$S^1 \ltimes \left[\mathrm{T}^4 \times \mathrm{T}^6/\Gamma \ltimes \mathrm{SO}(9,1)/\mathrm{F}\right] \ltimes \mathrm{E}_8$$

$\Gamma = \mathbb{Z}^6 \rightarrow$ compactification into Tori $\mathbb{T}^6 \simeq \mathbb{R}^6/\mathbb{Z}^6$

$\mathrm{F} = \mathbb{Z}_M \times \mathbb{Z}_N \times \mathbb{Z}_L \rightarrow N = 1$ SUSY preserved

Fischer, Ratz, Torrado and Vaudrevange, JHEP01(2013),1209.3906 [hep-th]

Abelian Orbifolding

$$S^1 \ltimes \left[\mathrm{T}^4 \times \mathrm{T}^6/\Gamma \ltimes \mathrm{SO}(9,1)/\mathrm{F}\right] \ltimes \mathrm{E}_8$$

$\Gamma = \mathbb{Z}^6 \rightarrow$ compactification into Tori $\mathbb{T}^6 \simeq \mathbb{R}^6/\mathbb{Z}^6$

$\mathrm{F} = \mathbb{Z}_M \times \mathbb{Z}_N \times \mathbb{Z}_L \rightarrow N = 0$ SUSY preserved

Fischer, Ratz, Torrado and Vaudrevange, JHEP01(2013),1209.3906 [hep-th]

The Full Model

$\mathcal{N}=1$ **SYM theory with a single E_8 vector superfield $\mathcal{V}_{(\mathbf{248})}(x,z_i)$ in 10d**

- Extra dimensions orbifolded as $\mathbb{T}_6/(\mathbb{Z}_3\times\mathbb{Z}_3)$ by identifying

$$\mathbb{Z}_3:\ (x,z_1,z_2,z_3)\sim(x,\omega^2 z_1,\omega^2 z_2,\omega^2 z_3),\quad \mathcal{V}_{(\mathbf{248})}\to e^{2i\pi q_8^F/3}\,\mathcal{V}_{(\mathbf{248})}$$
$$\mathbb{Z}_3:\ (x,z_1,z_2,z_3)\sim(x,\omega^3 z_1,\omega z_2,\omega^2 z_3),\quad \mathcal{V}_{(\mathbf{248})}\to e^{2i\pi q_8^C/3}\,\mathcal{V}_{(\mathbf{248})}$$

- $\mathbb{T}_6$ torus lattice defined by the translations (periodic boundary conditions)

$$\tau_i^1: z_i\to z_i+2\pi R_i,\quad \tau_i^2: z_i\to z_i+2\pi e^{i\pi/3}R_i,\quad \mathcal{V}_{(\mathbf{248})}(x,z_i)=U_i^r\mathcal{V}_{(\mathbf{248})}(x,z_i+\tau_i^r)$$

- Non-trivial gauge U_i^r transformations called Wilson lines

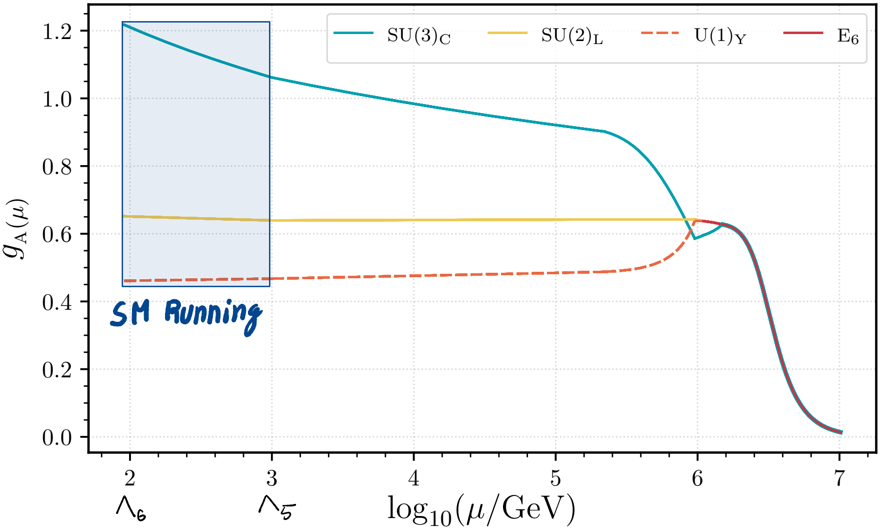
- Wilson lines further break the symmetry as they generate effective VEVs in extra-dim gauge vectors (scalars)

$$\text{4d vector:} \quad V(x,z_i) = \tilde{V}(x,z_i),$$
$$\text{4d scalars:} \quad \phi_i(x,z_i) = \tilde{\phi}(x,z_i) + \sum_r \alpha_i^{ar} \tau_i^r T_a,$$

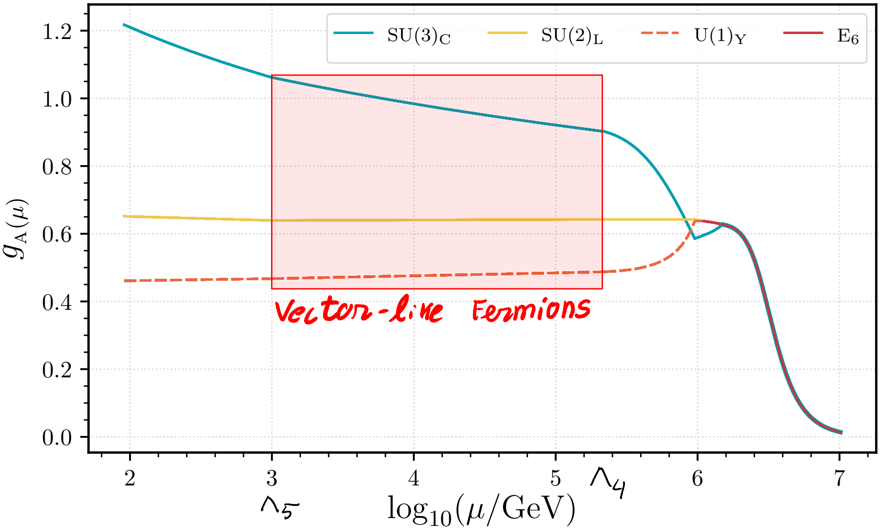
Model completely defined with:

1. 3 complex R_i (scales)
2. 6 complex arbitrary Wilson line dimensionless parameters $\to$ SM aligned
3. 1 single gauge coupling from E_8

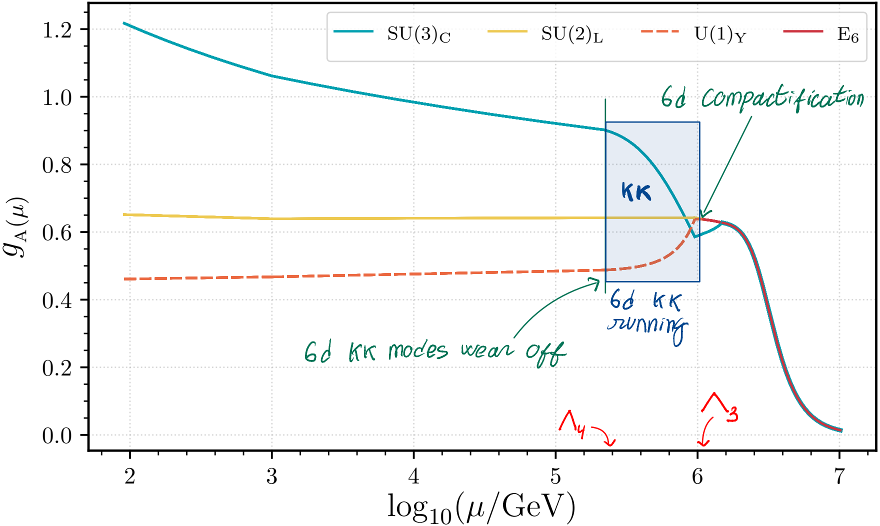
Gauge coupling unification



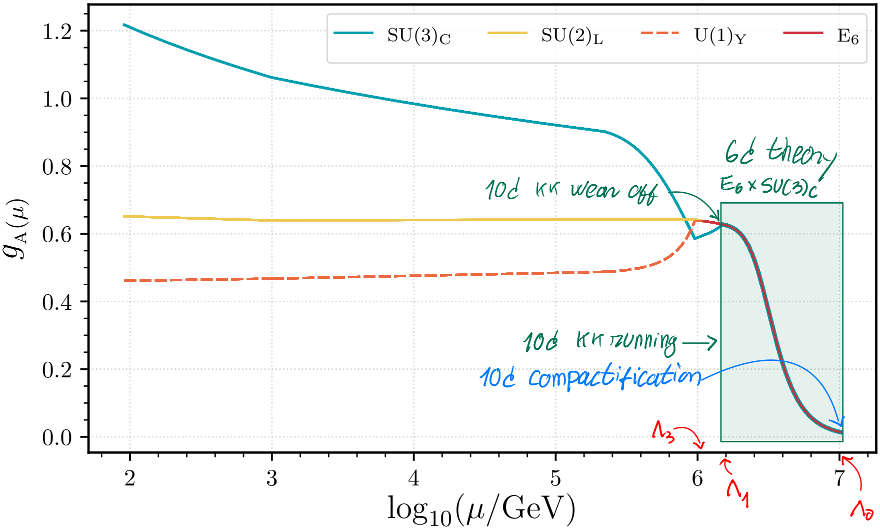
Gauge coupling unification



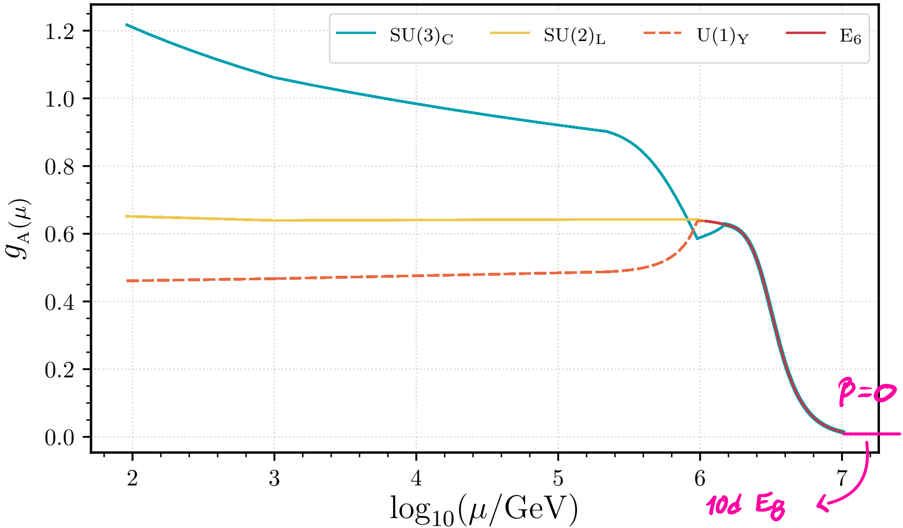
Gauge coupling unification



Gauge coupling unification



Gauge coupling unification

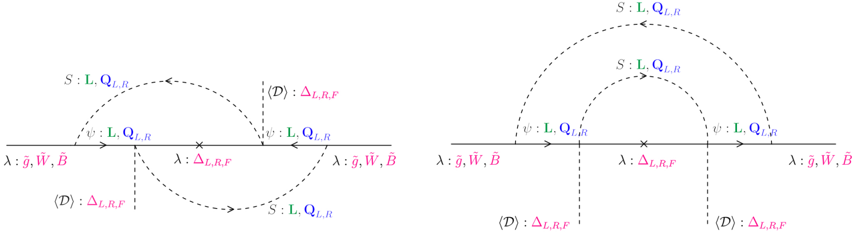


Unique and simple $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R} \times \mathrm{SU}(3)_\mathrm{F}$ superpotential

$$\mathcal{W} = g\phi_1\phi_2\phi_3 = g\epsilon^{ijk}\mathbf{L}^{l}{}_{mi}\mathbf{Q}_{R}{}^{m}{}_{j}\mathbf{Q}_{Llk}$$

- g is the universal gauge-Yukawa coupling (up to CGC)
- $\mathbf{L}^3$ absent due to anti-symmetry $\rightarrow$ **no tree-level lepton masses**
- Absence of bilinear terms $\rightarrow$ **no μ-problem**

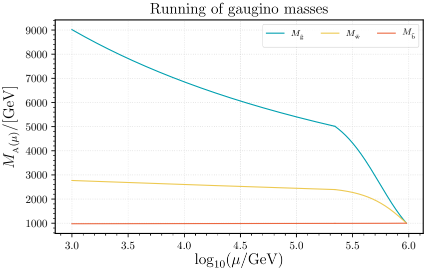
- Broken gauginos and scalar masses are of tree-level origin generated close to the compactification scale $1/R$
- $\langle \mathcal{D} \rangle$ preserves the SM and cannot directly give masses to SM-partner gauginos
- **Realized at two-loop order**



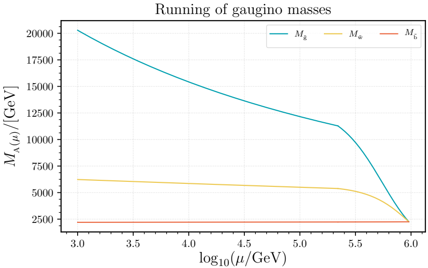
$$m_g \propto g^4 l^2 \frac{\langle \mathcal{D} \rangle^{5/2}}{\Lambda^4}$$

Gaugino masses are radiatively generated at two-loop at the Λ_3 scale and one can estimate

$$m_g(\Lambda_3) \approx 6^{5/2} g_3^4 l^2 \Lambda_3$$



(a) $\Lambda_3 \sim 10^6$ GeV with $l = 0.01$



(b) $\Lambda_3 \sim 10^6$ GeV with $l = 0.015$

KK modes relevant for keeping the lower unification scenario viable

Prospects for New Physics

- Scalar leptoquarks: 4 heavy $m \sim \Lambda_3$ and 2 light $m \sim \mathcal{O}\left(1 - 100 \text{ TeV}\right)$
  - Possibility to address R_K and $g-2$ anomalies?
- Gauginos: few to tenths of TeV (depending on theory parameters)
- Model predicts three generations of VLL doublets at TeV scale
  - Possibility to address $g-2$ anomaly?

Prospects for New Physics

- Scalar leptoquarks: 4 heavy $m \sim \Lambda_3$ and 2 light $m \sim \mathcal{O}\,(1 - 100\ \mathrm{TeV})$
  - Possibility to address R_K and $g-2$ anomalies?
- Gauginos: few to tenths of TeV (depending on theory parameters)
- Model predicts three generations of VLL doublets at TeV scale
  - Possibility to address $g-2$ anomaly?

JHEP

Published for SISSA by Springer

Received: *October 12, 2020*
Revised: *November 22, 2020*
Accepted: *November 23, 2020*
Published: *January 14, 2021*

Phenomenology of vector-like leptons with Deep Learning at the Large Hadron Collider

Felipe F. Freitas,[a] João Gonçalves,[a] António P. Morais[a] and Roman Pasechnik[b]

[a] *Departamento de Física da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications (CIDMA), Campus de Santiago, 3810-183 Aveiro, Portugal*
[b] *Department of Astronomy and Theoretical Physics, Lund University, Sölvegatan 14A, SE 223-62 Lund, Sweden*

E-mail: felipefreitas@ua.pt, jpedropino@ua.pt, aapmorais@ua.pt, Roman.Pasechnik@thep.lu.se

Abstract: In this paper, a model inspired by Grand Unification principles featuring three generations of vector-like fermions, new Higgs doublets and a rich neutrino sector at the low scale is presented. Using the state-of-the-art Deep Learning techniques we perform the first phenomenological analysis of this model focusing on the study of new charged vector-like leptons (VLLs) and their possible signatures at CERN's Large Hadron Collider (LHC). In our numerical analysis we consider signal events for vector-boson fusion and

JHEP01(2021)

Concluding remarks

- **First model featuring a complete low-scale unification of the SM with stable proton at experimental reach**
- Specific SUSY breaking
- Viable Yukawa structure
- Radiative EWSB
- Highly predictive power with $g_6(\Lambda_1) \approx 0.63$ and $0.01 < g_8(\Lambda_0) < 0.02$
- **Full calculation of the particle spectrum to fix the model's freedom**

Either rules it out or results in concrete and well defined new physics predictions with precise determination of scales, masses and couplings

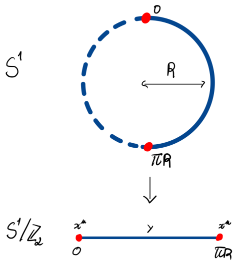
Concluding remarks

- **First model featuring a complete low-scale unification of the SM with stable proton at experimental reach**
- Specific SUSY breaking
- Viable Yukawa structure
- Radiative EWSB
- Highly predictive power with $g_6(\Lambda_1) \approx 0.63$ and $0.01 < g_8(\Lambda_0) < 0.02$
- **Full calculation of the particle spectrum to fix the model's freedom**

Either rules it out or results in concrete and well defined new physics predictions with precise determination of scales, masses and couplings

Manpower needed!!

Example of a $S^1/\mathbb{Z}_2$ orbifold that compactifies 5d $\to$ 4d in the fixed points 0 and πR



- Identify $\mathcal{T} : y \to y + 2\pi R$
- Periodic boundary conditions $\Phi(x^\mu, y + 2\pi R) = \mathcal{T}\Phi(x^\mu, y)$
- Particle in a box analogy

> Identify points on the circle under the action $\theta : y \to -y$

$$\Phi(x^\mu, -y) = \omega\Phi(x^\mu, y) \qquad \text{with eignevalue} \qquad \omega = \pm 1$$

> $\mathbb{Z}_2$ even and odd modes expansion

$$\sum_{n=-\infty}^{\infty} \Phi_+^{(n)}(x^\mu) \cos\frac{ny}{R} \qquad \sum_{n=-\infty}^{\infty} \Phi_-^{(n)}(x^\mu) \sin\frac{ny}{R} \qquad m_n = (n/R)^2 \qquad m_0 = 0$$

- Mode expansion yields an infinite tower of particles $\rightarrow$ Kaluza-Klein (KK) modes
- Only the 4d $\Phi_{+}^{(0)}(x^{\mu})$ mode is massless
- Only part of the original $\Phi(x^{\mu}, y)$ sits in each of the fixed points
  - $\Phi_{+}^{(n)}(x^{\mu})$ in $y = 0$
  - $\Phi_{-}^{(n)}(x^{\mu})$ in $y = \pi R$
- **Symmetry broken in the fixed points**

Defining the scales:

$$\{\mathrm{E}_8\}_{10d} \xrightarrow{\Lambda_0} \{\mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{C}\}_{6d}^{\mathrm{KK}} \xrightarrow{\Lambda_1} \{\mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{C}\}_{6d}^{0} \xrightarrow{\Lambda_2}$$
$$\{\mathrm{U}(1)_\mathrm{Y} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{C}\}_{4d}^{\mathrm{KK}-1} \xrightarrow{\Lambda_3} \{\mathrm{U}(1)_\mathrm{Y} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{C}\}_{4d}^{\mathrm{KK}-2} \xrightarrow{\Lambda_4}$$
$$\{\mathrm{U}(1)_\mathrm{Y} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{C}\}_{4d}^{0} \xrightarrow{\Lambda_5} \{\mathrm{U}(1)_\mathrm{Y} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{C}\}_{4d-\mathrm{NHDM}}^{0}$$

- $\Lambda_0 = 1/R_1$ is the GUT scale and where 10d $\rightarrow$ 6d compactification
- Λ_1 is where E_8 KK modes wear out
- $\Lambda_2 = 1/R_{2,3}$, 6d $\rightarrow$ 4d and $E_6 \rightarrow SU(3)_L \times SU(3)_R \times SU(3)_F$
- $\Lambda_3 \approx \Lambda_2$ Wilson-lines scale with SUSY and quartification breaking
- Λ_4 lightest KK modes wear out
- $\Lambda_5 \sim \mathcal{O}(\mathrm{TeV})$ scale of new physics

Fast power-law running in the region $\Lambda_0 \to \Lambda_1$

$$\beta^{(1)}_{g_{3,6}}(\mu) \approx \frac{\tilde{b}_{3,6}}{16\pi^2}\left[\frac{\pi^2}{3}\left(\frac{\mu}{\Lambda_1}\right)^6 - 1\right] g^3_{3,6}\,, \quad \tilde{b}_{3,6} = -5\,, \qquad g_3(\Lambda_0) = g_6(\Lambda_0) = g_8$$

Numerical scan

$\log_{10}\frac{\Lambda_0}{\mathrm{GeV}}$	$\log_{10}\frac{\Lambda_1}{\mathrm{GeV}}$	$\log_{10}\frac{\Lambda_2}{\mathrm{GeV}}$	$\log_{10}\frac{\Lambda_3}{\mathrm{GeV}}$	$\log_{10}\frac{\Lambda_4}{\mathrm{GeV}}$	$\log_{10}\frac{\Lambda_5}{\mathrm{GeV}}$	$g_8(\Lambda_0)$	$g_6(\Lambda_2)$	$g_{1,2,3}(m_Z)$
calculated	*calculated*	*calculated*	$[\Lambda_4, \Lambda_4^{1.15}]$	$[4, 15]$	3.0	*calculated*	*calculated*	*SM values*

Generating the electroweak scale

Proof of concept analysis:

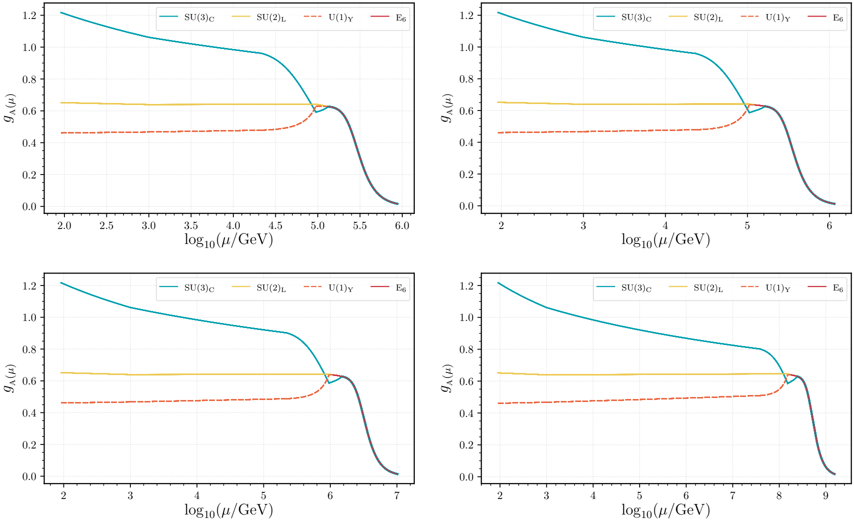
- Consider only the two lightest Higgs doublets H_u and H_d below Λ_3 scale
- Remaining scalars heavier than Λ_3 (up to a factor of 30)
- **Consider an effective 2HDM-like theory with exotic fermions**

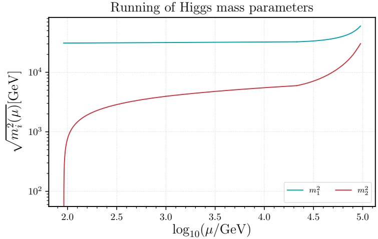
$$V(H_u, H_d) = m_1^2 H_d^\dagger H_d + m_2^2 H_u^\dagger H_u + \lambda_1 (H_d^\dagger H_d)^2 + \lambda_2 (H_u^\dagger H_u)^2 + \lambda_3 (H_d^\dagger H_d)(H_u^\dagger H_u) + \lambda_4 (H_d^\dagger H_2)(H_u^\dagger H_d) + \frac{1}{2}\lambda_5 \left[(H_u^\dagger H_d)^2 + \text{h.c.} \right] + m_{12}^2 \left(H_u^\dagger H_d + \text{h.c.} \right)$$

$$\mathcal{L} \supset y_t u^c Q H_u + y_b d^c Q H_d + y_{\tilde{b}1} \tilde{b} \tilde{H}_d H_d + y_{\tilde{b}2} \tilde{b} \tilde{H}_u H_u + y_{\tilde{w}1} \tilde{w} \tilde{H}_d H_d + y_{\tilde{w}2} \tilde{w} \tilde{H}_u H_u + M_{\rm E} \tilde{H}_u \tilde{H}_d + M_{\rm EL} \tilde{H}_u L + \text{h.c.}$$

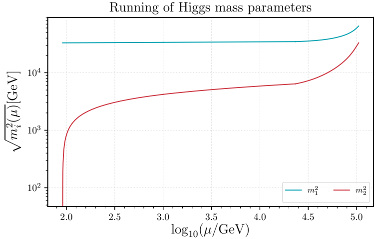
$$-\lambda_1 \approx -\lambda_2 \approx -\lambda_3 \approx \lambda_4 \approx \lambda_5 \approx \frac{1}{4} g_2^2 , \quad y_{\tilde{b}1} \approx y_{\tilde{b}2} \approx y_{\tilde{w}1} \approx \sqrt{2} g_1 , \quad y_{\tilde{w}2} \approx \sqrt{2} g_2 .$$

[Morais, Pasechnik, Porod, Eur.Phys.J.C 80 (2020) 12, 1162]

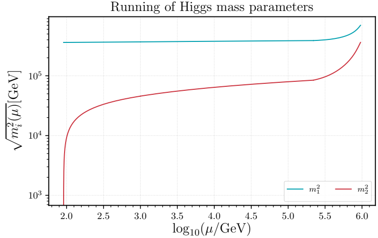

SU(3)C
SU(2)L
U(1)Y
E6
gA(μ)
log10(μ/GeV)



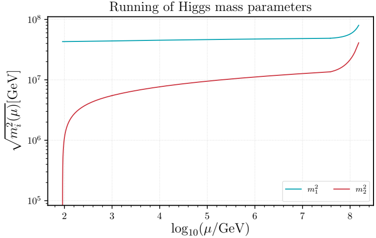
(a) $\sqrt{-m_{Hu}^2} = 186$ GeV, $m_{H_d} = 30.9$ TeV, $m_2 = 30.3$ TeV, $m_1 = 60.1$ TeV, $m_g = 1$ TeV.



(b) $\sqrt{-m_{Hu}^2} = 162$ GeV, $m_{H_d} = 33.1$ TeV, $m_2 = 33.2$ TeV, $m_1 = 65.0$ TeV, $m_g = 1$ TeV.



(c) $\sqrt{-m_{Hu}^2} = 161$ GeV, $m_{H_d} = 361$ TeV, $m_2 = 362$ TeV, $m_1 = 700$ TeV, $m_g = 1$ TeV.



(d) $\sqrt{-m_{Hu}^2} = 155$ GeV, $m_{H_d} = 42.9$ PeV, $m_2 = 41.1$ PeV, $m_1 = 80.0$ PeV, $m_g = 173$ TeV.

Elecroweak symmetry can be radiatively generated with the correct size

How often REWSB holds?

Λ_3/TeV	m_1/GeV	m_2/GeV	m_g/GeV	y_t	y_b
100	$[0.1\Lambda_3, \Lambda_3]$	$[\frac{1}{4}m_1, m_1]$	$[300, 3000]$	$[0.6, 0.85]$	$[0.3, 0.6]$