PROCEEDINGS OF SCIENCE

On a radiative origin of the Standard Model in non-supersymmetric trinification with global $\mathrm{SU}(3)_{\mathrm{F}}$

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We present a trinification-based grand unified theory incorporating a global $\mathrm{SU}(3)_{\mathrm{F}}$ family symmetry, that after spontaneous symmetry breaking leads to a left-right symmetric model. In addition to unification of gauge couplings, the model unifies Yukawa interactions and contains equivalent representations in the scalar and fermion sectors at high energy scales. Considering the minimal low-energy scenario with the least amount of light states, we show that the resulting effective theory enables dynamical breaking of its gauge group to that of the Standard Model by means of radiative corrections accounted for by the renormalisation group evolution at leading order. This result paves the way for a possible explanation of the SM breaking scale and fermion mass hierarchies.

Fourth Annual Large Hadron Collider Physics
13-18 June 2016
Lund, Sweden

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PoS(LHCP2016)241

	$\mathrm{SU}(3)_\mathrm{L}$	$\mathrm{SU}(3)_\mathrm{R}$	$\mathrm{SU}(3)_\mathrm{C}$	$\{\mathrm{SU}(3)_\mathrm{F}\}$
Fermions, Scalars				
$L, \tilde{L}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{3}$
Q_L , $\tilde{Q}_\mathrm{L}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$
Q_R , $\tilde{Q}_\mathrm{R}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{3}$

Table 1: Fermion and scalar field content in the trinification model. The fermions are 2-component left-handed fermions in the Weyl basis.

1. Introduction

The Standard Model (SM) of particle physics, though being exceedingly successful in its experimental verification, does contain an uncomfortably large number of *a priori* undetermined parameters, many of which take on seemingly unnatural values. In addition, the SM does not offer an explanation as to why all the observed fermions exist in three copies with identical quantum numbers with different masses. In [1] we investigate a possible way to resolve these issues in a theory based on a novel realisation of the well-studied trinification gauge group $\mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R} \times \mathrm{SU}(3)_\mathrm{C}\,(\ltimes \mathbb{Z}_3)$, originally proposed by Glashow in 1984 [2] (see also [3] and references therein for an introduction to trinification models). The fermion and scalar fields in our model form equivalent bi-fundamental representations under the gauge group, in addition to being fundamental representations of a global $\mathrm{SU}(3)_\mathrm{F}$ symmetry as shown in Tab. 1. The $\mathrm{SU}(3)_\mathrm{F}$ family symmetry, combined with the cyclic $\mathbb{Z}_3$ permutation symmetry of the gauge indices dramatically limits the number of possible renormalisable operators. All renormalisable operators consistent with this symmetry are also invariant under an accidental $\mathrm{U}(1)_\mathrm{A} \times \mathrm{U}(1)_\mathrm{B}$ symmetry where $\mathrm{U}(1)_\mathrm{B}$ leads to a conserved baryon number.

2. Radiative origin of the Standard Model gauge group

The most general renormalisable scalar potential for this theory has a minimum[1] where

$$\langle (\tilde{L}^i)^l{}_r \rangle = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{v_3}{\sqrt{2}} \end{pmatrix}^{i=3} . \tag{2.1}$$

This vacuum expectation value (VEV) structure spontaneously breaks the gauge and global symmetries of the model as

$$\begin{gathered} \mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R} \times \mathrm{SU}(3)_\mathrm{C} \times \{\mathrm{SU}(3)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{A} \times \mathrm{U}(1)_\mathrm{B}\} \\ \downarrow \\ \mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_{\mathrm{L+R}} \times \{\mathrm{SU}(2)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{X} \times \mathrm{U}(1)_\mathrm{Z} \times \mathrm{U}(1)_\mathrm{B}\}, \end{gathered} \tag{2.2}$$

where purely global groups are indicated by $\{\dots\}$. Guided by simplicity, we consider the region in parameter space where the scalar spectrum comprises two very light states $\tilde{h}$ and $\tilde{l}_\mathrm{R}$ compared

[1] In [1] we find, using the homotopy continuation method, that this a global minimum for a large region of the model's parameter space.

to the trinification scale, that transform under the unbroken group as indicated in Tab. 2. Both $\tilde{h}$ and $\tilde{l}_\mathrm{R}$ are embedded in $\tilde{L}$ before spontaneous symmetry breaking (SSB), and a suitable VEV in $\tilde{l}_\mathrm{R}$ would break $\mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{L+R}$ to the SM hypercharge gauge group $\mathrm{U}(1)_\mathrm{Y}$ after which the two $\mathrm{SU}(2)_\mathrm{L}$ doublets contained in the bi-doublet $\tilde{h}$ can potentially induce electro-weak symmetry breaking (EWSB).

	$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{SU}(2)_\mathrm{R}$	$\mathrm{SU}(3)_\mathrm{C}$	$\mathrm{U}(1)_\mathrm{L+R}$	$(\mathrm{SU}(2)_\mathrm{F})$	(X,Z,B)
$\tilde{h}$	$\mathbf{2}$	$\bar{\mathbf{2}}$	$\mathbf{1}$	0	$\mathbf{1}$	$(+2,0,0)$
$\tilde{l}_\mathrm{R}$	$\mathbf{1}$	$\bar{\mathbf{2}}$	$\mathbf{1}$	1	$\mathbf{2}$	$(-1,1,0)$

Table 2: Scalar field content in the Left-Right symmetric effective theory.

We integrate out all states with masses of $\mathscr{O}(v_3)$, which yields a left-right (LR) symmetric effective theory with the remaining light states. The new couplings in this theory are all related to the few couplings in the trinification theory through a matching procedure. After the matching is performed, we can run the new model parameters down in energy scale via the renormalisation group (RG). The running may alter the shape of the scalar potential, e.g. in such a way that a new $\mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{L+R}$ breaking minima appears at lower energies. This in particular will happen if the $\tilde{l}_\mathrm{R}$ squared mass-parameter runs negative, while certain stability conditions are satisfied by the other parameters in the scalar potential. The running needs to be terminated once the renormalisation scale again reaches masses of particles in the theory, whereby those particles need to be integrated out before further running is possible. We label this stopping scale by μ_r.

In [1] we perform a scan over the parameter space in the trinification theory, for points that lead to the desired breaking of the $\mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{L+R}$ gauge symmetry. The matching conditions are calculated at tree-level, and the running is performed at one-loop. In addition, we introduce in the scan a bias towards parameter points that lead to a light Higgs doublet. In Fig. 1 we show the RG evolution of several parameters in the LR-symmetric theory, for one such parameter space point in the high scale trinification theory. The left panel in Fig. 1 shows the running of gauge couplings, where we see that the SM values are roughly recovered[2] at the electro-weak (EW) scale by setting the unified gauge coupling $g \sim 0.61$ at a trinification breaking scale of $v_3 \sim 10^{12.2}$ GeV. To the right in Fig. 1, we show the running of squared masses in the LR-symmetric theory. The two vertical lines mark the scales at which m_R^2 first runs negative (right) and the scale μ_r at which the RG running is terminated (left), respectively. For this particular parameter point, m_R^2 turns negative at $\mu \sim 10^{12.0}$ GeV, below which a new $\mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{L+R}$ breaking minima appears in the scalar potential. In this minimum, the gauge bosons W' and Z' associated with the corresponding broken generators and an exotic quark acquire masses.

A part of the result of our scan is shown in Fig. 2, with $\{g, y, \lambda_3\}$ being parameters in the trinification theory at the scale v_3 that are relevant for our tree-level study. Here, g and y are the unified gauge and Yukawa couplings respectively while λ_3 is a scalar quartic coupling. The colour coding shows the ratio of the mass of the lightest Higgs doublet at $\mu = \mu_r$ and μ_r. If this ratio is small (i.e. blue-ish points in Fig. 2), the light Higgs doublet remains in the spectrum when running

[2]Note that the running here is performed all the way down to the EW scale, without decoupling the massive states at intermediate scales. Therefore, this calculation should only serve as a very rough estimate of the numerical values of the matching scale and the value of the trinification gauge coupling at this scale.

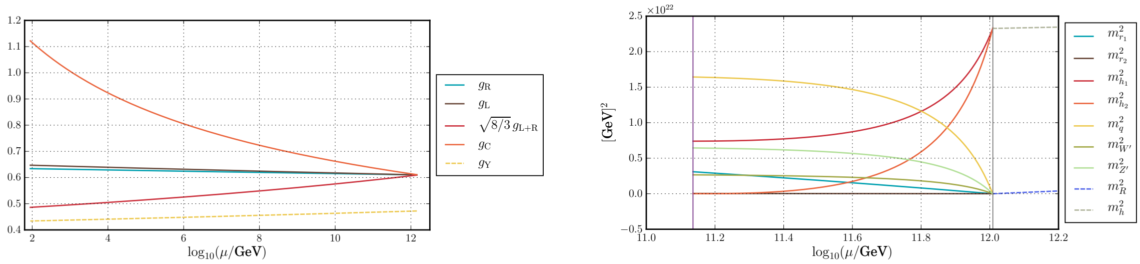

Figure 1: Left: Running of gauge couplings. Here, $g_\mathrm{Y} \equiv 2g_\mathrm{R}g_\mathrm{L+R}/\sqrt{g_\mathrm{R}+4g_\mathrm{L+R}}$ is the hypercharge gauge coupling. Right: RG evolution of mass parameters in the effective LR-symmetric theory.

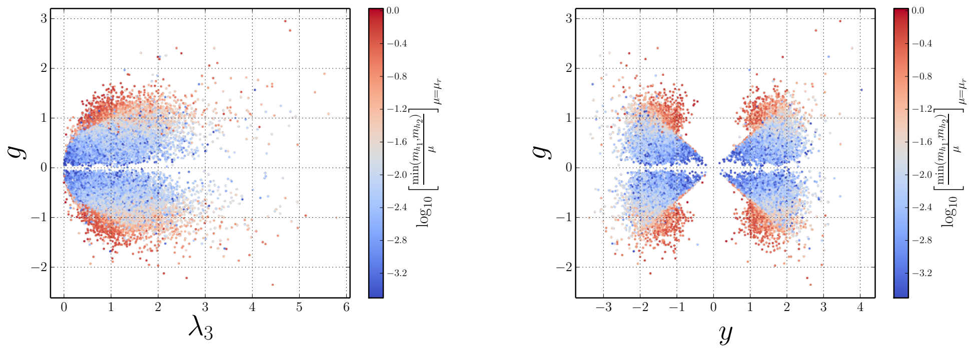

Figure 2: Parameter space points in the trinification theory that leads to a radiative breaking down to the SM gauge group. The colour scale indicates the ratio between the mass of the lightest Higgs doublet at the stopping scale μ_r and μ_r.

further down towards the EW scale. Remarkably, the considered model contains large parameter space regions where $\mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{L+R}$ is radiatively broken down to $\mathrm{U}(1)_\mathrm{Y}$ while a light Higgs doublet is kept in the spectrum.

3. Fermion sector at one-loop

The high scale trinification theory leads to unification of Yukawa couplings, in the sense that only one such interaction term for quarks at the GUT scale is allowed by the symmetries:

$$-y\,\varepsilon_{ijk}\,(\tilde{L}^i)^l{}_r\,(Q_\mathrm{L}{}^j)^c{}_l\,(Q_\mathrm{R}{}^k)^r{}_c + \mathrm{c.c.} + (\mathbb{Z}_3 \text{ permutations}). \tag{3.1}$$

Given the VEV in Eq. (2.1), this term provides masses to two out of the three exotic heavy quark states in the model (the third gets its mass mainly from $\langle\tilde{l}_\mathrm{R}\rangle$). Since the $\tilde{L}LL$ term is forbidden by the $\mathrm{SU}(3)_\mathrm{F}$ family symmetry, the model contains no lepton Yukawa terms at tree-level. However, due to the presence of the coloured scalars $\tilde{Q}_\mathrm{L,R}$, once the trinification symmetry is spontaneously broken, some components of L and its scalar counterpart $\tilde{L}$ will couple via Yukawa interactions according to the 1st and 2nd diagram in Fig. 3 (the third diagram provides a Majorana mass for the singlet component in L). The fact that Yukawa interactions are generated at different orders in perturbation theory can, combined with the RG flow, potentially explain the observed hierarchies in the Yukawa couplings in the SM.

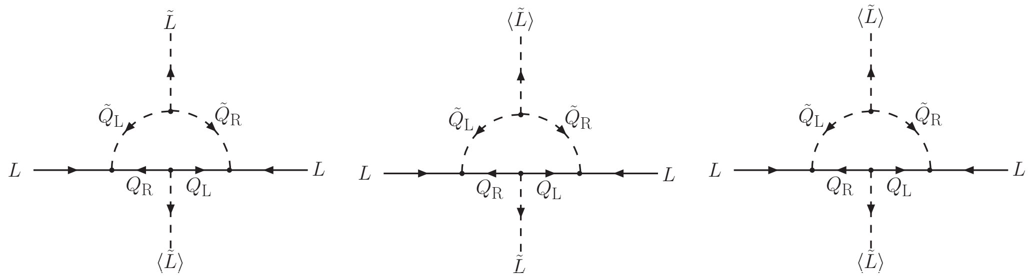

Figure 3: One-loop diagrams in the trinification theory that contribute to the low-energy lepton Yukawa couplings and provides a Majorana mass to the singlet component in *L*.

4. Conclusions

We have presented a model based on the well known trinification gauge group, accompanied by a global $\mathrm{SU}(3)_\mathrm{F}$ family symmetry, which is extraordinarily simple in terms of its structure and number of free parameters. After the trinifiaction symmetry in spontaneously broken at tree-level to a LR-symmetric group, the model is shown to exhibit a radiative breaking of LR symmetry down to the SM gauge group by means of RG running. Furthermore, the resulting low-energy scalar spectrum contains, for large regions in the high-scale theory parameter space, at least one light Higgs doublet that potentially can induce EWSB by the same radiative mechanism. Though only one Yukawa coupling exists in the high scale trinification theory, many Yukawa couplings with widely different values may exist in the corresponding low-energy theory, both due to the fact that they are generated at different loop orders and that the unified Yukawa coupling is split up due to RG running after spontaneous breaking of the trinification symmetry.

The tree-level matching together with one-loop RG evolution procedure is sufficient to show that the SM gauge group can be radiatively generated within the context of this model, but is not accurate enough to elucidate the low-energy phenomenology of the model. In addition to one-loop matching, future work will consider two-loop RGEs, after which the behaviour of the model at the EW scale will be studied in more detail. If indeed the SM is generated from this model as an effective theory, it offers a highly predicable extension to the SM with many new fields waiting to be probed at the LHC and future colliders.

References

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