TOTALLY ASYMPTOTICALLY FREE TRINIFICATION

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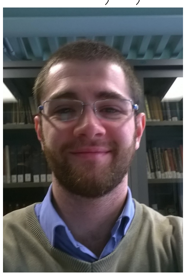

Reinterpreting the naturalness principle, we address the hierarchy problem, proposing a phenomenologically interesting extension of the SM with a gauge group $SU(3)_L \otimes SU(3)_R \otimes SU(3)_c$, such that all the gauge, Yukawa and quartic couplings can be extrapolated up to infinite energy. We analyze which set of scalar or fermionic particles are needed to accomplish this goal. Finally, we consider the predictions of these models about the recently measured diboson and diphoton anomalies.

1 Introduction

The new physics that should solve the Higgs naturalness problem has not been seen yet at LHC, so one could question if the principle of naturalness is still valid. In this work we want to reinterpret this principle, saying that power divergent contributions to the dimensionful parameters of the Standard Model (SM) are not physical, so we don't have to worry about how to cancel them. We call this framework "finite naturalness". [1] This assumption, that may seem unmotivated at first, makes sense if we assume that the new physics scale is not far from the actual energies of LHC and if we suppose that there are no scales bigger than that.

To do this, it is necessary that the model holds up to infinite energy. We search for models in which none of the couplings exit the perturbative regime, at all the scales, studying the renormalization group equations. This desired behavior is called "Total Asymptotic Freedom". [2] [a]

2 The model

First, the behavior of the SM has been considered. As all the abelian groups, the coupling of $U(1)_Y$ gets a Landau pole, and so it's not directly TAF. Considering, however, a SM in which this coupling is set to zero, can lead to predictions that are not too far from the experimental values. [2] Another way around to avoid Landau poles is to embed the hypercharge into a bigger

[a] In this work we suppose that gravity doesn't spoil this property of the model, so the TAF condition holds also at energies bigger than the Planck mass.

Field	spin	$\mathrm{SU}(3)_L$	$\mathrm{SU}(3)_R$	$\mathrm{SU}(3)_c$
$Q_R = \begin{pmatrix} u_R^1 & u_R^2 & u_R^3 \\ d_R^1 & d_R^2 & d_R^3 \\ d_R'^1 & d_R'^2 & d_R'^3 \end{pmatrix}$	1/2	1	3	$\bar{3}$
$Q_L = \begin{pmatrix} u_L^1 & d_L^1 & \bar{d}_R'^1 \\ u_L^2 & d_L^2 & \bar{d}_R'^2 \\ u_L^3 & d_L^3 & \bar{d}_R'^3 \end{pmatrix}$	1/2	3	1	$\bar{3}$
$L = \begin{pmatrix} \bar{\nu}_L' & e_L' & e_L \\ \bar{e}_L' & \nu_L' & \nu_L \\ e_R & \nu_R & \nu' \end{pmatrix}$	1/2	3	$\bar{3}$	1
H	0	3	$\bar{3}$	1

Table 1: *Field content of minimal weak-scale trinification.*

non-abelian group. In particular, we study the Trinification family of models, whose gauge group is $G_{333} = \mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R \otimes \mathrm{SU}(3)_c$. [b]

We first consider the properties of the simplest of the Trinification models, then we try to understand how to expand it to get the TAF behavior.

2.1 Minimal Trinification

Minimal Trinification is the smallest extension that contains the SM. Its particle content is summarized in Table 1. The scalar H is in the $(3_L, \bar{3}_R)$ representation and contains 3 Higgs doublets. We must introduce at least two bi-triplets, H_1 and H_2 to break G_{333} to the SM gauge group $\mathrm{U}(1)_Y \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(3)_c$, and this to $\mathrm{U}(1)_{em} \otimes \mathrm{SU}(3)_c$. The most generic vacuum expectation values that allow this pattern are

$$\langle H_n \rangle = \begin{pmatrix} v_{un} & 0 & 0 \\ 0 & v_{dn} & v_{Ln} \\ 0 & V_{Rn} & V_n \end{pmatrix}. \tag{1}$$

The vacuum expectation values denoted with a capital V trigger the first part of the pattern and are bigger than those with the small v, that break the SM group.

The three trinification gauge coupling constants (g_L, g_R, g_c) allow to reproduce those of the SM (g_3, g_2, $g_Y = \sqrt{3/5}\, g_1$) as

$$g_L = g_2, \qquad g_R = \frac{2 g_2 g_Y}{\sqrt{3 g_2^2 - g_Y^2}}, \qquad g_c = g_3\,. \tag{2}$$

It is important to note that g_R is not a free parameter, its value is sharply predicted: $g_R = 0.444$.

Considering the SM group unbroken (i.e. $v_{un} = v_{dn} = v_{Ln} = 0$), the SM vectors remain massless, while the others take a mass proportional to $V^2 \equiv \sum_n (V_n^2 + V_{Rn}^2)$. The lightest vectors are $W_R^{\pm}$, with a mass

$$M^2_{W_R^{\pm}} = \frac{g_R^2 V^2}{2}\left[1 - \sqrt{(1-2\alpha^2)^2 + 4\beta^2}\right]. \tag{3}$$

where $\alpha \equiv \sum_n V_{Rn}^2 / V^2$ and $\beta \equiv \sum_n V_n V_{Rn} / V^2$.

The SM chiral fermions are contained in a $Q_R \oplus Q_L \oplus L$ multiplet as described in Table 1. Each generation of $Q_R \oplus Q_L \oplus L$ contains 27 fermions that decompose under the SM gauge

[b] These models have been introduced as Grand Unification theories [3], and most of them provide also a permutation symmetry between the three sectors. We don't consider this case since this symmetry is broken by the predicted numerical values for the three gauge couplings.

group as the usual 15 SM chiral fermions, plus a vector-like lepton doublet $L' \oplus \bar{L}'$, a vector-like right-handed down quark $d'_R \oplus \bar{d}'_R$, and two neutral singlets, denoted as ν_R and ν' in Table 1.

The SM Yukawa couplings are obtained from the G_{333}-invariant interactions

$$-\mathscr{L}_Y = y^{ij}_{Qn}\, Q_{Li} Q_{Rj} H_n + \frac{y^{ij}_{Ln}}{2} L_i L_j H_n + \text{h.c.} \tag{4}$$

where summation over n and $i, j = \{1, 2, 3\}$ is implicit and with y_L symmetric under $i \leftrightarrow j$.

To get the right masses for all the fermions with only two scalar field, a big amount of fine-tuning is needed: to avoid this we can consider the models with three Higgses $H_{1,2,3}$. Having three Yukawa couplings y_{Q1}, y_{Q2}, y_{Q3} allows to naturally adjust the masses of the SM quarks to the known values and to set the masses of the new fermions above the experimental bounds.

2.2 *A trinification TAF model*

Minimal trinification has asymptotically free gauge one-loop β-functions

$$\frac{dg_i}{d\ln\mu} = b_i \frac{g_i^3}{(4\pi)^2}, \qquad \text{with} \qquad b_L = b_R = -5 + \frac{n}{3}, \qquad b_c = -5. \tag{5}$$

However, the quartics of minimal trinification do not satisfy the TAF conditions.

Since the particle content dictates the UV behavior of the couplings, we want to consider all the models obtained by adding a combination of extra vector-like fermions to the minimal one. The choices that keep the gauge couplings asymptotically free are finite in number, so a systematic search can be performed. [4]

An example of Trinification model that satisfy all TAF conditions is obtained adding to the minimal one (already containing the chiral fermions Q^i_L, Q^i_R and L^i) a vector-like family of quarks $Q_L \oplus \bar{Q}_L$ and/or $Q_R \oplus \bar{Q}_R$.

Now the Lagrangian contains also extra fermion mass terms M_L and M_R and new Yukawa couplings:

$$-\mathscr{L}_Y = M^{i'}_L Q_{Li'} \bar{Q}_L + M^{j'}_R Q_{Rj'} \bar{Q}_R + y^{ni'j'}_Q\, Q_{Li'} Q_{Rj'} H_n + y^n_{\bar{Q}}\, \bar{Q}_L \bar{Q}_R H^*_n + \frac{y^{nij}_L}{2} L_i L_j H^*_n + \text{h.c.} \tag{6}$$

where $i', j' = \{1, 2, 3, 4\}$. The scalar quartic potential remains as in the minimal case.

3 Diboson and diphoton anomalies

The Trinification models can provide also an explanation for the diboson excess at $\simeq 2$ TeV and the diphoton excess at $\simeq 750$ GeV. [5]

3.1 *Diboson excess*

LHC data showed an excess of di-boson events around 1.9 TeV in different channels. [6] We interpret this excess as the resonance of the $W^\pm_R$ gauge boson in the processes $pp \to W^\pm_R \to W^\pm Z$, $pp \to W^\pm_R \to W^\pm h$ and $pp \to W^\pm_R \to jj$. Moreover, no excess is seen in the $pp \to W^\pm_R \to \ell^\pm \nu$ channel, as predicted from our model.

We perform a global fit, assuming that W_R only decays into jj, WZ and Wh and using the theoretical prediction $\text{BR}(W_R \to WZ) = \text{BR}(W_R \to Wh)$. The result of the fit is $\tilde{g}_R = g_R \cos(\theta_D + \theta_R) \simeq 0.25$, where θ_D and θ_R parametrize the mixing angles between heavy fermions and $\text{SU}(2)_R$ vectors, respectively.

3.2 *Diphoton excess*

ATLAS and CMS showed an excess at 750 GeV[7] in the di-photon channel: it has been interpreted as a new scalar with mass $\approx$ 750 GeV. It is produced by a couple of gluons and decays in two photons through loops of extra fermions and/or scalars coupled to S by sizeable couplings.

Trinification has all the particles needed to follow this interpretation: extra scalars S as singlets and/or doublets in the Higgs $\mathcal{H}$ multiplets; extra fermions D' and L' that extend the SM chiral fermion content and receive masses only as yV; Yukawa couplings y that can be big enough to push the extra fermions above the experimental bounds.

In this model is possible to reproduce the $\gamma\gamma$ excess, keeping at the same time the production of ZZ and WW under the bounds.

4 Conclusions

Total asymptotic freedom could be a way to bypass the hierarchy problem, allowing a model to hold up to infinite energy: the power divergences of the dimensionful parameters lose physical meaning. A systematic search of the TAF behavior has been performed among the Trinification models, and a few models show this feature. Moreover, this family of theories can explain the di-boson excess at 1.9 TeV through the $W_R^\pm$ gauge boson and the diphoton excess at 750 GeV as the production of a new scalar, mediated by loops of extra scalars and/or fermions.

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