Totally asymptotically free Trinification

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Based on arXiv:1507.06848 by G.M.P., A. Strumia, S. Vignali
and arXiv:1512.07225 by G.M.P., A. Strumia, E. Vigiani

What is TAF

A model that can be extrapolated using the RGE up to infinite energy is

Totally Asymptotically Free

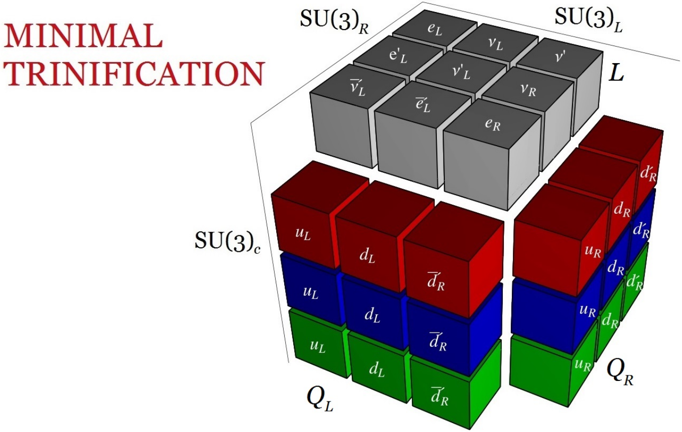
TAF models can bypass the hierarchy-naturalness problem: there are no cut-off scales, so power divergent corrections have no physical meaning.

[Farina, Pappadopulo, Strumia, arXiv:1303.7244;
Giudice, Isidori, Salvio, Strumia, arXiv:1412.2769]

Minimal Trinification

Is the SM TAF? No.

The coupling g_Y hits a Landau pole (like all the abelian groups). We embed it in a non-abelian group.



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Field	spin	$SU(3)_L$	$SU(3)_R$	$SU(3)_c$
$Q_R = \begin{pmatrix} u_R^1 & u_R^2 & u_R^3 \\ d_R^1 & d_R^2 & d_R^3 \\ d_R'^1 & d_R'^2 & d_R'^3 \end{pmatrix}$	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

Features of Trinification

- Spontaneous symmetry braking:

$$\langle H \rangle = \begin{pmatrix} v_u & 0 & 0 \\ 0 & v_d & v_L \\ 0 & V_R & V \end{pmatrix}$$

In this way

$$G_{\text{Trin}} \xrightarrow{V} G_{LRSM} \xrightarrow{V_R} G_{SM} \xrightarrow{v} \text{SU}(3)_c \otimes \text{U}(1)_{em}$$

- 3 Higgses are needed to give a mass $\sim yV$ to the new heavy fermions without fine-tuning.
- The charges of the particles are reproduced.
- To reproduce the right gauge couplings for the SM it predicts

$$g_R = \frac{2g_2 g_Y}{\sqrt{3g_2^2 - g_Y^2}} \approx 0.444.$$

- The lightest new vectors are the right-handed $W_R^{\pm}$.

Towards a TAF model

The particle content dictates the UV behavior for the (tens of) couplings.

For each, a complex (mathematical & computational) machinery estabilishes if the model is TAF or not.

Minimal Trinification is not TAF.
The simplest Trinification TAF model contains the minimal one plus a vector-like quark family $\tilde{Q}_L \oplus \bar{\tilde{Q}}_L$ and/or $\tilde{Q}_R \oplus \bar{\tilde{Q}}_R$.

Diboson excess

In Run 1 of LHC there were excesses ($\sim 3\sigma$) in some channels at an energy $\simeq 2$ TeV.
[see M.Pierini talk @ Moriond]

These anomalies can be fitted with the processes

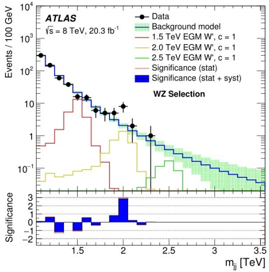
$$pp \to W_R^{\pm} \to W^{\pm} Z$$

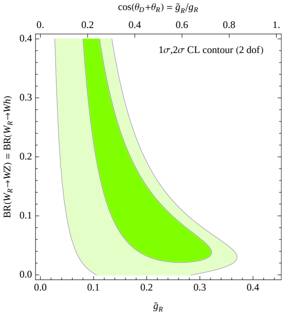
and

$$pp \to W_R^{\pm} \to W^{\pm} H.$$

$g_R \simeq 0.444$ is compatible with the excess.

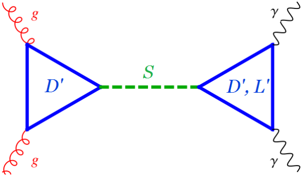
[ATLAS Coll. arXiv:1506.00962]

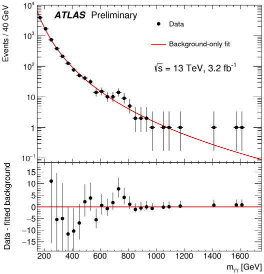


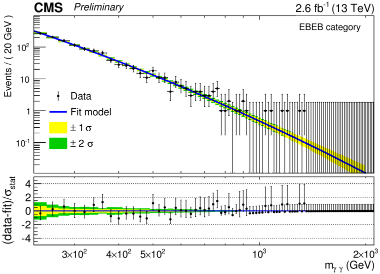


Diphoton excess

The 750 GeV excess may be one of the extra scalars in the Higgs multiplets.
[see the talks on Thursday!]







D' and L' are the extra heavy fermions that allow the production of the new scalar and its photonic decay.

A narrow resonance is predicted.

[ATLAS-CONF-2015-081, CMS-PAS-EXO-15-004]

Backup slides

How to find a TAF model

We rescale the couplings: given $t = \ln(\mu^2/\mu_0^2)/(4\pi^2)$

$$g_i^2(t) = \frac{\tilde{g}_i^2(t)}{t} \qquad y_a^2(t) = \frac{\tilde{y}_a^2(t)}{t} \qquad \lambda_m(t) = \frac{\tilde{\lambda}_m(t)}{t}$$

The one-loop RGEs become

$$\frac{d\tilde{g}_i}{d\ln t} = \frac{\tilde{g}_i}{2} + \beta_{g_i}(\tilde{g}); \ \frac{d\tilde{y}_a}{d\ln t} = \frac{\tilde{y}_a}{2} + \beta_{y_a}(\tilde{g},\tilde{y}); \ \frac{d\tilde{\lambda}_m}{d\ln t} = \tilde{\lambda}_m + \beta_{\tilde{\lambda}_m}(\tilde{g},\tilde{y},\tilde{\lambda})$$

In one line:

$$\frac{dx_I}{d\ln t} = V_I(x) \qquad \text{where } x_I = \{\tilde{g}_i, \tilde{y}_a, \tilde{\lambda}_m\}$$

Solving the **algebraic** system $\frac{dx_I}{d\ln t} = V_I = 0$, we find the **fixed points** x_∞: the couplings $\longrightarrow 0$ with fixed ratios.

How to expand?

New particles modify RGEs $\longrightarrow$ finite number of good models candidates to TAF.

	name	representation	Δb_i			Yukawas	
unstable	1	$(1,1,1)$	0	0	0	$1LH^*$	–
	8_L	$(8,1,1)$	2	0	0	$8_L LH^*$	–
	8_R	$(1,8,1)$	0	2	0	$8_R LH^*$	–
	$L' \oplus \bar{L}'$	$(3,\bar{3},1) \oplus (\bar{3},3,1)$	2	2	0	$L'LH$	$L'L'H + \bar{L}'\bar{L}'H^*$
	$Q'_L \oplus \bar{Q}'_L$	$(\bar{3},1,3) \oplus (3,1,\bar{3})$	2	0	2	$Q'_L Q_R H$	–
	$Q'_R \oplus \bar{Q}'_R$	$(1,3,\bar{3}) \oplus (1,\bar{3},3)$	0	2	2	$Q'_R Q_L H$	–
stable	$3_L \oplus \bar{3}_L$	$(3,1,1) \oplus (\bar{3},1,1)$	$\frac{2}{3}$	0	0	–	–
	$3_R \oplus \bar{3}_R$	$(1,3,1) \oplus (1,\bar{3},1)$	0	$\frac{2}{3}$	0	–	–
	$3_c \oplus \bar{3}_c$	$(1,1,3) \oplus (1,1,\bar{3})$	0	0	$\frac{2}{3}$	–	–
	8_c	$(1,1,8)$	0	0	2	–	–
	$6_L \oplus \bar{6}_L$	$(6,1,1) \oplus (\bar{6},1,1)$	$\frac{10}{3}$	0	0	–	–
	$6_R \oplus \bar{6}_R$	$(1,6,1) \oplus (1,\bar{6},1)$	0	$\frac{10}{3}$	0	–	–
	$6_c \oplus \bar{6}_c$	$(1,1,6) \oplus (1,1,\bar{6})$	0	0	$\frac{10}{3}$	–	–
	$\tilde{L} \oplus \bar{\tilde{L}}$	$(3,3,1) \oplus (\bar{3},\bar{3},1)$	2	2	0	–	–
	$\tilde{Q}_L \oplus \bar{\tilde{Q}}_L$	$(3,1,3) \oplus (\bar{3},1,\bar{3})$	2	0	2	–	–
	$\tilde{Q}_R \oplus \bar{\tilde{Q}}_R$	$(1,3,3) \oplus (1,\bar{3},\bar{3})$	0	2	2	–	–

Vector masses

The vev V_1 alone breaks $G_{333} \to \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} \otimes \mathrm{SU}(3)_c$. A $\mathrm{SU}(2)_L$ doublet H_L, a $\mathrm{SU}(2)_R$ doublet H_R and a Z' singlet acquire mass:

$$M_{H_L} = \frac{g_L}{\sqrt{2}} V_1, \qquad M_{H_R} = \frac{g_R}{\sqrt{2}} V_1, \qquad M_{Z'} = V_1 \sqrt{\frac{2}{3}(g_L^2 + g_R^2)}.$$

Let's take only V_n and V_{Rn}: SM group still unbroken.

Defining $V^2 \equiv \sum_n (V_n^2 + V_{Rn}^2)$, $\alpha \equiv \sum_n V_{Rn}^2 / V^2$ and $\beta \equiv \sum_n V_n V_{Rn} / V^2$, the gauge bosons are:

- a $\mathrm{SU}(2)_L$ doublet with 4 components: $M_{H_L} = g_L V/\sqrt{2}$;
- two charged fields $H_R^\pm$ with mass $M_{H_R^\pm} = g_R V/\sqrt{2}$
- two neutral fields H_R^0 with mass

$$M_{H_R^0}^2 = \frac{g_R^2 V^2}{4}\left[1 + \sqrt{(1-2\alpha)^2 + 4\beta^2}\right].$$

Vector masses

- the right-handed $W_R^\pm$ vectors (the lightest) with mass

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

- the Z_R and the Z_{B-L} vectors, that mix together. In the limit $V_{Rn} \ll V_n$ the mass eigenvalues are

$$M_{Z'} = V\sqrt{\frac{2}{3}(g_L^2 + g_R^2)}, \quad M_{Z''} \simeq |\beta| g_R V_R \sqrt{\frac{g_R^2/2 + 2g_L^2}{g_R^2 + g_L^2}}.$$

- The 12 SM vectors remain massless.

Quark masses with 3 Higgses

Let's assume that H_1 breaks G_{333} but preserves G_{SM} (i.e. $V_1 \neq 0$ and $v_{d1} = v_{u1} = v_{L1} = 0$).
The Yukawa couplings y_{Q1} and y_{L1} allow to give large enough masses $M_{d'_R} = V_1 y_{Q1} \gtrsim 700\text{GeV}$ and $M_{e'_R} = V_1 y_{L1} \gtrsim 200\text{GeV}$ to the extra primed fermions, without also giving too large masses to the SM fermions.
H_2 and H_3 can have the small Yukawa couplings needed to reproduce the light SM fermion masses,

$$m_e \sim \sum_{n=2}^{3} v_{dn} y_{Ln}, \qquad m_u \sim \sum_{n=2}^{3} v_{un} y_{Qn}, \qquad m_d \sim \sum_{n=2}^{3} v_{dn} y_{Qn}.$$