Phenomenology of Trinification models

Giulio Maria Pelaggi

Università di Pisa

16 Settembre 2016

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

Questions

Can the Standard Model be a complete theory?
Despite the experimental success, it can't.

Questions

Can the Standard Model be a complete theory?
Despite the experimental success, it can't.

How does gravity enter in this model?

Questions

Can the Standard Model be a complete theory?
Despite the experimental success, it can't.

How does gravity enter in this model?
How to describe the Dark Matter?

Questions

Can the Standard Model be a complete theory?
Despite the experimental success, it can't.

How does gravity enter in this model?
How to describe the Dark Matter?
Is there new physics "behind the corner"? $\rightarrow$ Naturalness problem

Questions

Can the Standard Model be a complete theory?
Despite the experimental success, it can't.

How does gravity enter in this model?
How to describe the Dark Matter?
Is there new physics "behind the corner"?$\rightarrow$ Naturalness problem

We hope for new observable physics and we imagine some.

A starting point

The radiative corrections of the SM to M_h are power divergent.

Finite Naturalness: the naturalness principle must be respected only by the physical corrections.
The quadratic divergences arise because of the formulation of the theory, and they should be ignored (as we do in dimensional regularization computations).

Total Asymptotic Freedom

In this context, we want to build a 4 dimensional QFT with dimensionless gauge, Yukawa and scalar couplings.

Total Asymptotic Freedom

In this context, we want to build a 4 dimensional QFT with dimensionless gauge, Yukawa and scalar couplings.

The model holds up to infinite energy, where all the couplings run to zero. There is no cut-off scale, so the power-divergent corrections have no physical meaning.

Total Asymptotic Freedom

In this context, we want to build a 4 dimensional QFT with dimensionless gauge, Yukawa and scalar couplings.

The model holds up to infinite energy, where all the couplings run to zero. There is no cut-off scale, so the power-divergent corrections have no physical meaning.

We compute the Renormalization Group equations of this theory searching for fixed flows: the couplings run to zero keeping their ratios fixed.
If the model admits a fixed flow it is Totally Aymptotically Free.

TAF SM

Is the SM TAF?

TAF SM

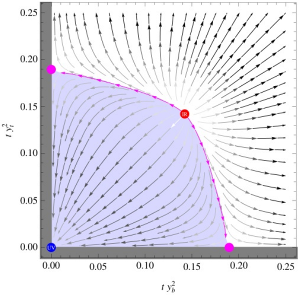
Is the SM TAF?
Yes: it admits fixed flows.

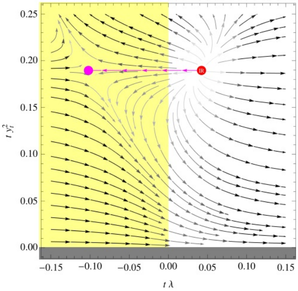
TAF SM

Is the SM TAF?

Yes: it admits fixed flows.

But it predicts $g_Y = 0$, $M_{\text{Top}} = 186\,\text{GeV}$, $M_h = 163\,\text{GeV}$, $M_\tau = 0$.





	$\tilde{y}^2_{t\infty}$	$\tilde{y}^2_{b\infty}$	$\tilde{y}^2_{\tau\infty}$	$\tilde{y}^2_{\nu\infty}$	Eigenvalues
Solution 1	227/1197	0	0	0	$+-++$
Solution 2	0	227/1197	0	0	$-+++$
Solution 3	227/1596	227/1596	0	0	$++++$
Solution 4	0	0	0	0	$--++$

	$\tilde{\lambda}_\infty$	Eig
Sol. 1	$\frac{-143+\sqrt{119402}}{4788} \approx +0.0423$	$+$
Sol. 2	$\frac{-143-\sqrt{119402}}{4788} \approx -0.1020$	$-$

[Giudice, Isidori, Salvio, Strumia, arXiv:1412.2769]

Trinification

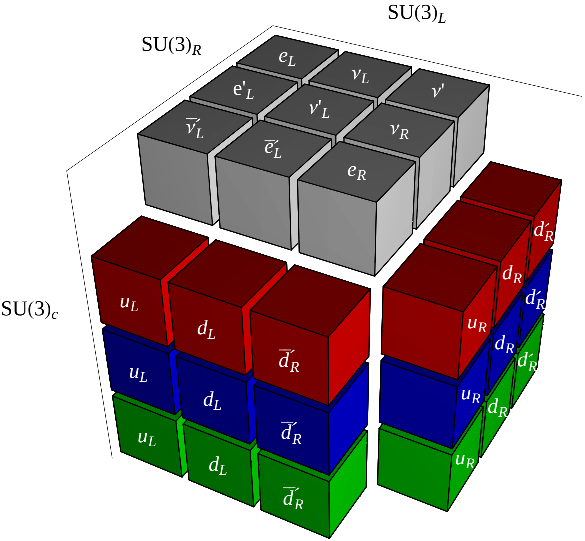
We embed the $\mathrm{U}(1)_Y$ into a bigger, non-Abelian group.
One of the few possibilities to reproduce the charges of the particles, avoiding proton decay, is Trinification.

$$G_{333} = \mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R \otimes \mathrm{SU}(3)_c$$

The Trinification coupling constants are related to the SM ones:

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

Minimal fermionic content



Symmetry breaking pattern

The Higgses are color-neutral bi-triplets, they have a VEV$\neq 0$:

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

Symmetry breaking pattern

The Higgses are color-neutral bi-triplets, they have a VEV$\neq 0$:

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

$$\begin{aligned} G_{333} = &\ \mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R \otimes \mathrm{SU}(3)_c \\ &\downarrow V_n, V_{Rn} \\ G_{SM} = &\ \mathrm{U}(1)_Y \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(3)_c \\ &\downarrow v_n \\ &\mathrm{U}(1)_{em} \otimes \mathrm{SU}(3)_c \end{aligned}$$

Towards a realistic Trinification TAF model

- With 1 Higgs it can't reproduce the SM fermion masses;

Towards a realistic Trinification TAF model

- With 1 Higgs it can't reproduce the SM fermion masses;
- with 2 Higgses it's impossible to make heavy new fermions keeping the SM ones light, unless the Yukawa are fine-tuned.

Towards a realistic Trinification TAF model

- With 1 Higgs it can't reproduce the SM fermion masses;
- with 2 Higgses it's impossible to make heavy new fermions keeping the SM ones light, unless the Yukawa are fine-tuned.
- 3 Higgses can reproduce "naturally" the fermion masses, but no TAF behavior.

Towards a realistic Trinification TAF model

- With 1 Higgs it can't reproduce the SM fermion masses;
- with 2 Higgses it's impossible to make heavy new fermions keeping the SM ones light, unless the Yukawa are fine-tuned.
- 3 Higgses can reproduce "naturally" the fermion masses, but no TAF behavior.

We introduce more fermions to change the RGEs: will the new couplings be asymptotically free?
Minimal Trinification with 3 Higgses plus a vector-like quark family $\tilde{Q}_L \oplus \bar{\tilde{Q}}_L$ and $\tilde{Q}_R \oplus \bar{\tilde{Q}}_R$ is TAF.

Diboson signal

$W_R^{\pm}$ is the lightest extra gauge boson of Trinification. It is obtained rotating two of the interaction eigenstates with an angle θ_R, written in terms of the VEVs.

The angle θ_D parametrizes the mixing between the d_R and d'_R quarks in the Q_R multiplet. It depends on the Yukawa couplings and the VEVs.

The W_R-quarks interaction term is then

$$\mathscr{L}_I = \frac{1}{\sqrt{2}} \left(\tilde{g}_R \bar{d}_R + \tilde{g}'_R \bar{d}'_R \right) \not{W}_R^{+} u_R + \text{h.c.}$$

where $\tilde{g}_R = g_R \cos(\theta_D + \theta_R)$ and $\tilde{g}'_R = g_R \sin(\theta_D + \theta_R)$.
The production cross section is

$$\sigma(pp \to W_R^{\pm}) = K \frac{\pi \tilde{g}_R^2}{6s} C_{\pm}(s),$$

Diboson signal

If all the new degrees of freedom are much heavier than it, $W_R^\pm$ can only decay into the SM quarks and into all the components of the Higgs doublet. No decay into leptons is predicted.

$$\Gamma(W_R^+ \to u\bar{d}) = \frac{\tilde{g}_R^2 |V_{ud}|^2}{16\pi} M_{W_R}, \qquad V \to \text{CKM matrix.}$$

$$\Gamma(W_R^\pm \to W^\pm Z) = \Gamma(W_R^\pm \to W^\pm h) = \frac{g_R^2}{192\pi} M_{W_R} \cos^2\theta_H \, .$$

θ_H is the mixing between the SM Higgs and the other components of $\mathcal{H}$. Total decay width:

$$\Gamma_{W_R} = \frac{g_R^2}{96\pi} M_{W_R} (18\cos^2(\theta_D + \theta_R) + \cos^2\theta_H).$$

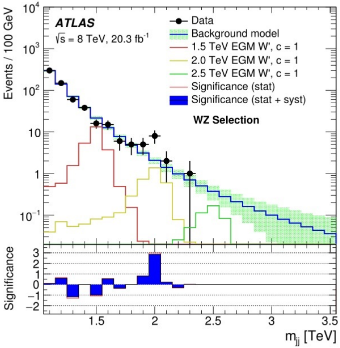
Diboson signal

In Run 1 of LHC there were excesses ($\sim 3\sigma$) in some channels at an energy $\simeq 2$ TeV.

These anomalies could be fitted with the processes

$$pp \to W_R^{\pm} \to W^{\pm}Z$$
$$pp \to W_R^{\pm} \to W^{\pm}h$$
$$pp \to W_R^{\pm} \to jj.$$

No excess has been seen in the di-lepton channel, as predicted.

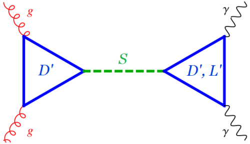


[ATLAS Coll. arXiv:1506.00962]

Diphoton signal

Trinification features a lot of scalar fields. We call S the second lightest scalar, after the SM Higgs.
Given the generic fermions $\mathcal{Q}_f$, scalars $\tilde{\mathcal{Q}}_s$ and vectors V with masses M_f, M_s and M_V, its interactions are described by

$$\mathscr{L}_I^S = \bar{\mathcal{Q}}_f(y_f + y_{5f}\gamma_5)\mathcal{Q}_f - S A_s|\tilde{\mathcal{Q}}_s|^2 + g_V M_V S|V_\mu|^2.$$



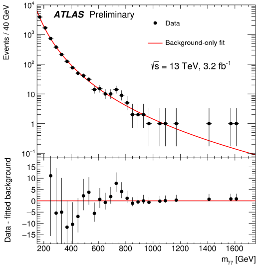
D' and L' are extra heavy fermions needed for the production and the decay of S.

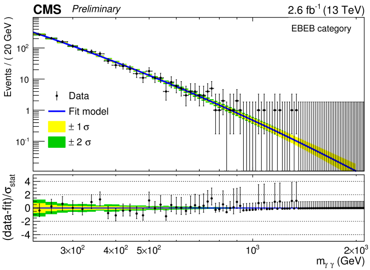
Diphoton signal

$$\frac{\Gamma(S\to gg)}{M}\approx 0.6\ 10^{-4}\left(y_{5D}^2+\frac{4}{9}y_D^2\right)\left(\frac{1\ \mathrm{TeV}}{M_{D'}}\frac{N_{D'}}{3}\right)^2$$

$$\frac{\Gamma(S\to\gamma\gamma)}{M}\approx 10^{-6}\left[6.7\left(y_{5E}\frac{N_{L'}}{3}\right)^2+\left(1.05y_E\frac{N_{L'}}{3}+1.15\frac{A_s}{M_s}\frac{N_s}{9}\right)^2\right]$$

A narrow resonance is predicted. The production of S could fit the 750 GeV excess.





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

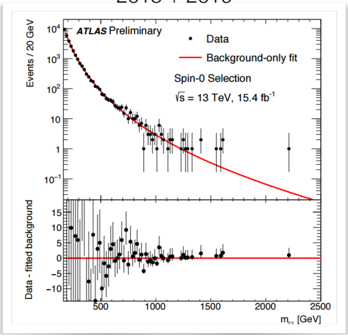
Bad news

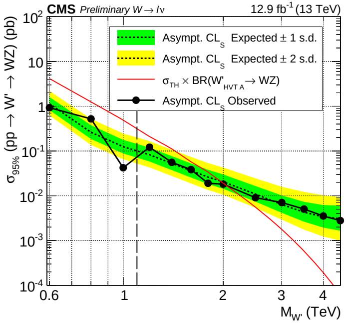
Neither the diboson nor the diphoton excess seem to be confirmed in the last data at LHC.

Bad news

Neither the diboson nor the diphoton excess seem to be confirmed in the last data at LHC.

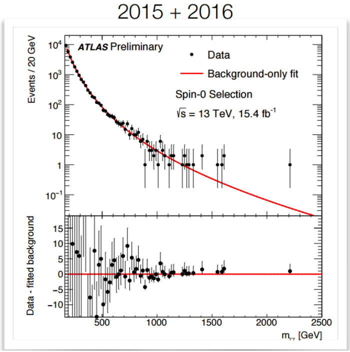
2015 + 2016

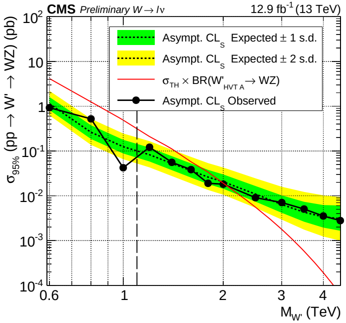




Bad news

Neither the diboson nor the diphoton excess seem to be confirmed in the last data at LHC.





The new physics was not behind this corner.

Asymptotic safety

Asymptotic safety: none of the couplings reach a Landau pole, and they asymptotically approach a constant value when $E \to \infty$.

What's the difference with TAF? Residual interactions at high energy.

Why should we study this behavior? If a $\mathrm{U}(1)$ model could become asymptotically safe, it would be predictive up to infinite energy.

Problem: the asymptotic value of the couplings could be big. Only precise choices of particle contents allow an interacting fixed point near the non-interacting point: in these cases the perturbation theory can be used.

Asymptotic safety

Consider a pure gauge $\mathrm{SU}(N_c)$ theory with $N_c^2 - 1$ gauge bosons A_μ^a and field strength $F_{\mu\nu}^a$. The Lagrangian is the usual Yang-Mills:

$$\mathscr{L}_{YM} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a.$$

The one-loop RGE for $\alpha_g = g^2 N_c/(4\pi)^2$ is

$$\beta_g = \frac{d\alpha_g}{d\ln\mu} = -B\alpha_g^2,$$

The only fixed point is the non-interacting one: $\alpha^* = 0$.

Asymptotic safety

Consider a pure gauge $\mathrm{SU}(N_c)$ theory with $N_c^2 - 1$ gauge bosons A_μ^a and field strength $F_{\mu\nu}^a$. The Lagrangian is the usual Yang-Mills:

$$\mathscr{L}_{YM} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a.$$

The one-loop RGE for $\alpha_g = g^2 N_c/(4\pi)^2$ is

$$\beta_g = \frac{d\alpha_g}{d\ln\mu} = -B\alpha_g^2,$$

The only fixed point is the non-interacting one: $\alpha^* = 0$.

If $B > 0$, the theory is asymptotically free.
If $B < 0$ asymptotic freedom is lost: but if $|B| \ll 1$, the running is slow and could allow the asymptotic safety considering two loops.

Asymptotic safety

With the two-loop terms, the RGE becomes

$$\beta_g = \frac{d\alpha_g}{d\ln\mu} = -B\alpha_g^2 + C\alpha_G^3.$$

A new fixed point arises at $\alpha^* = B/C$. It is asymptotically safe if $B < 0$ and $|B| \ll 1$ and $C < 0$.

The open problem is to find an appropriate particle content, in terms of fermions and scalars that could allow this behavior.

Backup

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	–	–

First results

Let's start from $G = \mathrm{SU}(N)$.
Fermions: $N_F = 5$ anomaly-free chiral families.
For each family there is one fermion ψ^S in the symmetric representation, and $N+4$ fermions in the anti-fundamental.
Scalars: $N_S = 2(N+4)$ in the fundamental representation.
The interaction terms are

$$\mathscr{L}_Y = y_{ijk} S_i^\dagger \psi_j^S \bar{\psi}_k$$

First results

The RGE for the gauge coupling is

$$\frac{dg}{d\ln\mu} = \frac{\beta_g^{(1)}}{(4\pi)^2} + \frac{\beta_g^{(2)}}{(4\pi)^4} + \cdots, \qquad \beta_g^{(1)} = \frac{34}{3} g^3,$$

$$\beta_g^{(2)} = \left(-\frac{9}{2} - \frac{38}{N} + \frac{257}{3} N + \frac{31}{2} N^2\right) g^5 - \left(\frac{3}{2} + \frac{5}{4} N\right) g^3 \sum_{ijk} y_{ijk}^2,$$

The particle content allow the coefficient of the $\beta_g^{(1)}$ to be small and independent on N.
For big N, the second term of the $\beta_g^{(2)}$ could overcome the first, allowing asymptotic safety.