Dynamical Scenarios for Anomalous Interactions involving $t, b$ quarks and bosons

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Abstract

In the present paper we explore various dynamical scenarios for New Physics (NP) which could be generated by very heavy particles and observed in the form of non-standard "low energy" interactions affecting the scalar sector, the gauge bosons and the quarks of the third family. Such interactions have been previously expressed in terms of 48 CP-conserving gauge invariant operators. We show that each scenario is characterized by a specific subset of such operators. Thus, if some traces of NP are ever found in the experimental data, then the comparison with the predictions of the various scenarios, should be able to guide the search towards the underlying dynamics generating it.

$^\dagger$Partially supported by the EC contract CHRX-CT94-0579.
Up to now the Standard Model (SM) has passed all tests and stands in an amazing agreement with the experimental data \cite{1, 2}. Minor discrepancies which are occasionally announced tend to disappear as the statistics is increasing \cite{2}. Nevertheless it is widely believed that there is some New Physics (NP) beyond SM to be discovered, which holds the secrets of the mysterious mechanism inducing the spontaneous breaking of the gauge symmetry and the Higgs properties\cite{3}.

Of course, it may turn out that the SM scalar field is just a parameterization of something yet unknown, and that no true Higgs particle really exists. In this context, the possibility that Higgs is not a particle but just a means inducing new strong non-perturbative interactions among the longitudinal $W$ and $Z$ bosons, has extensively been explored\cite{4}. This option, as well as the exciting one that new particles associated with NP will be produced in the present or future Colliders, are not addressed here. Instead, we concentrate on the possibility that the SM Higgs particle really exists and will be discovered some day in a Collider, but we assume that no other new particle will be seen in the foreseeable future. Moreover we assume that New Physics will appear in the form of slight modifications of the SM interactions among the Higgs and the other particles appearing in the standard model \cite{5}.

If the NP scale is sufficiently large, we could parameterize these new interactions in terms of $\text{dim} = 6$ $SU(3) \times SU(2) \times U(1)$ gauge invariant operators \cite{1}. In a recent work we have presented a complete list of all such operators, under the assumption that NP is CP invariant and that it only affects the interactions among the Higgs, the gauge bosons and the quarks of the third family \cite{7}. In such a framework, the gauge boson equations of motion cannot of course be used in order to reduce the number of the independent NP operators, since these equations mix-in leptons and light quarks also. On the other hand, the equations of motion for the scalar and the $t$ and $b$ quarks can still be used, since they do not mix families, provided we neglect all fermion masses except the top. Thus, we end up with a list containing 48 operators \cite{7}. We have found that thirteen of these operators contribute at tree level to $Z$-peak and lower energy observables; as a result of which eleven of them are quite strongly constrained, while somewhat softer constraints exist for $\mathcal{O}_{DW}$, $\mathcal{O}_{DB}$, see Eqs.\cite{1, 2} below and \cite{8, 9}. Among the remaining operators, 32 are at most very mildly constrained at present, one of them called $\mathcal{O}_{\Phi 3}$ gives no contribution to any conceivable measurement, while the experimental constraints on the two purely gluonic operators ($\mathcal{O}_G$ and $\mathcal{O}_{DG}$ below) are not yet known. In \cite{7}, we have also given the unitarity constraints on the aforementioned 32 operators.

The aim of the present paper is to investigate the implications and the possible conditions for the appearance of any such NP operator. We explore various dynamical scenarios involving naturally heavy particles which are subsequently integrated out leaving a low energy NP interaction expressed in terms of $\text{dim} = 6$ operators. We use the same philosophy as in \cite{10}, but in the present case we also include the possibility that gluon or quark involving operators are generated. We find interesting patterns and hierarchies that are specific to each scenario. When experimental data will be available in the various sectors that can be tested, our results should be useful in suggesting (selecting) what type of scenario and quantum numbers is NP based on.
These dynamical scenarios are builded following the idea that NP is caused solely by the scalar sector. Therefore we do not consider any extensions of the gauge group beyond the $SU(3) \times SU(2) \times U(1)$ level. Thus, our dynamical scenarios are just renormalizable models obeying $SU(3) \times SU(2) \times U(1)$ gauge invariance and containing, in addition to the usual standard particles, also a ”minimal” number of new scalar and/or fermion fields whose interactions respect (for simplicity) CP invariance. A common property for the masses of all these fields is that they are gauge symmetric, and may therefore be assumed to be sufficiently larger than the electroweak scale $v = (\sqrt{2}G^\mu_{\mu})^{-1/2} = 0.246 TeV$.

There are two distinct sets of such models, depending on whether the heavy particles which are responsible for generating the low energy NP interactions, cannot or can decay at tree level, to particles already existing in SM. These two sets lead in general to quite different NP operators at low energies. The dominant operators induced from Set I come from 1-loop diagrams involving a heavy particle running along the loop. Models of this kind, with either a heavy fermion or a scalar boson running along the loop, have been considered in [10] and lead to purely bosonic NP operators. In order to generate $dim = 6$ NP operators involving quarks also, we need to enrich these models by assuming the simultaneous existence of at least one heavy boson and one heavy fermion, and give non-trivial colour to one of these particles. In such a case, the dominant quark-involving NP operators are induced by 1-loop diagrams in which the heavy particle running along the loop changes its nature from boson to fermion.

In the Set II of models, characterized by the fact that the heavy particle can decay to standard model ones, the dominating $dim = 6$ NP operators are generated from tree diagrams involving again only heavy particle propagators. In this case, a single heavy boson field is sufficient to create $dim = 6$ NP operators inducing Higgs as well as quark affecting interactions, while a heavy fermion can only create quark involving operators [11].

Before starting enumerating the dynamical models, we first give the complete list of the $dim = 6$ $SU(3)_c \times SU(2) \times U(1)$ gauge invariant operators describing in general any kind of NP generated at high scale and affecting only the Higgs, the gauge bosons and the quarks of the third family. This list contains the bosonic operators [7, 12].

$$
\begin{align*}
\mathcal{O}_{DW} &= 2 \left( D_\mu \bar{W}^{\mu\rho}_{\nu} \right) \left( D^\rho \bar{W}_{\nu\nu} \right), \\
\mathcal{O}_{DB} &= 2 \left( \partial_\mu B^{\mu\rho} \right) \left( \partial^\nu B_{\nu\rho} \right), \\
\mathcal{O}_{BW} &= \frac{1}{2} \Phi^\dagger B_{\mu\nu} \gamma^\tau \bar{W}^{\mu\nu} \Phi, \\
\mathcal{O}_{\Phi_1} &= \left( D_\mu \Phi^\dagger \Phi \right) \left( \Phi^\dagger D^\mu \Phi \right), \\
\mathcal{O}_{DG} &= 2 \left( D_\mu \bar{G}^{\mu\rho}_{\nu\nu} \right) \left( D^\nu \bar{G}^{\rho\lambda}_{\nu\nu} \right), \\
\mathcal{O}_G &= \frac{1}{3!} \tilde{f}_{ijk} G^{i\mu\nu} G_j^{\rho\lambda} G_k^{\kappa\lambda} \mu,
\end{align*}
$$

$^{1}$The possibility that some higher dimensional operators may occasionally be dynamically enhanced will be ignored here [12].
\[ O_{\Phi 2} = 4 \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi) , \]  
\[ O_{\Phi 3} = 8 (\Phi^\dagger \Phi)^3 , \]  
\[ O_W = \frac{1}{3!} \left( \overrightarrow{W}_{\mu}^\nu \times \overrightarrow{W}_{\nu}^\lambda \right) \cdot \overrightarrow{W}_\mu^\lambda , \]  
\[ O_{W\Phi} = i (D_\mu \Phi)^\dagger \overrightarrow{\tau} \cdot \overrightarrow{W}_{\mu
u} (D_\nu \Phi) , \]  
\[ O_{B\Phi} = i (D_\mu \Phi)^\dagger B_{\mu
u} (D_\nu \Phi) , \]  
\[ O_{WW} = (\Phi^\dagger \Phi) \overrightarrow{W}_{\mu
u} \cdot \overrightarrow{W}_{\mu
u} , \]  
\[ O_{BB} = (\Phi^\dagger \Phi) B_{\mu
u} B_{\mu
u} , \]  
\[ O_{GG} = (\Phi^\dagger \Phi) G_{\mu\nu} \cdot G_{\mu\nu} , \]  
where
\[ \Phi = \left( \frac{\phi^+}{\sqrt{2}} (v + H + i\phi^0) \right) , \]  
\[ D_\mu = (\partial_\mu + i g Y B_\mu + i g' Y B_\mu + i \frac{g}{2} \overrightarrow{\tau} \cdot \overrightarrow{W}_\mu + i \frac{g}{2} \overrightarrow{\lambda} \cdot \overrightarrow{G}_\mu) , \]  
with \( v \simeq 246 GeV \), \( Y \) being the hypercharge of the field on which the covariant derivative acts, and \( \overrightarrow{\tau} \) and \( \overrightarrow{\lambda} \) the isospin and colour matrices applicable whenever \( D_\mu \) acts on iso-doublet fermions and quarks respectively.

In addition, the above list contains operators involving quarks of the third family. These are divided into three Classes [6, 7, 13] and are given by

**Class 1.**

\[ O_{qt} = (\bar{q}_L t_R) (\bar{t}_R q_L) , \]  
\[ O_{qt}^{(8)} = (\bar{q}_L \overrightarrow{x} t_R) (\bar{t}_R \overrightarrow{x} q_L) , \]  
\[ O_{tt} = \frac{1}{2} (\bar{t}_R \gamma_\mu t_R) (\bar{t}_R \gamma^\mu t_R) , \]  
\[ O_{tb} = (\bar{t}_R \gamma_\mu t_R) (\bar{b}_R \gamma^\mu b_R) , \]  
\[ O_{tb}^{(8)} = (\bar{t}_R \gamma_\mu \overrightarrow{x} t_R) (\bar{b}_R \gamma^\mu \overrightarrow{x} b_R) , \]  
\[ O_{qq} = (\bar{t}_R t_L) (\bar{b}_R b_L) + (\bar{t}_L t_R) (\bar{b}_L b_R) - (\bar{t}_R b_L) (\bar{b}_L t_R) - (\bar{t}_L b_R) (\bar{b}_L t_L) , \]  
\[ O_{qq}^{(8)} = (\bar{t}_R \overrightarrow{x} t_L) (\bar{b}_R \overrightarrow{x} b_L) + (\bar{t}_L \overrightarrow{x} t_R) (\bar{b}_L \overrightarrow{x} b_R) - (\bar{t}_R \overrightarrow{x} b_L) (\bar{b}_R \overrightarrow{x} t_R) - (\bar{t}_L \overrightarrow{x} b_R) (\bar{b}_L \overrightarrow{x} t_L) , \]  
\[ O_{t1} = (\Phi^\dagger \Phi) (\bar{q}_L t_R \Phi + \bar{t}_R \Phi^\dagger q_L) , \]  
\[ O_{t2} = i \left[ \Phi^\dagger (D_\mu \Phi) - (D_\mu \Phi^\dagger) \Phi \right] (\bar{t}_R \gamma^\mu t_R) , \]  
\[ O_{t3} = i (\Phi^\dagger D_\mu \Phi) (\bar{t}_R \gamma^\mu b_R) - i (D_\mu \Phi^\dagger \Phi) (\bar{b}_R \gamma^\mu t_R) , \]
\[ O_{Dt} = (\bar{q}_L D_\mu t_R) D^\mu \Phi + D^\mu \bar{\Phi} (D_\mu t_R q_L) \] , \hspace{2cm} (27)

\[ O_{tW\Phi} = (\bar{q}_L \sigma^{\mu\nu} \tau^t t_R) \Phi \cdot \bar{W}^{\mu\nu} + \Phi^t (\bar{t}_R \sigma^{\mu\nu} t_L) \cdot \bar{W}^{\mu\nu} \] , \hspace{2cm} (28)

\[ O_{tB\Phi} = (\bar{q}_L \sigma^{\mu\nu} t_R) \bar{\Phi} B_{\mu\nu} + \Phi^t (\bar{t}_R \sigma^{\mu\nu} q_L) B_{\mu\nu} \] , \hspace{2cm} (29)

\[ O_{tG\Phi} = \left[ (\bar{q}_L \sigma^{\mu\nu} \chi^a t_R) \bar{\Phi} + \Phi^t (\bar{t}_R \sigma^{\mu\nu} \chi^a q_L) \right] G^a_{\mu\nu} \] . \hspace{2cm} (30)

Class 2.

\[ O^{(1,1)}_{qq} = \frac{1}{2} (\bar{q}_L \gamma_\mu q_L) (\bar{q}_L \gamma^\mu q_L) \] , \hspace{2cm} (31)

\[ O^{(1,3)}_{qq} = \frac{1}{2} (\bar{q}_L \gamma_\mu \tau^t q_L) \cdot (\bar{q}_L \gamma^\mu \tau^t q_L) \] , \hspace{2cm} (32)

\[ O_{bb} = \frac{1}{2} (\bar{b}_R \gamma_\mu b_R) (\bar{b}_R \gamma^\mu b_R) \] , \hspace{2cm} (33)

\[ O_{qb} = (\bar{q}_L b_R) (\bar{b}_R q_L) \] , \hspace{2cm} (34)

\[ O^{(8)}_{qb} = (\bar{q}_L \bar{\chi} b_R) \cdot (\bar{b}_R \bar{\chi} q_L) \] . \hspace{2cm} (35)

\[ O^{(1)}_{\Phi q} = i (\Phi^\dagger D_\mu \Phi) (\bar{q}_L \gamma^\mu q_L) - i (D_\mu \Phi^\dagger \Phi) (\bar{q}_L \gamma^\mu q_L) \] , \hspace{2cm} (36)

\[ O^{(3)}_{\Phi q} = i \left[ (\Phi^\dagger \tau^t D_\mu \Phi) - (D_\mu \Phi^\dagger \tau^t \Phi) \right] \cdot (\bar{q}_L \gamma^\mu \tau^t q_L) \] , \hspace{2cm} (37)

\[ O_{\Phi b} = i \left[ (\Phi^\dagger D_\mu \Phi) - (D_\mu \Phi^\dagger \Phi) \right] (\bar{b}_R \gamma^\mu b_R) \] , \hspace{2cm} (38)

\[ O_{Db} = (\bar{q}_L D_\mu b_R) D^\mu \Phi + D^\mu \Phi^t (D_\mu b_R q_L) \] , \hspace{2cm} (39)

\[ O_{bW\Phi} = (\bar{q}_L \sigma^{\mu\nu} \tau^t b_R) \Phi \cdot \bar{W}^{\mu\nu} + \Phi^t (\bar{b}_R \sigma^{\mu\nu} \tau^t q_L) \cdot \bar{W}^{\mu\nu} \] , \hspace{2cm} (40)

\[ O_{bB\Phi} = (\bar{q}_L \sigma^{\mu\nu} b_R) \Phi B_{\mu\nu} + \Phi^t (\bar{b}_R \sigma^{\mu\nu} q_L) B_{\mu\nu} \] , \hspace{2cm} (41)

\[ O_{bG\Phi} = (\bar{q}_L \sigma^{\mu\nu} \chi^a b_R) \Phi G^a_{\mu\nu} + \Phi^t (\bar{b}_R \sigma^{\mu\nu} \chi^a q_L) G^a_{\mu\nu} \] , \hspace{2cm} (42)

\[ O_{b1} = (\Phi^\dagger \Phi) (\bar{q}_L b_R \Phi + \bar{b}_R \Phi^t q_L) \] . \hspace{2cm} (43)

Class 3.

\[ O_{qB} = \bar{q}_L \gamma^\mu q_L (\partial^\nu B_{\mu\nu}) \] , \hspace{2cm} (44)

\[ O_{qW} = \frac{1}{2} (\bar{q}_L \gamma_\mu \tau^t q_L) \cdot (D_\nu \bar{W}^{\mu\nu}) \] , \hspace{2cm} (45)

\[ O_{bB} = \bar{b}_R \gamma^\mu b_R (\partial^\nu B_{\mu\nu}) \] , \hspace{2cm} (46)

\[ O_{tB} = \bar{t}_R \gamma^\mu t_R (\partial^\nu B_{\mu\nu}) \] , \hspace{2cm} (47)

\[ O_{tG} = \frac{1}{2} (\bar{t}_R \gamma_\mu \chi t_R) \cdot (D_\nu \bar{G}^{\mu\nu}) \] , \hspace{2cm} (48)

\[ O_{bG} = \frac{1}{2} (\bar{b}_R \gamma_\mu \chi b_R) \cdot (D_\nu \bar{G}^{\mu\nu}) \] . \hspace{2cm} (49)
\[ O_{qG} = \frac{1}{2} \left( \bar{q}_L \gamma_\mu \vec{G}_{\mu} q_L \right) \cdot (D_\nu \vec{G}^\nu) \]  

(50)

We next turn to the results of the two sets of dynamical models mentioned above. We first present the results for both sets, and subsequently we discuss them.

Models of Set I. The minimal models in this set contain in addition to the standard particles, a new heavy scalar boson \( \Psi \) and a heavy left-right symmetric fermion \( (F_L, F_R) \) with various colour, isospin and hypercharge specifications. Their quantum numbers are such that they do not allow any tree level decay of the new heavy particles to standard model ones. Depending on the \( \Psi \) and \( F \) hypercharges, called \( Y_F \equiv y \) and \( Y_{\Psi} \) respectively, there are three different version-categories of the models of Set I characterized by the Yukawa-type interactions \( L_j \) \((j = 1 - 3)\) which couple the NP inducing heavy fields \( \Psi \) and \( F \) to any of \( t_R, q_L \equiv (t_L, b_L) \) or \( b_R \); (see (52, 53, 54) below). Thus, the interaction to be added to the SM Lagrangian in each of these cases is

\[
L_I = i \bar{F} \Psi F - \Lambda_{NP} \bar{F} F + D_\mu \Psi^\dagger D^\mu \Psi - \Lambda_{NP}^2 \Psi^\dagger \Psi + 2g_{\Psi}(\Psi^\dagger \Psi)(\Phi^\dagger \Phi) + L_j ,
\]

(51)

where we have for simplicity used a common large mass equal to \( \Lambda_{NP} \) for both the \( \Psi \) and \( F \) particles. The assumed interaction of NP with the third family quarks may take the form

\[
L_1 = f(t_R \Psi^\dagger F_L + h.c.) \quad \text{for Model 1} ,
\]

(52)

\[
L_2 = f(\bar{q}_L \Psi F_R + h.c.) \quad \text{for Model 2} ,
\]

(53)

\[
L_3 = f(\bar{b}_R \Psi^\dagger F_L + h.c.) \quad \text{for Model 3} .
\]

(54)

In each of these versions, we try four different assignments for the \( \Psi \) and \( (F_L, F_R) \) isospin and colour, which are given in Table 1.

In this Set, the dominant \( \text{dim} = 6 \) NP contribution arises at 1-loop level. Thus, integrating out the heavy states in (51), we get at a scale just below \( \Lambda_{NP} \), the NP contribution to be added to the SM Lagrangian

\[
\mathcal{L}_{NP} = \frac{1}{(4\pi \Lambda_{NP})^2} \left\{ - c_W g^3 \left[ \frac{1}{60} \mathcal{O}_W - \frac{c_G g_s^3}{30} \mathcal{O}_G \right] - c_{DW} \frac{g^2}{240} \mathcal{O}_{DW} - c_{DB} \frac{g^2}{120} \mathcal{O}_{DB} - c_{DG} \frac{g_s^2}{120} \mathcal{O}_{DG} - c_{WW} g_{\Psi} \frac{g^2}{4} \mathcal{O}_{WW} - c_{BB} g_{\Psi} g^2 \mathcal{O}_{BB} - c_{GG} g_{\Psi} \frac{g_s^2}{6} \mathcal{O}_{GG} - c_{\Phi 3} g_{\Psi} g_{\Phi 3} + c_{\Phi 2} \frac{g_{\Psi}^2}{2} \mathcal{O}_{\Phi 2} \right\}.
\]

\(^2\)Left-right symmetry for the fermion is imposed because it guarantees the absence of any anomalies.

\(^3\)For the purely bosonic operators we have used the Seeley-DeWitt expansion explained in [14].
As before, we only consider models involving scalar or a left-right symmetric bosonic operators are concerned, the results in (55) are similar to those in [10].

The interaction which should be added to the SM Lagrangian for the models 4-6B is given by

$$\mathcal{L}_4 = D_\mu \Psi \overleftrightarrow{D}^\mu \Psi - \Lambda_{NP}^2 \Psi \overleftrightarrow{D}^\mu \Psi + f_3[(\Psi \overleftrightarrow{D}^\mu \Phi)(\Phi \overleftrightarrow{D}^\mu \Phi) + \text{h.c.}]$$

$$+ f_1(\overline{T}_{R} \Psi L + \text{h.c.}) + f_2(\overline{b}_{R} \Psi q_{L} + \text{h.c.}) + \ldots,$$

$$\mathcal{L}_5 = \overline{t} F \overleftrightarrow{D}^\mu F - \Lambda_{NP} \overleftrightarrow{D}^\mu \Phi L + \ldots + f_l(\overline{T}_{R} \Phi L + \text{h.c.}),$$

$$\mathcal{L}_{6A} = \overline{t} F \overleftrightarrow{D}^\mu F - \Lambda_{NP} \overleftrightarrow{D}^\mu \Phi L + \ldots + f_l(\overline{T}_{R} \Phi L + \text{h.c.}),$$

$$\mathcal{L}_{6B} = \overline{t} F \overleftrightarrow{D}^\mu F - \Lambda_{NP} \overleftrightarrow{D}^\mu \Phi L + \ldots + f_l(\overline{T}_{R} \Phi L + \text{h.c.}),$$

where the dots in (56) stand for terms which are irrelevant for the tree diagrams dominating the low energy NP effective Lagrangian. Thus, at a scale just below $\Lambda_{NP}$, the $\dim = 6$ contributions to the effective NP interactions are respectively given by

$$\mathcal{L}_{NP/4} = \frac{1}{\Lambda_{NP}^2} (f_1^2 \mathcal{O}_{qt} + f_2^2 \mathcal{O}_{qb} + f_1 f_2 \mathcal{O}_{qq} + f_1 f_3 \mathcal{O}_{tq} + f_2 f_3 \mathcal{O}_{bq} + \frac{f_3^2}{12} \mathcal{O}_{q3}),$$
\[ L_{NP/5} = \frac{1}{2\Lambda_{NP}^2} \left[ f_t^2 \mathcal{O}_{\Phi t} + f_t^2 \left( -\mathcal{O}_{t2} + \frac{m_t\sqrt{2}}{v} \mathcal{O}_{t1} \right) + 2f_t f_b \mathcal{O}_{t3} \right], \]  
(61)

\[ L_{NP/6A} = -\frac{f_q^2}{4\Lambda_{NP}^2} (\mathcal{O}_{q_q}^{(1)} + \mathcal{O}_{q_q}^{(3)}), \]  
(62)

\[ L_{NP/6B} = \frac{f_q^2}{4\Lambda_{NP}^2} \left( \mathcal{O}_{q_q}^{(1)} + \mathcal{O}_{q_q}^{(3)} + \frac{m_t 2^{3/2}}{v} \mathcal{O}_{t1} \right). \]  
(63)

**Discussion.** Above we have considered 16 different renormalizable models based on $SU(3) \times SU(2) \times U(1)$ gauge invariance and divided into two Sets. The models are "minimal" in the sense that we are not extending the gauge group and they are containing the minimal number of scalar and/or fermion fields necessary in order to create some of the total number of the 14 bosonic and the 34 quark-involving $dim = 6$ CP conserving gauge invariant interactions.

Concerning these models, we first observe that 14 out the total number of the 48 aforementioned operators, were never created in any of them. These are the purely bosonic operators ($\mathcal{O}_{BW}, \mathcal{O}_{\Phi 1}, \mathcal{O}_{W \Phi}, \mathcal{O}_{B \Phi}$); the four-quark operators ($\mathcal{O}_{qt}^{(8)}, \mathcal{O}_{tb}^{(8)}, \mathcal{O}_{q_q}^{(8)}$) from Class 1 and $\mathcal{O}_{q_b}^{(8)}$ from Class 2; and the two-quark operators $\mathcal{O}_{Dt}$ and ($\mathcal{O}_{Db}, \mathcal{O}_{bW \Phi}, \mathcal{O}_{bB \Phi}, \mathcal{O}_{bG \Phi}$) from Class 1 and 2 respectively. With respect to this, there are three remarks to be made:

- The operators $\mathcal{O}_{BW}$ and $\mathcal{O}_{\Phi 1}$ would have been created in all models of Set I which involve an iso-doublet scalar field $\Psi$, provided we had added to (51) the renormalizable interaction term of the form $[10]$

\[
(\Psi^\dagger \overrightarrow{\tau} \Psi) \cdot (\Phi^\dagger \overrightarrow{\tau} \Phi). \]  
(64)

The reason we avoided adding this term is because both, $\mathcal{O}_{BW}$ and $\mathcal{O}_{\Phi 1}$ are quite strongly constrained by their tree level contribution to Z-peak observables $[13][14]$.

- The four-quark operators $\mathcal{O}_{tb}, \mathcal{O}_{tb}^{(8)}, \mathcal{O}_{qt}^{(8)}$ and $\mathcal{O}_{q_q}^{(8)}$, would also be generated if we had considered models more complicated then those appearing in Set I. For example $\mathcal{O}_{tb}$ would be realized if Models 1A or 1B were combined with 3A or 3B; by introducing in addition to the heavy fermion of hypercharge $Y_F$, two iso-douplet scalars carrying hypercharges $Y_F - 2/3$ and $Y_F + 1/3$ respectively.

- Contrary to the above, the four-quark operator $\mathcal{O}_{q_q}^{(8)}$, as well as the operators $\mathcal{O}_{W \Phi}, \mathcal{O}_{B \Phi}, \mathcal{O}_{Dt}, \mathcal{O}_{Db}, \mathcal{O}_{bW \Phi}, \mathcal{O}_{bB \Phi}$ and $\mathcal{O}_{bG \Phi}$ are never generated in any model of the type appearing in both sets I and II, even if we had increased the number of the iso-scalar and iso-doublet fermion or scalar fields, so far we neglect the quark masses except the top one.

We next comment on the comparison between the two Sets I and II. As we have already said, Set I contains models involving heavy scalars or fermions which cannot decay to standard model particles. On the opposite, to Set II belong models involving
heavy scalars or fermions which can decay to particles appearing in SM. The dominant $dim = 6$ NP operators are induced at tree level in Set II and at 1-loop level in Set I. The two Sets produce very different operators. Thus, the study of the low energy structure of NP can give information on the responsible high energy dynamics. In detail the relative characteristics of the two Sets are:

- **Bosonic operators**: The only bosonic operator arising in Set II, is the presently un-observable $O_{\Phi_3}$, which depends only on Higgs self interactions. Of course, this operator is generated at tree level in Set II only when the heavy particle is a boson; see Model 4. If the vacuum expectation value of a heavy scalar boson involved in the first of these models (Model 4), were allowed to acquire non vanishing vacuum expectation value, then the operators $O_{\Phi_1}$ and $O_{\Phi_2}$ would also be generated, [11]. But in any case, no anomalous triple gauge boson couplings can appear in the models of Set II; compare (60-63). This property would have remained true even if we had extended the gauge group and included new heavy gauge bosons coupling to SM particles at tree level. On the contrary, as seen from (55) and the Tables 2-4, almost all purely bosonic operators may be produced in models of the type presented in Set I. The only bosonic operators which we were not able to produce in models of Set I are $O_{W\Phi}$, $O_{B\Phi}$ [10]. It is also worth remarking that the models of Set II would be very little constrained by present data in the case that we put $f_2 = f_b = f_q = \tilde{f}_q = 0$ in (56, 57, 58, 59), which would be true if NP is only induced by top and Higgs new interactions.

- **4-quark operators**: The only four quark operators generated in the models of Set I, are $O_{tt}$ arising from Models 1A-1D; $O_{bb}$ arising from 3A-3D; and $O_{(1,1)}^{qq}$ and $O_{(1,3)}^{qq}$ produced in Models 2A-2D. Correspondingly, the only four-quark operators in Set II, are $O_{qt}$, $O_{qb}$ and $O_{qq}$, all of which appear only in Model 4 characterized by the existence of heavy scalars. Thus, there is no overlap for the four-quark operators produced in the two Sets.

- **2-quark operators of Class 1 and 2**: The operators $O_{tB\Phi}$, $O_{tW\Phi}$ and $O_{tG\Phi}$ appear only in Set I; while $O_{b_1}$, $O_{t3}$, $O_{(3)}^{qq}$ and $O_{\Phi_b}$ are only met in Set II. On the other hand, the operators $O_{t1}$, $O_{t2}$ and $O_{(1)}^{qq}$ appear in both sets.

- The operators of Class 3, (which formally are also two-quark operators), are only generated in models of Set I, and never in the Set II (at tree level).

Finally we comment on the possible magnitude of the NP couplings of the various operators. As seen from (55) together with Tables 2-4, the couplings of all the purely gauge depending NP operators $O_{DW}$, $O_{DB}$, $O_{DG}$, $O_{W}$ and $O_{G}$ are determined by the gauge principle. Thus, unless there is some strong non-perturbative enhancement, it seems that there is not much freedom to make the strength of these operators observable. The situation looks particularly severe for $O_{DW}$, $O_{DB}$ and $O_{W}$; while it may be better for $O_{G}$ and $O_{DG}$, where the strength is determined by the QCD coupling $g_s$, but the background is of course larger.
The situation may be more favorable for the Higgs and quark involving operators whose strength is always determined by the Yukawa couplings of the underlying dynamical theory. Since there is no a priori constraint on these Yukawa couplings, we could hope that some of them may be large. For example, they could become $f^2 \sim 4\pi$, which is allowed by the unitarity constraints [7]. Note in this respect that the SM top quark Yukawa coupling is of order one.

In conclusion our study has taught us several lessons:

- Each scenario leads to a specific selection among the list of admissible operators. This selection is a consequence of the quantum numbers assigned to the NP degrees of freedom. For example, the gluonic operators $O_G$ and $\bar{O}_{DG}$ appear naturally as soon as the heavy fermion or scalar integrated out, carries colour; in complete analogy to $O_W$ and $\bar{O}_{DW}$ appearing whenever the heavy new particles carry isospin. Similarly, the appearance of $O_{GG}$ and/or $O_{WW}$ follows whenever the heavy particle is a scalar carrying a non-vanishing colour and/or isospin quantum number respectively. We thus emphasize that the gluonic operators are at the same footing as the other bosonic operators, which is a feature not considered originally [12].

- In general, a heavy fermion loop in the models of Set I, will only generate purely gauge boson operators, while Higgs dependent bosonic operators will appear only when a heavy scalar particle runs around the loop [14]. On the other hand, the generation of quark operators in Set I needs that the heavy particle in the loop changes its nature from scalar to fermion. Correspondingly for Set II, where only tree level contributions are considered, a diagram involving a heavy fermionic propagator can obviously never generate bosonic operators.

- A natural hierarchy in the size of the couplings associated to the involved operators is also generated. Thus we find that there exist a set of operators which are never generated, while other sets could appear, but with reduced strengths determined by gauge couplings and loop-factors. On the other hand, the Higgs and heavy quark involving operators which are generated, can have a strong coupling being constrained at present only by unitarity considerations.

Summarizing, we conclude that the comparison of such a theoretical landscape with the present and future experimental data, should be very instructive when looking for hints about the origin and the basic structure of NP.
### Table 1: Models of Set I.

| Model | $Y_{\Psi}$ | $I_F$ | $I_{\Phi}$ | colour($F$) | colour($\Psi$) |
|-------|------------|-------|------------|-------------|---------------|
| 1A    | $y - 2/3$ | 1/2   | 1/2        | 1           | 3             |
| 1B    | $y - 2/3$ | 1/2   | 1/2        | 3           | 1             |
| 1C    | $y - 2/3$ | 0     | 0          | 1           | 3             |
| 1D    | $y - 2/3$ | 0     | 0          | 3           | 1             |
| 2A    | $1/6 - y$ | 1/2   | 0          | 1           | 3             |
| 2B    | $1/6 - y$ | 1/2   | 0          | 3           | 1             |
| 2C    | $1/6 - y$ | 0     | 1/2        | 1           | 3             |
| 2D    | $1/6 - y$ | 0     | 1/2        | 3           | 1             |
| 3A    | $y + 1/3$ | 1/2   | 1/2        | 1           | 3             |
| 3B    | $y + 1/3$ | 1/2   | 1/2        | 3           | 1             |
| 3C    | $y + 1/3$ | 0     | 0          | 1           | 3             |
| 3D    | $y + 1/3$ | 0     | 0          | 3           | 1             |

### Table 2: Non vanishing $c_a$-Parameters for Models 1A-1D; (see (55)).

| $c_a$ | 1A     | 1B     | 1C     | 1D     |
|-------|--------|--------|--------|--------|
| $c_W$ | 1      | -5     | 0      | 0      |
| $c_G$ | 1      | -2     | 1/2    | -1     |
| $c_{DW}$ | 11   | 25     | 0      | 0      |
| $c_{DB}$ | $6 \left( y - \frac{2}{3}\right)^2 + 16y^2$ | $2 \left( y - \frac{2}{3}\right)^2 + 48y^2$ | $3 \left( y - \frac{2}{3}\right)^2 + 8y^2$ | $(y - \frac{2}{3})^2 + 24y^2$ |
| $c_{DG}$ | 1      | 8      | 1/2    | 4      |
| $c_{WW}$ | 1      | 1/3    | 0      | 0      |
| $c_{BB}$ | $(y - \frac{2}{3})^2$ | $\frac{1}{3}(y - \frac{2}{3})^2$ | $\frac{1}{2}(y - \frac{2}{3})^2$ | $\frac{1}{6}(y - \frac{2}{3})^2$ |
| $c_{GG}$ | 1      | 0      | 1/2    | 0      |
| $c_{\Phi 2}$ | 1      | 1/3    | 1/2    | 1/6    |
| $c_{\Phi 3}$ | 1      | 1/3    | 1/2    | 1/6    |
| $c_{tt}$ | 1      | 1      | 1/2    | 1/2    |
| $c_{tB\Phi}$ | $\frac{1}{3} - y$ | $\frac{1}{3} - y$ | $\frac{1}{3} - y$ | $\frac{1}{3} - y$ |
| $c_{tG\Phi}$ | 1      | -1     | 1/2    | -1/2   |
| $c_{t1}$ | 1      | 1      | 1/2    | 1/2    |
| $c_{t\Phi}$ | 1      | 1      | 1/2    | 1/2    |
| $c_{tB}$ | $y + \frac{1}{3}$ | $y + \frac{1}{3}$ | $\frac{1}{2}(y + \frac{1}{3})$ | $\frac{1}{2}(y + \frac{1}{3})$ |
| $c_{tG}$ | 1      | 3      | 1/2    | 3/2    |
Table 3: Non vanishing $c_a$-Parameters for Models 2A-2D; (see (53)).

| $c_a$ | 2A | 2B | 2C | 2D |
|-------|----|----|----|----|
| $c_W$ | -2 | -6 | 3  | 1  |
| $c_G$ | 1/2| -2 | 1  | -1 |
| $c_{DW}$ | 8  | 24 | 3  | 1  |
| $c_{DB}$ | $3(\frac{1}{6} - y)^2 + 16y^2$ | $(\frac{1}{6} - y)^2 + 48y^2$ | $6(\frac{1}{6} - y)^2 + 8y^2$ | $2(\frac{1}{6} - y)^2 + 24y^2$ |
| $c_{DG}$ | 1/2| 8  | 1  | 4  |
| $c_{WW}$ | 0  | 0  | 1  | 1/3|
| $c_{BB}$ | $\frac{1}{2}(\frac{1}{6} - y)^2$ | $\frac{1}{2}(\frac{1}{6} - y)^2$ | $(\frac{1}{6} - y)^2$ | $\frac{1}{3}(\frac{1}{6} - y)^2$ |
| $c_{GG}$ | 1/2| 1/6| 1  | 1/3|
| $c_{\Phi 2}$ | 1/2| 1/6| 1  | 1/3|
| $c_{\Phi 3}$ | 1/4| 1/2| 1/2| 1/4|
| $c_{q q 1}^{(1,1)}$ | 1/4| 0  | 0  | 1/4|
| $c_{q q 1}^{(1,3)}$ | $\frac{1}{2}(\frac{1}{12} - y)$ | $\frac{1}{2}(\frac{1}{12} - y)$ | $\frac{1}{2}(\frac{1}{12} - y)$ | $\frac{1}{2}(\frac{1}{12} - y)$ |
| $c_{t B \Phi}$ | -1/2| -1/2| 1/2| 1/2|
| $c_{t W \Phi}$ | 1/2| -1/2| 1/2| -1/2|
| $c_{t 1}$ | 1/2| 1/2| 1/2| 1/2|
| $c_{t 2}$ | 1  | 1  | 1  | 1  |
| $c_{q B}$ | $y + \frac{1}{12}$ | $y + \frac{1}{12}$ | $y + \frac{1}{12}$ | $y + \frac{1}{12}$ |
| $c_{q W}$ | 3  | 3  | 1  | 1  |
| $c_{q G}$ | 1  | 3  | 1  | 3  |

Table 4: Non vanishing $c_a$-Parameters for Models 3A-3D; (see (53)).

| $c_a$ | 3A | 3B | 3C | 3D |
|-------|----|----|----|----|
| $c_W$ | 1  | -5 | 0  | 0  |
| $c_G$ | 1  | -2 | 1/2| -1 |
| $c_{DW}$ | 11 | 25 | 0  | 0  |
| $c_{DB}$ | $6(y + \frac{1}{3})^2 + 16y^2$ | $2(y + \frac{1}{3})^2 + 48y^2$ | $3(y + \frac{1}{3})^2 + 8y^2$ | $(y + \frac{1}{3})^2 + 24y^2$ |
| $c_{DG}$ | 1  | 8  | 1/2| 4  |
| $c_{WW}$ | 1  | 1/3| 0  | 0  |
| $c_{BB}$ | $(y + \frac{1}{3})^2$ | $\frac{1}{2}(y + \frac{1}{3})^2$ | $\frac{1}{2}(y + \frac{1}{3})^2$ | $\frac{1}{6}(y + \frac{1}{3})^2$ |
| $c_{GG}$ | 1  | 0  | 1/2| 0  |
| $c_{\Phi 2}$ | 1  | 1/3| 1/2| 1/6|
| $c_{\Phi 3}$ | 1  | 1/3| 1/2| 1/6|
| $c_{b B}$ | 2  | 2  | 1  | 1  |
| $c_{b G}$ | $2(y - \frac{1}{6})$ | $2(y - \frac{1}{6})$ | $y - \frac{1}{6}$ | $y - \frac{1}{6}$ |
| $c_{b G}$ | 2  | 6  | 1  | 3  |
Table 5: Models of Set II.

| Model | New Particle | $I$   | $Y$   |
|-------|--------------|-------|-------|
| 4     | Scalar $\Psi$| $1/2$ | $1/2$ |
| 5     | $F_L, F_R$   | $1/2$ | $1/6$ |
| 6A    | $F_L, F_R$   | 0     | $-1/3$|
| 6B    | $F_L, F_R$   | 0     | $2/3$ |

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