Tests of Higgs and Top Effective Interactions

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Abstract

We study the possibility to detect heavy physics effects in the interactions of Higgs bosons and the top quark at future colliders using the effective Lagrangian approach, where the SM Lagrangian is modified by non-renormalizable operators that are invariant under the full strong and electroweak group. The modification of the interactions may enhance the production of Higgs bosons at hadron colliders through the mechanisms of gluon fusion and associated production with a W boson or $tt$ pairs. The most promising signature is through the decay of the Higgs boson into two photons, whose branching ratio is also enhanced in this approach. As a consequence of our analysis we get a bound on the chromomagnetic dipole moment of the top quark.
1. Introduction. The standard model (SM) has been tested with success at the level of radiative corrections at LEP. However, several properties of the elementary particles are not explained within the model, like the large value found for the top quark mass or the nature of the Higgs mechanism, responsible for the generation of masses. Because of the lack of any experimental evidence on the Higgs boson, almost anything could be said about its nature. For instance, that it could be the remnant of some new physics that governs the world at deeper distances.

The present generation of colliders (LEP, FNAL) has tested only some portion of the parameter space of the Higgs sector within the SM and beyond; for the SM it is found that $m_H > 67$ GeV. It is expected that the next generation of colliders (LHC, NLC) will be decisive to further test the SM and to discover the nature of the Higgs mechanism.

The framework of effective Lagrangians, as a mean to parametrize physics beyond the SM in a model independent manner, has been used extensively recently. Two main cases have been discussed in the literature, the decoupling case, which assumes the existence of a light Higgs boson, and the non-decoupling case, where no Higgs boson is included at all. We shall consider here the decoupling case, which considers the SM as the low-energy limit of a weakly coupled and renormalizable full theory. Within this approach, the effective Lagrangian is constructed by assuming that the virtual effects of new physics modify the SM interactions in such a way that they are parametrized by a series of higher-dimensional nonrenormalizable operators written in terms of the SM fields. These operators respect the SM symmetries and are suppressed by inverse powers of the high-energy new physics scale $\Lambda$.

In this paper we study how the detection of the Higgs bosons at hadron colliders is affected when its couplings with gauge bosons and the top quark are modified within the effective Lagrangian approach. We shall focus mainly in the so called intermediate mass-region ($m_Z < m_H < 2m_Z$), which is the prefered region by the analysis of SM radiative corrections. We find that the modification to the SM interactions may enhance the cross-sections for the production of Higgs bosons through the reactions of gluon fusion and the associated production with a $W$ boson or $t\bar{t}$ pairs. Using a perturbative criteria and our result on the gluon fusion mechanism, we obtain a bound on the chromomagnetic dipole moment of the top quark.

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2. The effective Lagrangian. The effective Lagrangian for Higgs ($H^0$) and top ($t$) interactions with gauge bosons ($W, Z, \gamma$) and gluons ($g$), can be expanded as follows:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{\alpha_i}{\Lambda^n} O_i^n,$$

(1)

where $\mathcal{L}_{\text{SM}}$ denotes the SM renormalizable Lagrangian. The terms $O_i^n$ are higher-dimension (non-renormalizable) $SU(3) \times SU(2)_L \times U(1)$ invariant operators and $\alpha_i$ are unknown parameters, whose order of magnitude can be estimated because gauge invariance makes possible to establish the order of perturbation theory in which each operator can be generated in the full theory \[8\]. The coefficients of the operators which are generated at tree-level will be suppressed only by products of coupling constants, whereas those that can be generated at the one-loop level, or higher, will be further suppressed by a typical $16\pi^2$ loop factor.

One consequence of assuming that the full gauge symmetries of the SM should be respected by the new operators is that the lowest-dimension operators in (1) are of dimension-6. As we shall discuss below, in the case of the top quark this implies that the value expected for the chromomagnetic dipole moment may lay beyond the sensitivity of future experiments, and thus the bounds obtained in the literature for this moment \[9\] may be suppressed by an additional factor $v/\Lambda$, with $v = 254$ GeV the electroweak scale. This situation is similar to that found in the study of the 3-point vertices within the context of the effective Lagrangian approach: the use of the full SM gauge symmetry imposes a stronger bound \[11\] than the one obtained with the mere use of $U(1)_{\text{em}}$ gauge invariance \[10\].

In this paper we are interested in the gluon fusion mechanism ($gg \rightarrow H^0$), which in the SM occurs at the one-loop level (Fig. 1). This interaction involves both the strong and the Yukawa sectors of the SM. The top quark gives the leading contribution to the loop in the SM. The virtual effects of new physics could modify the $ggH$ interaction, and if the new physics is described at the scale $\Lambda$ by a perturbatively renormalizable theory, then its effects will decouple in the limit $v/\Lambda \rightarrow 0$. There are three possible sources of change for the $ggH$ effective vertex: the $H^0t\bar{t}$ interactions (Fig. 1-ii), the QCD vertex $gt\bar{t}$ (Figs. 1-iii,iv,v), and the effective contact term for the vertex $ggH$ induced by new physics effects (Fig. 1-vi).

We denote by $t_{L,R}$ the chiral components of the top quark; $q$ corresponds to the top-bottom doublet, $\phi, G$ are used for the Higgs doublet and gluon
fields, and \( W, B \) for the electroweak gauge bosons. We shall employ the notation \( O_X^{n,i} \) for an operator of type \( X \), with dimension \( n \), and \( i = t, l \) for tree- and loop-induced operators, respectively. The dimension-6 operator

\[
O_{t\phi}^{6,t} = (\phi^\dagger \phi) \bar{q} t_R \tilde{\phi}
\]

modifies the Yukawa interaction of the top-Higgs system. One operator that leads to modifications of the \( g t \bar{t} \) interaction, induced at the one-loop level, is given by:

\[
O_{Gt}^{6,l} = i \bar{q} G^{\mu\nu} \sigma_{\mu\nu} \bar{t} R,
\]

where \( G^{\mu\nu} = \lambda^a G_a^{\mu\nu} \), with \( \lambda^a \) denoting the Gell-Mann matrices. Also \( \sigma_{\mu\nu} = (i/2)[\gamma_\mu, \gamma_\nu] \), with \( \gamma_\mu \) denoting the Dirac matrices.

A contact term for the effective vertex \( ggH \) is induced also by operators of dimensions 6 and 8, generated at one-loop and tree levels, respectively, and have the following structure:

\[
O_{Gg}^{6,t} = (\phi^\dagger \phi) C_{\mu\nu}^a G_a^{\mu\nu},
\]

\[
O_{Gg}^{8,t} = (\phi^\dagger \phi)^2 C_{\mu\nu}^a G_a^{\mu\nu}.
\]

The operators (2-3) may also lead to some changes in the cross-section for the associated production of the Higgs boson with \( t \bar{t} \) pairs, which is also a relevant mechanism in the intermediate mass-region.

Another interesting aspect of the Higgs phenomenology, namely the associated production of the Higgs with a W boson, could be modified by the following set of dimension-6 operators, induced at tree-level, which modify the interaction of the Higgs boson with the \( W, Z \) bosons,

\[
O_{\phi 1}^{6,t} = (D_\mu \phi^\dagger)(D^\mu \phi),
\]

\[
O_{\phi 3}^{6,t} = (\phi^\dagger D_\mu \phi)(D^\mu \phi)^\dagger,
\]

with the covariant derivative given, in general, by:

\[
D_\mu = \partial_\mu - \frac{i}{2}(g' Y B_\mu + g \tau^i W^i_\mu + g_s \lambda^a G_a^\mu).
\]

\(^1\)We have included all the relevant operators which induce the \( H t t, H q q, H W W, \) and \( H ZZ \) vertices. On the other hand, there are also two other operators that can change the \( g t \bar{t} \) vertex: \( O_{qG}^{6,l} = i \bar{q} G^{\mu\nu} \gamma_\mu D_\nu q \), and \( O_{tG}^{6,l} = i \bar{t} R G^{\mu\nu} \gamma_\mu D_\nu t_R \), however, in order to keep the analysis as simple as possible we shall not consider them.
The field tensors for the gluons and electroweak gauge bosons are written as:

\[ G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu, \]
\[ W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g \varepsilon_{ijk} W^j_\mu W^k_\nu, \]
\[ B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu. \]

These operators modify the SM Feynman rules, which in turn will affect the decay rates and production cross-sections of the Higgs boson. The derivation of these rules, in terms of physical fields, is quite lengthy and will not be reproduced here. In what follows, we shall write directly our results for the formulae of the relevant reactions.

3. Testing Higgs and top interactions. One of the aims of the present paper is to study the operators that modify the production of Higgs bosons through gluon fusion, which is a relevant production mechanism in the so-called intermediate \((m_Z < m_H < 2m_Z)\) and heavy mass regions \((2m_Z < m_H < 600 \text{ GeV})\) \[13\]. The graphs that contribute to the effective vertex \(ggH\) are shown in Fig. 1, where the dots denote the new vertices induced by the operators of the effective Lagrangian.

Taking into account the operators \((2-7)\), we have computed the decay width \(\Gamma(H \to gg)\) in the effective Lagrangian approach, and the result is compared with the SM value through the following ratio:

\[ R_{Hgg} = \frac{\Gamma_{eff}(H \to gg)}{\Gamma_{SM}(H \to gg)} = \frac{|F_{eff}|^2}{|F_{SM}|^2}, \tag{9} \]

where

\[ F_{eff} = [1 - \frac{3}{2\sqrt{2}} z_1^2 z_2 \alpha_{\phiG}^{6,t}] F_{SM} + \left[ \frac{g m_t z_1^2}{4\sqrt{2} \pi^2 g_s m_W} \alpha_{\phiG}^{6,t} \right] F_{\phiG} \]
\[ -2 z_1^2 \alpha_{\phiG}^{6,t} + \left( \frac{4\pi v}{\Lambda} \right)^2 \alpha_{\phiG}^{8,t}, \tag{10} \]

with \(z_1 = v/\Lambda\), \(z_2 = v/m_t\), and \(g, g_s\) denote the weak and strong coupling constants and

\[ F_{SM} = -2t[1 + (1 - t) I(t)], \tag{11} \]
\[ F_{\phiG} = -5 \log \frac{\Lambda^2}{m_t^2} + 11 - 6t - 2tI^2(t) \]
\[ -2(3t - 5)\sqrt{t - 1} I(t), \tag{12} \]

with \(t = \frac{4m_t^2}{m_H^2}\) and the function \(I(t)\) is given by

\[ I(t) = \arctan(1/\sqrt{t - 1}), \text{ for } t > 1, \]
\[ = [\log(\eta_+ / \eta_-) + i\pi]/4, \text{ for } t < 1, \tag{13} \]
with $\eta_{\pm} = 1 \pm \sqrt{1 - t}$. The quantity $R_{Hgg}$ is useful in order to evaluate the cross-section for the gluon fusion reaction. At any energy it is given in terms of the SM result by $\sigma_{\text{eff}} = R_{Hgg} \sigma_{\text{sm}}$, for a given Higgs mass.

It seems convenient to comment here on a technical point about the calculation, namely the fact that the contribution from the operator $O_{6,t}^{6,t}$ to the loop (graph 1-ii) is finite. This happens because, after spontaneous symmetry breaking, the effective interaction $H^0 t \bar{t}$ is of dimension 4. On the other hand, the operator $O_{6,l}^{6,l} \phi t G$ induces a divergent contribution through the dimension-5 vertex $g t \bar{t}$. This divergence can be absorbed through the modern criteria of renormalizability [6, 12] for effective Lagrangians.

In our calculation, we have used a $\overline{\text{MS}}$-like scheme, where the scale parameter $\mu$, associated to the dimensional regularization procedure, is set equal to the energy scale $\Lambda$.

In order to proceed further, we need to know the values of the coefficients $\alpha_i$. Because QCD (as well as QED) has an exact gauge symmetry, it seems reasonable to assume that each time the gauge fields appears in the operators $O_X$, one should put the gauge coupling constants as a factor in $\alpha_X$. Thus, for a tree-level induced operator that contains the gauge fields $n$-times, one can write: $\alpha_X = g^n \eta_X$, whereas for the case of one-loop induced operators it will take the form $\alpha_X = g^n \eta_X / 16 \pi^2$. The factor $\eta_X$ is left free to include the products of other coupling constants (of broken symmetries or Yukawa couplings), as well as possible group factors for the heavy fields that could lay in larger representations of the QCD group. However, in order to present our numerical results, we shall fix $\eta = \pm 1$ and will choose the appropriate sign combinations that give the maximum and minimum values for the quantities of interest.

A priori, one could expect that the tree-level dimension-six operator $O_{6,t}^{6,t}$ should give the largest contribution to the loop, while the contribution of the operator $O_{6,l}^{6,l} \phi G t$ should be suppressed because it is one-loop generated. The loop-induced operator $O_{6,l}^{6,l} \phi G t$ is expected to be suppressed too. However, for small values of the scale $\Lambda$, the dominant contribution may arise from the

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2The effective Lagrangian is constrained by Lorentz and gauge invariance. These symmetry principles constraint in the same way the ultraviolet divergences of the theory. Since the effective Lagrangian already include the infinite tower of interactions allowed by these symmetries, then the counterterms needed to cancel every ultraviolet divergence are already included in the theory. On the other hand, predictibility of the theory depend strongly on the energies used ($E < \Lambda$) and the experimental accuracy.
contact terms, as we shall explain below.

The results are presented in Table 1, where we display the effects of each operator on the ratio (9). We can appreciate that there are significant changes coming from all the operators discussed here. The largest effect is due to the 8-dimensional operator $O_{8,G}^{t,t}$, which may enhance the ratio by a factor about 5.3, although this effect is only valid for $\Lambda \leq 3$ TeV. When both $\Lambda$ and $m_H$ grow, the largest effect comes from the operator $O_{6,t}^{t,t}$, as it was expected from the above rules.

The corresponding increase in the cross-section seems so large, that it might be possible to look for it at Tevatron. We found that the cross-section is only $\sigma \simeq 5.3$ pb, for $\sqrt{s} = 1.8$ TeV, $m_H = 100$ GeV. Thus, with a yearly integrated luminosity of 100 $pb^{-1}$, we should expect about 530 Higgs bosons per year. If the decay into a photon pair receives a similar enhancement in the effective Lagrangian approach ($B.R.(H \rightarrow \gamma\gamma) \simeq 5 \times 10^{-3}$, as it was found in [14]), then there will be only about 2.5 events per year, which seems difficult to search for. However, if the luminosity is increased, as it is expected in the upgraded Tevatron, with a yearly integrated luminosity of $2 \times 10^3$ $pb^{-1}$, then the number of events will be about 50, which seems quite likely to be detected because the signal is almost background free.

The enhancement in the cross-section could increase significantly the detection feasibility of the Higgs boson at the LHC. The most promising candidate for the final signature is again through the decay into a photon pair. If both $\sigma$ and the B.R. receive a similar enhancement (of about 5 times), then the number of events coming from $pp \rightarrow H + X \rightarrow \gamma\gamma + X$ may be about 25 times larger than the SM case, which should be then useful in order to detect the Higgs boson with the resolution expected for the invariant mass of photon pairs at the LHC [13].

The possibility of detecting a Higgs boson through the dominant decay mode ($H \rightarrow b\bar{b}$) is unlikely because of the QCD backgrounds, at least for the gluon fusion production, nor is the signature coming from the rare decay $H \rightarrow \mu^+\mu^-$. Although the branching ratio may be enhanced by an order of magnitude, as it was discussed in detail in [14], the event rate will not be large enough to compete with the background coming from the decay of the $Z$ into lepton pairs [13].

On the other hand, the operator $O_{6,G}^{t,t}$ gives also a significant contribution to the gluon fusion cross-section. In case this effect were observed it would signal new physics. We can also use this result to put a bound on the coef-
cient $\eta_{\phi G t}$. Using a simple perturbative constraint, namely that the effect
of the new operator should not be larger than the SM result, we obtain the
bound $\eta_{\phi G t} < 6.8(\Lambda/TeV)^2$. This in turn can be transformed into a bound
on the chromomagnetic dipole moment ($\mu_t$) for the top quark \cite{3},
\[ \hat{\mu}_t = \frac{m_t v \eta_{\phi G t}}{8 \pi^2 \Lambda^2}, \]
with $|\hat{\mu}_t| < 2.4 \times 10^{-3}$, $\hat{\mu}_t = m_t \mu_t / g_s$, and $\mu_t$ is the coefficient associated to
the term $i G^{\mu \nu} \sigma_{\mu \nu} \bar{t} t$, which in turn comes from the effective operator (3). Note
that our result given in (14) includes an additional suppressing $v/\Lambda$ factor
because the effective operator (3) is of dimension 6. This bound is stronger
than the one obtained previously, $\hat{\mu}_t < 0(1)$, by the use of $U(1)_{em}$ gauge
invariant $t\bar{t}G$ couplings on the $t\bar{t}$ production cross section in hadron-hadron
collisions \cite{3}.

The previous operators (2) and (3) may also modify the cross-section for
the production of the Higgs boson in association with a $t\bar{t}$ pair, which is
believed to be the most viable reaction for detection of a Higgs boson in
the intermediate-mass region. A similar analysis lead us to conclude that
the dominant effect will arise from the operator $O_{6t}^{\phi}$, whose effect may be
extracted from the following ratio:
\[ R_{Htt} = \frac{\sigma_{eff}(pp \rightarrow H + t\bar{t} + X)}{\sigma_{SM}(pp \rightarrow H + t\bar{t} + X)} = 1 - \frac{3}{2\sqrt{2}} z_1^2 z_2^2 \alpha_{\phi} \alpha_{6t}. \]
In this case we find that the largest increase in the corresponding cross-section
may be of the order of 20 percent. If we consider again the most viable signal,
namely through the decay of the Higgs into a photon pair, the increase in the
final event rate could be about 100 percent, which should be detectable
at the LHC since the SM signal was found already detectable \cite{13}. Under these
circumstances the signals coming from the SM and the effective theory will
be disentangled provided that the event rate is large enough. Eventhought
$R_{Htt} = 2$ seems clearly distinguishable, the precise confident level depends
in general on the Higgs mass.

Finally, we have also studied the modifications to the mechanism of as-
sociated production of Higgs with a W boson, due to the new 6-dimensional
operators. This reaction plays also a very important role for the detection
of a Higgs boson in the intermediate-mass region. The Feynman graphs for this process are shown in Fig. 2. Again, the dots denote the vertices induced by the new operators in the effective Lagrangian. From the discussion of the previous section, we can appreciate that the dominant contribution will come from the lowest dimension tree-level induced operators, which are the dimension-6 operators \( O_{\phi_{1,3}}^{6,t} \) that modify the interaction \( HWW \). The operators that modify the \( qqW \) vertex are one-loop induced operators and can be neglected.

We have evaluated the ratio of the effective cross-sections to the SM result. The form of the operators is such that the parton convolution part is factored out and we are left with only the ratio of partonic cross-sections. Thus our result is valid for both the FNAL and LHC cross sections,

\[
R_{HW} = \frac{\sigma_{eff}(pp \rightarrow H + W + X)}{\sigma_{SM}(pp \rightarrow H + W + X)} = 1 + 0.5(2\alpha_{\phi_1} - \alpha_{\phi_3})z_1^2, \tag{16}
\]

with \( z_1 \) defined in (10). For this type of operators the modification to the cross-section is independent of the Higgs mass. We find that the best values for the cross-section are only slightly modified. For instance, with \( m_H = 100 \) GeV we get that the ratio lies in the range: \( 0.903 < R_{HW} < 1.097 \), and thus the chances to detect the Higgs boson remain as good as in the SM, but does not seems likely to distinguish the effective theory signal from the SM one.

5.- Conclusions. We have studied the possibility to detect heavy physics in the interactions of the Higgs boson and the top quark at future colliders using the effective Lagrangian approach. It was assumed that the SM lagrangian is modified by non-renormalizable operators that are invariant under the full strong and electroweak group. We found that the lowest-order operators that modify the SM \( t\bar{t}g \) strong interaction are of dimension 6.

The modification to the Higgs and top interactions may enhance the Higgs production at hadron colliders, mainly through the mechanisms of gluon fusion and associated production with a \( t\bar{t} \) pair. It is found that the operator \( O_{\phi Gt}^{8,t} \) may lead to an enhancement in the cross-section by a factor of 5.3, which increases the possibilities to detect the Higgs boson at future colliders. It is found that the most promising signature comes from the decay into a gamma pair, which may receive a similar enhancement by the effective operators and makes plausible its detection at the LHC.
Similarly, the mechanism of associated production of the Higgs with a $t\bar{t}$ pair is also enhanced, this time only by about 20 percent. On the other hand, the associated production of the Higgs with a W boson is not modified substantially, which means that the possibilities to detect this signal are as good as in the SM, or in other words: *if a light Higgs boson exists, then its detection through this mode is quite model independent*.

We have also analyzed the possibility to use the gluon fusion mechanism to obtain a bound on the chromomagnetic dipole moment of the top. Using a simple perturbative constraint, namely that the effect of the new operator should not be larger than the SM result, we obtain the bound $\eta_{\delta G_t} < 6.8(A/TeV)^2$, which leads to a stronger bound on $\hat{\mu}_t$ than obtained previously in the literature.

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FIGURE CAPTION

Fig. 1 Feynman graphs that contribute to the loop induced $Hgg$ interaction.

Fig. 2 Feynman graphs that contribute to the mechanism of $H$ and $W$ associated production.

TABLE CAPTION

Table 1 Results for the contribution of the effective operators to the ratio $R_{Hgg}$. We have taken $m_H = 100$ GeV, and $\Lambda = 1$ TeV. The total value is obtained by adding the amplitudes arising from each operator, and then squaring the result.
| Operators  | $R^{\text{max}}_{H_{99}}$ | $R^{\text{min}}_{H_{99}}$ |
|------------|--------------------------|--------------------------|
| $O^{6,t}_{b\phi}$ | 1.204                    | 0.816                    |
| $O^{6,t}_{8G}$   | 1.325                    | 0.721                    |
| $O^{6,t}_{\delta G}$ | 1.199                  | 0.819                    |
| $O^{6,t}_{\epsilon G}$ | 3.873                  | 0.01                     |
| Total       | 5.339                    | $7.1 \times 10^{-5}$    |

Table 1
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9702413v1