Probing Hg contact interactions by $gg \rightarrow H$

at a high energy hadron collider

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Abstract

In this article we study the effect of Hg contact interactions on H production by gluon fusion at a hadron collider. Two such $d=6$ operators have been considered. The present precision for measuring $\alpha_s$ implies that the lower bound on the scale for the CP even operator $O_1$ must be around 2 TeV. Whereas the precision for measuring $d_n$ gives rise to a lower bound of about $10^5$ TeV on the scale for the CP odd operator $O_2$. We show that for the above lower bound $O_1$ can significantly affect the parton level cross-section for the process $gg \rightarrow H$. 
The excess of events over SM prediction reported by ZEUS and H1 experiments [1] at HERA in $e^+p \rightarrow e^+jX$ at $Q^2 > 15000$ GeV$^2$ have been given several attractive interpretations namely (a) s-channel leptoquark exchange [2] (b) R-parity violating squark exchange [2] and (c) eq four fermion contact interactions [3]. Assuming that the data does not favor an s-channel resonance then the effective Lagrangian containing LL, LR, RL and RR eq contact interactions provide the most model independent parametrization of possible new physics effects at HERA energy. Some of these works have even attributed the higgs $Q^2$ HERA excess to possible eq compositeness whose effects at low energies can be represented by the four fermion Lagrangian. If the eq contact interactions arise from TeV scale compositeness structure underlying the light SM particles then analogous effects could also arise elsewhere as for example through Hg contact interactions. The aim of this article is to study the effects of Hg contact interactions on Higgs production cross-section at a high energy hadron collider like LHC.

If the SM particles are composites of more elementary constituents associated with a compositeness scale $\Lambda$ where $\Lambda \gg v$, then its effects at lower energies can be parameterized in terms of non-renormalizable operators involving the light SM fields. A non-renormalizable operator $O_i$ of dimension $d_i$ ($d_i > 4$) will be associated with a coefficient $C_i = \pm \frac{a_i}{\Lambda^{d_i-4}}$. The dimensionless coefficient $a_i$ depends on the nature of new heavy physics associated with the scale $\Lambda$. For $d_i = 6$ the dimensionless coefficient $a_i$ is expected to lie between 1 and $4\pi$ if the new physics is intrinsically strong. However if the new heavy physics associated with the scale $\Lambda$ is intrinsically weak and the operator $O_i$ arises from loop level process then $a_i$ can be much smaller than 1. In this work however we shall take a phenomenological approach and not commit ourselves to either a strongly interacting or a weakly interacting new physics scenario. For $d_i = 6$ low energy measurements give rise to lower bounds on the combination $\frac{\Lambda}{\sqrt{|a_i|}}$ and includes the effects of $a_i$. The estimates presented in this work are therefore independent of the precise nature of new physics. The $\pm$ sign associated with $C_i$ determines whether the new physics contribution to some
physical amplitude interferes constructively or destructively with the SM effect.

The discovery of the higgs boson is clearly one of the most important goals of all high energy colliders. In SM, for a heavy top quark \((m_t > 100 \text{ Gev})\) and \(m_h \leq 500 \text{ Gev}\) the dominant contribution \([4]\) to higgs production at LHC is expected to arise from gluon fusion mechanism \([5]\), which proceeds through a triangle loop diagram. At tevatron energy the dominant higgs production mechanism is \(qq' \rightarrow WH\). In the gluon fusion process quarks of all flavor contribute to the loop diagram with the dominant contribution coming from heavy quarks \((m_t \geq \frac{m_h}{2})\). Being a loop induced process the production rate of a higgs boson by this process is highly sensitive to new physics effects. TeV scale compositeness effects could in principle make important contributions to the cross-section for the process \(gg \rightarrow H\). The effects of possible Tev scale compositeness on the process \(gg \rightarrow H\) can be expressed by means of following \(d = 6\) operators involving \(\phi\) and \(G_{\mu\nu}^a\)

\[G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f_{abc} G_\mu^b G_\nu^c\]

\[O_1 = (\phi^+ \phi) G_{\mu\nu}^a G^{\alpha \mu \nu} = \frac{(v + h)^2}{2} G_{\mu\nu} G^{\alpha \mu \nu}. \quad (1a)\]

\[O_2 = (\phi^+ \phi) \tilde{G}_{\mu\nu}^{\alpha \mu \nu} = \frac{(v + h)^2}{2} \tilde{G}_{\mu\nu} \tilde{G}^{\alpha \mu \nu}. \quad (2a)\]

Note that both \(O_1\) and \(O_2\) are invariant under the SM gauge group \(SU(3)\) \(c \times SU(2)\) \(l \times U(1)\) \(_y\). However while \(O_1\) is even under the discrete symmetries P and T, \(O_2\) is odd under the same transformations. In the following we shall consider their effects on low energy processes separately.

Effects of \(O_1\): Besides contributing to \(ggh\), \(gggh\) and \(ggggh\) vertices, \(O_1\) also modifies the canonical gluon K.E. term

\[L_{KE} = -\frac{1}{4} (1 - \frac{2a_1 v^2}{\Lambda_1^2}) G_{\mu\nu} G^{\alpha \mu \nu}. \quad (2)\]

Here \(\Lambda_1\) is the characteristic scale associated with the operator \(O_1\). Since \(O_1\) and \(O_2\)
have different symmetry properties under P and T they could a priori be associated with
different energy scales. Let us make a change of scale of \( A^a_\mu \): \( A^a_\mu \rightarrow A'^a_\mu = (1 - \frac{2a_1 v^2}{\Lambda^2_1})^{\frac{1}{2}} A^a_\mu \) so that the free part of \( L_{KE} \) has the canonical normalized form in terms of new fields namely
\[-\frac{1}{4}(\partial_\mu A'^a_\nu - \partial_\nu A'^a_\mu)(\partial^\mu A'^a_\nu - \partial^\nu A'^a_\mu).\]
However the ggg and gggg interaction vertices in \( L_{KE} \) can also be brought to the canonical form if the QCD coupling \( g \) is simultaneously subjected to a multiplicative renormalization: \( g \rightarrow g' = \frac{g}{(1 - \frac{2a_1 v^2}{\Lambda^2_1})^{\frac{1}{2}}} \). In the following discussion we shall drop the primes and all quantities will refer to primed ones. In the context of the SM \( \alpha_s \) is an unknown parameter. Therefore it is not possible to determine a lower bound on \( \Lambda_1 \) by exploiting the renormalization of \( \alpha_s \) due to new physics. If a first principle calculation of \((\alpha_s)_{sm}\) is available on the basis of a more fundamental theory we could determine a lower bound on \( \Lambda_1 \) from the difference between the experimental and predicted value of \( \alpha_s \). Nevertheless we can find an approximate lower bound on \( \Lambda_1 \) by demanding that the new physics contribution to \( \alpha_s \) be no greater than \( 2\sigma \) where \( \sigma \) is the experimental error in measuring \( \alpha_s \). Note that \((\alpha_s)_{sm}\) is the value of \( \alpha_s \) in the limit \( \Lambda_1 \rightarrow \infty \). The present global average of [6] of \( \alpha_s \) from different measurements is \( \alpha_s = .118 \pm .003 \) where .003 is the smallest systematic error in an individual result namely in the lattice result. We therefore require that \((\delta\alpha_s)_{new} \approx (\alpha_s)_{sm}[\frac{1}{(1 - \frac{2a_1 v^2}{\Lambda^2_1})^{\frac{1}{2}}} - 1] \approx \pm .006.\)
from which it follows that \( \frac{\Lambda_1}{\sqrt{|a_1|}} \geq 1.5 \text{ TeV} \) (for \( a_1 > 0 \)) and \( \frac{\Lambda_1}{\sqrt{|a_1|}} \geq 1.1 \text{ TeV} \) (for \( a_1 < 0 \)).
Next we shall consider the effect of \( O_1 \) on higgs production by gluon fusion at a high energy hadron collider. In SM the process \( gg \rightarrow H \) takes place through an intermediate triangular loop diagram. It can be described by the effective Lagrangian [7] (which is obtained by integrating over all quark flavors)

\[
L_{sm} \approx -\frac{1}{v} \frac{\alpha_s(m^2_H)}{12\pi} I H g^a_{\mu\nu} g^{a\mu\nu}
\]

where \( g^a_{\mu\nu} \) is the free part of the gluon field strength tensor.

\[
I = \sum_q I_q, \quad I_q = 3[2x_q + x_q(4x_q - 1)f(x_q)], \quad x_q = \frac{m_q^2}{m^2_H}
\]
\[ f(x_q) = -2\sin^{-1} \frac{1}{2\sqrt{x_q}} \] for \( x_q > \frac{1}{4} \)

\[ f(x_q) = \frac{1}{2}(\ln \frac{y_q}{y_a})^2 - \frac{x^2}{2} + i\pi \ln \frac{y_q}{y_a} \] for \( y_q < \frac{1}{4} \) and 

\[ y_q^\pm = \frac{1}{2} \pm \sqrt{\frac{1}{4} - x_q}. \]

In the large \( m_q \) limit \((x_q \gg 1)\) \( I_q \to 1 \), whereas in the small \( m_q \) limit \((x_q \ll 1)\) \( I_q \to 0 \).

If there are \( N \) heavy quark flavors with \( m_q \geq m_h \) then \( I \approx N \). For \( 100 \text{GeV} \leq m_h \leq 400 \text{GeV} \) only the top quark contribution is relevant in SM with three quark families. The effective Lagrangian that contains the SM as well as new physics sources for \( gg \to H \) is

\[
L_{\text{eff}} \approx \frac{1}{v}(\frac{a_1 v^2}{\Lambda_1^2} - \frac{\alpha_s(m_h^2)}{12\pi}I)Hg^a_{\mu\nu}g^{a\mu\nu} \quad (4)
\]

Hence for \( a_1 < 0 (a_1 > 0) \) there is constructive (destructive) interference between SM and new physics contributions. For \( m_h = 200 \text{GeV} \) and \( m_t = 175 \text{GeV} \), \( x_q \approx .766 \), \( I(x_q) \approx 1 \) and \( \alpha_s(m_h^2) \approx .107 \). If \( \frac{\Lambda_1}{\sqrt{|a_1|}} \approx 2.5 \text{TeV} \) we find that in the destructive interference scenario the lowest order parton level cross-section is 5.4 times its SM value. On the other hand for constructive interference the lowest order cross-section becomes 18.7 times its SM value for the same values of the parameters. Hence if \( \frac{\Lambda_1}{\sqrt{|a_1|}} \) is as low as 2.5 TeV, either sign of \( a_1 \) yields a cross-section which is significantly greater than the SM value. Keeping \( m_h = 200 \text{GeV} \) if we increase \( \frac{\Lambda_1}{\sqrt{|a_1|}} \) to 5 TeV we find that \( \frac{\sigma}{(\sigma)_{\text{SM}}} \approx .03 \) for destructive interference. Whereas for constructive interference \( \frac{\sigma}{(\sigma)_{\text{SM}}} \approx 3.3 \). Hence the ratio \( \frac{\sigma}{(\sigma)_{\text{SM}}} \) is a sensitive function of the scale of new physics. On the other hand if we keep \( \frac{\Lambda_1}{\sqrt{|a_1|}} \) fixed at 5 TeV but increase \( m_h \) to 400 GeV, the ratio \( \frac{\sigma}{(\sigma)_{\text{SM}}} \) remains almost the same as in the case of \( m_h = 200 \text{GeV} \).

Effects of \( O_2 \): We shall now consider the effect of \( O_2 \) on low energy measurements. \( O_2 \) changes the \( \theta \) parameter of the effective QCD Lagrangian \( L_{QCD}^{\text{eff}} = L_{QCD} + \frac{\theta \alpha_s G^a_{\mu\nu} \tilde{G}^{a\mu\nu}}{8\pi} \) to \( \theta + \delta \theta \) where \( \delta \theta = \frac{4\pi a e v^2}{\alpha_s \Lambda_2^2} \). When the electro-weak theory is appended to QCD, due to \( U(1)_A \) anomaly the CP violating phase from the quark mass matrix slips into the the QCD theta term. The result is that \( \theta + \delta \theta \) gets replaced by \( \bar{\theta} = \theta + \delta \theta + \text{arg}(det M) \). \( \bar{\theta} \) gives rise to electric dipole moment of neutron. Current algebra estimates \([8]\) give \( d_n \leq 3.6 \times 10^{-16} \bar{\theta} \)
However $\bar{\theta}$ is an unknown parameter in the context of the SM. So strictly speaking one cannot determine a lower bound on $\Lambda_2$ from the experimental bound on $\bar{\theta}$. However an approximate lower bound on $\Lambda_2$ can be derived by demanding that the new physics contribution to $d_n$ be no greater than $2\sigma$ where $\sigma$ is the experimental error in measuring $[9] d_n$. In this way we can arrive at the lower bound $\frac{\Lambda_2}{\sqrt{|a_2|}} \geq 85 \times 10^3$ Tev which is too large to be probed at any of the upcoming colliders. We shall therefore neglect the effect of $O_2$ on higgs production by gluon-gluon annihilation.

In conclusion in this article we have considered the effect of Hg contact interaction on the process $gg \rightarrow H$. Two such operators $O_1$ and $O_2$ were identified. The lower bound on the scale for the CP even operator $O_1$ was found to be around 2 TeV. Whereas the lower bound on the scale associated with the CP odd operator $O_2$ was found to be around $10^5$ TeV. The effect of $O_2$ on the process $gg \rightarrow H$ is therefore negligible. However the operator $O_1$ affects the parton level cross-section for the process $gg \rightarrow H$ significantly if $\frac{\Lambda_1}{\sqrt{|a_1|}}$ lies around its lower bound for either sign of $a_1$. For example if $a_1 > 0$ and $\Lambda_1 \approx 5$ TeV the effect of new physics reduces the cross-section to .03 times its SM value which would make the signal almost impossible to observe. On the other hand if $a_1 < 0$ and $\Lambda_1 \approx 2.5$ TeV the effects of new physics enhances the cross-section to almost 20 times its SM value. It should be noted that the lowest order cross-section for $gg \rightarrow h$ is also modified due to QCD radiative corrections in the context of the SM. Therefore to identify the new physics contribution from the difference between the observed and predicted values of the cross-section a precise estimate of QCD induced radiative corrections to $\sigma_{gg\rightarrow h}$ is essential.

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