Leptoquark Contribution to the Higgs Boson Production at the LHC Collider

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Abstract

In this report we study how a light-scalar leptoquark could affect the Higgs boson production cross-section at the LHC collider. We construct the most general renormalizable and gauge invariant effective Lagrangian involving the standard model particles and a scalar, isoscalar leptoquark, η. The total cross-section for $pp \rightarrow H + X$ is then calculated for different values of the unknown parameters λ_η, m_η and m_H.(Here λ_η is the coupling associated with the Higgs-leptoquark interaction.)

We find that if λ_η is moderately large and m_η is around a few hundred GeV, then the cross-section is significantly larger than the standard model value.

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Leptoquarks (LQ) occur naturally in many extensions of the standard model, *e.g.*, grand unified models, technicolor models and composite models of quarks and leptons. However if leptoquarks couple to the quark pair as well as to the quark-lepton pair then they give rise to rapid proton decay. This in turn requires that the leptoquark should be heavy, $m_{lq} \approx 10^{12} - 10^{15}$ GeV [1]. To evade this catastrophic strong bound it is usually assumed that leptoquarks couple only to the quark-lepton pair. To enable them to couple to a quark-lepton pair, leptoquarks must form a color triplet or antitriplet. They can form a singlet or doublet or triplet representation of weak SU(2) group and also carry weak hypercharge. The couplings and masses of leptoquarks that couple to quark-lepton pair are constrained by a variety of low energy processes, *e.g.*, pion and kaon decays [1], B and D meson decays, precision electroweak measurements at Z boson pole [2], Tevatron and HERA data. The Tevatron sets limits [3, 4] on m_{lq} (the mass of the leptoquark) from pair production processes. These bounds depend on the color and electroweak (EW) quantum numbers of the LQ. The bounds are most stringent (> 225 GeV) for the first generation LQ and become progressively weaker for the second (> 131 GeV) and third generation (> 95 GeV) LQs. HERA sets limits [3, 5] on m_{lq} from single production of leptoquarks. These limits depend on the value of g_{lq}, the Yukawa like coupling of the LQ to quark-lepton pair. For $g_{lq} = e$, the limits on a scalar, weak isoscalar, Q=$-\frac{1}{3}$, LQ are $m_{lq} > 237$ GeV for the first generation and $m_{lq} > 73$ GeV for the second generation. In this article we shall consider a third generation leptoquark whose coupling to q-l pairs of the first two generations are very small. This assumption will enable us to consider leptoquarks in the 100-200 GeV mass range and still be consistent with the above bounds. However, we note that if some crucial assumptions that go into arriving at the Tevatron bounds, *e.g.*, $B(eq) = 1$, can be relaxed, then second/first generation leptoquarks could still exist in $100 - 200$ GeV range. For example mixing between different multiplets of LQ's could reduce the branching ratios considerably. Furthermore since

the coupling g_{lq} will not enter our computations our results will also be valid for just a color triplet scalar.

As shown later the most general effective Lagrangian involving the standard model particles and the LQ includes an interaction term between the LQ and the Higgs boson. In

the presence of this interaction the coupling g_{lq} could contribute to $pp \to H + X$ through a loop diagram made up of a lepton and a leptoquark with the Higgs boson attached to the leptoquark line. The incoming quark and antiquark states are to be attached at the lepton and leptoquark junctions. g_{lq} could also contribute to $pp \to l^+ l^- + H + X$ through a tree level diagram. However it is not hard to see that the coupling g_{lq} of second or third generation LQ to quark-lepton pairs of first generation cannot play a significant role in Higgs boson production in our model at a pp collider. As an example, let us consider a third generation leptoquark. Then, first the coupling g_{lq} of third generation LQ to q-l pairs of first generation is expected to be very small ($g_{lq} \ll e$). Second a smaller luminosity of $q\bar{q}$ configurations at the LHC makes the contribution of g_{lq} to the Higgs boson production at the LHC much smaller than those computed here.

At the LHC, the dominant production mechanism for the standard model Higgs boson is through gluon-fusion mechanism [6] (see Fig. 1). If light LQs exist, there will be additional diagrams with the leptoquark loops (see Fig. 2). In this brief report, we shall compute the effect of these additional diagrams on the the Higgs boson production via this mechanism. In order to be consistent with the HERA bounds on m_{lq} we shall assume that g_{lq} is much smaller than e so that m_{lq} could lie in the range $100 - 200$ GeV. We shall then show that a low energy effective interaction between the higgs doublet and a scalar leptoquark can significantly modify the Higgs boson production cross-section at the LHC provided the corresponding coupling λ_η (the coupling associated with the Higgs-leptoquark interaction) is large enough, *i.e.*, of the same order as the yukawa coupling of the top quark, g_t. The phenomenological advantage of using the coupling λ_η is that unlike g_{lq} it is not unduly constrained by low energy experiments. For simplicity let us consider a scalar, weak isoscalar, $Q = -\frac{1}{3}$ leptoquark η. The form of the effective interaction between the LQ and the higgs scalar will depend on the EW quantum numbers of η and therefore they do affect the cross-section for the Higgs boson production.

If m_{lq} lies in the few hundred GeV range then the low energy effective Lagrangian suitable for describing physics in this energy range should involve η besides the usual SM particles. We shall require the low energy lagrangian to be renormalizable and invariant under $SU(3)_c \times$

$SU(2)_l \times U(1)_y$. We then have

$$L_{eff} = \tilde{L}_{sm} + (D_\mu \eta)^+ (D^\mu \eta) - V(\phi, \eta) + L_{ql}. \tag{1}$$

Here $L_{sm} = \tilde{L}_{sm} - V(\phi)$, $V(\phi) = -\mu^2 \phi^+ \phi + \lambda (\phi^+ \phi)^2$,

$$V(\phi, \eta) = V(\phi) + m_{0\eta}^2 \eta^+ \eta - \lambda_\eta (\phi^+ \phi) \eta^+ \eta + \frac{\lambda'}{4} (\eta^+ \eta)^2, \tag{2}$$

and,

$$L_{ql} = [g_l \bar{l}_L i\tau_2 q_L^c + g_r \bar{e}_R u_R^c] \eta + h.c. \tag{3}$$

Here λ_η is the dimensionless coupling associated with the Higgs-leptoquark interaction term. The LQ mass gets shifted from $m_{0\eta}$ to m_η after the electroweak symmetry breaking where $m_\eta^2 = m_{0\eta}^2 - \lambda_\eta \frac{v^2}{2}$. The Lagrangian L_{ql} gives the coupling of the third generation LQ η to the q-l pair of the third generation. Its coupling to quark-lepton pairs of first two generations has been neglected. In the unitary gauge the interaction term between ϕ and η can be written as $\lambda_\eta (\phi^+ \phi)(\eta^+ \eta) = \frac{\lambda_\eta}{2} (v^2 + 2vh + h^2) \eta^+ \eta$. Note that the above effective Lagrangian includes all possible terms subject to the constraints of renormalizability and gauge invariance and the assumption that η is an isoscalar. If η were a weak isodoublet then we should add the term $\lambda'_\eta (\phi^+ \eta)(\eta^+ \phi)$ to the effective Lagrangian. In unitary gauge this term can be expressed as $\lambda'_\eta \frac{(v+h)^2}{2} \eta^{+a2} \eta^{a2}$ where a is the color index and 2 stands for the $I_3 = -\frac{1}{2}$ component of η. After the electroweak symmetry breaking the term proportional to λ'_η causes the h boson to interact only with the down component of the LQ. Whereas the term proportional to λ_η causes the h boson to interact with both the isospin components of η with equal strength. The scalar potential of the standard model $V(\phi)$ is bounded from below for $\lambda > 0$. Further it produces a vacuum with the desired symmetry breaking properties. Here we need to find the conditions to be satisfied by the parameters of $V(\phi, \eta)$ so that it exhibits the same properties. In order that $V(\phi, \eta)$ is bounded from below the quartic part

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of it must be positive. It can be shown that this can happen if $\lambda > 0$, $\lambda' > 0$ and $\lambda_\eta < 0$ or $\lambda > 0$, $\lambda' > 0$ and $0 < \lambda_\eta < 2\sqrt{\lambda\lambda'}$. Finally in order that the vacuum does not break the $SU(3)_c$ symmetry $m_{0\eta}$ must satisfy the condition $m_{0\eta}^2 - \lambda_\eta \frac{v^2}{2} > 0$.

In the context of the standard model, the diagrams contributing to the Higgs boson production at the LHC via gluon fusion mechanism are displayed in Fig. 1. These diagrams involve a top quark loop with two gluons and a Higgs boson attached to it at the interaction vertices. The contribution of the diagrams to the amplitude is given by $M = M_1 + M_2$ where

$$
\begin{aligned}
M_1 &= -\frac{ig_t g_s^2}{2\sqrt{2}}\epsilon_{1\mu}(q_1,\lambda_1)\epsilon_{2\nu}(q_2,\lambda_2)\delta_{ab}\int\frac{d^4l}{(2\pi)^4}\frac{N_1}{D_1}, \\
M_2 &= -\frac{ig_t g_s^2}{2\sqrt{2}}\epsilon_{1\nu}(q_1,\lambda_1)\epsilon_{2\mu}(q_2,\lambda_2)\delta_{ab}\int\frac{d^4l}{(2\pi)^4}\frac{N_2}{D_2}, \\
\frac{N_1}{D_1} &= \frac{(l.\gamma + m_t)\gamma_\mu((l+q_1).\gamma + m_t)((l-q_2).\gamma + m_t)\gamma_\nu}{(l^2 - m_t^2)[(l+q_1)^2 - m_t^2][(l-q_2)^2 - m_t^2]}, \\
\frac{N_2}{D_2} &= \frac{(l.\gamma + m_t)\gamma_\mu((l+q_2).\gamma + m_t)((l-q_1).\gamma + m_t)\gamma_\nu}{(l^2 - m_t^2)[(l+q_2)^2 - m_t^2][(l-q_1)^2 - m_t^2]}.
\end{aligned}
$$

In the notations of Ref 5, we can write the total amplitude as,

$$
\begin{aligned}
M &= \frac{g_t}{2\sqrt{2}}\frac{g_s^2}{16\pi^2}\epsilon_{1\mu}(q_1,\lambda_1)\epsilon_{2\nu}(q_2,\lambda_2)\delta_{ab}[32m_t C_{\mu\nu}(q_1,q_2,m_t,m_t,m_t)\epsilon_1^\mu\epsilon_2^\nu \\
&\quad +16m_t(q_1.\epsilon_2\epsilon_1^\mu C_\mu(q_1,q_2,m_t,m_t,m_t) + q_2.\epsilon_1\epsilon_2^\mu C_\mu(q_2,q_1,m_t,m_t,m_t)) \\
&\quad +4m_t(-q_1.q_2\epsilon_1.\epsilon_2 + q_1.\epsilon_2 q_2.\epsilon_1)(C_0(q_1,q_2,m_t,m_t,m_t) + C_0(q_2,q_1,m_t,m_t,m_t)) \\
&\quad -8\epsilon_1.\epsilon_2 m_t B_0(q_1 + q_2,m_t,m_t)].
\end{aligned}
\tag{4}
$$

In the above $\epsilon_{1\mu}(q_1,\lambda_1)$ and $\epsilon_{2\nu}(q_2,\lambda_2)$ are the polarization vectors of the incoming gluons. λ_1 and λ_2 stand for the polarization states of the gluons and $l.\gamma = l^\mu\gamma_\mu$. Here B_0, C_0, C_μ, and $C_{\mu\nu}$ are scalar and tensor integrals, as defined in Ref 5. As noted below, we use the techniques of [9] to reduce the tensor integrals C_μ and $C_{\mu\nu}$ to scalar integrals.

Next consider the contribution arising from LQs. The coupling g_{lq} could contribute to the process $pp \to H + X$ through the parton level subprocess $q\bar{q} \to H$ that involves a loop diagram made up of a lepton and a LQ. However since for third generation LQ at a pp collider the relevant $g_{lq} \ll e$ the contribution of this subprocess can be neglected in comparison to

that of $gg \to H$. Leptoquarks have two distinct types of interaction vertices with gluons. In the first kind a single gluon line meets two lines. It is a derivative coupling and the Feynman rule for it is $-ig_s(p_{1\mu}+p_{2\mu})T_a$ where p_1 and p_2 are the incoming and outgoing momenta along the η lines. In the second kind of vertex two gluon lines meet two η lines. It is a dimension four coupling and the Feynman rule for it is $ig_s^2(T_aT_b + T_bT_a)g_{\mu\nu}$. Since leptoquarks form a fundamental representation of color, the same color Gellmann matrices appear in the above Feynman rules. Finally the Feynman rule for the interaction vertex of the Higgs boson with two η lines is $i\lambda_\eta v$. These rules give rise to three distinct Feynman diagrams for leptoquark contribution to the Higgs boson production. The corresponding amplitudes are given by

$$
\begin{aligned}
M_1' &= \frac{i}{2}g_s^2\lambda_\eta v\delta_{ab}\int\frac{d^4l}{(2\pi)^4}\frac{(2l+q_1).\epsilon_1(2l+2q_1+q_2).\epsilon_2}{(l^2-m_\eta^2)[(l+q_1)^2-m_\eta^2][(l+q_1+q_2)^2-m_\eta^2]}, \\
M_2' &= \frac{i}{2}g_s^2\lambda_\eta v\delta_{ab}\int\frac{d^4l}{(2\pi)^4}\frac{(2l+q_2).\epsilon_2(2l+2q_2+q_1).\epsilon_1}{(l^2-m_\eta^2)[(l+q_2)^2-m_\eta^2][(l+q_1+q_2)^2-m_\eta^2]}, \\
M_3' &= -ig_s^2\lambda_\eta v\delta_{ab}\int\frac{d^4l}{(2\pi)^4}\frac{\epsilon_1.\epsilon_2}{(l^2-m_\eta^2)[(l+q_1+q_2)^2-m_\eta^2]}.
\end{aligned}
\tag{5}
$$

As earlier, in the notations of the Ref. 5,

$$
\begin{aligned}
M' &= M_1' + M_2' + M_3' \\
&= -\frac{1}{2}\frac{g_s^2}{16\pi^2}\lambda_\eta v\delta_{ab}[4\epsilon_1^\mu\epsilon_2^\nu(C_{\mu\nu}(q_1,q_2,m_\eta,m_\eta,m_\eta) + C_{\mu\nu}(q_2,q_1,m_\eta,m_\eta,m_\eta)) \\
&\quad + 4\epsilon_1^\mu q_1.\epsilon_2 C_\mu(q_1,q_2,m_\eta,m_\eta,m_\eta) + 4\epsilon_2^\mu q_2.\epsilon_1 C_\mu(q_2,q_1,m_\eta,m_\eta,m_\eta) \\
&\quad - 2\epsilon_1.\epsilon_2 B_0(q_1+q_2,m_\eta,m_\eta)]
\end{aligned}
\tag{6}
$$

Note that the amplitudes M_1', M_2' M_3' are separately logarithmically divergent. However one can check that the individual logarithmic divergences cancel in the sum $M_1' + M_2' + M_3'$. The parton level standard model cross section can be determined from $|M_1 + M_2|^2$. On the other hand the parton level total cross section that includes the leptoquark contribution is to be determined from $|M_1 + M_2 + \delta M|^2$ where $\delta M = M_1' + M_2' + M_3'$ is the leptoquark contribution. Note that the nature of interference between the standard model amplitude and leptoquark amplitude reverses with the sign of λ_η. However in this work we shall consider only positive values of λ_η which gives rise to constructive interference with the standard

model amplitude. Further to average over polarization and color of incoming gluons we need to divide the parton level cross section by a factor of 256. After determining the parton level cross sections, we integrate them with the gluon density functions appropriate for the LHC environment.

To compute the amplitude, we have to calculate the loop integrals. The method of our calculation can be found in [8]. In brief, we have used Oldenborgh-Vermaseren techniques [9] to reduce the tensor integrals to scalar integrals. Here to complete the calculation we need only two scalar integrals. We have checked the cancellation of the ultraviolet divergences numerically as well as analytically. Afterwards, we evaluate the amplitude and its appropriate square numerically. We have convoluted the parton level cross-section with the set 3 (leading-order fits) of the CTEQ4 gluon distribution functions [10] which have been evolved to $Q^2 = \hat{s} = m_H^2$. Some results of our calculation are shown in Fig. 3 and Fig. 4. In Fig. 3 we show how the total cross section (σ_t) and the standard model cross-section σ_{sm} for the physical process $p + p \rightarrow H + X$ vary with m_H for $m_\eta = 150$ GeV and $\lambda_\eta = .7$. From the graph we find that at $m_H = 150$ GeV, $\sigma_t \approx 10.5$ pb whereas $\sigma_{sm} \approx 6.25$ pb which implies an enhancement of nearly 70% due to leptoquark contribution. In Fig. 4 we keep m_H fixed at 150 GeV and show how the total cross section varies with m_η for two different values of λ_η namely .8 and .4. Our results show that light leptoquarks ($m_\eta \approx 150 - 200$ Gev) with large enough coupling to standard model Higgs boson ($\lambda_\eta \approx g_t$) can lead to a significant enhancement in the Higgs boson production cross section relative to that in the standard model.

The major sources of uncertainties in our calculations are values of gluon distributions [11] and the scale at which these are evaluated. These overall uncertainties are expected to be of the order of $20 - 30\%$. We estimate this by varying the Q and also using leading order MRST parton distributions [12]. However, this uncertainty would not drastically affect the relative results (*i.e.*, between purely standard model results and the results with leptoquarks contributions). We have presented the leading order results. Higher order QCD corrections are known to modify the standard model results quite significantly. For example the next to leading order QCD corrections increase the cross section by around 30 % [13] over a large

range of higgs mass. However, higher order QCD corrections will modify the additional leptoquarks contribution in a similar way. Therefore, we would not expect the higher order QCD corrections to significantly alter our main conclusions.

The interaction term between the Higgs boson and the LQ η given by eqn.(2) could modify the Higgs boson decay properties. If $m_H > 2m_\eta$ then the Higgs boson will decay into a pair of LQ's of the second or third generation. This will modify the branching ratios of various Higgs boson decay modes. The consequences of this modifications will depend on the parameter λ_η. Each LQ will decay into a q-l pair of the corresponding generation. One useful new signature of Higgs boson production and its consequent decay will be "2 jets+ 2 leptons" with peaks in the mass distributions of each $q - l$ pair. In addition to this there will be other interesting signatures of the Higgs boson production.

In conclusion, we have shown that light leptoquarks of the third generation can significantly modify the cross-section for the Higgs boson production through the process $pp \rightarrow H + X$ provided its coupling to the Higgs boson is strong enough (*i.e.*, of the order of the yukawa coupling of the top quark). We have shown that for $\lambda_\eta = .7$ and $m_\eta = 150$ GeV the cross-section increases by as much as 70 % relative to its standard model value. The coupling λ_η is not constrained by available low energy as well as collider data. In fact the experimental conditions at the LHC will offer the first opportunity for probing such a coupling between light leptoquarks and the Higgs boson, if such particles exist. Our results will also apply to second or first generation leptoquarks if the branching ratios assumed in arriving at the Tevatron bounds are relaxed. More generally, our results will be applicable to color triplet scalar particles that interact with the Higgs boson in the manner prescribed in the text.

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Figure Captions

Fig. 1:   Diagrams for the process $gg \rightarrow H$ in the standard model.

Fig. 2:   Additional diagrams for the process $gg \rightarrow H$ with leptoquarks in the model.

Fig. 3:   Cross-section for $pp \rightarrow HX$ with $m_\eta = 150$ GeV and $\lambda_\eta = 0.7$.

Fig. 4:   Cross-section for $pp \rightarrow HX$ with $m_H = 150$ GeV and $\lambda_\eta = 0.4$ and 0.8.