Effect of contact interactions on higgs production cross-section at an $e^+e^-$ collider

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Abstract

New interactions appearing at a scale $\Lambda$ larger than the weak interaction scale $v$ can affect physical processes at energies below $\Lambda$ through non-renormalizable $SU(3) \times SU(2) \times U(1)_y$ invariant operators added to the standard model Lagrangian. In this article we investigate the effect of flavor conserving contact interactions on the total cross-section for the process $e^+e^- \rightarrow HZ$ at $\sqrt{s} = 500$ Gev. We find that for $\Lambda \approx 2.5$ Tev, which is consistent with LEP and SLD asymmetry measurements on $Z$ peak as well as theoretical estimates, these operators can increase the total cross-section by a factor of 3 relative to the SM for intermediate mass higgs boson.
The SM has been extremely successful in explaining all the experimental data so far. However in spite of its extraordinary phenomenological success many theorists regard the SM as an effective low energy theory valid below some cut off scale \(\Lambda\) of the order of a few Tev. One of the fundamental reasons behind this view is that the Higgs mass in the SM receives radiative corrections that diverges quadratically with the cut off \(\Lambda\) [1]. Hence to stabilize the higgs mass around the weak scale, which is the natural upper bound for \(m_H\), the cut off scale \(\Lambda\) should be of the order of a few Tev. New interactions can appear at or above the scale \(\Lambda\) involving new heavy particles. Their effects on physical processes at energies below \(\Lambda\) can be described by an effective Lagrangian containing \(SU(3)_c \times SU(2) \times U(1)_y\) invariant non-renormalizable operators involving only the light SM fields [2]. Since we shall be considering the effects of Tev scale new physics on higgs production cross-section the light SM fields should include \(\phi\). For the same reason the gauge symmetry will be assumed to be linearly realized on the SM fields. In addition to gauge symmetries one might also impose other constraints like baryon number and lepton number conservation. The non-renormalizable operators can be expressed as a systematic power series expansion in \(1/\Lambda\). The lowest dimensional operator will clearly have the most dominant effect at energies below \(\Lambda\). Further the effect of these non-renormalizable operators increases as the characteristic energy scale of the process under study approaches \(\Lambda\).

In this article we shall consider the effect of flavor conserving \(d=6\) operators involving leptons, scalar and gauge fields on intermediate mass \((m_H \approx 100-250\) Gev\) higgs production via the process \(e^+e^- \rightarrow HZ\) at \(\sqrt{s} = 500\) Gev. We find that for \(\Lambda \approx 2.5\) Tev the flavor conserving operators satisfy the LEP and SLD constraints on \(A_f^e\) and \(A_{LR}\). However the same value of \(\Lambda\) can increase the cross-section (if the new physics contribution interferes constructively with that of SM) for the process by a factor of 3 relative to that of the SM for a higgs mass of 150-200 Gev. On the other hand for destructive interference the cross-section decreases by a factor of .7 relative to SM for the same range of values of \(\Lambda\).
and $m_H$. The production and detection of intermediate higgs will be one of the important tasks of future $e^+e^-$ collider. The detection of such a higgs boson will be extremely difficult at hadron collider since the higgs decays mainly into $b\bar{b}$ which can remain hidden in the background arising from $t\bar{t}$ pair production [3]. It is therefore extremely important to consider the effects of Tev scale new physics on higgs production cross-section at future $e^+e^-$ colliders.

The effective Lagrangian is given by $L = L_{SM} + L_{\Lambda}$ where $L_{\Lambda} = \sum_i C_i O_i$. The coefficient $C_i$ is of the order of $\Lambda^{-2}$ where $\Lambda$ is the characteristic scale for the operator $O_i$. The operators $O_i$ of $d=6$ that can contribute to the process $e^+e^- \rightarrow HZ$ are [2]

$$
O_1 = (\bar{l}\gamma^\mu l) \frac{i}{2} [\Phi^+(D_{\mu}\Phi) - (D_{\mu}\Phi)^{\dagger}] \\
= \frac{v^2 g}{4c_w} \bar{e}_L \gamma^\mu e_L Z_{\mu} + \frac{vg}{2c_w} \bar{e}_L \gamma^\mu e_L Z_{\mu} H + \ldots 
$$

(1)

$$
O_2 = (\bar{e}\gamma^\mu e) \frac{i}{2} [\Phi^+(D_{\mu}\Phi) - (D_{\mu}\Phi)^{\dagger}] \\
= \frac{v^2 g}{4c_w} \bar{e}_R \gamma^\mu e_R Z_{\mu} + \frac{vg}{2c_w} \bar{e}_R \gamma^\mu e_R Z_{\mu} H + \ldots 
$$

(2)

$$
O_3 = (\bar{l}\gamma^\mu \tau_a l) \frac{i}{2} [\Phi^+(D_{\mu}\Phi) - (D_{\mu}\Phi)^{\dagger}] \\
= \frac{v^2 g}{4c_w} \bar{e}_L \gamma^\mu e_L Z_{\mu} + \frac{vg}{2c_w} \bar{e}_L \gamma^\mu e_L Z_{\mu} H + \ldots 
$$

(3)

$$
O_4 = (\bar{D}^\mu e)D_{\mu}\Phi + h.c. = \frac{ig v}{2\sqrt{2}c_w} [(\partial_{\mu}\bar{e}_R)e_L - \bar{e}_L(\partial_{\mu}e_R)]Z^\mu \\
+ \frac{ig}{2\sqrt{2}c_w} [(\partial_{\mu}\bar{e}_R)e_L - \bar{e}_L(\partial_{\mu}e_R)]HZ^\mu \\
+ \frac{igs_{w}^2}{\sqrt{2}c_w}(\bar{e}_Le_R - e_R\bar{e}_L)Z^\mu \partial_{\mu}H + \frac{ie}{\sqrt{2}}(\bar{e}_Re_L - e_L\bar{e}_R)A^\mu \partial_{\mu}H + \ldots 
$$

(4)
\[ O_5 = (D^\mu \bar{l}eD_\mu \Phi + h.c. = \frac{ig v}{2\sqrt{2}c_w} [\bar{e}_R (\partial_\mu e_L) - (\partial_\mu \bar{e}_L)e_R] Z^\mu \\
+ \frac{ig}{2\sqrt{2}c_w} [\bar{e}_R (\partial_\mu e_L) - (\partial_\mu \bar{e}_L)e_R] H Z^\mu \\
+ \frac{ig(c^2_w - s^2_w)}{2\sqrt{2}c_w} (\bar{e}_L e_R - e_R e_L) Z^\mu \partial_\mu H + \frac{ie}{\sqrt{2}} (\bar{e}_L e_R - e_R e_L) A^\mu \partial_\mu H + .... \quad (5) \]

\[ O_6 = (\bar{l} \sigma^{\mu \nu} \tau_3 e) \phi W^{3}_{\mu \nu} + h.c. \\
= -\frac{1}{\sqrt{2}} (\bar{e}_L \sigma^{\mu \nu} e_R) H (s_w F_{\mu \nu} + c_w Z_{\mu \nu}) + h.c. + .... \quad (6) \]

\[ O_7 = (\bar{l} \sigma^{\mu \nu} e) \phi B_{\mu \nu} + h.c. \\
= \frac{1}{\sqrt{2}} (\bar{e}_L \sigma^{\mu \nu} e_R) H (c_w F_{\mu \nu} - s_w Z_{\mu \nu}) + h.c. + .... \quad (7) \]

In the above we have expressed \( \phi \) in unitary gauge and have written only the resulting d=4, 5 and 6 operators involving charged lepton, scalar and neutral gauge fields that can contribute to precision measurements on Z peak and to \( e^+ e^- \rightarrow HZ \). On transforming the lepton fields from the gauge eigenstate basis to the mass eigenstate basis the operators \( O_6 \) & \( O_7 \) give rise to d=5 FCNC operators involving both \( Z_\mu \) and \( A_\mu \). In particular the coefficients \( C_6 \) and \( C_7 \) must satisfy the strong experimental bound [4] on the branching fraction for the process \( \mu \rightarrow e\gamma \) which implies that

\[ \frac{\Gamma_{\mu \rightarrow e\gamma}}{\Gamma_{\mu \rightarrow e\bar{\nu}_\mu}} \approx \frac{6\pi^2 v^6}{\Lambda^4 m^2_\mu} (c_w - s_w)^2 \sin^2 \theta_{12} \leq 5 \times 10^{-11}. \quad (8) \]

If we assume that \( \sin \theta_{12} \approx .2 \), the scale \( \Lambda \approx C_6^{-\frac{1}{2}} \approx C_7^{-\frac{1}{2}} \) associated with \( O_6 \) and \( O_7 \) must be greater than 3500 Tev. Such a huge scale for \( O_6 \) and \( O_7 \) can be avoided by assuming a symmetry that forbids FCNC vertices upon transformation from the gauge
basis to the mass basis. However the flavor diagonal terms of $O_6$ and $O_7$ must still satisfy the constraint [5] arising from the experimental value of $\frac{\Delta g_e}{2}$ which implies that

$$[(\frac{\Delta g_e}{2})_{\text{expt}} - (\frac{\Delta g_e}{2})_{\text{sm}}] = (\frac{\Delta g_e}{2})_{\text{new}} \approx \frac{2\sqrt{2}m_e v(c_w - s_w)}{\Lambda^2 e} \leq 0.27 \times 10^{-9}. \quad (9)$$

Hence the scale $\Lambda$ associated with the flavor diagonal terms of $O_6$ and $O_7$ must be greater than or of the order of 40 Tev which is considerably greater than the bound (2.5 Tev) on the scale associated with $O_1$, $O_2$ and $O_3$ that follows from Z pole precision measurements. We shall therefore ignore effect of $O_6$ & $O_7$ on the process $e^+ e^- \rightarrow HZ$.

The remaining operators $O_i$, $i=1$-5 do not contain any $ee\gamma$ vertex but they do contain $eeZ$ vertex. The scale associated with these flavor diagonal operators are best constrained by precision measurements on Z pole. However $O_1$, $O_2$ and $O_3$ affect Z pole physics through $d=4$ operators, but $O_4$ & $O_5$ contribute to the same through $d=5$ operators. Hence the constraint on $C_4$ and $C_5$ that follows from Z pole precision measurements is expected to be weaker than that on $C_1$, $C_2$ and $C_3$. If we assume that $C_4 = C_5 = \frac{1}{\Lambda}$ we get

$$C_4O_4 + C_5O_5 \approx \frac{ic_4 g}{\sqrt{2c_w}} (\bar{e}\gamma_5 e) Z^\mu \partial_\mu H. \quad (10)$$

where we have integrated by parts and have used the relation $\partial_\mu Z^\mu = 0$ for on shell Z boson. Note that $O_4$ and $O_5$ contributes to Z pole precision measurements through $d=5$ terms in contrast to $O_1$ – $O_3$ which contributes to the same via $d=4$ terms. Hence the constraint on $C_4$ and $C_5$ that follows from Z pole precision measurements is expected to be slightly weaker than that on $C_1$, $C_2$ and $C_3$. In this work we shall determine the scale associated with $O_1$, $O_2$ and $O_3$ from the LEP and SLD data and equate it to the scale associated with $O_4$ and $O_5$. The effective Lagrangian that contributes to the process $e^+ e^- \rightarrow HZ$ becomes

$$L_{\text{eff}} = \frac{g}{2c_w} [(1 - 2s_w^2) + \frac{v^2}{2}(C_1 + C_3)] \bar{e}_L \gamma^\mu e_L Z_\mu + \frac{g}{2c_w} [\frac{v^2}{2}(C_2 - 2s_w^2)] \bar{e}_R \gamma^\mu e_R Z_\mu$$
the $Z \bar{e} e$ vertex due to new physics. The total cross-section for $e^+ e^- \rightarrow HZ$ is given by

$$
\sigma_T = \sigma_{LR+RL} + \sigma_{LL+RR}
$$

$$
= \frac{1}{384\pi s} \frac{f(s, M_z, M_H)}{s} \left[ \left( \frac{2\pi\alpha (1 - 2s w^2)}{s_w c_w^2} (s - M_z^2) \right) + (C_1 + C_3) \right]^2 \\
+ \left( C_2 - \frac{2\pi\alpha}{s_w c_w^2} \right)^2 \left[ 12sM_z^2 + f^2(s, M_z, M_H) \right] \\
+ \frac{1}{64\pi v^2} \frac{f(s, M_z, M_H)}{s} C_4^2 f^2(s, M_z, M_H). \tag{12}
$$

where $f^2(s, M_z, M_H) = (s + M_z^2 - M_H^2)^2 - 4sM_z^2$. The first term arises from $e^-_L e^+_R + e^-_R e^+_L \rightarrow HZ$ and the second term from $e^-_L e^+_L + e^-_R e^+_R \rightarrow HZ$. We shall consider two distinct cases of new physics effects on $\sigma_T$. In the first scenario we shall assume that new physics effects on $\sigma_{LR+RL}$ interferes constructively with those of SM. A typical example of this scenario is $C_1 = C_3 = C_4 = -\frac{C_2}{2} = \frac{1}{\Lambda^2}$. In the second scenario the new physics effects on $\sigma_{LR+RL}$ will be assumed to interfere destructively with SM effects, an example of which is $C_1 = C_3 = -C_4 = -\frac{C_2}{2} = -\frac{1}{\Lambda^2}$. We shall assume a common value of $\Lambda=2.5$ Tev for both scenarios.

The operators $O_1$, $O_2$ and $O_3$ give rise to small corrections to the vector and axial vector couplings of Z boson to $e\bar{e}$. It is therefore important to consider the constraints on $C_1$, $C_2$ and $C_3$ that follow from LEP and SLD asymmetry measurements on Z peak and whether these constraints are consistent with the value of $\Lambda$ assumed above. We have $g^e_v = (g^e_v)_{sm} - \frac{v^2}{8} (C_1 + C_2 + C_3)$ and $g^e_a = (g^e_a)_{sm} + \frac{v^2}{8} (C_1 + C_3 - C_2)$. Hence in both scenarios $\delta g^e_v \approx 0$ and $\delta g^e_a \approx -\frac{v^2}{4} C_2$ i.e. new physics effects renormalizes the weak axial charge of the electron but does not affect its weak vector charge. On Z peak [6] we have $A_{LR} \approx (A_{LR})_{sm} [1 - \frac{\delta g^e_a}{(g^e_a)_{sm}}]$ and $A^f_{fb} \approx (A^f_{fb})_{sm} [1 - 2 \frac{\delta g^e_a}{(g^e_a)_{sm}}]$ provided $|\frac{\delta g^e_a}{(g^e_a)_{sm}}| \ll$
\[ \frac{\delta g_e}{(g_e)_m} \] It then follows that \((\delta A_{LR})_{new} \approx \pm \frac{v^2}{2(\Lambda^2 (g_e)_m)} \) and \((\delta A_{e fb}^g)_{new} \approx \pm \frac{v^2}{\Lambda^2 (g_e)_m} \) where the upper (lower) sign corresponds to destructive (constructive) interference scenario. The average values of \(A_{LR} \) and \(A_{e fb}^g \) reported by SLD and LEP [7] are \(A_{LR} = 1.56 \pm 0.08 \) and \(A_{e fb}^g = 0.160 \pm 0.024 \). The predicted values for these asymmetries in the context of the SM are \((A_{LR})_{sm} = 1.142 \pm 0.003 \) and \((A_{e fb}^g)_{sm} = 0.0151 \). The experimental bounds on \(\delta A_{LR} \) and \(\delta A_{e fb}^g \) are \(\frac{\delta A_{LR}}{(A_{LR})_{sm}} \approx 0.099 \) and \(\frac{\delta A_{e fb}^g}{(A_{e fb}^g)_{sm}} \approx 0.06 \). For \(\Lambda \approx 2.5 \) Tev the new physics contributions are given by \(\frac{\delta A_{LR}}{(A_{LR})_{sm}} \approx \pm 0.02 \) and \(\frac{\delta A_{e fb}^g}{(A_{e fb}^g)_{sm}} \approx \pm 0.04 \) both of which are clearly compatible with the experimental bounds. On the contrary the contribution of \(O_4 \) to \(A_{LR} \) at the Z pole is given by \(\frac{\delta A_{LR}}{(A_{LR})_{sm}} \approx -\frac{1}{2} \left(\frac{\epsilon^2}{(g_L^2 + g_R^2)}\right) \). The current SLD precision for measuring \(A_{LR} \) is about 5%. Hence even if \(\Lambda \) is as low as 400 Gev the contribution of \(O_4 \) to \(A_{LR} \) is far too small (about 0.78%) to be detected at SLD. In the following we shall equate the scale of \(O_4 \) and \(O_5 \) to that of \(O_1, O_2 \) and \(O_3 \). This will give us a lower bound on the cross-section for the process \(e^+e^- \rightarrow HZ \). Further if the positive sign of the phenomenological bounds on \(\delta A_{LR} \) and \(\delta A_{e fb}^g \) is taken seriously, experiments would seem to prefer the destructive interference scenario considered in this article, implying that the observed higgs production cross-section will be lower than that of the SM.

From eqn. 11 we find that for \(\sqrt{s} = 500 \) Gev and \(m_H = 150 \) Gev, \(\sigma_T \approx 160 \) fb (43 fb) for the constructive (destructive) interference case. This is to be compared with the SM prediction of \(\sigma_{sm} \approx 52 \) fb. When \(m_H \) is increased to 200 Gev, \(\sigma_T \) drops to 128 fb in the constructive case and to 33 fb in the destructive case. The corresponding value of the cross-section in the context of SM is 42 fb. In the case of constructive interference the dominant contribution to \(\sigma_T \) comes from \(\sigma_{LR+RL} \) whereas for destructive interference \(\sigma_{LL+RR} \) forms the dominant part. \(\sigma_T \) is therefore quite insensitive to the value of \(C_4 \) in the former case but depends quite strongly on it in the latter. For an integrated luminosity of 30 fb \(^{-1} \) [8] the effect of new physics would be to increase the number of HZ events by 3060 for constructive interference or decrease it by 390 for destructive interference. Note that at low energies (\(\sqrt{s} \approx 500 \) Gev) the dominant production mechanism for intermediate
mass higgs boson at an $e^+e^-$ collider is $e^+e^- \rightarrow HZ$ \[8\]. For higher energies ($\sqrt{s} \approx 1$ Tev) the dominant production mechanism becomes $e^+e^- \rightarrow \nu_e \bar{\nu}_e H$. However new physics affects the latter process only through small corrections (of the order of 1%) to the usual SM vertices. There is no $d=5$ or 6 operator for the vertex $\bar{e}e\nu_e H$ similar to the $\bar{e}eZH$ vertex. Hence the overall effect of Tev scale new physics on the process $e^+e^- \rightarrow \nu_e \bar{\nu}_e H$ is expected to be much smaller than that on $e^+e^- \rightarrow HZ$.

Some comments are in order about the reliability of the value of $\Lambda$, the scale of new physics, used in our analysis. The scale $\Lambda$ for new interactions should be related \[9\] to the amplitude $v$ ($v$ plays the role of $f_\pi$ in electro-weak theory) for producing scalar particles out of the vacuum through the relation $\frac{\Lambda}{v} = g_s$ where $g_s$ is the induced coupling for the low energy theory. According to theoretical estimates $g_s$ is expected to lie between 1 and $4\pi$. In low energy QCD for example $g_\rho = \frac{M_\rho}{f_\pi} \approx 6$. For $\Lambda \approx 2.5$ Tev we find that $g_s \approx 10$ which is in agreement with our theoretical expectations about new interactions underlying the EW theory.

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Figure Captions

Fig. 1. The cross-section for the process $e^+ e^- \rightarrow HZ$ for $m_H = 150$ Gev plotted against $\sqrt{s}$.

(a) constructive interference (b) standard model and (c) destructive interference.

Fig. 2 Same as Fig. 1 with $m_H = 200$ Gev.