Anomalous Couplings in the Higgs-strahlung Process

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Abstract

The angular distributions in the Higgs-strahlung process $e^+e^- \to HZ \to H\bar{f}f$ are uniquely determined in the Standard Model. We study how these predictions are modified if non-standard couplings are present in the ZZH vertex, as well as lepton-boson contact terms. We restrict ourselves to the set of operators which are singlets under standard $SU_3 \times SU_2 \times U_1$ transformations, CP conserving, dimension 6, helicity conserving, and custodial SU_2 conserving.

1. The Higgs-strahlung process [1]

$$e^+e^- \to HZ \to H\bar{f}f \tag{1}$$

together with the WW fusion process, are the most important mechanisms for the production of Higgs bosons in e^+e^- collisions [2,3]. Since the ZZH vertex is uniquely determined in the Standard Model (SM), the production cross section of the Higgs-strahlung process, the angular distribution of the HZ final state as well as the fermion distribution in the Z decays can be predicted if the mass of the Higgs boson is fixed [4]. These predictions may be modified when deviations from the pointlike coupling are present, which can occur in models with non-pointlike character of the Higgs boson itself or through interactions beyond the SM at high energy scales. Since the effective energy scale of the Higgs-strahlung process is set by the c.m. energy $\sqrt{s}$, while the fusion processes are essentially low-energy processes with an effective scale of the order M_W, new interactions manifest themselves more clearly in the total cross section and angular distributions for the Higgs-strahlung process (see also [5]).

2. Operator basis. Deviations from the pointlike coupling can occur in models with non-pointlike character of the Higgs boson itself or through interactions beyond the SM at high energy scales. We need not specify the underlying theory but instead we will adopt the usual assumption that these effects can globally be parameterized by introducing a set of dimension-6 operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{\alpha_i}{\Lambda^2}\mathcal{O}_i \tag{2}$$

The coefficients are in general expected to be of the order $1/\Lambda^2$, where Λ denotes the energy scale of the new interactions. However, if the underlying theory is weakly interacting, the α_i can be significantly smaller than unity, in particular for loop-induced operators. [It is assumed *a priori* that the ratio of the available c.m. energy to Λ is small enough for the expansion in powers of $1/\Lambda$ to be meaningful.]

If we restrict ourselves to operators [6] which are singlets under $SU_3 \times SU_2 \times U_1$ transformations of the SM gauge group, CP conserving, and conserving the custodial SU_2 symmetry, the following bosonic operators are relevant for the Higgs-strahlung process:

$$\mathcal{O}_{\partial\varphi} = \frac{1}{2}|\partial_\mu(\varphi^\dagger\varphi)|^2 \tag{3}$$

$$\mathcal{O}_{\varphi W} = \frac{1}{2}\varphi^\dagger \vec{W}^2_{\mu\nu}\varphi \tag{4}$$

$$\mathcal{O}_{\varphi B} = \frac{1}{2}\varphi^\dagger B^2_{\mu\nu}\varphi \tag{5}$$

where the gauge fields W^3, B are given by the Z, γ fields. This set of operators is particularly interesting because it does not affect, at tree level, observables which do not involve the Higgs particle explicitly. [It is understood that the fields and parameters are (re-)normalized in the Lagrangian $\mathcal{L}$ in such a way that the particle masses and the electromagnetic coupling retain their physical values.]

In addition, we consider the following helicity-conserving fermionic operators which induce contact terms contributing to $e^+e^- \to ZH$:

$$\mathcal{O}_{L1} = (\varphi^\dagger iD_\mu\varphi)(\bar{\ell}_L\gamma^\mu\ell_L) + \text{h.c.} \tag{6}$$

$$\mathcal{O}_{L3} = (\varphi^\dagger\tau^a iD_\mu\varphi)(\bar{\ell}_L\tau^a\gamma^\mu\ell_L) + \text{h.c.} \tag{7}$$

$$\mathcal{O}_{R} = (\varphi^\dagger iD_\mu\varphi)(\bar{e}_R\gamma^\mu e_R) + \text{h.c.} \tag{8}$$

[ℓ_L and e_R denote the left-handed lepton doublet and the right-handed singlet, respectively. The vacuum expectation value of the Higgs field is given by $\langle\varphi\rangle = (0, v/\sqrt{2})$ with $v = 246\,\text{GeV}$, and the covariant derivative acts on the Higgs doublet as $D_\mu = \partial_\mu - \frac{i}{2}g\tau^a W^a_\mu + \frac{i}{2}g' B_\mu$.] Helicity-violating fermionic operators do not interfere with the SM amplitude, so that their contribution to the cross section is suppressed by another power of Λ^2. The helicity-conserving fermionic operators modify the SM Zee couplings and are therefore constrained by the measurements at LEP1; however, it is possible to improve on the existing limits by measuring the Higgs-strahlung process at a high-energy e^+e^- collider since the impact on this process increases with energy [7].

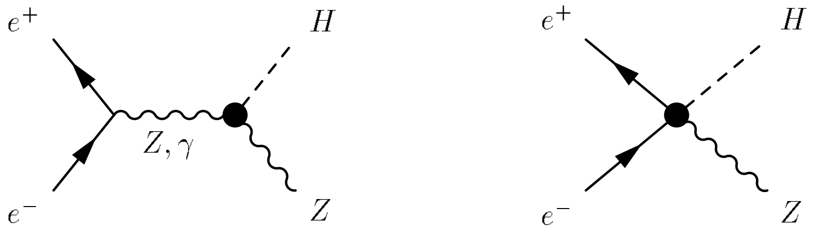

Figure 1: *Anomalous $ZZH/\gamma ZH$ couplings and e^+e^-ZH contact terms in the Higgs-strahlung process.*

The effective ZZH and the induced γZH interactions (Fig.1, left diagram) may be written

$$\mathcal{L}_{ZZH} = g_Z M_Z \left(\frac{1+a_0}{2} Z_\mu Z^\mu H + \frac{a_1}{4} Z_{\mu\nu} Z^{\mu\nu} H\right) \tag{9}$$

$$\mathcal{L}_{\gamma ZH} = g_Z M_Z \frac{b_1}{2} Z_{\mu\nu} A^{\mu\nu} H \tag{10}$$

where $g_Z = M_Z \sqrt{4\sqrt{2}G_F}$. Additional operators $Z_\mu Z^{\mu\nu}\partial_\nu H$ and $Z_\mu A^{\mu\nu}\partial_\nu H$ are redundant in this basis: They may be eliminated in favor of the other operators and the contact terms by applying the equations of motion. The remaining coefficients are given by

$$a_0 = -\frac{1}{2}\alpha_{\partial\varphi} v^2/\Lambda^2 \tag{11}$$

$$a_1 = 4g_Z^{-2}\left(c_W^2 \alpha_{\varphi W} + s_W^2 \alpha_{\varphi B}\right)/\Lambda^2 \tag{12}$$

$$b_1 = 4g_Z^{-2} c_W s_W \left(-\alpha_{\varphi W} + \alpha_{\varphi B}\right)/\Lambda^2 \tag{13}$$

where s_W and c_W are the sine and cosine of the weak mixing angle, respectively.

In the same way the $e\bar{e}HZ$ contact interactions (Fig.1, right diagram) can be defined for left/right-handed electrons and right/left-handed positrons

$$\mathcal{L}_{eeZH} = g_Z M_Z \left[c_L \bar{e}_L \not{Z} e_L H + c_R \bar{e}_R \not{Z} e_R H\right] \tag{14}$$

with

$$c_L = -2g_Z^{-1}\left(\alpha_{L1} + \alpha_{L3}\right)/\Lambda^2 \tag{15}$$

$$c_R = -2g_Z^{-1}\alpha_R/\Lambda^2 \tag{16}$$

Some consequences of these operators for Higgs production in e^+e^- collisions have been investigated in the past. Most recently, the effect of novel ZZH vertex operators and $\ell\ell ZH$ contact terms on the total cross sections for Higgs production has been studied in Ref.[7]. The impact of vertex operators on angular distributions has been analyzed in Refs.[8] and [9]. We expand on these analyses by studying the angular distributions for the more general case where both novel vertex operators and contact interactions are present. The analysis of angular distributions in the Higgs-strahlung process (1) allows us to discriminate between various novel interactions. In fact, the entire set of parameters a_0, a_1, b_1 and c_L, c_R can be determined by measuring the polar and azimuthal angular distributions as a function of the beam energy if the electron/positron beams are unpolarized. As expected, the energy dependence of the polar angular distribution is sufficient to provide a complete set of measurements if longitudinally polarized electron beams are available[1].

3. Total cross section and polar angular distribution. Denoting the polar angle between the Z boson and the e^+e^- beam axis by θ, the differential cross section for the process $e^+e^-_{L,R} \to ZH$ may be written as

$$\frac{d\sigma^{L,R}}{d\cos\theta} = \frac{G_F^2 M_Z^4}{96\pi s}\left(v_e \pm a_e\right)^2 \lambda^{1/2} \frac{\frac{3}{4}\lambda \sin^2\theta \left(1+\alpha^{L,R}\right) + 6\left(1+\beta^{L,R}\right) M_Z^2/s}{(1-M_Z^2/s)^2} \tag{17}$$

[1]Since we can restrict ourselves to helicity-conserving couplings, as argued before, additional positron polarization need not be required.

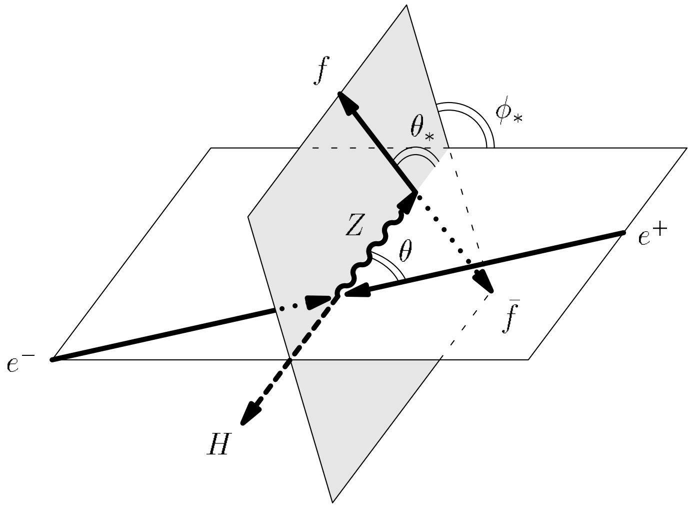

Figure 2: *Polar and azimuthal angles in the Higgs-strahlung process. [The polar angle θ_* is defined in the Z rest frame.]*

and the integrated cross section

$$\sigma = \frac{G_F^2 M_Z^4}{96\pi s} \left(v_e \pm a_e\right)^2 \lambda^{1/2} \frac{\lambda\left(1+\alpha^{L,R}\right) + 12\left(1+\beta^{L,R}\right) M_Z^2/s}{(1-M_Z^2/s)^2} \tag{18}$$

The Z charges of the electron are defined as usual by $a_e = -1$ and $v_e = -1 + 4s_W^2$. s is the c.m. energy squared, and λ the two-particle phase space coefficient $\lambda = [1-(m_H+m_Z)^2/s] \times [1-(m_H-m_Z)^2/s]$. The coefficients $\alpha(s)^{L,R}$ and $\beta(s)^{L,R}$ can easily be determined for the interactions in Eqs.(9) and (14):

$$\alpha(s)^{L,R} = 2a_0 + (s-M_Z^2)\frac{8c_W s_W}{v_e \pm a_e} c_{L,R} \tag{19}$$

$$\beta(s)^{L,R} = \alpha(s)^{L,R} + 2\gamma\sqrt{s}\, M_Z \left[a_1 + \frac{4c_W s_W}{v_e \pm a_e}\left(1 - \frac{M_Z^2}{s}\right) b_1\right] \tag{20}$$

where the boost of the Z boson is given by $\gamma = (s + M_Z^2 - M_H^2)/2M_Z\sqrt{s}$.

The modification of the cross section by the new interaction terms has a simple structure. The coefficient a_0 just renormalizes the SM cross section. By contrast, the contact interactions grow with s. [The ratio s/Λ^2 is assumed to be small enough for the restriction to dimension-6 operators to be meaningful.] The operators $\mathcal{O}_{\varphi W}$, $\mathcal{O}_{\varphi B}$ affect the coefficient in the cross section which is independent of θ. They damp the fall-off of this term, changing the $1/s^2$ to a $1/s$ behavior; however, these contributions remain subleading since they are associated with transversely polarized Z bosons which are suppressed at high energies compared with the longitudinal components. To illustrate the size of the modifications $\alpha(s)^{L,R}$ and $\beta(s)^{L,R}$, we have depicted these functions in Fig.3(a) for the special choice $\alpha_i = 1$.

4. Azimuthal distributions. The azimuthal angle ϕ_* of the fermion f is defined as the angle between the $[e^-, Z]$ production plane and the $[Z, f]$ decay plane (Fig.2). It corresponds to the azimuthal angle of f in the Z rest frame with respect to the $[e^-, Z]$ plane. On general grounds, the ϕ_* distribution must be a linear function of $\cos\phi_*$, $\cos 2\phi_*$, and $\sin\phi_*$, $\sin 2\phi_*$, measuring the helicity components of the decaying spin-1 Z state. The coefficients of the sine terms vanish for CP invariant theories. The $\cos\phi_*$ and $\cos 2\phi_*$ terms correspond to P-odd and P-even combinations of the fermion currents. The general azimuthal distributions are quite involved [4,8,9]. We therefore restrict ourselves to the simplified case in which all polar angles are integrated out, i.e., the polar angle θ of the Z boson in the laboratory frame and the polar angle θ_* of f in the Z rest frame. In this way we find for the azimuthal ϕ_* distribution:

$$\frac{d\sigma^{L,R}}{d\phi_*} \sim 1 \mp \frac{9\pi^2}{32}\,\frac{2\,v_f a_f}{v_f^2 + a_f^2}\,\frac{\gamma}{\gamma^2+2}\left(1 + f_1^{L,R}\right)\cos\phi_* + \frac{1}{2(\gamma^2+2)}\left(1 + f_2^{L,R}\right)\cos 2\phi_* \quad (21)$$

with

$$f_1(s)^{L,R} = M_Z\sqrt{s}\,\frac{(\gamma^2-1)(\gamma^2-2)}{\gamma(\gamma^2+2)}\left[a_1 + \frac{4 s_W c_W}{v_e \pm a_e}\left(1 - \frac{M_Z^2}{s}\right) b_1\right] \quad (22)$$

$$f_2(s)^{L,R} = 2M_Z\sqrt{s}\,\frac{\gamma(\gamma^2-1)}{\gamma^2+2}\left[a_1 + \frac{4 s_W c_W}{v_e \pm a_e}\left(1 - \frac{M_Z^2}{s}\right) b_1\right] \quad (23)$$

The cross section flattens with increasing c.m. energy in the Standard Model, i.e. the coefficients of $\cos\phi_*$ and $\cos 2\phi_*$ decrease asymptotically proportional to $1/\sqrt{s}$ and $1/s$, respectively. The anomalous contributions modify this behavior: The $\cos\phi_*$ term receives contributions which increase proportional to $\sqrt{s}$ with respect to the total cross section, while the $\cos 2\phi_*$ term receive contributions from the transversal couplings that approaches a constant value asymptotically. The size of the new terms in $f_{1,2}^{L,R}$ is shown in Fig.3(b) as a function of the energy. [The special choice $\alpha_i = 1$ we have adopted for illustration, implies $f_{1,2}^L = f_{1,2}^R$.]

5. High-energy limit. It is instructive to study the high-energy behavior of the coefficients in the limit $M_Z^2 \ll s \ll \Lambda^2$. In this case we obtain the simplified relations:

$$\alpha(s)^{L,R} \simeq \mp s \cdot 8 s_W c_W\, c_{L,R} + \mathcal{O}(v_e) \quad (24)$$

$$\beta(s)^{L,R} \simeq \alpha(s)^{L,R} + s\,(a_1 \mp 4 s_W c_W\, b_1) + \mathcal{O}(v_e) \quad (25)$$

and

$$f_1(s)^{L,R} \simeq \frac{s}{2}\,(a_1 \mp 4 s_W c_W\, b_1) + \mathcal{O}(v_e) \quad (26)$$

$$f_2(s)^{L,R} \simeq s\,(a_1 \mp 4 s_W c_W\, b_1) + \mathcal{O}(v_e) \quad (27)$$

Terms which are proportional to $v_e = -1 + 4s_W^2$ are suppressed by an order of magnitude. If longitudinally polarized electrons are available, the asymptotic value of the coefficients

a_1, b_1, c_L and c_R can be determined by measuring the polar angular distribution without varying the beam energy. The analysis of the azimuthal ϕ_* distribution provides two additional independent measurements of the coefficients a_1 and b_1. On the other hand, the set of measurements remains incomplete for fixed energy if only unpolarized electron/positron beams are used at high energies; in this case the coefficients cannot be disentangled completely without varying the beam energy within the preasymptotic region.

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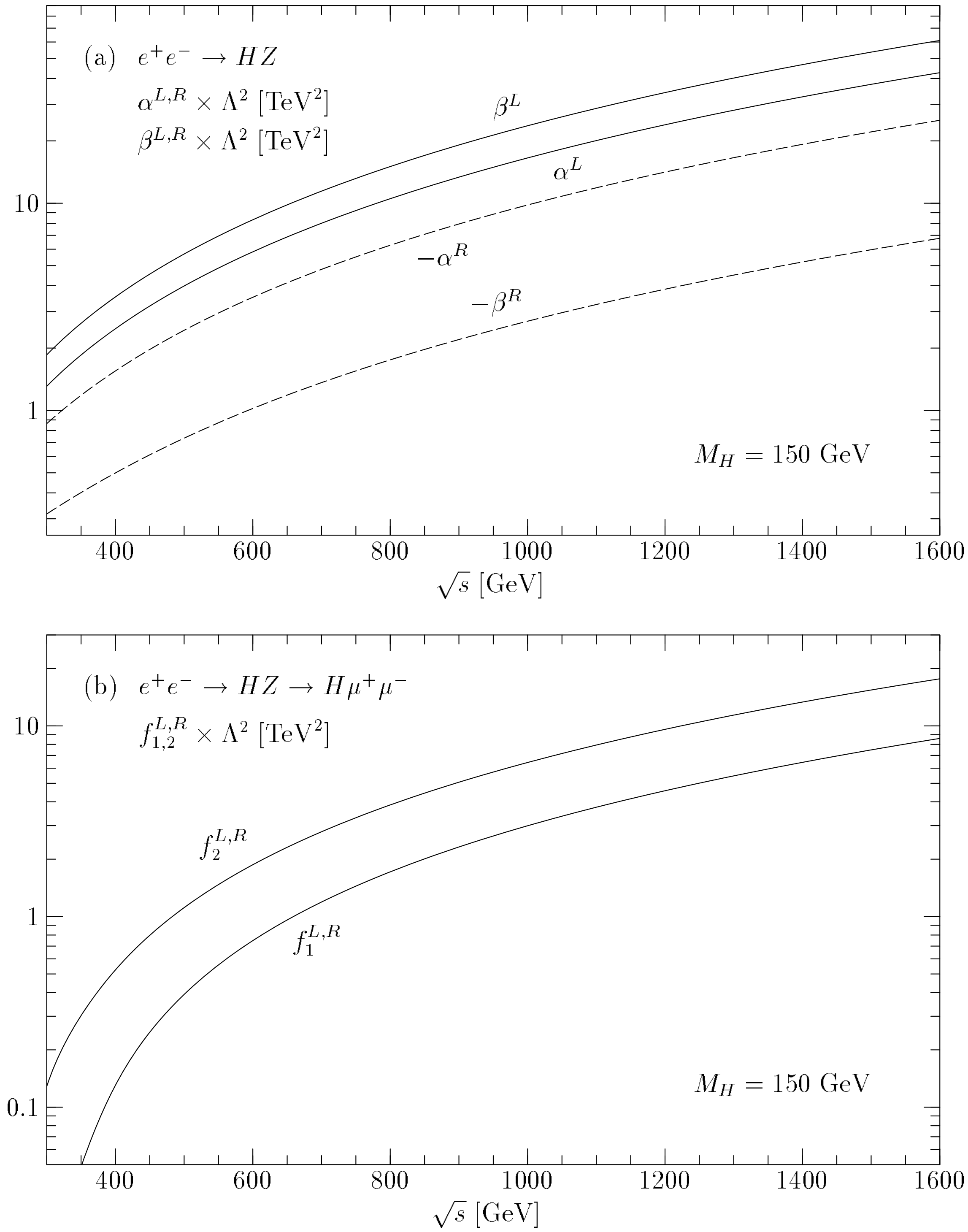

Figure 3: *Coefficients of the angular distributions as a function of the beam energy. Parameters are described in the text; in particular, $\alpha_i = 1$ has ben chosen in the effective Lagrangian Eq.(2). [The L, R coefficients of the azimuthal distribution coincide for the special choice $\alpha_i = 1$.]*