Higgs boson compositeness: from $e^+e^- \rightarrow ZH$ to $e^+e^- \rightarrow Z_L, W_L + \text{anything}$.

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Abstract

We assume that the Higgs doublet has a composite structure, respecting the main standard model properties, and therefore called Composite Standard Model (CSM), but leading (through Goldstone equivalence) to $Z_L$ and $W_L$ form factors. We illustrate how such a form factor affecting the $ZZ_L H$ coupling will be directly observable in $e^+e^- \rightarrow ZH$. We then show the spectacular consequences which would appear in the inclusive processes $e^+e^- \rightarrow Z_L + \text{anything}$. Such a form factor could also affect the $\gamma W^+_L W^-_L$ and $ZW^+_L W^-_L$ vertices and we show what effects this would generate in $e^+e^- \rightarrow W^+W^-$ (especially in $e^+e^-_R \rightarrow W^+_L W^-_L$) and in $e^+e^- \rightarrow W_L + \text{anything}$. We finally mention the $\gamma\gamma \rightarrow W^+W^-$ process and several other processes in hadronic collisions which could be similarly affected.

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1 INTRODUCTION

Higgs boson compositeness is an appealing possibility for understanding the peculiar features of the standard model \([1]\). Compositeness could even concern other sectors; substructures had been considered since a long time, see for ex. \([2]\), \([3]\), \([4]\), \([5]\). Several processes have been studied in order to test Higgs boson compositeness or the fact that the Higgs boson could be a portal to new sectors (possibly involving unvisible states), see ref.\([6]\), \([7]\), \([8]\).

In this paper we assume that Higgs boson compositeness reproduces (possibly in an effective way) the general features of the SM, in particular those resulting from gauge invariance and Goldstone equivalence. At low energy no anomalous coupling would be generated. As the energy increases we keep Goldstone equivalence which immediately ensures (at scale \(m_Z\)) a good behaviour of the \(W_L, Z_L\) amplitudes owing to the typical SM cancellations. But this means that \(W_L, Z_L\) amplitudes will be equivalent to the composite \(G^\pm, G^0\) ones and should reflect their compositeness properties, possibly the presence of a form factor (similarly to the hadronic case) with a new physics scale \(M\). Such a form factor should be close to 1 at low \(q^2\) but, after showing some structures around the new physics scale (\(q^2 \simeq M^2\)), it may decrease at very high \(q^2\). We will call models leading to such properties as Composite Standard Models (CSM).

Concerning the presence of a form factor in the \(ZZ_L H \simeq ZG^0 H\) coupling, the \(e^+e^- \to ZH\) process, studied theoretically and experimentally since a long time (see reviews and references in \([9]\), \([10]\)) should be particularly interesting as it is largely dominated by \(e^+e^- \to Z \to Z_L H\) at high energy, see \([11]\). This form factor could then be directly measured by the \(e^+e^- \to ZH\) cross section. We illustrate this possibility with a test form factor controlled by a new physics scale \(M\).

This process will then furnish the basic source of an input for predicting CSM effects in other processes. As an example we treat the case of the inclusive process \(e^+e^- \to Z_L + \text{anything}\).

We then look at the charged \(W_L\) case. We start with the simplest example given by \(e^+e^- \to W^+W^-\). A high energy description has been given in SM (and in MSSM) in ref.\([12]\). The Helicity Conservation rule (HC), ref.\([13]\), predicts the presence of four leading amplitudes, two for \(W^+_TW_T\) and two for \(W^+_LW^-_L\). The transverse amplitudes are larger than the longitudinal ones but have different angular dependences. So we study the importance of the \(W^+_TW^-_T \simeq G^+G^-\) contribution versus energy and angle, the effects of the presence of \(\gamma G^+G^-\) and \(ZG^+G^-\) form factors and their observability through the \(e^+e^- \to W^+W^-\) cross section with polarized or unpolarized \(e^\pm\) beams. We then also treat the case of the inclusive process \(e^+e^- \to W_L + \text{anything}\).

We finally mention other processes in which similar studies may be done. We say a few words about \(\gamma\gamma \to W^+W^-\). More complex processes with \(ZZ, WW, ZW\) production in hadronic collisions could also be studied.

Section 2 is devoted to the description of the \(e^+e^- \to ZH\) process and the possible determination of the form factor. The \(e^+e^- \to Z_L + \text{anything}\) process is then studied in Section 3. The charged cases \(e^+e^- \to W^+W^-\) and \(e^+e^- \to W_L + \text{anything}\) are treated in
Sections 4, 5 and the $\gamma\gamma \rightarrow W^+W^-$ process in Section 6. The summary and the possibility of other applications are discussed in Section 7.

2 THE $e^+e^- \rightarrow ZH$ PROCESS AS THE BASIC SIGNAL OF HIGGS COMPOSITENESS

The high energy properties of this process have been given in ref.\cite{11}. At Born level the helicity amplitudes consist in four $Z$-Transverse amplitudes ($\lambda = \pm \frac{1}{2}, \tau = \pm 1$)

$$F_{\lambda,\tau}^{\text{Born}} = -\frac{e^2 f_{ZZH} \sqrt{s}}{\sqrt{2}(s - m^2_Z)}[g_{eL}(\tau \cos \theta - 1)\delta_{\lambda,-} - g_{eR}(\tau \cos \theta + 1)\delta_{\lambda,+}] \tag{1}$$

and two $Z$-longitudinal amplitudes $\lambda = \pm \frac{1}{2}, \tau = 0$)

$$F_{\lambda,0}^{\text{Born}} = \frac{e^2 f_{ZZH} E_Z \sqrt{s} \sin \theta}{m_Z(s - m^2_Z)}[g_{eL}^Z\delta_{\lambda,-} - g_{eR}^Z\delta_{\lambda,+}] \tag{2}$$

At high energies the (HCns) rule \cite{13} requires

$$\lambda + \lambda' = \tau \tag{3}$$

and indeed the four transverse amplitudes which violate this rule (and are called HV) are suppressed like $m_Z/\sqrt{s}$. On the opposite the two longitudinal ones, which satisfy this rule (and are called HC) tend to constants

$$F_{\lambda,0}^{\text{Born}} \rightarrow \frac{e^2 f_{ZZH} \sin \theta}{2m_Z}[g_{eL}^Z\delta_{\lambda,-} - g_{eR}^Z\delta_{\lambda,+}] \tag{4}$$

These HC amplitudes agree with the direct computation of the Goldstone process $e^-e^+ \rightarrow G^0H$, and the relation $F_{\lambda,0}^{\text{Born}}(Z_0H) = iF_{\lambda,0}^{\text{Born}}(G^0H)$ when neglecting $m^2_Z/s$ terms.

In ref.\cite{11} the one loop contributions had also been computed and the explicit high energy expressions in the so-called SIM approximation have been given in its Appendix A.

As explained in the Introduction, we will assume that Higgs compositeness generates an $s$-dependent form factor $F_H(s)$ for the $ZG^0H$ coupling. So we can write, at Born and at one loop SIM level

$$F_{\lambda,0}^{\text{Comp}} \approx F_{\lambda,0}^{\text{SIM}} F_H(s) \tag{5}$$

The cross section given by
\[
\frac{d\sigma}{d\cos \theta} = \frac{\beta_Z}{128\pi s} \sum_{\lambda \tau} |F_{\lambda\tau}(\theta)|^2 ,
\]  

(6)

should allow to measure the form factor \( F_H(s) \). A first step could consist in neglecting the small HV amplitudes in which case one gets simply

\[
\frac{d\sigma^{\text{Comp}}}{d\cos \theta} \approx \frac{d\sigma^{\text{SM}}}{d\cos \theta} |F_H(s)|^2
\]

(7)
such that \( |F_H(s)|^2 \) can immediately be obtained from the ratio of the measured cross section over the predicted SM one. A more precise result can then be obtained by taking also into account the contribution of the small HV amplitudes.

In order to illustrate these properties we take a test form factor

\[
F_H(s) = \frac{\left(m_Z + m_H\right)^2 + M^2}{s + M^2}
\]

(8)

where \( M \) is a new physics scale taken as 0.5 TeV. Larger values of this scale would require higher energies to see similar effects.

In Figure 1 (upper panel) we can first see how much the \( Z_L \) production dominates the unpolarized cross section and then how its reduction due to the form factor affects it in a similar way. In the lower panel, for \( \sqrt{s} = 4 \) TeV, we show how the angular distribution (dominated by the \( \sin^2 \theta \) shape of \( Z_L \) production) is affected by the form factor.

Such a form factor which would be determined by this measurement could then constitute the basic input for predicting corresponding effects of compositeness in other processes. Another particularly interesting process would be \( \gamma\gamma \to ZH \) in which again the leading (HC) amplitude only involves \( Z_L H \) and is therefore directly sensitive to the considered compositeness effects. This amplitude starts however at one loop (see for example [14]) and a careful analysis is required.

In the next Section we discuss the inclusive process \( e^+e^- \to Z_L + \text{anything} \).

3 THE PROCESS \( e^+e^- \to Z_L + \text{anything} \)

At high energy and at leading order, with \( Z_L \simeq G^0 \), the SM contributions (apart from the above 2-body \( G^0 H \) process) consist in the 3-body processes \( G^0 t\bar{t}, G^0 H H, G^0 ZZ, G^0 WW \) and \( G^0 Z H, G^0 \gamma H \) channels. The first 4 channels proceed through \( e^+e^- \) annihilation into photon or \( Z \) followed by the 3-body production. The last 2 ones proceed respectively through \( e^+e^- \to ZZ \) and \( e^+e^- \to \gamma Z \), followed by \( Z \to G^0 H \).

We have computed the corresponding inclusive cross section

\[
\frac{d\sigma}{dx d\cos \theta}
\]

(9)

where \( x = \frac{2p}{s} \) is the reduced \( Z_L \) momentum, for fixed \( \theta \) angle with respect to the \( e^- \) direction; \( s = q^2 = (p_{e^+} + p_{e^-})^2 \).
We then affect the vertices involving $H$ or $G^0$ by the above $F_H(s)$ form factor adapting the variable $s$ to the corresponding virtual momentum squared. For simplicity we take the same form factor in all these cases. This is arbitrary but our aim is not to make a precise prediction but to see what type of modification could appear in the inclusive $x$ distribution.

In Figure 2 one can compare the resulting ”SM” and ”SMFF” curves for $\sqrt{s} = 4$ TeV with 2 choices of new physics scale, $M=0.5$ and 2 TeV; the form factor effect indeed consists in a strong reduction of the cross section.

For comparison we have also drawn in Fig.2 the $Z_L \simeq G^0$ inclusive distribution with the effect of new channels and with a crude parton-like effect typical of compositeness. We have first considered the production of pairs of new particles $(G^0 + H')$ one of these particles emitting the final $G^0$ (for example $G^0 \rightarrow G^0 + H$). We illustrate the effects of 3 such pairs with common masses $M_{1,2,3} = 0.5, 1, 1.5 TeV$. The corresponding shapes result from the phase space and from the internal propagator effects. These are pure ”kinematical shapes” and do not correspond to precise models which may contain further effects due to precise intermediate states or resonances. As already mentioned our aim is just to illustrate the sensitivity of the inclusive distribution to the presence of new contributions.

We then show the shape of a parton-like distribution generated like in the hadronic case by the following structure:

$$\frac{d\sigma}{dx d\cos \theta} = \Sigma_i \frac{d\sigma_i}{d\cos \theta} D_i(x)$$

(10)

We make an arbitrary illustration choosing as basic production cross section $\frac{d\sigma_i}{d\cos \theta}$ the standard $e^+e^- \rightarrow ZH$ process then followed by a normalized fragmentation function

$$\int_{1-\frac{M^2}{s}}^1 x D(x) dx = 1$$

(11)

with

$$D(x) = \frac{6}{(1 - \frac{M^2}{s})^3(1 - x - \frac{M^2}{s})}$$

(12)

which favours the low $x$ domain ($x < 1 - \frac{M^2}{s}$ corresponding to a set of new states with a mass larger than $M$).

Let us add that in SM the fraction of $e^+e^- \rightarrow Z_L +$ anything production within the unpolarized $e^+e^- \rightarrow Z +$ anything case depends on the energy and on the kinematical detection cuts, but should only be of the order of 10 percent. A small new physics signal only located in $Z_L$ would then not be immediately observable in the unpolarized case and would necessarily require a final $Z$ polarization analysis.
4 CONSEQUENCES FOR $e^+e^- \rightarrow W^+W^-$

We now look at the charged $W_L$ case. We will start with the simplest process, $e^+e^- \rightarrow W^+W^-$, observable at high energy at a future linear collider, see ref.\[15\] and we will then look at the inclusive process $e^+e^- \rightarrow W_L + \text{anything}$.

At Born level, as described in ref.\[12\], $e^+e^- \rightarrow W^+W^-$ is due to neutrino exchange in the t-channel and photon+$Z$ exchange in the s-channel, which lead at high energy to two HC Transverse-Transverse (TT) amplitudes ($\mu = -\mu' = \pm 1$)

$$F^{\text{Born}}_{\mp \mu \mp \mu} \rightarrow -\frac{e^2 \sin \theta (\mu - \cos \theta)}{4s_W^2(\cos \theta - 1)},$$

and two HC Longitudinal-Longitudinal (LL) amplitudes ($\mu = 0, \mu' = 0$)

$$F^{\text{Born}}_{-\frac{1}{2} 0 0} \rightarrow -\frac{e^2}{8s_W^2c_W^2} \sin \theta,$$

$$F^{\text{Born}}_{+\frac{1}{2} 0 0} \rightarrow \frac{e^2}{4c_W^2} \sin \theta,$$

which both tend to constant values. On the opposite the other (TT,LL or TL) amplitudes which are helicity violating (HV) vanish at high energy.

The one loop corrections to the HC amplitudes are also given in the SIM approximation in ref.\[12\]. It had been checked that the LL amplitudes agree with equivalence to $e^+e^- \rightarrow \gamma, Z \rightarrow G^+G^-$ amplitudes.

Note the dependence on the $e^+e^-$ polarization (with always $\lambda_{e^-} = -\lambda_{e^+}$). The left case ($\lambda_{e^-} = -\frac{1}{2}$) contributes to both TT amplitudes and to one LL amplitude, whereas the right one ($\lambda_{e^-} = +\frac{1}{2}$) only contributes to the other LL amplitude.

We will now assume that the $\gamma G^+G^-$ and $Z G^+G^-$ vertices are affected by the same type of form factor $F_H(s)$ as the above $ZG^0H$ vertex. This will concern the two LL amplitudes. The two TT amplitudes should not be affected. As these TT amplitudes are more important than the LL ones, and depend differently on the angle, in the unpolarized case one does not get a simple factorization of the form factor effect.

Only in the right-handed $e^+e^-$ polarization case involving only one LL amplitude one gets this factorization at high energy.

Hence we have computed both the unpolarized differential cross section

$$\frac{d\sigma}{d\cos \theta} = \frac{\beta_W}{128\pi s} \Sigma_{\lambda \mu' \mu} |F_{\lambda \mu' \mu}(\theta)|^2,$$

as well as the polarized differential cross section using right-handedly polarized electron beams $e_R^-$,

$$\frac{d\sigma^R}{d\cos \theta} = \frac{\beta_W}{64\pi s} \Sigma_{\mu \mu' \mu} |F_{+\frac{1}{2} \mu' \mu}(\theta)|^2,$$

with and without form factor effects.

In the illustrations we have chosen the same test form factor as in the above $ZH$ case,
Figure 3 (upper panel) shows the energy dependence of the unpolarized cross section and of the right polarization case. The lower panel shows their angular dependence at 4 TeV. Indeed one sees that the form factor effect leads to only few percent effect on the unpolarized cross section but generates a very large reduction of the right-handed polarized one. The angular dependencies confirm these effects. So $e^+e^- \rightarrow W^+W^-$, dominated by $e^+e^- \rightarrow W^+_L W^-_L$, should be a favoured place for observing this effect.

5 THE PROCESS $e^+e^- \rightarrow W_L + \text{anything}$

We now make a study of the inclusive $e^+e^- \rightarrow W_L + \text{anything}$ process similarly to the above $e^+e^- \rightarrow Z_L + \text{anything}$ case. Assuming the $W_L^\pm \simeq G^\pm$ equivalence we discuss the contributions to the inclusive process $e^+e^- \rightarrow G^+ + \text{anything}$. The basic SM terms (apart from the 2-body $e^+e^- \rightarrow G^- + W^+$) correspond to $G^-t\bar{b}$, $G^-HW^+$, $G^-ZW^+$ and $G^-\gamma W^+$ final states. The $G^-t\bar{b}$ case proceeds via $e^+e^- \rightarrow \gamma$ followed by the $3$-body production. The other 3 cases proceed, in addition, via $e^+e^- \rightarrow W^+W^-$ (via t- and s-channel exchanges) followed by $W^- \rightarrow G^-H, G^-W, G^-\gamma$.

We compute the resulting inclusive distributions, first with SM coupling s and secondly with $G^-$ and $H$ couplings affected by the above $F_H(s)$ form factor. Results can be seen in Figure 4 showing the important suppression of the SMFF cases (as in Figure 2), especially at large $x$.

We have then compared, like in the $Z_L$ case, the effects of new particle production and of a parton like distribution. The different shapes are globally similar to the ones observed in $e^+e^- \rightarrow Z_L + \text{anything}$ and confirm the power of such inclusive distributions for looking at possible compositeness signals.

We should also mention that in SM the $e^+e^- \rightarrow W_L + \text{anything}$ production, depends strongly on the kinematical conditions, and may only be of the order of 10 percent of the unpolarized $e^+e^- \rightarrow W + \text{anything}$ case, so that a clear observation of new effects may require a final $W$ polarization analysis.

6 ANOTHER EXAMPLE WITH $\gamma\gamma \rightarrow W^+W^-$

This process should be observable at a future $\gamma\gamma$ collider, for a recent review see [16]. At Born level it is described by 3 diagrams: two ones for $W$ exchange in the $t, u$ channels and one corresponding just to the four body $\gamma\gamma W^+W^-$ coupling. At high energy, among the 16 helicity amplitudes, the leading ones are the four TT ones, $(--+-;++,-+-+,+-++)$, and the two LL ones, $(-+00,+-00)$. One can check that at high energy, in the case of the LL amplitudes, very precise cancellations occur among

\[480 \text{eq.}(8)\]
the contributions of the three diagrams in order to avoid increasing behaviours violating unitarity. The final result agrees with the computation of the $\gamma\gamma \to G^+G^-$ process with similar three diagrams. This agreement does not occur separately for each diagram, but only after their addition as expected from the gauge invariance of the total amplitude.

One may now consider the effect of $G^\pm$ compositeness, i.e. a reduction at high energy of these LL contributions due to form factors in the Goldstone couplings. However, numerically, as it can be seen in Figure 5, it appears that, in SM, the LL amplitudes are about 4 times smaller than the TT ones and finally the LL contribution to the cross section is only of about 5 percent and probably unobservable. So in order to observe this strong modification of the LL contribution due to compositeness effects (also shown in Figure 5) a final $W$ polarization analysis would be required in order to only deal with $W_L^+W_L^-$ production.

7 CONCLUSIONS AND FURTHER DEVELOPMENTS

In this paper we have assumed that the Higgs doublet has a compositeness origin which reproduces in an effective way the main low energy SM features but may generate form factors which affect the Higgs couplings at high energy. Assuming that the Goldstone equivalence is also maintained we expect that the $Z_L \simeq G^0$ and $W_L^\pm \simeq G^\pm$ couplings will be affected in the same way (the CSM hypothesis).

We proposed to test these effects in simple $H$, $Z_L$ and $W_L$ production processes.

We have shown that the $e^+e^- \to ZH$ process, largely dominated by $e^+e^- \to Z \to Z_LH$ is directly sensitive to the $ZZ_LH$ coupling and to the presence of a form factor. Illustrations with an arbitrary choice of form factor have been given. This process could then furnish the basic input for further predictions. We have illustrated the case of $e^+e^- \to Z_L + \text{anything}$ which can show spectacular effects.

In a similar fashion we have then treated the charged case, i.e. the compositeness effects of $G^\pm \simeq W_L^\pm$. The simplest case is $W^+W^-$ production in $e^+e^-$ collision and we have also considered the inclusive case $e^+e^- \to W_L + \text{anything}$. We have finally looked at the $\gamma\gamma \to W^+W^-$ process. In order to get large signals one needs to isolate the polarized $W_L$ components.

We emphasize the fact that, in SM, $e^+e^- \to W_L^+W_L^-$ is dominant at high energy by using right-handedly polarized $e^-$ beams and could immediately give a signal of $W_L^\pm$ compositeness.

Other ways of $Z, W, H$ production could also be considered at hadronic colliders for example $ZH, WH, ZW, WW$ through gluon-gluon or $q\bar{q}$ collisions. Again a particular case is $gg \to ZH$ dominated by $Z_LH$ ([14]) but occurring at one loop. Properties of $Z_L$ and $W_L$ could also be studied through $Z_LZ_L, W_LW_L, Z_LW_L$ scattering but this deserves specific involved studies, see for example reviews in [17] [18] [19].
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Figure 1: Energy dependence (upper panel for $\theta = \pi/2$) and angular distribution (lower panel for $\sqrt{s} = 4$ TeV) of the $e^+e^- \rightarrow Zh$ cross section. SM refers to the standard unpolarized case, SML to the standard longitudinal $Z$ production, FF and LFF to the corresponding cases including the form factor effect.
Figure 2: Inclusive distributions for $e^+e^- \rightarrow Z_L + \text{anything}$ for $\sqrt{s} = 4$ TeV. Comparison of the pure SM contribution to the one with form factor effects (SMFF), to the addition of 3 pairs of new particles and to the addition of a parton-like contribution.
Figure 3: Upper panel: Energy distribution (for $\theta = \pi/2$) of the $e^+e^- \to W^+W^-$ cross sections (unpolarized (a) and right-handed polarized $e^-$ (b)). Lower panel: Angular distribution at 4 TeV of the $e^+e^- \to W^+W^-$ cross sections (unpolarized (c) and right-handed polarized $e^-$ (d)). Same notations as in Fig. 1 with L now referring to $W_L^+W_L^-$. 
Figure 4: Inclusive distributions for $e^+e^- \rightarrow W_L^- + \text{anything}$. Same comparisons as in Fig. 2.
Figure 5: Energy distribution (for $\theta = \pi/2$) of the $\gamma\gamma \rightarrow W^+W^-$ cross section. Same notations as in Fig. 1 and 3.