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# Learning about the strongly interacting symmetry breaking sector at the LHC

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## Abstract

In the present work we study the predictions for  $WZ$  and  $ZZ$  production at the LHC with the Electroweak Chiral Lagrangian (EChL) approach. Our analysis will be focused on the less favored case from the experimental point of view, in which the predictions for the gauge bosons scattering amplitudes are considered in the low energy range where, by construction of the low energy approach, they reveal no resonant behavior. The study includes the complete set of amplitudes for all the polarization states of the initial and/or final gauge bosons and makes no use of the Equivalence Theorem. We express the results in terms of the range of values of the chiral parameters that will be accessible at the LHC.

## 1. Introduction

One of the main goals of the LHC is to get as much information as possible about the electroweak symmetry breaking sector (ESBS) of the Standard Model (SM). If this sector is weakly interacting, some light modes below the TeV energy regime are expected to appear. The typical examples are the SM with a light Higgs particle and the Minimal Supersymmetric Standard Model. In contrast, a strongly interacting scenario is characterized by the absence of light modes. In this case, general considerations lead to the identities called Low Energy Theorems (LET) [1] that allow us to predict the general behavior of the Goldstone boson amplitudes irrespective of the details of the symmetry breaking mechanism. In fact, a very powerful theoretical framework has been developed in the last years, which provides a systematic phenomenological description of the ESBS in

the strongly interacting case. This description [2] is inspired in Chiral Perturbation Theory (ChPT) which is known to work very well in low energy pion physics [3]. The Chiral Lagrangian that is used to study the ESBS is  $SU(2)_L \times U(1)_Y$  gauge invariant,  $CP$  conserving and includes effective operators up to dimension four [4]. It will be referred here as the Electroweak Chiral Lagrangian (EChL). This approach incorporates from the beginning and by construction the LET in a model independent way. The details about the underlying ESBS physics are encoded in the values of the couplings or parameters  $\alpha_i$  of the EChL which, hopefully, will be measured at the LHC. By choosing properly these parameters one can reproduce different strongly interacting scenarios, as for instance the SM case with a heavy Higgs boson [5,6], Technicolor models [7], the BESS model [8], etc. The typical values of the chiral parameters in most of these scenarios are  $\alpha_i \leq 10^{-2}$ .

In the previous applications of the EChL to the LHC physics [9,10] the Equivalence Theorem (ET) played an essential role. This theorem [11] relates the  $S$  matrix elements of the longitudinal components of the gauge bosons with the corresponding ESBS Goldstone bosons, at energies much higher than  $M_W$ , thus simplifying enormously the practical computations. However, the fact that the ET should be applied only at high energies and the intrinsic low-energy character of the EChL put severe limits on their simultaneous application [12,13]. To solve this problem some other extra non-perturbative methods are needed such as unitarization procedures [14], dispersion relations [15] or the large  $N$  limit [16]. With any of these methods the use of the ET in the EChL approach is possible and, in addition, they can provide a description of resonant behavior in different channels. This kind of approach was followed in [9], where the use of the EChL, together with the ET and the Padé unitarization method allowed to describe two typical strongly interacting scenarios. Incidentally, the use of the Padé approximants seems to be the most reliable method as it has been tested in low energy pion physics and, in addition, it can be rigorously justified from dispersion relations [15]. The two mentioned scenarios are the SM with a Higgs-like scalar resonance that reveals mainly in  $Z_L Z_L$  production and the so-called QCD-like scenarios with a vector resonance (it includes the case of the technirho resonance) that emerges clearly in the  $W_L^\pm Z_L$  channel. For more details on this resonant model we refer the reader to [8].

All the resonant models studied so far, however, have the disadvantage of giving predictions only for longitudinal gauge bosons and of being valid just for energies much higher than  $M_W$ , in order to make the ET be a reliable approximation. This, in practice, implies a quite restrictive cut in the lowest invariant mass of the  $VV$  gauge boson pair of about 500 GeV and, in consequence, a significant lose in the signal rates.

We will follow here a different approach to study the ESBS at LHC which has been proposed in [17] and we refer the reader to this work for a full description of the method and for a more detailed analysis. The method *makes no use of the ET* nor any unitarization prescription but uses the EChL directly to compute the amplitudes for all the polar-

ization states of the initial and or final gauge bosons. It is technically more involved but is more complete than previous studies where just longitudinal polarizations were considered. Furthermore, it has the advantage that there are no restrictions on the lower end of the  $VV$  invariant mass since the ET is not used. The only limitation is that it must be applied in the low energy region, namely well below  $4\pi v \sim 3$  TeV ( $v = 246$  GeV), in order for the low energy effective theory defined by the EChL to give reliable predictions. On the other hand, for the energies considered here which in practice will be imposed by the kinematical cuts to lie below 1.5 TeV, the predictions for the gauge bosons scattering amplitudes reveal no resonant behavior. This situation with no resonances showing up is, in principle, more difficult to be tested experimentally.

The aim of this paper is, in summary, to study the possibilities for measuring the EChL parameters at LHC within this non-resonant EChL model. In particular we have chosen to study pair production of  $W^\pm Z$  and  $ZZ$  gauge bosons with the  $W$ 's and  $Z$ 's decaying into the cleanest leptonic ("gold-plated") channels:  $W \rightarrow \nu_e e, \nu_\mu \mu$  and  $Z \rightarrow e^+ e^-, \mu^+ \mu^-$ . The results will be expressed in terms of the range of values of the chiral parameters that will be accessible at LHC by means of these two channels.

## 2. The electroweak chiral parameters

Let us start fixing the notation for the electroweak chiral parameters,  $\alpha_i$ , which are the object of our study. These parameters appear in the definition of the EChL which is made of the complete set of  $SU(2) \times U(1)_Y$ , Lorentz,  $C$ , and  $P$  invariant operators up to dimension four. The EChL is given by

$$\mathcal{L}_{\text{EChL}} = \mathcal{L}_{\text{NL}} + \sum_{i=0}^{13} \mathcal{L}_i, \quad (1)$$

where  $\mathcal{L}_{\text{NL}}$  is the Lagrangian of the gauged non-linear sigma model

$$\begin{aligned} \mathcal{L}_{\text{NL}} = & \frac{1}{4} v^2 \text{tr} \left[ D_\mu U (D^\mu U)^\dagger \right] - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\ & - \frac{1}{2} \text{Tr} \left[ F_{\mu\nu} F^{\mu\nu} \right] + \mathcal{L}_{\text{GF}} + \mathcal{L} \end{aligned}$$

which is written down in terms of the parametrization of the would-be

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(GB) fields  $\pi_i$ , and the electroweak gauge boson fields  $W_\mu$  and  $B_\mu$

$$U = \exp\left(i \frac{\boldsymbol{\tau} \cdot \boldsymbol{\pi}}{v}\right), \quad W_\mu = \frac{W_\mu \boldsymbol{\tau}}{2}, \quad Y_\mu = \frac{B_\mu \tau_3}{2}. \quad (3)$$

The covariant derivative  $D_\mu U$  and the covariant field strength tensors are defined as

$$\begin{aligned} D_\mu U &= \partial_\mu U + ig W_\mu U - ig' U Y_\mu, \\ F_{\mu\nu}(x) &= \partial_\mu W_\nu(x) - \partial_\nu W_\mu(x) \\ &\quad + ig[W_\mu(x), W_\nu(x)], \\ \beta_{\mu\nu}(x) &= \partial_\mu B_\nu(x) - \partial_\nu B_\mu(x), \end{aligned} \quad (4)$$

$\mathcal{L}_{\text{GF}}$ , and  $\mathcal{L}_{\text{FP}}$  in Eq. (2) denote the gauge fixing and Fadeev–Popov Lagrangians respectively which in the present work will be chosen in the Landau gauge [4]. The  $\mathcal{L}_i$  terms in Eq. (1) are the  $SU(2)_L \times U(1)_Y$  invariant functions of the gauge vector bosons and the GB fields, other than  $\mathcal{L}_{\text{NL}}$ , and are made of 1 term of dimension two,  $\mathcal{L}_0$ , and 13 terms of dimension four,  $\mathcal{L}_i$ ,  $i = 1, 13$ . The electroweak chiral parameters  $\alpha_i$  appear in the definition of the  $\mathcal{L}_i$  terms which can be written as follows [4]:

$$\begin{aligned} \mathcal{L}_0 &= \frac{1}{4} g^2 \alpha_0 v^2 [\text{Tr}(TV_\mu)]^2, \\ \mathcal{L}_1 &= \frac{1}{2} g^2 \alpha_1 B_{\mu\nu} \text{Tr}(TF^{\mu\nu}), \\ \mathcal{L}_2 &= \frac{1}{2} ig \alpha_2 B_{\mu\nu} \text{Tr}(T[V^\mu, V^\nu]), \\ \mathcal{L}_3 &= ig \alpha_3 \text{Tr}(F_{\mu\nu}[V^\mu, V^\nu]), \\ \mathcal{L}_4 &= \alpha_4 [\text{Tr}(V_\mu V_\nu)]^2, \\ \mathcal{L}_5 &= \alpha_5 [\text{Tr}(V_\mu V^\mu)]^2, \\ \mathcal{L}_6 &= \alpha_6 \text{Tr}[(V_\mu V_\nu)] \text{Tr}(TV^\mu) \text{Tr}(TV^\nu), \\ \mathcal{L}_7 &= \alpha_7 \text{Tr}[(V_\mu V^\mu)] [\text{Tr}(TV^\nu)]^2, \\ \mathcal{L}_8 &= \frac{1}{4} g^2 \alpha_8 [\text{Tr}(TF_{\mu\nu})]^2, \\ \mathcal{L}_9 &= \frac{1}{2} ig \alpha_9 \text{Tr}(TF_{\mu\nu}) \text{Tr}(T[V^\mu, V^\nu]), \\ \mathcal{L}_{10} &= \frac{1}{2} \alpha_{10} [\text{Tr}(TV_\mu) \text{Tr}(TV_\nu)]^2, \\ \mathcal{L}_{11} &= \alpha_{11} \text{Tr}[(\mathcal{D}_\mu V^\mu)^2], \\ \mathcal{L}_{12} &= \frac{1}{2} \alpha_{12} \text{Tr}(T\mathcal{D}_\mu \mathcal{D}_\nu V^\nu) \text{Tr}(TV^\mu), \\ \mathcal{L}_{13} &= \frac{1}{2} \alpha_{13} [\text{Tr}(T\mathcal{D}_\mu V_\nu)]^2, \end{aligned} \quad (5)$$

where

$$\begin{aligned} T &= U \boldsymbol{\tau}^3 U^\dagger, \quad V^\mu = (D^\mu U) U^\dagger, \\ \mathcal{D}_\mu O(x) &= \partial_\mu O(x) + ig[W_\mu(x), O(x)] \end{aligned} \quad (6)$$

### 3. Searching for non-resonant strongly interacting VV signals

In the following we will analyze the possibilities of measuring the EChL parameters  $\alpha_i$  at LHC, by means of  $W^\pm Z$  and  $ZZ$  production, with the  $W$ 's and  $Z$ 's decaying into the cleanest leptonic channels:  $W \rightarrow \nu_e e$ ,  $\nu_\mu \mu$  and  $Z \rightarrow e^+ e^-$ ,  $\mu^+ \mu^-$ . It implies a reduction on the VV number of events given by the leptonic branching ratios:  $\text{BR}(WZ) = 0.013$  and  $\text{BR}(ZZ) = 0.0044$  respectively. All the number of events reported here include these reduction factors.

The parameters for LHC have been chosen as follows: The  $pp$  center of mass energy is  $\sqrt{s} = 14$  TeV and the luminosity is  $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ . The number of events presented in this work correspond to an integrated luminosity of  $L = 3 \times 10^5 \text{ pb}^{-1}$ .

The hadronic decays of the gauge bosons have not been considered here but a careful study including severe cuts on the final jets could provide additional valuable information. We have postponed also for later studies the case of like-sign  $W^\pm W^\pm$  production [18]. The most problematic channel is  $W^+ W^-$  due to the overwhelming background from top-anti-top production with the top quarks decaying into  $W$ 's and will not be studied here.

We consider the following subprocesses contributing to  $W^\pm Z$  and  $ZZ$  production respectively. All but the last one are considered here at tree level:

- (1)  $q\bar{q}' \rightarrow W^\pm Z$ ,
- (2)  $q\bar{q} \rightarrow ZZ$ ,
- (3)  $W^\pm Z \rightarrow W^\pm Z$ ,
- (4)  $W^\pm \gamma \rightarrow W^\pm Z$ ,
- (5)  $W^+ W^- \rightarrow ZZ$ ,
- (6)  $ZZ \rightarrow ZZ$ ,
- (7)  $gg \rightarrow ZZ$ .

The complete set of helicity amplitudes for the processes (1)–(6), corresponding to all possible helicity states of the initial and final electroweak gauge bosons, have been computed analitically using the EChL in [17]. These amplitudes (except incidentally

(2)) are functions of the chiral parameters  $\alpha_i$ . In addition, we have considered the subprocess number (7) which is known to give a non-negligible contribution to  $ZZ$  production [19]. It takes place in the SM *via* one-loop of quarks. For numerical computations the mass of the top quark in the loop has been fixed to  $m_t = 170$  GeV.

The quark–antiquark annihilation processes, (1) and (2), and the so-called  $VV$  fusion processes ( $V = W^\pm, Z$ ), (3)–(6), have a very different final-state kinematics. In the later the expectator quark jets are left behind when the incoming quarks radiate the initial  $V$ 's that then scatter. Thus, one could presumably separate the two kind of processes by requiring a tagged forward jet. In fact, a big effort is being done by the experimental physicists community in this concern. As we will see later on, the forward jet tagging may play an important role in searching for strongly interacting  $VV$  signals since they mainly (but not only) manifest in  $VV$  fusion processes. For comparison, we will present here our results for the two possibilities, both without and with jet tagging respectively.

A FORTRAN code has been written [17] that implements all the helicity amplitudes for the above (1)–(7) subprocesses and adds the appropriate combinations to provide a numerical prediction for producing all the possible final polarization states:  $V_L V_L, V_L V_T, V_T V_L, V_T V_T$ . We believe that it may be interesting to study them separately in case there is some possibility of discriminating a longitudinal from a transverse  $V$  experimentally. However, in this work we have not profited from this possibility and the final polarization states have been added to provide a total number of  $VV$  unpolarized events. On the other hand, the contributions from the various initial polarization states,  $V_L V_L, V_L V_T, V_T V_L$  and  $V_T V_T$ , in the fusion processes, must be computed separately since the structure functions for  $V_L$  and  $V_T$  are different.

In order to connect the subprocesses above to the  $pp$  initial state we have used the effective  $V$  approximation [20], the Weizsacker–Williams approximation [21] in the case of the  $\gamma$  initiated subprocess (4), and the EHLQ (set II) structure functions [22]. Other more realizable structure functions, as the MRSD- [23] and the GRVHO [24], have also been considered in the literature [17], but we do not expect the results on the accessible range for the chiral

parameters at LHC to be very affected by our choice of the structure functions. The total number of events does depend, however, on the choice of the structure functions but, hopefully, by the time LHC will start working they will be known with precision enough as to eliminate this kind of uncertainties.

The FORTRAN program gives, in summary, the total number of expected gold-plated events (including the important background from process (7)) for a given set of values of the chiral parameters  $\alpha_i$  and for a given set of cuts on the subprocess variables, namely, the maximum  $VV$  invariant mass,  $M_{VV}^{\max}$ , the minimum transverse momentum of the final  $Z$ ,  $P_{T \min}^Z$ , and the maximum rapidity of the final  $V$ ,  $y_{\max}^V$ .

In the present work we have restricted ourselves, for simplicity, to the minimal set of parameters corresponding to the operators that should be included to absorb the one-loop divergences of the lowest order lagrangian [4], namely,  $\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4$  and  $\alpha_5$  (all together named here  $\alpha$ ). In addition, we have set in this paper the following minimal cuts:

$$M_{VV}^{\max} = 1.5 \text{ TeV}, \quad P_{T \min}^Z = 300 \text{ GeV}, \quad y_{\max}^V = 2, \quad (7)$$

but the FORTRAN code is prepared to analyse the complete set of chiral parameters as well as to produce, starting from the minimal cuts in Eq. (7), a new set of optimal cuts for each particular channel.

Finally, we have to decide what is the signal of this non-resonant model and what is the background. Clearly, there is not a unique definition. We have proceeded in two ways.

(A) We have compared the predictions for  $VV$  production from the EChL for a given value of each  $\alpha_i$  parameter with respect to a reference model where the parameters are all set to zero (incidentally, this model is equivalent to the SM at tree level with a Higgs of infinite mass). Let  $N(\alpha_i)$  be the number of gold-plated events obtained from the EChL for the given  $\alpha_i \neq 0$  value (the rest of the other parameters are set to zero).

Let  $N(0)$  be the corresponding number of events for the reference model with  $\alpha = 0$ . In both rates we take the minimal cuts of Eq. (7).

We define the statistical significance of the signal

Table 1  
Gold-plated event rates for the reference model with  $\alpha = 0$

	Reference model ( $\alpha = 0$ )
$q\bar{q}' \rightarrow W^\pm Z^0$	197
$W^\pm Z^0 \rightarrow W^\pm Z^0$	88
$W^\pm \gamma \rightarrow W^\pm Z^0$	48
total $W^\pm Z^0$	333
$q\bar{q} \rightarrow Z^0 Z^0$	40
$gg \rightarrow Z^0 Z^0$	17
$W^+ W^- \rightarrow Z^0 Z^0$	24
$Z^0 Z^0 \rightarrow Z^0 Z^0$	0
total $Z^0 Z^0$	81

due to a  $\alpha_i \neq 0$  effect by means of the following variable:

$$r_i = \frac{|N(\alpha_i) - N(0)|}{\sqrt{N(0)}}. \quad (8)$$

Obviously, the larger the value of  $r_i$  the better the sensitivity of LHC to this particular parameter  $\alpha_i$ .

(B) We have also compared our predictions for  $N(\alpha_i)$  as defined in (A) with the corresponding SM predictions for the gold-plated events in the case of a light Higgs boson,  $M_H = 100$  GeV, and in the case of a heavy Higgs boson,  $M_H = 1$  TeV. We have computed the SM amplitudes for the subprocesses above (1)–(6) at tree level. The Higgs particle con-

Table 2  
Gold-plated event rates in the Standard Model with a light and a heavy Higgs boson

	SM	
	$m_H = 100$ GeV	$m_H = 1$ TeV
fusion $W^\pm Z^0$	106	119
$q\bar{q}' \rightarrow W^\pm Z^0$	197	197
total $W^\pm Z^0$	303	316
fusion $Z^0 Z^0$	17	43
$q\bar{q} \rightarrow Z^0 Z^0$	40	40
$gg \rightarrow Z^0 Z^0$	17	17
total $Z^0 Z^0$	74	100

The top quark mass is fixed to  $m_t = 170$  GeV.

tributes mainly via the fusion processes (3), (5) and (6). For numerical computations, we have included the Higgs width just in the Higgs- $s$ -channel of the processes (5) and (6).

The comparison with the light Higgs case is interesting since in so doing we are comparing two typical scenarios, a strongly and a weakly interacting one. The comparison with the  $M_H = 1$  TeV case teaches us how much our models separate from the “standard reference model” of a strongly interacting heavy Higgs.

Let  $N_{SM}(M_H)$  be the SM predictions for the given  $M_H$  value. The same minimal cuts of Eq. (7) are also applied here.

Table 3  
Sensitivity to  $\alpha_5$

	$\alpha_5$					
	$10^{-2}$	$-10^{-2}$	$5 \times 10^{-3}$	$-5 \times 10^{-3}$	$10^{-3}$	$-10^{-3}$
$W^\pm Z^0 \rightarrow W^\pm Z^0$	67	173	69	122	83	93
total $W^\pm Z^0$	312	418	314	367	328	338
$r_5  _{W^\pm Z^0}$	1.2 (1.8)	4.7 (7.3)	1.0 (1.6)	1.9 (2.9)	0.3 (0.4)	0.3 (0.4)
$W^+ W^- \rightarrow Z^0 Z^0$	62	21	39	18	26	22
$Z^0 Z^0 \rightarrow Z^0 Z^0$	18	18	4	4	$\sim 0$	$\sim 0$
total $Z^0 Z^0$	137	96	100	79	83	79
$r_5  _{Z^0 Z^0}$	6.2 (11.4)	1.7 (3.1)	2.1 (3.9)	0.2 (0.4)	0.2 (0.4)	0.2 (0.4)

The other parameters are set to zero. Comparison with the reference model,  $\alpha = 0$ . Only the predictions for the gold-plated events rates which are different than in the reference model are shown explicitly. Total rates include all the contributions from  $VV$  fusion, annihilation processes, and, for final state  $Z^0 Z^0$ , the  $gg$  fusion too. The quantities in parenthesis are the corresponding predictions if a 100% efficient jet tagging is considered.

Table 4  
The same as in Table 3, but for the  $\alpha_4$  parameter

	$\alpha_4$					
	$10^{-2}$	$-10^{-2}$	$5 \times 10^{-3}$	$-5 \times 10^{-3}$	$10^{-3}$	$-10^{-3}$
$W^\pm Z^0 \rightarrow W^\pm Z^0$	109	240	81	142	82	95
total $W^\pm Z^0$	354	485	326	387	327	340
$r_4  _{W^\pm Z^0}$	1.2 (1.8)	8.3 (13.0)	0.4 (0.6)	3.0 (4.6)	0.3 (0.5)	0.4 (0.6)
$W^+ W^- \rightarrow Z^0 Z^0$	36	20	28	21	25	24
$Z^0 Z^0 \rightarrow Z^0 Z^0$	18	18	4	4	$\sim 0$	$\sim 0$
total $Z^0 Z^0$	111	95	89	82	82	81
$r_4  _{Z^0 Z^0}$	3.3 (6.1)	1.6 (2.9)	0.9 (1.6)	0.1 (0.2)	0.1 (0.2)	$\sim 0$ ( $\sim 0$ )

The significance of a  $\alpha_i \neq 0$  effect is defined as

$$s_i = \frac{|N(\alpha_i) - N_{SM}(M_H)|}{\sqrt{N_{SM}(M_H)}} \quad (9)$$

#### 4. Results and conclusions

Our results for the number of gold plated events are summarized in Tables 1–7 and in Figs. 1–4. The predictions from the non-resonant EChL model,  $N(\alpha_i)$ , for various choices of the most relevant parameters,  $\alpha_5$ ,  $\alpha_4$  and  $\alpha_3$  are presented in Tables 3–7. The various contributions to both channels  $W^\pm Z$  and  $ZZ$  that come from the different processes have been presented separately, for illustration.

We have also scanned the other parameters,  $\alpha_0$ ,  $\alpha_1$  and  $\alpha_2$ , but it turns out that none of them (for the moderate values of  $\alpha_i \leq 10^{-2}$  being studied) give a significant effect.

Firstly, what we can learn from the tables when looking at the values of the variables  $r_i$  and  $s_i$  is that

Table 5  
Sensitivity to  $\alpha_3$

	$\alpha_3$	
	$10^{-2}$	$-10^{-2}$
$q\bar{q}' \rightarrow W^\pm Z^0$	149	284
$W^\pm Z^0 \rightarrow W^\pm Z^0$	90	86
$W^\pm \gamma \rightarrow W^\pm Z^0$	48	47
total $W^\pm Z^0$	287	417
$r_3  _{W^\pm Z^0}$	2.5	4.6
$W^+ W^- \rightarrow Z^0 Z^0$	25	24
total $Z^0 Z^0$	82	81
$r_3  _{Z^0 Z^0}$	0.1	$\sim 0$

Comparison with the reference model,  $\alpha = 0$

there are, indeed, significant effects for the case of  $\alpha_3$ ,  $\alpha_4$  and  $\alpha_5$ . These effects could be more important, of course, if more sizeable values of the parameters were scanned, but, as we have said already, we have preferred here to take the most plausible values

Table 6  
Sensitivity to  $\alpha_4$  and  $\alpha_5$  in  $W^\pm Z^0$  production

$W^\pm Z$	$\alpha_5$		$\alpha_4$		$\alpha_3$	
	$-10^{-2}$	$-5 \times 10^{-3}$	$-10^{-2}$	$-5 \times 10^{-3}$	$-10^{-2}$	$10^{-2}$
$N(\alpha_i)$	418	367	485	387	417	287
$s_i(M_H = 1 \text{ TeV})$	5.7 (9.3)	2.9 (4.7)	9.5 (15.5)	4.0 (6.5)	5.7	1.6
$s_i(M_H = 100 \text{ GeV})$	6.6 (11.2)	3.7 (6.2)	10.5 (17.7)	4.8 (8.2)	6.5	0.9

The rest of the other parameters are set to zero. Comparison with the Standard Model with a light Higgs particle ( $M_H = 100 \text{ GeV}$ ) and with a heavy Higgs ( $M_H = 1 \text{ TeV}$ ).

Table 7

The same as in Table 6 but for  $Z^0Z^0$  production.

ZZ	$\alpha_5$		$\alpha_4$	
	$10^{-2}$	$5 \times 10^{-3}$	$10^{-2}$	$5 \times 10^{-3}$
$N(\alpha_i)$	137	100	111	89
$s_i(M_H = 1 \text{ TeV})$	3.7 (5.6)	$\sim 0$ ( $\sim 0$ )	1.1 (1.7)	1.1 (1.7)
$s_i(M_H = 100 \text{ GeV})$	7.3 (15.3)	3.0 (6.3)	4.3 (9.0)	1.7 (3.6)

from the theoretical point of view which are of the order of or even smaller than  $10^{-2}$ .

Second, we also see from the tables that the LHC will be more sensitive to the parameter  $\alpha_3$  through the study of the  $q\bar{q}'$  annihilation processes, whereas the parameters  $\alpha_4$  and  $\alpha_5$  will be tested more clearly through the  $VV$  fusion processes. A previous study on  $\alpha_3$  through  $q\bar{q}'$  annihilation processes was done in [25]. On the other hand,  $\alpha_3$  can be related to the usual parameters,  $\kappa_V$ ,  $V = Z, \gamma$ , for anomalous  $VW^+W^-$  couplings whose effects on the annihilation processes have already been studied by other authors [26].

The sensitivity to the  $\alpha_4$  and  $\alpha_5$  parameters is high for the moderate values of  $\alpha_4$  or  $\alpha_5$  equal to  $\pm 10^{-2}$ . For instance, if we compare the predicted rates for  $ZZ$  production from the EChL for  $\alpha_5 = 10^{-2}$  (the rest of the  $\alpha_i$ 's are set to zero) with the predictions from the reference model with  $\alpha = 0$ , we get (see Table 3) an effect with a high statistical significance given by  $r_5 = 6.2$ . The same can be said for  $\alpha_4$  if we compare, for instance, the predictions for  $W^\pm Z$  production from the EChL for  $\alpha_4 = -10^{-2}$  (the rest of the  $\alpha_i$ 's are set to zero) with the reference model rates; we get (see Table 4)  $r_4 = 8.3$ . The improvement in the sensitivity to these two parame-

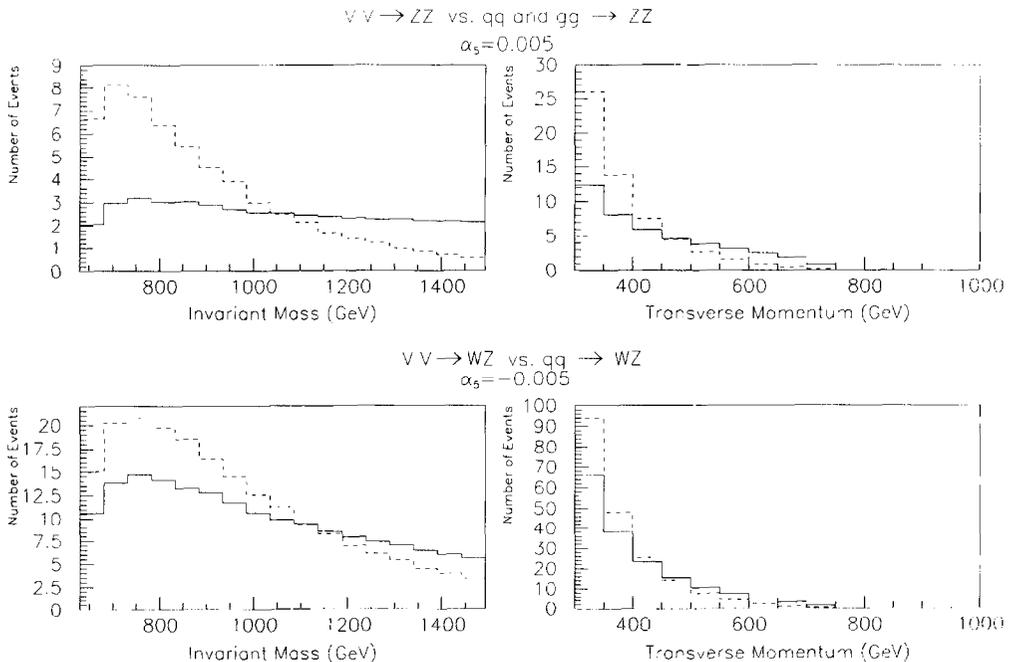


Fig. 1. Sensitivity to  $\alpha_5$  in the  $M_{VV}$  and  $P_T^Z$  distributions of gold-plated events. We have applied the minimal cuts as defined in the text. The solid lines are the predictions for the fusion processes in the non-resonant EChL model for two different values of the  $\alpha_5$  parameter (the other parameters are set to zero). The dashed lines are the predictions for the most relevant background processes. They include the rates from  $q\bar{q}'$  annihilation in the case of the  $WZ$  channel, and the rates from  $q\bar{q}$  and gluon fusion processes in the case of the  $ZZ$  channel.

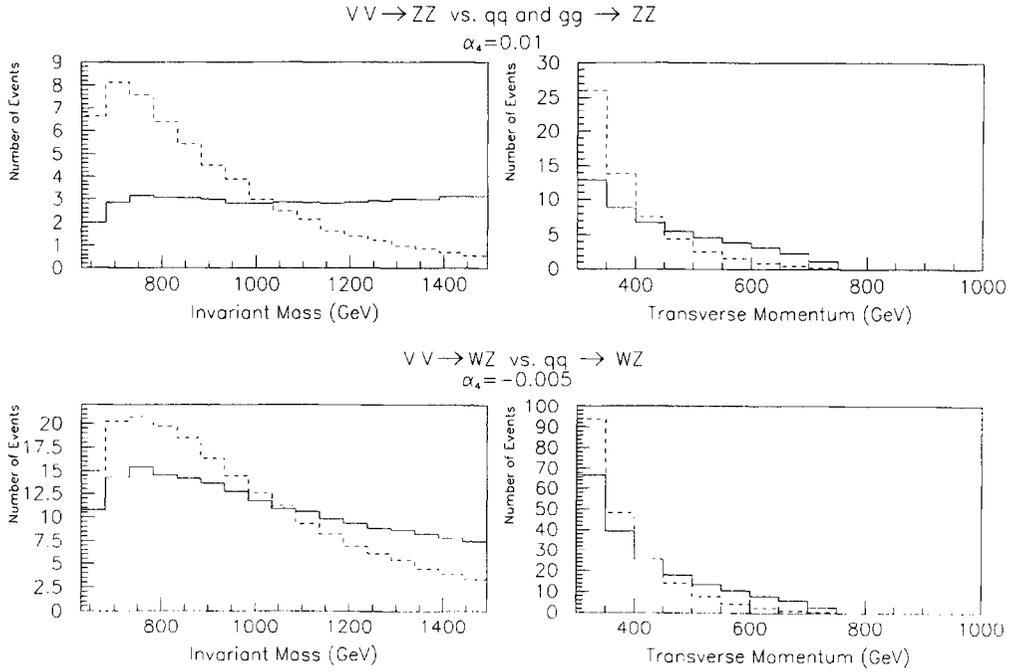


Fig. 2. The same as in Fig. 1, but for two different values of the  $\alpha_4$  parameter (the other parameters are set to zero).

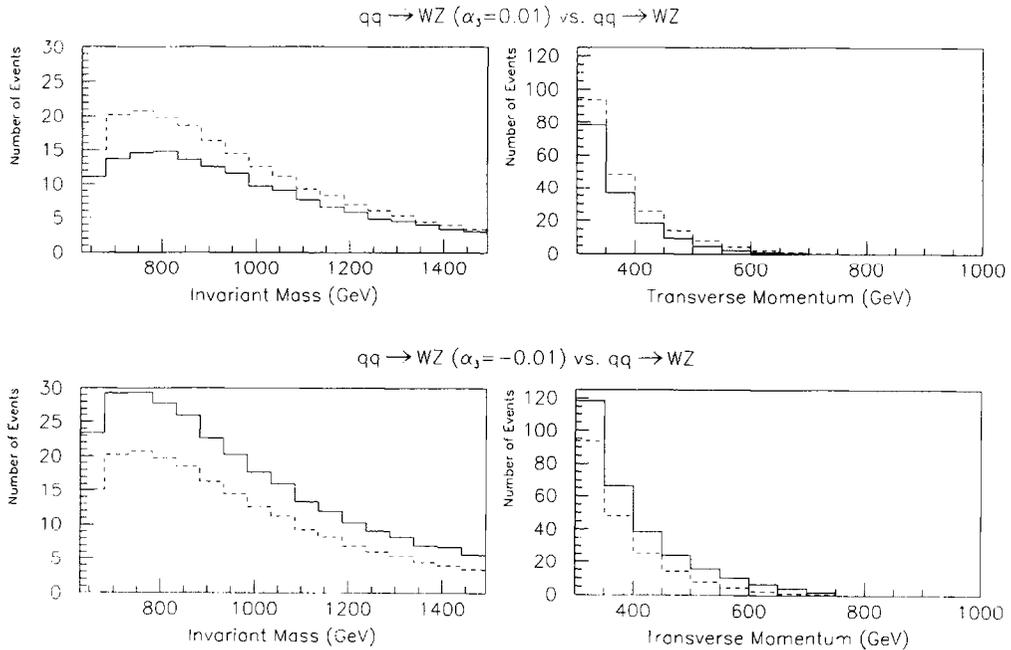


Fig. 3. Sensitivity to  $\alpha_3$  in the  $M_{WZ}$  and  $P_T^Z$  distributions of gold-plated events. We have applied the minimal cuts as defined in the text. Only rates from the  $q\bar{q} \rightarrow W^\pm Z$  process, where the effect of  $\alpha_3$  is larger, are shown. The solid lines are the predictions in the non-resonant EChL model for two values of  $\alpha_3$  (the other parameters are set to zero). The dashed lines are the predictions for the background in the SM.

ters if a 100% efficient jet tagging is achieved is obvious from Tables 3 and 4 (in this case one compares just the rates coming from genuine  $VV$  fusion processes). Thus, for the above chosen values,  $\alpha_5 = 10^{-2}$  and  $\alpha_4 = -10^{-2}$ , the statistical significance increases to  $r_5 = 11.4$  and  $r_4 = 13.0$  respectively.

Finally, it is also interesting to remark (see Tables 6 and 7) that the predictions from the EChL are clearly different than the predictions from the SM at tree level, with either a light or a heavy Higgs, and they are particularly separated in the case of  $M_H = 100$  GeV, as expected.

Perhaps, the comparison with the SM with a light Higgs boson is the most interesting one since it represents a typical weakly interacting scenario and we want to discriminate it as much as possible from the strongly interacting possibility which we represent with the EChL for the given value of  $\alpha_i$ . As can be seen from Tables 6 and 7, the sensitivity to  $\alpha_4$  and  $\alpha_5$  is quite high for the values of  $\alpha_4$  or  $\alpha_5$  equal to  $\pm 10^{-2}$ . For instance, when comparing with

the SM with  $M_H = 100$  GeV, we get for  $\alpha_5 = 10^{-2}$  a statistical significance in the  $ZZ$  channel of  $s_5 = 7.3$  that increases to  $s_5 = 15.3$  if jet tagging is considered. Similarly, for  $\alpha_4 = -10^{-2}$  in the  $W^\pm Z$  channel, we get  $s_4 = 10.5$  and  $s_4 = 17.7$  without and with jet tagging respectively. The sensitivity is still reasonably high for the smaller values of  $\alpha_4$  or  $\alpha_5$  equal to  $\pm 5 \times 10^{-3}$ . Thus, for  $\alpha_5 = 5 \times 10^{-3}$  we get, in the  $ZZ$  channel,  $s_5 = 3.0(6.3)$  without (with) jet tagging, and for  $\alpha_4 = -5 \times 10^{-3}$  we get, in the  $W^\pm Z$  channel,  $s_4 = 4.8(8.2)$  without (with) jet tagging.

On the other hand, and in order to provide information on the different kinematical structures of the final states for the various processes considered here, we have also produced some plots (see Figs. 1–4) with the distributions of the gold-plated events in the  $M_{VV}$  and  $P_T^Z$  variables. We have chosen here some particular values of the  $\alpha_i$  parameters for illustration. We see from the figures that choosing optimal cuts in these variables (or the corresponding ones of the final leptons) one could improve considerably the

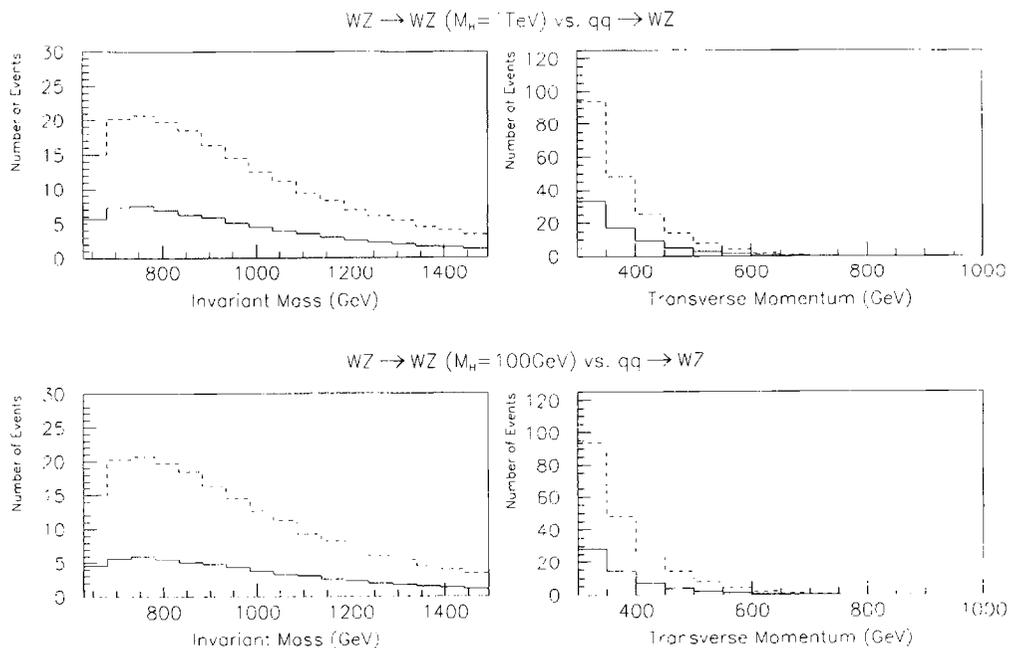


Fig. 4.  $M_{WZ}$  and  $P_T^Z$  distributions of gold-plated events in the Standard Model with a light ( $M_H = 100$  GeV) and a heavy ( $M_H = 1$  TeV) Higgs particle. We have applied the minimal cuts as defined in the text. The solid lines are the predictions from the fusion processes. The dashed lines are the predictions from the  $q\bar{q}'$  process.

sensitivity to the parameters. Probably, a higher value on  $P_{T \min}^Z$  (and/or  $M_{VV}^{\min}$ ) would help us in this concern.

In summary, after a systematic scanning of the electroweak chiral parameters  $\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4$  and  $\alpha_5$ , we conclude that the LHC will be sensitive to three of them,  $\alpha_3, \alpha_4$  and  $\alpha_5$  by analysing the leptonic gold-plated events in  $W^\pm Z$  and  $ZZ$  production. Furthermore, the sensitivity to  $\alpha_4$  and  $\alpha_5$  will improve considerably if forward jet tagging is achieved. Finally, in order to give the range of the chiral parameters values that will be accessible at the LHC we need to fix a criterion to define whether an effect (signal) due to a given  $\alpha_i \neq 0$  is statistically significant or not. For instance, if we define that a signal due to  $\alpha_i \neq 0$  is statistically significant whenever the variables in Eqs. (8) and Eqs. (9) satisfy  $r_i$  or  $s_i \geq 5$  then we conclude from the present study that the following range of chiral parameters will be accessible at the LHC:

$$|\alpha_3| \geq 10^{-2}, \quad |\alpha_4| \geq 10^{-2}, \quad |\alpha_5| \geq 10^{-2}.$$

If instead, we relax this criterion to the condition  $r_i$  or  $s_i \geq 3$ , then the following more ambitious range will be reached:

$$|\alpha_3| \geq 5 \times 10^{-3}, \quad |\alpha_4| \geq 5 \times 10^{-3},$$

$$|\alpha_5| \geq 5 \times 10^{-3}.$$

The accessible range of the above chiral parameters at the LHC will be enlarged for at least one order of magnitude with respect to the present accessible range at LEP [27].

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