Identification of Virtual New Physics Effects at a Linear Collider

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Abstract

It is shown that, at a 500 GeV LC, a number of different theoretical models would be unambiguously identified by their virtual effects. Negative limits in case of no signal identification are also derived.

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1 Introduction

When the future 500 GeV linear electron positron collider, to be called LC from now on, will become operative, several outstanding problems in the field of elementary particles physics will have been, hopefully, solved or at least understood. In particular, possible discoveries of one or of several Higgs bosons and of SUSY particles at LEP2, Tevatron and LHC might occur. Depending on these results, a number of orthogonal theoretical models would necessary die. For example, Higgs production would be the end of technicolour ideas, while models with anomalous gauge couplings in conventional formulations would not survive the discovery of supersymmetry. The latter might, in turn, be in serious trouble if a ”too” heavy Higgs were discovered, and this might cause difficulties to a number of theoretical models involving one extra $Z$ imbedded in a SUSY scenario.

This preliminary short and qualitative discussion has only shown that, at the time of LC future runs, three classes of theoretical models, that are still widely considered today as a possible alternative to a conventional ”minimal” scheme that includes supersymmetry as well, might well have been completely or partially discarded. We shall refer to these models as to models of ”technicolour type” (TC), models with anomalous gauge couplings (AGC) and models with one extra $Z (\equiv Z')$ respectively.

Keeping the previous remarks in mind, we shall proceed from now on assuming that all these three classes of models will still be meaningful at LC (for example, this might happen if no Higgs or SUSY particles were produced, with surviving windows in the low Higgs mass region). The following discussion will then be devoted to the possibility of identifying these competitor models from their virtual effects at LC in the extremely plausible hypothesis that no kind of direct production is alternatively allowed. It would be relatively simple to modify the discussion if some of the models became inadequate when LC will begin to run, or, also, if new types of models were at that time proposed.

The simple idea that is at the basis of the following discussion is the fact that, for any theoretical model with a sufficient low number of parameters $\equiv N$, a relationship exists between the relative effects of the model on certain suitable $N + 1$ experimental observables. This is fixed by the model, but at the same time completely free of the (arbitrary) $N$ parameters. The relationship can be in fact easily obtained by eliminating the parameters i.e. expressing them in terms of the considered relative effects. As a result of this operation, one can draw a certain figure in the $(N+1)$-dimensional space of the effects that is characteristic of the considered model.

An important example of the previous vague statement is provided by models with two free parameters. The corresponding three-dimensional figures that the models generate were called in a previous paper [1] ”reservations”. Clearly, to produce such figures, three experimental observables are requested.

Let us consider now the specific cases that were mentioned at the beginning. It was shown in previous references [2] that for a simple class of models of ”technicolour-type” a representation of four-fermion (neutral current) processes can be written, such that the effects of these models can be represented by two effective parameters. This special representation was called ”$Z$-peak subtracted representation”; we defer the interested reader to ref.[3] for more details. Therefore, for the previous class of TC models. three
(arbitrary) observables of the process \( e^+e^- \rightarrow f\bar{f} \) (\( f \) being a charged lepton or a quark) will be sufficient to draw the TC reservation.

The case of AGC models was also considered in ref. \[2\], taking as specific example that of a \( SU(2) \times U(1) \) invariant Lagrangian with only dimension six operators recently proposed \[3\]. Although the number of parameters of this model is apparently rather large, it was shown in ref. \[2\] that, in the \( Z \)-peak subtracted representation, only two parameters survive in the considered four-fermion process (with the possible exception of final \( b\bar{b} \) production). This would lead to possible 3d-figures, reservations for this model, as well.

The case of a possible \( Z' \) requires some care. In general, if the couplings with fermions of this extra \( Z \) are left free, for a process like \( e^+e^- \rightarrow f\bar{f} \) six effective parameters will enter, as discussed e.g. in a recent investigation \[4\]. This number can be reduced to two if only a final (charged) lepton-antilepton state is considered.

From the previous discussion it emerges that, if three suitable independent observables were available in the process \( e^+e^- \rightarrow f\bar{f} \), one would be able to draw reservations for the three different models here reviewed. If the respective reservations did not overlap, it would be possible to conclude that the models would be, in principle, clearly identifiable.

In practice, at LC with no polarized initial beams, one will be able to measure with satisfactory accuracy \[5\] in the final lepton channel the lepton (typically, muon, tau) cross section \( \sigma_l \) and the related forward-backward asymmetry \( A_{FB,l} \). These two observables would not be sufficient to draw reservations. This would be possible if a third independent leptonic observable were measured. The only realistic possibility would be represented by the measurement of \( A_{LR,l} \), the longitudinal polarization asymmetry for production of final leptonic states (at LC, this quantity would be quite different from the corresponding hadronic one, not like at LEP/SLC). The combination of \( A_{LR,l} \) with \( \sigma_l, A_{FB,l} \) would be sufficient to draw typical regions of effects for each of the three considered models.

If no initial state polarization were available, the most immediate realistic choice would be provided by the measurement of the total hadronic cross section, in particular by that for production of the five "light" \((u, d, s, c, b)\) quarks \((\equiv \sigma_5)\). The combined set of \( \sigma_\mu, A_{FB,l} \) and \( \sigma_5 \) would be sufficient to draw reservations for the two TC and AGC models. In Section 2 we shall be limited to this preliminary case.

## 2 The unpolarized case.

This discussion can be made clearer by writing at this point a few explicit formulae. In the \( Z \)-peak subtracted representation the theoretical expressions of the considered observables read, at c.m. squared energy \( \equiv q^2 \):

1) the charged lepton pair production cross section

\[
\sigma_l(q^2) = \sigma_l^{\text{Born}}(q^2) \left\{ 1 + \frac{2}{\kappa^2(q^2 - M_Z^2)^2} \left[ \kappa^2(q^2 - M_Z^2)^2 \Delta_\alpha(q^2) - q^4(R(q^2) + \frac{1}{2}V(q^2)) \right] \right\}
\] (1)
where \( \kappa \equiv \frac{\alpha M_Z}{3 \Lambda^2} \simeq 2.64 \), \( \Gamma_l \) is the Z width into \( l^+l^- \) and

\[
\sigma_l^{\text{Born}}(q^2) = \frac{4\pi \alpha^2 \left[ q^2 + \kappa^2(q^2 - M_Z^2) \right]}{3q^2 \left[ \kappa^2(q^2 - M_Z^2) \right]^2} \tag{2}
\]

2) its associated forward-backward asymmetry

\[
A_{FB,l}(q^2) = A_{FB,l}^{\text{Born}}(q^2) \left\{ 1 + \frac{q^4 - \kappa^2(q^2 - M_Z^2)^2}{\kappa^2(q^2 - M_Z^2)^2 + q^4 \left[ \Delta_\alpha(q^2) + R(q^2) \right]} + \frac{q^4}{\kappa^2(q^2 - M_Z^2)^2 + q^4 \left[ \Delta_\alpha(q^2) + R(q^2) \right]} \right\} \tag{3}
\]

where

\[
A_{FB,l}^{\text{Born}}(q^2) = \frac{3q^2 \kappa(q^2 - M_Z^2)}{2[q^4 + \kappa^2(q^2 - M_Z^2)^2]} \tag{4}
\]

3) the hadronic cross section \( \sigma_5(q^2) \) (\( \equiv \sigma_a(q^2) + \sigma_d(q^2) + \sigma_s(q^2) + \sigma_c(q^2) + \sigma_b(q^2) \)) for which a relatively simple approximate expression has been written [7]

\[
\sigma_5(q^2) \simeq N_4^{QCD}(q^2) \frac{4}{3} q^2 \left\{ \frac{11\alpha^2}{9q^4} \left[ \frac{1}{1 - \Delta_\alpha(q^2)} \right]^2 + \left[ \frac{3\Gamma_l}{M_Z} \frac{3\Gamma_{had}}{M_Z N_4^{QCD}(M_Z^2)q^2 - M_Z^2} \right] \left[ 1 - 2R(q^2) - s_1 c_1 V(q^2) \frac{32\Gamma_c}{10\Gamma_{had}} + \frac{48\Gamma_b}{13\Gamma_{had}} \right] \right\} + \left[ \frac{2\alpha}{q^2} \frac{2\tilde{v}_l}{q^2 - M_Z^2} \right] \sqrt{\frac{3\Gamma_l}{M_Z} \frac{3\Gamma_{had}}{M_Z N_4^{QCD}(M_Z^2)q^2 - M_Z^2} \frac{2}{9} \sqrt{\frac{\Gamma_c}{\Gamma_{had}}} + \frac{3}{\sqrt{3}} \sqrt{\frac{\Gamma_b}{\Gamma_{had}}} \right] \tag{5}
\]

where \( \Gamma_c, \Gamma_b, \Gamma_{had} \) are the Z widths into \( c\bar{c}, b\bar{b} \) and hadrons, and \( \tilde{v}_l \equiv 1 - 4s_l^2 \) where \( s_l^2 = 1 - c_l^2 \) is the effective Weinberg-Salam parameter measured on Z resonance.

The "Born" terms consist in fact of expressions where the Fermi constant, \( G_\mu \), has been systematically traded for quantities measured on Z resonance (in the case of lepton production, eqs.(1)-(4), the leptonic Z width \( \Gamma_l \) and the longitudinal polarization asymmetry at Z peak \( A(M_Z^2) \) are involved). One sees that the shifts from the Standard Model prediction will be contained in three functions \( \Delta_\alpha(q^2), R(q^2), V(q^2) \).

Their expressions in the three considered models contain in each case two parameters. The explicit formulae have been given in ref.[1] and [2]. In first approximation, they are rather simple. We consider first the case of the models with AGC. Here one finds, (neglecting irrelevant small contributions):

\[
\Delta_\alpha^{(AGC)}(q^2) = -8\pi\alpha \frac{q^2}{\Lambda^2} (f_{DW} + f_{DB}) \tag{6}
\]

\[
R^{(AGC)}(q^2) = 8\pi\alpha \frac{(q^2 - M_Z^2)}{\Lambda^2} \left[ \frac{c_1^2}{s_1^2} f_{DW} + \frac{s_1^2}{c_1^2} f_{DB} \right] \tag{7}
\]

\[
V^{(AGC)}(q^2) = 8\pi\alpha \frac{(q^2 - M_Z^2)}{\Lambda^2} \left[ \frac{c_1}{s_1} f_{DW} - \frac{s_1}{c_1} f_{DB} \right] \tag{8}
\]
where \( f_{DW} \), \( f_{DB} \) are the renormalized parameters that, in the considered example, are associated to the operators \( O_{DW} \) and \( O_{DB} \) involved in the effective Lagrangian of ref.\[3\] and that survive in the Z-peak subtracted representation. As one sees, the previous equations are linear in the two surviving parameters of the model. Eliminating the parameters leads to a very simple figure in the 3d-space of the relative deviations that is, in fact, that of a plane.

The result of this procedure is shown in Fig.(1), that represents, in the space of the three relative shifts on \( \sigma_l \), \( A_{FB,l} \) and \( \sigma_5 \), the corresponding reservations at \( \sqrt{q^2} = 500 \text{ GeV} \).

Fig.(1) (light grey domain) shows the region of a certain space where a signal of AGC origin would be identifiable, at least as a possible candidate. In the negative case of no signal detection, limits on the two previous parameters would be derivable from the combined analysis of the three considered observables. This problem has been fully discussed in a recent paper \[4\], where the potentially dangerous effect of (initial state) QED radiation have been also taken into account. The resulting exclusion regions for the parameters are shown in Fig.(2). Numerically, they can be summarized, at 95\% CL, by the following limits:

\[
|f_{DW}| \lesssim 0.025 \tag{9}
\]

\[
|f_{DB}| \lesssim 0.13 \tag{10}
\]

We now move to an example of a model of TC type. We shall choose a case in which two families of strong vector and axial-vector techniresonances exist, that would contribute the neutral gauge bosons self-energies and thus the coefficients \( \Delta_\alpha \), \( R \) and \( V \). This has been exhaustively discussed in a quite recent paper \[7\], to which we defer for details. In the particularly simple (but realistic) case in which for each family one ”light” resonance exists, such that the next resonances are ”reasonably” heavier, and assuming a certain self-consistent size of the strengths of their couplings, this model can be also described by two \( q^2 \)-dependent parameters, defined as:

\[
X(q^2) = \left( \frac{F^2_V}{M_V^2} \right) \left( \frac{1}{M_V^2 - q^2} \right) \tag{11}
\]

\[
Y(q^2) = \left( \frac{F^2_A}{M_A^2} \right) \left( \frac{1}{M_A^2 - q^2} \right) \tag{12}
\]

In terms of \( X \), \( Y \) the relative shifts of the three considered observables are:

\[
\frac{\delta \sigma_\mu^{(TC)}(q^2)}{\sigma_\mu} = \frac{\sigma_\mu^{(TC)} - \sigma_\mu^{(SM)}}{\sigma_\mu} = a_1(q^2)X(q^2) + b_1(q^2)Y(q^2) \tag{13}
\]

\[
\frac{\delta A_{FB,\mu}^{(TC)}(q^2)}{A_{FB,\mu}} = \frac{A_{FB,\mu}^{(TC)} - A_{FB,\mu}^{(SM)}}{A_{FB,\mu}} = a_2(q^2)X(q^2) + b_2(q^2)Y(q^2) \tag{14}
\]
\[
\frac{\delta \sigma_5^{(TC)}}{\sigma_5}(q^2) = \frac{\sigma_5^{(TC)} - \sigma_5^{(SM)}}{\sigma_5} = a_3(q^2)X(q^2) + b_3(q^2)Y(q^2)
\]  

(15)

where \( a_i, b_i \) are numbers whose value at LC is calculable, and \( F_V, F_A \) are the resonances’ strengths, conventionally defined.

Eqs.(13)-(15) generate the corresponding TC reservation. At 500 GeV, this is depicted in Fig.(1) (dark grey domain), where the same conventions used in the case of AGC have been adopted.

As one sees from a comparison of the domains in Figs.(1), the overlapping region between the two considered TC and AGC models is practically negligible. As a consequence, a virtual signal due to a model of the first type would be clearly distinguishable, at LC, from a model of the second type by a combined use of the three unpolarized observables that will be realistically measured with the expected accuracy.

As it was done for the first case of AGC models, negative bounds for the TC parameters in case of no observation of the related signal can be drawn. The discussion has been fully pursued in Ref.[7], leading to the following mass exclusion lower limits for the vector \((M_V)\) and axial vector \((M_A)\) resonance in case of a typical reasonable choice of the \((F_V, F_A)\) strengths:

\[
M_V \gtrsim 1.5 \text{ TeV}
\]

(16)

\[
M_A \gtrsim 0.9 \text{ TeV}
\]

(17)

In this discussion, we have assumed the non availability of initial longitudinal polarization. We shall examine in the next Section 3 the possible consequences of the opposite situation of polarization availability.

3 The polarized case.

Among the several quantities that can be measured in the process of electron-positron annihilation into a fermion-antifermion couple, the longitudinal polarization asymmetry \( A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \) has represented in the last few years an example of, least to say, remarkable theoretical interest. This is due to the known fact that, as it was stressed in a number of dedicated papers [8],[9],[10],[11], the properties of this observable on top of \( Z \) resonance are indeed special. In particular one can stress two main facts i.e. that \( A_{LR} \) is independent of the final produced state (this was shown in particular detail in Ref.[10]), and that it is particularly sensitive to possible virtual effects of a large number of models of new physics (this was exhaustively discussed in Refs.[9] and [10]). These features, that appear essentially unique, have deeply motivated the tough experimental effort at SLC [12] where \( A_{LR} \) has been (in fact, it is still being) measured to an extremely high precision [13], fully exploiting the fact that at a linear electron-positron collider it is ”relatively” easy to produce longitudinally polarized electron beams with a high and accurately known polarization degree[14]. This is not the case of a circular accelerator, and for this reason neither at LEP1 (in spite of the several impressive experimental studies
and efforts of recent years [13] nor at LEP2 a measurement of $A_{LR}$ has been, or will be predictably performed.

At LC it would be, again, ”relatively” easy to produce longitudinally polarized electron beams, which implies the possibility of measuring $A_{LR}$, for various possible final states. One might therefore wonder whether the special theoretical properties valid on top of $Z$ resonance will still be true and, if not, how they would be modified at about 500 GeV. This question has been answered in a very recent paper [14] which has investigated the general features of $A_{LR}$ at such a machine, showing that, from a theoretical point of view, this quantity still retains beautiful and interesting features, that make it particularly promising as a tool for investigating virtual effects of models of new physics. We defer the interested reader to ref.[14] for more details, and proceed by giving the theoretical expression of $A_{LR}$ that will be relevant for our purposes. In particular, from the discussion given in Section 1, we shall concentrate our attention on the final lepton states, for which the $Z$-peak subtracted representation of $A_{LR,l}^{(1)}$ reads, at one loop (specified by the notation $A_{LR,l}^{(1)}$):

$$A_{LR,l}^{(1)}(q^2) = g^2 \left[ \frac{\kappa(q^2 - M_Z^2) + q^2}{\kappa^2(q^2 - M_Z^2)^2 + q^4} A_{LR}(M_Z^2) \times \right.$$  

$$\left. \left\{ 1 + \left[ \frac{\kappa(q^2 - M_Z^2)}{\kappa^2(q^2 - M_Z^2) + q^2} - \frac{2\kappa^2(q^2 - M_Z^2)^2}{\kappa^2(q^2 - M_Z^2)^2 + q^4} \right] [\tilde{\Delta}\alpha(q^2) + R(q^2)] - \frac{4c_s l}{\bar{v}_l} V(q^2) \right\} \right) \quad (18)$$

where $\kappa$ has been defined after eq.(1).

To make practical use of this extra information, we shall assume an experimental accuracy in the measurement of $A_{LR,l}^{(1)}$ at LC of about $0.007$ (purely statistical), to be compared with the expected value $A_{LR,l}^{(1)}(500 \text{ GeV}) \simeq 0.07$. All our results can be easily rescaled if the experimental error is raised, or decreased. As a first example, we shall consider the case of a model with one extra $Z$ ($\equiv Z'$). For a final lepton state, this case can be classified in the $Z$-peak subtracted framework as one described by two parameters. More precisely, as it has been shown in a previous dedicated review [3], one finds

$$\tilde{\Delta}^{(Z')}(q^2) = -\frac{g^2}{M_{Z'}^2} \frac{1}{q^2} \frac{g_{Vl}^2}{4c_s l} (\xi_{VI} - \xi_{Al})^2$$

$$R^{(Z')}(q^2) = \frac{g^2 - M_{Z'}^2}{M_{Z'}^2 - q^2} \xi_{Al}^2$$

$$V^{(Z')}(q^2) = -\frac{g^2 - M_{Z'}^2}{M_{Z'}^2 - q^2} \frac{g_{Vl} \xi_{Al}}{2c_s l} (\xi_{VI} - \xi_{Al})$$

where we have used the definitions

$$\xi_{VI} = \frac{g_{Vl}'}{g_{Vl}}$$

$$\xi_{Al} = \frac{g_{Al}'}{g_{Al}}$$

(22)

(23)
with \( g_{vl} = \frac{1}{2}(1 - 4s_l^2) \); \( g_{Al} = -\frac{1}{2} \) and \( g'_{vl}, g'_{Al} \), the (arbitrary) \( Z' \) couplings to leptons.

As one sees, only two effective parameters, that could be taken for instance as 
\[ \xi_{vl} \frac{M_Z}{\sqrt{M_{Z'} - q^2}} \] and 
\[ (\xi_{vl} - \xi_{Al}) \frac{M_Z}{\sqrt{M_{Z'} - q^2}} \], enter the one-loop corrections \( \tilde{\Delta}_\alpha^{(Z')}(q^2) \), \( R^{(Z')}(q^2) \) and \( V^{(Z')}(q^2) \). This means that, as stated in Section 1, a proper combination of the theoretical expressions of the three leptonic quantities \( \sigma_l, A_{FB,l} \) and \( A_{LR,l} \) allows to derive the characteristic \( Z' \) reservation. This is shown in Fig.(3) for the LC case.

Assuming that \( A_{LR,l} \) can be measured, we can reconsider the two previous models of TC and AGC type examined in Section 1 and draw their reservations in the space of the three leptonic shifts observables \( \delta \sigma_l, \delta A_{FB,l} \) and \( \delta A_{LR,l} \). This is shown in Fig.(4). Then, a comparison of the different characteristic areas for the three models of TC, AGC and \( Z' \) type can be performed. As one sees from Fig.(3),(4), the common region to the three models is, again, very small. A nice consequence of the availability of initial beam polarization would be thus the possibility of disentangling in a clean way the possible effects of three respectable models of New Physics of rather different nature.

One should still add the fact that, for what concerns the \( Z' \) model, limits on its mass from absence of signals have been derived both in the presence and in the absence of polarization. They are summarized in other previous papers[17], and lie typically in the few TeV range at LC. We give, for illustration purposes, in Table 1, a few numerical values (with only statistical errors), corresponding to special "canonical" models, assuming the presence of polarization (this improves the bounds by factors that can be sizeable, depending on the model).

4 Conclusions.

In this short paper we have reviewed the main information that would be obtainable at LC, from a proper combined use of different observables, concerning three rather general and quite different models of New Physics. Our analysis shows that it would be possible to identify the possible origin of a signal with reasonable accuracy, particularly if longitudinal polarization were available for the initial electron beam. We have also derived limits on the "effective" parameters in the \( Z \) peak subtracted approach, assuming the absence of visible signals, that in the case of vector resonance masses lie typically in the TeV range. Our analysis can be easily generalized to the case of a similar machine with different c.m. energy, without changing any of the relevant features of our approach.

Acknowledgments

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Table 1: $Z'$ mass limits in left-right and $E_6$ models.

| $\alpha_{LR}$ | 0.8 | 1.2 | 1.4 | $\cos\beta_{E_6}$ | 0.5 | 1 |
|---------------|-----|-----|-----|-------------------|-----|---|
| $M_{Z'}$ (TeV) | 4.2 | 3.1 | 3.8 | $M_{Z'}$ (TeV)     | 4.1 |

| $\alpha_{LR}$ | 0.8 | 1.2 | 1.4 | $\cos\beta_{E_6}$ | 0.5 | 1 |
|---------------|-----|-----|-----|-------------------|-----|---|
| $M_{Z'}$ (TeV) | 4.2 | 3.1 | 3.8 | $M_{Z'}$ (TeV)     | 4.1 |
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Figure captions

Fig.1. Reservations for AGC models (light grey) and TC models (dark grey) in the space of relative shifts on $\sigma_l$, $A_{FB,l}$ and $\sigma_5$ at a 500 GeV LC. The central box represents the unobservable domain.

Fig.2 Constraints on AGC couplings from $e^+e^- \rightarrow f \bar{f}$ processes at 500 GeV without polarization. $\sigma_l$ (cross), $\sigma_5$ (diamond), $A_{FB,l}$ (box). The ellipse is obtained by combining quadratically the three bands.

Fig.3. Reservations for general $Z'$ models in the space of relative shifts on $\sigma_l$, $A_{FB,l}$ and $A_{LR,l}$ at a 500 GeV LC.

Fig.4. Reservations for AGC models (light grey) and TC models (dark grey) in the space of relative shifts on $\sigma_l$, $A_{FB,l}$ and $A_{LR,l}$ at a 500 GeV LC.
Fig. 1
Fig. 2
Fig. 3
Fig. 4