Residual New Physics Effects in the Heavy Quark Sector, Tests at LEP2 and Higher Energies

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Abstract

We discuss the sensitivity of the processes $e^+e^- \rightarrow t\bar{t}$ and $e^+e^- \rightarrow b\bar{b}$ to special sets of operators describing residual New Physics effects. Experimental data in this sector together with those expected in the bosonic sector should allow to constrain possible New Physics schemes with effective scales in the 10 TeV range.

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We assume that a certain dynamics generically called New Physics (NP) exists beyond the Standard Model (SM) and is responsible for many of its unexplained features like the mass generation mechanism, the structure of the scalar sector, the mass spectrum of the leptons, the quarks and the gauge bosons. This new dynamics involves heavy degrees of freedom characterized by an effective scale expected to be much higher than the electroweak scale, i.e. $\Lambda \gg M_W$. It is then natural to expect that the same dynamics which leads to the mass of the usual particles also generates some contributions to vertices among these particles. This is what is called residual NP effects. This picture suggests that these effects most probably affect particles especially concerned by the mass generation mechanism like $W_L$, $Z_L$ or heavy quarks which may then act as windows to NP. In addition through gauge interactions the other (light) particles may also get affected.

Recent hints for anomalous effects have appeared in $Z \rightarrow b\bar{b}$, i.e. $\Gamma(Z \rightarrow b\bar{b})$ is $1.8\sigma$ too high and $A_b$ is $2\sigma$ too low as compared to SM predictions, [1]. There also exist unexplained features in the high $p_T$ jets produced at Tevatron [2] and in high $q^2$ events at HERA [3].

To describe these residual effects in a model-independent way we shall use the effective lagrangian method. For $M_W \lesssim E \ll \Lambda$ by integrating out all NP degrees of freedom one obtains an effective Lagrangian describing the residual effects among usual particles. This Lagrangian has the following properties. It satisfies $SU(2) \times U(1)$ gauge invariance broken at the electroweak scale. The higgs particle may be light (its mass corresponding to the electroweak scale) or heavy; this is an open option. The lowest dimensions should be dominant, i.e. $d = 6$. In this report we will only (for simplicity) consider CP-conserving effects. With these assumptions one is able to draw a list of operators [4], each of them, $\mathcal{O}_i$, being associated to a certain dimensionful $(d - 4 = 2)$ coupling, $g_i$. These couplings are the free parameters of the description but they can be related to the NP scale by unitarity arguments [3]. As a $d = 6$ operator generates amplitudes growing with the energy, at some point a saturation of unitarity occurs. Heavy NP degrees of freedom should appear to cure it (creation of new particles, resonances,...). It is then natural to identify this energy value with the effective NP scale.

The general list of $\mathcal{O}_i$ involves various classes of bosonic and fermionic operators with specific features. Bosonic operators have been separated into “non-blind”, “blind” and even “super-blind” sets, depending on their appearance in $Z$-peak observables at tree or loop levels, [3], [4], [5]. The same concept has been extended to the list of heavy quark operators. In addition another feature has been added, the presence or not of a $t_R$ field (especially involved in mass generation), [6], [7]. Light fermion contributions and left-handed currents should a priori not be involved. Equations of motion for fermion fields have been used in order to eliminate derived operators. We did not do it for those concerning the gauge boson fields as this would bring into the game light fermionic currents [8]. Operators involving such derivative terms will constitute a third class to which we will devote a separate discussion [9].

Tests of bosonic operators were discussed in previous reports, for a review see [10]. Here, we report on the tests concerning the heavy quark sector, [9], [11], [12], [14], [15], [16].

Obviously, the heavy top should be a privileged place for looking for these effects, so we start with the process $e^+e^- \rightarrow t\bar{t}$ observable at LC [17]. Operators of Class 1 lead to modifications of the $\gamma t\bar{t}$ and $Zt\bar{t}$ couplings. The general form of such CP-conserving
vertices is given below:

\[-i\epsilon^\gamma_\mu J^\gamma_\mu = -ie_V^\gamma_\mu \bar{u}_t(p)[\gamma^\mu d^V_1(q^2) + \gamma^\mu \gamma^5 d^V_2(q^2) + (p - p')^\mu d^V_3(q^2)/m_t]v_t(p')\],

(1)

where \(\epsilon^\gamma_\mu\) is the polarization of the vector boson \(V = \gamma, Z\). The outgoing momenta \((p, p')\) refer to \((t, \bar{t})\) respectively and satisfy \(q \equiv p + p'\). The normalizations are determined by \(e_\gamma \equiv e\) and \(e_Z \equiv e/(2s_Wc_W)\), while \(d^V_\gamma\) are in general \(q^2\) dependent form factors. At tree level SM feeds a first set, called set (1), of three couplings:

\[d^V_1^{SM} = \frac{2}{3}, \quad d^V_2^{SM} = g_V t = \frac{1}{2} - \frac{4}{3} s^2_W, \quad d^V_3^{SM} = -g_{At} = -\frac{1}{2} .\]

(2)

SM at 1-loop and NP lead to additional \(q^2\)-dependent contributions to these couplings and to contributions to the second set, called set (2), containing \(d^V_2(q^2)\), \(d^V_3(q^2)\) and \(d^V_5(q^2)\). Departures from the SM (tree + 1-loop) are then defined as:

\[\bar{d}^V_j \equiv d^V_j - d^V_{j,SM} .\]

(3)

The explicit expressions of the contributions to the \(\bar{d}^V_j\) of each operator \(\mathcal{O}_i\) at tree level and at 1-loop are given in ref.\([10]\). We will now precisely determine the accuracy at which they can be observed or constrained.

Tests in \(e^+e^- \rightarrow t\bar{t}\)

The reaction \(e^+e^- \rightarrow t\bar{t}\) offers a way to determine all six couplings by studying the top quark spin density matrix elements. In fact the top quark properties are reconstructed through the decay chain \(t \rightarrow Wb, W \rightarrow l\nu\) or \(W \rightarrow q\bar{q}'\). The 4-dimensional angular distribution of this final state should allow to measure \(\rho^L_{\lambda\lambda}\), at any \(q^2\) and production angle \(\theta\) as each of them leads to a specific angular dependence \([10, 14]\). When \(e^-\) longitudinal polarization is available one deals with six independent informations \(\rho^L_{\lambda\lambda, +, -, +, -, \ldots}\) that can be expressed in terms of the six \(\gamma t\bar{t}, Zt\bar{t}\) couplings. Note that absolute measurements of density matrix elements (like the production cross section \(\sigma_{t\bar{t}}\)) are affected by the lack of precise knowledge of the \(t \rightarrow Wb\) decay width \([13, 19]\). On the opposite, asymmetries like forward-backward asymmetries or L-R asymmetries (ratios of cross sections) are free of this ambiguity. In order to reach pure informations on the \(\gamma t\bar{t}, Zt\bar{t}\) couplings we have tried to rely as much as possible on such observables.

In the general 6-parameter case this is not fully possible. For the first set of \(\bar{d}_j\) couplings, asymmetries only depend on two combinations of \(\bar{d}_j\). To get a third one, informations sensitive to the absolute normalization, like \(\sigma_{t\bar{t}}\), are required but they will depend on the top quark decay width. For the second set of couplings we do not have this problem; asymmetries alone are sensitive to ratios of the type \(\bar{d}/d_{SM}\) and allow to constrain the complete set (2). We have made applications to an LC collider \([17]\) with 0.5, 1 and 2 TeV and luminosity of 20, 80 and 320 \(fb^{-1}\) respectively leading to more than \(10^4\) events. A reconstruction and detection efficiency of 18 percent \([19]\) has been applied before computing the statistical accuracy for each observable. From this we have obtained the accuracy expected in the determination of the top quark density matrix elements and the constraints on the NP couplings \(\bar{d}_j\) (ellipsoid in 6-parameter space). Examples are shown in Fig 1a,b. The complete set of results is given in ref.\([14]\).
The essential features are the following. For couplings of set (1), as one information is missing when only asymmetries are used, a band of width $\pm 0.02$ appears. A constraint of the order of $\pm 0.05$ ($\pm 0.02$) is obtained when cross section measurements are added assuming an uncertainty of 20% (2%) on the top decay width. For couplings of set (2), asymmetries alone already allow to constrain the couplings at the level of $\pm 0.02$ in the unpolarized case and $\pm 0.01$ in the polarized case.

We have then studied some constrained cases. From the list of NP operators, keeping only those contributing at tree level to the $\gamma t\bar{t}$ and $Zt\bar{t}$ couplings, leaves only four free parameters associated to $O_{t2}, O_{Dt}, O_{tW\Phi}$ and $O_{tB\Phi}$. These contributions affect the $\gamma t\bar{t}$ couplings only through $\sigma^{\mu\nu}q_\nu$ type of vertices, imposing the relations

$$d_1^c = -2d_3^c, \quad d_2^c = 0,$$

so that the four parameters are $d_3^c, d_2_{1,2,3}^c$.

This set is further reduced to only three free parameters if one keeps only those operators which are generated in the type of dynamical models studied in ref. [11], namely, $O_{t2}, O_{tW\Phi}$ and $O_{tB\Phi}$. For these operators, in addition to the above single photon coupling, only two $Zt\bar{t}$ couplings appear, $\sigma^{\mu\nu}q_\nu$ and $\gamma(1 + \gamma^5)$, so that:

$$d_1^z = -2d_3^z,$$

and the three parameters left are $d_3^z, d_2_{1,2,3}^z$.

We have also made an illustration with a two-parameter model as suggested by the chiral description which only involves anomalous left-handed and right-handed $Zt\bar{t}$ couplings called $\kappa_{L,R}^{NC}$ in ref. [20].

In all these constrained cases the typical accuracy for both sets of couplings using only asymmetries is of the order of $\pm 0.02$ without polarization and it improves down to $\pm 0.01$ when polarization is available. Finally we have treated all the operator listed in Class 1, taking them one by one. Results can be found in Table 7 of ref. [14]. Essentially there are two levels of constraints. For the four operators contributing at tree level, $O_{t2}, O_{Dt}, O_{tW\Phi}$ and $O_{tB\Phi}$, the constraints reach effective scales lying in the 5 to 50 TeV range and are much stronger than the indirect ones already set by Z-peak results. On the contrary for the operators $O_{qt}, O_{qt}^{(8)}, O_{tb}$, that contribute at loop level, the constraints are expected not to be substantially improved. The scales lie in the 1-5 TeV range. However two more operators, that do not substantially contribute at Z-peak, $O_{tt}, O_{tG\Phi}$, although contributing at loop level, will get interesting constraints in the 5-10 TeV range.

Tests in $e^+e^- \rightarrow b\bar{b}$

We now discuss the $e^+e^- \rightarrow b\bar{b}$ channel. We want to show that it can give several interesting informations on particular operators. A priori this could seem unlikely because of the strong Z-peak constraints in the $b\bar{b}$ sector. In fact these constraints come from direct NP effects on $\gamma b\bar{b}$ and $Zb\bar{b}$ couplings ref. [21]; they are induced by operators of Class 2 contributing at tree level. The 0.5 percent accuracy of $\Gamma(Z \rightarrow b\bar{b})$ already pushes the NP scale for these operators in the 10 TeV range and this cannot be improved by measurements in the $e^+e^- \rightarrow b\bar{b}$ channel at higher energies. Operators of Class 1 get also
constrained through virtual (1-loop) contributions enhanced by $m_t^2/M_W^2$ factors. This enhancement, well-known in the SM case, occurs for certain NP operators, see ref.\[9\]. In some cases, as we have seen above with $O_{qt}$, $O_{qt}^{(8)}$, $O_{tb}$, Z peak measurements give better constraints than $e^+e^- \to t\bar{t}$ at high energies.

However, we have found that $e^+e^- \to b\bar{b}$ beyond Z-peak can improve the constraints for a certain set of "non-blind" operators, i.e. those containing derivatives of gauge fields (Class 3). For example a strong $q^2$ dependence appears in the modification of the gauge boson propagators due to $O_{DW}$, $O_{DB}$ ref.[22, 23], and in the $\gamma b\bar{b}$, $Zb\bar{b}$ couplings due to $O_{qW}$, $O_{qB}$, $O_{bB}$. Their effects in $e^+e^- \to b\bar{b}$ can also be easily computed through the use of equations of motion. For example in

$$\mathcal{O}_{DW} = 2 \left( D_\mu \overline{W}_\mu^{\rho} \right) \overline{D}_\nu W_\nu^{\rho} \right) ,$$

one uses

$$D_\mu \overline{W}_\mu^{\rho} = g \overline{J}_\mu^{(2)} - i \frac{g}{2} \left[ D_\nu \Phi^\dagger \overrightarrow{\tau} \Phi - \Phi^\dagger \overrightarrow{\tau} D_\nu \Phi \right] ,$$

$J_\mu^{(2)}$ being the $SU(2)$ current; and similarly for the other operators, see ref.[12]. They lead to an effective four-fermion ($e^+e^-)(b\bar{b})$ contact interaction. This is the origin of the enhancement of their contribution as compared to the Z tail contribution which decreases like $1/q^2$. Moreover this property allows to disentangle their contribution from the ones of all other operators by using the so-called "Z-peak subtraction method". Ref.[24]. It consists in using as inputs $\Gamma(Z \to f\bar{f})$, $A_f$ instead of $G_\mu$, $s_W^2$. This procedure automatically takes care of any NP effect at Z peak and leaves only room for those ones which can survive in the difference of structure functions of the type

$$F_i(q^2) - F_i(M_Z^2)$$

which are combinations of self-energies, vertices, box and NP contributions. In this way we get contributions from operators of Class 3, $\mathcal{O}_{DB}$, $\mathcal{O}_{DW}$, $O_{qW}$, $O_{qB}$, $O_{bB}$. At Z-peak they are mixed with all other operators. Beyond Z-peak all other operators do not contribute. $\mathcal{O}_{DB}$ and $\mathcal{O}_{DW}$ get already constrained from $e^+e^- \to l^+l^-$ and $e^+e^- \to q\bar{q}$. $O_{qW}$, $O_{qB}$, $O_{bB}$ can then be studied with the four observables $\sigma_b$, $A_{FB}^b$, $A_{LR}^b$, $A_{pol}^{(b)}$. At LEP2 polarization is not available and we only get two constraints for three operators. This is the origin of the band appearing in Fig.2 (illustrations for other couples of operators can be found in ref.[12]). At LC with polarization the system can be completely constrained leading to sensitivity limits on effective scales in the range 30-50 TeV, indeed a rather high level.

In conclusion, we summarize the panorama of the constraints already obtained or expected from future experiments for the whole set of $dim = 6$-operators. We give below the range of NP scales (in TeV) up to which values experiments can be sensitive.
For the bosonic operators:

- non-blind (LEP2) 17 (LC) 50 (LC)
- blind (TGC) 1.5 (LEP2) 20 (LC)
- superblind (Higgs) 7 (LEP2) 20 (LC), 70 (LC\gamma\gamma)

For heavy quark operators:

| Class | (LEP1) | (LC) |
|-------|--------|------|
| Class 1 | 5      | 10-50 (LC) |
| Class 2 | 10     | 10 (LC) |
| Class 3 | 8      | 30-50 (LC) |

Work is in progress for the case of the pure gluonic operators $O_G$, $O_{DG}$, $O_{GG}$.

As one can see, limits obtained or expected often lie in the 10 TeV range. This is a domain which covers several types of models beyond SM (Technicolour, extended gauges,...). Our hope is that experiments in various sectors will reveal certain correlations which could select a few operators of our list and give hints for the structure of new physics.

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Fig. 1  Observability limits in the 6-parameter case; (a) among couplings of set (1), (b) among couplings of set (2); from asymmetries alone (- - - -), from asymmetries and integrated observables with a normalization uncertainty of 2% (.......), 20% (———).
Fig. 2  Constraints from $e^+e^- \rightarrow b\bar{b}$ observables in the 3-free parameter case, projected on the $(f_{qB}, f_{bB})$ plane; at LEP2 (without polarization) (dotted), at NLC (without polarization) (solid), at NLC (with polarization) (ellipse).