Non-standard t production at the NLC

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Abstract

The top-quark system as a probe for new physics is considered using a consistent, gauge-invariant effective Lagrangian approach. The magnitude of new effects is estimated and the results are applied to top production through W fusion. Other processes are also briefly discussed.

1 Introduction

In this talk I will discuss the possibilities of detecting non-Standard Model physics thorough virtual effects at a high-energy linear collider. In the description of these effects I will use the effective Lagrangian formalism.

2 Effective Lagrangians

It is a commonly held belief that the Standard Model is but the low-energy limit of a more fundamental theory. In fact there is a myriad of models which reduce to the Standard Model at low energies (below, say, 1TeV) but which exhibit a plethora of new effects at smaller scales. I will adopt this paradigm with the added condition that there is an energy gap between the Standard Model scale $v \sim 250\text{GeV}$ and the scale of new physics $\Lambda$. One important goal of the approach I will follow (for general references see [1] and references therein) is to obtain reliable estimates (or reliable bounds) for $\Lambda$ using current data; this information can then be used to estimate the energy at which new colliders must operate.

Note that there are interesting models which do not satisfy $v \ll \Lambda$. For example, many supersymmetric theories predict light, non-Standard Model scalars of masses below 200GeV [2]. One can discuss such theories using the formalism to be developed below, but in order to do so the spectrum at low energies must be modified to include all the light supersymmetric particles. I will not consider this possibility here (see [3]).

Given the presence of a gap we can imagine integrating out all the heavy excitations of the theory. The effective interactions (for the light particles) generated in this manner are summarized in an effective Lagrangian.

Schematically, denoting the heavy fields by $\Phi$, the light fields by $\phi$, and the action for the theory underlying the Standard Model by $S(\Phi, \phi)$, then the effective action is

$$S_{\text{eff}}(\phi) = -i \ln \left[ \int |d\Phi| \exp(iS) \right]$$

Note that $S_{\text{eff}}$ will have a dependence on $\Lambda$, and that $\Lambda$ assumed much larger than any of the light physics scales (including the energy at the available experiments). Thus one can do an expansion in powers of $\Lambda$ [1]

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\[ S_{\text{eff}} = \sum_{n=-4}^{\infty} \frac{1}{\Lambda^n} \int d^4x \mathcal{L}_n \] (2)
where \( \mathcal{L}_n \) can be expanded as a linear combination of local operators,
\[ \mathcal{L}_n = \sum_a f_a^{(n)} \mathcal{O}_a^{(n)} \] (3)

(any logarithmic dependence on \( \Lambda \) is contained in the coefficients \( f_a^{(n)} \)).

The terms \( \mathcal{L}_n, n \leq 0 \) correspond to the Standard Model; the \( \Lambda \) dependence of these terms is unobservable [4]. The contributions \( \mathcal{L}_n, n > 0 \) summarize the virtual heavy-physics effects. If the action \( S \) is known then one can calculate the coefficients \( f_a^{(n)} \) in terms of the parameters of the heavy theory, but one can also take a complementary approach and parameterize all possible heavy physics effects using these quantities. This is the approach taken here.

There are no general statements concerning the global symmetry properties of the various terms \( \mathcal{L}_n \). It is quite possible for some terms to have a given global symmetry which is absent in others. A clear example is baryon number violation: the Standard Model, corresponding to \( \mathcal{L}_n, n \leq 0 \), automatically conserves \( B \) (ignoring possible instanton effects [5]); on the other hand there are contributions to \( \mathcal{L}_2 \) which violate \( B \) (for example, assuming the underlying theory to be the \( SU(5) \) GUT there are well-known baryon-violating operators of dimension 6 generated by the exchange of heavy vectors [6]).

In contrast local symmetries must permeate all the \( \mathcal{L}_n \) [7]. Since the Standard Model is assumed to be \( SU(3) \times SU(2) \times U(1) \) symmetric, the same will be true for all higher-dimensional operators \( \mathcal{O}_a^{(n)} \). Since each operator will then involve several interactions this can result in a reduction in the number of undetermined parameters.

For example, the dominating non-standard contributions to the triple and quartic gauge-boson vertices (excluding gluons) appear in \( \mathcal{L}_2 \) and involve only 4 independent coefficients. In contrast the most general Lorentz invariant expression for the triple gauge-boson (not including gluons) vertices involve 13 unknown coefficients \(^1\).

The effective approach described above is natural [8], consistent [1] and its predictions have been verified repeatedly (even for strongly coupled theories, see for example [9]).

### 3 Segregating operators

One important feature of the effective Lagrangian approach is the possibility of estimating the coefficients \( f_a^{(n)} \). It then becomes possible to isolate those operators whose coefficients are not \( a \) priori suppressed and will potentially generate the strongest deviations from the Standard Model.

The coefficients estimates strongly depends on the low energy scalar spectrum. I will consider two possibilities (for a more complicated scenario see [10]):

- **Light Higgs case**: the light spectrum is taken to correspond to that of the Standard Model with a single light doublet. In this case, assuming naturality [8], the heavy theory should be weakly coupled [11]. The dominating operators will then be those generated at tree level; the list of such operators appeared in Ref. [12]. Subdominant operators appear with coefficients suppressed by a factor \( \sim 1/(4\pi)^2 \).

- **Chiral case**: the light spectrum corresponds to that of the Standard Model with no physical scalars. In this case the symmetry breaking sector is strongly coupled [13] and the coefficients can be estimated using naive dimensional analysis [14].

With these estimates \( \Lambda \) has a direct interpretation. For the light Higgs case it represents the mass of a heavy excitation; for the chiral case it represents the scale at which the new interactions become apparent. In this talk I will consider only the light Higgs case.

\(^1\)Subdominant contributions to this vertex, generated by \( \mathcal{L}_{n \geq 3} \) will generate the remaining 9 contributions, but the corresponding coefficients are suppressed by a factor of \((v/\Lambda)^k, k \geq 2\).
The above estimates are verified in all models where calculations and/or data are available. In choosing processes with which to probe the physics underlying the Standard Model one should therefore concentrate on reactions where the dominating operators (those with the largest coefficients) contribute.

As an example one can study the $WW\gamma$ and $WWZ$ vertices (CP conserving) in the case where there are light scalars. The dominating (non-Standard Model) operators have dimension 6; there are two of them:

\[ \mathcal{O}_W = g^3 \epsilon_{IJK} W^I_{\mu} W^J_{\nu} W^K_{\rho} W^\rho_{\mu} \]
\[ \mathcal{O}_{WB} = g g' (\phi^I \tau^I \phi) W^I_{\mu} B^{\mu
u} \]

where $W^I_{\mu}$ and $B_{\mu\nu}$ denote the $SU(2)$ and $U(1)$ field-strengths respectively, with gauge coupling constants $g$ and $g'$; $I, J, \ldots$ denote $SU(2)$ indices and $\phi$ the Standard Model doublet. Gauge coupling constants are explicitly included since gauge field couple universally. Incidentally it is worth noting that $\mathcal{O}_W$ is the only CP conserving non-Standard Model operator generating vertices with $n \geq 4$ (electroweak) gauger bosons.

The effective Lagrangian contains terms $(f_W/\Lambda^2)\mathcal{O}_W + (f_{WB}/\Lambda^2)\mathcal{O}_{WB}$ which in terms of the usual notation [15] translates into

\[ \lambda_\gamma = \lambda_Z = \frac{6m_w^2 g^2 f_W}{\Lambda^2}; \]
\[ \Delta \kappa_\gamma = \Delta \kappa_Z = \frac{4m_W^2 f_{WB}}{\Lambda^2} \]

Since the operators are loop generated we have $f_W, f_{WB} \sim 1/(16\pi^2)$ and

\[ \lambda \sim \left( \frac{10\text{GeV}}{\Lambda} \right)^2; \quad \Delta \kappa \sim \left( \frac{15\text{GeV}}{\Lambda} \right)^2 \]

so that a measurement stating $\lambda < 0.05$ corresponds to $\Lambda > 45\text{GeV}$. In order to obtain non-trivial information about $\lambda$ from $\Delta \kappa$ we need to measure these coefficients to a precision of $\sim 10^{-4}$.

On the other hand the effective operator $(f_{ee\mu\mu}/\Lambda^2)(\bar{e}\gamma^\alpha e_L)(\bar{\mu}_L\gamma^\alpha \mu_L)$ is generated at tree level $(f_{ee\mu\mu} \sim 1)$ and current bounds [16] correspond to $\Lambda \gtrsim 0.8\text{TeV}$. This implies that any new (weakly-coupled) physics generating this operator will not be seen directly below this scale.

An example may serve to illustrate the above results. The effective Lagrangian describing neutron $\beta$ decay is $\mathcal{L}_{n\beta} \sim G_F (\bar{\nu}_\gamma \gamma p) (\bar{e}\gamma_{\nu} \nu)$, with $G_F \sim (\text{mass})^{-2}$. The above arguments suggest $G_F \sim 1/\Lambda^2$ with $\Lambda$ of the order of the mass of a heavy particle (up to coupling constants). But one could also have written $G_F = \vartheta/m_n^2$ where $m_n$ is the neutron mass, which is certainly fine, one must only remember that $\vartheta \sim (m_n/v)^2 \sim 10^{-5}$.

It is, of course, possible for some coefficients to be suppressed by an unknown symmetry. In this case one cannot distinguish between such a suppression and a large value of $\Lambda ^2$. In contrast there is no known mechanism for enhancing the above estimates by more than a factor $\lesssim 10$ [17]. For example, if one imagines that there are $N$ particles contributing to a given operator at the one-loop level the coefficient corresponding to this operator will be $\sim N/(4\pi)^2$ which can be $O(1)$ for $N = O(100)$. In this case, however, the theory cannot be analyzed using perturbation theory, in particular, the Higgs mass becomes of order $\Lambda$ and disappears from the low-energy spectrum [11].

### 4 Dominating operators involving the top quark

In the case where there are light scalars there are three types of operators involving the top quark generated at tree level. All these operators are $SU(3) \times SU(2) \times U(1)$ gauge invariant.

- **Four fermion interactions.** Examples are,

\[ (\bar{l}_R \gamma^\mu t_R) (\bar{e}_R \gamma^\mu e_R) \]
\[ (\bar{e}_L^c e_R) (\bar{b}_L t_R) - (\bar{e}_L e_R) (\bar{t}_R t_R) \]

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\[ \text{Which is not inconsistent: if new physics with scale } \Lambda \text{ does not generate a given operator } \mathcal{O}, \text{ it is still possible for some heavier physics with scale } \Lambda' \text{ to generate } \mathcal{O}; \text{ the bounds obtained then refer to } \Lambda'. \]

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• **Gauge-boson couplings.** For example

\[ i (\phi^\dagger D_\mu \phi) (\bar{t}_R \gamma^\mu t_R) \]  

(8)

where \( \phi \) denotes the Standard Model doublet.

• **Scalar couplings.** For example, in the unitary gauge,

\[ H^3 \bar{t}_L t_R \]  

(9)

where \( H \) denotes the physical scalar.

In contrast operators such as \((i\sigma_{\mu\nu} t) F^{\mu\nu}\) and \((i\gamma_\mu \partial_\nu t) F^{\mu\nu}\) are generated at one loop by the underlying theory and their coefficients are suppressed by a factor \( \sim 1/(4\pi)^2 \).

From this one can infer the types of reactions which involve the top quark and which can best probe the physics underlying the Standard Model. It is also possible to determine the type of new physics which generates the higher-dimensional operators. For example, the first of the operators in (7) would be generated by a heavy vector, the operators (8) are also generated by virtual heavy vector bosons [12], etc. In many reactions only one operator dominates the cross section, in these cases one can also specify the type(s) of new physics which are probed by this process under consideration.

## 5 Dominating new physics effects in \( t\bar{t} \) production through \( W \) fusion

One reaction where new physics effects might be probed is in \( t\bar{t} \) production through \( W \) fusion. This process is interesting among other reasons, because the cross section increases with energy \(^3\).

The new physics effects which can be probed in this process are those modifying the \( Wtb \), \( Ztt \), \( WWH \) and \( Htt \) vertices. The relevant operators are (the contributing graphs are given in fig. 1).

<table>
<thead>
<tr>
<th>Operator</th>
<th>Vertices affected</th>
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<tbody>
<tr>
<td>( \mathcal{O}_{\phi} = (\phi^\dagger \phi) (\bar{q}_L \phi) )</td>
<td>( Ht\bar{t} )</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{\phi}^{(1)} = i (\phi^\dagger D</em>\mu \phi) \bar{q} \gamma^\mu q )</td>
<td>( Zt\bar{t}, Ht\bar{t} )</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{\phi q}^{(2)} = i (\phi^\dagger \tau^I D</em>\mu \phi) \bar{q} \tau^I \gamma^\mu q )</td>
<td>( Zt\bar{t}, Wtb, Ht\bar{t} )</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{\phi u} = i (\phi^\dagger D</em>\mu \phi) \bar{t}_R \gamma^\mu t_R )</td>
<td>( Zt\bar{t}, Ht\bar{t} )</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{\phi b} = i (\phi^\dagger \tau^I D</em>\mu \phi) \bar{t}_R \gamma^\mu t_R )</td>
<td>( Wtb )</td>
</tr>
<tr>
<td>( \mathcal{O}<em>{\phi}^{(1)} = (\phi^\dagger \phi) [(D</em>\mu \phi)^\dagger (D_\mu \phi)] )</td>
<td>( WWH )</td>
</tr>
</tbody>
</table>

The existing data only bounds the \( Wtb \) coupling for which \( \Lambda > 500 \text{GeV} \) for a left-handed coupling and \( \Lambda > 300 \text{GeV} \) for a right-handed one. It is worth pointing out that the \( Zt\bar{t} \) coupling can be measured to a 1% accuracy at both the LHC and the NLC [20].

The total cross section proves to be a mediocre probe for new physics; see for example, fig 2.

A more sensitive probe is the forward-backward asymmetry, \( A_{FB} \) which can exhibit deviations of few \( \times 10% \) from the Standard Model prediction. Assuming an efficiency of 18% [21] we see from fig. 3 that a 1.5TeV NLC will be sensitive to scales \( \Lambda \) up to \( \sim 2.5 \text{TeV} \).

The most important contribution to this process is the \( t\)-channel \( b \) quark exchange and so this process is most sensitive to the \( Wtb \) vertex. The deviations from the Standard Model in this interactions come from a heavy \( W' \), as, for example in fig. 4.

\(^3\)The corresponding Standard Model calculations can be found in [18]. A related calculation at a \( \mu\mu \) collider can be found in [19].
6 Other processes

- A better probe of new physics involving the top quark is the reaction $e^+e^- \rightarrow t\bar{t}$ with which scales up to $\Lambda \leq 5\,\text{TeV}$ can be probed at a 1TeV NLC [22].

- As an example of reactions which probe physics not containing the top quark a good example is the process $e^+e^- \rightarrow ZH$ [23] which is strongly affected by an effective vertex of the form $\bar{e}\gamma_{\alpha\beta}eZ_{\beta}H$ generated by a heavy $Z'$ vector boson. The reach in $\Lambda$ of this process is presented in fig. 5; for details see [23].

7 Conclusions

The NLC will provide a very powerful tool for probing virtual non-Standard Model physics. The effective Lagrangian approach provides a rationale for the choice of processes to study, this method has been tested severally and its predictions and estimates agree with all known calculations and experiments. Among the processes involving the top quark the forward-backward asymmetry is sensitive to new physics both in the direct and the $W$-fusion reactions.

References


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4 This reaction has also been studied in the context of trip gauge boson vertices and CP violation [24].
Figure 2: Total cross section for $t\bar{t}$ production through $W$ fusion (calculated using the effective $W$ approximation); Standard Model: lower curve, Standard Model plus effective operators: top curve. The effective operator coefficients were all chosen to be $\pm 1$ with the signs chosen to give the maximum effect.


Figure 3: Deviation from the Standard Model in the forward-backward asymmetry in $t\bar{t}$ production through $W$ fusion


Figure 4: Possible modification of the $Wtb$ vertex due to the presence of a heavy $W'$. 


Figure 5: Reach in $\Lambda$ for the process $e^+e^- \rightarrow ZH$ (including LEP constraints and detection efficiency); $N_{SD}$ denotes the number of standard deviations from the Standard Model value.