Non-standard t production at the NLC

José Wudka†
Department of Physics
University of California-Riverside
California, 92521-0413

March 26, 2022

Abstract

I present a brief overview of the advantages of using a consistent effective Lagrangian approach in parameterizing virtual new physics effects. I then apply the formalism to certain top-quark processes.

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 a energy gap between the Standard Model scale $v \sim 250$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] (up to possible logarithmic factors),

$$S_{\text{eff}} = \sum_{n=-4}^{\infty} \frac{1}{\Lambda^n} \int d^4x \mathcal{L}_n$$

*Talk presented in Beyond the Standard Model V, April 29 - May 4, 1997, Kvikne’s Hotel, Balholm, Norway.
where $\mathcal{L}_n$ can be expanded as a linear combination of local operators,

$$\mathcal{L}_n = \sum_a f_a^{(n)} \mathcal{O}_a^{(n)}$$  \hspace{1cm} (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. 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); 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).

In contrast local symmetries must permeate all the $\mathcal{L}_n$. 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.

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

### 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, the heavy theory should be weakly coupled. 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 and the coefficients can be estimated using naive dimensional analysis.

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.

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.

---

1 Subdominant contributions to this vertex, generated by $\mathcal{L}_a \geq 3$ will generate the remaining 9 contributions, but the corresponding coefficients are suppressed by a factor of $(v/\Lambda)^k$, $k \geq 2$. 
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:

$$O_W = g^3\epsilon_{IJK}W^I_{\mu}W^J_{\nu}W^K_{\rho}$$
$$O_{WB} = gg' (\phi^\dagger \tau^I \phi) W^I_{\mu}B^{\mu\nu}$$

where $W^I_{\mu\nu}$ and $B_{\mu\nu}$ denote the $SU(2)$ and $U(1)$ field-strengths respectively, with gauge coupling constants $g$ and $g'$; $I, J, \text{ etc.}$ 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 $O_W$ is the only CP conserving non-Standard Model operator generating vertices with $\geq 4$ (electroweak) gauger bosons.

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

$$\lambda = \lambda_Z = \frac{6m_W^2 g^2}{\Lambda^2} f_W;$$
$$\Delta \kappa = \Delta \kappa_Z = \frac{4m_W^2}{\Lambda^2} f_{WB}$$

(5)

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

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

(6)

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

On the other hand the effective operator $(f_{e\mu\mu}/\Lambda^2)(\bar{e}_L \gamma^\alpha e_L)(\bar{\mu}_L \gamma^\alpha \mu_L)$ is generated at tree level $(f_{e\mu\mu} \sim 1)$ and current bounds \[16\] correspond to $\Lambda \gtrsim 0.8TeV$. 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 $\mathcal{L}_{n\beta} \sim G_F (\bar{n} \gamma^\alpha p)(\bar{e}_\gamma \alpha \nu)$, with $G_F \sim (\text{mass})^{-2}$. The above arguments suggest $G_F \sim 1/\text{Lambda}^2$ 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 $\Lambda$ \[4\]. 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 \[18\].

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,

$$\bar{t}_R \gamma^\mu t_R \bar{e}_R \gamma^\mu e_R$$
$$\bar{e}_L^c e_R \bar{b}_L t_R - \bar{e}_L e_R \bar{t}_L t_R$$

(where the second is suppressed since it violates chiral symmetry and contributes to the electron mass).

\[\text{Footnote:} \quad \text{Which is not inconsistent: if new physics with scale $\Lambda$ does not generate a given operator $\mathcal{O}$, it is still possible for some heavier physics with scale $\Lambda'$ to generate $\mathcal{O}$; the bounds obtained then refer to $\Lambda'$}\]
• **Gauge-boson couplings.** For example
\[ i \left( \phi^\dagger D_\mu \phi \right) (i R \gamma^\mu t_R) \]  
where $\phi$ denotes the Standard Model doublet.

• **Scalar couplings.** For example, in the unitary gauge,
\[ H^3 \bar{t}_L t_R \]  
where $H$ denotes the physical scalar.

In contrast, operators such as $(\bar{t} \sigma_{\mu \nu} t) F_{\mu \nu}$ and $(\bar{t} \gamma_\mu \partial_\mu t) F_{\mu \nu}$ 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 higher-dimensional operators. For example, the first of the operators in (8) would be generated by a heavy vector, the operators (9) 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.

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).

| Operator | Vertices affected |
|----------|-------------------|
| $O_{u\phi} = (\phi^\dagger \phi) \left( \bar{q} t_R \right)$ | $Ht\bar{t}$ |
| $O_{\phi q}^{(1)} = i \left( \phi^\dagger D_\mu \phi \right) \bar{q} t_R \gamma^\mu \bar{q}$ | $Zt\bar{t}, Ht\bar{t}$ |
| $O_{\phi q}^{(2)} = i \left( \phi^\dagger \gamma^\mu D_\mu \phi \right) \bar{q} t_R \gamma^\mu \bar{q}$ | $Zt\bar{t}, Wtb, Ht\bar{t}$ |
| $O_{Dq} = i \left( \phi^\dagger D_\mu \phi \right) t_R \gamma^\mu t_R$ | $Zt\bar{t}, Ht\bar{t}$ |
| $O_{\phi \phi} = i \left( \phi^\dagger \tau^\mu D_\mu \phi \right) t_R \gamma^\mu t_R$ | $Wtb$ |
| $O_{\phi}^{(1)} = \left( \phi^\dagger \phi \right) \left( (D_\mu \phi)^\dagger (D_\mu \phi) \right)$ | $WWH$ |

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. 3. 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. 4  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. 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

- Better probe of new physics involving the top quark are the reactions $qq \to t\bar{t}$ at the Tevatron and $e^+e^- \to t\bar{t}$ at a 1TeV NLC. In the first case a sensitivity to scales up to 850GeV can be reached and up to $\Lambda \leq 5$TeV for the second reaction.

- As an example of reactions which probe physics not containing the top quark a good example is the process $e^+e^- \to ZH$ which is strongly affected by an effective vertex of the form $(\bar{e}\gamma_\alpha e)Z^\alpha H$ generated by a heavy $Z'$ vector boson. The reach in $\Lambda$ of this process is presented in fig. 5 for details see [24].

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

\footnote{This reaction has also been studied in the context of trip gauge boson vertices and CP violation [25].}
processes involving the top quark the forward-backward asymmetry is sensitive to new physics both in the direct and the $W$-fusion reactions.

References

[1] S. Weinberg, Physica A96, 327 (1979). J. Polchinski, in: Recent directions in particle theory: from superstrings and black holes to the Standard Model, Theoretical Advanced Study Institute in High Elementary Particle Physics (TASI 92), Boulder, Colo., 1-26 Jun, 1992. Edited by J. Harvey and J. Polchinski. (World Scientific, 1993). H. Georgi, Ann. Rev. Nucl. Phys. Sci. 43, 209 (1994).

[2] See, for example, the proceedings of the DPF/DPB Summer Study on New Directions for High-Energy Physics (Snowmass 96), Snowmass, CO, 25 Jun - 12 Jul 1996. S. Dawson, lectures given at NATO Advanced Study Institute on Techniques and Concepts of High-energy Physics, St. Croix, U.S. Virgin Islands, 10-23 Jul 1996. [hep-ph/9612224]. H. Murayama and M.E. Peskin, Ann. Rev. Nucl. Phys. Sci. 46, 533 (1996) [hep-ex/9606003].

[3] D.D. Piriz and J. Wudka, in preparation.

[4] T. Appelquist and J. Carazzone, Phys. Rev. D11, 2856 (1975). See also J.C. Collins, Renormalization (Cambridge University Press, 1984).

[5] G. ‘t Hooft, Phys. Rev. Lett. 37, 8 (1976).
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.

[6] See, for example, P. Langacker, Phys. Rep. 72, 185 (1981) and references therein. J. Hisano et al., Nucl. Phys. B402, 46 (1993) [hep-ph/9207279].

[7] M. Veltman, Acta Phys. Pol. B12, 437 (1981).

[8] G. ’t Hooft, in proceedings of the Cargese Summer Institute on Recent Developments in Gauge Theories, edited by G. ’t Hooft et al. (Plenum Press, 1980)

[9] J. Gasser and H. Leutwyler, Nucl. Phys. B250, 465 (1985); Ann. Phys. 158, 142 (1984).

[10] J.M. Frere et al., Phys. Lett. B292, 348 (1992) [hep-ph/9207258]. M.A. Perez et al., Phys. Rev. D52, 494 (1995) [hep-ph/9506457].

[11] J. Wudka, Int. J. of Mod. Phys. A9, 2301 (1994) [hep-ph/9406205].

[12] C. Arzt et al., Nucl. Phys. B433, 41 (1995) [hep-ph/9405214].

[13] See for example, A. Pich, in proceedings of the Fifth Mexican School of Particles and Fields, Guanajuato, Mexico 1992 / edited by J.L. Lucio M. and M. Vargas (American Institute of Physics, 1994). [hep-ph/9303323] and references therein.

[14] A. Manohar and H. Georgi, Nucl. Phys. B234, 189 (1984). H. Georgi, Phys. Lett. B298, 187 (1993) [hep-ph/9207278].

[15] K. Hagiwara et al., Nucl. Phys. B282, 253 (1987).

[16] R.M. Barnett et al., Phys. Rev. D54, 1 (1996).

[17] M.B. Einhorn, in proceedings of the Workshop on Physics and Experiments with Linear $e^+e^-$ Colliders, Waikoloa, Hawaii, 26-30 April 1993, edited by F.A. Harris et al. (World Scientific, 1993). [hep-ph/9308331]. in proceedings of the International symposium on Unified symmetry: in the small and in the large, January 27-30, 1994 Coral Gables, Florida, edited by B.N. Kursunoglu et al. (Plenum Press, 1995) [hep-ph/9303323].

[18] R.P. Kauffman, Phys. Rev. D41, 3343 (1990). M. Gintner and S. Godfrey, in proceedings of the OCIP-C-96-5, Jun 1996 DPF / DPB Summer Study on New Directions for High-Energy Physics (Snowmass 96), Snowmass, CO, 25 Jun - 12 Jul 1996 [hep-ph/9612342]. T. L. Barklow, ibid. [hep-ph/9704217].

[19] Muon Quartet Collaboration (V. Barger et al.), in proceedings of the Conference on Future High-energy Colliders, Santa Barbara, CA, 21-25 Oct 1996 [hep-ph/9704291].
[20] F. Larios et al., Acta Phys. Pol. B27, 3741 (1996) (hep-ph/9609482).

[21] NLC ZDR Design Group, NLC Physics Working Groups (S. Kuhlman, et al.) Physics and Technology of the Next Linear Collider: A Report Submitted to Snowmass ’96 Report BNL 52-502, FERMILAB-PUB-96/112, LBNL-PUB-5425, SLAC-Report-485, UCRL-ID-124160, UC-41 (hep-ex/9605011).

[22] C.T. Hill and S.J. Parke, Phys. Rev. D49, 4454 (1994) (hep-ph/9312324).

[23] B. Grzadkowski, Report IFT-17-95 (hep-ph/9511274).

[24] B. Grzadkowski and J. Wudka, Phys. Lett. B364, 49 (1995) (hep-ph/9502415).

[25] T. Han and R. Sobey, Phys. Rev. D52, 6302 (1995) (hep-ph/9507409). A. Skjold and P. Osland, in proceedings of the 3rd Tallinn Symposium on Neutrino Physics, Lohusalu, Estonia, 7-11 Oct 1995. (hep-ph/9511453).