Measuring the $W$-$t$-$b$ Interaction at the ILC

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Abstract

The large top quark mass suggests that the top plays a pivotal role in Electroweak symmetry-breaking dynamics and, as a result, may have modified couplings to Electroweak bosons. Hadron colliders can provide measurements of these couplings at the $\sim 10\%$ level, and one of the early expected triumphs of the International Linear Collider is to reduce these uncertainties to the percent level. In this article, we propose the first direct measurement of the Standard Model $W$-$t$-$b$ coupling at the ILC, from measurements of $t\bar{t}$-like signals below the $t\bar{t}$ production threshold. We estimate that the ILC with 100 fb$^{-1}$ can measure a combination of the coupling and top width to high precision, and when combined with a direct measurement of the top width from the above-threshold scan, results in a model-independent measurement of the $W$-$t$-$b$ interaction of the order of $\sim 3\%$. 
1 Introduction

The mystery of electroweak symmetry breaking (EWSB) is the foremost problem in particle physics. Near-future colliders such as the Large Hadron Collider (LHC) and the International Linear Collider (ILC) are primarily motivated by their unique ability to make measurements which will reveal the mechanism of electroweak symmetry breaking. In the very least, a light Higgs is expected to be discovered. However, it is generally accepted that the physics at TeV energies will prove to be much richer than the minimal standard model (SM), and that the new paradigm will tie together many interesting puzzles, including the large hierarchy between the Planck and the electroweak scales, the nature of dark matter and dark energy, neutrino masses, and the puzzling pattern of flavor in both the quark and lepton sectors of the Standard Model.

At the center of many of these mysteries is the top quark. Its large mass, itself a manifestation of the broken electroweak symmetry, indicates that whatever the nature of the symmetry-breaking, it was communicated strongly to the top. In the minimal Standard model, this is represented by a large top Yukawa interaction and results in a special role for the top in Higgs physics. In the SM, the interactions with the gauge and Higgs bosons are predicted by the gauge structure, top mass, and unitarity of the CKM matrix. In models of physics beyond the Standard Model, the top often plays a special role in driving the electroweak symmetry breaking dynamics. In order to explore the possibility that the top plays a special role in EWSB, precise measurements of all top couplings are needed. In this article, we will explore how a future ILC can add to our knowledge of the $W$-$t$-$b$ interaction strength by looking for off-shell top quarks produced when the collider is running below the $t\bar{t}$ production threshold.

The charged current interaction of the top with the bottom quark and $W$ boson is predicted by the SM to be purely left-chiral with interaction strength,

$$g_{Wtb} \sim gV_{tb} \sim g,$$  \hfill (1)

where $g = e/\sin \theta_W$ is the $SU(2)_W$ coupling of the SM and $V_{tb}$ can be inferred from other elements using unitarity to be $0.9990 - 0.9992$ at the 90% CL\cite{1}. This coupling is of great practical importance in top physics, because it leads to the predominant decay mode $t \to Wb$. The observation of top in its expected channel (and lack of observation of other channels) \cite{2} is an indication that this decay is much larger than any competing decay mode. However, it does not allow for a measurement of the interaction, because the branching ratio ($BR$) is essentially unity, and thus does not depend sensitively on $g_{Wtb}$.

In models of physics beyond the Standard Model, the interaction may deviate from its SM expectation due to new strong dynamics \cite{3,4}, mixing of the top (and/or bottom) with a new vector-like family of quarks \cite{5,6}, or through mixing of the $W$ boson with some heavier $W'$ that prefers to couple to top \cite{7}. More generically, we can place bounds on the gauge invariant operators which extend the SM, and use these bounds to obtain information about the parameters of any theory which predicts a modification of the $W$-$t$-$b$ interaction. If we choose to realize the $SU(2)_L \times U(1)_Y$ of the SM non-linearly \cite{8}, as may be appropriate for theories in which EWSB is through unspecified or incalculable strong dynamics, the $W$-$t$-$b$ interaction is simply a free parameter corresponding to the operator,

$$g_{Wtb} \bar{t}\gamma^\mu W_\mu^+ P_L b + h.c.,$$ \hfill (2)
whose value is in principle predicted by the underlying strongly coupled theory. For extensions which realize the EW symmetry linearly, the coupling can be modified by dimension six operators \[\mathcal{O}_6\], an example of which is,

\[
\frac{1}{\Lambda^2} \left( \bar{Q}_3 D_\mu H \right) \gamma^\mu \left( H^\dagger Q_3 \right),
\] (3)

where the parentheses denote contractions of SU(2) indices and \(\Lambda\) represents the scale of new physics effects. Clearly, replacing the Higgs by its vacuum expectation value reduces Eq. (3) to terms including Eq. (2) with \(g_{Wtb} \sim v^2/\Lambda^2\). In our analysis, we focus on the lowest order (dimension 4) effects of Eq. (2). These are likely to be the first effects manifest in precision measurements. It is worth noting that as one sees from the generic operator above, most models will also modify other properties of the top quark, including its couplings to the Z boson and the Higgs. In such cases, a precise measurement of \(W-tb\) can be combined with other measurements to help unravel the nature of the underlying UV physics. For simplicity, we restrict ourselves to modifications of the left-chiral interaction, though right-chiral modifications are straightforward to include in our analysis.

Since top decays are ineffectual in measuring the \(W-tb\) interaction strength, one should use electroweak production processes whose rates are directly proportional to the coupling. Single top production at the Tevatron and LHC will fill this role. Discovery at the Tevatron seems likely by the end of its lifetime, and observation seems certain at the LHC. The uncertainties in rate at the LHC will be entirely dominated by systematics, and it is expected that a measurement of \(\delta V_{tb} \sim 10\%\) is possible [10]. Given the SM prediction inferred from unitarity at the better than percent level, it is important to consider other processes from which information about \(W-tb\) can be extracted. In particular, the International Linear Collider (ILC) represents a clean environment and is expected to achieve energies on the order of 500 GeV. It is an ideal place to learn about the top quark.

However, unlike many other top measurements, a direct test of the \(W-tb\) coupling is challenging at a \(\sim 500\) GeV \(e^+e^-\) collider. A scan over the \(tt\) threshold region is expected to yield precise measurements of many top parameters in the SM, including the top mass, width, and Yukawa coupling (see [11, 12] for projections), while above-threshold measurements may constrain anomalous, non-SM Lorentz structures [13]. Nevertheless, only an indirect measurement of the left-handed \(W-tb\) coupling is offered from the \(tt\) threshold region, by inferring its value from the SM relation and a precise value of the top width. If, for example, there is a small non-standard decay mode of top, it will alter the width and distort the inferred coupling. For example, if there is a small non-standard decay mode, the top’s total width becomes,

\[
\Gamma_t = \left( \frac{g_{Wtb}}{g} \right)^2 \frac{m_t^3}{2\sqrt{28\pi}} \left( 1 - \frac{M_W^2}{m_t^2} \right)^2 \left( 1 + \frac{2M_W^2}{m_t^2} \right) + \Gamma_{new},
\] (4)

where \(\Gamma_{new}\) represents some non-standard decay mode and we have neglected corrections of order \((m_b/m_t)^2\). It may be that this new decay mode can be observed in its own right, but if it is small or difficult to detect, it may be over-looked. In that case, the measurement of \(g_{Wtb}\) is actually distorted by the presence of the new physics itself.

Thus, it would be more desirable to have a direct measurement of \(W-tb\), by making use of a process which is directly proportional to it. Close to the \(tt\) threshold, sensitivity to the coupling is quite weak, because the rate is essentially the \(tt\) production cross section times the branching ratios.
for $t \rightarrow Wb$, which as explained above is not sensitive to $g_{Wtb}$. A $e\gamma$ collider can measure the rate of single-top production above threshold [14] to extract $g_{Wtb}$, but it is also worthwhile to see if the $e^+e^-$ running mode can be used to extract useful information below the $t\bar{t}$ threshold.

This article is outlined as follows. In Section 2 we explore $t\bar{t}$ below threshold and demonstrate the underlying dependence on $g_{Wtb}$. In Section 3 we examine how the signal may be extracted from the backgrounds, and determine our sensitivity to $g_{Wtb}$. We conclude in Section 4.

2 Leverage from Below the $t\bar{t}$ Threshold

Above the $t\bar{t}$ threshold, final state $W^+W^-b\bar{b}$ events have an uncut cross section of order 500 fb—dominated by $t\bar{t}$’s produced from s-channel $\gamma$’s and $Z$’s (see Figure 2). In the narrow top width approximation, the dominant piece of the cross section factors into a production cross section times the appropriate branching ratios:

$$
\sigma = \sum_{s_1s_2} \sigma \left( e^+ e^- \rightarrow t(s_1)\bar{t}(s_2) \right) BR \left( t(s_1) \rightarrow W^+b \right) BR \left( \bar{t}(s_2) \rightarrow W^-\bar{b} \right),
$$

where $s_{1,2}$ label the spin state of the $t$ and $\bar{t}$. Above threshold $\sigma$ has little or no dependence on $g_{Wtb}$. The $t\bar{t}$ production cross section is independent of $g_{Wtb}$, and the branching ratios are almost exactly unity.

Just below the $t\bar{t}$ threshold, the intermediate $t\bar{t}$ diagrams still contribute, along with other non-resonant Feynman diagrams, to the $W^+W^-b\bar{b}$ final state. At center-of-mass energies below $2m_t$ but still above $m_t$, the total rate is dominated by contributions from the virtual $t\bar{t}$ diagrams in a kinematic configuration where one top is on-shell and the other is off-shell. The rate becomes very sensitive to the $W-t-b$ interaction, essentially because the narrow width approximation is no longer valid when the top momentum is off-shell. The leading piece in the narrow width approximation
Figure 2: Rates for $e^+ e^- \rightarrow W^+ b W^- \bar{b}$ as a function of the center-of-mass energy for $g_{Wtb} = g_{SM}$ (black solid), $g_{Wtb} = 2g_{SM}$ (blue dashed), and $g_{Wtb} = g_{SM}/2$ (red dotted). Also shown for reference is the SM single top rate, $e^+ e^- \rightarrow tWb$ (violet dash-dot).

For the virtual top,

$$\frac{1}{(q_{t^*}^2 - m_t^2)^2 + m_t^2 \Gamma_t^2} \approx \frac{\pi}{m_t \Gamma_t} \delta\left(q_{t^*}^2 - m_t^2\right),$$

(6)

is zero, and one can no longer simply disentangle the cross section into production and decay rates.

This is illustrated in Figure 2, which plots the cross section as a function of energy for several values of $g_{Wtb}$, assuming a 175 GeV top mass and a 115 GeV Higgs mass. All analysis was performed using the MadEvent package \cite{15} at tree level. The cross-sections asymptote to the same value at both ends of the energy spectrum, as on-shell $t\bar{t}$ production dominates close to threshold and graphs not involving top dominate far below threshold. Both of these extremes are independent of the $W$-$t$-$b$ coupling, while energies in between these two extremes are suitable to measure $g_{Wtb}$. The inflection points in the intermediate region are due to the turn on of single-top and associated $W$ production (through graphs that do not contain a virtual top) at their 255 GeV threshold, and large $t\bar{t}^*$ contributions that dominate near $\sim 350$ GeV.

For our analysis, we assume a relatively large luminosity 100 fb$^{-1}$ of data collected at a single
center of mass energy. We avoid the region very close to $2m_t$ (despite its large rate), because the details of the transition from off-shell to on-shell do depend sensitively on the top width, which could obscure $g_{Wtb}$ if there are non-standard decay modes of the top. Instead, we focus on the energy $\sqrt{s} = 340$ GeV, just a few GeV above the peak statistical sensitivity to large deviations in $\delta g_{Wtb}$. Beam spread effects will not erase our sensitivity, but will contribute with a worse ratio of signal to background. The beam energy spread for a TESLA-like machine is expected to be at the 1% level \footnote{16} and its effect could be compensated by a more highly optimized choice of $\sqrt{s}$.

At 340 GeV, the fully interfering electroweak $W^+W^-b\bar{b}$ signal contains contributions from diagrams without any top propagators, that are reduced by requiring that the invariant mass of one $Wb$ system reconstruct to a top mass. The inclusion of the $tt$ diagrams enhances the cross section that passes an invariant top-mass cut by about a factor of two. This is not to say that single-top diagrams are unimportant; in fact, true single-top diagrams have maximum sensitivity to $g_{Wtb}$, while $tt$ diagrams have a sensitivity that decreases as $tt$ threshold is approached. From Figure 2, one can see that this sensitivity increases above the single top threshold, indicating that the $tt$ contribution is also important.

3 ILC Event Rates, Efficiencies and Backgrounds

We focus on the semi-leptonic six-body final state where one of the $W$’s decays to a pair of jets and the other $W$ decays into an readily tagged lepton: $e$, $\mu$ or $\tau$. To determine the variation of the signal that passes our cuts as a function of $g_{Wtb}$ and $\Gamma_t$, we calculate the variation in the rate of the intermediate final state $W^+bW^-\bar{b}$ and multiply by an overall efficiency factor. The efficiency is the Standard Model ratio of the six-body final state divided by the four-body final state, and intuitively is just the product of branching fractions and $b$-tagging efficiencies.

This efficiency factor oversimplifies the situation, as there can be interference in the full six-body final state, as well as new contributions from diagrams without the assumed $W^+W^-b\bar{b}$ intermediate state that manage to pass our cuts. These separate effects may change the dependence on $g_{Wtb}$ and $\Gamma_t$, but for small shifts of $g_{Wtb}$ are negligible and subdominant compared to our predicted statistical uncertainties, and less important compared to higher-order perturbative corrections. For example, shifting the top width by 100 MeV alters our efficiency from 14.5% to 14.4%. The purity of our sample (the ratio formed from the cross section of the fully interfering six-body final state to the decayed, on-shell $W^+W^-b\bar{b}$ state) is of order $\sim$ 90%. Thus, while the full six-body simulation will ultimately be important to extract the correct value of $g_{Wtb}$, we do not expect that our use of the four-body simulation leads to large changes in our estimation of the sensitivity with which $g_{Wtb}$ can be extracted.

In the four-body final state, we impose $|y| < 2$ and $p_t > 10$ GeV cuts on the $b$ jets and require that a single top mass is reconstructed to within 10 GeV, without assuming charge identification of the $b$ jets. In the six body final state with a negative sign lepton, we model the detector acceptance by requiring $p_t > 10$ GeV and $|y| < 2$ on all visible final state particles. In order to remove the non-top initiated backgrounds, we demand that both the untagged jets and the lepton/missing-energy system have an invariant mass within $\pm 5$ GeV of the $W$ mass, and that one top can be reconstructed from one of these $W$’s with either sign $b$ jet. The widths of the invariant mass acceptances are sufficiently broad for the few GeV jet energy uncertainty expected at the ILC \footnote{16}. We also assume a particle flow analysis that eliminates the need for strong lepton/jet isolation. We
Figure 3: The invariant mass of the hadronic “top” mass. The “No Cuts” histogram shows the distribution of the $jjb$ invariant mass, while the “After Cuts” histogram shows the invariant mass of the $jjb$ system after both $W$’s and a single top have been reconstructed.

Assume a $b$-tagging efficiency of 70%, and find that the SM is expected to produce $\sim 220$ events passing the cuts for $100 \text{ fb}^{-1}$ of luminosity.

The dominant background that is independent of the $W$-$t$-$b$ coupling comes from diagrams with an intermediate Higgs or $Z$ that decays to $b\bar{b}$, and could be eliminated by subtracting events with $b\bar{b}$ that have an invariant mass close to the (assumed known) Higgs and $Z$ masses. Still, most of these events are already cut out by demanding a single $t$ mass reconstruction (either leptonic or hadronic) as shown in Figure 3, which shows the invariant mass of the reconstructed hadronic “top”, which is the invariant mass of the $jjb$ system. The bump near 160 GeV represents the contribution from $t\bar{t}$ diagrams where the leptonic top is on-shell. We have considered the background from $4j+l+\nu$, where two of the light jets are mistagged as $b$’s. We find that the number of events that pass our cuts before applying the mis-tag probability is slightly smaller than the number of expected signal events, and thus the fake contribution after applying the double-mis-tagging probability is negligible.

The number of events observed will depend strongly on $g_{Wtb}$, the top mass, the top width, and (to some extent) the Higgs mass. It is expected that the ILC will determine the top and Higgs masses to order 100 MeV or better, which is enough to render the uncertainty in the rates from the uncertainty in these parameters order 1/10th of our expected statistical uncertainties, and thus are negligible. The remaining dependence on the width and $g_{Wtb}$ allows us to determine a combination of both these quantities. In Figure 4 we present the contours of constant event numbers in the plane of $g_{Wtb}$ and $\Gamma_t$ which reproduce the expected SM event rate of $\sim 220$ events (as the solid line). Also shown as the solid bands are the contours corresponding to 1σ and 2σ deviations from such a measurement (assuming that the SM rate is observed and considering purely statistical uncertainties since we expect these to dominate). The result is the expected bound one would obtain on $g_{Wtb}$ and $\Gamma_t$ if the SM rate is observed. Combining the below threshold cross section measurement with the $\Gamma_t$ extracted from the above-threshold scan allows us to extract both $g_{Wtb}$.
Figure 4: Curve corresponding to the region of the plane of $g_{Wtb}$ and $\Gamma_t$ which is degenerate with the SM event rate and its 1$\sigma$ and 2$\sigma$ deviations as the solid bands. Also overlaid is an expected measurement of $\Gamma_t$ from the on-shell threshold scan with an uncertainty of 100 MeV as the cross-hatched bands.

and $\Gamma_t$ independently. Alternately, one can go to lower energies where the sensitivity to $\Gamma_t$ is less, though at the price of the loss of some statistics. We have made the conservative assumption that $\Gamma_t$ will be known to order $\pm$100 MeV from the above threshold scan\cite{12}. From Figure 4 we see that given this assumption, $g_{Wtb}$ can be measured to the 3% level, which would represent better than a factor of 2 improvement compared to the LHC, and a major improvement in our understanding of the $W$-$t$-$b$ interaction.

4 Conclusions

The mass of the top quark is a strong indication that the top may play a fundamental role in the mechanics behind EWSB, or, if not, magnify the effects of any new physics through the lens of the large top Yukawa. If this new physics is sufficiently decoupled, shifts in the SM-like top couplings may be the only evidence left behind; it is no surprise that measuring the properties of the top quark will remain a collider focus for the next few decades.

Although single top production is usually ignored in $e^+e^-$ collisions, a measurement of $g_{Wtb}$ is not out of reach at the ILC. A significant amount of leverage is, counter-intuitively, provided by $t\bar{t}$ production below threshold. The results of our analysis are shown in Figure 5: we compute a 1$\sigma$ error in the $W$-$t$-$b$ coupling of order a few percent. This constraint is on par with the indirect
Figure 5: Expected bounds on SM-like couplings, axial $Z-t\bar{t}$ and left-handed $W-tb$, from direct LHC and ILC measurements. LHC bounds are shown in olive, ILC bounds in red. Superimposed are predicted deviations from representative models described in the text.

bound on $g_{Wtb}$ coming from the threshold measurement of the top-width, though the direct bound we present does not depend on a detailed understanding of all top decay modes and branching fractions, and thus is complementary to the measurement of the top width.

Figure 5 shows the new expected bounds on the SM-like top axial $Z-t\bar{t}$ and left-handed $W-tb$ interactions and the discriminating power the new bounds can place on new physics models. We include our results with the 1σ constraints on the independently varied axial $Z-t\bar{t}$ coupling from the LHC [17] and ILC [18], and the direct constraints on the left-handed $W-tb$ coupling from the LHC [10]. Predicted deviations from a few representative models are also superimposed: a Little Higgs model with T-parity, a model of topflavor, and a model with a sequential fourth generation whose quarks mix substantially with the third family. The Little Higgs $T$-parity model has a heavy top-partner, $T$, with mass 500 GeV (the numbers on the plot indicate the strength of the $h-T-t$ interaction) [19]; the topflavor model has a mixing angle $\sin \phi = .9$ (numbers indicate the mass of the heavy $Z'$) [7]. Top-seesaw models have the same mixing effect as the Little Higgs model, and thus trace out the same line in the plane of deviations in the $Z-t\bar{t}$ and $W-tb$ as the seesaw model parameters are varied.

Many improvements on our approximate results are possible. In particular, higher order QCD and EW corrections to the signal will be essential to include in a realistic analysis in order to obtain the desired accuracy in $g_{Wtb}$, particularly effects from initial state radiation and beamstrahlung, which will likely require stronger $\theta$ dependent cuts to cut down the resultant backgrounds. However, a consideration of the $4jbb$ final state could add a comparable amount of statistics to the semileptonic sample we’ve considered. Further, one could avoid the need for a large set of data at a single energy by performing several measurements of smaller integrated luminosities at a range of energies. This could allow one to use the energy dependent shape of the cross section as well as the normalization, and could potentially allow one to achieve comparable accuracy with much less integrated luminosity. We leave such refinements for future work.
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