Abstract

Recent studies done by the 'European Experimental Working Group on Top Quark Physics at the NLC', are briefly summarized. The studies concern three topics: threshold scan, measurement of the top Yukawa coupling and measurement of the top production and decay form factors.

1 Introduction

After several studies during the last ten years on the physics potential of a high energy linear e+e- collider (NLC) and its actual feasibility (see for instance references 1, 2), such a facility is emerging as a realistic complementary programme to the LHC effort. A linear e+e- collider with centre-of-mass energies in the range 350—1000 GeV has been shown to have a wide physics programme among which one of the most important topics is the detailed study of the properties of top quarks.

Top quarks will be copiously pair-produced at such a machine and, since they are heavier than the intermediate vector bosons, and maybe even heavier than the Higgs boson, it is not unreasonable to think that their properties might well be different from the ones of the lighter quarks and that they can shed some light over the mechanism of mass generation and provide valuable information for the understanding of flavour symmetries.

The dominant top production channel goes through the e+e- annihilation to a virtual photon or Z, which subsequently will decay to a tt pair. The tt production cross section is about 650 fb at \( \sqrt{s} = 500 \) GeV. The total production cross section, \( \sigma_{tt}(s) \), is particularly sensitive to the top Yukawa coupling and measurement of the top production and decay form factors.

2 Threshold scan studies

The large decay rate of the top quark implies that it decays before the toponia bound states have had time to form. More generally, \( \Gamma_t \) acts as an effective cut-off energy for non-perturbative QCD effects. This makes easier the studies and the predictions, in particular, near the tt production threshold.

The following topics in top quark physics will be discussed here: i) the measurements of the top quark mass and width in a centre-of-mass energy scan around threshold, ii) the possible direct determination of the ttH Yukawa coupling and iii) the determination of the top production and decay form factors.

3 Top quark mass and production form factors

The top quark mass is one of the most important phenomenological parameters in high energy physics. The measurement of the top mass and the possible determination of the top production and decay form factors are complementary programmes to the LHC effort. A linear e+e- collider with centre-of-mass energies in the range 350—1000 GeV has been shown to have a wide physics programme among which one of the most important is the detailed study of the properties of top quarks.

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The shape of the threshold is distorted by initial state radiation effects, which is about 2 GeV for \( m_t = 180 \) GeV. In all cases there will be two b jets. The total top quark width is given approximately by \( \Gamma_t \sim 0.18 \) GeV/mo, which is about 2 GeV for \( m_o = 180 \) GeV.

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The probability of charge confusion, relevant for the final result.

does not contribute significantly to the final result.

The position of the maximum of the momentum distribution was chosen because it was found to be rather insensitive to beam effects. The three observables are used in a \( \chi^2 \) fit assuming a nine-point scan around \( \sqrt{s} = 360 \text{ GeV} \) with an integrated luminosity of 5\,fb\(^{-1}\) in each point. Another 5\,fb\(^{-1}\) are assumed to be taken below the threshold in order to measure the background.

The fit has two free parameters: the top quark mass and \( \alpha_s \), which appears in the QCD dip potential. The resulting two-dimensional \( \chi^2 \) contours can be seen in Fig. 2. The overall precision expected in the top quark mass is around 200 MeV. The strong coupling constant at the Z scale is determined with a ±0.005 uncertainty. Most of the sensitivity comes from the total cross section measurement, with a non-negligible improvement coming from \( \frac{d\sigma}{dp} \). The forward-backward asymmetry does not contribute significantly to the final result.
The extra degree of freedom represented by \( \alpha_s \) can actually be viewed as a way to parameterize uncertainties in the binding QCD potential. For instance, in the scale at which the strong coupling constant has to be evaluated, or in the exact form of the long-distance part of the potential, although this has a limited impact due to the large top width.

The same data and observables can also be used to determine the top quark width. The forward-backward asymmetry is expected to be quite sensitive to the width. Since its origin lies in the interference of the \( S \) and \( P \)-wave amplitudes, a larger width implies more overlap between the two resonances and, therefore, larger asymmetry. The increase in \( \chi^2 \) when performing a fit similar to the one described above (nine energy points with 3 fb\(^{-1}\) each) with only \( \Gamma_t \) free is shown in fig. 3. The sensitivity of the asymmetry exists but it is rather modest. Including the three observables, the overall precision in the top quark total width will be around 10\%, for fixed values of \( m_t \) and \( \alpha_s \).

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### 3. Top Yukawa Coupling

Even if the MSM Higgs is found, the coupling to the other fundamental particles must be measured to check the Higgs mechanism. The Higgs coupling to fermions is proportional to the fermion mass squared, \( \lambda_f = (m_f/\sqrt{2})^2 \), in the standard model, the Yukawa coupling for the top quark is much larger than for any other fermion: \( \lambda_t \approx 0.5 \) whereas, for instance \( \lambda_b \approx 0.0004 \). Therefore, the top quark provides a unique opportunity to measure the Yukawa coupling.

The top Yukawa coupling might show its effects in several observables. It has some effect, for instance, in the interquark potential near the top production threshold and hence, indirectly affects the threshold observables discussed in the previous section. Rather than these sort of measurements, in this section we wanted to concentrate in the feasibility of a more direct measurement of this coupling.

For the direct measurement of the top Yukawa coupling, two different scenarios should be distinguished:

1. **"Heavy Higgs"** (\( M_H > 2m_t \)). In this case, the fermionic Higgs decays would predominantly be into \( HH \), which would compete with the bosonic Higgs decays. The Higgs could predominantly be produced either through the "standard" Bjorken mechanism \( e^+e^- \rightarrow HH \) or through the \( W \) fusion mechanism in \( e^+e^- \rightarrow WW \) and afterwards decay into \( H \). These processes constitute the basic mechanisms for Higgs searches and hence, have already been studied in that context by several authors.

2. **"Light Higgs"** (\( M_H \approx 2m_t \)). In this case, the fermionic Higgs decays would predominantly be into \( tt \). If the Higgs is heavier than twice the \( W \) or the \( Z \) mass they would compete with the bosonic decays. The Higgs could also be produced through "radiation" off a top ("Higgs-strahlung", see fig. 4). Since the detectability of this process had not been studied, that is the process that we want to discuss in detail.

#### 3.1 Theoretical aspects

The calculation of the "Higgs-strahlung" with only \( \gamma \)-exchange existed since long time\(^{14} \) and few years ago the complete calculation was also finished. Since at the NLC energies the \( \gamma \)-exchange contribution dominates by far, both calculations are in good agreement.

The total cross section, for any given value of \( M_H \), decreases at low \( \sqrt{s} \) due to phase space and also decreases at high \( \sqrt{s} \) due to unitarity. For the range of \( M_H < 700 \) GeV, the cross section is maximal around 750 GeV but reaches only \( 0(1-10) \) fb as can be gleaned from fig. 5.

Assuming "ideal" detection conditions (100% acceptance and 0% background) figure 6 shows for three different \( \sqrt{s} \) the sensitivity \( S \) to

![Figure 6](image_url)
and our selection procedure had the following steps:

\[ \chi^2 \text{ as a function of the Higgs mass, defined in such a way that} \]
\[ \Delta \chi^2 = \frac{1}{\sigma^2} \]
\[ \text{where } \sigma \text{ stands for the luminosity in } \text{fb}^{-1}. \]

Therefore, ideally one could make a measurement at the level of \( \Delta \chi^2 < 0.1 \) with 50 \( \text{fb}^{-1} \) for \( M_H < 240 \text{ GeV} \).

5.2 Experimental aspects

Using the calculation by Djouadi et al. we have written a complete M.C. event generator to make an experimental simulation of this process. The events have been processed with PYTHIA and smeared to simulate "standard detector" conditions.

Assuming that the Higgs decays with a 100% branching ratio into \( b \bar{b} \) (which is a good approximation for \( M_H < 160 \text{ GeV} \)) the signal consists in \( e^+e^- \rightarrow HZ \rightarrow W^+W^-b\bar{b}b \). By taking only hadronic \( W \) decays, then we have \( jjbjbjb \) so that the basic signature consists in a 8 jet event which has 4 \( b \) plus 4 non-\( b \) jets which can be selected using \( b \)-tagging plus 2 \( M_Bb \), 2 \( m_B \), and the \( M_B \) constraints. The analysis of the 4 \( b \) jet plus lepton and 4 jet plus 2 lepton configurations has not yet been carried out. We have simulated specifically the case in which \( M_B = 100 \text{ GeV} \) and our selection procedure had the following steps:

1. Require \( > 7 \) jets but force the event afterwards to have \( 8 \) jets.
2. Discard events with jets being just one lepton.
3. Apply \( b \)-tagging to the jets to classify them into \( b \) and non-\( b \) jets.

In this step we have assumed that \( b \) hadrons can be identified with very high efficiency (we take 100%) and a jet is assumed to be a \( b \) jet if, at least, half of its energy comes from \( b \) hadrons. Therefore the actual \( b \)-tagging efficiency that we assume is not 100% but it is still very high.
4. Find best \( W \)-mass combination for non-\( b \) jets.
5. Find best \( H \)-mass combination for \( b \) jets and require 80 GeV < \( M_B < 110 \text{ GeV} \).

Figure 7 shows the invariant mass distributions obtained. Concerning backgrounds, there are, for the signature that we have chosen to identify our signal, at least two potentially dangerous channels:

- \( (M_B < 2 \text{ rn}.) \)
- \( H \rightarrow H \)

The cross section is similar to the one of the signal but the requirement of \( Z \rightarrow b\bar{b} \) introduces an additional factor 10 decrease. The Higgs invariant mass cut could reduce in addition the background if the Higgs mass is slightly different from the \( Z \) mass, which is not the case for \( M_B = 100 \text{ GeV} \), our choice for the simulation. In our case, the signature of this process is irreducibly mixed with the one of the...
signal and hence, we have not directly simulated it but rather considered
that it would contribute unavoidably to about 10% of the signal.

(2) $e^+e^- \rightarrow \ell^\nu$ where, due to confusion in the jet assignment or due
to the actual production of additional $b\bar{b}$ pairs (for instance coming from
virtual gluon emission) the signal signature is diluted. In spite of the
a priori low probability of such a background, the fact is that, since the
cross section for $e^+e^- \rightarrow \ell^\nu$ is of about two orders of magnitude larger
than the one for the signal, some background might still be expected.
We have simulated this process by using JETSET.

The preliminary results of the selection for the signal and the back-
ground are shown in table 1. As can be seen in that table, even assuming
a 100% $b$-meson tagging efficiency, the total selection efficiency is smaller
than 30% and the signal to noise ratio is below 2. Therefore, our pre-
liminary conclusion is that the measurement seems to be at the limit
of being possible and, in any case, it is clear that a detailed simulation
of the background might still be expected.

We have simulated this process by using JETSET.

The production and decay of top quarks at a future linear collider pro-
vides opportunities to detect physics beyond the MSM. There can be
anomalous form factors associated to the production vertex which mod-
ify the $t\bar{t}$ coupling to the neutral electroweak current, and to the decay
vertex which modify coupling to the weak charged current. The presence
of such anomalous couplings, if large enough, would be observed in the
angular and energy distributions of the $t\bar{t}$ final state.

Top quarks are produced in $e^+e^-$ collisions with a high longitudinal
polarization. In contrast to lighter quarks, this polarization is not ob-
scured during hadronization because the top quark decays too quickly.
Consequently, the initial top helicity is transferred efficiently to the final
state.

The current operator can be written

$$\mathcal{L} = \gamma_\mu (F_+^\mu P_+ + F_-^\mu P_-) + \frac{\Delta m^2}{2M^2} (F_+^\mu P_+ + F_-^\mu P_-).$$

where $F^\mu$ are form factors. In the MSM, $F_+^\mu = F_-^\mu = F_0^\mu = 1$, $F_+^\mu =
g_1$, $F_-^\mu = g_2$, and $F_0^\mu = F_{\text{vir}}^\mu = 0$. A nonzero value for $F_+^\mu +
F_-^\mu$ would be caused by a magnetic quadrupole moment, and nonzero

![Figure 6: Ideal sensitivity function $S$ to $\lambda_3$ as a function of $M_H$ for different $E_{cm}$ (see text for the precise definition).](image)

![Figure 7: Reconstructed invariant mass distributions for the "Higgs-stabilizing" signal events. In the top mass distribution, the combinatorial background is also shown.](image)
value for $F'^{2}_{2} - F^{2}_{m}$ by a weak electric dipole moment. These would influence the production distributions for top quarks. If $F'^{2}_{2} / F^{2}_{m} < 0$, then there might be a $V + A$ admixture to the top charged current, or a $W_{p}$ boson. $F'^{2}_{2} / F^{2}_{m}$ is tested in the study of decay distributions of top quarks.

We have performed simple investigations of the production and decay distributions to estimate the statistical precision attainable at a future linear collider. The results are presented in the next two sections.

4.1 Production Vertex

The polar angle distribution of the $t\bar{t}$ pair contains, in addition to the usual $1 + \cos^2 \theta$ terms, a term proportional to $\sin^2 \theta$:

$$d\sigma/d\cos \theta = \sin^2 \theta \left[ F_1 (F_{11} + F_{11}) + \frac{1}{m_t^2} F_{21} (F_{21} + F_{21}) \right]$$

(3)

The normal spin-flip probability, proportional to $1/\sqrt{s}$, is augmented by a anomalous term which grows with energy.

The extra piece $(F_{11} + F_{21})$ in Eq. (3) increases the total cross section as well as changes the differential distribution. In order to extract information which was not already included in the cross section measurement, we chose to perform a maximum likelihood fit to the polar angle distribution to detect an anomalous $\sin^2 \theta$ piece:

$$F_{\text{fit}} = (1 - \delta) F_{\text{m}} + \delta F_{\text{anom}}$$

(4)

where $\delta$ is a single free parameter. (It is not the same symbol $\delta$ as used in Ref. 13.) The probability density for the MSM is assumed known (see for example Ref. 12); the anomalous piece is simply $\frac{1}{2} \sin^2 \theta$. A value for $\delta$ significantly greater than zero signals new physics.

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>500</th>
<th>750</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ (signal)</td>
<td>95</td>
<td>76.6</td>
<td>28.2</td>
</tr>
<tr>
<td>Events ($50 fb^{-1}$)</td>
<td>13.1</td>
<td>47.5</td>
<td>22.6</td>
</tr>
<tr>
<td>$t\bar{t}$ (background)</td>
<td>150</td>
<td>300</td>
<td>175</td>
</tr>
<tr>
<td>Events ($50 fb^{-1}$)</td>
<td>11.9</td>
<td>28.5</td>
<td>28.0</td>
</tr>
<tr>
<td>Signal/noise</td>
<td>1.2</td>
<td>1.7</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 2: Results of the experimental simulation for the Yukawa coupling measurement assuming an integrated luminosity of $50 fb^{-1}$.

<table>
<thead>
<tr>
<th>case</th>
<th>$\Delta \delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ideal</td>
<td>0.015</td>
</tr>
<tr>
<td>selection efficiency</td>
<td>0.026</td>
</tr>
<tr>
<td>acceptance (as function of $\theta$)</td>
<td>0.033</td>
</tr>
<tr>
<td>resolution</td>
<td>0.034</td>
</tr>
<tr>
<td>$R_{t}$ (15% probability)</td>
<td>0.038</td>
</tr>
<tr>
<td>backgrounds (20% contamination)</td>
<td>0.041</td>
</tr>
</tbody>
</table>

Samples generated with a top Monte Carlo program were fit to expression 4, and the distribution of $\delta$ examined to determine the statistical uncertainty. The toy program was tuned to approximate a full simulation for $m_t = 180$ GeV and $\sqrt{s} = 500$ GeV. At this energy the boost of the top quarks is sufficient to allow a reasonably precise measurement of their direction. It is not necessarily the most optimal energy for this measurement.

The top quark direction is taken to be the thrust axis of the event. An energetic, isolated electron or muon is needed to sign the angle. Simulations with PYTHIA give the efficiency of the selection, the resolution on the top direction, the acceptance as a function of polar angle, probability to miss the angle, and the non-top contamination. Detector performance was approximately that of the Aleph detector. All of these effects are incorporated in the toy program. An illustration of the reconstructed polar angle distribution is shown in Figure 8. The clear asymmetry from the top quark is evident despite the contamination, dominated by $W$ pairs and $b\bar{b}$, which peaks in the opposite direction.

The statistical sensitivity is given in Table 2, showing how it decreases as each realistic effect is included. Ultimately, the statistical error would be about $\Delta \delta = 0.04$, for an integrated luminosity of $50 fb^{-1}$.

4.3 Decay Vertex

The charged weak current in the MSM is pure $V - A$, leading to unambiguous predictions for the energy and angular decay distributions of leptons. A small admixture of $V + A$ interaction modifies these distributions; the difference between pure $V + A$ and pure $V - A$ is large for neutrinos in decays of down-type fermions, and for leptons in up-type fermions. The L3 Collaboration has used this difference to constrain the charged current in $b$ decays.
The theoretical work has been carried out by Jeiabek and others. The decay distributions are known including first order QCD corrections. They can be written in terms of a parameter $s$, such that $s_2 = (1 + s)/\sqrt{s + s^2}$ and $s_3 = (-1 + s)/\sqrt{s + s^2}$, so $s_2 = 0$ is the MSM and $s_3 = 0$ is pure $V + A$. (See Ref. 13 for complete expressions.) The experimental task is to constrain $s_3$ using as much information as possible from the lepton energy and direction, and if possible, from the neutrino.

These studies were performed using top decays simulated at threshold, since in this case the top spin points along the beam direction, and the energy and angle of the lepton in the lab frame are essentially the same as those in the top rest frame. An integrated luminosity of 100 fb$^{-1}$ was assumed.

The lepton energy and angular resolution is good enough so as to have little impact on the measurement. The neutrino measurement is less certain, due to unknown and variable losses to ISR, and detector acceptance. Nonetheless, a resolution of about 10% was obtained from the simulation. The energy and angular distributions for the lepton were condensed into a single "optimal" variable $w$, and for the neutrino, a separate variable $w$. The mean $w$ changes monotonically as a function of $s_3$.

The inclusion of more information results in a steeper line: a) lepton energy alone, b) neutrino energy and angle, c) neutrino energy and angle, d) lepton energy and angle, and e) lepton and neutrino energies and angles.

The increase in significance $\Delta w/\sigma_w$ as $s_3$ is increased. The inclusion of more information results in a steeper line: a) lepton energy alone, b) neutrino energy and angle, c) neutrino energy and angle, d) lepton energy and angle, and e) lepton and neutrino energies and angles.

**Acknowledgments**

We thank M. Chmeissani for his help in the early stages of this work. We are indebted to M. Jeiabek and his collaborators for providing us their computer programs for several of the studies discussed here, as well
References


