TOP QUARK PHYSICS AT A FUTURE e^+e^- LINEAR COLLIDER

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ABSTRACT

The physics potential of a Next e^+e^- Linear Collider with regards to top quark physics is discussed. Measurements in the vicinity of the $t\bar{t}$ production threshold yield a precise determination of the top quark mass and of the strong coupling constant α_S; the measurement is also sensitive to the top quark decay width and to its coupling to the Higgs field. Above threshold the top quark mass can be reconstructed from the $t\bar{t}$ final state. Angular correlations are sensitive to the form factors at the $t\bar{t}$ production and at the $t \to bW^+$ decay vertices. Searches for non standard final states, in particular for those predicted by minimal supersymmetry, are possible. Rare decay channels involving the $t\bar{t}H^0$ vertex may provide a unique opportunity to directly observe the top Yukawa coupling.

INTRODUCTION

Although the top quark has not been detected, there is ample indirect evidence for its existence from the isospin properties of the b quark (see: discussion in ref.[1]). Lower bounds on the top quark mass, m_t, are provided by direct searches at LEP and at hadron colliders [2], and precise measurements of the Z^0 lineshape at LEP suggest [3] the approximate bounds 120 GeV/$c^2 <$ $m_t <$ 180 GeV/c^2. It is therefore unlikely that LEP will discover the top quark ; on the other hand, existing or future hadron colliders are in a good position for doing so [4]. It will than be one of the goals of a Next High Energy e^+e^- Linear Collider (NLC hereafter) to measure in detail the top quark properties.

It is not within the scope of the present paper to discuss technical aspects related to the construction of the NLC. For the present discussion we rather assume the following properties which are necessary conditions for the efficient coverage of top quark physics: (a) The centre of mass energy, E_{cm} , can be varied from below the $t\bar{t}$ production threshold to $\approx$ 500 GeV. (b) A yearly "quantum" of integrated luminosity $\mathcal{L} = 10\ \mathrm{fb}^{-1}$ can be delivered. (c) The centre of mass energy is close to monochromatic (the effects of beam energy spread and beamstrahlung will be discussed later). (d) The electron beam can be longitudinally polarized. (e) Beam related backgrounds at the interaction point are reduced to a negligible level by adequate collimation. These properties, though requiring fine tuning of the collider parameters and careful design of the interaction region seem to be within reach [5].

Studies for an ideal detector layout are in progress. In global terms, detectors with properties similar to those currently installed at LEP and SLC are adequate for most purposes. Good geometric coverage, tracking and calorimetry, efficient electron and muon identification and b tagging by secondary vertex detection are the basic requirements. Most of the reported simulation work assumes a detector with such "standard" properties. (A "dead" cone with 10 degree half opening angle on either side of the interaction point is reserved for collimation against beam related backgrounds.)

The experimental approaches to tag top quark events are rather simple [6,7]. There is only one dominant production channel, the electroweak annihilation process $e^+e^- \rightarrow t\bar{t}$, and one dominant decay channel, $t \rightarrow bW^+$ [8]. Depending on the decay of the W boson, $t\bar{t}$ final states appear in three topologies: six jets (50%), 4 jets + 1 charged lepton (40%) and 2 jets + 2 charged leptons (10%). The $t\bar{t}$ cross section is typically of $\approx$ 1 pb. Although the main backgrounds from $e^+e^- \rightarrow q\,\bar{q} + \gamma$ + gluons ... (30 pb), $e^+e^- \rightarrow W^+W^-$ (10 pb) and $e^+e^- \rightarrow Z^0Z^0$ (1 pb) have high cross sections, these can be reduced by simple cuts based on event shape variables, jet-jet mass constraints and kinematic cuts, by selecting isolated high energy leptons and by identifying b flavour. One obtains typically a $t\bar{t}$ detection efficiency of 30% with a signal to background ratio of $\approx$10 in the 6 jet channel and 15% efficiency with much higher purity in the 4 jet + 1 lepton channel. Such event samples are adequate to treat the various physics issues which are discussed in the following sections.

May be the most outstanding property of the top quark which has largest impact on $t\bar{t}$ phenomenology is the very short lifetime, a consequence of the high mass and the rapid decay into $t \rightarrow bW^+$. The decay width Γ_t is proportional to the third power of m_t [8],

$$\Gamma_t \approx [0.18\ \mathrm{GeV}](m_t/m_W)^3$$

and amounts to $\approx$1 GeV for m_t=150 GeV/c^2. This has several important consequences: (i) The top lifetime is shorter than its revolution time in t$\bar{t}$ bound states. Toponium states can not develop and the rich spectrum typical for c$\bar{c}$ and b$\bar{b}$ is not present. (ii) Before the decay, the top quarks only separate to a distance of $\approx$0.01 fm. At such small distances perturbative QCD is a valid description of the t$\bar{t}$ system. (iii) The top quark decays before the t$\bar{t}$ system can hadronise. The production and decay vertices can thus be reconstructed at the parton level, and the initial top quark polarisation which probes the electroweak production process is reflected in final state distributions.

MEASUREMENTS AT THE t$\bar{t}$ PRODUCTION THRESHOLD

The rapid decay of the top quark acts as a "cutoff" against long range, non perturbative effects [9]. The shape of the excitation curve is therefore a precise prediction of perturbative QCD [9,10] and a sensitive measure of m_t and α_S . In a similar way, the differential cross section, $d\sigma/dP$ (where P is the intrinsic momentum of the top quark in the t$\bar{t}$ rest frame), also probes the QCD potential at short distance [11,12]. For illustration, Fig.1 shows the sensitivity of the excitation curve to α_S and the sensitivity of the differential cross section to m_t, for m_t=150 GeV/c^2. In practice, the value of m_t and α_S are extracted from a simultaneous measurement

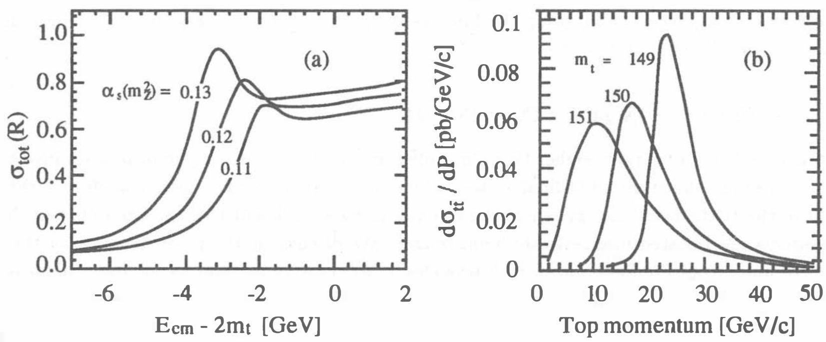

Fig. 1: (a) The t$\bar{t}$ excitation curve for m_t=150 GeV/$c^2$and its sensitivity to α_S. (b) The top momentum distribution for m_t=150 GeV/c^2 and E_{cm}=300 GeV and its sensitivity to m_t.

of the two distributions while the energy is varied over the t$\bar{t}$ threshold region. A detailed simulation was carried out by [13] (see also ref.[14]). The theoretical excitation curves and momentum distributions were modified by folding in initial state radiation, beam energy spread and beamstrahlung. To simulate the measurement a total luminosity of $\mathcal{L}$ = 10 fb^{-1} (1 year's "quantum") was distributed over 10 equidistand energy points. Realistic detection efficiencies and backgrounds were taken into account. The sensitivity of the measurement to m_t and α_S was obtained from a χ^2 fit where both parameters were varied independently. For m_t= 150 GeV/c^2, respectively, uncertainties of 300 MeV/c^2 and 0.006 were obtained (mainly statistical). For a top mass of 120 GeV/c^2 these numbers are 130 MeV/c^2 and 0.005, while for a top mass of 180 GeV/c^2, 520 MeV/c^2 and 0.009. The error on m_t is smaller by an order of magnitude than what is anticipated from hadron colliders [4]; as for α_S, it is similar to the error expected from the measurement of jet rates and hadronic event shapes at the NLC [15].

The excitation curve is also sensitive to Γ_t and to the (small) Yukawa coupling which acts as a supplementary attraction in the $t\bar{t}$ system and increases the cross section by a few percent [10]. The sensitivity was estimated [7] assuming perfect knowledge of m_t and α_S. For m_t=150 GeV/c^2 and $\mathcal{L}$ = 10 fb^{-1} the quoted error on Γ_t is ≈20%. On the other hand, if the Yukawa coupling has standard strength, the measurement is sensitive to Higgs boson masses not exceeding 120 GeV/c^2. Dedicated, high luminosity scans and precise assessment of the experimental systematic errors are required to further constrain these parameters.

The measurements just described put stringent requirements on the performence of the linear collider: an energy resolution of 10^{-3} is required if one aims to measure the detailed shape of the excitation curve. In addition to initial state radiation (which is independent of the collider design), there are two effects which degrade the monochromaticity of the c.m. energy, namely (i) the beam energy spread and (ii) beamstrahlung, that is the emission of hard photons by particles of one beam as they scatter off the electromagnetic field of the other beam. Even in the case of the most performing collider designs [5] (see also: Section 2 in ref.[6]) these effects would considerably degrade the sensitivity of the measurements. However, the sensitivity can be restored in part by monitoring the luminosity spectrum, $d\mathcal{L}/dE$, and by unfolding it from the measured distributions [16].

MEASUREMENTS IN THE $t\bar{t}$ CONTINUUM

Measurements at energies higher than $2m_t$ offer an equally rich spectrum of physics investigations through the study of $t\bar{t}$ final states. The most convenient c.m. energy is 50 to 100 GeV above the $t\bar{t}$ threshold energy where the top quarks have sufficient momentum and their decay products are boosted into separate hemispheres. We discuss (i) the reconstruction of the top quark mass from the final state which provides an alternative method to the determination at threshold and (ii) the measurement of the top quark form factors at the production and decay vertices.

(i) The top quark mass can be obtained from the measured four-vectors of the final state partons (jets). The procedure has been simulated for a detector with standard properties [6] where both the 6 jet and the 4 jet + 1 lepton final states were used (in the latter case the missing momentum vector was attributed to the neutrino). A kinematic fit was performed which used the beam energy and the W mass as constraints. After selection cuts to reduce the backgrounds the mass spectrum shown in Fig. 2 was obtained. From an event sample of $\mathcal{L}$ = 10 fb^{-1} the top mass was determined with a statistical accuracy of 150 MeV/c^2. The reconstructed mass was shifted by ≈500 MeV/c^2 with respect to the nominal top quark mass. The shift was traced to many effects which partially cancel each other, due to missing neutrinos, detector properties, to the shape of the luminosity spectrum and to uncertainties in the hadronisation process. In part these effects can be calculated or measured; there remains, however, a residual systematic uncertainty of ≈ 500 MeV/c^2. (In particular, hadronisation will have to be studied using the first large samples of $t\bar{t}$ events.) In conclusion it seems that this method is less accurate than the one based on the excitation curve. Nevertheless, the comparison will be an invaluable consistency check as the two methods are affected by widely different systematic errors.

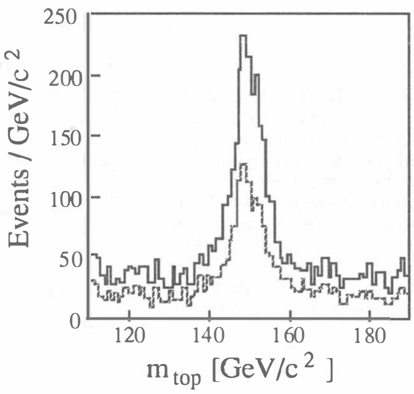

Fig. 2: The top quark mass reconstructed from the $t\bar{t}$ final state. Input values: m_t=150 GeV/c^2, E_{cm}=500 GeV, $\mathcal{L}$ = 7.5 fb^{-1}. Outer histogram: 6 jet final state; inner histogram: 4 jet + 1 lepton final state.

(ii) Following the discovery of the top quark, one of the key issues will be the detailed study of its production and decay properties and the comparison with standard model predictions. The production and decay currents, $j_\mu^{\gamma,Z}$ and j_μ^d, can be expressed in terms of left and right handed helicity components [17]:

$$j_\mu^a \sim \gamma_\mu(F_{1L}^a P_L + F_{1R}^a P_R) + (i\sigma_{\mu\nu}q_\nu/2m_t)[F_{2L}^a P_L + F_{2R}^a P_R]$$

($a = \gamma, Z, d$; $P_{L,R}$ are left and right handed projectors). For the form factors the standard model predicts

$$F_{1L}^{\gamma,Z} = F_{1R}^{\gamma,Z} = F_{1L}^d = 1$$

while all other form factors are zero. A non zero value for F_2 would indicate an anomalous magnetic or electric dipole moment of the top quark while a non zero value for F_{1R}^d indicates a right handed (V+A) component to the charged decay current.

Top quarks are produced polarised due to the γ-Z^0 interference. The rapid decay of the top quark prevents from depolarisation by the hadronisation process and, consequently, final state angular correlations truly reflect the initial top quark helicity. (This is at variance with light quarks where the formation of mesons and baryons and their subsequent decays destroy the memory on the initial helicity.)

Angular correlations are most conveniently measured in the 4 jet + 1 lepton final state where the lepton charge identifies the t and the $\bar{t}$. Beam polarisation, although not absolutely necessary, considerably increases the sensitivity to anomalous form factors.

Discussing first the $t\bar{t}$ production vertex, the cross section as a function of the $t\bar{t}$ production angle, $\theta_{t\bar{t}}$ (the angle to the beam axis), is sensitive to the top quark polarisation, and a deviation from the standard model prediction would reveal an anomalous magnetic moment as demonstrated in Fig.3. For a luminosity of $\mathcal{L} = 10$ fb^{-1}, the statistical sensitivity to the value of δ was estimated [18] as 0.01. In the standard model gluon exchange corrections induce an apparent magnetic moment which amounts to $\alpha_S/\pi \approx 0.04$ and set the scale for the precision

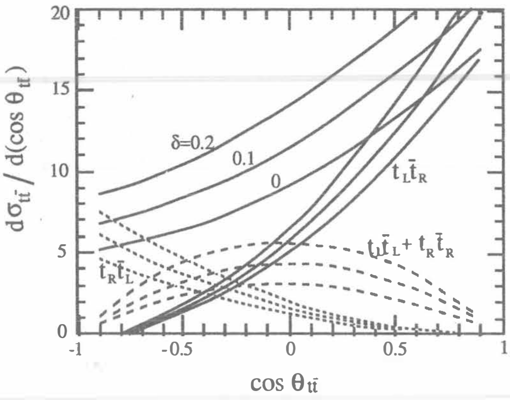

Fig. 3: Distribution of the $t\bar{t}$ cross section as a function of the production angle, and its decomposition into top helicity states. The sensitivity of the distribution to an anomalous magnetic moment, δ (in units of the Bohr magneton), is also shown. The curves are obtained for a left polarised electron beam.

required to look for effects beyond the standard model. An anomalous electric dipole moment of the top quark would manifest itself through a non zero expectation value for the CP-odd momentum tensor

$$T_{ij} = (q_+ - q_-)_i \frac{(q_+ \times q_-)_j}{| q_+ \times q_- |}$$

which is constructed from the lepton momentum components, $q_\pm$, using the 2 jet + 2 lepton final state (see ref.[19] for a detailed discussion). The statistical sensitivity for $\mathcal{L} = 10$ fb^{-1} is in the range (3 - 7)10^{-18} e.cm. Within the standard model, effects induced by CP-violation are smaller by several orders of magnitude, and one will have to invoke extended Higgs models or supersymmetry if an effect of comparable size is observed.

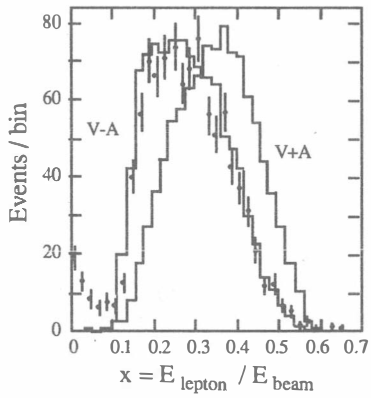

Fig. 4: Energy distribution of the lepton from $t \to bW^+ \to b(l\nu_l)$ decay for unpolarised beams. Inputs values: m_t=150 GeV/c^2, E_{cm}=305 GeV. The histograms correspond to the two extreme cases of a left handed (V-A) and a right handed (V+A) charged current. The "data" points correspond to $\mathcal{L} = 10$ fb^{-1}.

Turning to the top decay vertex, the most sensitive measure of the form factors is the event distribution in the plane of the two helicity angles χ_{Wt} and χ_{lW} [20] where the first is the W angle in the top quark rest frame and the second the lepton angle in the W rest frame. The sensitivity is substantially increased by selecting a $t\bar{t}$ sample with highly polarised top quarks. This can be done by using a polarised e^- beam and requiring for the production angle $\cos\theta_{t\bar{t}} > 0$, see Fig.3. The distribution in the two helicity angles is a precise prediction of the standard model. Non standard form factors, F^d_{1R} or F^d_2, induce local density variations which can be detected by a likelihood fit. The statistical sensitivity for $\mathcal{L} = 10$ fb^{-1} was estimated [18] to be at the 1% level. A right handed (V+A) coupling at the decay vertex also manifests itself in the energy distribution of the lepton from $W \to bl\nu_l$ decay [8], see Fig.4. The sensitivity for $\mathcal{L} = 10$ fb^{-1} and no beam polarisation was estimated as ≈5% [21].

RARE TOP QUARK DECAYS

The decay of the heavy top quark offers itself as a natural place to search for new particles. Minimal supersymmetry (MSSM) is an attractive first alternative to the standard model. Within that framework the two decay modes

$$t \to bH^+ \qquad \text{and} \qquad t \to \tilde{t}\tilde{\chi}^0$$

can occurr with branching fractions of a few percent. (H^+ is a charged Higgs boson, $\tilde{t}$ is the supersymmertic partner of the top quark and $\tilde{\chi}^0$ the lightest supersymmetric particle, the neutralino). One should keep in mind that if these particles have masses which allow the above decays to occurr, they will first be discovered by other means. Nevertheless, to search for these decays is important to determine the top quark couplings to non standard particles. The two decay channels are treated [22,23] in the theoretical context of supergravity

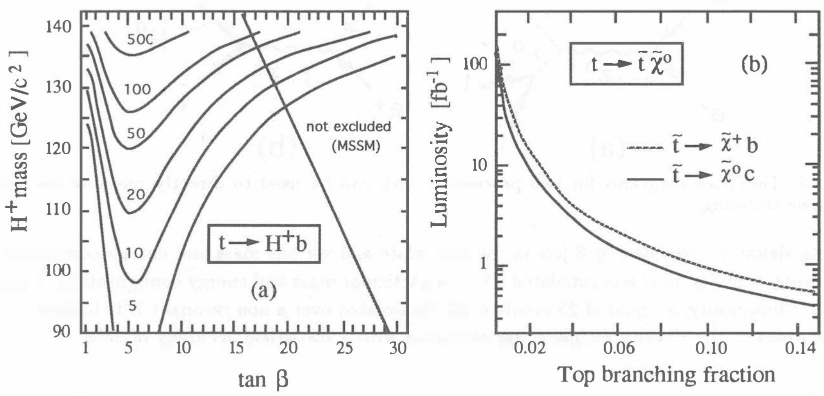

Fig. 5: (a) Sensitivity (3σ) in terms of the required luminosity in fb^{-1} to detect the $t \to bH^+$ decay for m_t=150 GeV/c^2 and E_{cm}=400 GeV. The region of the MSSM parameter space not excluded by present limits on SUSY particle masses is indicated. (b) Luminosity as a function of the top branching fraction, that is required to detect a (3σ) signal for the $t \to \tilde{t}\tilde{\chi}^0$ decay. Input values: E_{cm}=500 GeV, m_t=150, $m_{\tilde{t}} = 95$, $m_{\tilde{\chi}^+} = 50$ and $m_{\tilde{\chi}^0} = 35$ GeV/c^2.

by models with radiative breaking of the SU(2)xU(1) symmetry which reduce to MSSM at the low energy scale. Present experimental limits on supersymmetric particles impose restrictions to the MSSM parameter space but leave ample place for these decays to occurr [22]. (This will also be true after LEP200 assuming here that the searches will be negative.) (i) The decay $t \rightarrow bH^+$ followed by $H^+ \rightarrow \tau^+\nu_\tau$ leads to an excess of $\tau^\pm$ leptons and to an apparent violation of lepton universality which can be exploited as an experimental signature. Detailed simulations [24] have shown sensitivity to this decay over a large portion of the MSSM parameter space, see Fig.5 (a), especially at large $\tan\beta$, a region which is not excluded by present searches [22].

(ii) The $t \rightarrow \tilde{t}\tilde{\chi}^0$ decay is followed by $\tilde{t}$ decaying either to $c\tilde{\chi}^0$ or to $b\tilde{\chi}^+$ ($\tilde{\chi}^+$ is the chargino). In either case the final state has considerable missing energy in the hemisphere where the non standard top quark decay has occurred. This was used as a signature in a simulation [24] which resulted, for a particular choice of masses, in the sensitivity shown in Fig.5 (b). These studies demonstrate on the basis of a few examples the power of the NLC to reveal non standard decay channels of the top quark.

DIRECT OBSERVATION OF THE TOP YUKAWA COUPLING

Final states produced *via* the $t\bar{t}H^0$ vertex are of particular interest [8] as they offer perhaps a unique way to directly measure the top Yukawa coupling, g_t, and to verify its relation to the top mass,

$$g_t^2 = \sqrt{2}G_F\, m_t^2.$$

Depending on the masses of the top and Higgs particles, one of the two processes shown in Fig. 6 may occurr. The low cross section of a few fb makes the observation rather difficult despite a

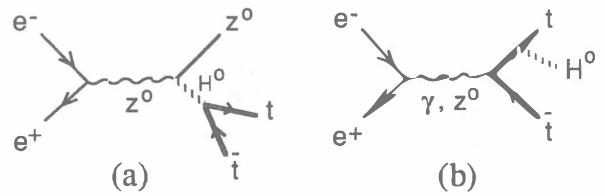

Fig. 6: Feynman diagrams for two processes which can be used to directly measure the top Yukawa coupling.

strong signature provided by 8 jets in the final state and various mass and energy constraints. The process in Fig. 6(a) was simulated [14] for a particular mass and energy configuration. Using 60 fb^{-1} luminosity, a signal of 25 events could be isolated over a non resonant $Z^0t\bar{t}$ background of 10 events. The Yukawa coupling was extracted with a statistical accuracy of 25%.

SUMMARY

The Next e^+e^- Linear Collider will offer a rich spectrum of precise measurements in the top quark sector. These are fundamental to test the standard model and to look beyond. The top quark mass will be measured with an accuracy of a few 100 MeV/c^2 which is better by an order of magnitude than what can be anticipated from hadron colliders. The $t\bar{t}$ system is a clean laboratory for perturbative QCD and allows one to measure α_S with an error of about 0.006;

this is comparable to the accuracy which is expected from the measurement of hadronic event shapes at the NLC. The top quark form factors at the production and decay vertices can be determined with an accuracy of a few percent. Deviations from the standard model predictions would indicate, for example, an anomalous magnetic or electric dipole moment of the top quark, or a right handed component in the charged decay current. Non standard decay channels such as those predicted by minimal supersymmetry can be searched for with high efficiency. Finally, if the relation between the top quark mass to the Higgs boson mass is favourable, there is hope to directly measure the top Yukawa coupling by observing final states which involve the $t\bar{t}H^0$ vertex. This physics programme puts stringent requirements onto the collider, especially with regards to the monochromaticity of the c.m. energy.

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