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Top quark physics at Linear Colliders

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Top quark production in the process $e^+e^- \rightarrow t\bar{t}$ at a future linear electron positron collider is an essential pillar of the physics programme that will be carried out with such a machine. For the first time it will be possible to study top quark pair production through electro-weak processes. This offers exciting possibilities to make high precision measurements at the top-pair threshold and, at higher energies, to determine the electroweak couplings of the top quark in an unambiguous way.

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1. Introduction

With the discovery of the Higgs Boson with a mass of $m_h \approx 125$ GeV by the LHC the Standard Model of particle physics is complete. The Standard Model is a quantum field theory featuring $SU(2)_L \times U(1)_Y$ symmetry. This symmetry is spontaneously broken at the electroweak scale leading to non-zero masses of the gauge bosons and the fermions. The breaking of the symmetry is associated to a scalar field that develops a non-zero vacuum expectation value. Today it is however unknown what is at the origin of the symmetry breaking and what generates the detailed shape of the Higgs potential. A special role in the search for physics beyond the Standard Model will be played by the top quark, or t quark. With a mass of about $m_t \approx 173$ GeV [1] it is the heaviest known elementary particle today and tantalisingly close to the electroweak symmetry breaking scale. Text passages in the following summary are largely inspired by Refs. [2] and [3].

2. The top quark

A linear electron positron collider such as ILC [4] or CLIC [5], briefly named LC hereafter, would be the first machine at which the t quark is studied using a precisely defined leptonic initial state. Therefore individual events can be analysed in more detail. It also changes the production mechanism for t quark pairs from the strong to the electro-weak interactions, which are a step closer to the phenomena of electro-weak symmetry breaking. Finally, this change brings into play new experimental observables – weak interaction polarisation and parity asymmetries – that are very sensitive to the coupling of the t quark to possible new interactions. It is very possible that, while the t quark might respect Standard Model expectations at the LHC, it will break those expectations when studied at the LC. Unless stated otherwise all results presented in the following are based on full simulation studies of the LC detectors ILD and CLIC detector.

2.1 $e^+e^- \to t\bar{t}$ at threshold

One of the unique capabilities of an e^+e^- linear collider is the ability to carry out cross section measurements at particle production thresholds. The accurately known and readily variable beam energy of a LC makes it possible to measure the shape of the cross section at any pair-production threshold within its range. Because of the leptonic initial state, it is also possible to tune the initial spin state, giving additional options for precision threshold measurements. The $t\bar{t}$ pair production threshold at a centre-of- mass energy $\sqrt{s} \approx 2m_t$ allows for precise measurements of the t quark mass m_t as well as the t quark total width Γ_t and the QCD coupling α_s. Because the top is a spin-$\frac{1}{2}$ fermion, the $t\bar{t}$ pair is produced in an angular S-wave state. This leads to a clearly visible rise of the cross section even when folded with e.g. the ILC luminosity spectrum as shown in Fig. 1.

A simultaneous fit may allow to extract simultaneously the t quark mass, it's width Γ_t and the top-Yukawa coupling y_t. In this case the expected statistical accuracies for $200\,\mathrm{fb}^{-1}$ of integrated luminosity are: $\delta m_t \approx 17$ MeV, $\delta\Gamma_t \approx 26$ MeV and $\delta y_t = 4.2\%$. The measurement of the latter becomes possible since the virtual exchange of the Standard Model Higgs boson enhances the cross section at threshold by about 9% The dependence of the t quark cross section shape on the t quark mass and interactions is computable to high precision with full control over the renormalisation scheme dependence of the top mass parameter. A recent publication [7] shows that the 1S mass

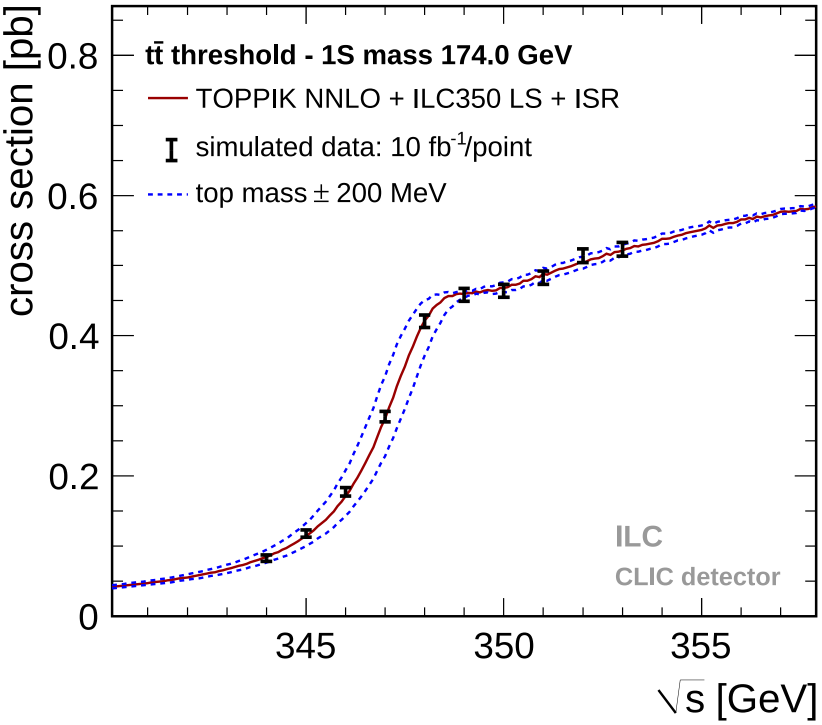

Figure 1: *Result of a simulation study of a top threshold scan that includes the luminosity spectrum of the ILC beams. The figure is taken from [6]*

as resulting from the described analysis can be translated to e.g. the $\overline{MS}$ mass, typically used in theoretical calculations to a precision of about 10 MeV.

2.2 Open top production

The Refs. [17, 3] report on the determination of CP conserving form factors and couplings based on a full simulation study of the reaction $e^+e^- \to t\bar{t}$ at a centre-of-mass energy of $\sqrt{s} =$ 500 GeV with 80% polarised electron beams and 30% polarised positron beams. The unique feature of linear colliders to provide polarised beams allow for a largely unbiased disentangling of the individual *L*eft and *R*ight handed couplings of the t quark to the Z^0 boson and the photon, $g^{\gamma,Z}_{L,R}$ or equivalently of the form factors $F^{\gamma,Z}_{(1,2),(V,A)}$. These quantities can be measured at the sub-percent level at a LC. This is, when referring to the results in [18, 19], considerably better than it will be possible at the LHC even with an integrated luminosity of $\mathscr{L} = 3000\,\text{fb}^{-1}$. The improving analyses of the LHC experiments, as e.g. [20], will however be observed with great interest.

Beam polarisation is a critical asset for the high precision measurements of the electroweak t quark couplings. Experimental and theoretical effects manifest themselves differently for different beam polarisations. It seems to be that the configuration positive electron beam polarisation is more benign in both, experimental aspects due to the suppression of migrations in the polar angle spectrum of the final state t quark, see e.g. [17, 3] and theoretical aspects due to the somewhat simpler structure of higher order electroweak corrections [21]. It is intuitively clear that the described facts

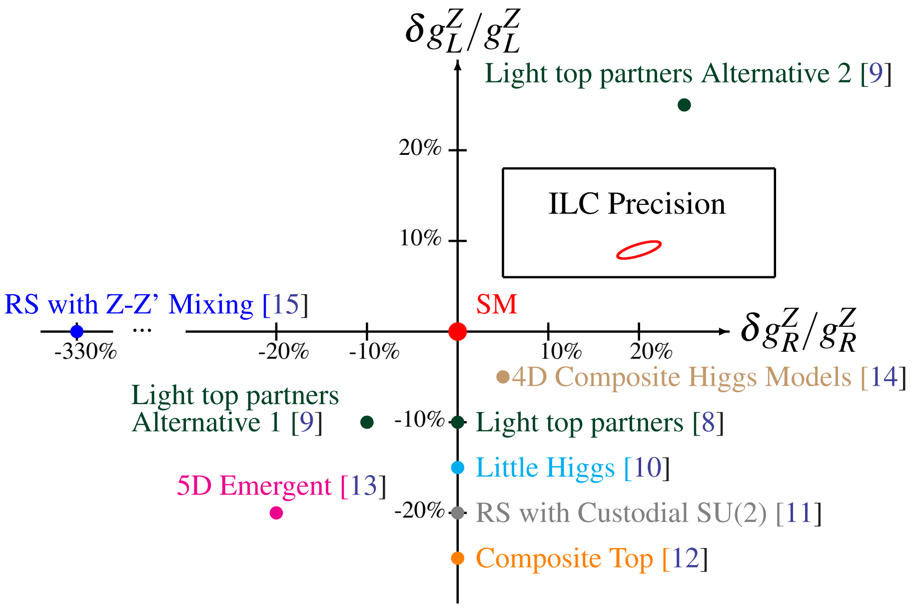

Figure 2: *Predictions of several models that incorporate Randall-Sundrum (RS) models and/or compositeness or Little Higgs models on the deviations of the left- and right-handed couplings of the t quark to the Z^0 boson. The ellipse in the frame in the upper right corner indicates the precision that can be expected for the ILC running at a centre-of-mass energy of $\sqrt{s} = 500$ GeV after having accumulated $\mathscr{L} = 500\,\mathrm{fb}^{-1}$ of integrated luminosity shared equally between the beam polarisations $\mathscr{P}_{e^-}, \mathscr{P}_{e^+} = \pm 0.8, \mp 0.3$. The original version of this figure can be found in [16].*

would greatly support the discovery of effects due to new physics. The precision as expected for a LC would allow for the verification of a great number of models for physics beyond the Standard Model. Examples for these models are extra dimensions and compositeness, see Fig. 2. The current results constitute therefore a perfect basis for discussions with theoretical groups. Note at this point that the community currently discusses running scenarios for the ILC that would yield up to eight times more luminosity [22] than has been assumed so far. Moreover it can be expected that the event reconstruction will be improved by e.g. the measurement of the b quark charge. Already from the achieved precision it is mandatory that systematics are controlled to the 1% level or better in particular for the measurement of the cross section. A study of systematic errors will therefore become very important and is addressed in ongoing studies.

Finally, the study presented in [21] based on generated events suggests that by exploiting the polarisation of the final state t quarks a simultaneous extraction of all anomalous top form factors, including the *CP* violating $F_{2,A}^{\gamma,Z}$, to a precision below the percent level is feasible. A detailed comparison between the advantages and drawbacks of the method applied there and the method presented in [3] is left for a future study.

3. Summary and outlook

Parameter	Initial Phase	Lumi-Upgrade	units	ref.
m_t	50	50	MeV (m_t(1S))	[6]
Γ_t	60	60	MeV	[23]
g_L^γ	0.8	0.6	%	[3]
g_R^γ	0.8	0.6	%	[3]
g_L^Z	1.0	0.6	%	[3]
g_R^Z	2.5	1.0	%	[3]
F_2^γ	0.001	0.001	absolute	[3]
F_2^Z	0.002	0.002	absolute	[3]

Table 1: Projected accuracies for top physics parameters at the two stages of the ILC program proposed in the report of the Joint Working Group on ILC Beam Parameters [22]. The relevant running phases for these projections are an initial phase with 500 fb^{-1} at 500 GeV, 200 fb^{-1} at 350 GeV, and a luminosity-upgraded phase with an additional 3500 fb^{-1} at 500 GeV . Initial state polarisations are taken according to the prescriptions of [22]. Uncertainties are listed as 1σ errors computed cumulatively at each stage of the program. These estimated errors include both statistical uncertainties and theoretical and experimental systematic uncertainties. The table has been extracted from [2].

At the example of the ILC the results discussed in the previous sections are summarised in Table 1. These are all based on full simulation studies of linear collider detectors and proof the outstanding potential for top physics at a LC. The studies at threshold and in the continuum have reached a level of maturity and precision that now the experimental sensitivity to higher order effects (QCD and electroweak) has to be studied as well the impact of issues arising from the full six-fermion final state. The results presented at the conference have triggered already considerable efforts on theoretical and experimental side that will be interesting to follow in the near future.

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