PROCEEDINGS OF SCIENCE

# Toward Precision Top Quark Measurements in $e^+e^-$ Collisions at Linear Colliders

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Linear lepton colliders offer an excellent environment for precision measurements of the top quark. An overview is given of the current prospects on the measurement of the top quark mass, rare top quark decays and top quark couplings at the International Linear Collider (ILC) and the Compact Linear Collider (CLIC).

*EPS-HEP 2017, European Physical Society conference on High Energy Physics*
*5-12 July 2017*
*Venice, Italy*

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PoS(EPS-HEP2017)470

## 1. Introduction

Up to now, top quarks have only been studied at hadron colliders, but there is a significant advantage of studying them at lepton colliders. Due to the relatively clean experimental conditions and the absence of QCD backgrounds a high experimental and theoretical precision can be reached at these colliders. Additionally, polarisation of electron and positron beams that is possible at linear colliders enhances that sensitivity by increasing selected cross sections and adding chiral observables.

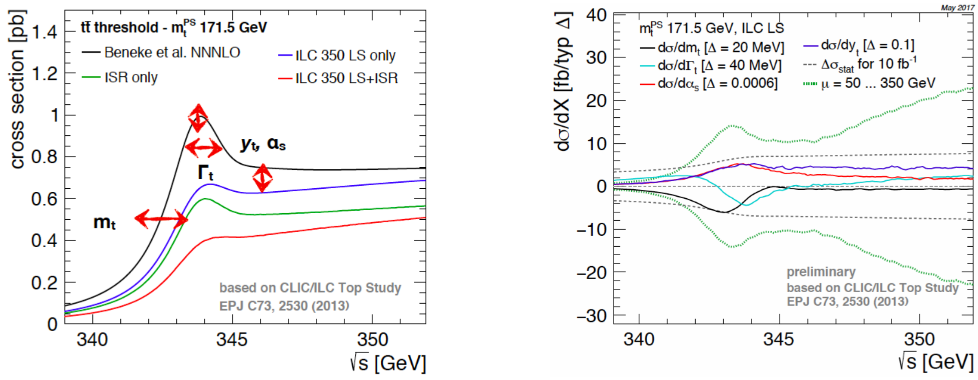
By operating the collider in energy steps around the top quark pair production threshold, which is situated at approximately 350 GeV, the mass and electroweak (EW) couplings of the top quark can be determined to high precision both experimentally and theoretically. Further, at 350 GeV and above the top quark pair production threshold $e^+e^-$ collisions are is an excellent tool for exploring possible physics scenarios that go beyond the Standard Model (BSM). By precision measurements of the EW couplings of the top quark new physics scenarios can be tested.

Two linear lepton colliders are currently proposed, the International Linear Collider (ILC) [1] and the Compact Linear Collider (CLIC) [2]. Both can reach energies beyond the top quark production threshold; CLIC is designed up to 3 TeV and ILC for 500 GeV, with a possible upgrade to 1 TeV. Both machines are designed to operate at several centre-of-mass energies, optimising their physics potential. The ILC at 250 GeV, 350 GeV and 500 GeV, collecting 2, 0.2, and 4 ab$^{-1}$, respectively [3] following the foreseen luminosity upgrade scenario. CLIC will be operated at 350, 380, 1500 and 3000 GeV, collecting 0.1, 0.5, 1.5 and 3 ab$^{-1}$ at these energies [4].

## 2. Top quark properties

The top quark properties (mass, width, and Yukawa coupling) are important parameters in the Standard Model. A precise measurement of these properties is therefore important to understand the special role of the top quark in electroweak symmetry breaking. The production cross section of top quark pairs around their production threshold depends on the top quark properties and on the strong coupling constant $\alpha_s$. A threshold scan, performed by repeated measurements of the cross section at several energy points around the top quark pair production threshold, allows to extract the top quark properties from a fit to the cross section versus energy [5]. Figure 1a illustrates how the shape of the cross section depends on the top quark properties, according to NNNLO QCD calculations [6]. As one can see the cross section is also influenced by initial state radiation (ISR) and the luminosity spectrum (LS) of the accelarator.

A threshold scan yields the most accurate measurement of the top quark mass. For a 10 step threshold scan where 10 fb$^{-1}$ is recorded at each step the experimental systematic uncertainly is of the order of 40 MeV, and the statistical uncertainty of the order of 20 MeV for ILC and about 10 % higher for CLIC, due to the larger energy spread in its luminosity spectrum. Due to the high experimental precision, QCD scale variations dominate the final uncertainty and are therefore taken into account in the analysis [8]. Figure 1b illustrates the cross section uncertainty due to QCD scale variations compared to the expected statistical uncertainties in a full ILC simulation using the International Large Detector (ILD) concept [9]. The current prospect on the uncertainty due to QCD scale variations is 40 MeV, and the uncertainty due to the value of $\alpha_s$ is, with the current




(a) (b)

Figure 1: (a) Threshold scan of the top quark pair production cross section from NNNLO QCD, illustrating the influence of the top quark properties, QCD and experimental conditions for the ILC [7]. (b) Uncertainty on the top quark pair production cross section due to QCD scale variations (green line) compared to expected statistical uncertainties at a linear collider [7].

world average, 35 MeV. Together this gives a total uncertainty on the top quark mass in the order of 40 - 75 MeV in the PS mass scheme. Converting to e.g., the $\overline{MS}$ scheme, increases the uncertainty due to $\alpha_s$ to 60 MeV [7]. At hadron colliders the total uncertainty on the mass is more than an order of magnitude larger than at lepton colliders, mainly due to the theoretical framework being much less well defined. The current experimental uncertainty on the top quark mass at the LHC is 480 MeV [10] and a projection for the HL-LHC estimates ultimately 170 MeV [11]. However, the theoretical uncertainty in translating the measured mass into a theoretically well defined mass is much larger, of the order of 1 GeV [11].

From the threshold scan one can also extract top quark properties simultaneously, e.g. the combination of mass and width, or the combination of mass and Yukawa coupling, using a 2D template fit of the cross section. The uncertainties increase with respect to the extraction of single quantities due to correlations, but improvement is expected by using additional observables such as momentum and forward-backward asymmetry $A_{FB}$ [7].

Above the top quark pair production threshold, in the continuum, one can extract the top quark mass directly over a large range of energies and probe the possible running of the top quark mass. The mass can be determined from radiative events, either with ISR or final state radiation (FSR). For events with ISR the cross section depends on the energy of the radiated photon and for events with FSR the radiated gluon energy depends on the mass of the top quark. While the ISR channel is most sensitive near the top quark pair production threshold, the FSR channel is sensitive over a large energy range. A recent particle level study showed very promising results; a precision in the order of 100 MeV can be reached [12]. Full simulation studies are in progress.

## 3. Rare top quark decays

The clean experimental environment at lepton colliders enables the study of rare top quark decays. For example, flavour changing neutral current (FCNC) decays are heavily suppressed in the Standard Model, but have much enhanced branching ratios, of the order of $10^{-2} - 10^{-4}$, in many BSM models. Observing such a decay would therefore point directly to the existance of new physics processes that are not included in the standard model. Two decay channels are being studied in full simulations at the moment; $t \to cH$ and $t \to c\gamma$, with the aim to determine the exclusion limits on the branching ratios. Selecting the signal events among the standard top quark pair decays relies heavily on the correct identification of $b$ quarks ($b$-tagging). These ongoing studies illustrate that very competitive limits for these FCNC channels can be reached at CLIC and ILC.

The $t \to cH$ decay is particularly difficult to measure at the LHC because the Higgs is hard to identify in the hadronic channel, while the reconstruction at lepton colliders is straightforward. The projected limits for HL-LHC with 3 ab$^{-1}$ at 14 TeV are of the order of $2 \times 10^{-4}$ [13]. For CLIC at 380 GeV with 500 fb$^{-1}$ the current analysis reaches $1.4 \times 10^{-4}$ in the fully hadronic decay channel [14]. For the $t \to c\gamma$ channel the most stringent measurement is $1.7 \times 10^{-3}$ from CMS at 8 TeV [15]. For HL-LHC improvement by one order of magnitude is expected [16]. The analysis for CLIC at 380 GeV shows that limits in the range of $10^{-4}$, and possibly smaller, are in reach at lepton colliders [17].

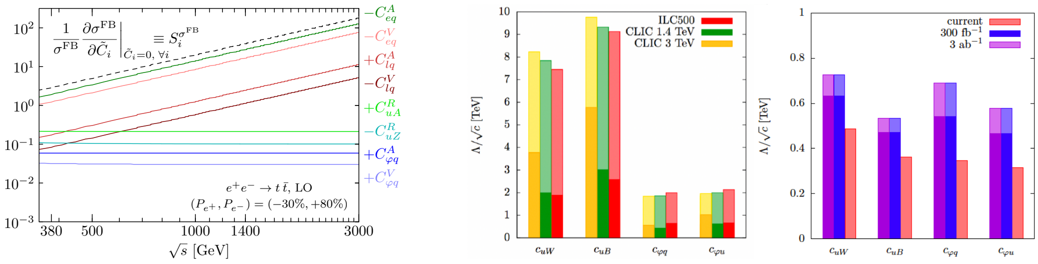
## 4. Electroweak couplings

The top quark provides the ideal environment for investigating the existence of BSM physics. With precision measurements of the EW couplings one can detect small deviations of standard model observables that can point to the presence of new physics processes. By combining the measurement of the top quark pair production cross section and the forward-backward asymmetry $A_{FB}$ for different beam polarities and energies, one can achieve a high precision of the top quark form-factors [18].

Such a global fit can also be cast into the parametrised form of dimension-6 operators in an effective field theory (EFT) approach [19, 20]. The precision on some of the coefficients benefit from a higher centre-of-mass energy, in particular coefficients associated with the 4-fermion contact interactions. This is illustrated in Fig. 2a, which shows the expected sensitivity of several coefficients as a function of the centre-of-mass energy. The coefficients were extracted from full simulations of the forward-backward asymmetry.

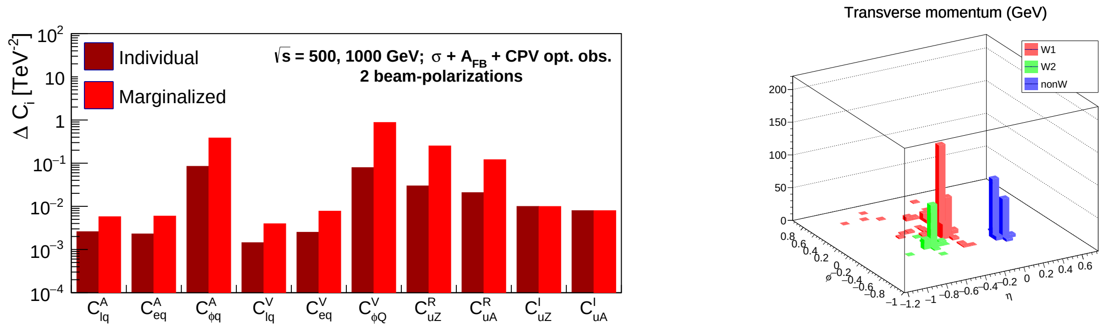
In the EFT framework one can test the presence of any type of new physics; the sensitivity to the new physics scale is presented in Fig. 2b for the ILC and CLIC on the left and for the LHC on the right. The superior sensitivity at CLIC and ILC compared to the LHC is clearly seen [21].

The global fit can be improved by using an optimal combination of observables, so-called optimal variables. This is currently done for a study of CP-violating couplings. CP-violating effects manifest themselves in top quark spin correlations that are propagated to the daughter particles of the short lived top quark. From the asymmetries constructed from the lepton 4-vector in semi-leptonic decays one can extract the corresponding form-factors [23]. In an EFT framework these CP-violating coefficients, $C_{uZ}$ and $C_{uA}$, show no difference between the individual fit (where only one variable is changed) and the marginalised fit (where all variables are allowed to vary at the same time), showing that these variables are optimal (see Fig. 3a). EW couplings can also be extracted at higher centre-of-mass energies as available in the CLIC baseline design with collisions at 1.5




(a) (b)

Figure 2: (a) Sensitivity of several dimension-6 EFT coefficients as a function of the centre-of-mass energy from the measurement of the forward-backward asymmetry [22]. (b) New physics scale, from a marginalised fit (in darker colours) and individual fit (in lighter colours), in reach for the ILC at 500 GeV (4 $ab^{-1}$) and CLIC at 1.4 TeV (1.5 $ab^{-1}$) and 3 TeV ($ab^{-1}$) and the LHC for different luminosities [21].




(a) (b)

Figure 3: (a) Limits for CP-conserving and CP-violating coefficients using cross-section, forward-backward asymmetry $A_{FB}$ and optimal CP-odd observables from an individual fit (dark red) and a marginalised fit (light red) extracted from a combination of simulations at 500 GeV (500 $fb^{-1}$) and 1 TeV (1 $ab^{-1}$) [22]. (b) Example of a top tagged event with identified subjets as reconstructed within a *fat* jet in a full CLIC simulation at 1.4 TeV.

and 3 TeV. At these energies several of the dimension-6 EFT coefficients show a large increase in sensitivity.

At high energies the top quarks are boosted, and their decay products are highly collimated as a result. They form so-called *fat* jets, where standard reconstruction techniques such as *b*-tagging, do not necessarily work. Top quarks are tagged by looking at the internal substructure of the jets. Various techniques have been studied to achieve this: parsing through the jet substructure as well as multivariate analysis using jet variables such as jet subjettiness, etc. In this way top quarks can be reconstructed, as illustrated in Fig. 3b, which shows a top tagged event where subjets have been identified within the collimated *fat* jet. The forward-backward asymmetry $A_{FB}$ is extracted using the semi-leptonic decay channel, where the charge of the top quark can be inferred from a precise identification of the lepton in the decay. The current estimate of the relative uncertainty on $A_{FB}$, from full CLIC simulations at 1.4 TeV, is 2% to 3% for both positive and negative electron beam helicity [24].

## 5. Conclusion

Linear lepton colliders enable the study of the properties of the top quark with very high precision. Additionally, beam polarisation enhances the physics reach and sensitivity to many BSM processes. A scan around the top quark pair production threshold provides the most accurate top quark mass measurement in a well defined theoretical mass scheme, enabling a $\overline{MS}$ mass precision of the order of 50 MeV. In contrast, at hadron colliders a precision of the order of 1 GeV can be reached, due to the dominating theoretical uncertainty. For rare top quark decays, such as FCNC decays, lepton colliders offer excellent exclusion limits, quite competitive with the expected results from HL-LHC. Precision measurements of electroweak couplings at lepton colliders offer a superior sensitivity to a large variety of BSM models; form-factors can be found with a precision at the % level, which is an order of magnitude better than what is predicted for the HL-LHC.

## References


[1] C. Adolphsen *et al.*, *The International Linear Collider Technical Design Report - Volume 3.II: Accelerator Baseline Design*, *ILC-REPORT-2013-040* [arXiv:1306.6328].

[2] L. Linssen *et al.*, *Physics and Detectors at CLIC: CLIC Conceptual Design Report*, *CERN-2012-003* [arXiv:1202.5940].

[3] T. Barklow *et al.*, *ILC Operating Scenarios*, *ILC-NOTE-2015-068* [arXiv:1506.07830].

[4] M. Boland *et al.*, *Updated Baseline for a staged Compact Linear Collider*, *CERN-2016-004* [arXiv:1608.07537].

[5] F. Simon, *A First Look at the Impact of NNNLO Theory Uncertainties on Top Mass Measurements at the ILC*, *MPP-2016-38* [arXiv:1603.04764].

[6] M. Beneke *et al.*, *Next-to-Next-to-Next-to-Leading Order QCD Prediction for the Top Antitop S-Wave Pair Production Cross Section Near Threshold in e+e- Annihilation*, *Phys. Rev. Lett.* **19** (192001), [arXiv:1506.06864].

[7] F. Simon (2017). Presented at the Workshop on top physics at the LC 2017, https://indico.cern.ch/event/595651.

[8] F. Simon, *Impact of Theory Uncertainties on the Precision of the Top Quark Mass in a Threshold Scan at Future e+e- Colliders*, *MPP-2016-325* [arXiv:1611.03399].

[9] T. Behnke *et al.*, *The International Linear Collider Technical Design Report - Volume 4: Detectors*, *ILC-REPORT-2013-040* [arXiv:1306.6329].

[10] The CMS collaboration, V. Khachatryan, *et al.*, *Measurement of the top quark mass using proton-proton data at $\sqrt{s} = 7$ and 8 TeV*, *Phys. Rev. D* **93** (072004), [arXiv:1509.040442].

[11] The CMS Collaboration, *Projected improvement of the accuracy of top-quark mass measurements at the upgraded LHC*, *CMS PAS FTR-13-017* .

[12] P. Gomis (2017). Presented at the Workshop on top physics at the LC 2017, https://indico.cern.ch/event/595651.

[13] The ATLAS Collaboration, *Expected sensitivity of ATLAS to FCNC top quark decays $t \to Zu$ and $t \to Hq$ at the High Luminosity LHC*, *ATL-PHYS-PUB-2016-019* .

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[14] A. F. Zarnecki (2017). Presented at the Workshop on top physics at the LC 2017, https://indico.cern.ch/event/595651.

[15] The CMS Collaboration, *Search for anomalous single top quark production in association with a photon in pp collisions at $sqrt(s) = 8$ TeV*, *Journal of High Energy Physics* **4** (35), [arXiv:1511.03951].

[16] The CMS Collaboration, *Updates on Projections of Physics Reach with the Upgraded CMS Detector for High Luminosity LHC*, *CMS-DP-2016-064* .

[17] N. van der Kolk (2017). Presented at the Workshop on top physics at the LC 2017, https://indico.cern.ch/event/595651.

[18] M. S. Amjad *et al.*, *A precise characterisation of the top quark electro-weak vertices at the ILC*, *IFIC/15-15, LAL 15-111* [arXiv:1505.06020].

[19] J. A. Aguilar-Saavedra, M. C. N. Fiolhais, and A. Onofre, *Top effective operators at the ILC*, *Journal of High Energy Physics* **7** (180), [arXiv:1206.1033].

[20] O. B. Bylund, *et al.*, *Probing top quark neutral couplings in the Standard Model Effective Field Theory at NLO QCD*, *CP3-16-03* [arXiv:1601.08193].

[21] M. Russell (2017). Presented at the Workshop on top physics at the LC 2017, https://indico.cern.ch/event/595651, based on [arXiv:1704.01782].

[22] Durieux, *et al.* (2017). To be published.

[23] W. Bernreuther, *et al.* (2017). To be published.

[24] R. Ström (2017). Presented at the Workshop on top physics at the LC 2017, https://indico.cern.ch/event/595651.