

## Top physics at CLIC and ILC

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**Aleksander Filip Żarnecki\***

**on behalf of the CLICdp collaboration and the ILC Physics and Detector Study**

*Faculty of Physics, University of Warsaw*

*E-mail: [Filip.Zarnecki@fuw.edu.pl](mailto:Filip.Zarnecki@fuw.edu.pl)*

Measurements of top quark production at  $e^+e^-$  colliders can provide a leap in precision in our knowledge of top quark properties and open a new window on physics beyond the Standard Model. In this contribution the top quark physics prospects of linear colliders is reviewed. Progress in detailed full-simulation studies is reported for the highlights of the program. We present the prospects for a measurement of the top quark mass and width in a scan of the beam energy through the pair production threshold, and discuss new studies of alternative measurements in continuum production, which are also capable of a precise determination of the mass in a rigorously defined mass scheme. A precision of 50 MeV on the  $\overline{MS}$  mass is expected when taking into account the dominant systematic uncertainties. Another key measurement is the study of the top quark couplings to electroweak gauge bosons, where form factors can be determined to 1% precision, an order of magnitude better than those from the full LHC program. New results extend the prospects to different center-of-mass energies and to CP violating form factors. Finally, new studies are presented indicating the possibility to detect Flavour Changing Neutral Current decays of the top quark at linear colliders, such as the decay  $t \rightarrow cH$ , to a branching ratio of  $BR(t \rightarrow cH) \sim 10^{-5}$ .

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\*Speaker.

## 1. Introduction

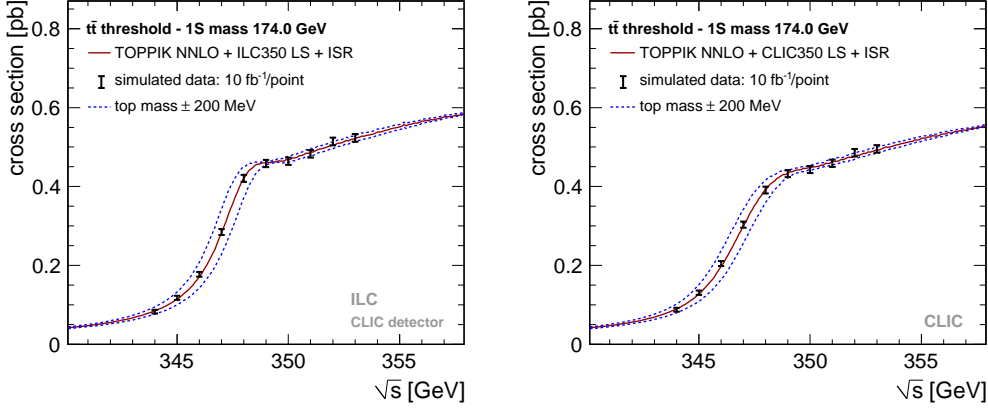
Top physics, together with Higgs boson studies and searches for Beyond the Standard Model (BSM) phenomena, is one of the three pillars of the research program for future high energy  $e^+e^-$  colliders. As top quark is the heaviest known elementary particle, with an expected value of the Yukawa coupling of the order of one, the precise determination of its properties is a key to the understanding of electroweak symmetry breaking. Together with the Higgs mass, the top mass value is crucial for testing the vacuum stability of the Standard Model. Determination of top properties is also essential for many “new physics” searches, as top quark gives large loop contributions to many precision measurements sensitive to BSM effects. Finally, as top is the only quark not forming a hadronic state, its production and decays allow for detailed tests of QCD calculations. Both future linear colliders, ILC and CLIC, provide the opportunity to study the top quark with unprecedented precision via direct production of  $t\bar{t}$  pairs in  $e^+e^-$  collisions.

## 2. Colliders and Experiments

The International Linear Collider (ILC) project is based on the technology of superconducting accelerating cavities. In the Technical Design Report (TDR) completed in 2013 [1], construction of a machine with a centre of mass energy of 500 GeV and a footprint of 31 km was proposed, with a possible upgrade to 1 TeV. The baseline design includes polarisation for both  $e^-$  and  $e^+$  beams, of 80% and 30%, respectively. The running scenario H-20, which was selected as the most promising [2], assumes collecting 500 fb<sup>-1</sup> of data at 500 GeV in the initial ILC stage, followed by 200 fb<sup>-1</sup> collected at the top pair production threshold and 500 fb<sup>-1</sup> at 250 GeV in the first 8 years of running. After the luminosity upgrade, an additional 3500 fb<sup>-1</sup> at 500 GeV and 1500 fb<sup>-1</sup> at 250 GeV could be accumulated in about 11 years.

The Conceptual Design Report (CDR) for the Compact Linear Collider (CLIC) was presented in 2012 [3]. CLIC is based on the two-beam acceleration scheme, required to generate a high RF gradient of about 100 MV/m. In the recently updated implementation plan for CLIC [4], a construction in three stages is proposed, with 5 to 7 years of data taking at each stage. The first stage with a footprint of 11 km will allow to reach an energy of 380 GeV, giving access to most Higgs boson and top quark measurements. The plan assumes collecting 500 fb<sup>-1</sup> at 380 GeV with additional 100 fb<sup>-1</sup> collected at the  $t\bar{t}$  threshold. The second and third construction stages at around 1.5 and 3 TeV, with expected integrated luminosities of 1500 fb<sup>-1</sup> and 3000 fb<sup>-1</sup>, will focus on the searches for BSM phenomena. However, they will also open possibilities for additional Higgs and top-quark measurements, such as the direct determination of the top Yukawa coupling. Polarisation of the electron beam is currently included in the CLIC baseline design, while positron polarisation is considered as a possible upgrade.

The detector concepts proposed for ILC and CLIC are based on jet reconstruction and jet energy measurements with the “Particle Flow” approach [5]. Single particle reconstruction and identification exploits high calorimeter granularity, and the best possible jet energy estimate is obtained by combining calorimeter measurements for neutral particles with precise track momentum measurements for the charged ones. Very efficient flavour tagging is possible with a high precision pixel vertex detector placed very close to the interaction point. The background to processes with



**Figure 1:** Simulated cross section measurements for top pair production at the threshold (background subtracted) with the luminosity spectra expected for ILC (left) and CLIC (right). Threshold scan with measurements at 10 energy points with  $10 \text{ fb}^{-1}$  each, simulated for the generator mass of 174 GeV (full line) as well as for a shift in mass of  $\pm 200 \text{ MeV}$  (dotted lines). Figure taken from [8].

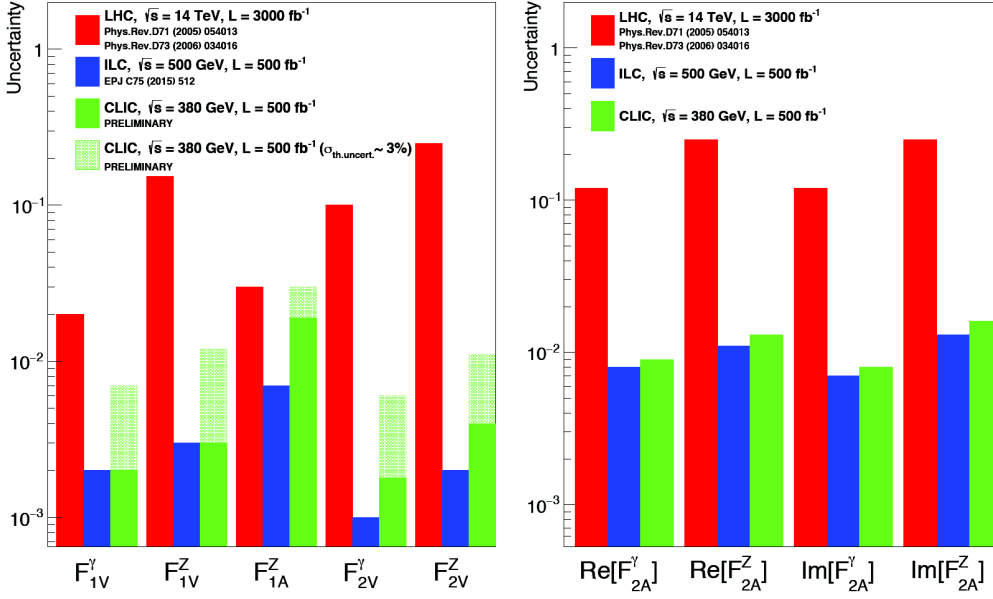
missing energy can be strongly suppressed thanks to very good detector hermeticity, with instrumentation extending down to a minimum angle of  $\theta_{min} \sim 5 \text{ mrad}$ . Although based on different technology choices, a similar performance is expected for the two ILC detector concepts: ILD and SiD [6]. Detailed simulation studies for CLIC were initially based on the adopted ILC concepts [7]. Recently, however, a dedicated detector model has become available for the analysis.

### 3. Top Quark measurements

#### 3.1 Mass and width

The dependence of the theoretical top pair production cross section on the centre of mass energy shows a clear resonance-like structure at the threshold, corresponding to a narrow  $t\bar{t}$  bound state. The shape of the cross section is very sensitive to top quark properties and model parameters: mass  $m_t$ , width  $\Gamma_t$ , Yukawa coupling  $y_t$  and strong coupling  $\alpha_s$ . In spite of the significant cross section smearing due to luminosity spectra and initial state radiation (ISR), a precise  $m_t$  measurement is possible already with  $100 \text{ fb}^{-1}$ . Detailed simulation studies were performed for both ILC and CLIC [8, 9] showing that with cross section measurements at 10 different values of collision energy, each with  $10 \text{ fb}^{-1}$  of data (see Fig. 1), a statistical accuracy of 15–20 MeV can be obtained. Theoretical uncertainties are currently estimated to be at the level of 40 MeV [11, 12], uncertainty from  $\alpha_s$  to about 30 MeV (for today’s world average) and experimental uncertainties (backgrounds, etc.) are estimated on the 10–20 MeV level. The total uncertainty expected on  $m_t$  is  $\sim 50 \text{ MeV}$ , while  $\Gamma_t$  could be extracted to about 40 MeV [13].

The main advantage of  $m_t$  determination from the threshold scan is that the extracted parameter is well defined from the theoretical point of view. Direct reconstruction of the top quark mass from its decay products has been considered for energies above the threshold (continuum) [8]. Competitive statistical precision can be expected ( $\sim 80 \text{ MeV}$  for  $100 \text{ fb}^{-1}$  at 500 GeV). However, the measurement suffers from significant theoretical uncertainties when converting the extracted  $m_t$  value to a particular mass scheme (as for the “standard” measurements at LHC).



**Figure 2:** Comparison of the uncertainties on the measured top-quark form factors (assuming SM values for the remaining form factors) expected for HL-LHC, ILC and CLIC. Considered are parity conserving (left) and parity violating (right) couplings. The form factors are extracted from the measured cross sections, forward backward asymmetry and helicity angle distribution in top quark decays.

Therefore, other methods of the top quark mass determination are also being studied. At high energies, the top quark mass could be reconstructed from radiative events  $e^+e^- \rightarrow t\bar{t}\gamma$ . Measurement of a threshold in the ISR photon energy distribution, corresponding to the  $t\bar{t}$  production threshold, should allow  $m_t$  extraction with a statistical precision of the order of 100 MeV [14]. Other methods proposed recently are based on the reconstruction of the  $b$ -jet energy distribution (“one prong” method) [15] or on the event shape analysis [16].

### 3.2 Electroweak couplings

The measurement of the top pair production above threshold is sensitive to the top quark electroweak couplings but also to possible higher order corrections due to different “new physics” scenarios. To constrain BSM contributions we consider the general form of the top quark couplings to  $Z$  and  $\gamma$ , which can be written in terms of eight form factors (only three of them contributing to the  $t\bar{t}$  production in the Standard Model). These form factors can be constrained through measurements of the total  $t\bar{t}$  production cross-section, forward-backward asymmetry and helicity angle distribution in top quark decays, for two polarisation combinations:  $e_L^-e_R^+$  and  $e_R^-e_L^+$ . Results of a detailed simulation study performed for ILC [17] and extended to CLIC [18] show that already with  $500 \text{ fb}^{-1}$ , all form factors can be constrained to 1% or below, while the HL-LHC will only be able to set limits in the 10% range (see Fig. 2). Further improvement of the linear collider precision is possible by improving  $b$ -jet charge reconstruction and particle identification, so that fully hadronic  $t\bar{t}$  decays can also be included in the analysis [19]. With 20 years of data taking at the ILC, the statistical precision of the coupling determination could be reduced to the level of 0.2%. However, to profit from an ILC luminosity upgrade theoretical and experimental uncertainties have to be controlled to the per mille level.

### 3.3 Yukawa coupling

The top Yukawa coupling can already be constrained from the scan of the top pair production threshold, as the cross section includes a contribution of about 9% from the virtual Higgs exchange [9]. With  $100 \text{ fb}^{-1}$  of data the coupling can be extracted with a statistical uncertainty of about 6%, assuming the  $\alpha_s$  value can be constrained from other measurements. The precision on  $y_t$  will therefore be dominated by theoretical uncertainties which are currently estimated to be at the level of 20%. When running at higher energies (at or above 500 GeV),  $y_t$  can be directly extracted from the measurement of  $e^+e^- \rightarrow t\bar{t}H$  events. Even with the excellent performance of linear collider detectors, which is required for good background suppression and efficient event selection, the measurement will be limited by statistics. With  $2 \times 500 \text{ fb}^{-1}$  of data collected at 500 GeV, the ILC experiment should measure  $y_t$  with a statistical uncertainty of about 11%, which can be reduced to 6.4% with  $4000 \text{ fb}^{-1}$  [20]. Significant improvement is expected when going to higher energies. Already by running at 540 GeV, the statistical uncertainty can be reduced by a factor of 2. A precision of 4-5% is also expected for ILC running at 1 TeV [21] or CLIC running at 1.4 TeV.

### 3.4 Rare decays

Flavor-Changing Neutral Current (FCNC) top quark decays are strongly suppressed in the Standard Model, with the expected branching ratios  $BR(t \rightarrow c X) \sim 10^{-15}$  to  $10^{-12}$  ( $X = \gamma, g, Z, H$ ). Observation of any such decay would be a direct signature for “new physics”. The decay  $t \rightarrow c H$  seems to be the most promising channel, as an enhancement up to  $10^{-2}$  is possible [22]. This decay is difficult to constrain at LHC, with expected HL-LHC limits of  $BR < 2 \cdot 10^{-4}$  [22, 23]. At  $e^+e^-$  colliders top pair production events with FCNC decay  $t \rightarrow c H$  can be identified based on the kinematic constraints and flavour tagging information. Although the signal selection efficiency is limited by large overlap in kinematic space with standard top pair events, parton level simulation results indicate that with high integrated luminosity this decay can be probed down to  $BR \sim 10^{-5}$  [14]. A full simulation study is ongoing.

## 4. Conclusions

A precise determination of top quark parameters is crucial for the validation of the Standard Model or any alternative BSM theory. Linear  $e^+e^-$  colliders, ILC and CLIC, offer unique opportunities for these measurements. A scan of the top pair production threshold will allow for mass and width measurements, while direct extraction of Yukawa and electroweak couplings require running at higher beam energies. High precision and background suppression capabilities of ILC and CLIC detectors will allow for per mille level measurements and searches for rare processes. However, even in a clean environment of  $e^+e^-$  collisions, top events reconstruction remains very challenging and imposes stringent requirements on the detector performance.

## References

- [1] C. Adolphsen *et al.*, *The International Linear Collider Technical Design Report - Volume 3.II: Accelerator Baseline Design, LC-REPORT-2013-040* [arXiv:1306.6328].
- [2] T. Barklow *et al.*, *ILC Operating Scenarios* [arXiv:1506.07830].

- [3] M. Aicheler *et al.*, *A Multi-TeV Linear Collider Based on CLIC Technology : CLIC Conceptual Design Report*, CERN-2012-007.
- [4] M. J. Boland *et al.* [CLIC and CLICdp Collaborations], *Updated baseline for a staged Compact Linear Collider*, CERN-2016-004 [arXiv:1608.07537].
- [5] M. A. Thomson, *Particle Flow Calorimetry and the PandoraPFA Algorithm*, Nucl. Instrum. Meth. A **611** (2009) 25 [arXiv:0907.3577].
- [6] T. Behnke *et al.*, *The International Linear Collider Technical Design Report - Volume 4: Detectors* [arXiv:1306.6329].
- [7] L. Linssen, A. Miyamoto, M. Stanitzki and H. Weerts, *Physics and Detectors at CLIC: CLIC Conceptual Design Report* [arXiv:1202.5940].
- [8] K. Seidel, F. Simon, M. Tesar and S. Poss, *Top quark mass measurements at and above threshold at CLIC*, *Eur. Phys. J. C* **73** (2013) 2530 [arXiv:1303.3758].
- [9] T. Horiguchi *et al.*, *Study of top quark pair production near threshold at the ILC* [arXiv:1310.0563].
- [10] K. Fujii *et al.*, *Physics Case for the International Linear Collider* [arXiv:1506.05992].
- [11] F. Simon, *A First Look at the Impact of NNNLO Theory Uncertainties on Top Mass Measurements at the ILC* [arXiv:1603.04764].
- [12] F. Simon, *Impact of Theory Uncertainties on the Precision of the Top Quark Mass in a Threshold Scan at future  $e^+e^-$  Colliders*, in proceedings of *38th International Conference on High Energy Physics*, PoS (ICHEP2016) 872 (2016) [arXiv:1611.03399].
- [13] A. Ishikawa, *Status and Plan for the Analyses of  $t\bar{t}$  near threshold at the ILC*, presented at *Top Physics at Lepton Colliders* workshop, Valencia, Spain 2015.
- [14] M. Vos *et al.*, *Top physics at high-energy lepton colliders* [arXiv:1604.08122].
- [15] K. Agashe, R. Franceschini, D. Kim and M. Schulze, *Top quark mass determination from the energy peaks of  $b$ -jets and  $B$ -hadrons at NLO QCD* [arXiv:1603.03445].
- [16] M. Butenschoen, B. Dehnadi, A. H. Hoang, V. Mateu, M. Preisser and I. W. Stewart, *Top Quark Mass Calibration for Monte Carlo Event Generators*, [arXiv:1608.01318].
- [17] M. S. Amjad *et al.*, *A precise characterisation of the top quark electro-weak vertices at the ILC*, *Eur. Phys. J. C* **75** (2015) 512 [arXiv:1505.06020].
- [18] M. Perello, *Electro-weak couplings of the top quark*, presented at *ECFA Linear Collider Workshop*, Santander, Spain 2016.
- [19] S. Bilokin, *Vertex charge reconstruction*, presented at *Top Physics at Lepton Colliders* workshop, Tsukuba, Japan 2016.
- [20] Y. Sudo, *Study of Direct top Yukawa Coupling Measurement at the ILC with  $\sqrt{s} = 500$  GeV*, presented at *Top Physics at Lepton Colliders* workshop, Tsukuba, Japan 2016.
- [21] T. Price, P. Roloff, J. Strube and T. Tanabe, *Full simulation study of the top Yukawa coupling at the ILC at  $\sqrt{s} = 1$  TeV*, *Eur. Phys. J. C* **75** (2015) 309 [arXiv:1409.7157].
- [22] K. Agashe *et al.* [Top Quark Working Group Collaboration], *Working Group Report: Top Quark* [arXiv:1311.2028].
- [23] The ATLAS Collaboration, *Expected sensitivity of ATLAS to FCNC top quark decays  $t \rightarrow Zq$  and  $t \rightarrow Hq$  at the High Luminosity LHC*, ATL-PHYS-PUB-2016-019.