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Search for non-Standard Model interactions of the top quark at the ILC

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Top quarks and in general heavy quarks are likely messengers to new physics. The scrutiny of these particles properties must be completed by the measurement of electroweak $q\bar{q}$ production at high energies, in particular for the top. Projects as the International Linear Collider will offer an extremely favorable and low-background environment of e^+e^- annihilation and high energy reach. This contribution reviews the opportunities for precision measurements of the top quark (and the other heavy quark) properties at the International Linear Collider. These include the measurements of the top quark mass and Yukawa coupling, the search for beyond-Standard-Model contributions to the top quark electroweak form factors, the search for CP violation in the top quark couplings and the constraints resulting from the global analysis within the Effective Field Theory (EFT) framework.

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1. Introduction

In the wide energy range, between 350 GeV and about 1 TeV, top pair production cross section in the e^+e^- colliders is higher than the Higgs production cross setion. A future Higgs factory, considered as the highest priority project for the particle physics, will therefore also be an efficient top factory, once the energy is increased above the top pair production threshold.

As the heaviest known particle, the top quark provides a unique probe of the SM. With the top quark giving large loop contributions to many precision observables, precise measurements of top production and its properties give us also unique sensitivity to new physics phenomena at large energy scales. Top-quark observables give complementary constraints on BSM scenarios to those coming from lighter quark measurements or precision Higgs studies.

The International Linear Collider (ILC) project is the most mature project for the future higgs factory based on the technology of superconducting accelerating cavities. The baseline running scenario for the staged ILC construction assumes starting at a centre-of-mass energy of 250 GeV followed by a 500 GeV stage and 1 TeV considered as the possible upgrade [1]. In the assumed 22-year running period the ILC is expected to deliver the integrated luminosities of about 2 ab^{-1} at 250 GeV and 4 ab^{-1} at 500 GeV, with an additional 200 fb^{-1} collected at the top-quark pair-production threshold around 350 GeV. The design includes polarisation for both e^- and e^+ beams, of 80% and 30%, respectively, which is the unique feature of the ILC. Polarisation is crucial for many precision measurements, control of systematic effects as well as for BSM searches. Two detector concepts, ILD and SiD, have been developed for the ILC [2, 3], both optimised for the Particle Flow reconstruction.

2. Threshold scan

Measurement of the threshold for top-quark pair production, $e^+e^- \to t\bar{t}$, is currently assumed to be the most precise method for top-quark mass determination and least sensitive to theoretical uncertainties. At the ILC, this process can be studied in two regimes. Differential threshold cross section can be reconstructed from the observation of the radiative events, $e^+e^- \to t\bar{t}\gamma$, with ILC running at 500 GeV, as shown in Fig. 1 (left). With 4 ab^{-1} of data the top quark mass can be extracted with statistical (total) precision of 110 MeV (150 MeV) [4]. Higher precision can be obtained with the dedicated energy scan. The baseline threshold scan scenario assumes running at 10 equidistant energy points taking 20 fb^{-1} of data for each value of the energy, as shown in Fig. 1 (right). A statistical uncertainty of about 20 MeV is expected from a mass and width fit [1], increasing to about 25 MeV when other parameters are also included in the fit [5]. With the optimised scan scenario, the uncertainty on the extracted top quark mass can be reduced by about 20%, see Fig. 2 (left). Further reduction should be possible, when differential top quark distributions are taken into account, see Fig. 2 (right) [6].

3. Top couplings

The shape of the threshold cross section is sensitive not only to the top quark mass and width, but also to other model parameters including the top-quark Yukawa coupling y_t. The expected

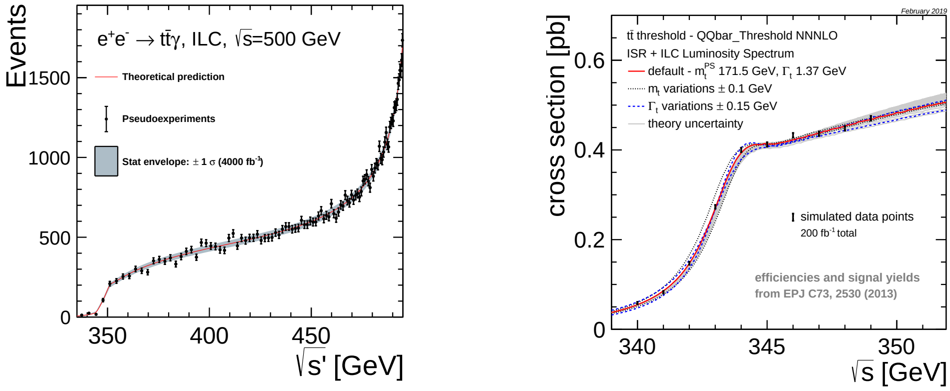

Figure 1: Left: top quark pair-production threshold reconstructed from the radiative events at 500 GeV ILC [4]. Right: baseline scenario for the dedicated top quark pair-production threshold scan at the ILC [1].

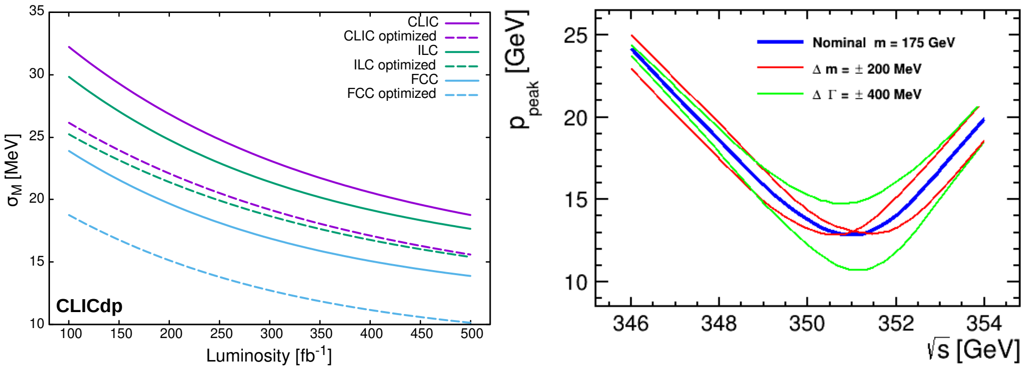

Figure 2: Left: expected uncertainty on the top-quark mass from the baseline threshold scan scenario (solid lines) and from scenarios optimised for mass and width measurement (dashed lines), as a function of the total scan luminosity for CLIC (magenta), ILC (green) and FCCee (cyan) luminosity spectra [5]. Right: sensitivity of the top quark momentum distribution peak position on the top quark mass and width, adapted from [6].

statistical uncertainty on y_t extracted from the threshold measurements is about 4% [1]. However, the measurement is highly sensitive to systematics effects [5] and the theoretical uncertainties are large.

At 500 GeV ILC a more direct extraction of the top quark Yukawa coupling becomes possible, based on the measurements of the associated production of a Higgs boson with a top quark pair, $e^+e^- \to t\bar{t}H$. With 4 ab^{-1} of data collected at 500 GeV ILC, expected precision of y_t determination from the reconstruction of $t\bar{t}H$ events is 6.4%, see Fig. 3 (left). With a rapid rise of the production cross section with energy, the measurement uncertainty can be decreased to 2.8% for ILC running at 550 GeV, see Fig. 3 (right) and further to 1% with of 8 ab^{-1} of data collected at 1 TeV [7].

Measurement of top quark pair production above the threshold provides direct access to top electroweak couplings. Possible BSM contributions are expected to affect not only the total production cross section but also differential distributions: forward-backward asymmetry and angular distributions in top decays. Expected polar angle distribution for t quark from $e^+e^- \to t\bar{t}$

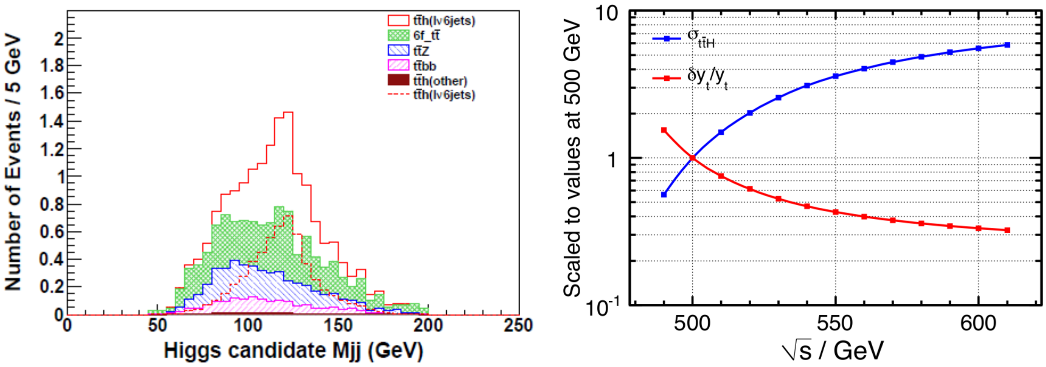

Figure 3: Direct measurement of the top quark Yukawa coupling in $e^+e^- \rightarrow t\bar{t}H$ process. Left: expected distribution of the reconstructed Higgs candidate mass for signal and background events for 1 ab^{-1} of data collected at 500 GeV ILC. Right: relative increase in the signal cross section and improvement in the top quark Yukawa coupling determination precision with the increase of the ILC collision energy.

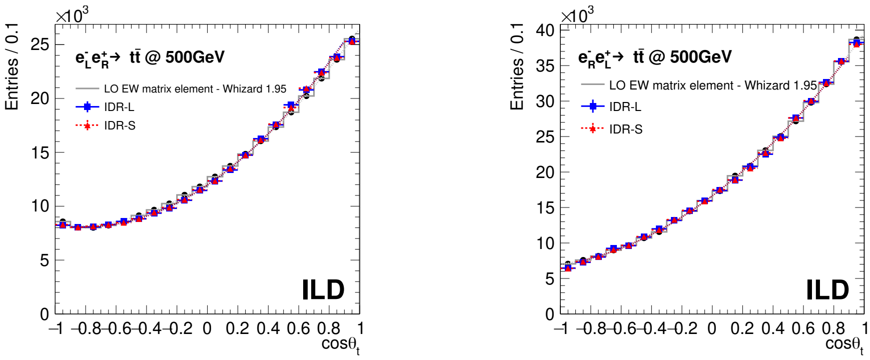

Figure 4: Polar angle distribution for t quark from $e^+e^- \rightarrow t\bar{t}$ scattering at 500 GeV ILC, for two beam polarisation combinations as indicated in the plot. Generator level distributions are compared with the expected reconstruction results for two ILD detector models [8].

scattering at 500 GeV ILC are presented in Fig. 4. By combining measurements for different electron and positron beam polarizations, and at different collision energies, simultaneous fit of all top electroweak couplings is possible. In Fig. 5 precisions on the electromagnetic top quark form factors expected after 500 GeV ILC is compared with those expected after the full HL-LHC running and at other colliders. For precision measurements at high energy e^+e^- collider reduction of the top quark coupling uncertainties by about two orders of magnitude is expected, compared to the HL-LHC estimates.

4. BSM constraints

Precision measurements of the top quark production and decays can be combined with other precision measurements, as Higgs boson couplings, Z and $W^{\pm}$ properties, production of other SM fermions, to constrain possible BSM effect at high energy scales. Results of the global fit to $b\bar{b}$ and $t\bar{t}$ precision measurements in the SMEFT framework are shown in Fig. 6 [10]. Significant increase

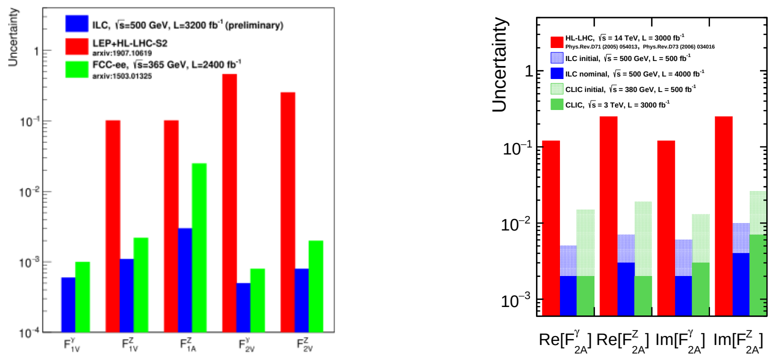

Figure 5: Comparison of the 68% C.L. limits on the CP-conserving (left) and CP-violating (right) form factors expected at the ILC and at other colliders, as indicated in the plots [9].

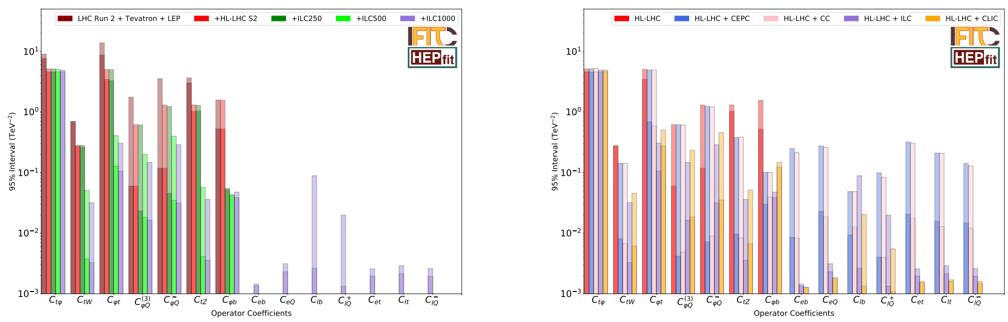

Figure 6: Results of the global fit to $b\bar{b}$ and $t\bar{t}$ precision measurements in the SMEFT framework [10]. Compared are the 95% CL limits on operator coefficients expected from subsequent stages of ILC running (left) and for different future e^+e^- collider concepts (right).

in sensitivity, relative to HL-LHC, is expected for most of the considered operator coefficients. While some of the operators can be constrained already at 250 GeV, high energy running for the future e^+e^- collider is crucial for constraining contributions of four-fermion interactions.

Loop corrections from new particles coupling to the top quark could also contribute to the single top quark production, $e^+e^- \to t\bar{q}\ /\ q\bar{t}$ (with q = u, c), already at the 250 GeV ILC. This process is absent in the SM (FCNC - Flavour Changing Neutral Currents) and observation of any such events would be a direct evidence for the BSM physics. Expected ILC bounds on the FCNC EFT operators contributing to single top production are presented in Fig. 7 [7]. Sensitivity extends up to $\mathcal{O}$(10 TeV) scales already at 250 GeV ILC.

5. Conclusions

Precise determination of top parameters is crucial for validation of the Standard Model or any alternative BSM theory. With high luminosity, increasing with energy, ILC will be not only Higgs but also top factory. With clean environment, high measurement precision and beam polarization per mile level coupling measurements will be possible and the sensitivity to BSM processes extends up to $\mathcal{O}$(10 TeV) scales already at 250 GeV ILC.

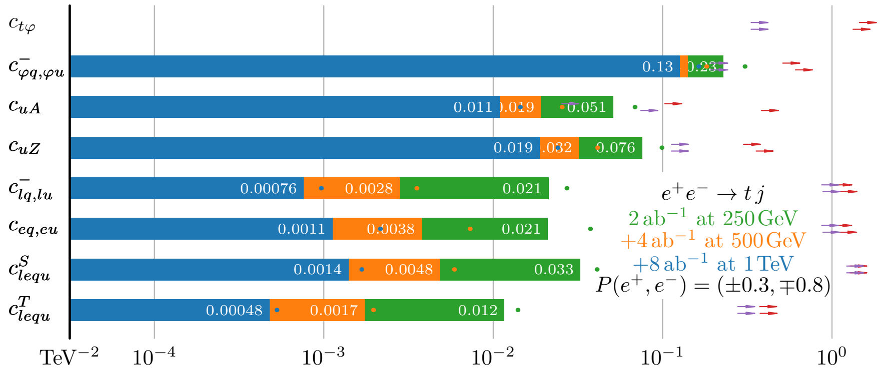

Figure 7: Expected ILC bounds on the FCNC EFT operators contributing to single top production [7].

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