IL NUOVO CIMENTO Vol. 37 C, N. 2 Marzo-Aprile 2014
DOI 10.1393/ncc/i2014-11736-0

Colloquia: LC13

Top EW couplings at Linear Colliders

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ricevuto il 17 Febbraio 2014

Summary. — In this talk, we present the latest study of $e^+e^- \to t\bar{t}$, based on a detailed simulation of the ILD detector concept, which assumes a centre-of-mass energy of $\sqrt{s} = 500\,\text{GeV}$ and a luminosity of $\mathcal{L} = 500\,\text{fb}^{-1}$, equality shared between the incoming beam polarisations of $\mathcal{P}_{e^-,e^+} = (\pm 0.8, \mp 0.3)$. The study comprises the cross sections, the forward-backward asymmetry and the slope of the helicity angle asymmetry. The vector and axial vector couplings are separately determined for the photon and the Z component. The tensorial CP-conserving coupling can be also extracted by assuming the other couplings to be the SM values. We show that the sensitivity to new physics would be dramatically improved with respect to what is expected from LHC for electroweak couplings.

PACS 14.65.Ha – Top quarks.
PACS 13.66.Jn – Precision measurements in e^-e^+ interactions.

1. – Introduction

The International Linear Collider project (ILC), as proposed in Japan, has a baseline staged in four phases: Higgs threshold ($\simeq 250\,\text{GeV}$); Top-quark threshold ($\simeq 350\,\text{GeV}$); Top-Higgs threshold ($\simeq 500\,\text{GeV}$); Vector-Vector mode (above $\simeq 800\,\text{GeV}$). While the first stage is presently the most appealing with the recent discovery of a Higgs-like boson, the next steps are essential ingredients of the program. In particular, the precision measurements of top properties to search for a signal beyond the Standard Model (SM) is one of the three pillars of linear collider projects together with the Higgs and W boson precision measurements. The fact that the top quark is the only matter field in the SM which has mass near the electroweak scale makes us wonder about a special role of the top quark in the electroweak symmetry breaking. The top physics programs at ILC can be summarized in brief as follows:

i) *Top mass, width and Yukawa coupling*: At the pair production threshold, the theoretical relation between the cross section line shape and the top quark mass allows for precise measurements of the top quark mass m_t as well as of other properties, such as its total width Γ_t and couplings, most notably the strong coupling α_s.

The total top-pair production cross section is quite well studied theoretically. In particular various QCD corrections have been computed at a very high precision (up to NNLL). Since the top kinetic energy is of the order of the top quark width, electroweak effects, which also include finite-lifetime and interference contributions, are crucial as well. This makes the cross section dependent on the experimental prescription concerning the reconstructed final state. Further developments in theoretical predictions for differential cross sections, such as the top momentum distribution or asymmetries, are foreseen.

The measurement of the top-Yukawa coupling is in principle also possible from the top threshold, but the precision is strongly limited by the fact that Higgs effects represent corrections suppressed by the inverse square of the Higgs mass.

ii) *Top Electroweak Couplings*: The measurements of top quark production are of high relevance for the discovery of new physics. At the ILC $t\bar{t}$ pairs would be copiously produced, about 570 kEvents for an integrated luminosity of $500\,\text{fb}^{-1}$, which corresponds to a few years of running. The advantage of searching for physics beyond the Standard Model (BSM) in top physics is that it allows eliminating nearly entirely the background from other SM processes. The high precision expected will allow for stringent tests of new physics up to several 10 TeV, where maybe also a new particle such as a Z' could appear. The ILC is capable of solving the puzzle on A_{FB} and A_{LR}, which is a heritage of LEP and SLC, and shedding light on the deviations observed in thed asymmetry measurements at the Tevatron.

In this talk, we discuss the latest simulation result for the item ii) and the future prospect.

2. – Top electroweak couplings

In $e^+e^- \to t\bar{t}$ (see fig. 1), one often uses the following parameterization of the ttV vertex (V being a neutral gauge boson) [1, 2]:

$$\begin{aligned}\Gamma_\mu^{ttV}(k^2,q,\bar{q}) &= \\ &-ie\left\{\gamma_\mu\left(F_{1V}^V(k^2)+\gamma_5 F_{1A}^V(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})_\mu\left(iF_{2V}^V+\gamma_5 F_{2A}^V(k^2)\right)\right\}.\end{aligned} \tag{1}$$

Within the SM, *i.e.* $V=\gamma$, Z, the form factors at the Born level are given by

$$\begin{aligned} &F_{1V}^{\gamma,\text{SM}} = -\frac{2}{3}, \qquad F_{1A}^{\gamma,\text{SM}} = 0, \qquad F_{1V}^{Z,\text{SM}} = -\frac{1}{4s_w c_w}\left(1-\frac{8}{3}s_w^2\right), \\ &F_{1A}^{Z,\text{SM}} = \frac{1}{4s_w c_w}, \qquad F_{2V}^{\gamma,\text{SM}} = Q_t\frac{(g-2)}{2}, \end{aligned} \tag{2}$$

where s_w and c_w are the sine and cosine of the Weinberg angle θ_W, respectively.

The top quarks decay predominantly into $t \to W^\pm b$, followed by the decay of $W^\pm$ into lepton plus neutrino or a quark anti-quark paris. In the present study, we focus on the "lepton+jets" final state, *i.e.* $e^+e^- \to t\bar{t} \to l^\pm \nu b\bar{b}q'\bar{q}$.

Top production and decays are very different from the other fermions, due to the emergence of many interesting angular correlations, which can be used to extract new physics information [3]. In this work, we introduce three independent observables:

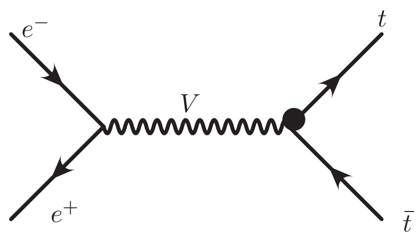

Fig. 1. – The Feynman diagram of the $e^+e^- \to t\bar{t}$ process. V can be a neutral gauge boson from the SM (*i.e.* γ/Z) or from new physics (Z' etc.). The new physics contributions can enter also in the $\bullet$ as a radiative correction.

– The cross section.

– The forward backward asymmetry A^t_{FB}. We count the number of events in the hemispheres of the detector with respect to the polar angle θ of the t quark, *i.e.*

$$A^t_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}\,. \tag{3}$$

– The slope of the distribution of the helicity angle.

Using the fact that, in the rest frame of the t quark, the angle of the lepton from the W boson is distributed linearly, *i.e.*:

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{hel}}} = \frac{1+\lambda_t\cos\theta_{\mathrm{hel}}}{2} = \frac{1}{2} + (2F_R - 1)\frac{\cos\theta_{\mathrm{hel}}}{2} \tag{4}$$

with $\lambda_t = 1$ for t_R and $\lambda_t = -1$ for t_L, we can measure its slope. Note that we define the angle θ_{hel} in the rest frame of the t quark with the z-axis defined by the direction of motion of the t quark in the laboratory [4].

The ILC will allow for polarized electron and positron beams. Thus, with the use of polarized beams, we can double the above observable for each configuration; *i.e.* total of six observables are available. Thus, one can, in principle, determine the six CP-conserving form factors. On the other hand, we have to keep in mind that near the $t\bar{t}$ threshold, the observables depend always on the sum $F_{1V} + F_{2V}$. Therefore, a full disentangling of the form factors will be imprecise for energies below about 1 TeV. Hence, in the present study either the four form factors $F_{1V,1A}$ are varied simultaneously, while the two F_{2V} are kept at their SM values, or vice versa. Throughout this article, the CP-violating form factors F^X_{2A} will be kept at their SM values.

3. – Result

The detailed results on the reconstruction efficiency, A^t_{FB} and θ_{hel} are given in the original paper [5]. The achievable precision of the form factor determination are summarized in table I and fig. 2 and are compared with results of earlier studies for a linear collider as published in the TESLA TDR [6] as well as with precisions obtained in a simulation study for the LHC. Note, that in the LHC and TESLA studies only one form

TABLE I. – *Sensitivities achievable at 68.3% CL for CP-conserving form factors* $\widetilde{F}^X_{1V,A}$ *at the LHC and at linear* e^+e^- *colliders. Note that the form factors appearing here are related to the form factors defined in eq.* (1) *via* $\widetilde{F}^X_{1V} = -(F^X_{1V} + F^X_{2V})$, $\widetilde{F}^X_{2V} = F^X_{2V}$, $\widetilde{F}^X_{1A} = -F^X_{1A}$, $\widetilde{F}^X_{2A} = -iF^X_{2A}$. *The assumed luminosity samples and, for* e^+e^- *colliders, the beam polarization, are indicated. In the LHC studies and in earlier studies for a linear* e^+e^- *collider as published in the TESLA TDR* [6] *study, only one coupling at a time is allowed to deviate from its SM value. In the present study, denoted as ILC DBD, either the four form factors* $\widetilde{F}_1$ *or the two form factors* $\widetilde{F}_2$ *are allowed to vary independently. The sensitivities are based on statistical errors only.*

Coupling	SM value	LHC [7] $\mathcal{L} = 300\,\text{fb}^{-1}$	e^+e^- [6] $\mathcal{L} = 300\,\text{fb}^{-1}$ $\mathcal{P}, \mathcal{P}' = -0.8, 0$	e^+e^- [*ILC DBD*] $\mathcal{L} = 500\,\text{fb}^{-1}$ $\mathcal{P}, \mathcal{P}' = \pm 0.8, \mp 0.3$
$\Delta\widetilde{F}^\gamma_{1V}$	0.66	+0.043	–	+0.002
		−0.041	–	−0.002
$\Delta\widetilde{F}^Z_{1V}$	0.23	+0.240	+0.004	+0.002
		−0.620	−0.004	−0.002
$\Delta\widetilde{F}^Z_{1A}$	-0.59	+0.052	+0.009	+0.006
		−0.060	−0.013	−0.006
$\Delta\widetilde{F}^\gamma_{2V}$	0.015	+0.038	+0.004	+0.001
		−0.035	−0.004	−0.001
$\Delta\widetilde{F}^Z_{2V}$	0.018	+0.270	+0.004	+0.002
		−0.190	−0.004	−0.002

factor was varied at a time, while, in the present study, two or four form factors are varied simultaneously. From the comparison between the numbers, it is justified to assume that the measurements at an electron-positron collider lead to a spectacular improvement and, thanks to the γ/Z^0 interference, an e^+e^- collider can fix the sign of the form factors. At the LHC the t quark couples either to the photon or to the Z^0. In that case the cross section is proportional to, *e.g.*, $(F^Z_{1V})^2 + (F^Z_{1A})^2$. The precision expected at the LHC cannot exclude a sign flip of either F^Z_{1V} or of F^Z_{1A}. On the one hand, the LEP bounds can exclude a sign flip for F^Z_{1A} which renders a much better precision for $\widetilde{F}^Z_{1A}$ compared with $\widetilde{F}^Z_{1V}$. Clearly, the precisions which can be obtained at the LHC are to be revisited in the light ofreal LHC data.

4. – Prospect: issue of theoretical uncertainties

We present a comprehensive analysis of the $t\bar{t}$ quark production using the semi-leptonic decay channel. Results are given for a centre-of-mass energy of $\sqrt{s} = 500\,\text{GeV}$ and an integrated luminosity of $\mathcal{L} = 500\,\text{fb}^{-1}$ shared equally between the beam polarizations. $\mathcal{P} = \pm 0.8$ and $\mathcal{P}' = \mp 0.3$. The sensitivity to the form factors as obtained in the present study for the ILC reaches to a per mil level, which would allow for the verification of new physics predictions. While further refinement of the experimental analysis and detailed study of the systematic error should be done, it is becoming clear

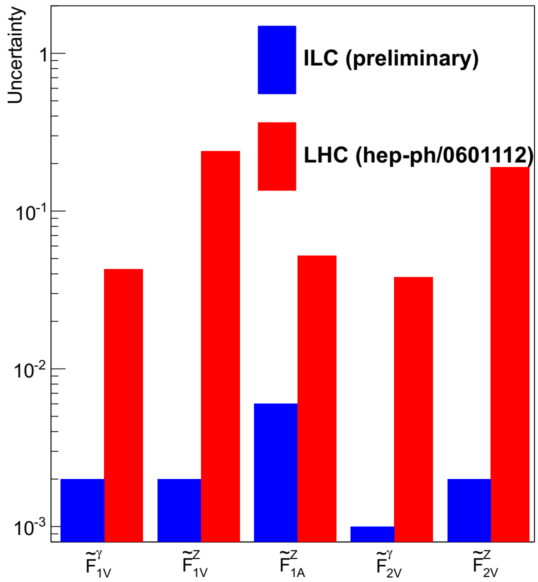

Fig. 2. – Comparison of statistical precisions on CP-conserving form factors expected at the LHC, taken from [7] and at the ILC. The LHC results assume an integrated luminosity of $\mathcal{L} = 300\,\text{fb}^{-1}$. The results for ILC assume an integrated luminosity of $\mathcal{L} = 500\,\text{fb}^{-1}$ at $\sqrt{s} = 500\,\text{GeV}$ and a beam polarization $\mathcal{P} = \pm 0.8$, $\mathcal{P}' = \mp 0.3$.

that the urgent issue to be resolved in this program is actually reducing the theoretical uncertainties. The QCD corrections for $e^+e^- \to t\bar{t}$ are known up to N^{3}LO [8-10] and the estimated theoretical uncertainties are at a per mil level. On the other hand, the electroweak corrections are known only at one-loop level [11,12], and the estimated errors in the cross section and in the forward-backward asymmetry are, respectively, about 5% and 10%, which exceeds the experimental precision. An advance of the theoretical efforts towards this direction is most appreciable. On the other hand, knowing the origin of the theoretical uncertainties, we may also look for new observables which receive milder electroweak corrections. Indeed, as mentioned earlier, the unique angular correlations of the top production and decay may be used to find such new observables.

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We would like to thank to the organizers for the invitation to LC13 at ETC* in Trento. The work of E.K. was supported in part by the ANR contract "LFV-CPV-LHC" ANR-NT09-508531.

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