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Top quark precision physics at a linear e^+e^- collider

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A linear e^+e^- collider can perform precision measurements of top quark properties, both at the $t\bar{t}$ threshold and in continuum production at $\sqrt{s} > 2m_t$. The prospects for extraction of precise values for the top quark mass and its couplings to the photon and Z-boson have been studied using a detailed detector model. These recent studies confirm that the top quark mass can be determined to approximately 100 MeV, while the characterization of the $t\bar{t}\gamma/Z$ vertex can reach a precision that is an order of magnitude better than the expectations at the LHC.

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1. Introduction

There is a broad consensus that a high-luminosity, high-energy e^+e^- collider yields excellent opportunities for precision tests of the Standard Model of particle physics. The combination of calculable electroweak production, strict control of the initial state with the relatively benign experimental environment and continued progress in detector R & D allow for a characterization of production processes that goes well beyond that of hadron colliders [1]. The potential of an e^+e^- collider operated above $m_Z + m_H$ to establish the exact relation of the new boson discovered by ATLAS and CMS to the electro-weak symmetry breaking mechanism, discussed elsewhere in these proceedings [2], has quickly become the focal point of the physics case for such a machine. However, a linear e^+e^- collider with a center-of-mass energy in the range from 250 GeV to 3 TeV offers a much broader range of opportunities. In this contribution the prospects of the linear collider (LC) experiments for a selection of precision measurements of top quark properties are discussed.

Two technological approaches exist to realize a linear e^+e^- collider. The International Linear Collider (ILC [3]) is based on superconducting RF cavities. With the accelerating gradient achieved to date, such a machine naturally covers a range from several hundred GeV (or even as low as m_Z in case of the GigaZ option) to 1 TeV. The Compact Linear Collider (CLIC [4]) pursues a more ambitious two-beam acceleration scheme, that raises the gradient to 100 MV/m and brings multi-TeV operation within reach.

Since the earliest prospect studies for a linear collider [5, 6, 7] detailed detector concepts have been worked out for the ILC [8, 9]. Recently, these concepts have been adapted to the more demanding environment at CLIC [10]. Detailed Monte Carlo models have been constructed of the detectors that greatly enhance the understanding of the potential and limitations of LC experiments. It is therefore possible now to revisit prospect studies taking into account experimental effects, that cannot be taken for granted in a complex final state such as that formed in the decay of the top quark pair.

The focus of these proceedings is on two measurements where the unique properties of the LC can greatly enhance the knowledge of the top quark. In Section 2 the potential of LC experiments to measure the top quark mass via a scan of the center-of-mass energy of a linear collider through the $t\bar{t}$ production threshold is presented. In Section 3 the prospects of a linear collider experiment to precisely characterize the $t\bar{t}Z/\gamma^*$ vertices are discussed. Section 4 contains a brief summary.

2. Top quark mass measurement

Thanks to its large mass the top quark plays a special role in the Standard Model and many of its extensions. A precise determination of its mass is a crucial ingredient to self-consistency tests of the Standard Model.

The Tevatron experiments have reported a wealth of top quark mass measurements that yield a combined measurement of 173.2 ± 0.6 (stat.) ± 0.8 (syst.) GeV [11]. The ATLAS and CMS experiments can take advantage of the enormously increased production rate at the LHC to improve this measurement. The most recent combination, based on 2011 data, indeed has a very small statistical error: $m_t = 173.3 \pm 0.5$ (stat.) $\pm$ 1.3 (syst.) GeV [12].

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The mass measurements mentioned so far are extracted from a comparison of a Monte Carlo template to the mass distribution of the (colour neutral) system formed by the top quark decay products. The result is interpreted as the top quark pole mass. The uncertainty inherent in this interpretation ultimately limits the precision that can be achieved with this procedure. An alternative at hadron colliders that offers a more rigorous interpretation is the extraction of the top quark mass from the measured cross section. D0, ATLAS and CMS have performed measurements with a precision of 5−7 GeV [13, 14, 15]. The sensitivity of this method seems to be insufficient to produce measurements with competitive precision.

The idea that a scan of the center-of-mass energy at an e^+e^- collider could yield a potentially high precision strategy for the determination of the top quark mass [16] was known well before the top quark was discovered. The authors of Reference [17] have shown that a precise top quark mass (and the top quark width, the strong coupling constant α_s and the top quark Yukawa coupling) can be extracted from a measurement of the $t\bar{t}$ cross section (and top quark momentum distribution and charge asymmetry) at several center-of-mass energy values around the $t\bar{t}$ production threshold. This procedure yields a precise top quark mass result that can be interpreted rigorously in a number of top quark mass schemes.

The calculation of the total top pair production cross section close to the threshold uses non-relativistic effective theories. Calculations have improved steadily over the years [18, 19, 20, 21] and now reach a precision of 2-3%.

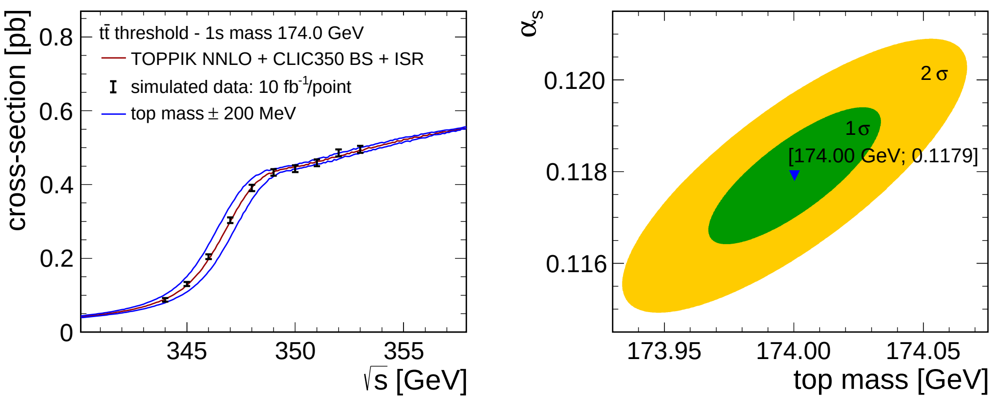

Figure 1: The production cross section versus center-of-mass energy (leftmost panel) at CLIC and the constraint in the (α_s, m_t) plane resulting from a fit to a 10 point scan with 10 fb^{-1} per point (rightmost panel). Both figures are taken from the full simulation study of Reference [22].

A recent study [22, 4, 23] has reassessed the prospect for this measurement. The authors use detailed studies of the accelerator to estimate the effect of beam energy spread for ILC and CLIC operation at $\sqrt{s} \sim 350$ GeV. Detector effects are simulated in full detail using GEANT4. The dependence of the production cross section on the center-of-mass energy is shown in the leftmost panel of Figure 1. With 100 fb^{-1}divided over ten $\sqrt{s}$ values the fit yields the constraint in the (α_s, m_t) plane shown in the rightmost panel. A statistical precision of the top quark mass in the 1S scheme of 33 MeV is obtained at CLIC in a combined fit together with the strong coupling constant, which is determined with a precision of 0.0009. With the ILC luminosity spectrum the uncertainties on m_t and α_s are reduced by 15−20% and 10%, respectively. Combined systematic uncertainties from theory and background understanding are expected to be of similar order as the statistical errors. The RMS width of the luminosity spectrum must be known to better than 20% to avoid large systematic uncertainties on the mass measurement. These new results with a complete treatment of beam energy spread and an evaluation of systematic uncertainties thus corroborate the longstanding expectation that the top quark mass can be determined to better than 100 MeV at the LC.

3. The $t\bar{t}Z$ and $t\bar{t}\gamma$ couplings

The top quark is the only quark that has escaped scrutiny at the previous generation of e^+e^- colliders. The efforts of the Tevatron and LHC experiments elucidate many aspects of top quark production and decay, but have limited potential to constrain the $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices. A precise characterization of these vertices may prove to be a very sensitive probe of physics Beyond the Standard Model.

Following the notation of Reference [24] the top quark couplings to photon and Z boson can be written as follows:

$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left(\gamma_\mu(\tilde{F}_{1V}^X(k^2)+\gamma_5\tilde{F}_{1A}^X(k^2)) + \frac{(q-\bar{q})_\mu}{2m_t}(\tilde{F}_{2V}^X(k^2)+\gamma_5\tilde{F}_{2A}^X(k^2))\right) \tag{3.1}$$

where $X=\gamma,Z$ and the $\tilde{F}$ satisfy $\tilde{F}_{1V}^V = -(F_{1V}^V+F_{2V}^V)$, $\tilde{F}_{2V}^V = F_{2V}^V$, $\tilde{F}_{1A}^V = -F_{1A}^V$ and $\tilde{F}_{2A}^V = -iF_{2A}^V$. Only three form factors are non-zero in the SM at tree level (F_{1V}^γ, F_{1V}^Z and F_{1A}^Z). Further form factors describe the (weak) electric dipole moment (F_{2A}^γ and F_{2A}^Z) and magnetic (F_{2V}^γ and F_{2V}^Z) dipole moment of the top quark.

Hadron colliders can probe some of these form factors through the study of associated production of top quark pairs with photons or Z bosons. The process $p\bar{p}\to t\bar{t}\gamma$ was observed at the Tevatron [26]. The LHC potential is estimated in the 2005 Snowmass report [24], assuming an integrated luminosity of 300 fb^{-1}at a center-of-mass energy of 14 TeV.

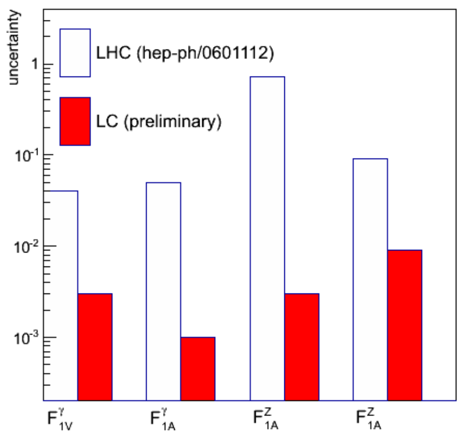

Figure 2: The prospects for measurements of the form factors discussed in the text, from Reference [25]. The LHC potential is based on the report of the 2005 Snowmass top/QCD working group [24].

Several studies [5, 24] have established that at a future Linear Collider operated at $\sqrt{s}=500$ GeV the top quark couplings to the photon and, particularly, the Z boson can be characterized much more precisely. To disentangle the photon and Z boson vertices, polarized electron beams are crucial. Recently, the authors of Reference [27] have revisited the LC potential using effective operators. A study of the fully hadronic final state using a detailed simulation show that measurement of the jet charge allows for efficient tagging of top and anti-top quarks [28]. The measurement of the charge asymmetry in $t\bar{t}$ production allows to constrain the $t\bar{t}Z$ vertex to the 5−10% level.

In Reference [25] the lepton+jets final state is evaluated in full detector simulation. In contrast to earlier explorations of the LC potential multiple form factors are allowed to deviate from their SM values. The resulting prospects for the measurement of the form factors F_{1V}^{γ}, F_{1A}^{γ}, F_{1V}^{Z} and F_{1A}^{Z} on 500 fb^{-1} of 500 GeV data are compared to the LHC potential from Reference [24] in Figure 2. Despite the increasing realism of these recent studies, the precision of the extracted form factors is similar, and in some cases even better than in older work, primarily due to a different choice of observables. The LC can thus improve the understanding of the $t\bar{t}\gamma$ and $t\bar{t}Z$ vertices by an order of magnitude.

4. Summary & discussion

A future linear e^+e^- collider with a center-of-mass energy that ranges from the electroweak scale to the multi-TeV regime and a large integrated luminosity (order ab^{-1}) offers an excellent opportunity for precision measurements of top quark properties. A 100 fb^{-1} scan of the center-of-mass energy of the collider around the $t\bar{t}$ production threshold allows for a precise extraction of the top quark mass in a rigorously defined mass scheme. A recent study based on a realistic simulation of the luminosity spectrum and a detailed model of the detector response predicts a precision of approximately 100 MeV. Measurement of differential cross section of $t\bar{t}$ pair production in the continuum ($\sqrt{s} = 500$ GeV) can be used to constrain anomalous contributions to the $t\bar{t}\gamma/Z$ vertices. The use of polarized beams allows to disentangle the contributions related to the photon and Z boson. The characterization of the form factors can thus reach a precision that exceeds that envisaged at the LHC by an order of magnitude.

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