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Top quark physics and QCD: Progress since the TESLA TDR[1]

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I review progress on investigations concerning top quark physics and QCD at a future linear e^+e^- collider that has been achieved since the presentation of the TESLA technical design report [1] in spring 2001. I concentrate on studies that have been presented during the workshop series of the Extended Joint ECFA/DESY Study on Physics and Detectors for a Linear Electron-Positron Collider.

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Top quark physics and QCD: Progress since the TESLA TDR[†]

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Abstract

I review progress on investigations concerning top quark physics and QCD at a future linear e^+e^- collider that has been achieved since the presentation of the TESLA technical design report [1] in spring 2001. I concentrate on studies that have been presented during the workshop series of the Extended Joint ECFA/DESY Study on Physics and Detectors for a Linear Electron-Positron Collider.

INTRODUCTION

Since the presentation of the TESLA technical design report [1] in spring 2001, important progress has been achieved and reported in the top quark/QCD working group of the Extended Joint ECFA/DESY Study on Physics and Detectors for a Linear Electron-Positron Collider. The common aim of these studies is to improve theoretical predictions and perform more realistic simulations in order to obtain an accurate understanding of top quark interactions and QCD phenomena at a linear collider. A basic issue is a precision determination of two fundamental parameters of the Standard Model, namely the top quark mass m_t and the strong coupling constant α_s. These parameters as well as the top quark width can be extracted from a scan of the $t\bar{t}$ threshold cross section with high accuracy, and I will report on the progress of the simulation of such a scan and of the refinements in the theoretical computation of the threshold cross section. Before that, I will summarize a recent study on the importance of a very precise measurement of m_t. Further topics covered here include new studies on top quark production and decay in the continuum and a summary of QCD-related studies. I concentrate on work reported at the ECFA/DESY workshops. A summary of top quark and QCD studies presented at the last International Linear Collider Workshop (LCWS02) is given in [2].

WHY DO WE WANT TO KNOW M_T VERY PRECISELY?

The physics impact of a very precise measurement of the top quark mass with $\delta m_t \lesssim 100$ MeV has been recently studied in detail [3]. An accurate knowledge of m_t strongly affects tests of the Standard Model (SM) and its extensions using electroweak precision observables. This is demonstrated in Fig. 1, where the prospective experimental errors of M_W and $\sin^2\theta_{\rm eff}$ at the LHC/LC and the GigaZ option of the LC are compared to theoretical predictions within the SM and the Minimal Supersymmetric extension of the SM (MSSM). Since these observables receive radiative corrections $\sim m_t^2$, an improvement from δm_t= 2 GeV (a value to be obtained at the LHC) to δm_t= 100 MeV leads to a significant reduction of the allowed parameter space both in the SM (about factor of 10) and in the MSSM (about a factor of 2). This will be very important in the effort to constrain new interactions in using electroweak precision observables. A precise knowledge of m_t also improves the indirect determination of the top quark Yukawa coupling from electroweak precision observables. Further, if one wants to obtain constraints on the MSSM by comparing a precise measurement of the Higgs boson mass with the theoretical predictions of m_h in this model, a precise value of m_t is mandatory due to the strong dependence ($\sim m_t^4$) of m_h on the top quark mass. For further details and other

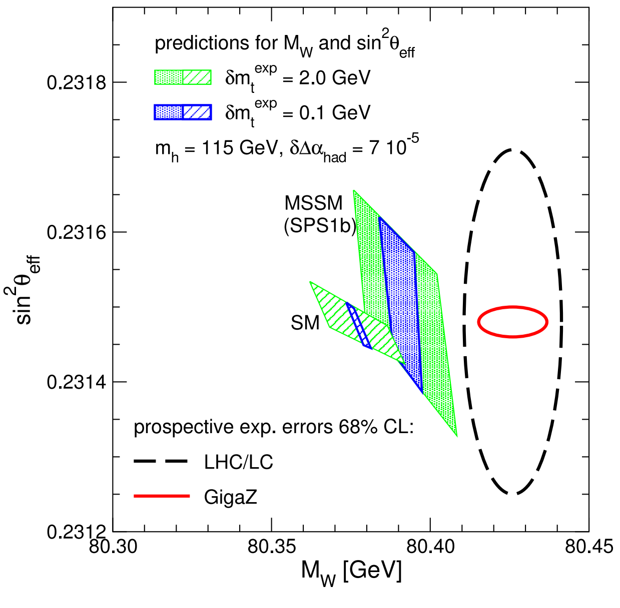

Figure 1: The predictions for M_W and $\sin^2\theta_{\rm eff}$ in the SM and the MSSM (SPS1b). Figure taken from [3].

[†] Much of the work reported in this talk was done by members of the Top and QCD working group of the Extended ECFA/DESY Study: W. Bernreuther (RWTH Aachen), G.A. Blair (London U.), E. Boos (Moscow State U.), P.N. Burrows (London U.), M.P. Casado (CERN), S.V. Chekanov (Argonne), S. Dittmaier (MPI München), M. Dubinin (Moscow U.), J. Fleischer (Bielefeld U.), A. Gay (IRES Strasbourg), T. Hahn (MPI München), S. Heinemeyer (München U.), A.H. Hoang (MPI München), W. Hollik (MPI München), K. Kolodziej (Silesia U.), S. Kraml (CERN), F. Krauss (CERN), J.H. Kühn (Karlsruhe U.), J. Kwiecinski (Inst. of Nucl. Phys. Krakow), A. Lorca (DESY Zeuthen), M. Maniatis (Hamburg U.), A.V. Manohar (UC San Diego), M. Martinez (Barcelona U.), R. Miquel (LBL Berkeley), V.L. Morgunov (DESY), W. Porod (Zürich U.), T. Riemann (DESY Zeuthen), M. Roth (Karlsruhe U.), T. Robens (Heidelberg U.), C. Schappacher (Karlsruhe U.), I.W. Stewart (MIT), C. Sturm (Karlsruhe U.), T. Teubner (CERN), P. Uwer (Karlsruhe U.), G. Weiglein (IPPP Durham), A. Werthenbach (CERN), M. Winter (IRES Strasbourg), P.M. Zerwas (DESY Hamburg). I also would like to thank B.A. Kniehl, A.A. Penin and M. Steinhauser for discussions.

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applications of a precision measurement of m_t, see [3].

TOP QUARK PAIR PRODUCTION CLOSE TO THRESHOLD

Update of $t\bar{t}$ threshold scan simulation

Recently, an updated $t\bar{t}$ threshold scan simulation has been performed [4]. It comprises several new features as compared to previous studies. First, three observables have been considered: the total cross section, the position of the peak of the top quark momentum distribution, and the forward-backward asymmetry. Second, a multiparameter fit with up to four parameters ($m_t,\ \alpha_s,\ \Gamma_t$ and the top quark Yukawa coupling λ_t) has been performed. Finally, apart from experimental systematic errors an estimate of the theoretical error in the cross section prediction has been included in the fits. An integrated luminosity of $\mathcal{L} = 300\,\mathrm{pb}^{-1}$ was distributed equally among 10 scan points, where one of them was placed well below threshold in order to determine directly the background. A theoretical error on the total cross section of $\Delta\sigma/\sigma = 3\%$ was assumed in the simulation (see below for a discussion). The results may thus give a good impression about the final experimental accuracy of the determination of the parameters. The expected scan results are shown in Fig. 2. From a two parameter fit for α_s and m_t the following estimates of their errors were obtained:

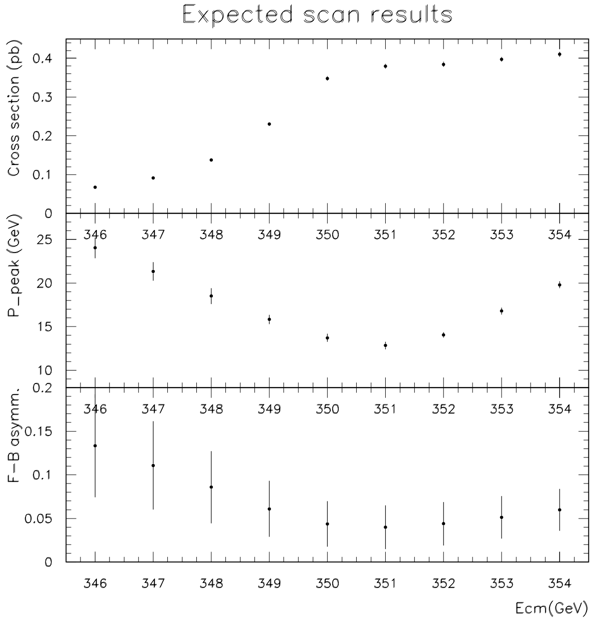

Figure 2: Expected scan result for the cross section, the peak of the top quark momentum distribution and the forward-backward charge asymmetry. Figure taken from [4].

$$\Delta m_t^{1S} = 16\ \mathrm{MeV}, \qquad \Delta\alpha_s = 0.0012. \tag{1}$$

Here, m_t^{1S} denotes the $1S$ mass of the top quark, the usage of which stabilises the location of the threshold with respect to higher order corrections and reduces the correlations between this mass and α_s. The correlation plot between m_t and α_s is shown in Fig. 3. The correlation coefficient is $\rho = 0.33$. While the cross section has the highest sensitivity on both m_t and α_s, the additional measurement of the peak of the momentum distribution reduces the errors and the correlation substantially.

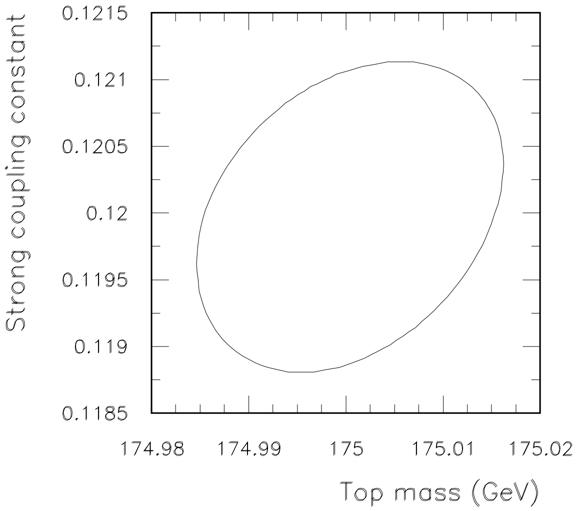

Figure 3: $\Delta\chi^2 = 1$ contour as a function of m_t^{1S} and $\alpha_s(M_Z)$. Figure taken from [4].

The size of the top quark width Γ_t determines how pronounced the $1S$ resonance is. A three-parameter fit for m_t, α_s and Γ_t gives:

$$\Delta m_t^{1S} = 19\ \mathrm{MeV},\ \Delta\alpha_s = 0.0012,\ \Delta\Gamma_t = 32\ \mathrm{MeV}. \tag{2}$$

This means that the top quark width can be determined with 2% accuracy, which is a factor of about 9 better than reported in earlier studies. This improvement is due to assuming a higher integrated luminosity, a better selection efficiency for $t\bar{t}$ events, a sharper TESLA beam spectrum and a better scanning strategy when using the $1S$ mass.

The sensitivity of a threshold scan to the top quark Yukawa coupling λ_t through a modification of the $t\bar{t}$ potential is not very large: if one performs a four-parameter fit with an external constraint on $\alpha_s(M_Z)$, the results are (for $M_H = 120$ GeV):

$$\begin{aligned} &\Delta m_t^{1S} = 31\ \mathrm{MeV}, \quad \Delta\alpha_s = 0.001\ (\mathrm{constr.}), \\ &\Delta\Gamma_t = 34\ \mathrm{MeV}, \quad \frac{\Delta\lambda_t}{\lambda_t} = ^{+0.35}_{-0.65}\ . \end{aligned} \tag{3}$$

Thus, constraining the top quark Yukawa coupling from a threshold scan is a challenging task. A better method is provided by analysing the associated Higgs production process $e^+e^- \to t\bar{t}H$ [5].

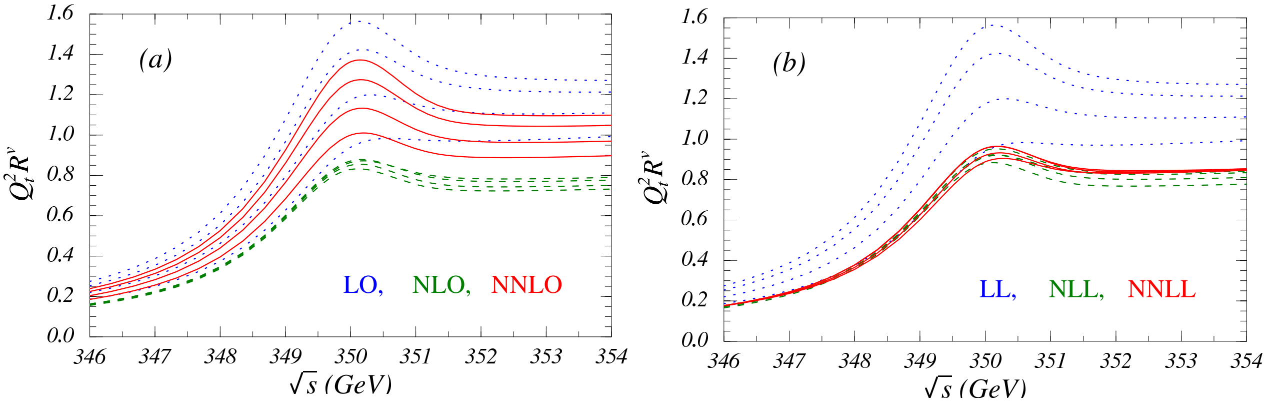

Figure 4: Results for the vector current R-ratio with fixed m_t^{1S} mass for fixed order and renormalization group improved predictions. The dotted, dashed, and solid curves in a) are LO, NLO, and NNLO, and in b) are LL, NLL, and NNLL order. For each order four curves are plotted for velocity renormalization scales $\nu = 0.1,\ 0.125,\ 0.2$ and 0.4. Figure taken from [10] (an update with very small changes was given in [12]).

The very accurate measurement of m_t^{1S} is certainly impressive; however, in order to use the top mass as an input for precision tests of the SM, we have to convert the $1S$ mass to the $\overline{\rm MS}$ mass. The current theoretical uncertainty in the perturbative relation between these two masses is of the order of 100 MeV [6].

Theoretical developments

The status of $t\bar{t}$ threshold cross section calculations in spring 2001 was as follows: Several groups had calculated the cross section at NNLO (for a synopsis of these results and further references, see [6]). The corrections turned out to be large, and the threshold location was found to be unstable under perturbative corrections when the top quark pole mass was used in the calculation. Further, a strong correlation between α_s and m_t limited the experimental precision of m_t to about 300 MeV. The usage of threshold masses [7, 8, 9] reduced this correlation and stabilized the position of the threshold significantly. However, the height of the cross section still suffered from large perturbative corrections of the order of 20 to 30 %, even when expressed in terms of a top quark threshold mass. In order to improve the prediction of the threshold cross section, the impact of a summation of QCD logarithms of ratios of the scales m_t, $m_t v$, and $m_t v^2$ was computed in [10, 11]. A comparison of the fixed order results and the renormalization group improved results is shown in Fig. 4. The remaining theoretical uncertainty of the cross section was estimated in [10] to be $\pm 3\%$. This number was obtained by varying the dimensionless velocity subtraction scale that separates hard, soft and ultrasoft momenta and by estimating the size of the one yet unknown NNLL contribution from the running at the production current. Very recently, the NNLL non-mixing contributions to the running of the production current have been determined [13]. It remains to be seen whether the $\pm 3\%$ estimate will withstand future refinements of the cross section calculations. For testing the convergence of the alternative fixed order (LO, NLO, NNLO, $\ldots$) perturbation series the computation of the NNNLO contributions is mandatory. Important progress has been recently achieved in this direction [14].

Electoweak effects have not yet been consistently included either at NNLL order or NNLO.

TOP QUARK PRODUCTION AND DECAY IN THE CONTINUUM

Mass determination from continuum production

In [15] the possibility of measuring the top quark mass in the continuum was investigated. The process $e^+e^- \to t\bar{t} \to 6$ jets was simulated including the QCD background. Top quarks were reconstructed by grouping the 6 jets into pairs of three-jet groups. Only three-jet groups which are produced back-to-back are accepted. The three-jet invariant mass distribution (see Fig. 5) then shows a prominent peak, the position of which is interpreted as the top quark mass. The statistical uncertainty of the peak position is 100 MeV for an integrated luminosity of 300 $\rm pb^{-1}$ at $\sqrt{s} = 500$ GeV. Experimental systematic errors have not yet been studied. Further, it is not clear yet how to relate this ‘kinematic mass‘ to the pole mass or other top quark mass definitions. The method was recently extended to semileptonic top decays [16].

Anomalous top quark couplings

A new analysis was started to evaluate the sensitivity of $e^+e^- \to t\bar{t}$ to anomalous top quark couplings [17]. The plan is to use PANDORA/PYTHIA and SIMDET in the simulation and try to find observables that optimize the sensitivity.

New theoretical studies and tools

In the following I briefly discuss further studies on top quark production and decay in the continuum that have been presented during the workshop series.

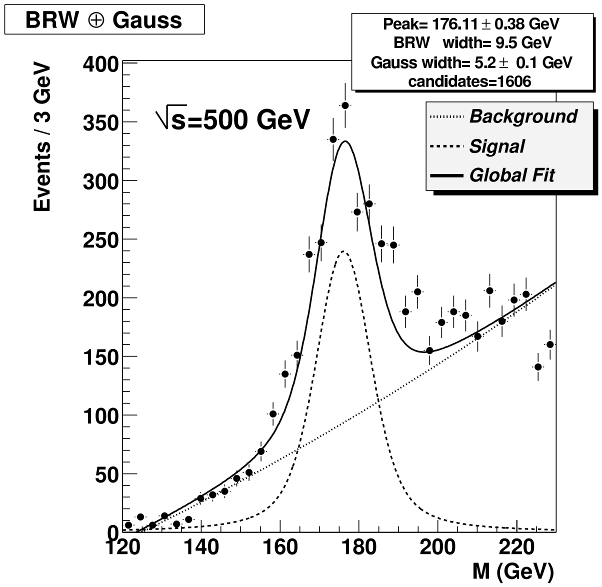

Figure 5: The invariant-mass distribution for three-jet clusters in $e^+e^- \to 6$ jets. Figure taken from [15].

- Several calculations of the electroweak one-loop radiative corrections to the process $e^+e^- \to t\bar{t}$ have been compared in detail [18]. The numerical agreement is excellent (see also Table 4 in [19]). The package `topfit` containing these corrections is publicly available [20].

- New tree level Monte Carlo generators (`AMEGIC++` [21], `eett6f` [22] and `LUSIFER` [23]) for the processes $e^+e^- \to 6$ fermions have been written (for details, see [19]). These programs allow to study in particular the non-resonant background to $t\bar{t}$ production and decay.

- In [24], the production of single top quarks in $e^+e^-, e^-e^-, e\gamma$ and $\gamma\gamma$ collisions was studied at tree level. By comparing all possible reactions, the best option turned out to be collisions of circular polarized photons with left-handed electrons. The cross section at $\sqrt{s} = 500$ GeV is $\sigma(\gamma_+ e_L^- \to \bar{t}b\nu) \sim 100$ fb, and this process is very sensitive to V_{tb} as well as to possible anomalous couplings. If one aims at an experimental precision of 1% for V_{tb}, the inclusion of higher order corrections is mandatory. The QCD corrections to this process have been computed very recently [25] and are of the order of 5%.

- The SUSY-QCD corrections to the production and decay of *polarized* top quarks in e^+e^- collisions have been computed in [26]. While the decay width and lepton energy spectrum can be modified at the percent level, top polarization observables are hardly affected by these corrections.

QCD STUDIES

Measurement of α_s

The primary goal of QCD studies at a linear collider is to measure the strong coupling constant α_s as precisely as possible. The aim is to reduce the current accuracy $\Delta\alpha_s(M_Z) = 0.003$ to a value of $\Delta\alpha_s(M_Z) = 0.001$ or smaller. In the context of QCD, such an accuracy is important, since *all* predictions of perturbative QCD are directly affected, in particular multi-jet cross sections at higher orders. Furthermore, an extrapolation of $\alpha_s(Q)$ to very high energy scales which is performed to test the hypothesis of Grand Unification needs precise initial conditions, and the uncertainty on α_s is currently the limiting factor of such tests. This is illustrated in Fig. 6, where the running of the inverse coupling constants is shown. The narrow error band on $1/\alpha_3$ in Fig. 6b corresponds to $\Delta\alpha_s(M_Z) = 0.001$. The techniques for a determination of $\alpha_s(M_Z)$ at TESLA have been described in detail in the TDR. In a recent study [28], the prospects of a measurement of α_s from GigaZ analyses have been investigated. The factor of ~ 100 in the size of the data sample as compared to LEP data together with the expected better performance of the detector give rise to the expectation that systematic errors may shrink by a factor of 3 to 5. This would mean that the experimental accuracy on α_s could be brought down to $(5-7) \times 10^{-4}$, the most sensitive observable being the inclusive ratio $\Gamma_Z^{\rm hadron}/\Gamma_Z^{\rm lepton}$. No theoretical errors are included in this analysis. At present, the theoretical uncertainty of α_s-determinations from $\Gamma_Z^{\rm hadron}/\Gamma_Z^{\rm lepton}$ is estimated to be of the same size as the current experimental accuracy [29]. In view of the prospective accuracy from a GigaZ run, there is an ongoing effort to compute more and more terms of the perturbation series for $\Gamma_Z^{\rm hadron}/\Gamma_Z^{\rm lepton}$ and related quantities like $R(s)$ and $\Gamma_\tau^{\rm hadron}/\Gamma_\tau^{\rm lepton}$. The most recent step in this direction has been the calculation of a gauge-invariant subset of the order α_s^4 contributions, namely the terms of order $\alpha_s^4 n_f^2$, where n_f is the number of fermion flavours [30].

The bottleneck of determinations of $\alpha_s(M_Z)$ from event shapes (like thrust distribution, jet rates etc.) is currently the insufficient theoretical precision of perturbative QCD calculations. Currently most shape variables are known to next-to-leading order accuracy, while for some observables resummed calculations are available. However, enormous progress towards the calculation of $e^+e^- \to 3$ jets to NNLO ($\mathcal{O}(\alpha_s^3)$) has been achieved within the last few years [31]. It is estimated that once these calculations are accomplished, the current theoretical uncertainty (obtained by a variation of the QCD renormalisation scale) of $\Delta\alpha_s(M_Z) \simeq 0.006$ will shrink by a factor of 3 to 5.

Saturation model for $\gamma\gamma$ and $\gamma^*\gamma^*$ processes

In [32] a saturation model has been constructed to describe the total cross section for $\gamma\gamma$ and $\gamma^*\gamma^*$ collisions at high energies. The $\gamma^*\gamma^*$ total cross section is assumed