Full simulation study of the top Yukawa coupling at the ILC at $\sqrt{s} = 1$ TeV

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We present a study of the expected precision for measurement of the top Yukawa coupling, $y_t$, in $e^+e^-$ collisions at a center-of-mass energy of 1 TeV and assuming a beam polarization of $P(e^-, e^+) = (-0.8, +0.2)$. Independent analyses of $t\bar{t}H$ final states containing at least six hadronic jets are performed, based on detailed simulations of SiD and ILD, the two candidate detector concepts for the ILC. We estimate that a statistical precision of $y_t$ of 4% can be obtained with an integrated luminosity of 1 ab$^{-1}$.

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I. INTRODUCTION

The discovery of a Standard Model (SM)--like Higgs boson, announced on July 4th, 2012 by the ATLAS and CMS collaborations [1, 2], was celebrated as a major milestone in particle physics. In the SM, the coupling strength of the Higgs boson to a fermion is given by $y_f = \sqrt{2m_f/v}$, where $m_f$ is the fermion mass and $v \approx 246$ GeV is the vacuum expectation value. Since the top quark is the heaviest known elementary particle, the measurement of the top Yukawa coupling, $y_t$, serves as the high endpoint to test this prediction. A sizable deviation in $y_t$ from the SM prediction is expected in various new physics scenarios, which motivates a precise measurement of $y_t$. For example, in composite Higgs models, where the Higgs boson is a pseudo-Nambu-Goldstone boson, $y_t$ could deviate up to tens of $\%$, even in the scenario that no new particles are discovered in LHC Run 2 data [3].

A recent study of the prospects of measuring $y_t$ at the LHC estimates that a precision of 14–15% (7–10%) is achievable with an integrated luminosity of 0.3 ab$^{-1}$ (3 ab$^{-1}$) [4]. For $e^+e^-$ collisions, detailed simulation studies have been carried out using the $t\bar{t}H$ process at various center-of-mass (CM) energies. At $\sqrt{s} = 500$ GeV [5, 7], where the $e^+e^- \rightarrow t\bar{t}H$ cross section is sharply rising, the precision is estimated to be about 10% for an integrated luminosity of 1 ab$^{-1}$, while at $\sqrt{s} = 800$ GeV [8, 9], it is estimated that $y_t$ can be measured to a precision of 5–6% for an integrated luminosity of 1 ab$^{-1}$.

The International Linear Collider (ILC) [10] is a proposed $e^+e^-$ collider with a maximum CM energy $\sqrt{s} = 1$ TeV. It has a broad physics potential that is complementary to the LHC and precision measurements of the Higgs couplings are an integral part of the physics program at this machine. We present studies of the measurement of the top Yukawa coupling in direct observation at the 1 TeV stage of the ILC. The studies are carried out in ILD and SiD [11], the two detector concepts for the ILC. They are performed with detailed detector simulations taking into account the main beam-induced backgrounds at the collider as well as the dominant background from other physics processes. Two final states are considered - events where both W bosons from the top quarks decay hadronically, and events where exactly one of the two W bosons decays leptonically.

The studies performed for the two detector concepts have large overlaps, and we highlight significant differences between the two analyses wherever applicable. This document is organized as follows: Section II gives an overview of the signal sample and the considered physics background. Section III gives brief overviews over the two ILC detector models. The tools for the generation of physics processes and the detector simulation and reconstruction are listed in Section IV. The two dominant sources of machine-induced background in the detectors are introduced in Section V. The techniques to reduce these backgrounds and reconstruct the top quarks and Higgs bosons are described in Section VI. Details of the event selection are given in Section VII and the results are presented in Section VIII. The dominant sources of systematic uncertainty are given in Section IX and the two analyses are summarized in Section X.

II. SIGNAL AND BACKGROUND PROCESSES

Figure 1 illustrates the lowest order Feynman diagrams for the process $e^+e^- \rightarrow t\bar{t}H$. The diagram for the reaction

(a) $e^+e^- \rightarrow t\bar{t}H$ is achieved with the main beam-induced backgrounds at the collider as well as the dominant background from other physics processes. Two final states are considered - events where both W bosons from the top quarks decay hadronically, and events where exactly one of the two W bosons decays leptonically.

The studies performed for the two detector concepts have large overlaps, and we highlight significant differences between the two analyses wherever applicable. This document is organized as follows: Section II gives an overview of the signal sample and the considered physics background. Section III gives brief overviews over the two ILC detector models. The tools for the generation of physics processes and the detector simulation and reconstruction are listed in Section IV. The two dominant sources of machine-induced background in the detectors are introduced in Section V. The techniques to reduce these backgrounds and reconstruct the top quarks and Higgs bosons are described in Section VI. Details of the event selection are given in Section VII and the results are presented in Section VIII. The dominant sources of systematic uncertainty are given in Section IX and the two analyses are summarized in Section X.

Figure 1. The lowest order Feynman diagrams for the process $e^+e^- \rightarrow t\bar{t}H$. In (a) the Higgs boson is radiated from a top quark and (b) is the background Higgs-strahlung process where the Higgs boson is radiated from the Z boson.
tion $e^+e^- \rightarrow Z^0H$ (Higgs-strahlung) with $Z^0 \rightarrow t\bar{t}$ which does not contain $y_t$ has a small yet non-negligible contribution to the total cross section. The size of this effect is studied by evaluating the change of the $e^+e^- \rightarrow t\bar{t}H$ cross section when modifying $y_t$ from the SM value. Using this procedure, we extract the factor $\kappa$ as defined by the relation $\Delta y_t/y_t = \kappa \Delta \sigma/\sigma$ for the SM value of $y_t$. In the absence of the Higgs-strahlung diagram, we would find $\kappa = 0.5$. Instead, we find $\kappa = 0.52$, indicating a non-negligible contribution from the Higgs-strahlung diagram to the total cross section at $\sqrt{s} = 1$ TeV. This factor is used in the extraction of the top Yukawa coupling precision. The correction will be known with good precision, because the Higgs coupling to the $Z$ boson can be extracted from measurements of $e^+e^- \rightarrow Z\bar{H}$ events at $\sqrt{s} = 250$ GeV with a statistical uncertainty of about $1.5%$ [12].

For this study the semileptonic and hadronic decays of the $t\bar{t}$ system were studied with the Higgs decaying via the dominant decay mode into a $b\bar{b}$ pair. For the fully hadronic decay channel this leads to a signature of eight hadronic jets, four of which are $b$ jets. In the semileptonic mode the final signal in the detector consists of six hadronic jets, four of which are $b$ jets, an isolated lepton, and missing energy and momentum from a neutrino. For isolated leptons, only the prompt electrons and muons are reconstructed and considered as signal, neglecting the decays into $\tau$ leptons. These two modes are reconstructed in independent samples and are combined statistically.

Irreducible backgrounds to these processes arise from the eight-fermion final states of $t\bar{t}Z$ where the $Z$ decays into a $b\bar{b}$ pair and $t\bar{t}b\bar{b}$ where the $t\bar{t}$ system radiates a hard gluon which forms a $b\bar{b}$ pair. A large background contribution also arises from $t\bar{t}$ due to the huge relative cross section compared to the signal. There is also a contribution from the other decay modes of the $t\bar{t}$ system such as the Higgs decaying to final states other than a $b\bar{b}$ pair and the fully leptonic decays of the top quarks.

An overview of the cross sections for the signal final states as well as for the considered backgrounds is shown in Table I. The numbers for “other $t\bar{t}H$” processes in this table do not include either of the signal final states (see text). The $t\bar{t}Z$ and $t\bar{t}g^*\rightarrow t\bar{t}b\bar{b}$ samples, where the hard gluon $g^*$ splits into a $b\bar{b}$ pair, do not contain events where both top quarks decay leptonically. The $t\bar{t}$ samples contain the SM decays of both $W$ bosons.

TABLE I. Production cross sections times branching ratios or production cross sections for the signal final states and for the considered backgrounds. All samples were generated assuming a Standard Model Higgs with a mass of 125 GeV. The numbers for “other $t\bar{t}H$” processes in this table do not include either of the signal final states (see text).

| Type               | Final state | $P(e^-)$ | $P(e^+)$ | $\sigma \times BR$ (fb) |
|--------------------|-------------|----------|----------|-------------------------|
| Signal             | $t\bar{t}H$ (8 jets) | $-80\% +20\%$ | $+80\%$ | $0.87$ |
| Signal             | $t\bar{t}H$ (6 jets) | $-80\% +20\%$ | $+80\%$ | $0.84$ |
| Signal             | $t\bar{t}H$ (6 jets) | $+80\% +20\%$ | $-80\%$ | $0.42$ |
| Background         | other $t\bar{t}H$ | $-80\% +20\%$ | $+80\%$ | $1.59$ |
| Background         | other $t\bar{t}H$ | $+80\% +20\%$ | $-80\%$ | $0.80$ |
| Background         | $t\bar{t}Z$     | $-80\% +20\%$ | $+80\%$ | $6.92$ |
| Background         | $t\bar{t}Z$     | $+80\% +20\%$ | $-80\%$ | $2.61$ |
| Background         | $t\bar{t}g^*\rightarrow t\bar{t}b\bar{b}$ | $-80\% +20\%$ | $+80\%$ | $1.72$ |
| Background         | $t\bar{t}g^*\rightarrow t\bar{t}b\bar{b}$ | $+80\% +20\%$ | $-80\%$ | $0.86$ |
| Background         | $t\bar{t}$      | $-80\% +20\%$ | $+80\%$ | $449$ |
| Background         | $t\bar{t}$      | $+80\% +20\%$ | $-80\%$ | $170$ |

For SiD a superconducting solenoid with an inner radius of 2.6 m provides a central magnetic field of 5 T. The calorimeters are placed inside the coil and consist of a 30 layer tungsten–silicon electromagnetic calorimeter (ECAL) with 13 mm$^2$ segmentation, followed by a hadronic calorimeter (HCAL) with steel absorber and instrumented with resistive plate chambers (RPC) – 40 layers in the barrel region and 45 layers in the endcaps. The read-out cell size in the HCAL is $10 \times 10$ mm$^2$. The iron return yoke outside of the coil is instrumented with 11 RPC layers with $30 \times 30$ mm$^2$ read-out cells for muon identification. The silicon-only tracking system consists of five layers of $20 \times 20$ mm$^2$ pixels followed by five strip layers with a pitch of 25 mm, a read-out pitch of 50 mm and a length of 92 mm per module in the barrel region. The tracking system in the endcap consists of four stereo-trip disks with similar pitch and a stereo angle of 12°, complemented by four pixelated disks in the vertex region with a pixel size of $20 \times 20$ mm$^2$ and three disks in the far-forward region at lower radii with a pixel size of $50 \times 50$ mm$^2$. All sub-detectors have the capability of time-stamping at the level of individual bunches, 337 ns apart, $\approx 1300$ to a train. This allows to separate hits originating from different bunch crossings. The whole detector will be read out in the 200 ms between bunch trains.

The ILD detector model is designed around a different optimization with a larger size. The ECAL and HCAL are placed inside a superconducting solenoid, which provide a magnetic field of 3.5 T. The silicon-tungsten ECAL has an inner radius of 1.8 m and a total thickness of 20 cm, with $5 \times 5$ mm$^2$ transverse cell size and 30 layers of longitudinal segmentation. The steel-scintillator HCAL has an outer radius of 3.4 m with $3 \times 3$ cm$^2$ transverse tiles.

III. DETECTOR MODELS

SiD [11] chapter 2] and ILD concepts [11] chapter 3] are designed to be the two general-purpose detectors for the ILC, with a 4 $\pi$ coverage, employing highly granular calorimeters for particle flow calorimetry.
and 48 layers longitudinal segmentation. ILD employs a hybrid tracking system consisting of a time projection chamber (TPC) which provides up to 224 points per track and silicon-strip sensors for improved track momentum resolution, which are placed in the barrel region both inside and outside the TPC and in the endcap region outside the TPC. The vertex detector consists of three double layers of silicon pixel sensors with radii ranging from 15 to 60 mm, providing a spatial resolution of 2.8 µm. An iron return yoke instrumented with a muon detector and a tail catcher is placed outside the yoke. In addition, silicon trackers and beam/luminosity calorimeters are installed in the forward region.

IV. ANALYSIS FRAMEWORK

The t\bar{t}, t\bar{t}Z, and t\bar{t}b\bar{b} samples were generated using the PHYSIM [13] event generator. The sample referred to as t\bar{t} in the following includes six-fermion final states consistent with the t\bar{t} decays but not limited to the resonant t\bar{t} production. The t\bar{t} events were generated using the WHIZARD 1.95 [14, 15] event generator. All samples were generated taking into account the expected beam energy spectrum at the \( \sqrt{s} = 1 \text{ TeV} \) ILC, including initial state radiation [16] and beamstrahlung. The spectrum was sampled from a simulation of beam events [17]. The model for the hadronization in PYTHIA 6.4 [18] uses a tune based on OPAL data [19, Appendix B.3].

Detailed detector simulations based on GEANT4 [20, 21] are performed. In the SiD analysis, the event reconstruction is performed in the org.lcsim [22] package. The ILD analysis uses the Marlin [23, 24] framework. Both analyses use the PandoraPFA [25] algorithm for calorimeter clustering and combined analysis of track and calorimeter information based on the particle flow approach. The LCFIPlus [11] Section 2.2.2.3] package is used for the identification of heavy flavor jets. The assumed integrated luminosity of the analysis is 1 ab\(^{-1}\), which is split equally between the two polarization configurations (+80%, −20%) and (−80%, +20%) for the polarization of the electron and positron beams (\(P_e, P_{e^+}\)). Detector hits from Beam-induced backgrounds from processes described in Section V are treated correctly in the simulation of the detector readout and in the reconstruction.

V. TREATMENT OF BEAM-INDUCED BACKGROUND

A. Properties of Beam-Induced Backgrounds

The ILC operating at \( \sqrt{s} = 1 \text{ TeV} \) has an instantaneous luminosity of \( 4.2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \). During the collision, a number of processes occur in addition to the primary scattering event. The production of incoherent electron-positron pairs results in an average of \( 4.5 \times 10^5 \) low-momentum particles per bunch crossing. We assume 4.1 hadronic events from two-photon processes (\( \gamma\gamma \rightarrow \text{hadrons} \)) with an energy greater than 300 MeV per signal event. Figure 2 shows the kinematic properties of the particles originating from these processes. They do not affect the reconstruction significantly, but present a challenge to the sub-detector occupancies and pattern recognition. The SiD analysis includes both effects, while the ILD analysis includes only the \( \gamma\gamma \rightarrow \text{hadrons} \) processes.

While the most energetic particles from incoherent pair production are primarily outside of the detector acceptance of both detectors, some low-\( p_T \) particles lead to an occupancy of up to 0.06 hits/mm\(^2\) per bunch crossing in the vertex detector and up to \( 5 \times 10^{-5} \) hits/mm\(^2\) per bunch crossing in the main tracker for the SiD detector model. They do not, however, impact on the energy reconstruction. Particles from \( \gamma\gamma \rightarrow \text{hadrons} \) processes on the other hand can have sizable values of \( p_T \) and reach the calorimeters, affecting the jet energy resolution. The beam-induced backgrounds do not degrade the tracking performance significantly [11].

The primary vertices of the beam-induced backgrounds are distributed with a Gaussian profile along the beam direction across the luminous region of 225 µm, taking into account the bunch length along the beam direction.
VI. EVENT RECONSTRUCTION

A. Suppression of Beam-Induced Backgrounds

The particles originating from beam-induced backgrounds as described in Sec. V tend towards low transverse momenta and small angles with respect to the beam axis. Different approaches are used to suppress the impact of the beam-induced backgrounds. For the SiD analysis, only the reconstructed objects in the range $20^\circ < \theta < 160^\circ$ are considered, because the $t\bar{t}H$ final state is produced via s-channel exchange and is not suppressed by this selection. In the ILD analysis, the longitudinally-invariant $k_T$ jet algorithm \cite{26,27} with a value of 1.2 for the $R$ parameter is employed to suppress the particles close to the beam axis. Only the particles grouped into the physics jets by the $k_T$ algorithm are considered further in the analysis. Figure 3 shows how the impact of the beam-induced backgrounds on the reconstructed Higgs mass is mitigated by the removal procedure. A modified version of the Durham jet finding algorithm \cite{28} then groups all particles in the event into a specified number of jets, without splitting decay products of secondary vertices across different jets.

B. Reconstruction of Isolated Leptons

Signal events with six jets contain one high-energy isolated lepton from the leptonic $W$ boson decay. No isolated leptons are expected in signal events with two hadronic $W$ decays. Hence the number of isolated leptons is an important observable in the signal selections for both final states.

The electron and muon identification criteria used in this study are based on the energy deposition in the ECAL and HCAL and the momentum measured by the tracker. Electrons candidate are selected by requiring that almost all of the energy deposition is in the ECAL and that the total calorimetric energy deposition is consistent with the momentum measured by the tracker. For the muon candidates, most of the energy deposition is in the HCAL, while the calorimetric energy is required to be small compared to the corresponding momentum measured by the tracker. A selection on the impact parameter reduces non-prompt leptons.

The SiD analysis uses the IsolatedLeptonFinder processor implemented in MarlinReco \cite{23} to identify leptons in regions with otherwise little calorimetric activity. The ILD analysis additionally exploits the transverse distance from the jet axis to identify leptons from leptonic $W$ decays.

The electron and muon identification capabilities of the reconstruction within a multi-jet environment were tested in a sample of four jets, one lepton and missing energy. The efficiency is defined as the fraction of leptons with correctly identified flavor in a sample of isolated lepton candidates. The purity is the ratio of the number of leptons of a given type stemming from a leptonic $W$ decay to the number of all identified isolated leptons of that type. An efficiency of 82% (89%) and purity of 95% (97%) for electrons (muons) is observed in ILD and 86% (86%) efficiency and 94% (95%) purity for electrons (muons) in SiD.

C. Jet Clustering and Flavor Identification

Depending on the signal definition for the semi-leptonic or hadronic final state, the Durham jet clustering algorithm is used in the exclusive mode to cluster the event into six or eight jets, respectively.

Heavy flavor identification is primarily used to remove the $t\bar{t}$ background. Both the six-jets and eight-jets final states contain four $b$ jets. The flavor tagging classifier for the measurement of $t\bar{t}H$ production was trained on events with six quarks of the same flavor produced in electron-positron annihilation. For the training, 60000 $c$ and $b$ jets, and 180000 light quark jets are used. These samples were chosen since the jets have similar kinematic properties as those in $t\bar{t}H$ signal events. The $t\bar{t}$ events contain no more than two $b$ jets from the top decays as do $\sim$80% of $t\bar{t}Z$.

Figure 4(a) shows the distribution of the response from the flavor-tagging multivariate selection for the jet that has the third-highest tagging probability. In both analyses, the shape of the distribution of the flavor tagging response, rather than a simple cut, is used. The background channels, in particular $t\bar{t}$, are dominated by the peak at low values. The peak at higher values in the $t\bar{t}$
Z channel is due to events with with four genuine b jets.

D. Reconstruction of W, top and Higgs Candidates

To form W, top and Higgs candidates from the reconstructed jets, the following function is minimized for the final state with eight jets:

$$\chi^2_{8 \text{ jets}} = \frac{(M_{12} - M_W)^2}{\sigma_W^2} + \frac{(M_{123} - M_t)^2}{\sigma_t^2} + \frac{(M_{45} - M_W)^2}{\sigma_W^2} + \frac{(M_{456} - M_t)^2}{\sigma_t^2} + \frac{(M_{78} - M_H)^2}{\sigma_H^2},$$

(1)

where $M_{12}$ and $M_{45}$ are the invariant masses of the jet pairs used to reconstructed the W candidates, $M_{123}$ and $M_{456}$ are the invariant masses of the three jets used to reconstruct the top candidates and $M_{78}$ is the invariant mass of the jet pair used to reconstruct the Higgs candidate. $M_W$, $M_t$ and $M_H$ are the nominal W, top and Higgs masses. The resolutions $\sigma_W$, $\sigma_t$ and $\sigma_H$ were obtained from reconstructed jet combinations matched to W, top and Higgs particles at generator level. The corresponding function minimized for the six-jets final state is given by:

$$\chi^2_{6 \text{ jets}} = \frac{(M_{12} - M_W)^2}{\sigma_W^2} + \frac{(M_{123} - M_t)^2}{\sigma_t^2} + \frac{(M_{45} - M_H)^2}{\sigma_H^2}.$$  

(2)

In the ILD analysis, the b tagging information is also used to reduce the number of combinations by forming the Higgs candidate from pairs of jets that have the highest value of the b-tagging classifier. The other jets in the event are used to form the top candidates.

VII. EVENT SELECTION

Events were selected using Boosted Decision Trees (BDTs) as implemented in TMVA [29]. The BDTs were trained separately for the eight- and six-jets final states. (BDTs) as implemented in TMVA [29]. The BDTs were trained to reject the leptonic W boson decay, finite values of $p_T^{\text{miss}}$ are reconstructed for six-jets signal events while $p_T^{\text{miss}}$ tends towards zero for eight-jets signal events;

- the visible energy of the event defined as the scalar sum of all jet energies;
- the masses $M_{12}$, $M_{123}$ and $M_{45}$ as defined in Section VI D.

For the eight-jets final state additionally the two variables $M_{456}$ and $M_{78}$ as defined in Section VI D are included.

The ILD analysis includes the helicity angle of the Higgs candidate as defined by the angle between the two b jet momenta in the dijet rest frame.

To select events, cuts on the BDT response are applied. The cuts were optimized by maximizing the signal significance given by: $\frac{S}{\sqrt{S+B}}$, where $S$ is the number of signal events and $B$ is the number of background events. As an example, the reconstructed top and Higgs masses in six-jets events after the cut on the BDT output are shown in Figure 5. The selection efficiencies (purities) for signal events are 33.1% (27.7%) and 56.0% (25.2%) for the six- and eight-jets analyses in ILD, respectively, and 30.5% (28.9%) and 45.9% (26.7%) in SiD. In Table II the expected yields are shown separately for all investigated final states.

| Detector | ILD | SiD |
|----------|-----|-----|
| Sample   | Before cuts | After Cuts |
|          | 6 jets | 8 jets | 6 jets | 8 jets |
| $t\bar{t}H$ 6 jets | 628.7 | 208.0 | 65.5 | 191.6 | 57.4 |
| $t\bar{t}H$ 8 jets | 652.7 | 21.1 | 365.6 | 1.6 | 299.4 |
| $t\bar{t}H \rightarrow$ other | 1197.5 | 28.8 | 25.3 | 33.0 | 16.6 |
| $t\bar{t}Z$ | 5332.4 | 126.1 | 260.5 | 105.6 | 187.1 |
| $t\bar{t}b\bar{b}$ | 1434.5 | 125.4 | 222.6 | 100.1 | 180.7 |
| $t\bar{t}$ | 308800.9 | 261.2 | 513.6 | 232.0 | 381.6 |

$y_t$ uncertainty

|          | 6.9% | 5.4% | 7.0% | 5.8% |
| combined | 4.3% | 4.5% |
for hadronically decayed tZ final state can be reconstructed in a similar fashion to the tZ analysis. For our nominal integrated luminosity of 1 ab$^{-1}$, the number of jets in the final state will be the same as in the tZH analysis. For our nominal integrated luminosities of 0.5 ab$^{-1}$ for each of the two polarization states, 1400 events are expected for ttH($\rightarrow b\bar{b}$) and 800 events are expected for tZ($\rightarrow b\bar{b}$), taking into account the Z($\rightarrow b\bar{b}$) branching ratio. Other hadronic decays of the Z boson will have large tt background due to the absence of the two b tags. Including leptonic decays of the Z boson will help increase the sensitivity to this channel. Overall, one can expect that the statistical uncertainty for tZ will be similar to that of tZH, i.e. at the few percent level.

The large cross section of tt events will allow for detailed systematic studies. While only a certain class of these events may enter the final selection, we estimate that the systematic uncertainty to the measurement of $\sigma_{tt}$...
the top Yukawa coupling can be measured with precision comparable to that of $t\bar{t}Z$.

Other sources of systematic uncertainty such as the luminosity measurement, jet energy scale, and flavor tagging are typically at the 1% level or better for $e^+e^-$ colliders. The uncertainty on $\text{BR}(H \rightarrow b\bar{b})$ is not taken into account in our calculation of the top Yukawa coupling from the $t\bar{t}H$ production cross section. It is expected that this quantity can be measured with a precision of better than 1% using $e^+e^- \rightarrow \nu\bar{\nu}H$ events [31,32].

X. SUMMARY

The physics potential for a measurement of the top Yukawa coupling at 1 TeV at the ILC is investigated. The study is based on detailed detector simulations using both the SiD and ILD detector concepts. Beam-induced backgrounds are considered in the analysis. The combination of results obtained for two different final states leads to a statistical uncertainty on the top Yukawa coupling of better than 4.5% for an integrated luminosity of 0.5 ab$^{-1}$ with $P(e^-, e^+) = (−80\%, +20\%)$ beam polarization configuration and 0.5 ab$^{-1}$ with $P(e^-, e^+) = (+80\%, −20\%)$ polarization. If 1 ab$^{-1}$ of data were recorded with only the $P(e^-, e^+) = (−80\%, +20\%)$ beam polarization configuration, the expected precision would improve to 4%.

The results from the studies presented in this paper demonstrate the robustness of the physics reconstruction of high jet multiplicity final states at $\sqrt{s} = 1$ TeV under realistic simulation conditions. The expected precisions for measurements of the top Yukawa coupling were found to be very similar for two different detector concepts.

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