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SIGNAL AND BACKGROUND IN  $e^+e^- \rightarrow t\bar{t}H^*$ KAROL KOŁODZIEJ<sup>†</sup>, SZYMON SZCZYPIŃSKI<sup>‡</sup>Institute of Physics, University of Silesia  
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We discuss the reaction of associated production of a top quark pair and a Higgs boson at the future  $e^+e^-$  linear collider that can be used to determine the top-Higgs Yukawa coupling. Taking into account decays of the top quarks and the light Higgs boson leads to reactions with 8 fermions in the final state which, in the framework of the Standard Model, receive contributions typically from many thousands Feynman diagrams. An overwhelming majority of the diagrams comprises the off resonance background to the resonant signal of associated production and decay of the top quark pair and Higgs boson. We address the signal and background issue by comparing cross-sections calculated with the signal diagrams only and with the complete sets of the diagrams.

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**1. Introduction**

If the Higgs boson exists in Nature then it will be most probably discovered at the LHC. However, its production and decay properties, which are crucial for verification of the electroweak (EW) symmetry breaking mechanism, can be best studied in a clean environment of the  $e^+e^-$  collisions at a linear collider. There are two projects of the linear collider being developed in a world wide collaboration: the International Linear Collider (ILC) [1], with the collision energy of 0.5–1 TeV, and the Compact Linear Collider (CLIC) [2], with the nominal collision energy of 3 TeV.

The Higgs boson mass constraints from direct searches at LEP give a lower limit of  $m_H > 114.4$  GeV at 95% C.L., the direct searches at

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Tevatron exclude the Standard Model (SM) Higgs boson mass in the region  $160 \text{ GeV} < m_H < 170 \text{ GeV}$  and the virtual effects it has on precision EW observables in the framework of SM strongly favor a light Higgs boson. These constraints indicate that the SM Higgs boson should be searched for in the mass range  $114.4 \text{ GeV} < m_H < 160 \text{ GeV}$  and, if it has been found, the  $t\bar{t}H$  Yukawa coupling  $g_{t\bar{t}H} = m_t/v$ , with  $v = (\sqrt{2}G_F)^{-1/2} \simeq 246 \text{ GeV}$ , can then be best determined in the reaction [3]

$$e^+e^- \rightarrow t\bar{t}H. \quad (1)$$

The lowest order Feynman diagrams of (1) are shown in Fig. 1, where we have neglected the diagrams with the Higgs boson coupling to  $e^+e^-$  and the  $g_{t\bar{t}H}$  coupling has been indicated by the gray circle. The diagrams in Fig. 1(a) and (b) dominate the cross-section of (1) therefore it is almost proportional to  $g_{t\bar{t}H}^2$ .

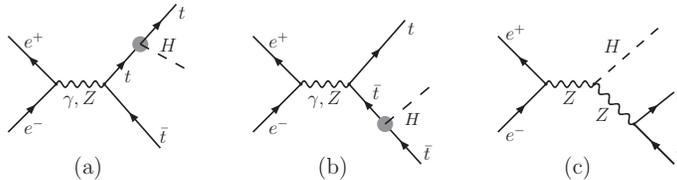


Fig. 1. Lowest order Feynman diagrams of reaction (1) in the unitary gauge.

As  $t$  and  $\bar{t}$  decay before they hadronize, predominantly into  $bW^+$  and  $\bar{b}W^-$ , the  $W$ 's decay into  $f\bar{f}'$ -pairs and, if  $m_H < 140 \text{ GeV}$ , the Higgs boson decays dominantly into a  $b\bar{b}$ -pair, reaction (1) is observed through reactions of the form

$$e^+e^- \rightarrow bf_1\bar{f}'_1\bar{b}f_2\bar{f}'_2b\bar{b}, \quad (2)$$

where  $f_1, f'_2 = \nu_e, \nu_\mu, \nu_\tau, u, c$  and  $f'_1, f_2 = e^-, \mu^-, \tau^-, d, s$ . Different channels of (2) are usually classified according to the decay channels of the  $W$  bosons. For example, the reactions

$$e^+e^- \rightarrow b\bar{b}b\bar{b}\tau^+\nu_\tau\mu^-\bar{\nu}_\mu, \quad (3)$$

$$e^+e^- \rightarrow b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu, \quad (4)$$

$$e^+e^- \rightarrow b\bar{b}b\bar{b}c\bar{s}s\bar{c} \quad (5)$$

represent the leptonic, semileptonic and hadronic detection channels of (1). In the unitary gauge of SM, neglecting the Yukawa couplings of the fermions lighter than  $c$ -quark and  $\tau$ -lepton, they receive contributions from 21 214, 26 816 and 240 966 lowest order Feynman diagrams, respectively. An overwhelming majority of the diagrams comprises background to the signal of

associated production and decay of the top quark pair and Higgs boson that in each channel gets contributions from 20 Feynman diagrams which involve 3 resonant propagators of the  $t$ - and  $\bar{t}$ -quarks and Higgs boson at a time. For example, the signal diagrams of (4) are shown in Fig. 2.

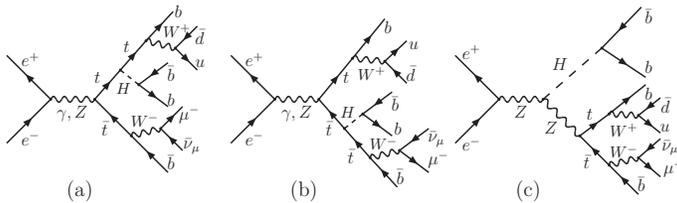


Fig. 2. Lowest order signal Feynman diagrams of (4). The remaining diagrams are obtained by permutations of the identical  $b$ - and  $\bar{b}$ -quarks.

In the present paper, we will address the signal and background issue by comparing cross-sections calculated with the 20 signal diagrams only, with the complete sets of the diagrams and with the neglect of the gluon exchange contributions. The comparison will be performed first in the presence of basic particle identification cuts and then with additional invariant mass cuts that should allow for identification of the top quarks, secondary  $W$  bosons and Higgs boson. We will also illustrate pure off mass shell effects by comparing the signal cross-section calculated with the full 8 particle kinematics and in the narrow width approximation.

## 2. Computational details

Because of large numbers of the Feynman diagrams the cross-sections of reactions (3), (4) and (5) must be computed in a fully automatic way. We will use to this end a recently released multipurpose Monte Carlo (MC) program `carlomat` [4].

The program itself is written in `Fortran 90/95` and it generates `Fortran` routines for the matrix element in the lowest order of SM for a user specified process, taking into account both the EW and quantum chromodynamics (QCD) contributions. Any kind of particles in the initial state, including quarks and gluons, are possible, with up to 12 external particles. The MC summing over helicities has been implemented in the program as an option, however, an explicit helicity summing is also possible. When doing so, spinors or polarization vectors representing particles, or building blocks of the Feynman diagrams, are computed only once, for all the helicities of the external particles they are made of, and stored in arrays. The program generates phase space parametrizations, which take into account peaks in every Feynman diagram. They are automatically implemented into a multi-

channel MC integration routine for the cross-section computation and event generation. Weights with which different kinematical channels contribute to the cross-section are adapted iteratively. It should be stressed at this point that the phase space integration is the most time consuming part of the program. The initial state radiation has been implemented recently and some extensions of the SM and effective models are being implemented at the moment.

### 3. Signal and backgrounds

The results presented in this section have been obtained with the initial physical parameters of [5]. In all tables presented below, the numbers in parenthesis show the MC uncertainty of the last decimal.

Let us concentrate on the semileptonic reaction (4). The easiest way to calculate the signal cross-section of associated production of the top quark-pair and Higgs boson is to apply the narrow width approximation that is given by

$$\sigma_{\text{signal}}^{\text{NWA}} = \sigma(e^+e^- \rightarrow t\bar{t}H) \times \frac{\Gamma_{W^+ \rightarrow u\bar{d}}}{\Gamma_W} \times \frac{\Gamma_{W^- \rightarrow \mu^- \bar{\nu}_\mu}}{\Gamma_W} \times \frac{\Gamma_{H \rightarrow b\bar{b}}}{\Gamma_H}, \quad (6)$$

where  $\sigma(e^+e^- \rightarrow t\bar{t}H)$  is the lowest order cross-section of (1), the  $\Gamma$ s are the lowest order widths and we have assumed  $\Gamma_{t \rightarrow bW^+}/\Gamma_t = \Gamma_{\bar{t} \rightarrow \bar{b}W^-}/\Gamma_t = 1$ . Then we calculate the signal cross-section  $\sigma_{\text{signal}}$  once more, taking into account the 20 signal diagrams of (4) and applying the full 8-particle kinematics, *i.e.*, integrating the squared matrix element of (4) over 20-dimensional phase space. The results for  $\sigma_{\text{signal}}^{\text{NWA}}$  and for the signal cross-section without cuts, denoted  $\sigma_{\text{signal}}^{\text{no cuts}}$ , are shown in the last two columns of Table I. Their comparison shows the pure off mass shell effects resulting from the fact that the top quarks and Higgs boson are produced and they decay while being off mass shell.

In the next step, we define the following basic cuts which should allow to detect events with separate jets and/or isolated charged leptons:

$$5^\circ < \theta(q, \text{beam}), \quad \theta(l, \text{beam}) < 175^\circ, \quad \theta(q, q'), \quad \theta(l, q) > 10^\circ, \\ E_q, E_l, \not{E}^T > 15 \text{ GeV} \quad (7)$$

and calculate the cross-sections of (4):  $\sigma_{\text{all}}$ , with the complete set of Feynman diagrams,  $\sigma_{\text{no QCD}}$ , without the gluon exchange diagrams and  $\sigma_{\text{signal}}$ , with the 20 signal diagrams of Fig. 2. To which extent cuts (7) reduce the signal can be seen by comparing  $\sigma_{\text{signal}}$  with  $\sigma_{\text{signal}}^{\text{no cuts}}$ . A comparison of  $\sigma_{\text{all}}$  and  $\sigma_{\text{no QCD}}$  with  $\sigma_{\text{signal}}$  shows the full lowest order SM and pure EW off resonance background. On the other hand, a comparison of  $\sigma_{\text{all}}$  with  $\sigma_{\text{no QCD}}$

TABLE I

Cross sections of reaction (4) at different c.m.s. energies with cuts (7) calculated: with the complete set of Feynman diagrams,  $\sigma_{\text{all}}$ , without gluon exchange diagrams,  $\sigma_{\text{no QCD}}$ , and with only the signal diagrams of Fig. 2,  $\sigma_{\text{signal}}$ . The last two columns show the total signal cross-section  $\sigma_{\text{signal}}^{\text{no cuts}}$  and the total cross-section in NWA  $\sigma_{\text{signal}}^{\text{NWA}}$  without cuts.

$\sqrt{s}$ [GeV]	$\sigma_{\text{all}}$ [ab]	$\sigma_{\text{no QCD}}$ [ab]	$\sigma_{\text{signal}}$ [ab]	$\sigma_{\text{signal}}^{\text{no cuts}}$ [ab]	$\sigma_{\text{signal}}^{\text{NWA}}$ [ab]
500	26.8(4)	7.80(3)	3.095(3)	3.796(3)	3.920(1)
800	100.2(8)	66.8(1)	46.27(2)	58.36(2)	60.03(2)
1000	93.1(3)	61.4(1)	40.18(2)	51.74(2)	52.42(3)
2000	47.4(2)	28.5(1)	15.14(3)	22.14(4)	20.68(3)

illustrates the size of the pure QCD background which, in spite of what could have been expected if taking into account low virtuality of the exchanged gluons, turns out to be surprisingly large. The cross-sections  $\sigma_{\text{all}}$  calculated with `carlomat` have been recalculated with `0'Mega/Whizard`. A satisfactory agreement within  $3\sigma$  for all reactions of (2) has been found [7].

At  $\sqrt{s} = 500$  GeV, where there is only very limited phase space volume for reaction (1), the cross-section depends substantially on the actual values of  $m_H$  and  $m_t$ . This dependence for reaction (4) is illustrated in Table II.

TABLE II

Lowest order cross-sections of (4) at  $\sqrt{s} = 500$  GeV for different values of  $m_H$  and  $m_t$ .

$m_t$ [GeV]	$m_H = 115$ GeV			$m_H = 130$ GeV		
	$\sigma_{\text{all}}$ [ab]	$\sigma_{\text{no QCD}}$ [ab]	$\sigma_{\text{signal}}$ [ab]	$\sigma_{\text{all}}$ [ab]	$\sigma_{\text{no QCD}}$ [ab]	$\sigma_{\text{signal}}$ [ab]
171	39.8(1)	20.21(5)	14.61(1)	29.9(1)	10.29(3)	4.670(4)
174.3	35.3(1)	16.41(4)	11.69(1)	26.9(1)	7.91(2)	3.095(3)
176	33.3(1)	14.52(4)	10.19(1)	25.4(1)	6.75(2)	2.365(2)

The off resonance background can be best reduced by imposing cuts on the invariant masses of two non  $b$  jets

$$60 \text{ GeV} < m(\sim b, \sim b') < 90 \text{ GeV}, \quad (8)$$

and of a  $b$  jet ( $b_1$ ) and the two non  $b$  jets that have already passed (8)

$$|m(b_1, \sim b, \sim b') - m_t| < 30 \text{ GeV}. \quad (9)$$

In the semileptonic channels, we impose a cut on the transverse mass of the lepton and missing energy system

$$m_T(l, \cancel{E}^T) < 90 \text{ GeV}, \quad (10)$$

and then combine it with another  $b$  jet ( $b_2$ ), and impose the cut

$$m_t - 30 \text{ GeV} < m_T(b_2, l, \cancel{E}^T) < m_t + 10 \text{ GeV}. \quad (11)$$

See Eqs (18) and (21) of [5] for the definitions of transverse masses in (10) and (11). Finally, we impose a cut on the other two  $b$  jets, ( $b_3$  and  $b_4$ ),

$$|m(b_3, b_4) - m_H| < m_{bb}^{\text{cut}}. \quad (12)$$

Cuts (8) and (10) should allow for identification of the  $W$  bosons, cuts (9) and (11) for identification of the top quarks and (12) for identification of the Higgs boson. The cross-sections of 3 different reactions representing the hadronic, semileptonic and leptonic channels of (2) are shown in Table III. We see that the background is substantially reduced. Let us note that a cut on the energy of a  $b$  quark:  $E_b > 40 \text{ GeV}$  or  $E_b > 45 \text{ GeV}$  together with  $m_{bb}^{\text{cut}} = 20 \text{ GeV}$  or  $m_{bb}^{\text{cut}} = 5 \text{ GeV}$  would also reduce the background, but it reduces the signal much more than cuts (8)–(11) [5].

TABLE III

Lowest order cross-sections of different channels of (2) at  $\sqrt{s} = 800 \text{ GeV}$  with angular and energy cuts (7) and the invariant mass cuts indicated above.

$e^+e^-$ Cuts:	$\rightarrow b\bar{b}b\bar{b}u\bar{d}s\bar{c}$ (8), (9), (12)		$\rightarrow b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$ (8)–(12)		$\rightarrow b\bar{b}b\bar{b}\tau^+\nu_\tau\mu^-\bar{\nu}_\mu$ (12)	
$m_{bb}^{\text{cut}}$ [GeV]	$\sigma_{\text{all}}$ [ab]	$\sigma_{\text{sig.}}$ [ab]	$\sigma_{\text{all}}$ [ab]	$\sigma_{\text{sig.}}$ [ab]	$\sigma_{\text{all}}$ [ab]	$\sigma_{\text{sig.}}$ [ab]
20	167.0(4)	128.4(1)	43.6(1)	33.93(2)	23.28(5)	13.48(1)
5	139.1(3)	128.0(1)	35.8(1)	33.10(2)	16.95(4)	13.47(1)
1	130.5(2)	127.7(1)	33.4(1)	32.82(2)	14.44(4)	13.46(1)

#### 4. Summary and outlook

We have addressed the signal and background issue in the reaction of associated production of the top quark pair and Higgs boson at the future  $e^+e^-$  linear collider that can be used to determine the top-Higgs Yukawa coupling. The background contributions are large for typical particle identification cuts. In particular, the QCD background is much bigger than it

could have been expected taking into account a possibly low virtuality of exchanged gluons. The background can be efficiently reduced by imposing invariant mass cuts allowing for the top and antitop quark, and Higgs boson identification. We have looked at the cross-section dependence on the Higgs boson and top quark masses. We have also illustrated pure off mass shell effects by comparing the signal cross-section calculated with the full 8 particle kinematics and in the NWA. Taking into account the size of cross-sections, the best place to measure the top-Higgs Yukawa coupling seems to be a linear collider operating at the centre of mass energy of about 800 GeV.

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