Off resonance background effects in $e^+e^- \to t\bar{t}H$

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Table of contents.

The Higgs mechanism plays very important role in the Standard Model. The particles acquire masses by interactions with Higgs field. If the Higgs boson is found, its properties must be measured. Some of those properties are couplings to other particles.

The couplings to fermions and gauge bosons are proportional to masses of these particles

$$g_{ffH} = \frac{m_f}{v}, \qquad g_{VVH} = \frac{2M_V^2}{v},$$

where $v = (\sqrt{2}G_F)^{-1/2} \simeq 246\mathrm{GeV}$.

The couplings to gauge bosons can be measured in:

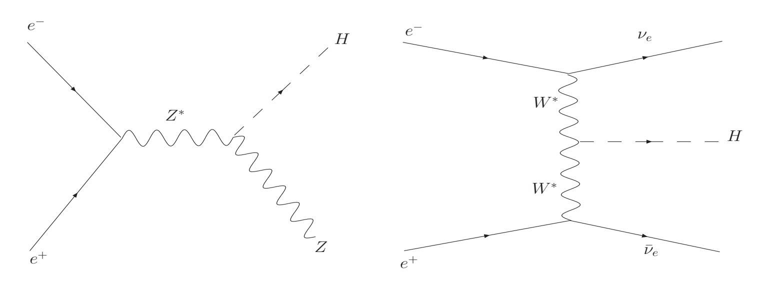
- the Higgsstrahlung process (dominates at low energies):

$$e^+e^- \to ZH,$$

- and the *WW* fusion process (dominates at high energies):

$$e^+e^- \to \overline{\nu}_e \nu_e W^* W^* \to \overline{\nu}_e \nu_e H.$$

Main production mechanisms of the SM Higgs boson at linear collider.



It is not so easy to measure the Yukawa couplings to fermions. The largest one is the Higgs top Yukawa coupling g_{ttH}

$$g_{ttH}^2 \simeq 0.5,$$

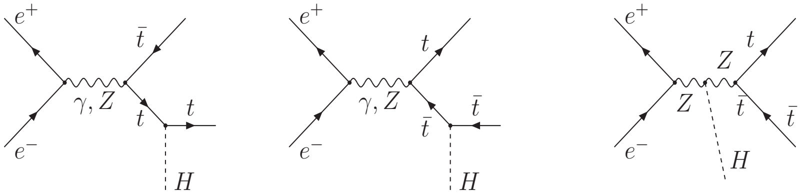
it can be compared with the Higgs bottom Yukawa coupling which is equal to

$$g_{bbH}^2 \simeq 4 \times 10^{-4}.$$

If $m_H < 2m_t$, then the Higgs top Yukawa coupling can be best determined in the process $e^+e^- \to t\bar{t}H$.[A. Djouadi, J. Kalinowski, P.M. Zerwas, Mod. Phys. Lett. A7 (1992) 1765]

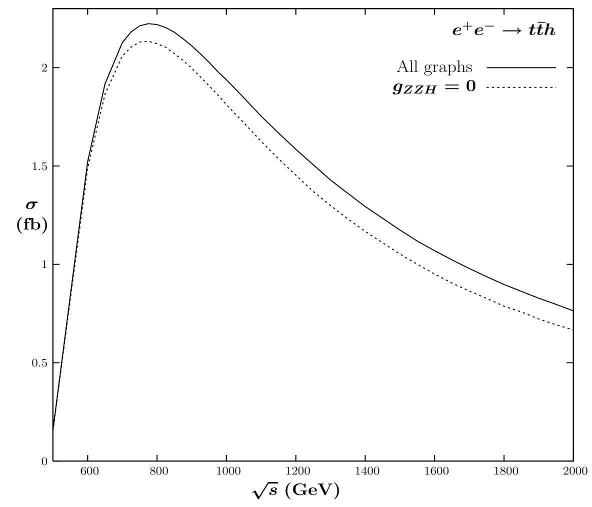
If $M_H > 2m_t$, then the Higgs top Yukawa coupling can be measured from the $H \to t\bar{t}$ branching ratio.

There are five Feynman diagrams contributing to the process $e^+e^- \to t\bar{t}H$.



Contribution from the Higgs bremsstrahlung off the Z line is small. Therefore the cross section of $e^+e^- \to t\bar{t}H$ is almost proportional to g^2_{ttH}.

The total cross section of $e^+e^- \to t\bar{t}H$ as a function of CMS energy.



The top and his antimatter partner, the antitop quark, and the Higgs boson are unstable particles. That is why we must consider their decays.

The top and antitop quark mostly decays into:

$$t \longrightarrow bW^+ \qquad or \qquad \bar{t} \longrightarrow \bar{b}W^-.$$

The Higgs boson decays into:

$$H \longrightarrow f\bar{f}' \qquad \text{or} \qquad H \longrightarrow W^+W^-.$$

We must also remember that the W boson can decay into:

$$W \longrightarrow q\bar{q}' \qquad \text{or} \qquad \mathrm{W} \longrightarrow \mathrm{l}\nu.$$

If we take into account those decays in the process $e^+e^- \longrightarrow t\bar{t}H$, this leads to reactions with 8 or 10 fermions in the final state.

Let us consider that $M_H < 140$ GeV, then the Higgs boson will decay dominantly into a $b\bar{b}$-quark pair.

The above fact causes that the reaction $e^+e^- \to t\bar{t}H$ will be detected at the ILC through reactions of the form

$$e^+e^- \to b\bar{b}b\bar{b}f_1\bar{f}_1' f_2\bar{f}_2'.$$

Becauese of the W decays, we get three possible channels of the above reaction:

- hadronic channel, e.g. $e^+e^- \to b\bar{b}b\bar{b}u\bar{d}s\bar{c}$ (I),
- semileptonic channel, e.g. $e^+e^- \to b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$ (II),
- leptonic channel, e.g. $e^+e^- \to b\bar{b}b\bar{b}\tau^+\nu_\tau\mu^-\bar{\nu}_\mu$ (III).

If we neglect the Higgs boson Yuakawa couplings to fermions lighter than c quark and τ lepton, there will be:

- 39342 Feynman diagrams for reaction I,
- 26816 Feynman diagrams for reaction II,
- 21214 Feynman diagrams for reaction III,

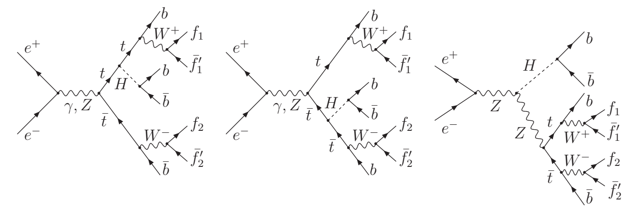
in the lowest order of the Standard Model in the unitary gauge.

Matrix element and phase space parametrisation for reactions I, II and III have been generated automaticly with a Fortran 90/95 program `carlomat` written by Karol Kołodziej.

Widths of the following particles W, H, t are calculated in the lowest order of SM.

To see background effects, we can compute the total cross section with the signal diagrams and compare it with results for reactions (I, II and III), where we include all Feynman diagrams.

Signal diagrams for a process with 8 fermions in the final state



Because of the b quarks permutations, there are 20 signal diagrams.

If we want to measure the Higgs top Yukawa coupling, we must impose some cuts to reduce background effects in all three reactions.

First we can define some basic cuts: lc sc hc dis

$$5^\circ < \theta(q, beam) < 175^\circ, \quad \theta(q, q') > 10^\circ, \quad E_q > 15\mathrm{GeV}, \tag{1}$$

$$5^\circ < \theta(l, beam) < 175^\circ, \quad \theta(l, q) > 10^\circ, \quad E_l > 15\mathrm{GeV}, \tag{2}$$

$$\not{E}^T > 15\mathrm{GeV}. \tag{3}$$

The numerical results for $e^+e^- \to b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$ process with the basic cuts.

$\sqrt{s}$ [GeV]	$\sigma_{\mathtt{all}}$ [ab]	$\sigma_{\mathtt{no\ QCD}}$ [ab]	$\sigma_{\mathtt{signal}}$ [ab]	$\sigma^{\mathtt{no\ cuts}}_{\mathtt{signal}}$ [ab]	$\sigma^{\mathtt{no\ cuts}}_{\mathtt{NWA}}$ [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)

Because of the fact that we have three different channels of our reactions, we need to use various sets of cuts to each of those reactions in order to reduce background effects correctly.

In the leptonic channel we used cuts (1 and 2) here
and the following cuts:

$$\not{E}^T > 30 \text{ GeV}, \qquad \theta(l, l') > 10^\circ$$

and

$$\left| \left[(p_{b'} + p_{b''})^2 \right]^{\frac{1}{2}} - m_H \right| < m_{bb}^{\text{cut}}.$$

In the semileptonic channel we used cuts (1, 2 and 3) here and the following cuts:
Non b jets invariant mass:

$$60 \text{ GeV} < \left[\left(p_{\sim b_1} + p_{\sim b_2} \right)^2 \right]^{\frac{1}{2}} < 90 \text{ GeV}.$$

The transverse mass of the muon-neutrino system:

$$\left[m_\mu^2 + 2 \left(m_\mu^2 + |\vec{p}_\mu^{\,T}| \right)^{\frac{1}{2}} |\vec{p}\!\!/^{\,T}| - 2\vec{p}_\mu^{\,T} \cdot \vec{p}\!\!/^{\,T} \right]^{\frac{1}{2}} < 90 \text{ GeV}.$$

The invariant mass of a one b jet and two non b jets:

$$\left| \left[\left(p_{b_1} + p_{\sim b_1} + p_{\sim b_2} \right)^2 \right] - m_t \right| < 30 \text{ GeV}.$$

The transverse mass m_T of a one b jet and the muon-neutrino system:

$$m_t - 30 \text{ GeV} < m_T < m_t + 10 \text{ GeV}.$$

where

$$m_T^2 = m^2 + 2\left(m^2 + |\vec{p}_{b_2}^{\,T} + \vec{p}_{\mu}^{\,T}|^2\right)^{\frac{1}{2}} \not{E}^T - 2\left(\vec{p}_{b_2}^{\,T} + \vec{p}_{\mu}^{\,T}\right) \cdot \vec{\not{p}}^{\,T}.$$

Invariant mass of two b jets:

$$\left| \left[(p_{b'} + p_{b''})^2 \right]^{\frac{1}{2}} - m_H \right| < m_{bb}^{\mathrm{cut}}.$$

Finally in the hadronic channel we used cut (1) here and the following cuts:
Non b jets invariant masses:

$$60 \text{ GeV} < \left[(p_{\sim b_1} + p_{\sim b_2})^2 \right]^{\frac{1}{2}} < 90 \text{ GeV},$$

$$60 \text{ GeV} < \left[(p_{\sim b_3} + p_{\sim b_4})^2 \right]^{\frac{1}{2}} < 90 \text{ GeV}.$$

The invariant masses of a one b jet and two non b jets:

$$\left|\left[(p_{b_1}+p_{\sim b_1}+p_{\sim b_2})^2\right]-m_t\right|<30\ \mathrm{GeV},$$

$$\left|\left[(p_{b_2}+p_{\sim b_3}+p_{\sim b_4})^2\right]-m_t\right|<30\ \mathrm{GeV}.$$

Invariant mass of two b jets:

$$\left|\left[(p_{b'}+p_{b''})^2\right]^{\frac{1}{2}}-m_H\right|<m_{bb}^{\mathrm{cut}}.$$

The numerical results for reactions I, II and III with m_{bb}^{cut}=20 GeV.

$e^+e^- \to$	$b\bar{b}b\bar{b}u\bar{d}s\bar{c}$		$b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$		$b\bar{b}b\bar{b}\tau^+\nu_\tau\mu^-\bar{\nu}_\mu$	
$\sqrt{s}$ [GeV]	$\sigma_{\mathtt{all}}$ [ab]	$\sigma_{\mathtt{sig}}$ [ab]	$\sigma_{\mathtt{all}}$ [ab]	$\sigma_{\mathtt{sig}}$ [ab]	$\sigma_{\mathtt{all}}$ [ab]	$\sigma_{\mathtt{sig}}$ [ab]
500	13.88(6)	8.70(2)	3.50(2)	2.384(3)	4.03(9)	0.863(2)
800	167.0(4)	128.4(1)	43.6(1)	33.93(2)	23.28(5)	13.48(1)
1000	139.4(3)	109.1(1)	35.3(1)	27.94(1)	21.70(5)	12.09(1)
2000	44.5(2)	36.37(4)	11.4(1)	9.223(6)	9.46(3)	4.95(2)

The numerical results for reactions I, II and III with $m_{bb}^{\rm cut}$=5 GeV.

$e^+e^- \to$	$b\bar{b}b\bar{b}u\bar{d}s\bar{c}$		$b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$		$b\bar{b}b\bar{b}\tau^+\nu_\tau\mu^-\bar{\nu}_\mu$	
$\sqrt{s}$ [GeV]	$\sigma_{\tt all}$ [ab]	$\sigma_{\tt sig}$ [ab]	$\sigma_{\tt all}$ [ab]	$\sigma_{\tt sig}$ [ab]	$\sigma_{\tt all}$ [ab]	$\sigma_{\tt sig}$ [ab]
500	10.17(4)	8.66(2)	2.62(1)	2.332(3)	1.89(7)	0.864(2)
800	139.1(3)	128.0(1)	35.8(1)	33.10(2)	16.95(4)	13.47(1)
1000	117.9(5)	109.0(1)	29.5(1)	27.52(1)	15.41(3)	12.10(1)
2000	38.1(1)	36.23(4)	9.76(4)	9.157(6)	6.49(3)	4.97(3)

The numerical results for reactions I, II and III with $m_{bb}^{\rm cut}$=1 GeV.

$e^+e^- \to$	$b\bar{b}b\bar{b}u\bar{d}s\bar{c}$		$b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$		$b\bar{b}b\bar{b}\tau^+\nu_\tau\mu^-\bar{\nu}_\mu$	
$\sqrt{s}$ [GeV]	$\sigma_{\tt all}$ [ab]	$\sigma_{\tt sig}$ [ab]	$\sigma_{\tt all}$ [ab]	$\sigma_{\tt sig}$ [ab]	$\sigma_{\tt all}$ [ab]	$\sigma_{\tt sig}$ [ab]
500	9.07(4)	8.65(1)	2.37(1)	2.312(3)	1.09(2)	0.860(1)
800	130.5(2)	127.7(1)	33.4(1)	32.82(2)	14.44(4)	13.46(1)
1000	110.6(2)	108.7(1)	27.8(1)	27.34(1)	13.08(6)	12.06(1)
2000	36.6(1)	36.09(2)	9.25(4)	9.136(6)	5.42(2)	4.97(1)

To reduce the background effects more effectively, we used additional cut on the energy of a b quark.

$$E_b > 40\ \mathrm{GeV},\ E_b > 45\ \mathrm{GeV}.$$

The numerical results for the semileptonic channel. $m_{bb}^{\mathrm{cut}} = 5$ GeV

	$E_b > 15\,[\mathtt{GeV}]$		$E_b > 40\,[\mathtt{GeV}]$		$E_b > 45\,[\mathtt{GeV}]$	
$\sqrt{s}$ [GeV]	$\sigma_{\mathtt{all}}$ [ab]	$\sigma_{\mathtt{sig}}$ [ab]	$\sigma_{\mathtt{all}}$ [ab]	$\sigma_{\mathtt{sig}}$ [ab]	$\sigma_{\mathtt{all}}$ [ab]	$\sigma_{\mathtt{sig}}$ [ab]
500	2.62(1)	2.332(3)	2.57(1)	2.32(1)	2.47(1)	2.22(1)
800	35.8(1)	33.10(2)	24.4(1)	23.07(3)	21.1(1)	20.03(3)
1000	29.5(1)	27.52(1)	20.0(1)	19.20(2)	18.0(1)	17.21(2)
2000	9.76(4)	9.157(6)	7.61(3)	7.28(1)	7.27(6)	6.90(1)

From the above results, we can see that the additional cuts work only at $\sqrt{s} = 500$ GeV.

The numerical results for the leptonic channel. $m_{bb}^{\mathrm{cut}} = 5$ GeV

	$E_b > 15\,[\mathtt{GeV}]$		$E_b > 40\,[\mathtt{GeV}]$		$E_b > 45\,[\mathtt{GeV}]$	
$\sqrt{s}$ [GeV]	$\sigma_{\mathtt{all}}$ [ab]	$\sigma_{\mathtt{sig}}$ [ab]	$\sigma_{\mathtt{all}}$ [ab]	$\sigma_{\mathtt{sig}}$ [ab]	$\sigma_{\mathtt{all}}$ [ab]	$\sigma_{\mathtt{sig}}$ [ab]
500	1.89(7)	0.864(2)	1.11(1)	0.849(2)	1.02(4)	0.808(2)
800	16.95(4)	13.47(1)	10.99(2)	9.37(1)	9.44(2)	8.13(1)
1000	15.41(3)	12.10(1)	10.07(2)	8.47(1)	8.92(2)	7.59(1)
2000	6.49(3)	4.97(3)	4.84(2)	4.01(2)	4.51(1)	3.84(2)

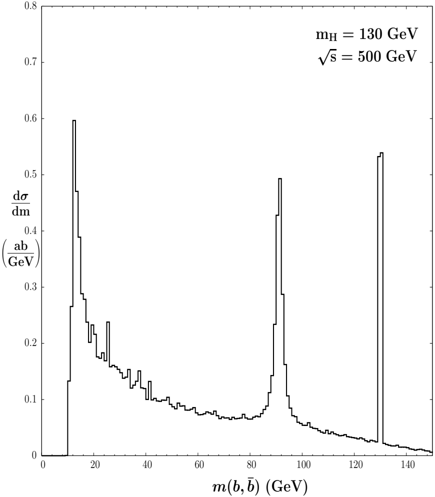
In the leptonic channel, the additional cuts are more efficient because we do not use cuts on invariant masses of W bosons and t quarks.

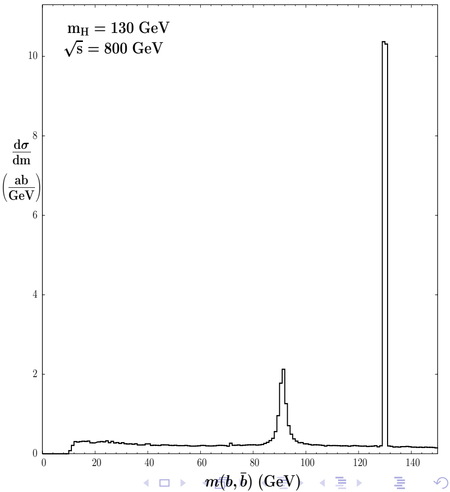
The results from the next slides were obtained with the following cuts (only semileptonic channel):

- 1, 2 and 3, here
- the invariant mass of non b jets,
- the transverse mass of the muon-neutrino system,
- the invariant mass of a one b jet and two non b jets,
- the transverse mass m_T of a one b jet and the muon-neutrino system.

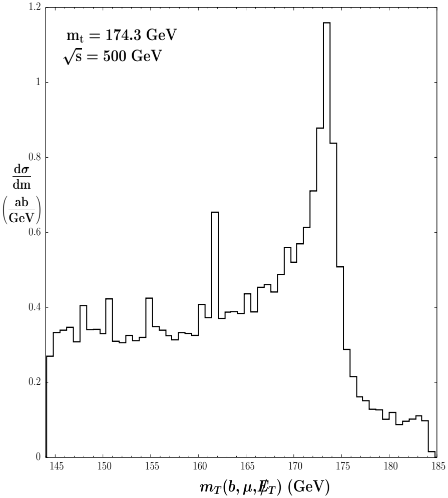
The last cut is taken in the following way: first we reconstruct all three possible m_T, then we check which one is the closest to m_t and finally, we check if the closest one has passed the cut.

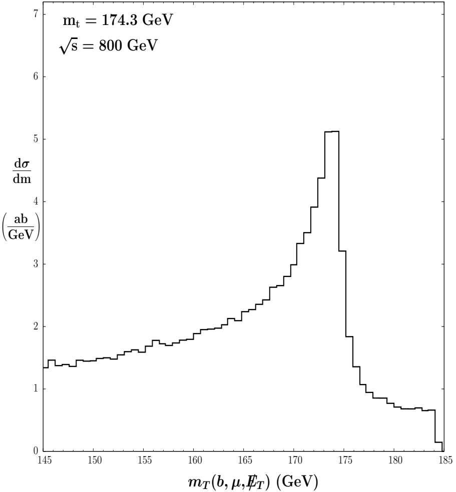
Differential cross section as a function of the invarinat mass of the two b jets, which remained after the above cuts.





Differential cross section as a function of the transverse mass.





The top Higgs Yukawa coupling can be direct determined trough the total cross section of the process $e^+e^- \to t\bar{t}H$.

The background effects in the $e^+e^- \to t\bar{t}H$ process have been shown for the light Higgs boson with $H \to b\bar{b}$ as a dominant decay mode.

The results have shown that the background effects are large.