Measuring the Higgs Boson Yukawa Couplings at an NLC

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We investigate the inclusive production of the Higgs boson with a heavy quark pair, $t\bar{t}$ or $b\bar{b}$, in e^+e^- collisions at high energy. The $\mathcal{O}(\alpha_s)$ QCD corrections are included.

I. INTRODUCTION

The search for the Higgs boson is one of the primary objectives of present and future colliders. Once the Higgs boson has been discovered, it will be important to measure its couplings to fermions and to gauge bosons. These couplings are completely determined in the Standard Model and the process $e^+e^- \to t\bar{t}h$ provides a direct mechanism for measuring the $t\bar{t}h$ Yukawa coupling. Since this coupling can be significantly different in a supersymmetric model from that in the Standard Model, the measurement would provide a means of discriminating between different models.

The associated production of a Higgs boson with a top quark pair in e^+e^- collisions has a small rate, around 1 fb for $\sqrt{s} = 500\ GeV$ and $M_h \sim 100\ GeV$. However, the signature, $e^+e^- \to t\bar{t}h \to W^+W^-b\bar{b}b\bar{b}$ is distinctive and a precise measurement may be possible.

A similar reaction in the b quark system, $e^+e^- \to b\bar{b}h$, is suppressed in the Standard Model due to the smallness of the $b\bar{b}h$ Yukawa coupling. In a supersymmetric model, however, this coupling can be enhanced for large values of the parameter $\tan\beta$. In addition, a supersymmetric model contains resonant contributions not present in the Standard Model such as, for example, the process $e^+e^- \to A^0 h_i^0, A^0 \to b\bar{b}$.

In order to extract the Yukawa couplings, precise predictions for the rates, including QCD corrections, are necessary. The QCD corrections to the associated production of a Higgs boson with a heavy quark pair have been computed by two groups [1,2] and are the subject of this note.

II. ASSOCIATED HIGGS-TOP QUARK PRODUCTION IN THE STANDARD MODEL

The Standard Model cross section for $e^+e^- \to t\bar{t}h$ occurs through both $s-$ channel photon and $s-$ channel Z exchange. [3,4]. The most relevant contributions are those in which the Higgs boson is emitted from a top quark leg, which are directly proportional to the $t\bar{t}h$ Yukawa coupling. The contribution when the Higgs boson is emitted from the Z boson is always less than a few per cent at $\sqrt{s} = 500$ GeV and can safely be neglected. In addition, at $\sqrt{s} = 500\ GeV$, the photon exchange contribution provides the bulk of the cross section.

The $\mathcal{O}(\alpha_s)$ inclusive cross section for $e^+e^- \to t\bar{t}h$ receives contributions from real gluon emission from the final quark legs,

$$e^+e^- \to t\bar{t}hg \quad , \tag{1}$$

and also from virtual gluon contributions to the lowest order process.

The real gluon emission is separated into a hard and a soft contribution by introducing an arbitary cutoff on the gluon momentum, E_{min}. The infrared divergences in the soft gluon emission are then regulated by the introduction of a small gluon mass, m_g. When the one-loop virtual and the real contributions are combined, the final result is finite and independent of both E_{min} and m_g. In Fig. 1, we show the various contributions to the total cross section. σ_1 is the complete $\mathcal{O}(\alpha_s)$ corrected rate,

$$\sigma_1 = \sigma_0 + \sigma_{virt} + \sigma_{hard} + \sigma_{soft} \quad . \tag{2}$$

The counterterms are included in σ_{virt}. The combination $\sigma_{virt}+\sigma_{soft}$ is independent of the gluon mass, but retains a dependence on E_{min} which is cancelled by σ_{hard}. At $\sqrt{s}=500$ GeV, the corrections are large and positive, significantly increasing the rate. The corrections are smaller at $\sqrt{s}=1$ TeV, with large cancellations between the hard and the virtual plus soft contributions.

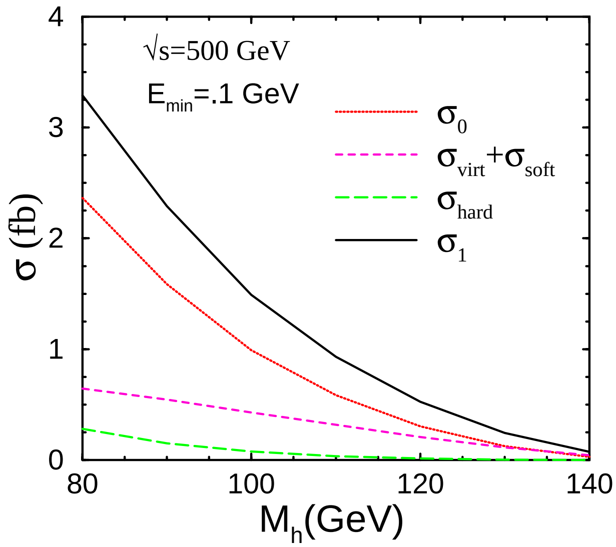

FIG. 1. QCD corrections to $e^+e^- \to t\bar{t}h$ at $\sqrt{s}=500$ GeV. σ_0 is the lowest order cross section and σ_1 is the complete $\mathcal{O}(\alpha_s)$ corrected rate. We take $M_t=175\ GeV$ and $\alpha_s(M_t^2)=.1116$.

The size of the QCD corrections can be described by a K factor,

$$K(\mu)\equiv\frac{\sigma_1}{\sigma_0}, \tag{3}$$

which is shown in Fig. 2. Note that after the cancellation of the ultraviolet divergences, the only μ dependence is in $\alpha_s(\mu)$. If $\mu=\sqrt{s}$, then $K(M_h=100\,\mathrm{GeV})$ is reduced to 1.4 from the value $K=1.5$ obtained with $\mu=M_t$ for $\sqrt{s}=500\ GeV$.

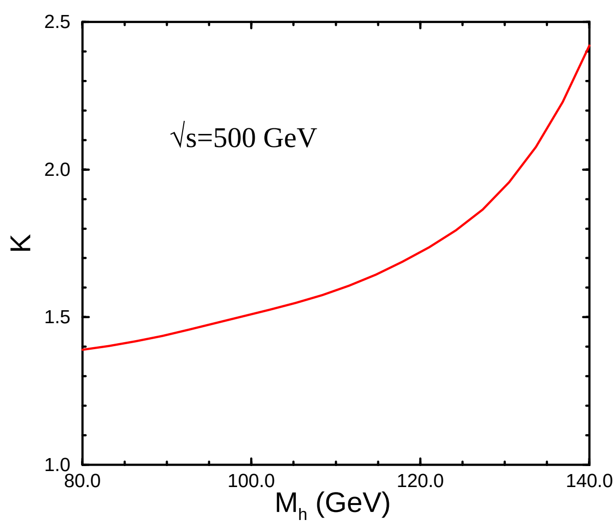

FIG. 2. Ratio of the $\mathcal{O}(\alpha_s)$ corrected rate to the lowest order cross section for $e^+e^- \to t\bar{t}h$ at $\sqrt{s}=500$ GeV. We take $M_t=175\ GeV$ and $\alpha_s(M_t^2)=.1116$.

III. ASSOCIATED HIGGS -TOP QUARK PRODUCTION IN A SUPERSYMMETRIC MODEL

In the minimal supersymmetric model, a top quark pair can be produced in association with either of the neutral Higgs bosons, $h_i = h^0, H^0$, or with the pseudoscalar, A^0. The production of the pseudoscalar is highly suppressed and the rate for $e^+e^- \to t\bar{t}A^0$ is less than 10^{-2} fb at $\sqrt{s} = 500\ GeV$ for all values of $\tan\beta$ and M_A. The rate for either $e^+e^- \to t\bar{t}h^0$ or $e^+e^- \to t\bar{t}H^0$ is greater than .75 fb throughout most of the $M_A - \tan\beta$ plane and we show this in Fig. 3. We see that this region includes much of the parameter space. The results shown in Fig. 3 are relatively insensitive to changing the squark masses or the mixing parameters of the supersymmetric sector.

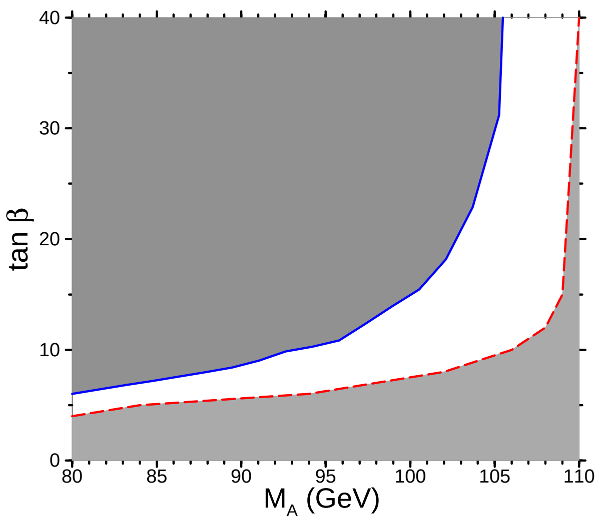

FIG. 3. Regions in the $M_A - \tan\beta$ plane where the cross section $e^+e^- \to t\bar{t}h^0$ or $e^+e^- \to t\bar{t}H^0$ is larger than .75 fb at $\sqrt{s} = 500$ GeV. The upper left hand region results from $e^+e^- \to t\bar{t}H^0$, while the region at the lower right is the result for $e^+e^- \to t\bar{t}h^0$. All NLO QCD corrections are included. The squarks are taken to have a common mass, $M_S = 500\ GeV$, and the mixing parameters are set to zero.

IV. ASSOCIATED HIGGS- BOTTOM QUARK PRODUCTION IN A SUPERSYMMETRIC MODEL

In the Standard Model, it will be difficult to extract the bottom quark-Higgs Yukawa coupling from a measurement of $e^+e^- \to b\bar{b}h$, since the coupling itself is tiny and the Z contribution is important, so that there is a significant dependence on the ZZh coupling. In the minimal supersymmetric model, however, there are 5 Higgs bosons, $\phi = h^0, H^0, A^0, H^\pm$, so that additional processes not present in the Standard Model may be useful to pin down the fermion-Higgs boson Yukawa couplings [5]. In addition, for certain values of $\tan\beta$, the $b\bar{b}\phi$ Yukawa couplings receive significant enhancements and so the processes $e^+e^- \to b\bar{b}\phi$ may be larger than in the Standard Model.

The physics for $b\bar{b}h_i^0$ production is significantly different from that of Higgs production with a $t\bar{t}$ pair. In the case of the b quark, there is a large resonant contribution from the process, $e^+e^- \to A^0h_i^0$, $A^0 \to b\bar{b}$. This enhancement occurs when $M_{h_i} \sim M_A$ and so is relevant for M_A below about 120 GeV for $e^+e^- \to b\bar{b}h_i^0$.

Fig. 4 shows the different contributions to the process $e^+e^- \to b\bar{b}h^0$ for $\tan\beta = 40$ at $\sqrt{s} = 500$ GeV. The curve labelled "$total_{NW}$" is the narrow width approximation to the A^0 resonance, while the curve labelled "AhZ" is only the contribution from the square of the resonant diagram. At small M_A (< 120 GeV), the narrow width approximation is an excellent approximation to the total rate for this value of $\tan\beta$. For smaller $\tan\beta$, the narrow width approximation becomes increasingly inaccurate, since the Z exchange contribution becomes more and more relevant. At large M_A, the rate is given predominantly by the Z boson exchange contribution and is typically between 5 and 10 fb.

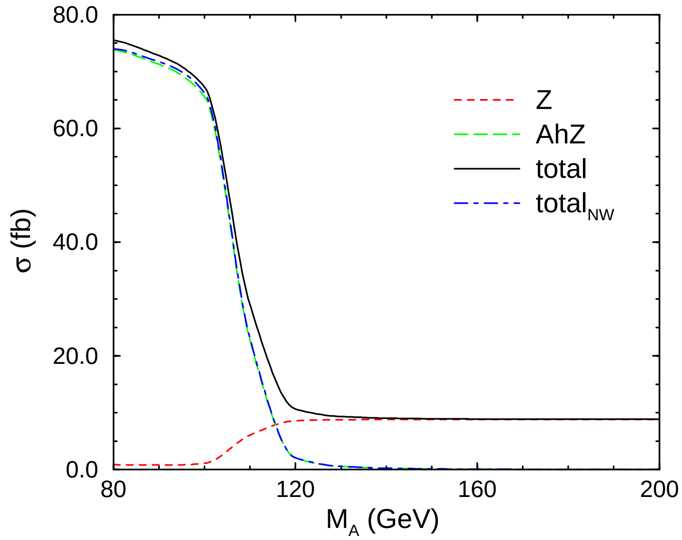

FIG. 4. Contributions to $e^+e^- \rightarrow b\bar{b}h^0$ at $\sqrt{s} = 500$ GeV for $\tan\beta = 40$. The curve labelled 'NW' is the narrow width approximation to the A^0 resonance contribution and includes QCD corrections in the resonance region. The squarks are assumed to have a common mass, $M_S = 500$ GeV, and the scalar mixing parameters are set to zero.

In the narrow width approximation, the QCD corrections to the rate are trivially included by including the QCD corrections to the pseudo-scalar width. Away from the pseudoscalar resonance, (large M_A), inclusion of the QCD corrections would require a complete calculation, which we do not include in the present analysis since the interesting region is near the resonance where the rate is enhanced.

For heavy Higgs production, H^0, the narrow width approximation is an excellent approximation for all values of $\tan\beta$ so the QCD corrections can be accurately included everywhere. For $\tan\beta < 5$, the cross section is larger than 20 fb even for $M_A \sim 200$ GeV. For $\tan\beta > 5$, the rate is greater than 20 fb for $M_A > 110$ GeV, as shown in Fig. 5. This process can potentially be used to probe the couplings of the heavier neutral Higgs boson and to obtain a precise measurement of the product of the Higgs couplings, $g_{bbH}\, g_{ZAH}$.

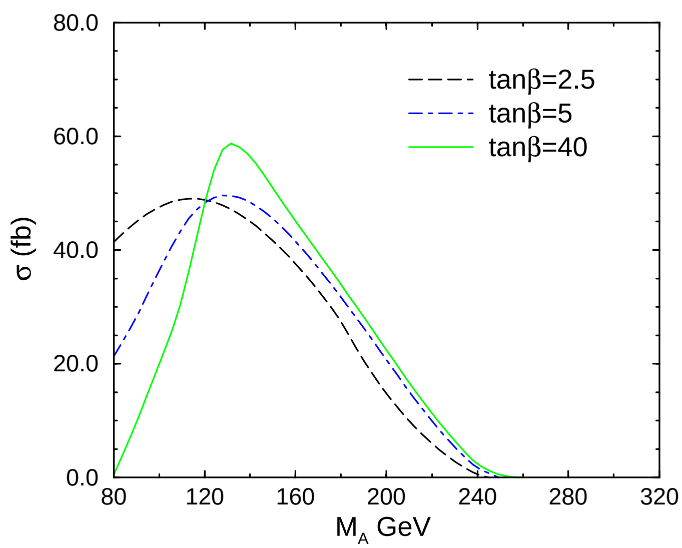

FIG. 5. Cross section for $e^+e^- \rightarrow b\bar{b}H^0$ at $\sqrt{s} = 500$ GeV including QCD corrections in the narrow width approximation. The squarks are assumed to have a common mass, $M_S = 500$ GeV, and the scalar mixing parameters are set to zero.

We can safely work in the narrow width approximation also for the case of $e^+e^- \rightarrow b\bar{b}A^0$ production. In fact, in this case the contributions of the h_i^0 resonances are completely dominant and the exact cross section can be distinguished from the one obtained using the narrow width approximation only at very high values of $\tan\beta$. The case $\tan\beta=40$ is illustrated in Fig. 6. Unlike $t\bar{t}A^0$ production, the process $e^+e^-\rightarrow b\bar{b}A^0$ is not suppressed relative to $e^+e^-\rightarrow b\bar{b}h_i$ production. For $M_a < 200\ GeV$, the cross secion is aways greater than 20 fb.

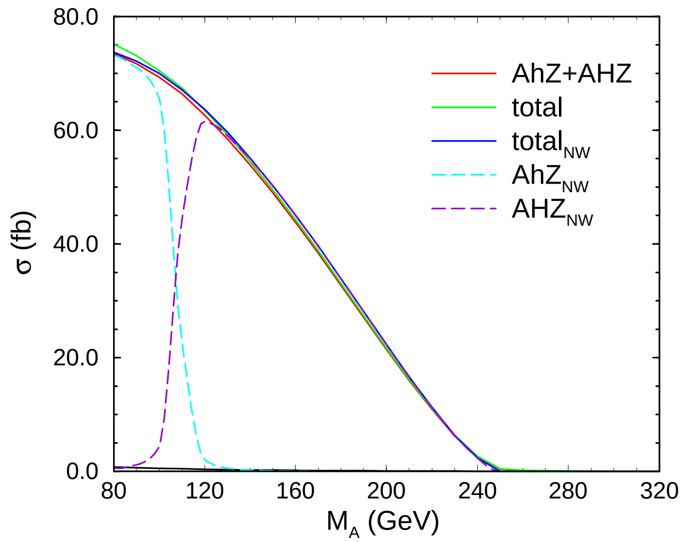

FIG. 6. Total and partial contributions to the cross section for $e^+e^-\rightarrow b\bar{b}A^0$ at $\sqrt{s}=500$ GeV at $\tan\beta=40$, including QCD corrections. The squarks are assumed to have a common mass, $M_S=500$ GeV and the scalar mixing parameters are set to zero.

V. CONCLUSION

We have computed the $\mathcal{O}(\alpha_s)$ corrected rate for $e^+e^-\rightarrow t\bar{t}h_i^0$. At $\sqrt{s}=500$ GeV, the corrections are large and positive and this process can be used to measure the $t\bar{t}h_i^0$ Yukawa couplings, both in the Standard Model and over much of the parameter space of the minimal supersymmetric model. In a supersymmetric model, the rates for $e^+e^-\rightarrow b\bar{b}\phi$ can be enhanced for large values of $\tan\beta$ and relatively small values of M_A. In such models, the QCD corrections can be accurately included using the narrow width approximation in the region where the scalar or pseudoscalar resonance dominates. The $b\bar{b}\phi$ production processes will measure a combination of Higgs Yukawa couplings.

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[1] S. Dawson and L. Reina, *Phys. Rev.* **D59** (1998) 054012.
[2] S. Dittmaier, M. Kramer, Y. Liao, M. Spira, and P. Zerwas, *Phys. Lett.* **B441** (1998) 383.
[3] K.J.F. Gaemers and G.J. Gounaris, *Phys. Lett.* **B77** (1978) 379.
[4] A. Djouadi, J. Kalinowski and P.M. Zerwas, *Zeit. Phys.* **C54** (1992) 255.
[5] S. Dawson and L. Reina, hep-ph/9812488.