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# THEORETICAL PROBLEMS OF HIGGS-BOSON PHYSICS AT THE NEXT LINEAR COLLIDER[†]

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## ABSTRACT

We discuss some theoretical aspects of standard-model (SM) Higgs-boson ($H$) phenomenology at the next $e^+e^-$ linear collider (NLC) with $300\,\text{GeV} \lesssim \sqrt{s} \lesssim 500\,\text{GeV}$. The topics include radiative corrections to $H$ production and decay; the study of the major signals and backgrounds including acceptance cuts, bremsstrahlung, and beamstrahlung; the determination of mass, spin, parity, and charge conjugation of $H$; and the $H$ discovery limit at $\sqrt{s} = 500\,\text{GeV}$.

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# THEORETICAL PROBLEMS OF HIGGS-BOSON PHYSICS AT THE NEXT LINEAR COLLIDER

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## ABSTRACT

**We discuss some theoretical aspects of standard-model (SM) Higgs-boson ($H$) phenomenology at the next $e^+e^-$ linear collider (NLC) with $300\,\mathrm{GeV} \lesssim \sqrt{s} \lesssim 500\,\mathrm{GeV}$. The topics include radiative corrections to $H$ production and decay; the study of the major signals and backgrounds including acceptance cuts, bremsstrahlung, and beamstrahlung; the determination of mass, spin, parity, and charge conjugation of $H$; and the $H$ discovery limit at $\sqrt{s} = 500\,\mathrm{GeV}$.**

## 1. Introduction

One of the great puzzles of contemporary elementary particle research is whether nature indeed makes use of the Higgs mechanism of spontaneous symmetry breaking to generate the observed particle masses. $H$ is the missing link sought for in order to verify this concept in the SM. Most of the $H$ properties are fixed, *e.g.*, its couplings to the gauge bosons, $g_{VVH} = 2^{5/4}G_F^{1/2}M_V^2$ ($V = W, Z$), and fermions, $g_{f\bar{f}H} = 2^{1/4}G_F^{1/2}m_f$, and the vacuum expectation value, $v = 2^{-1/4}G_F^{-1/2} \approx 246\,\mathrm{GeV}$. However, its mass, $M_H$, and its self-couplings, which depend on $M_H$, are essentially unspecified. Unitarity arguments in intermediate-boson scattering at high energies and considerations concerning the practicability of perturbation theory establish an $M_H$ upper bound at[1] $(8\pi\sqrt{2}/3G_F)^{1/2} \approx 1\,\mathrm{TeV}$. Lattice computations[2] suggest a somewhat lower

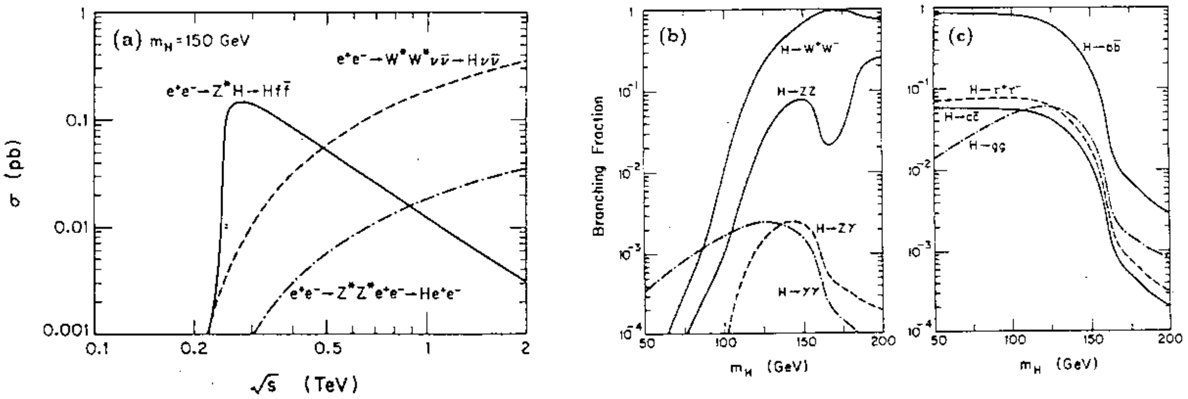

**Fig. 1** (a) Total cross sections vs $\sqrt{s}$ of $ZH$ production, $WW$ and $ZZ$ fusion for $M_H = 150\,\mathrm{GeV}$; branching fractions vs $M_H$ for the decays of $H$ into (b) $W^+W^-$, $ZZ$, $Z\gamma$, $\gamma\gamma$, (c) $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, and $gg$. For the loop-induced decays $m_t = 130\,\mathrm{GeV}$ has been assumed.

value, at 630 GeV. On the other hand, the non-detection of $Z \to f\bar{f}H$ signals at LEP 1 and SLC has ruled out the mass range below 62.5 GeV at the 95% confidence level.[3]

The principal $H$ production mechanisms at the NLC are $ZH$ associated production, $e^+e^- \to Z^* \to ZH$, and $WW$ fusion, $e^+e^- \to \nu_e\bar{\nu}_e(W^+)^*(W^-)^* \to \nu_e\bar{\nu}_eH$. The cross section of $ZH$ production peaks near $\sqrt{s} \approx M_Z + \sqrt{2}M_H$ and falls off like $1/s$ at high energies due to the $s$-channel $Z$-boson exchange. Contrariwise, the cross section of $WW$ fusion increases logarithmically with energy and eventually surpasses that of $ZH$ production. The $ZZ$ fusion mechanism, $e^+e^- \to e^+e^-Z^*Z^* \to e^+e^-H$, has weaker couplings and hence a much smaller cross section. The total cross sections of these three processes are shown in Fig. 1a vs $\sqrt{s}$ for $m_H = 150\,\mathrm{GeV}$. In Figs. 1b,c, the branching fractions of the major decay modes of $H$ are shown in the window $50\,\mathrm{GeV} \le M_H \le 200\,\mathrm{GeV}$. For $M_H \lesssim 135\,\mathrm{GeV}$, $H$ dominantly decays to $b\bar{b}$ pairs, while for higher $M_H$ the $WW^*$ mode wins out.

## 2. Radiative corrections

In $e^+e^-$ collisions the bulk of the radiative corrections is due to initial-state bremsstrahlung. In the case of $e^+e^-$ annihilation, such as $e^+e^- \to ZH$, these corrections are known[4] to $\mathcal{O}(\alpha^2)$ and the infrared-sensitive parts may be exponentiated. The pattern in which the leading logarithms arrange themselves is universal for all $e^+e^-$ collisions, including $WW$ and $ZZ$ fusion, and the dominant effects may be conveniently incorporated in the inclusive cross section by convoluting the respective Born result with energy spectral functions,[5] $\phi$. Similar functions, $\psi$, are available also for beamstrahlung.[6] The master formula reads

$$\begin{aligned}\frac{d^3\sigma}{dy\,d^2p_T}(s,y,p_T) &= \int_0^1 dx_-\,\psi(x_-)\int_0^1 dx_+\,\psi(x_+)\int_0^1 dy_-\,\phi(y_-)\int_0^1 dy_+\,\phi(y_+)\\ &\quad \frac{d^3\sigma_0}{d\hat{y}\,d^2p_T}\left(\hat{s} = x_-x_+y_-y_+s, \hat{y} = y + \frac{1}{2}\ln\frac{x_+y_+}{x_-y_-}, p_T\right)\theta\left(\hat{s}+\hat{t}+\hat{u}-M_H^2-M_X^2\right), \qquad (1)\end{aligned}$$

where $y$ and $p_T$ are the rapidity and transverse momentum of $H$ in the laboratory frame, respectively, and $M_X$ is the minimum invariant mass of the residual final-state system. In contrast to bremsstrahlung, beamstrahlung can be greatly suppressed by optimizing machine design and operation.

$ZH$ production will be the dominant source of $H$ at the NLC with $\sqrt{s} \lesssim 500\,\mathrm{GeV}$ and also weak corrections must be included in order to reliably predict its cross section. These are fully known to one loop.[7] The significance of the combined electroweak corrections is demonstrated in Fig. 2a. Figure 2b shows that, for the favourable DESY Linear Collider (DLC) narrow-band design, the unwanted beamstrahlung will be reduced to an almost unnoticeable level.

The electroweak corrections to the tree-level $H$ decays are well known.[8] For $M_H \lesssim 400\,\mathrm{GeV}$, they vary around +5% in the case of the bosonic modes and around −2% in the case of the $b\bar{b}$ and $\tau^+\tau^-$ modes, provided the Born coupling is expressed in terms of $G_F$. Due to a strong cancellation between specific top-quark triangle diagrams and the counterterm, the weak corrections to the $H \to b\bar{b}$ decay width are almost insensitive to $m_t$.

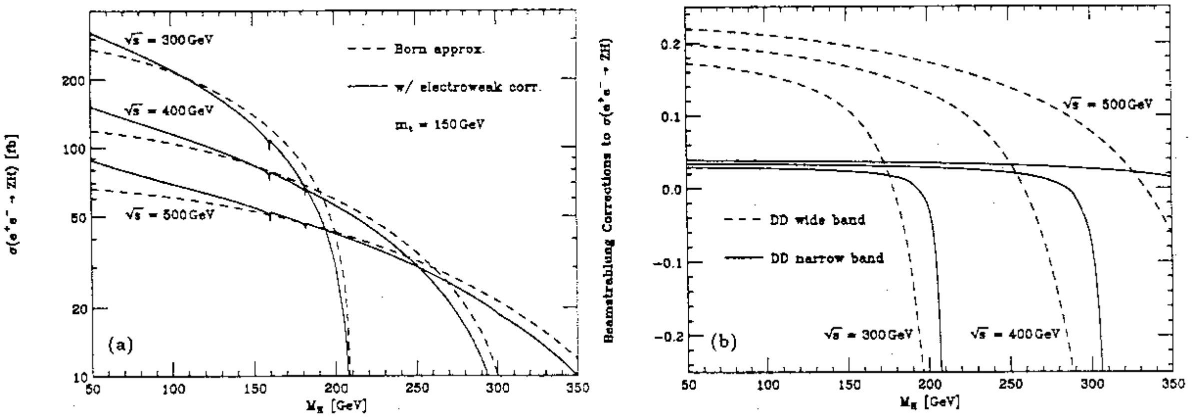

**Fig. 2** (a) Total cross section of $e^+e^- \rightarrow ZH$ w/o and w/ electroweak corrections. (b) Beamstrahlung corrections relative to the Born cross section for the DLC wide- and narrow-band designs.

QCD corrections are substantial for the $q\bar{q}$ and $gg$ decays of $H$. In the former case,[9] the main effect is to replace the pole mass of $q$ by its current mass, which reduces the $H \rightarrow b\bar{b}$ rate by 50–60% for $M_H \lesssim 2M_W$. On the other hand, QCD effects[10] enhance the $H \rightarrow gg$ rate by some 60%. For more details on quantum effects in $H$ physics, we refer to a very recent review article.[11]

## 3. Intermediate-mass Higgs boson

The NLC is arguably the ideal laboratory to detect the intermediate-mass $H$, with $M_Z \lesssim M_H \lesssim 2M_Z$, and to determine its quantum numbers.[12] $ZH$ production with subsequent $Z \rightarrow \mu^+\mu^-$ decay is fully constrained kinematically and the distribution over the recoil mass, $M_{\text{recoil}} = \left[(p_{e^-} + p_{e^+} - p_{\mu^+} - p_{\mu^-})^2\right]^{1/2}$, would exhibit a sharp peak at $M_H$, if it were not for bremsstrahlung, beamstrahlung, and beam-energy spread. In practice, the distribution is smeared out and exhibits a lower edge at $M_H$.

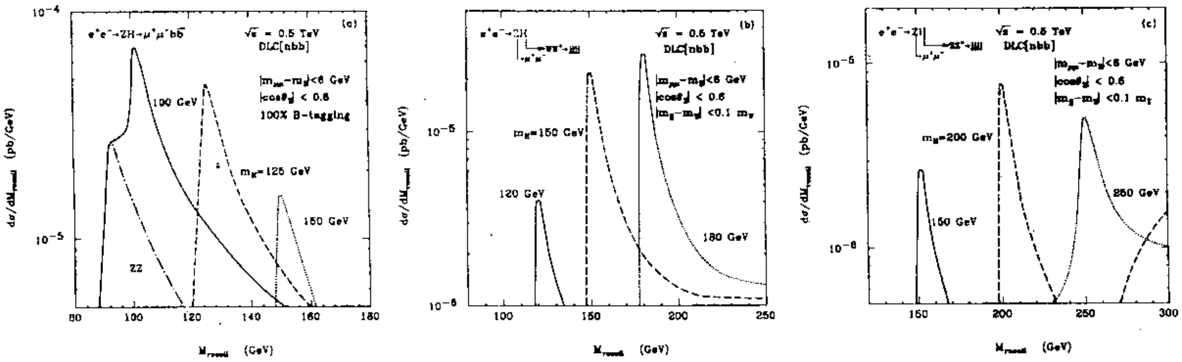

**Fig. 3** $M_{\text{recoil}}$ distribution for the $e^+e^- \rightarrow \mu^+\mu^- H$ signal with (a) $H \rightarrow b\bar{b}$, (b) $H \rightarrow WW^*$, and (c) $H \rightarrow ZZ^*$ decays plus the respective backgrounds after cuts for $\sqrt{s} = 500\,\text{GeV}$. Bremsstrahlung, beamstrahlung, and beam-energy spread are included and $m_t = 150\,\text{GeV}$ is assumed.

As for the $H \to b\bar{b}$ channel, which is significant for $M_H \lesssim 150\,\mathrm{GeV}$, the dominant backgrounds come from $e^+e^- \to ZZ^*, Z\gamma^*, \gamma^*\gamma^* \to \mu^+\mu^- b\bar{b}$ and $e^+e^- \to t\bar{t} \to b\bar{b}\mu^+\mu^-\nu_\mu\bar{\nu}_\mu$. They can be greatly suppressed by $b$ tagging and a cut $|\cos\sphericalangle(e^\pm, Z)| < 0.6$. For $H \to WW^* \to 4j$, which is appreciable for $M_H \gtrsim 120\,\mathrm{GeV}$, $ZWW^*$ continuum production is the main background. The $H \to ZZ^* \to 4j$ channel, which plays a major rôle for $M_H \gtrsim 150\,\mathrm{GeV}$, receives a background from $ZZZ^*$ continuum production; in addition, there is the a combinatorial background from $ZH \to (jj)(ZZ^*) \to (jj)(\mu^+\mu^- jj)$. The final results for $\sqrt{s} = 500\,\mathrm{GeV}$ are summarized in Fig. 3.

The SM $H$ has quantum numbers $J^{PC} = 0^{++}$. The observation of the $H \to \gamma\gamma$ decay or $\gamma\gamma \to H$ fusion would rule out $J = 1$ by the Landau-Yang theorem and fix $C = +1$. The latter also follows from the observation of the $H \to ZZ$ decay and $e^+e^- \to ZH$. $P$ can be extracted from the analyses of the final states of $e^+e^- \to ZH$ and $H \to VV$ ($V = W, Z$). The SM $V^\mu(p)V^\nu(k)H$ coupling is $2^{5/4}G_F M_V^2 g^{\mu\nu}$. For a hypothetical pseudoscalar Higgs, $A$, the corresponding coupling would be of the form $i\eta 2^{5/4} G_F \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma$, where $\eta$ is some dimensionless factor. Such a $ZZA$ coupling is realized, for instance, at one loop in the minimal supersymmetric standard model. For $e^+e^- \to ZH$, the threshold behaviour of the cross section is $\propto \beta$, where $\beta^2 = \left[1 - (M_Z + M_H)^2/s\right]\left[1 - (M_Z - M_H)^2/s\right]$, the $Z$-boson longitudinal degree of polarization is $1 - 8M_Z^2/\left(\beta^2 s + 12M_Z^2\right)$, and the angular distribution is $(1/\sigma)(d\sigma/d\cos\theta) = (3/4)\left(\beta^2 s \sin^2\theta + 8M_Z^2\right)/\left(\beta^2 s + 12M_Z^2\right)$, which is maximal in the central region of the detector. By contrast, the threshold behaviour of $e^+e^- \to ZA$ is $\propto \beta^3$, the $Z$ boson is bound to be transversely polarized, and $(1/\sigma)(d\sigma/d\cos\theta) = (3/8)(1 + \cos^2\theta)$, which is peaked in the beam directions. By the way, $e^+e^- \to ZZ$ is strongly peaked in the beam directions, which provides another check for $J$. In a scenario of $CP$ violation, where the $VVH$ coupling has both scalar and pseudoscalar components, the $e^+e^- \to Z^*H^* \to f\bar{f}f'\bar{f}'$ amplitude squared reads

$$\begin{aligned}
\overline{|\mathcal{T}|^2} &= N_f N_{f'} G_F^4 M_Z^8 m_{f'}^2 \frac{s s_Z \left(s_H - 4m_{f'}^2\right)}{D_Z(s) D_Z(s_Z) D_H(s_H)} \left\{ \left(v_e^2 + a_e^2\right)\left(v_f^2 + a_f^2\right) \right. \\
&\quad \times \left[ \left(1 + c_\theta^2\right)\left(1 + c_{\theta_*}^2\right) + 2\gamma^2 s_\theta^2 s_{\theta_*}^2 - \gamma s_{2\theta} s_{2\theta_*} c_{\phi_*} + s_\theta^2 s_{\theta_*}^2 c_{2\phi_*} \right] + 16 v_e a_e v_f a_f \left(c_\theta c_{\theta_*} - \gamma s_\theta s_{\theta_*} c_{\phi_*}\right) \\
&\quad + 4\kappa \left(v_e^2 + a_e^2\right) v_f a_f \left[2c_{\theta_*}\left(1 + c_\theta^2\right) - \gamma s_{2\theta} s_{\theta_*} c_{\phi_*}\right] + 4\kappa v_e a_e \left(v_f^2 + a_f^2\right)\left[2c_\theta\left(1 + c_{\theta_*}^2\right) - \gamma s_\theta s_{2\theta_*} c_{\phi_*}\right] \\
&\quad \left. + \kappa^2 \left(v_e^2 + a_e^2\right)\left(v_f^2 + a_f^2\right)\left(2 + 2c_\theta^2 c_{\theta_*}^2 - s_\theta^2 s_{\theta_*}^2 - s_\theta^2 s_{\theta_*}^2 c_{2\phi_*}\right) + 16\kappa^2 v_e a_e v_f a_f c_\theta c_{\theta_*} \right\}, \qquad (2)
\end{aligned}$$

where $v_f = 2I_f - 4s_w^2 Q_f$, $a_f = 2I_f$, $D_X(s) = \left(s - M_X^2\right)^2 + M_X^2\Gamma_X^2$, $\gamma = E_{Z^*}^{\mathrm{lab}}/\sqrt{s_Z}$, $\kappa = \eta\beta\gamma\sqrt{s s_Z}/M_Z^2$, $\theta = \sphericalangle(e^-, Z)$ in the laboratory frame, $\theta_*$ and $\phi_*$ define the $f$ flight direction in the $Z^*$ rest frame, $c_\theta = \cos\theta$, etc. Similarly, the $H \to Z^*Z'^* \to f\bar{f}f'\bar{f}'$ amplitude squared is found to be

$$\begin{aligned}
\overline{|\mathcal{T}|^2} &= \sqrt{2} N_f N_{f'} G_F^3 M_Z^8 \frac{s s'}{D_Z(s) D_Z(s')} \left\{ \left(v_f^2 + a_f^2\right)\left(v_{f'}^2 + a_{f'}^2\right) \right. \\
&\quad \times \left[ \left(1 + c_\theta^2\right)\left(1 + c_{\theta'}^2\right) + 2\gamma^2\gamma'^2(1 + \beta\beta')^2 s_\theta^2 s_{\theta'}^2 + \gamma\gamma'(1 + \beta\beta') s_{2\theta} s_{2\theta'} c_{\phi'} + s_\theta^2 s_{\theta'}^2 c_{2\phi'} \right] \\
&\quad - 16 v_f a_f v_{f'} a_{f'} \left[c_\theta c_{\theta'} + \gamma\gamma'(1 + \beta\beta') s_\theta s_{\theta'} c_{\phi'}\right] \\
&\quad + 4\lambda \left(v_f^2 + a_f^2\right) v_{f'} a_{f'} \left[2c_{\theta'}\left(1 + c_\theta^2\right) + \gamma\gamma'(1 + \beta\beta') s_{2\theta} s_{\theta'} c_{\phi'}\right] \\
&\quad - 4\lambda v_f a_f \left(v_{f'}^2 + a_{f'}^2\right)\left[2c_\theta\left(1 + c_{\theta'}^2\right) + \gamma\gamma'(1 + \beta\beta') s_\theta s_{2\theta'} c_{\phi'}\right] \\
&\quad \left. + \lambda^2 \left(v_f^2 + a_f^2\right)\left(v_{f'}^2 + a_{f'}^2\right)\left(2 + 2c_\theta^2 c_{\theta'}^2 - s_\theta^2 s_{\theta'}^2 - s_\theta^2 s_{\theta'}^2 c_{2\phi'}\right) - 16\lambda^2 v_f a_f v_{f'} a_{f'} c_\theta c_{\theta'} \right\}, \qquad (3)
\end{aligned}$$

where $\lambda = \eta\gamma\gamma'(\beta + \beta')\sqrt{ss'}/M_Z^2$, $\phi'$ is the angle between the $f\bar{f}$ and $f'\bar{f}'$ planes, $\theta$ is the angle between $f$ and the boost axis in the $Z^*$ rest frame, and similarly for $\theta'$. In the SM, $\kappa = \lambda = 0$. On the other hand, retaining only the $\kappa^2$ and $\lambda^2$ terms, one recovers the case of $A$. The angular dependences for $H$ and $A$ are very different. In particular, there is no $c_\phi$ term in the latter case.

## 4. High-mass Higgs boson

For a heavy $H$, with $M_H \gtrsim 2M_W$, the simplest and cleanest signal appears in the $m(VV)$ distribution of $e^+e^- \to Z^*H^* \to \mu^+\mu^-VV$, where $V = W, Z$ and invariant mass $m(\mu^+\mu^-) \approx M_Z$ is selected. This is not threatened by large backgrounds and requires no stringent cuts. Assuming an integrated luminosity of $50\,\mathrm{fb}^{-1}$ and 50% instrumental efficiency, a $\mu^+\mu^-jjjj$ signal of about 5 (3) events above a relatively small background may be expected[13] for $M_H = 250$ (300) GeV at $\sqrt{s} = 500$ GeV. To extend the discovery potential, one has to abandon the $\mu^+\mu^-$ tag.

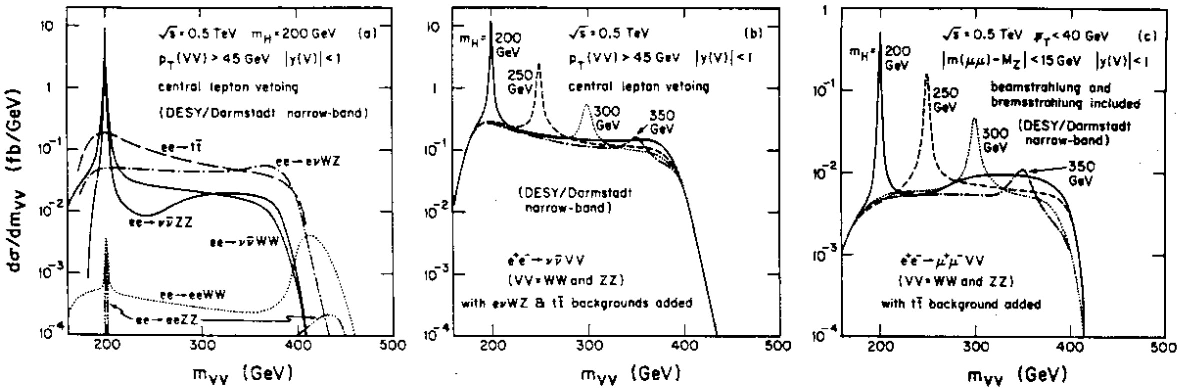

**Fig. 4** $m(VV)$ distributions after cuts of (a) the $\nu\bar{\nu}VV$ signals and backgrounds separately, for $M_H = 200$ GeV, (b) the $\nu\bar{\nu}VV$ signals and $e\nu WZ$ and $t\bar{t}$ backgrounds summed, and (c) the $\mu^+\mu^-VV$ signals and the corresponding $t\bar{t}$ background summed, for $M_H = 200, 250, 300, 350$ GeV. Bremsstrahlung, beamstrahlung, and beam-energy spread are included and $m_t = 150$ GeV is assumed.

The most promising signals have been identified in the channels $e^+e^- \to \nu\bar{\nu}VV$, where $V \to jj$ decays are detected.[13] The cross section for these signals is a factor of 10–40 times larger than that for the $\mu^+\mu^-VV$ signals. The $\nu\bar{\nu}H$ signal receives contributions both from $ZH$ production and $WW$ fusion. Various backgrounds from other $\nu\bar{\nu}VV$, $e\nu VV$, $eeVV$, and $t\bar{t}$ production mechanisms can be greatly suppressed by a $V$-rapidity cut, a missing transverse-momentum $[= p_T(VV)]$ cut, and a central-lepton veto. At $\sqrt{s} = 500$ GeV a detectable $\nu\bar{\nu}jjjj$ signal is predicted[13] up to masses of order $M_H = 300$–350 GeV. For the same luminosity and efficiency as above, a mass value $M_H = 300$ (350) GeV would imply about 30 (10) signal events in a narrow $m(jjjj)$ peak, with about 50 (15) background events under the peak. The final results are summarized in Fig. 4 for the DLC narrow-band design. With $200\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 1$ TeV it is possible[14] to cover the $M_H$ range way up to 700 GeV.

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## References

1. D. A. Dicus and V. S. Mathur, *Phys. Rev.* **D7** (1973) 3111; B. W. Lee, C. Quigg, and H. B. Thacker, *Phys. Rev. Lett.* **38** (1977) 883; M. Veltman, *Acta Phys. Pol.* **B8** (1977) 475.
2. M. Lüscher and P. Weisz, *Phys. Lett.* **B212** (1988) 472.
3. D. Treille, in these proceedings.
4. É. A. Kuraev and V. S. Fadin, *Sov. J. Nucl. Phys.* **41** (1985) 466; F. A. Berends, W. L. van Neerven, and G. J. H. Burgers, *Nucl. Phys.* **B297** (1988) 429; (E) **B304** (1988) 921; B. A. Kniehl, M. Krawczyk, J. H. Kühn, and R. G. Stuart, *Phys. Lett.* **B209** (1988) 337.
5. O. Nicrosini and L. Trentadue, *Phys. Lett.* **B196** (1987) 551; M. Skrzypek and S. Jadach, *Z. Phys.* **C49** (1991) 577; M. Cacciari, A. Deandrea, G. Montagna, and O. Nicrosini, *Z. Phys.* **C52** (1991) 421.
6. P. Chen, *Phys. Rev.* **D46** (1992) 1186.
7. J. Fleischer and F. Jegerlehner, *Nucl. Phys.* **B216** (1983) 469; B. A. Kniehl, *Z. Phys.* **C55** (1992) 605; A. Denner, J. Küblbeck, R. Mertig, and M. Böhm, *Z. Phys.* **C56** (1992) 261.
8. J. Fleischer and F. Jegerlehner, *Phys. Rev.* **D23** (1981) 2001; B. A. Kniehl, *Nucl. Phys.* **B352** (1991) 1; *ibid.* **B357** (1991) 439; *ibid.* **B376** (1992) 3; D. Yu. Bardin, B. M. Vilenskiĭ, P. Kh. Khristov, *Sov. J. Nucl. Phys.* **53** (1991) 152; A. Dabelstein and W. Hollik, *Z. Phys.* **C53** (1992) 507.
9. E. Braaten and J. P. Leveille, *Phys. Rev.* **D22** (1980) 715; S. G. Gorishny, A. L. Kataev, S. A. Larin, and L. R. Surguladze, *Mod. Phys. Lett.* **A5** (1990) 2703.
10. A. Djouadi, M. Spira, and P. M. Zerwas, *Phys. Lett.* **B264** (1991) 440.
11. B. A. Kniehl, DESY Report No. 93-069 (June 1993).
12. V. Barger, K. Cheung, A. Djouadi, B. A. Kniehl, and P. M. Zerwas, DESY Report No. 93-064, MAD/PH/749, UdeM-LPN-TH-93-143, and NUHEP-TH-93-12 (June 1993).
13. V. Barger, K. Cheung, B. A. Kniehl, and R. J. N. Phillips, *Phys. Rev.* **D46** (1992) 3725.
14. K. Hagiwara, J. Kanzaki, and H. Murayama, KEK Report No. 91-4 (March 1991); Y. Kurihara and R. Najima, *Phys. Lett.* **B301** (1993) 292.