Measuring the Higgs to $\gamma\gamma$ Branching Ratio at the Next Linear $e^+e^-$ Collider. *

J. F. Gunion and P. C. Martin

Davis Institute for High Energy Physics, University of California, Davis CA, 95616

ABSTRACT

We examine the prospects for measuring the $\gamma\gamma$ branching ratio of a Standard-Model-like Higgs boson ($h$) at the Next Linear $e^+e^-$ Collider when the Higgs boson is produced via $W^+W^-$-fusion: $e^+e^- \to \nu_{\tau} \bar{\nu}_{\tau} h$. In particular, we study the accuracy of such a measurement and the statistical significance of the associated signal as a function of the electromagnetic calorimeter resolution and the Higgs boson mass. We compare results for the $W^+W^-$-fusion production/measurement mode with the results obtained for the $e^+e^- \to Z^* \to Zh$ production/measurement mode in a parallel earlier study.

I. Introduction

Discovery and study of Higgs boson(s) will be of primary importance at a Next Linear $e^+e^-$ Collider (NLC). After discovery of a Higgs, the goal will be to determine as precisely as possible—independent of any model—its fundamental couplings and total width. Our concern is with a light Standard Model (SM) like Higgs boson which has a width too small for direct observation [1]. For such a Higgs boson, it will be necessary to determine $BR(h \to \gamma\gamma)$ in order to determine its total width and coupling constants. The procedure for ascertaining the Higgs total width and its $b\bar{b}$ partial width is outlined below.

(Estimated errors given are summarized in Ref. [2].)

- Measure $\sigma(Zh)$ (in the missing mass mode) and $\sigma(Zh)BR(h \to b\bar{b})$ and compute:

$$BR(h \to b\bar{b}) = \frac{\sigma(Zh)BR(h \to b\bar{b})}{\sigma(Zh)} ;$$

(1)

the error in $BR(h \to b\bar{b})$ so obtained is estimated at $\pm 8\%$ to $\pm 10\%$.

- Measure at the associated $\gamma\gamma$ collider facility the rate for $\gamma\gamma \to h \to b\bar{b}$ (accuracy $\pm 5\%$) which is proportional to $\Gamma(h \to \gamma\gamma)BR(h \to b\bar{b})$ and compute (accuracy $\pm 11\%$ to $\pm 13\%$):

$$\Gamma(h \to \gamma\gamma) = \frac{[\Gamma(h \to \gamma\gamma)BR(h \to b\bar{b})]}{BR(h \to b\bar{b})} .$$

(2)

- Finally, compute:

$$\Gamma_h^t = \frac{\Gamma(h \to \gamma\gamma)}{BR(h \to \gamma\gamma)} ; \quad \Gamma(h \to b\bar{b}) = \Gamma_h^{tot} BR(h \to b\bar{b}) .$$

(4)

The above technique determines both $\Gamma_h^{tot}$ and $\Gamma(h \to b\bar{b})$ in a model-independent way. This is desirable since knowledge of these fundamental Higgs properties is likely to be far more revealing than a simple measurement of $BR(h \to b\bar{b})$ alone. For example, in the minimal supersymmetric model (MSSM) parameters can be chosen such that the light Higgs, $h^0$, has total width and $b\bar{b}$ partial width that are both significantly different from the SM prediction, whereas the $b\bar{b}$ branching ratio is not. This occurs because the numerator and denominator, $\Gamma(h \to b\bar{b})$ and $\Gamma_h^{tot}$, respectively, differ by similar amounts from the SM predictions, so that the ratio of the two changes only slightly. In general, interpretation of any branching ratio is ambiguous. We must be able to convert the measured branching ratios to the partial widths that are directly related to fundamental couplings. This is possible only if we can determine $\Gamma_h^{tot}$ in a model-independent way.

Estimating the error in the determination of $BR(h \to \gamma\gamma)$ and how it propagates into errors in the determination of the total width and thence partial widths is very crucial. This is because the deviation of $BR(h \to \gamma\gamma)$ and the partial widths of a SM-like Higgs of an extended model from the predictions for the minimal SM Higgs boson may be small (as typical, for example, in the case of the $h^0$ of the MSSM when the pseudoscalar Higgs boson of the MSSM is heavy). It turns out that the dominant error in the partial width determinations will be that from the determination of $BR(h \to \gamma\gamma)$. Thus, it is vital that we determine the optimal procedures for minimizing the error in the latter.

Of course, deviations of $BR(h \to \gamma\gamma)$ itself from SM expectations could also be very revealing. In particular, by virtue of the fact that the coupling $h \to \gamma\gamma$ arises from charged loops, large deviations from SM predictions due to new particles (e.g. fourth generation, supersymmetry etc.) are possible. Regardless of the size of the deviations from SM predictions, determining $BR(h \to \gamma\gamma)$ at the NLC will be vital to understanding the nature of the Higgs boson and will provide an important probe of new physics that may lie beyond the SM.

II. SM Signal and Background

In this report we examine expectations in the case of the Standard Model Higgs boson, $h_{SM}$. We focus on the mass range $50 \text{ GeV} \lesssim m_{h_{SM}} \lesssim 150 \text{ GeV}$ for which $BR(h_{SM} \to \gamma\gamma)$ is large enough to be potentially measurable. For the $e^+e^- \to
The $\nu_e \bar{\nu}_e h_{SM}$ process that we are considering, the best rate is obtained by running the $e^+ e^-$ collider at the maximum possible energy. We adopt the canonical NLC benchmark energy of $\sqrt{s} = 500$ GeV.

Exact matrix elements are used for all calculations. For completeness, when calculating the signal ($S$) in the $Xh_{SM}$ final state (where $X$ is invisible), we include both production processes,

$$e^+ e^- \rightarrow W^+ W^- \nu_e \bar{\nu}_e \rightarrow \nu_e \bar{\nu}_e h_{SM},$$

(5)

$$e^+ e^- \rightarrow Z^* \rightarrow Z h_{SM},$$

(6)

with the subsequent decays:

$$h_{SM} \rightarrow \gamma \gamma \text{ and } Z \rightarrow \nu_i \bar{\nu}_i \text{ (i = e, \mu, \tau).}$$

(7)

When calculating the background ($B$) we include all processes contributing to

$$e^+ e^- \rightarrow \nu_i \bar{\nu}_i \gamma \gamma.$$  

(8)

In our parallel study of the $Z h_{SM}$ production/measurement mode, visible as well as invisible $Z$ decays were included in both signal and background.  

III. Cuts and Calorimeter Considerations

We compute both the signal and background rates for a small interval of the two-photon invariant mass, $\Delta m_{\gamma \gamma}(m_{h_{SM}})$, centered around $m_{h_{SM}}$. The $\Delta m_{\gamma \gamma}$ interval will depend upon the resolution of the electromagnetic calorimeter (as we shall shortly discuss) and is adjusted in conjunction with other kinematic cuts so that the statistical error in measuring $\sigma(e^+ e^- \rightarrow h_{SM} X) BR(h_{SM} \rightarrow \gamma \gamma), \sqrt{S + B}/S$, is minimized. After exploring a wide variety of possible cuts, we found that the smallest error could be achieved using the following:

$$|y_{\gamma_1}| \leq 2.0, \quad |y_{\gamma_2}| \leq 2.0,$$

(9)

$$p_T^{\gamma_1,2} \geq p_T^{\gamma_1,2 \ min}(m_{h_{SM}}), \quad p_T^{\gamma_1} + p_T^{\gamma_2} \geq p_T^{min}(m_{h_{SM}}),$$

(10)

$$M_{\text{missing}} = \sqrt{(p_{e+} + p_{e-} - p_{\gamma_1} - p_{\gamma_2})^2} \geq 130 \text{ GeV},$$

(11)

$$p_{T^\gamma}^{\gamma_1} = \sqrt{(p_{\gamma_1}^2 + p_{\gamma_2}^2)^2 + (p_y^2 + p_y^2)^2} \geq 10 \text{ GeV},$$

(12)

where $p_T^{\gamma_1,2}$ are the magnitudes of the transverse momenta of the two photons in the $e^+ e^-$ center-of-mass (by convention, $E_{\gamma_1} \geq E_{\gamma_2}$). The $M_{\text{missing}}$ cut effectively removes contributions from $e^+ e^- \rightarrow Z^* \rightarrow Z h_{SM}$ and the associated $e^+ e^- \rightarrow Z \gamma \gamma \rightarrow \nu \bar{\nu} \gamma \gamma$ backgrounds. This is desirable because at $\sqrt{s} = 500$ GeV the $S/B$ ratio for these $Z$-pole-mediated processes is much smaller than that for the $W^+ W^- - $fusion signal contribution and non-$Z$-pole backgrounds. Finally, the $p_{T^\gamma}^{\gamma_1}$ cut is used to eliminate contributions from events such as $e^+ e^- \rightarrow e^+ e^- \gamma \gamma$ where the $e^+$ and $e^-$ are lost down the beam pipe leaving the signature of $\gamma \gamma$ plus missing energy.

Four different electromagnetic calorimeter resolutions are considered:

I: resolution like that of the CMS lead tungstate crystal$^4$ with $\Delta E/E = 2\% / \sqrt{E} \oplus 0.5\% $\oplus $20\%/E$;

II: resolution of $\Delta E/E = 10\%/ \sqrt{E} \oplus 1\%$;

III: resolution of $\Delta E/E = 12\%/ \sqrt{E} \oplus 0.5\%$; and

IV: resolution of $\Delta E/E = 15\%/ \sqrt{E} \oplus 1\%$.

Cases II and III are at the ‘optimistic’ end of current NLC detector designs$^5$. Case IV is the current design specification for the JLC-1 detector$^6$. For each resolution case, we have searched for the $p_T^{\gamma_1 \ min}, p_T^{\gamma_2 \ min}, p_{T^\gamma}^{\min} \text{ and } \Delta m_{\gamma \gamma}$ values which minimize the error, $\sqrt{S + B}/S$, at a given Higgs boson mass. In Table I$^7$, we give these values as a function of Higgs mass $m_{h_{SM}}$. Listed in Table I are the signal and background rates for the $h_{SM}$ computed for these optimal choices. We assume that $m_{h_{SM}}$ will be known within $\Delta m_{h_{SM}} \ll \Delta m_{\gamma \gamma}$ and that the backgrounds can be accurately determined using data away from $m_{h_{SM}}$. All the results are for four years of running at $L = 50$ fb$^{-1}$ yearly integrated luminosity, i.e. a total of $L = 200$ fb$^{-1}$.

IV. Results and Discussion

We present the statistical errors for measuring $\sigma BR(h_{SM} \rightarrow \gamma \gamma)$ in the $W^+ W^- - $fusion measurement mode and compare with the results from our earlier, similar study of the $Z h_{SM}$ production measurement mode$^5$. We note that in the $Z h_{SM}$ case the optimal results to be reviewed are only obtained by tuning the machine energy close to the value which maximizes the $Z h_{SM}$ cross section for the given value of $m_{h_{SM}}$ and accumulating $L = 200$ fb$^{-1}$ at that energy. (The exact $\sqrt{s}$ values employed for the $Z h_{SM}$ measurement mode and the associated cuts, the nature of which differ somewhat from the ones presented here for the fusion mode, are detailed in Ref. [5].) Since the optimal $\sqrt{s}$ for the $Z h_{SM}$ mode is always substantially less than $500$ GeV, the deviation of so much luminosity to this single $\sqrt{s}$ value will only take place once the $h_{SM}$ has already been discovered at the LHC or while running the NLC at $\sqrt{s} = 500$ GeV. If the NLC is first operated at $\sqrt{s} = 500$ GeV, either because a Higgs boson has not been detected previously or because other physics (e.g. production of supersymmetric particles) is deemed more important, data for measuring $\sigma BR(h_{SM} \rightarrow \gamma \gamma)$ using the $W^+ W^- - $fusion measurement mode will be accumulated. We will see that both the detector resolution and the actual value of $m_{h_{SM}}$ will enter into the decision regarding whether or not to devote luminosity to the $Z h_{SM}$ measurement mode at a lower $\sqrt{s}$.

Figures 1-4 display plots of the statistical error, $\sqrt{S + B}/S$, and the statistical significance, $S/\sqrt{B}$, as functions of $m_{h_{SM}}$ for both $h_{SM} \rightarrow \gamma \gamma$ measurement modes. The following observations are useful:

- Figures 1 and 3 reveal that in resolution cases II-IV smaller errors are obtained in the $Z h_{SM}$ measurement mode for...
a Higgs mass between 50 GeV and 120 GeV, whereas the \( W^+W^- \) measurement mode yields smaller errors for 130 \( \lesssim m_{h_{SM}} \lesssim 150 \) GeV. In resolution case I, the \( Z_{h_{SM}} \) mode error is smaller for masses up to 130 GeV.

- The absolute minimal statistical error (as obtained if we set \( B = 0 \) and choose \( \Delta m_{\gamma\gamma} \) large enough to accept the entire Higgs signal) for 50 GeV \( \lesssim m_{h_{SM}} \lesssim 150 \) GeV is:
  \[ \pm 8\% \text{ to } \pm 15\% \text{ in the } Z_{h_{SM}} \text{ measurement mode; and} \]
  \[ \pm 15\% \text{ to } \pm 30\% \text{ in the } W^+W^- \text{ measurement mode}. \]

These numbers indicate the extent to which the accuracy is limited simply as a result of the very small event rates in the \( h_{SM} \to \gamma\gamma \) decay mode. The smaller error possible in the \( B = 0 \) limit in the \( Z_{h_{SM}} \) measurement mode is a result of the larger \( S \) values that can be achieved by running at the optimal \( \sqrt{S} \).

- The smallest errors are obtained in the 90 GeV \( \lesssim m_{h_{SM}} \lesssim 130 \) GeV. In this region the statistical errors (including the computed background) for the best calorimeter resolution case (case I) are:
  \[ \pm 19\% \text{ to } \pm 22\% \text{ in the } Z_{h_{SM}} \text{ measurement mode; } \]
  \[ \pm 22\% \text{ to } \pm 32\% \text{ in the } W^+W^- \text{ measurement mode}. \]

For the worst resolution case (case IV) the errors are:

- \[ \pm 29\% \text{ to } \pm 35\% \text{ in the } Z_{h_{SM}} \text{ measurement mode; } \]
- \[ \pm 26\% \text{ to } \pm 41\% \text{ in the } W^+W^- \text{ measurement mode}. \]

- Thus, if the detector does not have good electromagnetic calorimeter resolution, then the \( W^+W^- \)–fusion measurement mode is quite competitive with, and in some mass regions superior to, the \( Z_{h_{SM}} \) measurement mode. However, if the smallest possible errors are the goal, excellent resolution is required and one must use the \( Z_{h_{SM}} \) measurement mode techniques if \( m_{h_{SM}} \lesssim 130 \) GeV. The reasons behind these results are simple:

  - \( S/B \) tends to be substantial in the \( W^+W^- \)–fusion mode, implying relatively modest sensitivity to resolution, but \( S \) itself is limited (as noted earlier) so that even a \( B = 0 \) measurement would not have a small error.

  - \( S \) is larger in the \( Z_{h_{SM}} \) measurement technique (at the optimal \( \sqrt{S} \) for the given \( m_{h_{SM}} \) value) but \( B \) can only be made small enough for a big gain in \( \sqrt{S/B} \) if the mass interval accepted can be kept small.

- The plots also reveal that in the lower mass region, 50 \( \lesssim m_{h_{SM}} \lesssim 80 \) GeV, the error in the \( \sigma BR(h_{SM} \to \gamma\gamma) \) measurement would be substantially lower in the \( Z_{h_{SM}} \) mode, whereas in the upper mass region of 140 \( \lesssim m_{h_{SM}} \lesssim 150 \) GeV the errors are smaller in the \( W^+W^- \) measurement mode, especially if the resolution is not as excellent as assumed in case I.

\( ^3 \)This is the mass region predicted by the MSSM for the light Higgs, \( h^0 \).

Although observation of a clear Higgs signal in the \( \gamma\gamma \) invariant mass distribution is not an absolute requirement (given that we will have observed the \( h_{SM} \) in other channels and will have determined its mass very accurately) it would be helpful in case there are significant systematics in measuring the \( \gamma\gamma \) invariant mass. It is vital to be certain that \( \Delta m_{\gamma\gamma} \) is centered on the mass region where the Higgs signal is present. Figures 3 and 4 show plots of the statistical significance, \( S/\sqrt{B} \) vs. \( m_{h_{SM}} \). They show that the mass regions for which \( \geq 3\sigma \) measurements can be made depend significantly upon resolution.

- If excellent resolution (case I) is available then \( S/\sqrt{B} \geq 3 \) is achieved for 60 GeV \( \lesssim m_{h_{SM}} \lesssim 150 \) GeV in both the \( Z_{h_{SM}} \) and \( W^+W^- \)–fusion measurement modes.

- If the resolution is poor (case IV) then \( S/\sqrt{B} \geq 3 \) is achieved for 90 GeV \( \lesssim m_{h_{SM}} \lesssim 130 \) GeV in the \( Z_{h_{SM}} \) measurement mode and for 100 GeV \( \lesssim m_{h_{SM}} \lesssim 150 \) GeV in the \( W^+W^- \)–fusion mode.

We end this section by noting that the error in the determination of \( BR(h_{SM} \to \gamma\gamma) \) is not precisely the same as the error in the \( \sigma BR(h_{SM} \to \gamma\gamma) \) measurement. In the \( W^+W^- \)–fusion mode, Eq. (8) shows that errors in both \( BR(h_{SM} \to b\bar{b}) \) and \( \sigma(\nu\bar{\nu}h_{SM})BR(h_{SM} \to b\bar{b}) \) enter into the \( BR(h_{SM} \to \gamma\gamma) \) error. The error in \( BR(h_{SM} \to b\bar{b}) \) will be about \( \pm 8\% \pm 10\% \). The error in \( \sigma(\nu\bar{\nu}h_{SM})BR(h_{SM} \to b\bar{b}) \) will probably be about \( \pm 5\% \pm 7\% \). These errors must be added in quadrature with the \( \sigma(\nu\bar{\nu}h_{SM})BR(h_{SM} \to \gamma\gamma) \) error. In the \( Z_{h_{SM}} \) measurement mode, \( BR(h_{SM} \to \gamma\gamma) \) is computed as \( \sigma(Z_{h_{SM}})BR(h_{SM} \to \gamma\gamma)/\sigma(Z_{h_{SM}}) \). The \( \sim \pm 7\% \) error in \( \sigma(Z_{h_{SM}}) \) must be added in quadrature with the \( \sigma(Z_{h_{SM}})BR(h_{SM} \to \gamma\gamma) \) error. However, since the \( \sigma BR(h_{SM} \to \gamma\gamma) \) errors in both the \( W^+W^- \)–fusion and \( Z_{h_{SM}} \) measurement modes are always \( \gtrsim \pm 20\% \), quadrature additions of the magnitude summarized above will not be very significant. For example, for a \( \sigma BR \) measurement of \( \pm 20\% \) the quadrature additions would imply about \( \pm 21\% \pm 22\% \) errors for \( BR(h_{SM} \to \gamma\gamma) \) using the \( Z_{h_{SM}} \) (\( W^+W^- \)–fusion) measurement mode procedures.

V. Conclusions

We have studied the prospects for measuring \( \sigma BR(h \to \gamma\gamma) \) for a SM-like Higgs boson at the NLC. The measurement will be challenging but of great importance. We have compared results for two different production/measurement modes: \( W^+W^- \)–fusion and \( Z_{h_{SM}} \). In the mass range of 90 GeV to 130 GeV where \( BR(h_{SM} \to \gamma\gamma) \) is largest (a mass range that is also highly preferred for the light SM-like \( h^0 \) of the MSSM) the smallest errors in the measurement of \( \sigma BR(h_{SM} \to \gamma\gamma) \) that can be achieved with an excellent CMS-style calorimeter (resolution case I) are \( \gtrsim \pm 20\% \) using the \( Z_{h_{SM}} \) measurement mode and \( \gtrsim \pm 22\% \) using the \( W^+W^- \)–fusion measurement mode. For a calorimeter at the optimistic end of current plans for the NLC detector (cases II and III) the errors range from \( \sim \pm 25\% \) to \( \sim \pm 30\% \) for the \( Z_{h_{SM}} \) mode and from \( \sim \pm 26\% \) to \( \sim \pm 41\% \) for the \( W^+W^- \)–fusion mode. The \( Z_{h_{SM}} \) errors...
assume that the machine energy is tuned to the \((\leq 300 \text{ GeV})\) \(\sqrt{s}\) value which maximizes the \(Z_{SM}\) event rate, and that \(L = 200 \text{ fb}^{-1}\) is accumulated there, whereas the \(W^+W^-\) fusion errors assume that \(L = 200 \text{ fb}^{-1}\) is accumulated at \(\sqrt{s} = 500 \text{ GeV}\).

The desirability of running in the \(Z_{SM}\) measurement mode can only be determined once the Higgs mass is known. To take full advantage of such running would require that the calorimeter be upgraded to a resolution approaching the CMS level of resolution. For resolution cases II or III and \(m_{h_{SM}} \sim 120 \text{ GeV}\), the accuracy of the measurement would be \(\sim \pm 25\%\) in the \(W^+W^-\)–fusion measurement mode and \(\sim \pm 25\%\) in the \(Z_{SM}\) measurement mode, and there would be little point in running in the latter mode. For CMS resolution (case I), these respective errors become \(\sim \pm 22\%\) and \(\sim \pm 19\%\), a gain that is still somewhat marginal, especially given the fact that current estimates [8] are that the error on the \(\sigma BR(h_{SM} \rightarrow \gamma\gamma)\) measurement at the LHC would be comparable, of order \(\pm 22\%\) at \(m_{h_{SM}} = 120 \text{ GeV}\), so that statistics could be combined to give \(\sim \pm 15\%\) for either NLC measurement mode. However, for smaller \(m_{h_{SM}}\) values the LHC error will worsen significantly and the \(Z_{SM}\) measurement mode becomes increasingly superior to the \(W^+W^-\)–fusion mode, especially if the calorimeter resolution is excellent. For Higgs masses above \(m_{h_{SM}} \sim 120 \text{ GeV}\), little would be gained by using the \(Z_{SM}\) measurement mode; for the highest mass considered, \(m_{h_{SM}} = 150 \text{ GeV}\), using the \(Z_{SM}\) mode would be disadvantageous.

**Acknowledgements** We thank J. Brau, R. Van Kooten, L. Poggioli and P. Rowson for helpful conversations.

**REFERENCES**

[1] See J.F. Gunion, H.E. Haber, G.L. Kane and S. Dawson, *The Higgs Hunters Guide*, Addison-Wesley Publishing, and references therein.

[2] For a recent review, see J.F. Gunion, A. Stange, and S. Willenbrock, “Weakly-Coupled Higgs Bosons”, in *Electroweak Symmetry Breaking and New Physics at the TeV Scale*, edited by T.L. Barklow, S. Dawson, H.E. Haber, and J.L. Siegrist (World Scientific, Singapore, 1996).

[3] C.-H. Chen, M. Drees, and J.F. Gunion, Phys. Rev. Lett. 76, 2002 (1996).

[4] CMS Technical Proposal, CERN/LHCC 94-38 (1994).

[5] *Physics and Technology of the NLC*, BNL-52-502.

[6] JLC-I, JLC Group, KEK Report 92-16, as summarized by K. Fujii, *Proceedings of the 2nd International Workshop on “Physics and Experiments with Linear e+e− Colliders”*, eds. F. Harris, S. Olsen, S. Pakvasa and X. Tata, Waikoloa, HI (1993), World Scientific Publishing, p. 782.

[7] J.F. Gunion and P.C. Martin, preprint hep-ph/9607360

[8] L. Poggioli, preliminary result, Snowmass 1996.

### Table I: For resolution choices I, II, III and IV, we tabulate \(p_T^{\gamma_1} \text{min}, p_T^{\gamma_2} \text{min}, p_T^\gamma \text{min}\), and \(\Delta m_{\gamma\gamma}\) as a function of \(m_h\) (GeV).

| \(m_h\) | \(p_T^{\gamma_1} \text{min}\) | \(p_T^{\gamma_2} \text{min}\) | \(p_T^\gamma \text{min}\) | \(\Delta m_{\gamma\gamma}^{I}\) | \(\Delta m_{\gamma\gamma}^{II}\) | \(\Delta m_{\gamma\gamma}^{III}\) | \(\Delta m_{\gamma\gamma}^{IV}\) |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 50    | 30              | 10              | 40              | 0.7             | 2.0             | 2.1             | 2.3             |
| 60    | 30              | 10              | 60              | 1.0             | 2.2             | 2.3             | 2.7             |
| 70    | 30              | 20              | 65              | 1.1             | 2.4             | 2.7             | 3.2             |
| 80    | 30              | 20              | 70              | 1.3             | 2.7             | 2.7             | 3.6             |
| 90    | 30              | 20              | 70              | 1.4             | 3.1             | 3.1             | 4.1             |
| 100   | 40              | 20              | 75              | 1.8             | 3.4             | 3.4             | 4.5             |
| 110   | 40              | 20              | 85              | 2.0             | 4.2             | 4.2             | 5.0             |
| 120   | 40              | 20              | 95              | 2.2             | 4.6             | 4.6             | 5.4             |
| 130   | 50              | 20              | 100             | 2.3             | 4.9             | 4.7             | 5.9             |
| 140   | 50              | 30              | 110             | 2.5             | 5.3             | 4.8             | 6.3             |
| 150   | 50              | 30              | 120             | 2.4             | 5.4             | 5.1             | 6.8             |

### Table II: For resolution choices I, II, III and IV, we tabulate \(S\) and \(B\) as a function of \(m_{h_{SM}}\) (GeV) for \(L = 200 \text{ fb}^{-1}\).

| \(m_{h_{SM}}\) | \(S_I\) | \(B_I\) | \(S_{II}\) | \(B_{II}\) | \(S_{III}\) | \(B_{III}\) | \(S_{IV}\) | \(B_{IV}\) |
|----------------|--------|--------|-----------|-----------|-----------|-----------|-----------|-----------|
| 50             | 5.1    | 24     | 5.8       | 68        | 5.8       | 72        | 5.2       | 76        |
| 60             | 8.1    | 24     | 8.0       | 54        | 8.1       | 56        | 7.6       | 66        |
| 70             | 8.8    | 12     | 8.4       | 27        | 8.7       | 30        | 8.3       | 35        |
| 80             | 12     | 13     | 12        | 29        | 12        | 29        | 12        | 37        |
| 90             | 18     | 15     | 17        | 31        | 17        | 31        | 17        | 40        |
| 100            | 22     | 14     | 20        | 27        | 20        | 27        | 20        | 35        |
| 110            | 26     | 13     | 25        | 27        | 25        | 27        | 24        | 31        |
| 120            | 29     | 11     | 27        | 23        | 28        | 23        | 26        | 27        |
| 130            | 26     | 9.3    | 25        | 20        | 24        | 19        | 24        | 23        |
| 140            | 18     | 6.1    | 18        | 13        | 17        | 12        | 17        | 15        |
| 150            | 12     | 4.7    | 12        | 11        | 12        | 10        | 11        | 13        |
Figure 1: The fractional error in the measurement of $\sigma(\nu_\mu \bar{\nu}_e h_{SM}) q BR(h_{SM} \to \gamma \gamma)$ as a function of $m_{h_{SM}}$.

Figure 2: Results for $S/\sqrt{B}$ in the $W^+ W^-$-fusion production mode at $L = 200 \text{ fb}^{-1}$ as a function of $m_{h_{SM}}$.

Figure 3: The fractional error in the measurement of $\sigma(Z h_{SM}) BR(h_{SM} \to \gamma \gamma)$ as a function of $m_{h_{SM}}$.

Figure 4: Results for $S/\sqrt{B}$ in the $Zh_{SM}$ production mode at $L = 200 \text{ fb}^{-1}$ as a function of $m_{h_{SM}}$. 