Prospects for and Implications of Measuring the Higgs to Photon-Photon Branching Ratio at the Next Linear $e^+e^-$ Collider

John F. Gunion and Patrick C. Martin

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

Abstract

We evaluate the prospects for measuring $B(h \to \gamma\gamma)$ for a Standard-Model-like Higgs boson at the Next Linear $e^+e^-$ Collider in the $e^+e^- \to Z^* \to Zh$ and $e^+e^- \to \nu_e \bar{\nu}_e h$ production modes. Relative merits of different machine energy/luminosity strategies and different electromagnetic calorimeter designs are evaluated. We emphasize the importance of measuring $B(h \to \gamma\gamma)$ in order to obtain the total width of a light Higgs boson and thereby the $b\bar{b}$ partial width that will be critical in discriminating between the SM Higgs and the Higgs bosons of an extended model.

I. INTRODUCTION

One of the most important tasks of a Next Linear $e^+e^-$ Collider (NLC) will be to detect and study Higgs boson(s). For any observed Higgs boson, extraction of its fundamental couplings and total width in a model-independent manner will be a primary goal. Measurement of $B(h \to \gamma\gamma)$ turns out to be an absolutely necessary ingredient in extracting
the total width and $b\bar{b}$ coupling in the case of a light Higgs boson with mass \( < 130 \text{ GeV} \) and couplings similar to those of the Standard Model (SM) Higgs, $h_{SM}$, and therefore a total width that is too small to be directly observed. The procedure for obtaining the total and $b\bar{b}$ partial widths using $B(h \to \gamma\gamma)$ is the following:

- Determine $B(h \to b\bar{b})$ in $e^+e^- \to Z^* \to Zh$ and $e^+e^- \to e^+e^- h$ (ZZ-fusion) from the ratios $B(h \to b\bar{b}) = [\sigma(Zh)B(h \to b\bar{b})]/\sigma(Zh)$ (with $Z \to \ell^+\ell^-$, $\ell = e, \mu$) and $B(h \to b\bar{b}) = [\sigma(e^+e^- h)B(h \to b\bar{b})]/\sigma(e^+e^- h)$, respectively. For $L = 200 \text{ fb}^{-1}$ of data at $\sqrt{s} = 500 \text{ GeV}$, the error for $B(h \to b\bar{b})$ would be about $\pm 5\%$ [1].

- Measure at the associated $\gamma\gamma$ collider facility the rate for $\gamma\gamma \to h \to b\bar{b}$ (accuracy $\sim \pm 8\%$ [1] for $L = 50 \text{ fb}^{-1}$) proportional to $\Gamma(h \to \gamma\gamma)B(h \to b\bar{b})$ and compute (accuracy $\sim \pm 13\%$) $\Gamma(h \to \gamma\gamma) = [\Gamma(h \to \gamma\gamma)B(h \to b\bar{b})]/B(h \to b\bar{b})$.

- Measure $B(h \to \gamma\gamma)$ as described shortly, and then compute:

$$\Gamma_h^{\text{tot}} = \frac{\Gamma(h \to \gamma\gamma)}{B(h \to \gamma\gamma)}; \quad \text{and} \quad \Gamma(h \to b\bar{b}) = \Gamma_h^{\text{tot}} B(h \to b\bar{b}). \quad (1)$$

For a SM-like $h$, measurement of $B(h \to \gamma\gamma)$ at the NLC will be challenging because of its small size (at best of order a few times $10^{-3}$ [2]). One will measure $[\sigma(e^+e^- \to Zh)B(h \to \gamma\gamma)]$, $[\sigma(e^+e^- \to \nu_e\overline{\nu}_e h)B(h \to \gamma\gamma)]$ and $[\sigma(e^+e^- \to \nu_e\overline{\nu}_e h)B(h \to b\bar{b})]$ (the latter two being WW-fusion processes) and compute $B(h \to \gamma\gamma)$ via the $Zh$ and WW-fusion ratios,

$$\frac{[\sigma(Zh)B(h \to \gamma\gamma)]}{\sigma(Zh)} \quad \text{and} \quad \frac{[\sigma(\nu_e\overline{\nu}_e h)B(h \to \gamma\gamma)]B(h \to b\bar{b})}{[\sigma(\nu_e\overline{\nu}_e h)B(h \to b\bar{b})]}, \quad (2)$$

respectively. Errors in the above two $B(h \to \gamma\gamma)$ computations will be dominated by the errors in the $\sigma B(h \to \gamma\gamma)$ measurements. (The $e^+e^- h$ final state from ZZ-fusion provides a third alternative, but does not yield competitive errors because of a larger background.) Which of the ratios in Eq. (2) will yield the smallest errors for $B(h \to \gamma\gamma)$ is dependent upon

\[\text{For } m_{h_{SM}} \gtrsim 130 \text{ GeV}, \text{ a 2nd technique based on } WW^* \text{ decays emerges [1].} \]
many factors. In this Letter, we assess the relative merits of the $Zh$ and $WW$-fusion modes as a function of Higgs boson mass, machine energy, electromagnetic calorimeter resolution and luminosity/upgrade strategies.

The importance of a direct determination of $\Gamma_{h}^{\text{tot}}$ and $\Gamma(h \to b\bar{b})$ is due to the ambiguities associated with measuring only $B(h \to b\bar{b})$. Consider, for example, the light $h^0$ of the minimal supersymmetric model (MSSM). Model parameter choices are easily found such that $\Gamma(h^0 \to b\bar{b})$ is much larger than predicted for the $h_{SM}$ [2], but $B(h^0 \to b\bar{b})$ is only slightly larger than expected due to the fact that the numerator, $\Gamma(h^0 \to b\bar{b})$, and denominator, $\Gamma_{h^0}^{\text{tot}}$, are both increased by similar amounts. Extra (supersymmetric particle) decay modes could even enhance $\Gamma_{h^0}^{\text{tot}}$ further, and $B(h^0 \to b\bar{b})$ could be smaller than the SM prediction despite the fact that $\Gamma(h^0 \to b\bar{b})$ is enhanced. Equation (1) shows that the ability to detect deviations of $\Gamma_{h^0}^{\text{tot}}$ and $\Gamma(h \to b\bar{b})$ from SM expectations depends critically on the error in $B(h \to \gamma\gamma)$, which is very likely to be the dominant source of uncertainty. Of course, dramatic deviations of $B(h \to \gamma\gamma)$ from SM expectations are also a possibility, even if the $h$ is very SM-like in its couplings to the SM particles. Large effects can be caused by new particles (fourth generation, supersymmetric, etc.) in the one-loop graphs responsible for the $h \to \gamma\gamma$ coupling. Regardless of the size of the deviations from SM predictions, determining $B(h \to \gamma\gamma)$ will be vital to understanding the nature of the Higgs boson and will provide an important probe of, or limits on, new physics that may lie beyond the SM.

II. PROCEDURES

We consider SM Higgs masses in the range $70 - 150$ GeV; $B(h_{SM} \to \gamma\gamma)$ in units of $10^{-3}$ is 0.75, 1.0, 1.4, 1.8, 2.2, 2.6, 2.6, 2.2, 1.6 as $m_{h_{SM}}$ ranges from 70 to 150 GeV in steps of 10 GeV. In computing signals and backgrounds, we use exact matrix elements. To define $Z\gamma\gamma$ vs. $\nu_{e}\bar{\nu}_{e}\gamma\gamma$ events, we employ the recoil mass, $M_X = \sqrt{(p_{e^+} + p_{e^-} - p_{\gamma_1} - p_{\gamma_2})^2}$. We define $Z\gamma\gamma$ events as $X\gamma\gamma$ events for which $M_X$ is within the interval $[80, 100]$ (GeV). In this way, we can use all $Z$ decay modes while ensuring that the only significant background
is that from $Z\gamma\gamma$ non-Higgs diagrams. (Interference between signal and background $Z\gamma\gamma$ diagrams is small.) The $M_X$ cut also implies that for $X = \nu_e\overline{\nu}_e$ the signal is almost entirely from $Z^* \rightarrow Zh_{SM}$ (interference with the $WW$-fusion diagram being small). Conversely, we define $\nu_e\overline{\nu}_e\gamma\gamma$ events as $X\gamma\gamma$ events ($X = \nu_\ell\overline{\nu}_\ell$, $\ell = e, \mu, \tau$) such that $M_X \geq 130 \text{ GeV}$. This effectively leaves only the $WW$-fusion signal contribution and non-$Z$-pole background diagrams; interference is again small.

In both the $Z\gamma\gamma$ and $\nu_e\overline{\nu}_e\gamma\gamma$ modes, our goal will be to minimize the $\sigma B(h \rightarrow \gamma\gamma)$ error, defined as $\sqrt{S + B}/S$, where $S$ ($B$) is the number of Higgs signal (background) events. The first important choice is $\sqrt{s}$. For the $Z\gamma\gamma$ channel, the optimal $\sqrt{s}$ values are given by $\sqrt{s_{opt}}(m_{h_{SM}}) \sim 89 \text{ GeV} + 1.25m_{h_{SM}}$ (always close to the peak in the $Zh_{SM}$ cross section and $\leq 300 \text{ GeV}$ for $m_{h_{SM}} \leq 150 \text{ GeV}$). For the $\nu_e\overline{\nu}_e\gamma\gamma$ mode, the smallest errors are achieved when $\sqrt{s}$ is as large as possible. We give results for $\sqrt{s} = 500 \text{ GeV}$, at which $\sqrt{s}$ the $Z\gamma\gamma$ channel also remains useful. Next are the kinematical cuts. Because of the small signal rates, these cuts must be chosen to reduce the background as much as possible while retaining a large fraction of the Higgs signal events. Keeping in mind the fact that, as a function of $M_{\gamma\gamma}$, the Higgs resonance sits on a slowly varying background, a very crucial cut is to accept only events in a small mode-, $m_{h_{SM}}$- and detector-resolution-dependent (see later discussion) interval of $M_{\gamma\gamma}$ centered on $m_{h_{SM}}$ with width chosen so as to minimize $\sqrt{S + B}/S$. Additional one-dimensional and two-dimensional kinematic cuts for minimizing the error were extensively investigated.

- For the $Zh_{SM}$ mode, the best cuts we found are the following:

$$p_T^{\gamma_1,2} \geq \frac{m_{h_{SM}}}{4}, \quad p_T^{\gamma_1} + p_T^{\gamma_2} \geq p_T^{min}(m_{h_{SM}}), \quad (3)$$

where $p_T^{\gamma_1,2}$ are the transverse momenta of the two photons in the $e^+e^-$ center-of-mass. (By convention, $E_{\gamma_1} \geq E_{\gamma_2}$.) Within the statistics of our Monte Carlo study,

\[\dagger\] The Higgs mass will be very precisely measured at the NLC. The background level under the peak will be very precisely normalized using measurements with $M_{\gamma\gamma}$ away from $m_{h_{SM}}$.\[\dagger\]
the optimal $p_T^{\min}$ values at $\sqrt{s} = \sqrt{s_{\text{opt}}} (\sqrt{s} = 500 \text{ GeV})$ are given by $p_T^{\min}(m_{h_{\text{SM}}}) \sim 0.9m_{h_{\text{SM}}} - 10 \text{ GeV}$ ($p_T^{\min}(m_{h_{\text{SM}}}) \sim 200 \text{ GeV}$); for such $p_T^{\min}$, the photon rapidities are always within $|y_{\gamma_1}| \leq 1.2$ and $|y_{\gamma_2}| \leq 1.6$.

- In the $\nu_e\nu_e h_{\text{SM}}$ mode, the smallest error was achieved using the following cuts:

\[
|y_{\gamma_1}| \leq 2.5, \quad |y_{\gamma_2}| \leq 2.5, \\
p_{\gamma_1}^\text{vis} \geq p_{\gamma_1}^\text{vis}(m_{h_{\text{SM}}}), \\
p_{\gamma_2}^\text{vis} \geq p_{\gamma_2}^\text{vis}(m_{h_{\text{SM}}}), \\
p_T^{\text{vis}} = \sqrt{(p_{\gamma_1}^x + p_{\gamma_2}^x)^2 + (p_{\gamma_1}^y + p_{\gamma_2}^y)^2} \geq 10 \text{ GeV}.
\]

Within our Monte Carlo statistics, the optimal numerical choices (at $\sqrt{s} = 500 \text{ GeV}$) as a function of $m_{h_{\text{SM}}}$ are described by: $p_{\gamma_1}^{\min}(m_{h_{\text{SM}}}) \sim 0.16m_{h_{\text{SM}}} + 20 \text{ GeV}$, $p_{\gamma_2}^{\min}(m_{h_{\text{SM}}}) \sim 0.18m_{h_{\text{SM}}} + 1 \text{ GeV}$, and $p_T^{\min}(m_{h_{\text{SM}}}) \sim 0.5m_{h_{\text{SM}}} + 35 \text{ GeV}$. The $p_T^{\text{vis}}$ cut is needed to eliminate reducible backgrounds due to 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 [3].

We note that after the cuts of Eq. (3) or Eq. (4), the photons have substantially different energies, especially in the $WW$-fusion case.

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 and choice of $m_{h_{\text{SM}}}$, we determined the $\Delta M_{\gamma\gamma}$ value which minimizes $\sqrt{S + B}/S$ in the $Zh$ and $\nu_e\nu_e\gamma\gamma$ modes. The optimal $\Delta M_{\gamma\gamma}$ values for the $Zh$ mode at $\sqrt{s} = \sqrt{s_{\text{opt}}}$ and the $WW$-fusion mode at $\sqrt{s} = 500 \text{ GeV}$ are the same within Monte Carlo errors: $\Delta M_{\gamma\gamma}(I,II,III,IV)(\text{GeV}) \sim (0.015, 0.035, 0.035, 0.045)m_{h_{\text{SM}}}$. For $Z_{h_{\text{SM}}}$ production at $\sqrt{s} = 500 \text{ GeV}$, $\sqrt{S + B}/S$ is minimized for $\Delta M_{\gamma\gamma}(I,II,III,IV) \sim (0.015, 0.03, 0.03, 0.04)m_{h_{\text{SM}}}$.
The optimal $\Delta M_{\gamma\gamma}$, $p_{\text{T}}^{\text{min}}$, and $p_{\text{T}}^{\gamma_1,2\text{ min}}$ values specified above are ‘soft’; changes in the $p_{\text{T}}$ cuts by $\pm 5$ GeV or in $\Delta M_{\gamma\gamma}/m_{h_{\text{SM}}}$ by $\pm 0.005$ lead to $\leq 0.01$ change in $\sqrt{S+B}/S$.

### III. RESULTS AND DISCUSSION

The first two windows of Figure II show the statistical errors, $\sqrt{S+B}/S$, for measuring $\sigma B(h_{\text{SM}} \to \gamma\gamma)$ in the $Z^* \to Z h_{\text{SM}}$ and $\nu_e\nu_e h_{\text{SM}}$ (WW-fusion) measurement modes as a function of $m_{h_{\text{SM}}}$. We assume four years of $L = 50$ fb$^{-1}$/yr running, i.e. $L = 200$ fb$^{-1}$, at $\sqrt{s} = \sqrt{s_{\text{opt}}}$ ($\sqrt{s} = 500$ GeV) in the $Z h_{\text{SM}}$ (WW-fusion) cases, respectively. Comparing, we find that in resolution cases II-IV the $Z h_{\text{SM}}$ (WW-fusion) measurement mode yields smaller errors for $70 \lesssim m_{h_{\text{SM}}} \lesssim 120$ GeV ($130 \lesssim m_{h_{\text{SM}}} \lesssim 150$ GeV). In resolution case I, the $Z h_{\text{SM}}$ mode error is the smaller for masses up to 130 GeV. As a function of $m_{h_{\text{SM}}}$, the smallest errors are obtained for $100$ GeV $\lesssim m_{h_{\text{SM}}} \lesssim 130$ GeV.‡ For calorimeter resolutions II or III, the errors range from $\pm 25\%$ to $\pm 29\%$ for the ($\sqrt{s} = \sqrt{s_{\text{opt}}}$) $Z h_{\text{SM}}$ measurement and from $\pm 26\%$ to $\pm 33\%$ for the ($\sqrt{s} = 500$ GeV) WW-fusion measurement.

In the third window of Fig. II we plot the error obtained by combining the WW-fusion and $Z h_{\text{SM}}$ mode $\sigma B(h_{\text{SM}} \to \gamma\gamma)$ statistics for $L = 200$ fb$^{-1}$ accumulated at $\sqrt{s} = 500$ GeV. § This is close to the error for $B(h_{\text{SM}} \to \gamma\gamma)$ obtained by combining the two ratios in Eq. (2) given that errors for the other inputs are much smaller than the $\sigma B(h_{\text{SM}} \to \gamma\gamma)$ errors. Although the $Z h_{\text{SM}}$ mode error at $\sqrt{s} = 500$ GeV is always larger than the WW-fusion mode error, including the $Z h_{\text{SM}}$ measurement substantially improves the net $B(h_{\text{SM}} \to \gamma\gamma)$ error relative to that obtained using WW-fusion alone, especially at low $m_{h_{\text{SM}}}$. For $100$ GeV $\lesssim m_{h_{\text{SM}}} \lesssim 130$ GeV, the net error ranges from $\pm 23\%$ to $\pm 27\%$.

Although observation of a clear Higgs signal in the $\gamma\gamma$ invariant mass distribution is not

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‡ In the MSSM the light Higgs has $m_{h^0} \lesssim 130$ GeV.

§ We do not discuss the reverse situation, since the WW-fusion rate at $\sqrt{s_{\text{opt}}}$ is always $\lesssim 1/5$ of that for $Z h_{\text{SM}}$. 

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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 is significant systematic uncertainty in measuring the $\gamma\gamma$ invariant mass. It is vital to be certain that the $\Delta M_{\gamma\gamma}$ interval is centered on the mass region where the Higgs signal is present. Taking $\sqrt{s} = \sqrt{s_{\text{opt}}} \ (\sqrt{s} = 500 \text{ GeV})$ for the $Zh_{SM} (WW$-fusion) mode and $L = 200 \text{ fb}^{-1}$, we find $S/\sqrt{B} \geq 3$ in the following (resolution-dependent) regions:

- **case I**: $70 \leq m_{h_{SM}} \leq 150 \text{ GeV} \ (Zh_{SM})$, $80 \leq m_{h_{SM}} \leq 150 \text{ GeV}(WW$-fusion)
- **cases II/III**: $80 \leq m_{h_{SM}} \leq 140 \text{ GeV} \ (Zh_{SM})$, $90 \leq m_{h_{SM}} \leq 150 \text{ GeV}(WW$-fusion)
- **case IV**: $90 \leq m_{h_{SM}} \leq 130 \text{ GeV} \ (Zh_{SM})$, $100 \leq m_{h_{SM}} \leq 150 \text{ GeV}(WW$-fusion)

### IV. FINAL REMARKS AND CONCLUSIONS

We have studied the prospects for measuring $\sigma B(h \to \gamma\gamma)$ for a SM-like Higgs boson, with $70 \leq m_{h_{SM}} \leq 150 \text{ GeV}$, at the NLC. The measurements will be challenging but of great importance. We have compared results for two different production/measurement modes: $Z^* \to Zh$ and $WW$-fusion. Errors for the $WW$-fusion channel are minimized at full machine energy, $\sqrt{s} = 500 \text{ GeV}$. Errors in the $Zh$ channel are minimized if the machine energy is tuned to the ($\leq 300 \text{ GeV}$) $\sqrt{s} = \sqrt{s_{\text{opt}}}$ value which maximizes the $Zh$ event rate. The net error for $B(h_{SM} \to \gamma\gamma)$ is approximately given by combining the $WW$ and $Zh$ channel $\sigma B$ errors, since errors for other quantities entering the ratios of Eq. (2) are small.

At $\sqrt{s} = 500 \text{ GeV}$, the error obtained using only the $WW$-fusion channel measurement is significantly decreased by including the $Zh$ channel measurement. At $\sqrt{s} = \sqrt{s_{\text{opt}}}$, the $WW$-fusion channel can be neglected and the net error is essentially just that for the $Zh$ channel. At any $\sqrt{s}$ and in either channel, the better the electromagnetic calorimeter resolution, the smaller the error in $B(h_{SM} \to \gamma\gamma)$. For $100 \leq m_{h_{SM}} \leq 130 \text{ GeV}$, where $B(h_{SM} \to \gamma\gamma)$ is largest (a mass range that is also highly preferred for the light SM-like $h^0$ of the MSSM), and $L = 200 \text{ fb}^{-1}$, the net error assuming an excellent CMS-style calorimeter (resolution
case I) falls in the ranges $\sim \pm 18\%$ to $\sim \pm 20\%$ at $\sqrt{s} = \sqrt{s_{\text{opt}}}$ and $\sim \pm 18\%$ to $\sim \pm 22\%$ at $\sqrt{s} = 500$ GeV. For $L = 200$ fb$^{-1}$ and a calorimeter at the optimistic end of current plans for the NLC detector (cases II and III), the $100 \leq m_{h_{\text{SM}}} \leq 130$ GeV net error falls in the ranges $\sim \pm 25\%$ to $\sim \pm 29\%$ at $\sqrt{s} = \sqrt{s_{\text{opt}}}$ and $\sim \pm 22\%$ to $\sim \pm 27\%$ 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 will be accumulated with whatever calorimeter is part of the initial detector and a corresponding measurement of $B(h_{\text{SM}} \rightarrow \gamma\gamma)$ will result. The desirability of stopping data collection to upgrade the calorimeter and/or reconfigure the interaction region for full luminosity at the $Z h_{\text{SM}}$ cross section maximum must be carefully evaluated. Using the $L = 200$ fb$^{-1}$ errors of Fig. 1, we find that it is not advantageous to reconfigure for $\sqrt{s} = \sqrt{s_{\text{opt}}}$ if $m_{h_{\text{SM}}} \gtrsim 100$ GeV. The value of a calorimeter upgrade is also marginal for such $m_{h_{\text{SM}}}$. To illustrate, suppose the initial calorimeter has resolution II or III. For $m_{h_{\text{SM}}} = 120$ GeV, upgrading the calorimeter from II/III to I, and then accumulating a 2nd $L = 200$ fb$^{-1}$ at $\sqrt{s} = 500$ GeV after doing so, would yield a net $B(h_{\text{SM}} \rightarrow \gamma\gamma)$ error of $\pm 14\%$, as compared to $\sim \pm 15.5\%$ if no changes are made and a total of $L = 400$ fb$^{-1}$ is accumulated by simply running twice as long. For $m_{h_{\text{SM}}} = 150$ GeV, upgrading the resolution would yield (after the 2nd $L = 200$ fb$^{-1}$ run at $\sqrt{s} = 500$ GeV) $\sim \pm 22\%$ error vs. $\sim \pm 25\%$ if no calorimeter change is made. However, for small $m_{h_{\text{SM}}}$, reconfiguration and high resolution calorimetry both become quite valuable at the NLC. For example, if $m_{h_{\text{SM}}} = 70$ GeV (roughly the current LEP I/II limit), a 2nd $L = 200$ fb$^{-1}$ run with full $L$ at $\sqrt{s} = \sqrt{s_{\text{opt}}}$ and upgrade to resolution I would yield $\sim \pm 24\%$ error vs. $\sim \pm 38\%$ after a 2nd $L = 200$ fb$^{-1}$ run with no changes. For $m_{h_{\text{SM}}} = 70$ GeV, running from the beginning for $L = 400$ fb$^{-1}$ at the $\sigma(Z h_{\text{SM}})$ peak (as possible at full luminosity if $m_{h_{\text{SM}}}$ is known from

**It is best to continue to run at $\sqrt{s} = 500$ GeV if the interaction region is not reconfigured for full luminosity at the lower $Z h_{\text{SM}}$-channel $\sqrt{s_{\text{opt}}}$.
LHC data) with resolution I yields error of $\sim \pm 19\%$.

In evaluating different options/strategies, it is necessary to keep in mind that LHC data may allow a rather competitive error for $B(h_{SM} \to \gamma\gamma)$ \[\Box\]. One combines the $L = 600 \text{ fb}^{-1}$ (for ATLAS and CMS combined) LHC measurement of $B(h_{SM} \to \gamma\gamma)/B(h_{SM} \to b\bar{b})$ with the $L = 200 \text{ fb}^{-1}$, $\sqrt{s} = 500 \text{ GeV}$ NLC measurement of $B(h_{SM} \to b\bar{b})$ to obtain a value for $B(h_{SM} \to \gamma\gamma)$ with error $\sim \pm 16\%$ for $80 \leq m_{h_{SM}} \leq 130 \text{ GeV}$, rising to $\sim \pm 25\%$ for $m_{h_{SM}} \sim 140 \text{ GeV}$. If we combine this $B(h_{SM} \to \gamma\gamma)$ error with the net error for the ($Z h_{SM}$ plus $WW$-fusion mode, $\sqrt{s} = 500 \text{ GeV}$, $L = 200 \text{ fb}^{-1}$, resolution II/III) direct $B(h_{SM} \to \gamma\gamma)$ measurement at the NLC, the overall error for $B(h_{SM} \to \gamma\gamma)$ will be:

| $m_{h_{SM}}$ (GeV) | 80  | 100 | 110 | 120 | 130 | 140 | 150 |
|-------------------|----|----|----|----|----|----|----|
| Error             | $\pm 15\%$ | $\pm 14\%$, $\pm 13\%$ | $\pm 13\%$ | $\pm 18\%$ | $\pm 13\%$ | $\pm 18\%$ | $\pm 35\%$ |

For most Higgs masses, there would be little to gain from excellent (case I) resolution. For example, at $m_{h_{SM}} \sim 120 \text{ GeV}$, the above $\sim \pm 13\%$ found assuming NLC resolution cases II/III would only improve to $\sim \pm 12\%$ for NLC resolution case I. For $m_{h_{SM}} \sim 80 \text{ GeV}$, the NLC $h_{SM} \to \gamma\gamma$ decay determination of $B(h_{SM} \to \gamma\gamma)$ will only be of value if $L = 400 \text{ fb}^{-1}$ with calorimeter resolution I can be accumulated by the time $L = 300 \text{ fb}^{-1}$ per detector is accumulated at the LHC. Finally, if determining $\Gamma_{h_{SM}}^{\text{tot}}$, and thence $\Gamma(h_{SM} \to b\bar{b})$, is the dominant motivation for measuring $B(h_{SM} \to \gamma\gamma)$, then it is important to note that for $m_{h_{SM}} \gtrsim 130 \text{ GeV}$ $\Gamma_{h_{SM}}^{\text{tot}}$ is better determined using the $h_{SM} \to WW^{*}$ techniques discussed in Ref. \[\Box\]. For such $m_{h_{SM}}$, this fact and the small gain in $B(h_{SM} \to \gamma\gamma)$ error (especially if LHC data is available) argue against considering a calorimeter upgrade.

V. ACKNOWLEDGEMENTS

This work was supported in part by Department of Energy under grant No. DE-FG03-91ER40674 and by the Davis Institute for High Energy Physics. We would like to thank T. Barklow, J. Brau, P. Rowson, R. Van Kooten and L. Poggioli for helpful communications.
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FIG. 1. The fractional error in the measurement of $\sigma(\nu_e\bar{\nu}_e h_{SM}) B(h_{SM} \rightarrow \gamma\gamma)$ (at $\sqrt{s} = 500$ GeV) and $\sigma(Z h_{SM}) B(h_{SM} \rightarrow \gamma\gamma)$ (at $\sqrt{s} = \sqrt{s}_{opt}$) as a function of $m_{h_{SM}}$ assuming $L = 200$ fb$^{-1}$. Also shown is the fractional $\sigma B(h_{SM} \rightarrow \gamma\gamma)$ error obtained by combining $Z h_{SM}$ and $\nu_e\bar{\nu}_e h_{SM}$ channels for $L = 200$ fb$^{-1}$ at $\sqrt{s} = 500$ GeV. Results for the four electromagnetic calorimeter resolutions described in the text are given.