Higgs branching ratio study for DBD detector benchmarking in ILC

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Precise measurement of Higgs boson branching ratios (BRs) is one of the key issues for the International Linear Collider (ILC) project to reveal a particles mass generation mechanism via Higgs and particles mass coupling relation. Even though the Higgs boson accurate measurement will be conducted at the center-of-mass (CM) energy of 250 GeV to adapt the 125 GeV of the mass of Higgs-like particle observed at the Large Hadron Collider (LHC) experiments [1, 2], ILC will also keep an extendability of CM energy up to 1 TeV to explore the new particles. In order to demonstrate the detector capability even at the 1 TeV, Higgs BRs measurement is also assigned as one of the detector benchmarking process for the Detailed Baseline Design (DBD) study. In this study, measurement accuracies of the product of the cross section and branching ratio into; two jet final state of h → b¯b, c¯c, and gluons; four jet final state of h → WW∗ → 4j, are evaluated with a full detector simulation adopting the International Large Detector (ILD) [3].

Keywords: ILC, Higgs boson, Branching ratio

I. INTRODUCTION

Higgs boson branching ratio measurement at the CM energy of 1 TeV in ILC project is one of the detector performance benchmarking processes listed in Detailed Baseline Design document (DBD) to demonstrate the detectors performance capability at higher energy.

![Higgs production process via (a) Higgs-strahlung (e+e− → Zh) and (b) WW-fusion (e+e− → ννh)](a) (b)

FIG. 1: Higgs production process via (a) Higgs-strahlung (e+e− → Zh) and (b) WW-fusion (e+e− → ννh)

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At the CM energy below 500 GeV, Higgs boson mainly produced via Higgs-strahlung process: $e^+e^- \rightarrow Zh$ (Fig. 1 (a)) assuming a Higgs mass of 125 GeV and largest Higgs production cross section is obtained around the Zh production threshold of 250 GeV, as shown in Fig. 2. On the other hand, at the CM energy above 500 GeV, Higgs boson is mainly produced via WW-fusion process: $e^+e^- \rightarrow \nu_e\bar{\nu}_e h$ (Fig. 1 (b)) and much larger production cross section is obtained around the CM energy of 1 TeV than 250 GeV as shown in Fig. 2 (a) with assuming the P(e$^-$, e$^+$) = P(−0.8, +0.2) left-handed beam polarization. Higgs production cross section assuming the right-handed beam polarization of P(+0.8, −0.2) is also shown in Fig. 2 (b) and $\nu_e\bar{\nu}_e h$ production via WW-fusion process is suppressed at $\sqrt{s} = 1$ TeV.

![Higgs production cross sections](image)

**FIG. 2:** Higgs production cross sections as a function of CM energies at the Higgs mass of 125 GeV with (a) P(e$^-$, e$^+$) = P(−0.8, +0.2) left-handed and (b) P(+0.8, −0.2) right-handed beam polarizations.

In DBD benchmarking study, Standard Model (SM) Higgs BRs [3] are used to generate Higgs signal samples and Higgs BRs at different Higgs masses are shown in Fig. 3. Taking into account of the observation of Higgs-like particle in LHC experiments [1, 2], Higgs mass is selected as 125 GeV. From the Fig. 3, Higgs BRs measurement at the Higgs mass around 125 GeV is very suitable for accessing to the most of Higgs decay channels into both Fermions and Bosons. Higgs BRs at the Higgs mass of 125 GeV are summarized in Table I and Higgs mainly decays into $b\bar{b}$.
Higgs mass (GeV)

<table>
<thead>
<tr>
<th>Branching ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^2$</td>
</tr>
<tr>
<td>$10^1$</td>
</tr>
<tr>
<td>$10^0$</td>
</tr>
<tr>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

FIG. 3: SM Higgs BRs as a function of Higgs mass referred from [3].

TABLE I: Higgs BRs for each particle at the Higgs mass of 125 GeV.

<table>
<thead>
<tr>
<th>Higgs decay channels</th>
<th>bb</th>
<th>c$\bar{c}$</th>
<th>gg</th>
<th>WW$^*$</th>
<th>$\mu^+\mu^-$</th>
<th>$\tau^+\tau^-$</th>
<th>ZZ$^*$</th>
<th>$\gamma\gamma$</th>
<th>$Z\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs BRs</td>
<td>57.8%</td>
<td>2.7%</td>
<td>8.6%</td>
<td>21.6%</td>
<td>0.02%</td>
<td>6.4%</td>
<td>2.7%</td>
<td>0.23%</td>
<td>0.16%</td>
</tr>
</tbody>
</table>

II. SIMULATION AND RECONSTRUCTION TOOLS

A. ILD standard samples for DBD

In the detector benchmarking study for ILD DBD, standard Higgs signals (fzf) selecting its mass of 125 GeV and SM background samples were centrally generated employing whizard 1.95 [5]. All the generated standard signal and background samples are summarized in Table II.

From the Table II, Higgs is mainly produced via WW-fusion process thus large missing energy and transverse momentum is in final state forming multi-jets. Taking into account of this final state, $e\nu W$ and $\nu\nu Z$, WW/ZZ final state from $e^+e^- \rightarrow 4f$ channels are supposed to be major background, which makes mass peak around Z and closed to the Higgs mass peak. $e\gamma \rightarrow \nu qq$ from $e\gamma \rightarrow 3f$ channel also considered as major background, since electrons or photons escapes to the beam pipe, invisible particles contribute as missing energy. Two photon backgrounds of $\gamma\gamma \rightarrow \nu\nu qq$ are also considered as similar final state of signal channel.

Simulation and reconstruction were performed employing latest ilcsoft v01-16-p03 [5]. Gen-
TABLE II: Production cross sections and expected number of events of Higgs and supposed SM back-
grounds in this study assuming the integrated luminosity of 500 fb\(^{-1}\) for each beam polarization \(P(e^-, e^+) = P(\mp 0.8, \pm 0.2)\).

<table>
<thead>
<tr>
<th>Processes</th>
<th>(\sigma(-0.8, +0.2)) (fb)</th>
<th>(\sigma(+0.8, -0.2)) (fb)</th>
<th>(N(-0.8, +0.2))</th>
<th>(N(+0.8, -0.2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu\bar{\nu}h)</td>
<td>404</td>
<td>33</td>
<td>202,022</td>
<td>16,549</td>
</tr>
<tr>
<td>(q\bar{q}h)</td>
<td>18</td>
<td>12</td>
<td>8,885</td>
<td>6,058</td>
</tr>
<tr>
<td>(f\bar{f}h)</td>
<td>25</td>
<td>16</td>
<td>12,501</td>
<td>8,089</td>
</tr>
<tr>
<td>(ffh)</td>
<td>447</td>
<td>61</td>
<td>223,408</td>
<td>30,697</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Processes</th>
<th>SM backgrounds ((\sqrt{s} = 1) TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e^+e^- \to 2f)</td>
<td>7,780</td>
</tr>
<tr>
<td>(e^+e^- \to 4f)</td>
<td>27,028</td>
</tr>
<tr>
<td>(e^+e^- \to 6f)</td>
<td>693</td>
</tr>
<tr>
<td>(e\gamma \to 3f)</td>
<td>460,783</td>
</tr>
<tr>
<td>(e\gamma \to 5f)</td>
<td>1,370</td>
</tr>
<tr>
<td>(\gamma\gamma \to 4f)</td>
<td>3,137</td>
</tr>
</tbody>
</table>

Generated signals were passed through the detector simulation in Mokka \[4\] employing the latest ILD de-
tector model of ILD.o1.v05. Simulated hits were digitized and reconstructed in the MarlinReco \[8\].

III. SGV fast simulation

Due to the time limitation of the full detector simulation and reconstruction, several background
samples are separately simulated using SGV fast simulator \[9\], which can reproduce the Mokka
detector simulation well. Higgs signal and \(e^+e^- \to 2f\), \(4f\), \(6f\) channels are fully simulated and
reconstructed by full simulation but other \(e\gamma \to 3f\), \(5f\), and \(\gamma\gamma \to 4f\) are simulated with SGV
fast simulator. In this study, ILD standard generated and reconstructed samples are used. At
the analysis stage, each sample is scaled to be the integrated luminosity of 500 fb\(^{-1}\) or 1 ab\(^{-1}\)
and generated 100% polarized samples are mixed with appropriate factors to obtain the expected
\(P(e^-, e^+) = P(\mp 0.8, \pm 0.2)\) polarized beam condition.
A. Beam related $\gamma\gamma \rightarrow$ hadron background

At the CM energy of 1 TeV, beam induced backgrounds are not negligible even in the lepton collider and 4.1 events of $\gamma\gamma \rightarrow$ hadron backgrounds are estimated per one bunch crossing. For each simulated sample, $\gamma\gamma \rightarrow$ hadron backgrounds are overlaid on the simulated hits. But note that current reconstructed samples using SGV are not overlaid $\gamma\gamma$ backgrounds, but same $k_t$ algorithm is applied at the reconstruction stage. To treat these beam related backgrounds, $k_t$ jet clustering algorithm implemented in FastJet package is employed, which is commonly used for the hadron collider experiment to treat the beam related backgrounds.

In exclusive $k_t$ jet algorithm, beam induced particles are combined as beam jet ($J_{\text{beam}}$) and not used as clustered jets \[11\]. After applying the $k_t$ jet clustering, beam related PFOs mainly distributed at the forward region are well subtracted as shown in Fig. 4 (a) and exceeded visible particles are suppressed shown in Fig 4 (b).

In $k_t$ jet algorithm, following distance between particle $i$ and $j$ are calculated:

$$d_{ij} = \min\left(E_{ti}^2, E_{tj}^2\right) \cdot \frac{\Delta R_{ij}^2}{R^2}$$

\[1\]

where $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and $E_{ti}$, $y_{ij}$, and $\phi_{ij}$ are a transverse momentum, rapidity, and azimuthal angle of $i$ th particle and $R$ is a jet-radius parameter. If $d_{ij}$ is closed to the beam axis $d_{\text{beam}}$, these particles are merged as beam jet and these particles are treated as not related to any jets and removed. After removing $\gamma\gamma \rightarrow$ hadron backgrounds using $k_t$ algorithm, flavor tagging

![FIG. 4: $\gamma\gamma \rightarrow$ hadron background removal employing $k_t$ jet algorithm on (a) cos $\theta$ of PFOs and (b) invariant mass distribution in $\nu\bar{\nu}h$ channel with or without background overlay.](image-url)
is performed for all the clustered particles employing LCFIPlus \cite{12} implemented in MarlinReco package, which was coded in C++ and replaced from the previous LCFIVertex \cite{13} implemented in FORTRAN. Neuralnet output for b and c quarks; Btag, Ctag, and their combination of BCtag (=Ctag/(Btag+Ctag)) from LCFIPlus, are used as input of flavor templates.

\[ x - \text{likeness} = \frac{x_1 x_2}{x_1 x_2 + (1 - x_1)(1 - x_2)} \ (x = b, \ c, \ bc), \]  

where \( x_{1/2} \) is a neuralnet output of Btag, Ctag, and BCtag from LCFIPlus.

\section*{IV. \( h \rightarrow b \overline{b}, \ c \overline{c}, \ gg \) CHANNEL ANALYSIS}

\subsection*{A. Reconstruction and background reduction at \( \sqrt{s} = 1 \text{ TeV} \)}

For the \( h \rightarrow b \overline{b}, \ c \overline{c}, \) and \( gg \) channel analysis at the CM energy of 1 TeV, \( \gamma \gamma \rightarrow \) hadrons background should be considered. At first forced two jet clustering is applied employing exclusive \( k_t \) algorithm selecting \( R = 1.1. \)

![Graph showing reconstructed Higgs mass distribution](image)

\textbf{FIG. 5:} Reconstructed Higgs mass distribution employing \( k_t \) jet clustering algorithm with different \( R \) parameters for \( h \rightarrow b \overline{b}, \ c \overline{c}, \ gg \) selected by MC information.

After applying \( k_t \) jet clustering, LCFIPlus flavor tagging is applied for the particles clustered into jets and reclustered with jet clustering algorithm implemented in the LCFIPlus based on the Durham jet clustering algorithm \cite{14}. After the reconstruction procedure, event selection and background reduction is performed for each cut condition, summarized on the Table \textbf{III}.  

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TABLE III: Cut flow summary of $h \rightarrow b\bar{b}$, $c\bar{c}$, $gg$ channel analysis.

| 1. Visible energy on beam calorimeter | $E_{BCAL} < 50$ GeV |
| 2. Thrust value                      | Thrust $< 0.95$     |
| 3. Visible energy                    | $100 < E_{vis} < 400$ GeV |
| 4. Transverse visible momentum       | $P_{T} > 50$ GeV     |
| 5. Number of charged particle flow object | $N_{ChdPFO} > 15$ |
| 6. Azimuthal angle of Higgs flight direction | $|\cos \theta_h| < 0.95$ |
| 7. Reconstructed dijet mass          | $110 < M_{jj} < 150$ GeV |

In order to identify the electrons or photons going into beam pipe direction from $e\gamma$ or $\gamma\gamma$ process, energy on the beam calorimeter ($E_{BCAL}$) is used to eliminate the two photon backgrounds event. Further reduction of huge $e\gamma$ processes is efficiently obtained by cut on the thrust variable defined as:

$$\text{Thrust } T = \max_n \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|},$$

where $\vec{p}_i$ is a momentum of i-th particle and $\vec{n}$ is an unit vector of the thrust axis which maximize the thrust value $T$.

Since $\nu\bar{\nu}h$ final state has large missing energy and transverse momentum, cuts on the visible energy ($E_{vis}$) and visible transverse momentum ($P_{T}$) are applied to suppress fully hadronic decay and low $P_{T}$ channels. Cuts on the number of charged particle flow objects ($N_{ChdPFO}$) and azimuthal angle of the flight direction of reconstructed Higgs ($\cos \theta_h$) are required to suppress the leptonic decay channels or particles going into forward region. Finally Higgs signals are selected with its mass range between 110 to 150 GeV. All the cut variables and cut conditions are shown in Fig. 6.

After passing all the selections, selection efficiencies are obtained as 35.0% ($h \rightarrow b\bar{b}$), 37.3% ($h \rightarrow c\bar{c}$), and 35.9% ($h \rightarrow gg$), respectively. An example of reconstructed Higgs mass distribution requiring additional b-likeness cut ($b$-likeness $> 0.6$) to select $h \rightarrow b\bar{b}$ is shown in Fig. 7.

According to the Fig. 7, most of backgrounds are significantly eliminated by b-tagging.

In the DBD detector benchmarking study, both left- and right-handed $P(\pm 0.8, \pm 0.2)$ polarized beam runs are expected accumulating the integrated luminosity of same 500fb$^{-1}$ with each polarization. From the Fig. 2 (b), even though main signal production process is significantly reduced, but WW-fusion production process is still achieved the largest cross section at 1 TeV with respect to the $P(\pm 0.8, \pm 0.2)$ beam polarization. Hence same cut conditions are adopted even for right-handed polarization to select WW-fusion production process. Background reduction on right-handed polarization are summarized in Table VII.
FIG. 6: Cut variables for $h \to 2j$ channel reconstruction with integrated luminosity of 500 fb$^{-1}$ regarding $P(-0.8, +0.2)$ left-handed beam polarization.

### B. Template fitting and accuracies of $\sigma\text{BR}$

In order to evaluate the $\sigma\text{BR}$ with separating $h \to b\bar{b}$, $c\bar{c}$, and $gg$, we apply the flavor template fitting to employ the flavor-likeness template calculated as Eq. 2.

After the all above selections, signal flavor templates of $h \to b\bar{b}$, $c\bar{c}$, and $gg$ and background template of the all other Higgs decay channels and SM background are prepared. In order to
TABLE IV: Summary table of cut flow for $h \rightarrow b\bar{b}$, $c\bar{c}$, and $gg$ channel at $\sqrt{s} = 1$ TeV with $L = 500$ fb$^{-1}$ regarding $P(e^{-}, e^{+}) = P(-0.8, +0.2)$ polarization. Note that 3f, 5f, $\gamma \gamma \rightarrow 4f$ channels contributions were simulated and estimated using SGV fast simulation sample.

<table>
<thead>
<tr>
<th>Cut flow</th>
<th>Signals</th>
<th>Higgs other decays</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$h \rightarrow b\bar{b}$</td>
<td>$h \rightarrow c\bar{c}$</td>
</tr>
<tr>
<td>No cut</td>
<td>128,700</td>
<td>6,058</td>
</tr>
<tr>
<td>1. $E_{BCAL}$</td>
<td>125,021</td>
<td>5,875</td>
</tr>
<tr>
<td>2. Thrust</td>
<td>104,305</td>
<td>4,910</td>
</tr>
<tr>
<td>3. $E_{vis}$</td>
<td>96,807</td>
<td>4,572</td>
</tr>
<tr>
<td>4. $P_T$</td>
<td>74,849</td>
<td>3,577</td>
</tr>
<tr>
<td>5. $N_{ChdPFO}$</td>
<td>70,005</td>
<td>3,152</td>
</tr>
<tr>
<td>6. $</td>
<td>\cos \theta_h</td>
<td>$</td>
</tr>
<tr>
<td>7. $M_{jj}$</td>
<td>44,988</td>
<td>2,258</td>
</tr>
<tr>
<td>Efficiency</td>
<td>35.0%</td>
<td>37.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SM backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuts</td>
</tr>
<tr>
<td>No cut</td>
</tr>
<tr>
<td>1. $E_{BCAL}$</td>
</tr>
<tr>
<td>2. Thrust</td>
</tr>
<tr>
<td>3. $E_{vis}$</td>
</tr>
<tr>
<td>4. $P_T$</td>
</tr>
<tr>
<td>5. $N_{ChdPFO}$</td>
</tr>
<tr>
<td>6. $</td>
</tr>
<tr>
<td>7. $M_{jj}$</td>
</tr>
<tr>
<td>Efficiency</td>
</tr>
</tbody>
</table>

estimate the measurement accuracy of $\sigma BR(h \rightarrow s)$ ($s = b\bar{b}$, $c\bar{c}$, $gg$),

$$\sigma BR(s) = r_s \times \sigma BR^{SM}(s)$$  

where $\sigma BR(s)$ and $\sigma BR^{SM}(s)$ are observed and expected products of cross section and branching ratio and $r_s$ is a fluctuation from the SM prediction. From the Eq. 3, the measurement accuracy of $\sigma BR(s)$ is estimated as

$$\frac{\Delta \sigma BR(h \rightarrow s)}{\sigma BR} = \frac{\Delta r_s}{r_s}.$$  

Relative uncertainties of the $r_s$ are estimated with the binned log-likelihood fitting for flavor
templates. Assuming the Poisson statistics, probability of entry in each bin is determined as:

$$P_{ijk} = \frac{\mu^n e^{-\mu}}{n!},$$

(5)

where \( n \equiv N_{ij}^{\text{data}} \) is a expected number of data entries in \((i,j,k)\) bin, and \( \mu \) represents the sum of each template sample entries at \((i,j,k)\) bin, which is defined as \( N_{ijk}^{\text{template}} \):

$$N_{ijk}^{\text{template}} = \sum_{s=bb, cc, gg} r_s \cdot N_{ijk}^s + N_{ijk}^{\text{bkg}},$$

(6)

where \( N_{ijk}^s \) is a number of entries in each template bin predicted in SM and \( N_{ijk}^{\text{bkg}} \) is a sum of entries from \( h \rightarrow \text{others} \) and SM backgrounds in \((i,j,k)\) bin. Two dimensional images of the three dimensional \( b-\), \( c-\), and \( bc-\) flavor-likeness template samples for \( h \rightarrow b\bar{b}, c\bar{c}, gg, \) others, and SM backgrounds are shown in Fig. 8.

The uncertainty of the \( r_s \) is evaluated by the 5,000 times of Toy-MC with log-likelihood fitting by fluctuating the Data samples assuming the Poisson statistics in each bin. After applying template fitting, accuracies of \( \sigma BR \) are extracted from the Gaussian fitting for parameter \( r_s \).

Fitted results and extracted accuracies of \( \sigma BRs \) assuming the integrated luminosity of \( L = 500 \, \text{fb}^{-1} \) with both beam polarization \( P(e^-, e^+) = P(\mp 0.8, \pm 0.2) \) are summarized on the Table VII.

Concerning the precision measurement of the Higgs boson \( \sigma BRs \), left-handed beam polarization \( P(-0.8, +0.2) \) with accumulating the integrated luminosity of \( L = 1 \, \text{ab}^{-1} \) is also evaluated on the same table. Note that these results are only considered the statistical uncertainty of \( \sigma BR \).
TABLE V: Summary table of background reduction for $h \to bb$, $c\bar{c}$, and $gg$ at $\sqrt{s} = 1$ TeV with $\mathcal{L} = 500$ fb$^{-1}$ and $P(e^-, e^+) = P(+0.8, -0.2)$ right-handed beam polarization. Note that $3f, 5f, \gamma\gamma \to 4f$ channels contributions were simulated and estimated using SGV fast simulation sample.

<table>
<thead>
<tr>
<th>Cut flow</th>
<th>Signal $h \to bb$</th>
<th>$h \to c\bar{c}$</th>
<th>$h \to gg$</th>
<th>Other Higgs decays $h \to WW^*$</th>
<th>$h \to ZZ^*$</th>
<th>$h \to \tau\tau$</th>
<th>$h \to s\bar{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>17,768</td>
<td>812</td>
<td>2,566</td>
<td>6,592</td>
<td>830</td>
<td>1,992</td>
<td>10</td>
</tr>
<tr>
<td>1. E$_{BCAL}$</td>
<td>17,054</td>
<td>783</td>
<td>2,463</td>
<td>6,331</td>
<td>794</td>
<td>1,917</td>
<td>9</td>
</tr>
<tr>
<td>2. Thrust</td>
<td>10,999</td>
<td>512</td>
<td>1,628</td>
<td>3,743</td>
<td>457</td>
<td>1,068</td>
<td>7</td>
</tr>
<tr>
<td>3. E$_{vis}$</td>
<td>8,049</td>
<td>366</td>
<td>1,152</td>
<td>2,230</td>
<td>282</td>
<td>567</td>
<td>6</td>
</tr>
<tr>
<td>4. $P_T$</td>
<td>6,045</td>
<td>284</td>
<td>898</td>
<td>1,722</td>
<td>211</td>
<td>377</td>
<td>5</td>
</tr>
<tr>
<td>5. $N_{ChdPFO}$</td>
<td>5,608</td>
<td>248</td>
<td>882</td>
<td>1,328</td>
<td>171</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>6. $</td>
<td>\cos \theta_h</td>
<td>$</td>
<td>5,171</td>
<td>224</td>
<td>815</td>
<td>1,262</td>
<td>157</td>
</tr>
<tr>
<td>7. $M_{jj}$</td>
<td>3,542</td>
<td>172</td>
<td>537</td>
<td>354</td>
<td>56</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Efficiency</td>
<td>19.9%</td>
<td>21.2%</td>
<td>20.9%</td>
<td>5.4%</td>
<td>6.7%</td>
<td>0.2%</td>
<td>29.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cut flow</th>
<th>SM backgrounds $3f$</th>
<th>$5f$</th>
<th>$\gamma\gamma \to 4f$</th>
<th>$2f$</th>
<th>$4f$</th>
<th>$6f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>205,529,000</td>
<td>415,380</td>
<td>1,538,560</td>
<td>2,699,560</td>
<td>6,530,160</td>
<td>119,252</td>
</tr>
<tr>
<td>1. E$_{BCAL}$</td>
<td>92,815,300</td>
<td>310,618</td>
<td>1,374,030</td>
<td>2,288,410</td>
<td>2,288,410</td>
<td>103,473</td>
</tr>
<tr>
<td>2. Thrust</td>
<td>28,610,000</td>
<td>206,465</td>
<td>971,486</td>
<td>401,722</td>
<td>606,529</td>
<td>67,684</td>
</tr>
<tr>
<td>3. E$_{vis}$</td>
<td>4,870,840</td>
<td>131,761</td>
<td>662,748</td>
<td>135,701</td>
<td>252,878</td>
<td>17,727</td>
</tr>
<tr>
<td>4. $P_T$</td>
<td>1,947,590</td>
<td>60,325</td>
<td>225,666</td>
<td>8,963</td>
<td>130,966</td>
<td>12,774</td>
</tr>
<tr>
<td>5. $N_{ChdPFO}$</td>
<td>1,095,980</td>
<td>28,418</td>
<td>106,017</td>
<td>2,634</td>
<td>74,999</td>
<td>10,265</td>
</tr>
<tr>
<td>6. $</td>
<td>\cos \theta_h</td>
<td>$</td>
<td>1,060,520</td>
<td>23,195</td>
<td>94,914</td>
<td>1,497</td>
</tr>
<tr>
<td>7. $M_{jj}$</td>
<td>15,749</td>
<td>4,417</td>
<td>18,486</td>
<td>144</td>
<td>3,493</td>
<td>1,575</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$7.7 \times 10^{-5}$</td>
<td>$1.1 \times 10^{-2}$</td>
<td>$1.2 \times 10^{-2}$</td>
<td>$5.3 \times 10^{-5}$</td>
<td>$5.3 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

V. $h \to WW^*$ CHANNEL ANALYSIS

In the $h \to WW^*$ analysis, high energetic neutrinos are generated via the production process of $\nu\bar{\nu}h$, therefore $h \to WW^*$ fully hadronic decay channel ($h \to WW^* \rightarrow q\bar{q}q\bar{q}$) is analyzed with reconstructing four jet final state.

In order to suppress the $\gamma\gamma \rightarrow$ hadron backgrounds, exclusive four jet clustering with $k_t$ algorithm is applied for selecting $R = 0.9$. Owing to this algorithm, beam related backgrounds are well removed, then LCFIPlus flavor tagging is applied for all the reconstructed particles and re-clustered as four jets forcibly by Durham [11] base jet clustering in the LCFIPlus package.
FIG. 8: 2D image of the 3D flavor template samples for Data, h → b\bar{b}, c\bar{c}, gg, others, and SM BGs.

TABLE VI: Estimated measurement accuracies of \( \sigma BR \) for h → b\bar{b}, c\bar{c}, and gg channels at \( \sqrt{s} = 1 \) TeV with respect to the \( \mathcal{L} = 500 \) fb\(^{-1} \) for both \( P(e^-, e^+) = (\mp 0.8, \pm 0.2) \) beam polarizations or accumulating \( \mathcal{L} = 1 \) ab\(^{-1} \) regarding \( P(-0.8, +0.2) \) left-handed polarization. Here these results are taken only statistical uncertainties into account.

<table>
<thead>
<tr>
<th>Integrated luminosity</th>
<th>( 500 ) fb(^{-1} )</th>
<th>( 500 ) fb(^{-1} )</th>
<th>( 1 ) ab(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam polarization ( P(e^-, e^+) )</td>
<td>( P(-0.8, +0.2) )</td>
<td>( P(+0.8, -0.2) )</td>
<td>( P(-0.8, +0.2) )</td>
</tr>
<tr>
<td>( r_{bb} )</td>
<td>1.000±0.005</td>
<td>0.999±0.021</td>
<td>1.000±0.004</td>
</tr>
<tr>
<td>( r_{cc} )</td>
<td>1.002±0.057</td>
<td>1.034±0.380</td>
<td>1.001±0.039</td>
</tr>
<tr>
<td>( r_{gg} )</td>
<td>0.998±0.039</td>
<td>1.025±0.263</td>
<td>0.998±0.028</td>
</tr>
<tr>
<td>( \Delta \sigma BR / \sigma BR(h \rightarrow bb) )</td>
<td>0.54%</td>
<td>2.1%</td>
<td>0.39%</td>
</tr>
<tr>
<td>( \Delta \sigma BR / \sigma BR(h \rightarrow cc) )</td>
<td>5.7%</td>
<td>36.8%</td>
<td>3.9%</td>
</tr>
<tr>
<td>( \Delta \sigma BR / \sigma BR(h \rightarrow gg) )</td>
<td>3.9%</td>
<td>25.7%</td>
<td>2.8%</td>
</tr>
</tbody>
</table>

FIG. 9: Four jet reconstruction employing \( k_t \) algorithm with different \( R \) parameters.
At the Higgs mass of 125 GeV, one W should be off-shell and only one W has mass close to the W mass ($M_W$). The best jet pair combination is selected as closest dijet mass as $M_{WW}$, which has minimum mass difference of $|M_{jj} - M_W|$. Selected W candidate is defined as $W_1$ and remaining dijet is described as $W_2$, where they are mostly contributed from on-shell and off-shell W, respectively. After the jet clustering and pairing, following cuts are applied to suppress SM backgrounds and other Higgs decay channel contributions.

**TABLE VII: Cut summary of $h \rightarrow WW^{*}$ channel analysis.**

| 1. Visible energy on beam calorimeter | $E_{BCAL} < 50$ GeV |
| 2. Thrust | Thrust $< 0.95$ |
| 3. Visible energy | $100 < E_{vis} < 400$ GeV |
| 4. Visible transverse momentum | $P_T > 50$ GeV |
| 5. Total number of charged particle flow object | $N_{ChargedPFO} > 25$ |
| 6. Azimuthal angle of each jet | $|\cos \theta| < 0.90$ |
| 7. $Y_{34}$ value | $-\log_{10}(Y_{34}) < 3.0$ |
| 8. $Y_{23}$ value | $-\log_{10}(Y_{23}) < 2.2$ |
| 9. Sum of B-tagging output for four jets | $Btag_{4j} < 0.8$ |
| 10. $W_1$ mass (Closest to $M_W$) | $60 < M_{W_1} < 95$ GeV |
| 11. $W_2$ mass (Remaining dijet mass) | $15 < M_{W_2} < 60$ GeV |
| 12. Higgs mass | $110 < M_h < 140$ GeV |

First requiring energetic jets final state to suppress semi-leptonic decay channels in 2f and 4f ($WW, ZZ$) requiring large visible energy and transverse momentum. In addition, cut on $N_{PFO}$ and $N_j$ are required to suppress the leptonic and semileptonic decay channel from $WW \rightarrow \ell\nu qq$. Cuts on the threshold value of jet clustering $Y$ value used in the Durham jet algorithm from $i$ to $j=i+1$ jets ($-\log_{10}(Y_{ij})$) are applied to reduce non-four jets like events. In order to suppress the other Higgs decay channels contribution, mostly comes from the $h \rightarrow b\bar{b}$ by largest fraction of the Higgs decay; sum of Btag output for four jets is required ($Btag_{4j} < 0.8$). After applying b-tagging cut, remaining contribution from other Higgs decay channel is mainly coming from $h \rightarrow gg$.

Reconstructed Higgs mass distribution regarding $h \rightarrow WW^{*}$ hadronic decay channel is shown in Fig. 11. $P(+0.8, -0.2)$ right-handed beam polarization running with the same integrated luminosity of 500 fb$^{-1}$ is also estimated. According to the right-handed electron beam polarization, production process via $WW - fusion$ contributed by the $t$-channel diagram is suppressed, hence both main signal production channel $e_\mu e_\mu h$ and $WW$ background productions are reduced.

Therefore, same cut flow is applied as left-handed polarization case which optimized for $WW$-
After passing all the selections, signal significance $S/\sqrt{S+B}$, where $S$ is a number of selected signal samples and $B$ is a total number of background samples; is obtained from the final selected samples as 27.9 with $P(-0.8, 0.2)$ left-handed and 4.2 with $P(+0.8, -0.2)$ right-handed beam polarizations assuming the same integrated luminosity of $L = 500$ fb$^{-1}$.

As a result, $\Delta BR/\sigma BR(h \rightarrow WW^*)$ is estimated as 3.6% with $P(-0.8, +0.2)$ and 23.7% with $P(+0.8, -0.2)$ polarizations. Assuming further statistics of 1 ab$^{-1}$ only running with $P(-0.8, +0.2)$ left-handed polarization, measurement accuracy is expected to be improved as 2.5%. Note that
TABLE VIII: Summary table of background reduction on $h \rightarrow WW^* \rightarrow 4j$ channel assuming $\mathcal{L} = 500 \text{ fb}^{-1}$ with respect to the $\mathcal{P}(-0.8, +0.2)$ left-handed beam polarization at $\sqrt{s} = 1 \text{ TeV}$. Note that 3f, 5f, $\gamma\gamma \rightarrow 4f$ channels contributions were simulated and estimated using SGV fast simulation sample.

<table>
<thead>
<tr>
<th>Cut flow</th>
<th>Signal $h \rightarrow WW^* \rightarrow 4j$</th>
<th>Other Higgs decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>21,976</td>
<td>128,700</td>
</tr>
<tr>
<td>1. $E_{\text{BCAL}}$</td>
<td>21,348</td>
<td>124,986</td>
</tr>
<tr>
<td>2. Thrust</td>
<td>19,256</td>
<td>109,860</td>
</tr>
<tr>
<td>3. $E_{\text{vis}}$</td>
<td>14,534</td>
<td>82,950</td>
</tr>
<tr>
<td>4. $P_T$</td>
<td>12,185</td>
<td>67,792</td>
</tr>
<tr>
<td>5. $N_{\text{ChdPFO}}$</td>
<td>8,992</td>
<td>8,992</td>
</tr>
<tr>
<td>6. $</td>
<td>\cos \theta_j</td>
<td>$</td>
</tr>
<tr>
<td>7. Btag$_{4j}$</td>
<td>5,027</td>
<td>651</td>
</tr>
<tr>
<td>8. $-\log Y_{34}$</td>
<td>4,363</td>
<td>304</td>
</tr>
<tr>
<td>9. $-\log Y_{23}$</td>
<td>3,792</td>
<td>215</td>
</tr>
<tr>
<td>10. $M_{W1}$</td>
<td>3,177</td>
<td>162</td>
</tr>
<tr>
<td>11. $M_{W2}$</td>
<td>3,025</td>
<td>140</td>
</tr>
<tr>
<td>12. $M_h$</td>
<td>2,732</td>
<td>118</td>
</tr>
<tr>
<td>Efficiency</td>
<td>12.4%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cut flow</th>
<th>SM backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>223,628,000</td>
</tr>
<tr>
<td>1. $E_{\text{BCAL}}$</td>
<td>72,750,600</td>
</tr>
<tr>
<td>2. Thrust</td>
<td>23,633,100</td>
</tr>
<tr>
<td>3. $E_{\text{vis}}$</td>
<td>4,967,370</td>
</tr>
<tr>
<td>4. $P_T$</td>
<td>2,750,240</td>
</tr>
<tr>
<td>5. $N_{\text{ChdPFO}}$</td>
<td>289,052</td>
</tr>
<tr>
<td>6. $</td>
<td>\cos \theta_j</td>
</tr>
<tr>
<td>7. Btag$_{4j}$</td>
<td>168,176</td>
</tr>
<tr>
<td>8. $-\log Y_{34}$</td>
<td>89,374</td>
</tr>
<tr>
<td>9. $-\log Y_{23}$</td>
<td>51,723</td>
</tr>
<tr>
<td>10. $M_{W1}$</td>
<td>8,879</td>
</tr>
<tr>
<td>11. $M_{W2}$</td>
<td>6,064</td>
</tr>
<tr>
<td>12. $M_h$</td>
<td>2,568</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$1.1 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
TABLE IX: Summary table of background reduction in $h \to WW^* \to 4j$ channel assuming $\mathcal{L} = 500$ fb$^{-1}$ with respect to the $P(+0.8, -0.2)$ right-handed beam polarization at $\sqrt{s} = 1$ TeV. Note that 3f, 5f, $\gamma\gamma \to 4f$ channels contributions were simulated and estimated using SGV fast simulation sample.

<table>
<thead>
<tr>
<th>Cut values</th>
<th>Signal $h \to WW^* \to 4j$</th>
<th>Other Higgs decays $h \to bb$</th>
<th>$h \to cc$</th>
<th>$h \to gg$</th>
<th>$h \to ZZ^*$</th>
<th>$h \to \tau\tau$</th>
<th>$h \to ss$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>2,972</td>
<td>17,768</td>
<td>812</td>
<td>2,566</td>
<td>830</td>
<td>1,992</td>
<td>10</td>
</tr>
<tr>
<td>1. $E_{BCAL}$</td>
<td>2,870</td>
<td>17,048</td>
<td>782</td>
<td>2,463</td>
<td>794</td>
<td>1,906</td>
<td>9</td>
</tr>
<tr>
<td>2. Thrust</td>
<td>2,055</td>
<td>12,071</td>
<td>559</td>
<td>1,824</td>
<td>527</td>
<td>1,259</td>
<td>7</td>
</tr>
<tr>
<td>3. $E_{vis}$</td>
<td>1,126</td>
<td>6,456</td>
<td>315</td>
<td>981</td>
<td>242</td>
<td>430</td>
<td>5</td>
</tr>
<tr>
<td>4. $P_T$</td>
<td>928</td>
<td>5,218</td>
<td>255</td>
<td>811</td>
<td>191</td>
<td>302</td>
<td>5</td>
</tr>
<tr>
<td>5. $N_{ChdPFO}$</td>
<td>683</td>
<td>2,921</td>
<td>116</td>
<td>698</td>
<td>109</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>6. $</td>
<td>\cos \theta_j</td>
<td>$</td>
<td>405</td>
<td>1,589</td>
<td>67</td>
<td>411</td>
<td>64</td>
</tr>
<tr>
<td>7. Btag$4j$</td>
<td>381</td>
<td>48</td>
<td>58</td>
<td>382</td>
<td>39</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>8. $-\log Y_{34}$</td>
<td>327</td>
<td>22</td>
<td>21</td>
<td>221</td>
<td>32</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>9. $-\log Y_{23}$</td>
<td>284</td>
<td>16</td>
<td>15</td>
<td>155</td>
<td>27</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>10. $M_{W_1}$</td>
<td>237</td>
<td>12</td>
<td>12</td>
<td>128</td>
<td>22</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>11. $M_{W_2}$</td>
<td>212</td>
<td>10</td>
<td>10</td>
<td>107</td>
<td>19</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>12. $M_h$</td>
<td>193</td>
<td>8</td>
<td>9</td>
<td>95</td>
<td>17</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Efficiency</td>
<td>6.5%</td>
<td>0.0%</td>
<td>1.1%</td>
<td>3.7%</td>
<td>2.1%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

SM backgrounds

<table>
<thead>
<tr>
<th>Cut values</th>
<th>3f</th>
<th>5f</th>
<th>$\gamma\gamma \to 4f$</th>
<th>2f</th>
<th>4f</th>
<th>6f</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>205,530,000</td>
<td>415,380,000</td>
<td>1,538,560,000</td>
<td>2,699,560,000</td>
<td>6,530,160,000</td>
<td>119,252,000</td>
</tr>
<tr>
<td>1. $E_{BCAL}$</td>
<td>60,587,000</td>
<td>301,833,000</td>
<td>1,284,930,000</td>
<td>2,282,960,000</td>
<td>2,286,424,000</td>
<td>103,093,000</td>
</tr>
<tr>
<td>2. Thrust</td>
<td>15,111,000</td>
<td>249,963,000</td>
<td>1,102,330,000</td>
<td>486,424,000</td>
<td>626,178,000</td>
<td>82,263,000</td>
</tr>
<tr>
<td>3. $E_{vis}$</td>
<td>2,317,670</td>
<td>69,903,000</td>
<td>606,486,000</td>
<td>87,755,000</td>
<td>143,697,000</td>
<td>6,761,000</td>
</tr>
<tr>
<td>4. $P_T$</td>
<td>935,773</td>
<td>21,219,000</td>
<td>95,691,000</td>
<td>5,672,000</td>
<td>74,944,000</td>
<td>4,289,000</td>
</tr>
<tr>
<td>5. $N_{ChdPFO}$</td>
<td>96,284</td>
<td>3,251,000</td>
<td>11,092,000</td>
<td>117,000</td>
<td>13,979,000</td>
<td>2,712,000</td>
</tr>
<tr>
<td>6. $</td>
<td>\cos \theta_j</td>
<td>$</td>
<td>56,987,000</td>
<td>1,454,000</td>
<td>5,782,000</td>
<td>28,000</td>
</tr>
<tr>
<td>7. Btag$4j$</td>
<td>56,091,000</td>
<td>1,387,000</td>
<td>5,641,000</td>
<td>25,000</td>
<td>3,606,000</td>
<td>491,000</td>
</tr>
<tr>
<td>8. $-\log Y_{34}$</td>
<td>29,965,000</td>
<td>1,245,000</td>
<td>4,746,000</td>
<td>13,000</td>
<td>1,641,000</td>
<td>440,000</td>
</tr>
<tr>
<td>9. $-\log Y_{23}$</td>
<td>17,261,000</td>
<td>1,171,000</td>
<td>4,395,000</td>
<td>13,000</td>
<td>1,033,000</td>
<td>421,000</td>
</tr>
<tr>
<td>10. $M_{W_1}$</td>
<td>3,057,000</td>
<td>1,006,000</td>
<td>3,400,000</td>
<td>13,000</td>
<td>531,000</td>
<td>390,000</td>
</tr>
<tr>
<td>11. $M_{W_2}$</td>
<td>1,801,000</td>
<td>269,000</td>
<td>1,796,000</td>
<td>0,000</td>
<td>329,000</td>
<td>62,000</td>
</tr>
<tr>
<td>12. $M_h$</td>
<td>766,000</td>
<td>79,000</td>
<td>769,000</td>
<td>0,000</td>
<td>143,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$3.7 \times 10^{-6}$</td>
<td>$1.9 \times 10^{-4}$</td>
<td>$5.0 \times 10^{-4}$</td>
<td>0.0</td>
<td>$2.2 \times 10^{-5}$</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
FIG. 11: Reconstructed Higgs mass distribution for $h \to WW^*$ hadronic decay channel at $\sqrt{s} = 1$ TeV with respect to the $L = 500 \text{ fb}^{-1}$ with $P(-0.8, +0.2)$ beam polarization.

TABLE X: Measurement accuracies of $\sigma BR$ in $h \to WW^* \rightarrow 4j$ channel with respect to the $L = 500 \text{ fb}^{-1}$ for both $P(\mp 0.8, \pm 0.2)$ beam polarizations or accumulating $L = 1 \text{ ab}^{-1}$ regarding $P(-0.8, +0.2)$ left-handed polarization.

<table>
<thead>
<tr>
<th>Integrated luminosity</th>
<th>500 $\text{fb}^{-1}$</th>
<th>500 $\text{fb}^{-1}$</th>
<th>1 $\text{ab}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam polarization $P(e^-, e^+)$</td>
<td>$P(-0.8, +0.2)$</td>
<td>$P(+0.8, -0.2)$</td>
<td>$P(-0.8, +0.2)$</td>
</tr>
<tr>
<td>Signal significance $(S/\sqrt{S + B})$</td>
<td>27.9</td>
<td>4.2</td>
<td>39.7</td>
</tr>
<tr>
<td>$\Delta\sigma BR/\sigma BR(h \to WW^* \rightarrow 4j)$</td>
<td>3.6%</td>
<td>23.7%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

current cut based analysis still remains $h \to gg$ and ZZ contribution after the all cuts but not taken into account for the systematic uncertainty of $\sigma BR(h \to WW^*)$. Further improvement is needed to reduce the uncertainty from other Higgs decay channels.

VI. CONCLUSION

Measurement accuracies of the $\sigma BR$ for the Higgs decay channels of $h \to b\bar{b}, c\bar{c}, gg$, and $WW^* \rightarrow 4j$ are analyzed at the CM energy of 1 TeV. All results are summarized on Table XI assuming the $L = 500 \text{ fb}^{-1}$ and 1 $\text{ab}^{-1}$ regarding both $P(\mp 0.8, \pm 0.2)$ beam polarizations. Owing to the good background separation by B-tagging, $h \to b\bar{b}$ channel can also achieve good situation even with right-handed polarization, but that is degraded for other channel case significantly, which is mainly caused by $e\gamma \rightarrow \nuqq$ or $\gamma\gamma \rightarrowqqqq$. $h \to cc, gg, WW^*$ are affected by this background except for the $h \to bb$. $\gamma\gamma \rightarrowqqqq$ contribution is relatively increased with the right-handed beam.
polarization case. Note that all the results are only considered statistical uncertainty of $\sigma BR$ and systematic uncertainty from other decays and backgrounds should be also taken into account in further study.

TABLE XI: Summary table of the measurement accuracies of $\sigma BR$ at $\sqrt{s} = 1$ TeV assuming $\mathcal{L} = 500$ fb$^{-1}$ with $P(\mp 0.8, \pm 0.2)$ both polarizations or 1 ab$^{-1}$ only accumulating $P(-0.8, + 0.2)$ left-handed beam polarization. Results are only considered statistical uncertainty.

<table>
<thead>
<tr>
<th>Integrated luminosity</th>
<th>500 fb$^{-1}$</th>
<th>1 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam polarization $P(e^-, e^+)$</td>
<td>$P(-0.8, + 0.2)$</td>
<td>$P(0.8, + 0.2)$</td>
</tr>
<tr>
<td>$\Delta \sigma BR/\sigma BR(h \rightarrow b\bar{b})$</td>
<td>0.54%</td>
<td>2.1%</td>
</tr>
<tr>
<td>$\Delta \sigma BR/\sigma BR(h \rightarrow c\bar{c})$</td>
<td>5.7%</td>
<td>36.8%</td>
</tr>
<tr>
<td>$\Delta \sigma BR/\sigma BR(h \rightarrow gg)$</td>
<td>3.9%</td>
<td>25.7%</td>
</tr>
<tr>
<td>$\Delta \sigma BR/\sigma BR(h \rightarrow WW^* \rightarrow 4j)$</td>
<td>3.6%</td>
<td>23.7%</td>
</tr>
</tbody>
</table>

Acknowledgments

We would like to acknowledge the members who join the ILD Analysis and Software meeting for useful discussion of this work and to ILD software task group members who maintain the analysis tools and MC samples for DBD detector benchmarking study. Especially, Mikael Berggren, Jenny List, and Akiya Miyamoto for useful discussion and suggestion for this analysis, Frank Gaede and Jan Engels for production and manage large amount of simulation/reconstruction samples.

VII. BIBLIOGRAPHY

Appendix

Appendix A: Higgs BR study at 500 GeV

1. Reconstruction and background reduction at 500 GeV

At the CM energy of 500 GeV, large amount of reconstructed signal and SM background samples are available for which were produced the study of ILD Letter of Intent (LOI), even though these samples were generated employing the Higgs mass of 120 GeV in whizard-1.40. Higgs BRs are calculated by Pythia [17] instead of used in DBD analysis, where the BRs for $h \rightarrow b\bar{b}$, $c\bar{c}$, and $gg$ are BR($h \rightarrow b\bar{b}$) = 65.7%, BR($h \rightarrow c\bar{c}$) = 3.6%, and BR($h \rightarrow gg$) = 5.5%, respectively. These generated samples are also simulated with previous ILD00 detector model in Mokka. For the flavor tagging, LCFIVertex package [13] was used. In the $h \rightarrow b\bar{b}$, $c\bar{c}$, and $gg$ reconstruction, Durham jet clustering [14] was applied and forcibly clustered as two jet. Note that at the $\sqrt{s} = 500$ GeV, $\gamma\gamma$ beam induced background contribution is relatively smaller than 1 TeV, thus $\gamma\gamma \rightarrow$ hadron backgrounds were not overlaid to the samples.

In order to select the $\nu_e\bar{\nu}_e h$ WW-fusion process, at first cut on missing mass is applied to suppress Zh process. Cuts on $P_T$, $P_Z$, $P_{max}$, and $N_{chd}$ are required to suppress semi-leptonic decay channels. Finally Higgs signal is selected with the cut on reconstructed Higgs mass region.
TABLE XII: Cut flow for $\sqrt{s} = 500$ GeV analysis

| Cuts                        | $M_{\text{miss}}$ | $P_T > 20$ GeV | $|P_Z| < 150$ GeV | $P_{\text{max}} < 50$ GeV | $N_{\text{chd}} > 10$ | $100 < M_h < 130$ GeV |
|-----------------------------|-------------------|----------------|------------------|--------------------------|-----------------------|-----------------------|
| 1. Missing mass             | $M_{\text{miss}} > 220$ GeV |
| 2. Transverse visible momentum | $P_T > 20$ GeV |
| 3. Longitudinal visible momentum | $|P_Z| < 150$ GeV |
| 4. Maximum momentum PFO    | $P_{\text{max}} < 50$ GeV |
| 5. Number of charged tracks| $N_{\text{chd}} > 10$ |
| 6. Reconstructed Higgs mass | $100 < M_h < 130$ GeV |

TABLE XIII: Background reduction summary at $\sqrt{s} = 500$ GeV with $L = 500$ fb$^{-1}$ regarding $P(-0.8, +0.3)$ beam polarization. $\nu\ell\ell$ and $\ell\ell\ell\ell$ processes are completely suppressed.

<table>
<thead>
<tr>
<th>Cuts</th>
<th>$h \rightarrow b\bar{b}$</th>
<th>$h \rightarrow c\bar{c}$</th>
<th>$h \rightarrow gg$</th>
<th>$h \rightarrow \text{all}$</th>
<th>$\nu\ell\nu\ell$</th>
<th>$\nu\nu\ell\ell$</th>
<th>$\ell\ell\nu\nu$</th>
<th>$qq\nu\nu$</th>
<th>$ZWW$</th>
<th>$ZZZ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen</td>
<td>59,921</td>
<td>3,336</td>
<td>5,053</td>
<td>90,029</td>
<td>367,779</td>
<td>5,042,400</td>
<td>682,517</td>
<td>4,288,940</td>
<td>513,824</td>
<td>2,681</td>
</tr>
<tr>
<td>1</td>
<td>51,619</td>
<td>2,811</td>
<td>4,185</td>
<td>78,712</td>
<td>239,835</td>
<td>192,350</td>
<td>3,739</td>
<td>114,929</td>
<td>28,140</td>
<td>927</td>
</tr>
<tr>
<td>2</td>
<td>47,889</td>
<td>2,629</td>
<td>4,017</td>
<td>72,087</td>
<td>213,867</td>
<td>155,999</td>
<td>1,230</td>
<td>43,028</td>
<td>26,009</td>
<td>910</td>
</tr>
<tr>
<td>3</td>
<td>46,431</td>
<td>2,552</td>
<td>3,895</td>
<td>69,132</td>
<td>197,487</td>
<td>134,599</td>
<td>1,136</td>
<td>42,930</td>
<td>25,679</td>
<td>910</td>
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<tr>
<td>4</td>
<td>43,604</td>
<td>2,308</td>
<td>3,711</td>
<td>61,308</td>
<td>175,734</td>
<td>58,380</td>
<td>613</td>
<td>15,006</td>
<td>16,581</td>
<td>777</td>
</tr>
<tr>
<td>5</td>
<td>43,307</td>
<td>2,280</td>
<td>3,711</td>
<td>57,126</td>
<td>166,037</td>
<td>56,281</td>
<td>610</td>
<td>14,976</td>
<td>15,894</td>
<td>699</td>
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<tr>
<td>6</td>
<td>35,054</td>
<td>2,040</td>
<td>3,711</td>
<td>45,473</td>
<td>15,405</td>
<td>16,657</td>
<td>90</td>
<td>663</td>
<td>4,372</td>
<td>226</td>
</tr>
</tbody>
</table>

| Efficiency | 55.6% | 46.0% | 64.5% | 41.2% | $1.7 \times 10^{-2}$ | $2.2 \times 10^{-3}$ | $1.5 \times 10^{-4}$ | $1.7 \times 10^{-4}$ | $7.1 \times 10^{-3}$ | $7.4 \times 10^{-2}$ |

2. Measurement accuracies of $\sigma BR$ at the $\sqrt{s} = 500$ GeV

After applying all above cuts, flavor templates on $h \rightarrow b\bar{b}$, $c\bar{c}$, and $gg$ are prepared using the Neuralnet-output for b, c, bc flavor from LCFIVertex. 5,000 times of Toy-MC is applied and extracted the accuracies of $\sigma BR$. Fitted results by template fitting Toy-MC are shown in Fig. 12 and summarized on the Table XIV.

FIG. 12: Fitted $r_\sigma$ distribution for $h \rightarrow b\bar{b}$, $c\bar{c}$, and $gg$ at $\sqrt{s} = 500$ GeV with assuming the $L = 500$ fb$^{-1}$ and $P(-0.8, +0.3)$ left-handed beam polarization.
TABLE XIV: Reduction summary for $h \rightarrow bb$, $cc$, $gg$ channels at $\sqrt{s} = 500$ GeV assuming $\mathcal{L} = 500$ fb$^{-1}$ and $P(-0.8, +0.3)$ beam polarization at the Higgs mass of 120 GeV.

<table>
<thead>
<tr>
<th>Integrated luminosity</th>
<th>500 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam polarization $P(e^-, e^+)$</td>
<td>$P(-0.8, +0.3)$</td>
</tr>
<tr>
<td>$r_{bb}$</td>
<td>$1.000 \pm 0.006$</td>
</tr>
<tr>
<td>$r_{cc}$</td>
<td>$1.002 \pm 0.052$</td>
</tr>
<tr>
<td>$r_{gg}$</td>
<td>$1.000 \pm 0.050$</td>
</tr>
<tr>
<td>$\Delta \sigma \text{BR}/\sigma \text{BR}(h \rightarrow bb)$</td>
<td>$0.6%$</td>
</tr>
<tr>
<td>$\Delta \sigma \text{BR}/\sigma \text{BR}(h \rightarrow cc)$</td>
<td>$5.2%$</td>
</tr>
<tr>
<td>$\Delta \sigma \text{BR}/\sigma \text{BR}(h \rightarrow gg)$</td>
<td>$5.0%$</td>
</tr>
</tbody>
</table>