

Evaluation of measurement accuracies of the Higgs boson branching fractions in the International Linear Collider

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Precise measurement of Higgs boson couplings is an important task for International Linear Collider (ILC) experiments and will facilitate the understanding of the particle mass generation mechanism. In this study, the measurement accuracies of the Higgs boson branching fractions to the b and c quarks and gluons, $\Delta Br(H \rightarrow b\bar{b}, c\bar{c}, gg)/Br$, were evaluated with the full International Large Detector model (ILD_00) for the Higgs mass of 120 GeV at the center-of-mass (CM) energies of 250 and 350 GeV using neutrino, hadronic and leptonic channels and assuming an integrated luminosity of 250 fb^{-1} , and an electron (positron) beam polarization of -80% ($+30\%$). We obtained the following measurement accuracies of the Higgs cross section times branching fraction $(\Delta(\sigma \cdot Br))/\sigma \cdot Br$ for decay of the Higgs into $b\bar{b}$, $c\bar{c}$, and gg ; as 1.0%, 6.9%, and 8.5% at a CM energy of 250 GeV and 1.0%, 6.2%, and 7.3% at 350 GeV, respectively. After the measurement accuracy of the cross section $(\Delta\sigma/\sigma)$ was corrected using the results of studies at 250 GeV and their extrapolation to 350 GeV, the derived measurement accuracies of the branching fractions $(\Delta Br/Br)$ to $b\bar{b}$, $c\bar{c}$, and gg were 2.7%, 7.3%, and 8.9% at a CM energy of 250 GeV and 3.6%, 7.2%, and 8.1% at 350 GeV, respectively.

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I. INTRODUCTION

Precise measurement of the Higgs boson branching ratios (BRs) is an important task for the International Linear Collider (ILC) program. It is also crucial for the understanding of the nature of electro-weak symmetry breaking and provides a window to investigate physics beyond the standard model (SM). The relatively low background and well-defined initial state of the ILC experiments allow precise, model-independent study of the Higgs boson, which is not an easy task for Large

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Hadron Collider experiments [1, 2]. Measurements of the Higgs BRs to $b\bar{b}$ and $c\bar{c}$ decays at an e^+e^- linear collider were reported in Refs. [3–7]. In this study, we investigate the accuracies of BRs of the Higgs to $b\bar{b}$, $c\bar{c}$, and gg using Geant4 [8] based realistic simulation implemented with a proposed International Large Detector (ILD) [9].

In this study, we assume a Higgs mass of 120 GeV/ c^2 and an integrated luminosity of 250 fb $^{-1}$, and estimate the accuracies of the BRs at center-of-mass (CM) energies of 250 and 350 GeV. The former value is close to the threshold of Higgs production and thus is considered as initial target of ILC experiments. The latter is close to the threshold of top quark pair production; therefore, Higgs data can be corrected simultaneously with a top threshold study. The difference between kinematical conditions at 250 and 350 GeV could yield different detection efficiencies and thus different BR accuracies. The accuracies at 250 and 350 GeV under the same conditions are studied and compared.

The experimental conditions for this study are described in section II. We selected the Higgs events in three channels: neutrino, hadronic and leptonic. The event selection and background suppression processes are described in the section III. The derivation of the BRs is presented in the section IV, and the conclusion is given in the last section.

II. HIGGS PHYSICS IN THE ILC EXPERIMENT

A. ILC experiment and Higgs production

The ILC is a future electron-positron (e^-e^+) linear collider for experiments at an initial center-of-mass (CM) energy (\sqrt{s}) up to 500 GeV, which can be extended to 1 TeV. The production cross section of the Higgs boson is shown in Fig. 1(a) as a function of the CM energy for a Higgs mass of 120 GeV. At a low CM energy, the Higgs boson is produced primarily through the Higgs-strahlung $e^+e^- \rightarrow ZH$ process, which has a maximum around 250 GeV when the effect of the initial state radiation is considered. This is about 20 GeV higher than that without the initial state radiation. At the $\sqrt{s} = 350$ GeV, the total cross section is reduced, although the contribution of W/Z fusion is greater than that at 250 GeV. The decay BRs of the Higgs boson in the SM are shown as a function of its mass in Fig. 1(b). The Higgs decays mainly to $b\bar{b}$ if its mass is below 140 GeV and to WW^* in the case of a mass of above 140 GeV.

Higgs analysis modes are categorized in terms of the three Z boson decay channels: $Z \rightarrow \nu\bar{\nu}$ (neutrino), $q\bar{q}$ (hadronic), and $\ell^+\ell^-$ (leptonic), as shown in Fig. 2. We assumed the -80% and

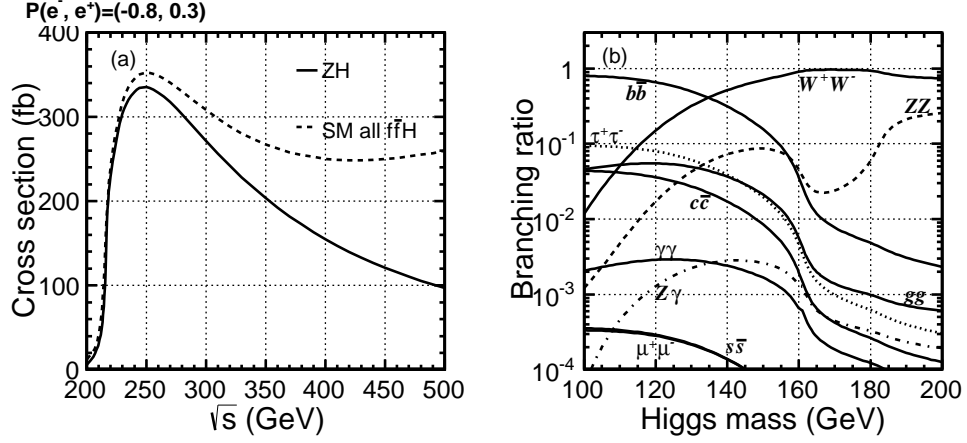


FIG. 1: (a) Production cross section of Higgs boson at a Higgs mass of 120 GeV through the Higgs-strahlung (ZH) (solid) and all $f\bar{f}H$ (dashed) processes assuming the -80% electron and +30% positron beam polarization. The cross section is calculated including the initial state radiation by Whizard [10]. (b) SM Higgs branching fractions as a function of Higgs mass with PYTHIA [11].

+30% polarization of the initial electrons and positrons, respectively, in order to enhance the Higgs signals.

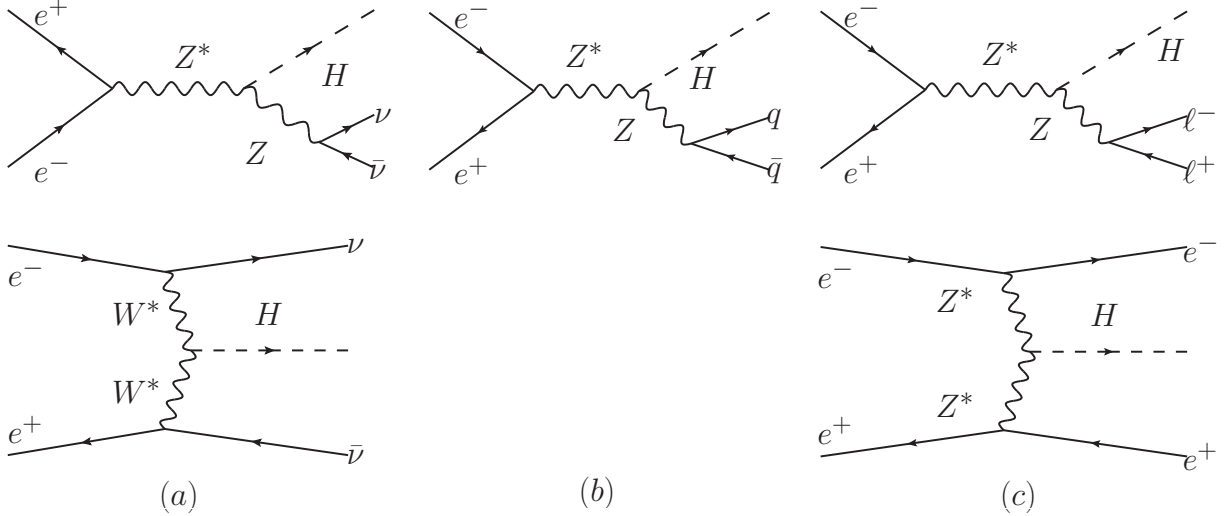


FIG. 2: Higgs boson production diagrams categorized according to the final states: (a) neutrino ($\nu\bar{\nu}H$), (b) hadronic ($q\bar{q}H$), and (c) leptonic ($\ell^+\ell^-H$) channels. Each channel is produced mainly through the Higgs-strahlung (ZH) process at low CM energies, although the neutrino and leptonic channels also include the WW and ZZ fusion processes, respectively.

B. ILD concept

We used the ILD [9] model for this study. The ILD, which is the validated detector concept for the ILC, is equipped with a highly segmented calorimeter and a hybrid tracking system consisting of gaseous, silicon-strip, and silicon-pixel trackers. They provide an excellent jet energy resolution by particle flow analysis, as well as excellent momentum resolution and vertex flavor tagging capability, which are necessary for measuring multi-jet final states in the ILC energy region. All sub-detector components of the ILD are shown in Fig. 3; which consists of silicon-pixel vertex detectors (VTX), silicon inner and outer detectors (SIT, SET), a time projection chamber (TPC), high-granularity electromagnetic and hadron calorimeters (ECAL, HCAL), a super-conducting solenoid magnet with a 3.5 T magnetic field, and an iron return yoke with a muon detector. In addition, forward silicon trackers (FTD, ETD) and beam/luminosity calorimeters (LCAL, LHCAL and BCAL) are installed in the forward region.

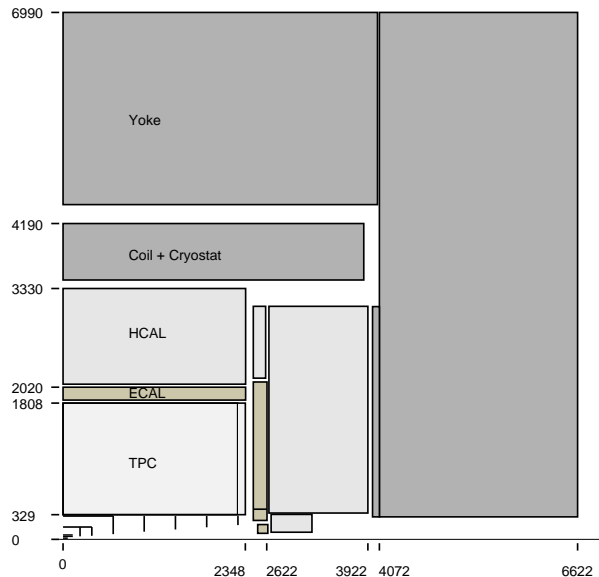


FIG. 3: Schematic view of the ILD detector.

The VTX system consists of three double layers of silicon pixel sensors with a $2.8 \mu\text{m}$ point resolution located at radii between 16 mm and 60 mm, the total radiation length being 0.74%. The impact parameter resolution (σ_{IP}) of the VTX system is $5 \mu\text{m} \oplus 10 \mu\text{m} \cdot \text{GeV}/c/p \sin^{3/2} \theta$. The TPC occupies a volume up to a radius of 1.8 m and a half-length in Z of 2.3 m, providing a stand-alone momentum resolution of $\sigma_{1/P_T} \sim 9 \times 10^{-5} \text{ GeV}^{-1}$. The SIT and SET are placed at the inner and outer sides of the TPC with 7 and $50 \mu\text{m}$ point resolutions in the $R - \phi$ and z directions, respectively. The overall momentum resolution of the tracking system (σ_{1/P_T}) is

$2 \times 10^{-5} \text{ GeV}^{-1} \oplus 1 \times 10^{-3} / P_T \sin \theta$ for the momentum range 1-200 GeV [9]. The ECAL consists of 24 X_0 tungsten absorbers with highly segmented ($5 \times 5 \text{ mm}^2$) readouts. The HCAL consists of 5.5 λ_I steel absorbers with a $3 \times 3 \text{ mm}^2$ scintillator tile readout. With the ILD particle flow algorithm package, PandoraPFA [12], a dijet energy resolution of $25\% / \sqrt{E} \text{ (GeV)}$ has been achieved for a 45-GeV dijet, which corresponds to a single-jet energy resolution of $\sigma_{E_j} / E_j = 3.7\%$ [9].

C. Analysis framework and Monte Carlo samples

Monte Carlo (MC) generator samples for the physics study were produced using the Whizard [10], and fragmentation and hadronization processes were simulated by PYTHIA [11]. The SM Higgs branching fractions in PYTHIA are 65.7%, 3.6%, and 5.5% for $b\bar{b}$, $c\bar{c}$, and gg , respectively. The generated particles were passed through the Geant4 [8] based detector simulator Mokka [13] with the ILD model. The simulated hits were digitized and then reconstructed by the MarlinReco package; then, the resulting skimmed data were analyzed. The statistics of the simulated Higgs signal samples were 500 fb^{-1} for both CM energies of both 250 and 350 GeV, whereas those for background processes varied with the signal-to-noise ratio (S/N). They are scaled in the analysis in order to obtain results corresponding to an integrated luminosity of 250 fb^{-1} . The major SM background processes for the $e^+e^- \rightarrow ZH$ analysis are $e^+e^- \rightarrow ZZ$ and W^+W^- ; thus we considered final sample states of $\nu\bar{\nu}q\bar{q}$, $\nu\ell q\bar{q}$, $\ell\ell q\bar{q}$, $\nu\nu\ell\ell$, $q\bar{q}q\bar{q}$ and $\ell\ell\ell\ell$. In addition, the $q\bar{q}$ and $t\bar{t}$ backgrounds were also considered for the neutrino and hadronic channels (but only for $\sqrt{s} = 350 \text{ GeV}$ because we used a top mass of $174.9 \text{ GeV}/c^2$). In the leptonic channel, most of the multi-jet backgrounds are well suppressed if dilepton identification is required; thus, only the $\ell\ell q\bar{q}$ and $\nu\ell q\bar{q}$ backgrounds were considered. We used the 250-GeV samples produced for the ILD letter of intent (LOI) studies [9]; thus, their beam parameters correspond to those defined in the ILC Reference Design Report [3]. On the other hand, the 350-GeV samples were newly produced for this study using the updated beam parameter SB2009 [14]. The instantaneous luminosities were 0.75 and $1 \times (10^{34} \text{ cm}^{-2}\text{s}^{-1})$ for 250 and 350 GeV, which yield integrated luminosities of 188 and 250 fb^{-1} , respectively, for about 3 years at 100 days of operation per year.

III. EVENT RECONSTRUCTION AND BACKGROUND SUPPRESSION

Depending on the Z decay mode, the analysis channels are categorized as the neutrino (dijet), hadronic (four-jets) and leptonic channels (dileptons + dijets), which are described in the following

subsections.

A. Neutrino channel ($\nu\bar{\nu}H$)

For neutrino channel analysis, particles in the event are first forcibly clustered into two jets by the Durham jet-finding algorithm. After the dijet clustering, background reductions are applied according to the selection criteria in Table I. At a CM energy of 250 GeV, the Higgs is produced almost at rest because it is close to the production threshold, whereas it is boosted at 350 GeV. Thus, the cut conditions are optimized to obtain the best S/N at each energy. In this channel, Z boson decays invisibly ($\nu\bar{\nu}$); thus, the $\nu\bar{\nu}q\bar{q}$ and $\nu\ell q\bar{q}$ processes in the SM are the main backgrounds. To reduce them, a cut on the missing mass (M_{miss}) is applied. Although this cut decreases the Higgs signal from the WW fusion process, the $\nu\ell q\bar{q}$, $\ell\ell q\bar{q}$ and $q\bar{q}q\bar{q}$ backgrounds are effectively reduced. $q\bar{q}$ background is reduced by the following kinematical cuts: the transverse momentum (P_t), longitudinal momentum (P_l), and maximum momentum (P_{max}). The $\ell\ell\ell$ background is well reduced by a cut on the number of charged tracks in an event (N_{chd}). In addition, the $\nu\ell q\bar{q}$ background reduction is improved by the Y_{12} and Y_{23} cuts. Y_{12} and Y_{23} are the maximum and the minimum of y values (scaled jet masses), respectively, required to cluster the event into two jets.

The background reductions for each cut are summarized in Table I for each CM energy. After all selection criteria are met, an additional likelihood ratio (LR) cut is applied to improve the background reduction. The LR is defined using the following variables: M_{miss} , the number of particles (N_{PFO}), Y_{12} , P_{max} , P_t , and M_{jj} . The likelihood cut positions are optimized to maximize signal significance and $LR > 0.165$ and $LR > 0.395$ are selected for CM energies of 250 and 350 GeV, respectively. The signal significance ($S/\sqrt{S+B}$) after all background reductions is also listed in Table with its efficiency, where S and B are the numbers of Higgs signal and background entries, respectively, after all cuts are applied. The remaining backgrounds are $\nu\ell q\bar{q}$ (60%), $\nu\bar{\nu}q\bar{q}$ (20%), and $q\bar{q}$ (10%) at both 250 and 350 GeV.

B. Hadronic channel ($q\bar{q}H$)

For hadronic channel analysis, particles in the event are first forcibly clustered into four jets. Next, a Higgs and Z candidate dijet pair that minimize the following χ^2 formula are selected from the four jets:

$$\chi^2 = \left(\frac{M_{j_1j_2} - M_Z}{\sigma_Z} \right)^2 + \left(\frac{M_{j_3j_4} - M_H}{\sigma_H} \right)^2, \quad (1)$$

TABLE I: Summary of the $\nu\bar{\nu}H$ channel background reduction assuming $\mathcal{L} = 250 \text{ fb}^{-1}$ with $P(e^-, e^+) = (-0.8, +0.3)$.

CM energy (GeV)	250			350		
Cut names	condition	Sig.	Bkg.	condition	Sig.	Bkg.
Generated		19360	44827100		26307	20855900
Missing mass (GeV)	$80 < M_{miss} < 140$	15466	6214050	$50 < M_{miss} < 240$	23202	5627040
Transverse P (GeV)	$20 < P_T < 70$	13727	549340	$10 < P_T < 140$	22648	2271090
Longitudinal P (GeV)	$ P_L < 60$	13342	392401	$ P_L < 130$	22459	2051010
# of charged tracks	$N_{chd} > 10$	12936	374877	$N_{chd} > 10$	21270	1936220
Maximum P (GeV)	$P_{max} < 30$	11743	205038	$P_{max} < 60$	20556	1167050
Y_{23} value	$Y_{23} < 0.02$	7775	74439	$Y_{23} < 0.02$	14992	465461
Y_{12} value	$0.2 < Y_{12} < 0.8$	7438	62584	$0.2 < Y_{12} < 0.8$	14500	413762
Di-jet mass (GeV)	$100 < M_{jj} < 130$	6691	19061	$100 < M_{jj} < 130$	12334	71918
Likelihood ratio	$LR > 0.165$	6293	10940	$LR > 0.395$	9543	11092
Significance (Efficiency)	$S/\sqrt{S+B}$	47.9 (32.5%)		$S/\sqrt{S+B}$	66.4 (36.3%)	

where $M_{j_1j_2/j_3j_4}$, $M_{Z/H}$ represent the dijet invariant masses paired from the four jets (j_{1-4}) and the Z and Higgs masses, respectively. Here $\sigma_Z = 4.7 \text{ GeV}$ and $\sigma_H = 4.4 \text{ GeV}$ are used for $\sqrt{s} = 250 \text{ GeV}$ and $\sigma_{Z/H} = 3.8 \text{ GeV}$ for $\sqrt{s} = 350 \text{ GeV}$. They are determined from the dijet mass distribution reconstructed from the true MC information. After the jet pairing, background reductions are applied.

To select the four-jet-like events, cuts on the number of charged tracks $N_{charged}$ and jet clustering parameter Y_{34} are applied. Y_{34} is the minimum scaled jet mass y required for four-jet clustering. The leptonic backgrounds ($llll$, $llq\bar{q}$) are reduced effectively by these selections. In addition, cuts on the thrust and thrust angle are applied to reduce the ZZ background, utilizing the difference between the event shape of the signal (spherical) and ZZ , $q\bar{q}$ (back-to-back). The numbers of $q\bar{q}q\bar{q}$ and $q\bar{q}$ background events are reduced by a cut on the angle between the Higgs candidate jets (θ_H). The WW and ZZ backgrounds are further suppressed by cuts on the Higgs and Z candidates after the kinematical constraint fit is applied to the four-jet system as follows. Each jet is parameterized by E_{j_i} , θ_i , and ϕ_i ($i = 1 - 4$) and fitted with constraints on the total energy ($\sum_i E_{j_i} = \sqrt{s}$), the total momentum ($\sum_i \vec{P}_{j_i} = 0$), and Higgs and Z mass difference ($|M_{j_1j_2} - M_{j_3j_4}| = |M_H - M_Z|$), where E_{j_i} , P_{j_i} , θ_i , and ϕ_i are the energy, momentum, and theta and phi angles of the i -th jet, respectively. After these cuts are applied, an additional cut is applied on the LR derived from

the following input variables: thrust, $\cos \theta_{\text{thrust}}$, minimum angle between all jets (θ_{min}), number of particles in Higgs candidate jets, fitted Z mass, and fitted Higgs mass. The likelihood cut position is selected to maximize signal significance; $LR > 0.375$ for 250 GeV and $LR > 0.15$ for 350 GeV. All background reduction procedures are summarized in Table II. The background fractions after all cuts are 80% $q\bar{q}q\bar{q}$ and 20% $q\bar{q}$ at 250 GeV and 60% $q\bar{q}q\bar{q}$, 30% $q\bar{q}$ and 10% $t\bar{t}$ at 350 GeV.

TABLE II: Summary of $q\bar{q}H$ channel background reduction assuming $\mathcal{L} = 250 \text{ fb}^{-1}$ with $P(e^-, e^+) = (-0.8, +0.3)$.

CM energy (GeV)	250			350		
Cut names	condition	Sig.	Bkg.	condition	Sig.	Bkg.
Generated		52507	45904900		36099	22210900
χ^2	$\chi^2 < 10$	32447	2608980	$\chi^2 < 10$	20207	1034810
# of charged tracks	$N_{\text{chd}} > 4$	25281	1120950	$N_{\text{chd}} > 4$	14900	305649
Y_{34} value	$-\log(Y_{34}) > 2.7$	25065	1002125	$-\log(Y_{34}) > 2.7$	14543	250995
thrust	thrust < 0.9	24688	935950	thrust < 0.85	13522	144560
thrust angle	$ \cos \theta_{\text{thrust}} < 0.9$	21892	696201	$ \cos \theta_{\text{thrust}} < 0.9$	12523	107025
Higgs jets angle	$105^\circ < \theta_H < 160^\circ$	20062	622143	$70^\circ < \theta_H < 120^\circ$	11185	77659
Z di-jet mass (GeV)	$80 < M_Z < 100$	16359	411863	$80 < M_Z < 100$	9468	45671
H di-jet mass (GeV)	$105 < M_H < 130$	16359	411863	$105 < M_H < 130$	9451	44399
Likelihood ratio	$LR > 0.375$	13726	166807	$LR > 0.15$	8686	25393
Significance (Efficiency)	$S/\sqrt{S+B}$	32.3 (26.1%)		$S/\sqrt{S+B}$	47.1 (24.1%)	

C. Leptonic channel ($\ell^+\ell^-H$)

For leptonic channel analysis, we considered the cases where the lepton is an electron or a muon. We considered only the $\ell\ell qq$ and $\ell\nu qq$ background processes. First, the following cuts were applied to selected isolated leptons:

- Lepton isolation: $E_{\text{cone}} < 20 \text{ GeV}$ (cone angle: 10°),
- Lepton track momentum:
 - $10 < E_{\text{lep}} < 90 \text{ GeV}$ at $\sqrt{s} = 250 \text{ GeV}$,
 - $10 < E_{\text{lep}} < 160 \text{ GeV}$ at $\sqrt{s} = 350 \text{ GeV}$,

where E_{cone} is the energy sum for particles within 10° of the lepton. The prompt lepton has a smaller E_{cone} than nonprompt leptons. Electrons and muons are identified from their charged tracks as follows:

- Electron ID: $\frac{E_{ECAL}}{E_{Total}} > 0.9, 0.7 < \frac{E_{Total}}{P} < 1.2$
- Muon ID: $\frac{E_{ECAL}}{E_{Total}} < 0.5, \frac{E_{Total}}{P} < 0.4,$

where E_{ECAL} , E_{Total} and P denote the *ECAL* energy associated with a track, total energy deposited in the *ECAL* and *HCAL*, and track momentum, respectively. If there are more than two isolated lepton candidates after the electron or muon identification, a pair whose invariant mass is closest to Z is selected. After dilepton identification, forced two-jets clustering is applied to the remaining particles and the following selections are applied. First, a dilepton mass ($M_{\ell\ell}$) cut, which should be consistent with the Z mass, is applied: $70 < M_{\ell\ell} < 110$ GeV for electrons and $70 < M_{\ell\ell} < 100$ GeV for muons. Because the ZZ or WW backgrounds are boosted to the forward region compared to the signal, a cut on the Z direction is applied: $|\cos\theta_Z| < 0.8$. Finally, cuts on dijet mass (M_{jj}) and a mass recoil to the lepton pair (M_{rec}) are applied to select the Higgs signal: $100 < M_{jj} < 140$ GeV and $70 < M_{rec} < 140$ GeV for electrons; $115 < M_{jj} < 140$ GeV and $70 < M_{rec} < 140$ GeV for muons. The background reduction procedures for the leptonic channel are summarized in Table III. After all cuts were applied, the background was dominated by the $llq\bar{q}$ whereas the $\nu lq\bar{q}$ was well suppressed.

IV. BRANCHING RATIO MEASUREMENT

After event selection, the measurement accuracies of the Higgs BRs to $b\bar{b}$, $c\bar{c}$, and gg are evaluated on the basis of a template fitting to the flavor likeness of the Higgs dijets obtained by using the LCFIVertexing package [15]. The probabilities of b and c quarks for each jet [b_i, c_i ($i = 1, 2$)] are calculated in LCFIVertex using neural net training with a $Z \rightarrow q\bar{q}$ samples at the Z -pole. In addition, another c probability ($bc_{1,2}$) is also calculated whose neural-net is trained only with $Z \rightarrow b\bar{b}$ sample as the background. For Higgs dijets, we define the flavor likeness X ($X = b, c, bc$) as follows from the x_i [$x_i = b_i, c_i, bc_i$ ($i = 1, 2$)] flavor probability of each jet:

$$X = \frac{x_1 x_2}{x_1 x_2 + (1 - x_1)(1 - x_2)}. \quad (2)$$

The flavor tagging performance in the $ZZ \rightarrow \nu\bar{\nu}q\bar{q}$ sample at the $\sqrt{s} = 250$ and 350 GeV is shown in Fig. 4. The $ZZ \rightarrow \nu\bar{\nu}q\bar{q}$ samples are compared for each CM energy because they form the

TABLE III: Summary of background reduction in the eeH and $\mu\mu H$ channels assuming $\mathcal{L} = 250 \text{ fb}^{-1}$ with $P(e^-, e^+) = (-0.8, +0.3)$.

CM energy (GeV)		250			350		
Cut names	e/μ	condition	Sig.	Bkg.	condition	Sig.	Bkg.
Generated	e		3137	4512520		2740	3822410
	μ		2917	4512520		1789	3822410
# of e/μ track ID	e	$N_e \geq 2$	2717	204403	$n_e \geq 2$	2270	179580
	μ	$N_\mu \geq 2$	2668	28175	$N_\mu \geq 2$	1631	23598
Di-lepton mass (GeV)	e	$70 < M_{\ell\ell} < 110$	2208	34162	$70 < M_{\ell\ell} < 110$	1425	51436
	μ	$80 < M_{\ell\ell} < 110$	2287	12901	$80 < M_{\ell\ell} < 100$	1406	13313
Z direction	e	$ \cos\theta < 0.8$	1797	21600	$ \cos\theta < 0.8$	1192	20874
	μ	$ \cos\theta < 0.8$	1889	8036	$ \cos\theta < 0.8$	1203	6250
Di-jet mass (GeV)	e	$100 < M_{jj} < 140$	1394	2721	$110 < M_{jj} < 140$	865	2019
	μ	$115 < M_{jj} < 140$	1445	1955	$115 < M_{jj} < 140$	855	1197
Recoil mass (GeV)	e	$70 < M_{rec} < 140$	1184	1607	$70 < M_{rec} < 140$	567	590
	μ	$70 < M_{rec} < 140$	1365	983	$70 < M_{rec} < 140$	638	465
Significance (Efficiency)	e	$S/\sqrt{S+B}$	22.4 (37.8%)		$S/\sqrt{S+B}$	16.7 (20.7%)	
	μ		28.2 (46.8%)			19.2 (35.7%)	

same final state as $Z \rightarrow q\bar{q}$, which was used to train the flavor tagging neural network. Figure 4 shows that no significant difference in the flavor tagging performance at $\sqrt{s} = 250$ and 350 GeV is observed for any of the flavors.

To evaluate the measurement accuracy of the BRs, the b -, c -, and bc -likenesses of the selected events were binned in a three-dimensional histogram and fitted with those of the template samples, which consist of $H \rightarrow b\bar{b}$, $c\bar{c}$, and gg and other background processes. Figure 5 shows the three-dimensional histogram projected to the two-dimensional b - and c -likeness axes for the hadronic channel. The probability of entries in each template sample bin is expected to be given by the Poisson statistics:

$$P_{ijk} = \frac{\mu^n e^{-\mu}}{n!} \left(n \equiv N_{ijk}^{data}, \mu \equiv N_{ijk}^{template} \right), \quad (3)$$

where P_{ijk} and N_{ijk}^{data} are the probability of entries and the number of data entries at the (i, j, k)

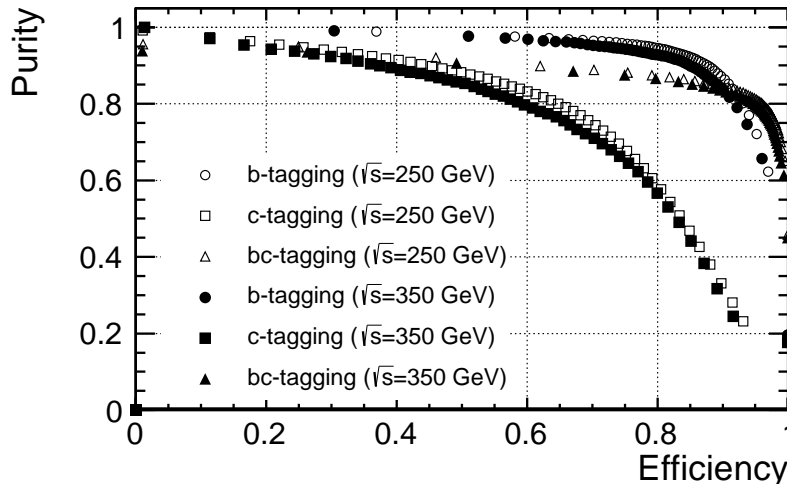


FIG. 4: Flavor tagging performance at CM energies of 250 and 350 GeV in $ZZ \rightarrow \nu\bar{\nu}q\bar{q}$ sample. Horizontal axis shows the efficiency of b/c jets; vertical axis shows the purity of tagged b/c jets.

bin, respectively. $N_{ijk}^{template}$ is given by

$$N_{ijk}^{template} = \sum_{s=b\bar{b}, c\bar{c}, gg} r_s \cdot N_{ijk}^s + N_{ijk}^{bkg}, \quad (4)$$

where N_{ijk}^s is the number of entries at the (i, j, k) bin in each $H \rightarrow b\bar{b}$, $c\bar{c}$, and gg template; N_{ijk}^{bkg} is the number of entries in the background template sample, which is the sum of the SM background events and the Higgs-to-nonhadronic decay events. Furthermore, $r_{b\bar{b}}$, $r_{c\bar{c}}$, and r_{gg} are the parameters to be determined by the template fitting. They are defined as the Higgs branching fractions to $H \rightarrow b\bar{b}$, $c\bar{c}$ and gg , respectively, normalized by that of the SM,

$$r_s = \frac{\sigma \cdot Br(H \rightarrow s)}{\sigma^{SM} \cdot Br(H \rightarrow s)^{SM}} \quad (s = b\bar{b}, c\bar{c}, gg). \quad (5)$$

Here σ is the Higgs production cross section and σ^{SM} and $Br(H \rightarrow s)^{SM}$ are the cross section and branching fraction in the SM, respectively. From Eq. (5), the measurement accuracies of $\sigma \cdot Br$ are obtained as follows;

$$\frac{\Delta(\sigma \cdot Br)}{\sigma \cdot Br}(H \rightarrow s) = \frac{\Delta r_s}{r_s} \quad (s = b\bar{b}, c\bar{c}, gg).$$

The r_s 's values were determined by a binned log likelihood fitting, where each bin probability is given by Eq. (3).

On the basis of the three-dimensional (3D) histogram, 5000 toy MC events were generated using the Poisson distribution function for each bin, which were fitted to obtain $r_{b\bar{b}}$, $r_{c\bar{c}}$, and r_{gg} . The

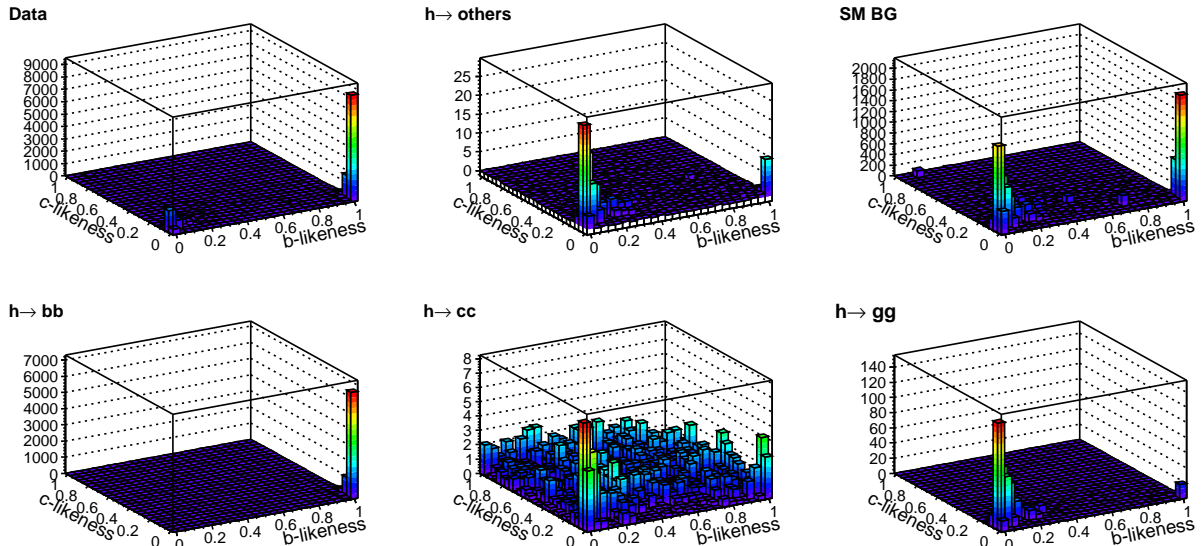


FIG. 5: Two-dimensional images of three-dimensional template samples for b -likeness vs. c -likeness

number of bins in the 3D histogram were optimized to minimize the statistical fluctuation in the fitted results caused by low-statistic bins. Bins with fewer than one entry were not used for the fitting. The distributions of $r_{b\bar{b}}$, $r_{c\bar{c}}$, and r_{gg} for template fitting to 1000 toy MC events are shown in Fig. 6. The error in r_s is determined by the Gaussian fittings to these distributions, which are shown in Tables IV and V for CM energies of 250 and 350 GeV, respectively.

The tables also show the accuracies after correction of the total cross section. From a study of the recoil mass in the process of $e^+e^- \rightarrow eeH$ and $\mu\mu H$, the accuracy of the total cross section ($\Delta\sigma/\sigma$) was estimated to be 2.5% at 250 GeV [9, 16]. For 350 GeV, we assumed an accuracy of 3.5% because the recoil mass measurement relies on the ZH process, whose cross section is inversely proportional to the square of the CM energy; thus, the accuracy of the total cross section measurement would be inversely proportional to the CM energy.

From Tables IV and V, we see that the Higgs cross section times branching ratio can be measured at about 1% for $H \rightarrow b\bar{b}$ and 7 to 9% for $H \rightarrow c\bar{c}$ and gg . The measurement is approximately 10 – 20% better at 350 GeV than at 250 GeV. The instantaneous luminosity at 350 GeV is 25% greater than that at 250 GeV according to the ILC beam parameters. Thus, for an equal running time, measurements at 350 GeV will give us about 20 – 30% better accuracy than those at 250 GeV. On the other hand, the accuracy of the BR to $b\bar{b}$, $\Delta Br/Br(H \rightarrow b\bar{b})$, is limited by the total cross section ambiguity; thus, measurement at 250 GeV gives us better results than that at 350 GeV. In the other decay channels, comparable BR measurements are possible even if the same

integrated luminosities are assumed.

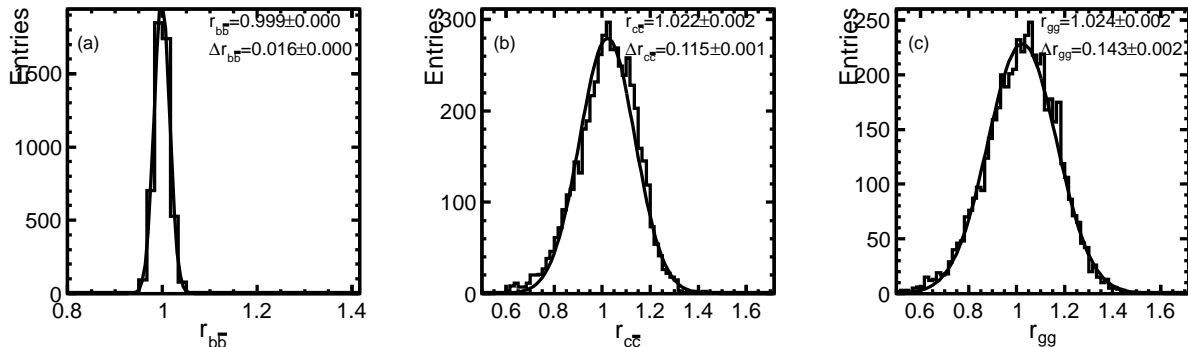


FIG. 6: Typical examples of (a) $r_{b\bar{b}}$, (b) $r_{c\bar{c}}$, and (c) r_{gg} distributions.

TABLE IV: Summary of template fitting results r_s and accuracies of $(\sigma \cdot Br)$ and Br after correcting σ for an accuracy of 2.5% at $\sqrt{s} = 250$ GeV assuming $\mathcal{L} = 250 \text{ fb}^{-1}$ with $(e^-, e^+) = (-0.8, +0.3)$.

	$\nu\bar{\nu}H$	$q\bar{q}H$	e^+e^-H	$\mu^+\mu^-H$	comb.
$r_{b\bar{b}}$	1.00 ± 0.02	1.00 ± 0.01	1.00 ± 0.04	1.00 ± 0.03	1.00 ± 0.01
$r_{c\bar{c}}$	1.02 ± 0.11	1.01 ± 0.10	1.02 ± 0.27	1.01 ± 0.23	1.02 ± 0.07
r_{gg}	1.02 ± 0.14	1.02 ± 0.13	1.05 ± 0.33	1.02 ± 0.24	1.02 ± 0.09
$\frac{\Delta(\sigma \cdot Br)}{\sigma \cdot Br}(H \rightarrow b\bar{b})$ (%)	1.7	1.5	3.8	3.3	1.0
$\frac{\Delta(\sigma \cdot Br)}{\sigma \cdot Br}(H \rightarrow c\bar{c})$ (%)	11.2	10.2	26.8	22.6	6.9
$\frac{\Delta(\sigma \cdot Br)}{\sigma \cdot Br}(H \rightarrow gg)$ (%)	13.9	13.1	31.3	33.0	8.5
$\frac{\Delta Br}{Br}(H \rightarrow b\bar{b})$ (%)	3.0	2.9	5.7	4.5	2.7
$\frac{\Delta Br}{Br}(H \rightarrow c\bar{c})$ (%)	11.4	10.5	31.3	22.8	7.3
$\frac{\Delta Br}{Br}(H \rightarrow gg)$ (%)	14.2	13.3	33.1	24.0	8.9

V. CONCLUSION

The measurement accuracy of the Higgs branching fractions, $H \rightarrow b\bar{b}$, $c\bar{c}$, and gg , were evaluated at $\sqrt{s} = 250$ GeV and 350 GeV. In terms of signal significance, $\sqrt{s} = 350$ GeV yields better background suppression than $\sqrt{s} = 250$ GeV for each channel. The combined results for measurement accuracies of the Higgs cross section times BRs $(\Delta(\sigma \cdot Br))/\sigma \cdot Br$ to $H \rightarrow b\bar{b}$, $c\bar{c}$, and gg are 1.0%, 6.9%, and 8.5% at CM energies of 250 GeV and 1.0%, 6.2%, and 7.3% at 350 GeV, respectively, assuming the same integrated luminosity of 250 fb^{-1} . At the ILC, the total Higgs

TABLE V: Summary of template fitting results r_s and accuracies of $(\sigma \cdot Br)$ and Br after correcting σ for an accuracy of 3.5% at $\sqrt{s} = 350$ GeV assuming $\mathcal{L} = 250 \text{ fb}^{-1}$ with $(e^-, e^+) = (-0.8, +0.3)$.

	$\nu\bar{\nu}H$	$q\bar{q}H$	e^+e^-H	$\mu^+\mu^-H$	comb.
$r_{b\bar{b}}$	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.05	1.00 ± 0.05	1.00 ± 0.01
$r_{c\bar{c}}$	1.02 ± 0.11	1.01 ± 0.10	1.02 ± 0.31	1.04 ± 0.32	1.01 ± 0.06
r_{gg}	1.02 ± 0.14	1.04 ± 0.14	1.04 ± 0.37	1.03 ± 0.34	1.02 ± 0.07
$\frac{\Delta(\sigma \cdot Br)}{\sigma \cdot Br}(H \rightarrow b\bar{b})$ (%)	1.4	1.5	5.3	5.1	1.0
$\frac{\Delta(\sigma \cdot Br)}{\sigma \cdot Br}(H \rightarrow c\bar{c})$ (%)	8.6	10.1	30.5	30.9	6.2
$\frac{\Delta(\sigma \cdot Br)}{\sigma \cdot Br}(H \rightarrow gg)$ (%)	9.2	13.7	35.8	33.0	7.3
$\frac{\Delta Br}{Br}(H \rightarrow b\bar{b})$ (%)	3.8	3.8	6.4	6.2	3.6
$\frac{\Delta Br}{Br}(H \rightarrow c\bar{c})$ (%)	9.2	10.6	30.7	31.1	7.2
$\frac{\Delta Br}{Br}(H \rightarrow gg)$ (%)	9.8	14.1	36.0	33.2	8.1

cross-section σ is measured using the Z recoil mass process. Using $\Delta\sigma/\sigma = 2.5\%$ for 250 GeV and assuming it is 3.5% at 350 GeV, Higgs BRs ($\Delta Br/Br$) to $b\bar{b}$, $c\bar{c}$, and gg are derived as 2.7%, 7.3%, and 8.9% at CM energies of 250 GeV and as 3.6%, 7.2%, and 8.1% at 350 GeV. Therefore, we conclude that the Higgs cross section times BR ($Br \times \sigma$) can be measured better at 350 GeV than at 250 GeV owing to the higher S/N at the higher energy. However, when the accuracy of the total cross section measurement by recoil mass measurement is considered, BR of $H \rightarrow b\bar{b}$ can be measured better at 250 GeV, even if the integrated luminosity is the same at both energies.

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