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Probing the dark sector via searches for invisible decays of the Higgs boson at the ILC

Yu Kato*, **Junping Tian and Satoru Yamashita on behalf of the ILD collaboration**
International Center for Elementary Particle Physics (ICEPP), The University of Tokyo, Japan
E-mail: katou@icepp.s.u-tokyo.ac.jp

Although the existence of Dark Matter (DM) has been suggested by various astrophysical observations, it has not yet been discovered today. We can assume a scenario in which the particles that account for the DM can interact with the Standard Model particles only through their couplings with the Higgs sector, the so-called Higgs-portal model. This model can be investigated by collider experiment, especially lepton collider is good at searching them through invisible decays of the Higgs boson.

In this study, we evaluate the search ability of International Linear Collider (ILC) for invisible decay of the Higgs using International Large Detector (ILD) full detector simulation. We estimate 95% C.L. upper limit (UL) on branching ratio of invisible Higgs decays and compare them between two center-of-mass energy conditions: $\sqrt{s} = 250$ GeV and 500 GeV.

In addition, we mention the complementarity of lepton collider experiment to the direct detection experiment about DM search ability.

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*Speaker.

1. Introduction

The Dark Matter (DM) is one of the mysteries left in the Standard Model (SM) of the particle physics. The existence of DM has been suggested by various astrophysical observations, and many exploratory experiments are currently underway. Although it has not yet been discovered, there are several constraints from experimental search.

One of the models that describes the interaction between DM and SM particles is the so-called Higgs-Portal model [1]. In this model, DM in the Universe interact only through their couplings with the Higgs sector of the theory. The simplest and model-independent approach is assuming the minimal Higgs sector, single doublet Higgs field structure, that leads to the SM Higgs boson which has been observed so far and the DM singlets with spin 0, 1 and 1/2. In this case, the phenomenology of the model would be described only by two parameters in addition to those of the SM: the mass of the DM state and its effective coupling to the Higgs boson. The relevant terms of the Lagrangians describing the spin 0, 1 and 1/2 DM particles interacting with the SM Higgs field Φ can be simply written as:

$$\Delta\mathcal{L}_S = -\frac{1}{2}M_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}\Phi^\dagger\Phi S^2 \tag{1.1}$$

$$\Delta\mathcal{L}_V = \frac{1}{2}M_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{HVV}\Phi^\dagger\Phi V_\mu V^\mu \tag{1.2}$$

$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi^2 \overline{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\overline{\chi}\chi\,. \tag{1.3}$$

This model can be searched by collider experiments. In the SM, Higgs can decay into two Z bosons which branching ratio is 2.62%. When both of them decay into neutrinos, Higgs disappears from the detector. In such case, the branching ratio should be about 0.1%. If there are any physics beyond the SM, for example DM ($m_{DM} < m_H/2$), the branching ratio of the invisible Higgs decay can exceed significantly.

Today, the observed (expected) limit of 19% (15%) is set by the CMS group [2] and 26% (17%) by the ATLAS group [3] at 95% C. L. in the LHC experiment. In addition, the HL-LHC prospect is estimated as 1.9% in Ref. [4]. In fact, measurement of missing energy is not easy with hadron collider because the initial state of collision is not very clear. On the other hand, the lepton collider, such as International Linear Collider (ILC) [5, 6, 7, 8, 9], can search for invisible decay with high accuracy by clean measurement environment and the recoil mass technique.

Therefore, we aim to evaluate the searchability of ILC for invisible decay of the Higgs boson. ILC is a linear lepton collider which collides electrons and positrons. Its total length is planned to be 20km which corresponds to center-of-mass energy of $\sqrt{s} = 250$ GeV and upgradable to 500 GeV or 1 TeV in the future which is a unique advantage of linear accelerators. In addition, the beam polarization is also powerful tool to suppress backgrounds derived from W boson.

In this study, we use International Large Detector (ILD) [9] which is one of the detector concepts for the ILC. ILD is designed to optimize Particle Flow Algorithm (PFA) [10] which enables to reconstruct and identify all the particles, especially hadron jets. The jet energy resolution of ILD could be 3 - 4% using PFA.

In this study, we aim to estimate 95% C.L. upper limit (UL) on branching ratio (BR) of invisible Higgs decay at the ILC with ILD full detector simulation.

2. Target Process

As a signal process in this study, we deal with the Higgs-strahlung process shown in Figure 1 with $H \to invisible$ and $Z \to q\bar{q}$ which are expected to be the most sensitive channels because of the high statistics. On the other hand, for the leptonic decays of Z, we would refer to previous study [11].

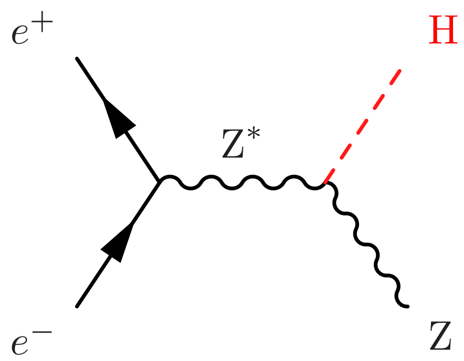

Figure 1: The diagram of Higgs-strahlung process

Against this signal process, the main background processes are $e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$ and $e^+e^- \to WW \to l\nu q\bar{q}$.

3. Simulation Conditions

In this section, the simulation conditions for collider, detector and event samples are described.

We assume two center-of-mass energy, $\sqrt{s} = 250$ GeV and 500 GeV, and two beam polarization parameters, $(P_{e^-}, P_{e^+}) = (\mp 0.8, \pm 0.3)$. Integrated luminosity for one beam pol. is 900 fb^{-1} for $\sqrt{s} = 250$ GeV and 1600 fb^{-1} for $\sqrt{s} = 500$ GeV based on 250 GeV ILC staging scenario [12].

We use the signal and background samples based on the ILC Technical Design Report [5, 6, 7, 8, 9]. The beam energy spectrum includes the effects by beamstrahlung and the initial state radiation. The beam backgrounds from $\gamma\gamma$ interactions are included in all signal and background processes. As a signal process, $e^+e^- \to q\bar{q}H$ with $H \to ZZ \to 4\nu$ is used adjusting $BR(H \to invisible) = 10\%$. The background processes from e^+e^- interactions are categorized according to the number of final-state fermions and whether Higgs is included: two fermions (2f), four fermions (4f) and SM Higgs processes.

We perform the detector simulation with Mokka [13]/ DD4Hep [14], a Geant4-based [15] full simulation, with the ILD detector model ILD_o1_v05 / ILD_l5_o1_v02 for $\sqrt{s} = 250$ / 500 GeV.

4. Analysis

We analyze in three steps: reconstruction, event selection and UL estimation.

4.1 Event Reconstruction

Events have been reconstructed using `PandoraPFA` [10] in the `Marlin` framework [16].

Isolated lepton tagging is performed with `IsolatedLeptonTagging` processor [17] to remove events which contain isolated leptons. We use the parameters summarized in Table 1 for `IsolatedLeptonTagging`, where E_{CAL} is the energy deposit in the calorimeter system, and p is the track momentum. A multivariate double cone method is used and a cut on MVA output is applied.

Table 1: Parameters for isolated lepton tagging.

variable	condition	
	electron	muon
E_{CAL}/p	0.5 - 1.3	< 0.3
p	> 5 GeV	> 5 GeV
$E_{\mathrm{ECAL}}/(E_{\mathrm{ECAL}}+E_{\mathrm{HCAL}})$	> 0.9	-
E_{yoke}	-	> 1.2 GeV
MVA cut for $\sqrt{s}=250$	> 0.5	> 0.5
MVA cut for $\sqrt{s}=500$	> 0.8	> 0.8

After Isolated lepton tagging, jet clustering forced to two jets is performed using `LCFIPlus` processor [18] and its clustering method is Durham algorithm. At the same time, beam background rejection is performed only at $\sqrt{s}=500$ GeV with rejection parameter α of 5.0.

4.2 Event Selection

After event reconstruction step, event selection is performed. As mentioned above, the branching ratio of $H \to invisible$ is assumed as 10% just for simplicity of event selection. The cut conditions and number of remaining events for $\sqrt{s}=250$ GeV are listed in Table 2 and 3 where significance is defined as $N_S/\sqrt{N_S+N_B}$. And also the recoil mass distribution after event selection is shown in Figure 2 for $\sqrt{s}=250$ GeV and Figure 3 for $\sqrt{s}=500$ GeV.

Table 2: Selection table for $\sqrt{s}=250$ GeV, $(P_{e^-},P_{e^+})=(-0.8,+0.3)$

cut condition	signal (efficiency)	all bkg (efficiency)	significance
No Cut	18917 (1.000)	1.417×10^{8} (1.000)	1.59
$N_{lep}=0$	18880 (0.998)	9.732×10^{7} (0.687)	1.91
Pre-Cut	18202 (0.962)	3.358×10^{6} (0.024)	9.91
$N_{pfo}>15\&N_{charged}>6$	17918 (0.947)	2.539×10^{6} (0.018)	11.2
$p_{Tjj}\in(20,80)$GeV	16983 (0.898)	1.368×10^{6} (0.010)	14.4
$M_{jj}\in(80,100)$GeV	14158 (0.748)	713194 (0.005)	16.6
$\lvert\cos\theta_{jj}\rvert<0.9$	13601 (0.719)	539921 (0.004)	18.3
$M_{recoil}\in(100,160)$GeV	13585 (0.718)	244051 (0.002)	26.8

Table 3: Selection table for $\sqrt{s} = 250$ GeV, $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$

cut condition	signal (efficiency)	all bkg (efficiency)	significance
No Cut	12776 (1.000)	7.785×10^7 (1.000)	1.45
$N_{lep} = 0$	12752 (0.998)	4.893×10^7 (0.628)	1.82
Pre-Cut	12270 (0.9609	1.329×10^6 (0.017)	10.6
$N_{pfo} > 15\&N_{charged} > 6$	12067 (0.945)	852285 (0.011)	13.0
$p_{Tjj} \in (50, 250)$GeV	11394 (0.892)	285847 (0.004)	20.9
$M_{jj} \in (80, 120)$GeV	9481 (0.742)	165798 (0.002)	22.6
$\lvert\cos\theta_{jj}\rvert < 0.98$	9126 (0.714)	130070 (0.002)	24.5
$M_{recoil} \in (80, 330)$GeV	9115 (0.713)	62979 (0.001)	33.9

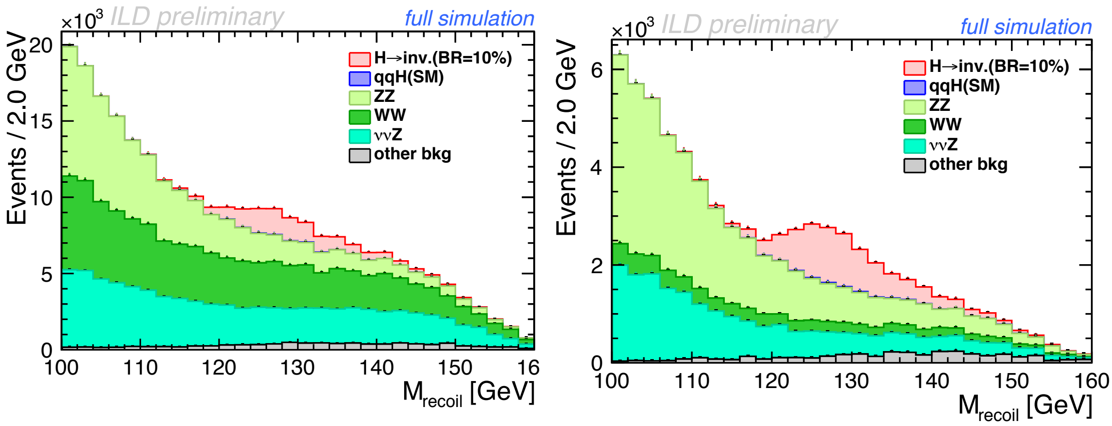

Figure 2: Recoil mass distribution after event selection at $\sqrt{s} = 250$ GeV. (left): $(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$, (right): $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$.

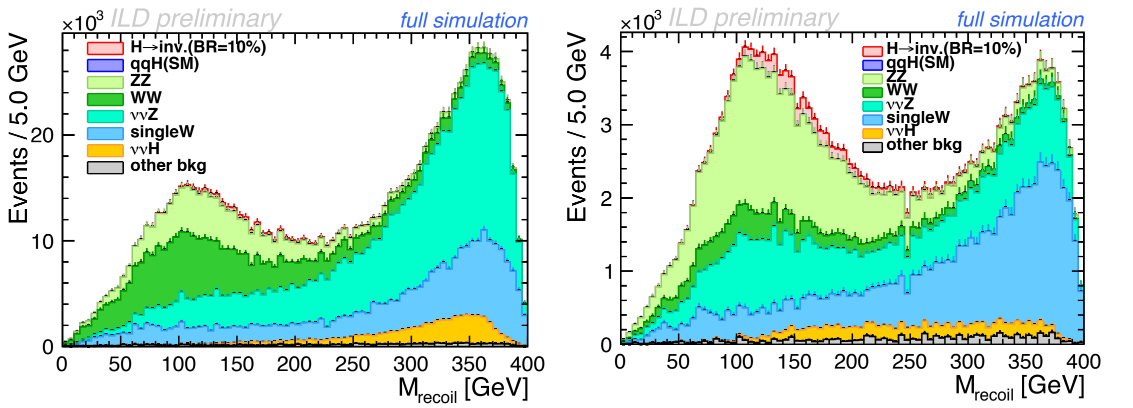

Figure 3: Recoil mass distribution after event selection at $\sqrt{s} = 500$ GeV. (left): $(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$, (right): $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$.

4.3 Upper Limit Estimation

After event selection, we estimate 95% C.L. UL on BR($H \to invisible$). First, we calculate significance fromN_S and N_B for each bin of the recoil mass distribution after selection and combine them in all bins (Root Mean Square). Then, UL is calculated with combined significance using following formula;

$$UL_{95\% C.L.}(\%) = \frac{10[\%] \times 1.65}{significance(BR = 10[\%])}. \tag{4.1}$$

5. Results

The results are summarized in Table 4 for $\sqrt{s} = 250$ GeV and Table 5 for $\sqrt{s} = 500$ GeV where the leptonic channel results are also converted from previous study[] and filled.

Table 4: 95% C.L. UL on BR($H \to invisible$) for $\sqrt{s} = 250$ GeV

Mode	(-0.8,+0.3)	(+0.8,-0.3)	combined
$Z \to q\bar{q}$	0.44%	0.31%	0.25%
$Z \to l\bar{l}$	1.06%	0.67%	0.57%
combined	-	-	0.23%

Table 5: 95% C.L. UL on BR($H \to invisible$) for $\sqrt{s} = 500$ GeV

Mode	(-0.8,+0.3)	(+0.8,-0.3)	combined
$Z \to q\bar{q}$	1.30%	0.98%	0.78%
$Z \to l\bar{l}$	2.03%	1.48%	1.19%
combined	-	-	0.65%

From these results, we can obviously say that the sensitivity is quite better at $\sqrt{s} = 250$ GeV than 500 GeV. In addition, the hadronic channel ($Z \to q\bar{q}$) has a dominant role for search for invisible Higgs decays. Moreover, comparing the final result of ILC-250, 0.23%, and HL-LHC prospect, 1.9%, ILC-250 gives a factor of 10 better than HL-LHC prospect.

Finally we would like to mention the impact of collider experiments on search for DM. Figure 4 from Ref. [19, 4] shows the limit of cross section between DM and nucleon as a function of DM mass. And the green line shows the ILC results. These plots tell us two important messages. One is that the collider experiments is more sensitive especially in low mass region and complementary to direct search experiments. The other is that ILC is comparable with the other lepton collider projects.

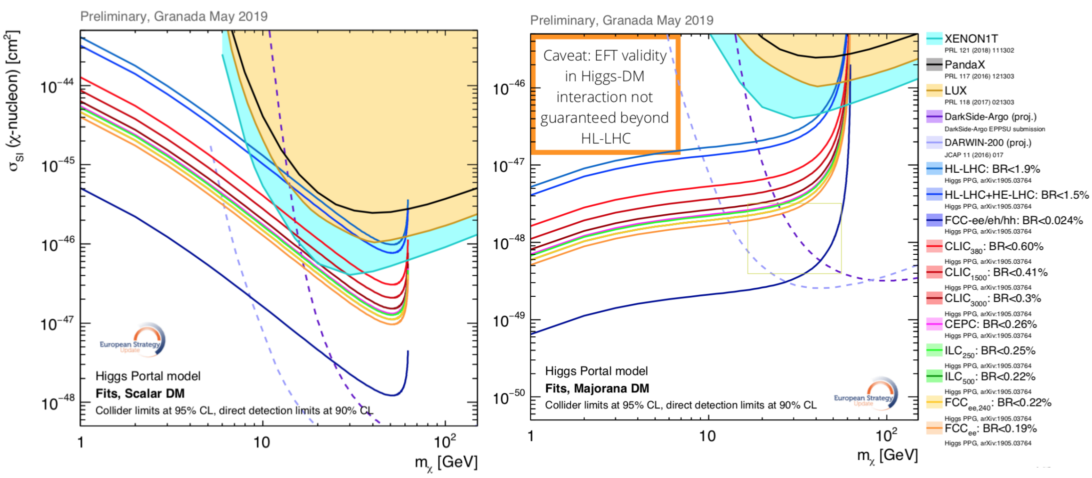

Figure 4: DM limitations. (left): Scalar DM, (right): Majorana DM.

6. Summary

We evaluated the searchability of ILC for invisible decay of the Higgs using ILD full detector simulation. Finally we obtained the 95% C.L. UL on BR($H \to invisible$) of 0.23% for 250 GeV ILC. This limitation is a factor of 10 better than the HL-LHC prospect. We also compared the DM search possibilities of the other lepton collider projects and direct detection experiments. We can say that ILC is comparable with the other lepton colliders and lepton collider project is complementary to direct search experiment.

References

[1] G. Arcadi, A. Djouadi, M. Raial, *Dark Matter through the Higgs portal*, arXiv:1903.03616.

[2] CMS Collaboration, *Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at $\sqrt{s} = 13$ TeV*, arXiv:1809.05937.

[3] ATLAS Collaboration, *Search for invisible Higgs boson decays in vector boson fusion at $\sqrt{s} = 13$ TeV with the ATLAS detector*, arXiv:1809.0668.

[4] J. de Blas, M. Cepeda, J. D'Hondt, R. K. Ellis, C. Grojean, B. Heinemann, et al., *Higgs Boson studies at future particle colliders*, arXiv:1905.03764.

[5] T. Behnke, J. E. Brau, B. Foster, J. Fuster, M. Harrison, J. M. Paterson et al., *The International Linear Collider Technical Design Report - Volume 1: Executive Summary.* , arXiv:1306.6327.

[6] H. Baer, T. Barklow, K. Fujii, Y. Gao, A. Hoang, S. Kanemura et al., *The International Linear Collider Technical Design Report - Volume 2: Physics.* , arXiv:1306.6352.

[7] C. Adolphsen, M. Barone, B. Barish, K. Buesser, P. Burrows, J. Carwardine et al., *The International Linear Collider Technical Design Report - Volume 3.I: Accelerator & in the Technical Design Phase.* , arXiv:1306.6353.

[8] C. Adolphsen, M. Barone, B. Barish, K. Buesser, P. Burrows, J. Carwardine et al., *The International Linear Collider Technical Design Report - Volume 3.II: Accelerator Baseline Design.* , arXiv:1306.6328.

[9] H. Abramowicz et al., *The International Linear Collider Technical Design Report - Volume 4: Detectors*, arXiv:1306.6329.

[10] M. A. Thomson, *Particle flow calorimetry and the PandoraPFA algorithm*, Nucl. Instrum. Meth. **A611** (2009) 25.

[11] J. Tian, *"Sensitivity of Higgs self-coupling in BSM & Higgs invisible decay using Z->ll"*, Presentation at the 41th ILC General Meeting of ILC Physics Subgroup.

[12] K. Fujii, C. Grojean, M. E. Peskin, T. Barklow, Y. Gao, S. Kanemura, et al., *Physics Case for the 250 GeV Stage of the International Linear Collider*, arXiv:1710.07621.

[13] P. Mora de Freitas, H. Videau, *"Detector simulation with MOKKA / GEANT4: Present and future"*, LC-TOOL-2003-010.

[14] M. Frank et al., *AIDASoft/DD4hep*, webpage: http://dd4hep.cern.ch/dd4hep/, 2018.

[15] GEANT4 Collaboration, *Geant4 — a simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003) 250.

[16] F. Gaede, *Marlin and LCCD: Software tools for the ILC*, Nucl. Instrum. Meth. **A559** (2006) 177.

[17] J. Tian, C. Duerig, *isolated lepton finder*, Presentation at High Level Reconstruction Week, 2015.

[18] T. Suehara, T. Tanabe, *LCFIPlus: A Framework for Jet Analysis in Linear Collider Studies*, Nucl. Instrum. Meth. **A808** (2016) 109.

[19] C. Doglioni, *Dark Matter at colliders*, Presentation at Open Symposium - Update of the European Strategy for Particle Physics.