ILD-PHYS-PROC-2019-006

Search for Extra Scalars Produced in Association with Muon Pairs at the ILC

Yan Wang[◇∗], **Jenny List**[◇], **Mikael Berggren**[◇]
[◇] *DESY, Notkestraße 85, 22607 Hamburg, Germany*
[∗] *IHEP, 19B Yuquan Road, Shijingshan District, Beijing, China*
E-mail: yan.wang@desy.de

on behalf of the International Large Detector concept group

We study the search for an extra scalar S boson produced in association with the Z boson at the International Linear Collider (ILC). The study is performed at center-of-mass energies of 500 GeV based on the full simulation of the International Large Detector (ILD). In order to be as model-independent as possible, the analysis uses the recoil technique, in particular with the Z boson decaying into a pair of muons. As a result, exclusion cross-section limits are given in terms of a scale factor k with respect to the Standard Model Higgs-strahlung process cross section. These predicted results, covering all possible searching regions of the extra scalars at the 500 GeV ILC, can be interpreted independently of the decay modes of the S boson.

1. Introduction

The motivation of our study is to find a new scalar S boson in the SZZ coupling since one or more extra scalars are predicted in many new physics models. However, the properties of 125 GeV scalar measured at the LHC is very similar to the Standard Model (SM) Higgs boson [1]. As a result, the new scalar's +coupling will be highly suppressed [2]. Furthermore, the LEP/LHC constraints on the extra scalars always rely on the model details. Thus, a more precise analysis with model-independent assumptions to a scalar with the small coupling is preferred. Although the OPAL collaboration has searched for light scalars (less than 100 GeV) in a model-independent way at LEP, the results are limited by the low luminosity [3]. The International Linear Collider (ILC) is a proposed electron-positron linear collider, whose luminosity will be over a thousand times higher than that of LEP, which makes the recoil mass technique more accurate to find such extra scalars [4]. And the ILC has higher center-of-mass energies, which will cover more searching regions for the extra scalar. A preliminary version of this analysis has been reported at LCWS2017 [5] and ICHEP2018 [6]. Thus, only the updates from ICHEP2018 is summarized in this contribution.

2. Event Generation and Detector Simulation

The signal is $e^+e^- \to S+Z$ production, where the Z boson decays to a pair of muons. The decay branching ratios of S are fixed as same as the 125 GeV Higgs boson, but no use would be made of this fact. As SM backgrounds, bremsstrahlung and initial state radiation (ISR) are explicitly considered for all events. The event samples are generated with 100% left-handed and right-handed beam polarization, using the Whizard 1.95 Monte Carlo (MC) event generator [7]. Then the samples are reweighted with beam polarizations of $\pm 80\%$ for the electron beam and $\pm 30\%$ for the positron beam.

The event samples are generated by Whizard1.95 with considering ISR effect. The Pythia is used for hadronization. The events are simulated with two detector configurations, the IDR-L model and IDR-S model , which is performed under DD4HEP framework based on Geant4. The $\gamma\gamma \to$ low Pt hadron and e^+e^- seeable pairs are generated based on the cross section model, and overlaid to all MC samples before the reconstruction. Then all the events are reconstructed using PandoraPFA algorithm in the Marlin framework to reconstruct individual final state particles, so-called Particle Flow Objects (PFOs). For the SM background, we use the samples generated in the context of the ILD Design Report [9], the fractions of integrated luminosity 4000 fb^{-1} are dedicated to $(-+,+-,++,--) = (40\%, 40\%, 10\%, 10\%)$. For the signal, totally 48 signal benchmark points are chosen in the range of $10 \le M_S \le 410$ GeV.

2.1 Event selection and Background Rejection

ILCSoft with the version of v02-00-02 is used for all the analysis. Firstly, we use updated version of IsolatedLeptonTagging, with $E_{CAL}/p < 0.5$, $p > 10$ GeV, MVA cut > 0.8. The E_{CAL} is the energy deposit in the calorimeter system, and p is the track momentum. A multivariate double cone method is used for muon isolation identification in this processor. With this processor, we require the event to have at least one μ^+ and one μ^- for further analysis.

$M_{\mu^+\mu^-}$	$\in [70,110]$Event reconstruction has been performed using the PandoraPFA algorithm to recon- struct individual final state particles, so-called Particle Flow Objects (PFOs), within the Marl
$P_T^{\mu^+\mu^-}$	$\in [0,245]$ GeV
$sigma(M_{mu^+mu^-})$	$\in [0,1]$ GeV
MVA_{2f}	$[0.75,1]$
MVA_{4f}	$[0.5,1]$
ISR photon veto	$E_\gamma^{central} < 230$ GeV & $E_\gamma^{forward} < 150$ GeV
M_{rec}	$\in [M_S - 20, 450] GeV$

Table 1: The cuts' values in this analysis.

Then, a pair of oppositely charged muons is selected by minimizing the following χ^2 function:

$$\chi^2(M_{\mu^+\mu^-}, M_{\texttt{rec}}) = \frac{(M_{\mu^+\mu^-} - M_Z)^2}{\sigma^2_{M_{\mu^+\mu^-}}} + \frac{(M_{\texttt{rec}} - M_S)^2}{\sigma^2_{M_{\texttt{rec}}}}, \tag{2.1}$$

where $M_{\mu^+\mu^-}$ and $M_{\texttt{rec}}$ are the invariant mass and the recoil mass of the muon pair, and $\sigma_{M_{\mu^+\mu^-}}$ and $\sigma_{M_{\texttt{rec}}}$ are resolusion of $M_{\mu^+\mu^-}$ and $M_{\texttt{rec}}$. After selecting the muon pair, the bremsstrahlung and final state radiation photons from the muons are combined with the muons.

The following Figures 1 shows the invariant mass distribution, reconstruction uncertanty (M_{PFO}-M_{MC}) distribution, and detector resolution $\sigma_{M_{\mu\mu}}$ distribution of $\mu^+\mu^-$ pair for two fermion backgrounds and the $M_S = 20$ signal process for IDR-L and IDR-S.

Similarly, we use ISRPhotonTagging to select isolated ISR photons. A multivariate double cone method is also used for photon isolation identification, with the MVA cut > 0.8. In Figures 2, it shows the isolated ISR photon tagging efficiency to the signal and background.

Background events are rejected by firstly considering kinematic variables only relied on muons (and the reconstructed Z boson): the invariant mass and transverse momentum of the muon pair, as well as the polar angle of the missing momentum.

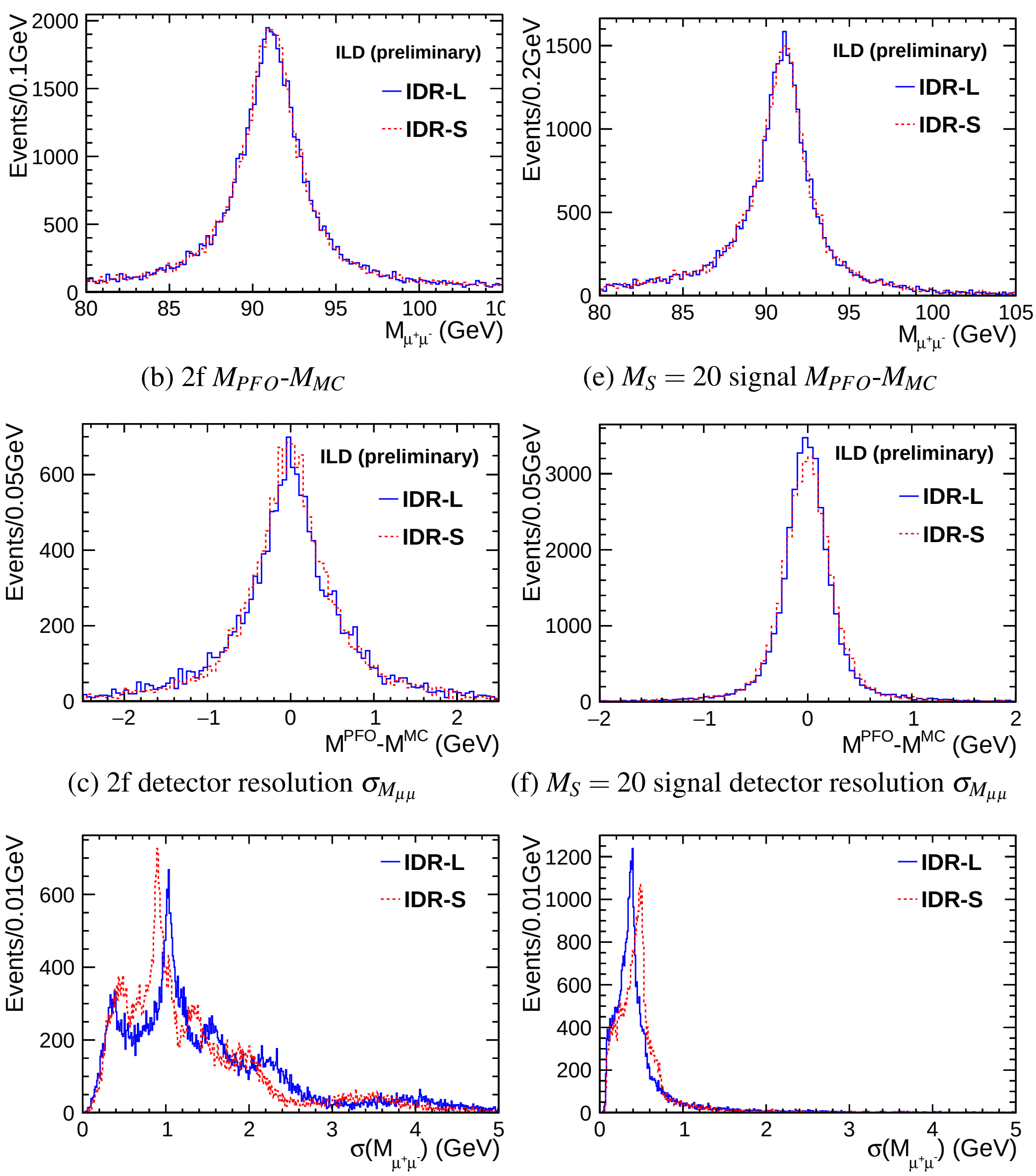
The multivariate analysis is used to improve sensitivity after preselection. A gradient boosted decision tree technique (BDTG) is used which is implemented in TMVA [10] in ROOT. Totally two BDTGs are used. The first one is trained using 6 input variables: muon pair invariant mass, the polar angle of each muon, the polar angle of the muon pair, the opening angle of the muon pair, and the $\pi - (\phi_{\mu^+} - \phi_{\mu^-})$, where $\phi_{\mu^\pm}$ is the azimuthal angles of the muons with respect to the beam line. Then, if a ISR photon is tagged, the two muons are boosted to the effective center-of-mass reference frame along the ISR photon. The other BDTG are trained with these effective muon pair invariant mass, the polar angle of each muon, the polar angle of the muon pair, the opening angle of the muon pair, and the $\pi - (\phi_{\mu^+} - \phi_{\mu^-})$. The first BDTG is trained for two fermion backgrounds. The second BDTG is trained for the four fermion backgrounds.

Finally, taking into account the ISR photon return effects, the two fermion background can be further rejected by ISR energy veto cuts. With these cuts, no information on the decay of S is needed, thus the expected results will be model-independent. A simplified cut table is shown in Table 2

The recoil mass distributions are obtained after these cuts in Figure 3. The events number after cuts for IDR-L and IDR-S, when $M_S = 20$ GeV, $(-,+)$ polarization and 4000 fb^{-1} luminosity, are summarized in Table 1 as an example.

3. Results

A likelihood analysis is applied for calculating 2 σ expected exclusion limits on k with a bin-



(a) 2f invariant mass distribution

(d) $M_S = 20$ signal invariant mass

(b) 2f M_{PFO}-M_{MC}

(e) $M_S = 20$ signal M_{PFO}-M_{MC}

(c) 2f detector resolution $\sigma_{M_{\mu\mu}}$

(f) $M_S = 20$ signal detector resolution $\sigma_{M_{\mu\mu}}$

Figure 1: The invariant mass distribution, reconstruction uncertanty (M_{PFO}-M_{MC}) distribution, and detector resolution $\sigma_{M_{\mu\mu}}$ distribution of $\mu^+\mu^-$ pair for two fermion backgrounds and the $M_S = 20$ signal process for IDR-L and IDR-S.

by-bin comparison between the signal and background recoil mass histograms for each benchmark points, where k is defined as

$$k = \frac{\sigma_{SZ}}{\sigma_{H_{SM}Z}(m_{H_{SM}} = m_S)}, \tag{3.1}$$

and k_{95} is the 2 σ exclusion limits for the cross section scale factor k hereinafter.

In Figure 5, a comparison of 2 σ exclusion limits between IDR-L and IDR-S is shown. The blue and red lines are the results for IDR-L and IDR-S. When $M_S < 340$ GeV, k_{95} is in the order of 10^{-1}, which could set strong model-independent constraints for the extra scalars. There is also

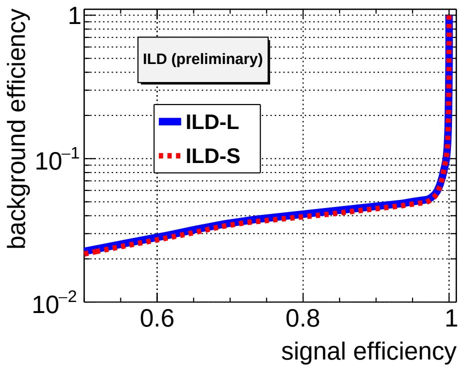


Figure 2: The isolated ISR photon tagging efficiency to the signal and background in IDR-L and IDR-S.

(a) IDR-L, $M_S = 20$ GeV

$\int Ldt = 4000 fb^{-1}$	nh_{20}	h_{e2}	$4f_l$	$4f_{sl}$	$2f_l$	*total bkg*	efficiency	significance
$M_{\mu^+\mu^-}$ & $P_T^{\mu^+\mu^-}$	20522.9	12028.9	268167	145352	1.95454e+06	2.38009e+06	1	13.2458
$sigma(M_{mu^+mu^-})$	19005.7	11757.5	217002	116560	713224	1.05854e+06	0.926073	18.309
MVA_{2f}	14016.2	10845	71403	65415.3	43906.1	191569	0.682954	30.9125
MVA_{4f}	8664.63	6071.61	9756.21	15000.9	13963.3	44792	0.422193	37.4756
ISR photon veto	8659.53	6071.61	9745.93	15000.9	4245.88	35064.3	0.421945	41.4128
M_{rec}	7396.92	6066.19	9615.85	14905.5	3030.35	33617.9	0.360423	36.5242

(b) IDR-S, $M_S = 20$ GeV

$\int Ldt = 4000 fb^{-1}$	nh_{20}	h_{e2}	$4f_l$	$4f_{sl}$	$2f_l$	*total bkg*	efficiency	significance
$M_{\mu^+\mu^-}$ & $P_T^{\mu^+\mu^-}$	20657.5	12041.2	270933	146041	1.96316e+06	2.39218e+06	1	13.2989
$sigma(M_{mu^+mu^-})$	19426.7	11829.9	229593	121850	944815	1.30809e+06	0.940419	16.8608
MVA_{2f}	14141.1	10911	72915.9	66134.5	49566.3	199528	0.68455	30.5923
MVA_{4f}	8786.63	6111.67	9996.22	15545.2	15210.2	46863.3	0.425348	37.2469
ISR photon veto	8781.81	6109.01	9995.1	15545.2	3593.12	35242.4	0.425115	41.8541
M_{rec}	7388.54	6092.86	9832.62	15473.3	2597.76	33996.5	0.357669	36.3192

Table 2: The cut table of IDR-L and IDR-S, when $M_S = 20$ GeV.

OPAL's 2 σ exclusion limits, which is about one or two order smaller than ILC results.

In Figure 5, we compare the exclusion limits for the different final state levels when using IDR-L model. The green dash line uses pythia stable particles. The red dash line uses the particles after detector simulation, but these particles are not reconstructed, especially many photons will become electron-position pairs. The blue line uses PFOs, which is well reconstructed with PFA. From this plot, we can see that in small mass region, there is still space for improvements.

4. Conclusions

By applying the recoil technique, the potential of the ILC to search for scalars has been investigated at $\sqrt{S} = 500$ GeV, with the full simulation of the ILD concept. The method is optimized to be independent of the scalar decay modes. 2 σ expected exclusion limits for the cross section scale factor k_{95} are shown for scalar mass from 10 GeV to 410 GeV when $\sqrt{S} = 500$. They are one or two orders of magnitudes more sensitive than LEP, and covering substantial new phase spaces.

Acknowledgements

We would like to thank the LCC generator working group and the ILD software working

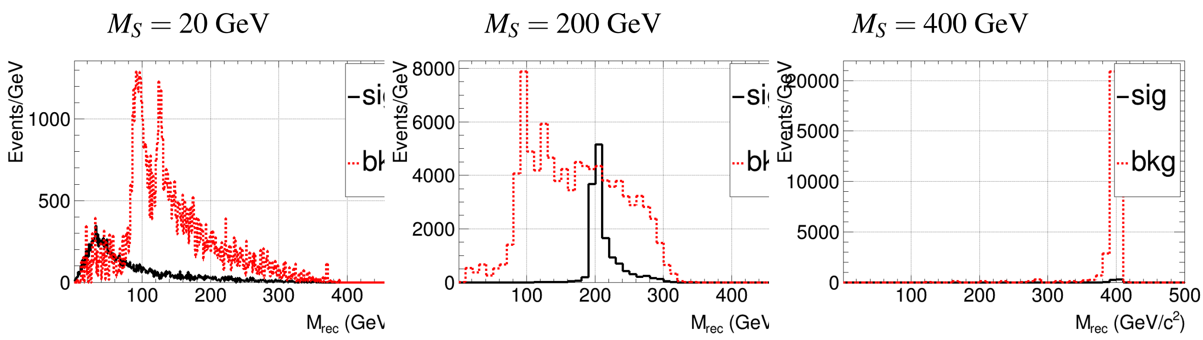


Figure 3: The recoil mass distributions after all cuts for signal and backgrounds, when $M_S = 20, 200, 400$ GeV and within IDR-L model.

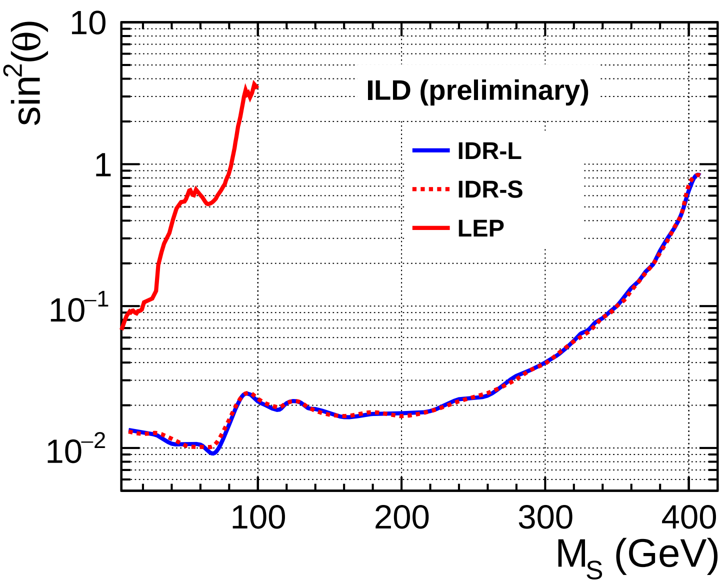


Figure 4: Preliminary Final Exclusion Limits for the cross section scale factor k for different scalar masses at 500 GeV ILC.

group for providing the simulation and reconstruction tools and producing the Monte Carlo samples used in this study. This work has benefited from computing services provided by the ILC Virtual Organization, supported by the national resource providers of the EGI Federation and the Open Science GRID. We are grateful for the support from Collaborative Research Center SFB676 of the Deutsche Forschungsgemeinschaft (DFG), Particles, Strings and the Early Universe, project B1. Y.W. is supported by the China Postdoctoral Science Foundation under Grant No. 2016M601134, and an International Postdoctoral Exchange Fellowship Program between the Office of the National Administrative Committee of Postdoctoral Researchers of China (ONACPR) and DESY.

References

[1] The ATLAS and CMS collaboration, "Measurements of the Higgs boson production and decay rates and constraints on its couplings fr $M_{\mu^+\mu^-} \in [70, 110]$ & $P_T^{\mu^+\mu^-} \in [0, 245]$om a combined ATLAS and

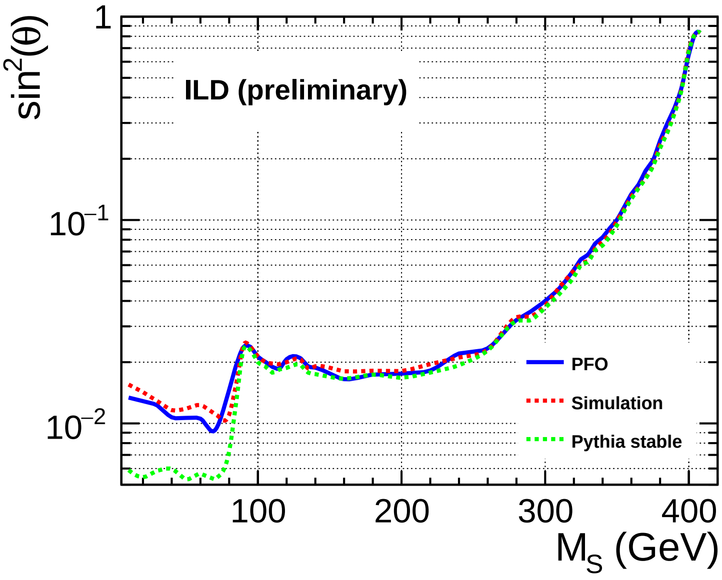


Figure 5: Exclusion Limits for the cross section scale factor k for different scalar masses, when comparing the reconstruction efficiency with pythia stable particles.

CMS analysis of the LHC pp collision data at $\sqrt{S} = 7$ and 8 TeV", JHEP 08 (2016) p.045.

[2] R. Aggleton et al., "Review of LHC experimental results on low mass bosons in multi Higgs models", JHEP 02 (2017) p. 035.

[3] G. Abbiendi , "Decay mode independent searches for new scalar bosons with the OPAL detector at LEP", Eur. Phys. J. C27 (2003) p. 311-329.

[4] D. M. Asner et al., "ILC Higgs Wh ite Paper", Proceedings, CSS2013 (2013) Minneapolis, USA, July 29-August 6, 2013.

[5] Y. Wang, J. List,and M. Berggren, "Search for Light Scalars Produced in Association with Muon Pairs for $\sqrt{s}$ = 250 GeV at the ILC", arXiv:1801.08164 [hep-ex].

[6] Y. Wang, J. List,and M. Berggren, "Search for Light Scalars Produced in Association with a Z boson at the 250 GeV stage of the ILC", ICHEP2018 Proceeding, PoS(ICHEP2018) 630.

[7] W. Kilian, T. Ohl and J. Reuter, "WHIZARD: Simulating Multi-Particle Processes at LHC and ILC", Eur. Phys. J. C **71**, 1742 (2011).

[8] H. Abramowicz et al., "The International Linear Collider Technical Design Report", ILC-REPORT-2013-040.

[9] ILD Detector Collaboration, "ILD Design Report" (2019).

[10] TMVA home page https://root.cern/tmva.

[11] R. Barate et al., "Search for the standard model Higgs boson at LEP", Phys. Lett. B565 (2003) p. 61-75.

[12] P. Drechsel, G. Moortgat-Pick, and G. Weiglein, "Sensitivity of the ILC to light Higgs masses", arXiv:1801.09662[hep-ph].