A MEASUREMENT OF $\sigma_{Zh}$ AT A FUTURE $e^+e^-$ COLLIDER
USING THE HADRONIC DECAY OF $Z$

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Abstract

A feasibility to use the hadronic decay mode of $Z$ for the model independant measurement of the total cross section of Higgs-strahlung process ($\sigma_{Zh}$) at a future $e^+e^-$ collider was studied. For the recoil mass measurement from hadronic decay of $Z$, a simple cut based analysis was applied on samples produced by the ILD full detector simulation at $\sqrt{s} = 350$ GeV and 500 GeV using the ILC beam parameters. At 350 GeV, a bump in the recoil mass distribution was reconstructed, and $\Delta\sigma_{Zh}/\sigma_{Zh} = 3.4\%$ was obtained assuming 165 fb$^{-1}$ data with $e^-(e^+)$ beam polarization of -80%(+30%) and +80%(-30%), respectively. At 500 GeV, clear Higgs boson peak in the recoil mass distribution was not seen, however, from the excess of the events, $\Delta\sigma_{Zh}/\sigma_{Zh} = 3.9\%$ was obtained assuming 500 fb$^{-1}$ data with $e^-(e^+)$ beam polarization of -80%(+30%).

1 Introduction

The total cross section of the Higgs-strahlung process ($\sigma_{Zh}$) can be measured model independently using the recoil mass technique at a future $e^+e^-$ collider. The $ZZh$ coupling strength derived from this measurement is a crucial input for investigating physics beyond the standard model though Higgs properties.

Previously, the recoil mass of the Higgs-strahlung process were studied for the case where $Z$ decays to $e^+e^-$ or $\mu^+\mu^-$ pairs; $Z$ momentum can be measured precisely thanks to a high precision tracking detector and a good signal to noise ratio in the recoil mass measurement has been reported (see ref. [1] and reference therein). In the case of ILC, 2.6% of the measurement precision for the total cross section, $\Delta\sigma_{Zh}/\sigma_{Zh}$, was expected from the recoil mass measurement by combining $e^+e^-$ and $\mu^+\mu^-$ channel at $\sqrt{s} = 250$ GeV with 250 fb$^{-1}$ data [1][2]. At 350 GeV, the recoil mass resolution is worse than the 250 GeV case, but similar precision[1] of the total cross section measurement is expected from a fast simulation study of $\mu^+\mu^-h$ channel [3], thanks to the better signal selection efficiency and the higher luminosity provided by ILC. At 500 GeV, the performance is degraded by further worse recoil mass resolution and increased standard model background, still a preliminary result of $\Delta\sigma_{Zh}/\sigma_{Zh}=4.8\%$ combining $e^+e^-$ and $\mu^+\mu^-$ channels were reported assuming 500 fb$^{-1}$ data.

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1 About 10% worse precision would be expected because the result on $\mu^+\mu^-h$ in ref. [3] could be scaled by ILC TDR luminosity to $\Delta\sigma_{Zh}/\sigma_{Zh}$ of 3.4% for 250 fb$^{-1}$ at 250 GeV and 3.7% 330 fb$^{-1}$ at 350 GeV, respectively.
with -80%(+30%) \(e^-(e^+)\) beam polarization \[2, 4\]. The recoil mass measurement by using the leptonic decay mode of \(Z\) is limited by the small branching ratio of \(Z\). In order to achieve a precision close to 1%, a measurement with higher luminosity has been proposed \[2\].

The branching ratio of \(Z\) to quark pair is about factor 10 larger than the sum of \(e^+e^-\) and \(\mu^+\mu^-\) mode. In this paper, we study a feasibility of recoil mass measurement using hadronic decay mode of \(Z\). The detectors for ILC are equipped with a particle flow calorimeter, aiming to achieve the jet energy resolution \((\Delta E/E)\) better than 30%/\(\sqrt{E}\) (GeV). The high precision jet energy measurement is crucial for this study.

Note that the recoil mass of Higgs-strahlung process is given by \(m_h^2 = E_{cm}^2 - 2E_{cm}E_Z + m_Z^2\) when the effect of beamstrahlung and bremsstrahlung is neglected, where \(m_h, m_Z, E_{cm}\), and \(E_Z\) are the mass of higgs, \(Z\), the center of mass energy and the energy of \(Z\). Therefore, the recoil mass resolution, \(\Delta m_h\), is given by \(\Delta m_h = (E_{cm}/m_h)\Delta E_Z\). If \(E_Z\) is measured by a PFO calorimeter, the relative energy resolution of jet is almost independent of the jet energy; in the case of ILD, \(\Delta E_Z/E_Z \sim 3\%\) for \(E_Z\) from 90 to 500 GeV is expected \[5\]. Therefore, \(\Delta m_h \propto E_{cm}^2/2m_h\), approximating \(E_Z \sim E_{CM}/2\) and the recoil mass resolution gets worse at higher energy.

On the other hand, the jet clustering is challenging near \(Zh\) threshold due to jet overlap, which limits the mass resolution of \(Z\) in jet mode. In this paper, we concentrate on the study at \(\sqrt{s} = 350\) GeV and 500 GeV, where jet are relatively sharp and separated.

We used events generated by Whizard 1.95 with ILC beam parameter \[5\]. ILD full detector simulation and reconstruction were used in order to take into account signal smearing by detector effects. The underlying low \(p_t\) hadron background events with an average number of events of 0.33 (1.7) at \(\sqrt{s} = 350(500)\) GeV and the beam crossing of 7mrad were taken into account as well.

## 2 Recoil mass measurement at \(\sqrt{s} = 350\) GeV

For the inclusive jet selection, the \(k_t\) jet algorithm implemented in Fastjet \[6\] was employed with the jet radius of 1.2 and \(p_{t,\text{min}} = 1.0\) GeV/c\(^2\) without restricting the number of reconstructed jets. Then all combinations of jet pairs were tried to find a jet pair of mass consistent with \(Z\). A good \(Z\) jet pair was selected by following conditions; (1) Squared transverse momentum \((k_t^2)\) of first jet was between 4000 to 6000 (GeV/c\(^2\))^2; (2) \(k_t^2\) of second jet was greater than 500 (GeV/c\(^2\))^2; (3) Jet pair energy was between 140 to 180 GeV; (4) Corrected mass of jet pair was between 85 to 100 GeV/c\(^2\); (5) No photon with energy greater than 80 GeV in the event.

With the selection (1) and (2), the clusters of \(Z\) and \(h\) in the scatter plot of the mass and the energy are clearly seen in the case of \(q\bar{q}h\) events as shown in Fig. 1a. In order to remove the observed correlation between the energy and the mass seen in the Fig. 1a, the four vector of the jet pair was multiplied by a factor, which was determined to remove the linear correlation between the energy and the mass. The corrected four vector was used to calculate the recoil mass. The scatter plot of the mass and the recoil mass after the correction is shown in Fig. 1b. The recoil mass of \(Z\) pair clustered near the input Higgs mass of 125 GeV/c\(^2\), while those for \(h\) pair were shifted from the right position because the correction factor was determined by \(Z\) candidate alone, which does not affect the result of this analysis. The last cut (5) was to remove one of the major background, \(e^+e^- \rightarrow q\bar{q}\gamma\). If more than one \(Z\) candidate was found, only first candidate was selected. Note that the output of Fastjet is sorted by descending order of jet \(p_t\).
For the background processes, following processes were considered; \( e^+e^- \rightarrow q\bar{q}, q\bar{q}q\bar{q}, q\ell\nu, \ell\ell\nu\bar{\nu}, tf, \) Higgs process other than \( q\bar{q}h \), and 2\( f \) and 4\( f \) processes created by \( \gamma\gamma \), and 3\( f \) and 5\( f \) processes created by \( e\gamma \) collisions. They were produced for the Snowmass study using the software tools prepared for the ILC DBD \cite{7}. Fig. 2a shows the recoil mass distribution of selected events. The red is the standard model background and the black is the signal contribution. Fig. 2b is the distribution after subtracting the standard model background.

Finally \( q\bar{q}h \) events were selected by requiring the recoil mass between 123 and 133 GeV/\( c^2 \). The number of signal and background events selected is summarized in Tab. 1 signal to noise ratio (S/N) was 0.049 for -80%(+30%) \( e^-/e^+ \) beam polarization, and 0.153 for +80%(-30%) \( e^-/e^+ \) polarization. Assuming 165 fb\(^{-1} \) data taking for each beam polarization configuration,
the number of signal events was 6194/4169 for -80% (+30%)/+80%(-30%) beam polarization. $q\bar{q}$, $q\bar{q}q\bar{q}$, and $q\bar{q}\ell\nu$ were major backgrounds while $q\bar{q}q\bar{q}$ contribution dominated in the case of -80% (+30%) beam polarization case. The expected accuracy of the $Zh$ total cross section measurement was 5.9% and 4.3% for -80%/+30% and +80%/-30% beam polarization, respectively. Combining two measurement, 3.4% accuracy was expected from the inclusive jet pair measurement.

The recoil mass study using $\mu\bar{\mu}$ channel at 350 GeV was reported in ref. [3] using LOI ILD full simulation and the Higgs mass of 120 GeV/c$^2$. This study compared the accuracy at 250 GeV and 350 GeV and concluded that the expected accuracy of the $Zh$ total cross section ad 250 GeV and 350 GeV were similar. As described previously, at 250 GeV, $\Delta\sigma/\sigma = 2.6\%$ is expected from the recoil mass measurement of $\mu\bar{\mu}$ and $ee$ channel. Assuming the same accuracy of 2.6% can be obtained at 350 GeV using $\mu\bar{\mu}$ and $ee$ channel, we can expect $\Delta\sigma/\sigma = 2.1\%$ by combining the result of the recoil mass measurement of inclusive two jet. If this measurement is combined with the 2.6% measurement at 250 GeV, we could expect $\Delta\sigma/\sigma = 1.6\%$ combining 250 GeV and 350 GeV data taking.

### 3 Recoil mass measurement at $\sqrt{s} = 500$ GeV

At $\sqrt{s} = 500$ GeV, the total cross section of $e^+e^- \rightarrow q\bar{q}h$ process is about 70 fb when the $e^- (e^+)$ beam polarization is -80% (+30%). About 35k such events are produced for 500 fb$^{-1}$ integrated luminosity. The resolution of jet energy and recoil mass are not as good as a lower energy measurement and leptonic channel, still, we could study this channel thanks to the relatively larger event statistics and the monotonic $Z$ and $H$ energy due to s-channel 2 body production.

The major background processes are those by 4-fermion $W^+W^-$, $Z^0Z^0$, and 2-fermion $q\bar{q}$ processes and it is not easy to get good S/N.

The energy of $Z$ from $Zh$ process at this energy is more than 200 GeV and jets from $Z$ are well collimated. Therefore, we reconstructed hadronically decayed $Z$ as a single jet by $k_t$ jet algorithm with a jet radius 1.2. From reconstructed jets, candidate jets were pre-selected
requiring the jet $p_T$ is greater than 50 GeV, the jet mass between 70 and 150 GeV/$c^2$ and the jet energy between 210 and 300 GeV. The scatter plot of the mass and the energy of the selected jet in $q\bar{q}h$ events are shown in Fig. 3a.

![Figure 3a and 3b](image)

Figure 3: The scatter plot of the energy and the mass of candidate jets before the energy correction (a) and that for the recoil mass and the mass after the correction.

With a fixed jet radius, both jet mass and jet energy were reduced if particles from $Z$ escaped from the jet radius, thus a positive correlation between mass and energy was seen as shown in Fig. 3. This correlation was removed by scaling jet momenta with a factor which linearly depended on jet energy. After the correction, a better separation between $Z$ jet and non-$Z$ jet were achieved as seen in Fig. 3b.

For the final selection, we further required (1) the corrected jet mass between 87 and 105 GeV/$c^2$, (2) the maximum energy of $\gamma$ in the event is less than 100 GeV (to suppress $q\bar{q}\gamma$ background events), (3) Number of particles in the jet is greater than 20, (4) Jet angle satisfies $|\cos \theta_{jet}| < 0.7$.

The recoil mass distribution of selected events without/with background subtraction are shown in Fig. 4. In this figure, the jet momenta before the correction was used to calculate the recoil mass. As background processes, the standard model samples produced for the ILC DBD study were considered. They included $2f/4f/6f$ standard model processes $4f/5f$ final states produced by $\gamma\gamma$ and $\gamma e^\pm$ collisions, and $ffh$ process except $q\bar{q}h$.

As the final selection, events with the recoil mass between 100 and 210 GeV/$c^2$ were selected. The S/N of this selection was 11113/175437=0.063. 43% backgrounds were due to 4-quark events through $ZZ$ and $WW$ processes. Other 4-fermion processes and 2-fermion hadron events constitutes 26% and 27% of background events, respectively. The number of events selected are summarized in Table 2. The signal significance for 500 fb$^{-1}$ is 3.9%.

The distribution of the recoil mass calculated from the corrected jet momenta is shown in Fig. 5. From the events with the mass between 130 to 170 GeV/$c^2$, we obtained the signal significance of 3.9% for 500 fb$^{-1}$ with $-80%(+30\%)$ $e^+(e^-)$ beam polarization.
Figure 4: The left figure is the recoil mass distribution of selected events at $\sqrt{s} = 500$ GeV with $e^-(e^+)$ beam polarization of -80% (+30%) and 500 fb$^{-1}$ integrated luminosity. The red histogram is for the standard model processes and the black histogram is with the $q\bar{q}h$ events added. The right figure is the distribution after subtracting the background contribution. Note that the jet momenta before the correction is used for the recoil mass calculation in this figure.

Figure 5: Same as Fig. 4 but the corrected jet momenta were used for the recoil mass calculation.
4 Conclusion

In this paper, a feasibility to measure the total cross section of the Higgs-strahlung process using the hadronic decay mode of $Z$ was studied. At $\sqrt{s} = 350$ GeV, Higgs peak in jet recoil mass distribution could be seen; Combining 165 fb$^{-1}$ measurements with the $e^+(e^-)$ beam polarization of -80%(+30%) and +80%(-30%), respectively, $\Delta \sigma_{ZH}/\sigma_{ZH} = 3.4\%$ was expected. At 500 GeV, it was hard to see a clear Higgs peak in the jet recoil mass distribution. However, from the excess of events in $q\bar{q}h$ like events, $\Delta \sigma_{ZH}/\sigma_{ZH} = 3.9\%$ was expected for 500 fb$^{-1}$ measurements with $e^-(e^+)$ beam polarization of -80%(+30%). The analysis was based on a cut base event selection. Further improvement would be possible with more sophisticated analysis.

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| process                  | No. of events |
|--------------------------|---------------|
| $q\bar{q}h$              | 11113         |
| $f\bar{f}h$              | 338           |
| $q\bar{q}$               | 47377         |
| $q\bar{q}q\bar{q}$       | 121086        |
| $q\bar{q}q\bar{q}$       | 6357          |
| $\gamma\gamma/\gamma e^\pm \rightarrow 2f/4f$ | 277          |
| $S/\sqrt{S+N}$           | 25.7          |

Table 2: The number of signal and background events after selection.
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