Impact of Tracker Design on Higgs and Slepton Measurements

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We have studied the impact of charged track resolution on Higgs mass and production cross section measurement in the process $e^+e^- \rightarrow Z^0H, Z^0 \rightarrow \ell^+\ell^-, H \rightarrow X$ for Higgs masses between 120 and 160 GeV, and on smuon mass measurement using smuon pair production for three different mass pairs, assuming the International Linear Collider (ILC) is operated at 500 GeV center of mass energies (CME) with integrated luminosities of 500 $fb^{-1}$. The effect of initial state radiation (ISR), beamstrahlung and beam energy spread on Higgs and smuon mass measurement are also estimated. Using fast Monte Carlo simulations of the 2001 North American baseline detector designs (LD and SD), we find that the ISR and beamstrahlung have significant impact on Higgs and smuon mass measurement; Charged track momentum resolution affect Higgs mass significantly with better track performance yielding better Higgs mass resolution and precision for the track momentum resolution improvement up to a factor of about 5; Track momentum resolution has little effect on the measurement precision of the Higgsstrahlung cross section, the branching ratio of $H \rightarrow C\bar{C}$, the smuon and neutralino masses; Beam energy spread better than about 0.2% has little effect on Higgs, smuon and neutralino masses; The SD detector provides a more accurate measurement than the LD of the Higgs mass.

1. Introduction

Precise measurements of Higgs boson mass and cross section are important goals in the future high energy $e^+e^-$ linear collider experiments [1, 2]. Precision electroweak data in the framework of the Standard Model predict the mass of the Higgs boson, allowing a crucial cross check of electroweak symmetry breaking models if and when the Higgs boson is discovered. In addition, measuring the production cross section accurately allows determination of absolute Higgs decay branching ratios. Another important goal of the ILC is to discover light supersymmetric particles, such as sleptons, and measure their masses and production cross sections etc. Here we explore the accuracy with which the Higgs and Higgsstrahlung cross section can be determined at a linear collider operated at 500 GeV CME, considering Higgs masses between 120 and 160 GeV with integrated luminosities of 500 $fb^{-1}$. For smuon and neutralino mass measurement, three different mass pairs with high (47 GeV), medium (28 GeV) and low (6 GeV) mass differences are considered using right-hand smuon pair production, with each smuon decaying into muon and neutralino. For this study, we use the 2001 North American baseline detector designs (LD for “Large” and SD for “Silicon”).

2. Higgs Property Measurement

The Higgs mass can be simply determined assuming recoil in the process $e^+e^- \rightarrow Z^0H, Z^0 \rightarrow \ell^+\ell^-, H \rightarrow X$ $(\ell = e,\mu)$. The recoil mass is defined as: $M_H^{\text{recoil}} = \sqrt{s - 2\sqrt{s} \cdot E_{\ell^+\ell^-} + M_{\ell^+\ell^-}^2}$, where $s$ is the CME squared, $E_{\ell^+\ell^-}$ is the energy of the lepton pair from $Z^0$ decay, while $M_{\ell^+\ell^-}$ is the pair’s invariant mass. The main backgrounds of this analysis are $e^+e^- \rightarrow Z^0Z^0, W^+W^-$, but other sources of contamination, including Bhabha events, dimuon and two photos events are also investigated.
2.1. Event Selection

Monte Carlo events in this analysis were generated by the Pandora(V2.2)-Pythia(V3.1) package \cite{3, 4} with latest patches which includes initial state radiation, beamsstrahlung, beam energy spread (full width is 0.11\%), hadron fragmentation and final state QCD/QED radiation. In addition, the electron beam is polarized to $-85\%$. The Java Analysis Studio (JAS) \cite{5} package was used to analyze fast detector simulation events, assuming the LDMAR01 and SDMAR01 baseline detectors \cite{1}.

These studies are performed for a Linear Collider operated at CME of 500 GeV with integrated luminosities of $500 \text{ fb}^{-1}$ each, assuming Higgs mass between 120 and 160 GeV. Events are selected using a cut-based approach, according to the following criteria \cite{6, 7}:

1. A candidate lepton must have an energy greater than 10 GeV
2. The polar angle of a lepton must satisfy $|\cos \theta_e| < 0.9$
3. There must be at least 2 lepton candidates in the event
4. The invariant mass of the lepton pair must lie within 5 GeV of the $Z^0$ mass
5. The polar angle of two-lepton system must lie in the barrel region, $|\cos \theta_{e+e^-}| < 0.6$
6. The opening angle between the two leptons should satisfy $|\cos \theta_{e+e^-}| > -0.7$
7. The energy of the most energetic photon should be less than 100 GeV.

Cut (5) is used to suppress $Z^0Z^0$ background, while Cut (6) rejects background from $WW$, Cut (7) removes events with one energetic photon from $Z\gamma$. The selection efficiency for signal is about 55-57\% for $\sqrt{s} = 500$ GeV, as listed in TABLE I. The signal efficiency using the same selection cuts is lower, 48-50\%, at a 350 GeV machine, mainly because the lower Lorentz boost of the leptons from $Z^0$ decay leads to a larger average opening angle. The major remaining background with the above selection cuts is $Z^0Z^0$ events for which the selection efficiency is about 1\%.

For the $Z^0Z^0$ cross section of $475 \pm 3.4 \text{ fb}$, about 2400 $Z^0Z^0$ events passed the selection cuts assuming the integrated luminosity of $500 \text{ fb}^{-1}$. The corresponding Higgs events in electron channel varies from about 570 to 650 for Higgs mass between 120 GeV and 160 GeV, with lower Higgs mass yielding more signal events because of larger production cross section.

| $m_{\text{higgs}}$ (GeV) | Cross Section (fb) | Eff(\%) | $\sigma_{m_H}$ (GeV) | $\Delta m_H$ (GeV) | Xsection(fb) | Eff(\%) | $\sigma_{m_H}$ (GeV) | $\Delta m_H$ (GeV) | Xsection(fb) |
|--------------------------|-------------------|---------|-----------------|-----------------|-------------|---------|-----------------|-----------------|-------------|
| 120                      | 2.34 ± 0.015      | 55.3    | 7.2             | 0.34            | 2.34±0.167  | 55.3    | 5.4            | 0.31            | 2.34±0.164  |
| 140                      | 2.15 ± 0.022      | 56.4    | 6.2             | 0.34            | 2.15±0.144  | 56.4    | 4.8            | 0.28            | 2.15±0.142  |
| 160                      | 2.01 ± 0.032      | 56.6    | 4.6             | 0.34            | 2.01±0.131  | 56.7    | 3.7            | 0.27            | 2.01±0.129  |

Table I: Selection efficiencies, Higgs mass resolution, precision and cross section of $e^+e^- \to ZH \to e^+e^-X$ for two baseline detectors, assuming ILC is operated at 500 GeV CME with Higgs masses between 120 and 160 GeV, integrated luminosity of $500 \text{ fb}^{-1}$.

2.2. Higgs Mass and Cross Section Measurement

The Higgs mass resolutions are obtained by fitting the peak region of $Z^0$ recoil mass spectra using a Gaussian distribution. A binned $\chi^2$ fit is performed with two free parameters, the Higgs mass and width. The $Z^0$ recoil mass resolution is about 4-7 GeV at $\sqrt{s} = 500$ GeV for the two baseline detectors, with better resolution obtained for the SD detector. This analytic fitting technique yields slightly larger measured mass because of the ISR and beamsstrahlung. This bias can be evaluated and corrected by fitting both data and Monte Carlo events with the same techniques. The Higgs mass precision obtained using this technique is about 0.6-1.2 GeV at $\sqrt{s} = 500$ GeV, with lower Higgs masses yielding larger uncertainties because of higher background contamination.

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The branching ratio of $H \rightarrow c\bar{c}$ strongly depends on the Higgs mass hypothesis. The expected branching

$$\Delta \sigma/\sigma_{ZH} = 500 \text{ GeV}$$

with only about 10% improvement for a track momentum resolution improvement by a factor of 10.

The precision of Higgs mass measured using the Monte Carlo template is about 0.3 GeV at $\sqrt{s} = 500 \text{ GeV}$, with the SD detector slightly better than LD, as shown in Table I. The cross sections of the Higgsstrahlung signal measured for the Higgs mass between 120 and 160 GeV are shown in Table II and Figure I e. The relative precision of the cross section is determined to be 6.4-7.2% at $\sqrt{s} = 500 \text{ GeV}$ for both baseline detectors and nominal integrated luminosity of 500 $fb^{-1}$. Slightly better precision is obtained by the SD design.

### 2.3. Impact of Track Momentum Resolution on Higgs Mass and Cross Section

In order to quantify the effect of charged track momentum resolution on Higgs mass and cross section measurement, the track momentum resolution is re-scaled by a factor ranging from 0.05 to 4. The results are shown in Figure I. The Higgs mass resolution and precision are improved by re-scaling the factor of track momentum resolution down to about 0.2, the purity ($N_{\text{signal}}/(N_{\text{signal}} + N_{\text{background}})$) and significance ($N_{\text{signal}}/\sqrt{N_{\text{background}}}$) of the Higgsstrahlung signal are also saturated around that point. The cross section is insensitive to charged track momentum resolution, with only about 10% improvement for a track momentum resolution improvement by a factor of 10.

### 2.4. Impact of Track Momentum Resolution on Branching Ratio of $H \rightarrow c\bar{c}$

The major background sources for $H \rightarrow C\bar{C}$ are $Z^0 Z^0$, $Z^0 H^0$ with $Z^0 \rightarrow c\bar{c}, b\bar{b}$, or $H \rightarrow b\bar{b}, W^+ W^-$, $gg$ etc. The branching ratio of $H \rightarrow b\bar{b}$, $W^+ W^-$ strongly depends on the Higgs mass hypothesis. The expected branching
ratio of $H \rightarrow c\bar{c}$ is 2.8% and 1.4% for 120 GeV and 140 GeV Higgs mass, respectively. In order to estimate the impact of track momentum resolution on the branching ratio of $H \rightarrow c\bar{c}$, we assume 50% c-tagging efficiency, with efficiencies of b quark and uds quark are 4.4% and 0.5%, respectively. The relative precision of the $H \rightarrow c\bar{c}$ branching ratio improves only 5-10% if we improve the track momentum resolution by a factor of 10. For integrated luminosity of 1000 $fb^{-1}$, the relative precision is about 39% for 120 GeV Higgs and 64% for 140 GeV Higgs with the nominal track resolution.

2.5. Effect of ISR, Beamstrahlung and Beam Energy Spread on $Z^0$ Recoil Mass

As is well known, the ISR and beamstrahlung broaden the $Z^0$ recoil mass distribution and make an extremely long tail. The final state radiation decreases the momentum of $Z^0$ and makes the apparent $Z^0$ recoil mass larger than the expected value. The effects of ISR, beamstrahlung, beam energy spread are shown in Figure 2, assuming a 120 GeV Higgs with SD design. As expected, the $Z^0$ recoil mass peaks at the correct Higgs mass if we turn off the ISR and the beamstrahlung. For default detector designs the effect of beam energy spread becomes important for a full width larger than about 0.2%. For the current ILC500 beam setup, the effect from the beam energy spread is negligible since its full width is 0.11%.

3. Slepton and Neutralino Mass Measurement

The study of supersymmetry (SUSY) particles is one of the most important goals for the future colliders. If SUSY exists in nature, there may be light superpartners with masses of a few hundred GeV, hence, accessible by a current proposed ILC which is expected to run at CME of 500 GeV to 1 TeV.

One of the “golden” channels to discover the SUSY particles is pair production of slepton with each slepton decaying into lepton and lightest SUSY particle (LSP) neutralino. The signature of these events is two energetic leptons ($e$ or $\mu$) with large missing momentum. In this paper, we use the right-hand smuon pair production for smuon and neutralino mass measurement, assuming the ILC operated at 500 GeV CME, 80% right polarization electron with integrated luminosity of 50 $fb^{-1}$. The smuon and neutralino masses can be determined by measuring endpoints of muon energy spectrum,

$$M^2_{\tilde{\mu}_R} = E^2_{cm} \cdot \frac{E_{min} \times E_{max}}{(E_{min} + E_{max})^2}$$

$$M^2_{\tilde{\chi}_1^0} = M^2_{\tilde{\mu}_R} \cdot \left\{1 - \frac{2E_{min} + E_{max}}{E_{cm}} \right\}$$

(1)
where, $E_{cm}$ is CME, $E_{min}$ and $E_{max}$ are low and high muon energy endpoints, respectively. For Snowmass 2001 SPS#1 point [8], the smuon and neutralino masses are 143 GeV and 96.1 GeV, respectively. The SUSY parameters (mSUGRA) are listed in the following, the universal scale mass $m_0 = 100$ GeV, the universal gaugino mass $m_{1/2} = 250$ GeV, the trilinear coupling in Higgs sector $A_0 = -100$ GeV, the ratio of two vacuum expectation values $\tan\beta = 10$, the Higgsino mixing parameter $\text{sign}(\mu) = +$.

The dependence of muon endpoint energy on the CME is shown in the left plot of Figure 3. For CME of 500 GeV, the low and high endpoint energies are 12.32 GeV and 124.77 GeV, respectively. The muon energy spectrum becomes wider with the increase of the CME.

The muon energy spectra for various beam setups are shown in the middle plot of Figure 3. Apparently, the ISR and beamstrahlung distort the endpoints of muon energy spectrum significantly. For instance, if we turn off ISR, beamstrahlung and beam energy spread, the measured smuon and neutralino mass precisions are 260 MeV and 167 MeV, respectively, assuming the integrated luminosity of 50 fb$^{-1}$ and 20% uniform random background contamination (20% of signal events after selection) over the full muon energy range. Then, we turn on the beam energy spread with full width of 0.11%, the measured smuon and neutralino mass precisions are 266 MeV and 172 MeV, degraded about 3%. If we turn on all ISR, beamstrahlung and beam energy spread, the smuon and neutralino mass precisions become 420 MeV and 294 MeV, respectively.

The dependence of the muon energy spectrum on track momentum resolution is studied and shown in the right plot of Figure 3. Apparently, the muon energy spectra are insensitive to track momentum resolution.

Based on equation (1), the relative error of smuon and neutralino masses can be written as,

$$\frac{\Delta M_{\mu R}}{M_{\mu R}^+} = A \sqrt{\frac{\Delta E_{min}^2}{E_{min}} + \frac{\Delta E_{max}^2}{E_{max}}} \quad (2)$$

$$\frac{\Delta M_{\chi_0^0}}{M_{\chi_0^0}} = \frac{M_{\mu R}^2}{M_{\chi_0^0}} \sqrt{\left( \frac{C}{E_{min}} - \frac{1}{E_{cm}} \right)^2 \Delta E_{min}^2 + \left( \frac{C}{E_{max}} - \frac{1}{E_{cm}} \right)^2 \Delta E_{max}^2} \quad (3)$$

where, $A = \frac{E_{max} - E_{min}}{2(E_{max} + E_{min})}$, $B = \frac{E_{max} + E_{min}}{E_{cm}}$, $C = A(1 - 2B)$ . The smuon and neutralino mass errors mainly come from relative errors of $E_{min}$ and $E_{max}$ determination. Three SUSY mass pairs with high (47 GeV), medium (28 GeV) and low (6 GeV) mass differences are considered. The selection cuts are, 1) two muons in the final state, 2) visible energy in the forward region less than $0.4 \times \sqrt{s}$, 3) total transverse momentum of event greater than 15 GeV to reduce most of $\gamma^*\gamma^*$ backgrounds if the detector can detect scattered electrons down to about 50 mrad and 4) $|\cos(\theta_{\mu})| < 0.9$.

The relative errors of $E_{min}$, $E_{max}$, $M_{\mu R}^+$ and $M_{\chi_0^0}$ versus charged track momentum resolution for high, medium and low mass differences are shown in Figure 4. The smuon mass error is dominated by the relative error of the low energy
endpoint $E_{\text{min}}$ although the absolute error of $E_{\text{max}}$ is larger than that of $E_{\text{min}}$. No apparent improvement on smuon and neutralino mass precision is obtained by improving the track momentum resolution. However, the mass precision will degrade if the track momentum resolution gets worse. The smuon and neutralino mass precisions are strongly affected by the background contamination. The mass precisions degrade about 15-30% when 20% uniform random background (20% of signal events after selection) is introduced. Considering the SUSY mass error is dominated by the relative error of $E_{\text{min}}$, it is important to reduce the background at low energy region to improve the mass precision.

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