Physics Prospects at the International Linear e^+e^- Collider

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The International Linear Collider (ILC) will have an extremely rich physics program and it will be an ideal experimental tool to explore the structure of the Electroweak Symmetry Breaking. If the Higgs mechanism is realised in Nature, the ILC will allow for a precise determination of the Higgs boson profile. Furthermore, alternative models of Electroweak Symmetry Breaking and theories beyond the Standard Model will be probed. In this paper the features of the machine are outlined, the detector performance goals are discussed and the physics potential of the linear collider is reviewed. The note is based on the talk given at the DIS-2007 Conference [1].

1 Introduction

Over the last few decades a consensus has emerged within the particle physics communities worldwide that the next big experimental facility after the Large Hadron Collider (LHC) at CERN should be an electron-positron linear collider, the International Linear Collider (ILC), operating at energies between a few hundred GeV and approximately one TeV. Owing to its striking features, such as tunable center-of-mass energy and polarisation of beams, the high energy reach, well defined initial state, clean environment and low backgrounds, the ILC has a high potential for the detailed exploration of the Electroweak Symmetry Breaking (EWSB) mechanism and theories beyond the Standard Model and will significantly complement the data which will be collected at the LHC.

2 Machine and Detector Performance Goals

In 2004 the cold superconducting technology had been recommended for the ILC [2]. Since then much effort has been invested by accelerator physicists worldwide to optimise the machine design against its cost. These efforts resulted in the Baseline Configuration Document published in the fall of 2006 [3]. It is planned that in the first phase, the ILC will be operated at center-of-mass energy of a few hundred GeV, thus covering the scale of electroweak symmetry breaking. The machine can then be upgraded to an energy of approximately 1 TeV in order to extend its discovery potential. With the design luminosity of $2 \cdot 10^{34}\text{s}^{-1}\text{cm}^{-2}$, one expects to collect about 500 fb^{-1} of data during a sub-TeV energy run of the ILC. A large part of these data will be collected with polarised electron (up to 80%) and positron (up to 50%) beams.

The ambitious physics program sets stringent requirements on the ILC detector performance. The overall tracking system must provide excellent momentum resolution for charged particles ($\delta(1/p_t) \leq 5 \cdot 10^{-5} \cdot p_t$) to facilitate e.g. precise reconstruction of the di-lepton recoil mass in the channel $ZH \to \ell^+\ell^- X$ or accurate determination of the kinematics in the lepton energy spectrum from final states, involving leptons and lightest stable Supersymmetric particle. Efficient reconstruction of multi-jet final states, resulting e.g. from double Higgs-strahlung processes, requires an excellent jet energy resolution. The benchmark goal for the ILC detector is $\delta E_{jet}/E_{jet} = 30\%/\sqrt{E_{jet}}$. Finally, a micro-vertex detector has to ensure an impact parameter resolution $\delta(IP) = 5\mu m \oplus 10\mu m/p \cdot \sin^{3/2}\theta$ to enable measurements of tauonic and hadronic branching fractions of the Higgs boson at the percent level. A number of detector concepts have emerged over the recent years offering a variety of technological ways to reach the detector performance dictated by the ILC physics program. The description of these concepts and possible technological solutions can be found in the corresponding detector outline documents [4].

3 Physics Program

In this section, the potential of the ILC is illustrated with two topics, chosen for reference, namely the study of the Higgs mechanism and exploration of supersymmetric models.

3.1 Higgs Physics

A detailed investigation of the Higgs mechanism implies the precise determination of the Higgs boson profile. The ILC is capable of detecting Higgs particle independently of its decay mode. This is done by exploiting the Higgs-strahlung process, $e^+e^- \to ZH$, with subsequent decay of the Z boson to electron or muon pairs. The signal manifests itself as a peak in the di-lepton recoil mass spectrum as illustrated in Fig. 1. Using this channel the Higgs-strahlung cross section and therefore the Higgs coupling to the Z boson can be determined in a model independent way with a relative accuracy of a few percent [5]. The mass of the Higgs boson is best measured with fully reconstructible final states, such as $ZH \to q\bar{q}b\bar{b}$, $ZH \to \ell^+\ell^-b\bar{b}$, $ZH \to q\bar{q}W^+W^- \to 6jets$, $ZH \to \ell^+\ell^-W^+W^- \to 2\ell + 4jets$. In these channels the kinematic fits, imposing 4-momentum conservation and constraining mass of the decay products of the Z boson to its nominal mass can be applied, improving the resolution on the Higgs boson mass m_H. Dedicated studies showed that m_H can be measured with an accuracy ranging from 40 to 70 MeV for m_H between 120 and 180 GeV [6].

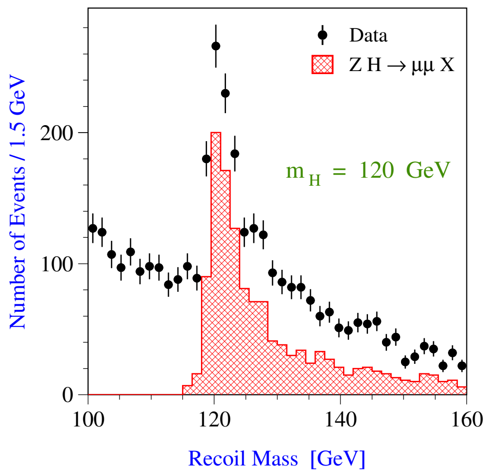

Figure 1: Di-muon recoil mass spectrum in the $ZH \to \mu^+\mu^- X$ channel.

If a signal is detected in the recoil mass spectrum, the measurement of the spin of the observed particle is crucial for its identification as the Higgs boson. It can be performed by analysing the energy dependence of the Higgs-strahlung cross section just above the kinematic threshold [7]. For a spin zero particle the rise of the cross section is expected to be $\sim \beta$, where β is the velocity of the boson in the center-of-mass system. For a spin one particle the rise is $\sim \beta^3$ and for spin two like $\sim \beta^5$. With a very small luminosity of about ten fb^{-1} per energy point the scalar nature of the Higgs boson can be established and other spin hypotheses are strongly disfavoured, as shown in Figure 2. There are particular scenarios for s=1 and 2, which show a threshold behaviour similar in shape to the s=0 one. This can be disentangled using angular information in addition.

Being responsible for the mass generation, the Higgs boson prefers to couple stronger to heavier particles. Hence, establishment of the mass-coupling relation will be a crucial test of the Higgs mechanism. The couplings of the SM particles to the Higgs boson can be accessed through the measurements of the Higgs decay branching ratios. For a light Higgs boson (m_H = 120 GeV), the attainable precision on the branching ratios ranges from 1% for $H \to b\bar{b}$ [8] to about 20% for the $H \to \gamma\gamma$ decay [9].

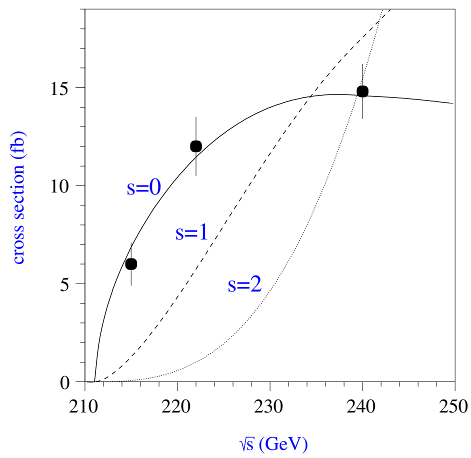

Figure 2: The threshold behaviour of the Higgs-strahlung cross section. The dots represent simulated data and the curves indicate theoretical predictions for various spin hypotheses.

A determination of the Higgs self-coupling along with the Higgs boson mass would allow for the reconstruction of the Higgs potential, thus providing a consistency check of the Higgs mechanism of EWSB. For a light Higgs boson the highest statistics channel to study the Higgs self-coupling is provided by the six-jet final states, resulting from the double Higgs-strahlung process, $e^+e^- \to ZHH$. Efficient reconstruction of these final states requires excellent jet energy resolution. Sensitivity can be further improved by utilising the $e^+e^- \to HH\nu\bar{\nu}$ channel. A dedicated studies [10] showed that for a jet energy resolution of $40\%/\sqrt{E_{jet}}$, a relative accuracy of 14(18)% on the Higgs self-coupling can be achieved with 2 ab^{-1} of data collected at center-of-mass energy of 500(1000) GeV. An improvement of the resolution to $30\%/\sqrt{E_{jet}}$ will reduce the amount of luminosity, needed to reach the same level of precision, by a factor of 2.2.

3.2 Supersymmetry

Supersymmetry (SUSY) is an attractive concept, which allows to overcome a number of inconsistencies with the SM. SUSY stabilises the hierarchy between electroweak and Planck scales, provides a clear path to Grand Unified Theories and introduces gravity in a natural way as a quantum field theory. In the minimal supersymmetric extension of the SM (MSSM) each conventional particle acquires a superpartner differing in spin by $\frac{1}{2}$. The LHC and ILC machines will explore SUSY in different and complementary ways. Heavy strongly interacting SUSY particles − scalar quarks and gluinos − will be produced with high rates in proton-proton collisions at the LHC. The ILC, on the other hand, will be an instrument for precise spectroscopy of electroweakly interacting SUSY particles. The corresponding sfermion sector comprises left- and right-handed superpartners of the SM leptons, while the non-strongly interacting gauginos mix with the higgsinos to form the corresponding mass eigenstates: two pairs of charginos $\tilde{\chi}_i^{\pm}$ (i = 1,2) and four neutralinos $\tilde{\chi}_i^0$ (i = 1..4). In the MSSM the multiplicative quantum number R-parity is conserved, R_p = +1 for SM particles and R_p = -1 for their supersymmetric partners. This implies the existence of a lightest supersymmetric particle (LSP), which is stable and to which all supersymmetric particles eventually decay. In most of the models the lightest neutralino $\tilde{\chi}^0_1$ is assumed to be the LSP. Scalar leptons are produced in e^+e^- collisions in pairs, $e^+e^- \rightarrow \tilde{\ell}^+_i\tilde{\ell}^-_j, \tilde{\nu}\bar{\tilde{\nu}}$ via s-channel Z/γ exchange or t-channel $\tilde{\chi}$ exchange for the first generation. The left-handed and right-handed states can be disentangled using the beam polarisation, e.g. $\tilde{\ell}_R\tilde{\ell}_R$ production has much larger cross section for right-handed electrons than for left-handed ones. Positron polarisation further enhances the effect. The isotropic two-body decays, $\tilde{\ell}^- \rightarrow \ell^-\tilde{\chi}^0_i$ and $\tilde{\nu}_\ell \rightarrow \ell^-\tilde{\chi}^+_i$, lead to an essentially flat lepton energy spectrum with a minimum and maximum energy ("endpoints"). From the kinematic "endpoints" the masses of the primary slepton and the secondary chargino or neutralino can be measured. Figure 3 shows an example of the reconstructed muon energy in the process $e^+_Le^-_R \rightarrow \tilde{\mu}^+_R\tilde{\mu}^-_R \rightarrow \mu^+\tilde{\chi}^0_1\mu^-\tilde{\chi}^0_1$. [11].

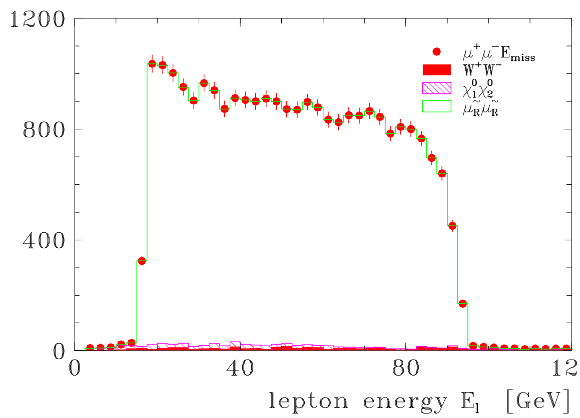

Figure 3: The spectrum of muon energy in the reaction $e^+_Le^-_R \rightarrow \tilde{\mu}^+_R\tilde{\mu}^-_R \rightarrow \mu^+\tilde{\chi}^0_1\mu^-\tilde{\chi}^0_1$. Center-of-mass energy is 400 GeV. Integrated luminosity is 200 fb^{-1}.

Alternatively, the mass information can be accessed via measurements of the slepton pair production cross section in the vicinity of the kinematic threshold [12]. Charginos and neutralinos are produced in pairs, $e^+e^- \rightarrow \tilde{\chi}^+_i\tilde{\chi}^-_j$, $e^+e^- \rightarrow \tilde{\chi}^0_i\tilde{\chi}^0_j$ via s-channel Z/γ exchange and t-channel $\tilde{e}$ and $\tilde{\nu}_e$ exchange and decay into lighter partners and gauge bosons or sfermion-fermion pairs $\tilde{\chi}_i \rightarrow Z/W\tilde{\chi}_j$, $\tilde{\chi}^\pm_1 \rightarrow \tilde{\tau}^\pm\nu_\tau \rightarrow \tau^\pm\nu_\tau\tilde{\chi}^0_1$, $\tilde{\chi}^0_2 \rightarrow \tilde{\ell}\ell \rightarrow \ell\ell\tilde{\chi}^0_1$. The most promising method to measure the lightest chargino and the next to the lightest neutralino masses is the threshold scan. Dedicated studies showed that the masses can be measured with a statistical precision of 0.55 GeV [12]. The mass of the next heavier neutralino, $\tilde{\chi}^0_2$, can be measured by threshold scan of $e^+_Re^-_L \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_2 \rightarrow 4\tau + 2\tilde{\chi}^0_1$. With an integrated luminosity of 100 fb^{-1}, distributed over five scan points, a precision on the mass of 1.2 GeV can be achieved. The heavy charginos and neutralinos can be detected via their associated production with the lighter ones, followed by the decays $\tilde{\chi}_j \rightarrow W/Z\tilde{\chi}_i$. The expected accuracy of the mass measurement of a few GeV is feasible [13].

Charginos are the mixture of Winos and Higgsinos. The Wino component is accessible via chargino pair production through t-channel exchange, which couples only to left-handed electrons. Hence, the mixing parameters in the chargino sector can be measured by varying the beam polarisation [14]. By measuring mixing in the chargino sector one gets access to the fundamental supersymmetric parameters, namely the gaugino mass parameter M_2, the Higgs mixing parameter μ and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$. In a similar way the properties of the neutralino system, which is mixture of Bino, Wino and two Higgsinos, can be determined. By measuring the dependence of neutralino pair production on the beam polarisation, in addition to the parameters M_2, μ and $\tan\beta$, the gaugino mass parameter M_1 can be extracted [12]. All these parameters are of utmost importance for the reconstruction of the low energy SUSY Lagrangian and for probing the underlying fundamental physics at higher scales.

4 Conclusion

The ILC physics potential is not limited to the study of the Higgs mechanism and the exploration of the SUSY. The ILC will have a high sensitivity to a wide spectrum of signatures predicted by other theoretical models, e.g. postulating extra spatial dimensions, extended gauge sector and additional heavy fermion fields. Alternative scenarios of EWSB, such as strongly interacting gauge fields or compositeness, will also be probed. Finally, precise measurements of the electroweak observables will allow to probe the physics via virtual effects. A comprehensive description of the physics program at the ILC can be found elsewhere [12]. A successful realization of this program requires universality of the detector from the hardware side and universality of thinking from the human side. Both are needed to embrace not only anticipated scenarios but also unexpected physics signatures, which Nature may provide us with.

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