Electroweak Physics at the ILC

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Abstract. Some aspects of electroweak physics at the International Linear Collider (ILC) are reviewed. The importance of precision measurements in the Higgs sector and in top-quark physics is emphasized, and the physics potential of the GigaZ option of the ILC is discussed. It is shown in particular that even in a scenario where the states of new physics are so heavy that they would be outside of the reach of the LHC and the first phase of the ILC, the GigaZ precision on the effective weak mixing angle may nevertheless allow the detection of quantum effects of new physics.

1. Introduction

The International Linear Collider (ILC) is a proposed electron–positron collider whose design is being addressed in the context of the Global Design Effort [1]. The ILC has been agreed in a world-wide consensus to be the next large experimental facility in high-energy physics (see Ref. [2] and references therein). The Reference Design Report for the ILC has been issued earlier this year [1], and the Engineering Design Report is currently in preparation.

The baseline design of the ILC foresees a first phase of operation with a tunable energy of up to about 500 GeV and polarised beams. Possible options include running at the Z-boson pole with high luminosity (GigaZ) and running in the photon–photon, electron–photon and electron–electron collider modes. The physics case of the ILC with centre-of-mass energy of 400–500 GeV rests on high-precision measurements of the properties of the top quark at the top threshold, the unique capability of performing a comprehensive programme of precision measurements in the Higgs sector, which will be indispensable to reveal the nature of possible Higgs candidates, the good prospects for observing the light states of various kinds of new physics in direct searches, and the sensitivity to detect effects of new physics at much higher scales by means of high-precision measurements [3].

The baseline configuration furthermore foresees the possibility of an upgrade of the ILC to an energy of about 1 TeV. The final choice of the energy and further possible machine and detector upgrades will depend on the results obtained at the LHC and the first phase of the ILC.

The information on TeV scale physics obtainable at the electron–positron collider ILC will be complementary to the one from the proton–proton collider LHC [4]. While the discovery of new particles often requires access to the highest possible energies, disentangling the underlying structure calls for highest possible precision of the measurements. Quantum corrections are influenced by the whole structure of the model. Thus, the fingerprints of new physics often only manifest themselves in tiny deviations. While in hadron collisions it is technically feasible to reach the highest centre-of-mass energies, in lepton collisions (in particular electron-positron collisions) the highest precision of measurements can be achieved. High-precision physics at the
ILC is made possible in particular by the collision of point-like objects with exactly defined initial conditions, by the tunable collision energy of the ILC, and by the possibility of polarising the ILC beams. Indeed, the machine running conditions can easily be tailored to the specific physics processes or particles under investigation. The signal-to-background ratios at the ILC are in general much better than at the LHC. In contrast to the LHC, the full knowledge of the momenta of the interacting particles gives rise to kinematic constraints, which allow reconstruction of the final state in detail. The ILC will therefore provide very precise measurements of the properties of all accessible particles. Direct discoveries at the ILC will be possible up to the kinematic limit of the available energy. Furthermore, the sensitivity to quantum effects of new physics achievable at the ILC will in fact often exceed that of the direct search reach for new particles at both the LHC and the ILC.

The ILC can deliver precision data obtained from running at the top threshold, from fermion and boson pair production at high energies, from measurements in the Higgs sector and of possible other new particles. Furthermore, running the ILC in the GigaZ mode yields extremely precise information on the effective leptonic weak mixing angle at the Z-boson resonance, $\sin^2 \theta_{\text{eff}}$, and the mass of the W boson, $M_W$ (the latter from running at the WW threshold). The GigaZ running can improve the accuracy in the effective weak mixing angle by more than an order of magnitude. The precision of the W mass would improve by at least a factor of two compared to the expected accuracies at the Tevatron and the LHC. Comparing these measurements with the predictions of different models provides a very sensitive test of the theory, in the same way as many alternatives to the Standard Model (SM) have been found to be in conflict with the electroweak precision data in the past.

In the following, some examples of electroweak physics at the ILC are discussed.

2. Higgs physics at the ILC
The high-precision information obtainable at the ILC will be crucial for identifying the nature of new physics. For instance, once one or more Higgs candidates are detected, a comprehensive programme of precision measurements will be necessary to reveal the properties of the new state(s) and to determine the underlying physics. The mass of the Higgs boson can be determined at the ILC at the permille level or better, Higgs couplings to fermions and gauge bosons can typically be measured at the percent level, and it will be possible to unambiguously determine the quantum numbers in the Higgs sector. Indeed, only the ILC may be able to discern whether the Higgs observed at the LHC is that of the SM or a Higgs-like (possibly composite) scalar tied to a more complex mechanism of mass generation. The verification of small deviations from the SM may be the path to decipher the physics of electroweak symmetry breaking. The experimental information from the ILC will be even more crucial if the mechanism of electroweak symmetry breaking in nature is such that either Higgs detection at the LHC may be difficult or the Higgs signal, while visible, would be hard to interpret.

A possible scenario giving rise to non-standard properties of the Higgs sector is the presence of large extra dimensions, motivated for instance by a “fine-tuning” and “little hierarchy” problem of supersymmetric extensions of the SM. A popular class of such models comprise those in which some or all of the SM particles live on 3-branes in the extra dimensions. Such models inevitably require the existence of a radion (the quantum degree associated with fluctuations of the distance between the 3-branes or the size of the extra dimension(s)). The radion has the same quantum numbers as a Higgs boson. As a consequence, there will in general be a mixing between the Higgs boson(s) and the radion. Since the radion has couplings that are very different from those of the SM Higgs boson, the physical eigenstates will have unusual properties corresponding to a mixture of the Higgs and radion properties. In such a situation the ILC could observe both the Higgs and the radion and measure their properties with sufficient accuracy to experimentally establish the Higgs-radion mixing effects.
If no clear Higgs signal has been established at the LHC, it will be crucial to investigate with the possibilities of the ILC whether the Higgs boson has not been missed at the LHC because of its non-standard properties. This will be even more the case if the gauge sector does not show indications of strong electroweak symmetry breaking dynamics. The particular power of the ILC is its ability to look for $e^+e^- \rightarrow ZH$ in the inclusive $e^+e^- \rightarrow ZX$ missing-mass distribution recoiling against the $Z$ boson. Even if the Higgs boson decays in a way that is experimentally hard to detect or different Higgs signals overlap in a complicated way, the recoil mass distribution will reveal the Higgs-boson mass spectrum of the model. The total Higgs-strahlung cross section will be measurable with an accuracy of about 2.5% for a Higgs boson with a mass of about 120 GeV. Should no fundamental Higgs boson be discovered, neither at the LHC nor at the ILC, high-precision ILC measurements will be a direct probe of the underlying dynamics responsible for particle masses. The LHC and the ILC are sensitive to different gauge boson scattering channels and yield complementary information [4].

3. Top and electroweak precision physics
The ILC is uniquely suited for carrying out high-precision top-quark physics. The mass of the top quark, $m_t$, is a fundamental parameter of the electroweak theory. It is by far the heaviest of all quark masses and it is also larger than the masses of all other known fundamental particles. The large value of $m_t$ gives rise to a large coupling between the top quark and the Higgs boson and is furthermore important for flavour physics. The top quark could therefore provide a window to new physics. The correct prediction of $m_t$ will be a crucial test for any fundamental theory. The top-quark mass also plays an important role in electroweak precision physics, as a consequence in particular of non-decoupling effects being proportional to powers of $m_t$. A precise knowledge of $m_t$ is therefore indispensable in order to have sensitivity to possible effects of new physics in electroweak precision tests [5].

The ILC measurements at the top threshold will reduce the experimental uncertainty on the top-quark mass to the level of 100 MeV or below [3, 6], i.e., more than an order of magnitude better than at the LHC [7], and would allow a much more accurate study of the electroweak and Higgs couplings of the top quark. A precision of $m_t$ significantly better than 1 GeV will be necessary in order to exploit the prospective precision of the electroweak precision observables. In particular, an experimental error on $m_t$ of 0.1 GeV induces an uncertainty in the theoretical prediction of $M_W$ and the effective weak mixing angle, $\sin^2 \theta_{\text{eff}}$, of 1 MeV and $0.3 \times 10^{-5}$, respectively [5], i.e., below the anticipated experimental error of these observables.

The impact of the experimental error on $m_t$ is even more pronounced in Higgs physics. In each model where the Higgs-boson mass is not a free parameter but predicted in terms of the other model parameters (as, e.g., in supersymmetry) the leading top-quark loop contribution induces a correction to the Higgs-boson mass of the form

$$\Delta m_h^2 \sim G_\mu N_C C m_t^4.$$  \hspace{1cm} (1)

Here $G_\mu$ is the Fermi constant, $N_C$ is the colour factor, and the coefficient $C$ depends on the specific model. Taking the Minimal Supersymmetric Standard Model (MSSM) as an example (including also the scalar top contributions and the appropriate renormalisation) $N_C C$ is given for the light $\mathcal{CP}$-even Higgs boson mass by

$$N_C C = \frac{3}{\sqrt{2} \pi^2 \sin^2 \beta} \log \left( \frac{m_{t_2} m_{\tilde{t}_2}}{m_t^2} \right).$$  \hspace{1cm} (2)

Here $m_{t_2, \tilde{t}_2}$ denote the two masses of the scalar tops. An LHC precision of $\delta m_t = 1$ GeV leads to an uncertainty of the prediction for $m_h$ induced by $\delta m_t$ of also about 1 GeV, corresponding to $\sim 2.5\%$. The ILC, on the other hand, will yield a precision of $\sim 0.2\%$ (assuming that...
uncertainties from unknown higher-order corrections can be brought sufficiently well under control). These uncertainties have to be compared with the anticipated precision of the future Higgs-boson mass measurements. With a precision of $\delta m_{h}^{\exp,\text{LHC}} \approx 0.2 \text{ GeV}$ \cite{8} the relative precision is at the level of $\sim 0.2\%$. Thus, the ILC precision on $m_t$ is mandatory in order to obtain a theoretical prediction for $m_h$ with the same level of accuracy as the anticipated experimental precision on the Higgs-boson mass.

4. Electroweak precision observables in the MSSM

The high-precision measurement of the effective leptonic weak mixing angle at the Z-boson resonance, $\sin^2 \theta_{\text{eff}}$, at GigaZ provides an extremely sensitive probe of quantum effects of new physics \cite{9}. In Ref. \cite{10} precision physics at the Z-boson resonance has been discussed in the context of the MSSM, based on state-of-the-art theoretical predictions. It has been analysed in particular whether the high accuracy achievable at the GigaZ option of the ILC would provide sensitivity to indirect effects of SUSY particles even in a scenario where the (strongly interacting) superpartners are so heavy that they escape detection at the LHC.

In Fig. 1 a scenario with very heavy squarks and a very heavy gluino is considered. It is based on the values of the SPS 1a’ benchmark scenario \cite{11}, but the squark and gluino mass parameters are fixed to 6 times their SPS 1a’ values. The other masses are scaled with a common scale factor except $M_A$, the mass of the $CP$-odd Higgs boson, which is kept fixed at its SPS 1a’ value. In this scenario the strongly interacting particles are too heavy to be detected at the LHC, while, depending on the scale-factor, some colour-neutral particles may be in the ILC reach. Fig. 1 shows the prediction for $\sin^2 \theta_{\text{eff}}$ in this SPS 1a’ inspired scenario as a function of the lighter chargino mass, $m_{\tilde{\chi}_1^\pm}$. The prediction includes the parametric uncertainty, $\sigma_{\text{para-ILC}}$, induced by the ILC measurement of $m_t$, $\delta m_t = 100 \text{ MeV}$, and the numerically more relevant prospective future uncertainty on $\Delta \alpha_{\text{had}}^{(5)}$, $\delta(\Delta \alpha_{\text{had}}^{(5)}) = 5 \times 10^{-5}$ \cite{12}. The MSSM prediction for $\sin^2 \theta_{\text{eff}}$ is compared with the experimental resolution with GigaZ precision, $\sigma_{\text{ILC}} = 0.000013$, using for simplicity the current experimental central value. The SM prediction (with $M_{H}^{\text{SM}} = M_h^{\text{MSSM}}$) is also shown, applying again the parametric uncertainty $\sigma_{\text{para-ILC}}$. 

Figure 1. Theoretical prediction for $\sin^2 \theta_{\text{eff}}$ in the SM and the MSSM (including prospective parametric theoretical uncertainties) compared to the experimental precision at the ILC with GigaZ option. An SPS1a’ inspired scenario is used, where the squark and gluino mass parameters are fixed to 6 times their SPS 1a’ values. The other mass parameters are varied with a common scale factor.
Despite the fact that no coloured SUSY particles would be observed at the LHC in this scenario, the ILC with its high-precision measurement of $\sin^2 \theta_{\text{eff}}$ in the GigaZ mode could resolve indirect effects of SUSY up to $m_{\tilde{\chi}^\pm} < \sim 500$ GeV. This means that the high-precision measurements at the ILC with GigaZ option could be sensitive to indirect effects of SUSY even in a scenario where SUSY particles have neither been directly detected at the LHC nor the first phase of the ILC with a centre of mass energy of up to 500 GeV.

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