LINEAR COLLIDER PROSPECTS ON ELECTROWEAK PHYSICS

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Prospects on electroweak physics at a future International Linear Collider (ILC) are summarized, including gauge coupling measurements, top quark physics and Higgs physics.

1 Introduction
A major goal of present and future research in high-energy physics is the understanding of the mechanism of mass generation and electroweak symmetry breaking (EWSB). Precision measurements in the electroweak sector of the Standard Model (SM) and its extensions allow us to tackle these questions both directly and indirectly via quantum effects. The clean environment of $e^+e^-$ colliders with high luminosity sets the basis for approaching this task. In the following I will exemplify with the help of some prominent results the prospects for electroweak measurements at future $e^+e^-$ colliders in the gauge boson, top quark and Higgs boson sector.

2 Electroweak gauge bosons
A primary goal for the study of gauge boson properties is to establish the non-Abelian nature of electroweak interactions. Very precise measurements constrain new physics at scales above the direct reach of the machine. Processes sensitive to triple gauge couplings in $e^+e^-$ collisions are $W$ production in pairs, $e^+e^- \to W^+W^-$, or singly in $e^+e^- \to We\nu$. At high luminosity and with the help of beam polarisation the triple couplings can be determined with an error of a few $10^{-4}$, see Table 1, so that new physics at high scales can be tested.

Anomalous quartic couplings can be probed in gauge boson scattering where six fermion final states have to be studied. Simulations have shown that at an $e^+e^-$-collider electroweak symmetry breaking scales up to 3 TeV can be probed covering the threshold region of strong $WW$ interactions.

3 Top quark physics
The top quark with a mass $m_t = 178 \pm 4.3$ GeV is the heaviest observed fermion. With its lifetime being much larger than the QCD scale top production and decay can be analysed within perturbative QCD. New interactions may be revealed through non-standard top decays.

The top quark mass can be precisely measured in threshold production. On the

Table 1. Single parameters fits ($1\sigma$) to triple gauge couplings with beam polarisation $P_{e^-/e^+} = 80/60\%$. Parametrisation as in Ref. 3.

| coupling | error $\times 10^{-4}$ |
|----------|------------------------|
| $\Delta g_1^Z$ | 2.8 $\pm$ 1.8 |
| $\Delta \kappa_1$ | 3.1 $\pm$ 1.9 |
| $\lambda_1$ | 4.3 $\pm$ 2.6 |
| $\Delta g_1^Z$ | 15.5 $\pm$ 12.6 |
| $\Delta \kappa_1$ | 3.3 $\pm$ 1.9 |
| $\lambda_1$ | 5.9 $\pm$ 3.3 |
| $\Delta \kappa_Z$ | 3.2 $\pm$ 1.9 |
| $\lambda_Z$ | 6.7 $\pm$ 3.0 |
| $g_2^Z$ | 16.5 $\pm$ 14.4 |
| $g_4^Z$ | 45.9 $\pm$ 18.3 |
| $\tilde{\kappa}_Z$ | 39.0 $\pm$ 14.3 |
| $\tilde{\lambda}_Z$ | 7.5 $\pm$ 3.0 |

$\sqrt{s} = 500$ GeV $\sqrt{s} = 800$ GeV

C,P-conserving, $SU(2) \times U(1)$ relations:

C,P-conserving, no relations:

not C or P conserving

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theoretical side a lot of progress in determining the threshold cross section has been made: Threshold masses have been introduced\(^7\) to stabilize the location of the threshold and to reduce the correlation between \(m_t\) and the strong coupling constant \(\alpha_s\). The overall normalization of the cross section has been improved by the introduction of renormalization group improved perturbation theory where large QCD logarithms are resummed\(^8\), see Fig.1. A full NNLL order prediction, though almost complete, is still missing. The present estimate on the cross section is still under discussion and of order \(\pm 6\%\)^{10}. In the alternative fixed order perturbation series important progress has been made for the NNNLO contributions\(^{11}\).

On the experimental side an updated \(t\bar{t}\) threshold scan simulation has been performed\(^{12}\). It includes not only experimental systematic errors but also an estimate of the theoretical error in the cross section prediction. By performing a multiparameter fit it takes into account the large correlations between the physical parameters. The top mass, the top width and \(\alpha_s(M_Z)\) can be extracted simultaneously with uncertainties of about 20 MeV, 30 MeV and 0.0012, respectively. The extraction of the top Yukawa coupling from a four parameter fit, however, suffers from an error of several tens of percent. The current theoretical error of about 100 MeV on the top quark mass has not been included.

Anomalous top quark couplings can be probed in continuum production at high energies\(^{13}\).

4 Higgs physics

The Higgs mechanism is a cornerstone in the electroweak sector of the SM and its supersymmetric (SUSY) extensions. It allows to generate particle masses without violating gauge principles. In order to establish the Higgs mechanism experimentally four steps have to be taken: the Higgs particle(s) must be discovered, the spin and CP properties have to be determined, the gauge and Yukawa couplings must be measured and finally the Higgs self-interactions are to be determined to reconstruct the Higgs potential itself.

The main SM Higgs boson production processes are Higgs-strahlung\(^{14}\) at low energies, \(e^+e^- \rightarrow ZH\), and \(WW\) fusion\(^{15}\) at high energies, \(e^+e^- \rightarrow H\nu\bar{\nu}\). The full electroweak (EW) corrections at one loop have been calculated for both the Higgs-strahlung\(^{16,17}\) and the fusion process\(^{17,18}\). They are of \(\mathcal{O}(10\%)\). By combining recoil mass techniques and reconstruction of the Higgs decay products, the accuracy on \(M_H\) is 40-80 MeV for intermediate Higgs bosons\(^{19}\). Furthermore, the Higgs boson couplings to massive gauge bosons are best probed in the two production processes. The accuracies on the total cross sections\(^{20}\) and branching ratios\(^{21}\) are summarized in Table 2.

| \(\frac{\delta \sigma}{\sigma}_{ZH}\) | 2.5...3 % |
| \(\frac{\delta BR}{BR}_{ZZ}\) | 17 % |
| \(\frac{\delta \sigma}{\sigma}_{WW}\) | 2.8...13 % |
| \(\frac{\delta BR}{BR}_{WW}\) | 5.1...2.1 % |

Table 2. Accuracies on SM Higgs boson production cross sections and branching ratios into \(WW/ZZ\) for \(M_H = 120\text{--}160\text{ GeV}\) (160 GeV for \(BR(H \rightarrow ZZ)\)).

The spin and CP properties can be determined in a model-independent way from the angular distribution of the \(Z\) boson in \(e^+e^- \rightarrow ZH\)^{22}. Another method exploits the threshold dependence of the excitation curve.
together with the angular distribution. An experimental study shows that already with $\int L = 20 \text{ fb}^{-1}$ the measurement of the threshold cross section at three c.m. energies allows the confirmation of the scalar nature of the Higgs bosons, see Fig.2. For $M_H < 2M_Z$ the spin can also be determined from the invariant mass spectrum in the decay $H \rightarrow ZZ^*$ supplemented by angular correlations.

The absolute values of the Higgs couplings are extracted from a global fit to the measurable observables, i.e. the production cross sections and measured branching ratios discussed above. This is the only method by which the couplings can be determined in a model-independent way. A program HFITTER has been developed for that purpose. Table 3 shows the achievable accuracies for the couplings. The coupling measurement serves as a first crucial test for the Higgs mechanism which predicts the couplings to be proportional to the mass of the respective particle.

| Coupling | $M_H = 120$ GeV | $140$ GeV |
|----------|-----------------|-----------|
| $g_{HW}$ | $\pm 0.012$     | $\pm 0.020$ |
| $g_{ZZ}$ | $\pm 0.012$     | $\pm 0.013$ |
| $g_{tt}$  | $\pm 0.030$     | $\pm 0.061$ |
| $g_{Hbb}$ | $\pm 0.022$     | $\pm 0.022$ |
| $g_{Hcc}$ | $\pm 0.037$     | $\pm 0.102$ |
| $g_{H\tau\tau}$ | $\pm 0.033$ | $\pm 0.048$ |

Table 3. Relative accuracy on the Higgs couplings assuming $\int L = 500 \text{ fb}^{-1}$, $\sqrt{s} = 500$ GeV ($\int L = 1 \text{ ab}^{-1}$, $\sqrt{s} = 800$ GeV for $g_{tt}$).

The lifetime $\Gamma_H$ of the Higgs, being rather small for $M_H \lesssim 200$ GeV, can be extracted indirectly by combining coupling with branching ratio measurements. In the WW channel accuracies of 4-13% for $M_H = 120-160$ GeV can be reached.

In the SM the trilinear and quartic Higgs self-couplings are uniquely determined by the mass of the Higgs particle. The measurement of $\lambda_{HHH}$ hence serves as a consistency check of the SM Higgs mechanism. At the ILC.

Figure 2. The threshold cross section $e^+e^- \rightarrow ZH \rightarrow t^+t^- + 2$ jets at three c.m. energies and the predictions for spin $s=0$ (full line), $s=1$ (dashed line) and $s=2$ (dotted line).

Figure 3. Precision on the top Higgs Yukawa coupling taking LHC and LC data. For comparison the precision for the LC alone is also shown.
it is accessible\textsuperscript{33} in double Higgs-strahlung \(e^+e^- \rightarrow ZHH\)\textsuperscript{34} at low energies and in WW fusion into Higgs pairs at high energies, \(e^+e^- \rightarrow HH\nu\nu\). Since the cross sections of only a few fb are rather small the highest possible luminosities are needed. Experimental studies have shown that \(\lambda_{HHH}\) can be extracted from \(e^+e^- \rightarrow ZHH\) with better than 20% for \(M_H = 120\) GeV and \(\sqrt{s} = 500\) GeV, \(\int \mathcal{L} = 1\) ab\textsuperscript{-1}\textsuperscript{36}. At a multi-TeV collider the expected error is about 8% for \(M_H = 120-180\) GeV\textsuperscript{37}. A further recent study reports a possible 10% measurement by exploiting WW fusion and Higgs-strahlung\textsuperscript{38}.

The Higgs sector of the Minimal Supersymmetric Extension of the SM (MSSM) consists of 5 Higgs particles, 2 CP-even, \(h, H\), one CP-odd, \(A\), and two charged ones, \(H^\pm\). The heavy Higgs particles can be produced in \(e^+e^-\) collisions in pairs, \(e^+e^- \rightarrow HA\). A recent experimental study has shown, that the \(H, A\) masses can be measured with a several hundred MeV accuracy for Higgs pair production far above the kinematic threshold\textsuperscript{39}. Charged Higgs bosons with \(M_{H^\pm} < \sqrt{s}/2\) can be pair produced. The expected mass resolution for \(M_{H^\pm} = 300\) GeV is 1.5%\textsuperscript{40}.

Furthermore, heavy MSSM Higgs bosons can be produced as \(s\) channel resonances in photon collisions\textsuperscript{41} for \(M_H/A \gtrsim 200\) GeV and medium values of \(\tan \beta\), a parameter region which is not accessible in the \(e^+e^-\) mode for masses above \(\sqrt{s}/2\) and in which the LHC might be blind for the \(H/A\) discovery. A simulation of the \(b\bar{b}\) final state\textsuperscript{42} (see Fig.4), finds that the cross section can be determined with a statistical precision of of 8-20%\textsuperscript{43}.

There are 6 CP invariant neutral trilinear Higgs self-couplings \(\lambda_{HHH}\) in the MSSM. They are accessible in WW/ZZ fusion into Higgs pairs, double Higgs-strahlung and triple Higgs production\textsuperscript{43,46}. All self-couplings can be determined from these cross sections up to discrete ambiguities provided they are large enough. Demanding the cross sections to exceed 0.01 fb and the effect of a non-zero Higgs self-interaction to be larger than 2 st.dev. for \(\int \mathcal{L} = 2\) ab\textsuperscript{-1} the coupling among three light Higgs bosons is accessible in large ranges of the \(M_A\)-\(\tan \beta\) parameter space, see Fig.6\textsuperscript{33}, other couplings are accessible through Higgs...
cascade decay channels.

![Figure 6. Sensitivity to $\lambda_{hh}$ in $e^+e^- \rightarrow Z hh$.](image)

In the past a plethora of further extensions of the SM beyond the MSSM has been proposed, as e.g. the CP violating MSSM\textsuperscript{47}, the next-to-minimal SUSY extension (NMSSM)\textsuperscript{48}, Little Higgs models\textsuperscript{49} etc. The precision measurements of couplings achievable at a future ILC will help to discriminate and constrain the various models.

5 Summary

The future ILC\textsuperscript{50} will provide us with precision measurements in the electroweak sector of the SM and SUSY extensions which will be mandatory to understand the Higgs mechanism in all its essential aspects and thus to understand the mechanism of mass generation and EWSB. The high precision on the measured observables allows for a sensitivity to new physics at high scales beyond the direct reach of the collider itself but also at the LHC.

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