Studies of electroweak symmetry breaking with a Linear Collider

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Abstract

The mechanism of electroweak symmetry breaking is one of the unsolved questions in particle physics. Probably LHC will give us first hints but not the final answer on this problem. In this paper it will be shown that a future linear collider will largely enhance our knowledge how the electroweak symmetry is broken.

1 Introduction

One of the most urgent problems in particle physics is the question how the electroweak symmetry is broken. All phenomena are successfully described by local gauge theories. However, these theories work only, if all particles are massless, which is clearly in contradiction to experiment. The standard solution to this problem is the Higgs mechanism. A scalar field with non-zero vacuum expectation value beaks the symmetry spontaneously and gives masses to the particles proportional to their coupling to the Higgs field.

In this scheme at least one neutral scalar particle, the Higgs boson, has to exist, which has not been found yet. The most serious problem of this scheme within the Standard Model is the so called hierarchy problem. The scattering amplitudes of massive particles grow with energy, eventually violating unitarity, if they do not get regulated by the Higgs exchange amplitude. The first process violating unitarity is WW $\rightarrow$ WW at $\sqrt{s} = 1.2\,\mathrm{TeV}$ requiring the Higgs mass to be below that value. On the other hand the Higgs mass receives radiative corrections if it is run down from the highest scale where the theory is defined to the weak scale. If the Standard Model is the final theory, which should be valid up to the Planck scale ($m_{\mathrm{Pl}} = \sqrt{\hbar c/G_N} \approx 10^{19}\,\mathrm{GeV}$) the corrections to the Higgs mass are also of the order of the Planck scale requiring an enormous amount of fine tuning to get the Higgs mass into the required range.

There are several solutions proposed for this problem. The most popular one is certainly Supersymmetry. This symmetry gives every fermion a bosonic partner and vice versa. The quadratic contributions to the Higgs mass of the particles and their partners cancel, keeping the Higgs mass small. Supersymmetry definitely predicts a relatively light Higgs. In addition the mass of the superpartners should be below the TeV scale so that one can expect to see them at next generation colliders.

Another possibility is that there are more than three space dimensions where the extra dimensions are compactified on a small scale. In these models gravity is much stronger and only appears so small because it has more dimensions to propagate. The Planck mass is in reality thus only around 1 TeV so that no hierarchy problem exists. In the compactified dimensions of those models a large number of Kaluza Klein excitations of the graviton should exist, which could be seen as real or virtual exchange particles at colliders. In addition some models predict a Higgs like particle, the radion, which can also mix with the Higgs, changing slightly its properties.

Also there could be new symmetries at the $\mathcal{O}(10\,\text{TeV})$ scale and the Higgs is a pseudo Nambu Glodstone Boson at this scale. In these so called little Higgs models two operators are needed to break the symmetry protecting the mass of the Higgs at the one loop level. Technically the Standard Model loop contributions to the Higgs mass are cancelled by new particles with the same spin as the Standard Model ones and masses around $1-3\,\text{TeV}$. One can thus expect Z' like states at this scale and the loop induced Higgs decays might be different from the Standard Model predictions.

If no light Higgs exists, electroweak interactions become strong at high energies and for example $WW \to WW$ violates unitarity at $\sqrt{s} = 1.2\,\text{TeV}$. The Higgs mechanism can be mimicked by a new strong interaction at this scale. Ideally at colliders one can see new resonances in this case, corresponding e.g. to the ρ and the ω in QCD, coupling to the longitudinal degrees of freedom of the gauge bosons. One also expects to see anomalous effects in the interactions amongst gauge bosons.

As can be seen from Figure 1 a) within the Standard Model present data strongly prefer a light Higgs, well consistent with Supersymmetry [2]. However, as shown in Figure 1 b) this constraint can be easily circumvented if new physics generates new, isospin violating, contributions to the ρ parameter ($\Delta\rho = \varepsilon_1$) [2, 3]. Also strong electroweak symmetry breaking is severely constraint by the LEP and SLD precision data. As an example an exact copy of QCD is excluded, however models can be built that are consistent with the data.

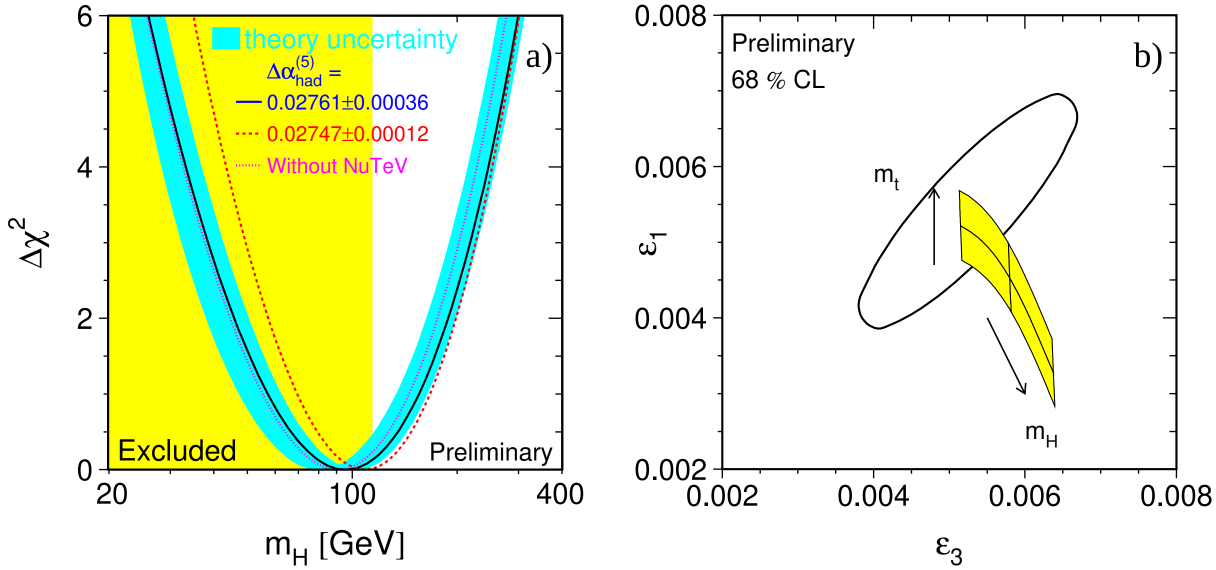

Figure 1: a) $\Delta\chi^2$ as a function of the Higgs mass for the electroweak precision data. b) ε_1 vs ε_3 for the electroweak data compared to the Standard Model.

The most important task of the LHC and a linear collider is certainly the search for the Higgs. The strategey then depends if a Higgs has been found and on its mass.

If a Higgs with a mass below around 130 GeV is found one has to see if its properties are consistent with the Standard Model or Supersymmetry. Superpartners have to be searched for and if they are found one has to address the question how Supersymmetry is broken.

If a Higgs with a mass below around 200 GeV is found it has to be verified that it is consistent with the Standard Model. Also one has to see if there is any sign of physics beyond the Standard Model.

If the Higgs mass is above 200 GeV one has to verify that the Higgs is really a Higgs and to search for the physics that mimics the light Higgs in the electroweak precision data.

If no Higgs is found at all one has on one hand to search through the exotic models where the Higgs might escape detection and on the other hand look for signals of strong electroweak symmetry breaking.

1.1 Experimentation at a Linear Collider

At a next generation lepton collider one wants to reach the energy range from the LEP energies up to around 1 TeV. For e^+e^-, circular machines are thus no longer possible because of the too large synchrotron radiation so that one has to use the linear collider technology. As seen from Figure 2 the typical cross sections are in the range from few fb up to few fb so that total luminosities from tens to hundreds pb^{-1} are needed.

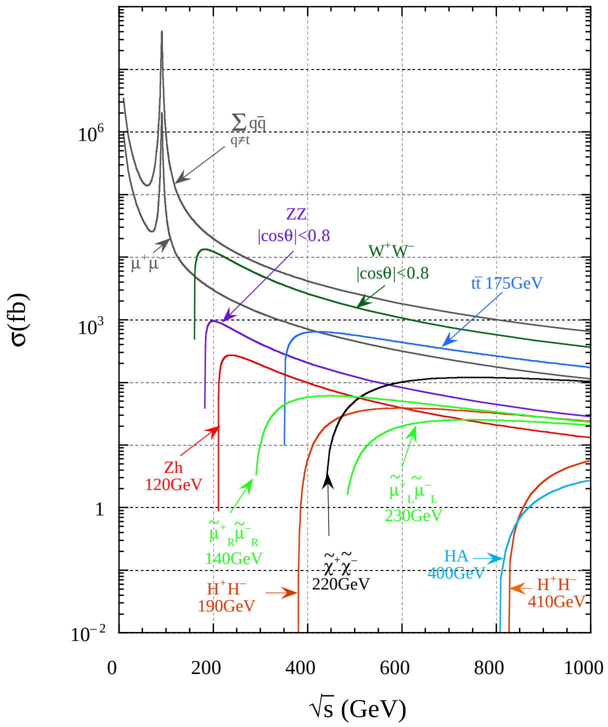

Figure 2: Cross sections for selected processes in the Linear Collider energy range.

The parameters of the different linear collider projects are similar [4], so that as an example TESLA is taken. In a first stage a centre of mass energy of $\sqrt{s} \leq 500$ GeV is planned which can be upgraded to around 1 TeV. The luminosity ranges from 50 fb^{-1}/year on the Z-resonance up to 500 fb^{-1}/year at 800 GeV. An electron polarisation of $\geq 80\%$ is possible while positrons might be polarised to $40 - 60\%$. In addition TESLA can also be run as a $\gamma\gamma$ collider.

With the design luminosity one expects few$\cdot 10^4$ $e^+e^- \to HZ$ events per year at $\sqrt{s} \approx 350\,\mathrm{GeV}$ ($m_H \approx 120\,\mathrm{GeV}$), 10^5 $e^+e^- \to t\bar{t}$ per year at $\sqrt{s} \approx 350\,\mathrm{GeV}$, $5 \cdot 10^5$ $e^+e^- \to q\bar{q}$/year and 10^5 $e^+e^- \to \mu^+\mu^-$/year not counting radiative return events and 10^6 $e^+e^- \to W^+W^-$/year at $\sqrt{s} = 500 - 1000\,\mathrm{GeV}$. If one runs back on the Z-resonance 10^9 events per year are possible.

2 Higgs Physics

If a Standard Model like Higgs exists at least the LHC should have found a particle compatible with it at the time the Linear Collider is running. The task of the Linear Collider is then to measure its properties and to show that this is really the particle responsible for mass generation. The LC records several ten thousand Higgses per year for a Higgs mass of 120 GeV and still a few thousand for a mass around 500 GeV. This allows, as shown in Figure 3 a) to measure the cross section $e^+e^- \to HZ$ to 2.5% in a model independent way reconstructing the recoil mass in events with leptonic Z decays [1]. The Higgs spin and parity can be measured uniquely from a threshold scan of the same process (Figure 3 b) with some additional information from angular correlations. Quite a couple of other measurements are possible [1]: The Higgs branching rations can be measured with a few % precision due to the excellent flavour tagging capabilities, the total Higgs width can be measured to a few % in a model independent way, the Higgs mass can be measured to $\sim 50\,\mathrm{MeV}$ with constraint fits similar to the W mass at LEP, the Ht Yukawa coupling can be measured to 5%, the Higgs self-couplings can be established with 10-20% precision and the $\gamma\gamma$H couplings can be measured to $\sim 3\%$ at a photon collider.

These measurements can be used to constrain models significantly. Figure 4 a) shows the sensitivity of the $b\bar{b}$ branching ratio of the Higgs to the mass of the pseudoscalar Higgs, A, in the minimal supersymmetric model (MSSM) [5]. The LC data are sensitive to A masses up to around 700 GeV in a region of the parameter space where the LHC sees nothing but a Standard Model like Higgs. As shown in Figure 4 b) the ZHH coupling can be used to distinguish the Standard Model and the MSSM from the next to minimal supersymmetric model with an additional Higgs singlet [6].

As another example Figure 5 shows possible modifications of the loop induced Higgs decays $H \to \gamma\gamma$ and $H \to gg$ in a little Higgs model [7]. If the scale is only around $f = 1\,\mathrm{TeV}$ in both decays effects might be visible. For a higher scale only the $H \to \gamma\gamma$ measured at a photon collider seems to be sensitive.

3 Supersymmetry

Supersymmetry is at present the best motivated solution of the hierarchy problem and has received most attention in the studies up to now. If the R-parity is conserved the lightest supersymmetric particle (LSP) is also an excellent candidate for the dark matter in the universe. Naturalness requires the masses of the lightest superpartners to be below around

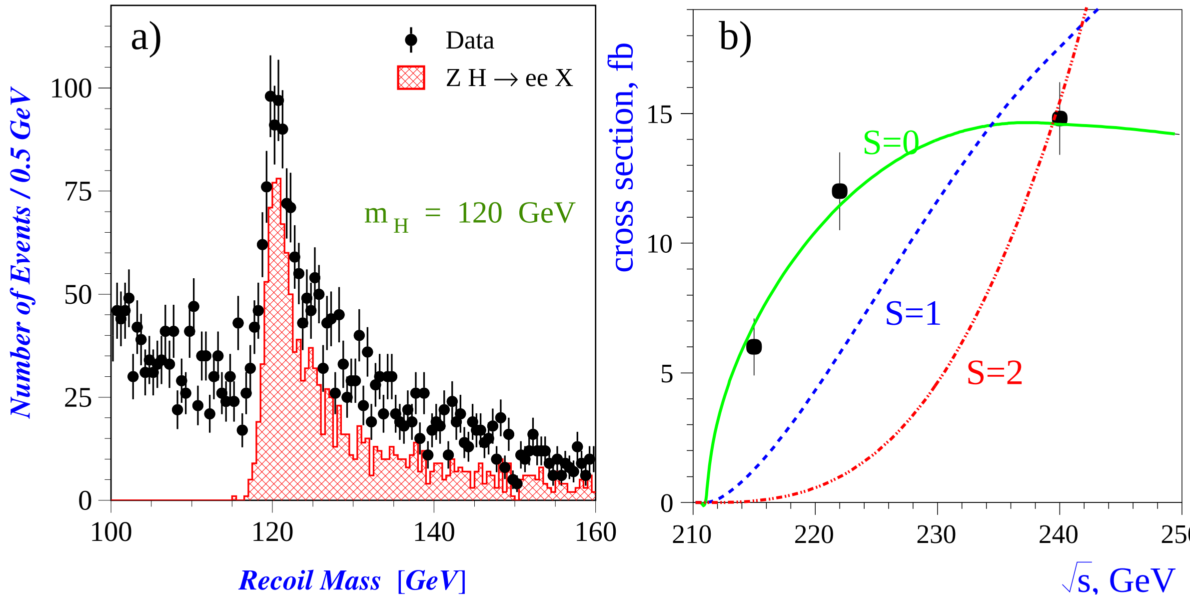

Figure 3: a) Recoil mass distribution for $e^+e^- \to e^+e^- X$ b) cross section $e^+e^- \to HZ$ in the threshold region for different values of the Higgs spin.

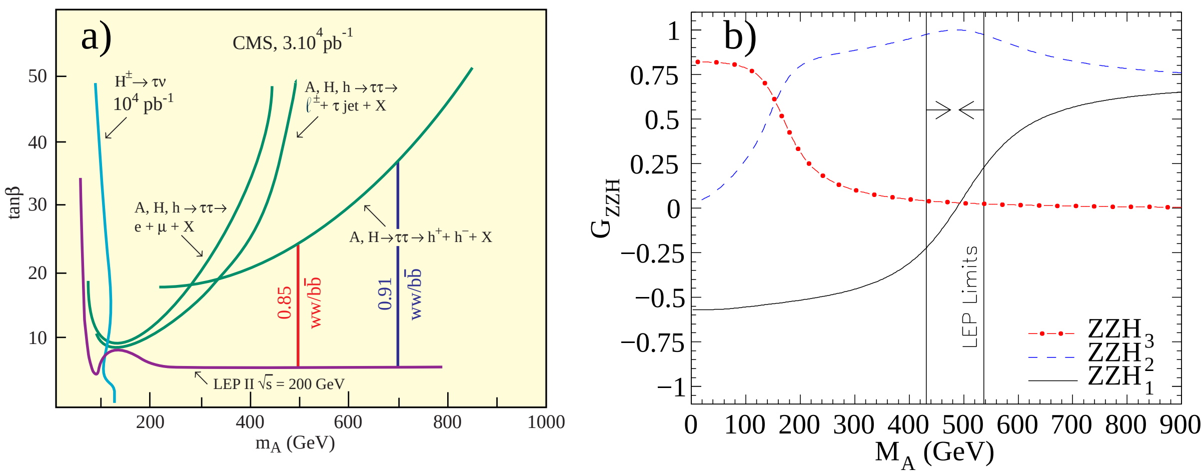

Figure 4: a) Sensitivity of the Higgs branching ratios to m_A in the MSSM. b) Ratio of the HZZ coupling in the NMSSM and the MSSM/SM.

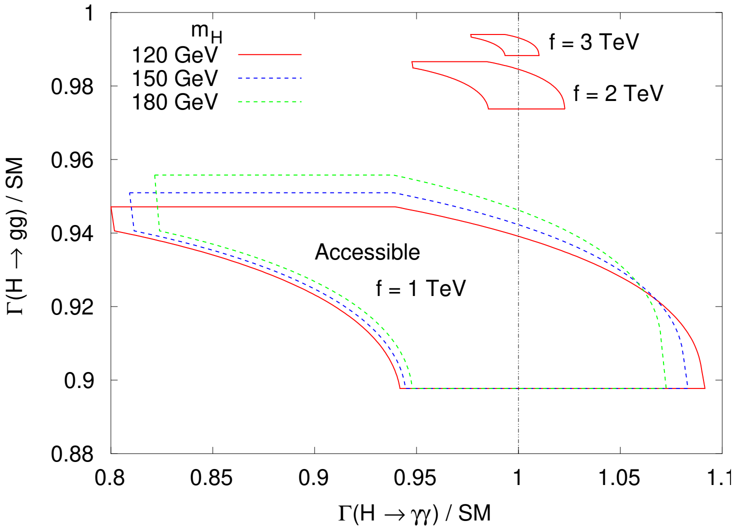

Figure 5: Possible effects for the loop induced Higgs decays in little Higgs models.

1 TeV, however details depend on the mechanism and parameters of symmetry breaking which are largely unknown. In most scenarios the LHC produces large numbers of squarks and gluinos, while sleptons and gauginos might be seen only in cascades. Because of the invisible LSP the LHC can measure only mass differences pretty accurately, while the absolute scale is known with only relatively bad precision.

In case indications for SUSY at the LHC are found the linear collider first has to prove that the new particles are really from Supersymmetry. It has then to measure as many particle properties as possible to try to reconstruct the breaking scheme and to get the properties of the LSP as an input to cosmology.

If the SUSY scale is not too high all sleptons and most charginos and neutralinos could be in the energy range of the linear collider. Apart from the lighter stop, which can be relatively light because of mixing, it is improbable that also squarks and gluinos can be seen.

Masses of superpartners can in general be measured either by threshold scans or by several reconstruction techniques. Threshold scans are especially precise if the threshold suppression is proportional to the particle velocity β like for $\mathrm{e^+e^-} \rightarrow \chi_1^+\chi_1^-$ (Fig. 6 a)) or $e^-e^- \rightarrow \tilde{e}^-\tilde{e}^-$. In this case the precision is in the per mille range. Right handed selectrons and smuons normally decay into a charged lepton and a neutralino (LSP) and their masses and the one of the LSP can be reconstructed from the endpoints of the decay-lepton energy spectrum (Fig. 6 b)). Since the sleptons have spin zero this measurement they decay isotropically in they rest frame and the mass measurement is thus is completely model independent.

The linear collider mass measurements improve the mass measurements of the LHC significantly. Figure 7 a) shows as an example the case where the LC has only access to the lightest gauginos mass while the LHC sees more of them. In this case the LHC measurement of M_2 can be improved by more than an order of magnitude using the M_1 measurement of the LC. In the likely case that the squarks are not visible at the LC also their mass measurement from can be improved by roughly a factor three using the LSP

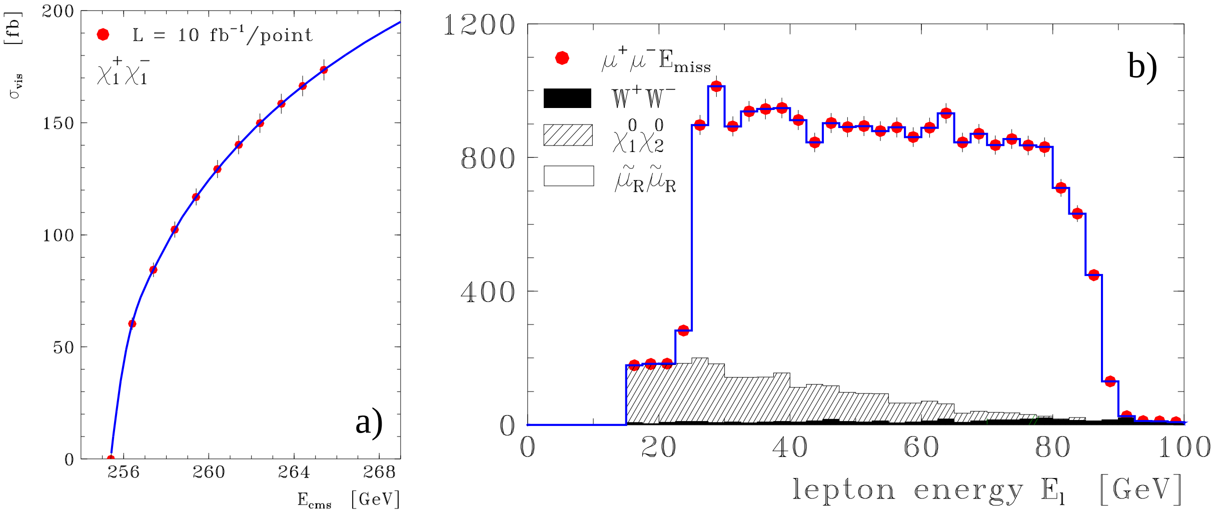

Figure 6: a) Simulated threshold scan for $e^+e^- \to \chi_1^+\chi_1^-$. b) Muon energy spectrum from $e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$.

mass from the LC (Fig. 7 b)).

Coupling measurements are up to now only studied using cross sections for polarised beams. In principle, however, further information can be obtained from production angle distributions, which are sensitive to the mixture of s- and t-channel production and from branching ratio measurements. Nevertheless all couplings can be reconstructed if the full spectrum is in the LC energy range.

As a first example figure 8 a) shows the stop pair production cross section for different beam polarisations as a function of the stop mixing angle for a fixed mass of the $\tilde{t}_1$[8]. Figure 8 b) shows the precision that can be obtained from the cross sections for left and right handed electrons on the mass and the mixing angle. These two parameters have a large influence on the radiative corrections in the Higgs sector and a good knowledge of them is therefore needed to interprete the Higgs measurements.

The chargino mass matrix contains the parameters M_2, μ and $\tan\beta$. Since this matrix is not symmetric, two mixing angles ϕ_L and ϕ_R are needed to diagonalise it. If the $\chi_1^\pm$ mass is known both mixing angles and thus M_2, μ and $\tan\beta$ can be reconstructed from the $\chi_1^\pm$ pair production cross section, even if only the $\chi_1^\pm$ is accessible (Fig. 9) [9]. The precision is, however, much better if both charginos are seen.

The neutralino mass matrix contains in addition the Bino mass parameter M_1 which follows from $m_{\chi_1^0}$ and $m_{\chi_2^0}$ once the chargino sector has been explored. $\chi_1^0\chi_2^2$ production proceeds via t-channel exchange of a selectron. The production cross section depends thus on the $e\tilde{e}\chi_{1,2}^0$ coupling which follows from the $ee\gamma$ and eeZ couplings by the Supersymmetry relation. Fig. 10 shows the possible precision of this coupling if the cross section for both beam polarisations is measured[10]. Such measurements are crucial to prove that the new particles that are seen are really superpartners of the Standard Model particles.

When enough parameters of supersymmetric particles are measured one can try to reconstruct the fundamental parameters of the supersymmetric theory. In a first step the parameters at the weak scale can be obtained from the masses and cross section as already

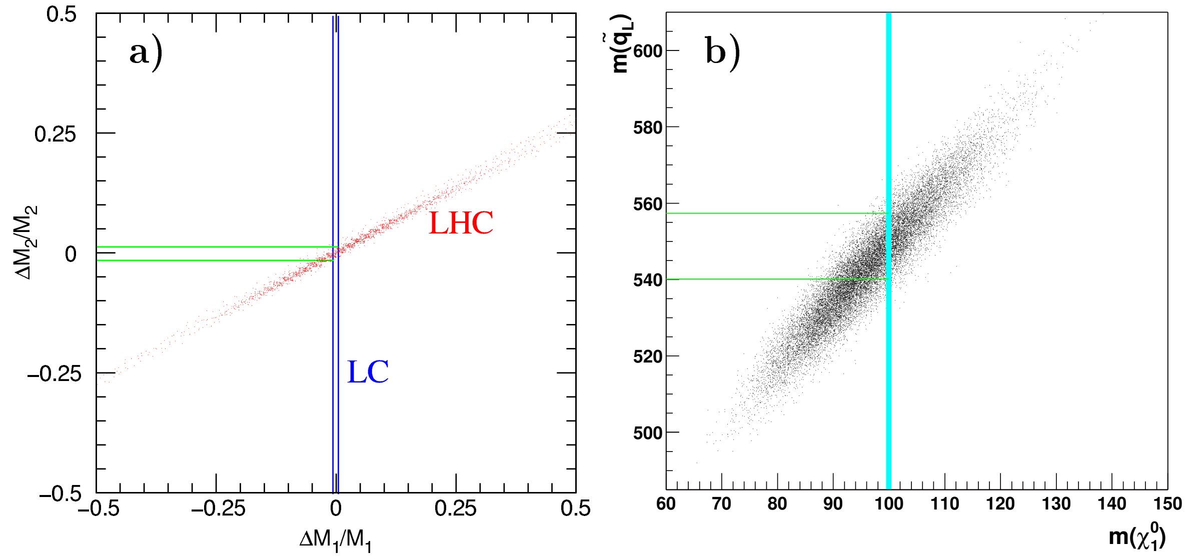

Figure 7: a) Combination of the LHC $M_1 - M_2$ measurement with a LC measurement of M_1. b) Combination of the LHC $m(\chi_1^0) - m(\tilde{q})$ measurement with a LC measurement of $m(\chi_1^0)$.

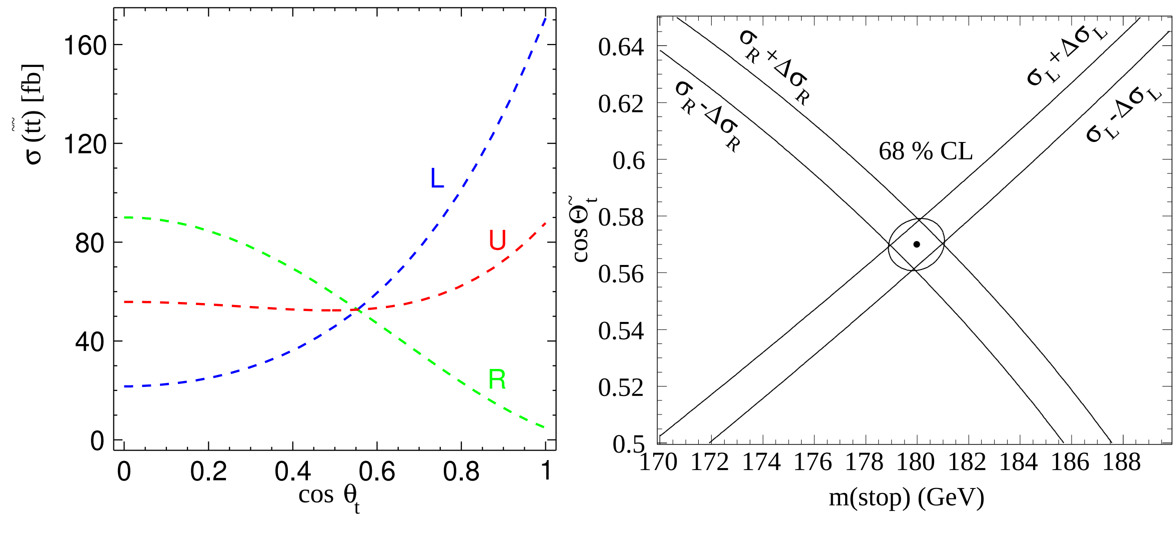

Figure 8: a) Cross section for stop production with lefthanded, righthanded and unpolarised beams as a function of the stop mixing angle. b) Contour of the cross section measurement with left- and right-handed beams in the stop mass – mixing angle plane.

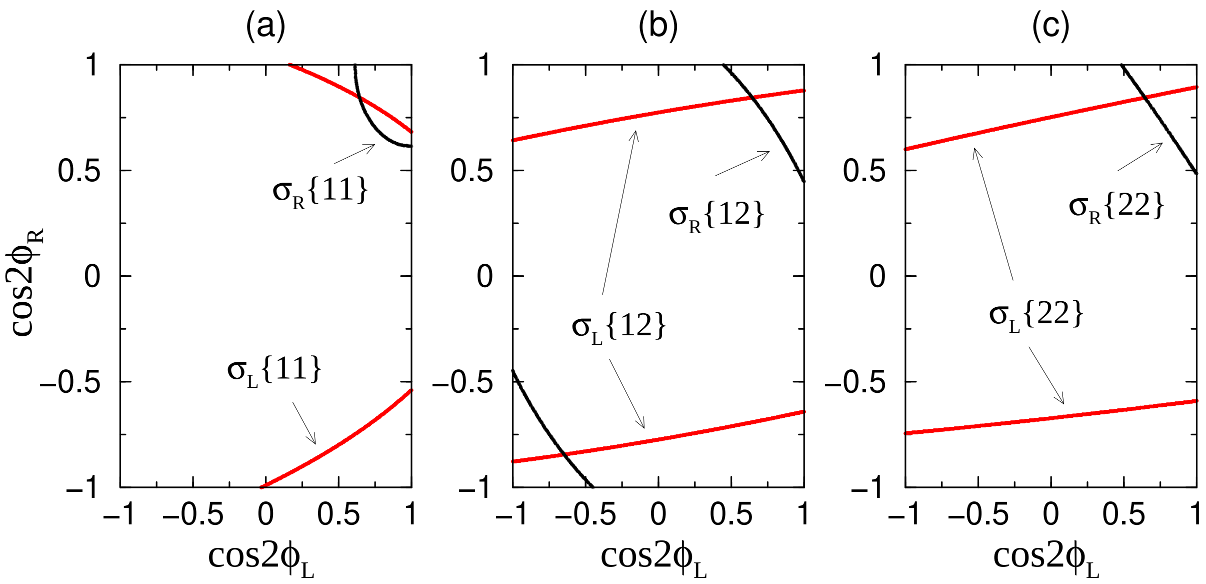

Figure 9: Contours in the $\cos 2\phi_L - \cos 2\phi_R$ plane from a cross section measurement with left- and right-handed electron beams for $\chi_1^+\chi_1^-$ (a), $\chi_1^\pm\chi_2^\mp$(b) and $\chi_2^+\chi_2^-$ (c) production.

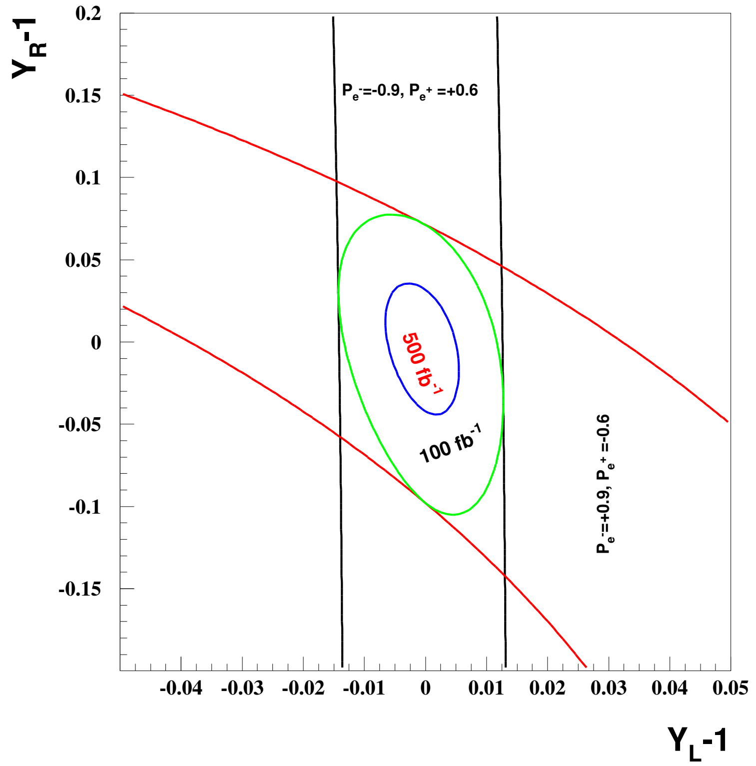

Figure 10: Measurement of the $e\tilde{e}\tilde{Z}$ coupling from $\chi_1^0\chi_2^0$ production.

shown for some examples. In a second step these parameters can be extrapolated to the GUT scale using the renormalisation group equations. These extrapolations are almost model independent and contain important information on the underlying mechanism of Supersymmetry breaking. Since the errors can blow up considerably during the extrapolation the ultimate precision is needed for this. Also it is important to extrapolate the parameters for as many different particles as possible, especially also strongly interacting ones. Fig. 11 shows these extrapolations for gauginos and sfermions in a SUSY model with unification at the GUT scale [11]. One can see the need for precise measurements especially for squarks.

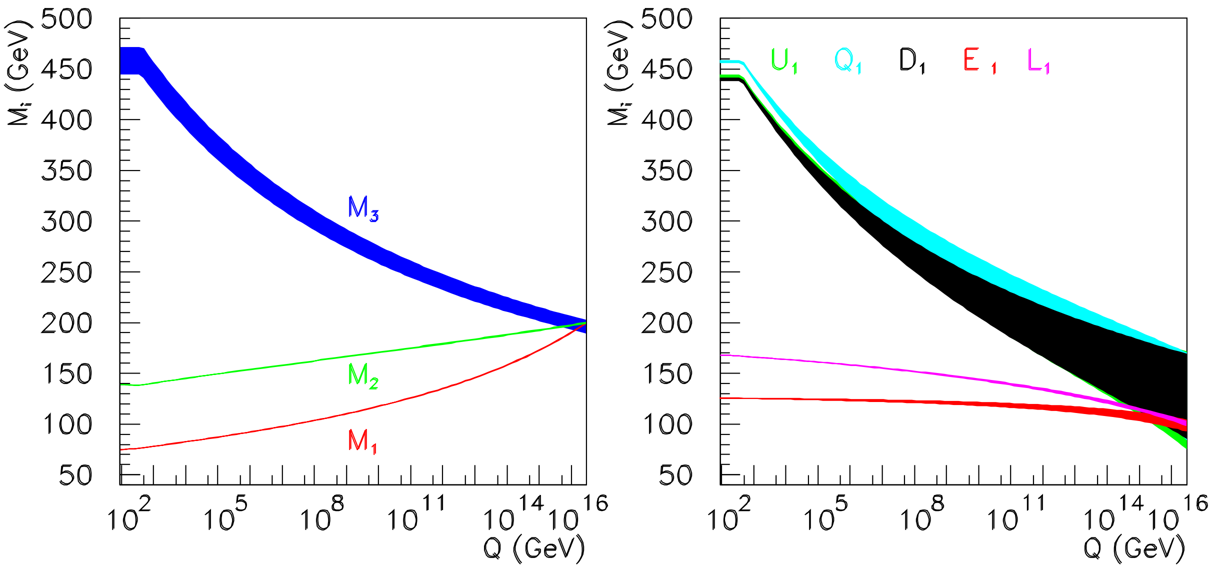

Figure 11: Extrapolation of low energy SUSY parameters to the GUT scale for a MSUGRA model.

4 Strong Electroweak Symmetry Breaking

If no elementary Higgs particle exists electroweak interactions become strong at a scale around 1 TeV. The vector bosons can then get their mass by a new strong interaction at this scale in a similar way as mesons get mass from QCD. In these models the longitudinal vector bosons are the Goldstone bosons of the new interactions similar to the pions in QCD. Correspondingly their interactions at high energy can be identified with the pion interactions at low energy, a relation known as the "Low energy Equivalence Theorem" (LET) [12]. The most intuitive channel to test these models is longitudinal vector boson scattering shown in figure 12. In an effective Lagrangian formulation vector boson scattering can be described by 11 parameters, five of them do not influence the triple gauge couplings. These five parameters reduce to two (α_4, α_5) if custodial SU(2) invariance is required. The sensitivity to these parameters of the processes $W^+W^- \to ZZ$ and $W^+W^- \to W^+W^-$ at $\sqrt{s} = 800\,\mathrm{GeV}$ has been analysed [13] and the results are shown in figure 13. The results translate into a new physics scale of $\Lambda \approx 3\,\mathrm{TeV}$ ($\Lambda = 4\pi v/\sqrt{\alpha}$) which coincides with the value required by unitarity.

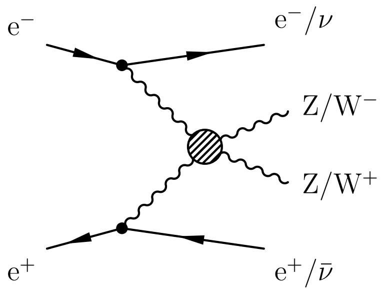

Figure 12: Generic Feynman diagram for vector boson scattering at a linear collider.

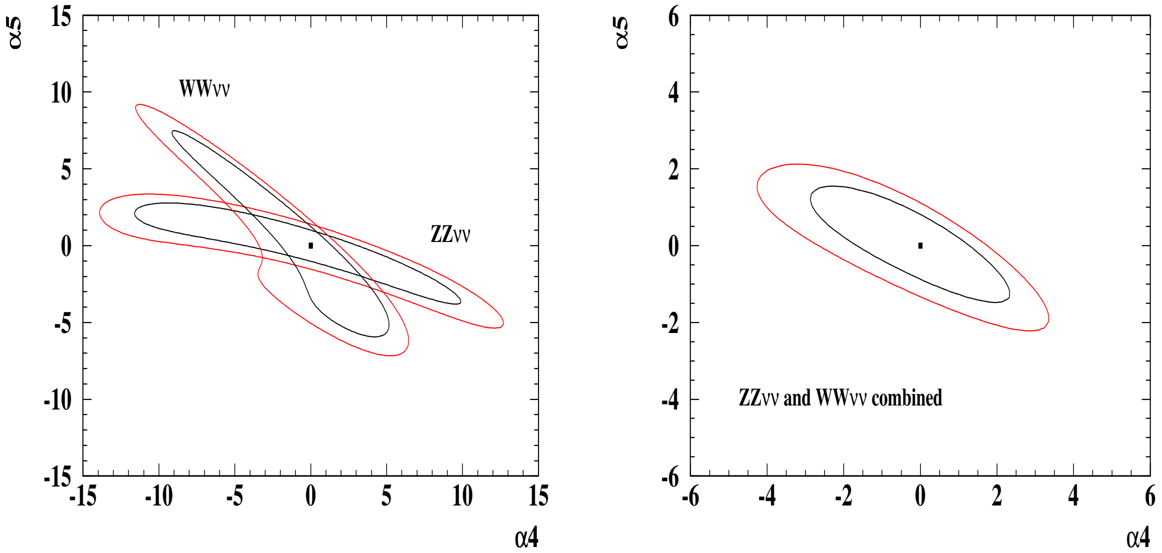

Figure 13: Sensitivity to α_4 and α_5 at $\sqrt{s} = 800\,\mathrm{GeV}$ from $e^+e^- \to \nu\nu W^+W^-$ and $e^+e^- \to \nu\nu ZZ$. The inner and outer contours represent 68% and 90% c.l. ($\mathcal{L} = 1000\ \mathrm{fb}^{-1}$, $\mathcal{P}_{e^-} = 0.8$, $\mathcal{P}_{e^+} = 0.4$).

It turns out that a higher sensitivity can be reached by the analysis of W-pair production. In the same way as the ρ-meson is seen in $e^+e^- \to \pi^+\pi^-$, I=J=1 resonances should be visible in pair production of longitudinal W-bosons. As an example figure 14 a) shows the effect of a 1.7 TeV ρ like resonance. Even at $\sqrt{s} = 500\,\mathrm{GeV}$ the effect is large enough to be visible.

In a model dependent analysis the effect of a techni-ρ meson has been parameterised as a complex form factor for longitudinal W-pair production [14]. The form factor at a given centre of mass energy depends on the mass and the width of the techni-ρ. The LET is the limit for infinite mass. As can bee seen from figure 14 b) at $\sqrt{s} = 800\,\mathrm{GeV}$ one can clearly separate the LET from the Standard Model and one is sensitive to the techni-ρ mass up to around 2.5 TeV.

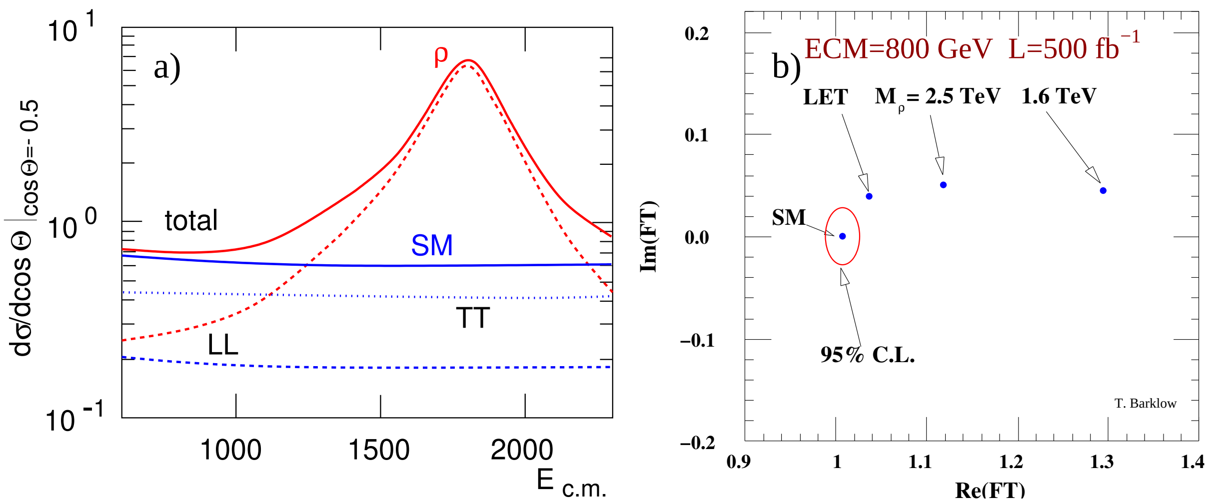

Figure 14: a) Cross section for (longitudinal) W-pair production in the presence of a techni-ρ resonance. b) Sensitivity to a ρ like resonance in W-pair production at $\sqrt{s} = 800\,\mathrm{GeV}$ and $\mathcal{L} = 500\ \mathrm{fb}^{-1}$.

In a model independent analysis the triple gauge couplings can be described in terms of three new operators with coupling constants α_1, α_2 and α_3 which can be calculated from the usual parameterisation of the triple gauge couplings in terms of g_1^Z, κ_γ and κ_Z. Unfortunately only two combinations of the three αs can be obtained that way. α_1, however, can be obtained from $\sin^2\theta^l_{eff}$ and m_W, which can also be measured precisely at a linear collider. Figure 15 shows the expected precision on $\alpha_{1,2,3}$ at a linear collider, which is about an order of magnitude better than at LHC [1]. The α limits translate into a new physics scale of $\Lambda > \mathcal{O}(10,\ \mathrm{TeV})$ much larger than the unitarity limit of 3 TeV.

5 Two-Fermion Production at High Energy

Fermion pair production is sensitive to new physics at high energy which interferes with the Standard Model amplitude. If the scale of the new physics is m_NP the interference term is suppressed by a factor s/m^2_NP. High masses can thus be reached because of the

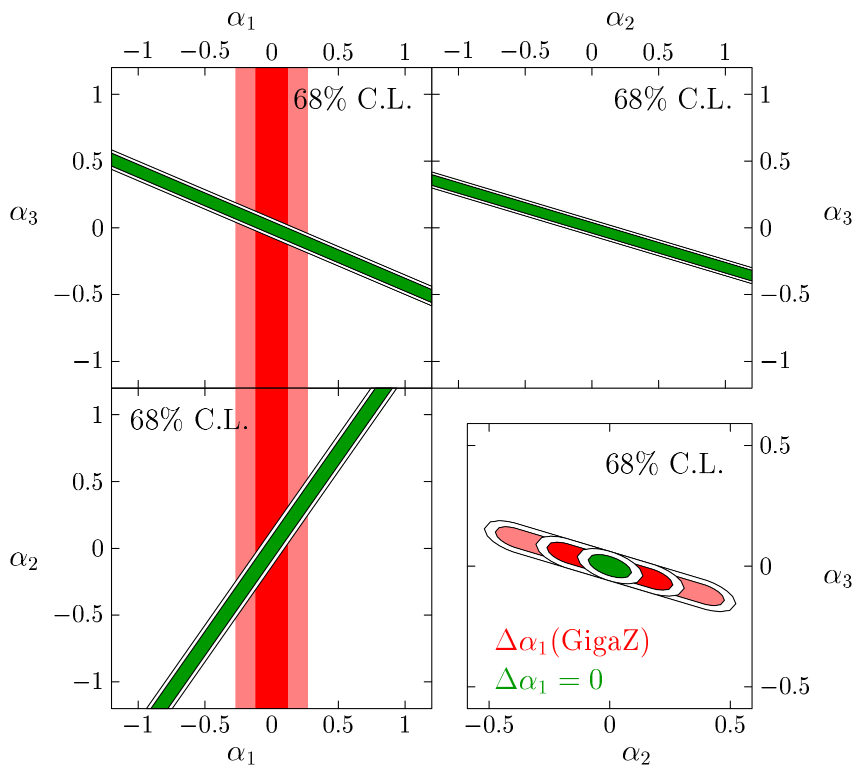

Figure 15: Sensitivity to the effective couplings $\alpha_{1,2,3}$ from the measurement of the triple gauge couplings at a linear collider and from the Z-pole precision data. For the Z-pole constraint the outer region is without and the inner region with the accurate m_{W} measurement. In the lower right plot the $\alpha_2 - \alpha_3$ plane with $\alpha_1 = 0$ or with the Z-pole constraint is shown.

high luminosity of the linear collider. The different couplings of the new physics can be disentangled by measuring cross sections for different beam polarisations and forward backward asymmetries. Cross sections can be measured for leptons, b, c and untagged quarks, while forward-backward asymmetries are not available for the untagged quarks.

If a model containing a Z' is assumed, all parameters except the Z' mass are fixed and all observables can be used to set a mass limit. Figure 16 shows the possible mass limit reachable at a LC and at LHC, where the LHC searches for bumps in the $\ell^+\ell^-$ mass distribution [15]. In general the LC and LHC limits are comparable, however the LC is sensitive to the interference term so that its limits vary stronger within the models.

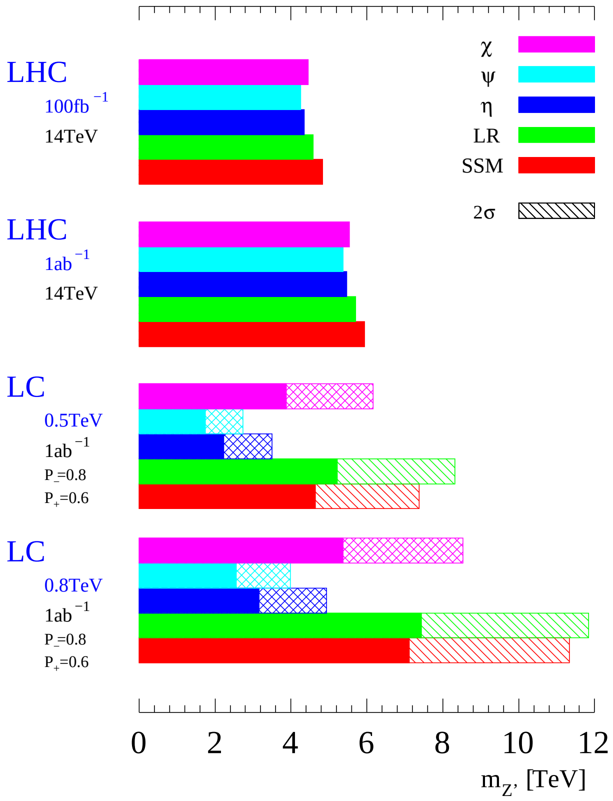

Figure 16: Mass reach for a Z' in different models for LHC and LC. The solid bars correspond to a 5σ discovery, while the dashed ones correspond to a 2σ exclusion.

In a model independent analysis the LC is sensitive to the normalised leptonic couplings

$$a_f^N = a'_f\sqrt{\frac{s}{m_{Z'}^2 - s}}, \quad v_f^N = v'_f\sqrt{\frac{s}{m_{Z'}^2 - s}}.$$

The hadronic observables depend on the product of the leptonic and hadronic couplings of the Z' and they can only be used to measure the hadronic couplings once the leptonic ones are already established.

Figure 17 a) shows the possible measurement of the Z' normalised couplings for a 6 TeV Z' which cannot be seen at LHC [15]. Different types of E_6 models can clearly be separated. In the ideal case LHC sees a resonance and measures its mass, so that the LC can measure the absolute couplings. Figure 17 b) shows this case for several centre of mass energies and Z' masses [1].

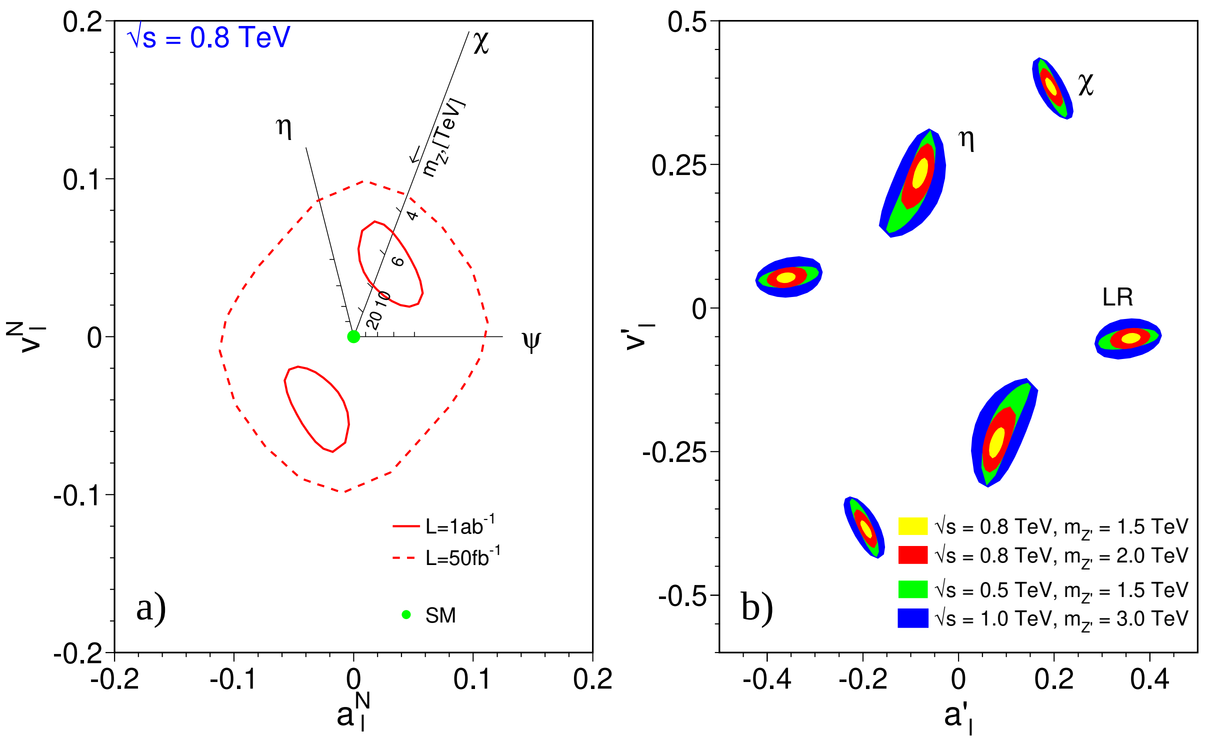

Figure 17: a)Measurement of normalised Z' couplings at TESLA. The χ-model with $m_{Z'} = 6\,$TeV is assumed for the central value. b) Measurement of the Z' couplings at a linear collider for different Z' masses and centre of mass energies.

In a similar way as the LC is sensitive to Z' bosons it can see the exchange of Kaluza Klein excitations of the graviton in models with large extra space dimensions. Extra space dimensions can be separated from the Standard Model up to a Planck mass of 8 TeV, similar to LHC [1]. The interesting question, however, if a deviation has been found, is if this deviation is due to extra space dimensions or a Z'. The key difference between the two models is that the graviton has spin two. If one defines the moments $\langle P_n \rangle = \int dz \frac{1}{\sigma}\frac{d\sigma}{dz} P_n(z)$ $(z = \cos\theta)$, where the P_n are the Legendre polynomials one has $\langle P_n \rangle = 0$ for $n > 2$ if only scalar and vector particles are exchanged. In the case of graviton exchange, however, there is $\langle P_{3,4} \rangle \neq 0$ [16]. This enables a unique identification of graviton exchange up to a scale of $4-5$ TeV. If transverse beam polarisation is available one can even go further[17]. In this case an azimuthal asymmetry exists, which varies with the polar angle, $\cos\theta$. As can be seen from figure 18 this asymmetry is symmetric in $\cos\theta$ for vector and scalar exchange while it is asymmetric in the presence of tensors. With this asymmetry the SM and extra space dimensions can be distinguished up to 22 TeV for $\sqrt{s} = 1\,$TeV, the highest reach at a next generation collider. Graviton exchange can be uniquely identified up to masses of $10\sqrt{s}$.

One of the most important two-fermion analyses at a linear collider is the measurement

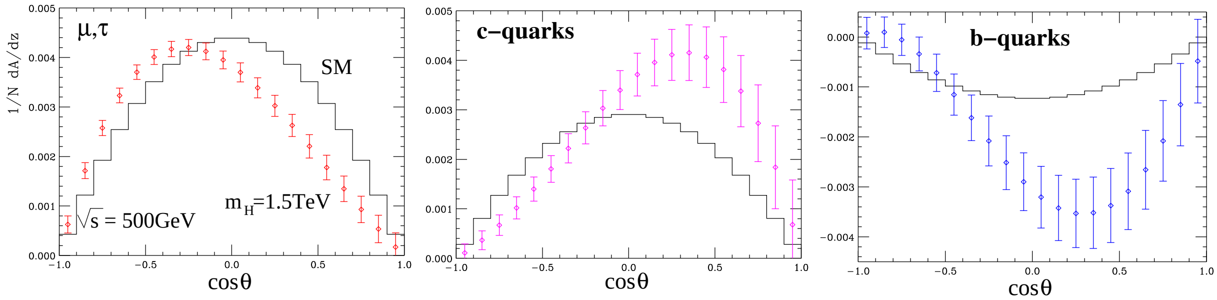

Figure 18: Azimuthal asymmetry with transverse beam polarisation as a function of the polar angle for leptons b- and c-quarks for the Standard Model and for $M_H = 1.5$ TeV.

of the top quark mass. The top quark is not only interesting in itself. Because of its large mass it also leads to large radiative corrections that one needs to control to understand completely different fields of physics. In the radiative corrections to the electroweak couplings the top mass enters quadratically and a top mass precision below 1 GeV is needed to match the expected precision in $\sin^2\theta^l_{eff}$ from GigaZ running. In the radiative corrections to the Higgs system in the MSSM the top mass enters even with the fourth power leading to a sensitivity of $\Delta m_{\mathrm{h}}/\Delta m_{\mathrm{t}} \sim 1$. One thus needs the top mass to the same precision as the Higgs mass to make optimal use of the Higgs parameters in MSSM interpretations [18].

The large QCD corrections at threshold make the measurement of the top mass rather challenging. However with the appropriate mass definition and next-to-next-to leading log corrections this region seems under control now [19]. With a ten-point scan around the top-pair threshold a precision of $\Delta m_{\mathrm{t}} = 34\,\mathrm{MeV}$, $\Delta\Gamma_{\mathrm{t}} = 42\,\mathrm{MeV}$ and $\Delta\alpha_s = 0.0023$ seems possible [20]. In the $\overline{\mathrm{MS}}$ scheme this should lead to $\Delta m_{\mathrm{t}}(\overline{\mathrm{MS}}) \approx 100\,\mathrm{MeV}$.

6 Precision Measurements at Lower Energies

With a linear collider like TESLA it should be possible to run near the peak of the Z resonance and to record 10^9 Z decays in less than a year of running. This statistics can be used to measure $\sin^2\theta^l_{eff}$ from the left-right asymmetry with very high precision. If also positrons can be polarised the beam polarisation can be measured from data keeping also the systematics very small. A total precision of $\Delta\sin^2\theta^l_{eff} \sim 0.00001$ is thus possible [21]. This precision, however, needs to be matched by the accuracy with which $\alpha(m_{\mathrm{Z}})$ can be predicted. An improvement in the precision of $\alpha(m_{\mathrm{Z}})$ of a factor better than five with respect to today's precision is thus needed [22].

Near the W-pair threshold a luminosity of 100 fb^{-1}/year is possible. This allows for a measurement of the W-mass with $\Delta m_{\mathrm{W}} = 6\,\mathrm{MeV}$ [23]. It should however be noted that both measurement pose extreme requirements of the machine, especially on the understanding of the beam energy and it is currently under study if this is possible. In addition to the $\sin^2\theta^l_{eff}$ measurement GigaZ might also allow for a measurement of the strong coupling constant of $\Delta\alpha_s(m_{\mathrm{Z}}) = 0.0006$.

Figure 19 shows the improvements on the results shown in figure 1 due to these measurements. As two possible applications of these measurements in figure 20 the indirect measurement of the $\tilde{t}_2$ mass from $\sin^2\theta^l_{eff}$ and m_W, if other parameters from the SUSY and Higgs sector are known, [24] and on the knowledge of the GUT scale [25] are shown. In all studied physics scenarios such applications of the precise GigaZ results can be found. In cases where most degrees of freedom are known the extremely precise knowledge of $\sin^2\theta^l_{eff}$ allows a good estimation of the missing ones. In scenarios with enough degrees of freedom to vary ε_1 and ε_3 independently the precise m_W measurement is extremely important to reduce the correlation between the two.

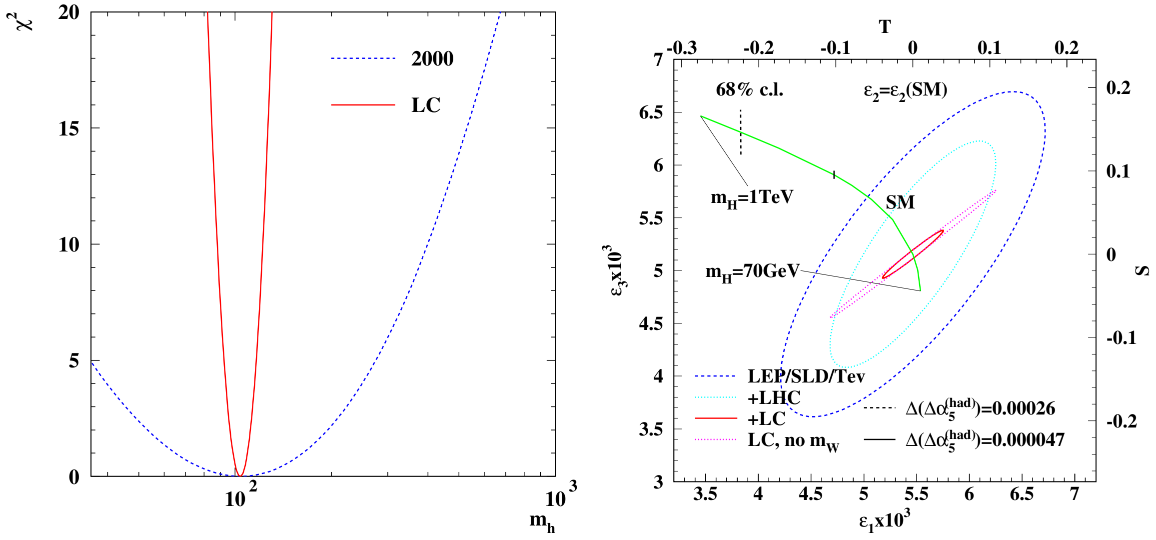

Figure 19: Improvement in the precision of the indirect Higgs mass (left) and the ε-parameters due to GigaZ (right).

7 Conclusions

A linear collider in the energy range up to around 1 TeV has the potential to enlarge our knowledge on electroweak symmetry breaking significantly.

If a light Higgs exists, especially in conjunction with Supersymmetry, many new particles will be visible and a huge amount of information can be obtained from such a machine. The linear collider has the potential to identify the mechanism of electroweak symmetry breaking and to measure the detailed properties of the dark matter particle needed to understand cosmology.

If no light Higgs exists the measurement of triple and quartic gauge boson interactions will give first hints towards a theory of strongly interacting symmetry breaking, however for a detailed understanding higher energies are needed.

In all cases a linear collider is complementary to the LHC and we finally need both of them to understand electroweak symmetry breaking.

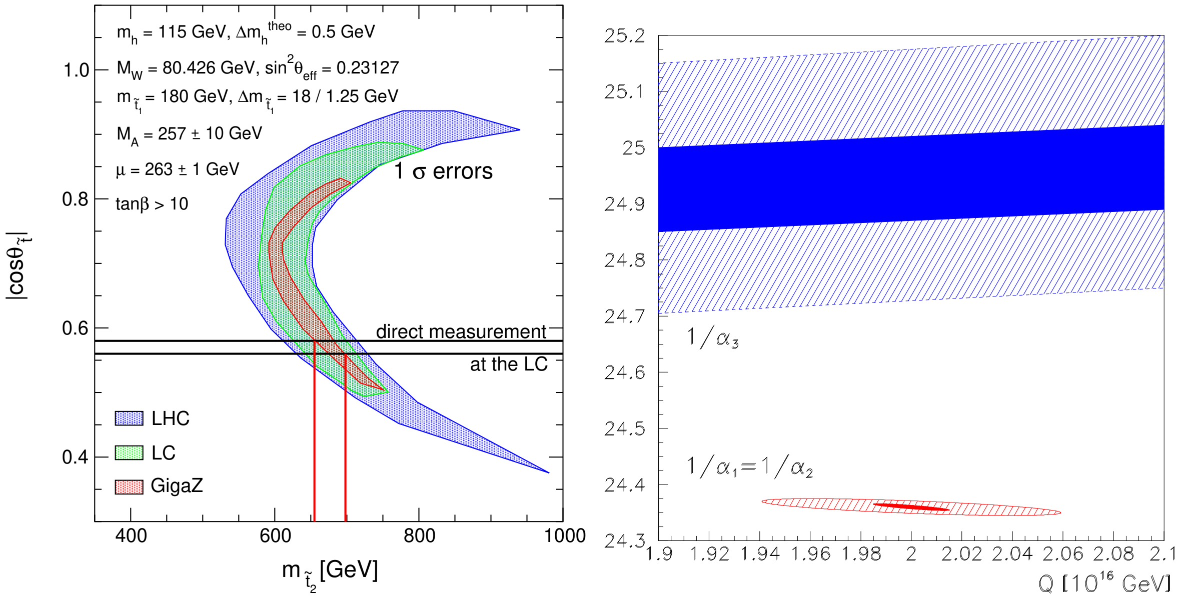

Figure 20: Left: prediction of the $\tilde{t}_2$ mass from the electroweak precision data if the other relevant parameters are known using LHC, LHC+LC and LHC+LC+GigaZ data. Right: improvement of the coupling constant extrapolation to the GUT scale due to the GigaZ data.

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