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Physics aspects of polarized e^+ at the linear collider[1]

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Abstract

Polarized e^- and e^+ at the International Linear Collider play an important role for discovering physics beyond the Standard Model and for precisely unravelling the structure of the underlying physics. The physics programme at the first energy stage at $\sqrt{s} = 500$ GeV benefits strongly from the polarization of both beams. But also at 1 TeV as well as at a possible multi-TeV design of a linear collider, CLIC, the physics output is greatly enriched by beam polarization. An overview is given of the impact of providing polarized e^+ at the linear collider in addition to polarized e^- for physics studies in top, Higgs, supersymmetry and further models of physics beyond the Standard Model.

1 Overview

1.1 Physics programme at the ILC

The International Linear Collider (ILC) will start with a first energy phase of $\sqrt{s} \leq 500$ GeV, which is perfectly suited to precision top and Higgs studies. Precise measurements of the properties of the top quark, which is by far the heaviest known elementary particle, will greatly advance our understanding of the underlying physics at the quantum level [1]. Electroweak precision data indicate in the Standard Model (SM) a light Higgs with a mass below about 207 GeV (see Fig. 1). It will be crucial to precisely determine the mass, couplings, spin and CP properties of the new particle in order to experimentally establish the mechanism of electroweak symmetry breaking.

A further highlight of expected physics at the ILC will be the discovery and determination of new physics beyond the SM. The most prominent candidate for new physics is supersymmetry (SUSY). Fits with electroweak precision data and experimental bounds from collider and cosmological experiments are consistent with light SUSY, indicating that the energy range of $\sqrt{s} = 500$–1000 GeV will be perfectly suited to the discovery and the precise measurements of the properties of SUSY particles, at least their light spectrum. These results, together with results from the Large Hadron Collider (LHC), will allow us to unravel the underlying structure of the theory and to predict the properties of expected heavy SUSY particles.

Some new physics scales could be too large to be directly accessible at the LHC or at the ILC. The ILC also has a large discovery potential, complementary to that of the LHC, for indirect searches of physics beyond the kinematic limit. Manifestations of such new interactions can be probed through deviations of cross sections from the SM predictions, and indirect bounds on the new energy scales and coupling constants can thereby be derived.

[1]Talk given at the Polarized Positrons Workshop 'POSIPOL', CERN, 26–28 April 2006

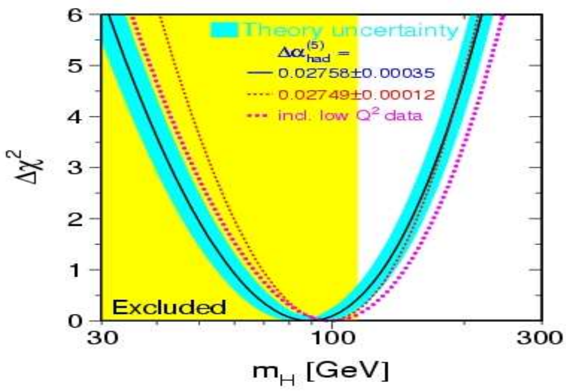


Figure 1: The study of Higgs particles will present a central part of the ILC physics programme. Measurements of electroweak precision observables at LEP, SLD, CDF and D0 including the direct exclusion limit from LEP-2 predict that the mass of the Higgs in the SM $m_H \leq 207$ GeV (95% CL) [2]. In supersymmetric theories the limit is at about $m_h \sim 135$ GeV [3].

The results from the ILC, together with those of the LHC, will outline the needed requirements and energy scale for a multi-TeV linear collider, CLIC, whose feasibility studies are currently being designed.

1.2 Polarized beams at linear colliders

a) History and future

The use of polarized beams plays an important role in the whole physics programme of a linear collider. A prominent example from history to demonstrate the importance of beam polarization is the measurement of the electroweak mixing angle at the SLC (the SLAC Linear Collider) with a precision of $\Delta \sin\theta_{\rm eff} = 0.00026$ [2]. At LEP, in spite of the very high luminosity but without polarization of the beams for the physics runs, a precision of $\Delta \sin\theta_{\rm eff} = 0.00029$ [2] was reached.

The polarization of the electron beam is foreseen for the baseline design of the ILC [4]. A high degree of at least 80% longitudinal polarization is envisaged, but new results indicate that even 90% should be achievable. Two different sources for the production of polarized e^+ are currently under discussion, either via undulator radiation (preferred solution for the ILC facility) or via laser-backscattering processes (preferred solution for the CLIC design), both leading to a longitudinal polarization degree of about 60% for the e^+ beam without any loss in luminosity. Higher e^+ polarization of about 75% is possible at a cost in luminosity. With spin rotators the longitudinal polarization can be rotated to provide also transversely polarized beams for physics studies.

b) Introductory remarks and definitions

In [5], it is shown that the full potential of the ILC could be realized only with the polarization of both the e^- and e^+ beams. Polarized e^+ serve either as i) a substantial factor for the physics results or/and also as ii) a rather easily obtainable lucrative factor. Both i) and ii) are important to optimize the physics outcome.

Physics processes occur through e^-e^+ annihilation ('s-channel diagrams') and scattering ('t, u-channel diagrams'). In annihilation diagrams the helicities of the incoming beams are coupled to each other, whereas in scattering processes, they are coupled to those of the final particles and therefore are directly sensitive to their chiral properties. In processes where only (axial-) vector interactions are contributing, the cross section with polarized beams is given by:

$$\sigma(P_{e^-}P_{e^+}) = (1 - P_{e^-}P_{e^+})\sigma_{\rm unpol}[1 - P_{\rm eff}A_{\rm LR}], \tag{1}$$

where $A_{\rm LR}$ denotes the left–right asymmetry and $P_{\rm eff}$ the effective polarization, given by $P_{\rm eff} = [P_{e^-} - P_{e^+}]/[1 - P_{e^-}P_{e^+}]$. Polarized e^+ lead to the improvement of the effective polarization and enhance the precision in measurements of the left–right asymmetry (see Fig. 2), which are, for instance, often exploited in the high-precision studies of the SM.

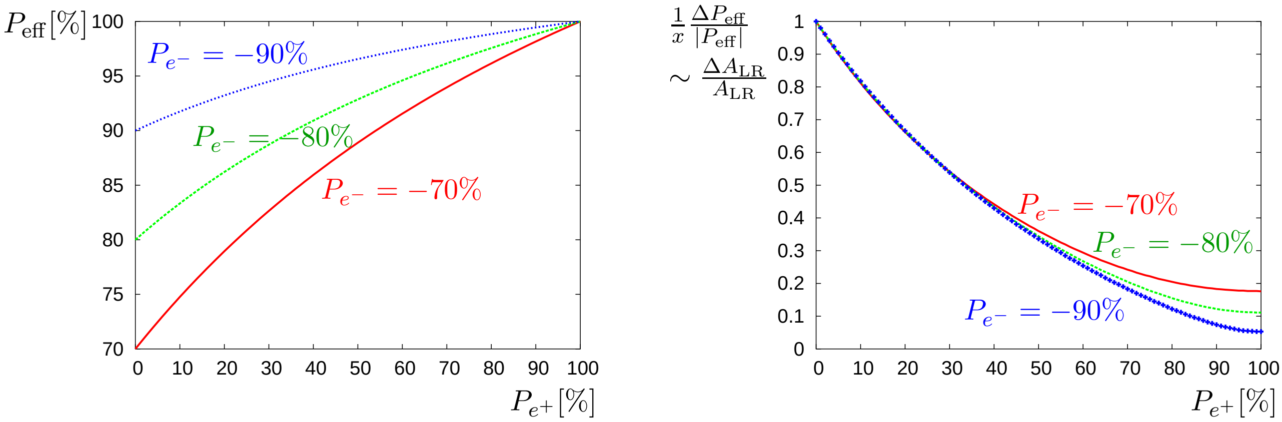


Figure 2: Left: effective polarization as a function of positron polarization. Right: relative uncertainty on the effective polarization $\Delta P_{\rm eff}/|P_{\rm eff}| \sim \Delta A_{\rm LR}/A_{\rm LR}$, normalized to the relative polarimeter precision $x = \Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+}$.

In addition to the enhancement in the effective polarization, which is important for many precision studies in the SM, the polarization of both beams enables detailed analyses of the properties of new particles and of new kinds of interactions, as well as of indirect searches with high sensitivity for new physics in a widely model-independent approach. In the following an overview is given about some physics examples; more details and more examples can be found in [5].

2 Polarized beams in top searches

a) Determination of electroweak properties

A linear collider provides an ideal tool to probe the couplings of the top quark to the electroweak gauge bosons. The neutral electroweak couplings are accessible only at lepton colliders, because top quarks at hadron colliders are pair-produced by gluon exchange.

The most general $(\gamma, Z)t\bar{t}$ couplings can be written as

$$\Gamma^{\mu}_{t\bar{t}\gamma,Z} = ie\left\{\gamma^{\mu}[F^{\gamma,Z}_{1V} + F^{\gamma,Z}_{1A}\gamma^5] + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t}[F^{\gamma,Z}_{2V} + F^{\gamma,Z}_{2A}\gamma^5]\right\}, \tag{2}$$

where F^{γ}_{1V}, F^{Z}_{1V}, F^{Z}_{1A} denote the only form factors that are different from zero in the SM.

Polarization effects have been studied at the top threshold [6]. In the SM the main production process occurs via γ, Z exchange. To determine the SM top vector coupling v_t, one has to measure the left–right asymmetry $A_{\rm LR}$ with high accuracy. With an integrated luminosity of $\mathcal{L}_{\rm int} = 300$ fb^{-1}, precisions in $A_{\rm LR}$ and v_t of about 0.4% and 1%, respectively, can be achieved at the ILC. The gain in using simultaneously polarized e^- and e^+ beams with $(P_{e^-}, P_{e^+}) = (\mp 80\%, \pm 60\%)$ is given by the higher effective polarization of $P_{\rm eff} = 95\%$ compared to the case of only polarized electrons with $|P_{e^-}| = 80\%$. This leads, according to Fig. 2, to a reduction of the relative uncertainty $\Delta A_{\rm LR}/A_{\rm LR} \simeq \Delta P_{\rm eff}/P_{\rm eff}$ by a factor of about 3.

Limits to all the above mentioned form factors have also been derived in the continuum at $\sqrt{s} = 500$ GeV for unpolarized beams and $(|P_{e^-}|, |P_{e^+}|) = (80\%, 0)$. It has been estimated that the polarization of both beams with $(|P_{e^-}|, |P_{e^+}|) = (80\%, 60\%)$ leads to an increase of the $t\bar{t}$ cross section by a factor of about ~ 1.5 and improves again the bounds by about a factor 3 [5]. Complete simulations are still missing.

b) Limits for CP- and FCN-violating couplings

Searches for anomalous $t\bar{t}\gamma$ and $t\bar{t}Z$ couplings can be made by studying the decay energy and angular distributions of l^+ (l^-) or b $(\bar{b})$ in $e^+e^- \to t\bar{t}$ followed by the subsequent decays $t \to l^+\nu_l b$ $(\bar{t} \to l^-\bar{\nu}_l\bar{b})$. Focusing on CP violation, a suitable observable is represented by the forward–backward charge asymmetry [7, 8]. With $\sqrt{s} = 500$ GeV, $\mathcal{L}_{\rm int} = 500$ fb^{-1}, and 60% reconstruction efficiency for either lepton or b, the forward–backward charge asymmetry could be measured at the 5.1σ (2.4σ) level for b-quarks (leptons) assuming CP-violating couplings of the order of 5×10^{-2} and unpolarized beams. Having both beams 80% polarized, the reach on $\mathcal{A}^f_{\rm CP}$ would even increase up to 16σ (3.5σ).

Flavour-changing neutral (FCN) couplings of the top quark are relevant to numerous extensions of the SM, and can represent an interesting field for new-physics searches. Limits on top FCN decay branching ratios can be obtained from top-pair production, with subsequent $\bar{t}$ decay into γ, Z plus light quark governed by the FCN anomalous tVq couplings ($V = \gamma, Z$ and $q = u, c$), $e^+e^- \to t\bar{t} \to W^+bV\bar{q}$, or from single top production $e^+e^- \to t\bar{q} \to W^+b\bar{q}$ mediated by the anomalous couplings at the production vertex. Single-top production is more sensitive to top anomalous couplings, but top decays help to disentangle the type of anomalous coupling involved. Beam polarization is very efficient in significantly reducing the background and is therefore particularly important in limits obtained from single-top production. The background is essentially dominated by the $W^+ + 2$jets final state, with W^+ decaying into $l\nu$ and one jet misidentified as a b-jet.

With polarization $(80\%, 0)$, the background decreases by a factor of $1/(1-P_{e^-}) \approx 5$ while keeping 90% of the signal. With $(80\%, -45\%)$ the background is reduced by a factor of $1/(1-P_{e^-})(1+P_{e^+}) \approx 9$ and the signal is increased by 20% with respect to the case of no polarization [9]. In conclusion, S/B and $S/\sqrt{B}$ are improved by factors of 2.1 and 1.7, respectively. Already with e^- and e^+ polarization (80%, 45%), as an example, the 3σ discovery limits on the vector (γ^μ) coupling at $\sqrt{s} = 500$ GeV is improved by a factor of 3 (a factor of 1.7 with respect to only electron polarization) and the limits on the tensor $(\sigma^{\mu\nu})$ coupling at $\sqrt{s} = 800$ GeV by a factor of about 2.6 (a factor 1.8 with respect to electron polarization only).

c) Transversely-polarized beams in top studies

The observation of CP violation in e^+e^- collisions requires either the measurement of the polarization of the final-state particles or the availability of polarized beams. Transverse polarization of initial beams defines one more direction, and can provide CP-odd asymmetries without having to measure final-state polarizations directly. This may represent an advantage, e.g. as regards the statistical significance of the signal. Both beams, however, have to be polarized, otherwise all effects at the leading order from transverse polarization vanish for $m_e \to 0$ (suppression by $m_e/\sqrt{s}$).

In e.g. $e^+e^- \to t\bar{t}$ production, only (pseudo-) scalar or tensor currents associated with a new-physics scale can lead to CP-odd observables at the leading order in the new interaction, if transversely-polarized beams are used. They are due to the interference between these new currents and the γ and Z exchanges in the s-channel. These interference terms cannot be seen with longitudinally-polarized or unpolarized beams: both beams, e^- and e^+, have to be transversely polarized. The corresponding new-physics scale Λ can be bounded at the 90% confidence level, at about 7 TeV, with $\sqrt{s} = 500$ GeV and $(P_{e^-}, P_{e^+}) = (80\%, 60\%)$; see [10, 5] for details.

3 Polarized beams in Higgs analyses

A striking and unique goal of physics at a linear collider will be the clear establishment of the mechanism of the electroweak symmetry breaking, which requires the precise measurement of all Higgs couplings. Beam polarization does play an important lucrative factor in determining the Higgs properties at energies $\sqrt{s} \leq 500$ GeV.

a) Separation of the production processes
Assuming a light SM Higgs with $m_H \leq 130$ GeV, which is the range preferred by both fits of precision observables in the SM [11] and predictions of SUSY theories (see e.g. [3]), Higgs-strahlung dominates for $\sqrt{s} \lesssim 500$ GeV and WW fusion for $\sqrt{s} \gtrsim 500$ GeV. At a LC with $\sqrt{s} = 500$ GeV and unpolarized beams, the two processes have comparable cross sections. Beam polarization can be used to enhance the HZ contribution with respect to the WW fusion signal, and vice versa, and to suppress the dominant SM background of WW production significantly. Table 1 shows that there is a gain of a factor $(1.26/0.08)/(0.87/0.20) \sim 4$ in the ratio $\sigma(HZ)/\sigma(H\nu\bar{\nu})$ when left-handed polarized positrons are used in addition to right-handed polarized electrons.

b) Determination of general Higgs couplings
Using an optimal-observable method, which allows the minimization of statistical uncertainties on the couplings, we can reach a high accuracy in the determination of the general ZZH and $Z\gamma H$ couplings. In [12] it was shown that beam polarization is essential for determining the sensitivity to the seven general couplings. Simultaneous polarization of the e^+ and e^- beams results in an increase in the sensitivity, so that for $\sqrt{s} = 500$ GeV, $\mathcal{L}_{\rm int} = 300$ fb^{-1} and $(P_{e^-}, P_{e^+}) = (\pm 80\%, 60\%)$, the sensitivity is improved by about 30% with respect to the case of $(\pm 80\%, 0)$.

c) Measurement of the top Yukawa couplings
By virtue of its large mass, the top quark has the largest Yukawa coupling to the Higgs boson of all fermions: $g_{ttH} \simeq 0.7$, to be compared for instance with $g_{bbH} \simeq 0.02$. It plays a key role in the mechanism of electroweak symmetry breaking and mass generation. Therefore, an accurate measurement of the top–Higgs Yukawa coupling is particularly important. At the LHC a determination of the Yukawa coupling with a precision of about 20% is expected; however, some model assumptions have to be made.

At the linear collider the process $e^+e^- \to t\bar{t}H$ provides the best opportunity for a direct and precise determination of the top–Higgs Yukawa coupling through the cross-section measurement. This measurement is particularly challenging because of the smallness of the $t\bar{t}H$ cross section, e.g. $\sigma_{ttH} \simeq 2.5$ fb for $m_H = 120$ GeV at $\sqrt{s} = 800$ GeV, and of the very large background, dominated by $t\bar{t}$+jets. Since, in the Baseline Configuration Document (BCD) for the ILC [4], $\sqrt{s} = 500$ GeV is chosen for the first stage of the ILC, it is important to assess the feasibility of measuring the top Yukawa coupling at this energy. At $\sqrt{s} = 500$ GeV, the $t\bar{t}H$ cross section is reduced by a factor of about 10 with respect to $\sqrt{s} = 800$ GeV, e.g. $\sigma_{ttH} \simeq 0.2$ fb for $m_H = 120$ GeV.

A preliminary estimate [13] yields $\Delta g_{ttH}/g_{ttH} \simeq 24\%$ for $m_H = 120$ GeV, assuming $\mathcal{L}_{\rm int} = 1000$ fb^{-1} but unpolarized beams. The usage of beam polarization plays an important role by increasing the cross section. As shown in eq. (1), there are two enhancement factors that can be exploited: $(1 - P_{e^+}P_{e^-})$ and $[1 - P_{\rm eff}A_{\rm LR}]$ (in the case of SM $t\bar{t}H$ production, $A_{\rm LR} \simeq +0.44$). A recent study [14] at $\sqrt{s} = 500$ GeV has shown that for $(P_{e^-}, P_{e^+}) = (-0.8, +0.6)$ the $t\bar{t}H$ cross section can be increased by a factor of about ~ 2.1, resulting in an improvement in the precision of g_{ttH} of 45%. In the case where no positron polarization is available, $(P_{e^-}, P_{e^+}) = (-0.8, 0)$, the improvement would only be 19%. The precision in measuring the Yukawa coupling g_{ttH} can be improved by a factor of about 2.5 with respect to the case of having only polarized electrons. Polarized e^+ can therefore play a substantial role in the determination of the top Yukawa couplings at the first stage of the ILC, also improving the predicted precision at the LHC significantly.

d) Measurement of the triple Higgs couplings

The determination of the Higgs potential is crucial to establish the Higgs mechanism. Therefore also the triple Higgs couplings have to be precisely measured, either in the HHZ or in the $HH\nu\bar{\nu}$ final state. At $\sqrt{s} = 500$ GeV the triple Higgs couplings can only be determined in the HHZ channel; former studies [15, 16] with unpolarized beams predict a precision of 22%.

To determine the triple Higgs couplings in the $HH\nu\bar{\nu}$ final state, higher energies are definitely needed. At 3 TeV at CLIC the WW fusion process is kinematically enhanced and a precision of up to about 13% [17] for the determination of the triple Higgs coupling is predicted.

However, both studies have been done only for unpolarized beams. Complete simulations with polarized beams and realistic detector simulations and background suppression are still missing. However, it is estimated that at least a further increase of about 50% is expected. Regarding the moderate precision at $\sqrt{s} = 500$ GeV, using both beams polarized can be a rather substantial improvement factor for the obtainable precision in the triple Higgs coupling.

Beam polarization	$e^+e^- \to H\nu\bar{\nu}$	$e^+e^- \to HZ$	$e^+e^- \to W^+W^-$	$e^+e^- \to ZZ$
$(+80\%, 0)$	0.20	0.87	0.20	0.76
$(-80\%, 0)$	1.80	1.13	1.80	1.25
$(+80\%, -60\%)$	0.08	1.26	0.10	1.05
$(-80\%, +60\%)$	2.88	1.70	2.85	1.91

Table 1: Scaling factors of Higgs production, in Higgs-strahlung and WW fusion, and of the dominant SM background processes WW and ZZ production, at $\sqrt{s} = 500$ GeV, for several polarization configurations compared with the unpolarized case [18, 19].

4 Polarized beams in searches for supersymmetry

One of the most promising candidates for physics beyond the SM is supersymmetry. SUSY can solve open problems of the SM as, for instance, the hierarchy problem; it enables gauge unification and provides candidates for cold dark matter. Furthermore SUSY models have high predictive power, and precise calculations for future experiments can be made. This new symmetry predicts that every SM particle has a SUSY partner that has the same quantum numbers as their SM partner, with the exception of the spin. To really establish supersymmetry experimentally, all model assumptions and implications have to be verified. Furthermore the fundamental underlying parameters have to determined precisely. Since the number of new parameters is large, even in the Minimal Supersymmetric Standard Model (MSSM), there are 105, this task may be very challenging.

One crucial question is how large the scale of this new symmetry is predicted to be. In order to be consistent with electroweak precision measurements and cosmological bounds, at least some of the electroweak interacting SUSY particles are predicted to be rather light and should be accessible at the ILC with $\sqrt{s} = 500$ GeV. In a recent study [20] a parameter fit was applied within the Constrained MSSM (CMSSM), leading to the prediction of, for instance, light neutralinos $\tilde{\chi}^0_{1,2}$ and a light chargino $\tilde{\chi}^\pm_1$, so that the processes $\tilde{\chi}^0_1\tilde{\chi}^0_2$ and $\tilde{\chi}^+_1\tilde{\chi}^-_1$ should be accessible at the ILC (Fig. 3).

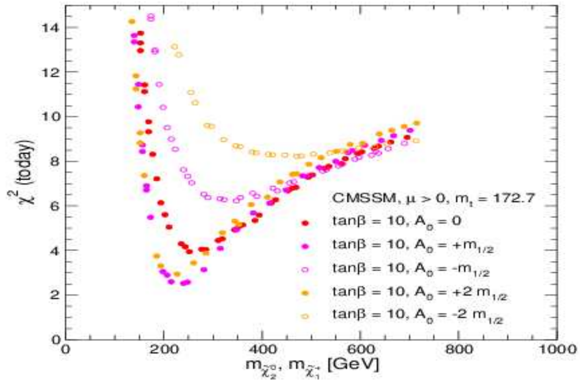


Figure 3: The χ^2 function for the electroweak observables M_W, $\sin^2\theta_{\rm eff}$, $(g-2)_\mu$, BR$(b \to s\gamma)$ and M_h evaluated in the CMSSM for $\tan\beta = 10$ and $m_t = 172.7 \pm 2.9$ GeV, matching the central value of the relic neutralino density indicated by WMAP [20].

a) Parameter determination

In [21] it has been demonstrated that already these light pairs are sufficient to determine the fundamental SUSY parameters and to predict the heavier SUSY particles. Polarized e^+ lead to an essential lucrative factor and can become rather substantial to suppress background processes. Followed by combined analyses at the LHC and the ILC [22], a promising framework to unravel precisely the structure of the SUSY model is provided, even if the complete SUSY particle spectrum is not accessible. Polarized e^- and e^+ beams are crucial in that context, not only to enhance the cross section and to suppress background processes, but also to provide more observables, which are essential for determining the parameters with as few model assumptions as possible. This fact is even more important in cases where only a part of the particle spectrum is accessible, for instance at the first energy stage of the ILC with $\sqrt{s} = 500$ GeV.

b) Tests of the quantum numbers in the scalar particle sector

Prominent examples of the scalar SUSY sector are the selectrons and spositrons $\tilde{e}^{\pm}_{\rm L,R}$, which have to be associated to their chiral SM partners, the left- and right-chiral electrons and positrons. This association can be directly tested in the production of the pairs $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$ produced only in the t-channel process. The process must be experimentally separated from the pair $\tilde{e}^+_{\rm R}\tilde{e}^-_{\rm R}$ produced also in the s-channel. It has been shown that even a highly polarized electron beam will not be sufficient to separate the pairs, since both can be produced with almost identical cross sections and have the same decay; see Fig. 4 (left lower plot). Applying simultaneously polarized positrons, the pairs get different cross sections, can be isolated, and the $\tilde{e}^+_{\rm L}$ and $\tilde{e}^-_{\rm R}$ can be identified by charge separation; see Fig. 4 (left upper plot) [23, 5].

As another consequence of SUSY, the SU(2) and U(1) SUSY Yukawa couplings have to be identical to the corresponding SM gauge couplings. Assuming that the masses and mixing parameters of the neutralinos have been predetermined in the gaugino/higgsino sector, the production cross sections of $\tilde{e}^+_{\rm R}\tilde{e}^-_{\rm R}$ and $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$ can be exploited to derive the Yukawa couplings. However, in the case where the two pairs have almost identical cross sections and decay modes, the different combinations of $\tilde{e}_{\rm R}$ and $\tilde{e}_{\rm L}$ can only be distinguished by the initial beam polarization of the two beams; see Fig. 4 (right panels) [24, 5].

c) Mass measurements in the continuum

A striking tool at the linear collider are threshold scans, leading, for instance, to mass measurements of some of the SUSY particles with a precision even below the per mil level [16]. Since threshold scans cost luminosity, it is important to optimize the needed energy steps a priori via measurements in the continuum. In [25, 5] examples have been shown to measure $m_{\tilde{\mu}_{\rm L}}$ and $m_{\tilde{\mu}_{\rm R}}$ very accurately

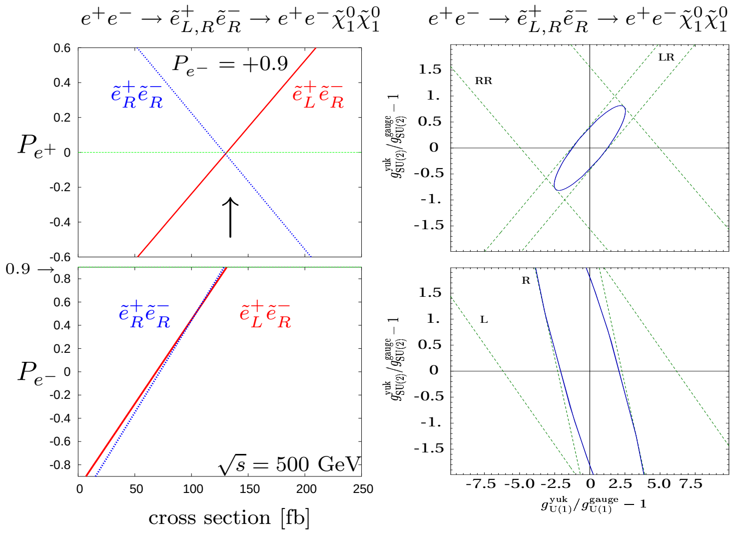


Figure 4: Left: Test of chiral quantum numbers – separation of the selectron pair $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$ is not possible with e^- polarization alone, $P_{e^-} = +90\%$ (lower plot). If both beams are polarized, the RR configuration separates the pairs $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$, $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm L}$ (see arrow, upper plot) [5]. Right: Test of Yukawa couplings – 1σ bounds on the determination of the U(1) and SU(2) Yukawa couplings between e^+, $\tilde{e}^+_{\rm R,L}$, $\tilde{\chi}^0_i$; R (L) means $P_{e^-} = +90\%$ (-90%) (lower plot) and RR, LR means $(P_{e^+}, P_{e^-}) = (+60\%, +90\%)$, $(-60\%, +90\%)$ (upper plot). Both studies are done at $\sqrt{s} = 500$ GeV [5].

up to about 2 per mil in the continuum; the dominant WW background has been sufficiently suppressed only if both beam are polarized: the signal-to-background-ratio is about 0.07 (0.45) with $P_{e^-} = +80\%$ ($P_{e^-} = +80\%$, $P_{e^+} = -80\%$). The polarization of the e^+ beams plays a lucrative factor in this example, but is rather substantial for the background suppression.

Furthermore, such a precise knowledge of the SUSY particle masses is also important to derive the mass of the lightest SUSY particle, the LSP, very accurately in decay spectra. The LSP presents a promising cold dark matter candidate, and therefore a precise knowledge of its properties is crucial.

Such an optimization of threshold scans by accurate continuum measurements is important for all linear collider designs, for the ILC as well as for CLIC. Polarized e^+ provide an essential lucrative factor to reach the physics goals in that context.

d) Transversely-polarized beams for CP searches

CP-violating phases can be determined via T-odd observables, by exploiting spin correlations of the decaying fermions; see [26]. In [27] the use of specific asymmetries with only longitudinally-polarized beams for the determination of CP phases has been optimized. In the case of neutralinos (Majorana fermions), it is, however, even possible to construct CP-odd asymmetries in the production process $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ with transversely-polarized beams [28]. Both beams have to be polarized. In order to measure $A_{\rm CP}$, it is necessary to reconstruct the directions of the neutralinos. This can be done by analysing the subsequent decays. This asymmetry can lead to rather high values, even for small phases, i.e. the parameter range preferred by experimental bounds from the electric dipole moments. The use of transversely-polarized beams therefore keeps open an occasionally important possibility to detect even small CP-violating phases.

e) R-parity-violating SUSY model

The polarization of both beams allows us to probe directly the spins of particles produced in resonances. In a R-parity-violating SUSY model a spin-0 particle is produced in the s-channel, the scalar neutrino, with $\mu^+\mu^-$ in the final state. Since the sneutrino couples only to left-handed $e^\pm$, the peak is strongest for the LL polarization configuration. Such a signature would point directly to the presence of a spin-0 resonance, as in Fig. 5 (left plot). The SM background is strongly suppressed and one gets a $S/B \sim 11$ for $(P_{e^-}, P_{e^+}) = (-80\%, -60\%)$, whereas for $(P_{e^-}, P_{e^+}) = (-80\%, 0\%)$ the

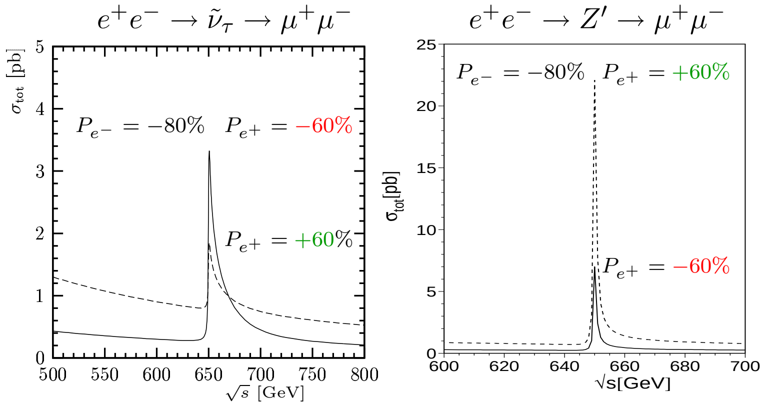


Figure 5: In a R-parity-violating SUSY model, a spin-0 particle is produced in resonances, the scalar neutrino. The LL polarization configuration points directly to the presence of a spin-0 resonance (left plot). Conversely, a spin-1 resonance, e.g. the Z', is strongest for the LR configuration (right plot) [5].

ratio is only $S/B \sim 4$ [29, 5]. Conversely, in the case of a spin-1 resonance, e.g. the Z' particle in the SSM model, Fig. 5 (right plot), the corresponding resonance peak would be strongest for the LR configuration, with a similar polarization dependence as the SM background [30, 5]. This example shows how clearly one could disentangle the form of the interaction if both beams are polarized.

5 Polarized beams in indirect searches

Some new physics scales, such as those characterizing gravity in models with extra dimensions or the compositeness scale of quarks and leptons, could be too large to be directly accessible at energies of present and future accelerators. Therefore it will be important to develop strategies for indirect searches beyond the kinematic limit for new physics. It is important, however, to get the large model dependence under control. Thanks to the clear signatures, its high luminosity and beam polarization, the ILC also has a large discovery potential in indirect searches, in a largely model-independent approach.

a) Contact-interaction analysis in Bhabha scattering

Effective contact interactions (CI) represent a general tool for parametrizing at 'low energy' the effects of non-standard dynamics characterized by exchanges of very high-mass states between the SM particles.

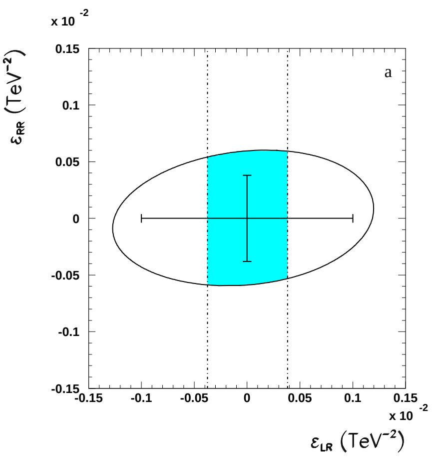


Figure 6: In Bhabha scattering the four-fermion CIs are parametrized by three parameters ($\epsilon_{\rm RR}$, $\epsilon_{\rm LR}$, $\epsilon_{\rm LL}$). The t-channel contributions depend only on $\epsilon_{\rm LR}$, whereas the s-channel contribution depends only on pairs ($\epsilon_{\rm RR}$, $\epsilon_{\rm LR}$), ($\epsilon_{\rm LR}$, $\epsilon_{\rm LL}$). In order to derive model-independent bounds it is necessary to have both beams polarized. Tight bounds up to 5×10^{-4} TeV^{-2} can be derived via a χ^2 test assuming that no deviations from the SM are measured in the observables σ_0, $A_{\rm FB}$, $A_{\rm LR}$ and $A_{\rm LR,FB}$ (within the experimental 1 σ uncertainty). The study was done at $\sqrt{s} = 500$ GeV [31, 5].

b) Neutral extra gauge bosons

Extra neutral gauge bosons Z' can be probed by their virtual effects on cross sections and asymme-

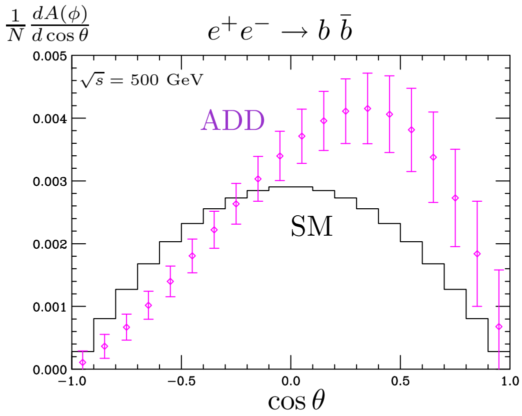


Figure 7: One representative example is the unique distinction between extra dimensions in the models of Randall-Sundrum (RS) and Arkani-Hamed, Dimopoulos, Dvali (ADD). With transversely-polarized beams a new asymmetry in $\sin 2\phi$ can be constructed. The new asymmetry vanishes for both the SM and the RS scenario, so that a non-zero value unambiguously signals the ADD graviton exchange. Such a model distinction is achievable up to ≥ 3 TeV [5].

tries. For energies below the Z' resonance, measurements of fermion-pair production are sensitive to the ratio of Z' couplings and Z' mass. Positron-beam polarization with $(P_{e^-}, P_{e^+}) = (80\%, 60\%)$ would improve the measurement of the $b\bar{b}$ couplings of the Z', even without knowledge of the Z' mass by about a factor 1.5, compared with $P_{e^-} = 80\%$ only. In the studied example at $\sqrt{s} = 1000$ GeV the mass of the Z' was 5 TeV [32, 5]. The crucial point is the fact that the systematic errors can be significantly reduced when both beams are polarized.

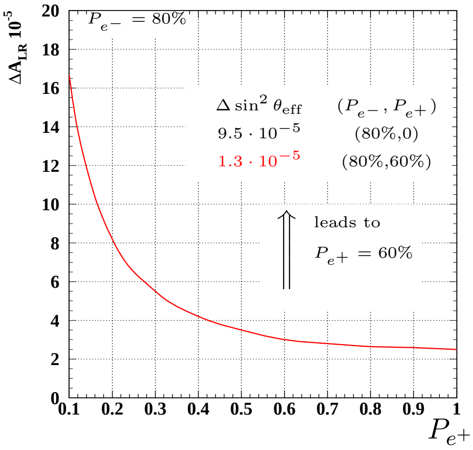
c) Transversely-polarized beams and distinction of graviton models
Transversely-polarized beams are sensitive to non-standard interactions, which are not of the current–current type, such as those mediated by spin-2 gravitons or (pseudo)scalar exchanges, even in indirect searches. Sensitivities to a high mass scale of, for instance, an extra-dimensional model are achievable. Even different models with large extra dimensions can be distinguished; see Fig. 7 [33, 5]. The study was done for $\sqrt{s} = 500$ GeV. Success in identifying new physics even in indirect searches using polarized e^- and e^+ beams would represent a big step forward for our understanding of fundamental interactions. Both beams have to be polarized to observe effects from transversely-polarized beams at the linear collider.

6 Polarized beams in high-precision measurements at GigaZ

Extremely sensitive tests of the SM can be performed with the help of electroweak precision observables. These can be measured with very high accuracy at the GigaZ option of the ILC, i.e. running with high luminosity at the Z-boson resonance. Measuring accurately the left–right asymmetry allows a determination of the effective weak mixing angle $\sin^2\theta_{\rm eff}$ with the highest precision. However, in order to exploit the gain in statistics at GigaZ, the relative uncertainties on the beam polarization have to be kept below 0.1%. This ultimate precision cannot be reached with Compton polarimetry, but by using a modified Blondel scheme, which requires the polarization of both beams; see Fig. 8 [34, 5]. So far the GigaZ option is only discussed as a later upgrade for the ILC. But physics arguments could require that a quick and cheap upgrade path to GigaZ be provided straight after the $\sqrt{s} = 500$ GeV stage.

Because of the gain of about 1 order of magnitude in the accuracy of $\sin^2\theta_{\rm eff}$, the bounds on m_h in the SM improve by about 1 order of magnitude (see Fig. 9), and the allowed range of $m_{1/2}$ is reduced by a factor of about 5 when using $(|P_{e^-}|, |P_{e^+}|) = (80\%, 60\%)$ instead of $(|P_{e^-}|, |P_{e^+}|) = (80\%, 0\%)$; see Fig. 10 [35, 5]. Such a piece of information could become essential to outline the needed energy scale for future linear-collider options and it will be of great importance to get the most accurate information from the GigaZ option.

Figure 8: With the polarization of both beams, using the Blondel scheme, assuming 80% polarization for electrons and 60% for positrons, an accuracy of $\Delta \sin^2\theta_{\rm eff} = 1.3 \times 10^{-5}$ can be achieved in the leptonic final state [16]. A polarization degree of $P_{e^+} \sim 60\%$ is sufficient, assuming $\Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+} = 0.5\%$.



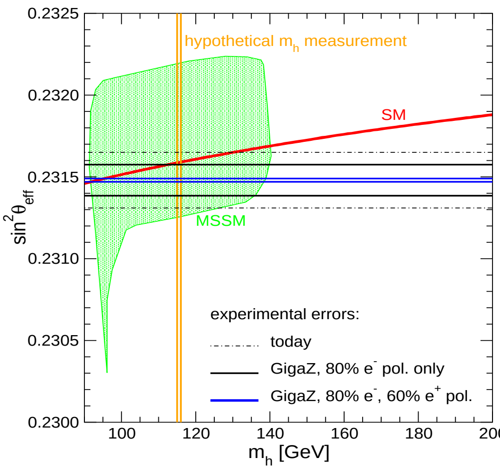
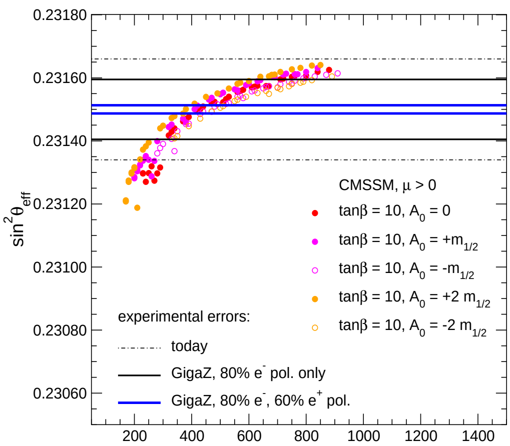


Figure 9: The theoretical predictions for $\sin^2\theta_{\rm eff}$ in terms of m_h, the mass of the Higgs boson in the SM or the mass of the lightest Higgs boson in the MSSM, respectively, are compared with the experimental accuracies obtainable at GigaZ [5]. The bounds on m_h in the SM are improved by about 1 order of magnitude with $(|P_{e^-}|, |P_{e^+}|) = (80\%, 60\%)$ instead of $(|P_{e^-}|, |P_{e^+}|) = (80\%, 0\%)$;

Figure 10: The precision measurement of $\sin^2\theta_{\rm eff}$ yields constraints on the allowed range for the SUSY mass parameter $m_{1/2}$ in a specific model, the CMSSM. The allowed range of $m_{1/2}$ is reduced by a factor of about 5 when using $(|P_{e^-}|, |P_{e^+}|) = (80\%, 60\%)$ instead of $(|P_{e^-}|, |P_{e^+}|) = (80\%, 0\%)$. Experimental constraints from LEP searches and cold-dark-matter searches have been taken into account [5].



7 Conclusions

It is generally agreed that the clean and precise environment of e^+e^- collisions at the ILC is ideally suited to the search for new physics and for determining precisely the underlying structure of the new interactions. This physics case is independent of the results of the LHC. The results of both the LHC and the ILC will be crucial to assess the physics programme in the multi-TeV energy region of the CLIC design. The physics potential of both the ILC and CLIC will greatly benefit from the availability of polarized e^- and e^+ beams.

Polarization of both beams at the ILC would be ideal for facing both expected and unforeseen challenges in physics analyses, for instance to fix the chirality of the couplings and to enable the higher precision for the polarization measurement itself as well as for polarization-dependent observables. It provides a powerful tool for studying SM physics as well as new physics, such as precisely analyzing the top and Higgs properties, discovering new particles, analyzing signals model-independently and resolving precisely the underlying model. We have demonstrated that the full potential of the ILC will be realized only with a polarized positron beam together with a polarized electron beam [5]. That is in particular relevant for the first energy stage of the ILC at $\sqrt{s} = 500$ GeV, since otherwise only limited experimental information on the new physics might be available.

Polarized e^+ in addition to polarized e^- lead to substantial improvements and/or lucrative statistical enhancements in the physics analyses. In some cases the lucrative character becomes also substantial to optimize the outcome at the ILC at $\sqrt{s} = 500$ GeV. For instance, in many top analyses a factor 3 can be gained when using $(|P_{e^-}|, |P_{e^+}|) = (80\%, 60\%)$ instead of $(|P_{e^-}|, |P_{e^+}|) = (80\%, 0\%)$. Also challenging Higgs studies, for instance the analyses of the top Yukawa couplings and the triple Higgs couplings, that are of great importance for the understanding of the electroweak symmetry breaking, benefit by a factor up to 2.5 when using $(|P_{e^-}|, |P_{e^+}|) = (80\%, 60\%)$ instead of $(|P_{e^-}|, |P_{e^+}|) = (80\%, 0\%)$.

Having two polarized beams available is crucial for uniquely determining the properties and the quantum numbers of new particles, and for testing fundamental model assumptions, as we have demonstrated in the specific example of supersymmetry. The larger number of observables accessible with two polarized beams provides better tools for revealing the structure of the underlying physics, determining new physics parameters, getting background processes and systematic uncertainties under control and enabling model-independent analyses.

Furthermore, with both beams polarized, one has the possibility to exploit transversely-polarized beams for physics studies. This option provides new and efficient observables for the detection of possible sources of CP violation. Additionally, it is a unique tool for distinguishing between different models with extra spatial dimensions, far below the threshold of the spin-2 excitations.

To fully exploit high-precision tests of the Standard Model at GigaZ, both beams must be polarized. The measurement of the electroweak precision observables is of utmost importance to test the SM and to derive precise bounds on the Higgs mass as well as to determine possible parameter ranges of new physics as, for instance, in supersymmetry. Improvements up to an order of magnitude can be obtained when using $(|P_{e^-}|, |P_{e^+}|) = (80\%, 60\%)$ instead of $(|P_{e^-}|, |P_{e^+}|) = (80\%, 0\%)$. Such precise predictions from indirect searches either at $\sqrt{s} = 500$ GeV or at GigaZ will be crucial to outline the physics programme of future linear collider options and to determine the physics potential of possible high-energy designs.

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