Polarized Beams for Top, Higgs and SUSY Searches

CERN-PH-TH/2005-138

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Polarized e^- and e^+ play an important role for discovering physics beyond the Standard Model and for precisely unravelling the structure of the underlying physics at the International Linear Collider (ILC). Some results from top, Higgs and Supersymmetry studies with polarized beams are briefly summarized.

1. INTRODUCTION

The International Linear Collider (ILC) will start with a first energy phase of $\sqrt{s} = 500$ GeV, which is perfectly suited for precision top and Higgs studies. Also light supersymmetric particles may be studied in detail. 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 200 GeV. It will be crucial to precisely determine the mass, couplings, spin and CP-properties of the new particle in order to experimentally establish the Higgs mechanism and disentangle the mechanism of electroweak symmetry breaking.

The use of polarized beams plays an important role in the physics programme of the ILC. The polarization of the electron beam is foreseen for the baseline design [2]. A high degree of polarization, at least 80%, is envisaged, but new results indicate that even 90% should be achievable. In [3], it is shown that the full potential of the ILC could be realized only with the polarization of both the e^- and e^+ beams.

Different positron sources for a linear collider are under discussion: one could either use a conventional source, which produces unpolarized positrons via a multi-GeV electron beam in conjunction with a thick high-Z target, or a photon-based source which produces positrons via pair production from multi-MeV photons in conjunction with a rather thin target. The latter method could produce polarized positrons if circularly polarized photons are produced either in multi-laser-backscattering processes or in undulator-radiation with a sufficiently long helical undulator. In the Basic Configuration Design (BCD) [4] of the ILC the helical undulator has now been chosen as the mature source, the laser-based source being discussed as an viable alternative design.

In the following we concentrate on physics studies with beam polarization in top and Higgs physics and in Supersymmetry (SUSY). The polarization of both beams is essential for the detailed analyses of the properties of new particles and of new kinds of interactions. It even enables a mostly model-independent approach and high sensitivity in indirect searches for new physics. In addition it enhances the effective polarization and the precision in measurements of the left–right asymmetry, see Fig. 1, which are exploited in the high-precision studies of the SM. For more details and examples, see [3, 5, 6].

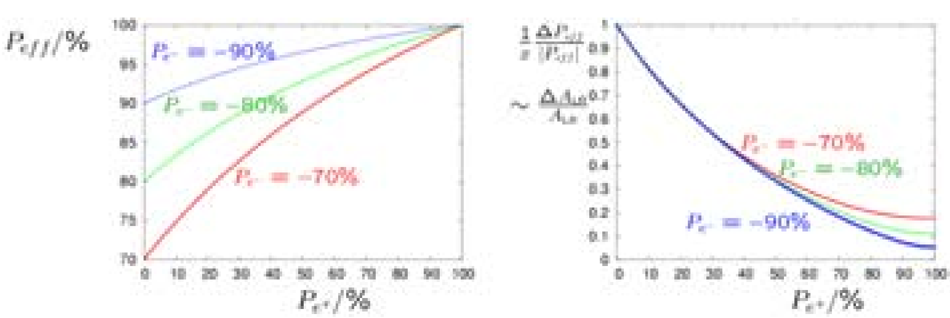

Fig. 1: Left: Effective polarization as a function of positron polarization Right: Relative uncertainty on the effective polarization, $\Delta P_{\mathrm{eff}}/|P_{\mathrm{eff}}| \sim \Delta A_{\mathrm{LR}}/A_{\mathrm{LR}}$, normalized to the relative polarimeter precision $x = \Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+}$.

2. NEW PHYSICS IN TOP SEARCHES

2.1. 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 via gluon exchange.

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

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

where the only form factors different from zero in the SM are

$$F^{\gamma}_{1V} = \frac{2}{3}, \quad F^{Z}_{1V} = \frac{1}{2\sin(2\theta_W)}\left(1 - \frac{8}{3}\sin^2\theta_W\right), \quad F^{Z}_{1A} = -\frac{1}{2\sin(2\theta_W)}. \tag{2}$$

Polarization effects have been studied at the top threshold [7]. In the SM the main production process occurs via γ, Z exchange. To determine the SM top vector coupling, $v_t = (1 - \frac{8}{3}\sin^2\theta_W)$, one has to measure the left–right asymmetry A_{LR} with high accuracy. With an integrated luminosity of $\mathcal{L}_{\mathrm{int}} = 300$ fb^{-1}, precisions in A_{LR} and v_t of about 0.4% and 1%, respectively, can be achieved at the LC. 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 $P_{\mathrm{eff}} = 95\%$ with respect to the case of only polarized electrons with $|P_{e^-}| = 80\%$. This leads, according to Fig. 1, to a reduction of the relative uncertainty $\Delta A_{\mathrm{LR}}/A_{\mathrm{LR}} \simeq \Delta P_{\mathrm{eff}}/P_{\mathrm{eff}}$ by about a factor of 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 about a factor ~ 1.5 and improves again the bounds by about a factor 3 [8]. True simulations are still missing.

2.2. Limits for FCNC- and CP-violating couplings

Searches of 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 [9]

$$\mathcal{A}^f_{\mathrm{CP}}(P_{e^-}, P_{e^+}) = \frac{\int_{\theta_0}^{\pi/2} d\cos\theta_f \frac{d\sigma^-}{d\cos\theta_f} - \int_{\pi/2}^{\pi-\theta_0} d\cos\theta_f \frac{d\sigma^+}{d\cos\theta}}{\int_{\theta_0}^{\pi/2} d\cos\theta_f \frac{d\sigma^-}{d\cos\theta_f} + \int_{\pi/2}^{\pi-\theta_0} d\cos\theta_f \frac{d\sigma^+}{d\cos\theta}}, \tag{3}$$

where $d\sigma^{\mp}$ refer to f and $\bar{f}$ polar angle distribution in the e^+–e^- c.m. frame, respectively (with $f = l, b$), and θ_0 is a polar angle cut. The asymmetry (3) is a genuine measure of CP violation and, actually, for $f = l$ it is sensitive exclusively to the CP violation at the $t\bar{t}$ production vertices. Conversely, for $f = b$ the anomalous structure of Wtb appears. With $\sqrt{s} = 500$ GeV, $\mathcal{L}_{\mathrm{int}} = 500$ 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 $\mathcal{A}^f_{\mathrm{CP}}$ would even increase up to 16σ (3.5σ)[9].

Flavour-changing neutral (FCN) couplings of the top quark are relevant to numerous extensions of the SM, and 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^++2jets 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 [10]. 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 are improved by a factor of 3 (a factor of 1.7 for electron polarization only) and the limits on the tensor $(\sigma^{\mu\nu})$ coupling at $\sqrt{s} = 800$ GeV by about a factor 2.6 (a factor 1.8 for electron polarization only).

2.3. Transversely-polarized beams in top studies

Transverse polarization of initial beams defines one more direction, and can provide CP-odd asymmetries without the need for directly measuring final-state polarizations. However, both beams have to be polarized, otherwise all effects from transverse polarization vanish in the limes $m_e \to 0$ (suppression $\sim m_e/\sqrt{s}$). In $e^+e^- \to t\bar{t}$ production, for instance, only (pseudo-) scalar or tensor currents, originating for example from scalar leptoquarks, associated with a new-physics scale can lead to CP-odd observables at 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 [11]. These interference terms cannot be seen with longitudinally-polarized or unpolarized beams. One can construct a CP-odd, up–down asymmetry, as

$$A(\theta) = \left[\int_0^\pi \frac{d\sigma^{+-}}{d\Omega} d\phi - \int_\pi^{2\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi\right] \Big/ \left[\int_0^\pi \frac{d\sigma^{+-}}{d\Omega} d\phi + \int_\pi^{2\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi\right], \tag{4}$$

where the superscripts denote opposite transverse polarization of e^-, e^+ and ϕ is the azimuthal angle. The corresponding new-physics scale Λ can be bounded at the 90% confidence level, at about 7–10 TeV, with plausible assumptions on the centre-of-mass energy and the values of transverse beam polarizations; see [3] for details.

3. POLARIZED BEAMS IN HIGGS ANALYSES

3.1. Standard Model Higgs searches

The study of Higgs particles will represent a central part of the ILC physics programme. Beam polarization does not play a key role in determining the Higgs properties; however, it is very helpful for separating the production processes, suppressing the dominant background processes, and improving the accuracy in determining the general couplings. If a light Higgs with $m_H \leq 130$ GeV is assumed, which is the range preferred by both fits of precision observables in the SM and predictions of SUSY theories (see e.g. [12]), Higgs-strahlung dominates for $\sqrt{s} \leq 500$ GeV and WW fusion for $\sqrt{s} \geq 500$ 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. With the scaling factors of 1.26 with $(P_{e^-}, P_{e^+}) = (+80\%, -60\%)$ compared with 0.87 with $(P_{e^-}, P_{e^+}) = (+80\%, 0)$ for the HZ signal, and the corresponding factors 0.08 compared with 0.20 for the $H\nu\bar{\nu}$ signal, one gains a factor of about 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 [3, 13].

Using an optimal-observable method, which allows the minimization of statistical uncertainties on the couplings, we are able to obtain high accuracy in the determination of the general ZZH and $Z\gamma H$ couplings. In [14] it was shown that beam polarization is essential to determine 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 20–30% with respect to the case of $(\pm 80\%, 0)$.

3.2. Heavy Higgs production in the MSSM

Searches for heavy SUSY Higgs particles can be extremely challenging for both the LHC and the ILC. Exploiting single Higgs-boson production in $e^+e^- \to \nu\bar{\nu}H$ extends the kinematical reach considerably. The MSSM Higgs sector is characterized by two parameters at tree level, the mass of the pseudoscalar Higgs boson, m_A, and $\tan\beta$.

Over large parts of the whole parameter space, i.e. $m_A \gg m_Z$, the lightest CP-even Higgs boson, h, of the MSSM is SM-like, and the coupling of the heavy CP-even Higgs boson to two gauge bosons is suppressed [15]. In this case only the pair production channel $e^+e^- \to HA$ contributes at full strength. Since for large values of m_A the heavy Higgs bosons A and H are approximately mass-degenerate, $m_A \approx m_H$, the pair production channel $e^+e^- \to HA$ is limited by kinematics to the region $m_H < \sqrt{s}/2$. If the rare process $e^+e^- \to \nu\bar{\nu}H$, governed by the suppressed coupling of H to two gauge bosons, can be exploited, the kinematic reach of the linear collider can be extended. In [16] it was shown that higher-order contributions to the couplings of the heavy Higgs boson to the gauge bosons can remedy the suppression. This leads to considerably higher cross sections in certain domains of the MSSM parameter space and makes the process potentially accessible at the linear collider. This requires a high integrated luminosity and polarized beams. While an 80% polarization of the electron beam results in a cross section that is enhanced by a factor 1.8, the polarization of both beams, i.e. 80% polarization for electrons and 60% for positrons, would roughly yield an enhancement by a factor of 2.9. The enhancement of the cross section by the beam polarization can extend the kinematic reach by roughly 10% with respect to the case of unpolarized beams [16], which might be rather crucial in that challenging part of the parameter space.

4. SOME NEWS FROM SUPERSYMMETRY

4.1. The sfermion sector

SUSY predicts that the new particles carry the same quantum numbers as their SM partner particles, with the exception of the spin, which differs by half a unit. Prominent examples are the scalar particles, the selectrons/spositrons $\tilde{e}^{\pm}_{\mathrm{L,R}}$, which have to be associated to their SM partners, the left- and right-chiral electrons/positrons.

To test such assumptions, the pairs $\tilde{e}^+_{\mathrm{L}}\tilde{e}^-_{\mathrm{R}}$, which are produced only in the t-channel process must be experimentally separated from the pair $\tilde{e}^+_{\mathrm{R}}\tilde{e}^-_{\mathrm{R}}$, which are 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 are produced with almost identical cross sections and have the same decay. Applying simultaneously polarized positrons, the pairs get different cross sections, can be isolated, and the $\tilde{e}^+_L$ and $\tilde{e}^-_R$ can be identified by charge separation; see Fig. 2 (left panel) [3].

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 $\tilde{e}^+_{\mathrm{R}}\tilde{e}^-_{\mathrm{R}}$ and $\tilde{e}^+_{\mathrm{L}}\tilde{e}^-_{\mathrm{R}}$ can be exploited to derive the Yukawa couplings. However, in the case where the two pairs have almost identical cross sections and decay modes, $\tilde{e}^{\pm}_{\mathrm{R,L}} \to e^{\pm}\tilde{\chi}^0_1$, the different combinations of $\tilde{e}_{\mathrm{R}}$ and $\tilde{e}_{\mathrm{L}}$ can only be distinguished by the initial beam polarization of both beams, see Fig. 2 (right panel) [3].

In the third generation of sfermions, Yukawa terms give rise to a mixing between the 'left' and 'right' states $\tilde{f}_{\mathrm{L}}$ and $\tilde{f}_{\mathrm{R}}$ ($\tilde{f} = \tilde{t}, \tilde{b}, \tilde{\tau}$). Information on the mixing angle can be obtained by measuring production cross sections with different combinations of beam polarizations. The mixing angle can be determined even more precisely from the left–right asymmetry $A^{\mathrm{obs}}_{\mathrm{LR}} = (\sigma_{-+} - \sigma_{+-})/(\sigma_{-+} + \sigma_{+-})$, because here the kinematical dependence on $m_{\tilde{t}_1}$ drops out, as shown in Table I. One gains about a factor of 1.6 in the accuracy of $\cos\theta_{\tilde{t}}$ and about a factor of 1.4 in that of $m_{\tilde{t}}$ when $(|P_{e^-}|, |P_{e^+}|) = (90\%, 60\%)$, to be compared with only $(|P_{e^-}|, |P_{e^+}|) = (90\%, 0)$, respectively.

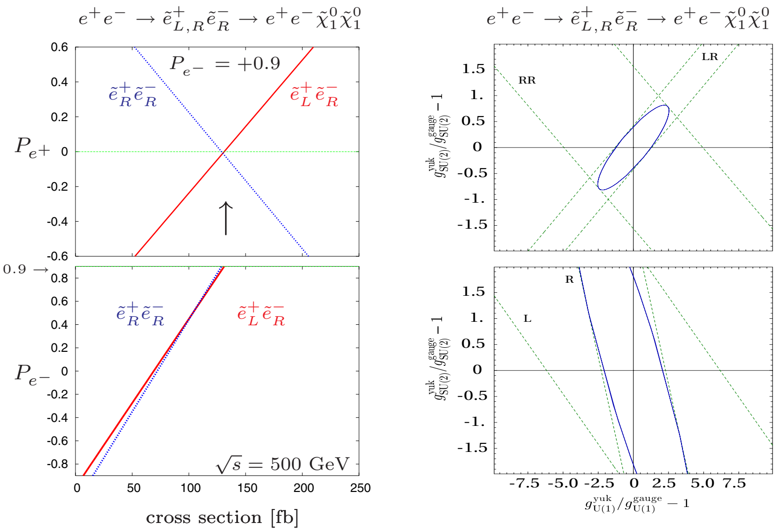

Fig. 2: Left panel: Test of chiral quantum number – separation of the selectron pair $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$ is not possible with e^- polarization alone, e.g. $P_{e^-} = +90\%$ (lower plot). If, however, both beams are polarized, the RR configuration separates the pairs $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$, $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm L}$ (see arrow, upper plot).
Right panel: Test of Yukawa couplings – 1σ bounds on the determination of the supersymmetric U(1) and SU(2) Yukawa couplings between e^+, $\tilde{e}^+_{\rm R,L}$ and $\tilde{\chi}^0_i$ from selectron cross-section measurements; R (L) means $P_{e^-} = +90\%$ (-90%) (lower plot). In the upper plots both beams are polarized with the values $(P_{e^+}, P_{e^-}) = (-60\%, +90\%)$ (LR) and $(+60\%, +90\%)$ (RR) [3].

Table I: Parameters for the cases studied, cross sections, assumed statistical errors and resulting precisions on $m_{\tilde{t}_1}$ and $\cos\theta_{\tilde{t}}$ [3].

Case	$\mathcal{L}_{\rm int}$	P_{e^-}	P_{e^+}	σ_{-+}	σ_{+-}	$\Delta\sigma^{\rm stat.}_{-+}$	$\Delta\sigma^{\rm stat.}_{+-}$	$\Delta m_{\tilde{t}_1}$	$\Delta\cos\theta_{\tilde{t}}$ from $\sigma(\tilde{t}_1\tilde{t}_1)$	$\Delta\cos\theta_{\tilde{t}}$ from $A_{\rm LR}$
1	100 fb^{-1}	∓ 0.9	0	44 fb	27 fb	4.7%	6.3%	1.1%	3.6%	2.3%
3	100 fb^{-1}	∓ 0.9	± 0.6	69 fb	40 fb	3.1%	4.4%	0.8%	2.3%	1.4%

4.2. Transversely-polarized beams for CP searches in the gaugino/higgsino sector

CP-violating phases can be determined via T-odd observables exploiting spin correlations of the decaying fermions. In the case of neutralinos (Majorana fermions), it is even possible to construct CP-odd observables in the production process if transversely-polarized beams are available [17]: the following CP-odd asymmetry is defined as

$$A_{\rm CP}(\theta) = \frac{1}{\sigma}\left[\int_0^{\frac{\eta}{2}} - \int_{\frac{\eta}{2}}^{\frac{\pi}{2}+\frac{\eta}{2}} + \int_{\frac{\pi}{2}+\frac{\eta}{2}}^{\pi+\frac{\eta}{2}} - \int_{\pi+\frac{\eta}{2}}^{\frac{3\pi}{2}+\frac{\eta}{2}} + \int_{\frac{3\pi}{2}+\frac{\eta}{2}}^{2\pi}\right]\frac{{\rm d}^2\sigma}{{\rm d}\phi\,{\rm d}\theta}{\rm d}\phi\ , \text{ with } A_{\rm CP} = \left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi}\right] A_{\rm CP}(\theta)\,{\rm d}\cos\theta, \quad (5)$$

where $\eta = (\phi_- + \phi_+) \in [0,\pi]$. In order to measure $A_{\rm CP}$ it is necessary to reconstruct the directions of the neutralinos, which can be done by analysing the subsequent decays [17]. This asymmetry can lead to rather high values even for small phases, which might become essential for observing such new kinds of CP violation.

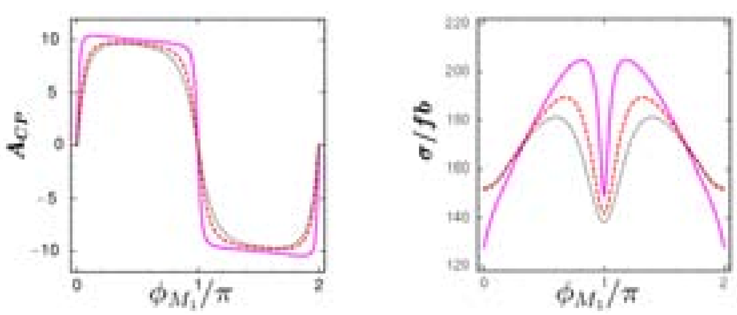

Fig. 3: CP asymmetry $A_{\rm CP}$ (left) and cross section $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$ (right) as a function of ϕ_{M_1} for $\sqrt{s} = 500$ GeV and transverse beam polarizations $(P^T_{e^-}, P^T_{e^+}) = (100\%, 100\%)$. To go to realistic values of polarization, one has to simply multiply $A_{\rm CP}$ with the product $P^T_{e^-}P^T_{e^+}$. The different lines indicate different values of $\tan\beta = 3, 10, 30$ [17].

5. CONCLUSIONS

The use of polarized electrons and positrons is essential in the maximal exploitation of the physics potential of the ILC with its first energy stage of $\sqrt{s} = 500$ GeV. High-precision measurements of the top quark and the Higgs boson will be absolutely crucial to advance our understanding of the underlying physics at the quantum level and to pave the way for detecting even small hints for new physics at a much higher scale. In this contribution some studies for using polarized beams in the top, Higgs and SUSY sectors have been summarized. Even if only a partial spectrum is accessible, powerful tests of the properties of the new particles can be made if polarized beams are available. The polarization of both beams therefore serves as a superior experimental tool to face the (expected and unforeseen) challenges of possible new physics, as well as to make the high-precision studies of the top and Higgs sector. More examples, details and studies of further new-physics models with polarized electron and positron beams can be found in [3].

Acknowledgments

I would like to thank the organizers of Snowmass 2005 for the pleasant atmosphere at the workshop and for financial support. Furthermore I would like to thank all authors of the report [3] for their active and lively collaboration. I am particularly indebted to Per Osland and Nello Paver for their great help in editing the physics part of the polarization report.

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