

## News from Polarized $e^-$ and $e^+$ at the ILC

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The proposed International Linear Collider (ILC) is well-suited for discovering physics beyond the Standard Model and for precisely unravelling the structure of the underlying physics. The physics return can be maximized by the use of polarized beams, in particular the simultaneous polarization of the  $e^-$  as well as the  $e^+$  beam. Ongoing physics studies are accompanied by currently active R&D on the machine part for generating polarized beams and for measuring the polarization with high precision at the ILC. Some new results from the physics case and from the technical aspects of the polarization of both beams are shortly summarized.

### 1. INTRODUCTION

It is well-accepted that beam polarization will play an important role in the programme of the now being planned International Linear Collider (ILC). The polarization of the electron beam is already foreseen for the baseline design [1]. A high degree of at least 80% polarization is envisaged, but new results indicate that even 90% should be achievable. A polarized electron beam would already provide a valuable tool for measuring precisely the Standard Model (SM) processes and for diagnosing candidates of new physics.

Polarizing simultaneously the electron and the positron beam is currently discussed as a possibility for the ILC. In the report [2] it is shown that the full potential of the linear collider could be realized only with the polarization of the  $e^-$  and  $e^+$  beam. In addition to most precise studies of the SM and detailed analysis of the properties of new particles and of new kinds of interactions, the polarization of both beams would also enable indirect searches with high sensitivity for new physics in a widely model-independent approach. Consequently, very active R&D is currently ongoing for all beam polarization issues: polarized  $e^\pm$  sources, polarization transport, polarization measurement as well as reliability aspects. In the following a short summary is given about the news from this interesting field, all physics examples can be found in [2]. For more details see also further contributions in these proceedings [3].

### 2. NEWS FROM THE PHYSICS CASE FOR POLARIZED $E^-$ AND $E^+$

A main task of future experiments in high-energy physics will not only be to discover physics beyond the Standard Model (SM) but also to reveal the structure of the underlying physics and to determine precisely the model. It is expected that the clean signatures and in particular the precise measurements made possible by a high-luminosity linear collider at a known and tunable beam energy are perfectly suited to complement and extend all kinds of new physics discoveries made by the Large Hadron Collider (LHC), which is scheduled to start end of the year 2007.

#### 2.1. Direct searches for physics beyond the SM

One of the best motivated extensions of the SM is Supersymmetry (SUSY). This theory predicts that all new SUSY particles carry the same quantum numbers as their SM partner particles with the exception of the spin which differs by half a unit. A prominent example are the scalar particles, the selectrons/spositron  $\tilde{e}_{L,R}^\pm$ , which have to be associated to their SM-partners, the left- and right-chiral electrons/positrons.

To test such assumptions one has to separate experimentally the pairs  $\tilde{e}_L^+ \tilde{e}_R^-$  produced only in the  $t$ -channel process from the pair  $\tilde{e}_R^+ \tilde{e}_R^-$  from the  $s$ -process. There exist scenarios where even a highly polarized electron beam will not be sufficient to separate the pairs, because both pairs 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. 1 (left panel).

Another consequence of supersymmetry is, that 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  $\tilde{e}_R^+\tilde{e}_R^-$  and  $\tilde{e}_L^+\tilde{e}_R^-$  can be exploited to derive the Yukawa couplings. However, in case that almost both pairs have almost identical cross sections and decay modes,  $\tilde{e}_{R,L}^\pm \rightarrow e^\pm \tilde{\chi}_1^0$ , the different combinations of  $\tilde{e}_R$  and  $\tilde{e}_L$  can only be distinguished by the initial beam polarization of both beams, see fig. 1 (right panel).

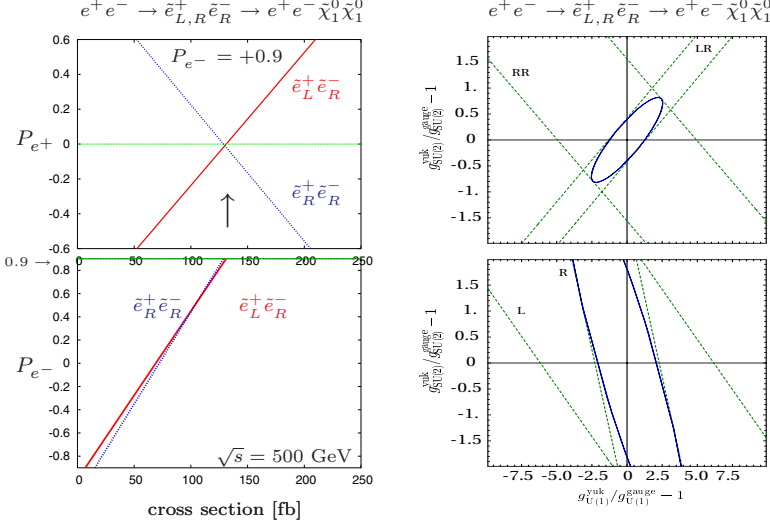


Fig. 1: Separation of the selectron pair  $\tilde{e}_L^+\tilde{e}_R^-$  in  $e^+e^- \rightarrow \tilde{e}_{L,R}^+\tilde{e}_{L,R}^- \rightarrow e^+e^- 2\tilde{\chi}_1^0$  is not possible with electron polarization alone. If, however, both beams are polarized, the cross sections differ and the RR configuration separates the pair  $\tilde{e}_L^+\tilde{e}_R^-$  (left panel). Right panel:  $1\sigma$  bounds on the determination of the supersymmetric U(1) and SU(2) Yukawa couplings between  $e^+$ ,  $\tilde{e}_{R,L}^+$  and  $\tilde{\chi}_1^0$  from selectron cross-section measurements. In the lower plots only electron beam polarization is used for two values  $P_{e^-} = +90\%$  (R) and  $P_{e^-} = -90\%$  (L). In the upper plots both beams are polarized with the values  $(P_{e^+}, P_{e^-}) = (-60\%, +90\%)$  (LR) and  $(+60\%, +90\%)$  (RR).

As can be seen from these examples, the availability of polarized positrons may be absolutely essential for the determination of the underlying physics, further SUSY examples see [2].

The polarization of both beams allows to probe directly, not only the chiral quantum numbers as shown in Fig. 1, but also to test the spin of produced particles in resonances.

A prominent example is the production of a spin-0 particle, e.g. the scalar neutrino in  $\mu^+\mu^-$  production. Since the sneutrino couples only to left-handed  $e^\pm$ , the peak is strongest for the configuration LL:  $(P_{e^-}, P_{e^+}) = (-80\%, -60\%)$  which points directly to resonance production of spin-0 particles: the SM background is strongly suppressed and one gets a  $S/B \sim 11$ , whereas with  $(P_{e^-}, P_{e^+}) = (-80\%, 0\%)$  one obtains only  $S/B \sim 4$ , see fig. 2 (left panel). Since one has not completely polarized beams, the signal is still not fully suppressed in the configuration LR. Conversely, in the case of a spin-1 resonance, e.g. from the  $Z'$  particle, the corresponding resonance curve would have the strongest peak for the LR configuration with a similar polarization dependence as the SM background, see fig. 2 (right panel).

This simple example shows how one could directly test the kind of the interaction if the polarization of both beams were available.

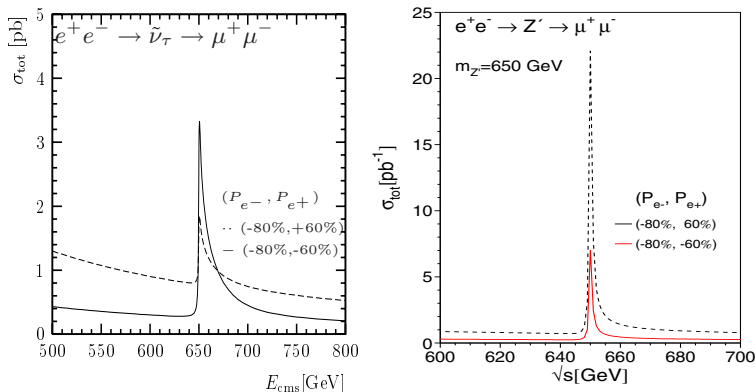


Fig. 2: Sneutrino production in the R-parity-violating model versus  $Z'$  production in the SSM model. Resonance production for  $e^+e^- \rightarrow \tilde{\nu}_\tau \rightarrow \mu^+\mu^-$  (left panel) and for  $e^+e^- \rightarrow Z' \rightarrow \mu^+\mu^-$  (right panel) for different configurations of beam polarization:  $(P_{e^-}, P_{e^+}) = (-80\%, +60\%)$  (dashed),  $(-80\%, -60\%)$  (solid).

Beam polarization is also important for SUSY mass determination in the continuum. In many cases the worst background is  $WW$  pair production which can be significantly reduced using right-handed polarized  $e^-$  and left-handed polarized  $e^+$ . One gains a factor of about 2.6 in the ratio  $S/\sqrt{B}$  with  $(P_{e^-}, P_{e^+}) = (+80\%, -80\%)$  compared to  $(+80\%, 0)$ . With polarized  $e^-$  and  $e^+$  beams the muon-energy edges, at around 65 and 220 GeV, can clearly be reconstructed.

Muon energy spectrum:  $\mu^+\mu^-$  events (incl.  $W^+W^-$ ) at  $\sqrt{s} = 750$  GeV

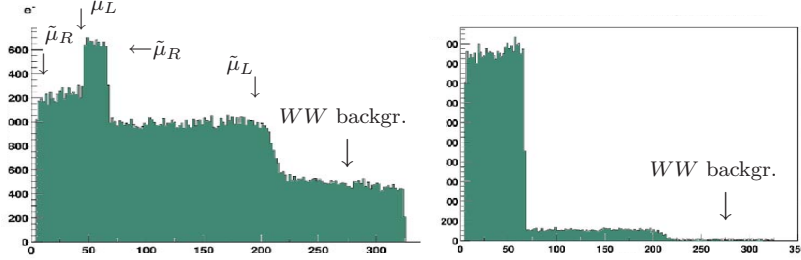


Fig. 3: The slepton masses can be determined in the continuum up to a few GeV uncertainty. This shows the real importance of positron polarization for a clear observation of the energy edge associated to the  $\tilde{\mu}_R$ .

Another example of new physics, where also the background suppression is important, is the search for direct signatures of massive spin-2 gravitons. A signature for direct graviton production, envisaged in formulations of gravity with extra spatial dimensions, is a relatively soft photon and missing energy. The major background process is  $\gamma\nu\bar{\nu}$  production. Since the neutrino coupling is only left-handed, the background has nearly maximal polarization asymmetry and, consequently, polarized electron and positron beams are extremely effective in suppressing the  $\gamma\nu\bar{\nu}$  effects. Compared with the case of only polarized electrons, the background process can be suppressed by a factor of about 2 whereas the signal will be enhanced by a factor of about 1.5.

In general, such enhancements of cross sections and the ratio  $S/B$  may be particularly important just at the edge of the kinematical reach of the machine. Enabling a look just around such a corner with the help of polarized positrons may thus be crucial and motivates possible future upgrades.

## 2.2. Indirect searches for large scales of new physics

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 future as well as present accelerators. Therefore it will also be important to develop strategies for indirect searches beyond the kinematical limit for new physics. Due to the clear signatures and the high luminosity the ILC has also a large discovery potential for indirect searches in a largely model-independent approach.

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

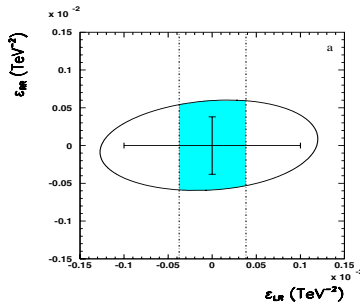


Fig. 4: In Bhabha scattering the four-fermion CIs are parametrized by three parameters  $(\epsilon_{RR}, \epsilon_{LR}, \epsilon_{LL})$ . The  $t$ -channel contributions depend only on  $\epsilon_{LR}$ , whereas the  $s$ -channel contribution only on pairs  $(\epsilon_{RR}, \epsilon_{LR})$ ,  $(\epsilon_{LR}, \epsilon_{LL})$ . In order to derive model-independent bounds it is necessary to have both beams polarized. Tight bounds up to  $5 \cdot 10^{-4} \text{ TeV}^{-2}$  can be derived via a  $\chi^2$  test assuming that no deviation from the SM are measured within the experimental one- $\sigma$  uncertainty in the observables  $\sigma_0$ ,  $A_{FB}$ ,  $A_{LR}$  and  $A_{LR,FB}$ .

Extra neutral gauge bosons  $Z'$  can be probed by their virtual effects on cross sections and asymmetries. For energies below a  $Z'$  resonance, measurements of fermion-pair production are sensitive only to this ratio of  $Z'$  couplings and  $Z'$  mass. Positron-beam polarization with  $(P_{e^-}, P_{e^+}) = (80\%, 40\%)$  improves e.g. considerably, by about a factor 1.4 compared to  $P_{e^-} = 80\%$  only, the measurement of the  $b\bar{b}$  couplings of  $Z'$ . The crucial point is the fact that the systematic errors can be significantly reduced when both beams are polarized.

### 2.3. One more joker to find even tiny hints for new physics

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  $\sin^2 \theta_{\text{eff}}$  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 both beams polarized.

With the polarization of both beams using the Blondel scheme, i.e. 80% polarization for electrons and 60% polarization for positrons, an accuracy of  $\Delta \sin^2 \theta_{\text{eff}} = 1.3 \times 10^{-5}$  can be achieved in the leptonic final state [4].

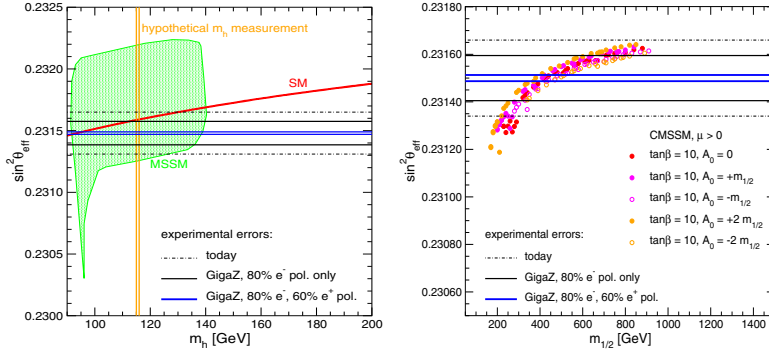


Fig. 5: The theoretical predictions for  $\sin^2 \theta_{\text{eff}}$  in terms of  $m_h$ , the mass of Higgs-boson in the SM or the mass of the lightest Higgs boson in the MSSM, respectively, are compared with the experimental accuracies obtainable at GigaZ (left panel). Right panel: the allowed range for the SUSY mass parameter  $m_{1/2}$  is given in a specific model, the CMSSM. Experimental constraint from LEP searches and cold dark matter searches have been taken into account.

Due to the gain in about one order of magnitude in the accuracy of  $\sin^2 \theta_{\text{eff}}$ , the bounds on  $m_h$  in the SM improve by about one order of magnitude and the allowed parameter space for  $m_{1/2}$  is reduced by about a factor five when using  $(|P_{e-}|, |P_{e+}|) = (80\%, 60\%)$  instead of  $(|P_{e-}|, |P_{e+}|) = (80\%, 0\%)$ .

### 2.4. Transversely-polarized beams

With the polarization of both beams one more powerful tool would be available at the ILC, namely the use of transversely-polarized beams. Transversely polarized beams enhance the physics potential significantly in SM physics as well as in different new physics models: new CP-sensitive observables can be constructed in general and azimuthal asymmetries can be exploited which is particularly important in SUSY searches for new CP-violating sources, further detailed examples in [2]. These asymmetries are also sensitive to new kinds of interactions, e.g. spin-2 graviton exchanges in specific extra dimension models. However, both beams have to be polarized, otherwise all effects from transverse polarization vanish in the limes  $m_e \rightarrow 0$  (suppression  $\sim m_e/\sqrt{s}$ ).

Furthermore, an example from SM physics for an additional plus of having transversely-polarized beams in testing the electroweak gauge group is the unique access of one specific triple gauge coupling. In the SM the most general parametrization of the gauge-boson self-interactions leads to 14 complex parameters. It turns out that for most couplings longitudinally-polarized  $e^-$  and  $e^+$  beams are sufficient with the exception of the one specific couplings,  $\tilde{h}_+ = \text{Im}(g_1^R + \kappa^L)/\sqrt{2}$ , which is only accessible with transversely-polarized beams. Concerning the determination of the other TGC one gains about a factor 1.8 when applying both beams longitudinally polarized instead of only polarized electrons.

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, see Fig.6.

The success to identify new physics even in indirect searches via polarized  $e^-$  and  $e^+$  beams represents a step forward in our understanding of fundamental interactions.

## 3. NEWS FROM TECHNICAL ASPECTS OF POLARIZED $E^-$ AND $E^+$ BEAMS AT THE ILC

### Positron sources at the ILC

Several possibilities as positron source for the ILC are under discussion: **a)** a conventional, non-polarized source, **b)**

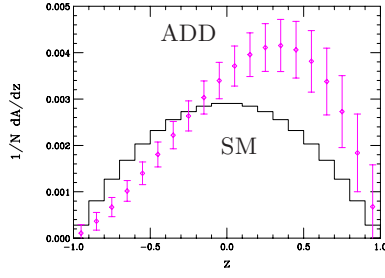


Fig. 6: One representative example is the distinction between extra dimensions in the models of Randall-Sundrum (RS) and Arkani-Hamed, Dimopoulos, Dvali (ADD). The azimuthal distributions in the SM as well as the RS-model have to be absolutely symmetric whereas the asymmetric behaviour of the azimuthal asymmetry in the ADD-model clearly shows the effects of the spin-2 graviton. For such a model test with transversely-polarized beams the polarization of both beams is required.

a helical undulator-based polarized source, c) a laser-based polarized source.

The conventional positron source assumes a primary electron of 6.2 GeV, the nominal ILC beam current and bunch structure for the  $e^+$  beam generation and a thick target of about  $\geq 4$  radiation length (r.l.) Tungsten [6]. The polarized sources b) and c) use circularly-polarized photons (generated via undulator radiation or Compton-backscattering of laser light) and need only a thin target of about 0.5 r.l..

Solution b) needs an high-energy electron beam ( $\geq 150$  GeV), whereas in c) only a few-GeV  $e^-$  beam is needed, which can be generated in a stand-alone linac. The main technical challenge for c) is, however, to provide lasers with very high intensity. The impact of the linked operation of an undulator-based source on the overall machine performance is still under discussion but recent results show [5] that it can be greatly reduced by using an additional low-intensity electron keep-alive beam. Contrary, such polarized sources provides a much smaller  $e^+$  beam divergence resulting in a large safety margin, less heat load of the target, a higher capture efficiency and allows to the the  $e^+$  source for a smaller damping ring acceptance compared with a conventional  $e^+$  source [6].

- The proof-of-principle experiment for the undulator-based polarized-positron source is the currently running project E-166 at SLAC. It uses the 50 GeV FFTB to generate via a 1-m long helical undulator polarized photons which are then converted at a thin target into polarized positrons. The polarization of the photons as well as the positrons will then be analyzed and compared with the theoretical simulations. Since the photon spectrum, the chosen target material and thickness are similar to those foreseen for the possible ILC design, polarized positrons will be produced with the same polarization characteristics as expected at the ILC. Already the first run led to a large amount of excellent data and has shown that undulator radiation provides a feasible stable  $e^+$  source. The second run is scheduled for September 2005 and final results are expected at the end of the year.

- Helical undulator prototypes for a specific ILC design are currently developed under guidance of the AsteC group at the Daresbury Laboratory, U.K.. Two designs are discussed: the first device uses superconducting magnets and the second one an Halbach undulator with permanent magnets. The decision between both technologies is foreseen for this year.

- Concerning the laser-based source a prototype experiment was ongoing at KEK, which demonstrated that the polarization transfer from the laser to the circularly polarized photons as well as from the polarized photons to the positrons is as expected.

## Polarization measurement and spin manipulations

For both, polarized electrons as well as polarized positrons, the polarization measurement will be done with Compton polarimetry. Depending on the final choice of a beam head-on design or a crossing angle design, the polarimeter could be installed upstream or/and downstream. For both designs a magnet chicane system seems to be very useful: for a upstream polarimeter a chicane enables to retain maximum coverage of the electron detector; for a downstream polarimeter a chicane is needed to discern between Compton-edge electrons and the low energy disrupted primary electrons.

The expected polarimeter precision at the ILC is expected to be  $\Delta P_{e^-}/P_{e^-} \sim \Delta P_{e^+}/P_{e^+} \leq 0.5\%$ , up to 0.1%–0.2%. For such a polarimeter either a specialized high-power laser or a conventional laser amplified by a Fabry-Perot cavity is needed [3]. To get even higher precision  $\Delta P/P < 0.1\%$ , it is needed to use the Blondel scheme for polarization measurement. This schemes requires polarized positrons and in particular to switch the polarizations of both beams independently. To keep systematics under control a fast switching is desired.

- Pulse-to-pulse switching of the positron polarization can be accomplished by utilizing slow kicker magnets. A pair of dipoles is turned on between pulse-trains to deflect the beam through solenoids to rotate the spin to the

opposite helicity. With such a system, the change of positron polarization can happen between pulse-trains, which is fast enough to keep any systematics well under control.

- To provide transversely-polarized beams, one just has to change the spin rotator settings —consisting of two solenoids and a bend-rotation system, while minimizing the emittance dilution— just after the damping system. Such a device will allow one to set the spins at any arbitrary orientations by the time they reach the IP. Longitudinal Compton polarimeters can monitor that the longitudinal polarization stays close to zero. Applying periodically ( $\sim$  every 1-2 days), one should achieve a precision of  $\Delta P^T/P^T \sim 1\%$ .

## 4. CONCLUSIONS AND OUTLOOK

In Ref. [2] many examples from the Standard Model as well as from numerous models beyond the Standard Model have shown in detail that having simultaneously polarized  $e^-$  and  $e^+$  beams will provide a very efficient tool for direct as well as indirect searches for new physics. The option of polarizing both beams provides a powerful tool for studying new physics studies at the ILC, such as discovering new particles, analyzing signals model-independently and resolving precisely the underlying model. These arguments refer to Standard Model physics as well as to many new physics models, providing an ideal preparation for any unexpected new physics interactions. Polarized  $e^+$  serves as a superior experimental tool to face the (expected and unforeseen) challenges of possible new physics followed by a precise revealing of the underlying model.

One should keep in mind that the given examples, however, by no means exhaust the whole phenomenology of simultaneously polarized electron and positron beams, still studies are ongoing and further ideas for the exploitation of both beams polarized are coming up.

Techniques and engineering designs for a polarized-positron source are well advanced. Potential disadvantages concerning luminosity, commissioning and operating issues appear to be under control, e.g. with an additional low-energy keep-alive beam. Consideration can therefore now be given to including a polarized-positron source already in the baseline design.

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