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 of the ILC can be maximized by the use of polarized beams, in particular the simultaneous polarization of the e^- and the e^+ beam. Ongoing physics studies are accompanied by 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 on the physics case and on the technical aspects of the polarization of both beams are briefly summarized.

1. INTRODUCTION

It is well accepted that beam polarization will play an important role in the programme of the International Linear Collider (ILC). The polarization of the electron beam is 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 Standard Model (SM) processes and for diagnosing candidates of new physics.

Polarizing simultaneously the electron and the positron beam is currently discussed as an upgrade possibility for the ILC. In the report of the polarization working group POWER (POlarization at Work in Energetic Reactions) [2], it is shown that the full potential of the linear collider could be realized only with the polarization of both the e^- and e^+ beams. In addition to high-precision studies of the SM and detailed analyses 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 other 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 SM but also to reveal the structure of the underlying physics and to determine the model precisely. 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 that will be made at the Large Hadron Collider (LHC), which is scheduled to start in 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 new SUSY particles that 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 $\tilde{e}^\pm_{\rm L,R}$, which have to be associated to their SM partners, the left- and right-chiral electrons/positrons.

To test such assumptions, the pairs $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$ produced only in the t-channel 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 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) [2].

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, $\tilde{e}_{\rm R,L}^{\pm} \to e^{\pm}\tilde{\chi}_1^0$, the different combinations of $\tilde{e}_{\rm R}$ and $\tilde{e}_{\rm L}$ can only be distinguished by the initial beam polarization of both beams, see Fig. 1 (right panel) [2].

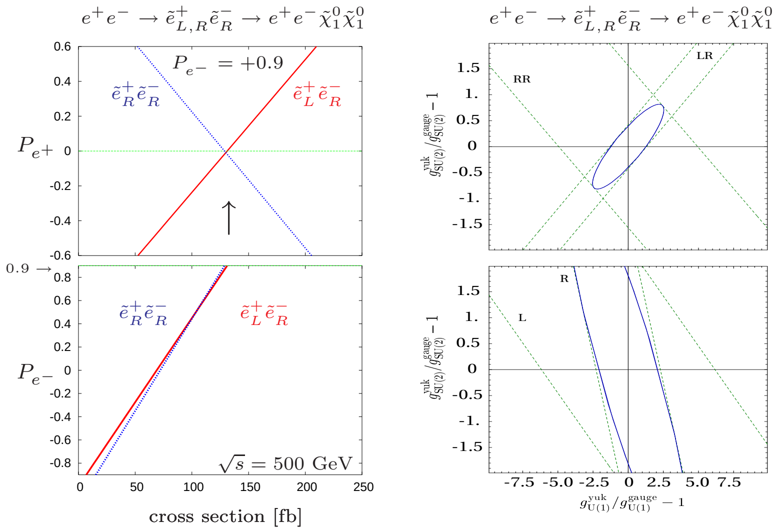

Fig. 1: *Left panel: Test of chiral quantum number – separation of the selectron pair $\tilde{e}_{\rm L}^+\tilde{e}_{\rm R}^-$ is not possible with e^- polarization alone, e.g. $P_{e^-} = +90\%$ (lower plot). If, however, both beams are polarized, the RR configuration separates the pairs $\tilde{e}_{\rm L}^+\tilde{e}_{\rm R}^-$, $\tilde{e}_{\rm L}^+\tilde{e}_{\rm L}^-$ (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 $\tilde{\chi}_i^0$ 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).

As can be seen from these examples, the availability of polarized positrons may be absolutely essential for the determination of the underlying physics.

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

A prominent example is the production of a spin-0 particle, e.g. the scalar neutrino in $\mu^+\mu^-$ production [2]. 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 we obtain 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 100%-polarized beams are not possible, the signal is still not fully suppressed in the LR configuration. Conversely, in the case of a spin-1 resonance, e.g. from a 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 can directly probe the nature of the interaction if the polarization of both beams is available.

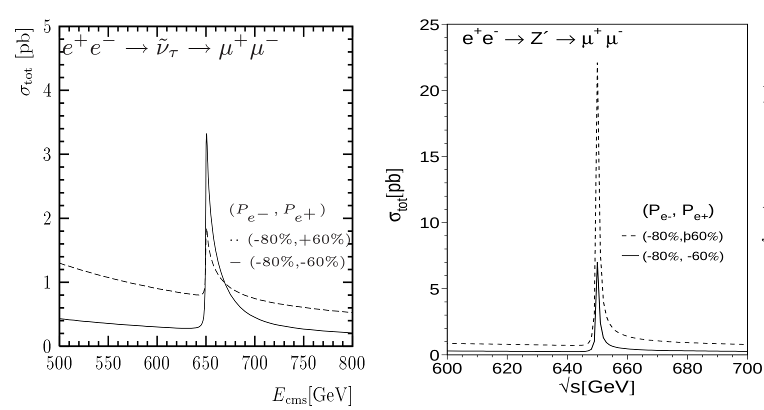

Fig. 2: *Direct probe of spin-0 in resonance production – sneutrino production in the R-parity-violating model versus Z' production in the SSM Z' model. Resonance production for $e^+e^- \to \tilde{\nu}_\tau \to \mu^+\mu^-$ (left panel) and for $e^+e^- \to Z' \to \mu^+\mu^-$ (right panel) for different configurations of beam polarization:*
$(P_{e^-}, P_{e^+}) = (-80\%, +60\%)$ *(dashed),*
$(-80\%, -60\%)$ *(solid).*

Beam polarization is also important for mass measurements of SUSY particles 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^+. A factor of about 2.6 can be gained 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.

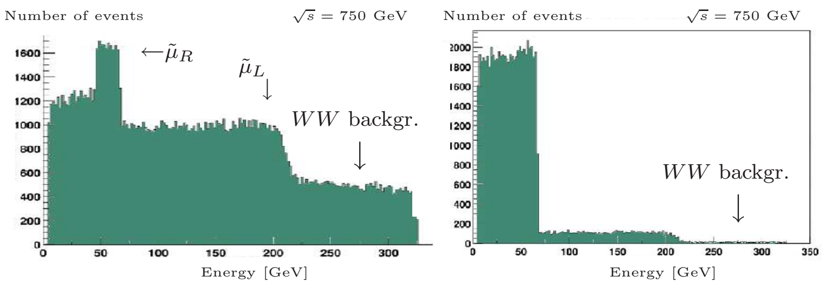

Fig. 3: *Muon energy spectrum: $\mu^+\mu^-$ events (incl. W^+W^-). Left panel: W^+W^- background is dominant for $(P_{e^-}, P_{e^+}) = (-80\%, +80\%)$, so that the edges cannot clearly be reconstructed. Right panel: Only with polarized e^- and e^+ beams both muon-energy edges, at around 65 GeV and 220 GeV, can be reconstructed with $(P_{e^-}, P_{e^+}) = (+80\%, -80\%)$. This leads to a smuon masses determination in the continuum up to a few GeV uncertainty.*

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 efficient 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 of the ratio S/B may be particularly important 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 be crucial and may motivate possible 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 present and future accelerators. Therefore it will be important to develop strategies for indirect searches beyond the kinematical limit for new physics. Thanks to the clear signatures and its high luminosity, the ILC also has a large discovery potential in 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 of very high-mass states between the SM particles.

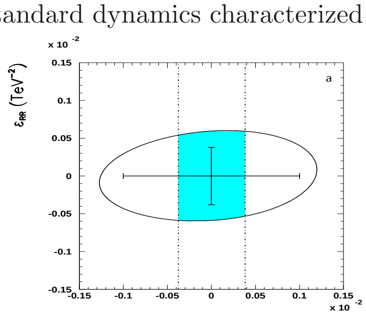

Fig. 4: *In Bhabha scattering the four-fermion CIs are parametrized by three parameters ($\epsilon_{\rm RR}$, $\epsilon_{\rm LR}$, $\epsilon_{\rm LL}$). The t-channel contributions depend only on $\epsilon_{\rm LR}$, whereas the s-channel contribution depends only on pairs ($\epsilon_{\rm RR}$, $\epsilon_{\rm LR}$), ($\epsilon_{\rm LR}$, $\epsilon_{\rm LL}$). 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).*

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 to the ratio of Z' couplings and Z' mass. Positron-beam polarization with $(P_{e^-}, P_{e^+}) = (80\%, 40\%)$ improves considerably, by about a factor 1.4 compared with $P_{e^-} = 80\%$ 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 opportunity 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 $\sin^2\theta_{\rm eff}$ 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.

With the polarization of both beams, using the Blondel scheme, assuming 80% polarization for electrons and 60% for positrons, an accuracy of $\Delta\sin^2\theta_{\rm eff} = 1.3\times10^{-5}$ can be achieved in the leptonic final state [4].

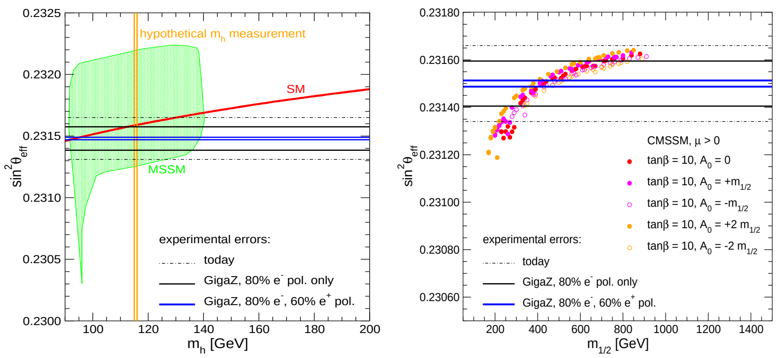

Fig. 5: *The theoretical predictions for* $\sin^2\theta_{\rm eff}$ *in terms of* m_h*, the mass of the Higgs boson in the SM or the mass of the lightest Higgs boson in the MSSM, respectively, are compared with the experimental accuracies obtainable at GigaZ (left panel). Right panel: The precision measurement 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. Experimental constraints from LEP searches and cold-dark-matter searches have been taken into account.*

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, 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 $(|P_{e^-}|,|P_{e^+}|) = (80\%, 0\%)$.

2.4. Transversely-polarized beams

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

Furthermore, an example from SM physics of an additional benefit of having transversely-polarized beams in testing the electroweak gauge group is the unique access to one specific triple gauge coupling (TGC). 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 coupling, $\tilde{h}_+ = {\rm Im}(g_1^{\rm R} + \kappa^{\rm L})/\sqrt{2}$, which is only accessible with transversely-polarized beams. Concerning the determination of the other TGC the gain is of a factor of about 1.8, when applying both beams longitudinally polarized instead of only polarized electrons.

Transversely polarized beams provide sensitivity to non-standard interactions, which are not of the current–current type, such as those mediated by tensor or (pseudo)scalar exchanges. This is the case even in indirect searches, see Fig. 6.

The possibility to identify new physics even in indirect searches when applying polarized e^- and e^+ beams represents a further step forward in our understanding of fundamental interactions.

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

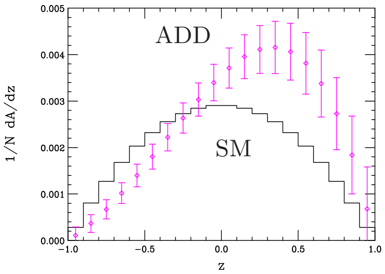

Fig. 6: *One representative example is the distinction between extra dimensions in the models of Randall–Sundrum (RS) and Arkani-Hamed–Dimopoulos–Dvali (ADD). The azimuthal distributions in the SM as well as the RS–model have to be absolutely symmetric, whereas the asymmetric behaviour of the azimuthal 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.*

Positron sources at the ILC

Several possibilities for a positron source for the ILC are under discussion: **a)** a conventional, non-polarized source, **b)** 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 ≥ 4 radiation lengths (r.l.) of tungsten [6]. The polarized sources *b*) and *c*) use circularly-polarized photons (generated via undulator radiation or a Compton-backscattering of laser light) and need only a thin target of about 0.5 r.l.

Solution b) needs a 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 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. On the contrary, such polarized sources provide a much smaller e^+ beam divergence, resulting in a large safety margin, less heat load of the target, a higher capture efficiency and allow an e^+ source for a damping-ring acceptance smaller than for 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 that are then converted at a thin target into polarized positrons. The polarization of the photons as well as the positrons will then be analysed and compared with the theoretical simulations. Since the photon spectrum, the chosen target material and the 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 the guidance of the Daresbury and Rutherford Laboratories, U.K. Two designs are discussed: the first device uses superconducting magnets and the second one a Halbach undulator with permanent magnets. The choice between the two 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 and 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 an upstream polarimeter, a chicane enables us 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, $\Delta P/P < 0.1\%$, the Blondel scheme for polarization measurement must be used. This scheme requires polarized positrons and, in particular, that the polarization of the two beams be switched 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 so as to deflect the beam through solenoids to rotate the spin to the opposite helicity. With such a system, the change of positron polarization can be made between pulse-trains, which is fast enough to keep any systematics well under control.

• To provide transversely-polarized beams, we just have 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 us to set the spins at any arbitrary orientation by the time they reach the interaction region. Longitudinal Compton polarimeters can monitor that the longitudinal polarization stays close to zero. Applying periodically ($\sim$ every 1–2 days), a precision of $\Delta P^{\mathrm{T}}/P^{\mathrm{T}} \sim 1\%$ should be achieved.

4. CONCLUSIONS AND OUTLOOK

In Ref. [2] many examples within the Standard Model, as well as from numerous models beyond it have demonstrated in detail that simultaneous polarization of the 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 at the ILC, such as discovering new particles, analysing signals model-independently and precisely resolving the underlying model. 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 SM processes possible.

One should keep in mind that the given examples, however, by no means exhaust the whole phenomenology of simultaneously polarized electron and positron beams. Many 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 challenges concerning luminosity, commissioning and operating issues appear to be under control, e.g. with an additional low-energy keep-alive beam. Therefore, consideration can now be given to including a polarized-positron source already in the baseline design.

Acknowledgments

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