Physics Applications of Polarized Positrons

S. Riemann
DESY Zeuthen, Platanenallee 6, D-15738 Zeuthen, Germany

Abstract

With the LHC a new era of measurements at the energy frontier has started, and exciting new discoveries are expected. However, also measurements at the precision frontier will be necessary to fully understand the underlying physics model. The programme for the e^+e^- collider projects ILC and CLIC is focused on precision tests of the Standard Model and new physics beyond it at the TeV scale. Polarized positron beams play a crucial role in these analyses. Here, the advantages as well as the requirements using also polarized positron beams for measurements at e^+e^- colliders are discussed.

1 Introduction

So far, the particle physics experiments have confirmed the Standard Model (SM) with excellent precision. Neither significant deviations from the SM predictions nor new physics phenomena have been obtained. Based on the global analysis of the measurements it is expected that the SM Higgs boson has a mass of $\mathcal{O}(100)$ GeV. The fundamental question whether the Higgs boson exists will be answered soon by the measurements at the LHC, and the experiments are well prepared to discover and probe new physics beyond the SM. But the full understanding of phenomena obtained at the LHC is only possible if complementary measurements from lepton colliders are available. The precise knowledge of type, energy and helicity of the interacting particles allows to test theoretical models at the level of quantum corrections up to higher orders. The microscopic world of electroweak interactions is not left-right symmetric and so are new phenomena suggested by various extensions of the SM. The chiral structure of interactions can be analyzed best using high-energy lepton colliders with polarized beams. However, the production of an intense, highly polarized electron beam with high energy is simple in comparison to the generation of the corresponding polarized positron beam.

But the flexibility and the substantial advantages justify the effort necessary to create the polarized positron beam.

In this paper important features of measurements at e^+e^- colliders with polarized beams are discussed. Section 2 presents few selected examples for precision physics with polarized beams. In subsections 2.1–2.3 the basics of measurements with polarized beams are introduced. The experimental requirements to utilize polarized positron beams are described in section 3. Section 4 summarizes.

2 Physics with Polarized Positrons

The era of precision electroweak measurements [2] at high energies was based on experiments at the Large Electron Positron Collider (LEP) at CERN and at the SLAC Linear Collider (SLC). The Standard Model has been confirmed with extremely high precision, up to loop corrections. Its parameters have been determined and the mass of the SM Higgs boson has been predicted. One of the important SM parameters that describe the electroweak symmetry breaking is the weak mixing angle, $\sin^2\theta_W$. The measurement of this observable was performed by the four LEP collaborations, ALEPH, DELPHI, L3 and OPAL, and by the SLD collaboration; the results and details can be found in reference [2]. It was impressive to see that the SLD collaboration achieved a slightly more precise measurement of this parameter than the four LEP collaborations combined although the latter obtained a more than 30 times higher number of Z bosons created in e^+e^- collisions. The crucial point was the polarized electron beam which increased the sensitivity to the left-right asymmetry of the Z boson coupling to fermions. If SLD would have used also polarized positrons a further reduction of the uncertainty by a factor of about two would have been possible.

This simple Gedankenexperiment demonstrates the potential of polarized beams in high energy particle physics experiments. The precise test of the SM at high energies as well as the understanding of new phenomena benefit substantially if electron and positron beams are polarized. A comprehensive overview of physics with both beams – electrons and positrons – polarized is given in reference [1]. Here, some of the basics are emphasized.

First, few remarks about the requirements for measurements at the precision frontier. Future lepton colliders have to complement and to attend the physics goals achieved with the LHC. This implies physics at center-of-mass energies between 200 GeV and 1 (3) TeV. Two projects are under development: the International Linear Collider (ILC) [3] with energies between 200 GeV and 1 TeV and the possibility to run also at the Z boson resonance,

$\sqrt{s} = 91.2\,\text{GeV}$, and the Compact Linear Collider (CLIC) [4] foreseen for energies up to 3 TeV. To interprete the results and to examine the SM and possible extensions, the precision of measurements must be better than the size of higher order corrections to the observables. With other words: Only high intensities (combined with a highly sophisticated detector) allow to detect the huge number of events for all interesting processes which is necessary to perform measurements with uncertainties at and below the percent-level. However, it is not at all easy to produce a beam with the required high luminosity. Since the cross sections in lepton colliders fall as $\sigma \sim 1/E^2$, the increase of energy by a factor f has to be compensated by a factor f^2 for the luminosity to keep the number of events almost constant. Further, the stability of energy and luminosity must be very high – below 0.1% for the ILC – and the precise measurements of energy and luminosity must be possible. Similar requirements exist for the beam polarization. As shown in the SLD experiment at SLC, electron beam polarization of 80% is possible and measurable with a precision of 0.5% [2]. Further improvements are possible at the ILC [5]. In the following features of precision measurements using polarized beams are discussed.

2.1 Fermion-Pair Production in the s-Channel

Some important advantages of physics with colliding polarized beams can be explained best for the fermion-pair production process. Photon and Z boson are spin-1 particles, and in the SM they are exchanged in this process, $\mathrm{e^+e^-} \to \mathrm{Z}, \gamma \to \mathrm{f\bar{f}}$. The Feynman diagram in lowest order is shown in figure 1. For longitudinally polarized beams, the cross section can be written as

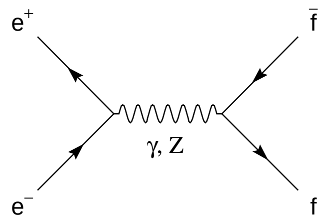

Figure 1: The Feynman diagram in lowest order for the fermion-pair production; in the SM, photon and Z boson are exchanged (J=1).

$$\sigma_{\mathcal{P}_{e^-}\mathcal{P}_{e^+}} = \frac{1}{4}\left[(1-\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\,\sigma_{\rm LR} + (1+\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\,\sigma_{\rm RL} + (1-\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\,\sigma_{\rm LL} + (1+\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\,\sigma_{\rm RR}\right]\,, \quad (1)$$

with the electron beam polarization $\mathcal{P}_{e^-}$ and the positron beam polarization $\mathcal{P}_{e^+}$. $\sigma_{\rm LR}$ denotes the cross section if the electron beam is 100% left-handed polarized ($\mathcal{P}_{e^-} = -1$), and the positron beam 100% right-handed polarized ($\mathcal{P}_{e^+} = +1$). The other cross sections, $\sigma_{\rm RL}$, $\sigma_{\rm LL}$ and $\sigma_{\rm RR}$, are defined correspondingly. Since the exchange of the spin-1 particles, photon and Z boson, in the fermion-pair production is only possible for $J = 1$, the cross sections $\sigma_{\rm RR}$ and $\sigma_{\rm LL}$ are zero in the SM[1]. Figure 2 shows the possible combinations of electrons and positrons with helicities ± 1. It is not excluded that further – yet unknown – particles contribute either to processes with $J = 1$ or $J = 0$. If these particles are not too heavy they can be studied by precise measurements of the process $\rm e^+e^- \to f\bar{f}$.

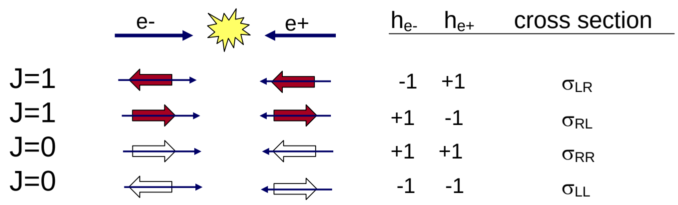

Figure 2: Helicity combinations in collisions of electrons and positrons and the corresponding contributions to the cross section.

The cross section (1) can be expressed with

$$\sigma_{i,j} \;=\; \frac{1}{4}\sigma_u \left[1 - \mathcal{P}_{\rm e^+}\mathcal{P}_{\rm e^-} + A_{\rm LR}\left(-\mathcal{P}_{\rm e^+} + \mathcal{P}_{\rm e^-}\right)\right] , \qquad (2)$$

where A_{LR} is the left-right asymmetry caused by the different coupling strength of Z bosons to left- an right-handed fermions, and the indices i, j describe the sign of the polarization: σ_{-+}, σ_{+-}, σ_{++}, σ_{--}. Taking into account beams with realistic polarization, $|\mathcal{P}| < 1$, the measured cross sections for the different helicity combinations are

$$\sigma_{-+} \;=\; \frac{1}{4}\sigma_u \left[1 + |P_{e^+}P_{e^-}| + A_{LR}\left(+|P_{e^+}| + |P_{e^-}|\right)\right] \qquad (3)$$

$$\sigma_{+-} \;=\; \frac{1}{4}\sigma_u \left[1 + |P_{e^+}P_{e^-}| + A_{LR}\left(-|P_{e^+}| - |P_{e^-}|\right)\right]$$

$$\sigma_{++} \;=\; \frac{1}{4}\sigma_u \left[1 - |P_{e^+}P_{e^-}| + A_{LR}\left(-|P_{e^+}| + |P_{e^-}|\right)\right] \qquad (4)$$

$$\sigma_{--} \;=\; \frac{1}{4}\sigma_u \left[1 - |P_{e^+}P_{e^-}| + A_{LR}\left(+|P_{e^+}| - |P_{e^-}|\right)\right]$$

[1]The cross section for the exchange of Higgs bosons ($J = 0$) yields only tiny contributions and is neglected.

where σ_u denotes the cross section with unpolarized beams. The cross sections σ_{++} and σ_{--} ($J = 0$) are zero for $\mathcal{P}_{e^-} = \mathcal{P}_{e^+} = \pm 1$, in contrast to $\sigma_{+-} \neq 0$ and $\sigma_{-+} \neq 0$ for $\mathcal{P}_{e^-} = -\mathcal{P}_{e^+} = \pm 1$ ($J = 1$). It is easy to see that in case of unpolarized electron and positron beams half of the collisions is spent for helicity combinations that yield $\sigma = 0$. Figure 2 illustrates the combinations and resulting cross section contributions.

If the electron beam is 100% longitudinally polarized, but the positron beam is unpolarized, one half of the measurements is performed with the orientation $\mathcal{P}_{e^-} = +1$, the other half with $\mathcal{P}_{e^-} = -1$. Also in this case initial state helicity combinations occur that do not contribute to the cross section. Hence, only half of the possible helicity combinations yields $\sigma \neq 0$.

However, if both beams are 100% polarized and $\mathcal{P}_{e^-} = -\mathcal{P}_{e^+}$, all possible combinations of initial state helicity amplitudes contribute to the cross section measurement and the luminosity is enhanced compared to the case of unpolarized beams. Figure 3 demonstrates these options.

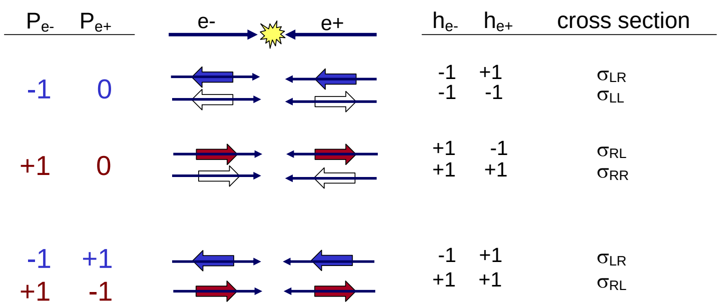

Figure 3: Helicity combinations in collisions of a longitudinally polarized electron and unpolarized positron beam (upper part) and in collisions with both beams polarized. The corresponding helicities of the initial state particles as well as the contributions to the cross section are shown.

2.2 Cross Sections

It is an important result, that the effective luminosity can be substantially enhanced if both beams are polarized. The unpolarized cross section, σ_u, is given by the sum

$$\sigma_u = \frac{1}{4}\left(\sigma_{+-} + \sigma_{-+} + \sigma_{--} + \sigma_{++}\right) . \quad (5)$$

Using unpolarized beams, σ_u is measured obtaining the number N_u of events for the integrated luminosity $\mathcal{L}$,

$$\sigma_u = \frac{N_u}{\mathcal{L}} \,. \tag{6}$$

If the electron beam is 100% polarized but the positron beam unpolarized, and the luminosity is equally distributed to collisions with $\mathcal{P}_{e^-} = -1$ and $\mathcal{P}_{e^-} = +1$, one finds

$$\sigma_u = \frac{\sigma_{+0} + \sigma_{-0}}{2} = \frac{N_{+0} + N_{-0}}{\mathcal{L}/2} = \frac{N_u}{\mathcal{L}} \,. \tag{7}$$

If also the positron beam is polarized, the unpolarized cross section is

$$\sigma_u = \frac{\sigma_{-+} + \sigma_{+-}}{2} = \frac{N_{+-} + N_{-+}}{\mathcal{L}/2} = \frac{N_u}{(1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-})\,\mathcal{L}} \,. \tag{8}$$

The luminosity is effectively enhanced,

$$\mathcal{L}_{\rm eff} = (1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-})\,\mathcal{L} \,, \tag{9}$$

resulting in a smaller statistical error of the measurement. With positron beam polarization of $|\mathcal{P}_{e^+}| = 0.4$ (0.6), the effective luminosity can be increased by about 30% (50%) having an electron beam polarization of $|\mathcal{P}_{e^-}| = 0.8$. In the same way, also processes beyond the SM, e.g. due to the exchange of spin-0 particles, can be enhanced. However, in that case also runs with combinations of the initial state helicities are necessary that are 'inefficient' with respect to the SM cross sections. But the flexibility to chose the desired initial state helicities improves the precision of SM measurements as well as the sensitivity to new phenomena beyond the SM.

It must be mentioned that the uncertainties for the left-handed and right-handed cross section measurements, $\delta\sigma_{+-}$, $\delta\sigma_{-+}$, include also the error of the polarization measurement. For $\delta\mathcal{P}_{e^+}/\mathcal{P}_{e^+} = \delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-} = \delta\mathcal{P}/\mathcal{P}$ the additional error contribution due to the beam polarization measurement is

$$\frac{\delta\sigma_{ij}}{\sigma_{ij}} = \frac{\delta\mathcal{P}}{\mathcal{P}} \sqrt{2\mathcal{P}_{e^+}^2\mathcal{P}_{e^-}^2 + A_{\rm LR}^2\left(\mathcal{P}_{e^+}^2 + \mathcal{P}_{e^-}^2\right)} \,, \tag{10}$$

which is unimportant for small relative polarization errors and small $A_{\rm LR}$. However, for high luminosities larger $1\,{\rm ab}^{-1}$ and $\delta\mathcal{P}/\mathcal{P} = 0.25\%$, this contribution can approach the magnitude of the statistical error of the cross section measurement. The corresponding contribution to the uncertainty of the unpolarized cross section is

$$\frac{\delta\sigma_u}{\sigma_u} = \frac{\mathcal{P}_{e^+}\mathcal{P}_{e^-}}{1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-}} \sqrt{\left(\frac{\delta\mathcal{P}_{e^+}}{\mathcal{P}_{e^+}}\right)^2 + \left(\frac{\delta\mathcal{P}_{e^-}}{\mathcal{P}_{e^-}}\right)^2} \,. \tag{11}$$

and increases slightly the uncertainty of the measurement. The knowledge of the contributions (10) and (11) is important for precision measurements with high luminosities and high beam polarizations. Large errors on the polarization measurement could limit the precision to measure unpolarized quantities, or the right-handed and left-handed cross-sections, σ_{LR} and σ_{RL}, correspondingly.

2.3 Left-Right Asymmetry

The left-right asymmetry A_{LR} is an important observable to measure the left- and right-handed coupling of bosons to fermions. It is defined as

$$A_{\mathrm{LR}} = \frac{\sigma_{\mathrm{LR}} - \sigma_{\mathrm{LR}}}{\sigma_{\mathrm{LR}} + \sigma_{\mathrm{LR}}} . \tag{12}$$

Since in realistic beams $|\mathcal{P}| < 1$, A_{LR} is derived from measurements by

$$A_{\mathrm{LR}} = \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}} = \frac{A_{\mathrm{LR}}^{\mathrm{meas}}}{\langle \mathcal{P}_{\mathrm{eff}} \rangle} \tag{13}$$

with the effective polarization, $\mathcal{P}_{\mathrm{eff}}$:

$$\mathcal{P}_{\mathrm{eff}} = \frac{-\mathcal{P}_{\mathrm{e}^-} + \mathcal{P}_{\mathrm{e}^-}}{1 - \mathcal{P}_{\mathrm{e}^-}\mathcal{P}_{\mathrm{e}^+}} \tag{14}$$

The effective polarization is larger than the individual $\mathrm{e}^\pm$ beam polarizations; 80% polarization of the electron beam are increased to an effective polarization of almost 95% using a 60% polarized positron beam. Because of error propagation the uncertainty of the effective polarization is substantially decreased. Assuming that the relative error for polarization measurement of the electron and positron beam is $\delta\mathcal{P}_{\mathrm{e}^+}/\mathcal{P}_{\mathrm{e}^+} = \delta\mathcal{P}_{\mathrm{e}^-}/\mathcal{P}_{\mathrm{e}^-} = \delta\mathcal{P}/\mathcal{P}$, the uncertainty of the effective polarization yields

$$\frac{\delta\mathcal{P}_{\mathrm{eff}}}{\mathcal{P}_{\mathrm{eff}}} = \frac{\delta\mathcal{P}}{\mathcal{P}} \frac{\sqrt{\left(1 - \mathcal{P}_{\mathrm{e}^+}^2\right)^2 \mathcal{P}_{\mathrm{e}^-}^2 + \left(1 - \mathcal{P}_{\mathrm{e}^-}^2\right)^2 \mathcal{P}_{\mathrm{e}^+}^2}}{\left(\mathcal{P}_{\mathrm{e}^+} + \mathcal{P}_{\mathrm{e}^-}\right)\left(1 + \mathcal{P}_{\mathrm{e}^+}\mathcal{P}_{\mathrm{e}^-}\right)} . \tag{15}$$

Assuming 80% (90%) electron polarization, and an uncertainty of the polarization measurement of $\delta\mathcal{P}/\mathcal{P} = 0.25\%$[5], the error of the effective polarization is reduced by a factor 3.7 if the positron beam is 60% polarized. This fact is important for precise A_{LR} measurements with large integrated luminosity. In this case the error contribution due to the polarization uncertainty could dominate the total error, δA_{LR}, given by

$$\delta A_{\mathrm{LR}} = \sqrt{\frac{1 - \mathcal{P}_{\mathrm{eff}}^2 A_{\mathrm{LR}}}{\mathcal{P}_{\mathrm{eff}} N} + A_{\mathrm{LR}}^2 \left(\frac{\delta\mathcal{P}_{\mathrm{eff}}}{\mathcal{P}_{\mathrm{eff}}}\right)^2} . \tag{16}$$

2.4 u,t-Channel Processes

In sections 2.1–2.3 some basic advantages are discussed for s-channel processes. Without going into detail it should be mentioned that the search for new phenomena benefits from polarized positrons also if u- and t-channel processes are considered. In u- and t-channel processes the helicity of the particle's final state is directly coupled to the helicity of the initial state fermion, it does not depend on the helicity of the second incoming beam particle. This gives a direct access to the helicity of the exchanged particle and allows an enhancement or suppression of specific processes. An example is the production of single W bosons, $e^+e^- \rightarrow W\, e\, \nu$, which is one basic process to study CP violation. For more details and examples, in particular the sensitivity to supersymmetric phenomena, the interested reader is strongly encouraged to consult reference [1] .

2.5 W^+W^- Pair Processes

The precise measurement of the Three-Gauge-Boson-Coupling (TGC) in the process $e^+e^- \rightarrow Z, \gamma \rightarrow W^+W^-$ allows a test of the weak gauge structure as described by the SM, and it is very sensitive to new physics scenarios. Since the SM defines the TGC, deviations of precision measurements from the SM prediction are hints to new phenomena. To select this process with high efficiency, the contribution of the neutrino exchange in the t-channel, $e^+e^- \rightarrow \nu \rightarrow W^+W^-$ (see figure 4), is suppressed using a polarized electron beam. A further improvement is possible with polarized positrons in addition to polarized electrons.

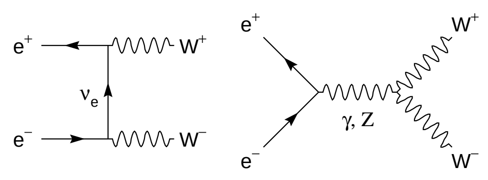

Figure 4: Feynman diagrams for the process $^+e^- \rightarrow W^+W^-$. Only the right diagram is important to measure TGC.

2.6 Higgs Factory

The Higgs boson is a scalar particle which can be produced in e^+e^- annihilation by the Higgsstrahlung or boson fusion (see figure 5). The dominating process is determined by the Higgs mass which is not yet known. In case of a light Higgs boson as suggested by the electroweak precision measurements at LEP and SLD [2], the Higgsstrahlung is dominating. With polarized positrons the Higgs production can be enhanced by a factor $(1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-})$. If the Higgs boson is heavy, it is produced via WW fusion, $e^+e^- \to \nu_e\bar{\nu}_e H$. This process can be enhanced (or suppressed) by the factor $(1 + \mathcal{P}_{e^+})(1 - \mathcal{P}_{e^-})$ choosing the proper sign of the $e^\pm$ polarizations. For $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (-80\%, +60\%)$, the WW fusion process is enhanced by a factor of 2.88 in comparison to unpolarized beams.

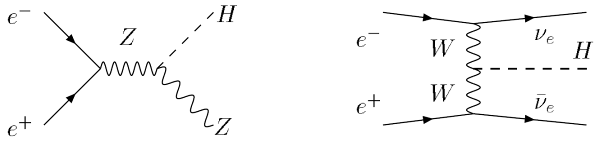

Figure 5: Feynman diagrams for Higgs production processes: Higgsstrahlung process (left) and WW boson fusion (right).

2.7 GigaZ Option

Electroweak precision measurements at the Z resonance were performed by the experiments ALEPH, DELPHI, L3 and OPAL at LEP and SLD at SLC. Taking into account the results for the top quark mass and the W boson mass, the SM has been confirmed at the one-loop level of quantum corrections. The results of LEP and SLD are in good agreement, however, the A_{LR} measurement at SLD results in values for the weak mixing angle or correspondingly for the Z boson couplings to fermions that are slightly different from that determined by the LEP experiments. Running at the Z resonance again by utilizing polarized $e^\pm$ beams and a much higher luminosity would substantially improve the accuracy of electroweak measurements. This option is called GigaZ since the luminosity available at the ILC allows to produce and record about 10^9 Z bosons within few months of running. High-luminosity measurements at the Z resonance combined with updated precise results for the W boson mass, the top-quark mass, and hopefully the Higgs boson mass allow excellent consistency tests of the SM and provide a high sensitivity to models beyond the SM. This would also to test whether the slightly differing values for observables measured at LEP and SLD is a fluctuation as assumed so far, or whether it is due to a certain yet unknown phenomenon. At GigaZ a relative precision of less than 5×10^{-5} can be achieved for the effective weak mixing angle – more than 10 times better than the values achieved with LEP/SLD measurements. This allows precise conclusions on new physics models, e.g. supersymmetry. The GigaZ option requires very precise measurements of energy, luminosity and beam polarization. If both beams are polarized, the Blondel scheme [6] can be applied to determine the beam polarization and A_{LR} simultaneously with highest precision [7].

2.8 Transversely Polarized Beams

Finally it must be mentioned that also collision of transversely polarized beams are interesting. They allow access to helicity correlations, CP violating effects and new phenomena like extra dimension [8]. The contribution to the differential cross section due to transverse polarization is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \sim \mathcal{P}_{\perp}^{\mathrm{e}^+} \mathcal{P}_{\perp}^{\mathrm{e}^-} \sin\theta \cos 2\phi\,, \tag{17}$$

which is zero if one of the colliding beams is unpolarized. New physics phenomena yield additional terms resulting in substantially modified differential cross sections. For example, extra dimensions differential cross sections measured for transversely as well as longitudinally polarized beams with angular distributions typical for special classes of models. Hence, physics runs with transversely polarized beams will help to distinguish between models and to resolve ambiguities.

3 Requirements for Physics

Polarized positron and polarized electron beams offer the best flexibility and an improved sensitivity to fulfill the physics programme for future high energy lepton colliders. Unfortunately, it is quite difficult to produce an intense polarized positron beam for a high energy linear collider. The ILC baseline design proposes to generate the positrons using photons created in an undulator passed by a high energy electron beam [9]. Since the photon yield in a helical undulator is higher up to a factor 2 than in a planar undulator, the ILC positron source design is based on a helical undulator. The photons generated in a helical undulator are circularly polarized. If they hit the positron production target, longitudinally polarized electron-positron pairs are created. The scheme has been tested successfully in the proof-of-principle experiment E-166 at SLAC [10].

Using a helical undulator, the ILC will provide a polarized positron beam. The degree of polarization is determined by the parameters of the undulator and the source design. The opening angle of the photon beam decreases with the electron energy, $\propto 1/\gamma$. The polarization of the photons is distributed such that a collimation of the photon beam increases its average polarization. The loss of intensity has to be compensated using a longer undulator. For more details see the references [11, 12] .

In order to exploit the positron and electron beam polarization for physics measurements, the degree of polarization must be kept up to the interaction point. Therefore spin rotation systems upstream the damping ring rotate the particle spins from the longitudinal to the vertical direction, parallel (or anti-parallel) to the magnetic field in the damping ring. Downstream the turnaround the spins are rotated back to the longitudinal direction so that the beams have the desired polarization at the IP.

The electron and positron beam polarization is measured at the IP using Compton polarimeters. To meet the high precision requirements, the relative uncertainty of the polarization measurement must be at the level of (few) per-mille.

One important issue must be mentioned: The direction of the helical undulator winding determines the orientation of the photon polarization and therefore the sign of the positron polarization. Switching to the opposite orientation of positron beam polarization requires an additional spin-flip equipment. This point is discussed in the subsection 3.3. It should be remarked that in a polarized positron source based on Compton back-scattering the helicity reversal can be easily realized by switching the polarization of the laser light.

3.1 Polarimetry at the Interaction Point

The beam polarization at the interaction point is measured using Compton polarimeters. In order to determine the luminosity-weighted longitudinal polarization at the interaction point (IP) at the ILC, one polarimeter is located at the beginning of the Beam Delivery System upstream the IP, the other in the extraction line downstream the IP. The two polarimeters are highly complementary. The upstream polarimeter has a clean environment and a much higher counting rate; the fast polarization measurement is important to detect correlations. The downstream polarimeter measures the polarization of the outgoing beam. Since the background in the downstream polarimeter is high and the beam is disrupting after the IP, the counting rate is substantially smaller than in the upstream polarimeter. But the downstream polarimeter has access to depolarization effects: Due to the small bunch sizes high electromagnetic fields act between the particles in the crossing bunches and induce the radiation of hard photons. The resulting depolarization has to be taken into account to attain the required precision of the polarization measurement. The combination of both polarimeters allows the determination of the luminosity-weighted polarization; cross checks between both polarimeters are possible. Measurements without collisions can be used to control the spin transport through the Beam Delivery System. However, due to the large beam disruption at CLIC the downstream polarimeter will not work with the required precision.

Present studies and test measurements show that at the ILC a precision of $\delta\mathcal{P}/\mathcal{P} \approx 0.25\%$ can be achieved [5] for the longitudinal polarization. For comparison: the precision for the polarization measurement reached with the Compton polarimeter at the SLD experiment was $\delta\mathcal{P}/\mathcal{P} = 0.5\%$. The measurement of the transverse polarization at the IP is under study.

3.2 Positron Polarimetry at the Source

Since the production of an intense positron beam needs some effort the degree of polarization should also be measurable at the positron source. At the electron source a Mott polarimeter is used. Due to the design and the parameters of a polarized positron source it is not recommended to apply a Mott polarimeter. Instead, a Bhabha polarimeter located at beam energies of few hundred MeV is a promising option [13].

3.3 Frequency of Helicity Reversal

As discussed in section 2, a substantial enhancement of the effective luminosity is possible with polarized beams. But the increase by the factor $(1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+})$ is only possible in case of an efficient pairing of initial states $(+-)$, $(-+)$. This requires the same helicity reversal frequencies for the electron and the positron beam. The polarization of the electron beam can be flipped easily by reversing the polarity of the laser beam which hits the photocathode. A fast and random flipping between the beam polarization orientations reduces systematic uncertainties substantially (see also reference [2]). The orientation of the positron beam polarization can be reversed using a spin rotator. However, it is impossible to switch the high magnetic field in the spin rotator within very short time, e.g. from train to train as possible for the electron beam. There is no gain for the effective luminosity if the helicity of the positrons is reversed from run to run (or even less often) and the the helicity of the electrons train-by-train. Further, to control systematic effects, a very high long-term stability is necessary. A possible solution of this problem would be to kick the positron beam to parallel spin rotation lines with opposite magnetic fields, similar as suggested in reference [14] .

The precision measurements require almost identical intensities and polarizations for the left- and right-handed oriented beams. The measured left-right asymmetry is related to the left-right asymmetry by

$$A_{\rm LR} = \frac{A_{\rm LR}^{\rm meas}}{\langle \mathcal{P}_{\rm eff} \rangle} \, . \tag{18}$$

If the luminosities and degrees of polarization are identical for σ_{-+} and σ_{+-}, one gets

$$A_{\rm LR} = \frac{N_{-+} - N_{+-}}{N_{-+} - N_{+-}} \frac{1}{\langle \mathcal{P}_{\rm eff} \rangle} \, . \tag{19}$$

Also for fast helicity reversal small differences in luminosity and polarization occur between the running modes $(+-)$ and $(-+)$. They have to be taken into account,

$$A_{\rm LR} = \frac{A_{\rm LR}^{\rm meas}}{\langle \mathcal{P}_{\rm eff} \rangle} + \frac{1}{\langle \mathcal{P}_{\rm eff} \rangle} \left[(A_{\rm LR}^{\rm meas})^2 A_{\mathcal{P}} + \langle \mathcal{P}_{\rm eff} \rangle \Delta_{\mathcal{P}} + A_{\mathcal{L}} + \ldots \right] \, , \tag{20}$$

where $A_{\mathcal{L}}$ and $A_{\mathcal{P}}$ are the left-right asymmetries of the integrated luminosity and of the beam polarization; the asymmetries of residual background, the center-of-mass energy, detector acceptance and efficiency are not shown in equation (20). The contribution $\Delta_{\mathcal{P}}$ depends on $\Delta\mathcal{P}_{\rm e^+}\mathcal{P}_{e^-} + \Delta\mathcal{P}_{\rm e^-}\mathcal{P}_{e^+}$ with $\Delta\mathcal{P}_{\rm e}$ as difference between + and − sign of the beam polarization. A slower helicity reversal for the positron than for the electron beam yields different luminosities for the running modes $(+-)$ and $(-+)$, and also the degree of polarization could vary. The resulting corrections in equation (20) could be large. The corrections to $A_{\rm LR}$, i.e. $A_{\mathcal{L}}$, $A_{\mathcal{P}}$ and $\Delta_{\mathcal{P}}$, must be determined and should be as small as possible. In particular, the uncertainty of $A_{\mathcal{L}}$ and $\Delta_{\mathcal{P}}$ should be at the per-mille level to achieve the desired high precision for $A_{\rm LR}$.

Detailed studies are ongoing to evaluate the influence of parallel spin rotation lines on the final physics performance with polarized beams, and to find alternative solutions with fast and flexible helicity reversal at the undulator-based positron source.

4 Summary

Precision measurements of SM physics and phenomena beyond the SM can be performed at future linear e^+e^- colliders. They will extend and complement the achievements of the LHC. The best conditions are provided if high luminosity, a wide energy range and polarized beams are available. In particular, the flexible choice of initial state helicities is desired to reveal unexpected phenomena and their nature.

The polarization of both beams, electrons and positrons, affords substantial advantages: The occurrence of desired processes can be enhanced. The effective luminosity for s-channel processes with exchange of spin-1 particles can be increased by the factor $(1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+})$ if the luminosity is equally distributed to running modes with the initial state helicities $(+-)$ and $(-+)$. The uncertainty of the effective polarization is reduced which is important for precision measurements of left-right asymmetries. Among many arguments to have polarized positrons it should be emphasized: If signals from physics beyond the SM are found, a much better distinction between models is possible than with only one polarized beam. For the GigaZ option the electron and the positron beam must be polarized to achieve the required precision for the $A_{\rm LR}$ and polarization measurement. In order to benefit from these advantages, it must be possible to reverse the helicity of positrons as frequent as the helicity of electrons. Hence, for a positron source based on a helical undulator an additional facility is necessary to realize the fast spin flip for the positrons.

Finally, it should be emphasized that a positron source based on a helical undulator will provide a polarized positron beam; the degree of polarization depends strongly on the undulator parameters and the energy of the electrons passing through. One may ask what minimum degree of positron polarization is necessary. Recent ILC studies [1, 15] show that for $\mathcal{P}_{e^+} > 30\%$ the physics analyses clearly benefit from polarized electron and positron beams. Of course, a high degree of positron polarization is desired and can be realized by photon beam collimation for the undulator-based source (see also reference [16]). Thus, an excellent feasibility is provided to perform the high energy linear collider physics programme at the precision frontier.

Acknowledgments

I would like to thank my collaborators, in particular Gudrid Moortgat-Pick and Jenny List for discussions about physics with polarized positron beams. I am grateful to Prof. Jie Gao and his local team for organizing this successful POSIPOL 2011 Workshop. I enjoyed the interesting sessions, the fruitful discussions, the social program and the stay in Beijing.

References

[1] G. Moortgat-Pick, *et al.*, Phys. Rept. **460**, 131 (2008) [hep-ph/0507011].

[2] ALEPH, DELPHI, L3 and OPAL and SLD and LEP Electroweak Working Group and SLD Electroweak Group and SLD Heavy Flavour Group Collaborations, Phys. Rept. **427**, 257 (2006) [hep-ex/0509008].

[3] J. Brau, (Ed.) *et al.* [ILC Collaboration], arXiv:0712.1950 [physics.acc-ph];
G. Aarons *et al.* [ILC Collaboration], arXiv:0709.1893 [hep-ph];
T. Behnke, (Ed.) *et al.* [ILC Collaboration], arXiv:0712.2356 [physics.ins-det].

[4] R.W. Assmann *et al.*, CERN-2000-008; E. Accomando *et al.*, hep-ph/0412251;
http://project-clic-cdr.web.cern.ch/project-CLIC-CDR/

[5] S. Boogert, M. Hildreth, D. Käfer, J. List, K. Mönig, K. C. Moffeit, G. Moortgat-Pick and S. Riemann *et al.*, JINST **4**, P10015 (2009) [arXiv:0904.0122 [physics.ins-det]].

[6] A. Blondel, Phys. Lett. B **202**, 145 (1988) [Erratum-ibid. **208**, 531 (1988)].

[7] J. Erler J *et al.*, Phys. Lett. B **486**, 125 (2000).

[8] T. G. Rizzo, [arXiv:1011.2185 [hep-ph]];
T. G. Rizzo, JHEP **0308**, 051 (2003) [hep-ph/0306283];
T. G. Rizzo, JHEP **0302**, 008 (2003) [hep-ph/0211374].

[9] V.E. Balakin and A.A. Mikhailichenko, Budker Institute of Nuclear Physics Report No. BINP 79-85, 1979; R.C. Wingerson, Phys. Rev. Lett. **6**, 446 (1961).

[10] G. Alexander *et al.*, Nucl. Instrum. Meth. A **610**, 451 (2009) [arXiv:0905.3066 [physics.ins-det]]; G. Alexander *et al.*, Phys. Rev. Lett. **100**, 210801 (2008).

[11] A. Ushakov *et al.*, these proceedings, arXiv:1202.0752 [physics.acc-ph].

[12] W. Gai, these proceedings.

[13] G. Alexander *et al.*, EUROTeV-Report-2008-091.

[14] K. Moffeit *et al.*, SLAC-TN-05-045.

[15] M. Berggren, arXiv:1007.3019 [hep-ex].

[16] F. Staufenbiel *et al.*, these proceedings, arXiv:1202.5987 [physics.acc-ph].