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The use of Positron Polarization for precision Measurements

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Abstract

For most physics topics at e^+e^--colliders the possibility to polarize one beam, normally the electrons, is sufficient. However, often the precision of the analyses is limited by the uncertainty of the polarization measurement. In this note is is shown how the accuracy of the polarization measurement can be improved, if both beams can be polarized.

1 Introduction

It is without doubt that beam polarization at a linear collider is extremely useful in many respects. Processes with lepton-W couplings require the electrons to be left handed. Contrary to the γ, the Z couples differently to left and right handed fermions so that beam polarization can be used to disentangle Z- and γ-contributions to specific processes like W-pair production. In models with extra Z$'$, polarization helps to measure the couplings of the Z$'$ to fermions and in supersymmetric models polarization can be used to measure mixing angles.

In most cases the availability of electron polarization is in principle sufficient so that the need for positron polarization is often debated. However, optimistically electron polarization can be measured with an accuracy of 0.5% as currently done at SLD [1] and depolarization effects in the interaction can be of the same size. For a high luminosity collider like TESLA this can strongly limit the use of beam polarization. For instance in the measurement of triple gauge couplings of the W the uncertainty due to a 0.5% error on the beam polarization is of similar size as the expected statistical error.

At TESLA electrons should be polarizable to about 80% using the same technology as at SLD. However, if instead of a wiggler a helical undulator is used in the positron source, also positron polarization of about 60% seems possible. In the following it will be shown how positron polarization can improve in several ways the precision of the polarization measurement.

2 Polarimeter measurements

If electron and positron polarization are available, in most cases they can be combined to an effective polarization. As an example in the analysis of the left-right asymmetry for s-channel vector particle exchange the effective polarization is

$$\mathcal{P}_{\rm eff} = \frac{\mathcal{P}_{e^+} + \mathcal{P}_{e^-}}{1 + \mathcal{P}_{e^+}\mathcal{P}_{e^-}}$$

with $\mathcal{P}_{e^-}$ ($\mathcal{P}_{e^+}$) being the electron (positron) polarization. Assuming that e^+ and e^- polarization can be measured with the same relative accuracy, x, the relative error on the effective polarization becomes

$$\frac{\Delta\mathcal{P}_{\rm eff}}{\mathcal{P}_{\rm eff}} = x\frac{\sqrt{\left(1-\mathcal{P}_{e^+}^2\right)^2\mathcal{P}_{e^-}^2 + \left(1-\mathcal{P}_{e^-}^2\right)^2\mathcal{P}_{e^+}^2}}{(\mathcal{P}_{e^+} + \mathcal{P}_{e^-})(1 + \mathcal{P}_{e^+}\mathcal{P}_{e^-})}$$

If a relative error, y, is fully correlated between the two beam polarizations, like depolarizing effects from beamstrahlung or errors from the setup of the two identical polarimeters the error becomes

$$\frac{\Delta\mathcal{P}_{\rm eff}}{\mathcal{P}_{\rm eff}} = y\frac{1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-}}{1 + \mathcal{P}_{e^+}\mathcal{P}_{e^-}}$$

Figure 1 shows the error reduction as a function of the positron polarization for $\mathcal{P}_{e^-} = 80\%$. For $\mathcal{P}_{e^+} = 60\%$ one gains a factor four for independent errors and a factor three for correlated errors.

If only electron polarization is available the polarization enters linearly in the cross section formulae. It is thus sufficient to know the average polarization. If both beams

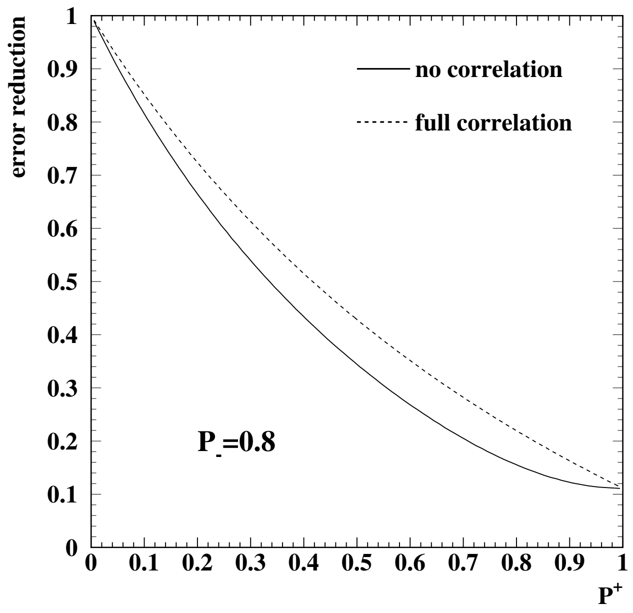

Figure 1: Reduction of the error on the effective polarization due to error propagation for zero and full correlation between the electron and positron polarization measurements.

are polarized the product of the polarizations enters as well so that one needs to track correlated time variations using polarimeters. However if a statistical precision of 1% per bunch crossing can be reached, as it seems possible [2], this should be no problem.

3 The Blondel scheme

If a process $e^+e^- \to f\bar{f}$ is mediated by pure s-channel vector-particle exchange the cross section for the different polarization states can be written as

$$\sigma = \sigma_u \left[1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\rm LR}(\mathcal{P}_{e^+} - \mathcal{P}_{e^-})\right], \tag{1}$$

where $\mathcal{P}_{e^+}$ and $\mathcal{P}_{e^-}$ are the longitudinal polarizations of the positrons and electrons measured in the direction of the particle's velocity. σ_u is the unpolarized cross section and $A_{\rm LR}$ the left-right asymmetry. If the signs of the two polarizations can be switched independently four cross sections can be measured for four unknowns. From these cross sections the polarizations can be obtained, if $A_{\rm LR} \neq 0$ [3]:

$$\mathcal{P}_{e^\pm} = \sqrt{\frac{(\sigma_{+-} + \sigma_{-+} - \sigma_{++} - \sigma_{--})(\mp\sigma_{+-} \pm \sigma_{-+} - \sigma_{++} + \sigma_{--})}{(\sigma_{+-} + \sigma_{-+} + \sigma_{++} + \sigma_{--})(\mp\sigma_{+-} \pm \sigma_{-+} + \sigma_{++} - \sigma_{--})}}$$

where in σ_{ij} i denotes the sign of the positron- and j the sign of the electron-polarization. This method has some clear advantages. There are no intrinsic limitations by polarimeter systematics and the polarization is measured for the colliding particles, so some effects like the depolarization due to beamstrahlung are accounted for and the measurement is automatically luminosity weighted. However, since cross section products are involved also this measurement is affected by correlation effects. As a drawback of this method some luminosity needs to be spent with same helicities for both beams which is not very interesting for most physics processes.

To measure the polarization with the Blondel scheme two processes have been considered,

- $e^+e^- \to f\bar{f}$ with $\sqrt{s'} \approx \sqrt{s}$;
- radiative return events ($e^+e^- \to Z\gamma \to f\bar{f}\gamma$).

The cross section and left right asymmetry for the two processes at $\sqrt{s} = 350$ and $500\,\mathrm{GeV}$ is given in table 1. Both cross sections scale approximately with $1/s$. The high energy

$\sqrt{s}$	σ_{RR}	$A_{\mathrm{LR}}(RR)$	σ_{HE}	$A_{\mathrm{LR}}(HE)$
340 GeV	17 pb	0.19	5 pb	0.50
500 GeV	7 pb	0.19	2 pb	0.50

Table 1: Cross section and asymmetry for high energy and radiative return $f\bar{f}$ events.

events can be measured with high efficiency and almost no background. However the analysis relies on the assumption of s-channel vector-exchange, so for analyses like the search for Kaluza-Klein towers from extra dimensions or R-parity violating sneutrinos the results cannot be used.

On the contrary radiative return events contain on-shell Z-decays which are well understood from LEP1 and SLD. In about 90% of the events the high-energy photon is lost in the beampipe. These events can be reconstructed kinematically and most backgrounds can be rejected. However, at TESLA energies the cross section for the fusion process $e^+e^- \to Ze^+e^-$ is of the same order as the signal. In those events one electron has almost the beam energy and stays at low angle while the other is extremely soft and also often lost in the beampipe resulting in a $\sim 30\%$ background of Zee events in the radiative return sample. The only way Zee events can be rejected is to ask for a photon seen above 7° where photons and electrons can be separated by the tracking detectors. Applying some additional event selection cuts on the hadronic mass and the balance of the event about 9% of the radiative return events are accepted with only a small Zee background. However in these events the slow electron is seen in the detector, so that they can easily be rejected by vetoing on an isolated electron.

Assuming $\mathcal{P}_{e^-} = 80\%$, $\mathcal{P}_{e^+} = 60\%$, an integrated luminosity of $500\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 340\,\mathrm{GeV}$ and 50% or 10% of the luminosity spent with both beam polarizations with the same sign table 2 shows the obtainable errors on the two polarizations and their correlation. Due to the scaling of the cross sections the errors are about a factor $\sqrt{2}$ larger at 500 GeV. It should be noted that the relative errors scale approximately with the product of the polarizations.

Radiative corrections to the form of equation (1) have been checked with the KK MonteCarlo [4]. For the high energy events and for the radiative return events with a seen photon they are negligible. For the radiative return events where the photon is lost in the beampipe, which are not used in this analysis, the corrections are on the percent level.

Because of the high losses in the selection of the radiative return events the errors on the single polarizations seem rather large. However the large negative correlation reduces

	$\mathcal{L}_{\pm\pm}/\mathcal{L} = 0.5$			$\mathcal{L}_{\pm\pm}/\mathcal{L} = 0.1$		
	HE	rr	WW	HE	rr	WW
$\Delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-}$ [%]	0.10	0.51	0.07	0.21	1.11	0.11
$\Delta\mathcal{P}_{e^+}/\mathcal{P}_{e^+}$ [%]	0.12	0.53	0.11	0.15	1.13	0.21
corr	-0.49	-0.91	0	-0.56	-0.93	-0.52

Table 2: Relative polarization error using the Blondel scheme for $\sqrt{s} = 340\,\mathrm{GeV}$, $\mathcal{L} = 500\,\mathrm{fb}^{-1}$, $\mathcal{P}_{\mathrm{e}^-} = 0.8$, $\mathcal{P}_{\mathrm{e}^+} = 0.6$ (HE = High energy events, rr = radiative return, WW = W-pair production).

the error substantially for the effective polarizations needed in the analysis. Table 3 compares the errors on the effective polarizations for the setups shown in table 2 and for polarimeter measurements assuming 0 or 50% correlation between the two polarimeters.

The effective polarizations considered are:

- $\mathcal{P}_{\mathrm{eff}} = \frac{\mathcal{P}_{e^-}+\mathcal{P}_{e^+}}{1+\mathcal{P}_{e^-}\mathcal{P}_{e^+}}$, relevant for A_{LR} with s-channel vector exchange;
- $\mathcal{P}_{e^-}\mathcal{P}_{e^+}$, relevant for the cross section suppression/enhancement with s-channel vector exchange;
- $\mathcal{P}_{e^-} + \mathcal{P}_{e^+} - \mathcal{P}_{e^-}\mathcal{P}_{e^+}$, relevant for the cross section suppression/enhancement for t-channel W-pair production.

Due to the high anticorrelation even the results from the radiative return analysis with one tenth of the luminosity at the low cross sections are competitive to polarimetry with an optimistic 0.5% error.

	value	Rel. error [%]							
		$\mathcal{L}_{\pm\pm}/\mathcal{L} = 0.5$			$\mathcal{L}_{\pm\pm}/\mathcal{L} = 0.1$			Polarimeter	
		HE	rr	WW	HE	rr	WW	$\rho=0$	$\rho=0.5$
$(\mathcal{P}_{e^-}+\mathcal{P}_{e^+})/(1+\mathcal{P}_{e^-}\mathcal{P}_{e^+})$	0.95	0.02	0.08	0.02	0.05	0.17	0.02	0.13	0.16
$\mathcal{P}_{e^-}\mathcal{P}_{e^+}$	0.48	0.11	0.22	0.13	0.18	0.42	0.18	0.71	0.87
$\mathcal{P}_{e^-}+\mathcal{P}_{e^+}-\mathcal{P}_{e^-}\mathcal{P}_{e^+}$	0.92	0.03	0.12	0.03	0.06	0.25	0.03	0.19	0.21

Table 3: Relative error on the effective polarizations for the discussed setups and $\sqrt{s} = 340\,\mathrm{GeV}$, $\mathcal{L} = 500\,\mathrm{fb}^{-1}$, $\mathcal{P}_{\mathrm{e}^-} = 0.8$, $\mathcal{P}_{\mathrm{e}^+} = 0.6$. For the polarimeter a total error of 0.5% has been assumed. (HE = High energy events, rr = radiative return, WW = W-pair production).

4 Polarization measurements from W production

W-pair production proceeds via s-channel Z- or γ-exchange and via t-channel neutrino exchange (see Fig. 2). Since only left handed electrons and right handed positrons couple to W-bosons the t-channel production can be completely switched off by choosing the wrong electron or positron polarization. The large forward peak in W-pair production is completely dominated by the t-channel exchange, so that the left-right asymmetry in this region is essentially one independent of possible anomalous gauge couplings. This feature makes it possible to measure polarization from the data even if only one beam is polarized.

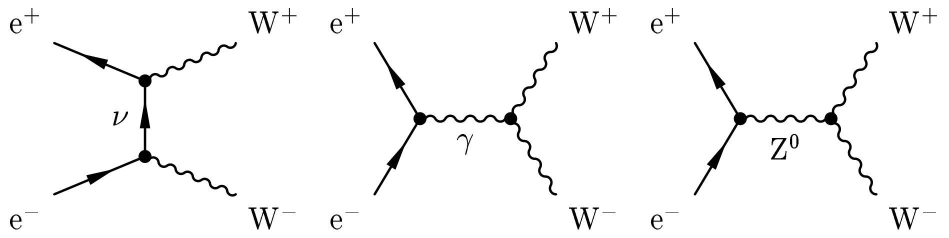

Figure 2: Feynman graphs for the production of W-pairs in e^+e^--annihilation.

To estimate the possible precision of a polarization measurement using W-pair production a simple study has been done with analytical formulae for stable W production [5]. Only mixed decays have been considered with a cut of $\Theta_W > 11^\circ$. In the analysis the W-production angle and the polar decay angles with the usual ambiguity for hadronically decaying Ws have been used. The polarization has been fitted simultaneously with the anomalous couplings and a free normalization. With $\mathcal{P}_{e^-} = 0.8$, $\mathcal{L} = 500\,\mathrm{fb}^{-1}$ and $\sqrt{s} = 350\,\mathrm{GeV}$ a polarization error of $\Delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-} = 0.1\%$ has been achieved with negligible correlations with the couplings.

If the absolute values of the two helicity states are not the same the measured polarization is modified, however the effect on the couplings is very small. With $\mathcal{P}_{e^-} = \pm|\mathcal{P}_{e^-}| + \delta\mathcal{P}_{e^-}$ the change in the measured polarization is $\Delta\mathcal{P}_{e^-}^{(\mathrm{meas})} = 0.8\delta\mathcal{P}_{e^-}$, while for $\delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-} = 1\%$ the change in the couplings is about one tenth of a standard deviation.

Similarly the electron and positron polarizations can be measured, if some luminosity with all four helicity combinations is available. With equal luminosity at all combinations and $\mathcal{P}_{e^-} = 0.8$, $\mathcal{P}_{e^+} = 0.6$ one gets $\Delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-} \approx 0.1\%$ and $\Delta\mathcal{P}_{e^+}/\mathcal{P}_{e^+} \approx 0.2\%$ and negligible correlations between the polarizations and between the polarization and the couplings. If only 10% of the luminosity is spent on the equal helicities the polarization errors increase by roughly a factor two with -50% correlation. The results for W-pair production are also listed in tables 2 and 3. Since the W-pair production study was done with Born level stable Ws only, the statistical precision is probably trustable within about a factor two. It has, however, been shown, that radiative corrections in the interesting region are below one per mille [6], so that the method is theoretically safe. The energy scaling of the precision is identical to the one in fermion pair production.

In principle also single W production can be used to measure the beam polarization. Single W^- production is sensitive to the electron polarization while single W^+ production is sensitive to positron polarization. However no quantitative studies have been made for this process.

5 Conclusions

If only electron polarization is available it can be measured in a model independent way only with polarimeters, which might be limited to about 0.5%. If one assumes that W-pair production is described by t-channel neutrino exchange plus the usual effective Lagrangian for the triple gauge couplings, this process might be used to measure the polarization to the per mille level.

If also positron polarization is available one gains immediately a factor three to four in the polarimeter measurement due to error propagation. In addition the polarization can be measured with variants of the Blondel scheme in different processes. These schemes always involve some physics assumptions, so that not all methods proposed here are applicable to all analyses. On the other hand, if in a specific analysis the physics information is in principle contained already in one beam polarization the additional information given by the four different helicity combinations can be used to measure the polarization within the analysis as outlined for specific examples in this note. These schemes offer the possibility to measure the polarization-combination, needed in the analysis to better than a per mille.

However all these methods still require polarimeters for relative measurements. In the Blondel scheme like analyses one always has to make the assumption that the absolute value of polarization stays constant and only the sign flips. The difference between the absolute values has thus to be measured by polarimetry. In addition the Blondel scheme itself as well as the effective polarizations needed involve products of the polarizations. That also makes it necessary to track time dependencies of the polarizations with polarimeters.

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References

[1] SLD Collaboration, K. Abe et al., Phys. Rev. Lett. **84** (2000) 5945.

[2] P. Schuler, *Polarimeter studies for TESLA*, Talk at the International Workshop on Linear Colliders, Fermilab 24 - 28 October 2000, to appear in the proceedings.

[3] A. Blondel, Phys. Lett. **B202** (1988) 145.

[4] S. Jadach et al. Comp. Phys. Comm. **130** (2000) 260.

[5] M. Bilenky et al., Nucl. Phys. **B409** (1993) 22.

[6] J. Fleischer et al., Z. Phys. **C42** (1989) 408; Phys Rev **D49** (1994) 2174; Comp. Phys. Comm. **85** (1995) 29;
F. Jegerlehner, private communication.