Polarisation Measurement using Annihilation Data at a Linear Collider

Klaus Mönig*
DESY-Zeuthen

The beam polarisation at e^+e^--colliders may be measured with polarimeters at the 0.25% level. For precision analyses of high cross section processes this may not be sufficient. In this note it will be shown how the beam polarisation can be obtained with better precision using e^+e^--annihilation data.

1. Introduction

It is without doubt that beam polarisation at a linear collider is extremely useful in many respects. In most cases the availability of electron polarisation is in principle sufficient so that the need for positron polarisation is often debated. However, optimistically electron polarisation can be measured with an accuracy of around 0.25% which is a factor of two better than currently done at SLD [1] and depolarisation effects in the interaction can be of the same size. For a high luminosity collider this can strongly limit the use of beam polarisation. For instance in the measurement of triple gauge couplings of the W the uncertainty due to a 0.25% error on the beam polarisation is of similar size as the expected statistical error.

At TESLA electrons should be polarisable 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 polarisation of about 60% seems possible. In the following it will be shown how the beam polarisation can be measured with annihilation data. These methods often require positron polarisation. Due to a favourable error propagation in most cases positron polarisation reduces the error for the effective polarisation relevant in the analysis also when the polarisation is measured with polarimeters.

2. Polarimeter measurements

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

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

As an example for an electron polarisation of 80% and a positron polarisation of 60% the relative error on $\mathcal{P}_{\mathrm{eff}}$ is a factor four smaller than the polarimeter error if the two polarisation measurements are independent. Even if the two polarimeter errors are fully correlated the gain is still a factor three.

If only electron polarisation is available the polarisation enters linearly in the cross section formulae. It is thus sufficient to know the average polarisation. If both beams are polarised the product of the polarisations 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.

*Klaus.Moenig@desy.de

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 polarisation states can be written as $\sigma = \sigma_u \left[1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{LR}(\mathcal{P}_{e^+} - \mathcal{P}_{e^-})\right]$, where $\mathcal{P}_{e^+}$ and $\mathcal{P}_{e^-}$ are the longitudinal polarisations of the positrons and electrons measured in the direction of the particle's velocity. σ_u is the unpolarised cross section and A_{LR} the left-right asymmetry. If the signs of the two polarisations can be switched independently four cross sections can be measured for four unknowns. From these cross sections the polarisations can be obtained, if $A_{LR} \neq 0$ [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-polarisation. This method has some clear advantages. There are no intrinsic limitations by polarimeter systematics and the polarisation is measured for the colliding particles, so some effects like the depolarisation 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 polarisation with the Blondel scheme two processes have been considered, $e^+e^- \to f\bar{f}$ with $\sqrt{s'} \approx \sqrt{s}$ and radiative return events ($e^+e^- \to Z\gamma \to f\bar{f}\gamma$). The cross section for the high energy $f\bar{f}$-production is 5 pb (2 pb) at $\sqrt{s} = 350\,(500\,\mathrm{GeV})$ and 17 pb (7 pb) for the radiative return. The left-right asymmetry is around 50% for the high energy and 20% for the radiative return, almost independent of energy.

The high energy 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 polarisations with the same sign the upper part of Table I shows the obtainable errors on the two polarisations 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 polarisations.

Radiative corrections to the polarisation measurement have been checked with the KK Monte-Carlo [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 polarisations seem rather large. However the large negative correlation reduces the error substantially for the effective polarisations needed in the analysis. The lower part of Table I compares the errors on the effective polarisations for the measurements with events and with polarimeters assuming 0 or 50% correlation between the two polarimeters.

The effective polarisations 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 and $\mathcal{P}_{e^-} + \mathcal{P}_{e^+} - \mathcal{P}_{e^-}\mathcal{P}_{e^+}$, relevant for the cross section suppression/enhancement for t-channel W-pair production. Due to the high anti-correlation even the results from the radiative return analysis with one tenth of the luminosity at the low cross sections are interesting.

Table I Relative errors using events and polarimeters for the two beam polarisations and the different effective polarisations ($\sqrt{s} = 340\text{GeV}$, $\mathcal{L} = 500\,\text{fb}^{-1}$, HE = High energy events, rr = radiative return, WW = W-pair production).

	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	$\rho = 0$	$\rho = 0.5$
$\Delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-}$ [%]	0.8	0.10	0.51	0.07	0.21	1.11	0.11	0.25	0.25
$\Delta\mathcal{P}_{e^+}/\mathcal{P}_{e^+}$ [%]	0.6	0.12	0.53	0.11	0.15	1.13	0.21	0.25	0.25
corr		−0.49	−0.91	0	−0.56	−0.93	−0.52	0	0.50
$(\mathcal{P}_{e^-} + \mathcal{P}_{e^+})/(1 + \mathcal{P}_{e^-}\mathcal{P}_{e^+})$	0.95	0.02	0.08	0.02	0.05	0.17	0.02	0.07	0.08
$\mathcal{P}_{e^-}\mathcal{P}_{e^+}$	0.48	0.11	0.22	0.13	0.18	0.42	0.18	0.35	0.43
$\mathcal{P}_{e^-} + \mathcal{P}_{e^+} - \mathcal{P}_{e^-}\mathcal{P}_{e^+}$	0.92	0.03	0.12	0.03	0.06	0.25	0.03	0.09	0.11

4. Polarisation measurements from W production

W-pair production proceeds via s-channel Z- or γ-exchange and via t-channel neutrino exchange. 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 polarisation. 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 polarisation from the data even if only one beam is polarised.

To estimate the possible precision of a polarisation 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 polarisation has been fitted simultaneously with the anomalous couplings and a free normalisation. With $\mathcal{P}_{e^-} = 0.8$, $\mathcal{L} = 500\,\text{fb}^{-1}$ and $\sqrt{s} = 350\text{GeV}$ a polarisation 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 polarisation 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 polarisation is $\Delta\mathcal{P}_{e^-}^{(\text{meas})} = 0.8\delta\mathcal{P}_{e^-}$, 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 polarisations can be measured, if some luminosity with all four helicity combinations is available. The results for W-pair production are also listed in Table I. The correlations between the polarisations and the couplings are negligible. 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 polarisation. Single W^- production is sensitive to the electron polarisation while single W^+ production is sensitive to positron polarisation. However no quantitative studies have been made for this process.

5. Conclusions

If only electron polarisation is available it can be measured in a model independent way only with polarimeters, which might be limited to about 0.25%. 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 polarisation to the per mille level.

If also positron polarisation is available one gains immediately a factor three to four in the polarimeter measurement due to error propagation. In addition the polarisation 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 polarisation the additional information given by the four different helicity combinations can be used to measure the polarisation within the analysis as outlined for specific examples in this note. These schemes offer the possibility to measure the polarisation-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 polarisation 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 polarisations needed involve products of the polarisations. That also makes it necessary to track time dependencies of the polarisations with polarimeters.

References

[1] SLD Collaboration, K. Abe et al., Phys. Rev. Lett. **84** (2000) 5945.
[2] V.Gharibyan, N.Meyners, P.Schuler, *The TESLA Compton Polarimeter*, LC-DET-2001-047.
[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.