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Beam Polarisation and Triple Gauge Couplings in $e^+e^- \to W^+W^-$ at the ILC

Jenny List[*†]
DESY
E-mail: jenny.list@desy.de

A unique feature of a future e^+e^- linear collider is the ability to provide longitudinal polarised beams. In order to fully exploit their benefits, the luminosity weighted average polarisation needs to be known with permille-level precision. Three complementary methods for measuring the beam polarisation from the collision data are presented. All studies are based on realistic full simulation of the ILD and SiD detector concepts. They include semi-leptonic and fully hadronic W-pair production in e^+e^- annihilation at the ILC at centre-of-mass energies of 500 GeV and 1 TeV as well as all relevant physics and accelerator-related backgrounds. Assuming that the angular distributions of W-pair production are described by the Standard Model, the longitudinal polarisation of the electron and positron beams is measured with high accuracy. The W-pair events and the angular distributions for the semi-leptonic final state are also used to determine the triple gauge couplings. Results from a simultaneous measurement of the beam polarisations and the TGCs show that they can be determined independently and thus the method would not be compromised by indirect contributions from physics beyond the Standard Model.

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[*]Speaker.
[†]On behalf of the ILD and SiD Detector Concept Studies

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1. Introduction

In the Standard Model of particle physics (SM), electroweak interactions are described by a local gauge theory. Due to the non-abelian nature of the corresponding gauge group $SU(2)_L \times U(1)_Y$, the gauge bosons can self-interact in triple and quartic gauge vertices. The interaction of two W bosons with a Z boson or a photon inparticular is referred to as charged triple gauge vertices. The most general lorentz-invariant description of these W^+W^-Z and $W^+W^-\gamma$ vertices comprises 14 complex couplings. If C and P conservation is assumed, this reduces to 6 real couplings: g_1^γ, g_1^Z, k_γ, k_Z, λ_γ and λ_Z. In addition, g_1^γ can be fixed by electromagnetic gauge invariance, and finally the enforcement of the $SU(2)_L \times U(1)_Y$ gauge relation leaves 3 real couplings in the so-called LEP scheme:

$$\begin{aligned} \Delta k_Z &= -\Delta k_\gamma \tan^2\theta_W + \Delta g_1^Z \\ \lambda_\gamma &= \lambda_Z \end{aligned}$$

The SM predicts $g_1^Z = k_\gamma = 1$, $\lambda_\gamma = 0$. Beyond the SM, vertex corrections from new particles could modify the effective values of these couplings. Therefore measuring the triple gauge couplings (TGCs) with the best experimentally achievable precision provides an important test of the SM and an indirect search for new phenomena.

Our current knowledge is mainly based on fits to LEP and LHC data. The most precise determinations are obtained from single-parameter fits, where one of the three charged TGCs is allowed to vary while the other two are fixed to their SM predictions. With precisions of $2-4\%$, the LEP measurements still provide the highest accuracy, but the recently published results from ATLAS based on $4.6\,\mathrm{fb}^{-1}$ of 7 TeV data reaches similar sensitivity [1].

The expected impact of a future e^+e^- Linear Collider has been estimated already many years ago based on fast simulation, see e.g. [2]. In terms of single parameter fits, the precision is expected to improve by two orders of magnitude. Moreover, beam polarisation will allow to break the correlation between g_1^Z and κ_γ, thus qualitatively improving the precision of multi-parameter fits. Ultimatively, including runs with transversely polarised beams, all 28 real parameters of the 14 complex couplings could be accessed, without assumptions on C and P conservation, providing qualitatively new information from what is accessible today. While the polarisation of both beams is an essential tool to gain sensitivity to all 28 parameters, the precision to which polarisation is known is the potentially limiting systematic uncertainty. To be more precise, the decisive quantity is the luminosity weighted polarisation average over the analysed data set.

The significant expected gain of knowledge about TGCs and the potential systematic limitation motivates more detailed studies of the simultaneous extraction of TGCs and the beam polarisation based on up-to-date design of the accelerator [3] and the two proposed detector concepts, SiD and ILD [4]. All studies presented here have been performed in full, `Geant4`-based detector simulation, including realistic beam energy spectra, beamstrahlung and all relevant physics and accelerator backgrounds. The results will be given as a function of the integrated luminosity, where one "Snowmass year" (equivalent to 10^7 s) of design accelerator operation corresponds to $\sim 250\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 500\,\mathrm{GeV}$ and $\sim 500\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 1\,\mathrm{TeV}$.

2. Methods to extract the beam polarisation

The strategy to determine the beam polariation at the ILC is based on three core ingredients:

1. Laser Compton polarimeters up- and downstream of the interaction point provide instantaneous measurements required for polarisation tuning and to resolve time dependencies and correlations. They are designed to reach $\delta P/P = 0.25\%$, where the largest contribution of $\sim 0.2\%$ is expected to be the overall scale uncertainty.

2. Spin tracking between the polarimeters and the interaction point as well as measurements of the depolarisation in collision will allow to translate the measurements at the polarimeter locations to the interaction point with systematic effects in the order of a few permille.

3. Finally a long-term calibration of absolute scale at interaction point can be obtained from e^+e^- collisions themselves, for instance from W pair production or, especially at higher center-of-mass energies of $\sqrt{s} > 1\,\text{TeV}$, from single W or Z production.

For the third point, several methods have been investigated here. The so-called "modified Blondel scheme" [6] exploits the polarisation asymmetry of the total cross-section:

$$| P_{e^\pm} | = \sqrt{\frac{(\sigma_{-+} + \sigma_{+-} - \sigma_{--} - \sigma_{++})(\pm\sigma_{-+} \mp \sigma_{+-} + \sigma_{--} - \sigma_{++})}{(\sigma_{-+} + \sigma_{+-} + \sigma_{--} + \sigma_{++})(\pm\sigma_{-+} \mp \sigma_{+-} - \sigma_{--} + \sigma_{++})}}, \tag{2.1}$$

where σ_{+-} is the total cross-section for $P(e^+, e^-) = (+x\%, -y\%)$, etc. This assumes that the absolute values of the polarisations stay the same when the helicity is flipped, i.e., $P_+(e^-) = -P_-(e^-)$ and $P_+(e^+) = -P_-(e^+)$. This is only realistic if for both beams the helicity can be reversed on much shorter time-scales than any other effect influencing the collision conditions. The validity of this assumption can be verified by polarimeter measurements up to the accuracy achieved by these devices. Furthermore, data taking with all four beam helicity configurations is needed. However the luminosity does not need to be shared equally between the like-sign and the (more interesting) opposite-sign configurations, but with 10 to 20% of like-sign luminosity the performance of equal sharing is nearly reached. Finally it should be noted that this method is only valid as long as there is no contributions from new physics which exhibits another polarisation dependency than expected in the SM.

In particular in the case of W pair production, additional information can be extracted from angular distributions. Since the contribution from t-channel neutrino exchange exhibits a much stronger polarisation dependence than the s-channel diagrams and at the same time is strongly forward peaked, the production angle $\cos\theta_W$ of e.g. the W^- boson can be exploited to constrain the polarisation further. At the same time, the t-channel diagram does not contain a triple gauge boson vertex. This offers the potential to disentangle the effects of anomalous triple gauge couplings from those of the beam polarisation.

This can be further augmented to a double-differential measurement by including also the dependence on the W decay angle in the restframe of the W boson, $\cos\theta_{decay}$, which is sensitive to the polarisation of the W's. In semi-leptonic events, $\cos\theta_{decay}$ can be reconstructed conveniently by boosting the charged lepton into the restframe of its mother W boson, which is known from the

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well defined initial conditions of the collision and the fully reconstructable hadronically decaying W. In fully hadronic events, the average polar angle of the jets the restframe of their mother W boson is used. Both differential methods can be applied either to just one data-set with one helicity configuration or, much more powerfully to data-sets with different helicity configurations.

3. Results at $\sqrt{s} = 500$ GeV

At a center-of-mass energy of 500 GeV, the single differential method has been studied in full simulation of the ILD detector concept [5]. Figure 1 shows the relative precision on the beam polarisations as a function of the integrated luminosity, assuming an equal share of the luminosity between the four helicity configurations. In the left panel, the absolute value of the positron polarisation is assumed to be 30%, while the right graphic applies to the upgrade scenario of 60% positron polarisation. It can be clearly seen that a higher value of the absolute polarisation leads to significantly smaller uncertainties: In case of $|P(e^+)| = 30\%$, the relative precision reaches 0.25%, comparable to what is expected from the polarimeter measurements. For $|P(e^+)| = 60\%$, this already reduces to 0.1%, while for the electron beam with $|P(e^-)| = 80\%$ a relative precision of 0.05% is reached with and integrated luminosity of 1 ab^{-1}. Furthermore, figure 1 demonstrates that indeed the determination of the TGCs factorizes from the polarisation measurement, since the same precision is obtained from fixing the TGCs to their SM values (red stars / blue triangles) and from a simultaneous fit of TGCs and polarisation (open diamonds / crosses).

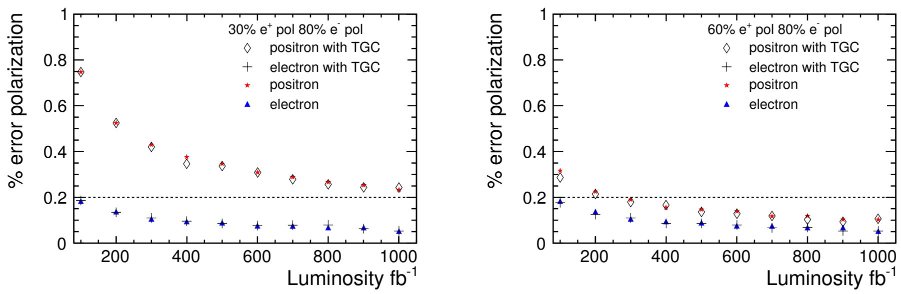

Figure 1: Precision of Polarisation measurement vs integrated luminosity at $\sqrt{s} = 500$ GeV with TGCs either fixed to their SM values or as free parameters. Left: $|P(e^+)| = 30\%$, Right: $|P(e^+)| = 60\%$

Figure 2 shows the precisions on the three TGCs obtained from a simultaneous fit of the three couplings on the two beam polarisations, again as a function of the integrated luminosity and assuming $|P(e^+)| = 30\%$. For all three couplings, precisions of a few 10^{-4} are reached. Increasing the positron polarisation does not lead to significant improvements in this case. However a comparison of the left and right panel shows that in particular the result for λ_γ improves significantly if enough lumonisity is accumulated, which allows a finer binning of the $\cos\theta_W$ distributions (right panel).

Figure 3 finally investigates the impact of the assuption of equal absolute values of the beam polarisation. Instead of assuming $P_+(e^-) = -P_-(e^-)$ and $P_+(e^+) = -P_-(e^+)$, one could instead try to fit the four polarisation values as independent parameters. However this leads only to percent-level precisions and would limit the achievable precision on the TGCs. Instead one can assume

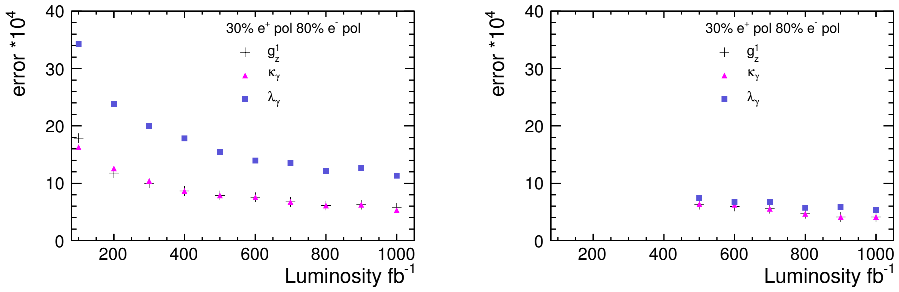

Figure 2: Precision on TGCs as function of integrated luminosity at $\sqrt{s} = 500$ GeV. Left: standard binning, Right: finer binning possible only for large data sets.

that the absolute values of the polarisations are nearly equal, apart from a small difference. This difference is known to the precision of the polarimeters, i.e. $\pm\delta P/P|_{pol} = 0.25\%$. The result when taking this additional uncertainty into account is displayed as open diamonds / crosses in figure 3, compared to the previous result for exactly equal absolute values (red stars / blue triangles). In case of the electron beam and for the positron beam with $|P(e^+)| = 60\%$ (right panel), the impact of the polarimeter uncertainty limits the final precision to 0.15%. For $|P(e^+)| = 30\%$, the precision is not sufficient to be sensitive to the additional uncertainty. If a polarimeter precision of $\delta P/P = 0.25\%$ is indeed achieved, the impact of a non-perfect helicity flip on the TGC determination is negligible.

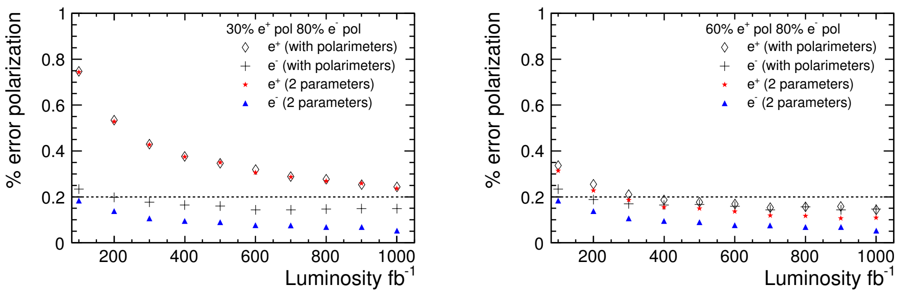

Figure 3: Precision of Polarisation measurement vs integrated luminosity at $\sqrt{s} = 500$ GeV with and without assuming an exact helicity flip. Left: $|P(e^+)| = 30\%$, Right: $|P(e^+)| = 60\%$

4. Results at $\sqrt{s} = 1$ TeV

The extraction of the beam polarisation from W pair production was chosen as one of the benchmark analyses studied by both the ILD and SiD detector concepts at a center-of-mass energy of 1 TeV for the ILC Technical Design Report [4]. Figure 4 shows the relative uncertainty ion the polarisation achieved with the total cross-section method (left) and with the single-differential method (right), both pursued by ILD and both assuming an equal split of the integrated luminosity between the four helicity configurations. In addition, the single-differential method has also been evaluated for the case that the data are only taken in the two opposite-sign configurations (right, full lines). Even in this most pessimistic case, the differential method out-performs the total cross-section method. When at least 10 to 20% of luminosity are spent on the like-sign configurations, the precision improves significantly and reaches ultimatively 0.4% for the positrons and 0.1% for the electrons. But these values are still worse than for $\sqrt{s} = 500$ GeV. This is due to the fact that for higher center-of-mass energies, the events are even more forward boosted. Therefore the acceptance losses become larger and at the same time the detector resolution becomes worse compared to the more squeezed sensitive range of the polar angle distribution. However the cross-sections for single boson production become very sizable and these processes should be exploited in addition for ultimate performance.

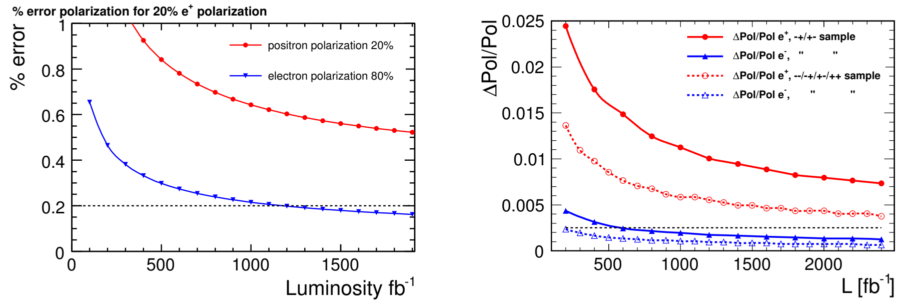

Figure 4: Precision of Polarisation measurement vs integrated luminosity at $\sqrt{s} = 1$ TeV. Left: from total cross-section Right: from single differential cross-section $d\sigma/d\cos\theta_W$.

The double-differential method was pursued by the SiD analysis. Figure 5 shows the double differential distributions after event selections in the $\cos\theta_{decay}$ vs $cos\theta_W$ plane for $P(e^+,e^-) = (+1,-1)$ (left) and $P(e^+,e^-) = (-1,+1)$ (right). This clearly shows that both variables contain imformation on the beam polarisation.

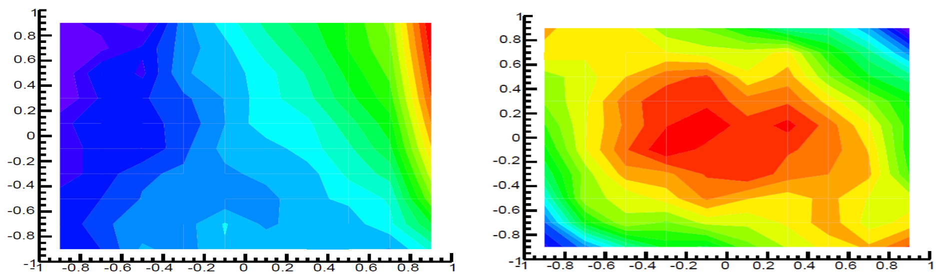

Figure 5: Polarisation measurement from double differential cross-section at $\sqrt{s} = 1$ TeV: Event yield after selection in the $\cos\theta_{decay}$ vs $cos\theta_W$ plane. Left: $P(e^+,e^-) = (+1,-1)$. Right: $P(e^+,e^-) = (-1,+1)$

Table 1 summarizes the results obtained for an integrated luminosity of 1 ab^{-1} split equally between the two opposite-sign helicity configurations. When combining both data sets, precisions of 0.25% for the electrons and 1.45% for the positrons have been obtained. This is very comparable to the ILD results under the same conditions: 0.2% for the electron beam and 1.2% for the positron beam (c.f. figure 4).

5. Conclusions

At a future e^+e^- Linear Collider, significant qualitative and quantitative improvements in our experimental knowledge on triple gauge couplings is expected. Beam polarisation and its

$1000\,\mathrm{fb}^{-1}$, equal share $+-$, $-+$	$\cos\theta$ range	$P(e^+,e^-)$	$\delta P(e^-)/P(e^-)$	$\delta P(e^+)/P(e^+)$
avoid TGC region	$0.8 < \cos\theta < 1$	$(+0.2,-0.8)$	15%	38.5%
avoid TGC region	$0.8 < \cos\theta < 1$	$(-0.2,+0.8)$	0.58%	11.5%
assume SM	$-1 < \cos\theta < 1$	$(+0.2,-0.8)$	7.25%	19%
assume SM	$-1 < \cos\theta < 1$	$(-0.2,+0.8)$	0.51%	9%
assume SM	$-1 < \cos\theta < 1$	combined	0.25%	1.45%

Table 1: Polarisation measurement from double differential cross-section at $\sqrt{s} = 1$ TeV: relative uncertainties on the polarisations for an integrated luminosity of $1\,\mathrm{ab}^{-1}$ split equally between the two opposite-sign helicity configurations.

precise measurement are crucial ingredients in this enterprise. The process $e^+e^- \to W^+W^-$ allows a simultaneous determination of charged triple gauge couplings and the beam polarisations. In particular, g_1^Z, k_γ, λ_γ can be determined to the level of 10^{-4} in a simultaneous fit. Ultimatively, all 28 coupling parameters, including the C and/or P violating ones can be accessed. The luminosity weighted average beam polarisations can be measured to the 10^{-3} level by three complementary methods. In the future, they could be combined to one optimal observable. The extraction of the luminosity weighted average polarisation from W pair production will provide an important absolute scale calibration of the polarisation for all other physics channels as well. The polarisation determination profits significantly from a small, say 10 to 20% fraction data taken in the like-sign beam helicity configurations. An as high as possible degree of positron polarisation is essential for a precise measurement of the positron polarisation. If the helicity flip is not exact, the difference needs to be measured with the polarimeters, which ultimately limits the extraction of the beam polarisations from W pair production. Further improvements, in particular at high center-of-mass energies, are expected from including also single boson production.

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