MOTIVATION FOR POLARISED $E^-$ AND $E^+$ BEAMS

GUDRID MOORTGAT-PICK
IPPP, University of Durham, DH1 3LE Durham, UK

A future Linear Collider is well suited for discovering physics beyond the Standard Model, for revealing the structure of the underlying physics as well as for performing high precision tests of the Standard Model. The use of polarised beams will be one of the powerful tools for reaching these goals. This paper highlights some recent studies of having both beams simultaneously polarised which allows to use longitudinally as well as transversely polarised beams.

1 Introduction And Overview

The International Linear Collider (ILC) in the energy range up to about 1 TeV has a large potential for the discovery of new particles and, due to its clear signatures, is perfectly suited for the precise analysis of physics beyond the Standard Model (SM) as well as for testing the SM with an unprecedented accuracy\(^1\). An option for the ILC is to operate in the GigaZ mode, i.e. to run with very high luminosity at the $Z$ and $WW$ threshold. This will enable the most sensitive tests of the SM ever made. Precision studies in this energy range, in particular in the electroweak sector, allows to detect even marginal traces of deviations from the SM predictions. This provides sensitivity to the effects of heavy states of New Physics (NP) even if they might not be directly produced at the LHC or the first energy phase of the ILC.

An important tool of the ILC is the use of polarised beams. Already in the base line design it is foreseen to polarise the electron beam. One expects a high polarisation degree between 80% and 90%, see e.g.\(^2\). Having both beams polarised (concerning possible designs for polarising $e^+$ at a LC, see\(^3,4\)) leads to several additional advantages: direct analysis of the interaction structure of NP, increased sensitivity to non-standard as well as SM couplings, improved accuracy in measuring the polarisation (see also\(^5\)), higher effective polarisation $P_{eff} = (P_{e^-} - P_{e^+})/(1 - P_{e^-} P_{e^+})$, and enhanced signal and suppressed background rates for specific processes with a suitably chosen polarisation configuration; in addition also the possibility is provided to use transversely polarised beams (for further overview reports see e.g.\(^6,7\)).

\(^{a}\)Summary of talks given at the Polarisation and Electroweak sessions at LCWS04.
A comprehensive report is in preparation in which the physics arguments for having both beams polarised are summarised in detail. In the report also an overview about possible technical designs for producing polarised beams and for measuring the polarisation is given. In the following we briefly summarise some recent studies with longitudinally as well as transversely polarised beams.

2 Both Beams Longitudinally Polarised

Concerning the possible helicity combinations in the interactions one has to distinguish two cases:

a) in annihilation diagrams the helicities of the incoming beams are coupled to each other, whereas

b) in scattering diagrams the helicities of both incoming beams are directly coupled to the final particles.

In case a) in the SM only the recombination into a vector particle with the total angular momentum \( J = 1 \) is possible (in the limit \( m_e \to 0 \)), i.e. both beams have to carry opposite sign of helicities. Only models of NP (in this limit) might allow to produce also scalar particles, so that \( J = 0 \) would be allowed, which results in same sign helicities of the incoming beams. In case b) the scattering diagrams could result in a vector, fermionic or scalar particle; the helicity of the incoming particle is directly coupled to the vertex and is independent of the helicity of the second incoming particle. Therefore all helicity configurations are possible.

a) Verifying quantum numbers of new particles

We show how crucial it may be to have both beams polarised and choose one representative example in Supersymmetry (Susy), which is one of the best motivated theory candidates for physics beyond the SM. At the LHC and the ILC, one has – after observing signals of new physics – to prove for instance, that it is indeed Susy, i.e. to verify the Susy predictions: in particular, Susy particles have to carry the same quantum numbers as their SM partners (with the exception of the spin which differs by half a unit). Thus Susy transformations
associate chiral (anti)fermions to scalars, i.e. $e_{L,R}^- \leftrightarrow \tilde{e}_{L,R}^-$ but $e_{L,R}^+ \leftrightarrow \tilde{e}_{L,R}^+$. In order to prove this association a simultaneous polarisation of both beams is decisive\(^7\). The process $e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$ occurs via $\gamma$ and $Z$ exchange in the annihilation channel and via neutralino $\tilde{\chi}_0$ exchange in the scattering channel. The association can be directly tested only in the latter channel. The use of polarised beams serves to separate both channels.

In our example, Fig. 1, by isolation of the pair $\tilde{e}_L^+\tilde{e}_L^-$ applying right-handed polarisation of both beams ($RR$ configuration), i.e. $P_{e^+} > 0$ and $P_{e^-} > 0$. The electron masses are close together, $m_{\tilde{e}_L} = 200$ GeV, $m_{\tilde{e}_R} = 195$ GeV, so that both $\tilde{e}_L$, $\tilde{e}_R$ show the same decay, $\tilde{e}_{L,R} \rightarrow \tilde{\chi}_0 e$. Even extremely high electron polarisation, $P_{e^-} \geq +90\%$, is not sufficient to disentangle the pairs $\tilde{e}_{L}^+\tilde{e}_L^-$ and $\tilde{e}_R^+\tilde{e}_R^-$ and to test their association to the chiral quantum numbers, since both cross sections are very close to each other, Fig. 1 (left). Only with right-handed polarisation of both beams the pair $\tilde{e}_L^+\tilde{e}_L^-$ is clearly separated, see Fig. 1 (right). In addition, all SM background events, e.g. from $W^+W^-$, are strongly suppressed with this $RR$ configuration.

**b) Gain in statistics and suppression of backgrounds**

In many cases of NP models, e.g. in Susy models, the predicted production cross sections of the new particles could be very small and the use of a suitable polarisation of both beams may be decisive for observing the signal (and saving running time). Simulations have been done to suppress SM background processes with the help of polarised beams in new physics searches, where $W^+W^-$ production presents one of the worst SM backgrounds. However, it can be easily suppressed with right-handed electron/left-handed positron beams. The reduction of the $W^+W^-$ cross section is $\sigma_{\text{pol}}/\sigma_{\text{unpol}} = 0.2$ (0.1) for $P_{e^-} = +80\%$, $P_{e^+} = 0$ ($P_{e^-} = +80\%$ and $P_{e^+} = -60\%$); see Figure 2 (left)\(^7\) for $P_{e^-} = +90\%$, $P_{e^+} = -80\%$.

The background suppression may be decisive for the detection of new particles and the precise determination of their properties, e.g. the accurate measurement of $m_{\tilde{\mu}}$ in the continuum. In the case of $\tilde{\mu}^+\tilde{\mu}^-$ production we have only annihilation via $\gamma$ and $Z^0$ exchange, therefore the initial beam configurations $LR$ and $RL$ are favoured. The predominant background for the signal is $W^+W^-$ production. In\(^{10}\) an example is given, in which the masses are
\( \tilde{\mu}_R = 178.3 \text{ GeV}, \quad \tilde{\mu}_L = 287.1 \text{ GeV}. \) In Fig. 2 (right) the expected muon energy distribution for an integrated luminosity of 500 fb\(^{-1}\) at \( \sqrt{s} = 750 \text{ GeV} \) and the polarisation configuration \( P_{e^-} = +80\%, \quad P_{e^+} = -80\% \) is shown. The background from \( W^+W^- \) decaying into the \( \mu\nu \) final state is included. Only with polarised \( e^- \) and \( e^+ \) beams both edges, at around 65 GeV and at around 220 GeV, can be clearly reconstructed. The slepton masses can be determined in the continuum up to a few GeV, which is important to test e.g. slepton non-universality\(^{11}\). The mass reconstruction is even more involved in the case of selectrons. The \( e^+e^- \) energy spectra subtraction technique has been successfully applied to remove SM background\(^{10}\). Polarisation of both beams is needed to guarantee sufficient statistics. The mass measurements in the continuum are very important to outline strategies for further threshold scans for specific particles, cf.\(^1\).

In\(^{12}\) it has been shown that the use of polarised beams could in addition be needed to distinguish between different Susy models, the MSSM and the NMSSM. Susy models often lead to a large number of additional free parameters and new sources for CP violation. Small effects are expected in most CP violating Susy processes. Suitable observables for uniquely resolving the CP structure of the underlying physics are T-odd asymmetries. Using polarisation of both beams may be important to enhance the cross sections and to get sufficient statistics\(^8,13\).

A further example for the importance of having both beams polarised in order to suppress SM background for new physics searches can be seen in the process \( e^+e^- \rightarrow \gamma G \), the direct search for gravitons. The predominant background is \( e^+e^- \rightarrow \gamma \nu_\mu \bar{\nu}_e \). Given the near maximal polarisation asymmetry of the background, polarised beams are extremely effective in suppressing the background: the ratio \( S/\sqrt{B} \) increases by a factor 2.1 when using \( (P_{e^-}, P_{e^+}) = (+0.8, 0) \) and by a factor 4.4 when using \( (+0.8, -0.6), \) see\(^{14}\). The reach of the LC in the quest for evidence of extra dimensions is thus extended and leads to a similar discovery reach as at the LHC in a, however, more model-independent way\(^{14}\).

c) **High precision SM tests at GigaZ**

In the SM the left–right asymmetry \( A_{LR} \) of \( e^+e^- \rightarrow Z^0 \rightarrow f \bar{f} \) depends only on the effective leptonic weak mixing angle:

\[
\begin{array}{c|c|c|c}
\text{HE} & \text{rr} & \text{WW} \\
\hline
\mathcal{L}_{\pm\pm}/\mathcal{L} &= 0.5: & 0.02 & 0.08 & 0.02 \\
\Delta P_{\text{eff}}/P_{\text{eff}}/\% &= 0.05 & 0.17 & 0.02 \\
\end{array}
\]
$P_T(e^-) = 80\%, P_T(e^+) = 60\%$

| $g_1^T$ | $g_2^T$ | $h_+$ | $h_-$ |
|---------|---------|-------|-------|
| Sensi. ($\times 10^{-3}$) |
| Long (80%, 60%) | 1.9 | 1.6 | - | 2.5 |
| Trans (80%, 60%) | 2.8 | 2.4 | 3.2 | 3.7 |

$\delta = \Im (g_1^T \pm \kappa R) / \sqrt{2}$

$g_1^T = 4 \sin^2 \theta_W g_1^T + (2 - 4 \sin^2 \theta_W) \xi g_1^T$

$g_2^T = 4 \sin^2 \theta_W g_2^T - 4 \sin^2 \theta_W \xi g_1^T$

$\xi = s / (s - m_Z^2)$

Figure 4: Left: Differential azimuthal asymmetry distribution for $e^+e^- \rightarrow c\bar{c}$ at a 500 GeV LC assuming a luminosity of $500 fb^{-1}$. The histograms are the SM predictions while the data points assume the ADD model with $M_H = 1.5$ TeV; Right: $1\sigma$ statistical errors on the real and the imaginary parts of TGCs ($CP$ conserving) in the presence of general anomalous couplings at $\sqrt{s} = 500$ GeV with different beam polarisations.

The statistical power of the data sample can be fully exploited only when $\delta(A_{LR}(pol)) < \delta(A_{LR}(stat))$. For $10^8 - 10^9$ Z’s this occurs when $\delta(P_{eff}) \leq 0.1\%$. In this limit $\delta(\sin^2 \theta_{eff}) \sim 10^{-5}$, which is more than an order of magnitude smaller than the present value of this error. Thus it will be crucial to minimise the error in the determination of the polarisation. The desired precision is attainable with the Blondel Scheme: it is not necessary to know the beam polarisation itself with such an extreme accuracy, since $A_{LR}$ can be directly expressed via polarised cross sections. It has been worked out in $15$ that with transversely polarised beams a unique distinction between effects of graviton exchange and of ‘conventional’ contact interactions is possible. The interference between SM and spin-2 exchange amplitudes shows a general difference in the $z$-dependence ($z = \cos \theta$) of the terms which are sensitive to the azimuthal angle. In particular, the existence of the odd $z$ contributions is clearly a signal for spin-2 exchange, see Fig. 4 (left).

3 Both Beams Transversely Polarised:

Searches For Gravitons, TGCs And CP Violation

One elegant tool for new physics searches that becomes only available if both $e^-$ and $e^+$ beams are polarised at the LC are transversely polarised beams. In that case the cross sections can generally be written as:

$$\sigma = (1 - P_{e^+} P_{e^-}) \sigma_{unp} + (P_{e^+}^L - P_{e^-}^L) \sigma_{pol}^L + P_{e^+}^T P_{e^-}^T \sigma_{pol}^T.$$

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It has been shown in $16$ that transversely polarised beams may also be crucial for the determination of a specific triple gauge coupling, $h_+$, that is not
accessible with only longitudinally polarised beams, see Fig. 4 (right).

Furthermore it has been shown in\textsuperscript{17} that transversely polarised beams also enhance the sensitivity to CP-odd observables at leading order from interferences of (pseudo-) scalar or tensor currents with $\gamma$ and $Z$ channels in general inclusive processes, $e^+e^- \to A + X$.

4 Summary

The ILC in the TeV range with its clean initial state of $e^+e^-$ collisions is ideally suited to search for New Physics. It allows to precisely determine quantities of the Standard Model as well as of New Physics and to reveal the structure of the underlying physics. The use of polarised beams plays a decisive role in this context. The simultaneous polarisation of both beams, longitudinally as well as transversely, significantly expands the physics potential, e.g. for verifying and determining the properties of new particles, for increasing signal rates and suppressing background processes, and for providing higher sensitivity to non–standard couplings and to CP effects of new physics.

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