Chapter 4

CLIC Running Options

4.1 Staged Energy Approach

4.2 Polarization

4.2.1 Impact of e^- and e^+ Beam Polarization

Beam polarizations of the initial particles provide access to the chirality and the interaction structure of the production processes [1]. The chiral structures of interactions in various processes can be identified independently and unambiguously. This provides the possibility of determining the quantum numbers of the interacting particles and testing stringently model assumptions. Several of these tests are not possible with polarized electrons alone (even if a 100% polarization could be achieved).

A polarized electron beam would already provide a valuable tool for stringent tests of the Standard Model and for diagnosing new physics. In addition to enabling more detailed studies of directly accessible new particles and a precise analysis of their interaction properties, the polarization of both beams would also strongly improve indirect searches for new physics. For instance, simultaneously polarized beams are required to derive model-independent bounds for contact interactions and in particular to get systematics in hadronic final states under control.

The availability of simultaneously polarized beams offers also the option to exploit effects from transversely polarized beams that enter only bilinear in the cross section and related expressions. Transversely polarized beams offer, however, access to specific azimuthal asymmetries sensitive to CP-violating or tensor-like interactions.

It is expected to achieve a high polarization degree of at least $P_{e^-} \geq 80\%$ for the electron beam and a polarized e^+ beam with $P_{e^+} = 60\%$ without loss in luminosity. In order to fully exploit the polarization of the beams, one also has to measure precisely the actual degree of polarization and to flip the helicity of the polarizations, therefore high precision polarimetry is a mandatory requirement. At the SLC, one achieved already a precision of $\Delta P_{e^-}/P_{e^-} \sim 0.5\%$ with Compton polarimetry measured via a magnetic spectrometer. The goals for a future linear collider are even more challenging and one aims for $\Delta P_{e^\pm}/P_{e^\pm} \leq 0.25\%$.

A comprehensive overview of the physics case for the use of polarized electron and positron beams at a linear collider as well as a technical status report of the available polarized $e^\pm$ sources is given in [1].

4.2.1.1 Longitudinally-polarized beams

Longitudinal polarization is defined as the ensemble of particles with definite helicity $\lambda = -\frac{1}{2}$ left– or $+\frac{1}{2}$ right-handed: $P = [\#N_R - \#N_L]/[\#N_R + \#N_L]$. Since the initial leptons can be regarded as being massless, the helicity corresponds to their chirality.

Polarized cross sections: In processes, where only (axial-)vector interactions are contributing in e^+e^- annihilation, the dependence on beam polarization of the cross section can be expressed via the unpolarized cross section σ_0, the left-right asymmetry $A_{\mathrm{LR}} = [\sigma_{\mathrm{LR}} - \sigma_{\mathrm{RL}}]/[\sigma_{\mathrm{LR}} + \sigma_{\mathrm{RL}}]$ (with σ_{LR}, etc. denoting the cross section for fully left-handed polarized electron and right-handed polarized positron beams) and two polarization dependent factors, namely the effective polarization ($P_{\mathrm{eff}} = [P_{e^-} - P_{e^+}]/[1 - P_{e^-}P_{e^+}]$) and the effective luminosity , $\mathscr{L}_{\mathrm{eff}} = \frac{1}{2}[1 - P_{e^-}P_{e^+}]\mathscr{L}$, with $\mathscr{L}_{\mathrm{eff}}/\mathscr{L}$ reflecting the number of interacting particles).

$$\begin{aligned} \sigma_{P_{e^-}P_{e^+}} &= (1 - P_{e^-}P_{e^+})\,\frac{\sigma_{\mathrm{RL}} + \sigma_{\mathrm{LR}}}{4}\left[1 - \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}\,\frac{\sigma_{\mathrm{LR}} - \sigma_{\mathrm{RL}}}{\sigma_{\mathrm{LR}} + \sigma_{\mathrm{RL}}}\right] \\ &= 2\mathscr{L}_{\mathrm{eff}}\,\sigma_0\,[1 - P_{\mathrm{eff}}A_{\mathrm{LR}}], \end{aligned} \tag{4.1}$$

Effective polarization: The effective polarization reaches $P_{\text{eff}} = 90\%$ for $\{P_{e^-}, P_{e^+}\} = \{90\%, 0\}$ but $P_{\text{eff}} = 97\%$ for $\{P_{e^-}, P_{e^+}\} = \{\pm 90\%, \mp 60\%\}$.

Effective luminosity: The ratio of colliding and interacting particles can only be enhanced if P_{e^+} is available: from the value $\mathscr{L}_{\text{eff}} = \frac{1}{2}$ for unpolarized positrons up to $\mathscr{L}_{\text{eff}}/\mathscr{L} = 0.77$ for $\{P_{e^-}, P_{e^+}\} = \{\pm 90\%, \mp 60\%\}$.

Suppression of Standard Model background processes: With the appropriate configuration of beam polarization a more efficient control of background processes can be obtained. The higher signal-to-background ratio may be crucial for finding manifestations of particles related to new physics and determining their properties. It may also be crucial for disentangling cascade chains from heavier, almost mass degenerated particles.

A prominent example is the suppression of background from W-pairs: with $(P_{e^-}, P_{e^+}) = (+80\%, 0)$ one scales $W^+ W^-$ production by a factor 0.20, with $(P_{e^-}, P_{e^+}) = (+80\%, -60\%)$ by about a factor of 0.10. Another example is direct graviton production, $e^+e^- \to \gamma G$. The major SM background is determined by $e^+e^- \to \gamma\nu\bar{\nu}$. The contribution from $e^+e^- \to \gamma Z \to \gamma\nu\bar{\nu}$ can easily be eliminated by cutting out the E_γ region around the corresponding Z-peak, but there remains a significant, continuous distribution in E_γ from $e^+e^- \to \gamma\nu\bar{\nu}$ that has similar behaviour as the signal. Since the neutrino couples only left-handed, the background has nearly maximal polarization asymmetry and can be effectively suppressed via beam polarization: with $(P_{e^-}, P_{e^+}) = (+80\%, 0)$ one enhances $S/\sqrt{B}$ by about a factor 2.2, with $(P_{e^-}, P_{e^+}) = (+80\%, -60\%)$ by about a factor of 5.

Left-right asymmetry: The left-right asymmetry A_{LR} is very powerful in both high precision analyses at lower energies as well as new physics searches at the energy frontier, see [1] and references therein. The relative uncertainty for any left-right asymmetry is given by the expected polarimeter precision and can only be decreased if polarized e^+ are available: with $(P_{e^-}, P_{e^+}) = (\pm 90\%, \mp 60\%)$ the uncertainty $\Delta A_{\text{LR}}/A_{\text{LR}}$ is reduced by about a factor 3.4, see Figure 4.1.
Note: there is no gain in accuracy if only polarized electrons are available, not even with $P(e^-) = 100\%$.

Supersymmetry: One of the most promising candidate for physics beyond the Standard Model is Supersymmetry (SUSY). The LHC has a large discovery potential to detect coloured SUSY particles up to 2.5 TeV. The main task of the future linear collider will be to really establish SUSY, i.e. to verify experimentally and determine all model parameters and assumptions, as e.g. couplings and quantum numbers. Polarized e^- and e^+ are crucial to verify SUSY chiral quantum numbers and Yukawa couplings. Depending on the SUSY parameter space, these topics often can not be probed by even 100% polarized electrons [1].

As an example we take the slightly modified CLIC benchmark scenario 'Model I' (with $m_{\tilde{e}_{\text{L,R}}} =$ 700, 680 GeV) and study whether the pair $\tilde{e}^+_{\text{R}}\tilde{e}^-_{\text{R}}$ (red line) can be separated from the pair $\tilde{e}^+_{\text{L}}\tilde{e}^+_{\text{R}}$ (green line). Latter has a unique association between the chirality of the incoming $e^\pm$ and the quantum number of the produced SUSY partner $\tilde{e}^\pm$ at the vertex of the pure t-channel vertex. With unpolarized e^+ these two pairs lead to similar cross sections even for highly polarized electrons, $P(e^-) = +80\%$, see Figure 4.2 for $\sqrt{s} = 1500$ GeV. If, however, simultaneously polarized e^+ are available as, e.g. $P(e^+) = +60\%$, only the pair $\tilde{e}^+_{\text{L}}\tilde{e}^+_{\text{R}}$ survives.

A large number of available observables is crucial for disentangling and determining the new physics parameters (e.g. the 105 parameters in the MSSM) in a largely model-independent approach. However, even if the full spectrum may be kinematically accessible, the rates can be very small and the reconstruction of the cascade chains of the heavier states may be extremely challenging so that only a limited information is available. Polarized e^+ are not only essential to enhance the rates by about a factor of two (in addition to polarized e^-), but also to provide essential observables.

As an example, we take again the CLIC benchmark scenario 'Model I' in order to study the neutralino/chargino production. In Table 4.1 we list only those corresponding cross sections for unpolarized beams that are larger than 1 fb. It will be very challenging to identify and deduce any information from the heavier pairs $\tilde{\chi}_2^+\tilde{\chi}_2^-$, $\tilde{\chi}_3^0\tilde{\chi}_4^0$ due to their cascades via $W^\pm$, Z and h decays and diverse topologies. As shown in [2], it is sufficient to study only $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^0\tilde{\chi}_2^0$ production to determine the fundamental parameters if polarized beams are available. The polarization of both beams is therefore not only crucial for enhancing the rates (up to about a factor of three) but is also required to provide more observables to unravel the parameters.

Table 4.1: The production cross section of $e^+e^- \to \tilde{\chi}_i\tilde{\chi}_j$ pairs in scenario 'Model I' that result in > 1 fb are listed. All other pairs lead to smaller cross sections < 1 fb. Beam polarization is essential to enhance the rates but also to provide substantially more observables.

$\sqrt{s}$ (TeV)	$(P(e^-), P(e^+))$	$\tilde{\chi}_1^+\tilde{\chi}_1^-$	$\tilde{\chi}_2^+\tilde{\chi}_2^-$	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	$\tilde{\chi}_2^0\tilde{\chi}_2^0$	$\tilde{\chi}_3^0\tilde{\chi}_4^0$
3.0	unpolarized	10.7	11.6	2.6	4.0	4.8
	$(-80\%, 0)$	19.3	18.0	4.8	7.1	5.6
	$(+80\%, 0)$	2.2	5.2	–	–	4.0
	$(-80\%, +60\%)$	30.9	28.4	7.6	11.4	8.5
	$(-80\%, -60\%)$	7.7	7.6	1.9	2.9	2.7
	$(+80\%, -60\%)$	–	6.0	–	–	5.7
	$(+80\%, +60\%)$	3.4	4.4	–	1.3	2.3
1.5	unpolarized	16.5	–	2.5	1.4	–
	$(-80\%, 0)$	29.7	–	4.4	2.5	–
	$(+80\%, 0)$	3.3	–	–	–	–
	$(-80\%, +60\%)$	47.4	–	7.1	3.9	–
	$(-80\%, -60\%)$	11.9	–	1.8	1.0	–
	$(+80\%, -60\%)$	1.3	–	–	–	–
	$(+80\%, +60\%)$	5.3	–	–	–	–

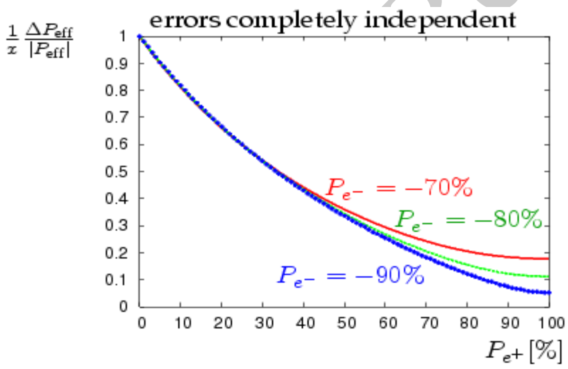

Fig. 4.1: The relative uncertainty of $\Delta A_{LR}/A_{LR} \sim \Delta P_{\rm eff}/P_{\rm eff}$, normalized to the relative polarimeter precision, $x = \Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+}$.

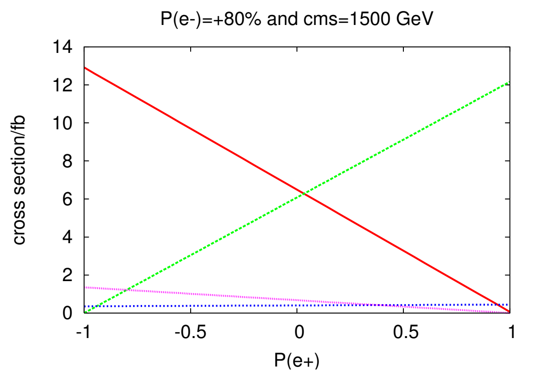

Fig. 4.2: Cross section for $e^+e^- \to \tilde{e}_L^+\tilde{e}_R^+$ (green), $\tilde{e}_R^+\tilde{e}_R^-$ (red) for variable P_{e^+} in 'Model I' with $m_{\tilde{e}_{L,R}} = 700, 680$ GeV. Rates for $\tilde{e}_L^+\tilde{e}_L^-$, $\tilde{e}_R^+\tilde{e}_L^+$ are below < 1 fb.

4.2.1.2 Impact of transversely polarized beams

In order to exploit the effects of transversely polarized beams the polarization of both beams is required, otherwise all effects at leading order from transverse polarization vanish for $m_e \to 0$ (suppression by $m_e/\sqrt{s}$). Transversely polarized beams open up new possibilities:

CP-violation in SUSY:
Provides new observables to detect non-standard interactions, including possible new sources of

CP-violation which occur naturally, for instance, in Supersymmetry.

Extra dimension models:
Enhancement of the sensitivity to graviton interactions and enables one to draw a distinction between different scenarios of extra spatial dimensions, even far below the resonance production threshold.

Triple-gauge couplings:
Access to specific triple-gauge couplings which cannot be extracted with only longitudinally polarized beams.

4.3 Determination of the luminosity spectrum

References

[1] G. A. Moortgat-Pick *et al.*, The role of polarised positrons and electrons in revealing fundamental interactions at the Linear Collider, *Phys. Rept.*, **460** (2008) 131–243, hep-ph/0507011

[2] K. Desch *et al.*, SUSY parameter determination in combined analyses at LHC/LC, *JHEP*, **02** (2004) 035, hep-ph/0312069