Impact of polarized e^- and e^+ beams at a future Linear Collider and a Z-factory

Part II – Physics beyond the Standard Model

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Abstract. Polarization of both beams at a future Linear Collider would be ideal for facing both expected and unforeseen challenges in searches for new physics: fixing the chirality of the couplings and enabling the higher precision for the polarization measurement itself as well as for polarization-dependent observables, it provides a powerful tool for studying new physics at the future Linear Collider, such as discovering new particles, analyzing signals model-independently and resolving precisely the underlying model. Techniques and engineering designs for a polarized–positron source are well advanced. Potential constraints concerning luminosity, commissioning and operating issues appear to be under control. This article mainly treats with the impact of polarized beams on physics beyond the Standard Model, whereas the fundamentals in polarization as well as the gain in electroweak precision physics are summarized in the corresponding part I [1].

1. Introduction

The first exploration of the TeV energy scale is expected to be made with proton–proton collisions at the Large Hadron Collider (LHC). Its discoveries would be complemented by results from the electron–positron International Linear Collider (ILC), that is currently already in a mature technical design phase and by results from a multi-TeV option of a linear collider (LC), CLIC, awaiting its prototype feasibility experiments in the next years. It is expected that the clean signatures and in particular the precise measurements made possible by a high luminosity LC at a known and tunable beam energy will bring revolutionary new insights into our understanding of the fundamental interactions of nature and the structure of matter, space and time. In the hunt for physics beyond the Standard Model (SM), only small signs may be visible, and the ILC provides already optimal conditions for searching for the unexpected.

The physics return from the investment in the linear collider would be maximized by providing polarized electron and positron beams. It is recognized that beam polarization can play an important role in the ILC programme, and polarization of the electron beam is already foreseen for the baseline design [2]. A high degree of at least 80% polarization is already envisaged, and new results indicate that even 90% may be achievable. A polarized electron beam would already provide a valuable tool for scrutinizing the SM and diagnosing new physics.

The possibility of polarizing the positron beam is currently discussed as one upgrade option for the ILC. In the report [3] it is shown that the full potential of the ILC will be realized only with a polarized positron beam together with a polarized electron beam. In addition to detailed studies of the SM and properties of new particles, as well as new kinds of interactions, the polarization of both beams would also enable indirect searches with high sensitivity for new physics in a largely model-independent approach. In the following a short summary about the impact of beam polarization in new physics searches is given, whereas in part I, [1], the focus is on the impact of beam polarization for electroweak high precision studies. This article closes with a short overview of technical issues and their current status.

2. The physics case for polarized positrons

2.1. Direct searches for new physics with longitudinally-polarized beams

The dominant processes in e^+e^- experiments are annihilation (s-channel) and scattering (t-channel) processes. In t-channel processes the helicities of the electrons and positrons can be related directly to the chirality and properties of the (new) particles produced. In annihilation processes the helicities of the electron and positron are related by the spin of the particle(s) exchanged in the s-channel. Suitable combinations of the electron and positron beam polarizations may be used to enhance significantly signal rates and also to suppress efficiently unwanted background processes. These capabilities are particularly welcome in outlining searches for new physics, where in many cases only very small rates are predicted. An increased signal/background ratio combined with high luminosity provides a promising environment for discoveries even at the edge of the kinematical reach.

If both beams are polarized, in t-channel processes the helicities/chiralities of the electron and positron can be related directly to the properties of any produced (new) particles and its interactions. The ability to adjust independently the polarizations of both beams simultaneously provides unique possibilities for probing directly the properties of the produced particles. In particular, it becomes possible to access directly their quantum numbers and chiral couplings, with a minimal number of assumptions.

2.1.1. Examples in searches for Supersymmetry One of the best motivated extensions of the SM is Supersymmetry (SUSY). This theory predicts that all new SUSY particles carry the same quantum numbers as their SM partner particles, with the exception of the spin, which differs by half a unit. A prominent sector is represented by partners of the left– and right–chiral electrons/positrons, the scalar selectrons/spositron $\tilde{e}^{\pm}_{L,R}$, which have to be associated to their SM-partners.

To probe their quantum numbers one has to separate experimentally the pairs $\tilde{e}^+_L\tilde{e}^-_R$ produced only by a t-channel process from the pair $\tilde{e}^+_R\tilde{e}^-_R$ produced by an s-channel process. In quite a number of scenarios even a highly polarized electron beam will not be sufficient to separate such pairs, because both pairs are produced with almost identical cross sections and have the same decays, see Fig. 1 (lower plot). With polarized positrons in addition to polarized electrons, the pairs have different cross sections and the $\tilde{e}^+_L$ and $\tilde{e}^-_R$ can be distinguished by charge conjugate separation, Fig. 1(upper plot). As seen from this example, polarized positrons may be essential when probing properties of new physics.

The polarization of both beams allows one to probe directly not only the chiral quantum numbers as shown in Fig. 1, but also the spins of particles produced in resonances.

A prominent example in an R–parity violating SUSY model is the production of a spin-0 particle, the scalar neutrino, with $\mu^+\mu^-$ in the final state. Since the sneutrino couples only to left-handed $e^{\pm}$, the peak is strongest for the LL polarization configuration, a signature that would point directly to the presence of a spin-0 resonance, Fig. 2. The SM background is strongly suppressed and one gets a $S/B \sim 11$ for $(P_{e^-}, P_{e^+}) = (-80\%, -60\%)$, whereas for $(P_{e^-}, P_{e^+}) = (-80\%, 0\%)$ the ratio is only $S/B \sim 4$. Conversely, in the case of a spin-1 resonance, e.g. the Z' particle in the SSM model, see Fig. 3, the corresponding resonance peak would be strongest for the LR configuration, with a similar polarization dependence as the SM background. This simple example shows how one can disentangle the form of interaction if both beams are polarized.

2.2. Indirect searches for new physics with longitudinally-polarized beams

Some new physics scales, such as those characterizing gravity in models with extra dimensions or the compositeness scale of quarks and leptons, could be too large to be directly accessible at the energies of present as well as future accelerators. Therefore it will also be important at the ILC to devise indirect search strategies for new physics, with high sensitivity and large model-independence. Indeed, the ILC has a large discovery potential for indirect searches beyond the kinematical limit. Effective interactions represent a general framework for the low-energy parametrization of the effects of non-standard dynamics due to exchanges between SM particles of very heavy states with masses beyond the available accelerator energy. This is the case of the four-fermion contact interactions (CI) inspired by compositeness but applicable much more generally, and of the mass scales characterizing models of gravity in large extra dimensions. Manifestations of such new interactions can be probed through deviations of cross sections from the SM predictions, and indirect bounds on the new energy scales and coupling constants can thereby be derived.

Longitudinal polarization of both beams is decisive for deriving model-independent bounds on the different possible couplings. With both beams polarized, the error in $\Delta P/P$ is reduced, the accuracy of the $A_{\rm LR}$ measurement is considerably enhanced, for instance, an polarization degree of $P_{e^+} = 60\%$ reduces the relative error $\Delta A_{\rm LR}/A_{\rm LR}$ by more than a factor 3. Furthermore more observables can be defined, which enables one to disentangle and constrain the different couplings in a model-independent approach.

2.2.1. Example from contact interactions For example, in Bhabha scattering the four–fermion contact interactions (CI) are parametrized by three couplings ($\epsilon_{\rm RR}$, $\epsilon_{\rm LR}$, $\epsilon_{\rm LL}$). The t–channel contributions depend only on $\epsilon_{\rm LR} = \epsilon_{\rm RL}$, whereas the s–channel contribution depends only on the pairs ($\epsilon_{\rm RR}$, $\epsilon_{\rm LR}$), ($\epsilon_{\rm LR}$, $\epsilon_{\rm LL}$). In order to derive model–independent bounds, it is necessary to have both beams polarized. Tight bounds up to 5×10^{-4} TeV^{-2} at 95% CL can be derived. It has been assumed that no deviations from the SM are measured within the experimental uncertainty in the observables, i. e. the combinations of polarized cross sections σ_{++}, σ_{+-} and σ_{-+}, see Fig. 4.

2.2.2. Example from Z' model Extra neutral gauge boson Z' can be probed by their virtual effects on cross sections and asymmetries. For energies below a Z' resonance, measurements of fermion–pair production are sensitive only to the ratio of Z' couplings and Z' mass. As an example, beam polarizations $(P_{e^-}, P_{e^+}) = (80\%, 60\%)$ would improve the measurement of the $b\bar{b}$ couplings of the Z' without knowledge of the Z' mass by about a factor 1.5, compared to $P_{e^-} = 80\%$ only, see Fig. 5. The crucial point is the fact that the systematic uncertainties can be significantly reduced when both beams are polarized.

2.3. Searches for new physics with transversely-polarized beams

With both beams polarized, another powerful tool would be available at the ILC, namely the use of transversely-polarized beams, which enhances the physics potential significantly in SM physics as well as in different new physics models. However, both beams have to be polarized, otherwise all effects at the leading order from transverse polarization vanish for $m_e \to 0$ (suppression by $m_e/\sqrt{s}$).

New CP–sensitive observables can be constructed in general, and azimuthal asymmetries can be exploited. These new observables are important e. g. in SUSY searches for the resolution of new CP–violating phenomena. They further enlarge the number of observables available to constrain the new physics parameters. Since e.g. in SUSY many of the 105 free parameters are possible CP-violation phases, such tools may become particularly important in the direct searches for SUSY.

2.3.1. Example from extra dimensions In that context, the use of transversely-polarized beams offers new observables to detect non-standard interactions which are not of the current-current type, such as those mediated by spin-2 gravitons or (pseudo)scalar exchanges even in indirect searches. Sensitivities to a high mass scale of e.g. the extra dimension model up to ≥ 3 TeV are achievable, enabling even a model distinction.

The success to identify new physics even in indirect searches via polarized e^- and e^+ beams would represent a step forward of utmost importance for our understanding of fundamental interactions.

One representative example is the distinction between extra dimensions in the models of Randall–Sundrum (RS) and Arkani–Hamed, Dimopoulos, Dvali (ADD). With transversely–polarized beams a new asymmetry in $\sin 2\phi$ can be constructed, which is sensitive to the cut–off independent imaginary parts of the amplitude originating from the exchange of the (almost) continuous spectrum of ADD gravitons. Below the graviton resonance poles no imaginary parts emerge in the RS model, if one neglects the (small) widths with respect to the masses. The new asymmetry therefore vanishes for both the SM and the RS scenario, so that a non–zero value unambiguously signals the ADD graviton exchange, see Fig. 6. Such a model distinction is achievable up to ≥ 3 TeV.

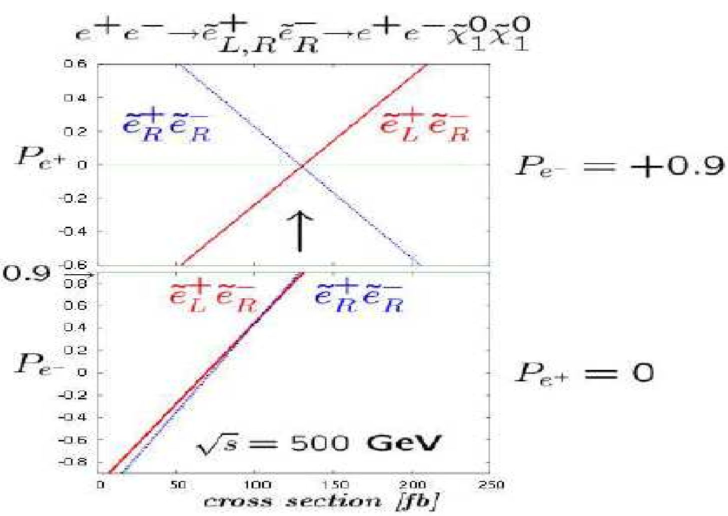

Figure 1. Separation of the selectron pair $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$ in $e^+e^- \to \tilde{e}^+_{\rm L,R}\tilde{e}^-_{\rm L,R} \to e^+e^-2\tilde{\chi}^0_1$ is not possible with electron polarization only (lower panel). If, however, both beams are polarized, the cross sections (upper panel) differ and the RR configuration, e. g. $(P_{e^-}, P_{e^+}) = (+90\%, +60\%)$ [3] clearly separates the pair $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$. The SUSY parameters are chosen as in scenario S1 in [3].

3. Technical issues

3.1. Status of the Linear Collider

Two accelerator technologies are discussed for a linear collider.

a) In the energy range of $\sqrt{s} = 0.5$–1 TeV the superconducting technology, as implemented in the International Linear Collider (ILC), is the mature concept [7] to provide the expected unique scientific opportunity and enter a new precision frontier. The Reference Design Report (RDR) has been finished in 2007 [8]. No technical obstacles are predicted for the ILC design, but careful studies of possible cost saving changes for the current design have

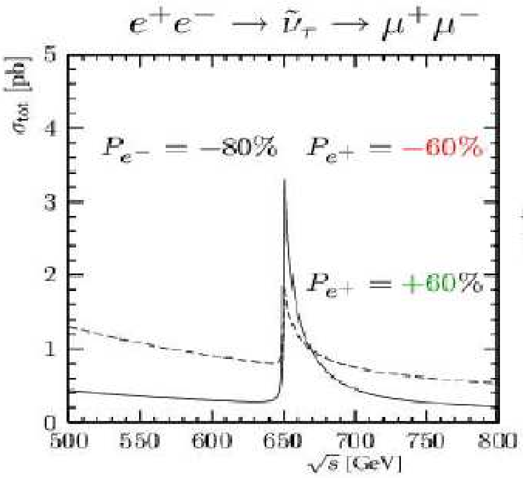

Figure 2. Sneutrino production in the R-parity-violating model: resonance production for $e^+e^- \to \tilde{\nu}_\tau \to \mu^+\mu^-$ (left panel) [3] for different configurations of beam polarization: $(P_{e^-}, P_{e^+}) = (-80\%, +60\%)$ (dashed), $(-80\%, -60\%)$ (solid). The striking effects of the spin-0 s-channel exchange can be enhanced using the LL configuration of beam polarization. The study was made at $\sqrt{s} =$ 650 GeV for $m_{\tilde{\nu}} = 650$ GeV, $\Gamma_{\tilde{\nu}} = 1$ GeV and the R-parity-violating couplings $\lambda_{131} = 0.05$ and $\lambda_{232} = 0.05$.

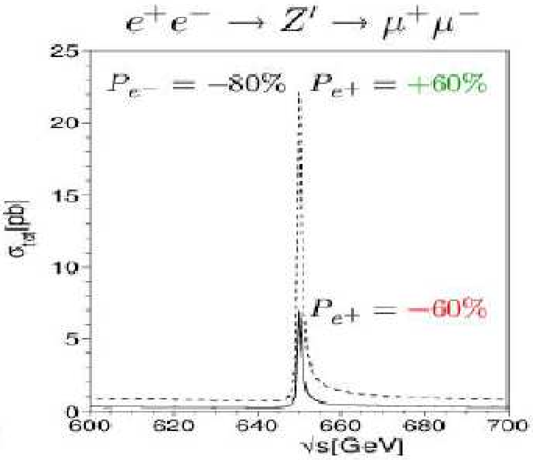

Figure 3. Z' prouction in the SSM model with a Z'-coupling of about 0.2, $m_{Z'} =$ 650 GeV and a very small width of about ≤ 1 GeV: resonance production for $e^+e^- \to Z' \to \mu^+\mu^-$ (right panel) [3]. The strong peak enhancement for the LR configuration with $(P_{e^-}, P_{e^+}) = (-80\%, +60\%)$ (dashed) is clearly dominant, whereas for the LL configuration $(P_{e^-}, P_{e^+}) = (-80\%, -60\%)$ (solid) —although not completely suppressed, due to only partial polarization— the signal is much smaller.

to be done with regard to their possible impact on the physics potential of the machine. The Technical Design Phase (TDP) of the ILC is under the responsibility of the 'Global Design Effort' (GDE).
Starting the industrial engineering phase, the optimization of, for instan ce, the cavities shapes are under study. Higher gradients up to 59 MV/m have alrea dy been achieved in single cells with so-called 're-entrant' cavities, developed by Cornell and KEK. Concerning the industrial cavity production, an averag e of 36 MV/m in nine-cell cavities has been achieved [9].

b) For achieving higher energies of $\sqrt{s}$ in the multi-TeV range a normalconducting two-beam acceleration concept is discussed, the Compact Linear Collider (CLIC). A conceptual design report is foreseen for 2010, where the key feasibility issues of the CLIC technology are foreseen to be demonstrated as well as the preliminary performance and a first cost estimation.

A fruitful ILC/CLIC collaboration has been started to address common R&D issues in the civil engineering & conventional facilities, beam delivery system, beam dynamics and detectors, more details see [9]. Comparing the potential of the two linear collider technologies several technical issues have to be taken into account that may have impact on the physics potential. Many precision measurements at a linear collider depend crucially on machine parameter more than on the achievable detector precision. For instance, the average energy loss i.e. beamstrahlung, has impact on the precision achievable via threshold scans and (polarized) cross sections. Beamstrahlung is predicted to be 2.4% at ILC with $\sqrt{s} = 500$ GeV (ILC500), 7% at CLIC with $\sqrt{s} = 500$ GeV (CLIC500) and 29% at CLIC technology with $\sqrt{s} = 3000$ (CLIC3000). A formidable experimental challenge arises from the short (0.5 ns) bunch spacing

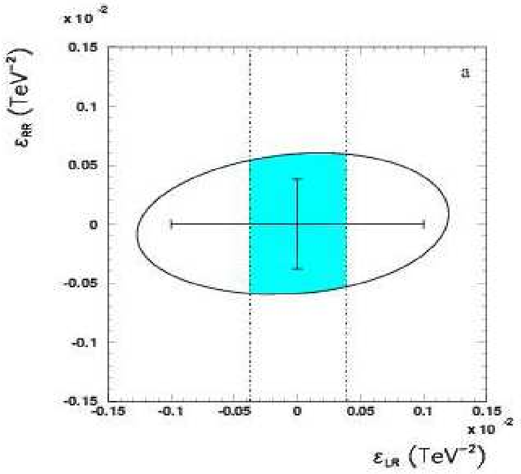

Figure 4. Contact-interaction in Bhabha scattering process $e^+e^- \to e^+e^-$: Allowed areas at 95% C.L. in the plane $(\epsilon_{\rm LR}, \epsilon_{\rm RR})$. The study was done at $\sqrt{s}$ = 0.5 TeV, $\mathcal{L}_{\rm int}(e^+e^-)$ = 50 fb^{-1}, $(|P_{e^-}|, |P_{e^+}|) = (80\%, 60\%)$. Vertical dashed lines indicate the range allowed for $\epsilon_{\rm LR}$ by $\hat{\sigma}_{{\rm LR},t}$. The cross indicates the constraints obtained by taking only one non-zero parameter at a time instead of two simultaneously non-zero and independent parameters [4].

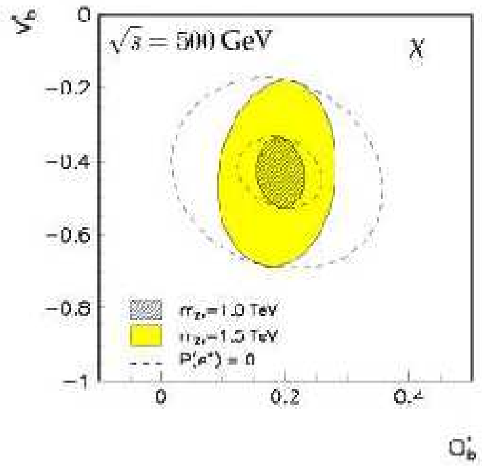

Figure 5. Determination of Z' couplings and masses with polarized beams: 95% C.L. contours for the axial $(a_b^{'})$ and vector $(v_b^{'})$ couplings of the Z' for $M_{Z'}$ = 1.0, 1.5 TeV in the χ realization of an E_6-model [5] model with $\sqrt{s}$ = 500 GeV and $\mathcal{L}_{\rm int}$ = 500 fb^{-1}. The solid line corresponds to $P_{e^+} = 60\%$, the dashed lines to $P_{e^+} = 0$ [5]; a_b', v_b' denote the couplings of Z' to the b-quarks.

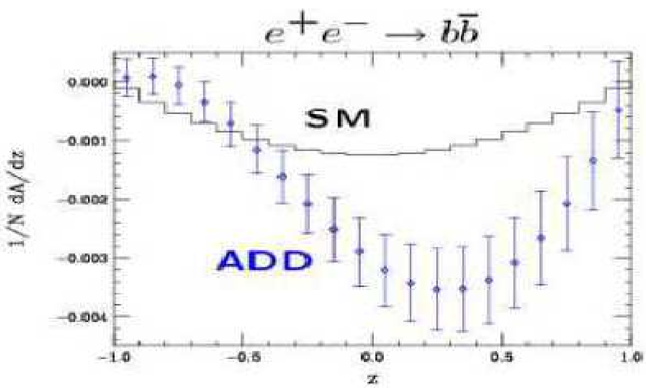

Figure 6. Differential azimuthal asymmetry distribution for $e^+e^- \to f\bar{f}$, e.g. $b\bar{b}$, at a 500 GeV LC assuming a luminosity of 500 fb^{-1}, $z = \cos\theta$. The histograms are the SM predictions while the data points assume the ADD model with M_H = 1.5 TeV; $(P^{\rm T}_{e^-}, P^{\rm T}_{e^+}) = (80\%, 60\%)$ [6].

at CLIC. Severe impact on the achievable precision due to pile-up of soft hadronic interactions can arise unless unprecedented time-stamping capability both for charged and neutral particles can be implemented into the CLIC detectors.Detailed simulations will be needed for achieving conclusive results concerning the physics potential of the different desig ns. Therefore a staged approach between the different design may be beneficial [9].

3.2. Polarized positron sources

The two main methods for positron production under consideration for the ILC are a photon-based source and a 'conventional' source. The photon-based source uses multi-MeV photons and relatively thin targets (less than a radiation length thick) to produce positrons. If the photons are circularly polarized, the positrons (and electrons) are spin polarized. This positron polarization can be preserved in the subsequent capture, acceleration, damping, and transport to the collision point(s). The conventional source uses a multi-GeV electron drive beam in conjunction with thick, high-Z targets to produce positrons from the resultant electromagnetic cascade in the target. The positrons produced by this method cannot be polarized. These two schemes ultimately present very similar engineering challenges while at the same time having distinct attributes and drawbacks. It is emphasized, however, that only the photon-based schemes offer the promise of positron polarization.

Circularly-polarized photons are required for the generation of longitudinally-polarized positrons via $e^{\pm}$ pair production in a thin target. The photons are in the energy range of a few MeV up to about 100 MeV. Because the target is typically a fraction of a radiation length thick, high strength materials, such as titanium alloys, can be considered as opposed to conventional targets, where high-Z, high-density materials are required to minimize the emittance of the produced positrons. The two methods for generating the polarized photons under consideration are:

- a high-energy electron beam ($\geq$150 GeV) passing through a short period, helical undulator. The E-166 experiment at SLAC, was a demonstration of this undulator-based polarized positron production scheme with great success [10].
- Compton backscattering of laser light off a GeV energy-range electron beam. The concept is being tested in an experiment which is currently running at KEK [11].

In both schemes a positron polarization of about $|P_{e^+}| \geq 60\%$ is expected at the ILC. It is expected to reach a polarization degree of $P_{e^+} \sim 60\%$ without any loss of luminosity, higher polarization seems to be achievable at cost of luminosity. But already within the baseline confguration a polarization of the positron beam of about 30% may be achievable [12].

Both schemes would be applicable for the ILC design [2] and also adaptable for a possible future multi-TeV LC design, CLIC.

3.3. Polarimetry requirements

In order to fully exploit the polarization of the beams, one also has to measure precisely the actual degree of polarization. Therefore high precision polarimetry is mandatory. 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 at the ILC are even more challenging and one aims for $\Delta P(e^{\pm})/P(e^{\pm}) \leq 0.25\%$. In order to achieve such a precision, Compton polarimeters in combination with a dedicated chicane system and Cerenkov detectors are implemented as upstream polarimeter. A downstream polarimeter is further required and is applicable due to the crossing angle. Further details, see [13]. Such a dual measurement enables machine feedback and provides access to a precise determination of the luminosity-weighted polarization at the interaction point if precise spin tracking is provided, see [14].

The main depolarization effects at a LC are the following two effects: the classical spin precession that is described via the Thomas–Bargmann-Michel-Telegdi equation (T-BMT) and the quantum-mechanical spin-flip process (Sokolov-Ternov effect). The largest effects are predicted for the beam-beam interaction region due to the strong field of the oncoming beam. Due such a strong field environment, higher-order quantum effects have to be calculated and taken into account as well, further details see [15]. The resulting depolarization effects have been evaluated and compared for the ILC RDR and the current CLIC design, see Table 1. Smaller depolarization effects are expected to occur in the damping rings, the spin rotators and the beam delivery system, but they have to be included. This work is still ongoing.

4. Conclusions

To face the (expected and unforeseen) challenges of possible new physics followe d by a precise reaveling of the underlying model requires the polarization of both beams as a superior experimen tal tool. It enables to probe directly new physics properties, to detect maybe even tiny traces of new CP-violating sources, to handle possible background processes from e.g. new physics itself. Furthermore it leads to higher statistics, better control of systematics and higher precision in polarization dependent observables as left-right asymmetries . Polarization of both beams at the ILC are therefore an ideal preparation for 'the unexpected' and it might be advisable to use this powerful and variable option already from the beginning. An upgrade of the machine and the complete implementation of another polarized-p ositron source at an later stage would require again a careful commissioning of a new source wh ich causes in any case losses in the total time of running. Therefore in case that a polarized source is already feasible at the start of th e ILC design and no major differences concerning the reliability and commissioning of the polarized-positron source compared to t he conventional positron source is expected, the implementation of the polarized-positron source should at least be completely designed and is foreseen for the baseline set-up.

Table 1. Depolarization effects in the beam-beam interaction region for ILC with fully polarized beams (100/100), with partially polarized beams (80/30) and for the CLIC-G design [16].

Effect	Depolarization ΔP_{lw}		
Design	ILC 100/100	ILC 80/30	CLIC-G
T-BMT (spin precession)	0.17%	0.14%	0.10%
ST (spin flip process)	0.05%	0.03%	3.4%
incoherent pairs	0.0%	0.0%	0.06%
coherent pairs	0.0%	0.0%	1.3%
total	0.22%	0.17%	4.8%

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