Physics case for polarized e^+ – Some examples from the Polarization report[1]

A high degree of at least 80% polarization is envisaged for the e^- beam, but new results indicate that even 90% should be achievable. A degree of $P(e^+) \geq 60\%$ is discussed for the positron beam.

- **Introductory remarks**
  Physics processes occur through e^-e^+ annihilation ('s'-channel diagrams) and scattering ('t, u'-channel diagrams). In annihilation diagrams the helicities of the incoming beams are coupled to each other, whereas in scattering processes, they are coupled to those of the final particles and therefore are directly sensitive to their chiral properties. In such processes only $P(e^+)$ can uniquely test the couplings of the final 'new' particles.

  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 $m_e/\sqrt{s}$) .

- **Statistical issues**
  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, the left-right asymmetry $A_{\rm LR}$ and two polarization dependent factors, the effective polarization ($P_{\rm eff} = [P_{e^-} - P_{e^+}]/[1 - P_{e^-}P_{e^+}]$) and the effective luminosity ($\mathcal{L}_{\rm eff} = \frac{1}{2}[1 - P_{e^-}P_{e^+}]\mathcal{L}$ with $\mathcal{L}_{\rm eff}/\mathcal{L}$ reflecting the number of interacting particles). The effective polarization reaches $P_{\rm eff} = 90\%$ for $\{P_{e^-}, P_{e^+}\} = \{90\%, 0\}$ but $P_{\rm eff} = 95\%$ (97%) for $\{P_{e^-}, P_{e^+}\} = \{\pm 80\%, \mp 60\%\}$ ($\{P_{e^-}, P_{e^+}\} = \{\pm 90\%, \mp 60\%\}$).

  The ratio of colliding and interacting particles can only be enhanced if P_{e^+} is available: from the value $\frac{1}{2}$ for unpolarized positrons up to $\mathcal{L}_{\rm eff}/\mathcal{L} = 0.74$ (0.77) for $\{P_{e^-}, P_{e^+}\} = \{\pm 80\%, \mp 60\%\}$ ($\{P_{e^-}, P_{e^+}\} = \{\pm 90\%, \mp 60\%\}$).

  The relative uncertainty for any left-right asymmetry $A_{\rm LR}$ is given by the expected polarimeter precision ($\Delta P/P \sim 0.5\%$ up to 0.2%) and can only be decreased if polarized e^+ are available: with $\{P_{e^-}, P_{e^+}\} = \{\pm 80\%, \mp 60\%\}$ ($\{\pm 90\%, \mp 60\%\}$) the uncertainty $\Delta A_{\rm LR}/A_{\rm LR}$ is reduced by about a factor 3.2 (3.4).

- **Relevance of $P(e^+)$ up to 500 GeV and in case that LHC found new physics**
  One of the most promising candidates for physics beyond the SM is Supersymmetry (SUSY). The LHC has a large discovery potential to detect coloured SUSY particles up to 2.5 TeV. To really establish SUSY, all model assumptions and implementations have to be verified experimentally. Furthermore the underlying parameters have to be precisely determined as model-independent as possible. Parameter fits within the SUSY parameter space, consistent with electroweak precision measurements and cosmological bounds, predict that some of the electroweak interacting SUSY particles should be accessible at the ILC with 500 GeV.

  Polarized e^- and e^+ are crucial to verify SUSY quantum numbers and Yukawa couplings. These effects can not be fulfilled by even 100% polarized electrons. Furthermore polarized e^+ are needed to provide more observables in order to determine the SUSY parameters, in particular if only limited experimental information is available since it is expected to access only the light spectrum at low energy.

[1] G. Moortgat-Pick et al., hep-ph/0507011; updated version and an executive summary accessible at www.ippp.dur.ac.uk/~gudrid/power

Polarized e^+ are also required to derive model-independent bounds in indirect searches for new physics, e.g. for contact interactions and in particular to get systematics in hadronic final states under control.

The distinction between different models of large extra dimensions, the ADD and the RS model, can be uniquely performed even in indirect searches up to a high scale of about 3 TeV if transversely polarized beams are available.

- **Relevance of $P(e^+)$ up to 500 GeV and in case that LHC found only the Higgs**
  It will be crucial to precisely determine the mass, couplings, spin and CP properties of the new particle, i.e. the Higgs, in order to establish experimentally the mechanism of electroweak symmetry breaking. To reach this goal the precise measurement of the top Yukawa couplings and the triple Higgs couplings is needed. Both are very challenging, in particular at $\sqrt{s} = 500$ GeV because of the expected small cross sections.

  At the LHC a precision of about 20% is expected (however, under some model assumptions). A precision of 24% for the top Yukawa coupling and $m_H = 120$ GeV is expected at the ILC with $\mathcal{L} = 1000$ fb^{-1}. At the ILC the improvement factor is about 2.5 when using $\{P_{e^-}, P_{e^+}\} = \{\pm 80\%, \mp 60\%\}$ compared with $\{P_{e^-}, P_{e^+}\} = \{\pm 80\%, 0\%\}$ and are crucial to improve the bounds from the LHC.

  Even more challenging is the measurement of the triple Higgs couplings at $\sqrt{s} = 500$ GeV, predictions expect a precision of about 22%-30% only. No true simulation results exist so far for the inclusion of polarized beams. However, an improvement of about a factor 2 is estimated when using both beams polarized.

- **Relevance of $P(e^+)$ up to 500 GeV and in case that LHC did not find anything**
  Precise measurements of the properties of the top quark, which is by far the heaviest known elementary particle, will greatly advance our understanding of the underlying physics at the quantum level. The precise measurement of the electroweak couplings and deviations from their Standard Model (SM) prediction can only be done at the ILC. The enhancement factor of about 3 in the determination of the electroweak couplings with $\{P_{e^-}, P_{e^+}\} = \{\pm 80\%, \mp 60\%\}$ compared to $\{P_{e^-}, P_{e^+}\} = \{\pm 80\%, 0\%\}$ or also $\{P_{e^-}, P_{e^+}\} = \{\pm 90\%, 0\%\}$ is crucial.

  Polarized e^+ are also crucial to outline possible high new scales. The kind of new possible interactions (scalar, tensor) could be tested with transversely polarized beams up to a high scale of 7 TeV.

- **Relevance of $P(e^+)$ up to an upgrade energy of $\sqrt{s} = 1$ TeV**
  The physics potential of the 1 TeV upgrade depends significantly on the results of the LHC and the ILC at 500 GeV. To reach the maximal outcome at the first stage will greatly improve the upgrade approval. In that context, polarized e^+ may play the crucial role in exploiting the full potential of the ILC at the 500 GeV stage.

  At the 1 TeV stage polarized e^+ will continue to be crucial for the verification of model assumptions, the determination of the kind of interaction and to provide model-independent results and will further improve all physics analysis by about the same factors given in the table.

- **GigaZ**
  Extremely sensitive tests of the SM can be performed with the help of electroweak precision observables. These are measurable with unprecedented accuracy only at the GigaZ option. To reach such a precision the polarization of both beams is required.

The improvement factor with both beams polarized compared to polarized e^- is about one order of magnitude.

Such a precision leads to an improvement of the Higgs bounds to also about one order of magnitude and concerning new physics models, e.g. to a further constraining of the possible allowed parameter range in Supersymmetry (SUSY) by about a factor 5.

So far the GigaZ option is only discussed as a later upgrade for the ILC. But physics arguments could require that a quick and cheap upgrade path to GigaZ be provided straight after the $\sqrt{s} = 500$ GeV stage, also calling for an easy path towards the option of polarized e^+.

Case	Effects for $P(e^-) \longrightarrow P(e^-)$ and $P(e^+)$	Gain& Requirement
Standard Model:		
top threshold	Electroweak coupling measurement	factor 3
$t\bar{q}$	Limits for FCN top couplings improved	factor 1.8
CPV in $t\bar{t}$	Azimuthal CP-odd asymmetries give access to S- and T-currents up to 10 TeV	$P^{\rm T}_{e^-} P^{\rm T}_{e^+}$ required
W^+W^-	Enhancement of $\frac{S}{B}$, $\frac{S}{\sqrt{B}}$	up to a factor 2
	TGC: error reduction of $\Delta\kappa_\gamma$, $\Delta\lambda_\gamma$, $\Delta\kappa_Z$, $\Delta\lambda_Z$	factor 1.8
	Specific TGC $\tilde{h}_+ = {\rm Im}(g_1^{\rm R} + \kappa^{\rm R})/\sqrt{2}$	$P^{\rm T}_{e^-} P^{\rm T}_{e^+}$ required
CPV in γZ	Anomalous TGC $\gamma\gamma Z$, γZZ	$P^{\rm T}_{e^-} P^{\rm T}_{e^+}$ required
HZ	Separation: $HZ \leftrightarrow H\bar{\nu}\nu$	factor 4
	Suppression of $B = W^+\ell^-\nu$	factor 1.7
$t\bar{t}H$	Top Yukawa coupling measurement at $\sqrt{s} = 500$ GeV	factor 2.5
Supersymmetry:		
$\tilde{e}^+\tilde{e}^-$	Test of quantum numbers L, R and measurement of $e^{\pm}$ Yukawa couplings	P_{e^+} required
$\tilde{\mu}\tilde{\mu}$	Enhancement of S/B, $B = WW$ $\Rightarrow m_{\tilde{\mu}_{\rm L,R}}$ in the continuum	factor 5-7
HA, $m_A > 500$ GeV	Access to difficult parameter space	factor 1.6
$\tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}^0\tilde{\chi}^0$	Enhancement of $\frac{S}{B}$, $\frac{S}{\sqrt{B}}$	factor 2–3
	Separation between SUSY models, 'model-independent' parameter determination	
CPV in $\tilde{\chi}^0_i\tilde{\chi}^0_j$	Direct CP-odd observables	$P^{\rm T}_{e^-} P^{\rm T}_{e^+}$ required
RPV in $\tilde{\nu}_\tau \to \ell^+\ell^-$	Enhancement of S/B, $S/\sqrt{B}$	factor 10 with LL
	Test of spin quantum number	
Extra Dimensions:		
$G\gamma$	Enhancement of S/B, $B = \gamma\nu\bar{\nu}$,	factor 3
$e^+e^- \to f\bar{f}$	Distinction between ADD and RS models	$P^{\rm T}_{e^-} P^{\rm T}_{e^+}$ required
New gauge boson Z′ :		
$e^+e^- \to f\bar{f}$	Measurement of Z' couplings	factor 1.5
Contact interactions:		
$e^+e- \to f\bar{f}$	Model independent bounds	P_{e^+} required
Precision measurements of the Standard Model at GigaZ:		
Z-pole	Improvement of $\Delta\sin^2\theta_W$	$\sim$ factor 10
	Improvement of Higgs bounds	$\sim$ factor 10
	Constraints on CMSSM parameter space	factor 5
CPV in $Z \to b\bar{b}$	Enhancement of sensitivity	factor 3

Summary table: the case of having both beams polarized is compared with the case of using only polarized electrons, in most cases $(|P_{e^-}|, |P_{e^+}|) = (80\%, 60\%)$ versus $(|P_{e^-}|, |P_{e^+}|) = (80\%, 0\%)$ at $\sqrt{s} = 500$ GeV, details see polarization report; B (S) denotes background (signal); CPV (RPV) means CP (R-parity) violation, FCN means flavour changing courrents, TGC denotes triple gauge couplings. details see Polarization report and references therein.