Physics with polarized beams: motivation and requirements

- **Physics requirements**
  - on the machine
  - on polarization
- **Physics case for polarized beams**
  - general features
  - at $\sqrt{s}$=500 GeV
  - with the baseline design
  - at GigaZ/WW threshold: see next talk by Georg
- **Summary tables and conclusions**

ICFA Parameter Group

- 'Scope Document no.1' (2003) and 'no.2' (2006): baseline
  - 'full luminosity of $2 \times 10^{34} cm^{-2} s^{-1}$'
  - 'beam energy stability and precision below tenth of percent level.'
  - 'Machine interface must allow measurements of beam energy and diff. lumi spectrum with similar accuracy.'
  - 'electron beams with polarisation of at least 80% within whole energy range.'
- Options:
  - 'e^+ polarisation ~50% in whole energy range wo sign. loss of lumi...., Reversal of helicity ... between bunch crossings.'
  - GigaZ: e^+ polarisation+frequent flips essential; energy stability+calibration accuracy below tenth of percent level.'

Physics requirements for the ILC

- *Have to be seen on basis of possible LHC results!*
- **Needed accuracy**
  - expected: for most physics studies $\Delta P/P=0.5\%$ (0.25%) sufficient; for precision measurements $\Delta P/P<0.1\%$ required
- **Since polarization@IP = lumi-weighted polarization ≠ polarization@polarimeter**
  - Depolarization effects have to be well under control !
  - main effects during beam-beam: ST and T-BMT effects
  - total 0.2% (see EPAC06, consistent with works of K. Thompson/A. Weidemann)
  - updates of theoretical methods under work
- **Two polarimeters important to fulfill requirements**

Physics case for polarized e^- and e^+

- comprehensive overview given in 'POWER' report
  - hep-ph/0507011, now in press as Physics reports
  - see also 'executive summary' at

    www.ippp.dur.ac.uk/~gudrid/source/
- Goals: Polarized beams required to
  - analyze the structure of all kinds of physics
  - improve statistics: enhance rates, suppress backgrounds
  - get systematic uncertainties under control
- Discoveries via deviations from SM predictions in precision measurements !
  - important in particular at sqrt{s}≤500 GeV!

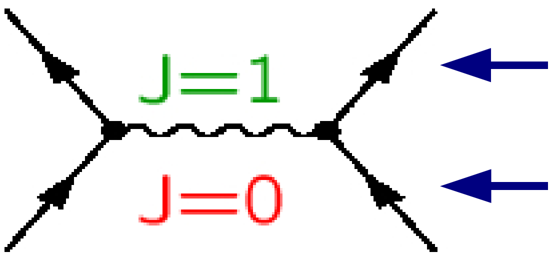
Baseline design

- **Undulator-based source with helical undulator (~100m length)**
  - most mature source:

    fits lumi requirements, DR acceptance, less activation problems, less thermal problems, easy upgrade path to polarization,...
- **Specific feature:**
  - could provide polarization already in baseline (if collimator, polarimeter, fast kicker povided)
  - 30% seems to be easily achievable, maybe even 45% (see Andriy)
- **Such start-polarization can be easily destroyed, of course ...**
  - but useful physics could already be done with little effort !

General features

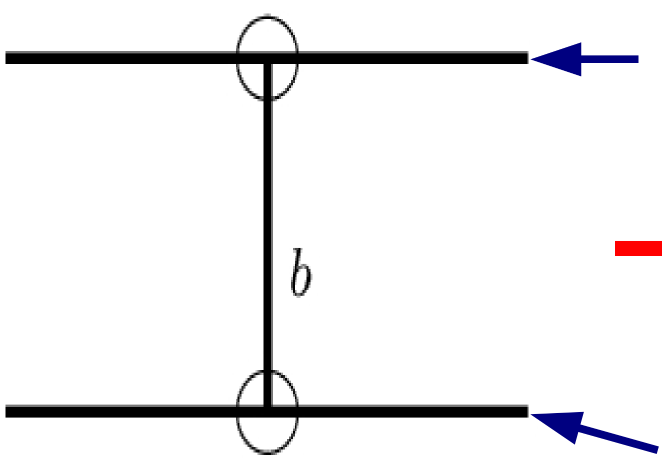
- Def.: left-handed = P(e±)<0 'L' right-handed= P(e±)>0 'R'
- Which configurations are possible in annihilation channels?



LR, RL: SM and(?) NP (γ, Z)

LL, RR: NP !

- Which configurations are possible in scattering channels?



depends on P(e+)

helicity of e- not coupled

with helicity of e+ !

depends on P(e-) !

→ all combinations LL,LR,RL,RR can contribute

General features II

- For many processes (V, A interactions) one can write:

$$\sigma(P_{e-}\, P_{e+}) = (1 - P_{e-}\, P_{e+})\, \sigma_0\, [1 - P_{eff}\, A_{LR}]$$

- Effective polarization
  - Peff:=(Pe—Pe+)/(1-Pe-Pe+)==(#LR-#RL)/(#LR+#RL)
- Fraction of colliding particles
  - Leff/ L=1/2 (1-Pe- Pe+)=(#LR+#RL)/(#all)

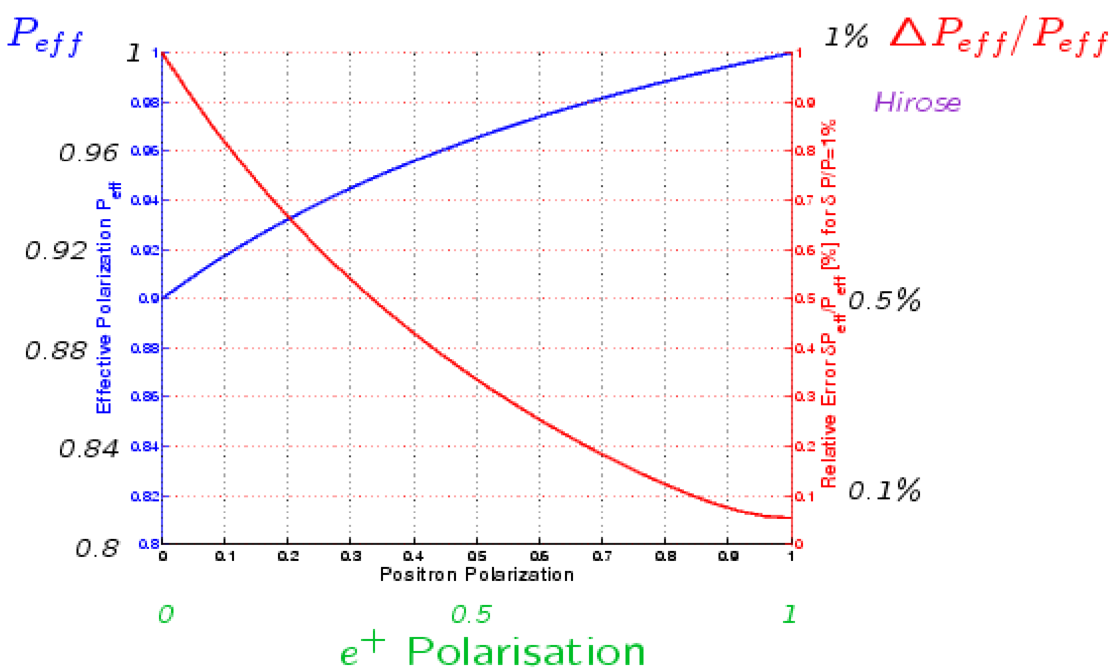
	RL	LR	RR	LL	P_{eff}	$\mathcal{L}_{eff}/\mathcal{L}$
$P(e^-) = 0$, $P(e^+) = 0$	0.25	0.25	0.25	0.25	0.	0.5
$P(e^-) = -1$, $P(e^+) = 0$	0	0.5	0	0.5	-1	0.5
$P(e^-) = -0.8$, $P(e^+) = 0$	0.05	0.45	0.05	0.45	-0.8	0.5
$P(e^-) = -0.8$, $P(e^+) = +0.6$	0.02	0.72	0.08	0.18	-0.95	0.74

General features Iii

- **Gain in 'effective luminosity' only with P_{e-} and P_{e+}**
  - **~similar flip frequency for e- and e+ needed, otherwise this gain is lost! (see also Sabines talk yesterday!)**
- **Gain in accuracy for A_{LR}:**

$$\Delta P_{eff} = \left(\frac{\partial P_{eff}}{\partial P_{e^-}}\right)\Delta P_{e^-} + \left(\frac{\partial P_{eff}}{\partial P_{e^+}}\right)\Delta P_{e^+}$$

$$= \left(\frac{\partial P_{eff}}{\partial P_{e^-}}\right)\left(\frac{\Delta P_{e^-}}{P_{e^-}}\right)P_{e^-} + \left(\frac{\partial P_{eff}}{\partial P_{e^+}}\right)\left(\frac{\Delta P_{e^+}}{P_{e^+}}\right)$$



$$\frac{\Delta P_{eff}}{P_{eff}} = \frac{1+P_{e^-}P_{e^+}}{1-P_{e^-}P_{e^+}}\left(\frac{\Delta P}{P}\right)$$

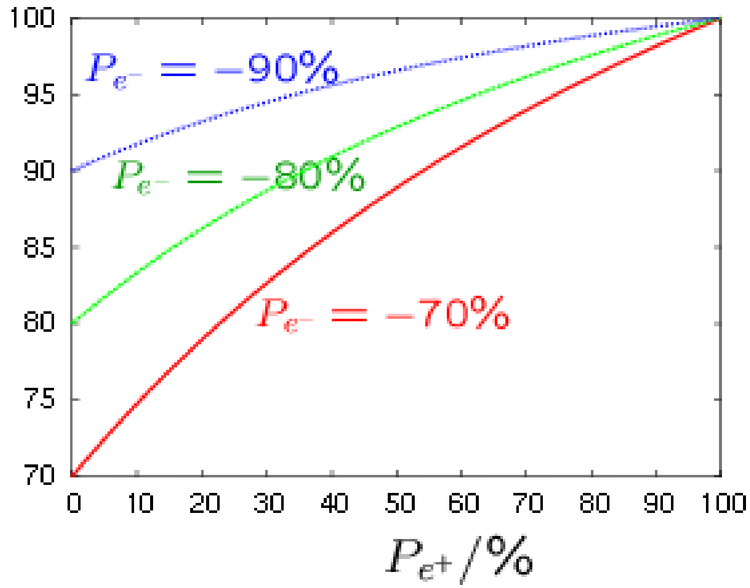
~Δ A_{LR} /A_{LR}

- **the gain for A_{LR} a priori independent on flip frequency but flipping desired to keep flexibility**

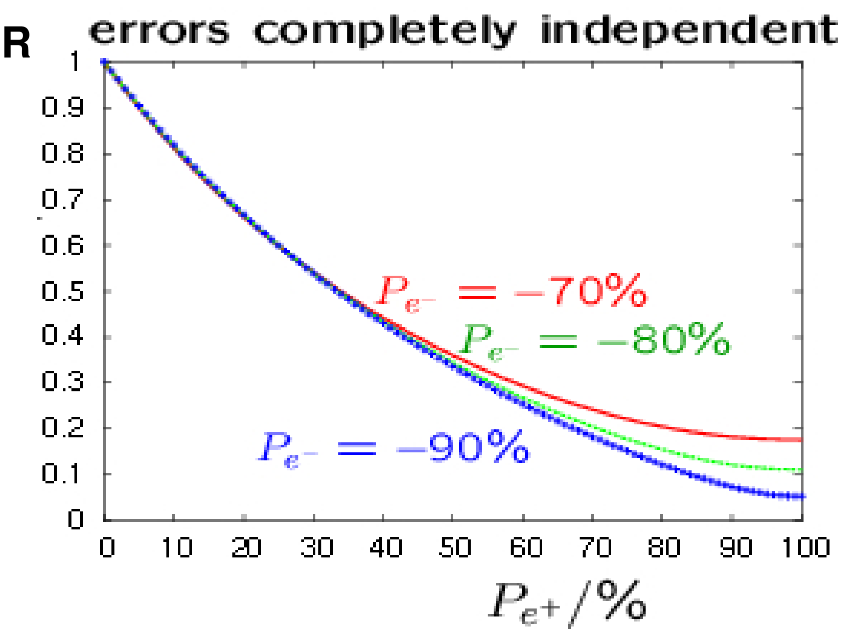
General features IV

- **Statistics**

P_{eff} /%



~$\Delta A_{LR}/A_{LR}$



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(80%,60): P_{eff} = 95%	(90%,60%): P_{eff} =97%	(90%, 30%): P_{eff} =94 %
$\Delta A_{LR}/A_{LR}$ = 0.3	$\Delta A_{LR}/A_{LR}$ = 0.27	$\Delta A_{LR}/A_{LR}$ =0.5
gain: factor~3	factor>3	factor~2

- **NO gain with only pol. e- (even if '100% ') !**

'Top' physics

- **Current average:** $m_{top} = 172.6 \pm 1.4$ GeV
- **Expectations at the LHC:**
  - $\Delta m_{top} \sim 1$ GeV
  - Yukawa couplings $\sim$ 20 % (with slight model assumptions)
- **Expectations at the ILC:**
  - Mass via threshold scans: $m_{top} \sim 100$ MeV (theory dominant)
  - Yukawa couplings via $t\bar{t}H$: difficult due to small rates, but < 20%
  - Unique access to electroweak couplings
- **Why are top properties so important?**
  - m_{top} is dominant uncertainty for elw. precision observables
  - ILC precision mandatory already now to exploit theory at quantum level!

Unique access to electroweak couplings

- **Process: e+ e- → $t\bar{t}$ (test of couplings t → γ, Z)**

$$\Gamma^{\mu}_{t\bar{t}\gamma,Z} = ie\{\gamma^{\mu}[F^{\gamma,Z}_{1V} + F^{\gamma,Z}_{1A}\gamma^5] + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t}[F^{\gamma,Z}_{2V} + F^{\gamma,Z}_{2A}\gamma^5]\}$$

- **Studies at threshold:**

$v_t = (1 - \frac{8}{3}\sin^2\theta_W)$ **via** A_{LR}

$\Rightarrow \Delta A_{LR}/A_{LR} \sim \Delta P_{eff}/P_{eff}$

→ **up to per mille level**

Form factor	SM value	$\sqrt{s} = 500\,\mathrm{GeV}$		$\sqrt{s} = 800\,\mathrm{GeV}$	
		$p = 0$	$p = -0.8$	$p = 0$	$p = -0.8$
F^Z_{1V}	1		0.019		
F^Z_{1A}	1		0.016		
$F^{\gamma,Z}_{2V} = (g-2)^{\gamma,Z}{}_t$	0	0.015	0.011	0.011	0.008
$Re\, F^{\gamma}_{2A}$	0	0.035	0.007	0.015	0.004
$Re\, d^{\gamma}_t$ $[10^{-19}$ e cm$]$	0	20	4	8	2
$Re\, F^Z_{2A}$	0	0.012	0.008	0.008	0.007
$Re\, d^Z_t$ $[10^{-19}$ e cm$]$	0	7	5	5	4
$Im\, F^{\gamma}_{2A}$	0	0.010	0.008	0.006	0.005
$Im\, F^Z_{2A}$	0	0.055	0.010	0.037	0.007
F^W_{1R}	0	0.030	0.012		
$Im F^W_{2R}$	0	0.025	0.010		

- **Can be improved via polarized beams:**

⇒ (80%,0)→(80%,60%): factor 3!

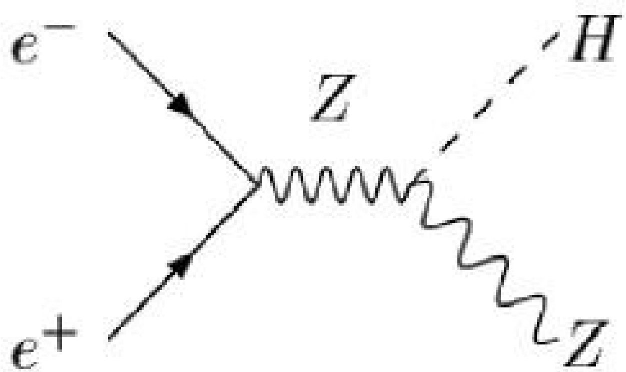
(80%,0) → (80%,30%): factor 2

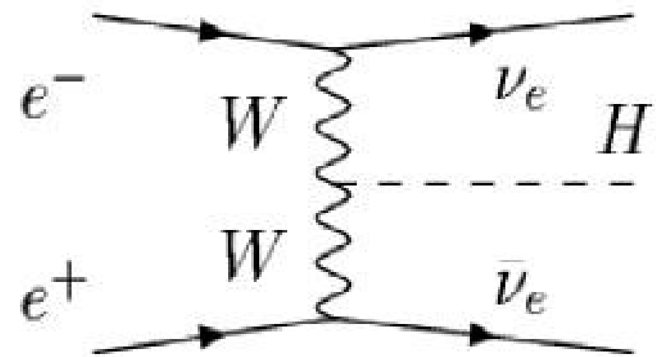
Determination of Higgs properties

- Expectations at the LHC:
  - Higgs mass: up to Δm_H =100-200 MeV
  - Higgs couplings: 15%-40% (with some model assumptions)
  - Higgs spin: challenging
- Expectations at the ILC:
  - at top threshold ($\sqrt{s}$=350 GeV) and at $\sqrt{s}$=500 GeV up to Δm_H=50 MeV !
  - absolute couplings: 1-5 %
  - Establishing of ew sym. breaking: triple Higgs couplings at 500 GeV up to 22%
  - Higgs spin: clear access via threshold scan
  - non-Standard Higgs properties: CP-properties
  - disentangling of light SUSY Higgs and SM Higgs via precision measurements of couplings

Physics with a light (SM-like) higgs

- Light Higgs, e.g. mH=130 GeV: HZ and H νν similar rates at 500 GeV





- P(e-), P(e+) needed for:
  - separation
  - background suppression
- σ(H Z) / σ (H νν):

(+80%,0) → (+80%,-60%)

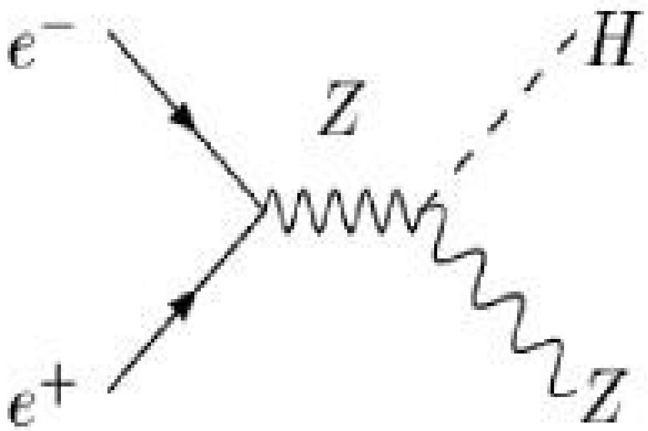
→ improves by factor 4!

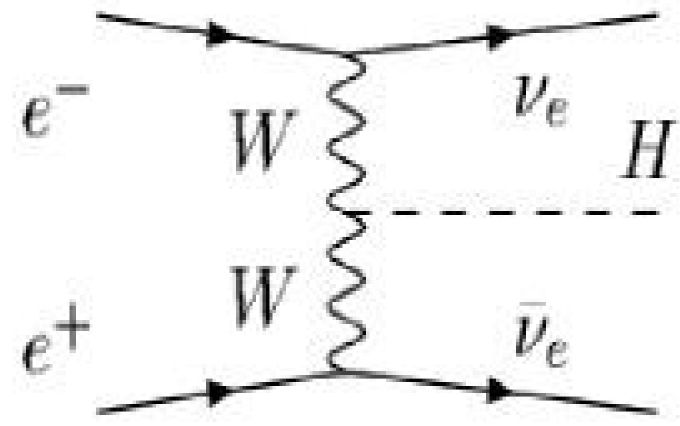
Configuration (P_{e^-}, P_{e^+})	Scaling factors $e^+e^- \to H\nu\bar{\nu}$	$e^+e^- \to HZ$
$(+80\%, 0)$	0.20	0.87
$(-80\%, 0)$	1.80	1.13
$(+80\%, -60\%)$	0.08	1.26
$(-80\%, +60\%)$	2.88	1.70
(+80%, -30%)	0.14	1.06
(-80%, +30%)	2.34	1.42

- (+80%,0) → (+80%, -30%): ratio HZ / $H\nu\bar{\nu}$ → gain ~ factor 2

Higgs couplings

- Couplings determination: high rates and lumi needed





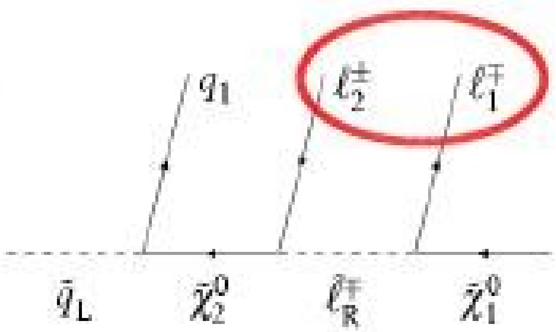
- measurement of couplings in Higgs-strahlungs process at $\sqrt{s}$=350 GeV
- beam polarization (80%,0) ⟶ (80%, 60%): improvement by about 30%
- triple Higgs couplings: e.g. in HHZ at $\sqrt{s}$=500 up to 22% (unpolarized beams)
- estimate: further gain of 30%-50% precision if both beams polarized

Top-Higgs Yukawa couplings

- **Expectations at the LHC:**
  - Yukawa couplings up to ~20% (with some model assumptions)
- **Expectations at the ILC:**
  - process t t H: difficult due to small rates (but threshold effects!)
  - accuracy about 24% for mH=120 GeV (unpolarized beams)
  - improvement factor 2.5 when (80%, 0%) -> (80%,60%)
  - due to gain in ΔA_{LR} accuracy
- **Precise measurement important**
  - in general
  - also for distinction between SM and SM-like Higgs ...

Further SUSY particles

- Whats needed for establishing SUSY?
  - Spin verification: via analysis of angular distributions
  - Couplings measurement: Yukawa couplings = gauge couplings
  - Precise mass measurements
  - Unraveling the SUSY breaking mechanism and test unification
  - 'model- independent' determination of the parameters (105 already in the MSSM!)
- Expectations at the LHC:
  - Coloured SUSY partners: discovery reach $m_{\tilde{q},\tilde{g}}$< 2-2.5 TeV
  - Non-coloured partners: a) via Drell-Yan m_{χ} < 250 GeV
    b) via cascade decay chains
  - Parameter determinations: in specific SUSY breaking models

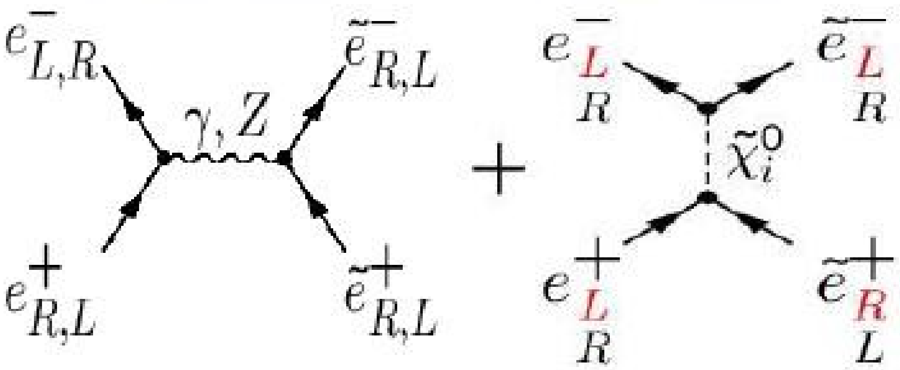


- Particularly promising field for LHC/ILC interplay studies !

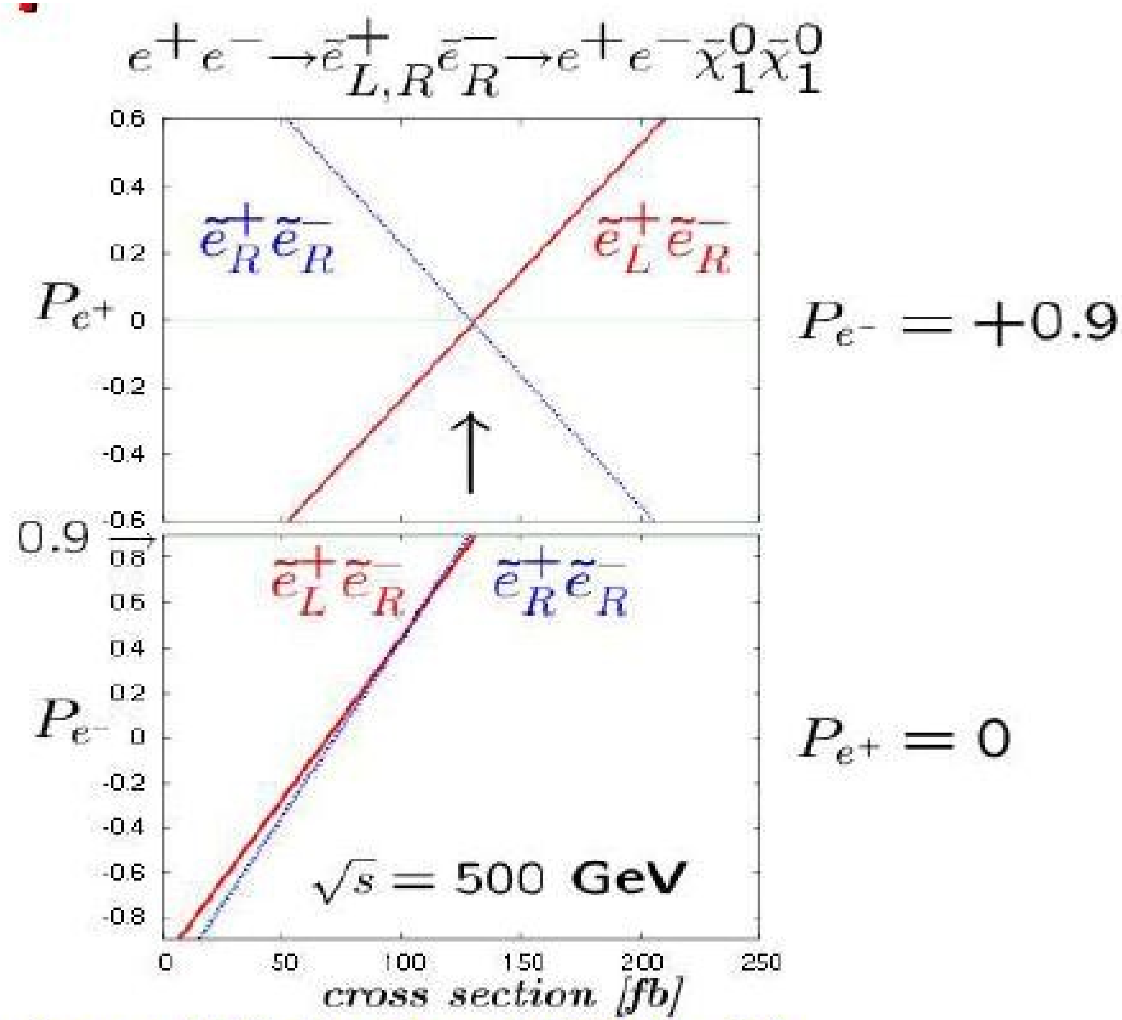
Properties of SUSY particles

- Association of chiral electrons to scalar partners $e^-_{L,R} \leftrightarrow \tilde{e}^-_{L,R}$ and $e^+_{L,R} \leftrightarrow \tilde{e}^+_{R,L}$:

s-channel t-channel



1. separation of scattering versus annihilation channel



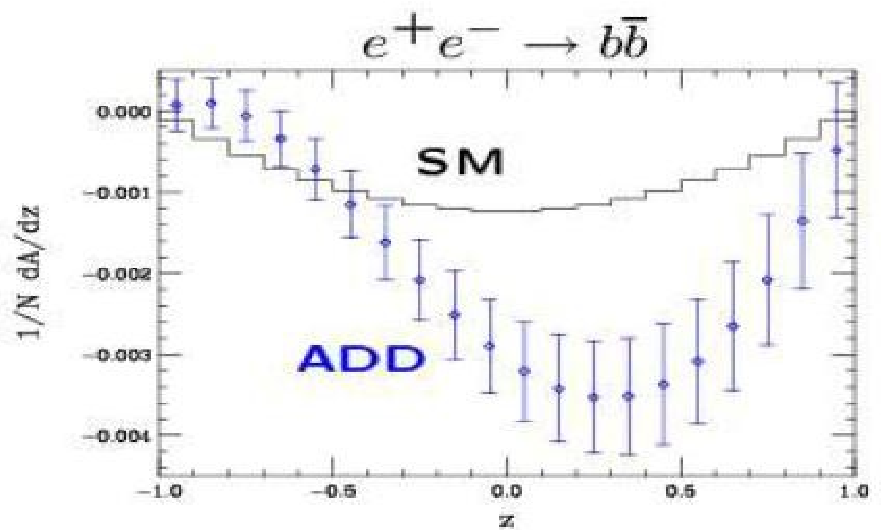
2. test of 'chirality': only $\tilde{e}^+_L\tilde{e}^-_R$ survives at P(e-) > 0 and P(e+) > 0 !

→ (90%,60%)~200 fb / 50 fb ~ 4 , (90%, 30%)~ 175 fb / 75 fb ~ 2.3

- *Even high P(e-) not sufficient, P(e+) is substantial!*

Transversely polarized beams

- Remember: only effects detectable if P(e-) and P(e+)
  - ➛ enables to exploit azimuthal asymmetries
- Offers the construction of CP-odd observables in neutralino production
- Offers distinction between SM and different models of extra dimensions



- Since $P_T(e^-) \times P_T(e^+)$-dependence:
  - ➛ effects decrease by about a factor 2 when using (80%,30%) instead of (80%60%)

⟶ Transversely polarized beams very effective, need polarized e^- and e^+ !

Summary table of POWER report

- **Comparison with (80%,0): estimated gain factor when**

most (80%, 60%) (80%, 30%)

Case	Effects for $P(e^-) \longrightarrow P(e^-)$ and $P(e^+)$	Gain& Requirement	most (80%, 60%) (80%, 30%)
Standard Model:			
top threshold	Electroweak coupling measurement	factor 3	**gain factor 2**
$t\bar{q}$	Limits for FCN top couplings improved	factor 1.8	**gain factor 1.4**
CPV in $t\bar{t}$	Azimuthal CP-odd asymmetries give access to S- and T-currents up to 10 TeV	$P^T_{e^-} P^T_{e^+}$ required	**P^T_{e-} P^T_{e+} required factor 1.3 worse**
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 $\tilde{h}_+ = \mathrm{Im}(g_1^R + \kappa^R)/\sqrt{2}$	$P^T_{e^-} P^T_{e^+}$ required	**P^T_{e-} P^T_{e+} required**
CPV in γZ	Anomalous TGC $\gamma\gamma Z, \gamma ZZ$	$P^T_{e^-} P^T_{e^+}$ required	
HZ	Separation: $HZ \leftrightarrow H\bar{\nu}\nu$	factor 4	**gain factor 2**
	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	**gain factor 1.6**

Conclusions

- ILC(500) physics has to be seen on basis of LHC results
  - e.g. in ttH ILC(500) only superior to LHC if both beams polarized ...
- P(e+) essential to reveal the new physics (CP, SUSY, ED)
- P(e+) essential to match required accuracy at ILC(500)
  - Higgs mechanism and couplings
  - Properties and quantum numbers of new particles
- Transversely polarized beams unique ~ P(e-)P(e+)
- P(e+)=30% from the start: already sufficient for some cases!

  (but quick upgrade path to higher P(e+)>=60% desired, of course.)
  - sufficiently qick helicity flipping needed
  - we could destroy polarization, but wouldn't that be stupid?