# The physics aspects of polarized e+

## *POSIPOL 2006*

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- Introduction
- The Physics case for polarized e- and e+
  - Top and Higgs
  - Supersymmetry and other kinds of new physics
  - Constraints from high-precision tests at Gigaz
- Conclusion

# Goals of physics at the LC

- Discovery of New Physics (NP)
  - complementary to the LHC
  - large potential for direct searches
  - impressive potential also for indirect searches
- Unraveling the structure of NP
  - precise determination of underlying dynamics and parameters
  - model distinction through model-independent searches
- High precision measurements
  - test of the Standard Model (SM) with unprecedented precision
  - even smallest hints of NP could be observed

→ **Beam polarization = decisive tool for direct and indirect searches!**

# General remarks for all kind of searches

- Expected: e- polarization of about 90% ....... won't such high P(e-) suffice?
- Precision measurements require:
  - high statistics! Often only small rates in new models.......
  - determine and testing the properties of the particles
  - determination of the kind of interactions
  - verify/falsify the underlying model
  - some thresholds scans of new particles needed: cost luminosity, can be optimized via good measurements in the continuum
  - deviations from Standard Model predictions may lead to discovery of NP in indirect searches: high energy and high lumi needed
- Beam polarization of e- and e+: either a) substantial and/or b) lucrative!

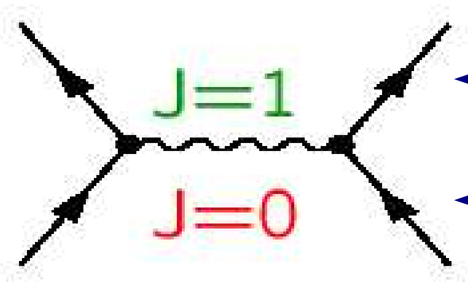
# Polarization report

## `The role of polarized positrons and electrons in revealing fundamental interactions at the Linear Collider'

- Physics case for polarized e- and e+ established
  - 150 pages, ~ 80 authors, ~ 35 institutes (CERN, DESY, Fermilab, KEK, SLAC)
  - incl. 90 pages physics, 20 pages machine, 20 pages polarimetry
  - GMP et al., hep-ph/0507011, submitted to Physics Reports
  - *http://www.ippp.dur.ac.uk/~gudrid/power*
  - *Thanks to all authors and special to S. Riemann, P. Osland, N. Paver, R. Pitthan, P.Schueler, J. Sheppard and M. Woods !*
- *Executive summary, 12 pages, same webpage*
- News from physics with polarized beams in Standard Model Physics, Supersymmetry, Extra Dimensions and other kinds of new physics
  - focus on use of P(e+) compared to P(e-) only

# General remarks about the coupling structure

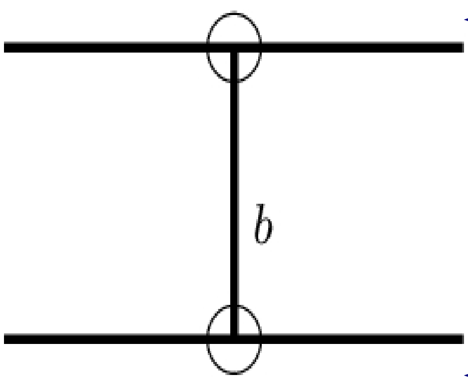
- Def.: left-handed = P(e±)<0 'L' right-handed= P(e±)>0 'R'
- Which configurations are possible in annihilation channels?




contributions from LR, RL: SM and(?) NP (γ, Z)

contributions only from LL, RR: NP !

- Which configurations are possible in scattering channels?




depends on P(e+)!

helicity of e- not coupled

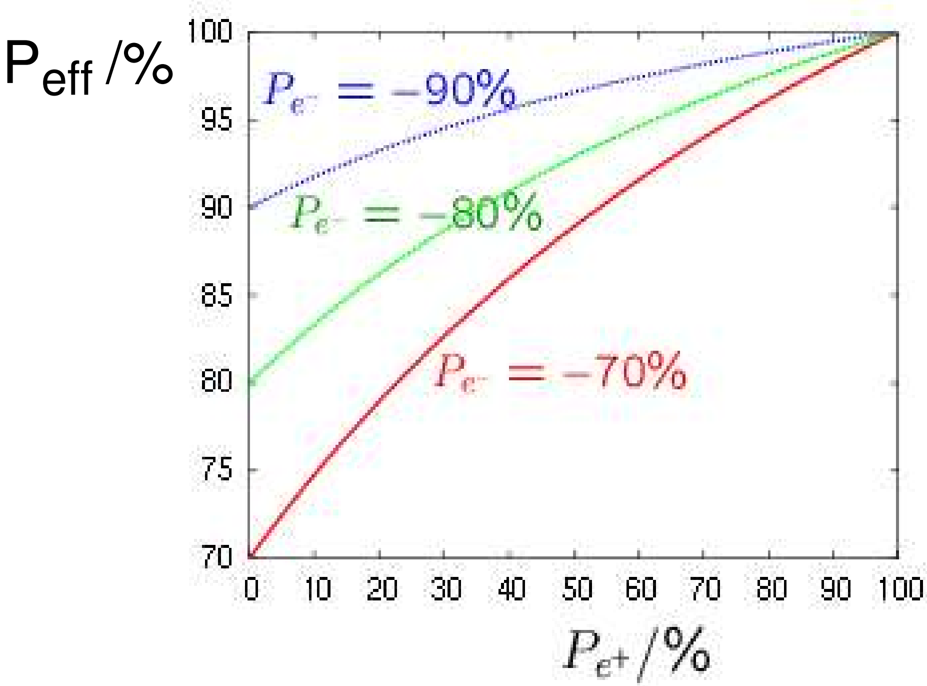
with helicity of e+ !

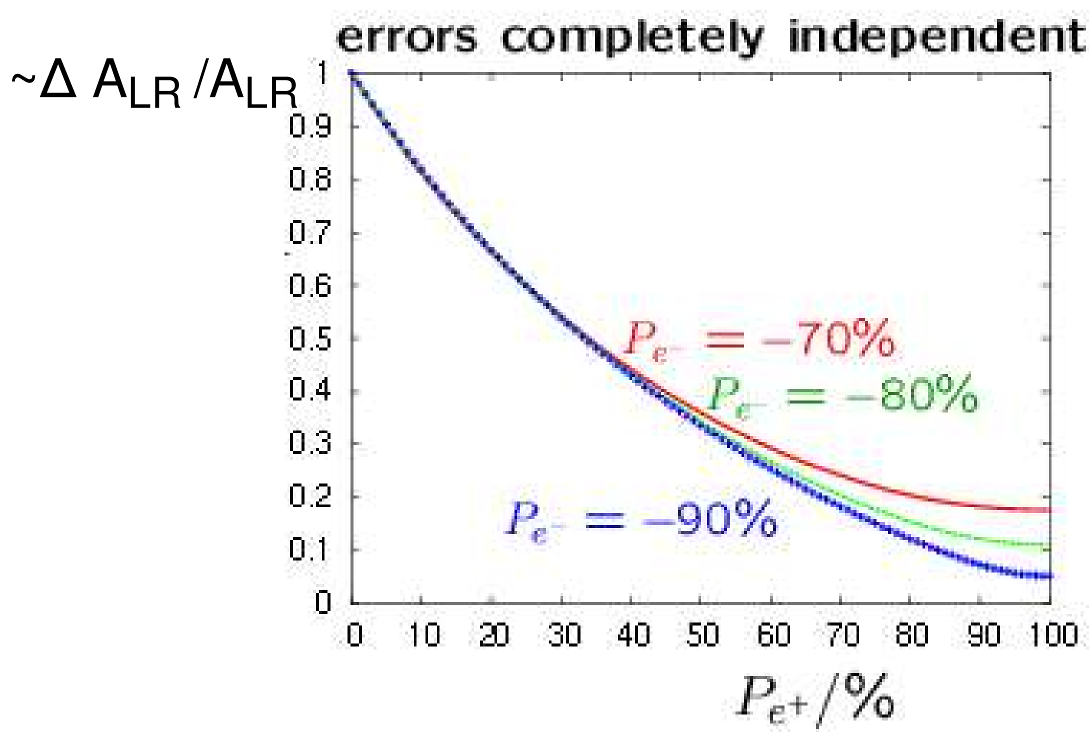
depends on P(e-) !

# Well-known statistical examples -- warm-up

- **A warm-up: gain effective polarization $P_{eff}$ and $A_{LR}$**
  - For many processes (V, A interactions) the cross section is given by:

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




- **P(e+) = strong 'lucrative' factor → both beams should be polarized!**
  - P(e+) of about 60% sufficient with $\Delta P / P = 0.5\%$ for physics studies

# `Safe physics' -- determination of top 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 $A_{LR}$

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

⇒ (80%,0)→(80%,60%): factor 3!

- **Studies at $\sqrt{s} = 500$ GeV:**

only for $P_{e^-}$ so far!!!

estimated:

⇒ (80%,0)→(80%,60%): factor 3!

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

# Higgs searches in the Standard Model

- **Where do we expect the Higgs?**

  → **$m_H$ < 207 GeV (95% CL)**

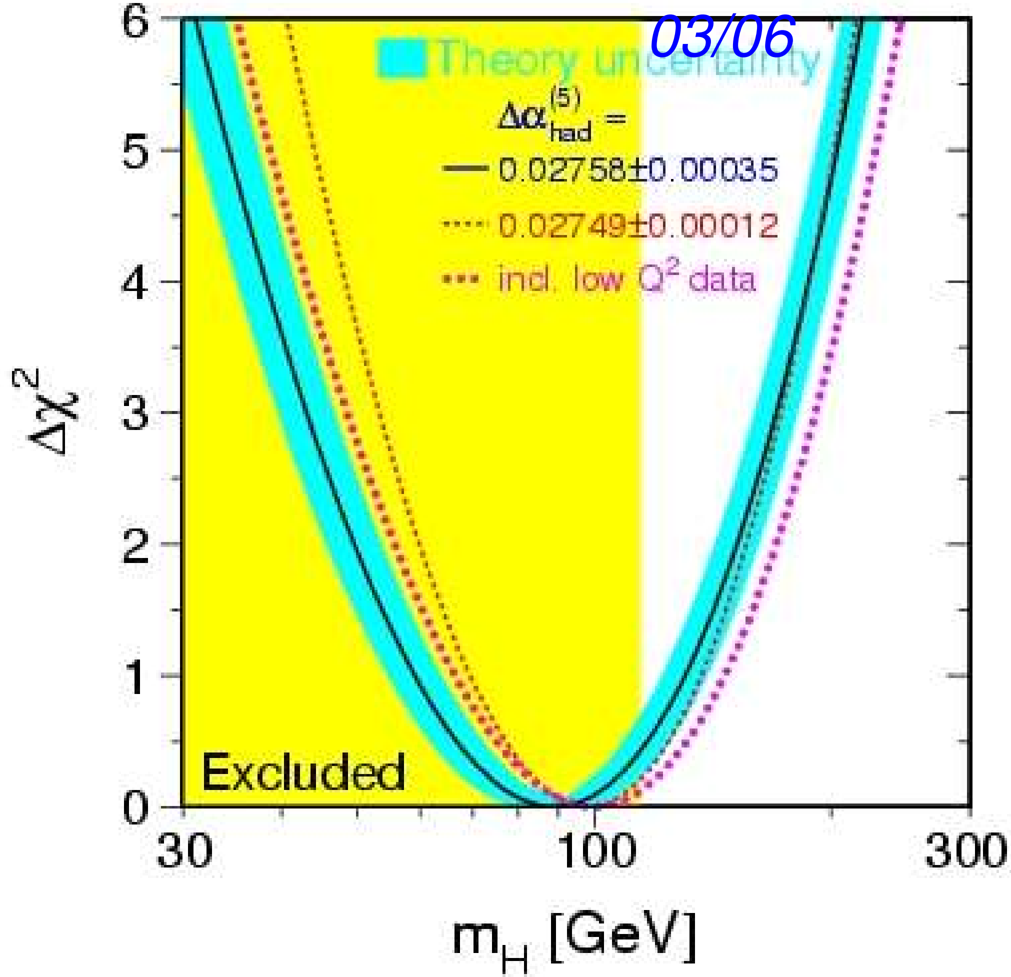
  **(LEP, SLD, CDF, D0 + LEP-2 direct limit)**

- **Light Higgs expected but heavier Higgs not excluded!**

- **'Higgs' task for the LC:**
  ***mass measurement, spin verification, couplings determination***

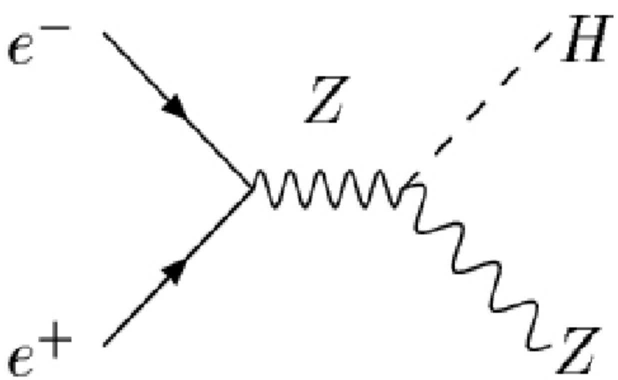
→ **Establish the mechanism of elctroweak symmetry breaking!**

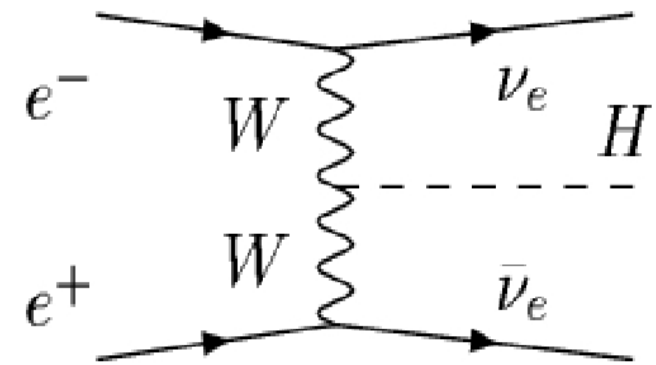
*LEPEWWG 03/06*



# Beam polarization for Higgs searches

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




- **P(e-), P(e+) needed for:**
  - **separation**
  - **background suppression**

| 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 |

- σ(H Z) / σ **(H νν):**

**(+80%,0) → (+80%,-60%)**

→ **improves by factor 4!**

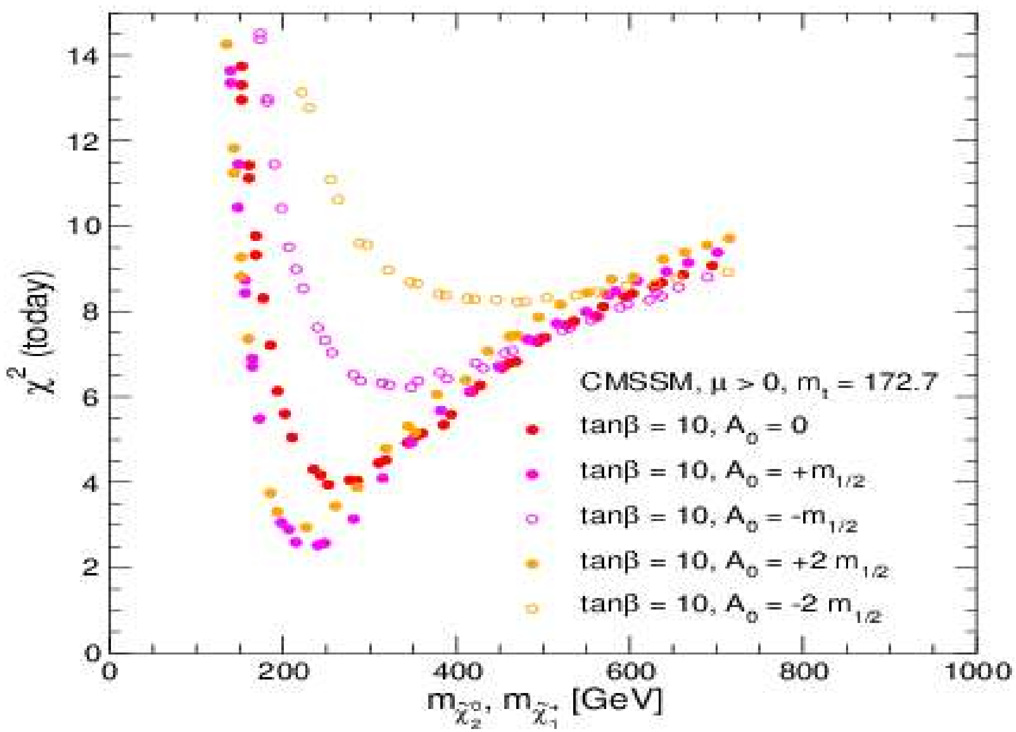
# Further Higgs topics

- Mass measurement in the continuum: at LHC up to 100-200 MeV and at the LC at top threshold ($\sqrt{s}$=350 GeV) and at $\sqrt{s}$=500 GeV up to 50 MeV !
  - threshold scans (i.e. at $\sqrt{s}$=205-300 GeV) mainly needed for spin verification, but due to excellent masses from continuum, only about 3 energy steps needed
- 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: either in HHZ or in HH$\nu\nu$: at $\sqrt{s}$=500 up to 22% and at 3 TeV up to 13% (both cases: unpolarized beams)
  - estimate: further gain of 30%-50% precision if both beams polarized (CLIC rep)
  - side remark: P(e+) always helps even if Signals scales like Background in S /$\sqrt{}$ B
- Polarized e+ very useful even in Higgs physics (factor 4 in separation, 30% in couplings, etc.), in particular at $\sqrt{s}$=350 GeV and 500 GeV

# Now new physics -- Supersymmetry

- One of the most promising candidates for physics beyond the Standard Model (SM) is Supersymmetry (SUSY)
  - model with high predictive power
  - every SM particle gets a SUSY partner with the same quantum numbers ( with the only exception of the spin quantum number)
  - all these assumption have to be checked experimentally!

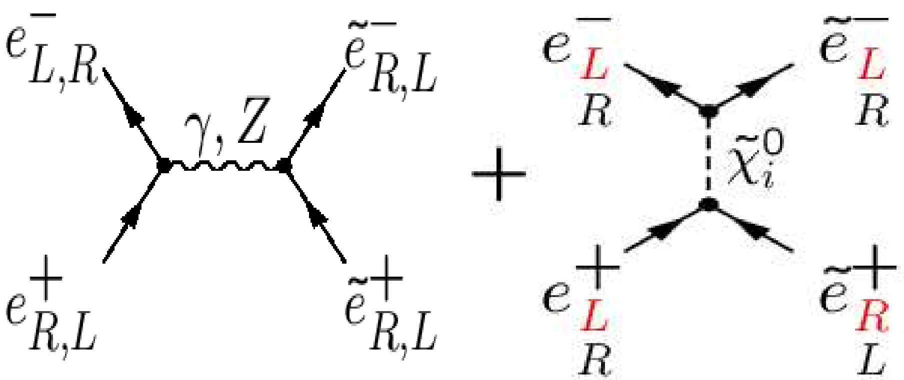
- In which range do we expect SUSY?
  - at least some light particles should be accessible at 500 GeV
  - best possible tools needed to get maximal information out of only the partial spectrum

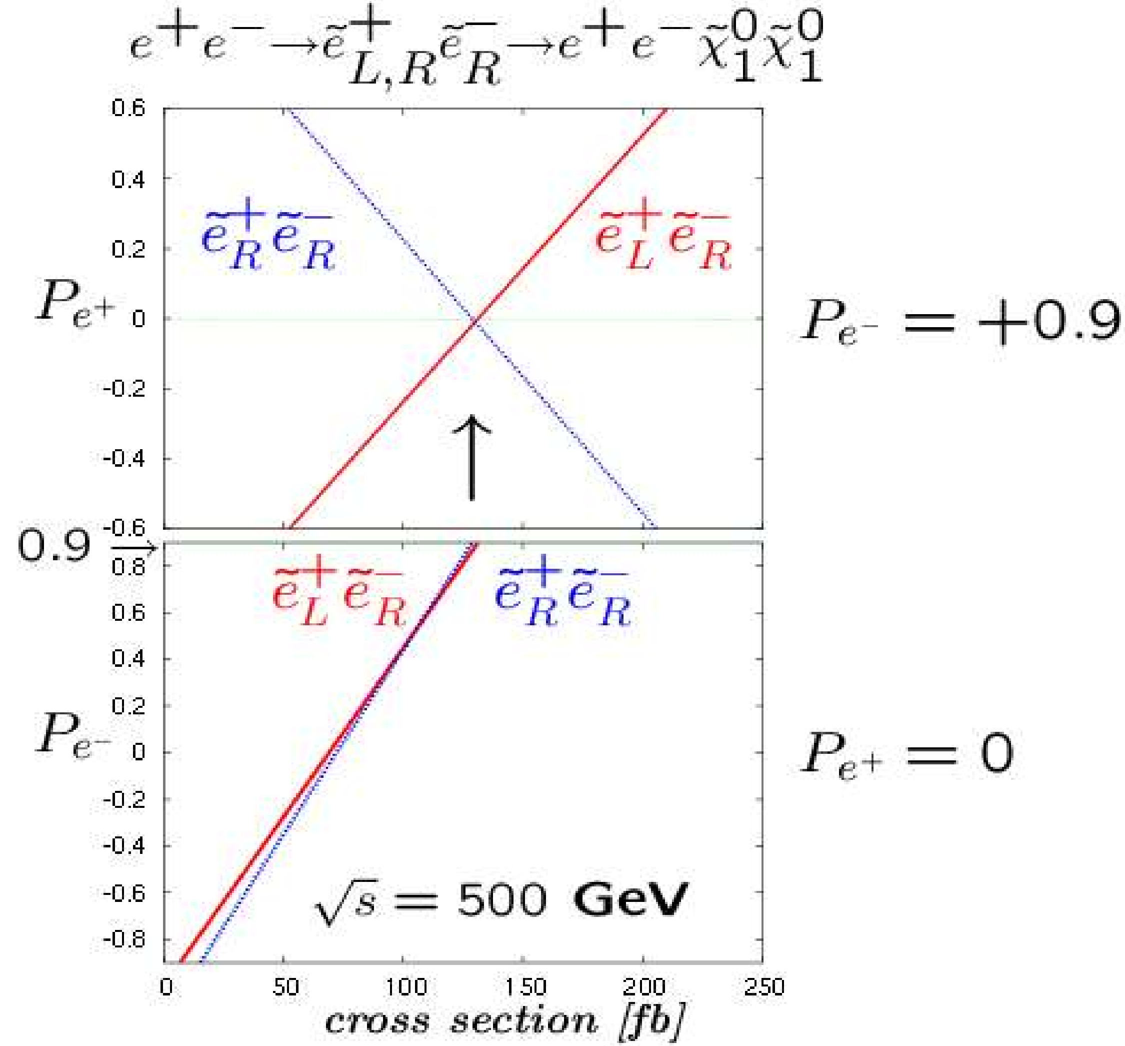


# Test of SUSY quantum numbers

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

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

# SUSY mass measurement im continuum

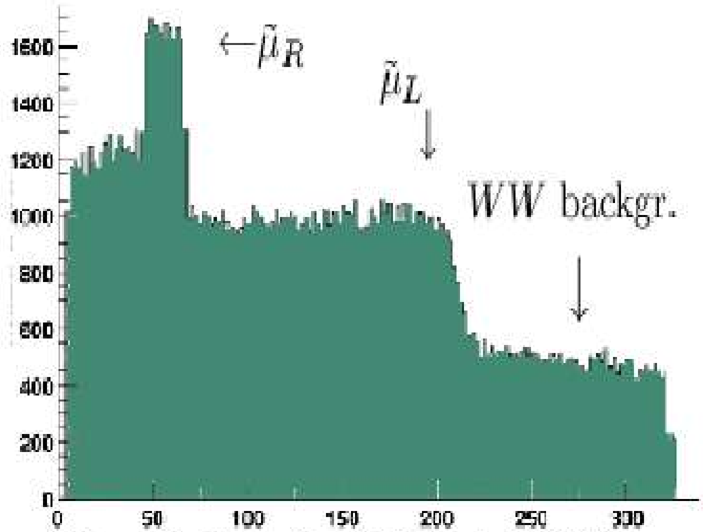
- **To optimize threshold scans: precise continuum measurements important!**
- **Worst SM background is WW-pair production**
  - **e.g.** $e^+e^- \rightarrow \tilde{\mu}^+_{L,R}\tilde{\mu}^-_{L,R}$

*Muon energy spectrum:* $\mu^+\mu^-$ *events (incl.* $W^+W^-$*) at* $\sqrt{s} = 750$ *GeV*

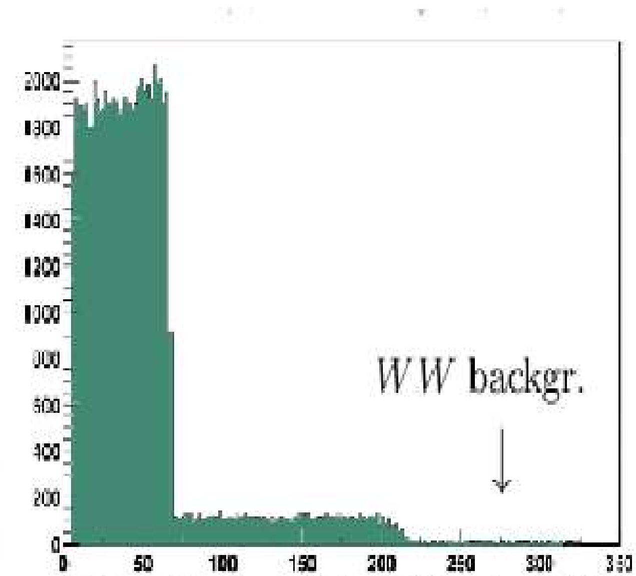
- **Strong WW-backgr.:**
  - **all edges observable only with P(e-) and P(e+)**
  - **at 65 GeV and 220 GeV**

**S / B = 0.07 (+80%,0)**

**S / B= 0.46 (+80%,-80%)**




$(P_{e^-}, P_{e^+}) = (-80\%, +80\%)$

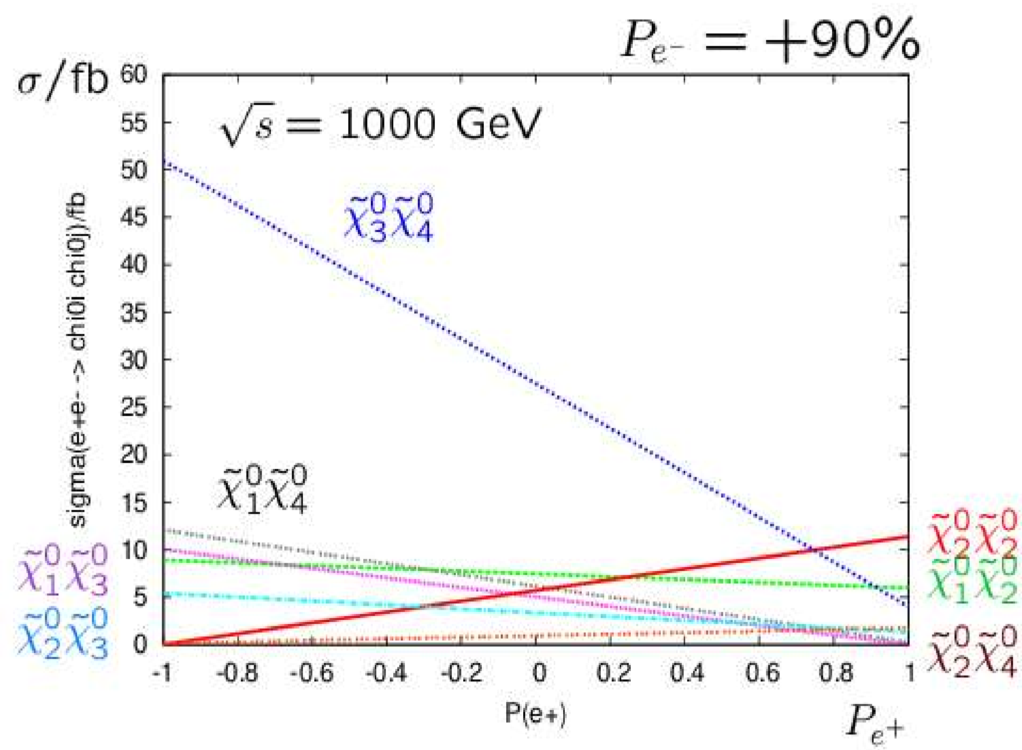



$(P_{e^-}, P_{e^+}) = (+80\%, +80\%)$

- $\Delta(m_{\tilde{\mu}_{L,R}}) \sim$ **few GeV if both beams are polarized !**

# SUSY parameter determination

- **The 'minimal' SUSY model has already 105 new parameters**
  - ➔ **experimental challenge to determine them as model-independent as possible**
- **Complicated interplay of SUSY parameters**
  - ➔ **as many as possible observables needed!**
  - ➔ **particularly important if only partial spectrum accessible**
  - ➔ **disentangling of channels**
  - ➔ **P(e+) gain in cross sections up to factor ~2 wrt to P(e-) only**
  - ➔ **successful examples worked for LHC/ILC interplay! (hep-ph/0410364)**

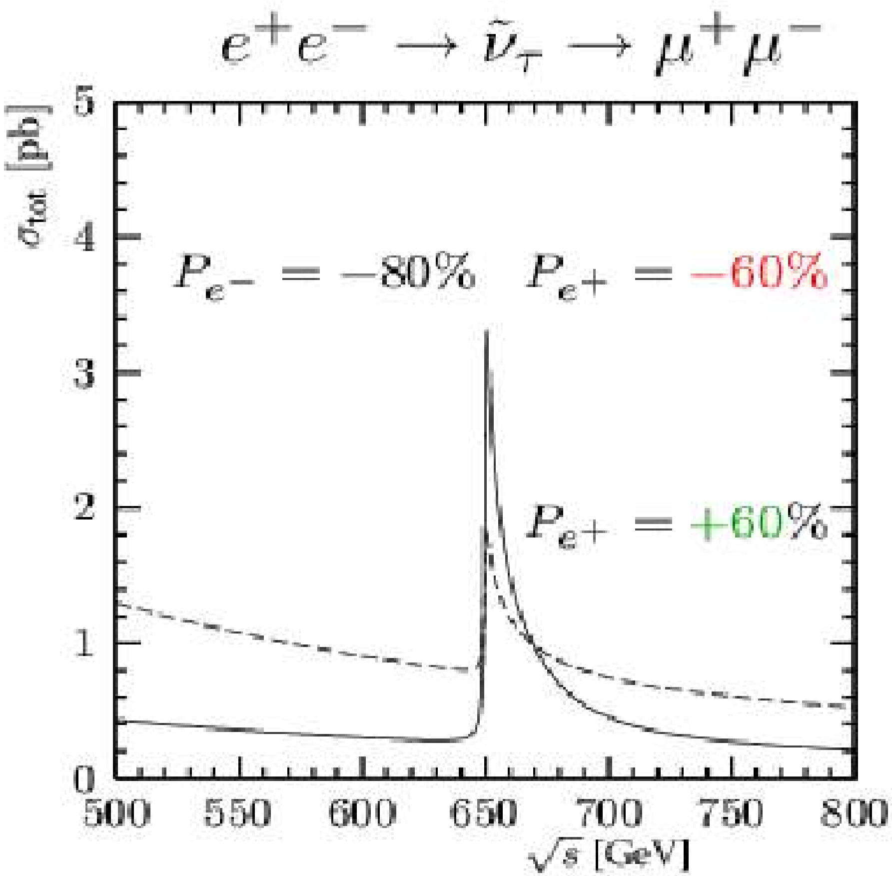


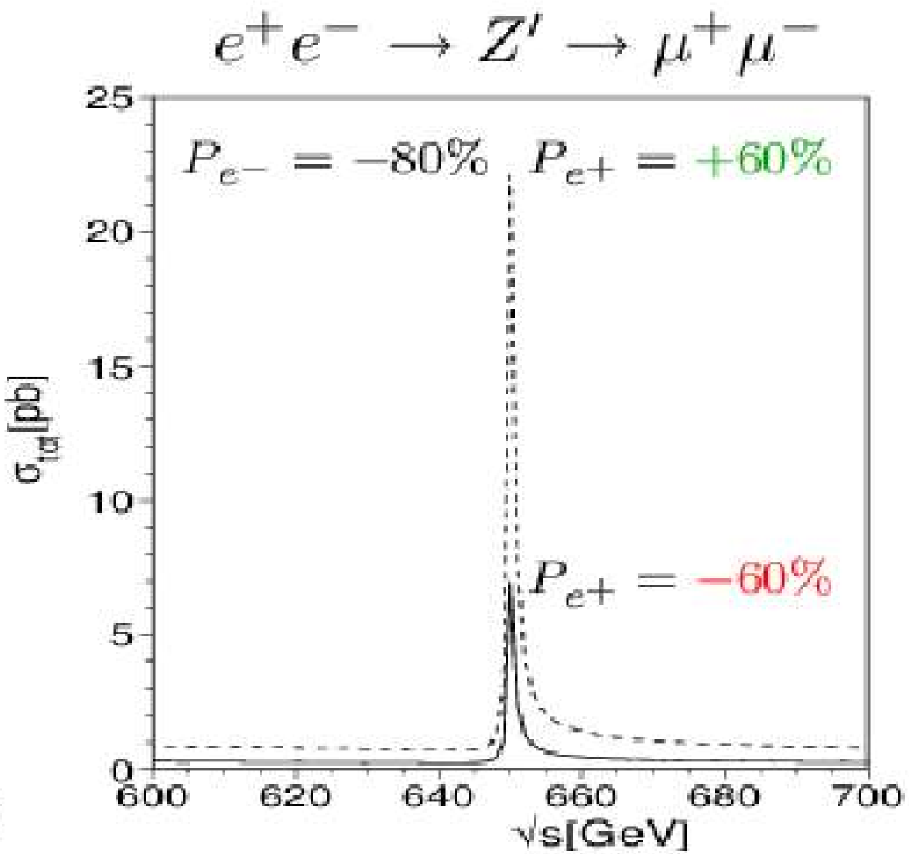

- **P(e-) and P(e+) extremely useful !**

# Extended SUSY models (R-parity violation)

- Scalar particle exchange in s-channel: e+ e- → $\tilde{\nu}_\tau$ → μ+μ-

→ `spin 0-$\tilde{\nu}_\tau$' favours LL configuration, but e.g. an extra gauge boson Z' in the extended SM favours LR!



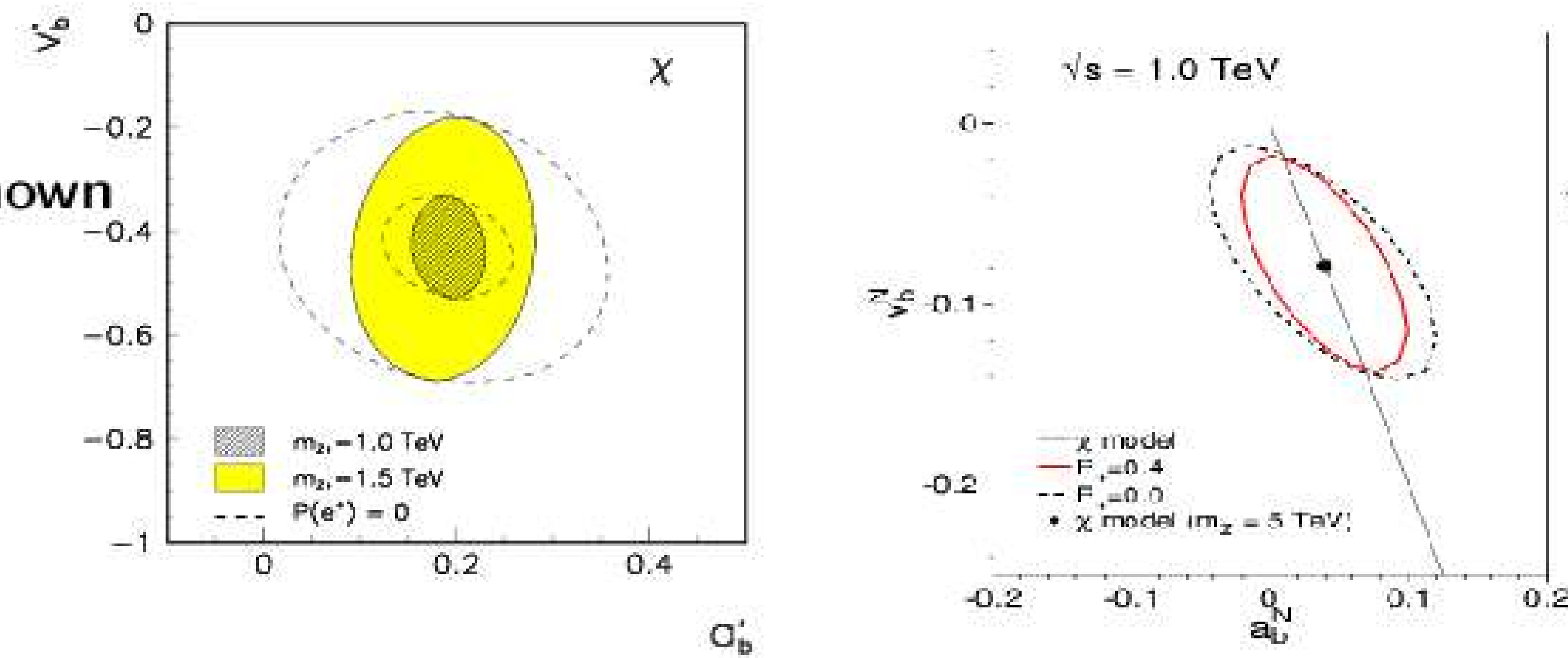




- direct test of spin in resonance production if both beams are polarized !

# Polarization in indirect searches

- **Who guarantees that we will ever reach the new scale?.............**
- **Indirect searches important --- however strongly model-dependent**
  - **e.g. searches for contributions of extra gauge bosons Z' in e+ e- ⟶ $f \bar{f}$ :**

$m'_Z$ known

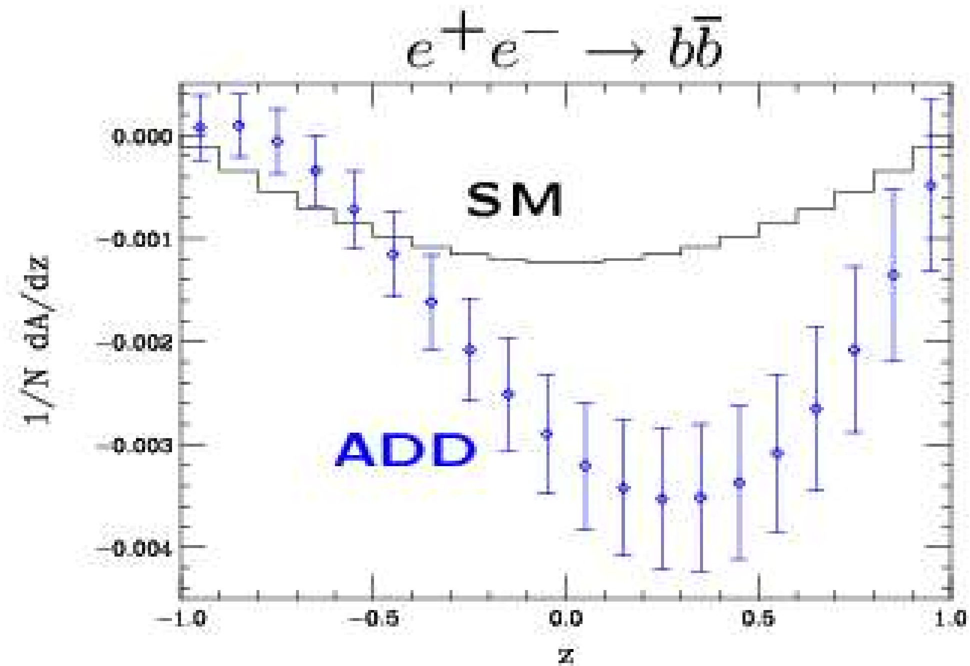



$m'_Z$ unknown

  - **determination of couplings and mass: gain factor with P(e+)~1.6 cf. P(e-) only**
- **E.g. P(e+) decisive for model-independent bounds in contact interactions**

# Indirect searches: extra dimensions

- **Transversely** polarized beams (only effects detectable of $P(e^-)$ and $P(e^+)$ !)
  - ➼ enables to exploit azimuthal asymmetries !
- **Distinction** between SM and different models of extra dimension:
  - ➼ asymmetry signals contribution from spin-2 graviton




- Access to new CP-violating kind of interactions in tt, $\gamma Z$, $W^+ W^-$

**→ Transversely polarized beams very effective, need polarized $e^-$ and $e^+$ !**

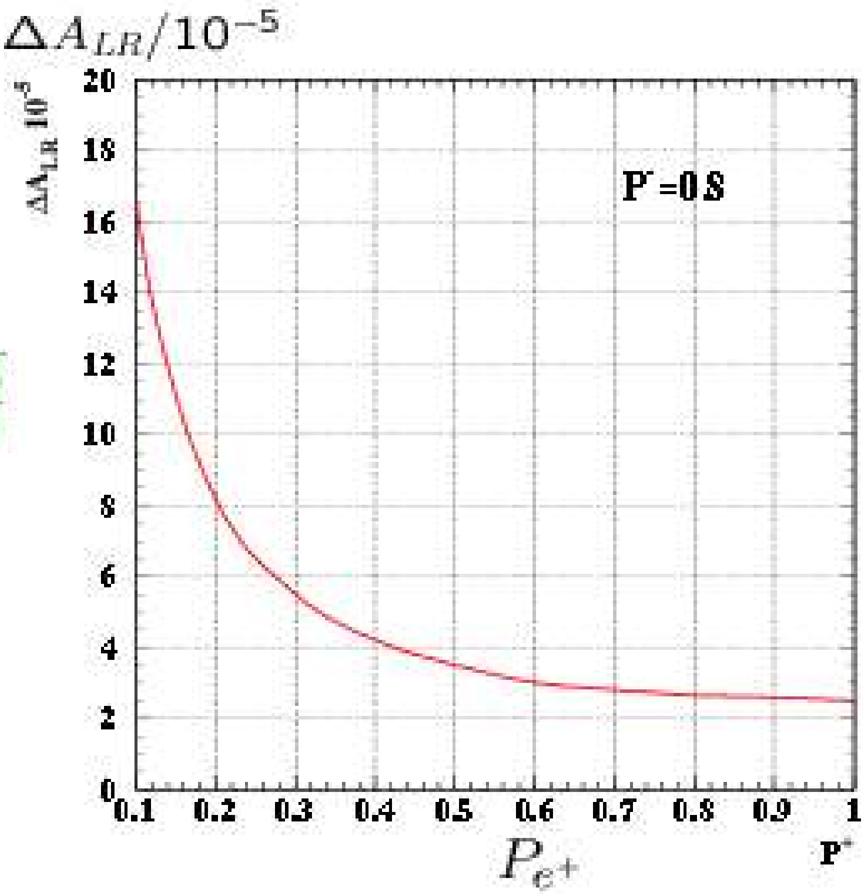
# Last-but-not-least: SM physics tests at GigaZ

- **Measurement of $\sin^2\theta_{eff}$ in $e^+e^- \rightarrow Z \rightarrow f\bar{f}$ :**

  **usually $\Delta P/P \sim 0.5\%$ sufficient**
  **(maybe $\Delta P/P \sim 0.25\%$ reachable !)**

$$A_{LR} = \frac{2(1-4\sin^2\Theta^{\ell}_{eff})}{1+(1-4\sin^2\Theta^{\ell}_{eff})^2}$$

$$\overset{Blondel}{=} \sqrt{\frac{(\sigma^{RR}+\sigma^{RL}-\sigma^{LR}-\sigma^{LL})(-\sigma^{RR}+\sigma^{RL}-\sigma^{LR}+\sigma^{LL})}{(\sigma^{RR}+\sigma^{RL}+\sigma^{LR}+\sigma^{LL})(-\sigma^{RR}+\sigma^{RL}+\sigma^{LR}-\sigma^{LL})}}$$




- **with** $\Delta P/P \sim 0.5\%$ **and $P(e^-)=80\%$ only:**

$$\Rightarrow \Delta \sin^2\theta^{\ell}_{eff} = 9.5\times 10^{-5}$$

(• with $\Delta P/P = 0.25\%$ and $P_{e^-} = 90\%$:

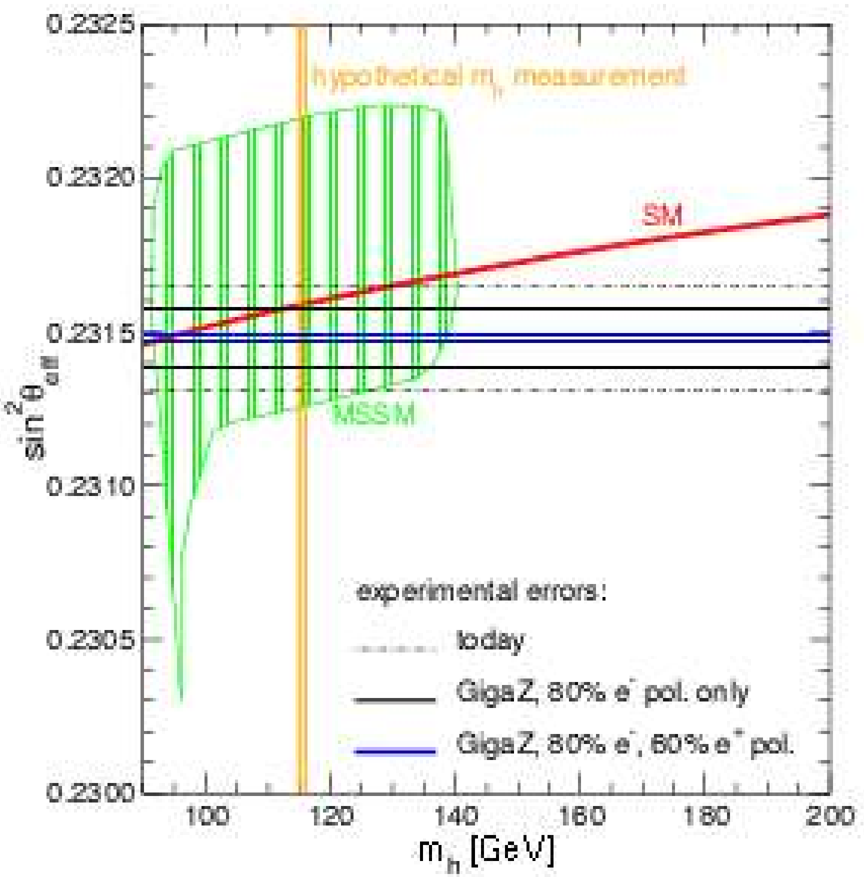
$$\Rightarrow \Delta \sin^2\theta^{\ell}_{eff} = 5\times 10^{-5}\ )$$

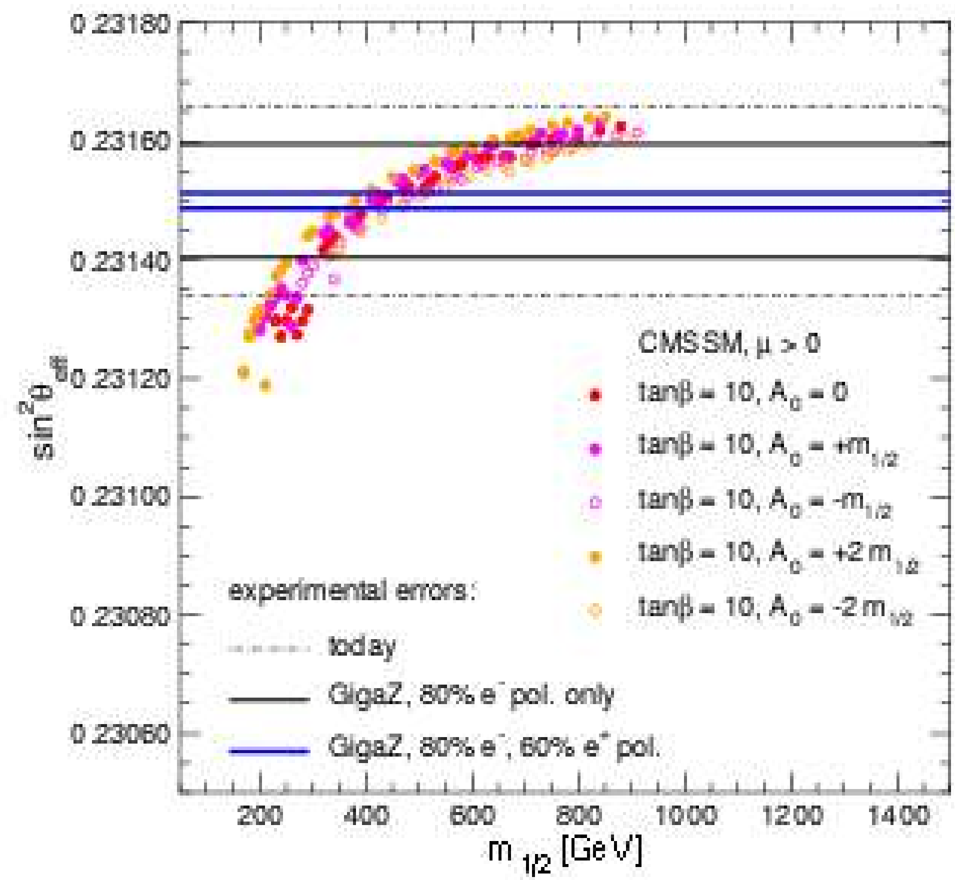
- **with Blondel scheme: [ $P(e^-)$,$P(e^+)$ ]= [80%,60%] :** $\Rightarrow \Delta \sin^2\theta^{\ell}_{eff} = 1.3\times 10^{-5}$

# Impact of GigaZ precision for SUSY searches

- **Gain of about one order of magnitude in** $\sin^2\theta_{eff}$ :

  → **Prediction/constraints for $m_h$ and $m_{1/2}$**




- **`Gain': bounds on SM $m_H$ ~ order of magnitude, on $m_{1/2}$ ~ factor 5!**

# Many more examples in hep-ph/0507011

- **Summary table of the polarization report:**

| Case | Effects | Gain& Essentiality |
|---|---|---|
| **SM:** | | |
| top threshold | Improvement of coupling measurement | factor 3 |
| $t\bar{q}$ | Limits for FCN top couplings reduced | factor 1.8 |
| CPV in $t\bar{t}$ | Azimuthal CP-odd asymmetries give | $P^T_{e^-} P^T_{e^+}$ required |
| | access to S- and T-currents up to 10 TeV | |
| $W^+W^-$ | 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 |
| CPV in $\gamma Z$ | Anomalous TGC $\gamma\gamma Z$, $\gamma Z Z$ | $P^T_{e^-} P^T_{e^+}$ required |
| $HZ$ | Separation: $HZ \leftrightarrow H\bar{\nu}\nu$ | factor 4 with RL |
| | Suppression of $B = W^+\ell^-\nu$ | factor 1.7 |
| **SUSY:** | | |
| $\tilde{e}^+\tilde{e}^-$ | Test of quantum numbers $L$, $R$ | $P_{e^+}$ required |
| | and measurement of $e^\pm$ Yukawa couplings | |
| $\tilde{\mu}\tilde{\mu}$ | Enhancement of $S/B$, $B = WW$ | factor 5-7 |
| | $\Rightarrow m_{\tilde{\mu}_{L,R}}$ in the continuum | |
| $\tilde{t}_1\tilde{t}_1$ $(\tilde{b}_1\tilde{b}_1, \tilde{\tau}_1\tilde{\tau}_1)$ | Improvement in determination of $m_{\tilde{t}_1}$ and $\theta_{\tilde{t}}$ | factor 1.4 |
| $HA$, $m_A > 500$ 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 | $P^T_{e^-} P^T_{e^+}$ 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 | |
| **ED:** | | |
| $G\gamma$ | Enhancement of $S/B$, $B = \gamma\nu\bar{\nu}$, | factor 3 |
| $e^+e^- \to f\bar{f}$ | Distinction between ADD and RS modes | $P^T_{e^-} P^T_{e^+}$ required |

# Concluding remarks

- P(e+) only gains, independent in which direction the NP points!
  - 'enhances luminosity' in direct and indirect searches
  - enables separate study of couplings (properties of SUSY particles!)
  - improves signal vs background, e.g. factor in light Higgs searches!
  - enables 'model-independence' in indirect searches
  - enhances precision in Standard Model tests (GigaZ, WW threshold)

→ Polarization more important than 'pure' luminosity

- P(e+) crucial for 'being prepared for the Unexpected' !

→ full potential of the ILC could only be realized with $P(e^-)$ and $P(e^+)$

  - in particular important at $\sqrt{s} = 500$ GeV ('maximize' results, outline of upgrades!)
  - high accuracy guaranteed: expected depolarization less than ~1% !

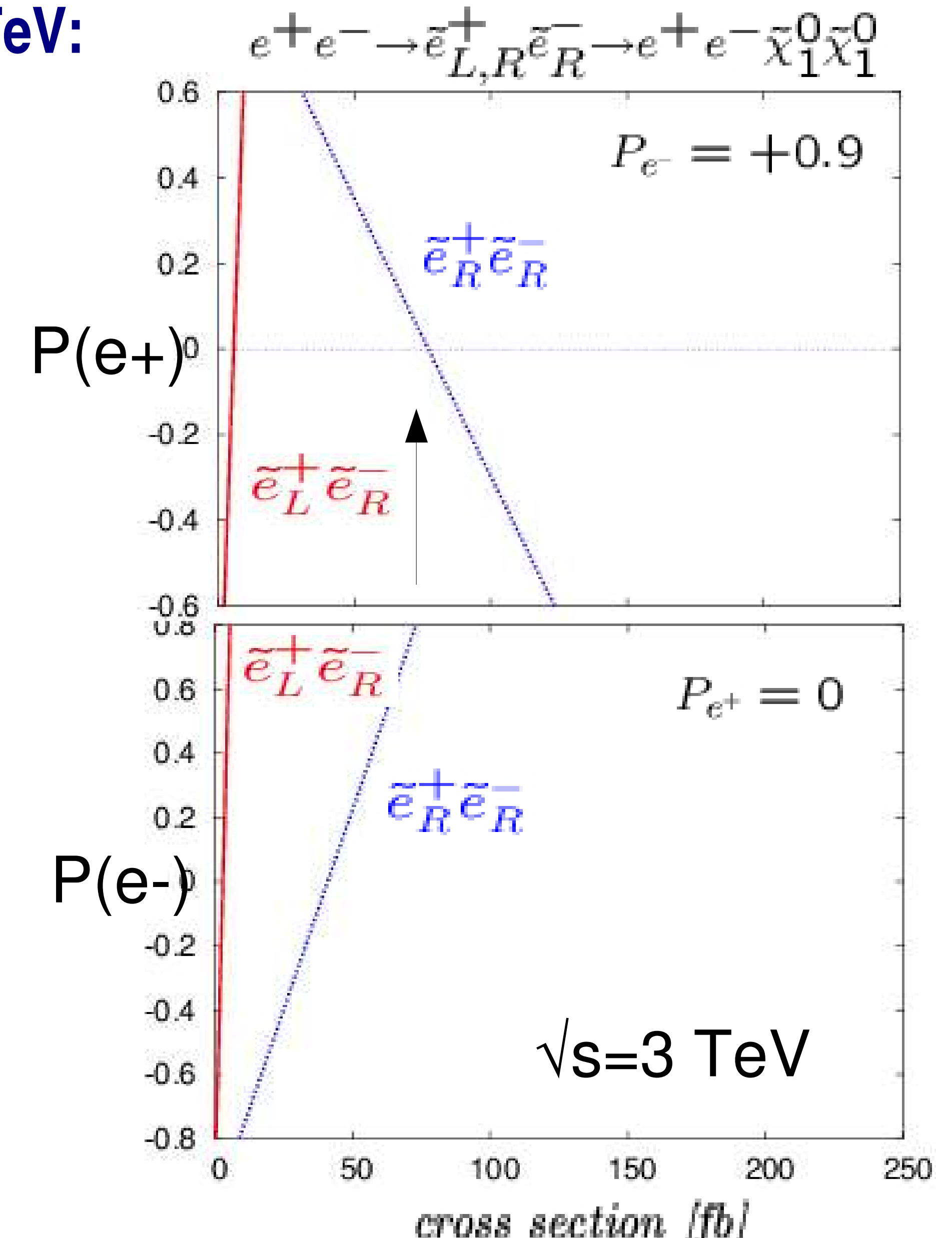
→ potential of CLIC in the multi-TeV region would also strongly benefit

  - high accuracy problem? ... depolarization has to be under control

# Selectron quantum numbers at 3 TeV

- **Same scenario, same pairs and same polarization as before but change $\sqrt{s}$ = 500 GeV ⟶ 3 TeV:**

  - scattering channel kinematically suppressed
  - no separation of wanted $\tilde{e}_L^+ \tilde{e}_R^-$
  - no test of quantum numbers




- **Tunable energy needed, also at multi-TeV region**

  - here: back to 500 GeV