Impact of polarized positrons for top/QCD and electroweak physics

Gudrid Moortgat-Pick
Hamburg University

- **Introduction**
- **SB2009**
- **Summary polarized beams in top/qcd physics**
- **Summary polarized beams in ew theories**
- **Summary and open questions/ideas**

Introduction

- **Physics case for polarized e^- and e^+**
  - **Comprehensive overview, hep-ph/0507011, Phys.Rept., 460 (2008)**
  - **See also executive summary on:**

  www.ippp.dur.ac.uk/LCsources/
- **Polarized beams required to**
  - **Analyze the structure of all kinds of interactions**
  - **Improve statistics: enhance rates, suppress background processes**
  - **Get systematic uncertainties under control**
- **Discoveries via deviations from SM predictions in precision measurements!**
  - **Important in particular at $\sqrt{s} \leq 500$ GeV !**

Why are polarized beams required?

- **Please remember:**
  - **excellent e- polarization ~78% at SLC:**
  - **led to best measurement of $\sin^2\theta = 0.23098 \pm 0.00026$**

    on basis of $L \sim 10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- **Compare with results from unpolarized beams at LEP:**
  - **$\sin^2\theta = 0.23221 \pm 0.00029$ but with $L \sim 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$**

➡ **polarization can even compensate order of magitude in luminosity for specific observables !**

But what are the precision requirements?

Reminder: requirements for precision frontier'

ICFA Parameter Group for a future LC:

- 'Scope Document no.1' (2003) and 'no.2' (2006): baseline
  - 'full luminosity of 2 x $10^{34}cm^{-2}s^{-1}$'
  - '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.'

SB2009

- **Comparison:**
  - RDR baseline: P(e+)~30% up to 45% (w/o collimator)
  - P(e+)=22% at $\sqrt{s}$=500 GeV
    P(e+)=31% at $\sqrt{s}$=200 GeV

  Is such a low degree appropriate for physics goals?

- **Concentrate on few examples**
  - For new SB2009 outline
  - Weight it w.r.t. LHC expectations

Physics: pol.cross sections in general

Polarized cross sections can be subdivided in:

$$\sigma_{P_{e^-}P_{e^+}} = \frac{1}{4}\{(1+P_{e^-})(1+P_{e^+})\sigma_{\mathrm{RR}} + (1-P_{e^-})(1-P_{e^+})\sigma_{\mathrm{LL}} \\ +(1+P_{e^-})(1-P_{e^+})\sigma_{\mathrm{RL}} + (1-P_{e^-})(1+P_{e^+})\sigma_{\mathrm{LR}}\},$$

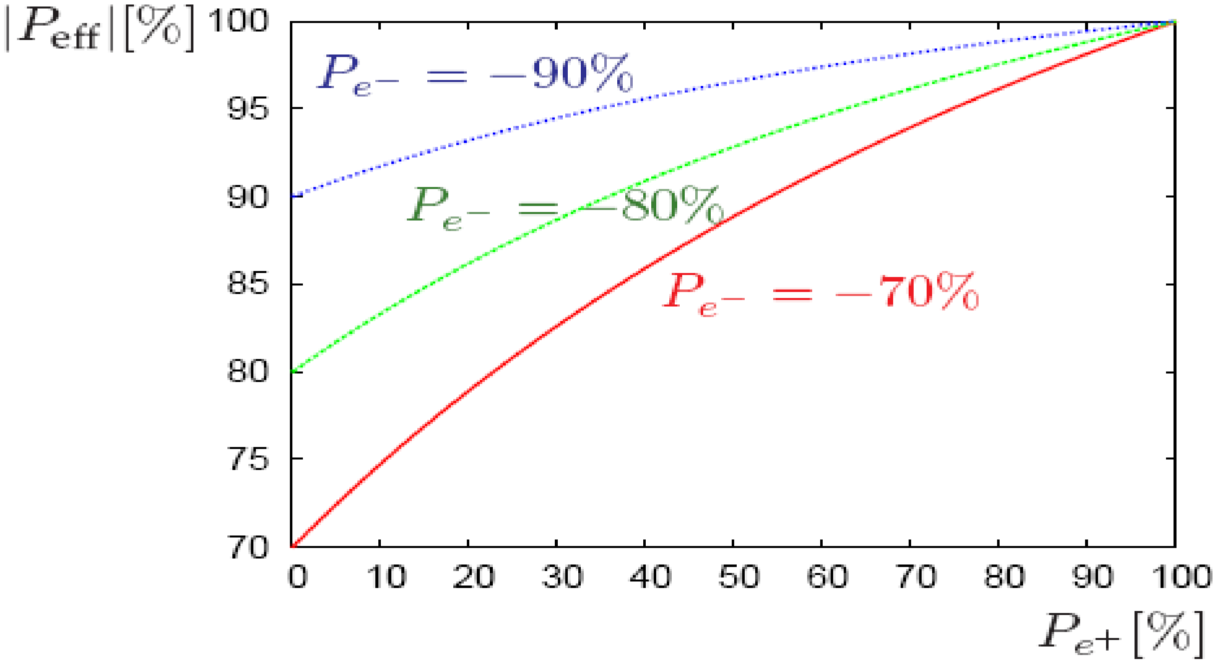
σ_{RR}, σ_{LL}, σ_{RL}, σ_{LR} are contributions with fully polarized L, R beams.

In case of a vector particle only (LR) and (RL) configurations contribute:

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

Effective polarization

Effective polarization: $$P_{\text{eff}} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+} P_{e^-}}$$



- **(80%,60%): P_{eff}=95%, (90%,60%): P_{eff}=97%, (90%,30%): P_{eff}=94%**
- **(80%,22%): P_{eff}= 87%, (90%,22%): P_{eff}= 93%**

Relation between P_{eff} and A_{LR}

- **How are P_{eff} and A_{LR} related?**

$$A_{\rm LR} = \frac{1}{P_{\rm eff}} A_{LR}^{\rm obs} = \frac{1}{P_{\rm eff}} \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}},$$

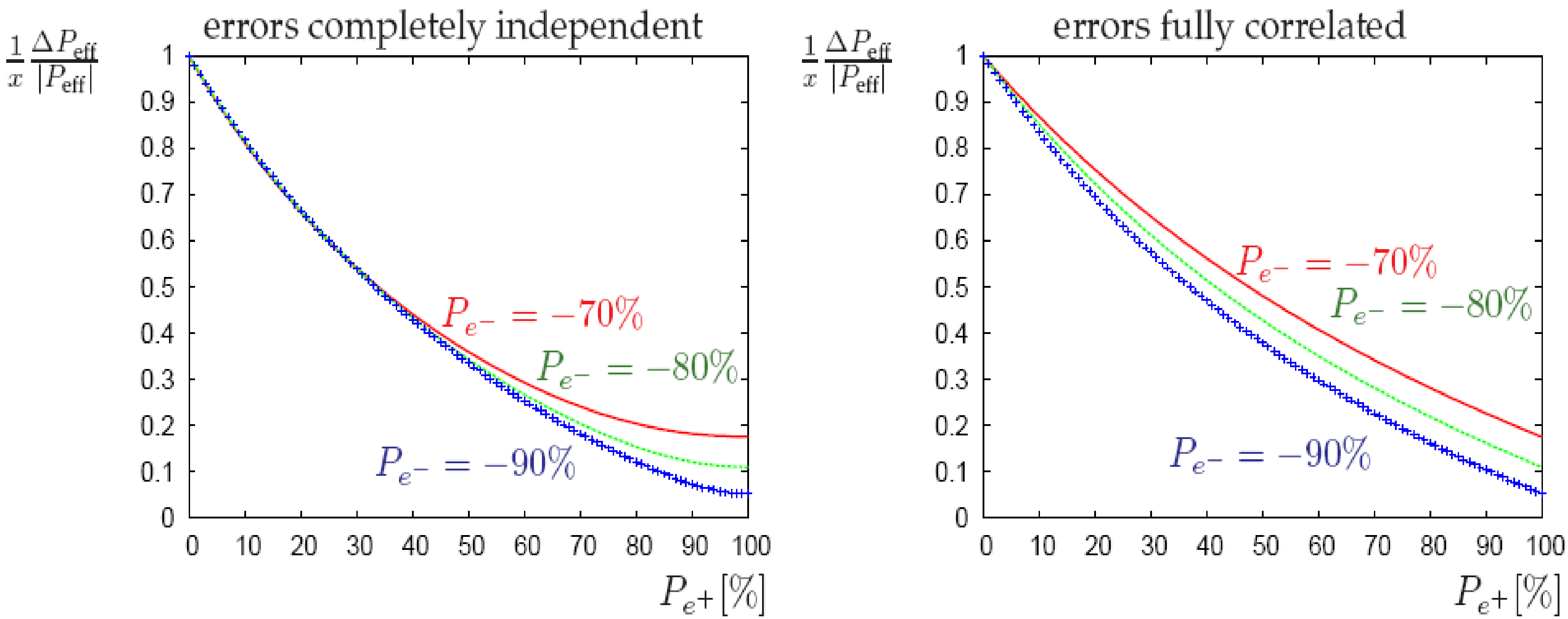
That means: $$\left|\frac{\Delta A_{\rm LR}}{A_{\rm LR}}\right| \sim \left|\frac{\Delta P_{\rm eff}}{P_{\rm eff}}\right|$$

- **With pure error propagation (and errors uncorrelated), one obtains:**

$$\frac{\Delta P_{\rm eff}}{P_{\rm eff}} = \frac{x}{(|P_{e^+}| + |P_{e^-}|)\,(1 + |P_{e^+}||P_{e^-}|)} \sqrt{(1 - |P_{e^-}|^2)^2 P_{e^+}^2 + (1 - |P_{e^+}|^2)^2 P_{e^-}^2}$$

With $$x \equiv \Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+}$$

Gain in accuracy due to P(e+)



- (80%,60): P_{eff} = 95% (90%,60%): P_{eff} =97% (90%, 30%): P_{eff} =94 %

  $\Delta A_{LR}/A_{LR}$ = 0.3 Δ A_{LR}/A_{LR} = 0.27 Δ A_{LR}/A_{LR} =0.5

- **(80%,22%): $\Delta A_{LR}/A_{LR}$= 0.64** **(90%,22%): $\Delta A_{LR}/A_{LR}$= 0.64**

→ **NO gain with only polarized e^- !**

Pol. in top/qcd:
Unique access to top ew properties

- **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**

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

⇒ (80%,0)→(80%,60%): factor 3!

(80%,0)→(80%,30%): factor 2

(80%,0) ⟶ (80%,22%): factor 1.6

Form factor	SM value	$\sqrt{s} = 500\,\text{GeV}$		$\sqrt{s} = 800\,\text{GeV}$	
		$p = 0$	$p = -0.8$	$p = 0$	$p = -0.8$
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
$\mathrm{Re}\,d^{\gamma}_t\ [10^{-19}\ e\ \mathrm{cm}]$	0	20	4	8	2
$\mathrm{Re}\,F^{Z}_{2A}$	0	0.012	0.008	0.008	0.007
$\mathrm{Re}\,d^{Z}_t\ [10^{-19}\ e\ \mathrm{cm}]$	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		

Flavour changing neutral couplings

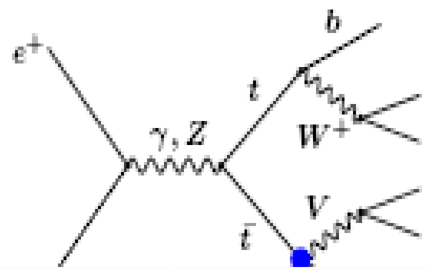
- Single top:
  → more sensitive
- top pairs+decays:
  → better for disentangling
- Results:

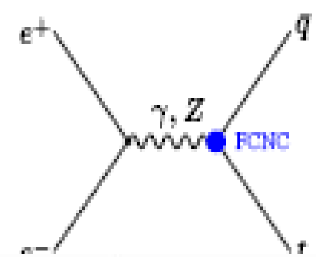
vector couplings:

(80%,0)→(80%,45%): **~1.7**

tensor couplings:

(80%,0)→(80%,45%): **~1.8**





	unpolarized beams	$\lvert P_{e^-}\rvert = 80\%$	$(\lvert P_{e^-}\rvert, \lvert P_{e^+}\rvert) = (80\%, 45\%)$
	$\sqrt{s} = 500$ GeV		
$BR(t \to Zq)(\gamma_\mu)$	6.1×10^{-4}	3.9×10^{-4}	2.2×10^{-4}
$BR(t \to Zq)(\sigma_{\mu\nu})$	4.8×10^{-5}	3.1×10^{-5}	1.7×10^{-5}
$BR(t \to \gamma q)$	3.0×10^{-5}	1.7×10^{-5}	9.3×10^{-6}
	$\sqrt{s} = 800$ GeV		
$BR(t \to Zq)(\gamma_\mu)$	5.9×10^{-4}	4.3×10^{-4}	2.3×10^{-4}
$BR(t \to Zq)(\sigma_{\mu\nu})$	1.7×10^{-5}	1.3×10^{-5}	7.0×10^{-6}
$BR(t \to \gamma q)$	1.0×10^{-5}	6.7×10^{-6}	3.6×10^{-6}

What in top-Higgs physics?

- **$t\bar{t}H$ couplings:**
  - Interplay between $(1-P_{e-}P_{e+})$ and $(1-P_{eff}\,A_{LR})$: *(A. Juste in 2005)*

    (-80%,+60%): $\sigma(ttH)^{Pol}/\,\sigma(ttH)\sim 2.1$ ⟶ $g_{ttH}^{Pol}/g_{ttH}\sim 45\%$

    (-80%,0%): ~1.4 ⟶ ~19%
  - 'My' Personal estimates:

    (-80%,+30%): ~1.7 ⟶ ~31%

    (-80%,+22%): ~1.6 ⟶ ~27%

- **Study was done at $\sqrt{s}$=500 GeV**
  - since A_{LR}~constant up to ~1TeV: factors also valid at ~800 GeV

⟶ **more detailed studies absolutely desirable!!!**

Triple gauge couplings in WW

$$\frac{\mathcal{L}^{WWV}}{ig_{WWV}} = g_1^V V^\mu \left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right) - \kappa_V W^-_\mu W^+_\nu V^{\mu\nu} - \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\mu W^-_{\rho\nu}$$
$$+ \; ig_4^V W^-_\mu W^+_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu)$$
$$+ \; ig_5^V \varepsilon^{\mu\nu\rho\sigma} \left[(\partial_\rho W^-_\mu) W^+_\nu - W^-_\mu (\partial_\rho W^+_\nu)\right] V_\sigma$$
$$- \; \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}{}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta},$$

CP conserving and CP-violating couplings

- Access to triple gauge couplings:
  - Example: rotate to 'optimal observables'
  - $\longrightarrow$ use transversely polarized beams as well

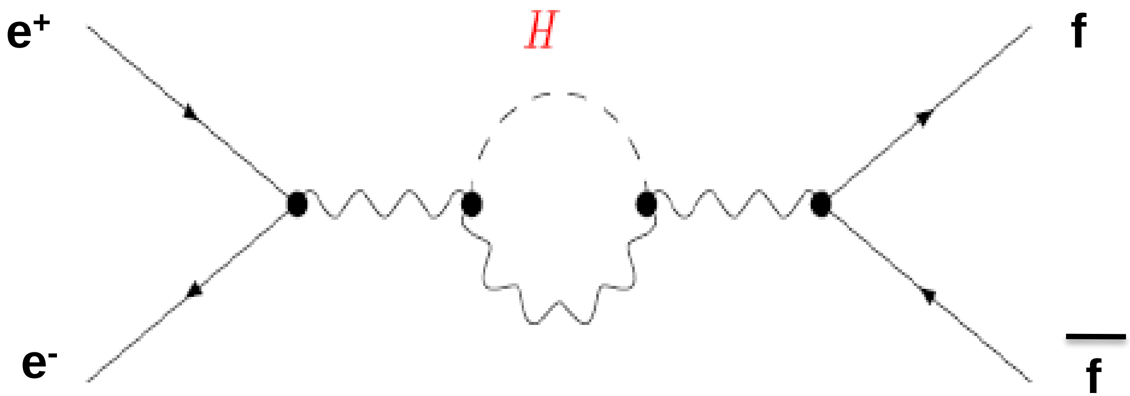
$\sqrt{s} = 500$ GeV	Im g_1^L	Im κ^L	Im λ^L	Im g_5^L	$\tilde{h}_-$	$\tilde{h}_+$	Im λ^R	Im g_5^R
No polarization	2.7	1.7	0.48	2.5	11	—	3.1	17
$(P_{e^-}, P_{e^+}) = (\mp 80\%, 0)$	2.6	1.2	0.45	2.0	4.5	—	1.4	4.3
$(P_{e^-}, P_{e^+}) = (\mp 80\%, \pm 60\%)$	2.1	0.95	0.37	1.6	2.5	—	0.75	2.3
$(P^T_{e^-}, P^T_{e^+}) = (80\%, 60\%)$	2.6	1.2	0.46	2.0	3.7	3.2	0.98	4.4

- gain factor of 1.8 when (80%,0) $\rightarrow$ (80%,60%), (80%,22%) …?
- Access to $\tilde{h}_+$ with $P_T(e-)P_T(e+)$: $\rightarrow$ (80%,30%) ~0.5 (80%,60%)
  $\rightarrow$ (80%,22%) ~0.4 (80%,60%)

Can be compensated with P_{e-}=90% !

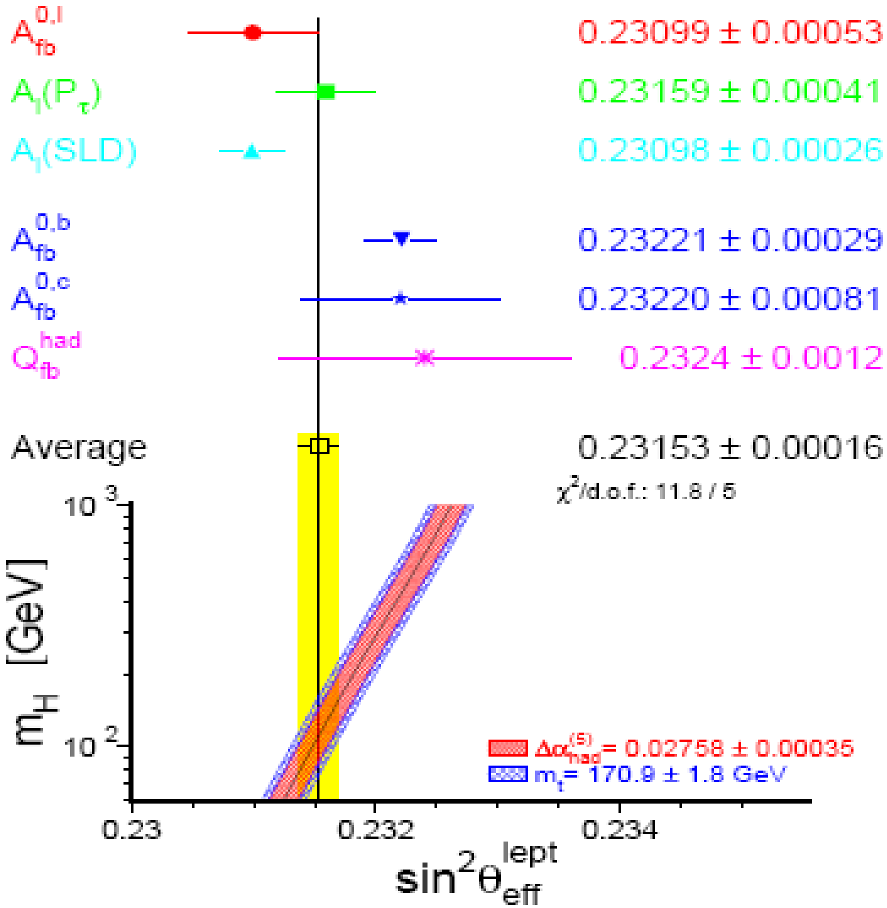
Why indirect searches at a e^+e^- Z-factory?

- **Electroweak precision physics**



  - **Sensitivity to quantum effects of new physics**
    - **All states contribute, including the ones that are too heavy to be produced directly**
    - **Probing the underlying physics and the properties of new particles**

Experimental situation



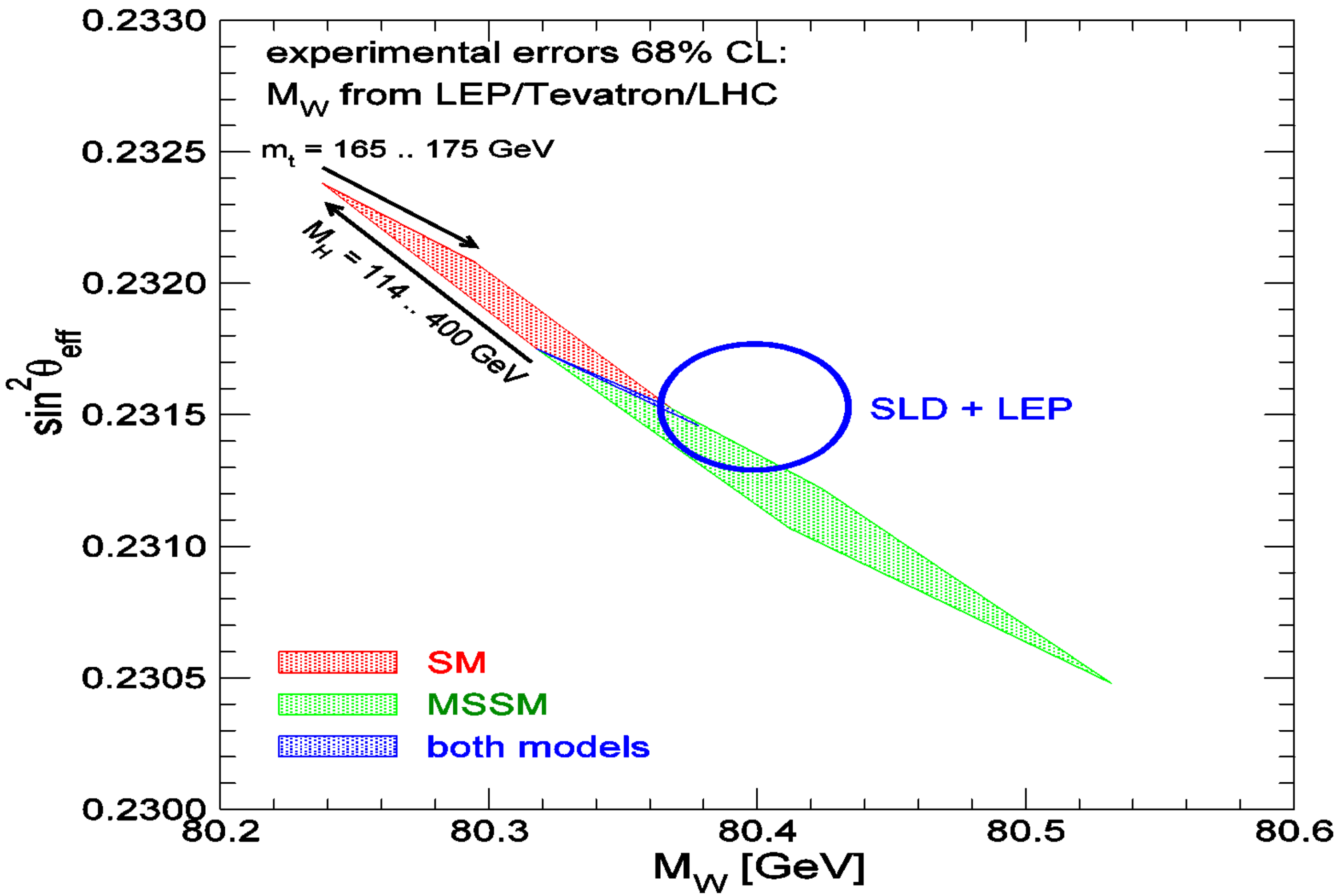
LEP:
$\sin^2\theta_{eff}(A_{FB}{}^b)$= 0.23221±0.00029

SLC:
$\sin^2\theta_{eff}(A_{LR})$= 0.23098±0.00026

World average:
$\sin^2\theta_{eff}$ = 0.23153±0.00016

Large impact of discrepancy between the two most precise measurements

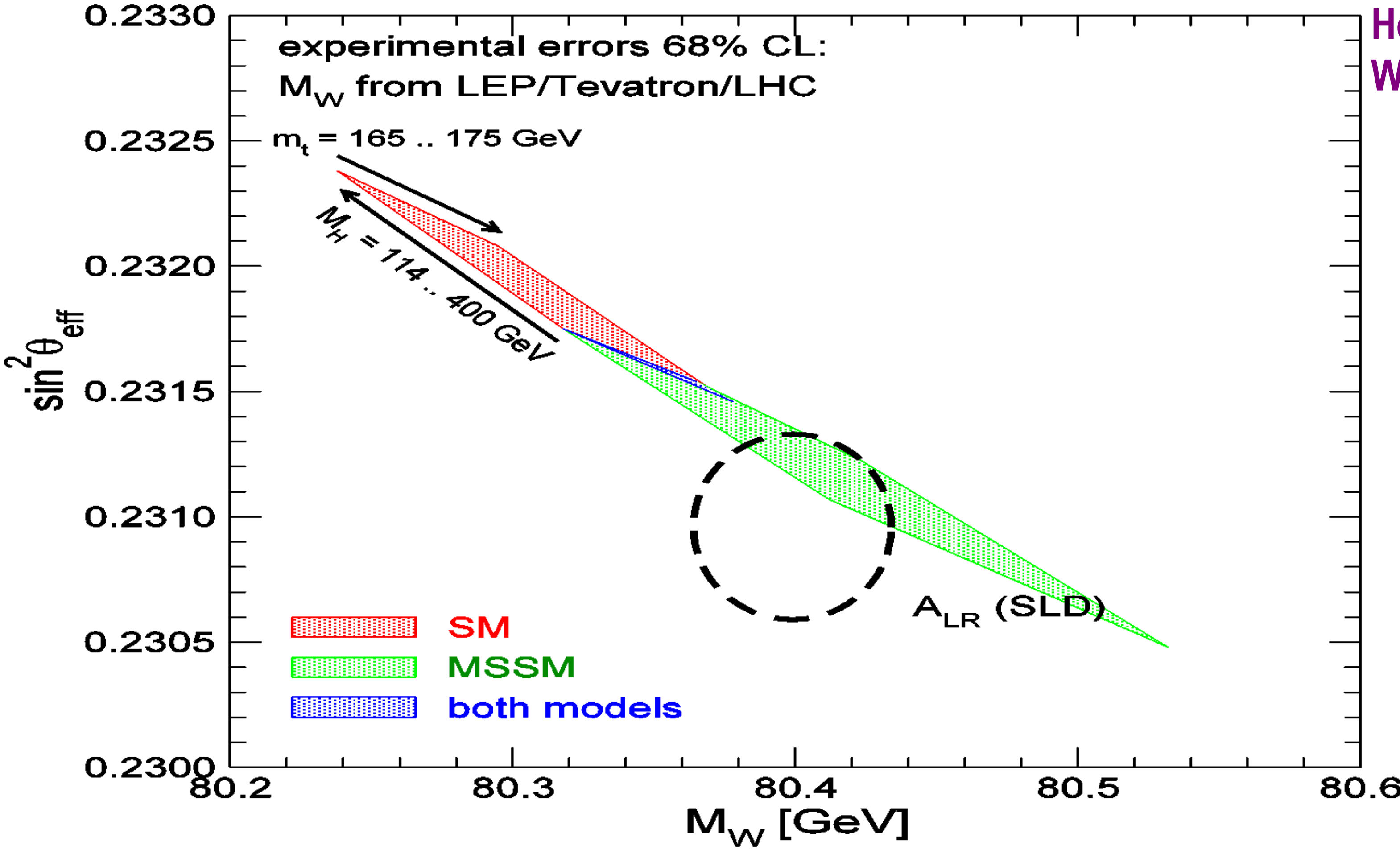
M_W vs. central value $\sin^2\theta_{eff}$



Heinemeyer, Weiglein

→ Consistent with SM and SUSY

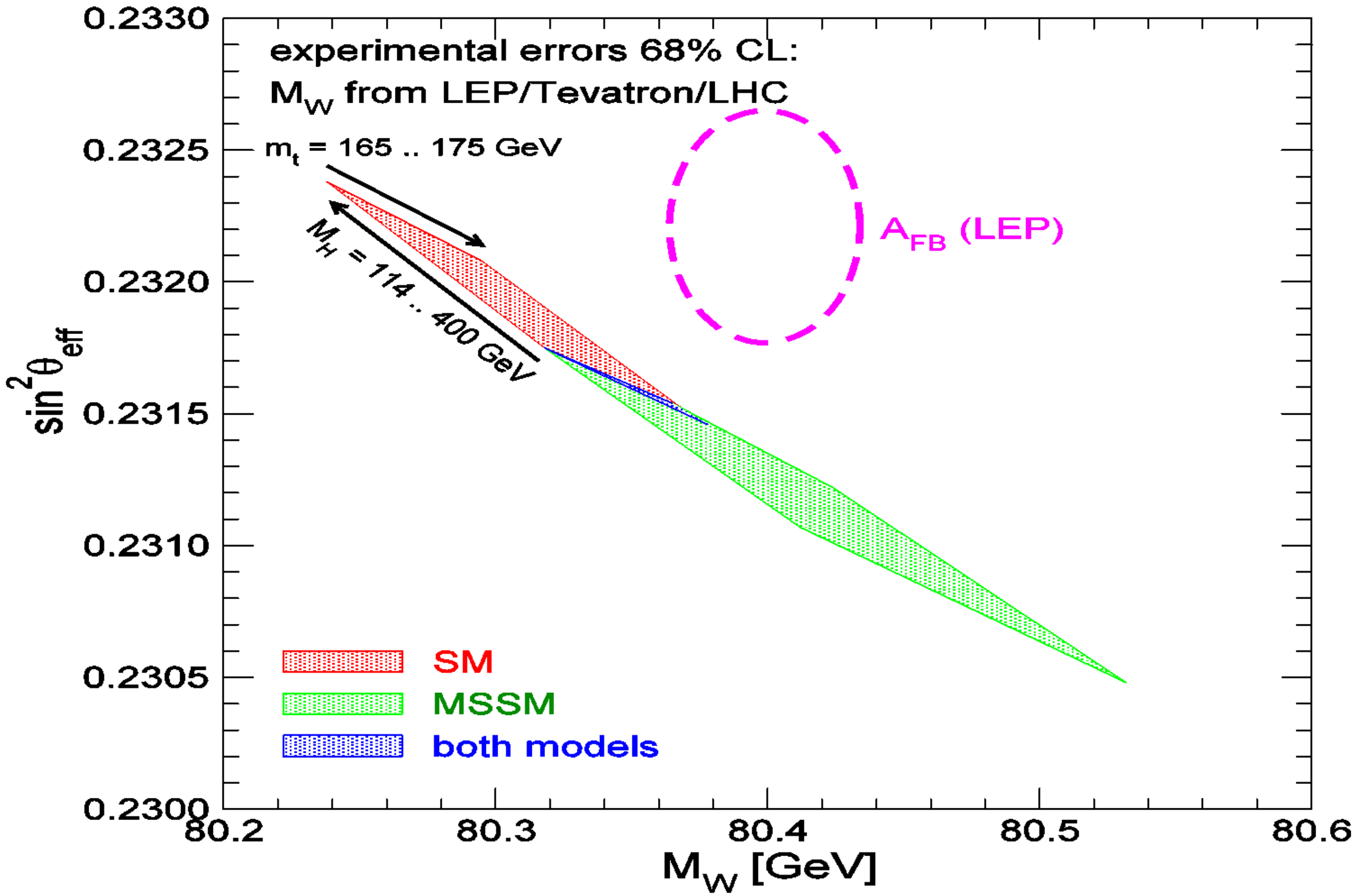
M_W vs. A_{LR}(SLD)-value $\sin^2\theta_{eff}$



Heinemeyer, Weiglein

→ **not consistent with the SM**

M_W vs. A_{FB}(LEP)-value $\sin^2\theta_{eff}$



Heinemeyer, Weiglein

→ **neither consistent with the SM nor SUSY**

- **precise $\sin^2\theta_{eff}$-measurement has the potential to rule out both models**

$\sin^2\theta_{eff}$ at the Z-factory

- **Measure both A_{FB} and A_{LR} in same experiment !**

  → with improved precision w.r.t. LEP and SLC

  → resolve discrepancy and interpret it w.r.t. new physics@LHC

- **Which precision should one aim for?**
  - Theoretical uncertainties: $\Delta\sin 2\theta_{eff}^{ho} \sim 5\text{x}10^{-5}$ (currently)
  - Uncertainties from input parameters: Δm_Z, $\Delta\alpha_{had}$, m_{top}
    - Δm_Z=2.1 MeV: $\Delta\sin^2\theta_{eff}^{para} \sim 1.4\text{x}10^{-5}$
    - $\Delta\alpha_{had} \sim 35$ (5 future) x 10^{-5} : $\Delta\sin^2\theta_{eff}^{para} \sim 12$ (1.7 future)x10^{-5}
    - $\Delta m_{top} \sim 1$ GeV (LHC): $\Delta\sin^2\theta_{eff}^{para} \sim 3\text{x}10^{-5}$
    - $\Delta m_{top} \sim 0.1$ GeV (ILC): $\Delta\sin^2\theta_{eff}^{para} \sim 0.3\text{x}10^{-5}$

→ ***If $\Delta\sin^2\theta_{eff} \sim 3\text{x}10^{-5}$ achievable: big physics impact***

$\sin^2\theta_{eff}$ at the Z-factory

- **Measure both A_{FB} and A_{LR} in same experiment !**

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    - yesterday Davier: $\Delta\alpha_{had} \sim 10\mathrm{x}\ 10^{-5}$: $\Delta\sin^2\theta_{eff}^{para} \sim 3.4\mathrm{x}10^{-5}$
    - $\Delta m_{top} \sim 1$ GeV (LHC): $\Delta\sin^2\theta_{eff}^{para} \sim 3\mathrm{x}10^{-5}$
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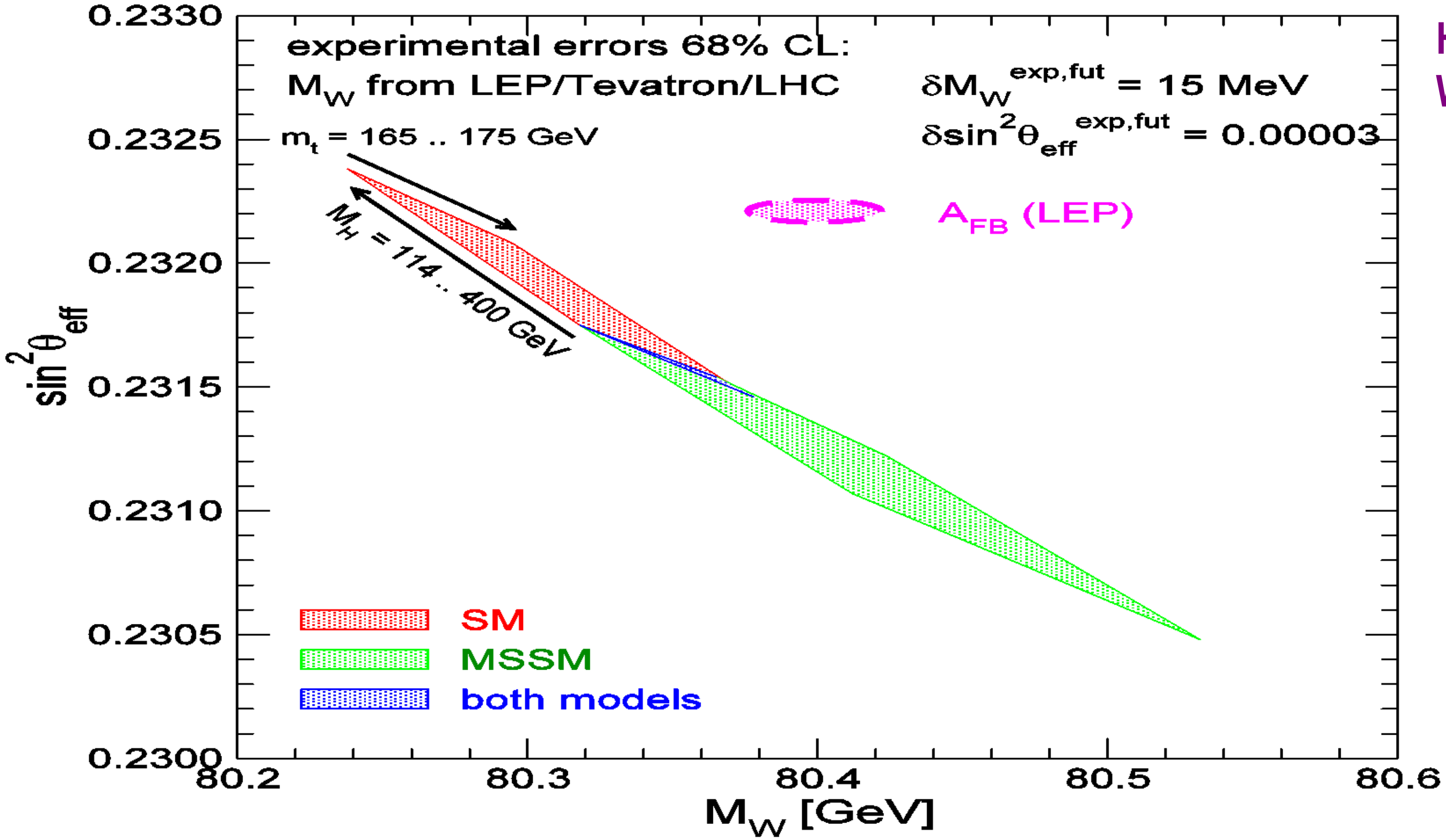
Possible result of a Z-factory



Heinemeyer,
Weiglein

→ *would unambiguously rule out SM+MSSM !*

What's the role of polarization?

- **Statistical uncertainty of A_{LR}**
  - If only polarized electrons (from source):

    $\rightarrow \Delta A_{LR}$ depends mainly on polarimeter resolution $\Delta P/P \sim 0.5\%$-1%
  - If both beams are polarized: apply

    Blondel scheme: $A_{LR} = f(\sigma_{LR}, \sigma_{RL}, \sigma_{LL}, \sigma_{RR})$

    $\rightarrow$uncertainty depends on $\Delta\sigma_{LL}$, $\Delta\sigma_{LR}$, $\Delta\sigma_{RL}$, $\Delta\sigma_{RR}$ not on $\Delta P/P$!

    $\rightarrow$Some running in LL and RR required: ~10% of time
- **Assume**
  - $P(e^-)=90\%$
  - Vary $P(e^+)= 22\%, 30\%, 50\%$

How many Z's are needed for $\Delta\sin^2\theta_{eff}=3\times10^{-5}$ or even 1.3×10^{-5}?

As comparison: lumi(GigaZ)= 10^9 Z's in ~70 days

Required polarization & years

- **Remember:** currently $\Delta\sin^2\theta_{eff}=1.6\text{x}10^{-4}$
- $P(e^-)=90\%$, $\Delta P/P=0.5\text{-}1\%$ (for $e^\pm$)

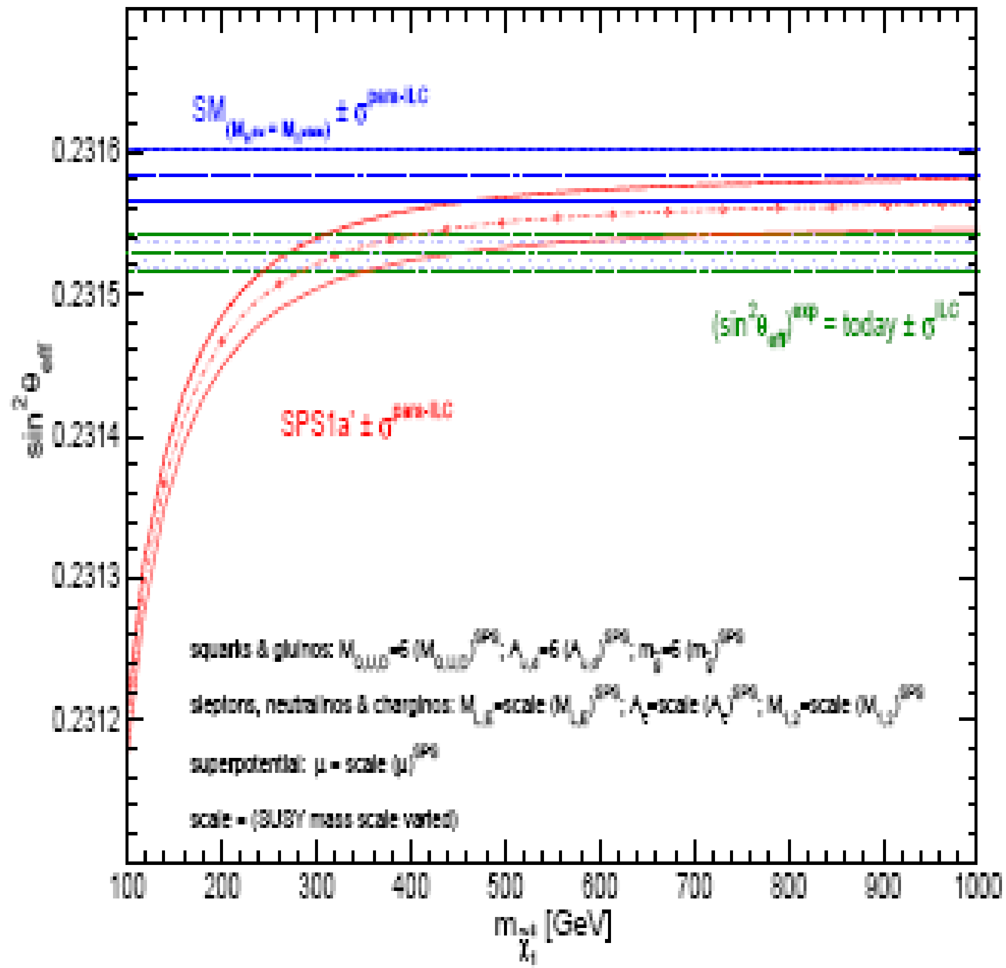
$P(e^+)$	#Z's	$\Delta\sin^2\theta_{eff}$	
0%	$4.5\text{x}10^7$	$1.0\text{x}10^{-4}$	No further progress
	$9.0\text{x}10^8$	$9.8\text{x}10^{-5}$	
22%	$1.7\text{x}10^9$	$3.0\text{x}10^{-5}$	$3\text{x}10^{-5}$: high sensitivity to new physics!
30%	$7.7\text{x}10^8$	$3.0\text{x}10^{-5}$	
50%	$2.3\text{x}10^8$	$3.1\text{x}10^{-5}$	
22%	$9.1\text{x}10^9$	$1.3\text{x}10^{-5}$	'GigaZ': full exploitation only if m_{top}=0.1 GeV
30%	$4.1\text{x}10^9$	$1.3\text{x}10^{-5}$	
50%	$1.4\text{x}10^9$	$1.3\text{x}10^{-5}$	

- **Polarization of both beams is mandatory !**

→ ***GigaZ precision does need high polarization of $e^\pm$!***

Help in challenging LHC scenarios ?

- **Assume only Higgs@LHC but no hints for SUSY:**
  - Really SM?
  - Help from $\sin^2\theta_{eff}$?
- **If GigaZ precision:**
  - i.e. Δm_{top}=0.1 GeV…
  - Deviations measurable
- **$\sin^2\theta_{eff}$ can be the crucial quantity !**



What else at the Z-pole? Plans…

- Measurement of Γ_l
- Measurement of α_s
- Couplings/mixing of Z'-Z studies
- Flavour physics
- …. further ideas?

Summary table and gain factor

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

hep-ph/0507011

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

Case	Effects for $P(e^-) \longrightarrow P(e^-)$ and $P(e^+)$	Gain& Requirement	
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	$P^T_{e^-} P^T_{e^+}$ required	P^T_{e-} P^T_{e+} required
	access to S- and T-currents up to 10 TeV		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

Summary table and gain factor

hep-ph/0507011
P(e+)=30%

- Estimated gain factor when only

Case	Effects for $P(e^-) \longrightarrow P(e^-)$ and $P(e^+)$	Gain& Requirement
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	$P^T_{e^-} P^T_{e^+}$ 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 and open studies?

- Polarized $e^{\pm}$ beams required for many ew precision studies
- Some effects can only be achieved with polarized e^- and e^+:
  - access to specific triple gauge coulings
  - accuracy in ΔA_{LR} (important for many studies!)
  - precision measurements on $\sin^2\theta_{eff}$ at the Z-pole
- New strawman baseline design foresees P(e+)~22%:
  - can be compensated in some cases by achieving P(e-)=90%
  - results in some studies to practically no physics gain!
- 'Cheap and easy' tools for reinstallation of at least 30% should be done (e.g. via implementation of a collimator)
  - Otherwise powerful tool for some studies is lost!
- *Further ideas / proposals?*