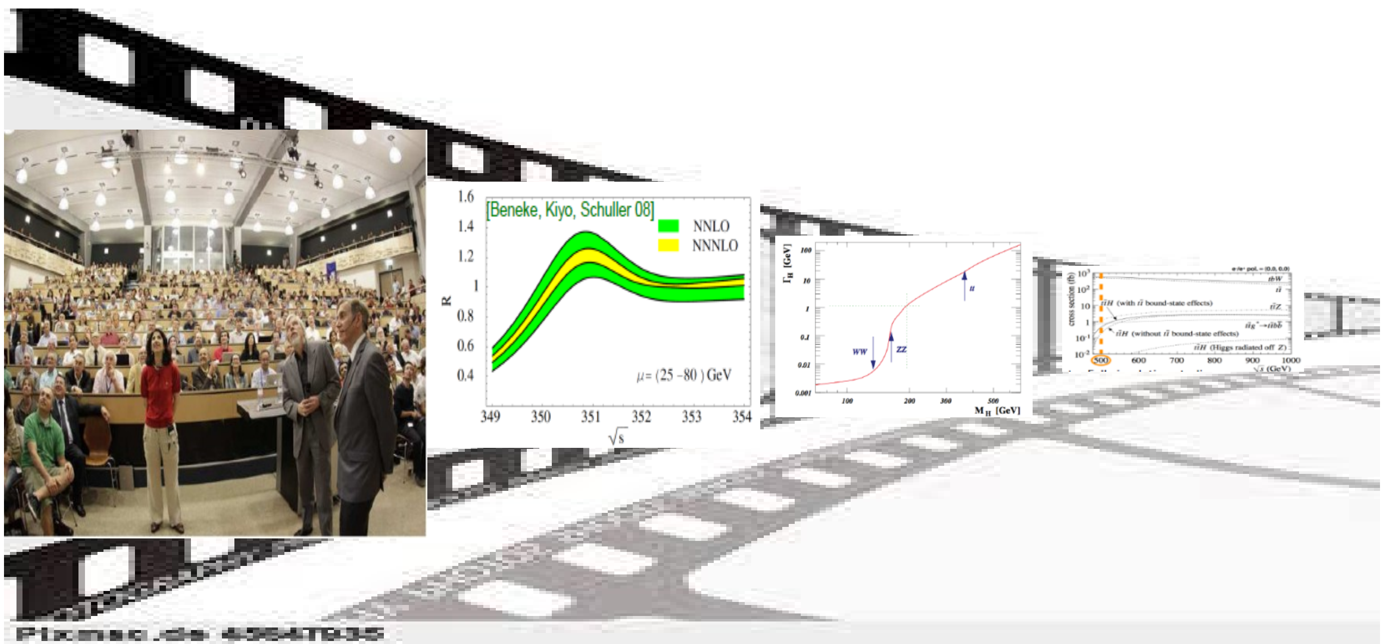
Impact of beam polarization in top physics

G. Moortgat-Pick
(Uni Hamburg/DESY)



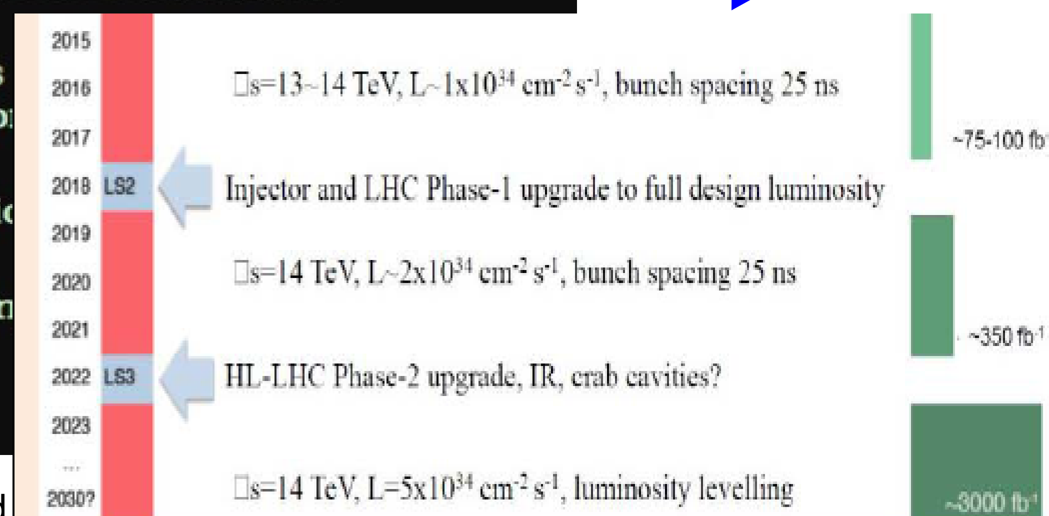
LINEAR COLLIDER COLLABORATION

Very encouraging politics!

Possible Timeline

- July 2013
  - Non-political evaluation of 2 Japanese candidate sites complete, followed by down-selecting to one
- End 2013
  - Japanese government announces its intent to bid
- 2013~2015
  - Inter-governmental negotiations
  - Completion of R&Ds, preparatio
- ~2015
  - Inputs from LHC@14TeV, decisi
- 2015~16
  - Construction begins (incl. biddin
- 2026~27
  - Commissioning

LHC timeline



Preface

- Strong physics case with m_H~125 GeV
- However:
  - LHC run (lumi, pile-up) was perfectly well, better analysis results than expected (in that time)
  - Very encouraging (and optimistic) estimates for $\sqrt{s}$=14 TeV
- We have to compete with that … in the physics landscape of 2025!!!
  - Very engaging activities in Japan, but the LC is not yet approved !
  - We need the best and optimized performance as possible: have to offer 'new' tools to improve the quality of analyses
  - The 'LC' just as little add-on to LHC will not 'fly' !

Status LHC results -- in short

- Discovery of a SM-like Higgs around m_H~125 GeV
  - Is an absolute revolution!
  - Completely new type
  - Not clear whether a SM-Higgs

`The properties of the Higgs boson, to be discovered at the LHC, must be thoroughly investigated in a good condition at the ILC'
(K. Kawagoe, Feb 12)

- Limits in SUSY coloured sector (approx.):
  - m_g,m_q>1 TeV
  - 3rd generation: much weaker
- Limits on Z', W': ~2 TeV
- And more limits on ED, exotics, 4th generation etc.

Physics left for a Linear Collider? Which energy steps?

The LC physics offer

- **Staged approach:**
  - $\sqrt{s}$=240 GeV, `Higgs frontier‘
  - $\sqrt{s}$=350 GeV, `Top frontier‘
  - $\sqrt{s}$=500 GeV, `Design energy frontier‘
  - ($\sqrt{s}$=91 GeV, `Precision frontier‘)
  - $\sqrt{s}$=1000 GeV, `Energy upgrade‘
- **`New’ features, impact on ‘quality’ (and quantity):**
  - Flexible energy (threshold scans)
  - Polarized e- and e+ beams

What has changed since Polarisationreport?

Technical remarks

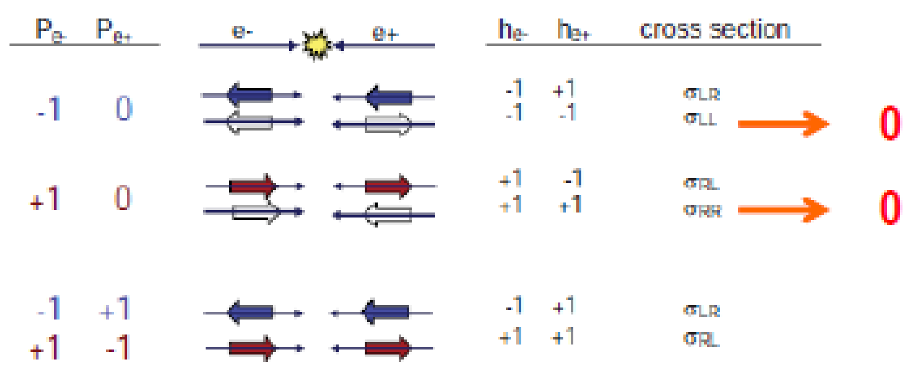
- **P(e-) ~ 80-90%**
- **P(e+) (always yield ≥1.5 imposed):** *A. Ushakov, LC note*

  √s=240 GeV: P(e+)=40% √s=350 GeV: P(e+)=56%

  √s=500 GeV: P(e+)=59% √s=1 TeV: P(e+)=54%

- **Measurent of polarization:** *J. List e.al*
  - Compton polarimetry (up- and down-stream): δP/P=0.25%
  - Via WW-process (lumi-weighted!): δP/P(e-)~0.1%, δP/P(e+)~0.2-0.3% *I. Marchesini, A.Rosca*

- **Helicity reversal required:**
  - Fast reversal to benefit from higher $L_{eff}=(1-P_{e-}P_{e+})L$

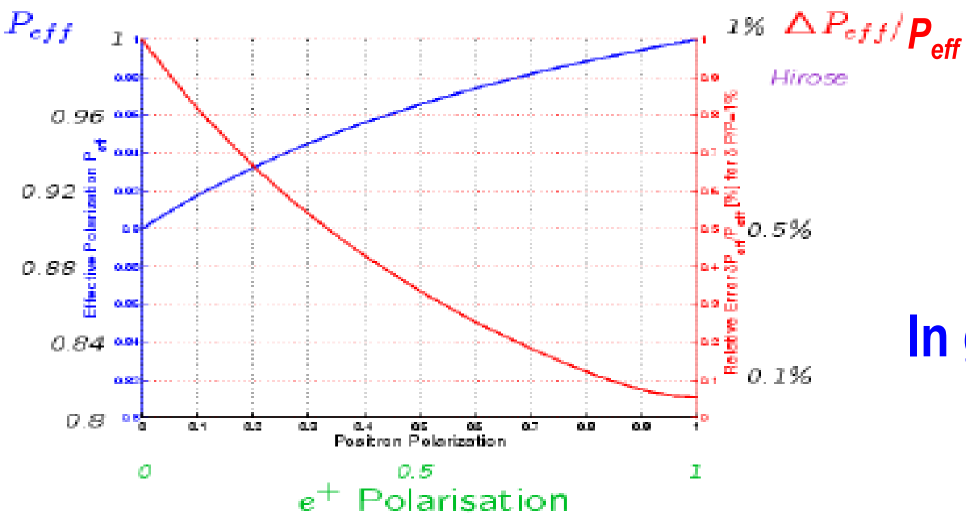


Quantitative P(e+) effects

- **If only (axial)vector couplings involved (SM):**
  - $\sigma_{pol} = \sigma_{unpol} \, (L_{eff} / L) \, (1 - P_{eff} A_{LR})$

S. Riemann, LC note

$$\mathcal{P}_{\rm eff} = \frac{-\mathcal{P}_{e^-} + \mathcal{P}_{e^-}}{1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+}} \quad > P_e$$



If #events large:
$\delta P_{eff}/P_{eff} \sim \delta A_{LR}/A_{LR}$

In general:

$$\delta A_{\rm LR} = \sqrt{\frac{1 - \mathcal{P}_{\rm eff}^2 A_{\rm LR}}{\mathcal{P}_{\rm eff} N} + A_{\rm LR}^2 \left(\frac{\delta \mathcal{P}_{\rm eff}}{\mathcal{P}_{\rm eff}}\right)^2}$$

- **Enhancement of L_{eff}** ⟵ **More interactions!**
- **Reduction of δP_{eff}** ⟵ **Higher accuracy**
- **Better S/B, S/√B**

P_{eff} and L_{eff} for the staged approach

- **With the listed parameters:**

$\sqrt{s}$	$P(e^-)$	$P(e^+)$	$P_{\rm eff}$	$\mathcal{L}_{\rm eff}/L$	$\frac{1}{x}\Delta P_{\rm eff}/P_{\rm eff}$
total range	$\mp 80\%$	0%	$\mp 80\%$	1	1
250 GeV	$\mp 80\%$	$\pm 40\%$	$\mp 91\%$	1.3	0.43
$\geq$350 GeV	$\mp 80\%$	$\pm 55\%$	$\mp 94\%$	1.4	0.30
total range	$\mp 90\%$	0%	$\mp 90\%$	1	1
250 GeV	$\mp 90\%$	$\pm 40\%$	$\mp 96\%$	1.4	0.43
$\geq$350 GeV	$\mp 90\%$	$\pm 55\%$	$\mp 97\%$	1.5	0.29

← **No gain!** (total range, $\mp 80\%$)

← **No gain!** (total range, $\mp 90\%$)

Gain in polarization! (Almost 100%)

Gain in number of interactions!

Gain in precision by more then a factor 3! (large N)

- **Just by switching on P(e+)!**

'New tools': Qualitative P(e+) effects

- **Access to chirality**

  In practically all new physics models

  - Chirality of particles/interactions has to be identified
  - Since for E>>m: chirality = helicity = polarization

- **Access to specific asymmetries** ($\tilde{\nu}$, heavy leptons, …, see LC notes)

$$A_{\rm double} = \frac{\sigma(P_1,-P_2)+\sigma(-P_1,P_2)-\sigma(P_1,P_2)-\sigma(-P_1,-P_2)}{\sigma(P_1,-P_2)+\sigma(-P_1,P_2)+\sigma(P_1,P_2)+\sigma(-P_1,-P_2)},$$

- **Exploitation of transversely-polarized beams** (~ P_{e-} P_{e+})
  - Access to tensor-like interactions (Extra dimensions, etc.)
  - Access to CP-violating phenomena
  - Access to specific triple gauge couplings
  - Optimize top quark polarization

Polarization report: not really changes required!

hep-ph/0507011

Case	Effects	Gain	
SM:			
top threshold	Improvement of coupling measurement	factor 3	
tq	Limits for FCN top couplings reduced	factor 1.8	
CPV in $t\bar{t}$	Azimuthal CP-odd asymmetries give access to S- and T-currents up to 10 TeV	$P_{e^-}^T P_{e^+}^T$ required	← P_{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 $\tilde{h}_+ = \mathrm{Im}(g_1^R + \kappa^R)/\sqrt{2}$	$P_{e^-}^T P_{e^+}^T$ required	} ← P_{e+} required
CPV in γZ	Anomalous TGC $\gamma\gamma Z$, $\gamma Z Z$	$P_{e^-}^T P_{e^+}^T$ 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 and measurement of $e^\pm$ Yukawa couplings	P_{e^+} required	← P_{e+} required
$\tilde{\mu}\tilde{\mu}$	Enhancement of S/B, $B = WW$ $\Rightarrow m_{\tilde{\mu}_{L,R}}$ 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 $\frac{S}{B}$, $\frac{S}{\sqrt{B}}$ Separation between SUSY models, 'model-independent' parameter determination	factor 2–3	
CPV in $\tilde{\chi}_i^0\tilde{\chi}_j^0$	Direct CP-odd observables	$P_{e^-}^T P_{e^+}^T$ required	← P_{e+} required
RPV in $\tilde{\nu}_\tau \to \ell^+\ell^-$	Enhancement of S/B, $S/\sqrt{B}$ Test of spin quantum number	factor 10 with LL	
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	$P_{e^-}^T P_{e^+}^T$ required	← P_{e+} required
Z':			
$e^+e^- \to f\bar{f}$	Measurement of Z' couplings	factor 1.5	
CI:			
$e^+e^- \to q\bar{q}$	Model independent bounds	P_{e^+} required	← P_{e+} required
Precision measurements of the Standard Model at GigaZ:			
Z-pole	Improvement of $\Delta\sin^2\theta_W$	factor 5–10	} ← P_{e+} required
	Constraints on CMSSM space	factor 5	
CPV in $Z \to b\bar{b}$	Enhancement of sensitivity	factor 3	

Staged approach

- $\sqrt{s}$=240 GeV, `Higgs frontier': HZ production
  - Determination of couplings to c, b,g

$\Delta(\sigma^*BR)/(\sigma^*BR)$	250 GeV/250 fb^{-1} P = (-0.8,+0,3)	350 GeV/250 fb^{-1} P = (-0.8,+0,3)
$H \to bb$	1.0%	1.0%
$H \to cc$	6.9%	6.2%
$H \to gg$	8.5%	7.3%

>factor 10 better than HL-LHC

LC unique

LC unique

[H.Ono, A: Miyamoto] EPJC (2013) 73

- Scaling factor about $\sigma_{pol}/\sigma_{unpol}$~(1-0.151 P_{eff}) * L_{eff}/L
  - With P_{e+}=0%: $\sigma_{pol}/\sigma_{unpol}$~1.13
  - With P_{e+} =30%: $\sigma_{pol}/\sigma_{unpol}$~1.44
  - With P_{e+} =40%: $\sigma_{pol}/\sigma_{unpol}$~1.55 (about 37% increase comp. to 0%)

Higgs +top sector

- $\sqrt{s}$=350 GeV: Higgs couplings and width:
  - In Higgsstrahlung: $\sigma_{pol}/\sigma_{unpol}$~(1-0.151 P_{eff}) * L_{eff}/L

    With P_{e+}=0%: $\sigma_{pol}/\sigma_{unpol}$~1.13
    With P_{e+} =30%: $\sigma_{pol}/\sigma_{unpol}$~1.44
    With P_{e+} =55%: $\sigma_{pol}/\sigma_{unpol}$~1.71 (about 50% increase comp. 0%)

  - In WW-Fusion: $\sigma_{pol}/\sigma_{unpol}$~(1- P_{eff}) * L_{eff}/L

    With P_{e+}=0%: $\sigma_{pol}/\sigma_{unpol}$~1.90
    With P_{e+} =30%: $\sigma_{pol}/\sigma_{unpol}$~2.40
    With P_{e+} =55%: $\sigma_{pol}/\sigma_{unpol}$~2.95 (about 55% increase comp. 0%)

- **Important: Higgs width**
  (needed for BR's, model-ind. Coupl.)

250 GeV	11.0 %
350 GeV	3.6 %
500 GeV	3.2 %

[Dürig; Meyer,KD]

Still improvement possible!

Top sector

- $\sqrt{s}$=500 GeV: top electroweak and top-Yukawa couplings:
  - Top electroweak couplings:
    measurable %-level!
    Higher accuracy if P_{e+}=55%

Coupling	SM value	LHC [1] $\mathcal{L} = 300$ fb^{-1}	e^+e^- [6] $\mathcal{L} = 300$ fb^{-1} $\mathcal{P}, \mathcal{P}' = -0.8, 0$	e^+e^- [ILC DBD] $\mathcal{L} = 500$ fb^{-1} $\mathcal{P}, \mathcal{P}' = \pm 0.8, \mp 0.3$
$\Delta \tilde{F}^{\gamma}_{1V}$	0.66	$^{+0.043}_{-0.041}$	–	$^{+0.002}_{-0.002}$
$\Delta \tilde{F}^{Z}_{1V}$	0.23	$^{+0.240}_{-0.620}$	$^{+0.004}_{-0.004}$	$^{+0.003}_{-0.003}$
$\Delta \tilde{F}^{Z}_{1A}$	-0.59	$^{+0.052}_{-0.060}$	$^{+0.009}_{-0.013}$	$^{+0.005}_{-0.005}$
$\Delta \tilde{F}^{\gamma}_{2V}$	0.015	$^{+0.038}_{-0.035}$	$^{+0.004}_{-0.004}$	$^{+0.003}_{-0.003}$
$\Delta \tilde{F}^{Z}_{2V}$	0.018	$^{+0.270}_{-0.190}$	$^{+0.004}_{-0.004}$	$^{+0.006}_{-0.006}$

  - Yukawa couplings: g_{ttH}

R. Yonamine, T. Tanabe, K. Fujii

	500 GeV/ 1 ab^{-1}	1000 GeV/ 2 ab^{-1}
$\Delta g_{ttH}/g_{ttH}$	10%	4.6%

[E_{CM} = 500 GeV, L= 1 ab^{-1}, Pol= (-0.8,+0.3)]

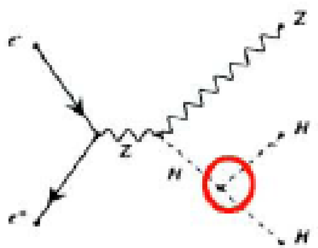
LHC estimates: about $\Delta\lambda_{ttH}$~10% at HL-LHC (14 TeV, 3000fb^{-1})

'Measure' for importance of beam polarization:

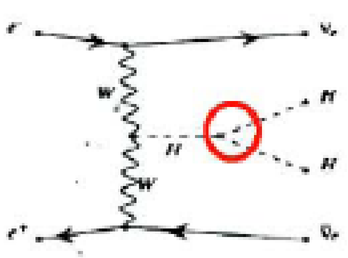
- If only P_{e-}=80%: improvement of Δg_{ttH}~19% comp. with P_{e-}=0
- With P_{eff}=89%: improvement of Δg_{ttH}~42% (actual value)
- With P_{eff}=97%: improvement of Δg_{ttH}~47%

$\sqrt{s}$=500GeV: Trilinear Higgs couplings

- **Very important for establishing Higgs mechanism!**
  - **LHC estimates:**
    - about $\Delta\lambda_{HHH}$~32% at HL-LHC (14 TeV, 3000fb^{-1})
  - **At LC: Very challenging (small rates , lots of dilution+backg.)**



$d\lambda/\lambda = 1.8\ d\sigma/\sigma$



$d\lambda/\lambda = 0.85\ d\sigma/\sigma$

500 GeV 2 ab^{-1} P=(-0,8,0,3)

	$\Delta\lambda/\lambda$
ILC 500/2ab^{-1}	44%
ILC 1000/2ab^{-1}	18%

[J.Tian LC-REP-2013-003]

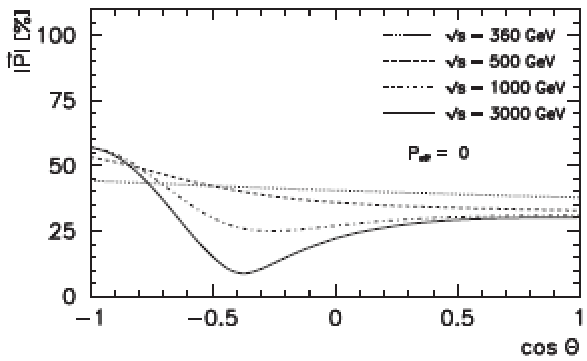
state-of-the-art today

  - **Further improvement with P_{e+} =55% instead of P_{e+} =30%:**
    - **Same scaling factors as given before**
    - **about 50% enhancement comp. to P_{e+}=0%**

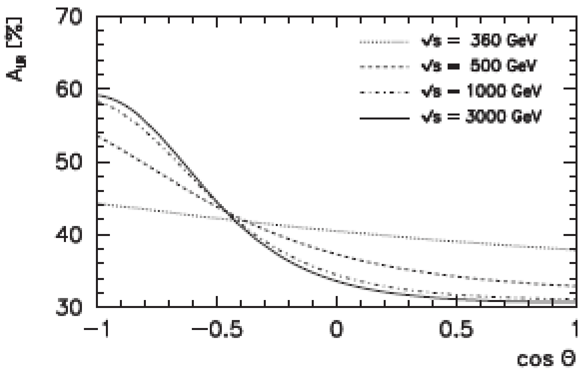
Top polarization

- **Top=3rd generation:**
  J. Koerner, LC note
  - polarization = analyzing tool for SM/BSM couplings
- **With beam polarization:**
  - P_{top} can be tuned maximal/minimal

$$A_{FB} = \frac{3}{4}\,\frac{g_{44} + P_{\rm eff}\,g_{14}}{g_{11} + P_{\rm eff}\,g_{41}} = 0.61\,\frac{1 - 0.27 P_{\rm eff}}{1 - 0.33 P_{\rm eff}}\,.$$



  - Left-right asymmetry (at NLO):



- **P_{top}=max for P_{eff}~1**
  - P_{eff}= -1 favoured (more stable)
- **P_{top}=0 for P_{eff}~0.4**

Effects of transverse beams

- **Transversely-polarized beams in e+e- -> tt**
  - probe scalar- and tensor-like interactions

Ananthanarayan, Patra, Rindani

- **Parametrization via eff. four-Fermi operators:**

$$\mathcal{L}^{4F} = \sum_{i,j=L,R} \left[S_{ij}(\bar{e}P_i e)(\bar{t}P_j t) + T_{ij}(\bar{e}\frac{\sigma_{\mu\nu}}{\sqrt{2}}P_i e)(\bar{t}\frac{\sigma^{\mu\nu}}{\sqrt{2}}P_j t) \right]$$

- **Use angular distributions with P^T_{e+} P^T_{e+}**
  - Sensitive to azimuthal angle: specific asymmetries
  - Assumed 100% beams

- **Sensitive to small S-,T-admixtures**
  - Keep this option…

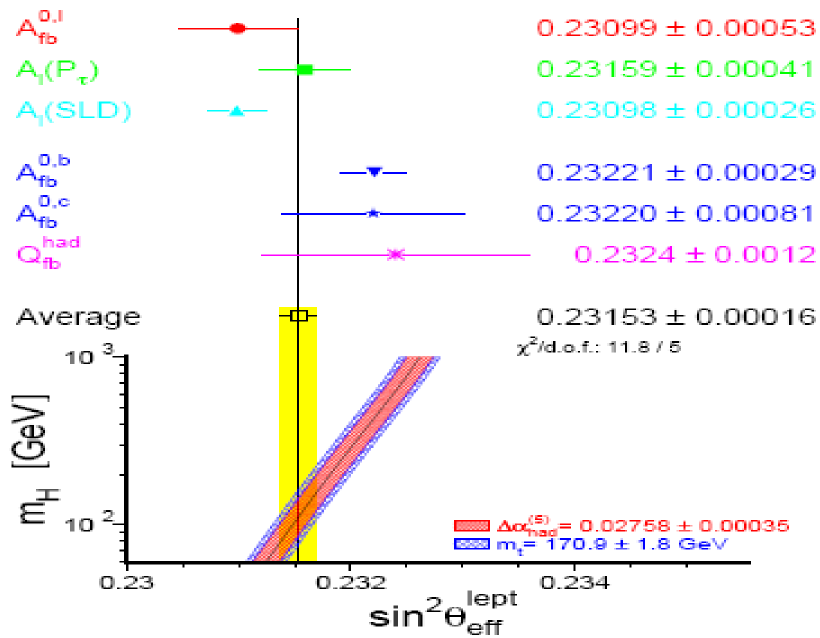
$\sqrt{s}$	Case	Coupling	Individual limit from asymmetries			
			$A_1(\theta_0)$	$A_2(\theta_0)$	$A_1^{FB}(\theta_0)$	$A_2^{FB}(\theta_0)$
500GeV	$+-$	ReS		$2.3 \times 10^{-3}\,\mathrm{TeV}^{-2}$		
		ReT				$5.2 \times 10^{-3}\,\mathrm{TeV}^{-2}$
		ImT	$1.2 \times 10^{-3}\,\mathrm{TeV}^{-2}$		$1.0 \times 10^{-2}\,\mathrm{TeV}^{-2}$	
	$++$	ImS	$2.3 \times 10^{-3}\,\mathrm{TeV}^{-2}$			
		ReT		$1.2 \times 10^{-3}\,\mathrm{TeV}^{-2}$		$1.0 \times 10^{-2}\,\mathrm{TeV}^{-2}$
		ImT			$5.2 \times 10^{-3}\,\mathrm{TeV}^{-2}$	

What if nothing else than H is found now?

But the exciting Higgs story has just started….

- **Since m_H is free parameter in SM at tree level**
  - Crucial relations exist, however, between m_{top}, m_W and $\sin^2\theta_{eff}$
  - If nothing else appears in the electroweak sector, these relations have to be urgently checked in order to
    - a) distinguish between SM and Higgs in BSM models (remember $\Delta m_H \sim m^4_{top}$ in BSM!)
    - b) Close the SM picture ?
- **Which strategy should one aim?**
  - exploit precision observables and check whether the measured values fit together at quantum level
  - m_Z ,m_W,α_{had}, $\sin^2\theta_{eff}$ und m_{top}
- **Exploit \`GigaZ' option: high lumi run at $\sqrt{s}$ = 91 GeV**

Higgs story has just started … $\sqrt{s}$=91 GeV



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

Goal GigaZ: $\Delta\sin\theta$=1.3 10^{-5}

- **Uncertainties from input parameters: Δm_Z, $\Delta\alpha_{had}$, m_{top} ,…**

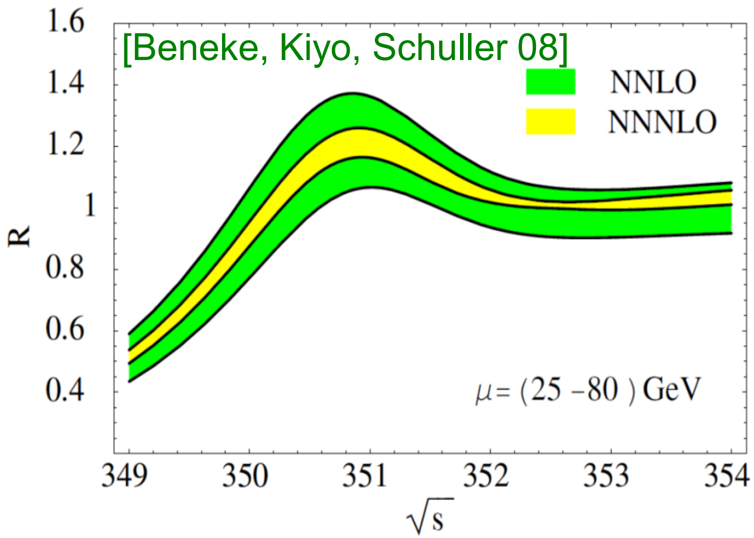
Heinemeyer, Kraml, Porod, Weiglein

- Δm_Z=2.1 MeV: $\Delta\sin^2\theta_{eff}^{para}$~1.4x$10^{-5}$
- $\Delta\alpha_{had}$~10 (5 future) x 10^{-5} : $\Delta\sin^2\theta_{eff}^{para}$~3.6 (1.8 future)x$10^{-5}$
- Δm_{top}~1 GeV (Tevatron/LHC): $\Delta\sin^2\theta_{eff}^{para}$~3x$10^{-5}$
- Δm_{top}~0.1 GeV (ILC): $\Delta\sin^2\theta_{eff}^{para}$~0.3x$10^{-5}$

Higgs story has just started …

$\sqrt{s}$=91 GeV

- **But such a precision requires Δm_{top}=0.1 GeV**



Important shift due to non-logarithmic NNNLO terms

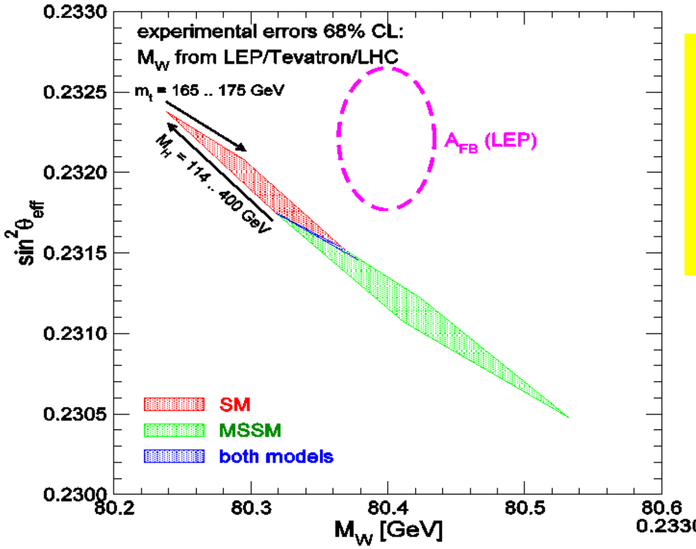
$\sqrt{s}$=350 GeV

- **LC: Peak position remains stable: m_t=100 MeV expected accuracy confirmed!**
- **However: dedicated threshold scan required!**

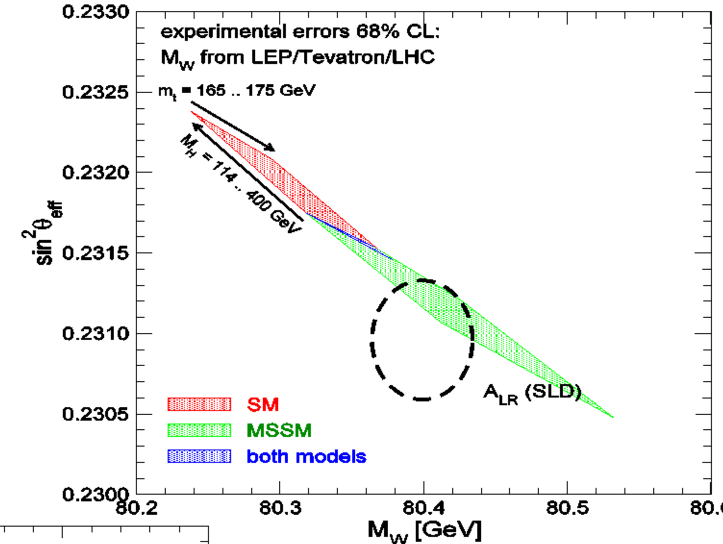
To close the story… GigaZ $\sqrt{s}=91$ GeV

- **Measure $\sin^2\theta_{eff}$ via A_{LR} with high precision: $\Delta\sin\theta = 1.3\ 10^{-5}$**

Heinemeyer, Hollik, Weber, Weiglein



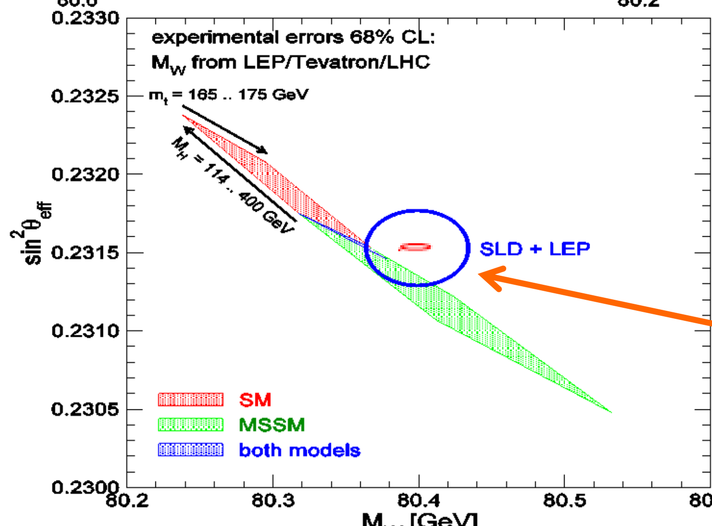
← LEP value disfavours both, SM+MSSM



↑ SLD value disfavours SM

World average → happy with both!

Central value has large impact !!!

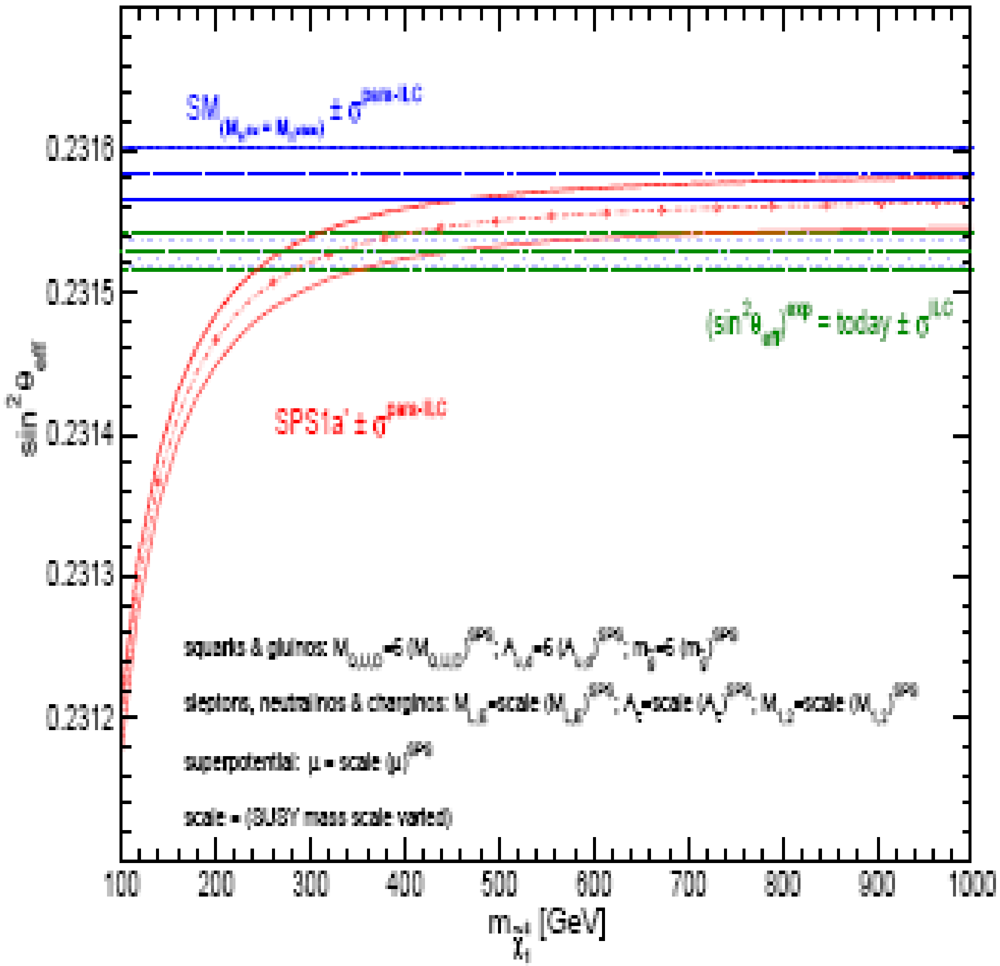


GigaZ precision!

What else could we learn? √s=91 GeV

- **Assume only Higgs@LHC but no hints for SUSY:**
  - **Really SM?**
  - **Help from $\sin^2\theta_{eff}$?**

Heinemeyer, Hollik, Weber, Weiglein



- **If GigaZ precision:**
  - **i.e. Δm_{top}=0.1 GeV…**
  - **Deviations measurable**

- **$\sin^2\theta_{eff}$ can be the crucial quantity to reveal effects of NP!**

Conclusions

- Beam polarization gives 'added-value' to ILC
  - Provides 'new' analysis tools comp. with LHC
- Positron polarization adds both:
  - quantity (Peff, Leff,top polarization) and quality (access to chirality, transverse polarization, new assymmetries)
- Important from beginning (Higgs + top!)
  - Optimizes physics potential
  - Crucial to compete with LHC options!
  - And…..do not forget GigaZ option: the ultimate electroweak safety option!!!