Physics of polarized beams at the ILC

G. Moortgat-Pick
(Uni Hamburg/DESY)

- **Status**
- **Polarization issues in top and Higgs physics**
- **Outlook**

LINEAR COLLIDER COLLABORATION

Status

Congratulations to the Kitakami region!

Site selection has been made !

+ positive statements from AsiaHEP, ACFA
+ JAHEP proposal for ILC from 250 GeV upgrade to higher energies

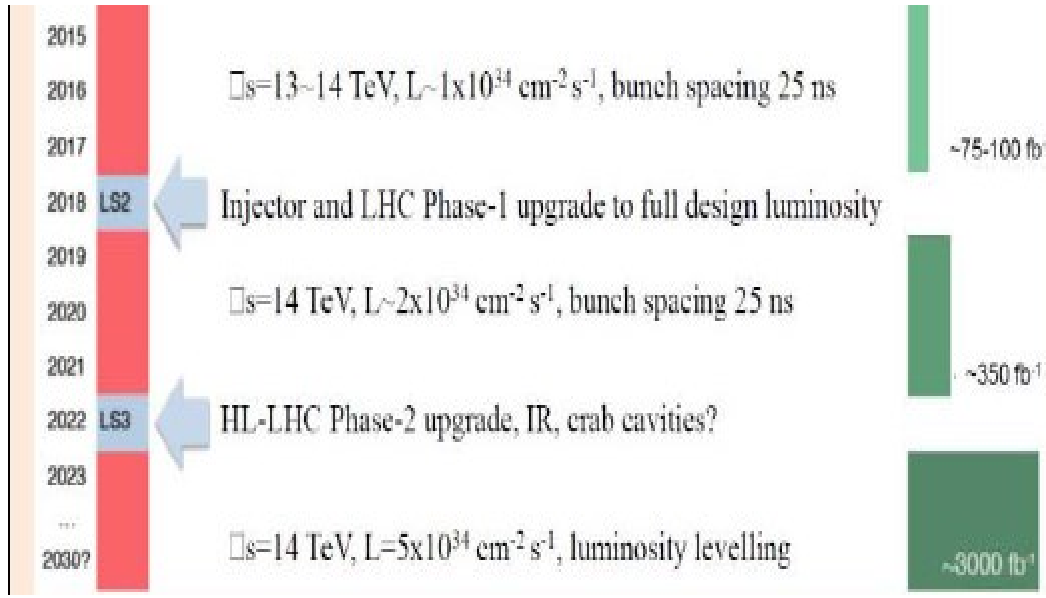
That's a big step towards our goal!

Why still some caution?

- We have a Higgs! That's great.
- Why do we need to know all its properties with best precision? Because that's the bridge between 'micro' and 'macro' cosmos.
- We have the Top! That's great.
- Why do we need to know all its properties with best precision? Because that's the bridge to understand dynamics of EWSB.
- Excellent top physics at LHC (and HL-LHC) That's great!
- But no sign of new physics ….so far That's strange.
- What do we really need from the ILC to be competitive?

Prospects LHC physics

- **LHC timeline:**
  - from ~2023 on: 2^{nd} phase of high lumi run at LHC
  - ~2030: 3000 fb^{-1} !!!



- **ILC prospects:**
  - maybe first runs with $\sqrt{s}$=250 GeV ('Higgs physics')
  - *Physics potential of the ILC best as possible required in order to be competitive !*

The full ILC physics offer

- **Staged approach:**
  - $\sqrt{s}$=250 GeV, `Higgs cross section, mass + couplings'
  - $\sqrt{s}$=350 GeV, `Higgs width + top mass'
  - $\sqrt{s}$=500 GeV, `Special Higgs- and top couplings+BSM'
  - ($\sqrt{s}$=91 GeV, `Precision frontier + indirect BSM frontier')
  - $\sqrt{s}\geq$1000 GeV, `Closing the Higgs picture+more BSM? '
- **'New' features, impact on 'quality' (and 'quantity'):**
  - Flexible precise energy
  - Perform threshold scans
  - Polarized beams

Our charge!

Technical remarks beam polarization

- $P(e^-) \sim 80\text{-}90\%$
- $P(e^+)$ (always yield ≥1.5 imposed, i.e. 'full' lumi):

A. Ushakov, LC note

$\sqrt{s}$=240 GeV: P(e+)=40%

$\sqrt{s}$=350 GeV: P(e+)=56%

$\sqrt{s}$=500 GeV: P(e+)=59%

$\sqrt{s}$=1 TeV: P(e+)=54%

- Measurent of polarization:
  - Compton polarimetry (up- and down-stream): $\delta P/P=0.25\%$
  - Via WW-process (lumi-weighted!): $\delta P/P(e-)\sim 0.1\%$, $\delta P/P(e+)\sim 0.2\text{-}0.3\%$

I. Marchesini, A.Rosca

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	← No gain!
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	← No gain!
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	

Gain in polarization! (Almost 100%)

Gain in number of interactions!

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

- Maximizing physics gain just by switching on $P(e^+)$ .....!

‛New quality' effects via P(e+)

- **Access to chirality**

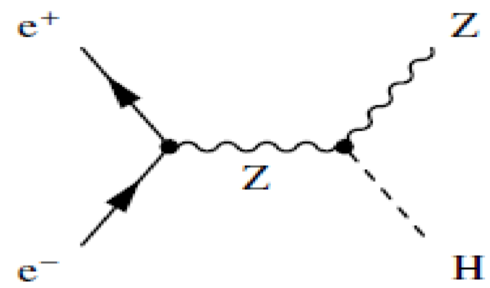
  Practically in all new physics models
  - Chirality of particles/interactions has to be identified
  - Since for E>>m: chirality = helicity = polarization
- **Access to specific asymmetries** (both beam pol. required)

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

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

Process: Higgs Strahlung $\sqrt{s}$=250 GeV

- $\sqrt{s}$=250 GeV: dominant process
- Why crucial?
  - allows model-independent access!
  - Absolute measurement of Higgs cross section σ(HZ) and g_{HZZ}: crucial input for all further Higgs measurements !



$\sqrt{s}$	250 GeV
Int. $\mathcal{L}$	250 fb-1
$\Delta(\sigma)/\sigma$	2.5%
$\Delta(g_{HZZ})/g_{HZZ}$	1.3%

← Model independent!

  - Reconstructed recoil mass distributions (eeX, μμX): ΔmH=32 MeV
  - Model independent coupling measurement

Polarization at the Higgs frontier

$\sqrt{s}$=250 GeV

- $\sqrt{s}$=250 GeV, Higgs strahlung, HZ production
  - Determination of couplings to c, b,g

Δ(σ*BR)/(σ*BR)	250 GeV/250 fb^{-1} P = (-0.8,+0.3)	350 GeV/250 fb^{-1} P = (-0.8,+0.3)	
H→bb	1.0%	1.0%	>factor 10 better than HL-LHC
H→cc	6.9%	6.2%	LC unique
H→gg	8.5%	7.3%	LC unique

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

- Scaling factor about $\sigma_{pol}/\sigma_{unpol} \sim (1-0.151\, P_{eff}) * L_{eff}/L$
  - With P_{e+}=0%: $\sigma_{pol}/\sigma_{unpol} \sim 1.13$
  - With P_{e+}=30%: $\sigma_{pol}/\sigma_{unpol} \sim 1.44$
  - With P_{e+}=40%: $\sigma_{pol}/\sigma_{unpol} \sim 1.55$ (about 8% increase comp. to 30%)

Higgs couplings

$\sqrt{s}$=350 GeV

- $\sqrt{s}$=350 GeV: improvement for Higgs couplings

  – 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 20% increase comp. 30%)

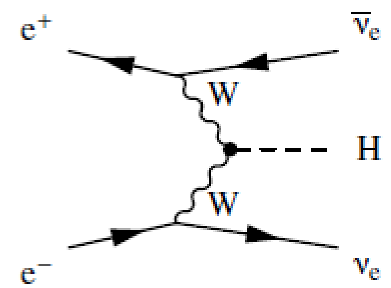
  – In WW-Fusion: $\sigma_{pol}/\sigma_{unpol}$~(1- P_{eff}) * L_{eff}/L

  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 23% increase comp. 30%)

Higgs width

$\sqrt{s}$=350 GeV

- $\sqrt{s}$=350 GeV: Access to Higgs total width :
  - Total width for mH=125 GeV: T_h^{tot} ~4 MeV!
  - Does need WW-fusion



	$\Delta T_h^{tot}/T_h^{tot}$
250 GeV:	13%
350 GeV:	~7%
500 GeV:	~5-6%
1 TeV:	~ 4%

Scaling factor:

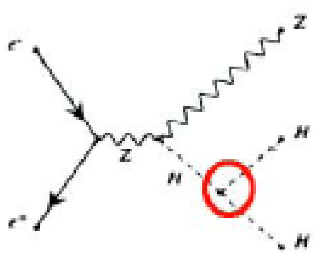
$\sigma_{pol}/\sigma_{unpol}$~(1- P_{eff}) * L_{eff}/L

- Higgs width crucial for absolute BR's, couplings and model discrimination!
- Enhancement of P_{eff} and L_{eff} important!

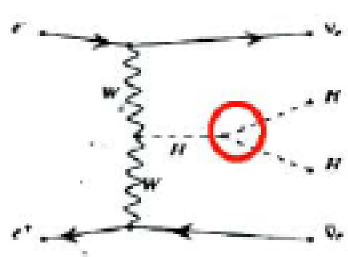
Trilinear Higgs couplings

$\sqrt{s}$=500 GeV

- **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 quark production at ILC

- **Top very special role: heaviest fundamental fermion**
  - **most strongly coupled to EWSB sector!**
  - **Intimately related to the dynamics behind the EWSB mechanism**
  - **Precision mass measurement m_{top}~100 MeV**
  - **M_{top} affects M_H, M_W, M_Z via radiative corrections**
  - **Top quark couplings open also a window to new physics !**

$\sqrt{s}$=350 GeV

Top electroweak coupling

$\sqrt{s}=500$ GeV

- $\sqrt{s}=500$ GeV: chiral structure of ew top couplings:
  - expected to be sensitive to BSM sources
  - Measurement of ‘g_{ttZ}’ and ‘$g_{tt\gamma}$’ rather unique for a LC!

- Use different observables
  - Cross section
  - A_{FB}
  - helicity angle

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} $\mathcal{P},\mathcal{P}'=\pm0.8,\mp0.3$
$\Delta\tilde{F}^{\gamma}_{1V}$	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	$^{+0.270}_{-0.190}$	$^{+0.004}_{-0.004}$	$^{+0.006}_{-0.006}$

- Couplings measurable at %-level
  - thanks to the different observables
  - To runs with different beam polarization configurations P(e-), P(e+)

⟶ Role of e+ polarization: allowed to vary form factors independently!

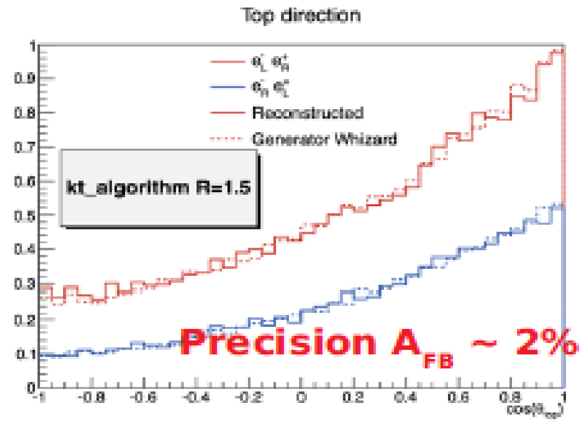
Top electroweak coupling

$\sqrt{s}$=500 GeV

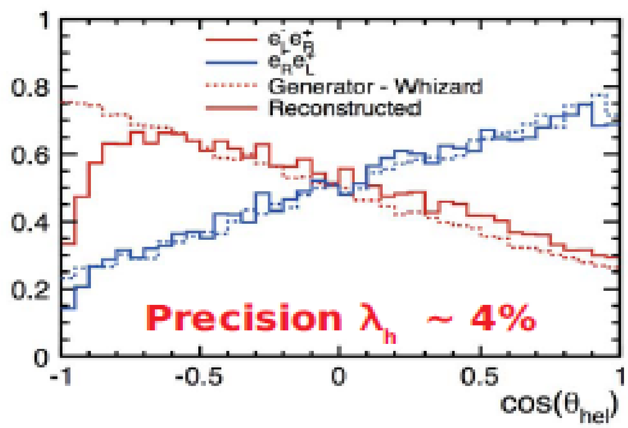
Results of full simulation study for DBD at $\sqrt{s}$ = 500 GeV

LC-REP-2013-007

Precision: x section ~ 0.5%



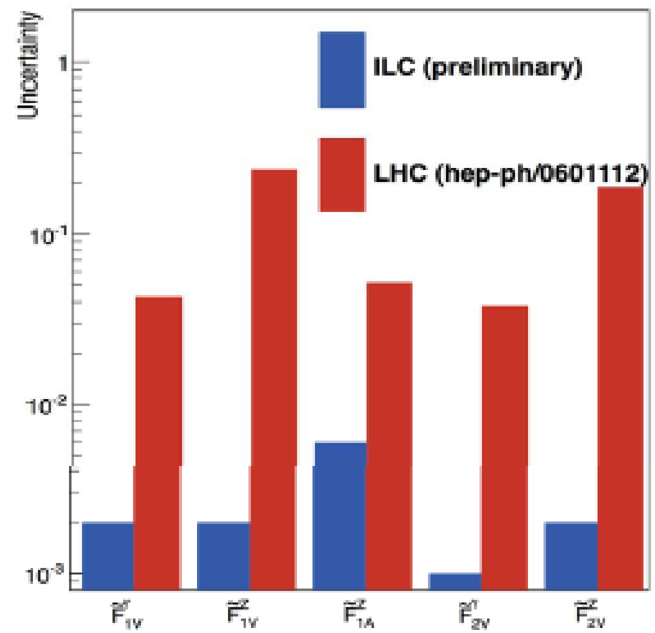
Precision A_{FB} ~ 2%



Precision λ_h ~ 4%

=>

Precision of couplings



ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})

15

Top Yukawa coupling

$\sqrt{s}$=500 GeV

- $\sqrt{s}$=500 GeV: top-Yukawa couplings:
  - At this energy: ttH is close to threshold
  - But thanks to threshold effects: σ enhancement by factor 2!
  - Key role in dynamics of ew symmetry-breaking
- Direct measurement of Yukawa couplings: g_{ttH}
  - With P(e-,e+)=(-80%,+30%) and 1600 fb $^{-1}$

    $\Delta g_{ttH} / g_{ttH} < 16\%$

    but model-independent!

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

With P_{eff}= 89% -> 97%: further improvement of Δg_{ttH}

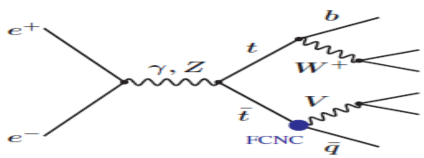
- $\sqrt{s}$=1000 GeV:
  - With P(e-,e+)=(-80%,+20%) and 2500 fb $^{-1}$

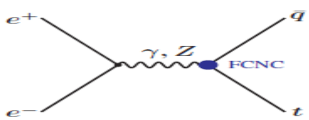
    $\Delta g_{ttH} / g_{ttH} < 4\%$!

Top FCNC

$\sqrt{s}$=500-800 GeV

- **Flavour-changing neutral couplings**
  - Relevant for many BSM
  - Can be studied in top pair or single top production





  - Using polarized beams (3σ, based on 300-500 fb^{-1}) :

	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}

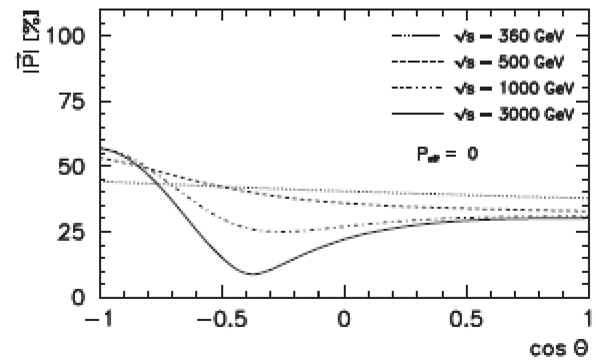
Exceeding LHC !

- **At the LC: sensitivty up to 10^{-6} to FCNC couplings!**

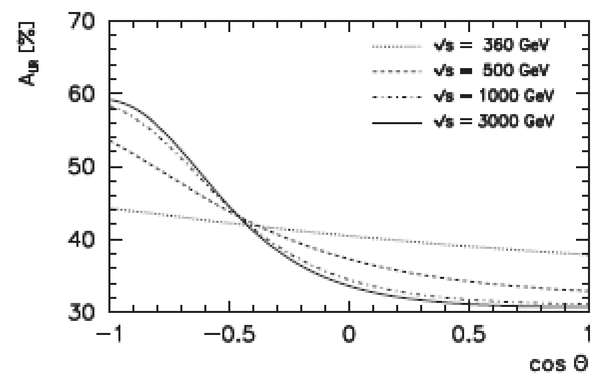
Top polarization

- **Top=3rd generation:** *Koerner et al.*
  - polarization = analyzing tool for SM/BSM couplings
  - Window to new physics!
- **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 $\sqrt{s}$=500 GeV

- Transversely-polarized beams in e+e- -> tt
  - probe scalar- and tensor-like interactions
- Probes of models with extra dimension
- Use angular distributions with P^T_{e+} P^T_{e+}
  - Sensitive to azimuthal angle: specific asymmetries
  - New study:
  - Assumed 100% beams
- Sensitive to small **Scalar,Tensor-admixtures**

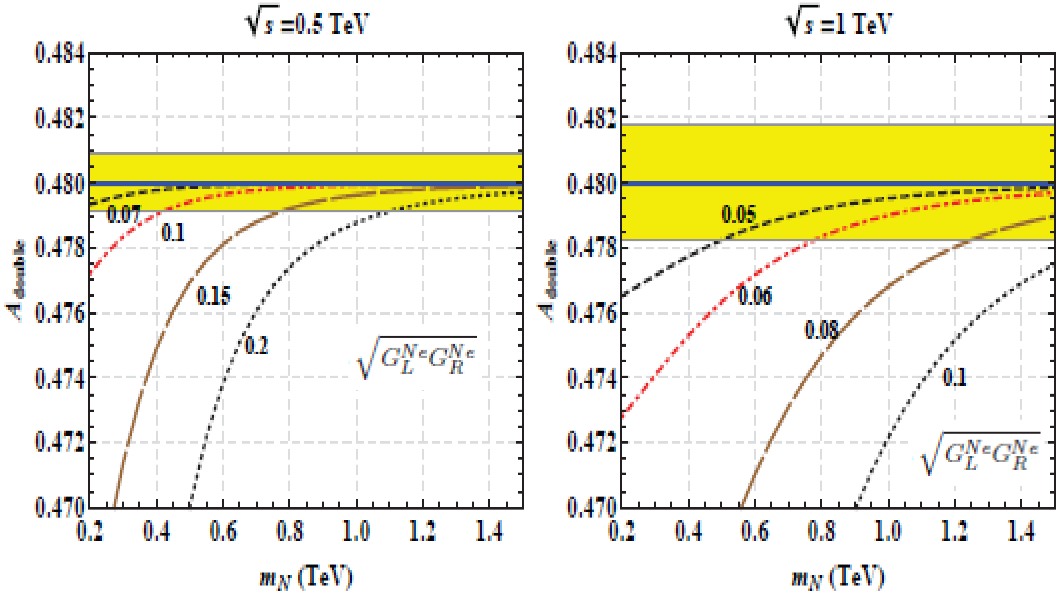
$\sqrt{s}$	Case	Coupling	Individual limit from asymmetries			
			$A_1(\theta_0)$	$A_2(\theta_0)$	$A_1^{FB}(\theta_0)$	$A_2^{FB}(\theta_0)$
500GeV	$+-$	$\mathrm{Re}S$		$2.3 \times 10^{-3}\,\mathrm{TeV}^{-2}$		
		$\mathrm{Re}T$				$5.2 \times 10^{-3}\,\mathrm{TeV}^{-2}$
		$\mathrm{Im}T$	$1.2 \times 10^{-3}\,\mathrm{TeV}^{-2}$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

P(e+) in WW in exotic searches

$\sqrt{s}$=500 GeV

- **Study: e+e- -> W+W-**
  - Very sensitive to leptonic vertices and trilinear gauge couplings
  - Well-known: transverse beams only access to CP trilinear couplings
  - Long. beams: New study for cont. of heavy neutral boson or heavy leptons
- **Model identification = exclusion of competitive models (incl. SM)**
  - Double polarization asymmetries very useful:

$$A_{\rm double} = P_1 P_2 \frac{(\sigma^{RL}+\sigma^{LR})-(\sigma^{RR}+\sigma^{LL})}{(\sigma^{RL}+\sigma^{LR})+(\sigma^{RR}+\sigma^{LL})}.$$



$$A_{\rm double}^{\rm SM} = A_{\rm double}^{Z'} = A_{\rm double}^{\rm AGC}$$

Sensitive to effects from such models and model distinction already at 500 GeV!

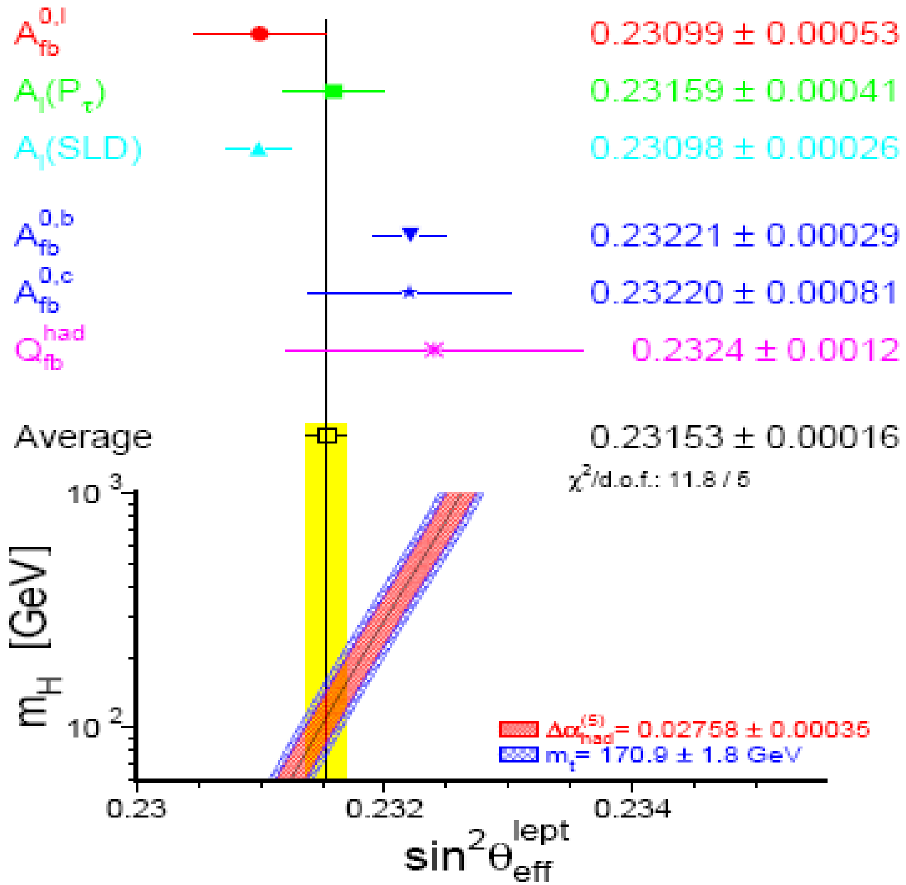
What if nothing else than H is found now?

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
- 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
  - Pe-=80% and Pe+=60% required !

    (If only Pe-=90% : precision ~factor 4 less!)

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

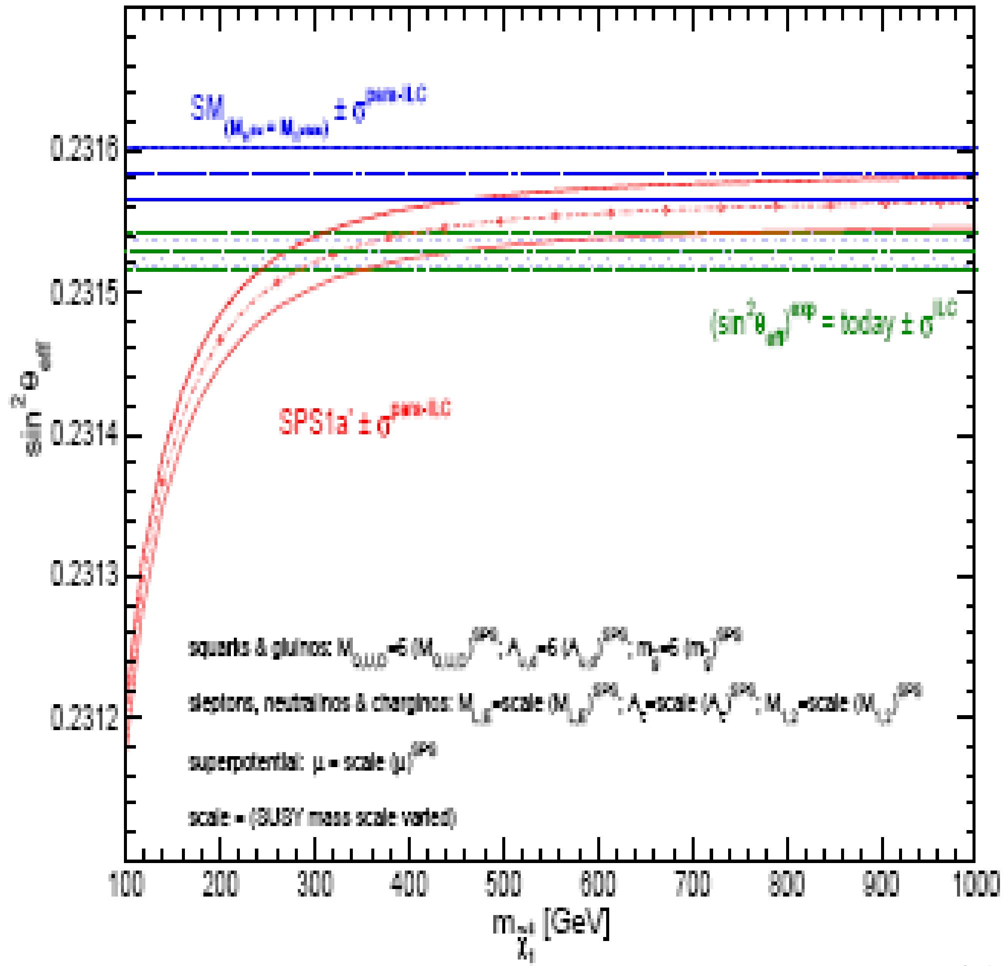
World average:

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

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

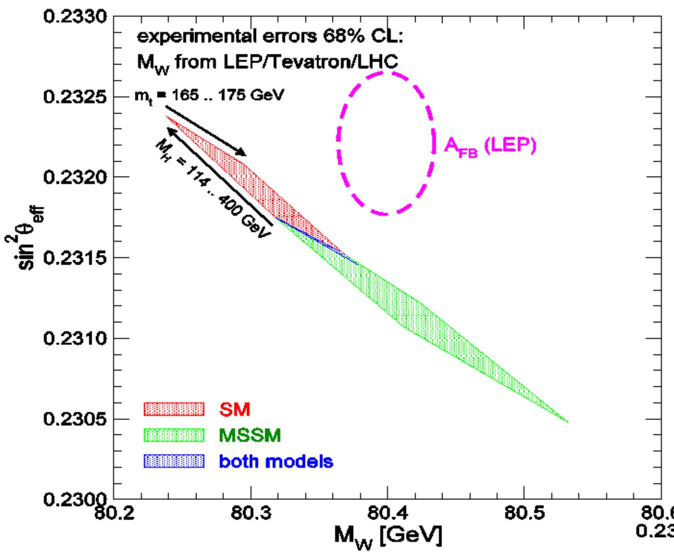
What else could we learn? $\sqrt{s}$=91 GeV

- **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 to reveal effects of NP!**

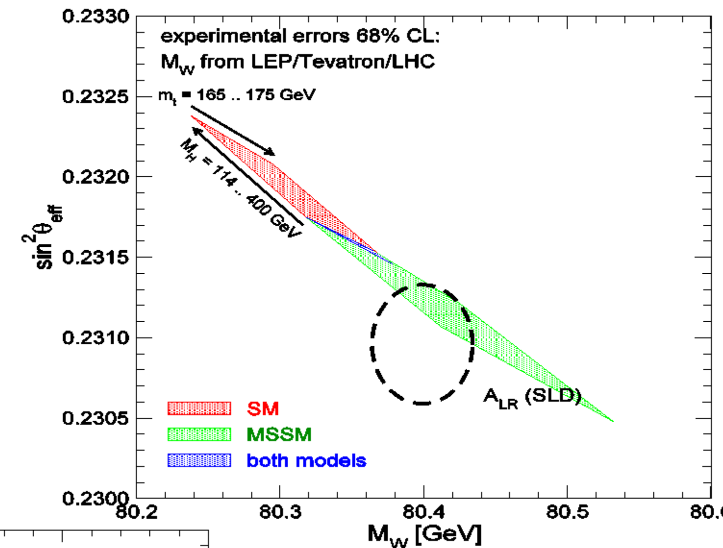


To close the story… GigaZ $\sqrt{s}=91$ GeV

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



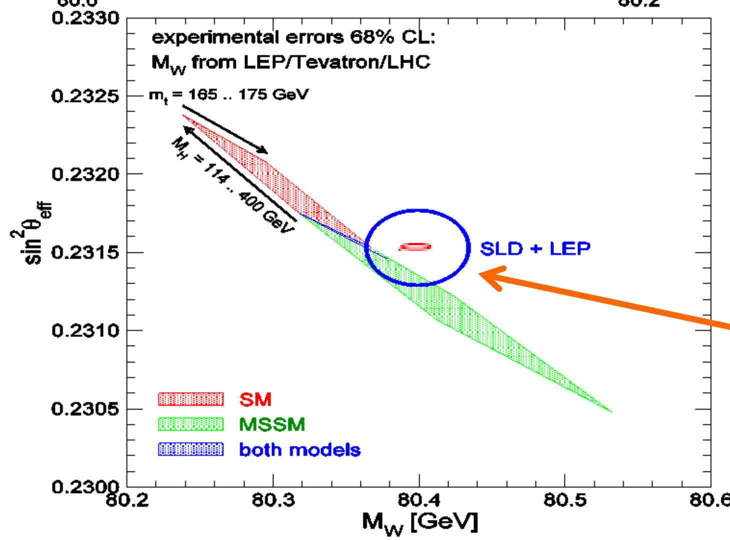
← LEP value disfavours both, SM+MSSM



↑ SLD value disfavours SM

World average → happy with both!

Central value has large impact !!!



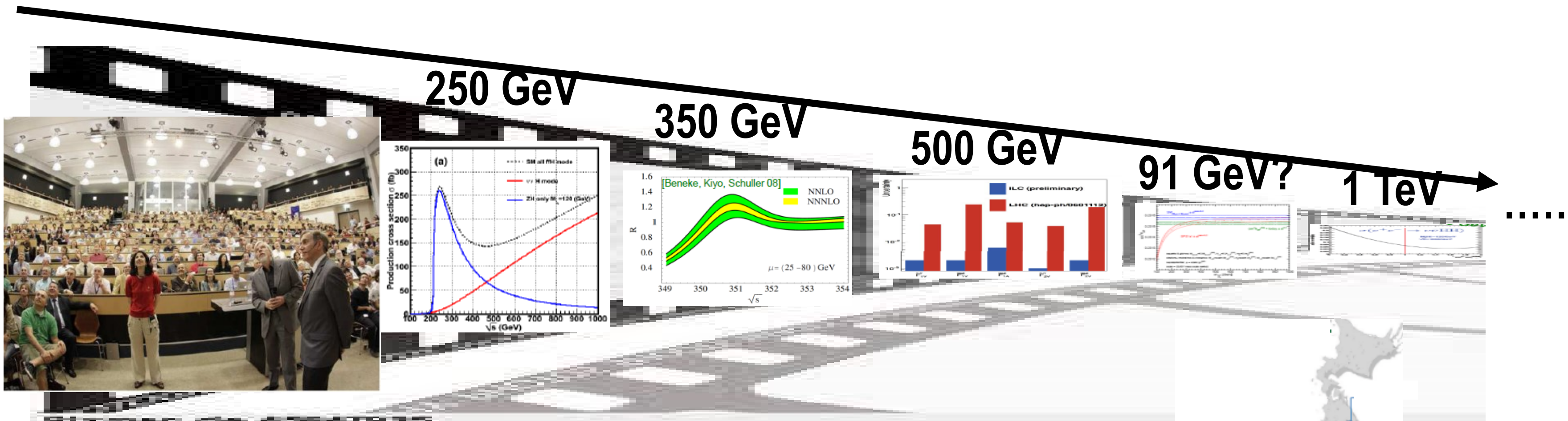
GigaZ precision!

Conclusions

- Beam polarization gives 'added-value' to ILC
  - longitudinally as well as transversely polarized beams
  - Provides 'new' analysis tools comp. with LHC
- Positron polarization quality and quantity
  - gain in lumi
  - gain in polarization
  - less uncertainties
  - access to 'new' physics windows
- Important from beginning (Higgs + top + WW !)
  - Optimizes physics potential
  - Crucial to compete with LHC options!
  - And…..do not forget GigaZ option: play a safety !!!

Outlook

- The ILC offers new tools already in top and Higgs physics:
  - Optimized physics potential with long+transv. polarized beams
  - complements and extends the HL-LHC capabilities !
  - sensitive to new physics via quantum effects
- Allows to fully exploit GigaZ! …keeping our 'savety margin'



The ILC Physics case is well justified!