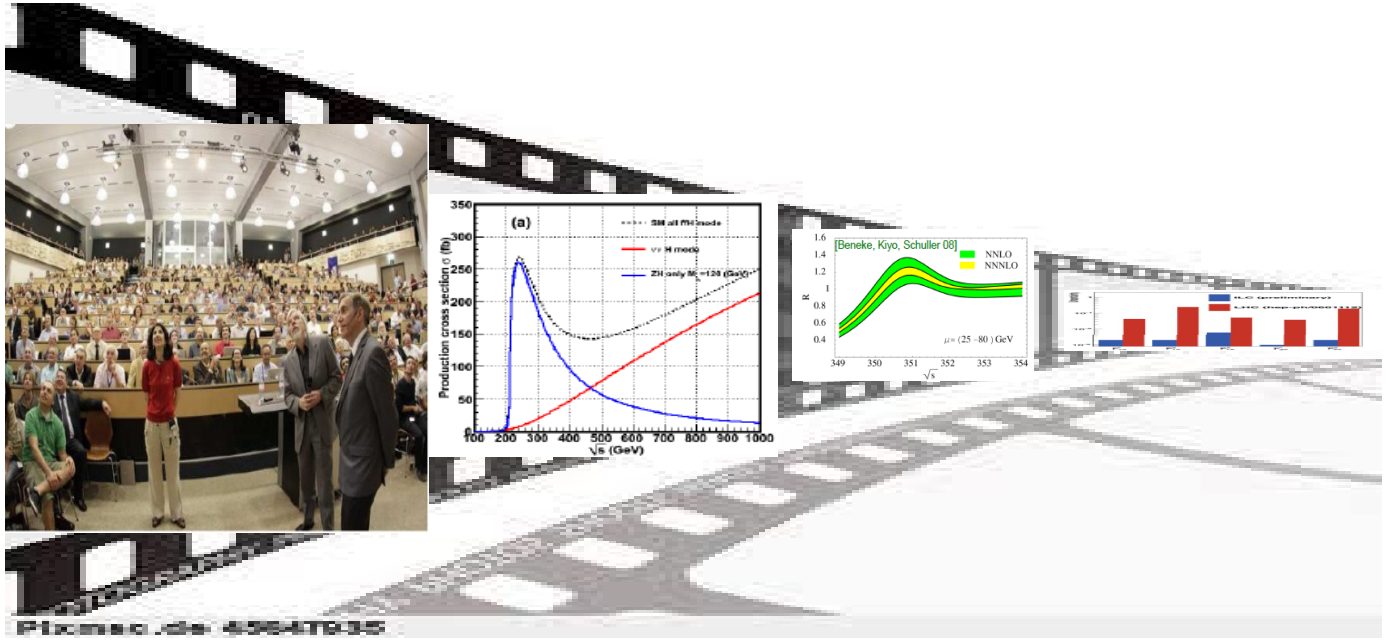
Impact of beam polarization on the LC physics potential for a staged approach

G. Moortgat-Pick, S. Riemann

(Uni Hamburg/DESY)



LINEAR COLLIDER COLLABORATION

What is the motivation?

- 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!
- Do we really also need the LC?

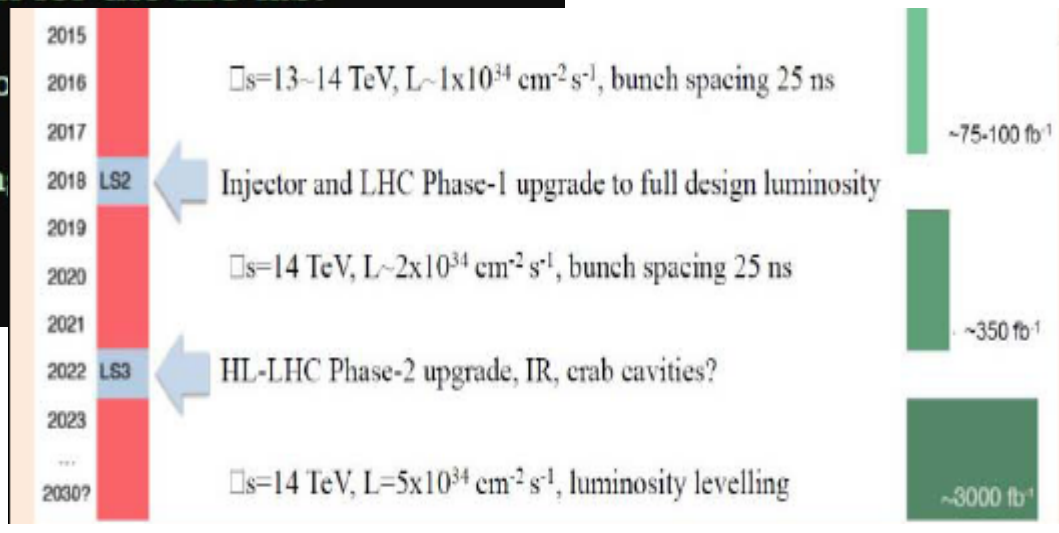
…a great chance might just be ahead….

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, preparation for the ILC lab.
- ~2015
  - Inputs from LHC@14TeV, decisio
- 2015~16
  - Construction begins (incl. biddin
- 2026~27
  - Commissioning

LHC timeline



ILC might start @ times HL-LHC!

Preface

- **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)

- **In short -- some LC capabilities:**

As e.g. Δm_{top}~0.1 GeV, $coup_{ttH}$~3%, H: BR's~1(b)-7(c)%, Γ_h~5%, $\Delta\lambda$~17%

Further improvement via lumi-upgrade, see Tians'talk!

- **Very active: many new LC studies and reports….**
  - *ILC TDR (since June 12, 2013)*
  - *CLIC CDR 2012*
  - *Collection of LC notes (DESY123h) online*
  - *2 more LC reviews under work*

Focus of my talk
(in p. 1st article in Desy123h, 1210.0202)

The LC 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 e- and e+ beams

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%

See talk by J. List

- **Measurent of polarization:**
  - **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

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!

← No gain!

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**

  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** ($\tilde{\nu}$, heavy leptons, …, see later)

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

- **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

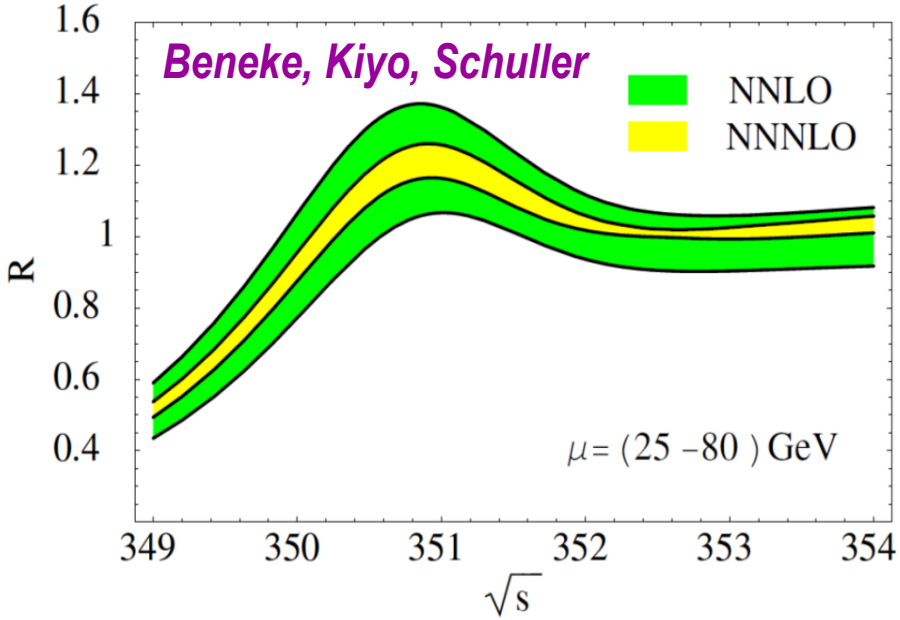
Top production at the LC

- **Top very special role: heaviest fundamental fermion**
  - **most strongly coupled to EWSB sector,**
  - **Intimately related to the dynamics behind the SB mechanism**
  - **M_{top} affects M_H, M_W, M_Z via radiative corrections**
- **At LHC/Tevatron: Δm_{top}~1 GeV**
  - **Crucial: relation between measured mass to a well-defined parameter that is a suitable theoretical input, as $\overline{MS}$ mass**
  - **Relation affected by non-perturbative contr. = limiting factor**
- **At the LC, e^+e^- -> t t: measure 'threshold mass'**
  - **Relation to well-defined m_{top}, theoret. well under control**
  - **Threshold scan: Δm_{top}~100 MeV (incl. theo+exp. uncertainties!)**

Top mass

$\sqrt{s}$=350 GeV

- **Threshold scan:**



Important shift due to non-logarithmic NNNLO terms

- **LC: Peak position remains stable: Δm_t=100 MeV**
- **includ. exp uncertainty of ~30 MeV + theo. uncertainty ~70 MeV**
- **expected accuracy confirmed by full simulation studies!**
- **Dedicated threshold scan required with about ~100fb^{-1}**

See talk by R. Poeschl

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} $\mathcal{P}, \mathcal{P}' = \pm 0.8, \mp 0.3$
$\Delta\tilde{F}^{\gamma}_{1V}$	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	$^{+0.270}_{-0.190}$	$^{+0.004}_{-0.004}$	$^{+0.006}_{-0.006}$

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

→ Powerful test of the chiral structure!

See talk by R. Poeschl

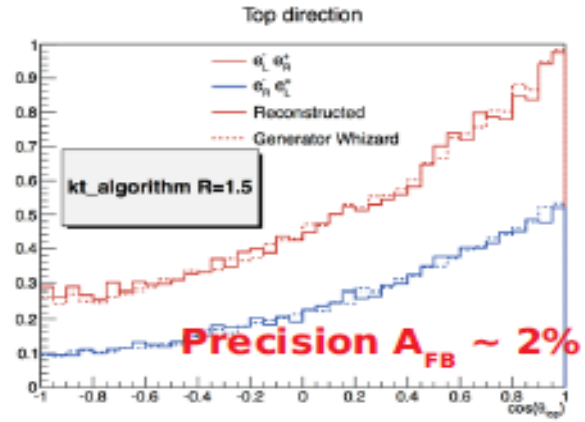
√s=500 GeV

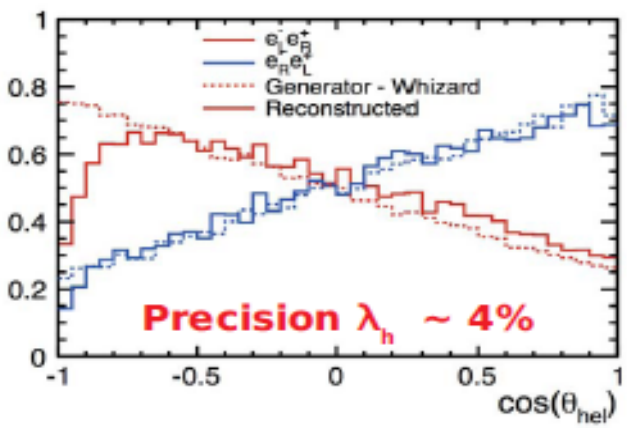
Top electroweak coupling

Results of full simulation study for DBD at √s = 500 GeV

LC-REP-2013-007

Precision: x section ~ 0.5%





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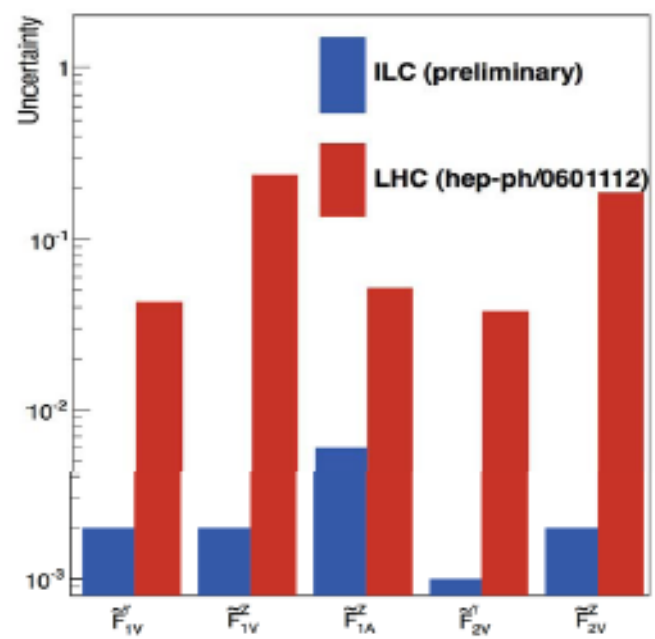
Precision of couplings



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

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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})

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

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

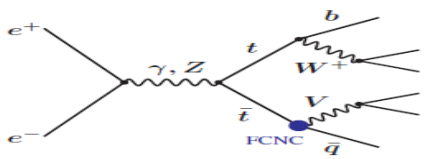
See J. Tian's talk!

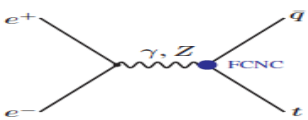
- In combination: $\Delta g_{ttH} / g_{ttH}$<2%

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}

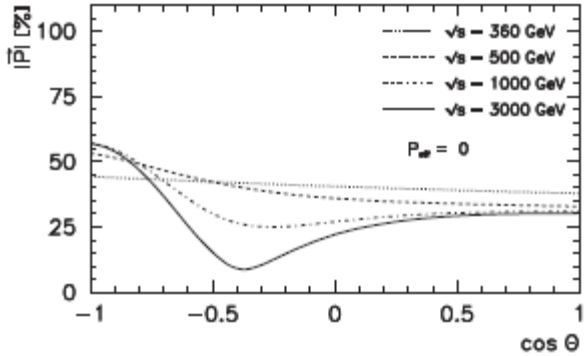
Exceeding LHC !

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

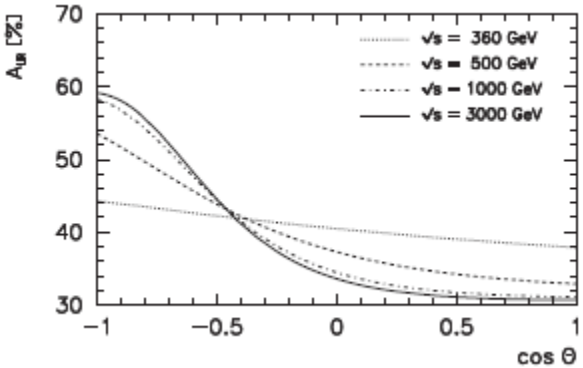
Top polarization

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

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



  - 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

Ananthanarayan, Patra, Rindani

- **Transversely-polarized beams in e+e- -> tt**
  - **probe scalar- and tensor-like interactions**
- **Parametrization via eff. four-Fermi operators:**

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

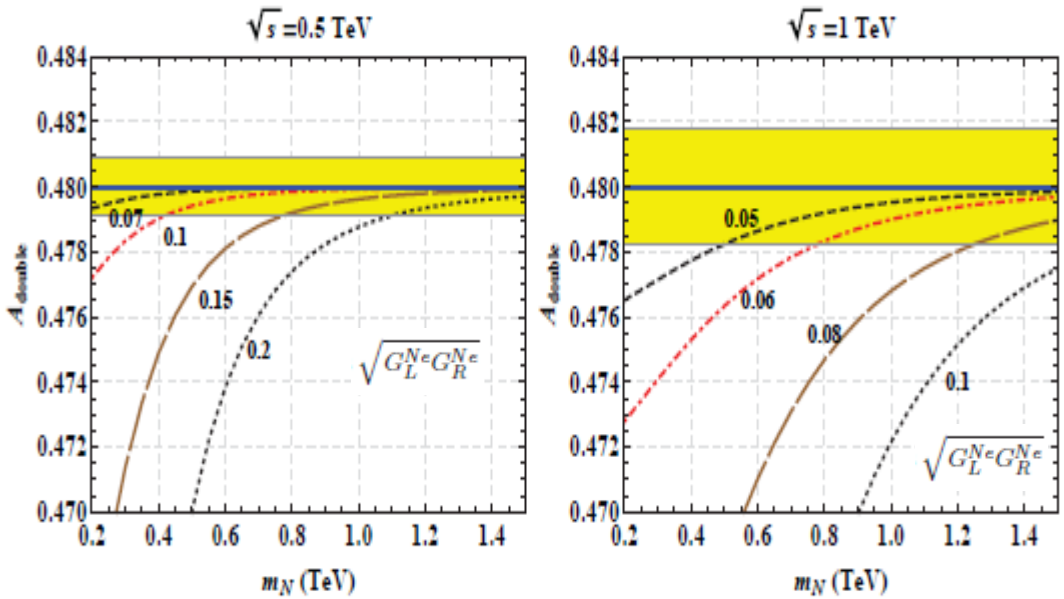
- **Use angular distributions with P^T_{e+} P^T_{e+}**
  - **Sensitive to azimuthal angle: specific asymmetries**
  - **Assumed 100% beams**
- **Sensitive to small S-,T-admixtures**

$\sqrt{s}$	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		2.3×10^{-3}TeV^{-2}		
		ReT				5.2×10^{-3}TeV^{-2}
		ImT	1.2×10^{-3}TeV^{-2}		1.0×10^{-2}TeV^{-2}	
	++	ImS	2.3×10^{-3}TeV^{-2}			
		ReT		1.2×10^{-3}TeV^{-2}		1.0×10^{-2}TeV^{-2}
		ImT			5.2×10^{-3}TeV^{-2}	

Other exotics: heavy Leptons

- **Study: e+e- -> W+W-**
  - Very sensitive to leptonic verrtices and trilinear gauge couplings
  - New heavy neutral boson or heavy leptons can contribute
  - E.g., E6 inspired model are consistent with Z's but also new heavy leptons (SU(2))
- **Model identification = exclusion of competitive models (incl. SM)**
  - Double polarization asymmetries very useful:

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



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

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

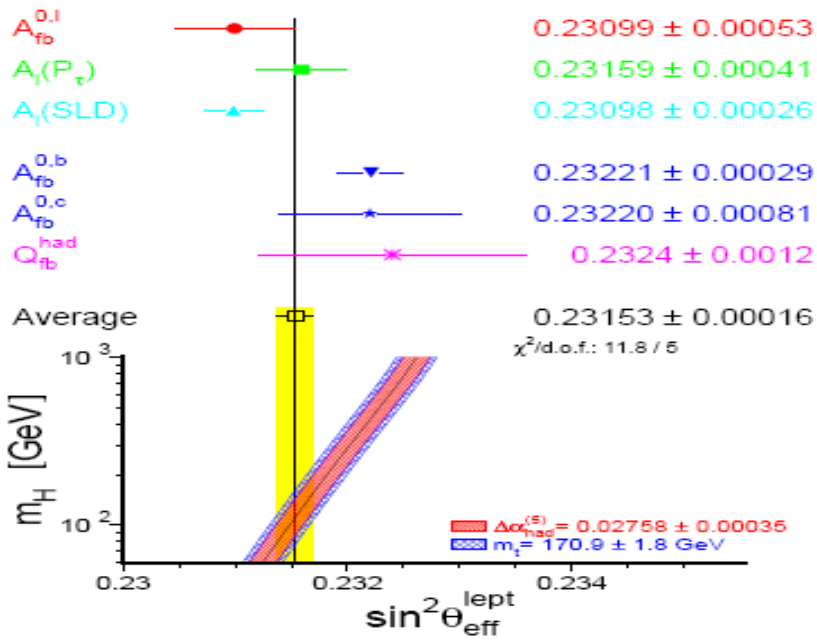
What if nothing else than H is found now?

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}

- **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$10^{-5}$

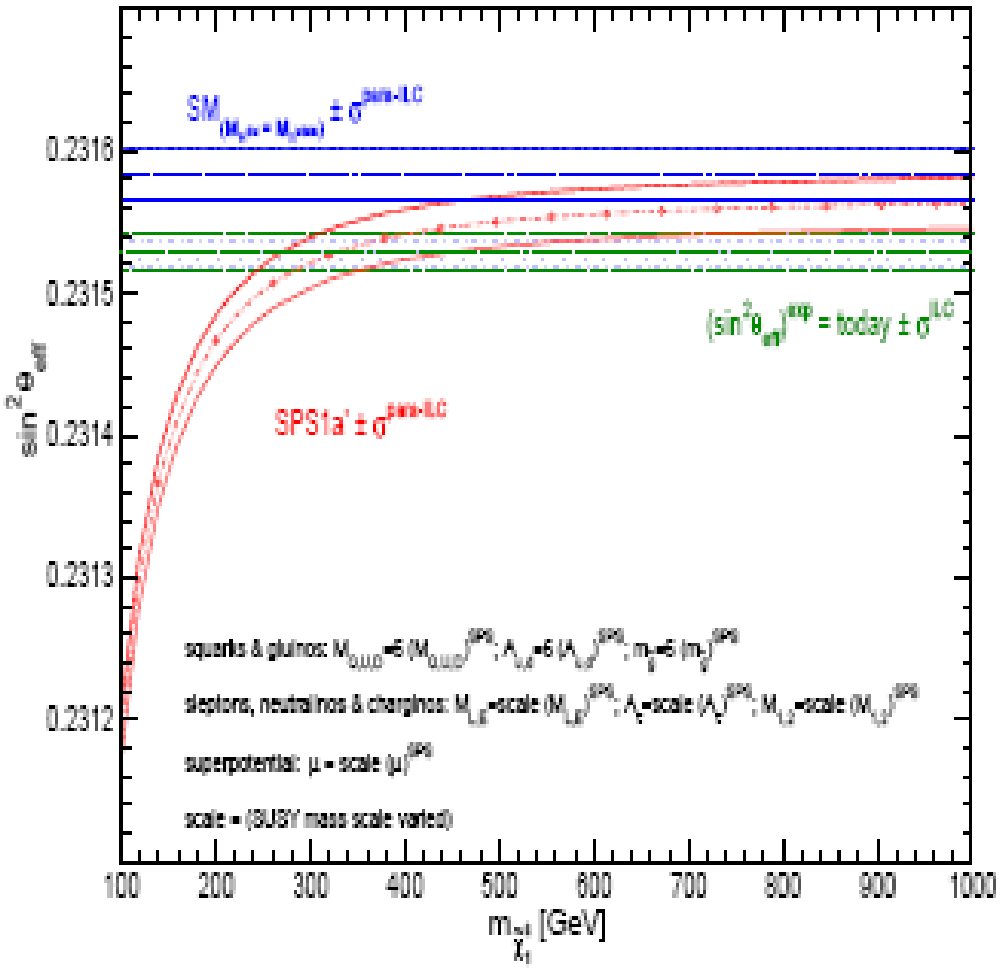
What else could we learn? $\sqrt{s}$=91 GeV

- **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!**

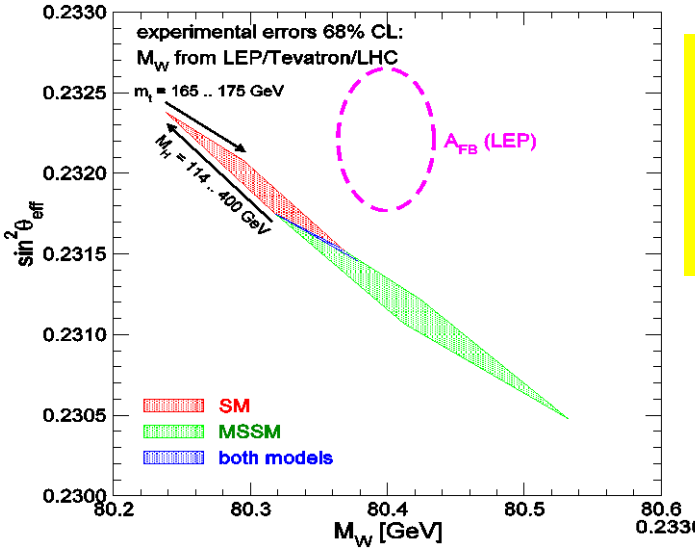
Heinemeyer, Hollik, Weber, Weiglein



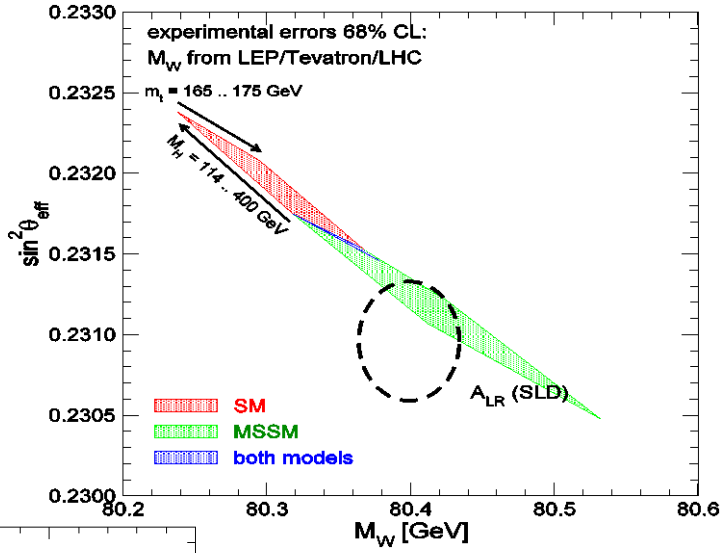
To close the story… GigaZ

$\sqrt{s}$=91 GeV

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



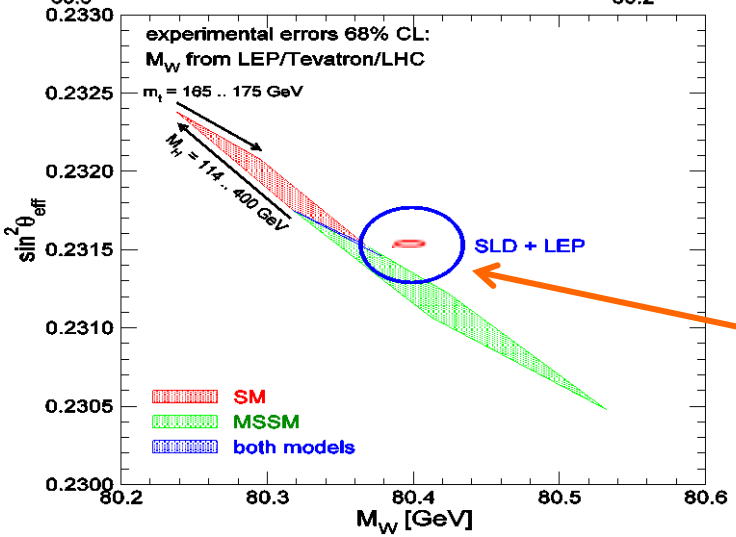
← *LEP value disfavours both, SM+MSSM*



↑ *SLD value disfavours SM*

World average → happy with both!

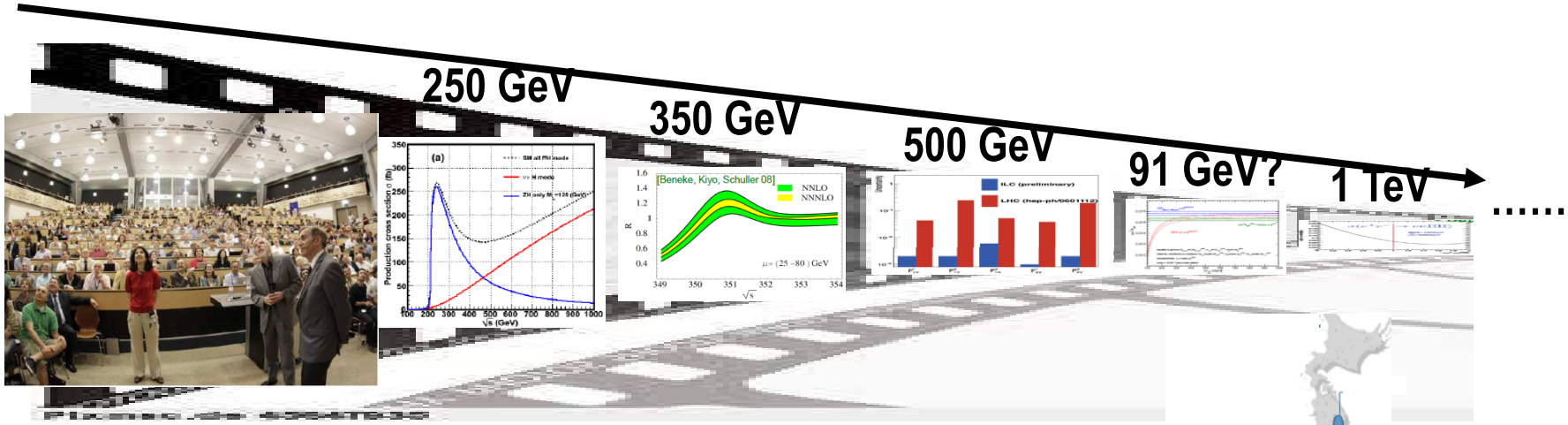
Central value has large impact !!!



GigaZ precision!

Top +EW Physics at the LC

- **The LC offers new tools and a staged approach:**
  - **Δm_{top}=100 MeV (incl. exp+theo uncertainties), ew coupling @%-level**
  - **complements and extends the HL-LHC capabilities**
  - **sensitiv to quantum effects of the top and to BSM@top**
- **LC allows to fully exploit GigaZ! ...keeping our 'savety margin'**



Physics case is well justified!

Shouldn't we shake the hands?