ILC overview in top quark physics

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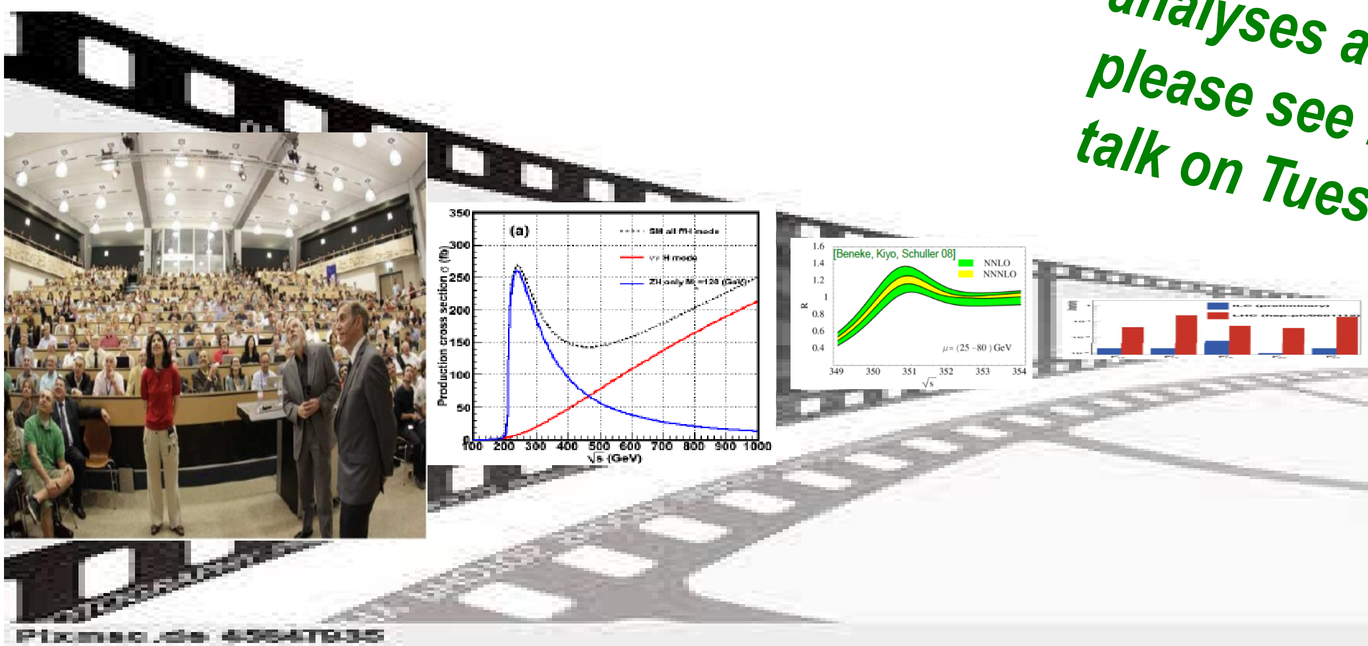
Detailed exp. details concerning top analyses at a LC, please see R. Poeschl's talk on Tuesday!



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?

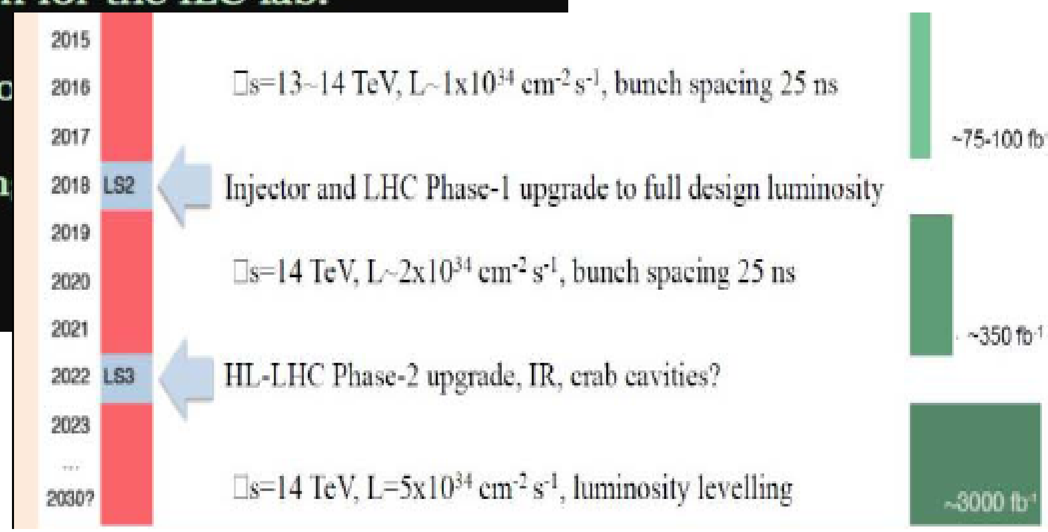
…a great chance might just be ahead….

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



But is it justified by physics?

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, $coup_{tth}$~5%
H: BR's~ 1 (b)-7(c)% ,Γ_h~3%, $\Delta\lambda$~18%,
CP, mixed states

- 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

‘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

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

Top mass

$\sqrt{s}$=350 GeV

- Threshold scan: depends on m_{top}, Γ_{top}, α_s
- Cross section σ(e+e- -> t t): color singlet tt bound state
  - experimentally very clean, s-wave state
  - Theoretically clean w.r.,t. non-perturbative effects

$$R \equiv \frac{\sigma(e^+e^- \to t\bar{t})}{\sigma_0} = \left(\frac{6\pi N_c e_t^2}{m_t^2}\right) \mathrm{Im}\, G_c(\vec{0}, \vec{0}; E + i\Gamma_t)$$

  - Coulomb Green function, related to Coulomb wave functions:

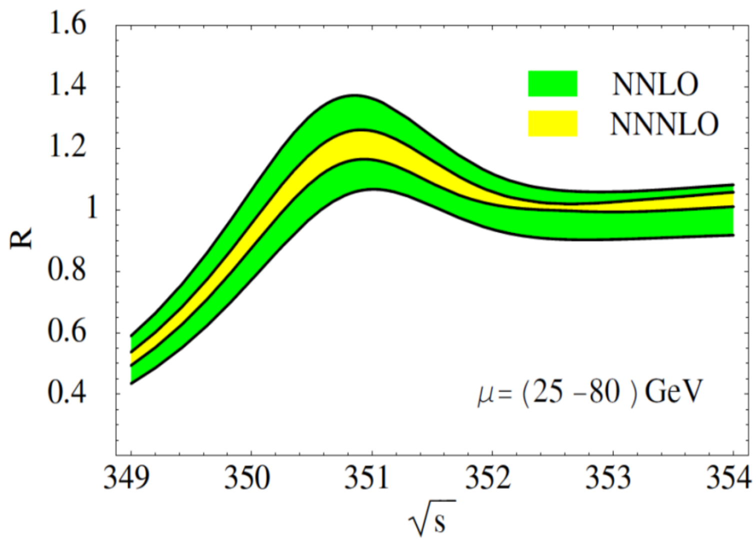
$$G_c(\vec{0}, \vec{0}; E + i\Gamma_t) = \sum_n \frac{\psi_n(0)\psi_n^*(0)}{E_n - E - i\Gamma_t} + \text{non-pole.} \qquad |\psi_n(0)|^2 = (m_t \alpha_s C_F)^3/(8\pi n^3)$$

  - Resonance structure washed out by large with~1.5 GeV
- Precise theory predictions needed to extract m_{top}, Γ_{top}, α_s

Top mass

$\sqrt{s}$=350 GeV

- **Threshold scan:**



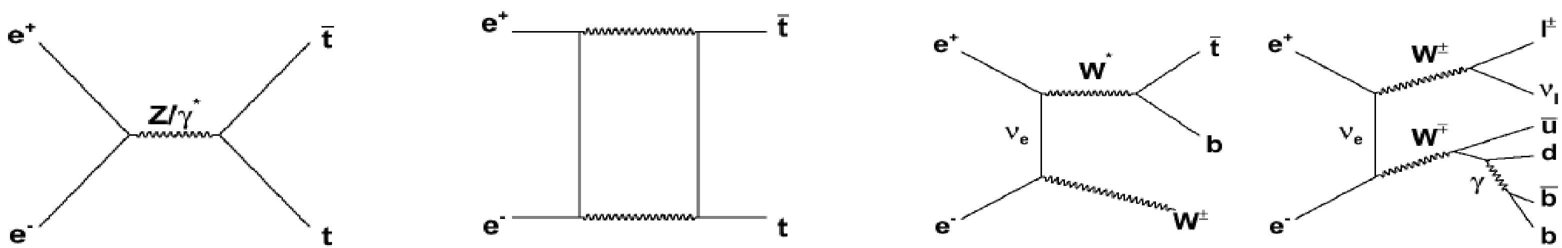
Important shift due to non-logarithmic NNNLO terms

- LC: Peak position remains stable: m_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}

Top electroweak coupling

$\sqrt{s}$=500 GeV

- $\sqrt{s}$=500 GeV: top electroweak couplings:
  - expected to be sensitive to BSM sources
  - Measurement of ‘g_{ttZ}’ and ‘$g_{tt\gamma}$’ rather unique for a LC!
- Study: e+e- -> tt -> l νbbqq



Born level ‘higher order’ contr. Subdominant, since α_{EW} dependent

- Parametrization via form factors

$$\mathcal{F}^L_{ij} = -F^\gamma_{ij} + \left(\frac{-\frac{1}{2} + s_w^2}{s_w c_w}\right)\left(\frac{s}{s - m_Z^2}\right) F^Z_{ij}$$

$$\mathcal{F}^R_{ij} = -F^\gamma_{ij} + \left(\frac{s_w^2}{s_w c_w}\right)\left(\frac{s}{s - m_Z^2}\right) F^Z_{ij} \,,$$

Top electroweak coupling

$\sqrt{s}$=500 GeV

- $\sqrt{s}$=500 GeV: chiral structure of top couplings
  - Cross section ~maximal at this energy
  - Top's have sufficient velocity
  - A_{FB} well developed
- 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 thanks to
  - the different observables
  - runs with different beam polarization configurations P(e-), P(e+)

⟶ Powerful test of the chiral structure!

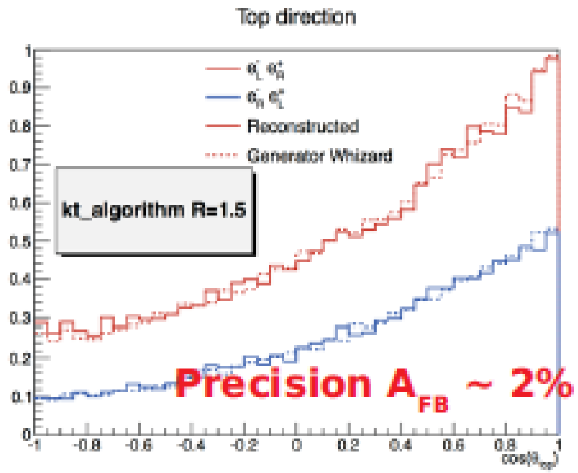
Roman Poeschl, Lyon, Mai 2013

$\sqrt{s}$=500 GeV

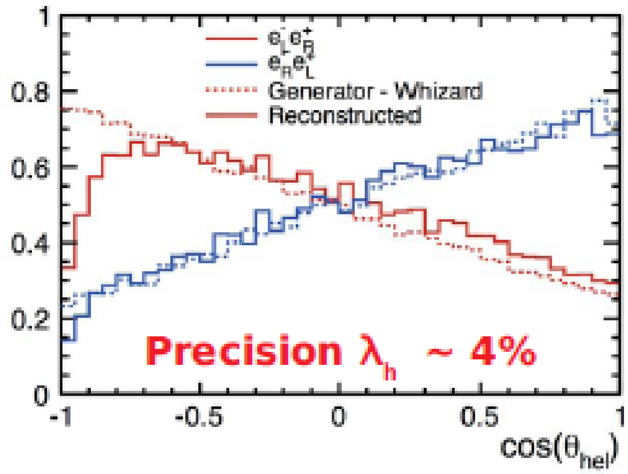
Results of full simulation study for DBD at $\sqrt{s}$ = 500 GeV

LC-REP-2013-007

Precision: x section ~ 0.5%



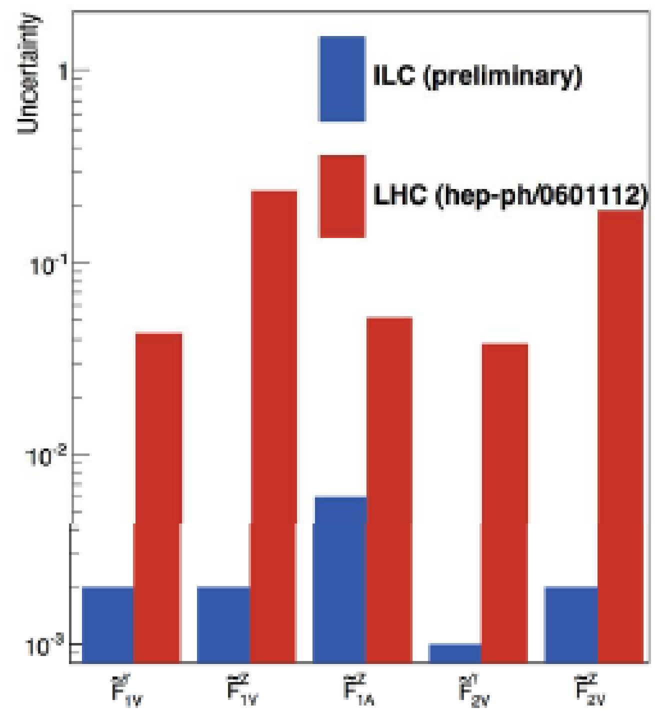
Precision A_{FB} ~ 2%



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})

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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
  - Yukawa couplings: g_{ttH}

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

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

R. Yonamine, T. Tanabe, K. Fujii

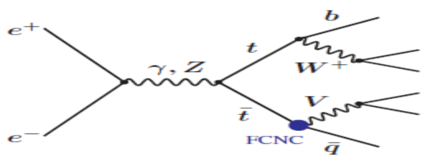
LHC estimates: about Δg_{ttH}~10% at HL-LHC (14 TeV, 3000fb^{-1})

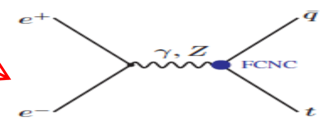
- $\sqrt{s}$=1000 GeV: Δg_{ttH} / g_{ttH}<4%

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}

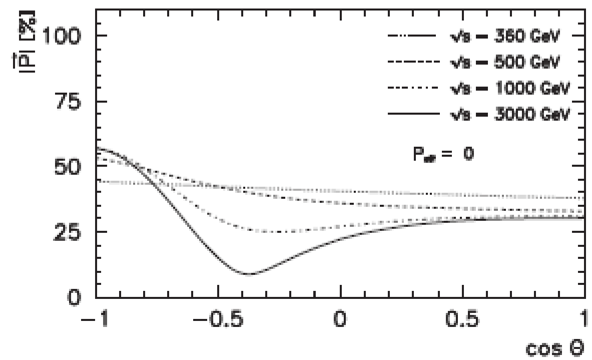
Exceeding LHC !

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

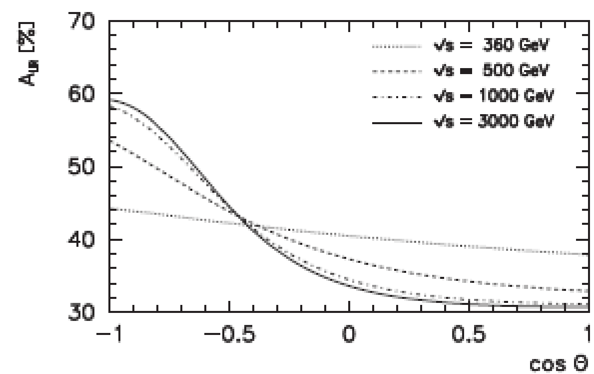
Top polarization

- **Top=3rd generation:**
  - 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 $\sqrt{s}$=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}	

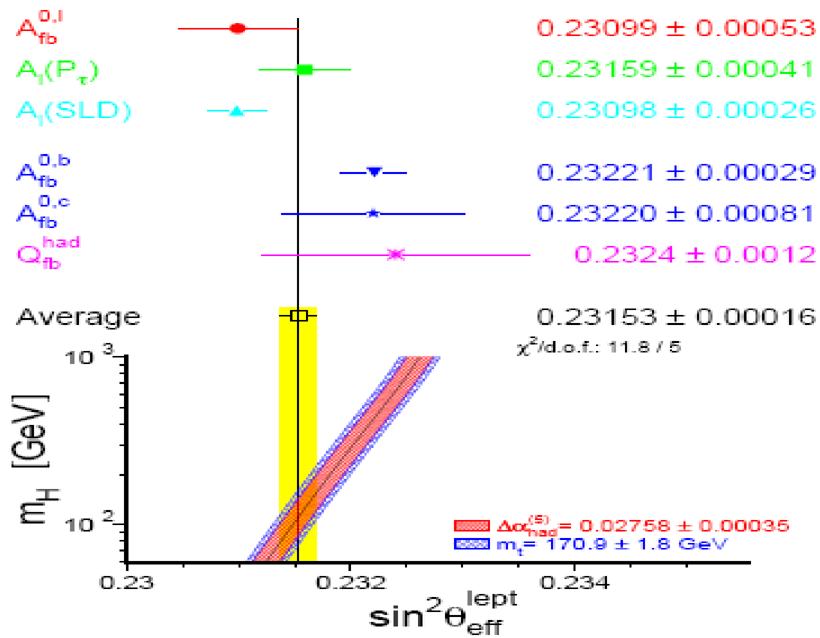
What if nothing else than H is found now?

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} ,…**

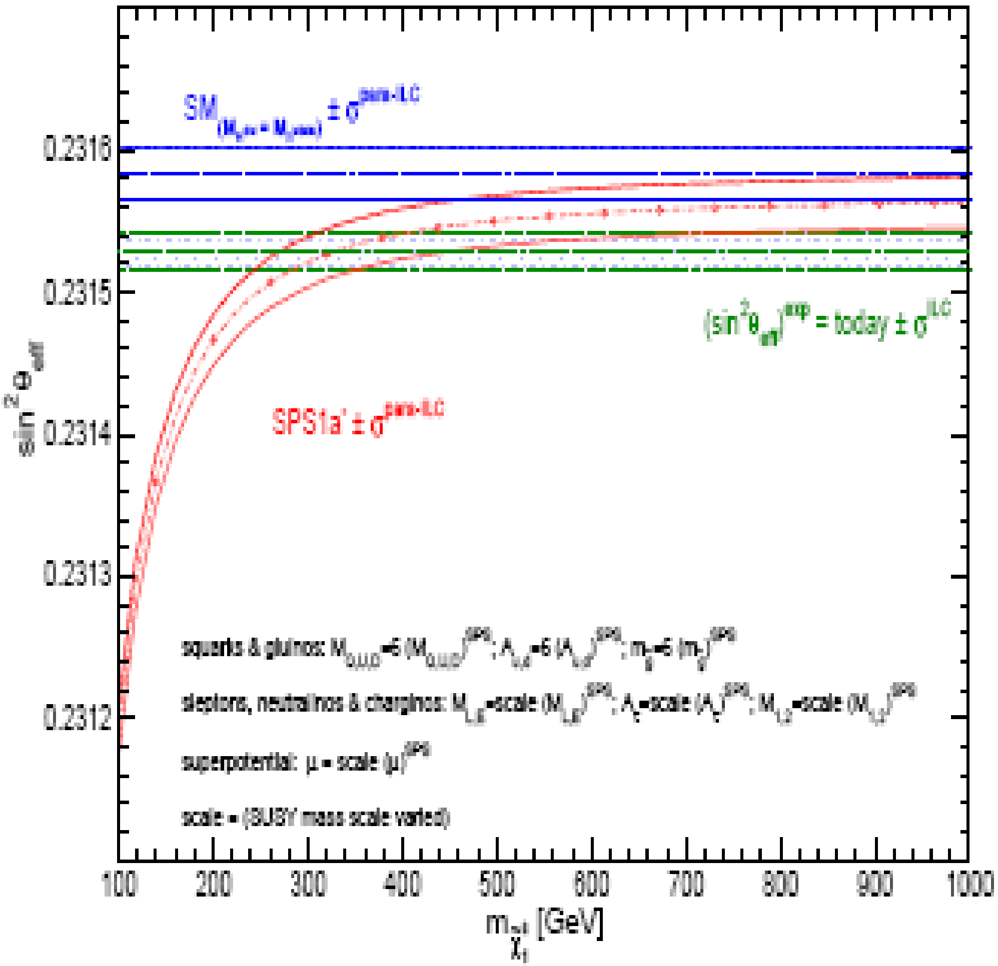
Heinemeyer, Kraml, Porod, Weiglein

- 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 $\sin^2\theta_{eff}$?

Heinemeyer, Hollik, Weber, Weiglein

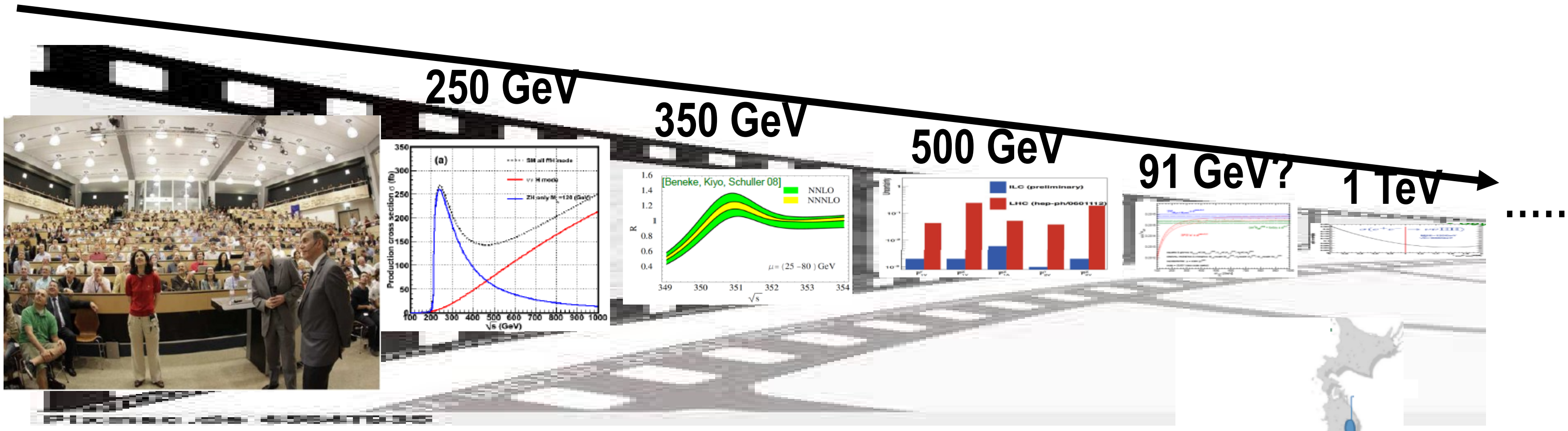


- **If GigaZ precision:**
  - i.e. Δm_{top}=0.1 GeV…
  - Deviations measurable

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

Top 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
- Allows to fully exploit GigaZ! …keeping our 'savety margin'



Physics case is well justified!

Maybe shouldn't we shake the hands?