# *Physics case for a LC based on LHC results and expectations*

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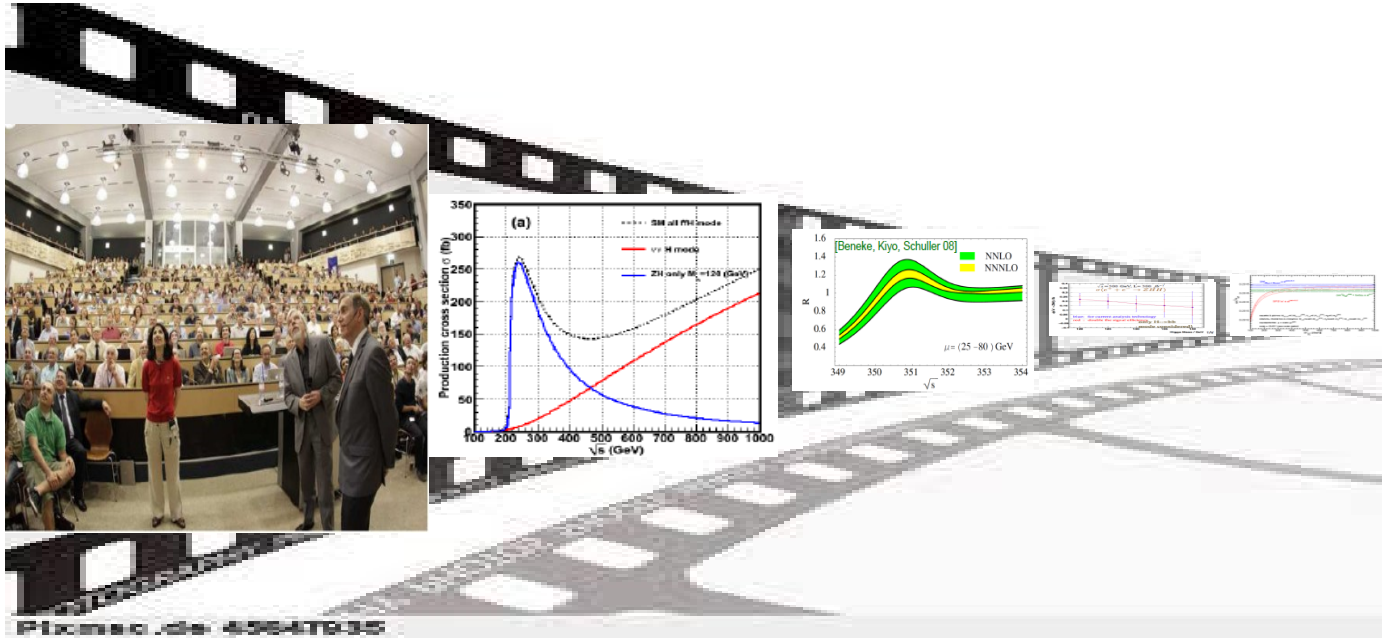



LINEAR COLLIDER COLLABORATION

# What is the motivation?

- We have a Higgs! That's great.
- But does it really behave as Higgs/Brout/Englert want? Or are here hints for BSM? We do need to know all its properties with best precision.
- Why is the Higgs so spectacular? Because that's the bridge between 'micro' and 'macro' cosmos.
- We have the LHC and the HL-LHC. That's great!
- Do we really also need the LC?

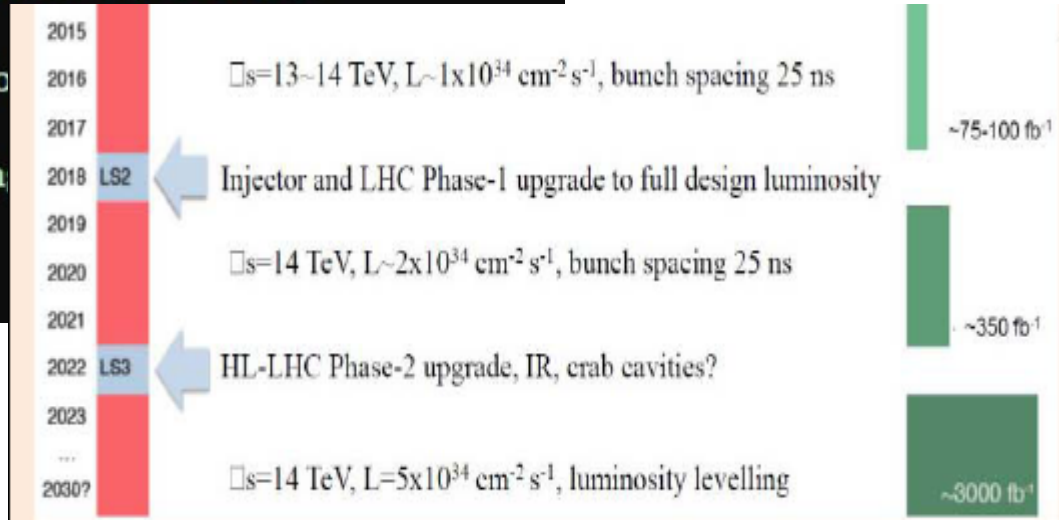
*…a great chance might just be ahead….*


*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)*

- **Limits in SUSY coloured sector (approx.):**
  - $m_g, m_q$>1 TeV but 3rd generation: much weaker
  - EW part: Bounds in Drell-Yan (mainly only in simplified models)
- **Limits on Z', W': ~2-2.5 TeV**
- **And more limits on ED, exotics, 4th generation etc.**
- **Very active: many new LC studies and reports….**
  - *ILC TDR (since June 12, 2013) and 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**

# EW @ LC: start with Higgs summary

- **Staged energy approach: choose 250GeV, 350GeV, etc.**
  - **250 GeV: 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 distri. (eeX, μμX): ΔmH=32 MeV**

**Model independent determination of couplings to c, b,g,τ**

| 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->ττ | 4.2% | | |

- **Estimate: about 3 years running time needed on √s=250 GeV**

# Summary on Higgs results, cont

- **$\sqrt{s}$=350 GeV: Further improvement in Higgs couplings (TDR)**
  - **Access to Higgs total width (~4 MeV for 125 Higgs): $\Delta T_h^{tot}/T_h^{tot}$ ~7%**
  - **Access to CP-parity in mixed states: construct CP-odd observables via angular distribution in τ-decays: s-ps mixing-angle up to $6^0$**
- **$\sqrt{s}$=500 GeV: Further improvement in width $\Delta T_h^{tot}/T_h^{tot}$ ~ 5%**
  - **First access to Top-Yukawa coupling: $\Delta g_{ttH}/g_{ttH}$~10%**
  - **First access to trilinear couplings: $\Delta\lambda/\lambda$ ~ 44%**
  - **Many studies based on $2ab^{-1}$**
- **$\sqrt{s}$=1000 GeV: $\Delta T_h^{tot}/T_h^{tot}$ ~4%, $\Delta g_{ttH}/g_{ttH}$~4.6%, $\Delta\lambda/\lambda$ ~ 18%**

**LHC estimates: about $\Delta g_{ttH}$~10% and $\Delta\lambda/\lambda$ ~32% at HL-LHC (14 TeV, $3000fb^{-1}$), however under strong assumptions!**

- **Full LC up to 1 TeV: *beats HL-LHC by more than factor~2 and allows model-independent approaches!***

# 'New tools' for new physics: polarization

- **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** (**ν, heavy leptons, …, see LC notes**)

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

- **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**

# What's about BSM/SUSY?

- **SUSY: still strongly motivated and beautiful, but**
  - **so far, no hints of a signal at LHC, only rather high exclusion limits in the coloured sector**
  - **But Higgs mass of mH=125GeV measured:**
    - **Strong impact on SUSY models !**
  - **But only Constrained models (CMSSM,…) + Simpl. Models under tension!**
- **Further hints from theory? From (g-2)μ and 'naturalness':**

$$\delta a_\mu(\text{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu}$$

$$\frac{M_Z^2}{2} \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2$$

  - **Rather small value for μ-parameter ~200 GeV required!**
- ***Conclusions: some SUSY particles very light and probably not the simplest model …. Open playground for the LC!***

# LC: Parameters from $e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1$@NLO

- **Strategy:** Use NLO corrected masses and $\sigma_{L,R}$ at $\sqrt{s}$=350,500
  - Use in addition $A_{FB}$
  - Fit of $M_1$, $M_2$, $\mu$, tan$\beta$ and stop sector $mt_1$, $mt_2$ and $\cos\theta_{\tilde{t}}$
  - Compare mass accuracy from
    - Threshold scans
    - Continuum measurement

| Parameter | Threshold fit | | Continuum fit | |
|---|---|---|---|---|
| $M_1$ | $125 \pm 0.3$ | $(\pm 0.7)$ | $125 \pm 0.6$ | $(\pm 1.2)$ |
| $M_2$ | $250 \pm 0.6$ | $(\pm 1.3)$ | $250 \pm 1.6$ | $(\pm 3)$ |
| $\mu$ | $180 \pm 0.4$ | $(\pm 0.8)$ | $180 \pm 0.7$ | $(\pm 1.3)$ |
| $\tan\beta$ | $10 \pm 0.5$ | $(\pm 1)$ | $10 \pm 1.3$ | $(\pm 2.6)$ |
| $m_{\tilde{\nu}}$ | $1500 \pm 24$ | $(^{+60}_{-40})$ | $1500 \pm 20$ | $(\pm 40)$ |
| $m_{\tilde{t}_1}$ | $400^{+180}_{-120}$ | (at limit / at limit) | – | |
| $m_{\tilde{t}_2}$ | $800^{+300}_{-170}$ | $(^{+1000}_{-290})$ | $800^{+350}_{-220}$ | (at limit / at limit) |

→ Relevance of threshold scans and sensitivity to heavy masses

- **Impact also on dark matter prediction:**
  - Precision needed for accurate DM prediction: accuracy of the NLO corrected parameters → 5% uncertainty in DM prediction

# Gauge boson couplings

- **WW/ZZ scattering, and WW final state:**
  - Close relation between WWγ and WWZ
  - Footprints of new physics via trilinear gauge couplings
  - New simulations at 500 and 800: probe < per mille
  - Up to an oder of magnitude better than 14TeV LHC
- **Strong dynamics for EWSB:**
  - Even for light Higgs possible
  - Composite Higgws models: $L \sim v^2/\Lambda^2_{comp}$
- **Precision measurements in VV-> VV, VV-> HH and e+e→ HZ**
  - Sensitiv to composite scale:

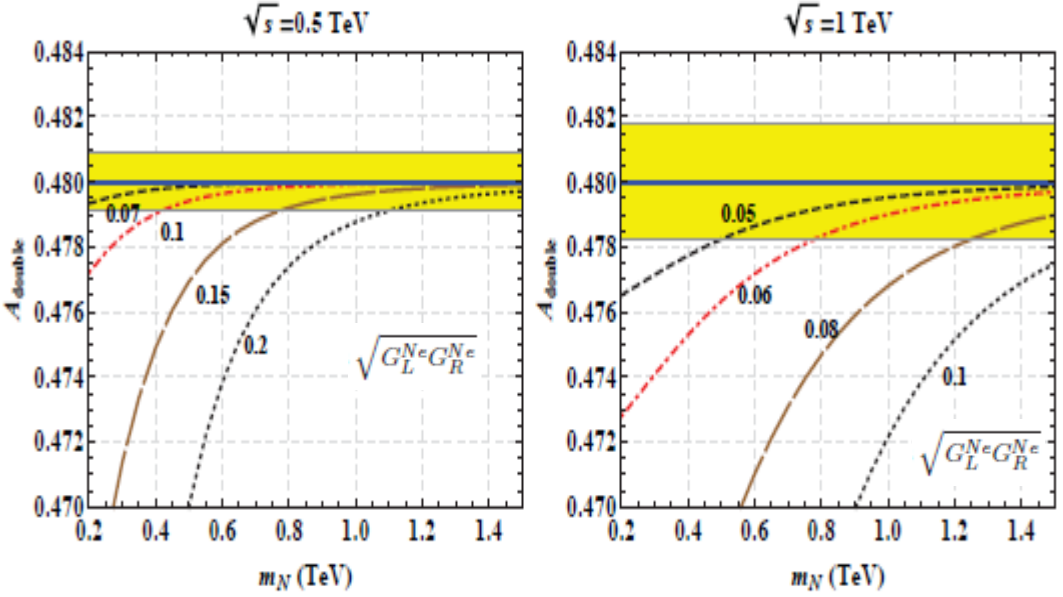
14 TeV LHC, 100 $fb^{-1}$ LHC: 7 TeV
500 GeV LC ,1 $ab^{-1}$: 45 TeV
3 TeV LC, 1 $ab^{-1}$: 60 TeV

High sensitivity to multi-TeV scale already at a 500 GeV LC!

# 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:

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




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

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

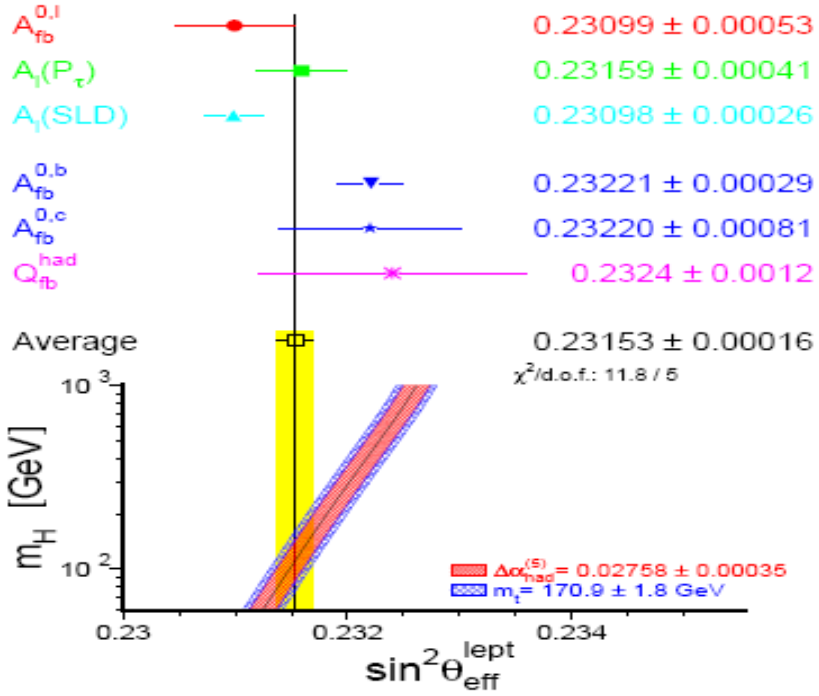
# *What if nothing else than H is found now?*

## *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**
  - **$m_Z$ ,$m_W$,$\alpha_{had}$, $\sin^2\theta_{eff}$ 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

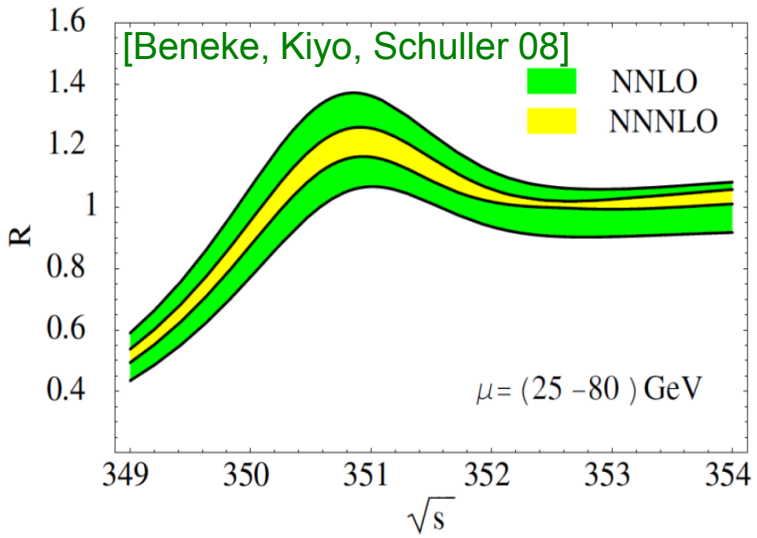
*Goal GigaZ: Δsinθ=1.3 $10^{-5}$*

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

| | |
|---|---|
| $\Delta m_Z$=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$10^{-5}$ |
| $\Delta m_{top}$~1 GeV (Tevatron/LHC): | $\Delta\sin^2\theta_{eff}^{para}$~3x$10^{-5}$ |
| $\Delta m_{top}$~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 $\Delta m_{top}$=0.1 GeV




Important shift due to non-logarithmic NNNLO terms

$\sqrt{s}$=350 GeV

- LC: Peak position remains stable: $m_t$=100 MeV (includ. Exp+theory uncertainty!) expected accuracy confirmed!
- Dedicated threshold scan required (~30fb$^{-1}$)!

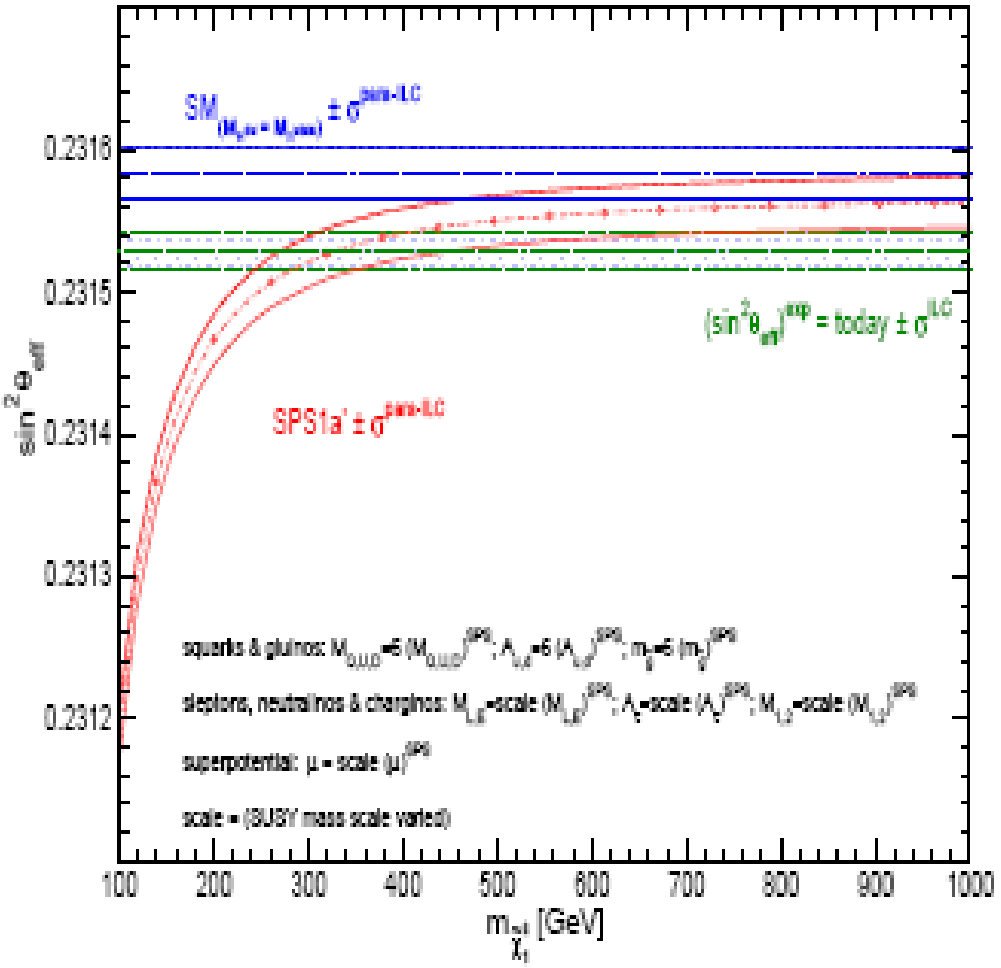
- Unce

Weiglein

- $\Delta m_{top}$~0.1 GeV (ILC): $\Delta \sin^2\theta^{lept}_{eff}$~0.3x10$^{-5}$

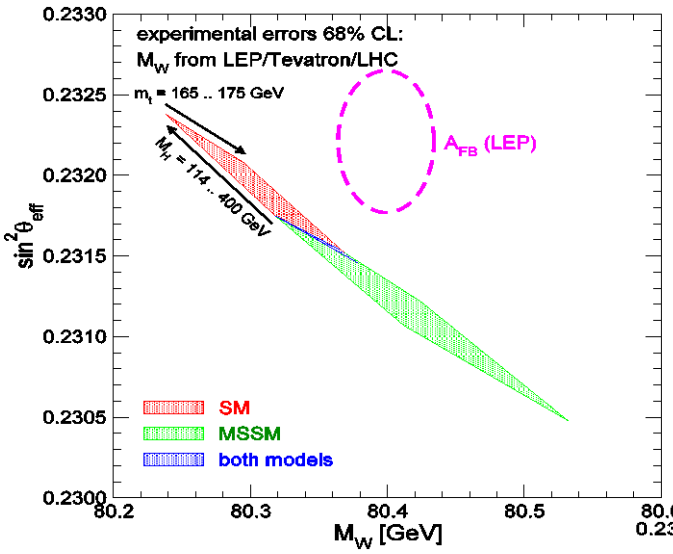
# What else could we learn? $\sqrt{s}$=91 GeV

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

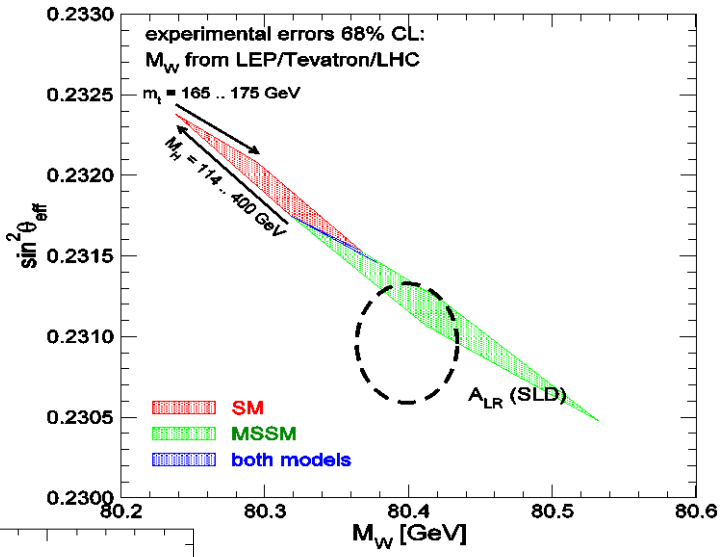


# To close the story… GigaZ $\sqrt{s}$=91 GeV

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



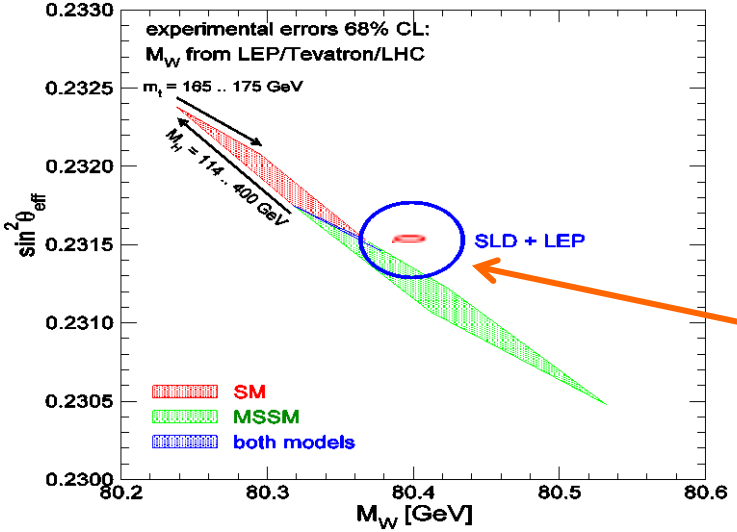

← *LEP value disfavours both, SM+MSSM*




↑ *SLD value disfavours SM*

*World average → happy with both!*

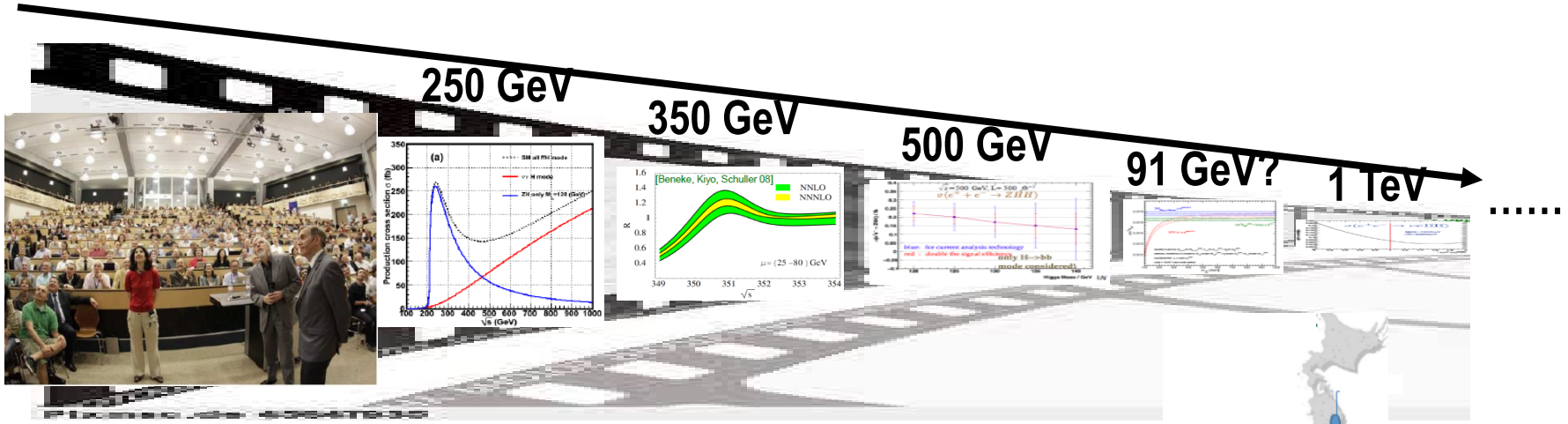
**Central value has large impact !!!**




*GigaZ precision!*

# EW Physics at the LC

- The LC offers new tools and a staged approach:
  - complements and extends the HL-LHC capabilities
  - access to quantum effects, CP-effects in Higgs, top, BSM, …
  - high precision measurements mandatory to resolve the structure
- Maybe need to go back to GigaZ! …keeping our 'savety margin'




*Physics case is well justified!*

*Maybe shouldn't we shake the hands?*