

# Exploring Quantum Physics at the ILC (White Paper)\*

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In collaboration with

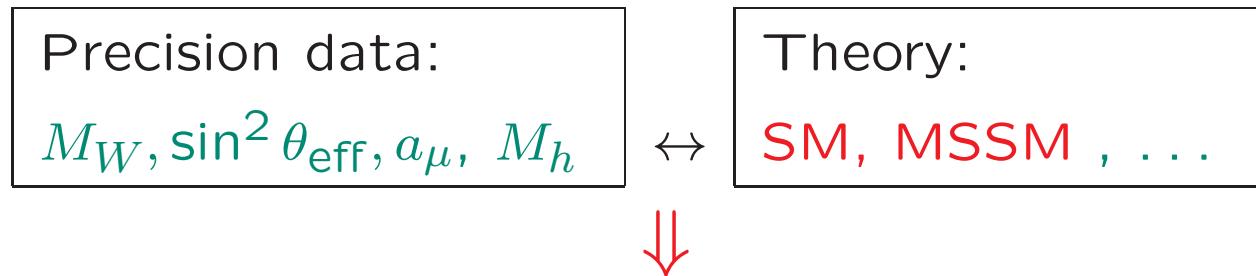
*K. Hagiwara, P. Langacker, K. Moenig, M. Tanabashi, G.W. Wilson*

1. Introduction
2. Many Examples for Quantum Physics at the ILC  
 $(M_W, \sin^2 \theta_{\text{eff}}, m_t, \alpha_s, M_H, Z', W', \dots)$
3. Conclusions

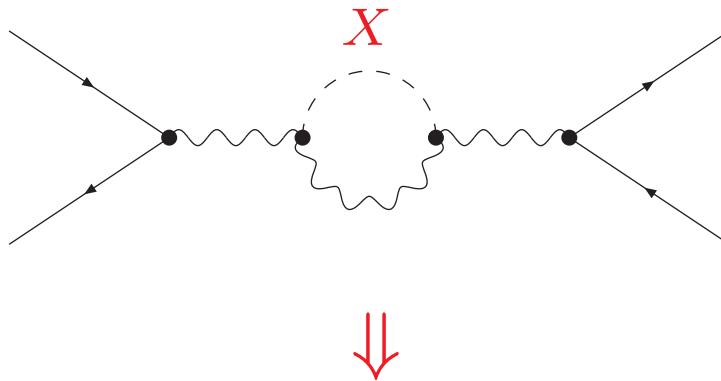
\* first version with the convenors, not finished yet!

## 1. Introduction

Comparison of observables with theory:



Test of theory at quantum level: Sensitivity to loop corrections, e.g.  $X$



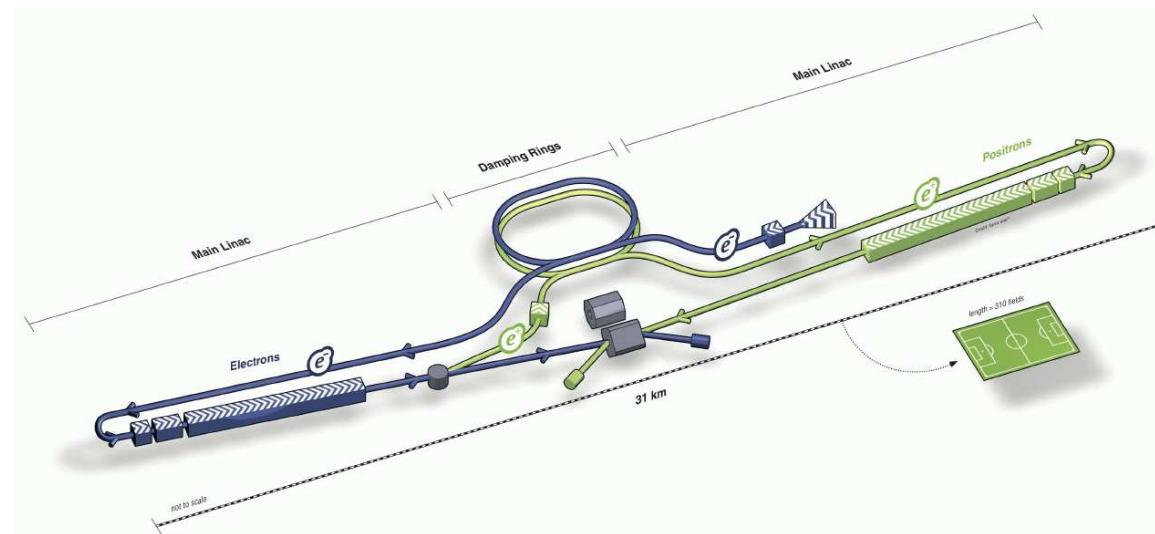
BSM: limits on  $M_X$

Very high accuracy of measurements and theoretical predictions needed

## ILC: Linear $e^+e^-$ collider, $\sqrt{s} = 250 - 1000 \text{ GeV}$

based on superconducting cavities (cold technology)

Schematic:



Energies:  $\sqrt{s} = 250 \text{ GeV}, 350 \text{ GeV}, 500 \text{ GeV} \dots 1000 \text{ GeV} \dots 91 \text{ GeV}$

Possible features:

- two detectors in one interaction region (push-pull)
- undulator based  $e^+$  source
- polarized beams for  $e^-$  and  $e^+$  ( $P_{e^-} = 80\%$ ,  $P_{e^+} = 60\%$ )
- tunable energy
- GigaZ: high luminosity running at the  $Z$  pole

## 2. Many Examples for Quantum Physics at the ILC

⇒ review the ILC physics potential

- A)  $W$  boson mass,  $M_W$
- B)  $Z$  pole observables,  $\sin^2 \theta_{\text{eff}}$
- C) top quark mass,  $m_t$
- D) strong coupling constant,  $\alpha_s$
- E) the Higgs boson mass,  $M_H$
- F) Global electroweak fits,  $M_H^{\text{fit}}$
- G) Anomalous gauge boson couplings
- H) Extra gauge bosons,  $Z', W'$

## 2A) The $W$ boson mass

Experimental accuracy:

Today: LEP2, Tevatron:  $M_W^{\text{exp}} = 80.385 \pm 0.015 \text{ GeV}$

- ILC:**
- polarized threshold scan
  - kinematic reconstruction of  $W^+W^-$
  - hadronic mass (single  $W$ )

$$\delta M_W^{\text{exp,ILC}} = 5 - 6 \text{ MeV}$$

Theoretical accuracies:

intrinsic today:  $\delta M_W^{\text{SM,theo}} = 4 \text{ MeV}, \quad \delta M_W^{\text{MSSM,today}} = 5 - 10 \text{ MeV}$

intrinsic future:  $\delta M_W^{\text{SM,theo,fut}} = 2 \text{ MeV}, \quad \delta M_W^{\text{MSSM,today}} = 3 - 5 \text{ MeV}$

parametric today:  $\delta m_t = 0.9 \text{ GeV}, \quad \delta(\Delta\alpha_{\text{had}}) = 10^{-4}, \quad \delta M_Z = 2.1 \text{ MeV}$

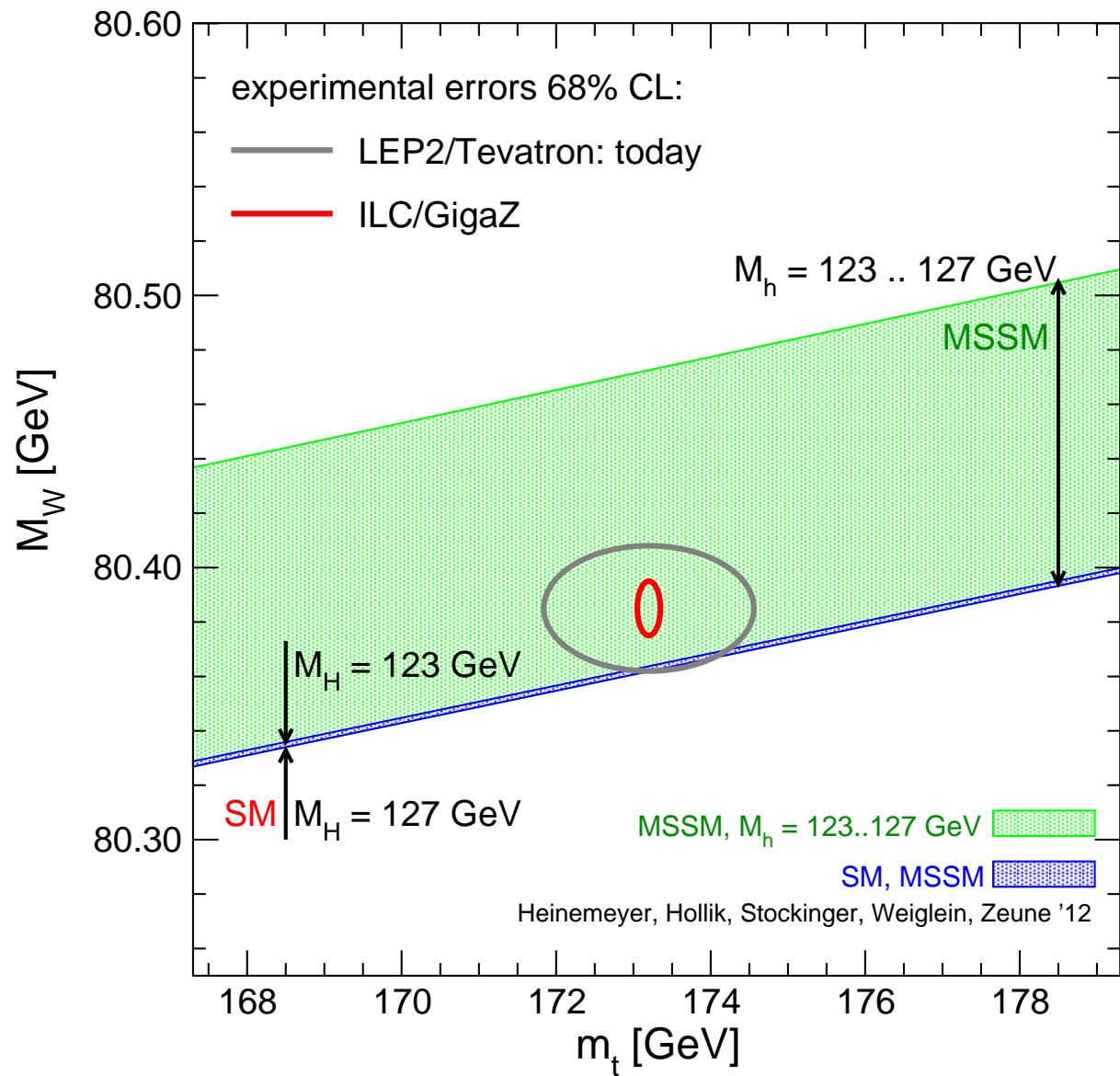
$\delta M_W^{\text{para},m_t} = 5.5 \text{ MeV}, \quad \delta M_W^{\text{para},\Delta\alpha_{\text{had}}} = 2 \text{ MeV}, \quad \delta M_W^{\text{para},M_Z} = 2.5 \text{ MeV}$

parametric future:  $\delta m_t^{\text{ILC}} = 0.1 \text{ GeV}, \quad \delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5 \times 10^{-5}$

$\Delta M_W^{\text{para,fut},m_t} = 1 \text{ MeV}, \quad \Delta M_W^{\text{para,fut},\Delta\alpha_{\text{had}}} = 1 \text{ MeV}$

## Physics Example: Prediction for $M_W$ in the SM and the MSSM :

[S.H., W. Hollik, D. Stockinger, G. Weiglein, L. Zeune '12]

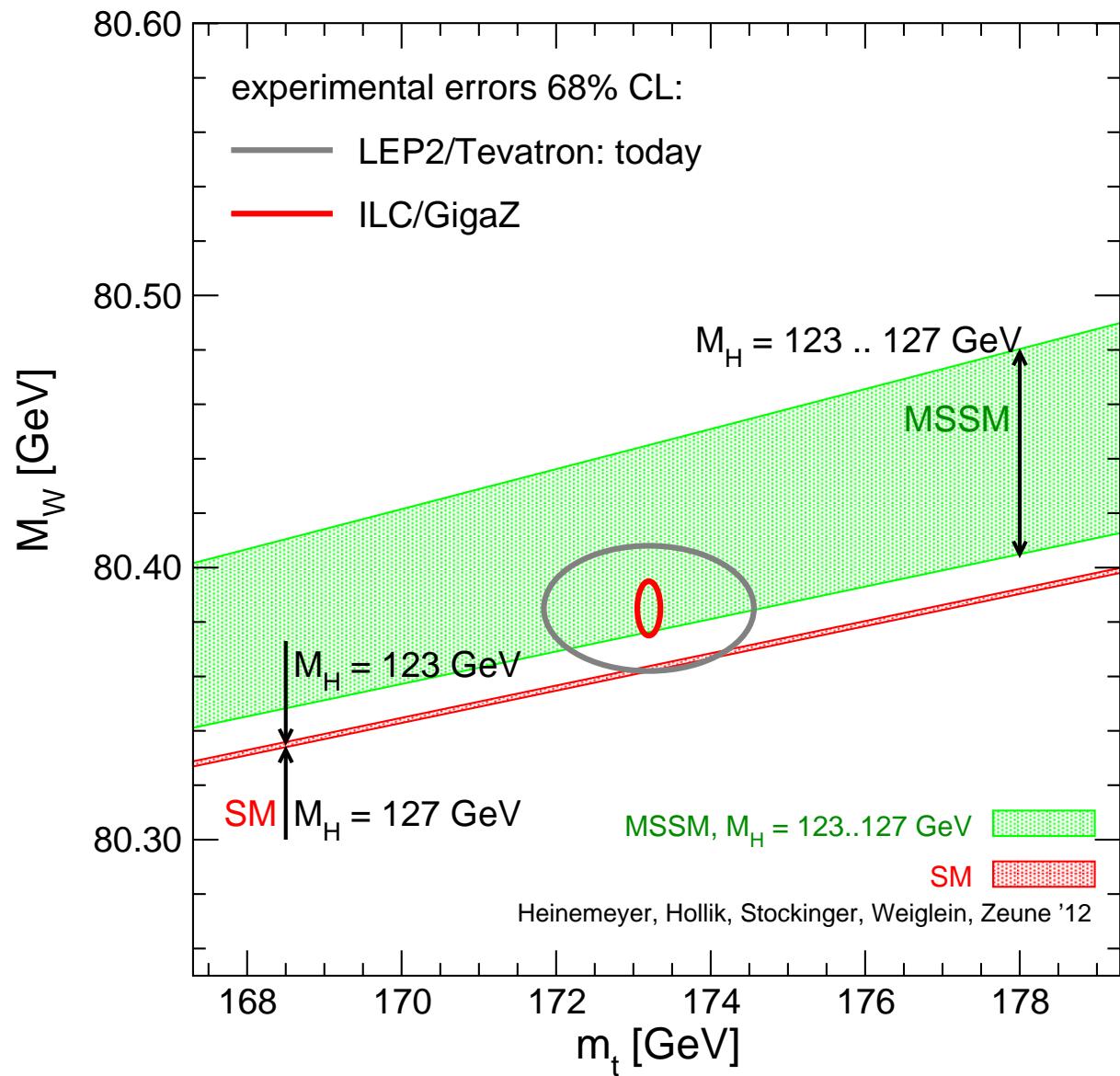


**MSSM band:**  
scan over  
SUSY masses

**overlap:**  
SM is MSSM-like  
MSSM is SM-like

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## 2B) Z pole observables

Main player: effective weak leptonic mixing angle:  $\sin^2 \theta_{\text{eff}} \Rightarrow \text{GigaZ}$

Experimental accuracy:

Today: LEP, SLD:  $\sin^2 \theta_{\text{eff}}^{\text{exp}} = 0.23153 \pm 0.00016$

ILC/GigaZ: both beams polarized, Blondel scheme

$$\delta \sin^2 \theta_{\text{eff}}^{\text{exp,ILC}} = 0.000013$$

Theoretical accuracies:  $[10^{-5}]$

intrinsic today:  $\delta \sin^2 \theta_{\text{eff}}^{\text{SM,theo}} = 4.7$     $\delta \sin^2 \theta_{\text{eff}}^{\text{MSSM,today}} = 5 - 7$

intrinsic future:  $\delta \sin^2 \theta_{\text{eff}}^{\text{SM,theo,fut}} = 1.5$     $\delta \sin^2 \theta_{\text{eff}}^{\text{MSSM,today}} = 2.5 - 3.5$

parametric today:  $\delta m_t = 0.9 \text{ GeV}$ ,  $\delta(\Delta\alpha_{\text{had}}) = 10^{-4}$ ,  $\delta M_Z = 2.1 \text{ MeV}$

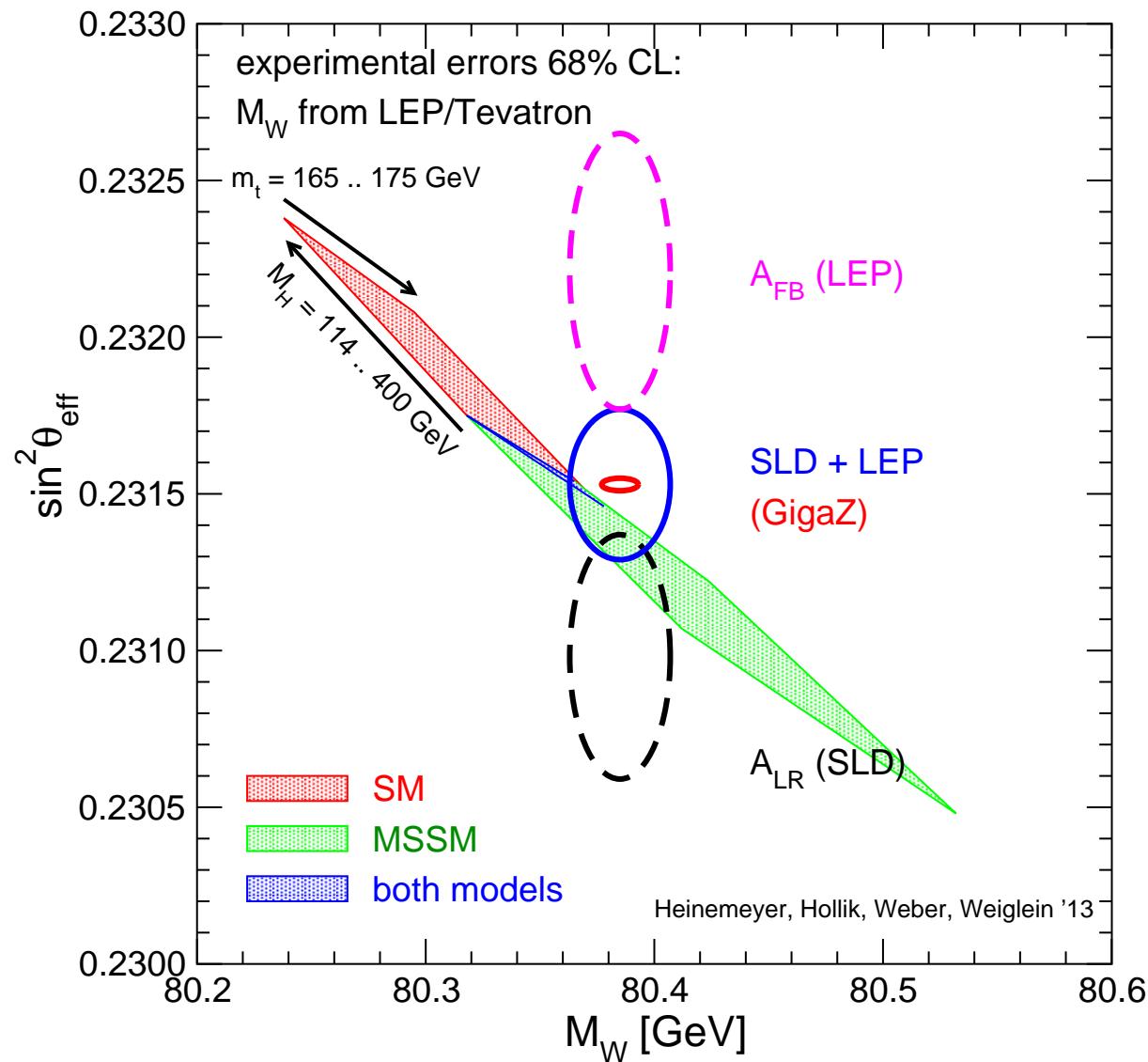
$$\delta \sin^2 \theta_{\text{eff}}^{\text{para},m_t} = 7, \quad \delta \sin^2 \theta_{\text{eff}}^{\text{para},\Delta\alpha_{\text{had}}} = 3.6, \quad \delta \sin^2 \theta_{\text{eff}}^{\text{para},M_Z} = 1.4$$

parametric future:  $\delta m_t^{\text{ILC}} = 0.1 \text{ GeV}$ ,  $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5 \times 10^{-5}$

$$\Delta \sin^2 \theta_{\text{eff}}^{\text{para,fut},m_t} = 0.4, \quad \Delta \sin^2 \theta_{\text{eff}}^{\text{para,fut},\Delta\alpha_{\text{had}}} = 1.8$$

# Physics Example: Pred. for $M_W$ and $\sin^2 \theta_{\text{eff}}$ in the SM and the MSSM :

[S.H., W. Hollik, A. Weber, G. Weiglein '13]



**MSSM band:**  
scan over  
SUSY masses

overlap:  
SM is MSSM-like  
MSSM is SM-like

**SM band:**  
variation of  $M_H^{\text{SM}}$

## 2C) The top quark mass

### What is the top mass?

Particle masses are **not** direct physical observables  
one can only measure cross sections, decay rates, . . .

Additional problem for the top mass:

**what is the mass of a colored object?**

Top pole mass is not IR safe (affected by large long-distance contributions), cannot be determined to better than  $\mathcal{O}(\Lambda_{\text{QCD}})$

### Measurement of $m_t$ :

- At Tevatron, LHC:

kinematic reconstruction, fit to invariant mass distribution

⇒ “MC” mass, close to “pole” mass?

$$\delta m_t^{\text{exp,LHC}} \lesssim 1 \text{ GeV}$$

- At the ILC: unique possibility

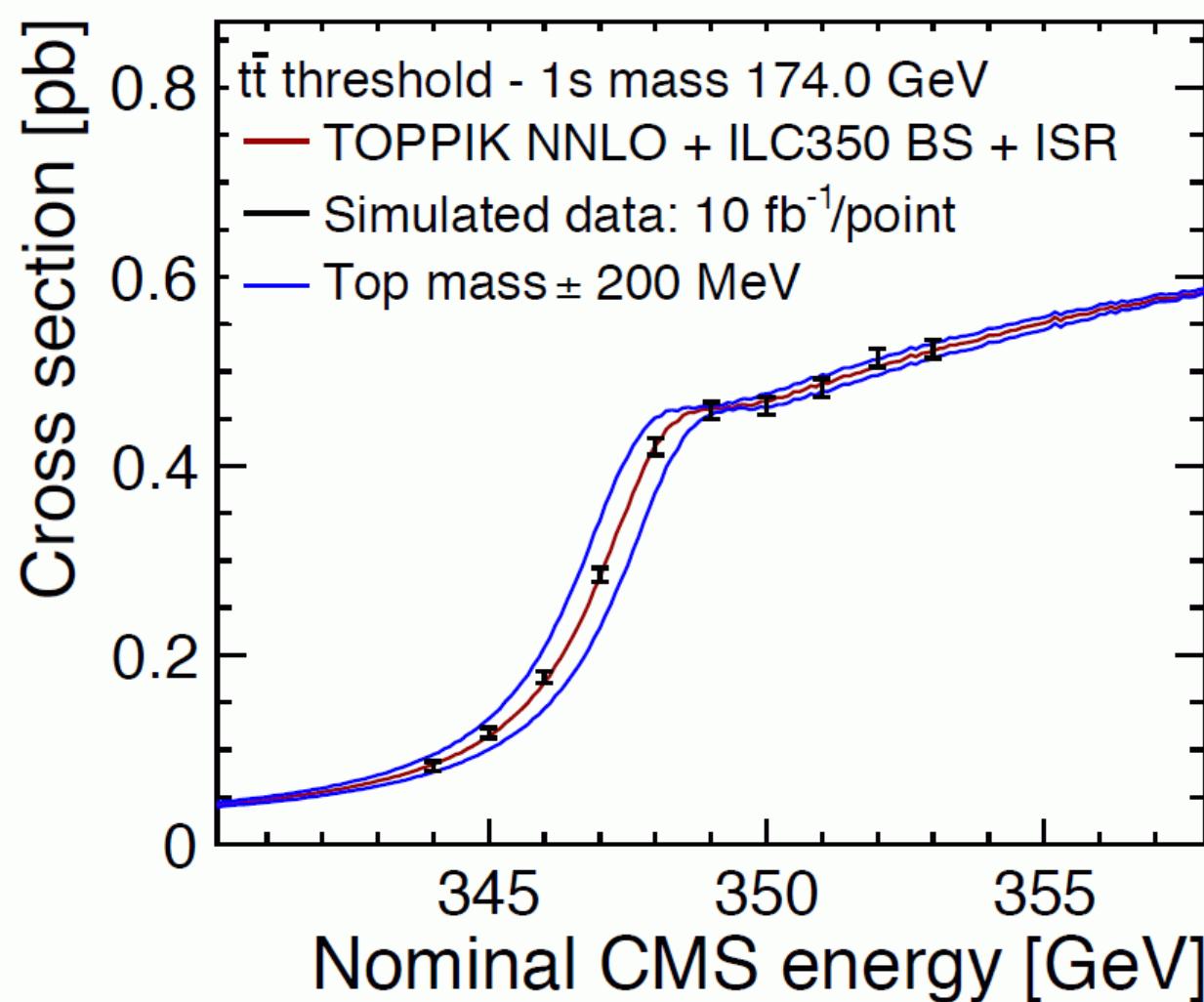
threshold scan ⇒ threshold mass ⇒ **SAFE!**

transition to other mass definitions possible,

$$\delta m_t^{\text{exp,ILC}} \lesssim 0.03 \text{ GeV}$$

At the ILC: unique possibility  
threshold scan  $\Rightarrow$  threshold mass  $\Rightarrow$  **SAFE!**

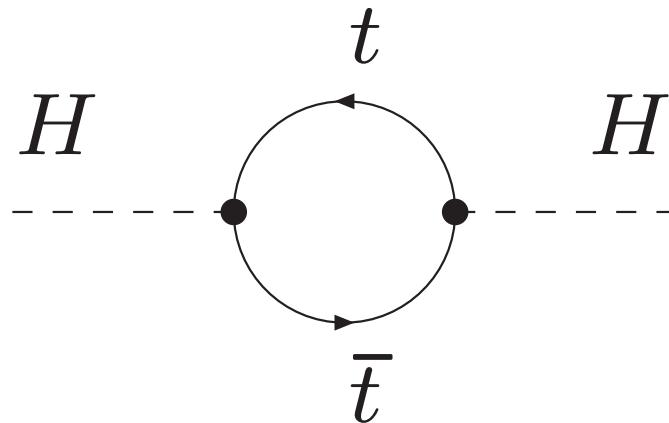
[ILC TDR '13]



transition to other mass definitions possible  $\Rightarrow \delta m_t^{\text{exp+theo}} \lesssim 0.1 \text{ GeV}$

## Top/Higgs physics in BSM:

Nearly any model: large coupling of the Higgs to the top quark:



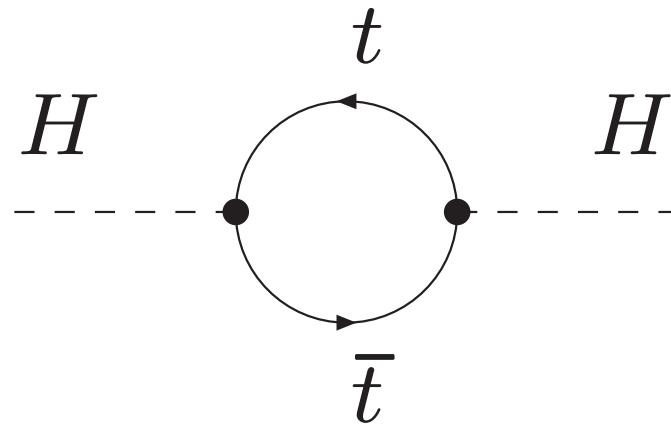
⇒ one-loop corrections  $\Delta M_H^2 \sim G_\mu m_t^4$

⇒  $M_H$  depends sensitively on  $m_t$  in all models where  $M_H$  can be predicted (SM:  $M_H$  is free parameter)

SUSY as an example:  $\Delta m_t \approx \pm 1 \text{ GeV} \Rightarrow \Delta M_h \approx \pm 1 \text{ GeV}$

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⇒ Precision Higgs physics needs ILC precision top physics

## 2D) The strong coupling constant

Today:

$$\delta\alpha_s \gtrsim 0.002$$

ILC/GigaZ:

$$\text{From } R_l : \delta\alpha_s^{\text{GigaZ}} \lesssim 0.001$$

$$\text{Fit to } Z \text{ lineshape obs.} : \delta\alpha_s^{\text{ILC}} = 0.0005$$

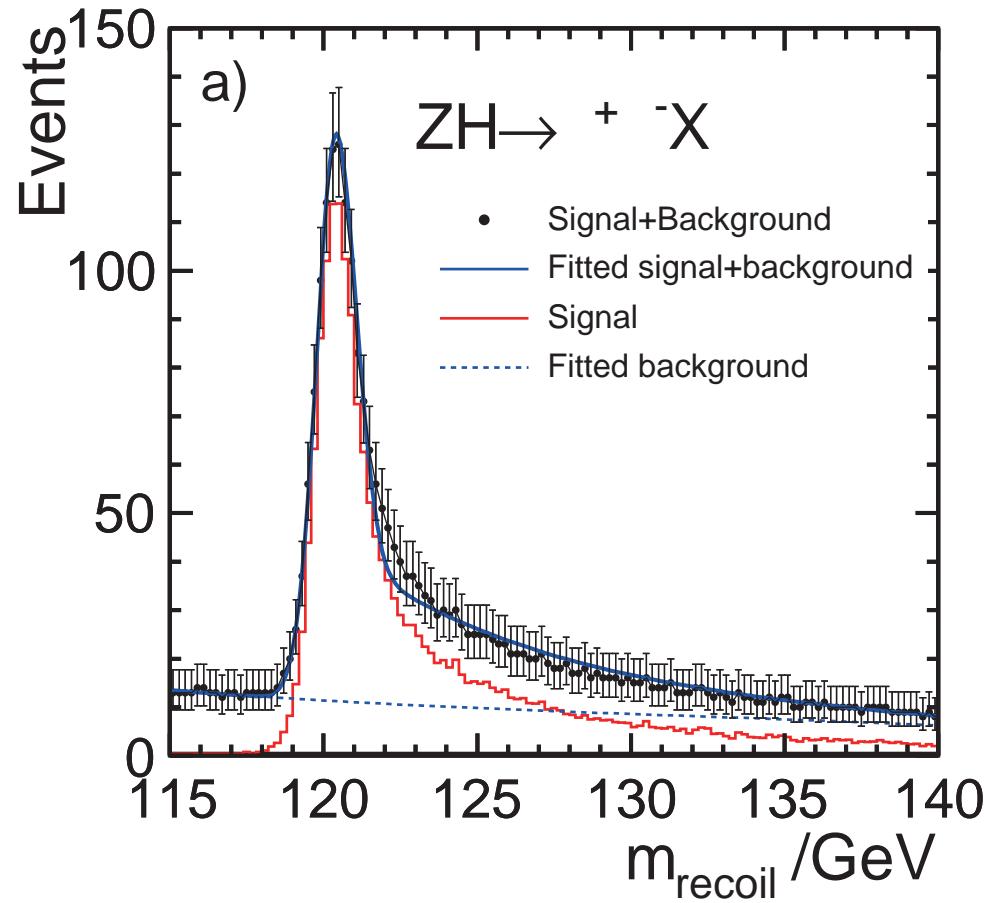
⇒ Important reduction for more precise higher-order corrections

## 2E) The Higgs boson (mass)

Model independent cross section measurement

[ILC TDR '13]

Z-recoil method:  $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- X$



$$\delta M_H^{\text{exp,ILC}} \lesssim 0.05 \text{ GeV}$$

Similarly good precision for nearly all Higgs obs.!

## 2F) Global electroweak fits $\Rightarrow$ Indirect determination of $M_H^{\text{SM}}$ :

[LEPEEWG '12]

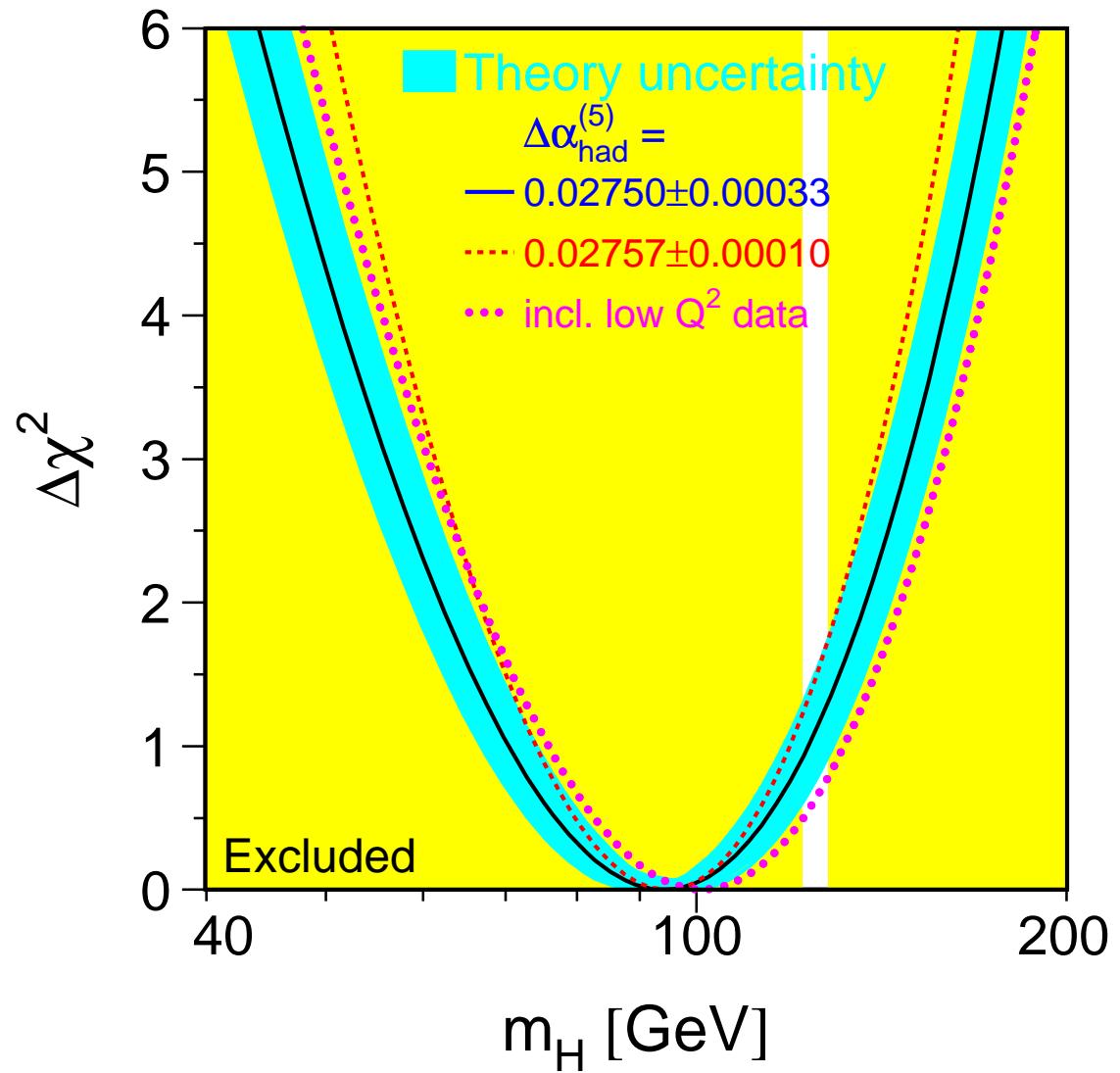
$$\Rightarrow M_H = 94^{+29}_{-24} \text{ GeV}$$

$$M_H < 152 \text{ GeV, 95% C.L.}$$

Assumption for the fit:

SM incl. Higgs boson

$\Rightarrow$  no confirmation of  
Higgs mechanism



$\Rightarrow$  Fits (relatively) well with the observed value!

## Improvement with ILC precision:

obs \ prec	today	ILC/GigaZ
$M_W$ [MeV]	15	5 – 6
$\sin^2 \theta_{\text{eff}}$ [ $10^{-5}$ ]	16	1.3
$m_t$ [GeV]	0.9	0.1

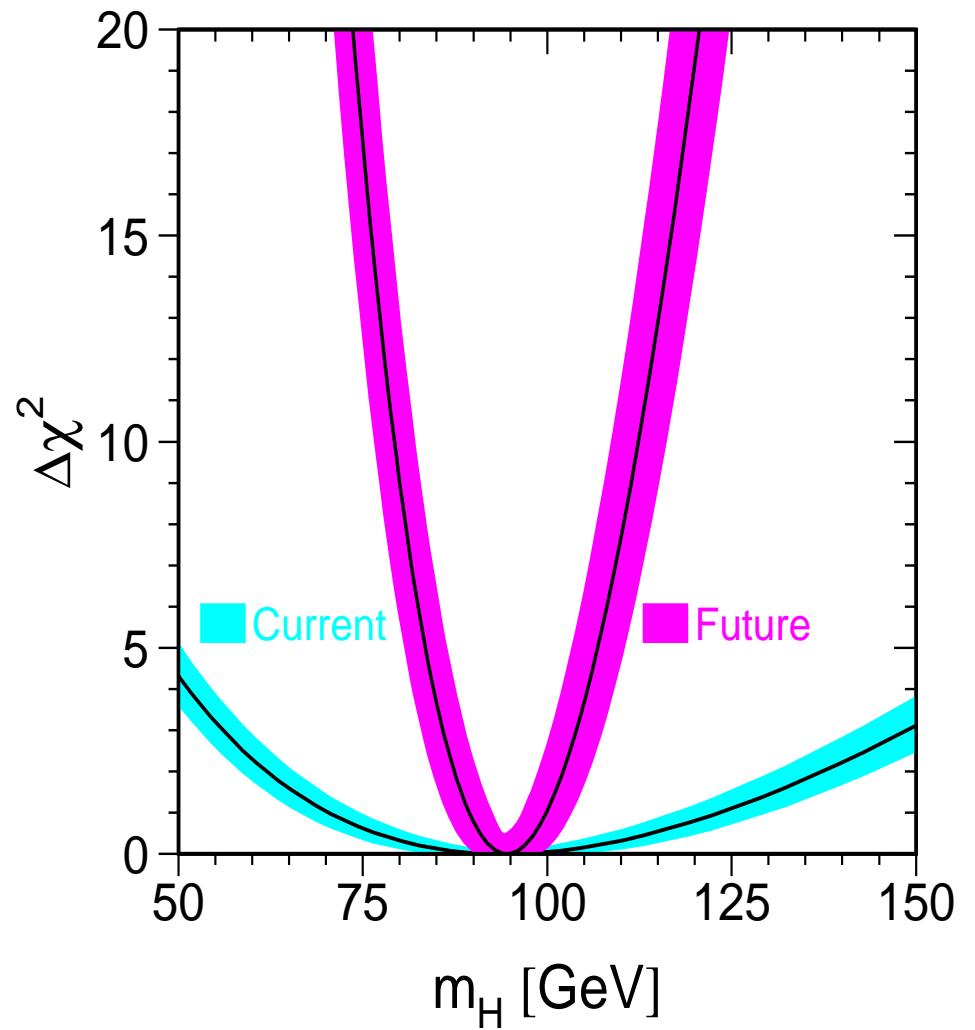
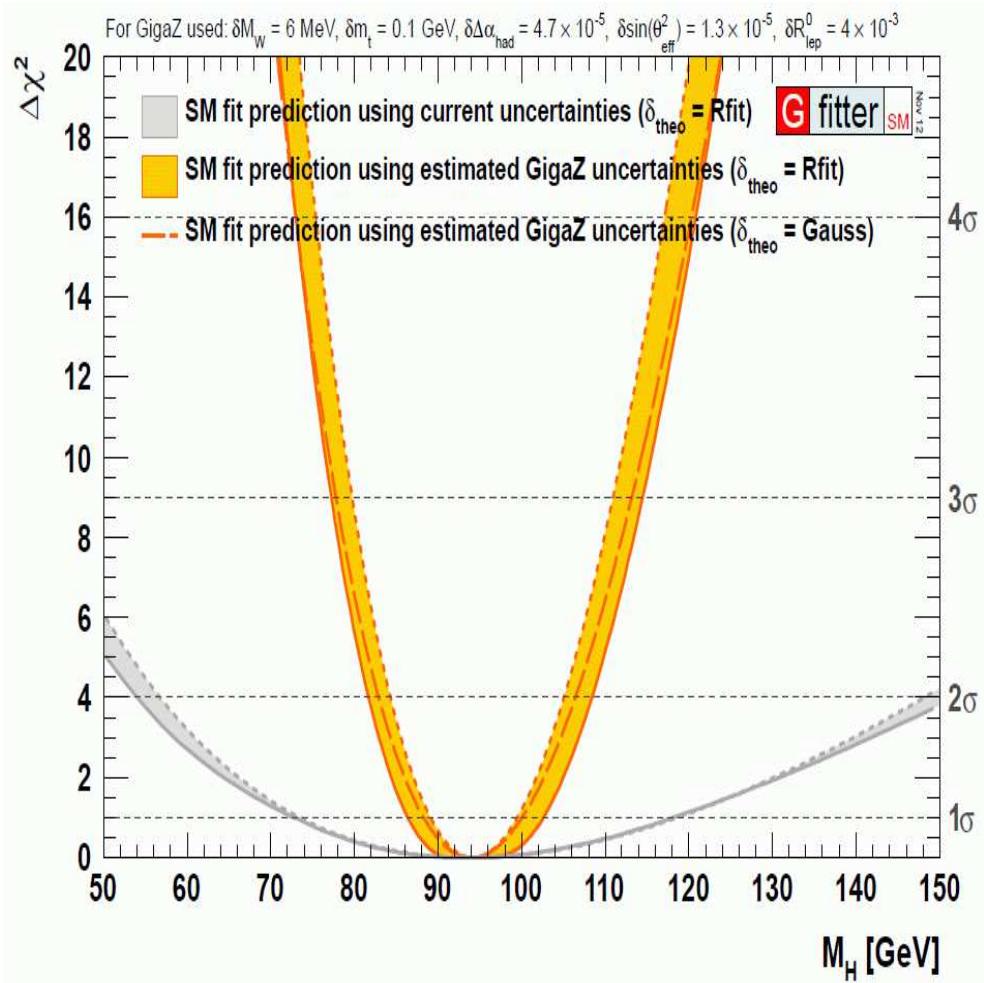
obs \ prec	$\delta m_t$	$\delta \Delta \alpha_{\text{had}}$	$\delta M_Z$	$\delta m_t, \text{fut}$	$\delta \Delta \alpha_{\text{had}, \text{fut}}$
$M_W$ [MeV]	5.5	2	2.5	1	1
$\sin^2 \theta_{\text{eff}}$ [ $10^{-5}$ ]	7	3.6	1.4	0.4	1.8

obs \ prec	SM theo	SM fut	MSSM theo	MSSM fut
$M_W$ [MeV]	4	2	5 – 10	3 – 5
$\sin^2 \theta_{\text{eff}}$ [ $10^{-5}$ ]	4.7	1.5	5 – 7	2.5 – 3.5

→ strong improvement possible!

# Most precise $M_H$ test with the ILC:

[GFitter '13] [LEPEWWG '13]



$$\Rightarrow \delta M_H^{\text{ind}} \lesssim 10 \text{ GeV}$$

$\Rightarrow$  extremely sensitive test of SM (and BSM) possible

## 2G) Anomalous gauge boson couplings

⇒ search for deviations in triple and quartic gauge boson couplings

Example: Lagrangian for TGC:

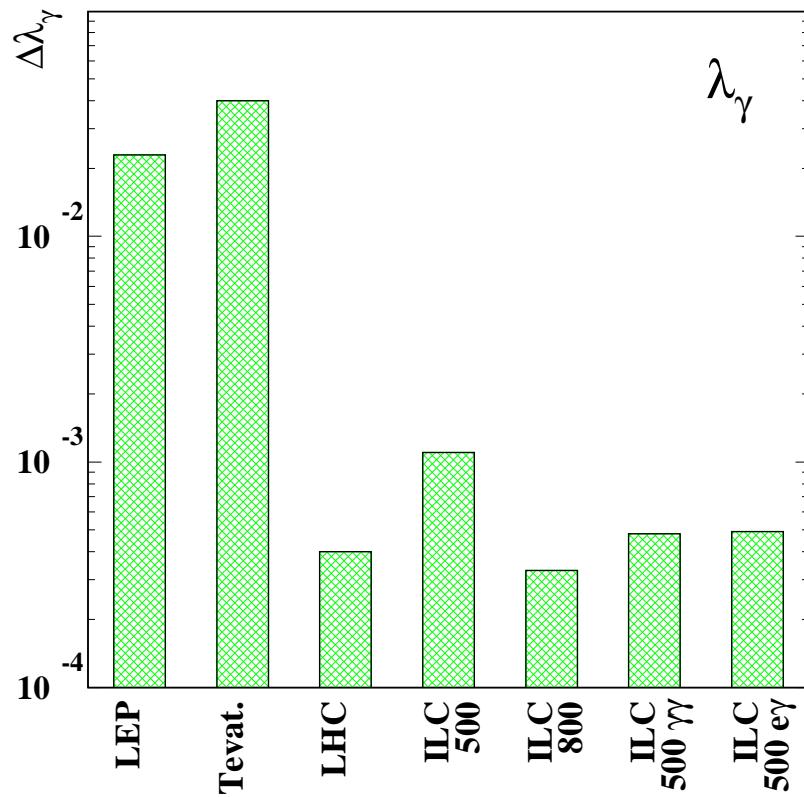
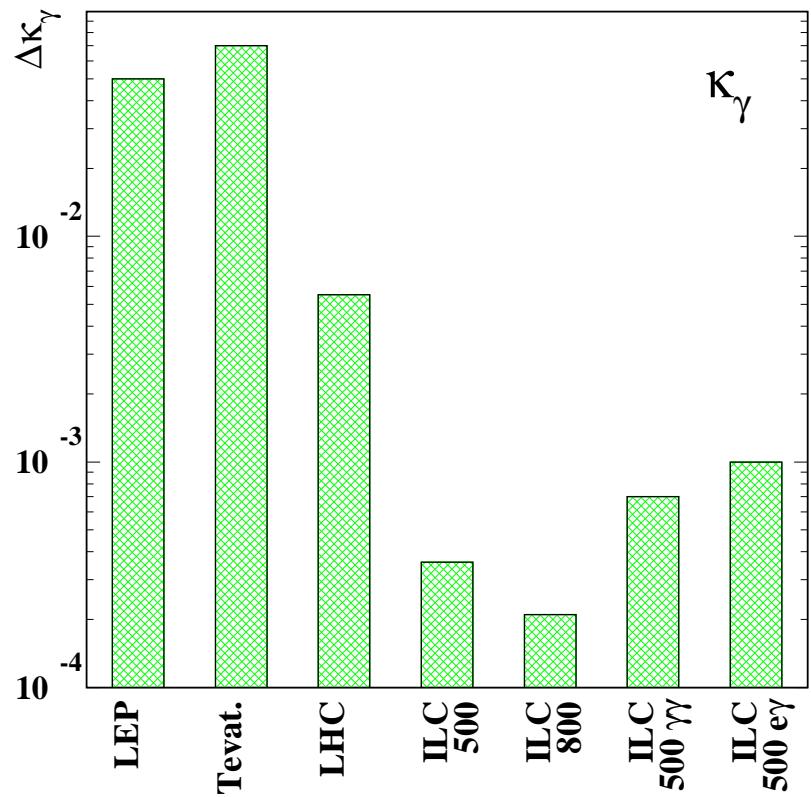
$$\begin{aligned}\mathcal{L}_{\text{TGC}} = & ig_{WWV}^V \left( g_1^V (W_{\mu\nu}^+ W^{-\mu} - W^{+\mu} W_{\mu\nu}^-) V^\nu + \kappa^V W_\mu^+ W_\nu^- V^{\mu\nu} \right. \\ & + \frac{\lambda^V}{M_W^2} W_\mu^\nu W_\nu^{-\rho} V_\rho^\mu + ig_4^V W_\mu^+ W_\nu^- (\partial^\mu V^\nu + \partial^\nu V^\mu) \\ & - ig_5^V \epsilon^{\mu\nu\rho\sigma} (W_\mu^+ \partial_\rho W_\nu^- - \partial_\rho W_\mu^+ W_\nu^-) V_\sigma \\ & \left. + \tilde{\kappa}^V W_\mu^+ W_\nu^- \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}^V}{M_W^2} W_\mu^\nu W_\nu^{-\rho} \tilde{V}_\rho^\mu \right)\end{aligned}$$

with

$$V = \gamma, Z; W_{\mu\nu}^\pm = \partial_\mu W_\nu^\pm - \partial_\nu W_\mu^\pm, V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \text{ and } \tilde{V}_{\mu,\nu} = \epsilon_{\mu\nu\rho\sigma} V_{\rho\sigma} / 2$$

$$\text{SM: } g_1^{\gamma,Z} = \kappa^{\gamma,Z} = 1, \quad g_{4,5}^{\gamma,Z} = \tilde{\kappa}^{\gamma,Z} = 1, \quad \lambda^{\gamma,Z} = \tilde{\lambda}^{\gamma,Z} = 0$$

⇒ deviations indicate BSM physics (no deviations observed so far)



⇒ strong improvement possible for  $\kappa_\gamma$ !

(More examples need to be worked out . . . ?)

## 2H) Extra gauge bosons

Probe extra gauge bosons  $Z'$ ,  $W'$  via  $e^+e^- \rightarrow 2f, 4f$

Particular high reach for  $Z'$  via  $e^+e^- \rightarrow Z' \rightarrow 2f$  via mixing of  $Z$  and  $Z'$   
⇒ total cross section, forward-backward asymmetry, . . .  
⇒ even better with both beams polarized!

$Z'$  can arise from

- larger gauge groups, e.g.  $SO(10) \rightarrow SU(3) \times SU(2) \times U(1)U'(1)$
- Kaluza-Klein models (as “ $Z$  partner”)
- . . .

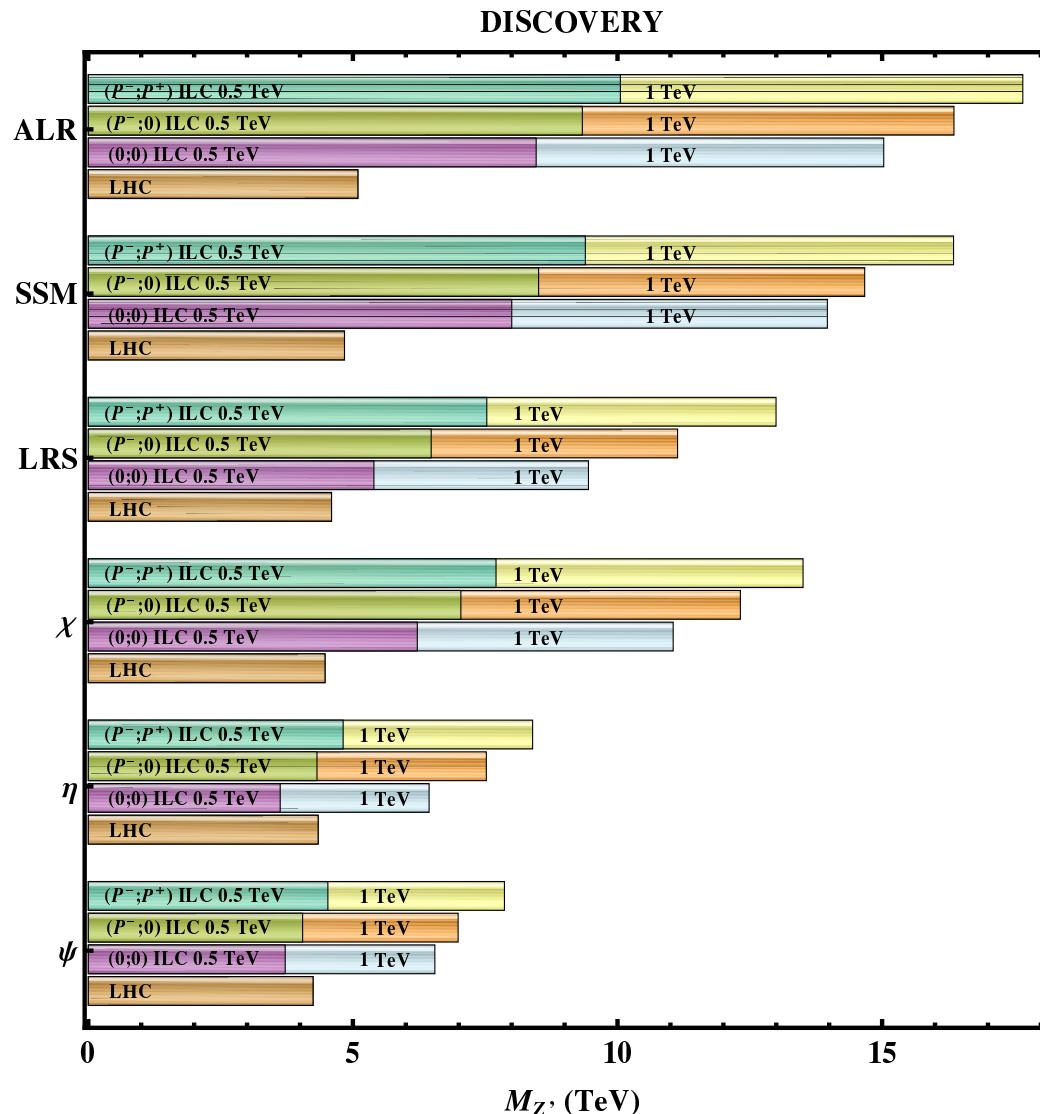
Various models in the literature: “ALR”, “SSM”, “LRS”,  $\chi$ ,  $\eta$ ,  $\psi$ , . . .

→ discovery reach

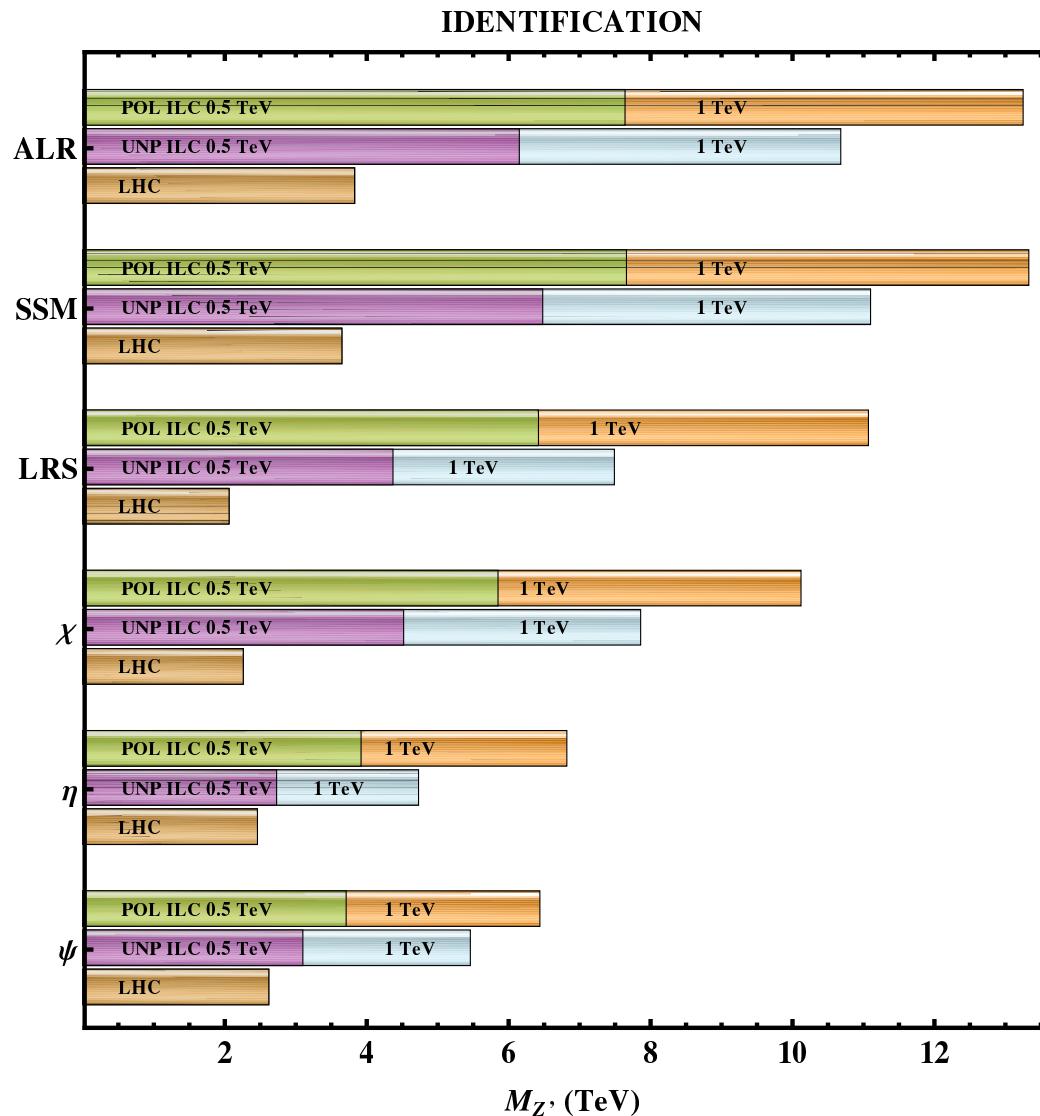
→ identification reach

## ILC discovery potential:

[P. Osland, A. Pankov, A. Tsytrinov '09]



⇒ discovery potential: 7 – 17 TeV



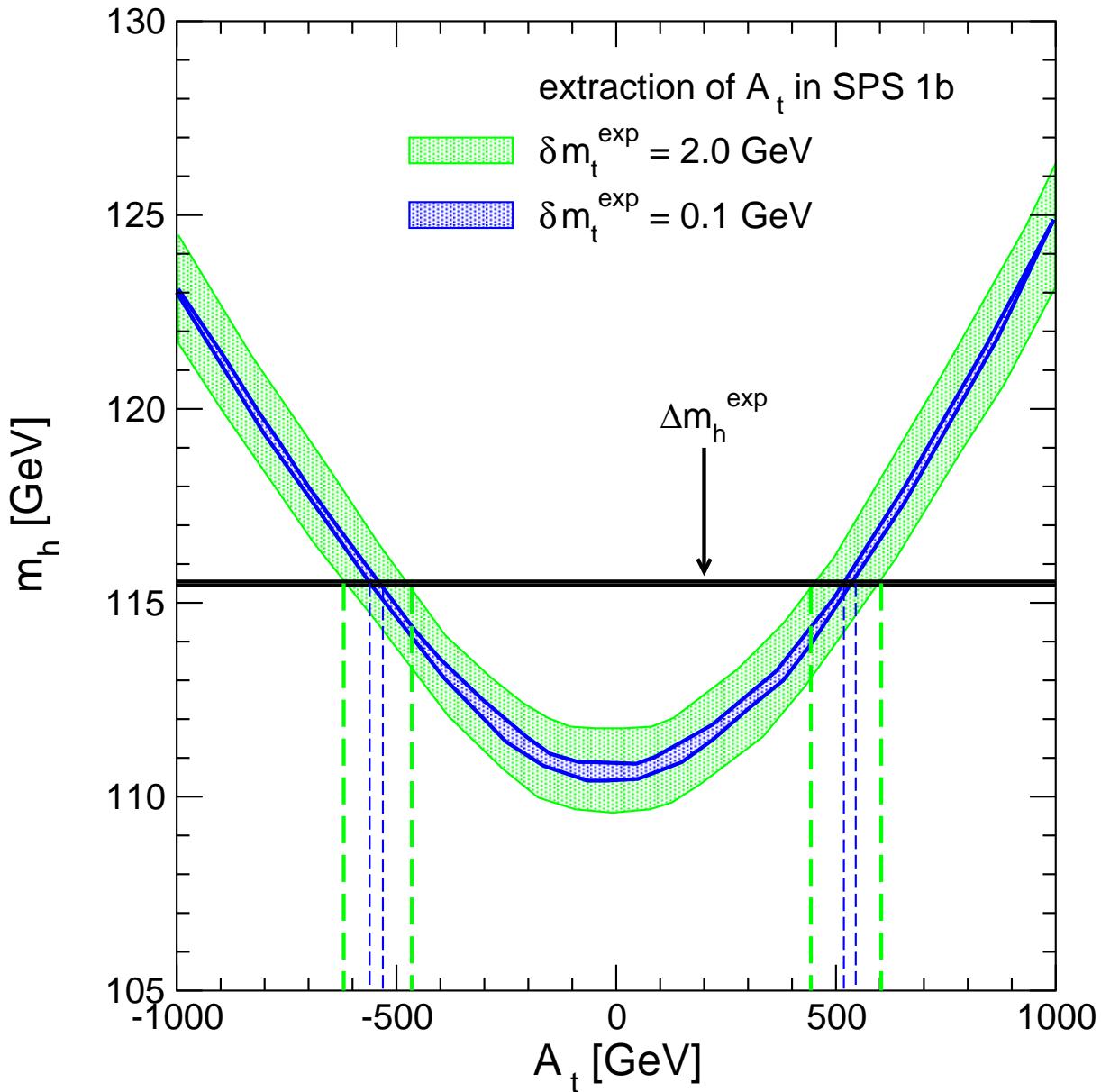
⇒ identification potential: 6 – 13 TeV

### 3. Conclusions

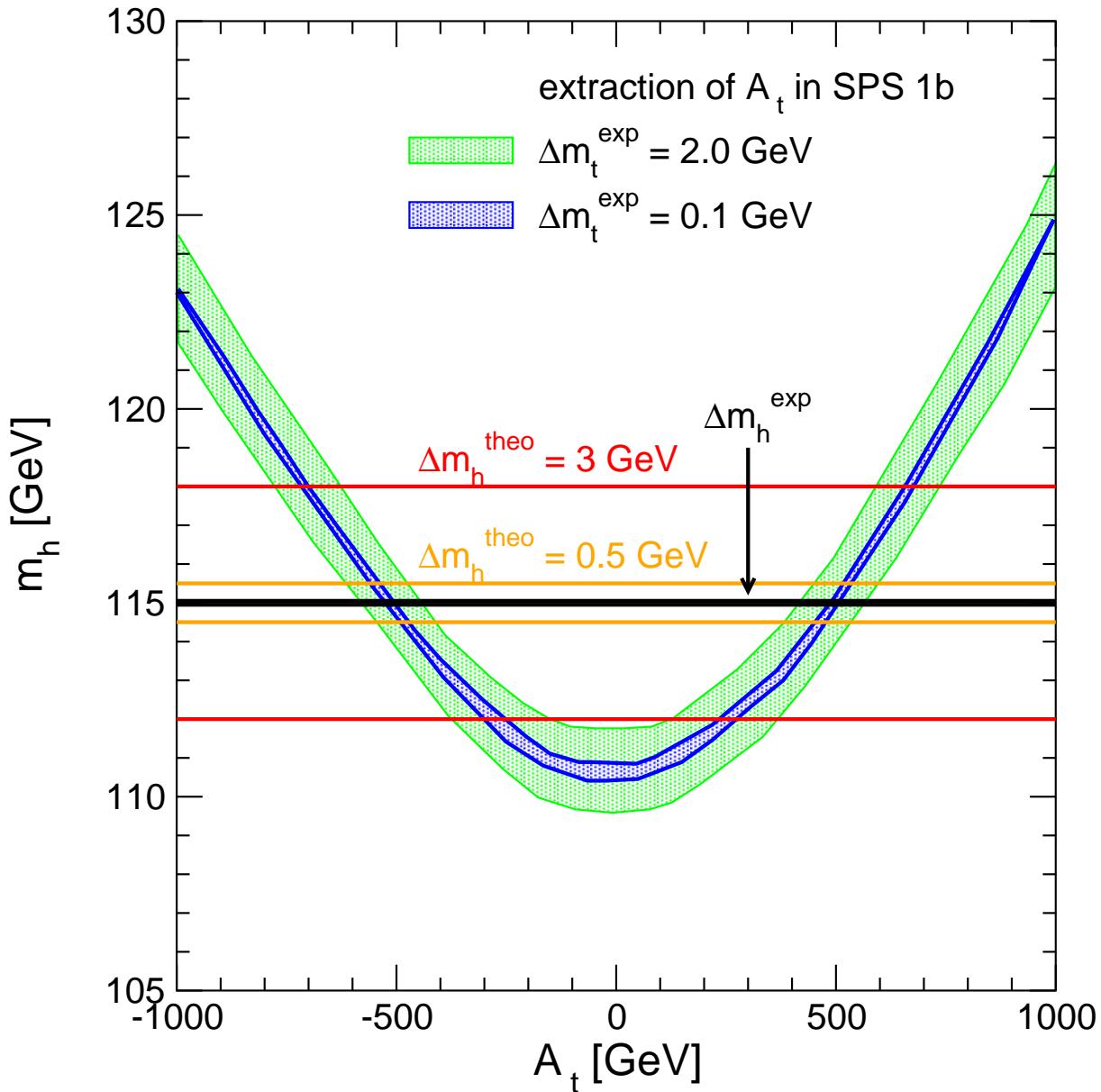
- Quantum physics can be a valuable tool to investigate SM, BSM
- ILC offers many possibilities:
  - $M_W$ ,  $\sin^2 \theta_{\text{eff}}$ : main EWPO  
→ tests of SM and MSSM
  - $m_t$ : crucial input parameter for many calculations  
ILC offers clean threshold mass
  - Higgs observables at the per-cent level,  $\delta M_H \lesssim 50$  MeV
  - Indirect determination of  $M_H$ :  $\delta M_H \lesssim 10$  GeV
  - Anomalous gauge couplings:  
factor 10 improvement possible . . .
  - Heavy gauge bosons:  $Z'$ ,  $W'$ :  
search reach up to 17 TeV
- ILC offers excellent prospects to test, SM, MSSM, BMSSM, . . .

Back-up

## Example of application: $M_h$ prediction as a function of $A_t$



## Example of application: $M_h$ prediction as a function of $A_t$



SPS1b:

$m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$  known,  
 $A_t$  unknown

$\tan \beta, M_A$  known,  
realistic experimental  
errors assumed

⇒ extraction of  $A_t$  possible

⇒  $\Delta m_h^{\text{theo}}$  has to be  
under control

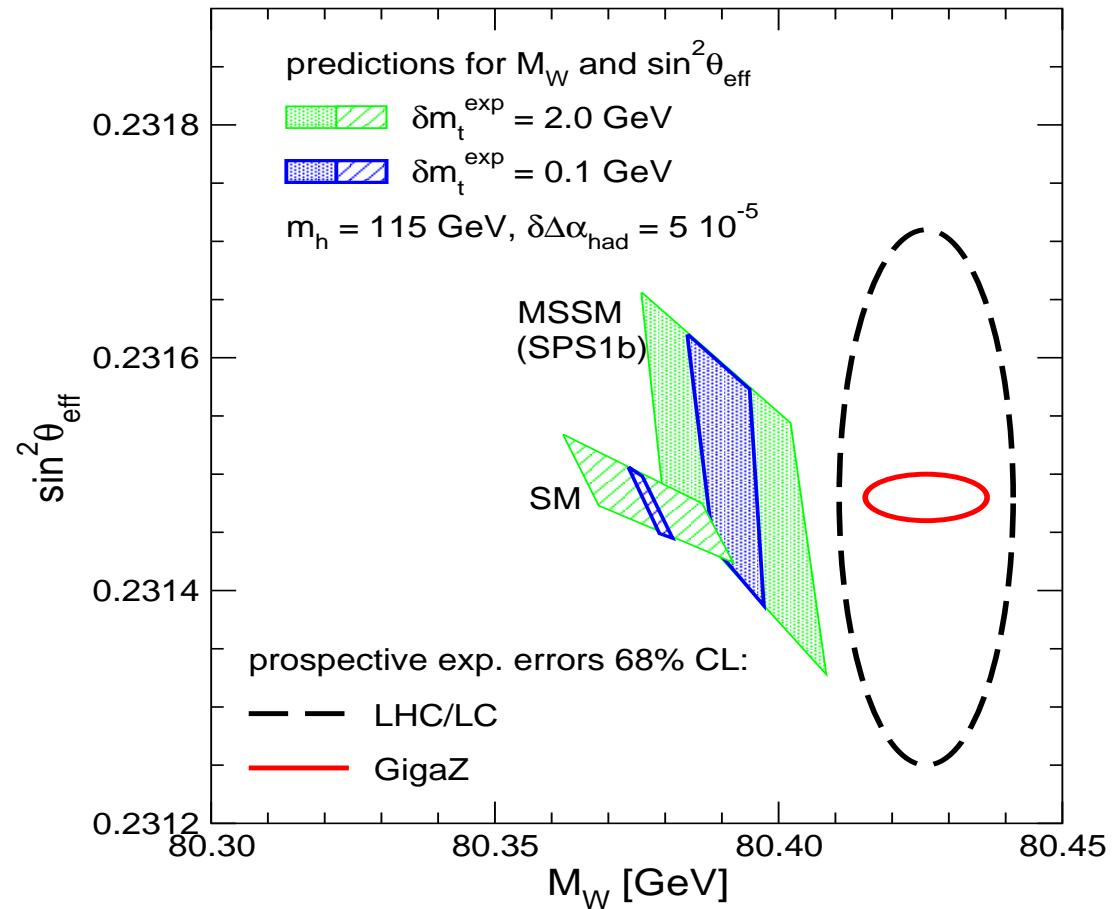
⇒ crucial for SUSY fits

## Possible future scenario:

[S.H., S. Kraml, W. Porod, G. Weiglein '03]

SM:  $M_H = 115$  GeV

MSSM: SPS 1b  
all SUSY parameters varied  
within realistic errors



$\delta m_t = 0.1$  GeV vs.  $\delta m_t = 2$  GeV

⇒ SM: improvement by a factor  $\sim 10$

⇒ MSSM: improvement by a factor  $\sim 2 - 3$