The Top Mass in the SM and MSSM (and BMSSM)

Sven Heinemeyer, IFCA (CSIC, Santander)

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1. What to expect from m_t @ the LC

2. Implications for the SM

3. Implications for SUSY

4. Implications for other models

5. Conclusions

1. What to expect from GigaZ and m_t @ the LC

(Sad) Reality: LC will start in 2020 earliest

World of High Energy Physics in the year 2020:

Both LHC detectors will have accumulated $\sim 300\,\text{fb}^{-1}$

Initial LHC physics goals are accomplished:

– state compatible with a Higgs found
  corresponding couplings measured to 10–30%
– SUSY-like signatures observed (if realized at the EW scale)
  (or not . . . ???)
– Extra dimensions or . . . -like signatures observed
  (or not . . . ???)

LHC may await luminosity upgrade

What can LC/GigaZ add?

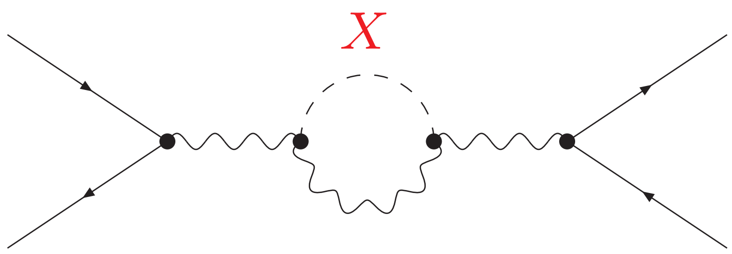
Important test for **any** model:

Comparison of observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\text{eff}}, a_\mu$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

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



$\Downarrow$

SM: limits on M_X

Very high accuracy of measurements and theoretical predictions needed

Important: three different types of errors:

Experimental error ($\Rightarrow$ included in the figure):

– current error

– future expectations

$\Rightarrow$ sets the scale, has to be matched by other errors

Theory error:

$\Rightarrow$ error due to missing higher order corrections

– only estimates possible

– even more complicated for the future

Parametric error:

– current uncertainty in the prediction due to error in the input parameters

– future uncertainty

$\Rightarrow$ focus on SM parameters

$\Rightarrow$ derive information about (unknown) SUSY(?) parameters
(BSM parametric uncertainties highly model dependent)

Precision observables: M_W, $\sin^2\theta_{\text{eff}}$, M_h, $(g-2)_\mu$, b physics, ...

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1 + \Delta r)$$

$\Updownarrow$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[A. Sirlin '80] , [W. Marciano, A. Sirlin '80]

$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

$\sim \log \frac{M_Z}{m_f}$ $\qquad$ $\sim m_t^2$ $\qquad$ $\log(M_H/M_W)$

$\sim 6\%$ $\qquad$ $\sim 3.3\%$ $\qquad$ $\sim 1\%$

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loop corrections

B) Effective mixing angle:

$$\sin^2\theta_{\rm eff} = \frac{1}{4\,|Q_f|}\left(1 - \frac{\mathrm{Re}\,g_V^f}{\mathrm{Re}\,g_A^f}\right)$$

Higher order contributions:

$$g_V^f \to g_V^f + \Delta g_V^f, \quad g_A^f \to g_A^f + \Delta g_A^f$$

Experimental errors of the precision observables:

	today	Tev./LHC	LC	GigaZ
$\delta \sin^2\theta_{\rm eff}(\times 10^5)$	16	16	–	1.3
δM_W [MeV]	15	$\le$15	10	7
δm_t [GeV]	0.9	$\le$1	0.2	0.1

Relevant SM parametric errors: $\delta(\Delta\alpha_{\rm had}) = 5 \times 10^{-5}$, $\delta M_Z = 2.1$ MeV

	$\delta m_t = 2$	$\delta m_t = 1$	$\delta m_t = 0.1$	$\delta(\Delta\alpha_{\rm had})$	δM_Z
$\delta \sin^2\theta_{\rm eff}$ [10^{-5}]	6	3	0.3	1.8	1.4
ΔM_W [MeV]	12	6	1	1	2.5

Current and future errors:

Current:

$$\delta m_t^{\text{exp}} = 0.9 \text{ GeV}, \qquad \delta(\Delta\alpha_{\text{had}}) = 3.5 \times 10^{-4}$$

$$\delta M_W^{\text{theory,SM}} \approx \pm 4 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{theory}} \approx \pm 10 \times 10^{-5}$$

$$\delta m_t : \quad \delta M_W^{\text{para}} \approx \pm 5.5 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{para}} \approx \pm 7 \times 10^{-5}$$

$$\delta(\Delta\alpha_{\text{had}}) : \quad \delta M_W^{\text{para}} \approx \pm 6.5 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{para}} \approx \pm 13 \times 10^{-5}$$

$$\delta M_W^{\text{exp}} \approx \pm 15 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{exp}} \approx \pm 16 \times 10^{-5}$$

Future:

$$\delta M_W^{\text{theory}} \gtrsim \pm 2 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{theory}} \gtrsim \pm 2 \times 10^{-5}$$

$$\delta m_t : \quad \delta M_W^{\text{para}} \approx \pm 1 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{para}} \approx \pm 0.4 \times 10^{-5}$$

$$\delta(\Delta\alpha_{\text{had}}) : \quad \delta M_W^{\text{para}} \approx \pm 1 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{para}} \approx \pm 1.8 \times 10^{-5}$$

$$[\text{GigaZ}] : \quad \delta M_W^{\text{exp}} \approx \pm 7 \text{ MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{exp}} \approx \pm 1.3 \times 10^{-5}$$

The top is guaranteed at the LC ⇒ sure physics case

Top-quark mass is a fundamental parameter of the electroweak theory

By far the largest quark mass,
largest mass of all known fundamental particles

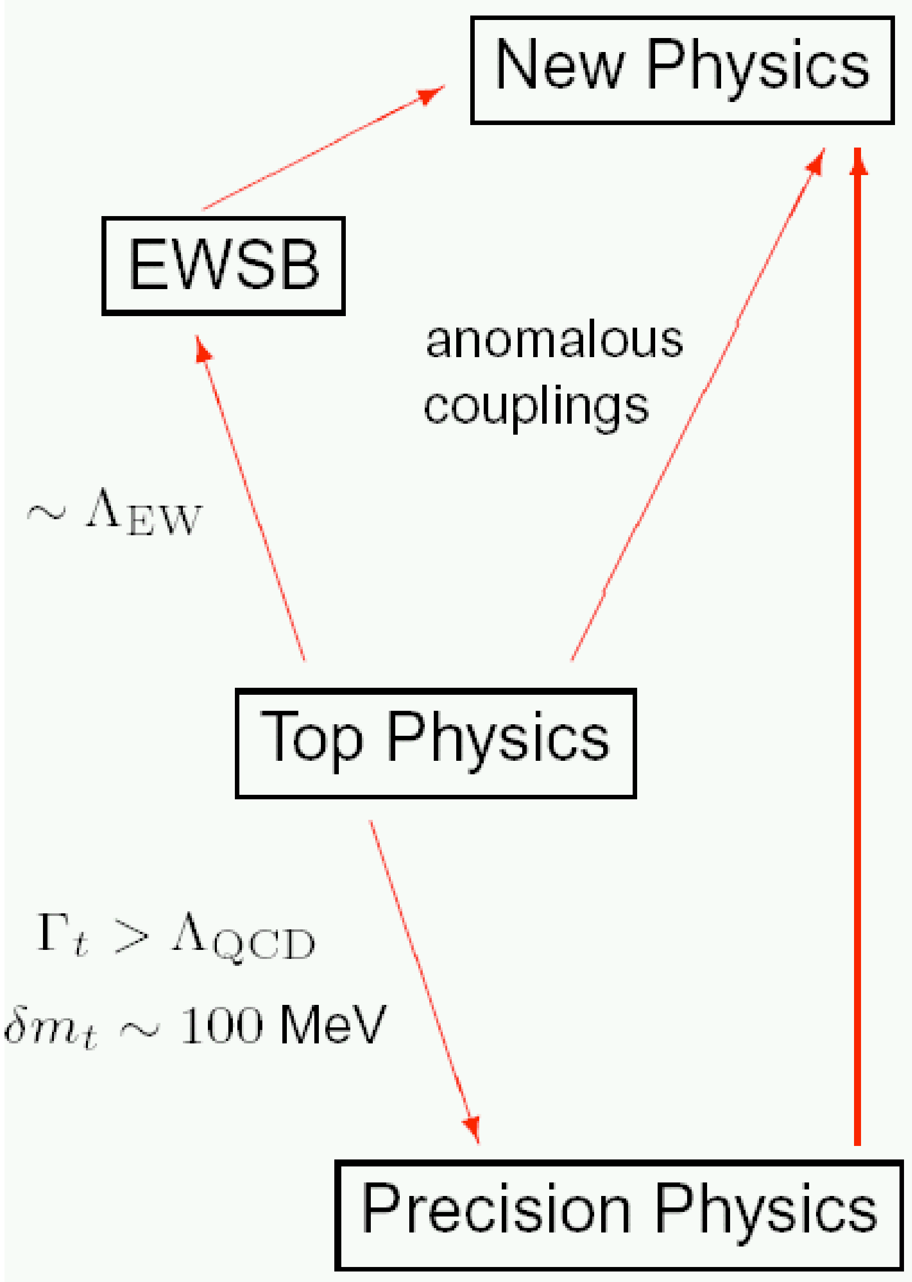
Window to new physics?

Large coupling to the Higgs boson; physics of flavor;
prediction of m_t from underlying theory?

Radiative corrections

⇒ non-decoupling effects proportional to powers of m_t

⇒ Need to know m_t very precisely in order to have sensitivity to effects of new physics



EWSB: just a heavy quark?
special role for t in EWSB?
strong constraint on any model

Precision physics:
$\delta m_t^{\rm exp}$ leading parametric uncertainty
$\to$ could obscure new physics

SUSY: m_t crucial input parameter
drives SSB/unification

Little Higgs: heavier top

Tevatron: "rough" measurements of mass, couplings, BRs

LHC: the same (but better!) & more

LC: high precision of everything

What is the top mass?

Particle masses are not 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 $\mathcal{O}(\Lambda_{\rm QCD})$

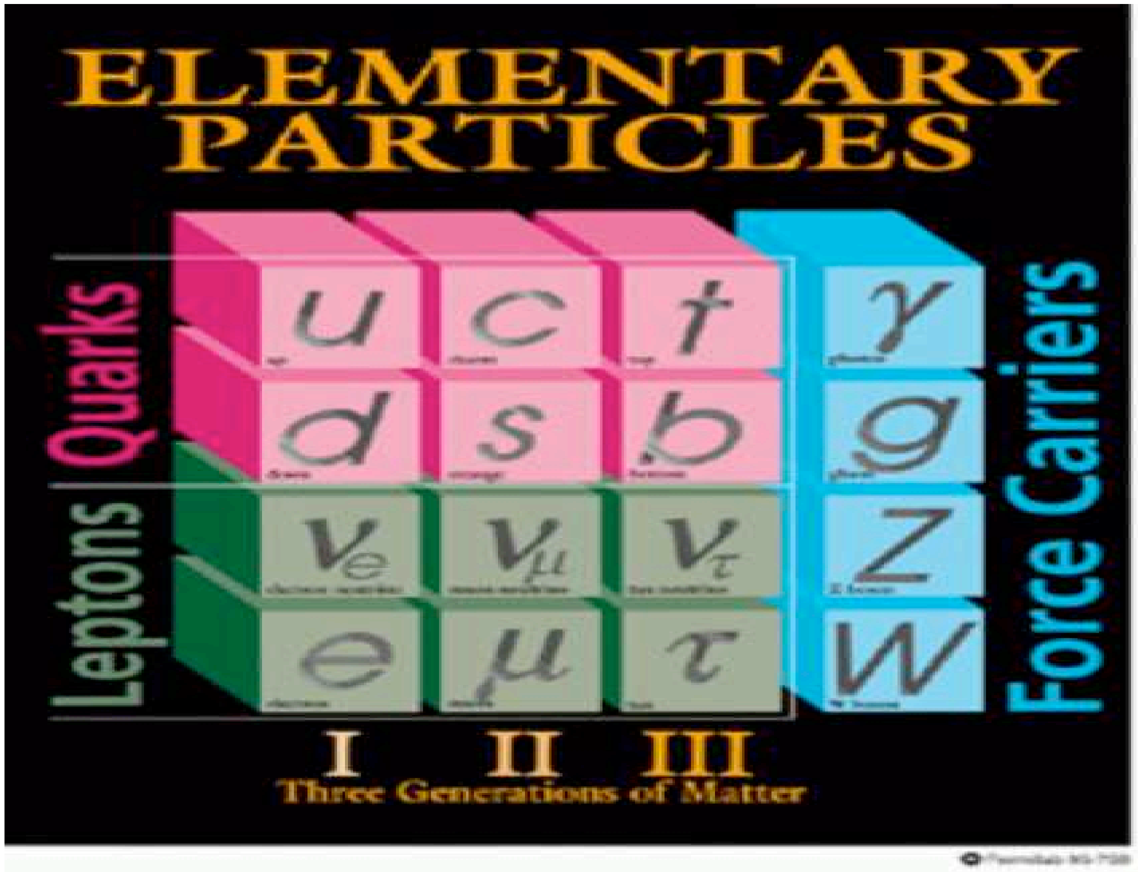
Measurement of m_t:

- At Tevatron, LHC:
  kinematic reconstruction, fit to invariant mass distribution
  $\Rightarrow$ "pole" mass

- At the LC:
  mainly from threshold behavior $\Rightarrow$ threshold mass $\Rightarrow$ **SAFE!**

2. Implications for the SM

Current status of knowledge: the Standard Model (SM)



⇒ Last remaining free parameter: M_H

Comparison of SM prediction of M_W with direct measurements:

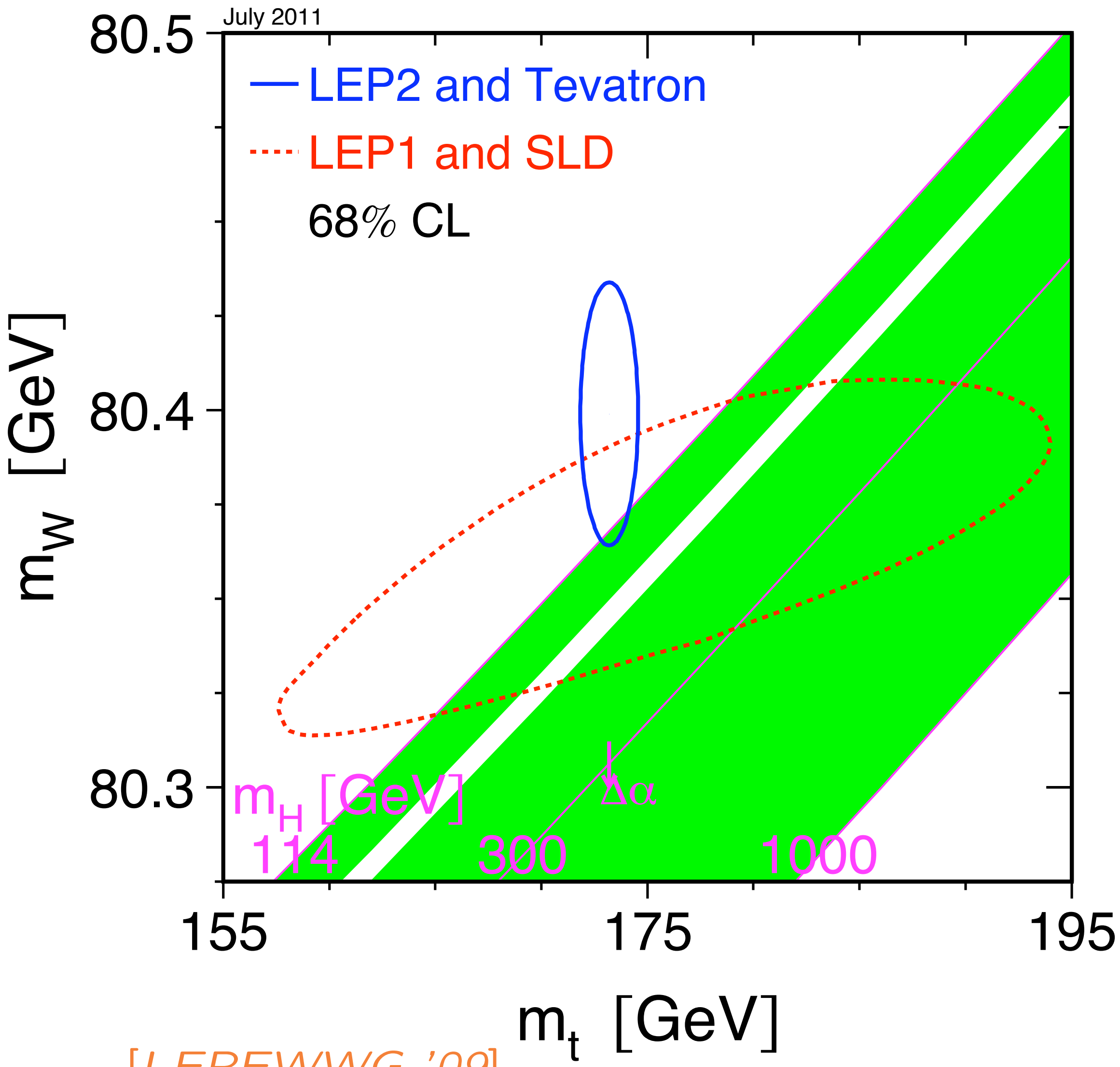
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2}\log\left(\frac{M_H}{M_W}\right)$$

general for EWPO:

$$\Delta \sim g_2^2\left[\log\left(\frac{M_H}{M_W}\right) + g_2^2\frac{M_H^2}{M_W^2}\right]$$

leading term: $\log(M_H)$

first term $\sim M_H^2$ with g_2^4



[LEPEWWG '09]

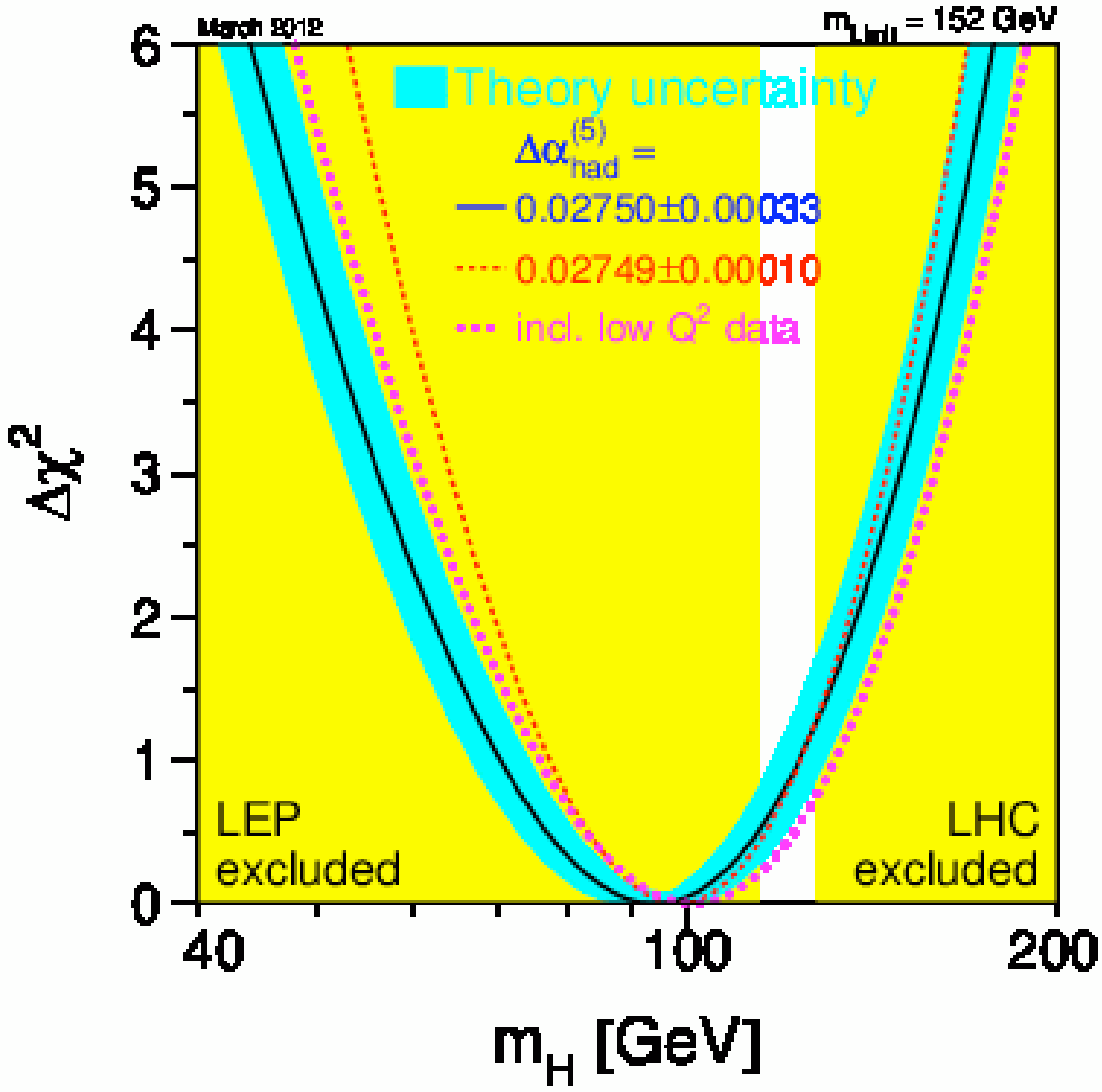
⇒ light Higgs boson preferred

Global fit to all SM data:

[*LEPEWWG '09*]

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

$M_H < 152$ GeV, 95% C.L.



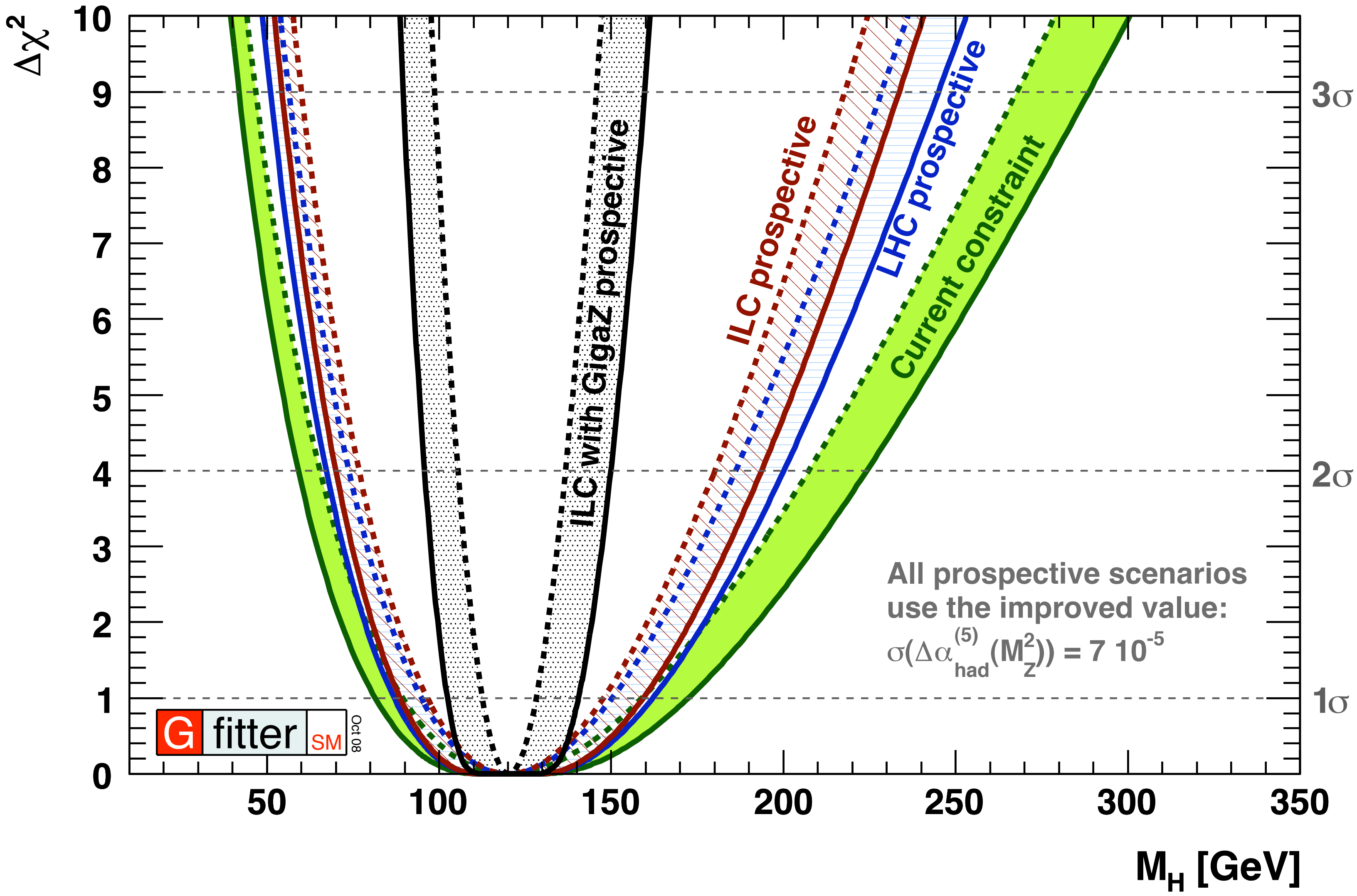
Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 160$ GeV

GigaZ: Improvement in the Blue Band plot:

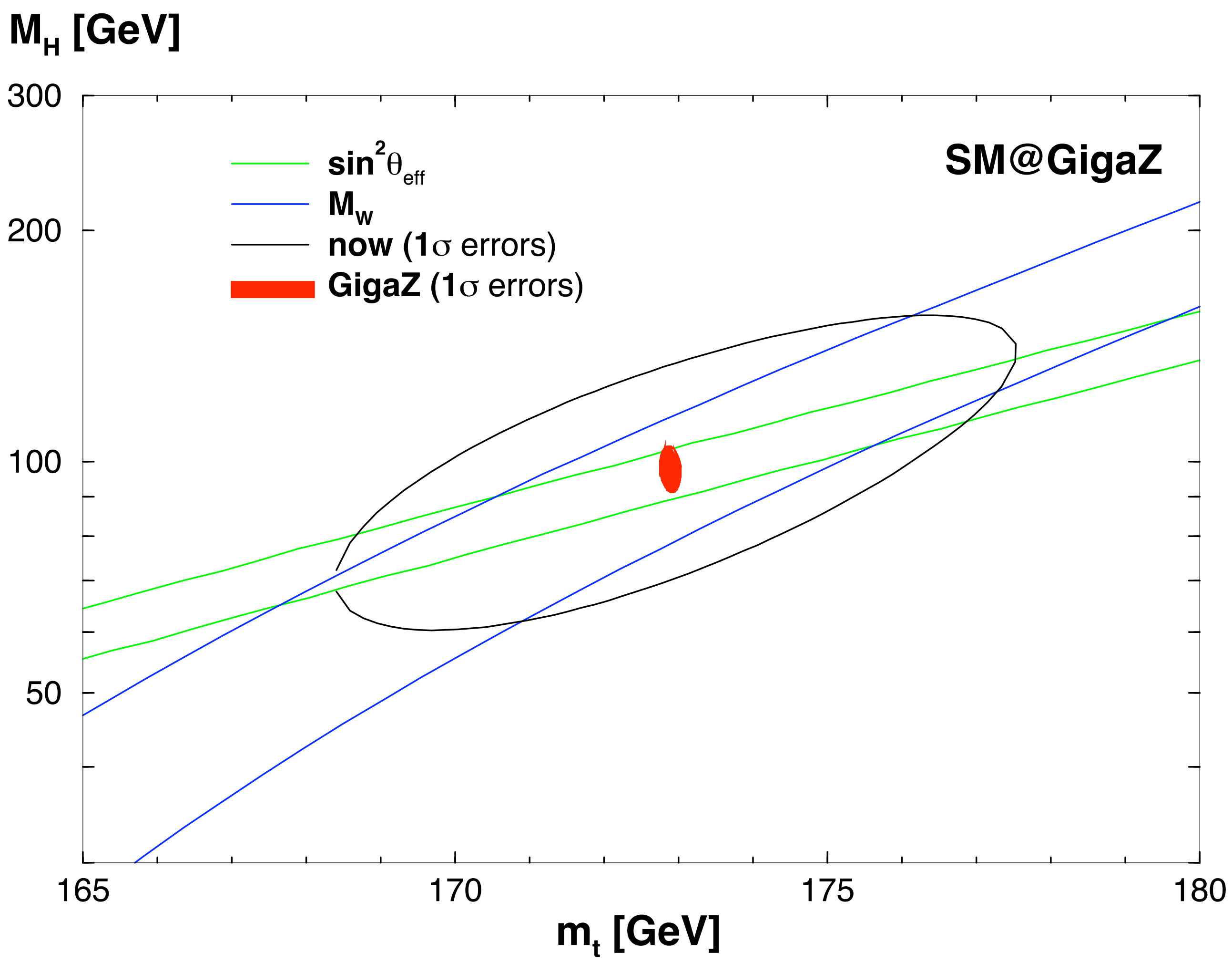
[*GFitter '09*]



(note: artificially $M_H^{SM} = 120$ GeV)

GigaZ: $\Rightarrow$ Improvement in M_H determination:

[J. Erler, S.H., W. Hollik, G. Weiglein, P. Zerwas '00]



3. Implications for SUSY

- Precision observables to test the MSSM

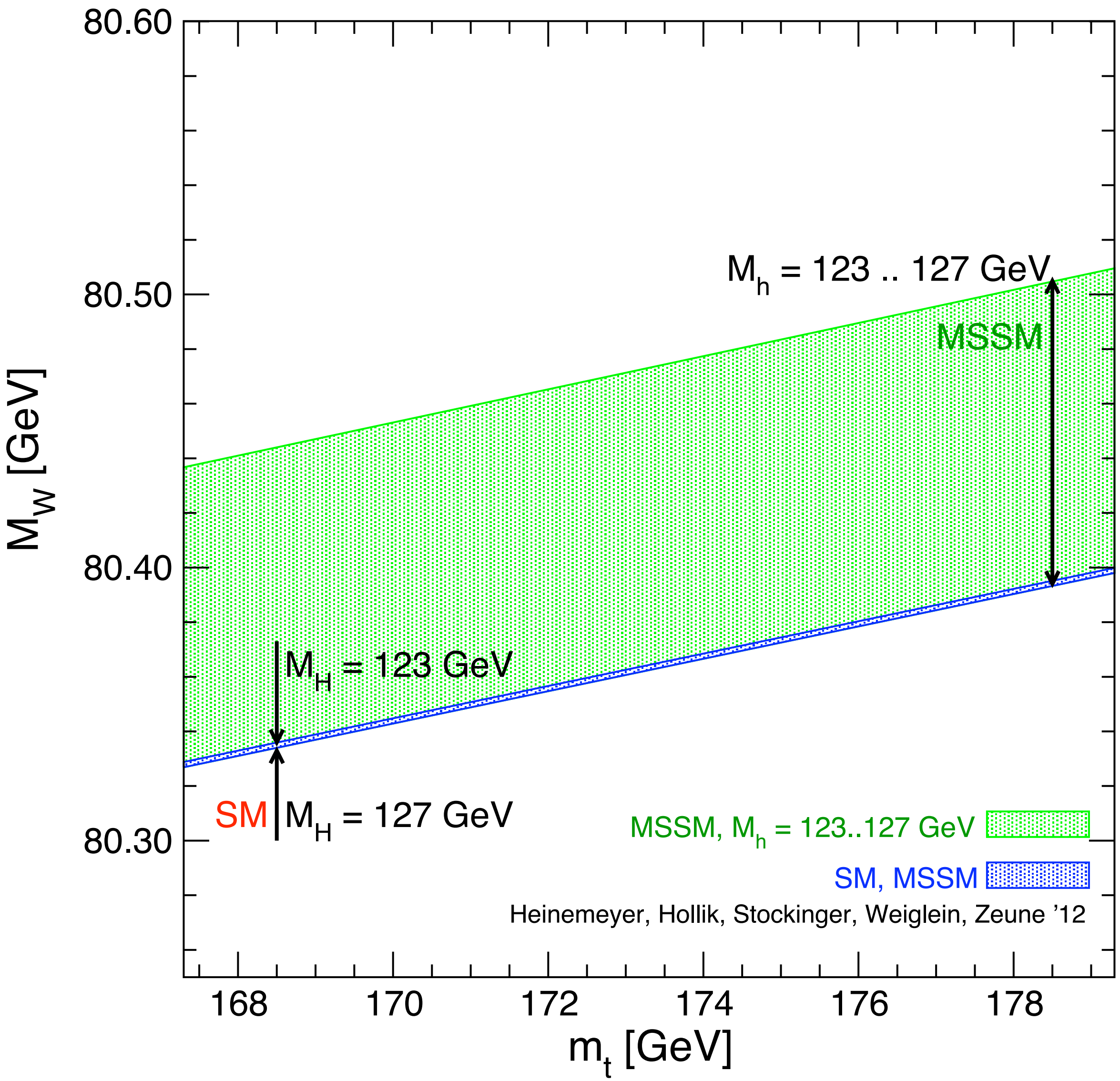
- top mass measurement for the MSSM Higgs sector

- discriminate between SM and MSSM

- limits on MSSM extensions

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

SM band:
variation of M_H^{SM}

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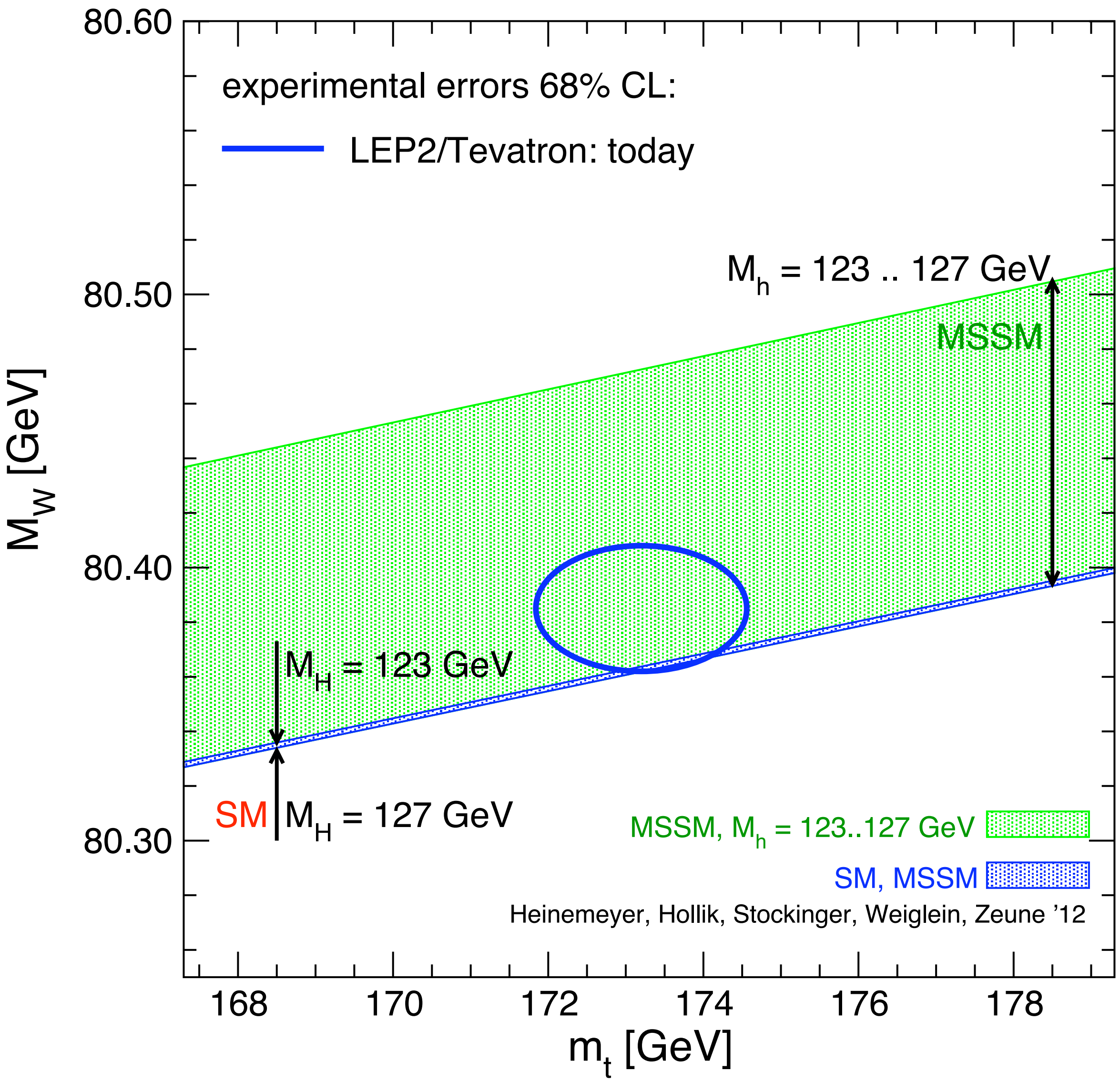

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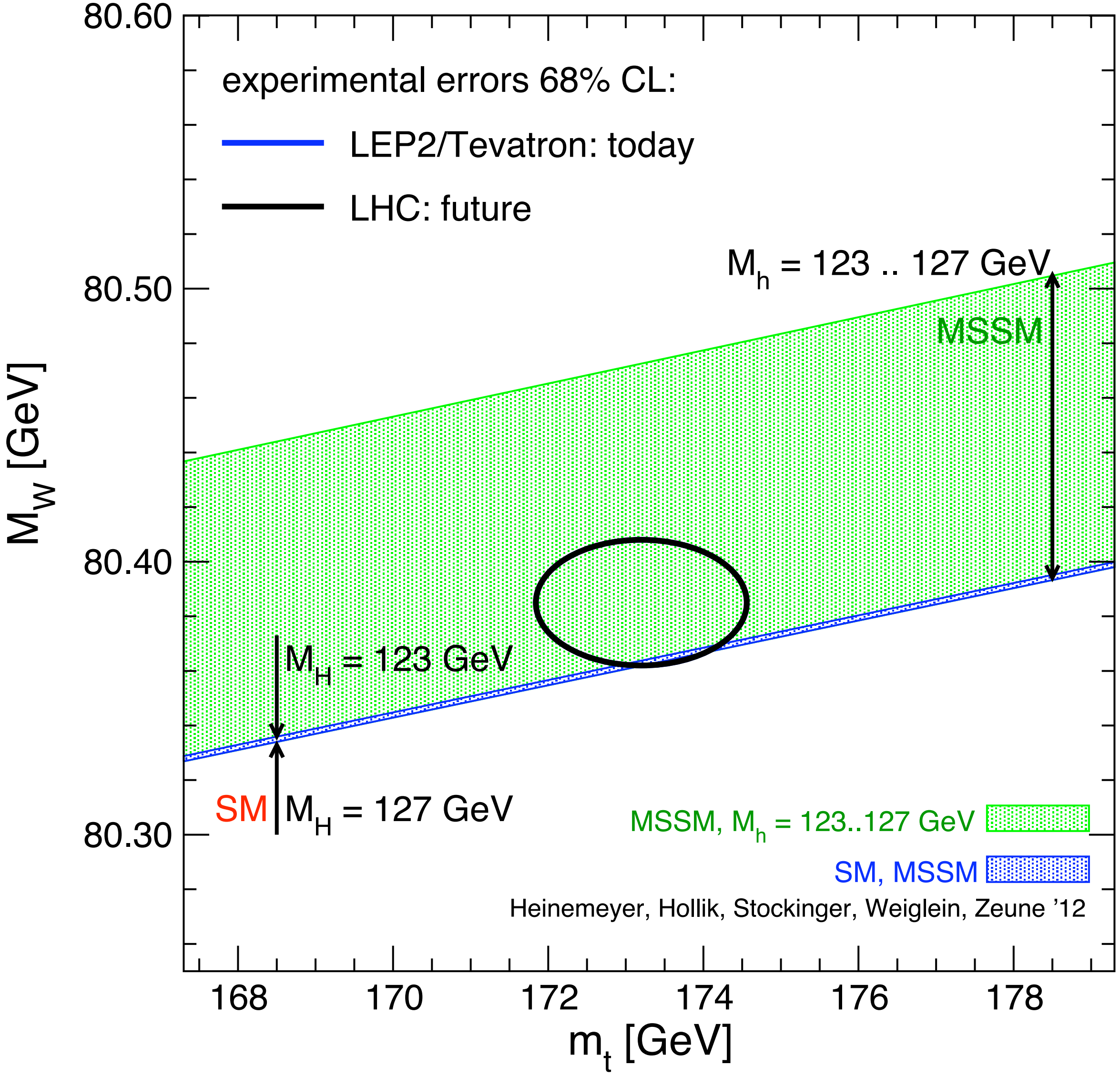

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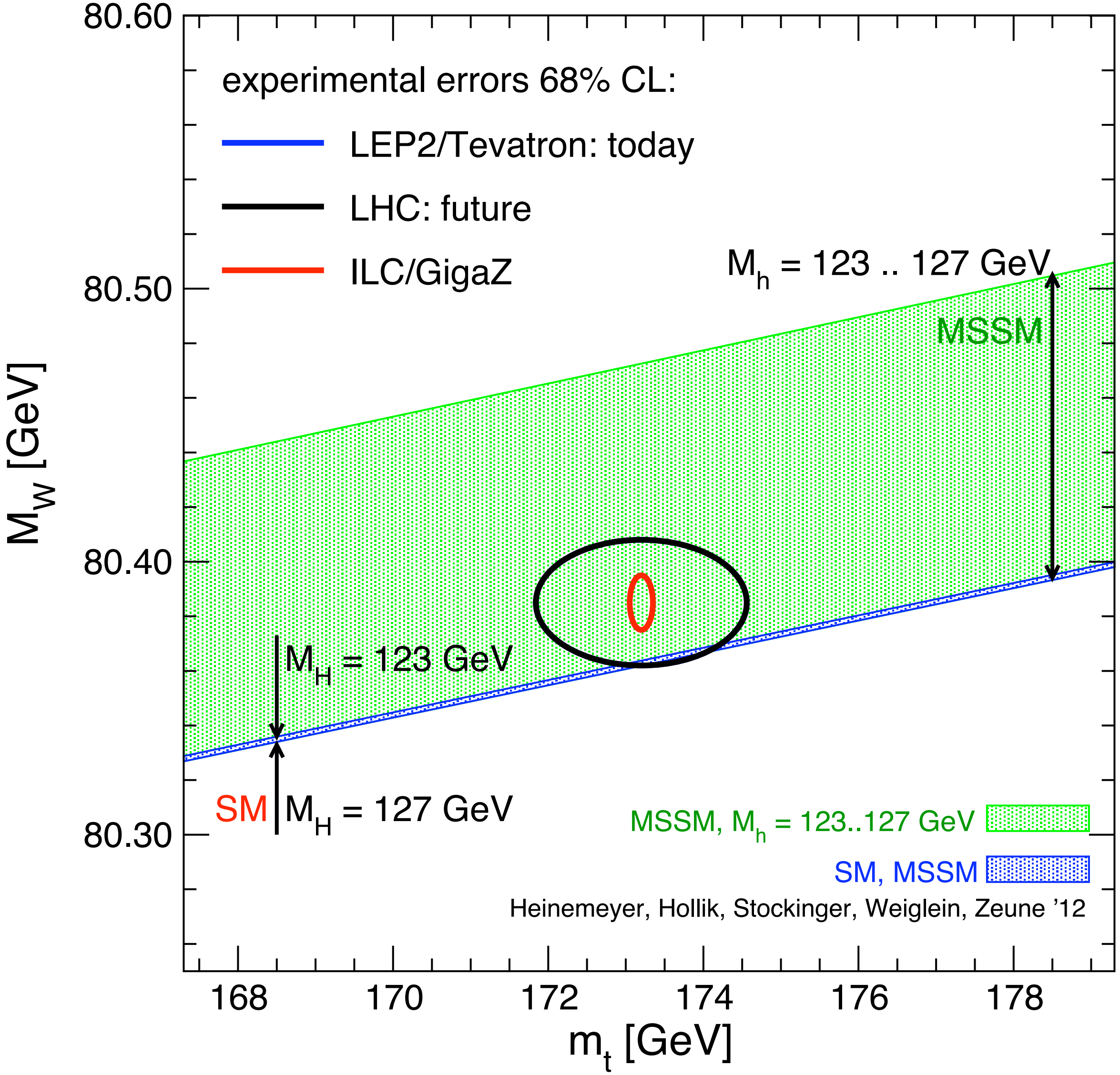

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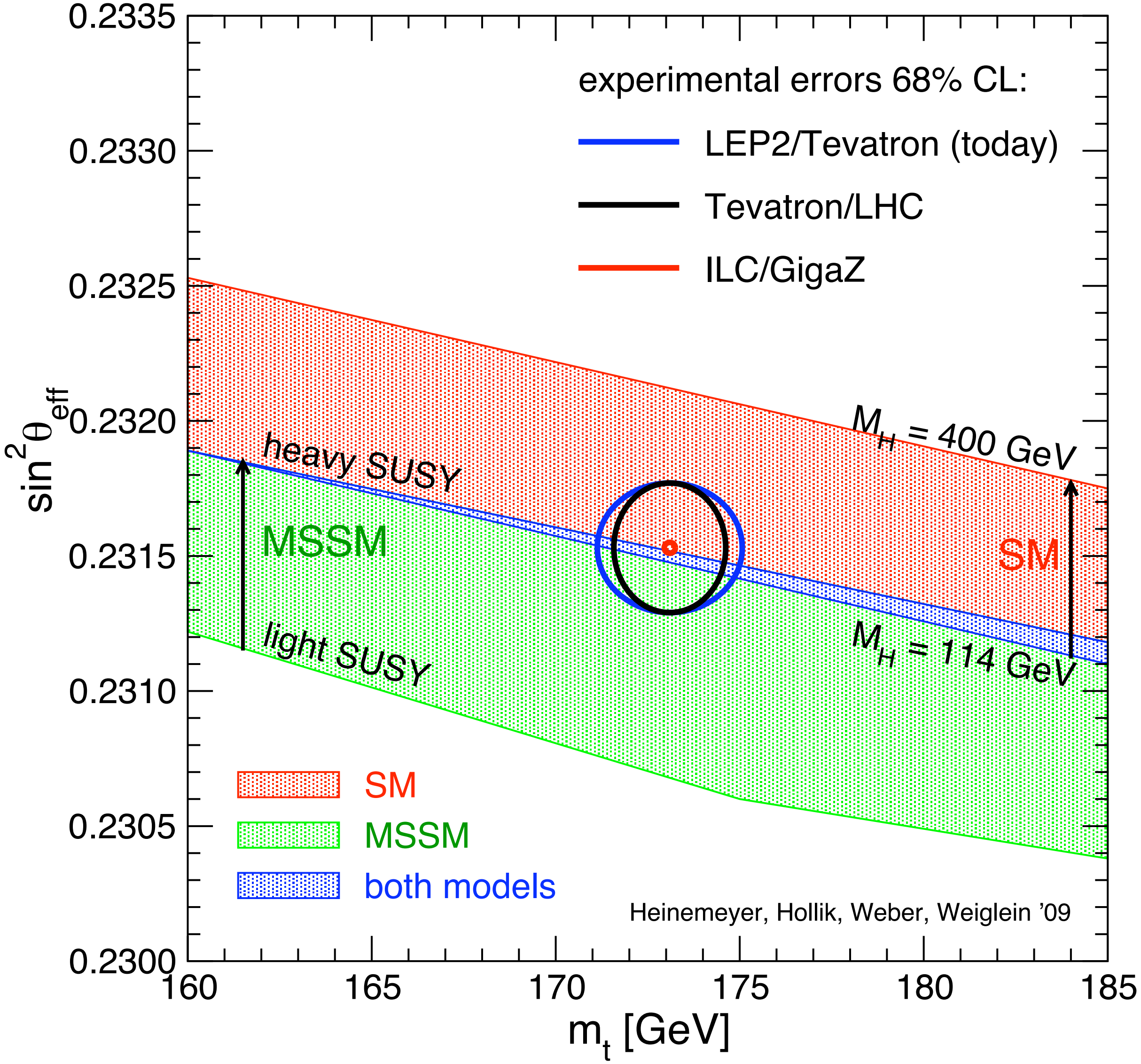
MSSM is SM-like

SM band:
variation of M_H^{SM}

Prediction for $\sin^2\theta_{\rm eff}$ in the SM and the MSSM :

[S.H., W. Hollik, A. Weber, G. Weigelin '07]



MSSM band:
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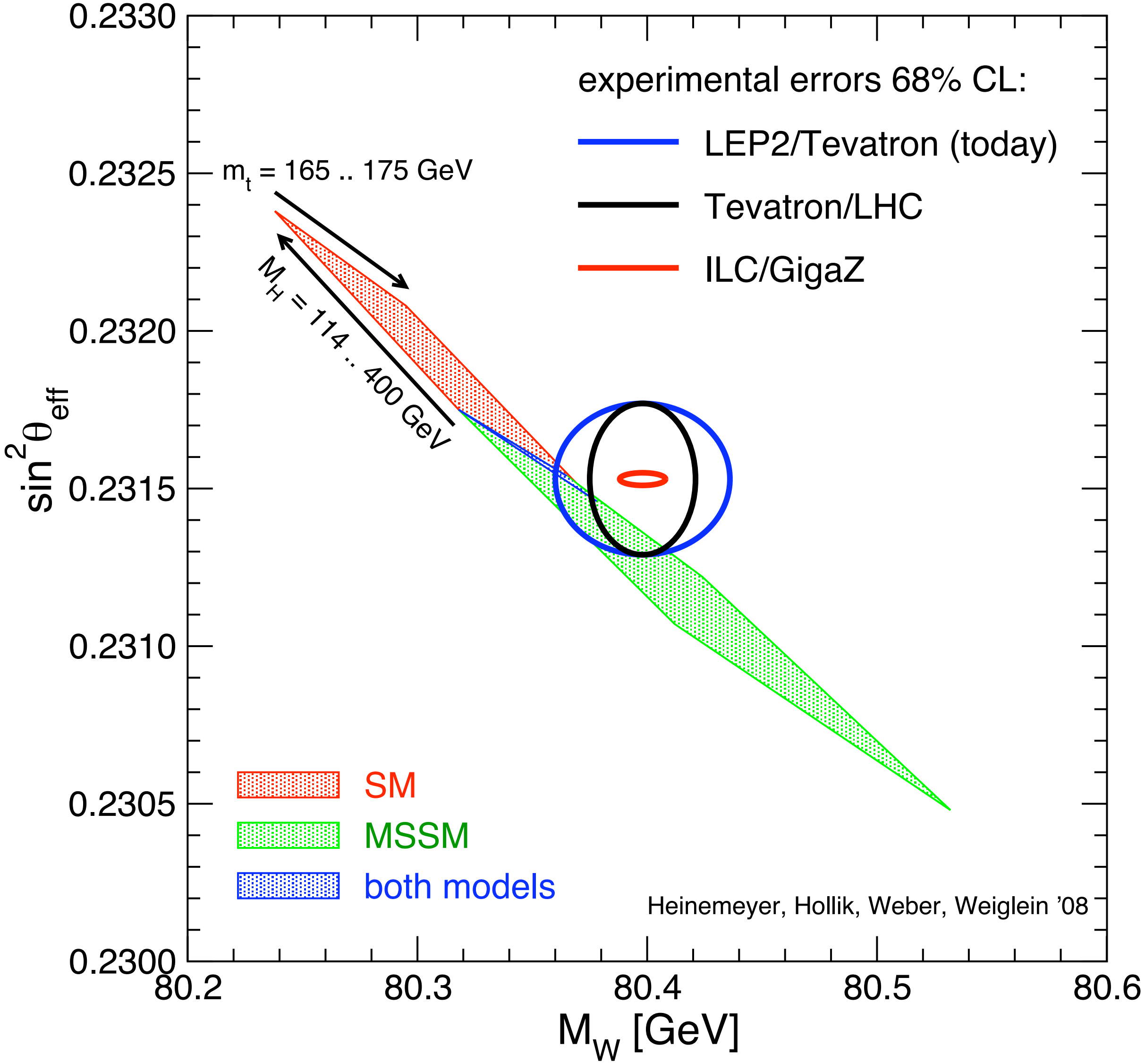
SUSY masses

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

SM band:
variation of $M_H^{\rm SM}$

Prediction for M_W and $\sin^2\theta_{\rm eff}$ in the SM and the MSSM :

[S.H., W. Hollik, A. Weber, G. Weiglein '07]



MSSM band:
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overlap:
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MSSM is SM-like

SM band:
variation of $M_H^{\rm SM}$

Possible future scenario:

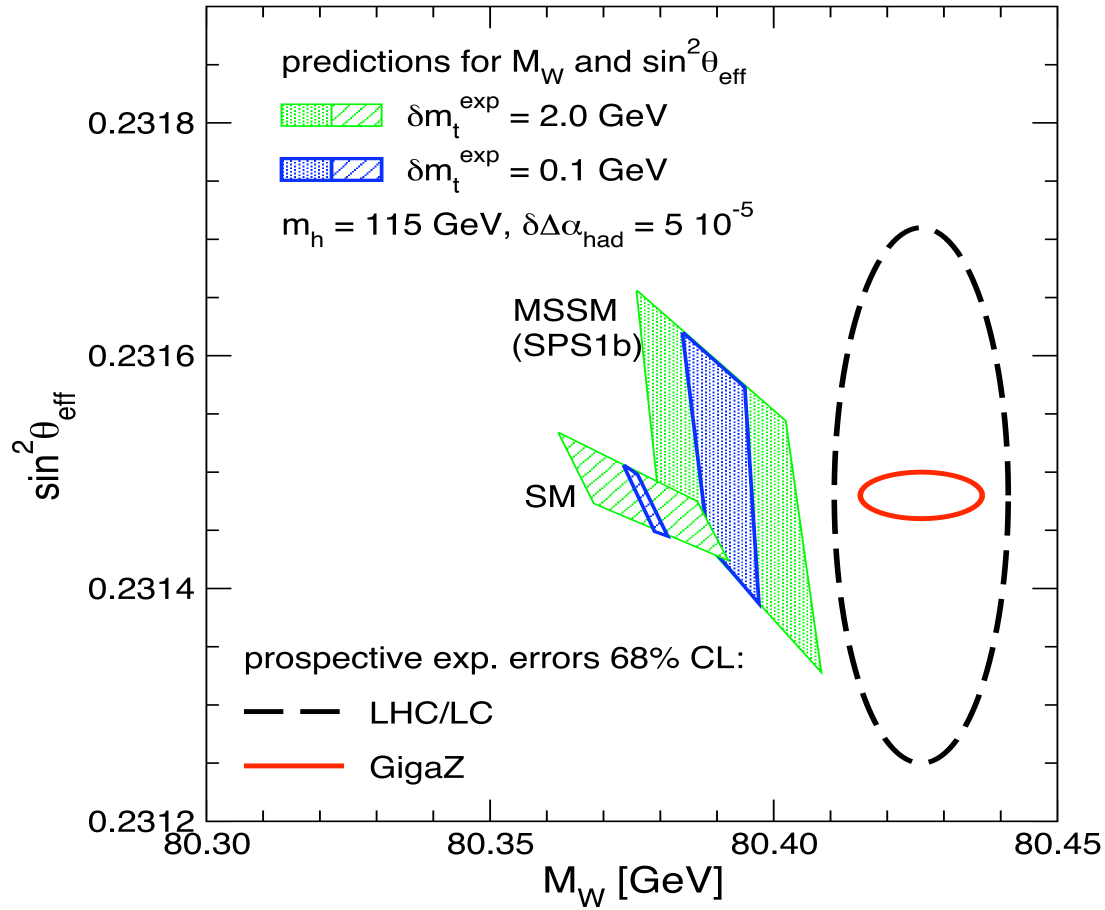
[*S.H., S. Kraml, W. Porod, G. Weiglein '03*]

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

$\Rightarrow$ SM: improvement by a factor ~ 10

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

Scenario with no SUSY particles at the LHC:

→ $\sin^2\theta_{\rm eff}$ investigation

→ SPS 1a with heavy scalars

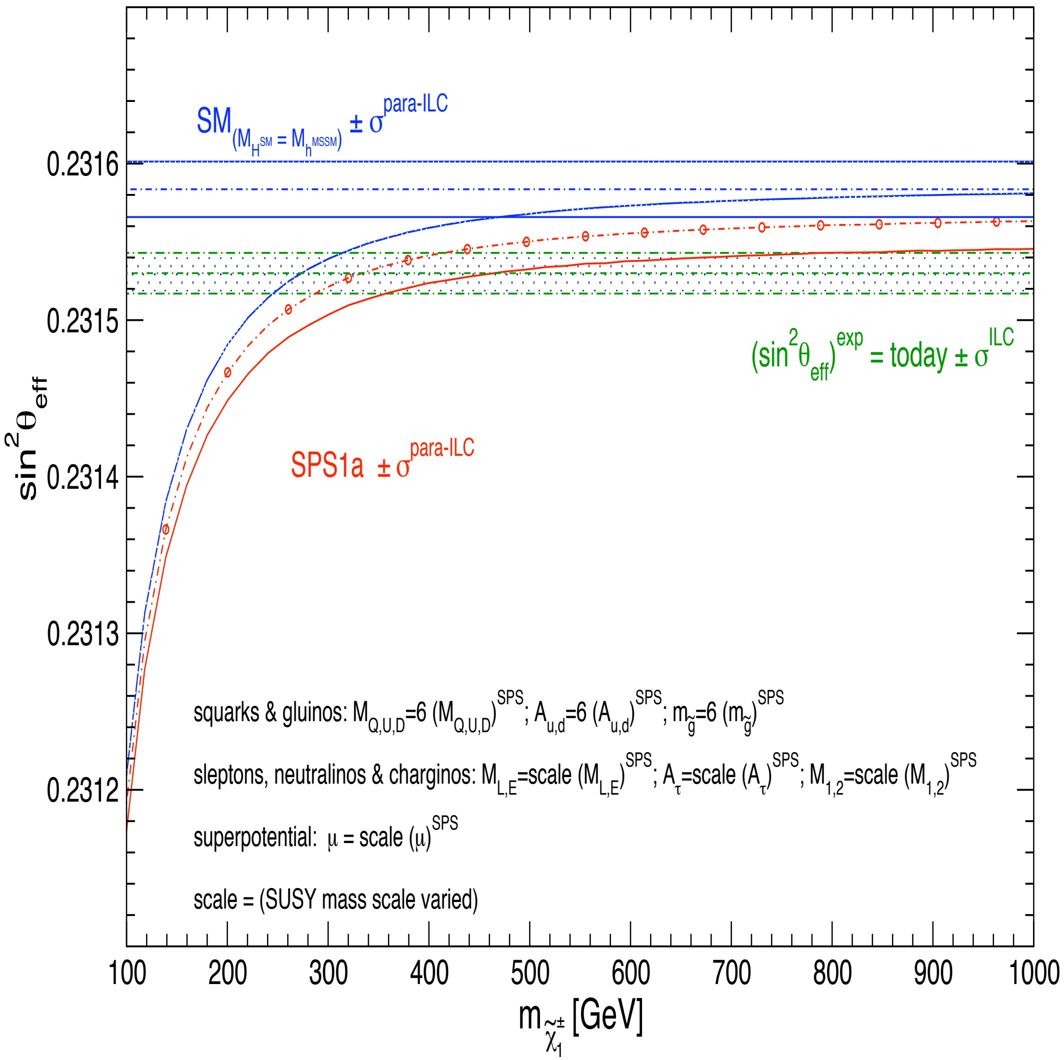
SM prediction

vs.

MSSM (SPS 1a) prediction

vs.

LC resolution



⇒ the LC(1000)/GigaZ could detect SUSY directly/indirectly

Theoretical prediction of the lightest MSSM Higgs boson mass: M_h

Contrary to the SM: M_h is not a free parameter

MSSM tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \ln \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$

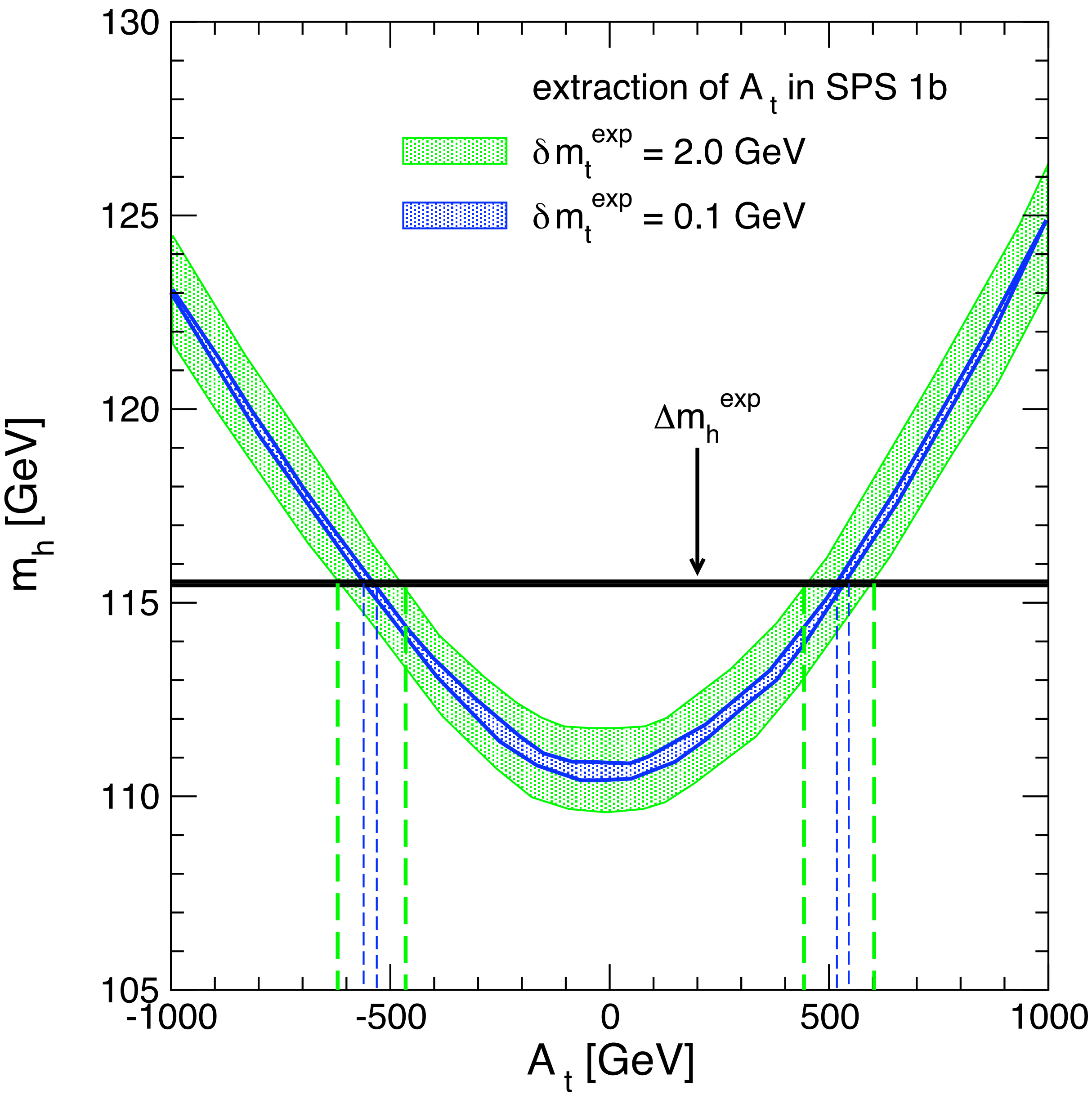
> The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Measurement of M_h, Higgs couplings $\Rightarrow$ test of the theory

LHC: $\Delta M_h \approx 0.2$ GeV
LC: $\Delta M_h \approx 0.05$ GeV

$\Rightarrow M_h$ will be (the best?) electroweak precision observable

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

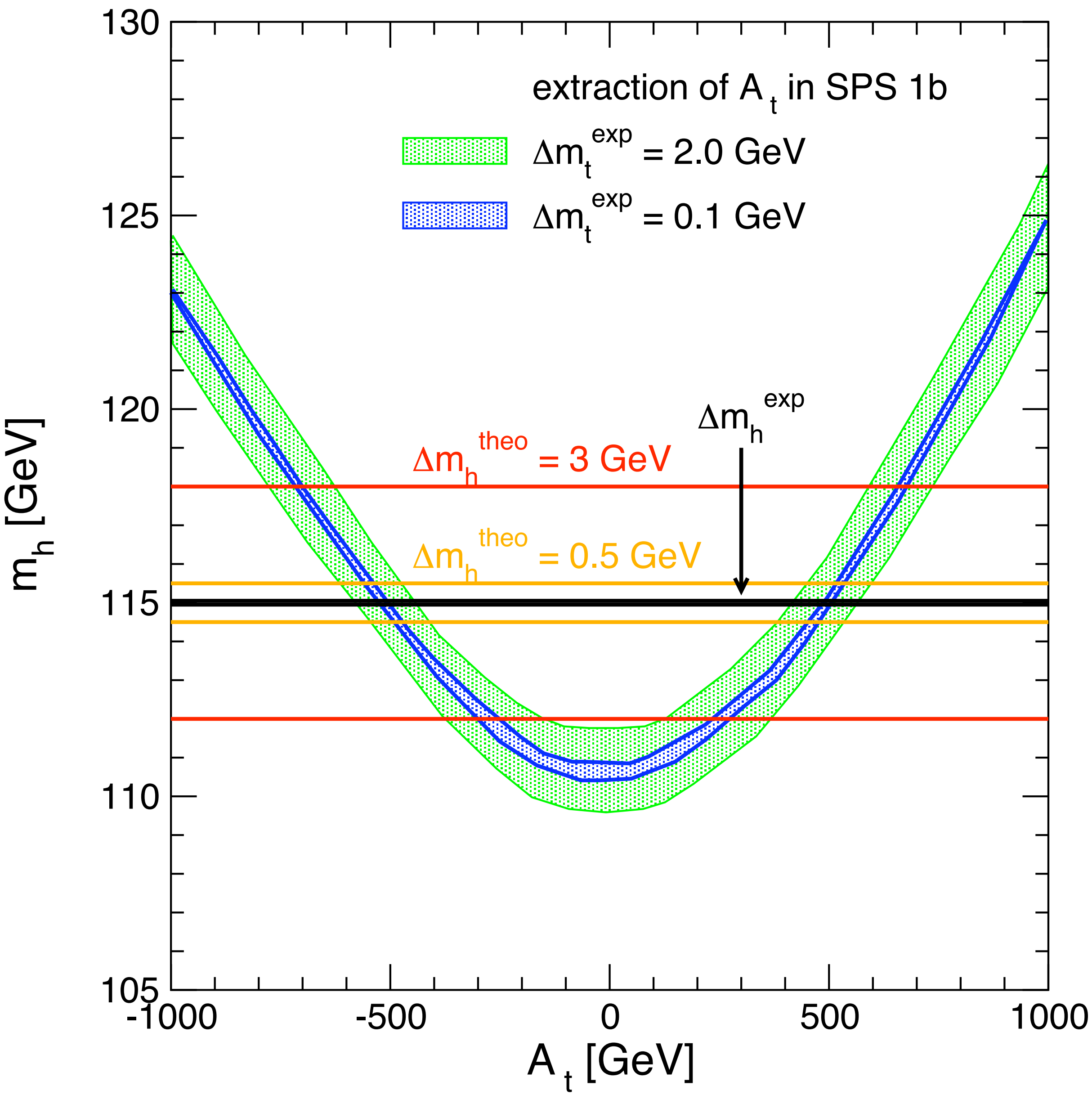
$\tan\beta, M_A$ known,

realistic experimental errors assumed

$\Rightarrow$ extraction of A_t possible

but theory errors neglected!

Example of application: M_h prediction as a function of A_t



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$\tan\beta, M_A$ known,

realistic experimental errors assumed

$\Rightarrow$ extraction of A_t possible

$\Rightarrow$ Δm_h^{theo} has to be under control

$\Rightarrow$ crucial for SUSY fits

4. Implications for other models

Precision observables in BMSSM:

Problem: Theorists are lazy . . .
No "real" precision observables are calculated

At most: S, T, U (with $U = 0$ . . .)
[M. Peskin, T. Takeuchi '92]

$$\Delta\rho \sim -\alpha T$$

$$\rho = \frac{1}{1 - \Delta\rho} \qquad \Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2} \qquad \Delta\rho^{\text{SM}} \sim m_t^2$$

(leading, process independent terms)

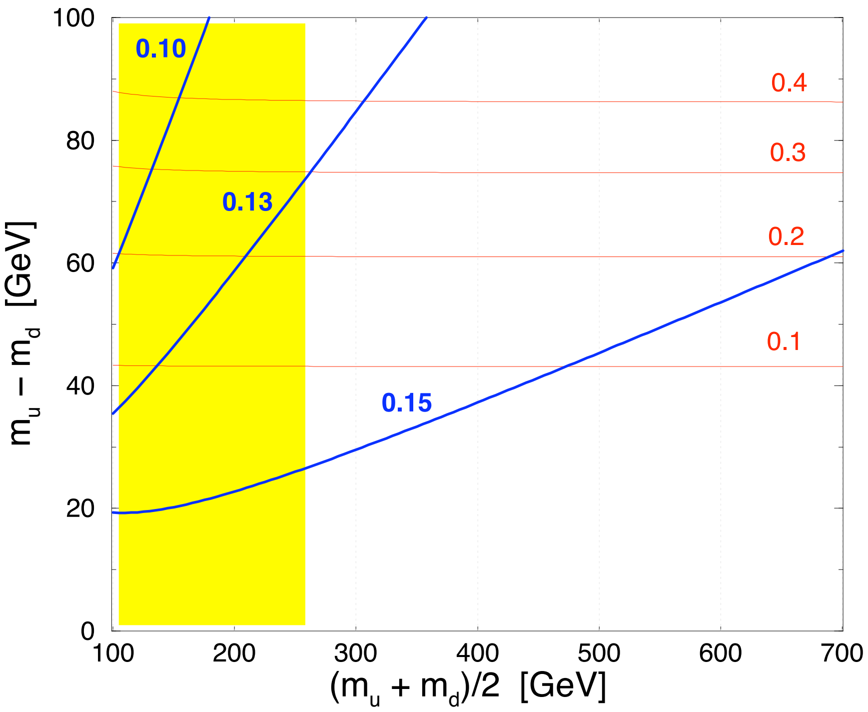
$\Delta\rho$ gives the main contribution to EW observables:

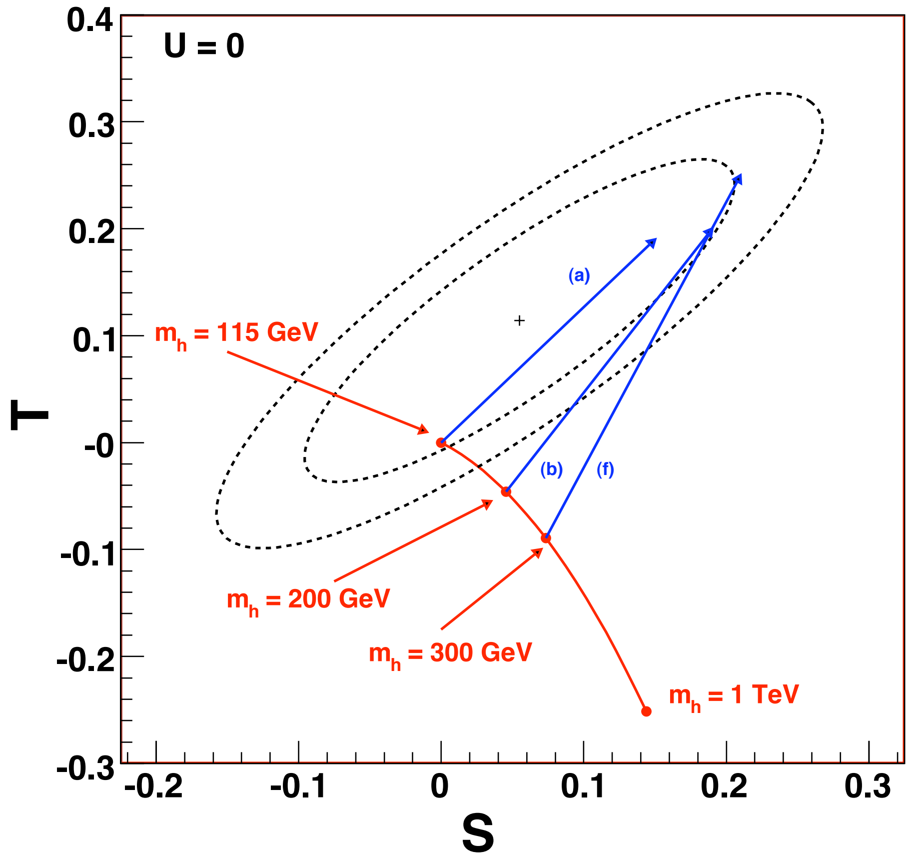
$$\Delta M_W \approx \frac{M_W}{2} \frac{c_W^2}{c_W^2 - s_W^2} \Delta\rho, \qquad \Delta \sin^2\theta_W^{\text{eff}} \approx -\frac{c_W^2 s_W^2}{c_W^2 - s_W^2} \Delta\rho$$

Example for SM4:

SM4 = SM + 4th generation of quarks and leptons

[*G. Kribs, T. Plehn, M. Spannowsky, T. Tait '07*]

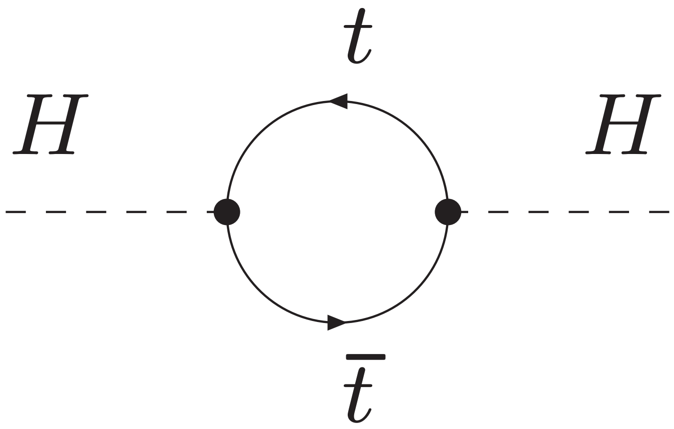




⇒ to play this game requires LC precision for m_t!

Higgs physics in BSM:

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



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

$\Rightarrow$ 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: $\Delta m_t \approx \pm 1$ GeV $\Rightarrow$ $\Delta M_h \approx \pm 1$ GeV

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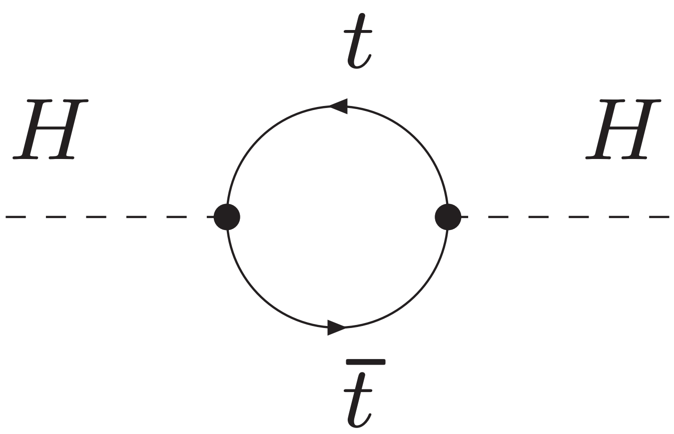

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SUSY as an example: $\Delta m_t \approx \pm 1$ GeV $\Rightarrow$ $\Delta M_h \approx \pm 1$ GeV

$\Rightarrow$ Precision Higgs physics needs precision (LC!) top physics

Tricky scenario:

The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the LC with GigaZ?

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A: Of course!

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The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the LC with GigaZ?

A: Of course! Or better: even more!

The LC+GigaZ provides:

– precise Higgs coupling measurements (LC)

– precision observable measurements (GigaZ)

– precise top mass measurement (LC/GigaZ)

⇒ Only the LC+GigaZ can find deviations from the SM predictions via the various precision measurements

⇒ Only the LC+GigaZ can point towards extensions of the SM

5. Conclusions

- What does LC/GigaZ add to the LHC measurements?
  - The LC will add a precise m_t measurement (+ much more)
  - GigaZ will add precise measurements of M_W, $\sin^2\theta_{\text{eff}}$ and m_t

  $\Rightarrow$ crucial for indirect model testing

- SM: precise indirect determination of M_H

- MSSM: strong constraints on the parameter space:
  - possibly: discriminate between SM and MSSM
  - precise m_t crucial for precision Higgs physics
    $\to$ extraction of A_t (crucial for SUSY fits)

- Other models: much less advanced, mostly S, T, U
  - M_H is not a free parameter (as in nearly any BSM):
    precise m_t crucial for precision Higgs physics
  - "only" a SM-like Higgs at the LHC: LC+GigaZ are the only option!