Electroweak Precision Tests at GigaZ

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Fermilab, 10/00

based on collaboration with
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1. Introduction

2. Precision Tests of the SM

3. Precision Tests of the MSSM

4. Conclusions

1. Introduction

Definition:

$\left.\begin{array}{l}\text{LC at low energies: high precision}\\ \text{high luminosity } (\sim 10^9 \text{ Z/year})\end{array}\right\}$ **GigaZ**

– at the Z peak (one year): 6×10^8 b quarks
– at the Z peak (via A_{LR}): $\Delta \sin^2\theta_{\rm eff}$
– at the 2 W threshold (one year): ΔM_W

Expected accuracy:

	LEP2/Tev.	LHC	LC	GigaZ
M_W	30 MeV	15 MeV	15 MeV	6 MeV
$\sin^2\theta_{\rm eff}$	0.00018	0.00018	0.00018	0.00001
m_t	3 GeV	2 GeV	0.2 GeV	0.2 GeV
m_h	?	0.2 GeV	0.05 GeV	0.05 GeV
$M_{\rm SUSY}$	?	10%	0.1%	0.1%

What can we learn from improved accuracy in M_W and $\sin^2\theta_{\rm eff}$?

Precision Observables (POs):

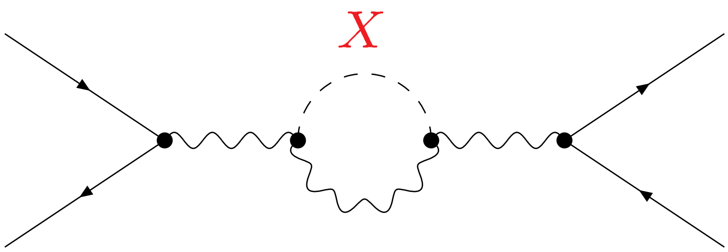
Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$\Delta\rho, \Delta r, M_W, \sin^2\theta_{\rm eff}$	$\leftrightarrow$	SM, MSSM , ...

$$\Downarrow$$

Test of theory at quantum level:

Sensitivity to loop corrections



$$\Downarrow$$

Improve indirect constraints on unknown parameters: $m_h, m_{\tilde{t}}, \cdots$

Effects of "new physics"?

Precision observables M_W, $\sin^2\theta_{\rm eff}$:

1.) Theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$:

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

$\Updownarrow$

loop corrections

SM prediction for Δr, one-loop:

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

$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_w^2}{s_w^2}\Delta\rho + \Delta r_{\text{rem}}(m_h)$$

$$\sim \log\frac{M_Z}{m_f} \qquad \sim m_t^2$$

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

2.) Effective mixing angle:

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

Higher order contributions:

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

Indirect determination of m_t from precision data:

$$m_t = 172^{+14}_{-11} \text{ GeV}$$

direct measurement:

$$m_t = 174.3 \pm 5.1 \text{ GeV}$$

One-loop corrections to precision observables:

$$\sim m_t^2$$
$$\sim \log m_h$$

$\Rightarrow$ Very high accuracy of measurements and theoretical predictions needed

<u>Theoretical uncertainties:</u>

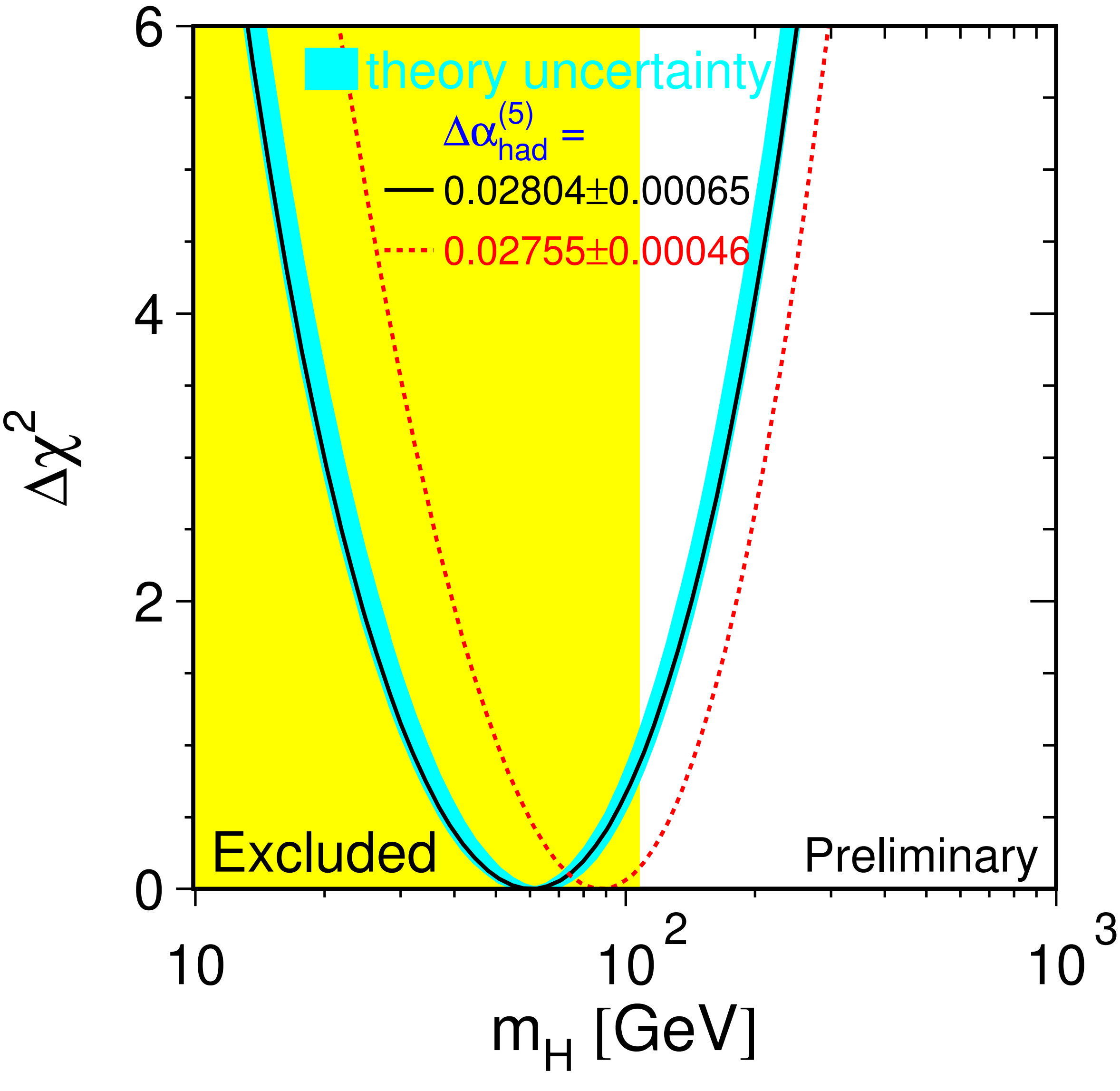
– unknown higher-order corrections

– exp. error of input parameters: m_t, $\Delta\alpha_{\text{had}}$, ...

<u>Todays theoretical uncertainty:</u>

$$\delta M_W^{\text{theo}} \approx 6 \text{ MeV}$$
$$\delta \sin^2\theta_{\text{eff}}^{\text{theo}} \approx 0.00004$$

Global fit to all data in the SM:
[*LEPEWWG '00*]



(⇒ $M_H < 188$ GeV, 95% C.L.)

Recently:
Shift by ~ 30 GeV due to BES II analysis

⇒ $M_H < 210$ GeV, 95% C.L.

What if SUSY will be discovered?

Assume: SUSY particles accessible at next
generation of colliders

In unconstrained MSSM: 105 new parameters :

masses, mixing angles, complex phases, $\tan\beta$

$\Rightarrow$ Parameter determination is difficult task

Is the model consistent with data?

Patterns of SUSY breaking?

(M-SUGRA, GMSB, AMSB, ...)

Indirect information from precision observables
complementary to direct production processes

Stringent direct test of SUSY:

Light Higgs boson h required

Tree level: $m_h < M_Z$

Yukawa couplings: $\frac{e\, m_t}{2 M_W s_w}$, $\frac{e\, m_t^2}{M_W s_w}$, $\ldots$

Dominant corrections to m_h from $t - \tilde{t}$-sector :

$$\sim \quad \frac{m_t^4}{M_W^2} \log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right)$$
$$\approx \quad \frac{m_t^4}{M_W^2} \log\left(\frac{(M_{\text{SUSY}}^2 + m_t^2)^2 - m_t^2 X_t^2}{m_t^4}\right)$$

$\tilde{t}$ -mass-matrix:

$$M_{\tilde{t}}^2 = \begin{pmatrix} M_{\text{SUSY}}^2 + m_t^2 + DT_1 & m_t X_t \\ m_t X_t & M_{\text{SUSY}}^2 + m_t^2 + DT_2 \end{pmatrix}$$

$\Rightarrow m_h \lesssim 135$ GeV

[S.H., W. Hollik, G. Weiglein '99]

<u>High-precision measurement of m_h:</u>

$$\begin{aligned} \text{LHC}: &\quad \delta m_h \approx 0.2\ \text{GeV} \\ \text{LC}: &\quad \delta m_h \approx 0.05\ \text{GeV} \\ \text{Muon Collider}: &\quad \delta m_h \approx 0.1\ \text{MeV} \end{aligned}$$

$\Rightarrow m_h$ will be precision observable!

SM:

free parameters: m_t, m_h

$\to$ direct contribution via loop effects

$\Rightarrow$ Prediction for precision observables
M_W, $\sin^2\theta_{\text{eff}}$

MSSM:

free parameters: $m_t, M_{\text{SUSY}}, X_t$

$\to$ direct contribution via loop effects

$\to$ indirect effect via contribution to m_h

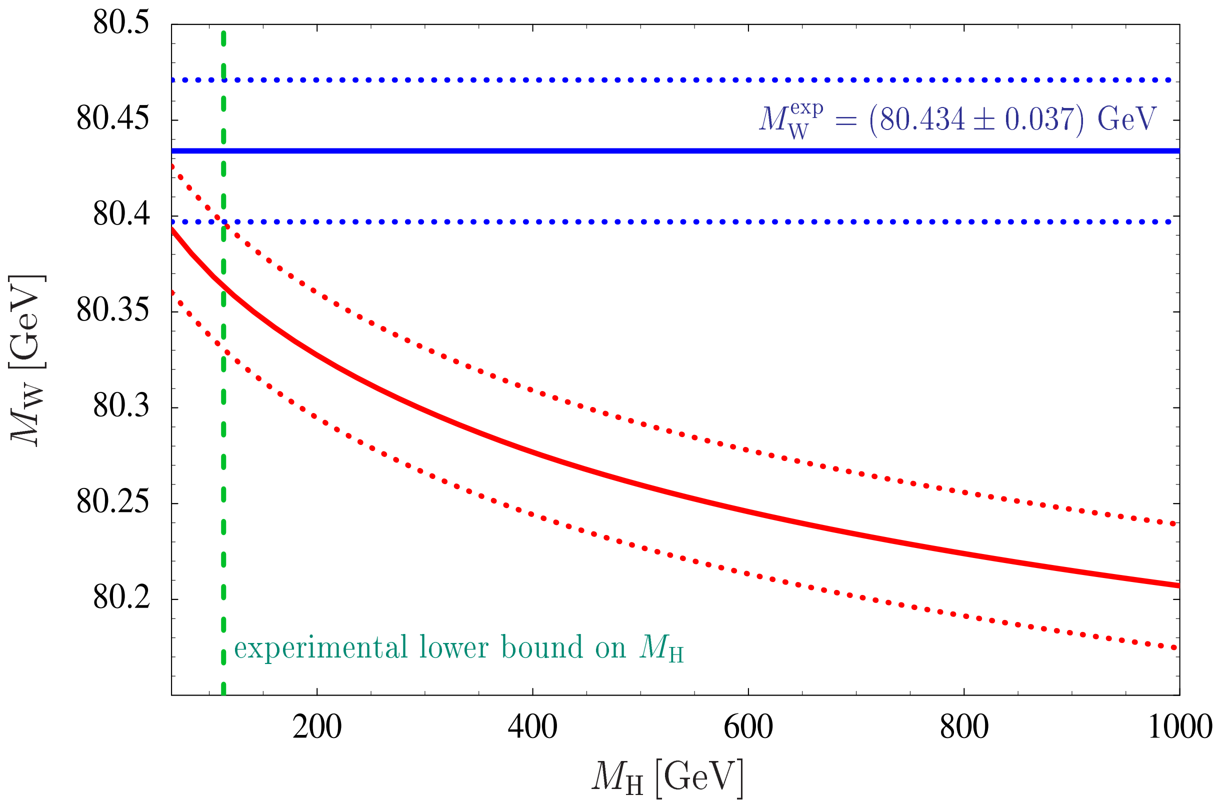
$\Rightarrow$ Prediction for precision observables
M_W, $\sin^2\theta_{\text{eff}}$

Prediction for precision observable m_h

2. Precision tests of the SM:

Present situation:

SM prediction for M_W vs. experimental result:
[*A. Freitas, S.H., W. Hollik, W. Walter, G.Weiglein '00*]



$$(\delta \sin^2\theta_{\mathrm{eff}} = 17 \times 10^{-5}, \quad \delta M_W = \pm 37 \text{ MeV})$$

$\Rightarrow$ no overlap at the $1\,\sigma$ level

Theoretical uncertainty dominated by uncertainty in input parameters: m_t, M_H, ...

Future theoretical uncertainties:

Parametric uncertainties from experimental errors of input parameters:

$$\begin{aligned}
\delta m_t &= \pm 130\ \text{MeV} & \Rightarrow\ & \delta M_W \approx \pm 1\ \text{MeV} \\
& & & \delta \sin^2\theta_{\text{eff}} \approx \pm 0.4 \times 10^{-5} \\
\delta m_h &= \pm 50\ \text{MeV} & & \\
\delta \alpha_s &= \pm 1 \times 10^{-3} & & \\
\delta M_Z &= \pm 2.1\ \text{MeV} & \Rightarrow\ & \delta M_W \approx \pm 2.5\ \text{MeV} \\
& & & \delta \sin^2\theta_{\text{eff}} \approx \pm 1.4 \times 10^{-5} \\
\delta(\Delta\alpha) &= \pm 5 \times 10^{-5} & \Rightarrow\ & \delta M_W \approx \pm 1\ \text{MeV} \\
& & & \delta \sin^2\theta_{\text{eff}} \approx \pm 1.8 \times 10^{-5}
\end{aligned}$$

$\Rightarrow$ Error of M_Z non-negligible!

Estimate for future theoretical uncertainties:

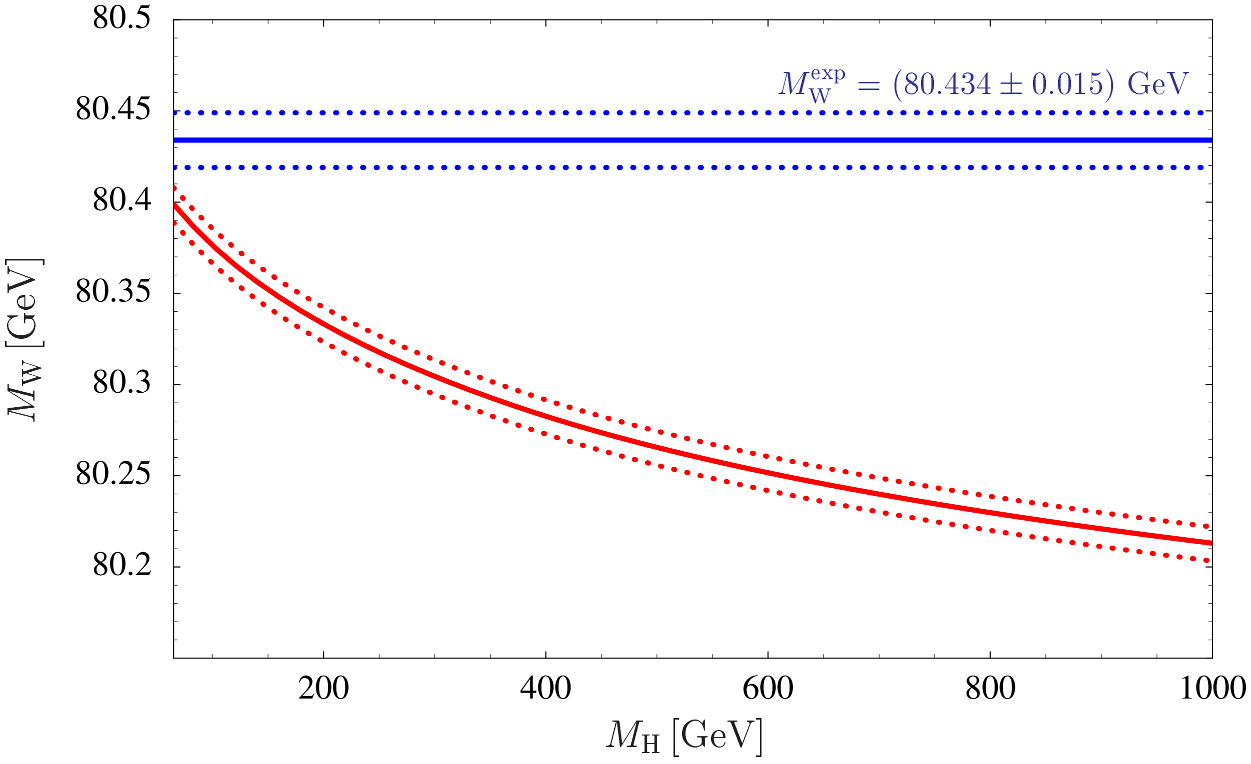
– unknown higher-order corrections

– $\delta(\Delta\alpha)$ uncertainty

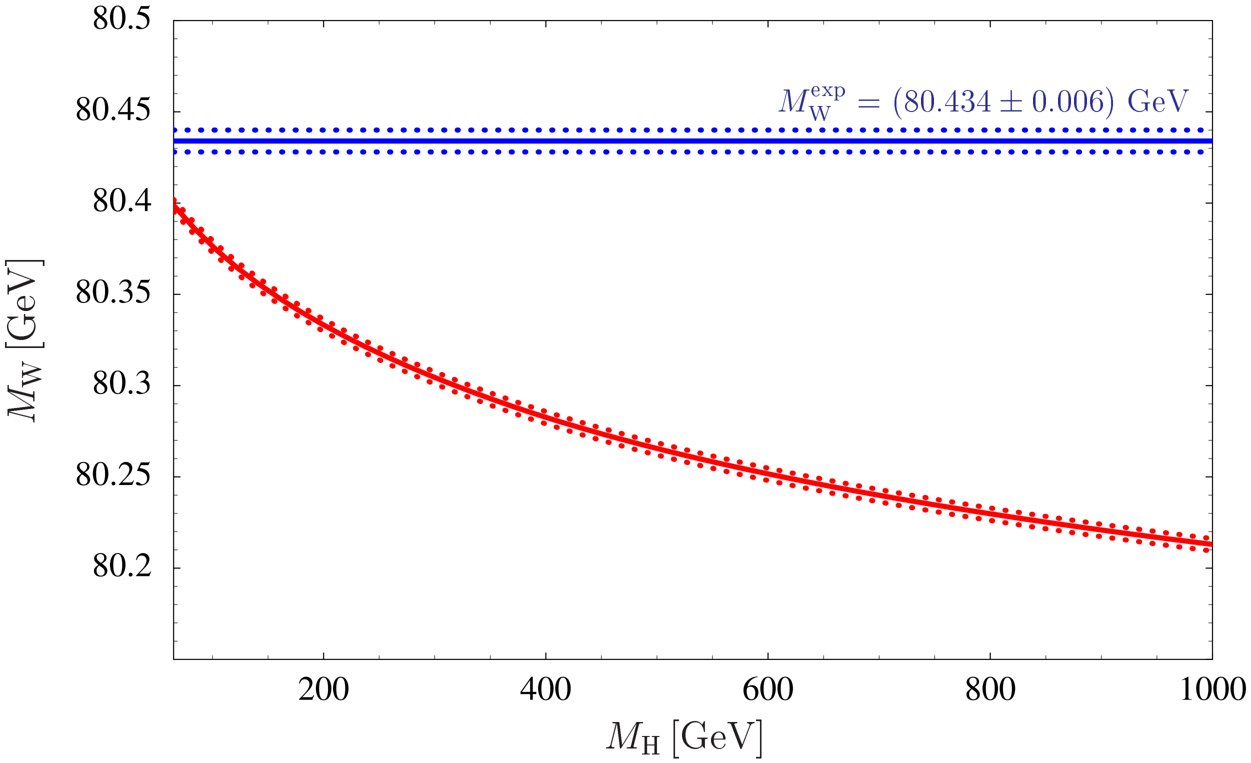
$$\delta M_W^{\text{theo}} \approx \pm 3\ \text{MeV}, \quad \delta \sin^2\theta_{\text{eff}}^{\text{theo}} \approx \pm 3 \times 10^{-5}$$

$M_W(m_h)$ in the SM, prospective future accuracies:

LHC precision:



GigaZ precision:

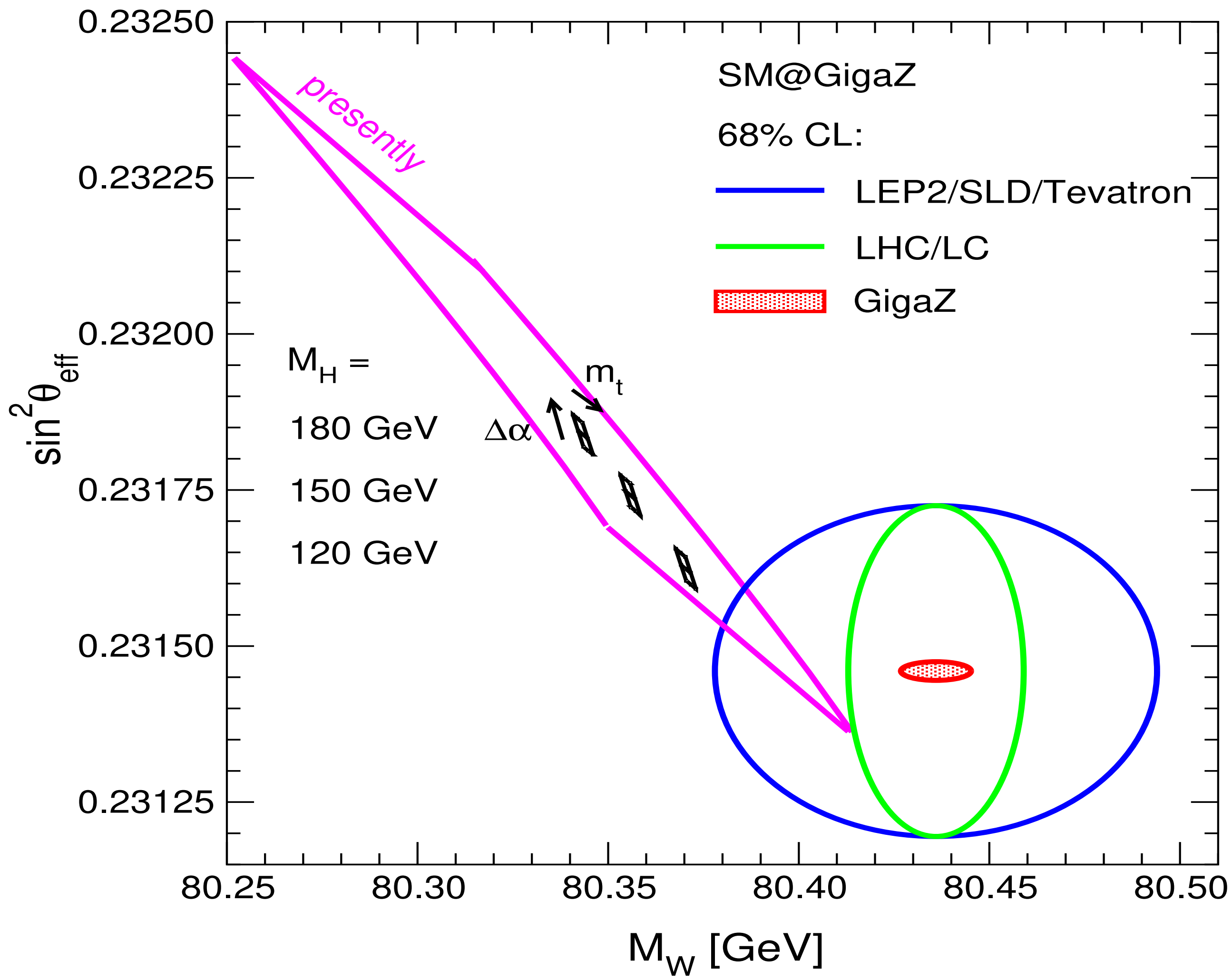


SM prediction for M_W and $\sin^2\theta_{\mathrm{eff}}$

vs. prospective accuracies at

LEP2/SLD/Tevatron , LHC/LC , GigaZ:

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

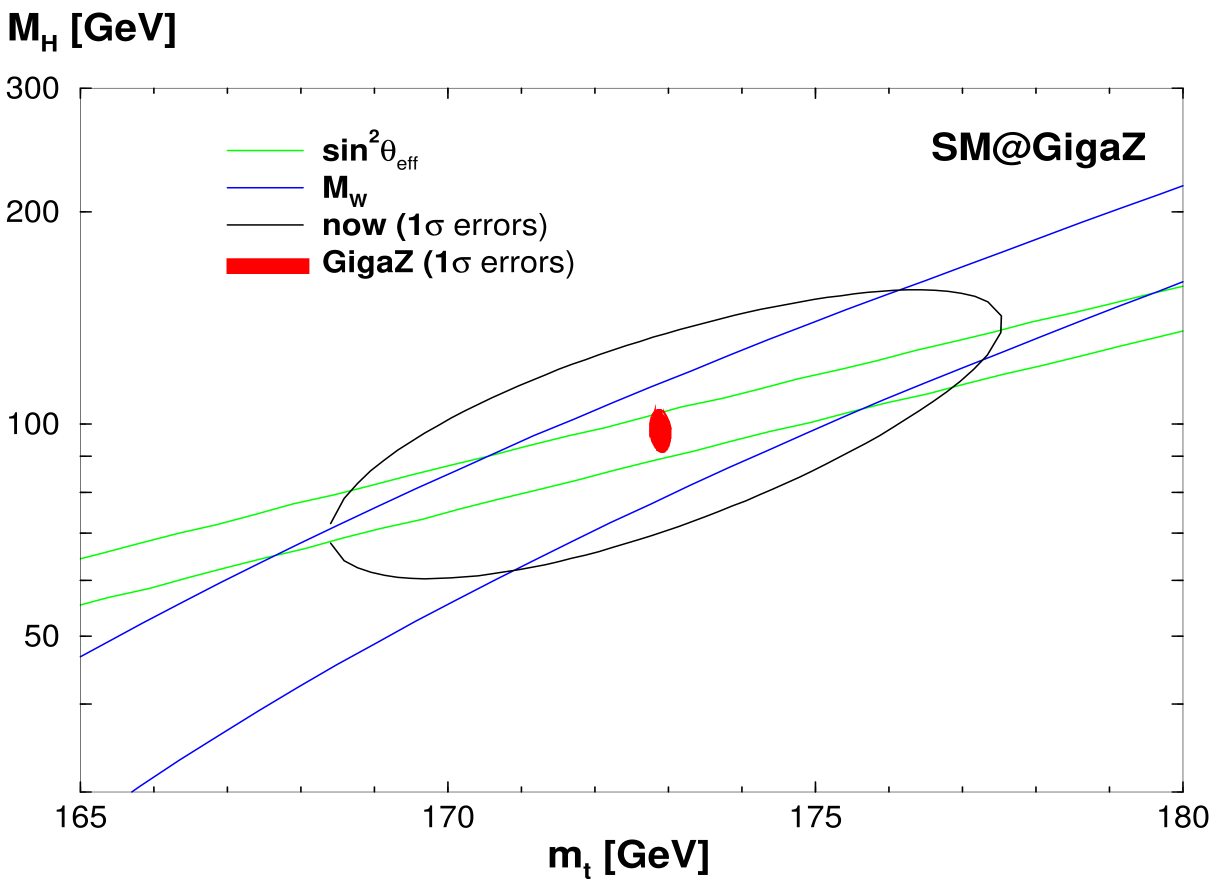


$\Rightarrow$ ultimate precision test of the SM

extreme high sensitivity to new physics scales

Indirect determination of m_t, M_H at GigaZ:

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



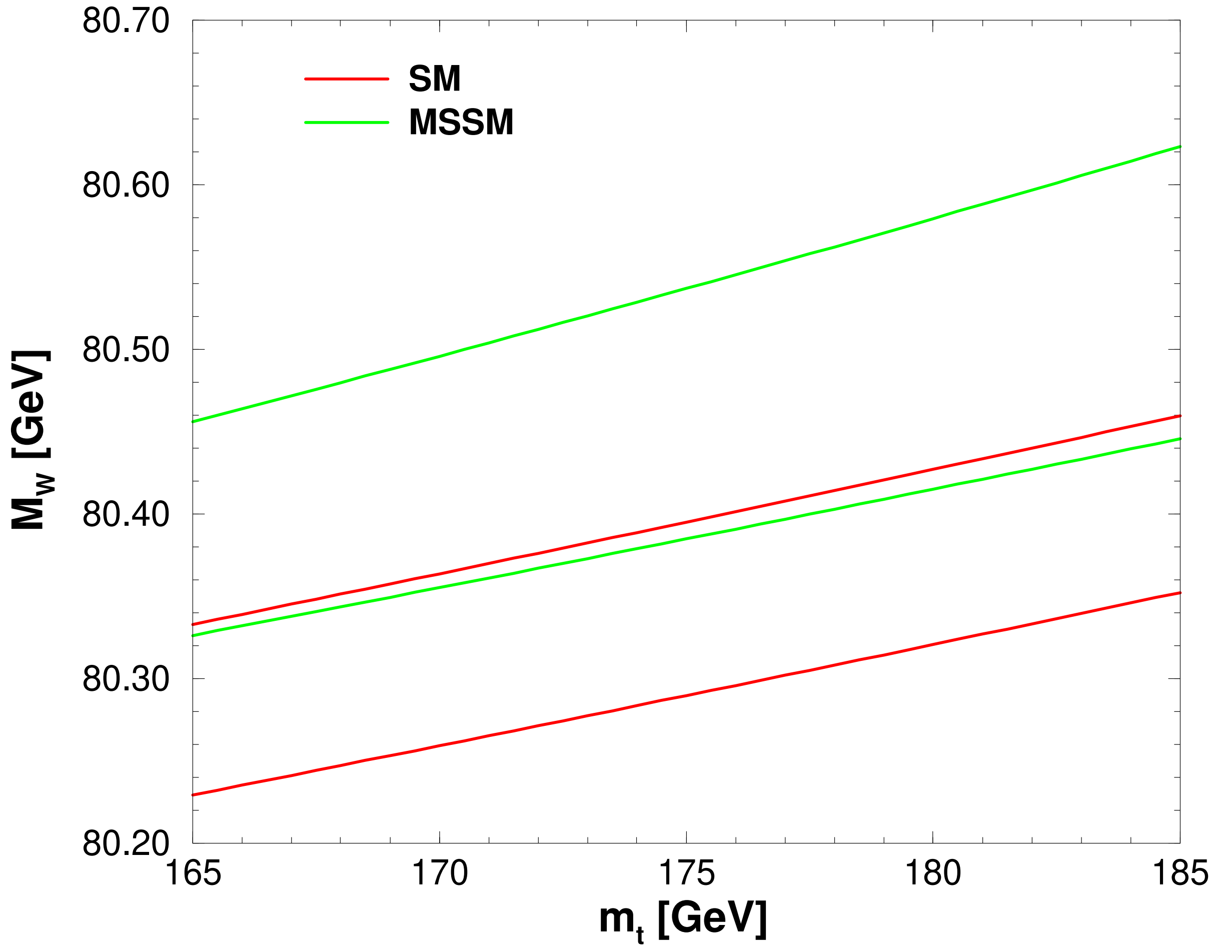
Expected precisions of indirect M_H-determinations:

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

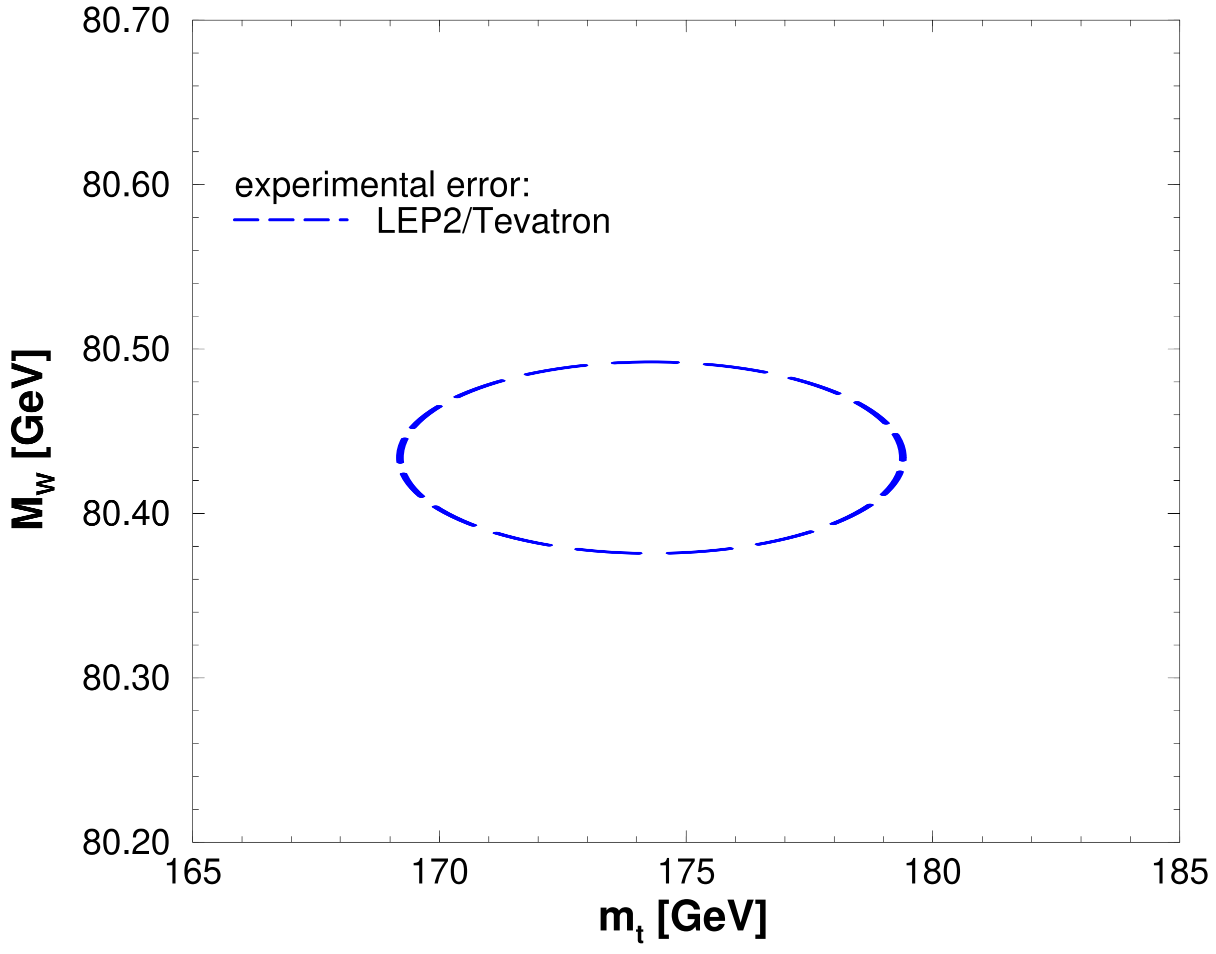
	M_W	$\sin^2\theta_{\mathrm{eff}}$	all
now	229 %	62 %	61 %
Tevatron Run IIA	77 %	46 %	41 %
Tevatron Run IIB	39 %	28 %	26 %
LHC	28 %	24 %	21 %
LC	18 %	20 %	15 %
GigaZ	12 %	7 %	7 %

3. Precision tests of the MSSM

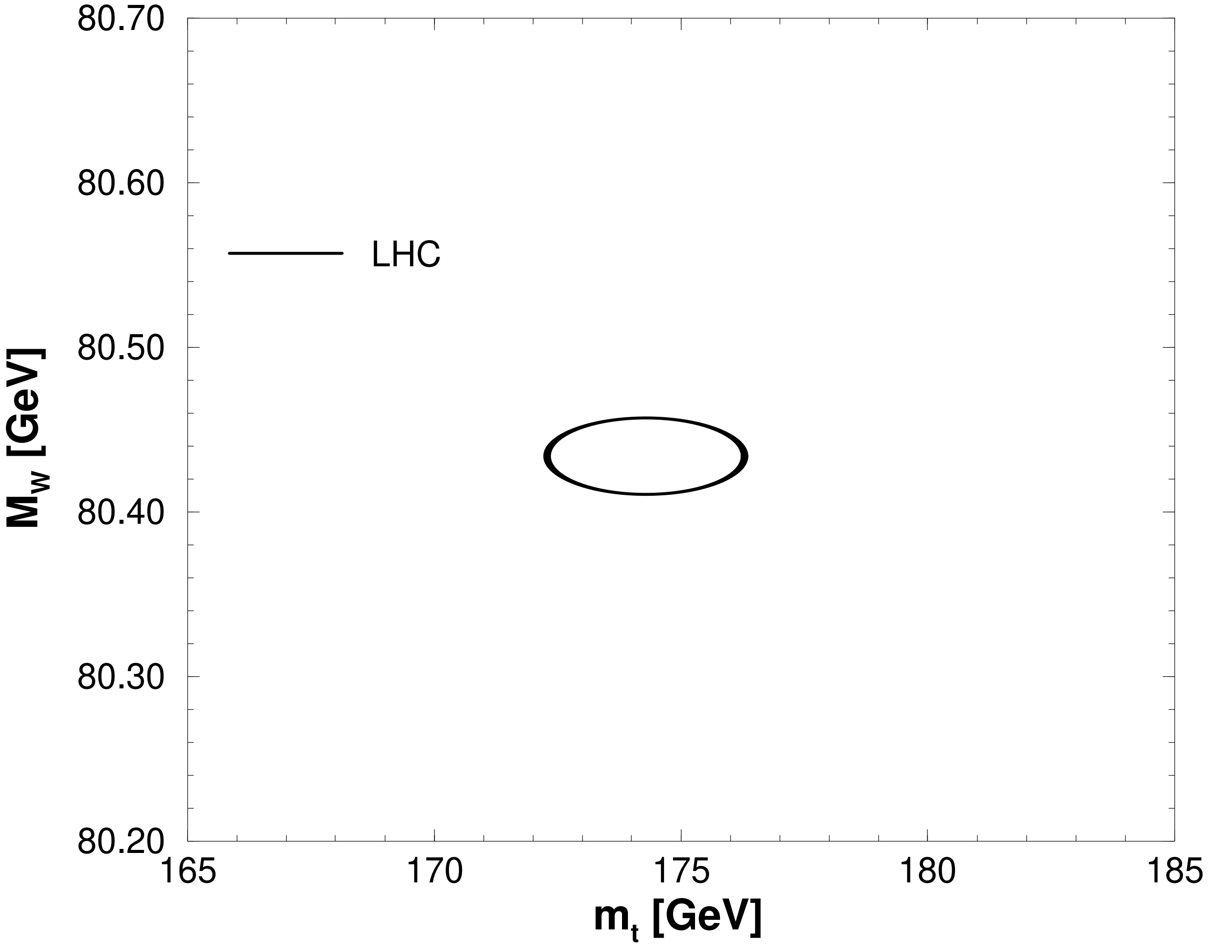
Prediction for M_W in the SM and the MSSM :
Assumption: no SUSY particles found at LEP2



SM uncertainty: unknown Higgs mass
MSSM uncertainty: unknown masses
of SUSY particles



80.70
80.60
80.50
80.40
80.30
80.20
165
170
175
180
185
experimental error:
LEP2/Tevatron
M_W [GeV]
m_t [GeV]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M_W [GeV]
LHC
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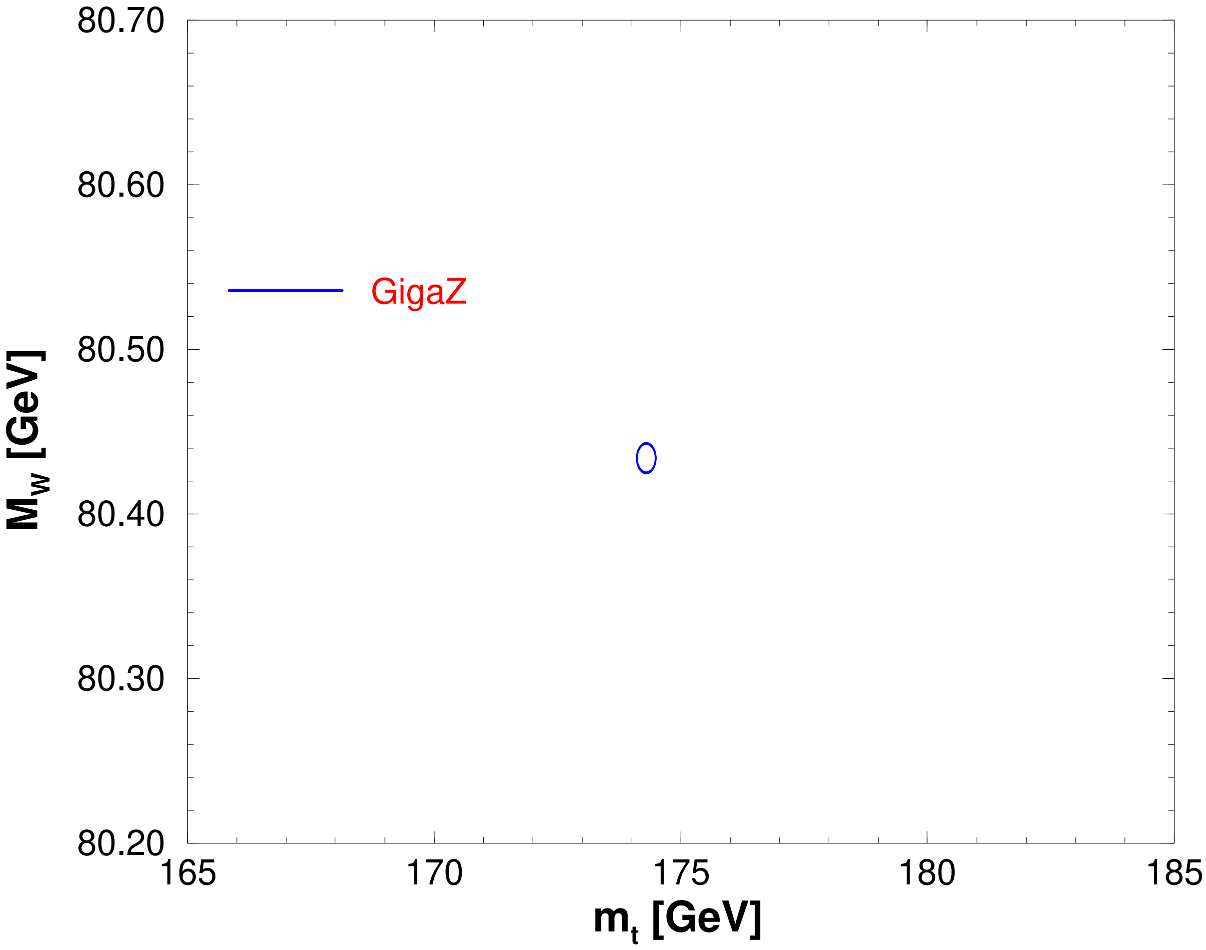
m_t [GeV]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80.60
80.50
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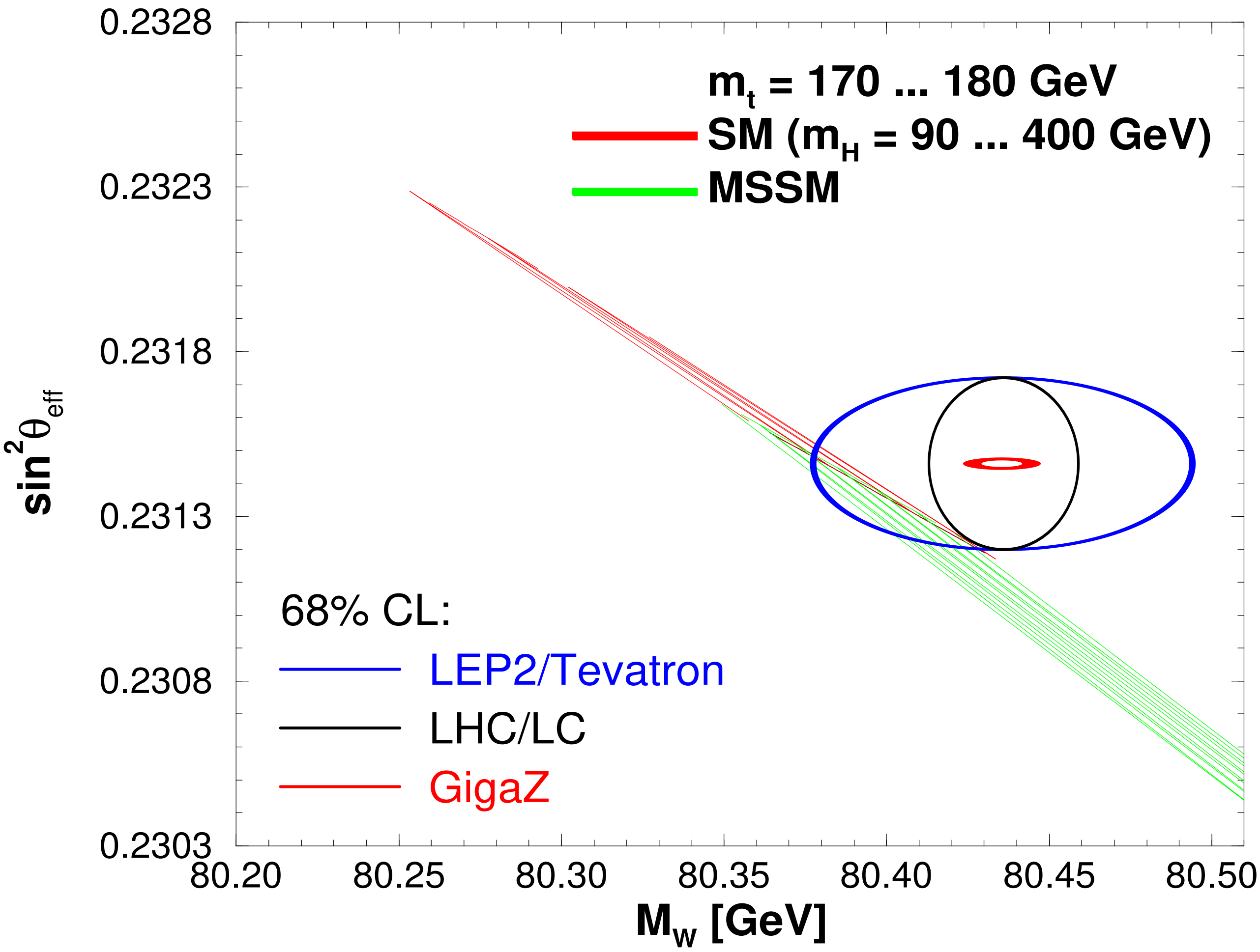
80.30
80.20
GigaZ
M_W [GeV]
165
170
175
180
185
m_t [GeV]

Prediction for M_W, $\sin^2\theta_{\rm eff}$ in the SM and MSSM
vs. prospective accuracies at
LEP2/SLD/Tevatron , LHC/LC, GigaZ:



⇒ large improvement of experimental accuracy:

LEP2/SLD/Tevatron → LHC/LC → GigaZ

⇒ Very sensitive test of theory

The Higgs mass as a precision observable

(Scenario I:)

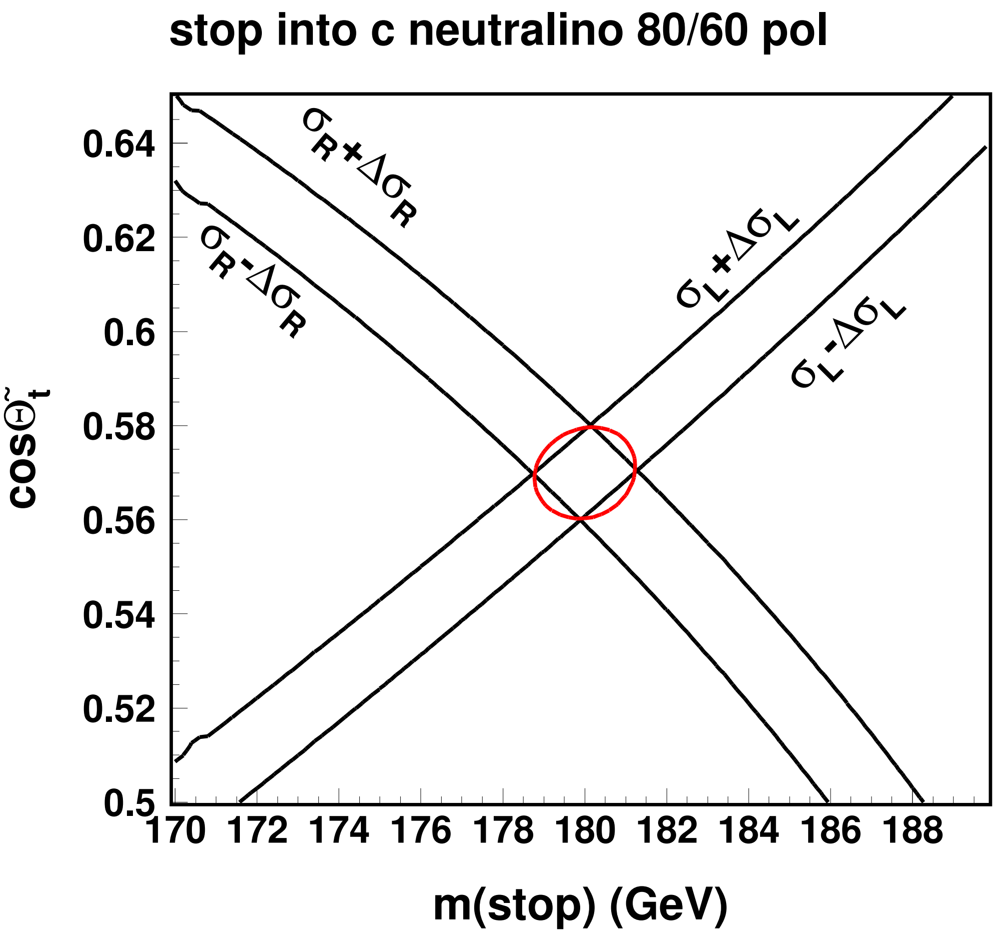
$\rightarrow$ Combination of direct and indirect information on $\tilde{t}$ sector parameters:

Direct information:

$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$ at high luminosity LC

(80% pol. e^- beam, 60% pol. e^+ beam, $\sqrt{s} = 500$ GeV, $\mathcal{L} = 500$ fb^{-1})

[*R. Keränen, H. Nowak, A. Sopczak '00*]



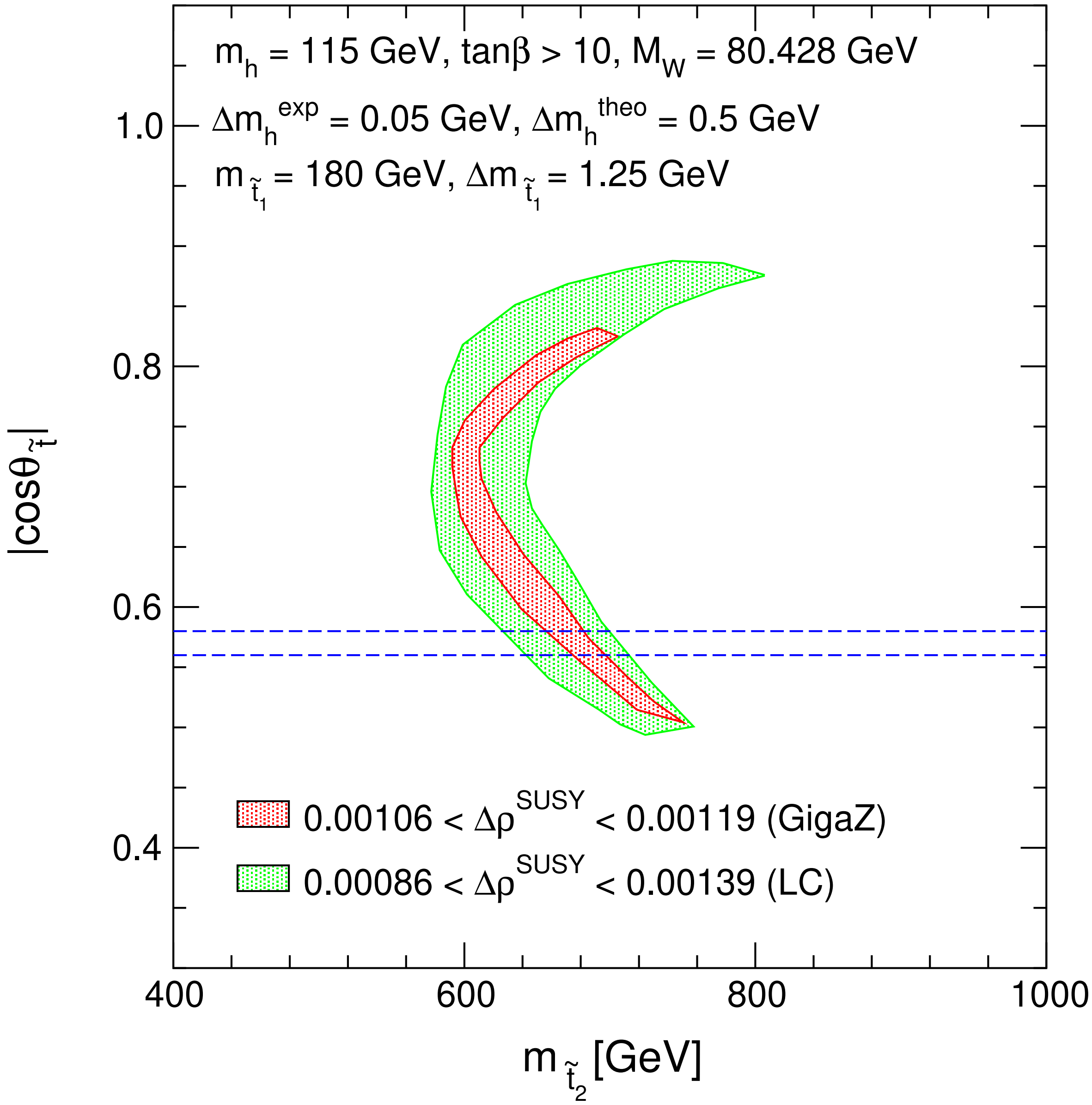
$\Rightarrow$ precise direct determination of $m_{\tilde{t}_1}$ and $\theta_{\tilde{t}}$

Indirect information:

Constraints on $m_{\tilde{t}_2}$, $\theta_{\tilde{t}}$ from precision observables $m_h, M_W, \sin^2\theta_{\text{eff}}$ at LC and GigaZ :

[S.H., G. Weiglein '00]

Allowed region in $m_{\tilde{t}_2}$-$\cos\theta_{\tilde{t}}$ plane:
($M_A = 257 \pm 10$ GeV, $\tan\beta > 10$):



Complementary of direct and indirect information

$\Rightarrow$ Indirect determination of $m_{\tilde{t}_2}$ with high precision

Scenario II:

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

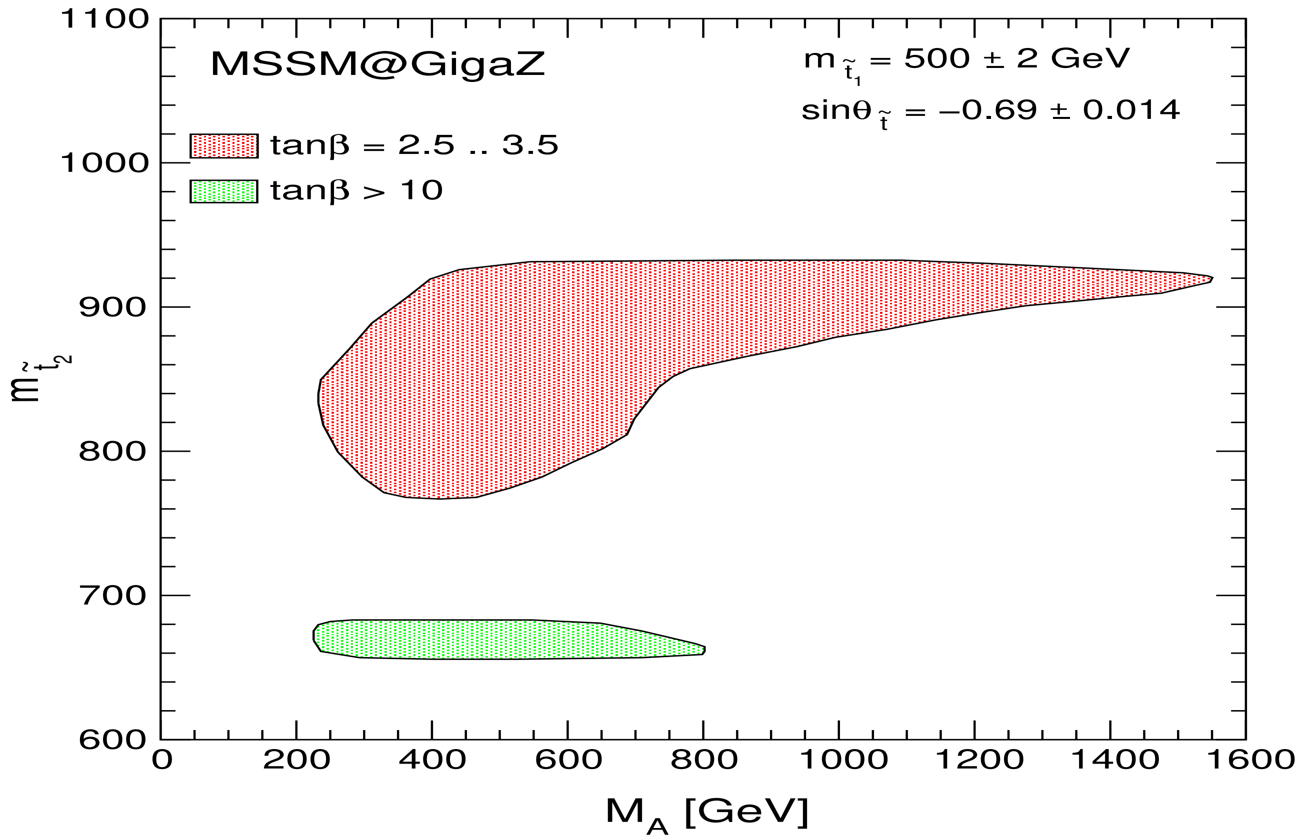
no experimental information on $m_{\tilde{t}_2}$, M_A

$2.5 < \tan\beta < 3.5$ or $\tan\beta \geq 10$
(from measurements in gaugino sector)

$M_W = 80.4 \pm 0.006$ GeV, $\sin^2\theta_{\text{eff}} = 0.23140 \pm 0.00001$
$m_h = 115 \pm 0.05$ GeV, $\delta m_h^{\text{theo}} = \pm 0.5$ GeV

$m_{\tilde{t}_1} = 500 \pm 2$ GeV, $\sin\theta_{\tilde{t}} = -0.69 \pm 2\%$, $A_b = A_t \pm 10\%$,
$\mu = -200 \pm 1$ GeV, $M_2 = 400 \pm 2$ GeV, $m_{\tilde{g}} = 500 \pm 10$ GeV

Allowed region in M_A-$m_{\tilde{t}_2}$ plane:



⇒ Constraints on $m_{\tilde{t}_2}$, upper bound on M_A

Scenario III:

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

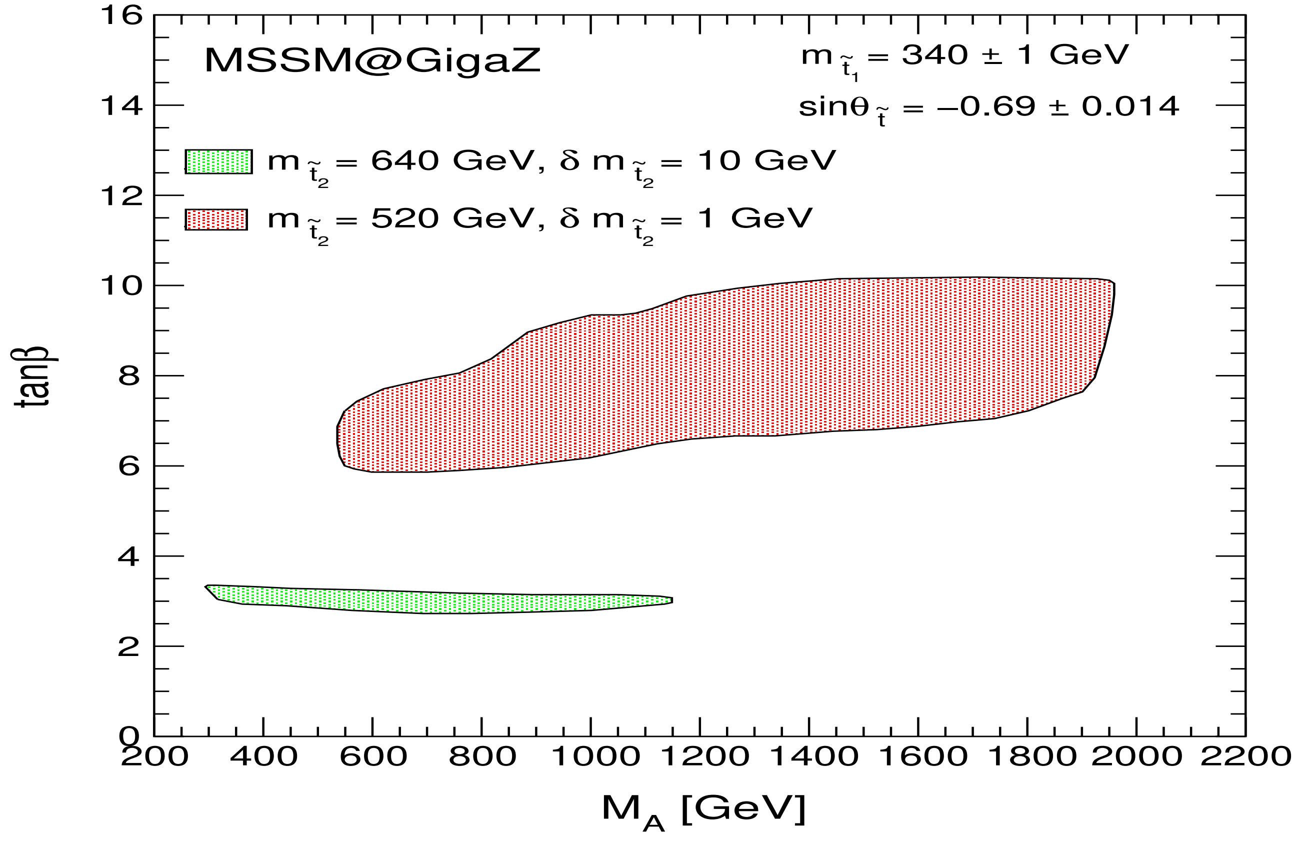
no experimental information on $\tan\beta$, M_A

$m_{\tilde{t}_2} = 520 \pm 1$ GeV   or $m_{\tilde{t}_2} = 640 \pm 10$ GeV

$M_W = 80.4 \pm 0.006$ GeV, $\sin^2\theta_{\rm eff} = 0.23138 \pm 0.00001$
$m_h = 110 \pm 0.05$ GeV, $\delta m_h^{\rm theo} = \pm 0.5$ GeV

$m_{\tilde{t}_1} = 340 \pm 1$ GeV, $\sin\theta_{\tilde{t}} = -0.69 \pm 2\%$, $A_b = -640 \pm 60$ GeV,
$\mu = 316 \pm 1$ GeV, $M_2 = 152 \pm 2$ GeV, $m_{\tilde{g}} = 496 \pm 10$ GeV

Allowed region in M_A-$\tan\beta$ plane:



$\Rightarrow$ Constraints on $\tan\beta$, upper bound on M_A

4. Conclusinos

- **GigaZ:** $\to$ $\delta M_W = 6$ MeV,
  $\delta \sin^2\theta_{\rm eff} = 0.00001$

  Combined with high precision of LC for

  m_h , m_t, $m_{\tilde{t}}$, ...

  $\Rightarrow$ Highly sensitive test of SM and MSSM

- SM:
  Indirect determination of M_H:

  $$\delta M_H / M_H \approx 7\%$$

- MSSM:
  - via m_h as precision observable:
    Combination of direct and indirect constraints in the $\tilde{t}$ sector: determination of $m_{\tilde{t}_2}$
  - Constraints on $\tan\beta$
  - upper bound on M_A possible

- High sensitivity to scales beyond SM and MSSM