Constraining SUSY with Electroweak Precision Observables

Sven Heinemeyer, IFCA (Santander)

Warsaw, 06/2008

based on collaboration with
W. Hollik, A.M. Weber and *G. Weiglein*

1. Introduction

2. Calculation of the electroweak precision observables

3. Numerical results

4. Conclusions

1. Introduction

Q: How to detect Supersymmetry (or any other BSM)?

A: Two possible ways:

- Search for new SUSY particles

new SUSY particles found
$\Updownarrow$
SM ruled out

Problem:
SUSY particles are too heavy for todays colliders, only lower limits of $\mathcal{O}(100\text{ GeV})$.

$\rightarrow$ waiting for Tevatron (2008/09. . . ?)
$\rightarrow$ waiting for LHC (2009/10. . . ?)

- Search for indirect effects of SUSY
  via Precision Observables

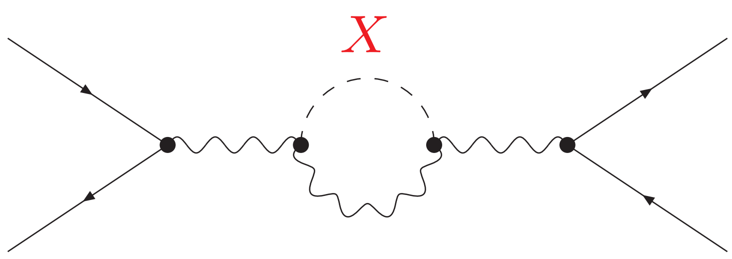
Precision Observables (POs):

Comparison of electro-weak precision observables with theory:

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

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections



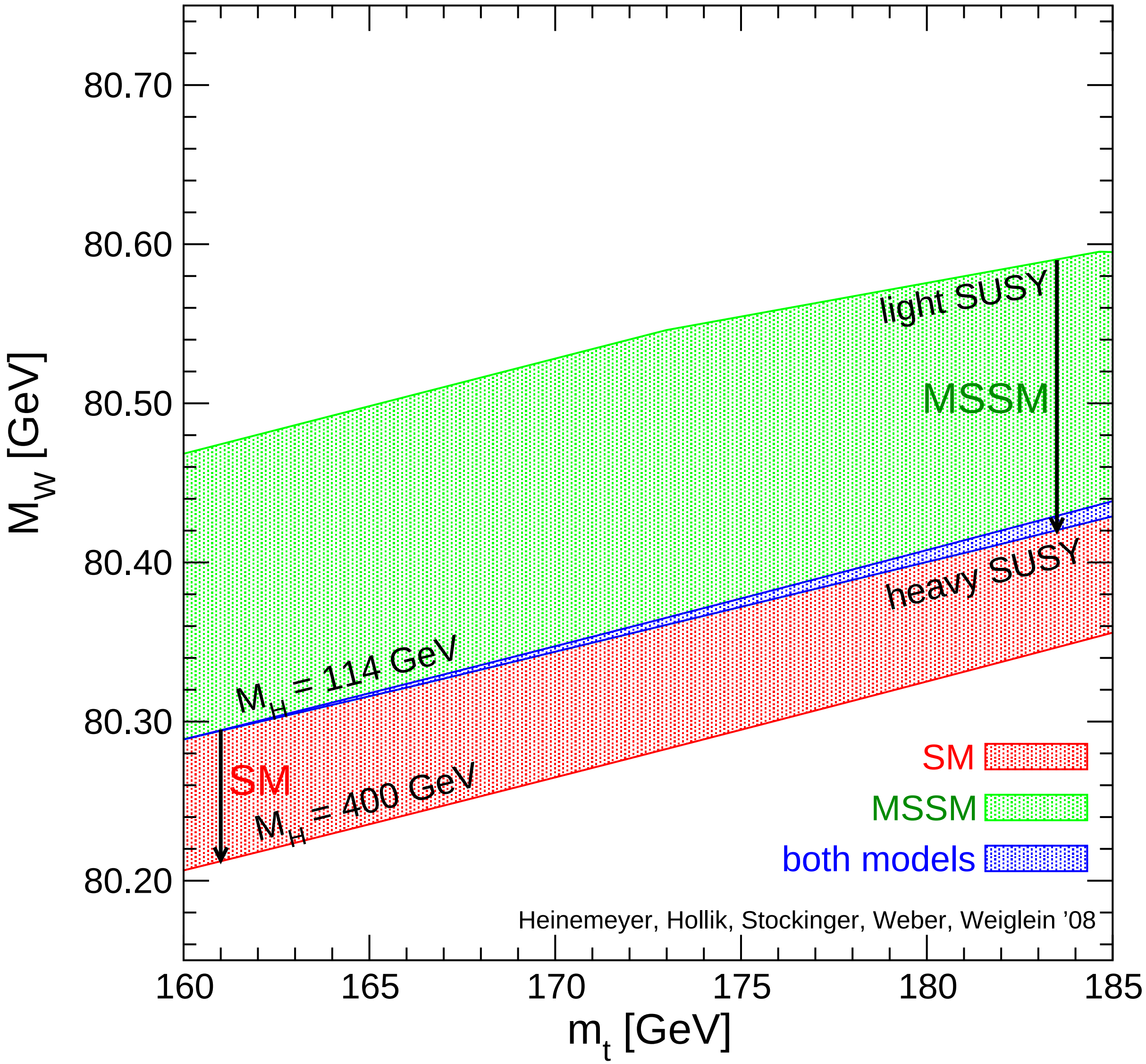
$\Downarrow$

Very high accuracy of measurements and theoretical predictions needed

- Which model fits better?
- Does the prediction of a model contradict the experimental data?

Example: Prediction for M_W in the SM and the MSSM :

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



MSSM band:
scan over
SUSY masses

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

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

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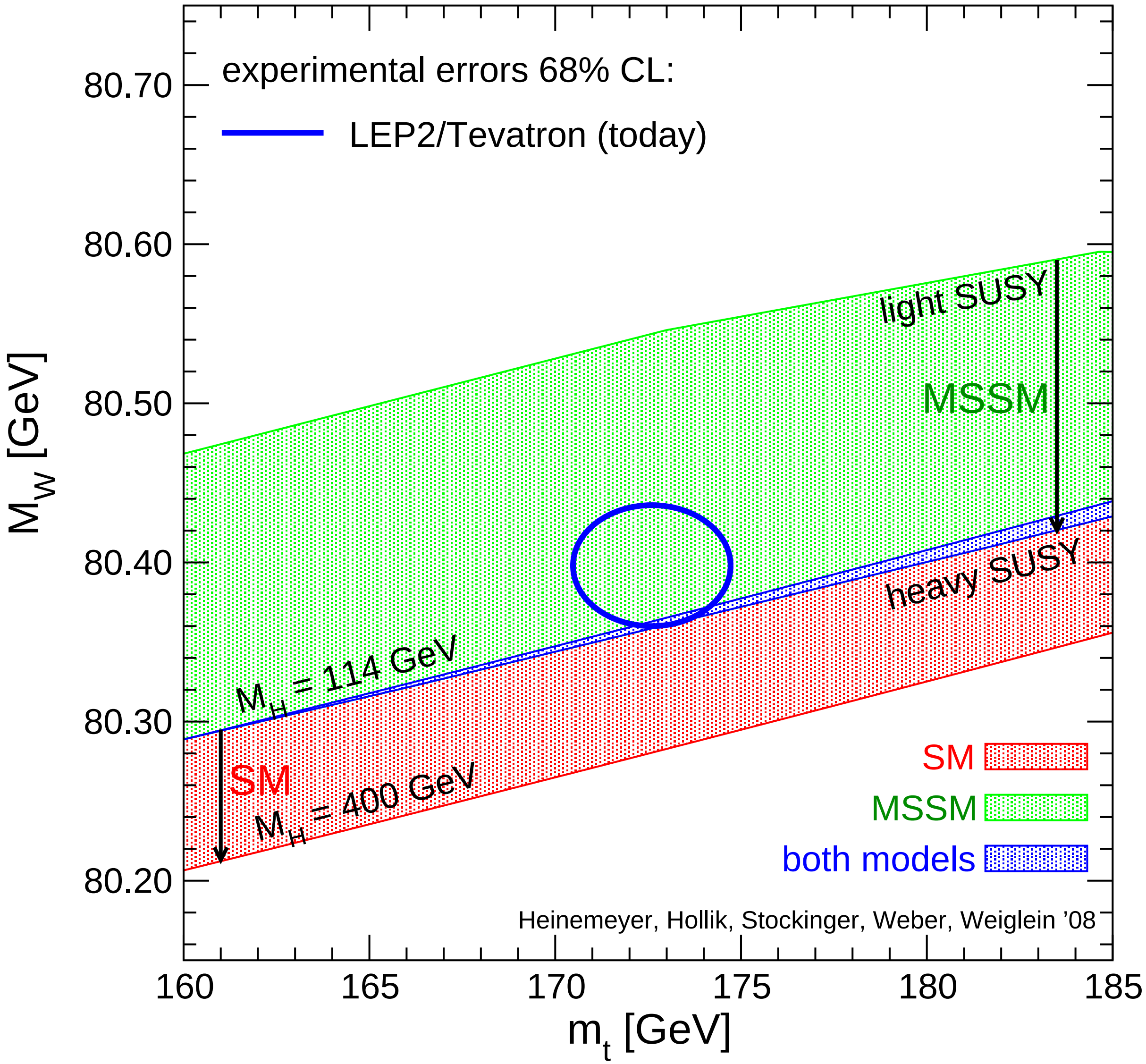

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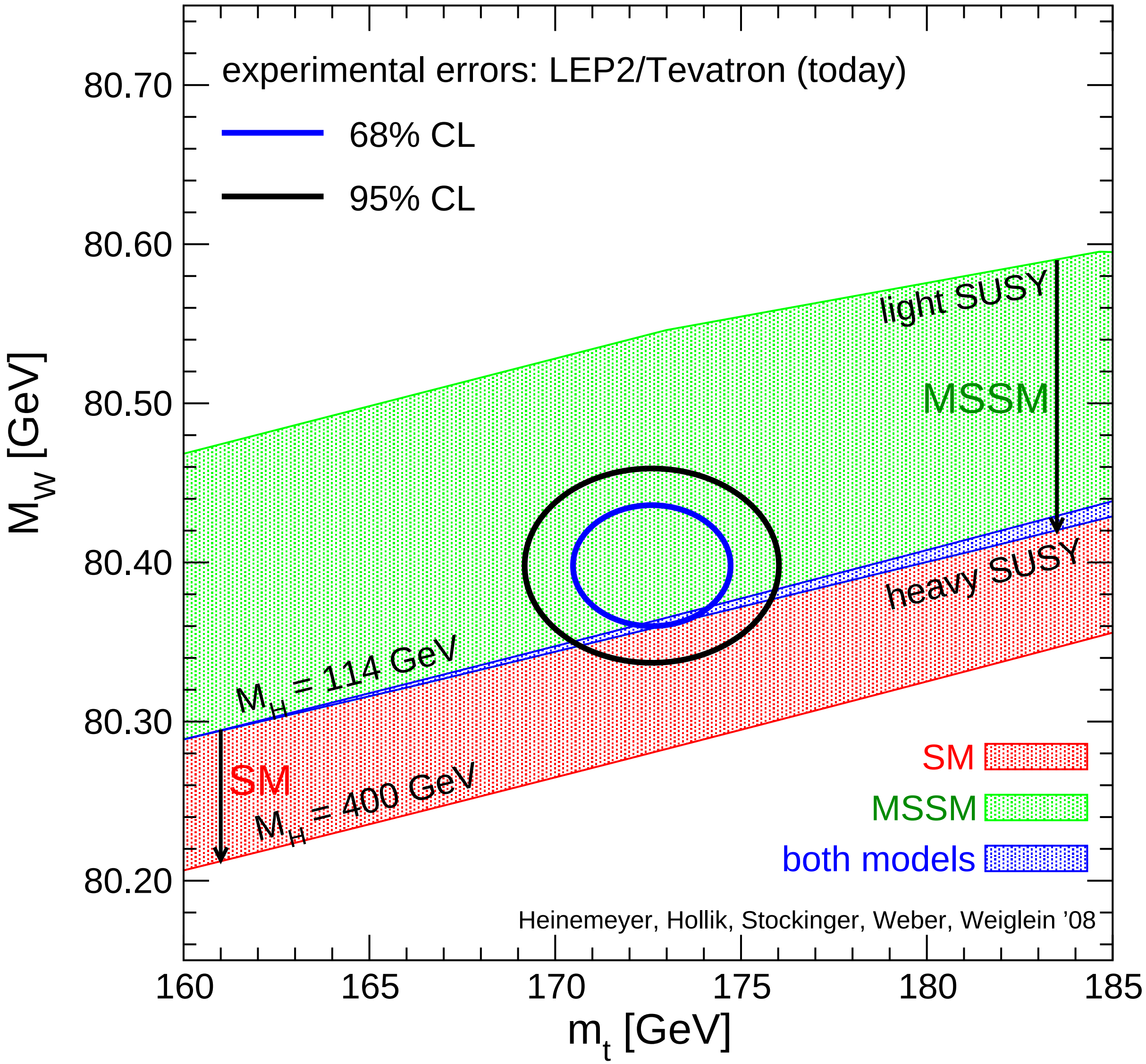

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The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\Big[u, d, c, s, t, b\Big]_{L,R} \quad \Big[e, \mu, \tau\Big]_{L,R} \quad \Big[\nu_{e,\mu,\tau}\Big]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\Big[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\Big]_{L,R} \quad \Big[\tilde{e}, \tilde{\mu}, \tilde{\tau}\Big]_{L,R} \quad \Big[\tilde{\nu}_{e,\mu,\tau}\Big]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

Problem in the MSSM: many complex parameters

$\tilde{t}/\tilde{b}$ sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan\beta$, $X_b = A_b - \mu^* \tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t^* \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b^* \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

soft SUSY-breaking parameters A_t, A_b also appear in ϕ-$\tilde{t}/\tilde{b}$ couplings

$SU(2)$ relation $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$

$\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Results for EWPO fit in the SM: *[LEPEWWG '08]*

Pull distributions:

Variable	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
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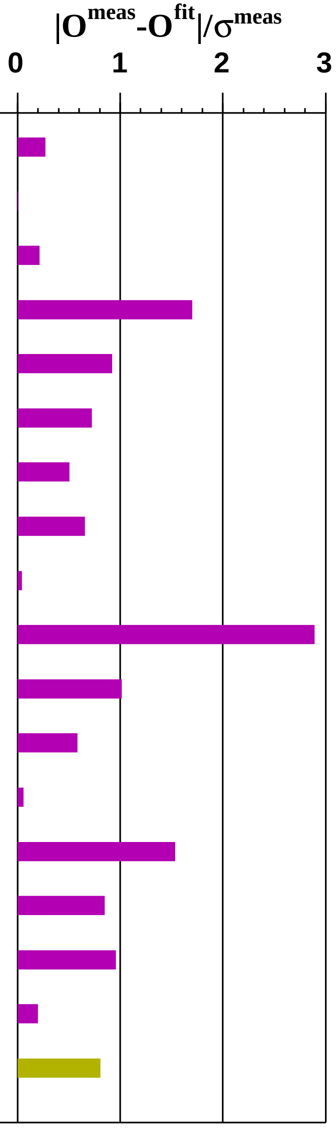
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
m_t [GeV]	170.9 ± 1.8	171.3
Γ_W [GeV]	2.140 ± 0.060	2.091



Probability: 15%

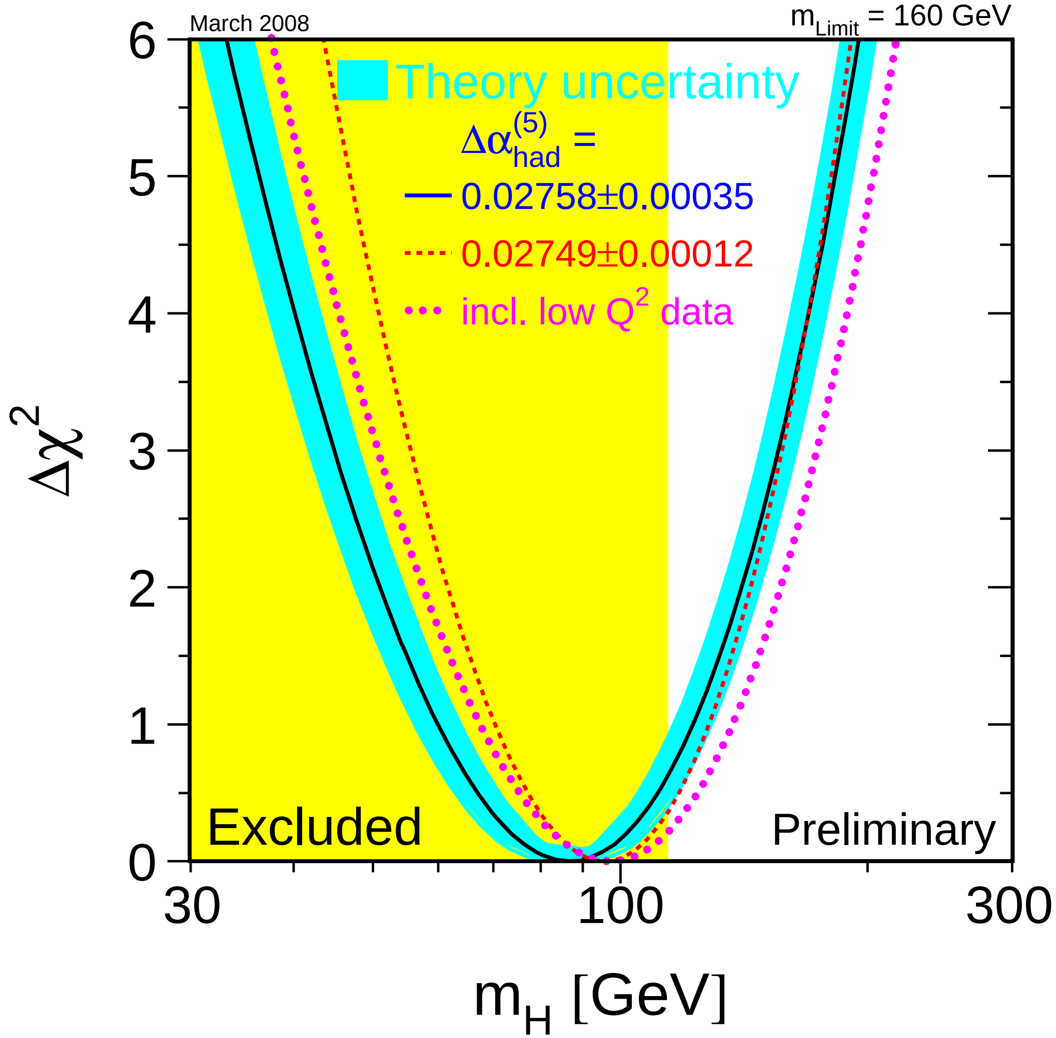
Within the SM: fit for the last unknown parameter: M_H^{SM}

Global fit to all SM data:

[*LEPEWWG '08*]

$\Rightarrow$ $M_H = 87^{+36}_{-27}$ GeV

$M_H < 160$ 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, $M_H \lesssim 150$ GeV

2. Calculation of the electroweak precision observables

$\mathcal{O} = M_W$, $\sin^2\theta_{\rm eff}$ $(A_{\rm FB}^{b,c}, A_{\rm LR}^{e,\mu})$, R_l, R_b, $\sigma_0^{\rm had}$, ...

Wanted: same precision for MSSM as for the SM

⇒ Combination of SM and MSSM result

→ use best available SM result

→ add all available MSSM corrections
recalculation of full 1L result, now incl. full complex phase dependence

→ subtract double counting

⇒ decoupling limit ok ($M_{\rm SUSY} \to \infty$)

... but some corrections included only via their SM part

⇒ best solution

Calculation of M_W, $\sin^2\theta_{\text{eff}}$, Γ_Z:

1.) Theoretical prediction for M_W in terms

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

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

$\Updownarrow$

loop corrections

2.) Effective mixing angle:

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

Higher order contributions:

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

3.) Total Z width:

$$\Gamma_Z=\sum_X\Gamma(Z\to X\bar{X})$$

including higher-order corrections for all the channels

Other observables:

4.) R_b:

$$R_b = \frac{\Gamma_b}{\Gamma_{\rm had}} = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}$$

5.) R_l:

$$R_l = \frac{\Gamma_{\rm had}}{\Gamma_l} = \frac{\Gamma(Z \to \text{hadrons})}{\Gamma(Z \to \text{leptons})}$$

6.) hadronic peak cross section $\sigma^0_{\rm had}$:

$$\sigma^0_{\rm had} = 12\,\pi \frac{\Gamma_e \Gamma_{\rm had}}{M_Z^2 \Gamma_Z^2}$$

7.) . . .

More details about our calculation:

- Complex phases in the squark sector enter only via shift in squark masses (explicit dependence drops out)

$$|X_t|^2 = |A_t|^2 + |\mu \cot\beta|^2 - 2|A_t| \cdot |\mu| \cot\beta \cos(\phi_{A_t} + \phi_\mu)$$
$$|X_b|^2 = |A_b|^2 + |\mu \tan\beta|^2 - 2|A_b| \cdot |\mu| \tan\beta \cos(\phi_{A_b} + \phi_\mu)$$

  Only some phase combinations are physical, other phases can be rotated away. Examples for physical combinations:

$$\phi_{A_t} + \phi_\mu$$
$$\phi_{A_b} + \phi_\mu$$

- Higgs mass dependence of the two-loop contributions is know to be very strong
  $\Rightarrow$ we use *FeynHiggs* (`www.feynhiggs.de`)

- All one-loop calculations have been performed with *FeynArts* and *FormCalc*
  [*T. Hahn et al. '00 - '07*]

Treatment of the phase dependence beyond one-loop order

Phase dependence at the two-loop level approximated by a simple interpolation based on:

full phase dependence at the one-loop level, $\mathcal{O}^{1L}(\phi)$,

two-loop results for real parameters, $\mathcal{O}^{full}(0)$, $\mathcal{O}^{full}(\pi)$

⇒ Two-loop result for complex phase ϕ:

$$\mathcal{O}^{full}(\phi) = \mathcal{O}^{1L}(\phi) + \left[\mathcal{O}^{full}(0) - \mathcal{O}^{1L}(0)\right] \times \frac{1+\cos\phi}{2} + \left[\mathcal{O}^{full}(\pi) - \mathcal{O}^{1L}(\pi)\right] \times \frac{1-\cos\phi}{2}$$

3. Numerical results

Investigation of:

- M_{SUSY} dependence
- m_t dependence
- phase dependence
- special scenarios
- parameter scan
- ...

Together with other observables:

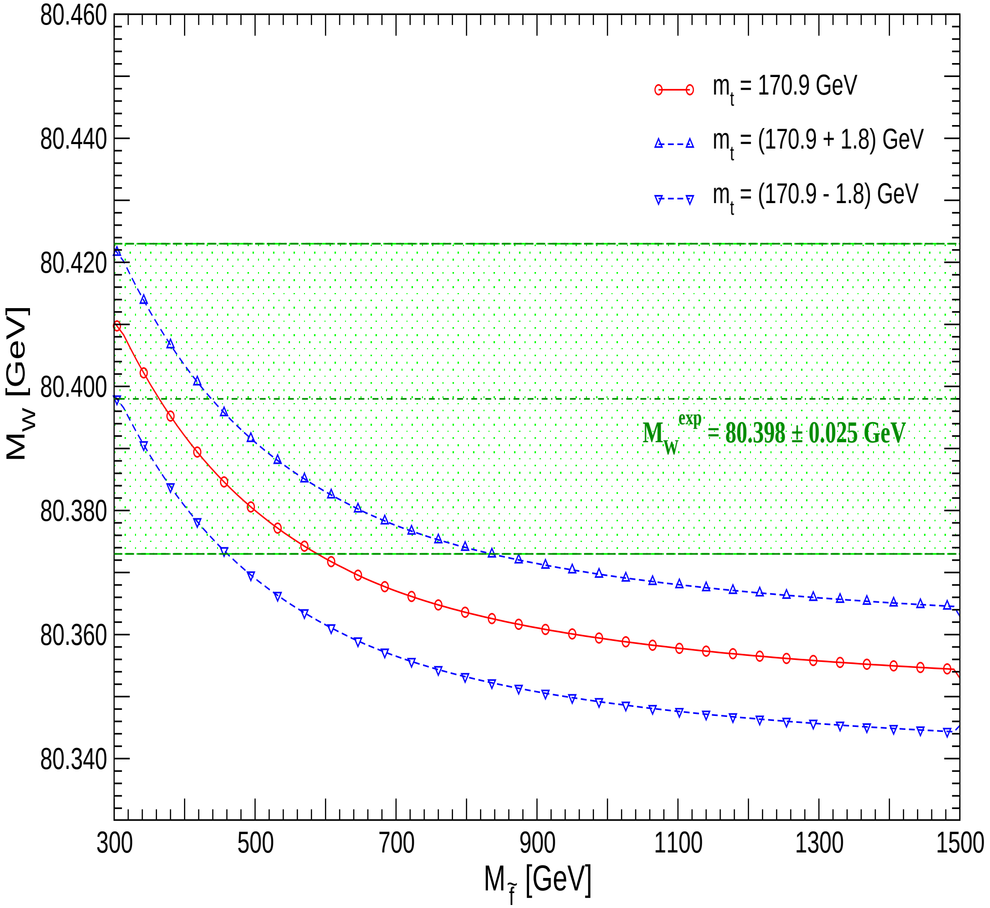
M_h^{SUSY} determination (similar to Blue Band in the SM)

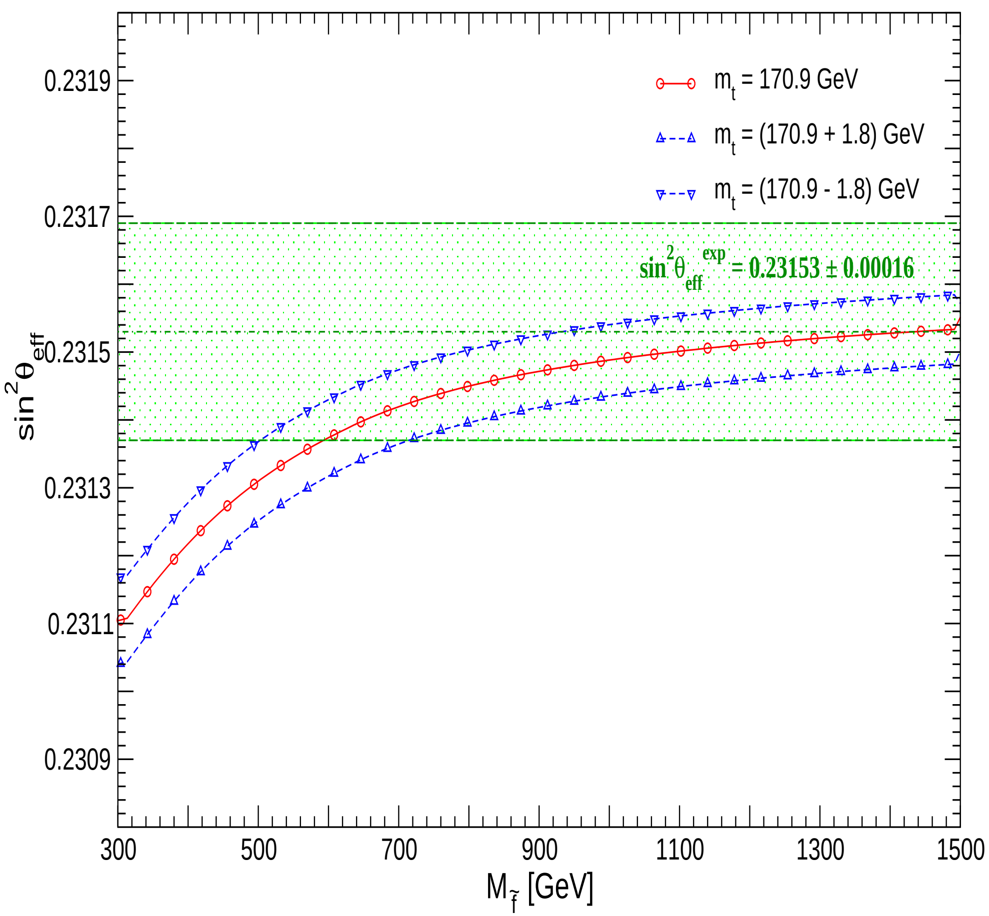
Experimental precision:

observable	central exp. value	$\sigma \equiv \sigma^{\text{today}}$	σ^{LHC}	$\sigma^{\text{ILC/GigaZ}}$
M_W [GeV]	80.398	0.025	0.015	0.007
$\sin^2\theta_{\text{eff}}$	0.23153	0.00016	0.00020–0.00014	0.000013
Γ_Z [GeV]	2.4952	0.0023	—	0.001
R_l	20.767	0.025	—	0.01
R_b	0.21629	0.00066	—	0.00014
σ^0_{had}	41.540	0.037	—	0.025

$\Rightarrow$ ILC/GigaZ precision yields a very strong improvement

A) M_{SUSY} and m_t dependence (I)

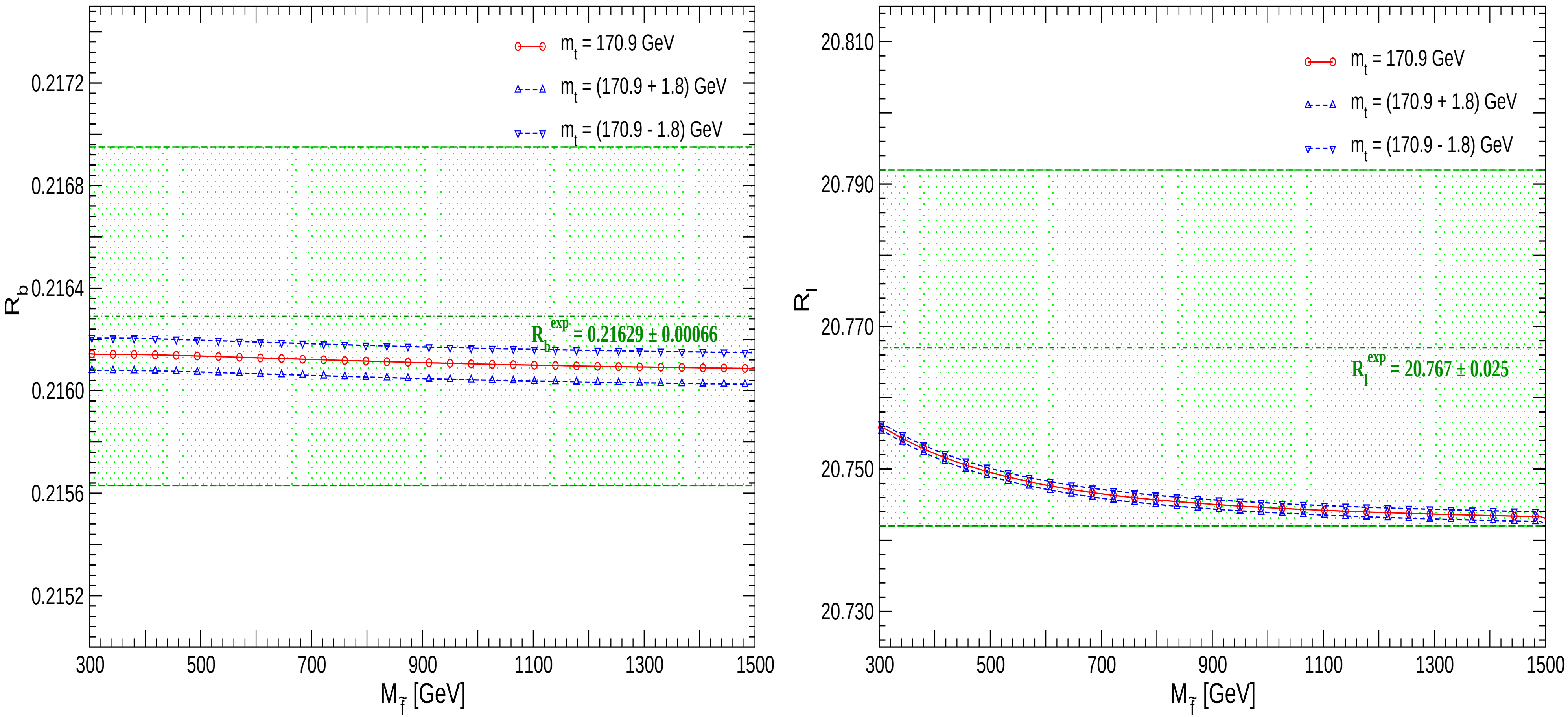




⇒ strong M_{SUSY} dependence

⇒ important m_t dependence

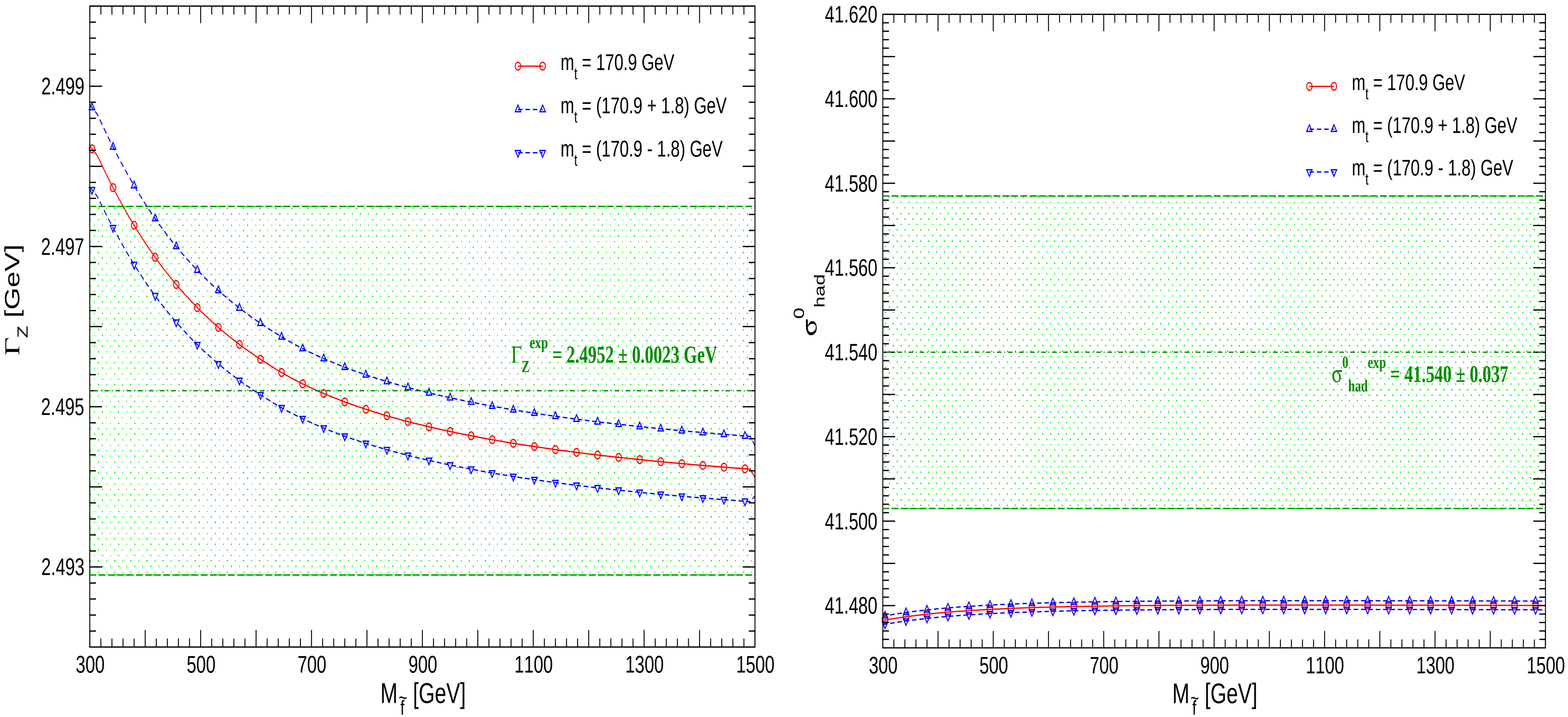
A) M_{SUSY} and m_t dependence (II)



$\Rightarrow$ weak M_{SUSY} dependence

$\Rightarrow$ weak m_t dependence

A) M_{SUSY} and m_t dependence (III)



⇒ relevant M_{SUSY} dependence only for Γ_Z

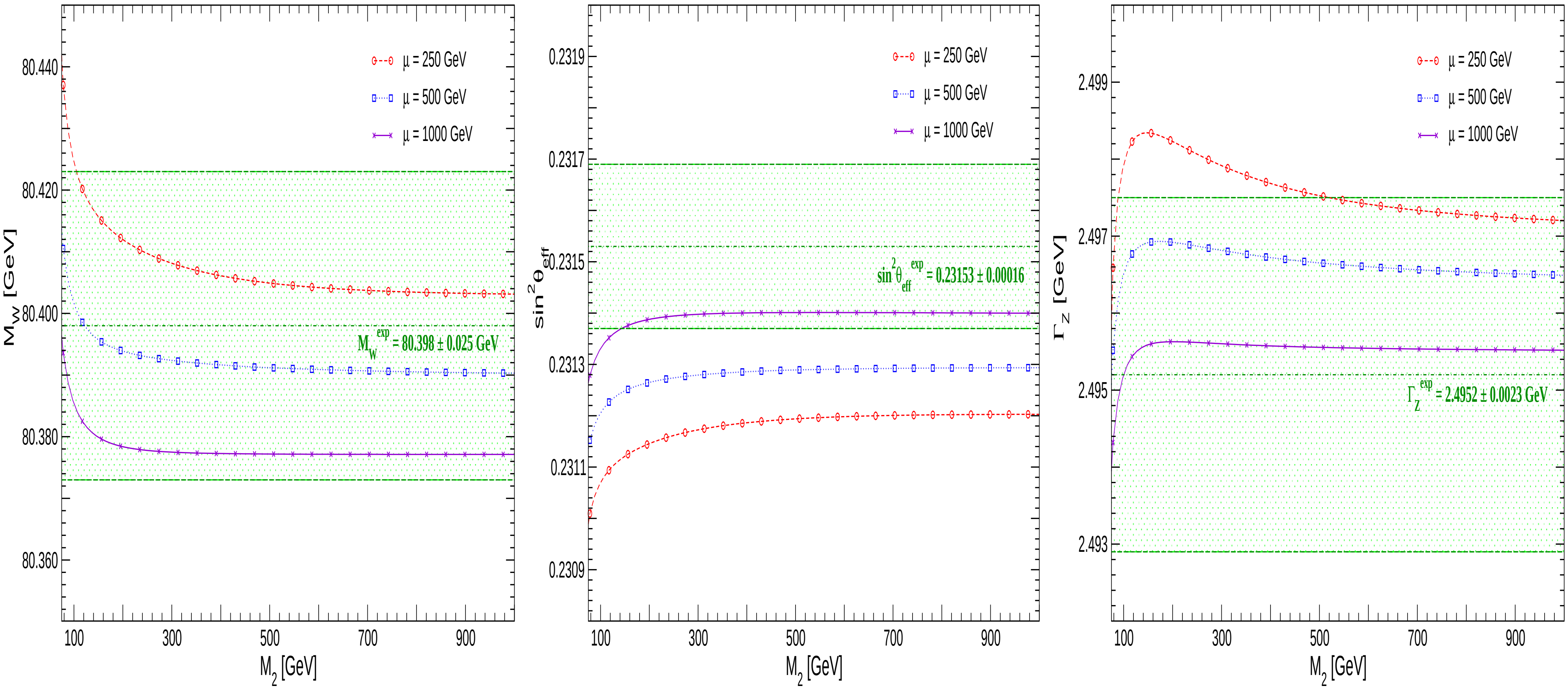
⇒ relevant m_t dependence only for Γ_Z

Parametric uncertainties:

$$\delta m_t^{\text{exp}} = 1.4 \text{ GeV} \quad \Rightarrow \quad \begin{aligned} \delta M_W^{\text{para},m_t} &= 9 \text{ MeV} \\ \delta \sin^2\theta_{\text{eff}}^{\text{para},m_t} &= 4.2 \times 10^{-5} \\ \delta\Gamma_Z^{\text{para},m_t} &= 0.34 \text{ MeV} \end{aligned}$$

$$\delta(\Delta\alpha_{\text{had}}^{(5)}) = 3.5 \times 10^{-4} \quad \Rightarrow \quad \begin{aligned} \delta M_W^{\text{para},\Delta\alpha_{\text{had}}^{(5)}} &= 6.3 \text{ MeV} \\ \delta \sin^2\theta_{\text{eff}}^{\text{para},\Delta\alpha_{\text{had}}^{(5)}} &= 12 \times 10^{-5} \\ \delta\Gamma_Z^{\text{para},\Delta\alpha_{\text{had}}^{(5)}} &= 0.32 \text{ MeV} \end{aligned}$$

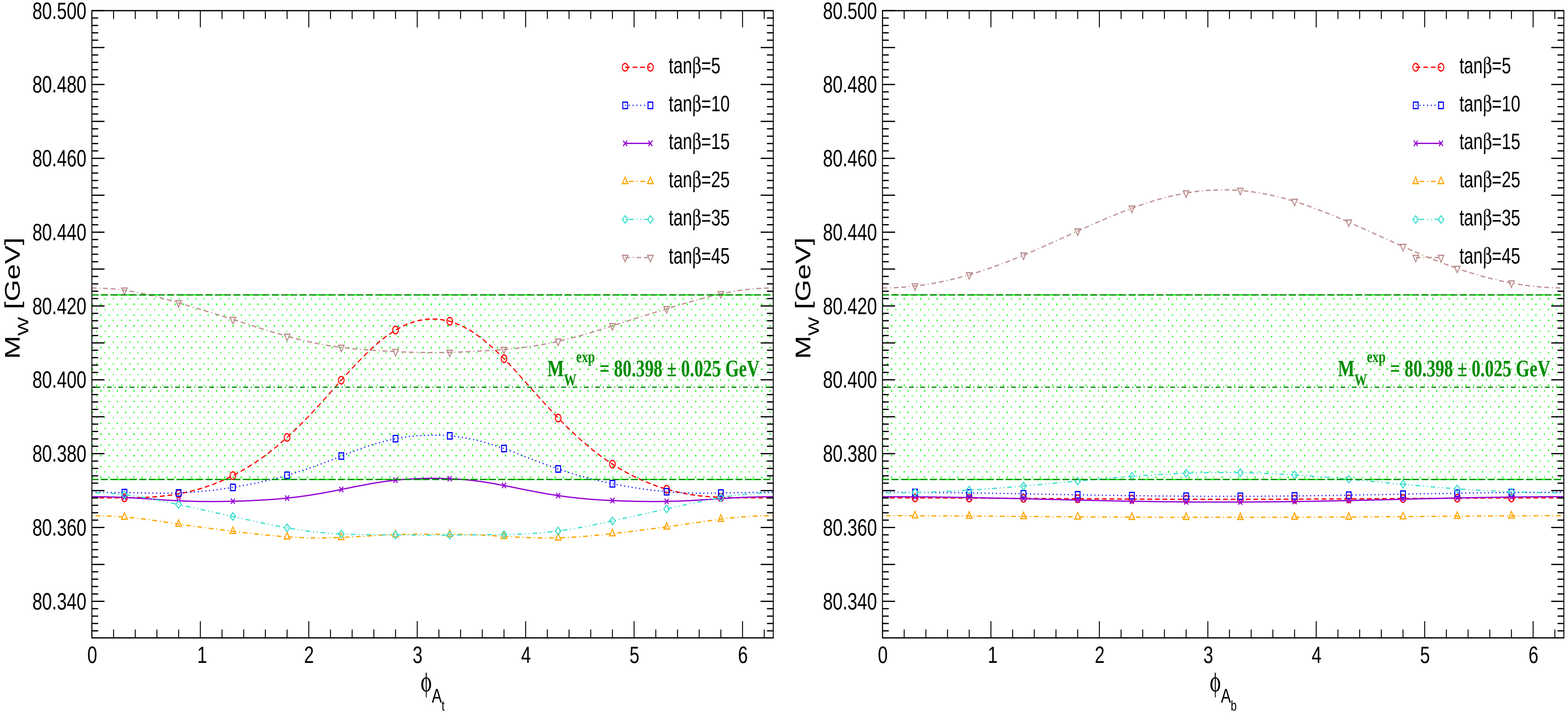
B) Dependence on μ and M_2:



⇒ strong dependence on μ

⇒ strong dependence on M_2 for small M_2

C) Dependence on ϕ_{A_t} and ϕ_{A_b} (for $\phi_\mu = 0$) (I):



⇒ strong dependence on ϕ_{A_t}

⇒ strong dependence on ϕ_{A_b} for large $\tan\beta$ ($\rightarrow$ light sbottom)

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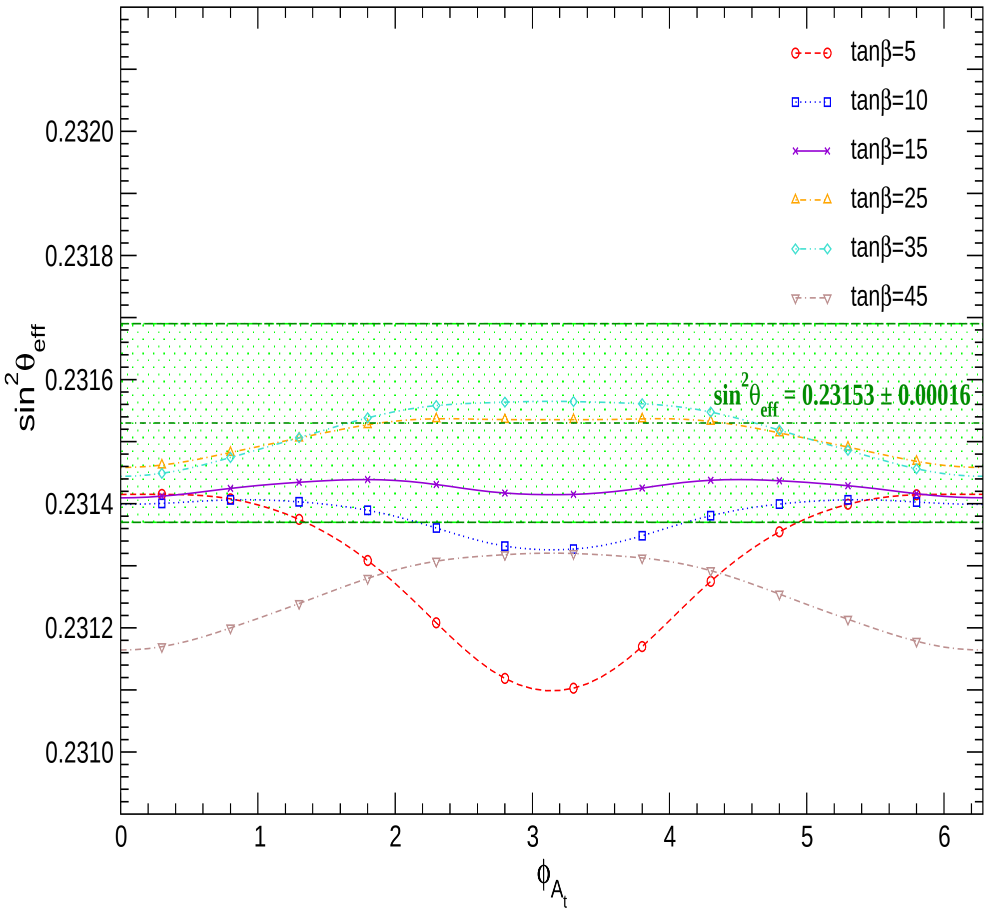

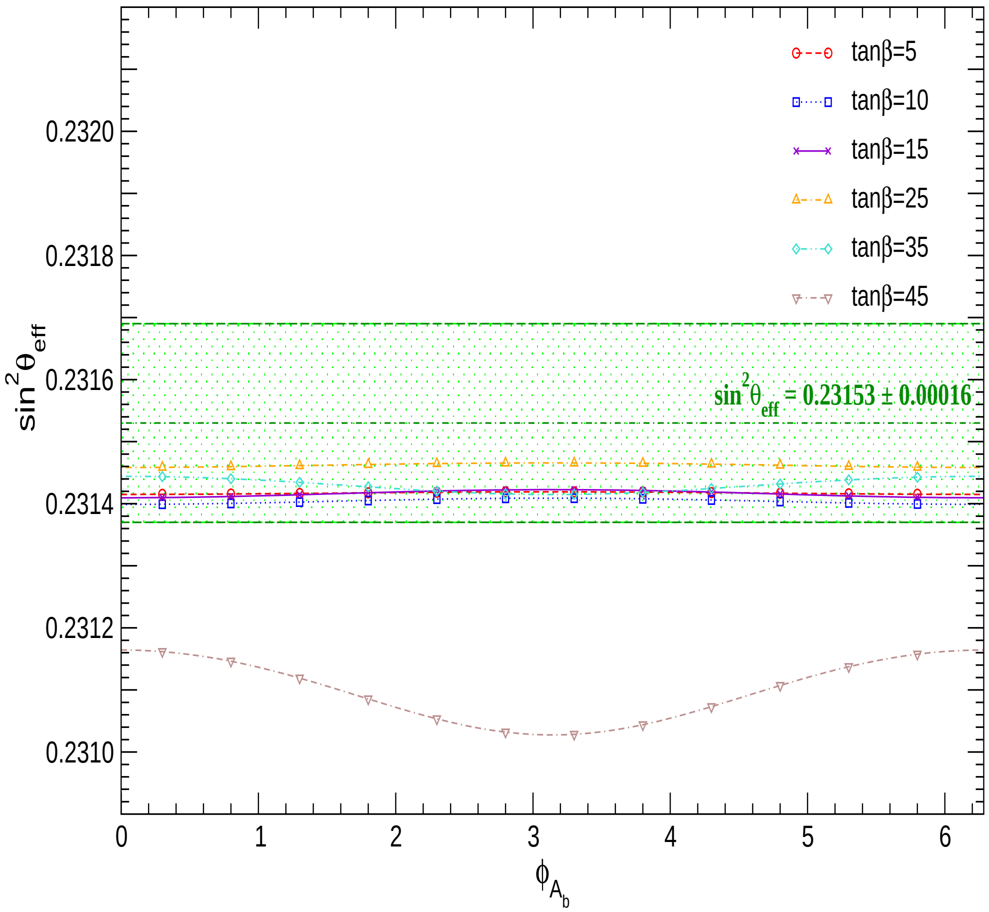

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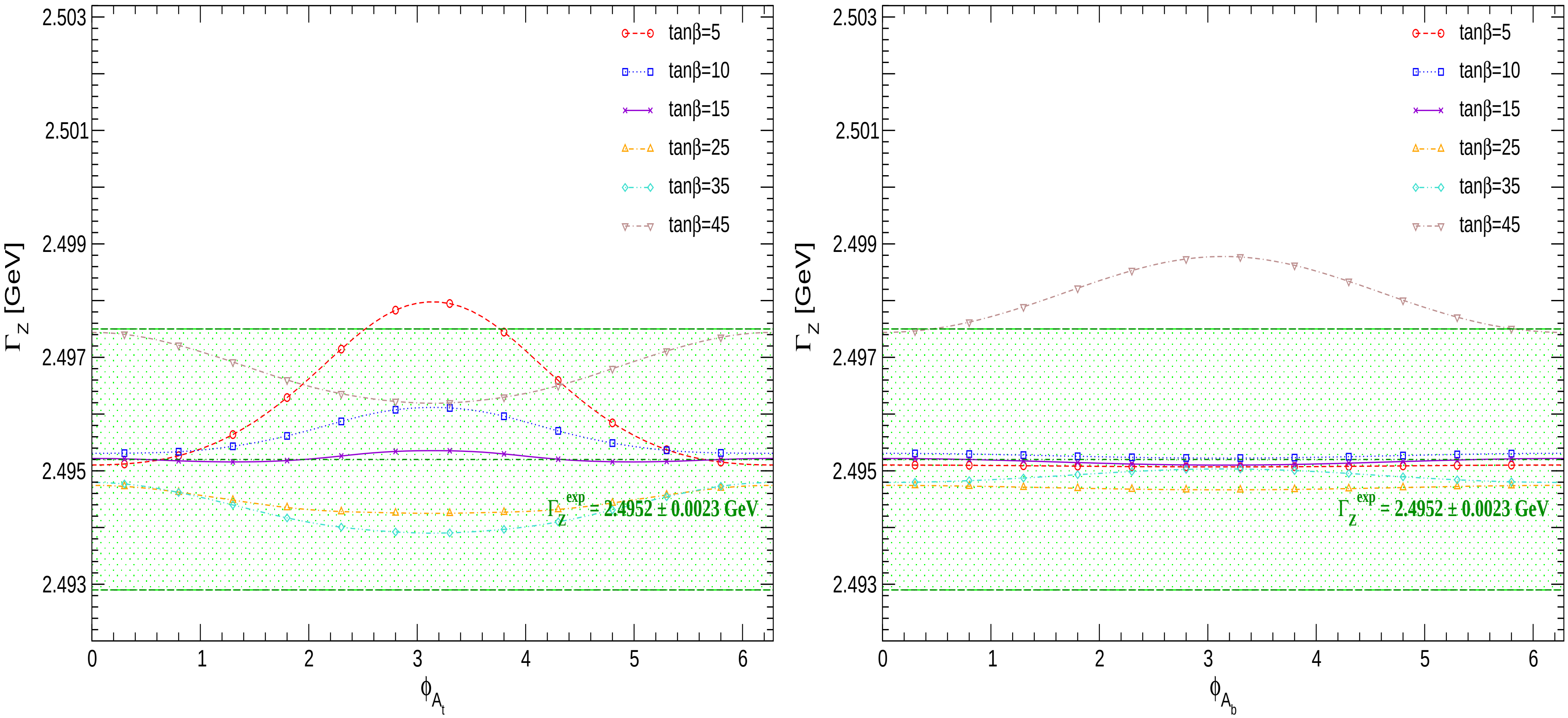

$\Rightarrow$ strong dependence on ϕ_{A_t}

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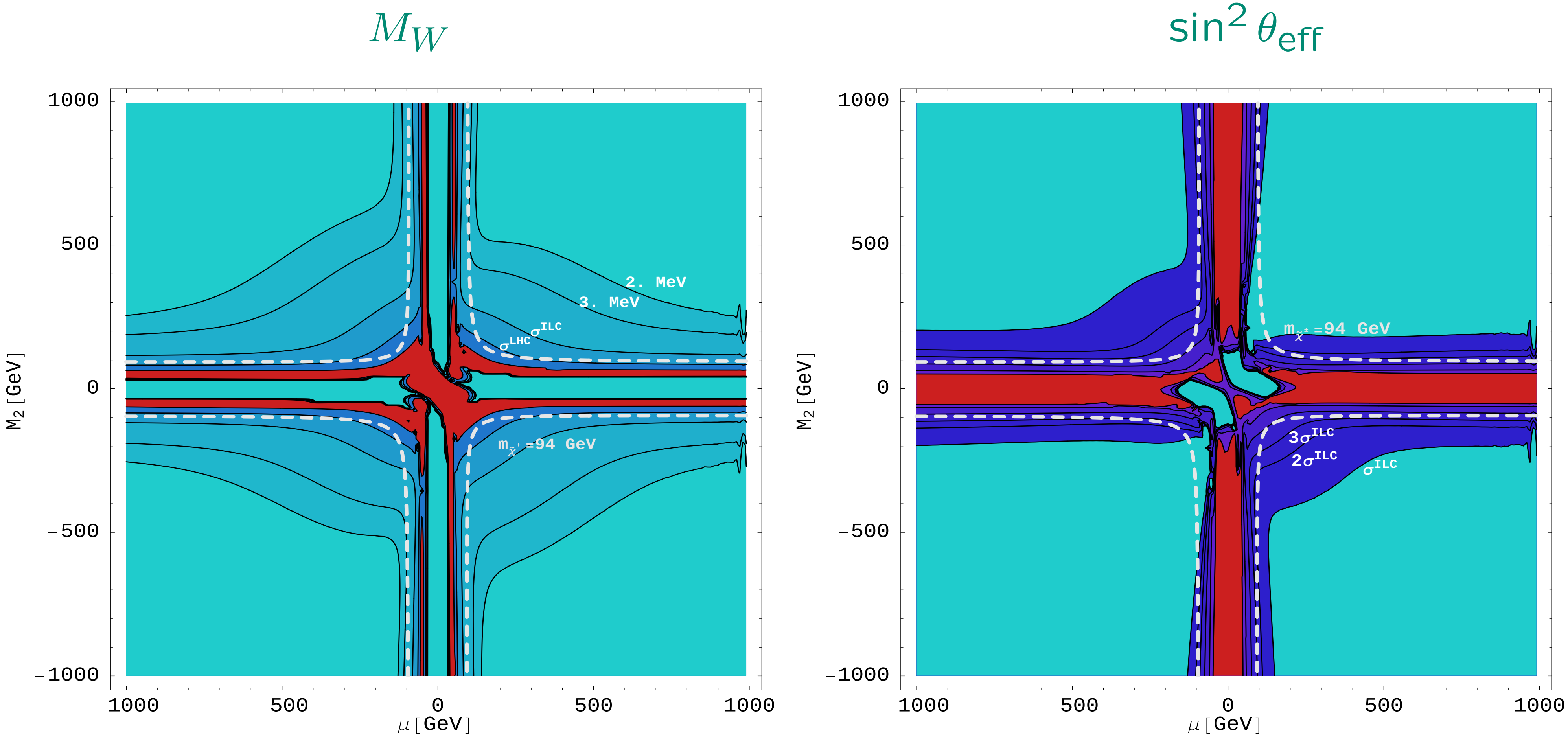
D) M_W and $\sin^2\theta_{\text{eff}}$ in Split SUSY:

[*N. Arkani–Hamed, S. Dimopoulos '04*] [*G. Giudice, A. Romanino '04*]

$\rightarrow$ deviations to the SM with $M_H^{\text{SM}} = M_h$:



$\Rightarrow$ even with ILC precision hardly any effect visible

E) Scenario with no SUSY particles at the LHC:

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

→ SPS 1a with heavy scalars

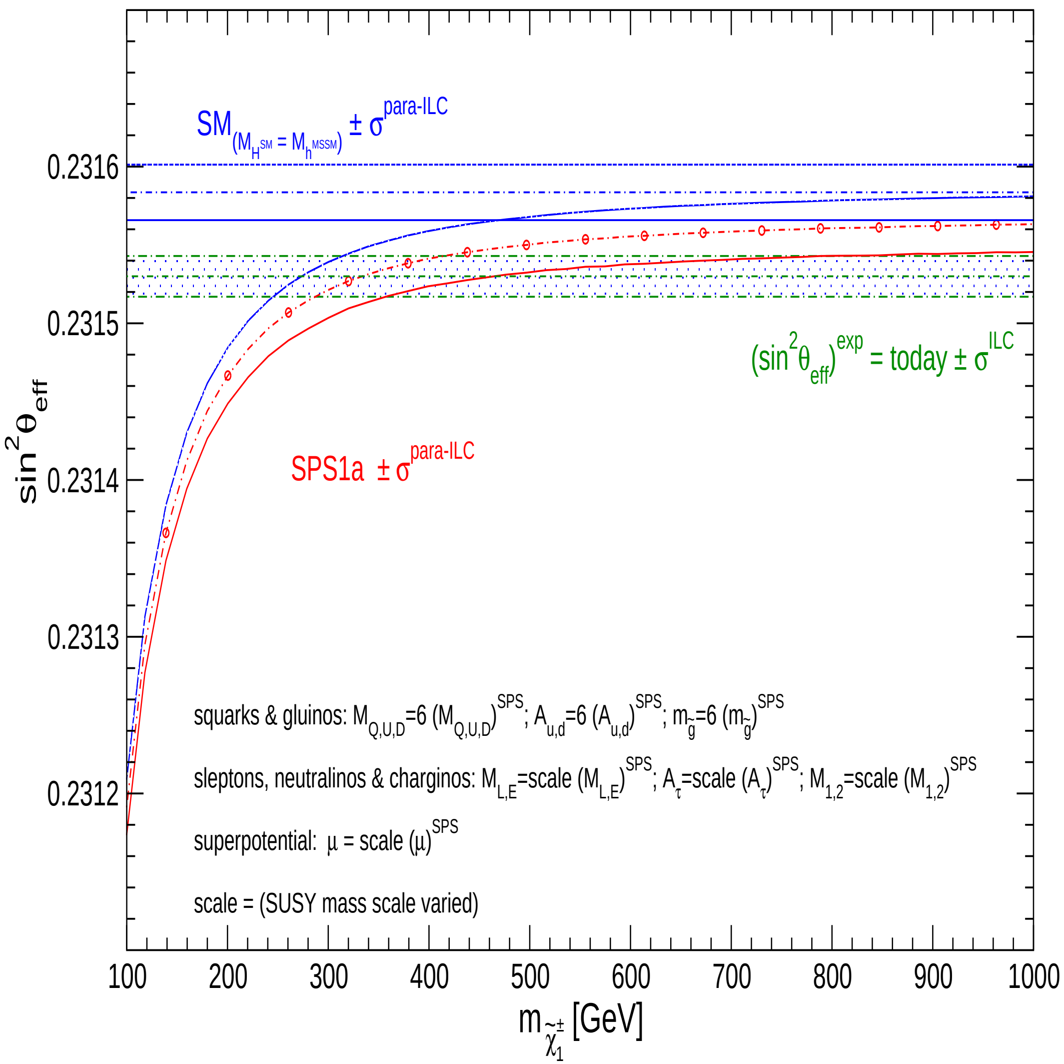
SM prediction

vs.

MSSM (SPS 1a) prediction

vs.

ILC resolution



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

F) Parameter scans in the (full) MSSM:

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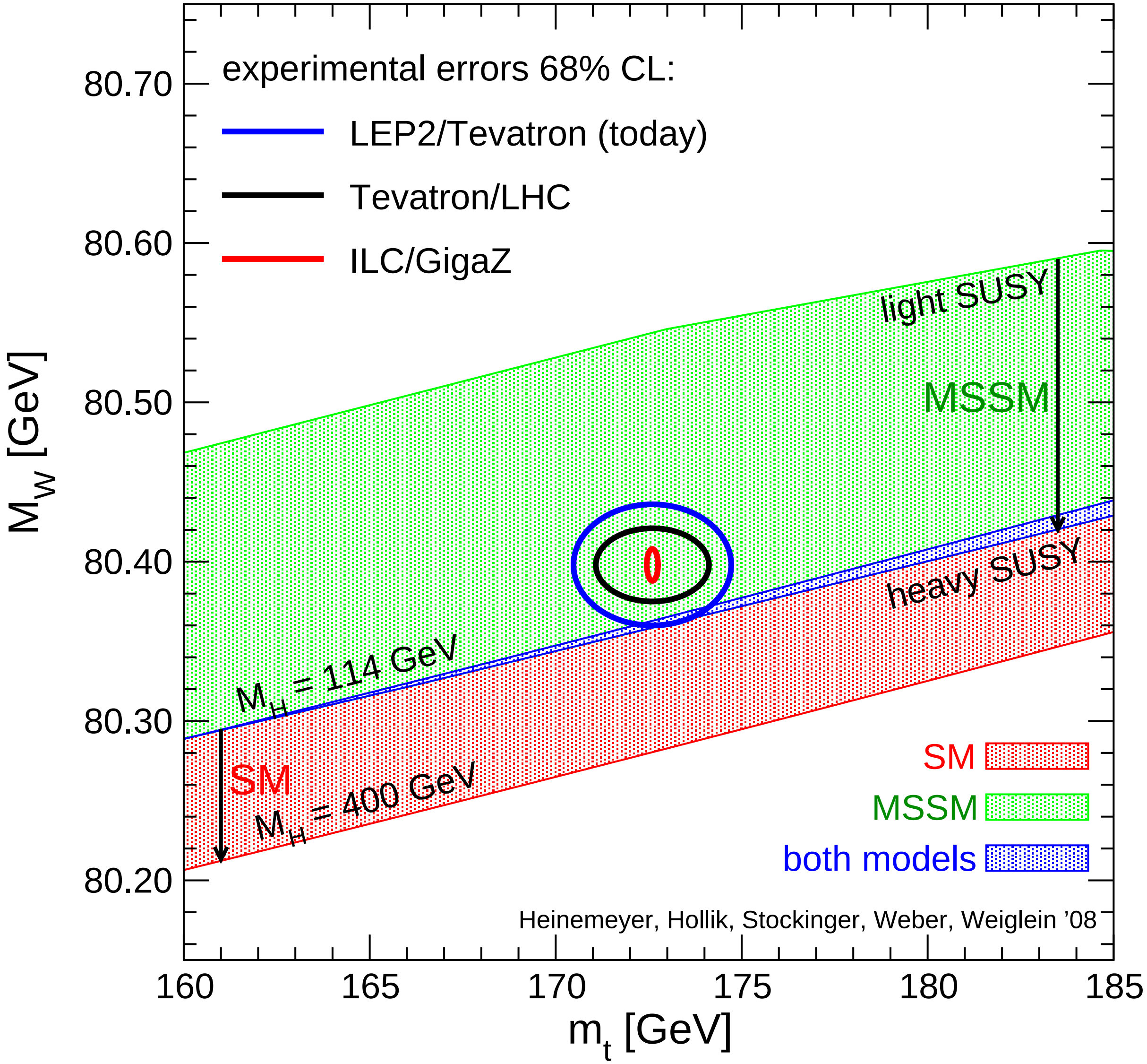

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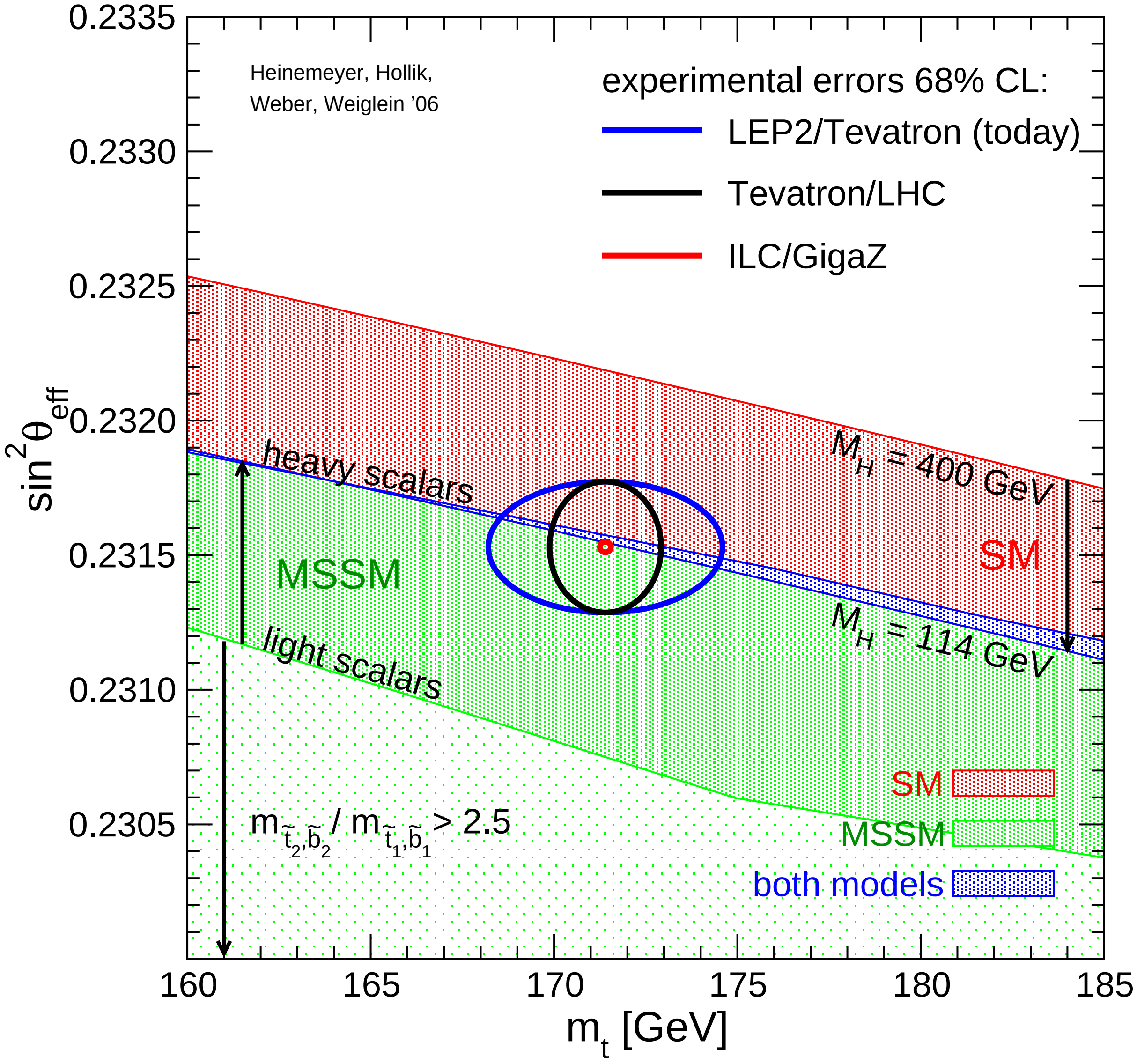
Prediction for $\sin^2\theta_{\text{eff}}$ in the SM and the MSSM :



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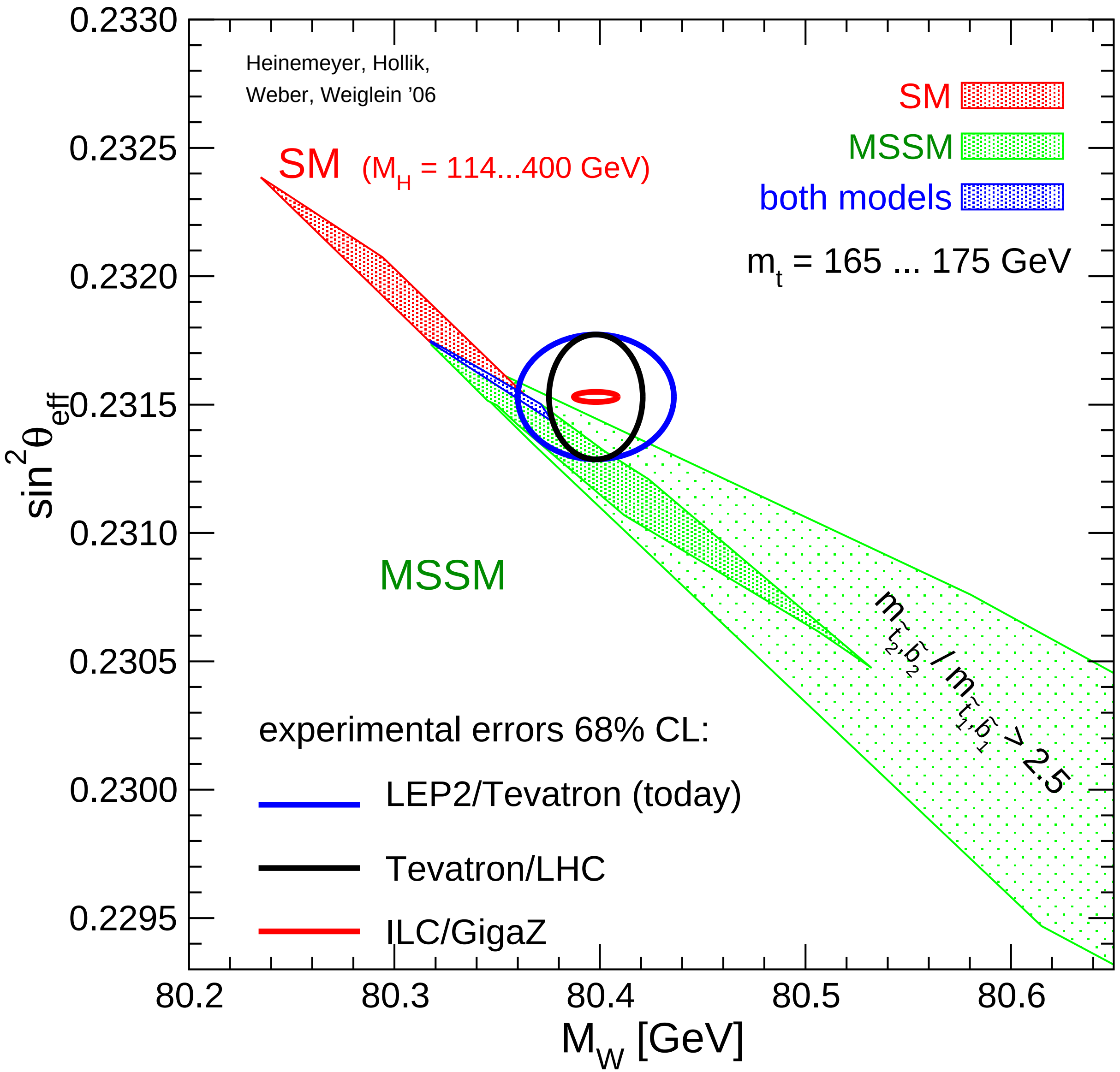
Prediction for M_W and $\sin^2\theta_{\rm eff}$ in the SM and the MSSM :

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



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Prediction of M_h in the CMSSM/mSUGRA

[*Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, Weiglein '07*]

– combine all electroweak precision data as in the SM
– combine with B physics observables
– combine with CDM and $(g-2)_\mu$
– include SM parameters with their errors: $m_t, \ldots$

– scan over the full CMSSM parameter space ($m_{1/2}$, m_0, A_0, $\tan\beta$)

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⇒ preferred CMSSM parameters
⇒ preferred M_h values
⇒ LHC/ILC reach

Pull distributions:

[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, Weiglein '07]

CMSSM

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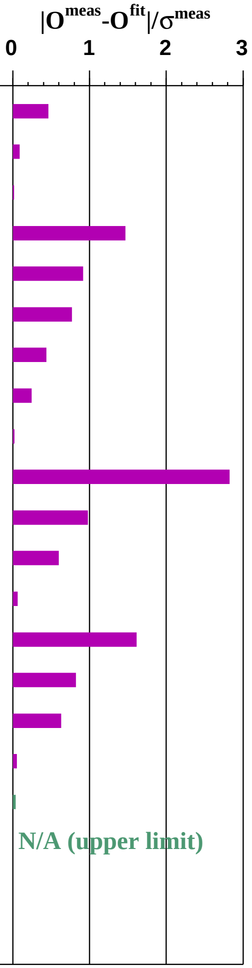
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.382
m_t [GeV]	170.9 ± 1.8	170.8
$R(b\to s\gamma)$	1.13 ± 0.12	1.12
$B_s\to\mu\mu$ [$\times 10^{-8}$]	< 8.00	0.33
Δa_μ [$\times 10^{-9}$]	2.95 ± 0.87	2.95
Ωh^2	0.113 ± 0.009	0.113



SM

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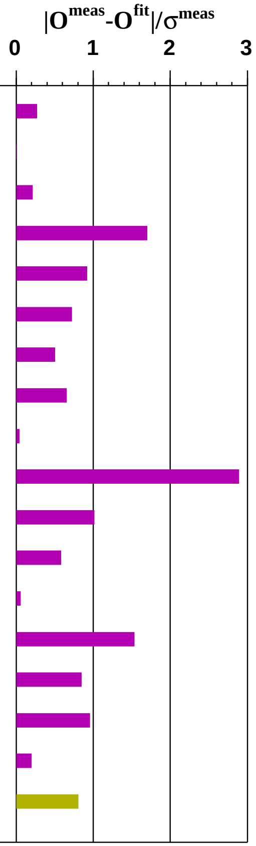
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
m_t [GeV]	170.9 ± 1.8	171.3
Γ_W [GeV]	2.140 ± 0.060	2.091



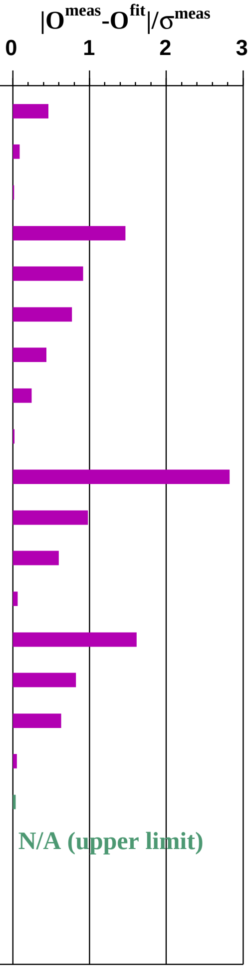
$\Rightarrow$ note the new observables: BR$(b \to s\gamma)$, $(g-2)_\mu$, CDM

Pull distributions:

[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, Weiglein '07]

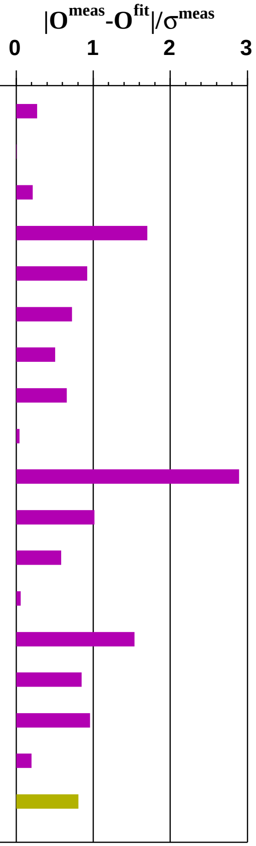
CMSSM

Variable	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02774
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952
σ^0_{had} [nb]	41.540 ± 0.037	41.486
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01641
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21613
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.382
m_t [GeV]	170.9 ± 1.8	170.8
$R(b \to s\gamma)$	1.13 ± 0.12	1.12
$B_s \to \mu\mu$ [$\times 10^{-8}$]	< 8.00	0.33
Δa_μ [$\times 10^{-9}$]	2.95 ± 0.87	2.95
Ωh^2	0.113 ± 0.009	0.113



SM

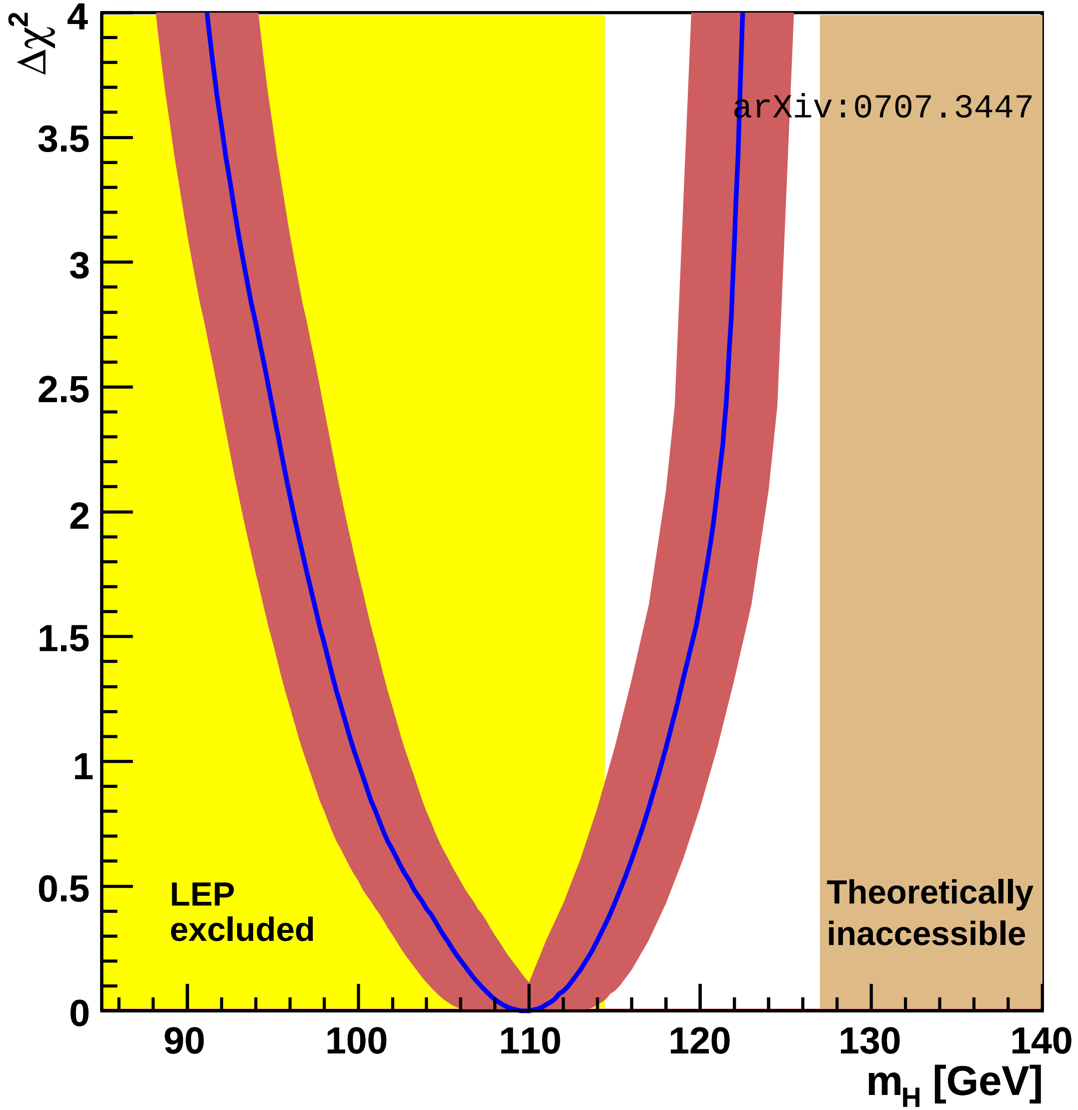
Variable	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
m_t [GeV]	170.9 ± 1.8	171.3
Γ_W [GeV]	2.140 ± 0.060	2.091



Probabilities: 24% / 20%   15% / 15% (incl. / excl. M_h)

Red band plot:

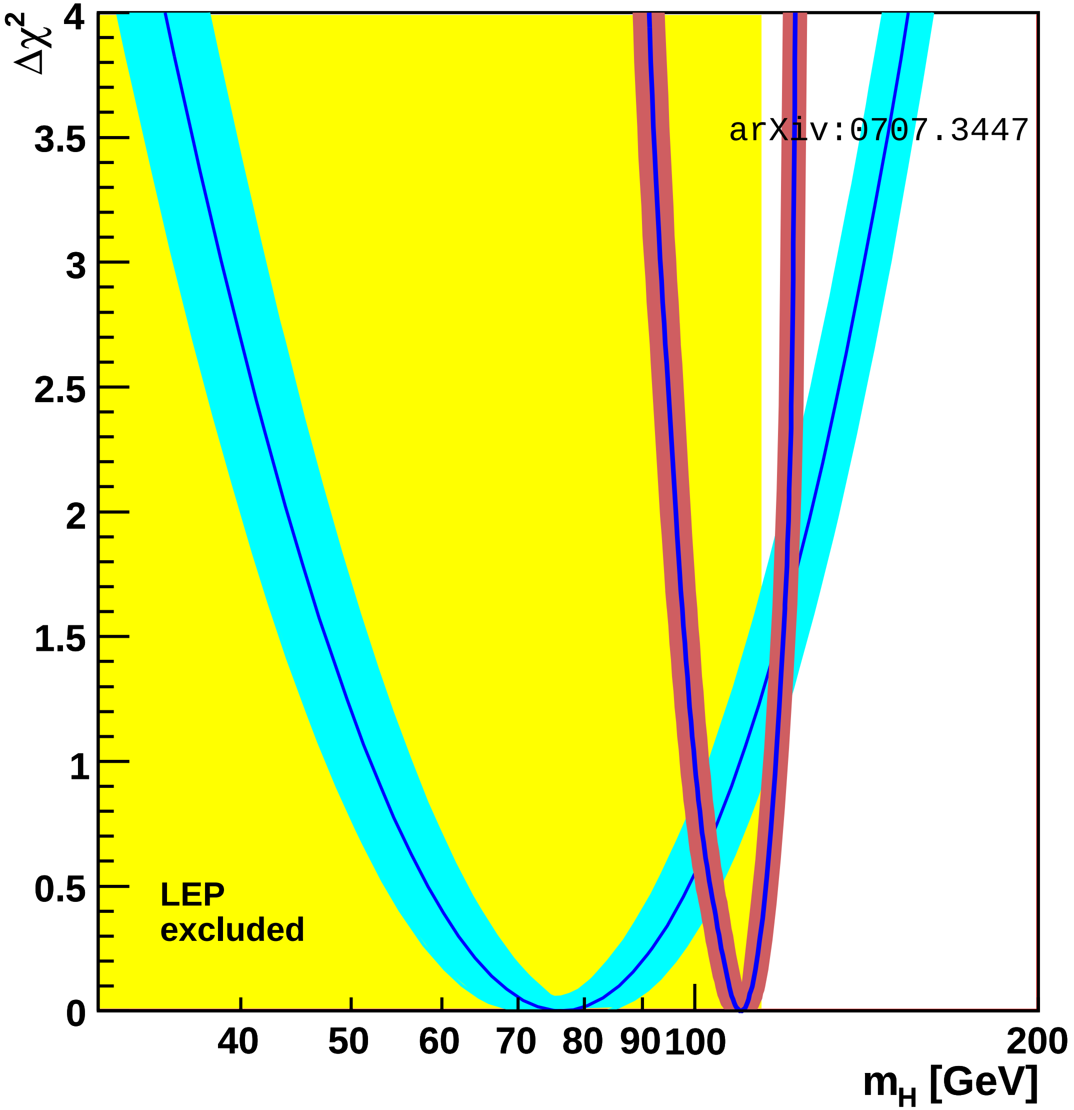
[*Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, Weiglein '07*]



$$M_h = 110^{+8}_{-10}\,(\text{exp}) \pm 3(\text{theo})\ \text{GeV}$$

Blue/Red band plot:

[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, Weiglein '07]



CMSSM (despite its simplicity) is better than the SM

4. Conclusinos

- Precision observables
  - can give valuable information about the "true" Lagrangian
  - can provide bounds on SUSY parameter space

- SM: Blue band plot: $\Rightarrow M_H^{\text{SM}} = 87^{+36}_{-27}$ GeV (too light for LEP bounds?)

- electroweak precision observables (EWPO):
  $\mathcal{O} = M_W,\ \sin^2\theta_{\text{eff}}\ (A_{\text{FB}}^{b,c},\ A_{\text{LR}}^{e,\mu}),\ R_l,\ R_b,\ \sigma_0^{\text{had}},\ \ldots$

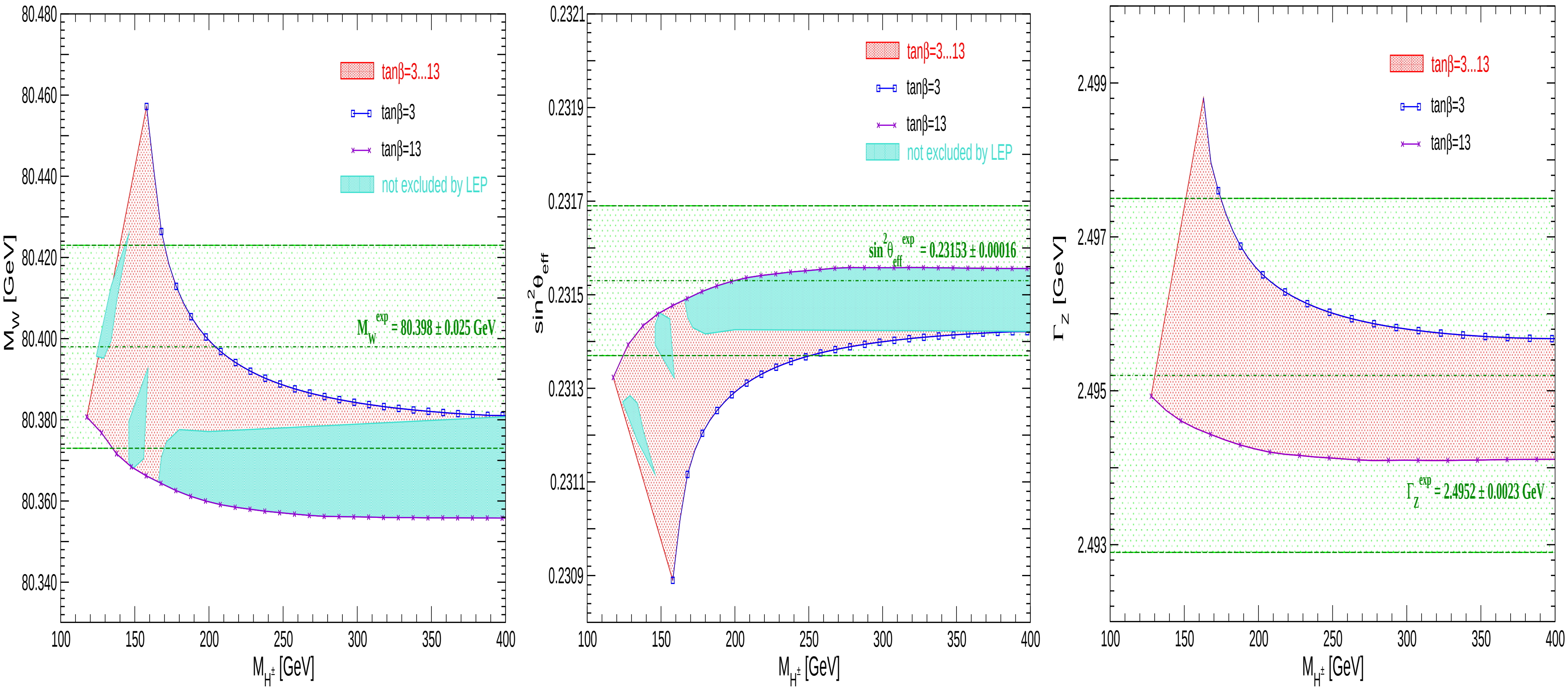
- best MSSM prediction = full (available) SM result
  + all existing MSSM corrections
  e.g. full 1L incl. complex phases
  − double counting

- SUSY dependencies:
  - strong dependence only for M_W, $\sin^2\theta_{\text{eff}}$, Γ_Z
  - strong dependence on M_{SUSY}, μ, M_2, m_t, ...
  - strong dependence on ϕ_{A_t}
  - strong dependence on ϕ_{A_b} for large $\tan\beta$

- CMSSM/mSUGRA: Red band plot: $\Rightarrow M_h^{\text{CMSSM}} = 110 \pm 8 \pm 3$ GeV

Back-up

Can EWPO close the CPX holes?



⇒ No! EWPO do not have a strong impact on CPX holes

CPX holes: ZZh_1 coupling small ⇒ small change in EWPO

Remaining theoretical (intrinsic) uncertainties of M_W:

[*J. Haestier, S.H., D. Stöckinger, G. Weiglein '05*]

[*S.H., W. Hollik, D. Stöckinger, A.M. Weber, G. Weiglein '06*]

Estimate missing SUSY corrections order by order:

- $\mathcal{O}\left(\alpha_t^2, \alpha_t\alpha_b, \alpha_b^2\right)$: beyond existing leading contributions
- $\mathcal{O}\left(\alpha\alpha_s\right)$: beyond $\Delta\rho$ approx.
- $\mathcal{O}\left(\alpha\alpha_s^2\right)$
- $\mathcal{O}\left(\alpha^2\alpha_s\right)$
- $\mathcal{O}\left(\alpha^3\right)$
- missing phase dependence at two-loop

$\Rightarrow$ evaluate for $M_{\text{SUSY}} = 300, 500, 1000$ GeV

Combine with SM uncertainty: $\delta M_W^{\text{SM,intr.}} = 4$ MeV

$$\delta M_W^{\text{SUSY,intr.}} = 5 - 11 \text{ MeV}$$

(depending on M_{SUSY})