EWPO in the (C)MSSM

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Rochester, 02/2013

1. Introduction

2. EWPO in the CMSSM

3. EWPO in the MSSM

4. Conclusions

1. Introduction

Comparison of observables with theory:

Precision data:

$M_W, \sin^2\theta_{\rm eff}, a_\mu$

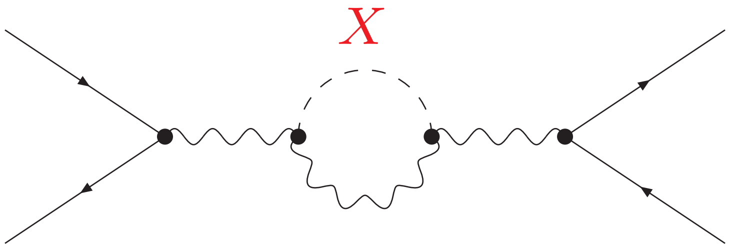
↔

Theory:

SM, MSSM , . . .

⇓

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



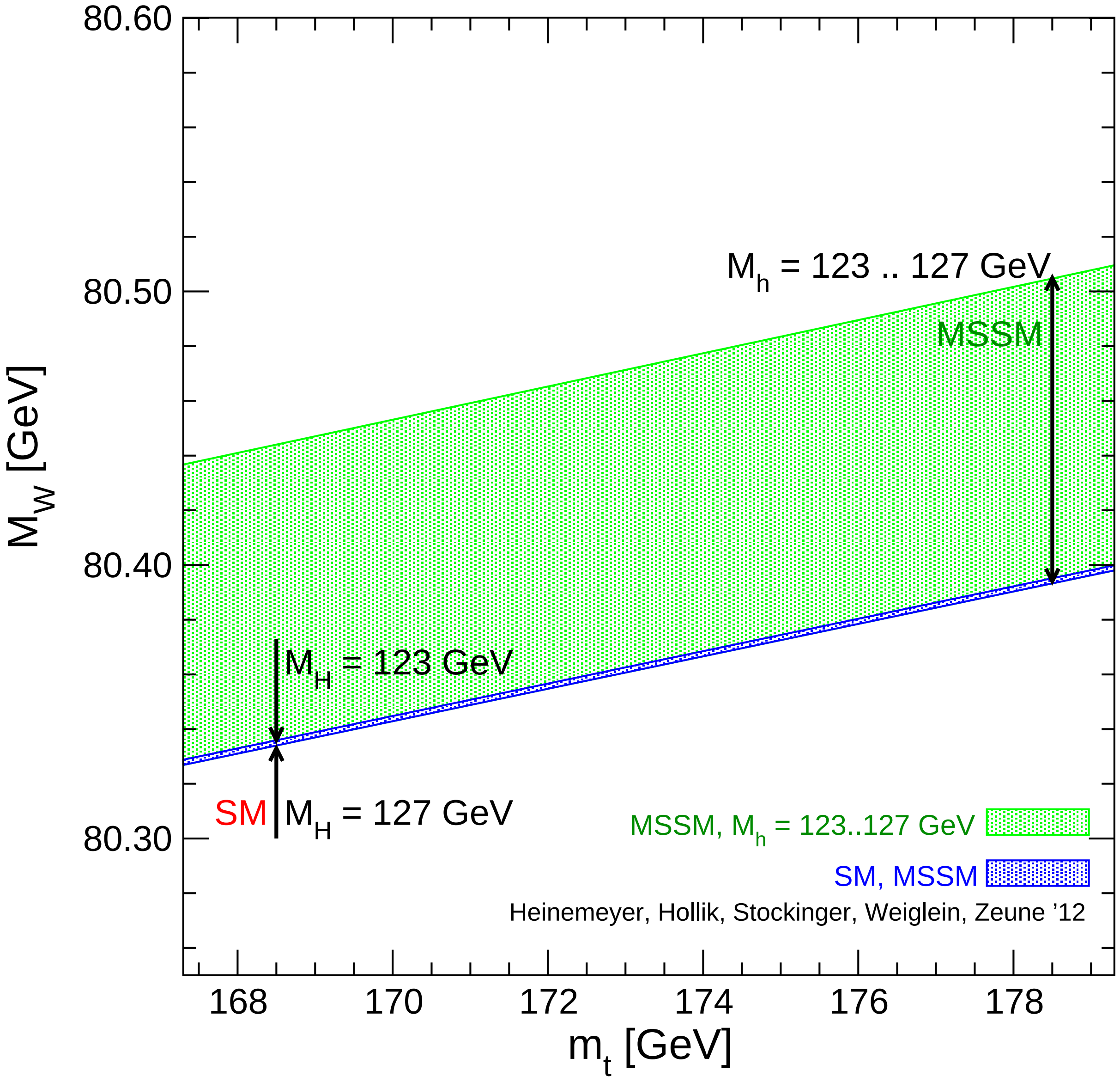
⇓

SM: limits on M_X

Very high accuracy of measurements and theoretical predictions needed

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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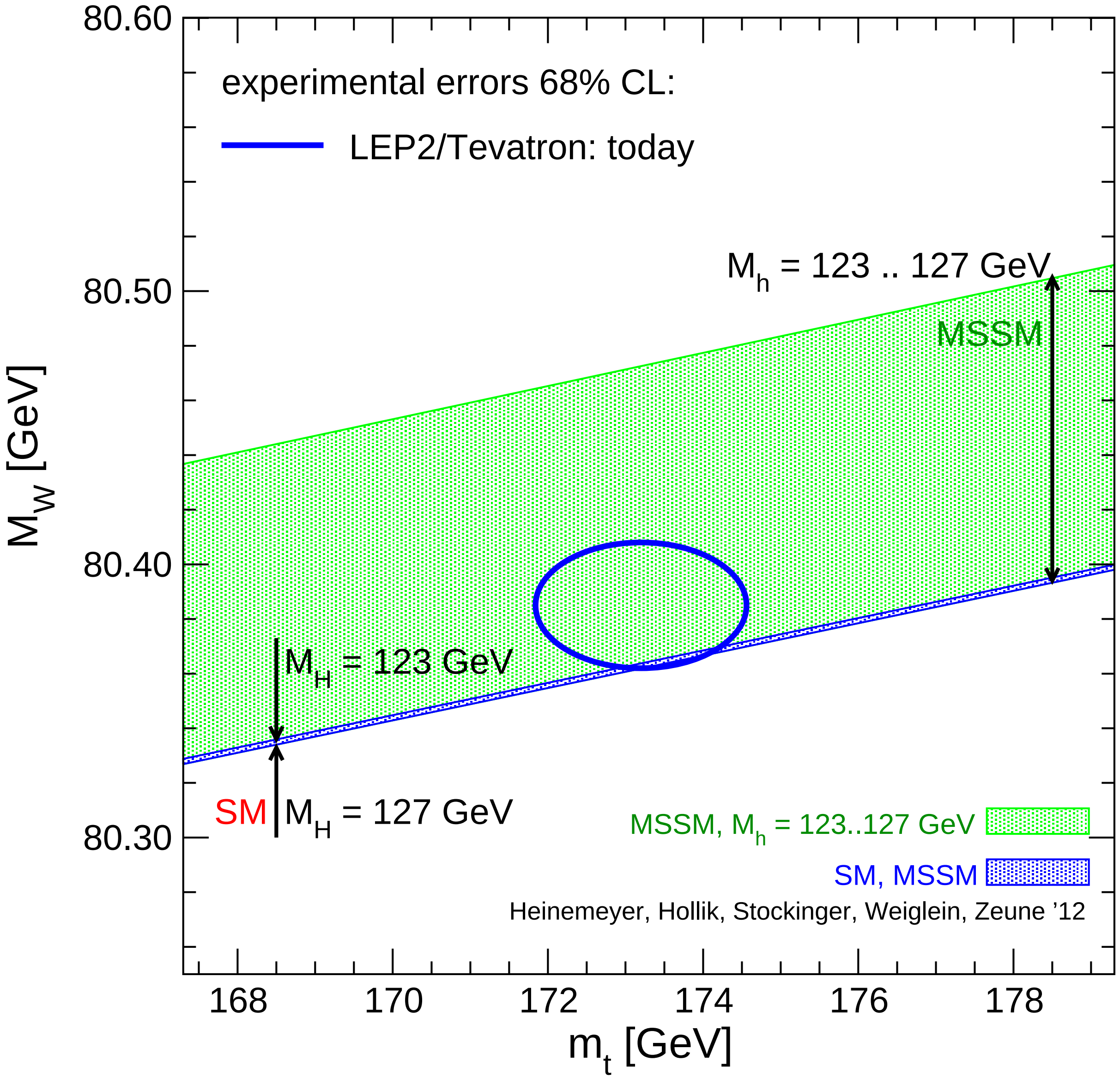

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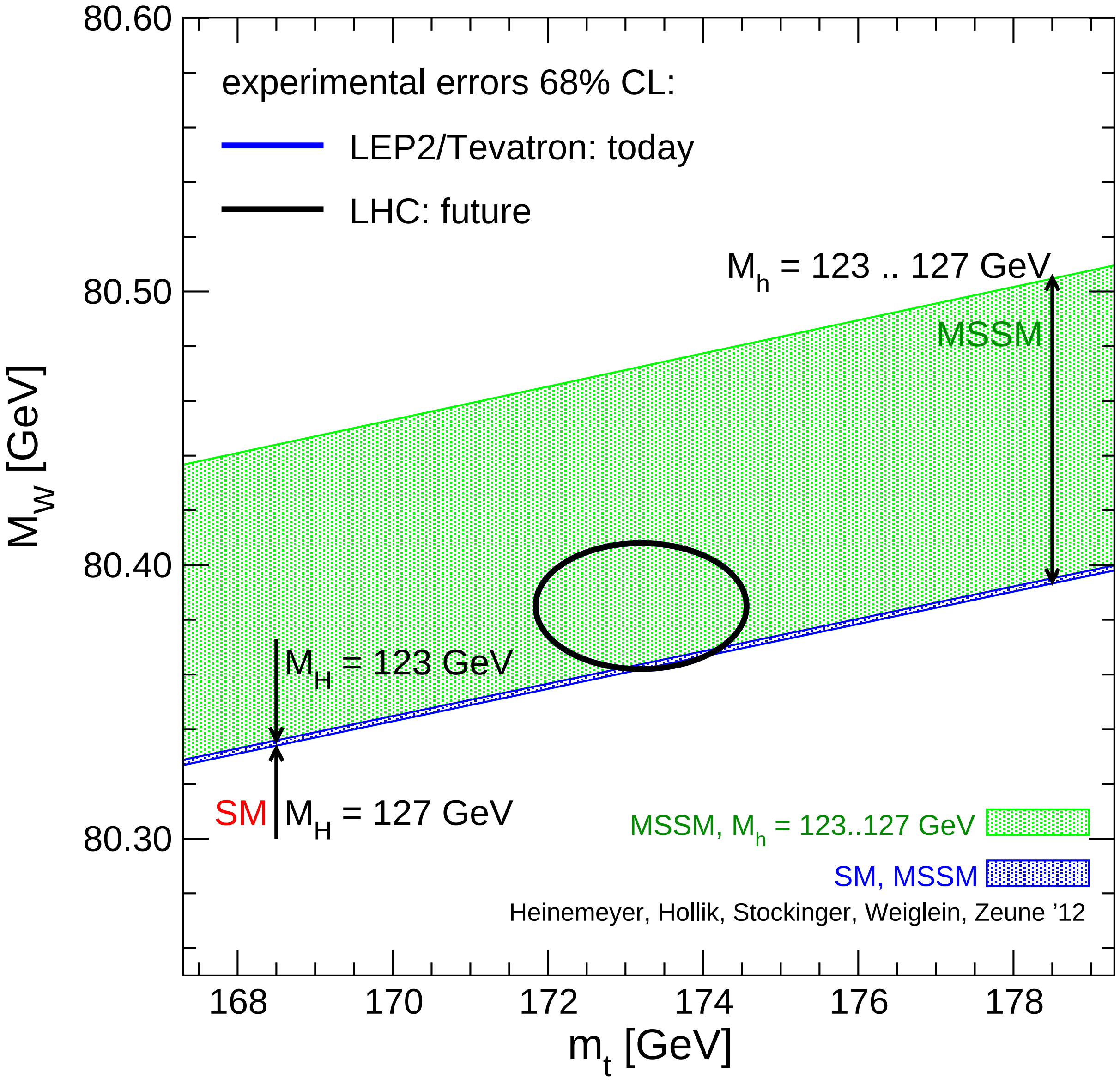

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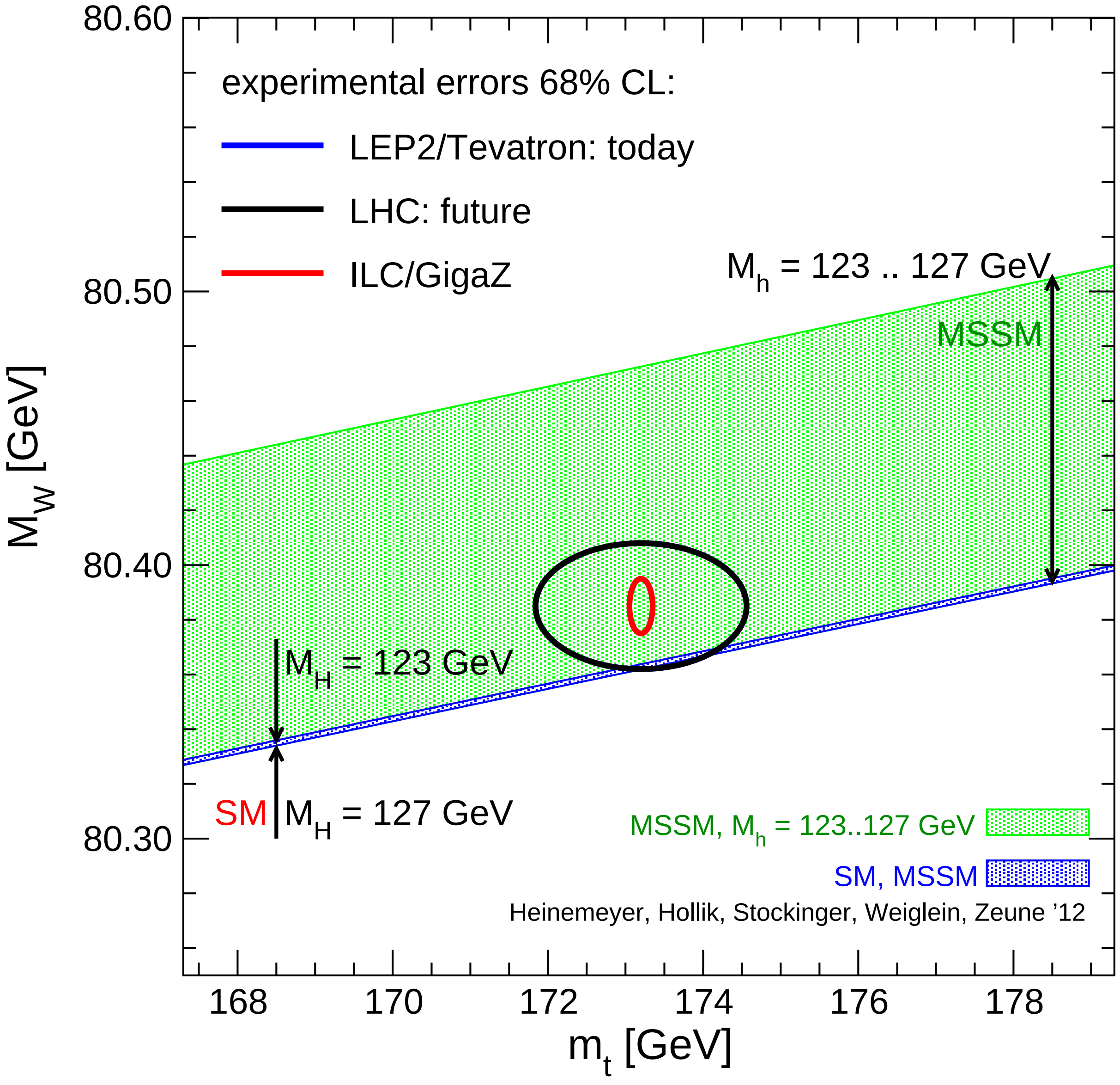

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What about the **ERRORS ?**

Three different types of errors:

Experimental error (⇒ included in the figure):
– current error
– future expectations
⇒ sets the scale, has to be matched by other errors

Theory error:
⇒ 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
⇒ focus on SM parameters

⇒ derive information about (unknown) SUSY parameters
(SUSY parametric uncertainties highly model dependent)

Precision observables in the SM and the MSSM

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*]

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

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

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

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$$\Updownarrow$$

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:

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

Comparison of SM prediction of M_W with direct measurements:

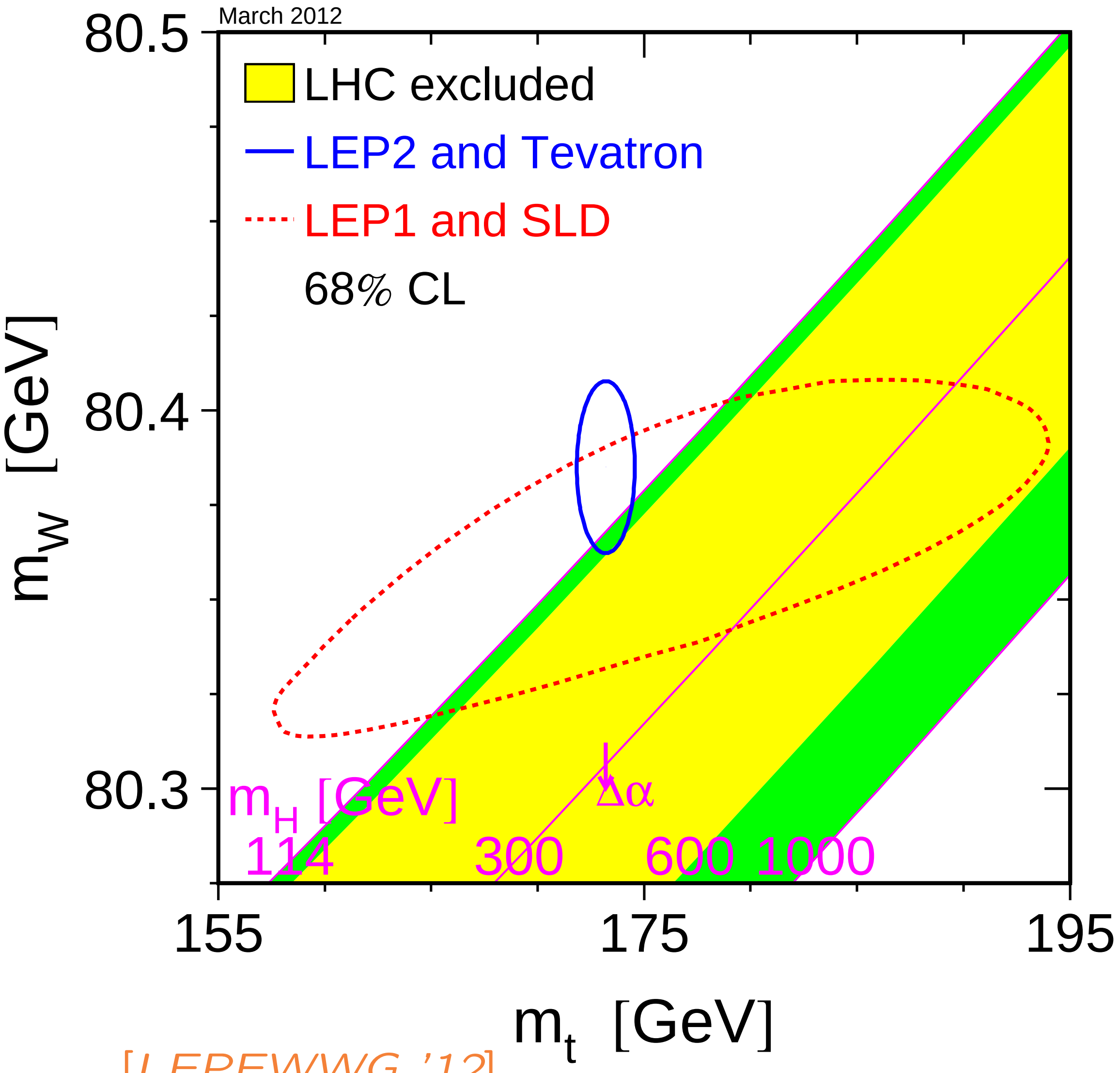
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2}\log\left(\frac{M_H}{M_W}\right)$$

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

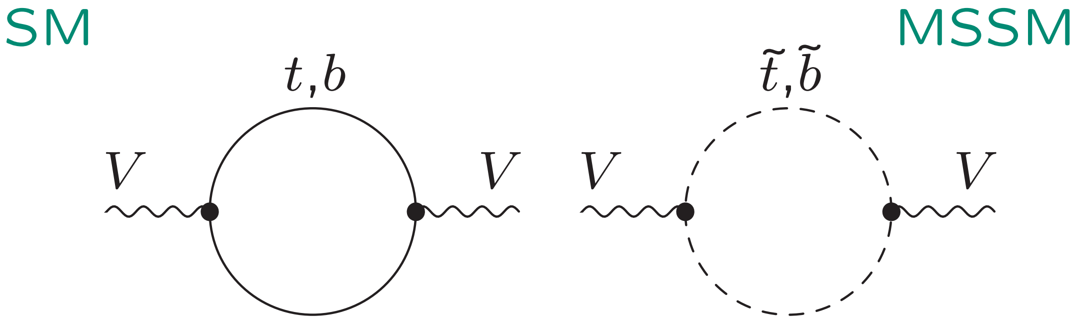


[LEPEWWG '12]

⇒ light Higgs boson preferred

Differences between the MSSM and the SM:

1.) New contributions from SUSY particles:



2.) CPV effects via new complex phases

3.) large Yukawa corrections: $\sim m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

4.) large corrections from the $b/\tilde{b}$ sector for large $\tan\beta$

5.) non-decoupling SUSY effects: $\sim \log\frac{M_{\text{SUSY}}}{M_W}$

Corrections to M_W, $\sin^2\theta_{\mathrm{eff}}$ → approximation via the ρ-parameter:

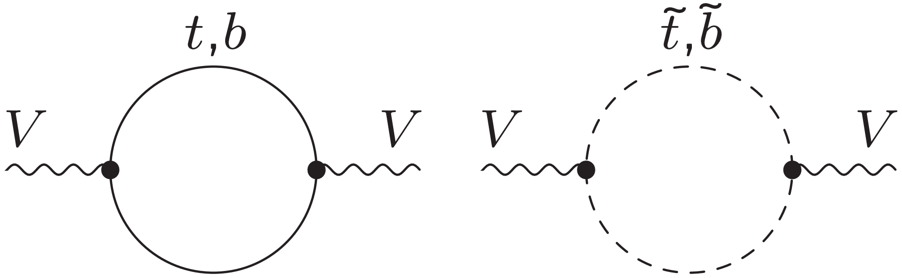
ρ measures the relative strength between neutral current interaction and charged current interaction

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

(leading, process independent terms)

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

$$\Delta M_W \approx \frac{M_W}{2} \frac{c_{\mathrm{W}}^2}{c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2} \Delta\rho, \qquad \Delta \sin^2\theta_W^{\mathrm{eff}} \approx -\frac{c_{\mathrm{W}}^2 s_{\mathrm{W}}^2}{c_{\mathrm{W}}^2 - s_{\mathrm{W}}^2} \Delta\rho$$



$\Delta\rho^{\mathrm{SUSY}}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\Rightarrow M_W^{\mathrm{SUSY}} \gtrsim M_W^{\mathrm{SM}}$

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	$\leq$15	10	7
δm_t [GeV]	0.9	$\leq$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:

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

$$\text{SM}: \delta M_W^{\text{theory}} \approx \pm 4\ \text{MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{theory}} \approx \pm 4.7 \times 10^{-5}$$

$$\text{MSSM}: \delta M_W^{\text{theory}} \approx \pm(5-10)\ \text{MeV}, \quad \delta \sin^2\theta_{\text{eff}}^{\text{theory}} \approx \pm(5-7) \times 10^{-5}$$

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

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

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

Future:

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

$$\text{MSSM}: \delta M_W^{\text{theory}} \gtrsim \pm (3-5)\ \text{MeV}, \quad \delta \sin^2\theta_{\text{eff}}^{\text{theory}} \gtrsim \pm (2.5-3.5) \times 10^{-5}$$

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

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

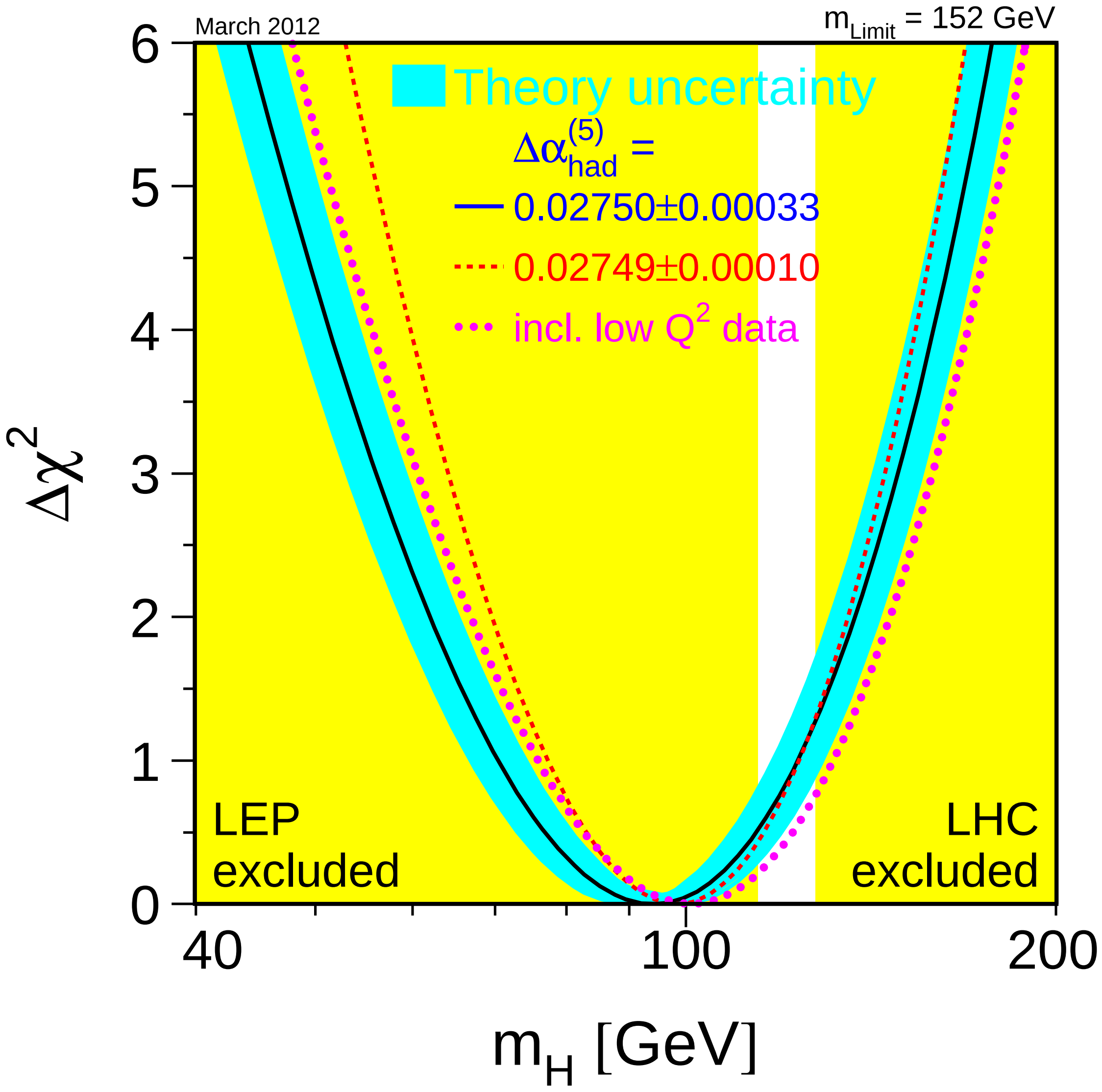
$$\text{[GigaZ]}: \quad \delta M_W^{\text{exp}} \approx \pm 7\ \text{MeV}, \qquad \delta \sin^2\theta_{\text{eff}}^{\text{exp}} \approx \pm 1.3 \times 10^{-5}$$

Indirect determination of M_H^{SM}:

[LEPEWWG '12]

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

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



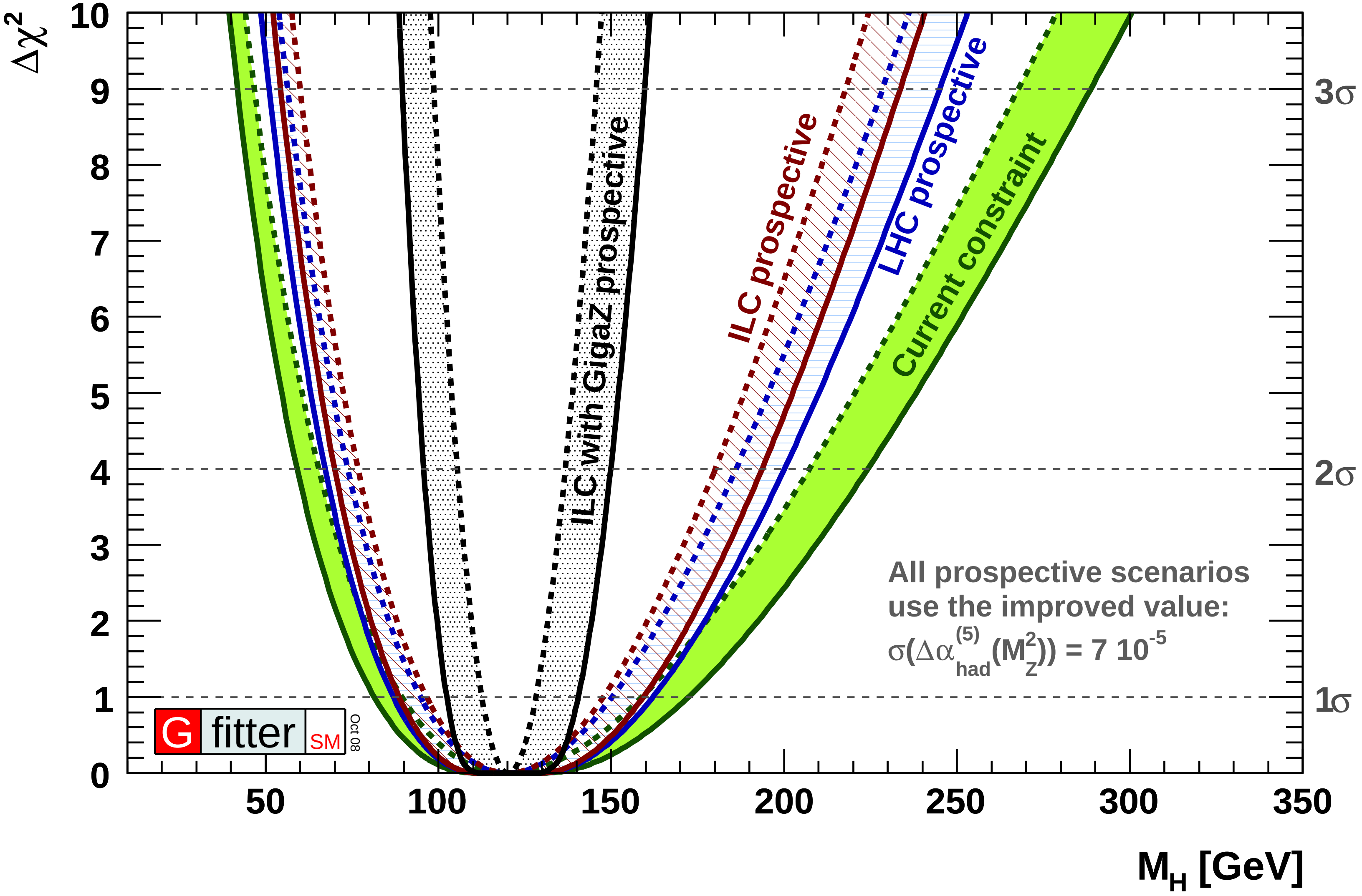
Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

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

Improvement in the Blue Band plot:

[GFitter '09]



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

2. EWPO in the CMSSM

⇒ see back-up for definitions

- Electroweak precision observables (EWPO) ?
- B physics observables (BPO) ?
- Cold dark matter (CDM) ?

⇒ combination of EWPO, BPO, CDM ?

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EWPO M_W : information on $m_{\tilde{t}}$, $m_{\tilde{b}}$ or M_A, $\tan\beta$ or . . .

EWPO $(g-2)_\mu$: information on $\tan\beta$ and/or $m_{\tilde{\chi}^0}$, $m_{\tilde{\chi}^\pm}$ and/or $m_{\tilde{\mu}}$, $m_{\tilde{\nu}_\mu}$

BPO BR$(b \to s\gamma)$: information on $\tan\beta$ and/or $M_{H^\pm}$ and/or $m_{\tilde{t}}$, $m_{\tilde{\chi}^\pm}$

CDM (LSP gives CDM) : information on $m_{\tilde{\chi}^0_1}$ and $m_{\tilde{\tau}}$ or M_A or . . .

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⇒ combination makes only sense if all parameters are connected!

⇒ GUT based models: CMSSM, NUHM1, . . .

Testing SUSY with m_t and M_W

Sensitive test of any model:

Fit m_t and/or M_W and compare with experimental values:

$$\begin{aligned} m_t^{\rm exp} &= 173.1 \pm 1.3 \text{ GeV} \\ M_W^{\rm exp} &= 80.399 \pm 0.023 \text{ GeV} \end{aligned}$$

[*LEPEWWG '09*]

[*TevEWWG '09*]

$$m_t^{\text{fit,SM,excl.}\,M_W} = 172.6^{+13.3}_{-10.2} \text{ GeV}$$

$$m_t^{\text{fit,SM,incl.}\,M_W} = 179.3^{+11.6}_{-8.5} \text{ GeV}$$

$$M_W^{\text{fit,SM,excl.}\,m_t} = 80.363 \pm 0.032 \text{ GeV}$$

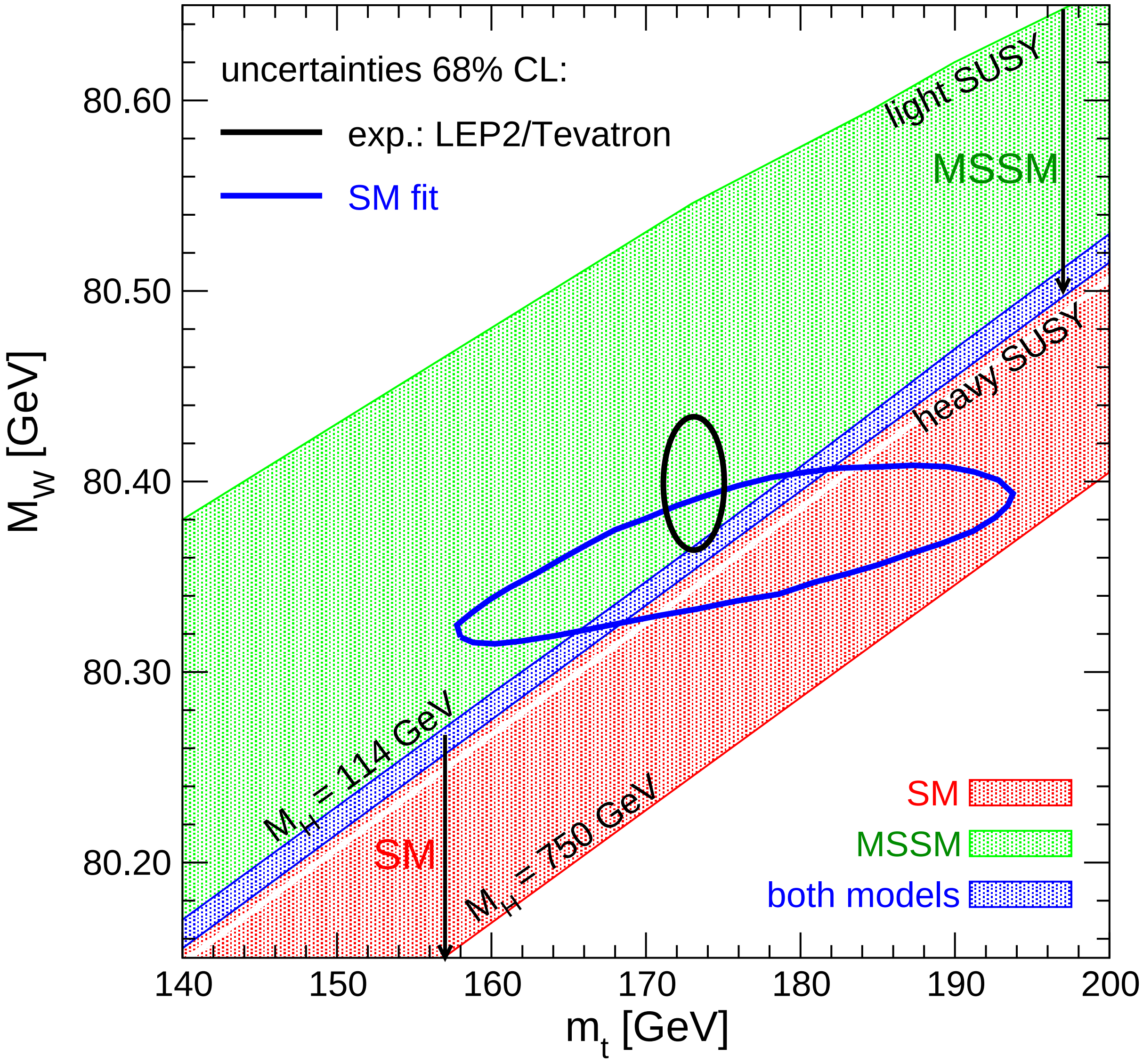
$$M_W^{\text{fit,SM,incl.}\,m_t} = 80.364 \pm 0.020 \text{ GeV}$$

$\Rightarrow$ non-trivial success of the SM

$\Rightarrow$ quantum corrections up to two-loop needed

Comparison of direct and indirect determination of m_t and M_W in the SM and the MSSM :

[2009]



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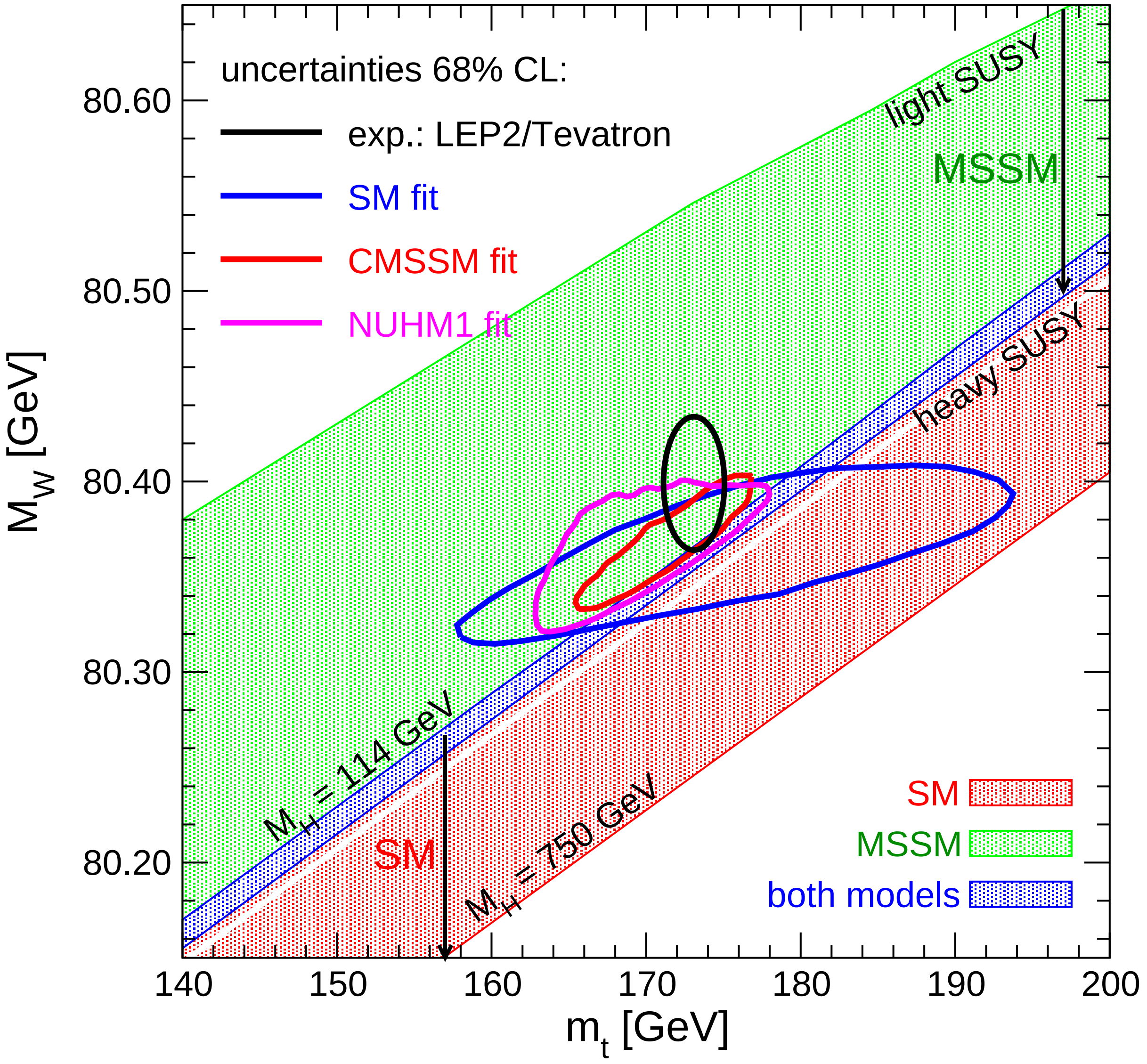

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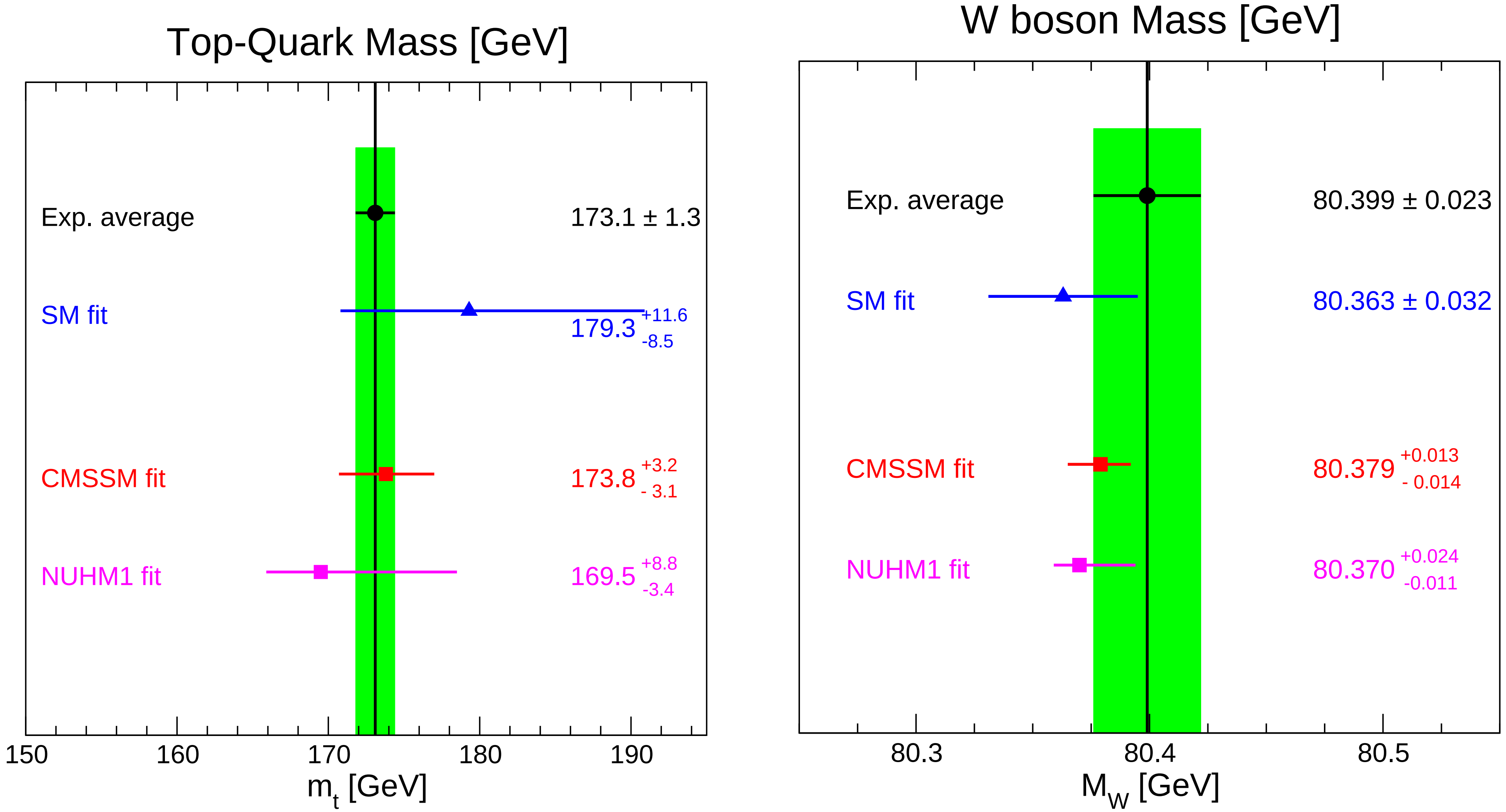
M_W fit: M_W not included, m_t fit: m_t not included

(SM fit: M_H not included – CMSSM/NUHM1 fit: M_h included)

[2009]



⇒ CMSSM and NUHM1 fit amazingly well m_t and M_W

⇒ better than the SM: smaller errors, better best-fit points

3. EWPO in the MSSM

Questions:

1. Can one model be favored over the other now?

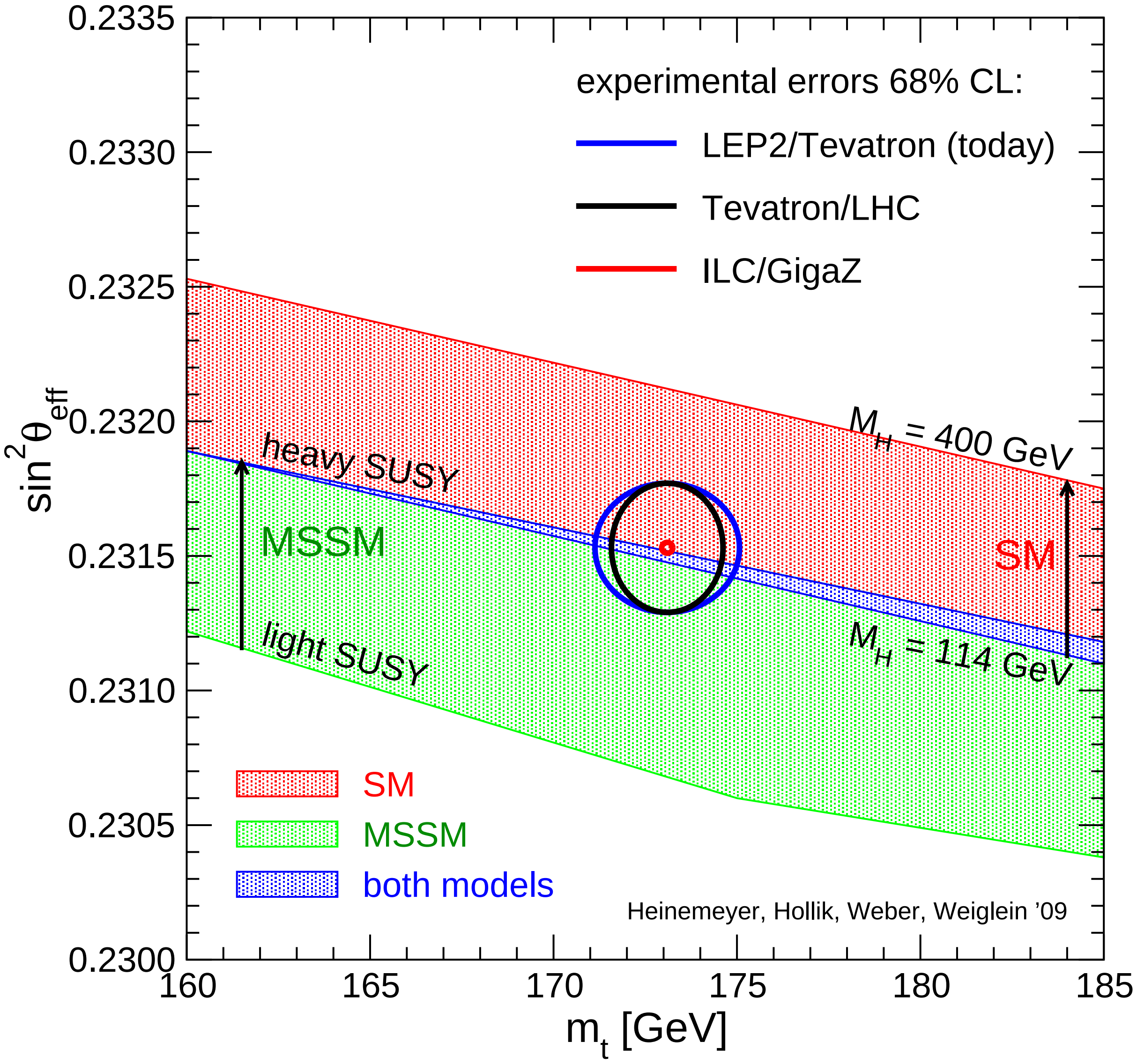
2. Can one model be favored over the other with LC/GigaZ precision?

3. Can certain MSSM parameters be favored by the EWPO?

⇒ focus on M_W and $\sin^2\theta_{\text{eff}}$
⇒ most precise and best calculated EWPO in the MSSM

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

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



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Scenario with no SUSY particles at the LHC:

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

→ SPS 1a with heavy scalars

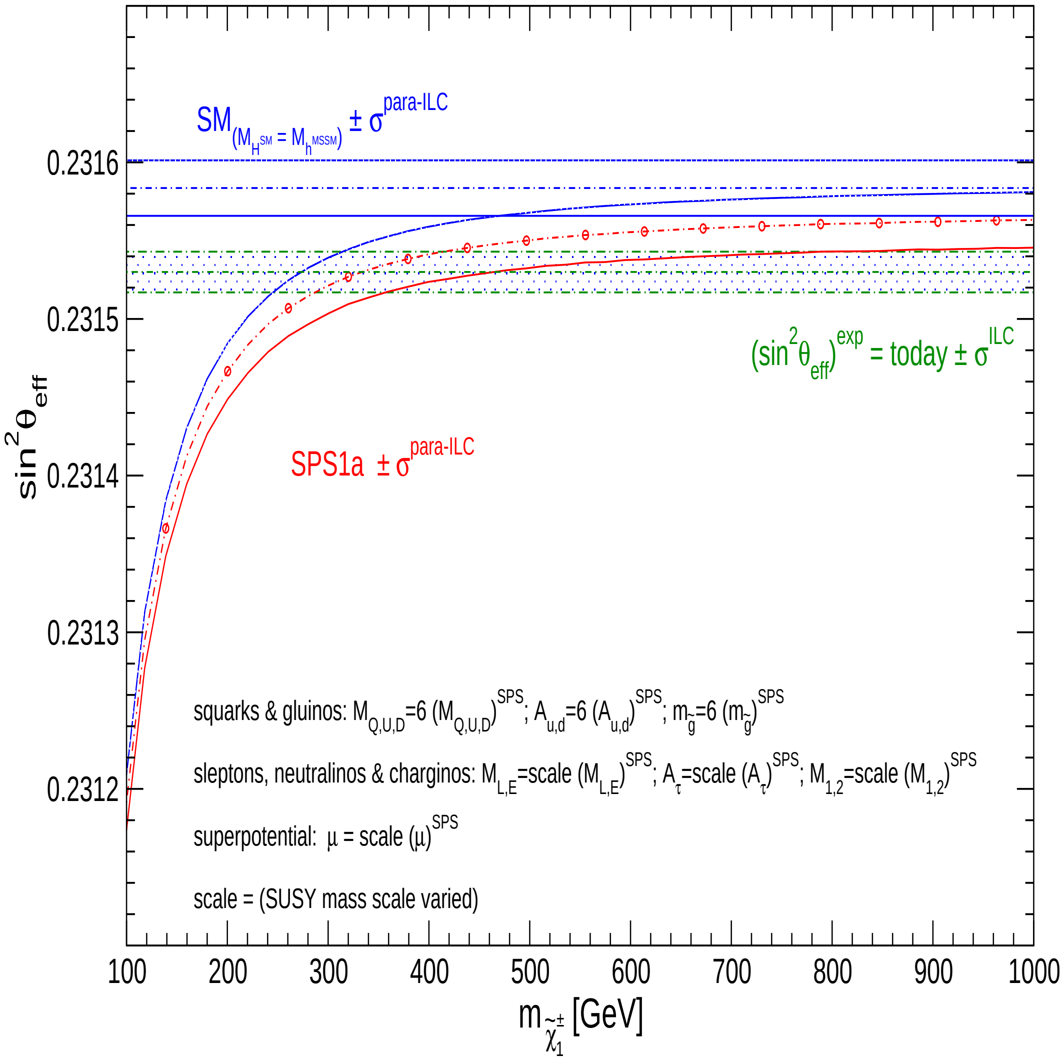
SM prediction

vs.

MSSM (SPS 1a) prediction

vs.

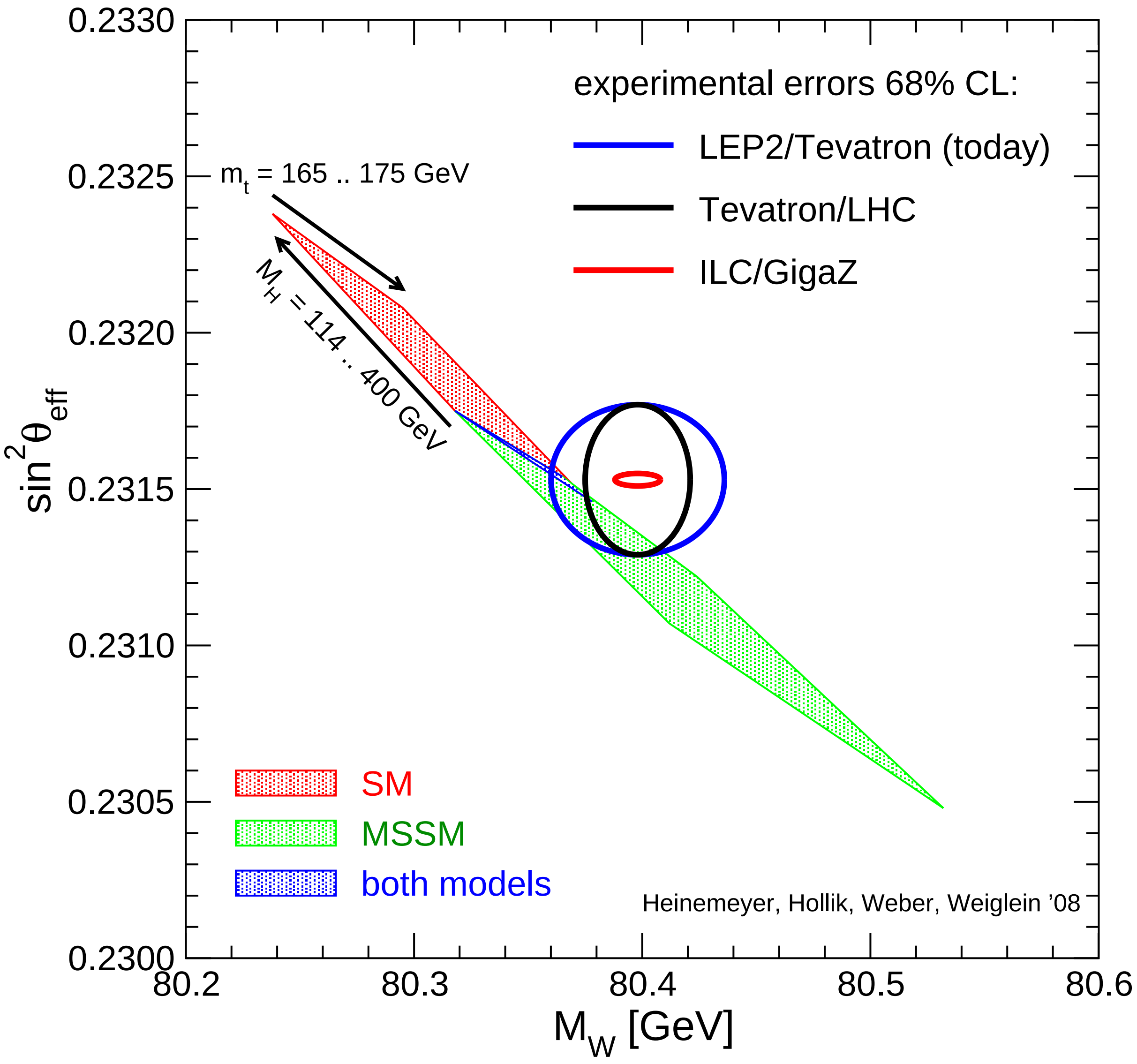
LC resolution



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

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

[S.H., W. Hollik, A. Weber, G. Weigelein '10]



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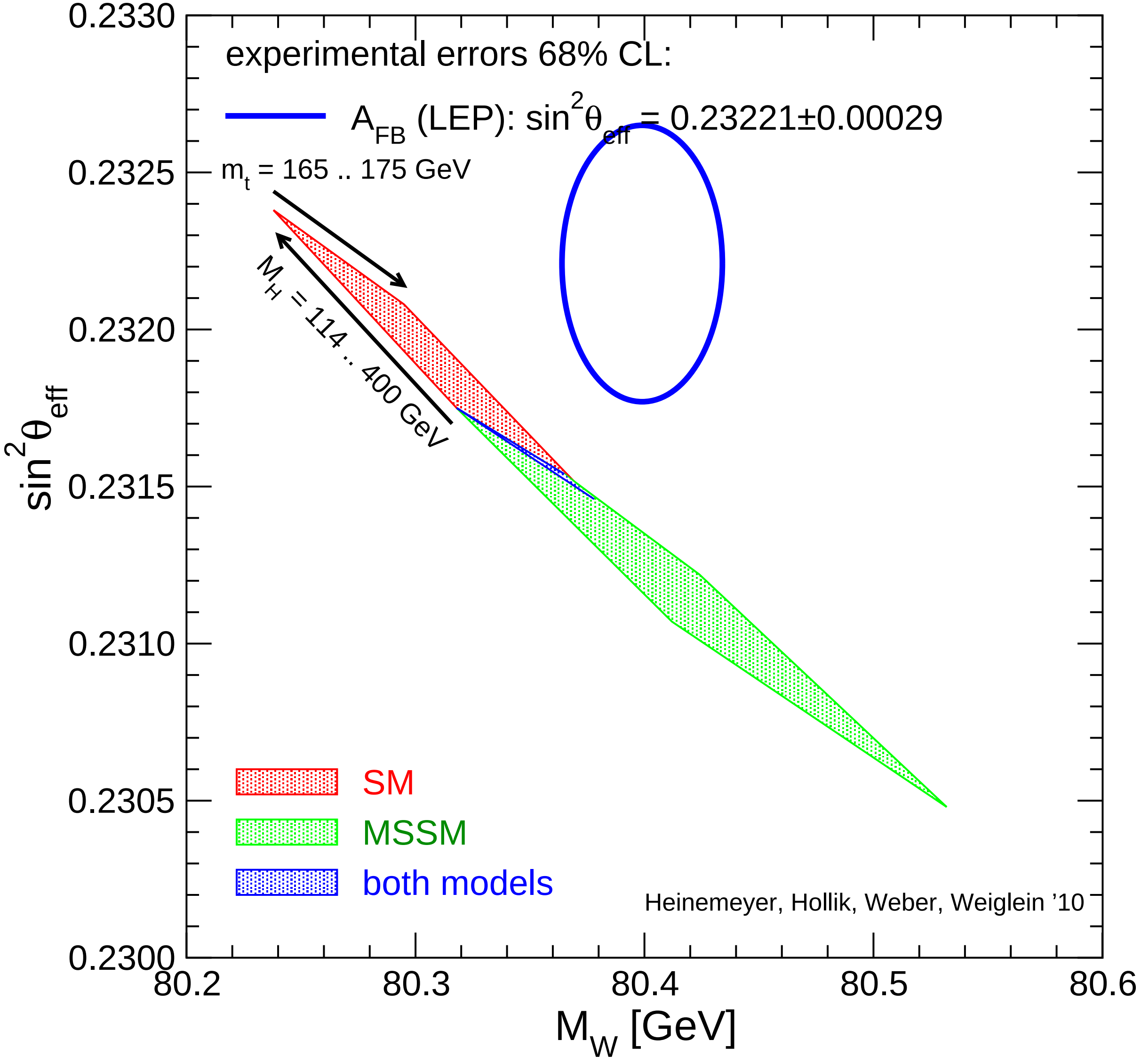

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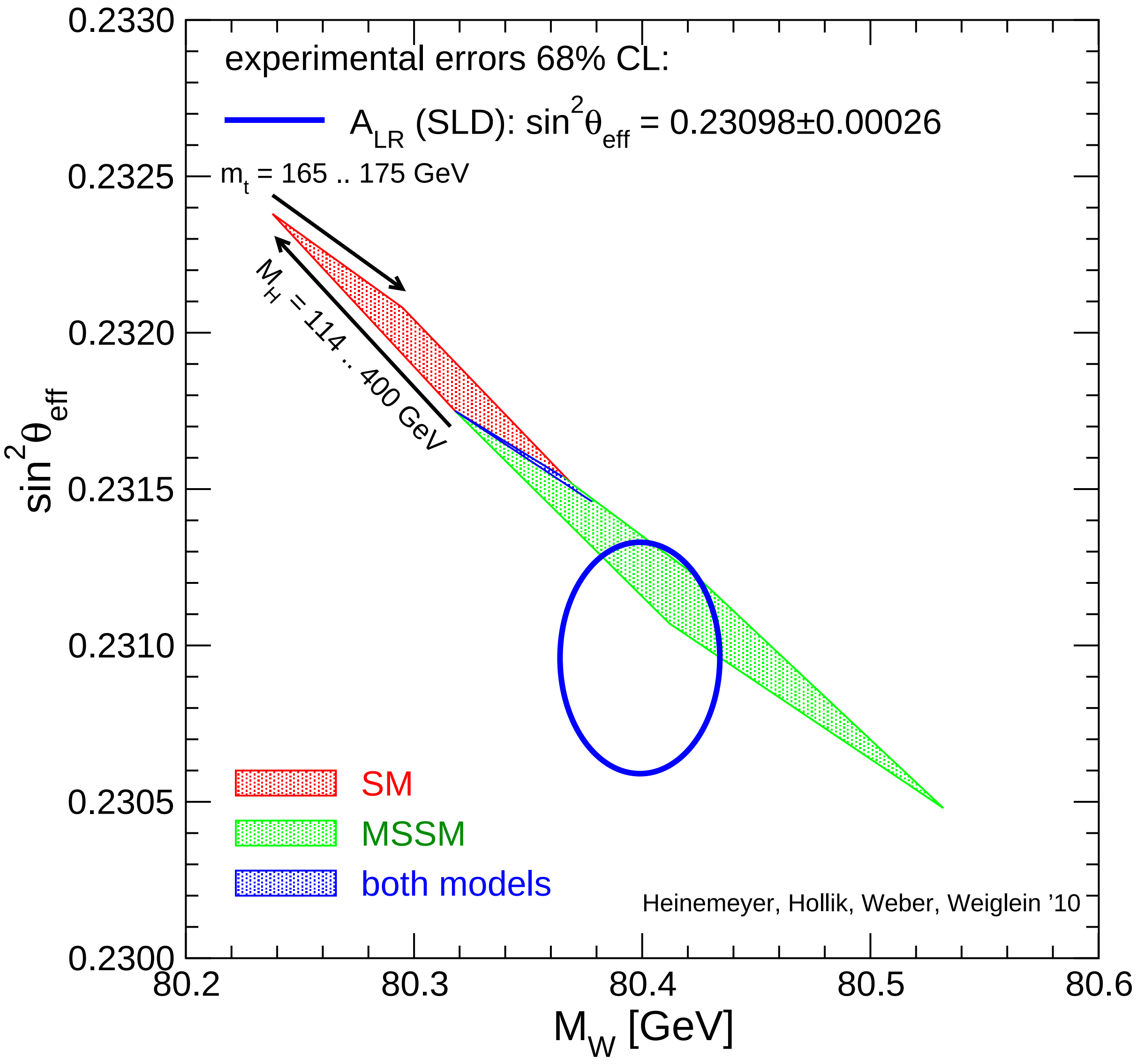

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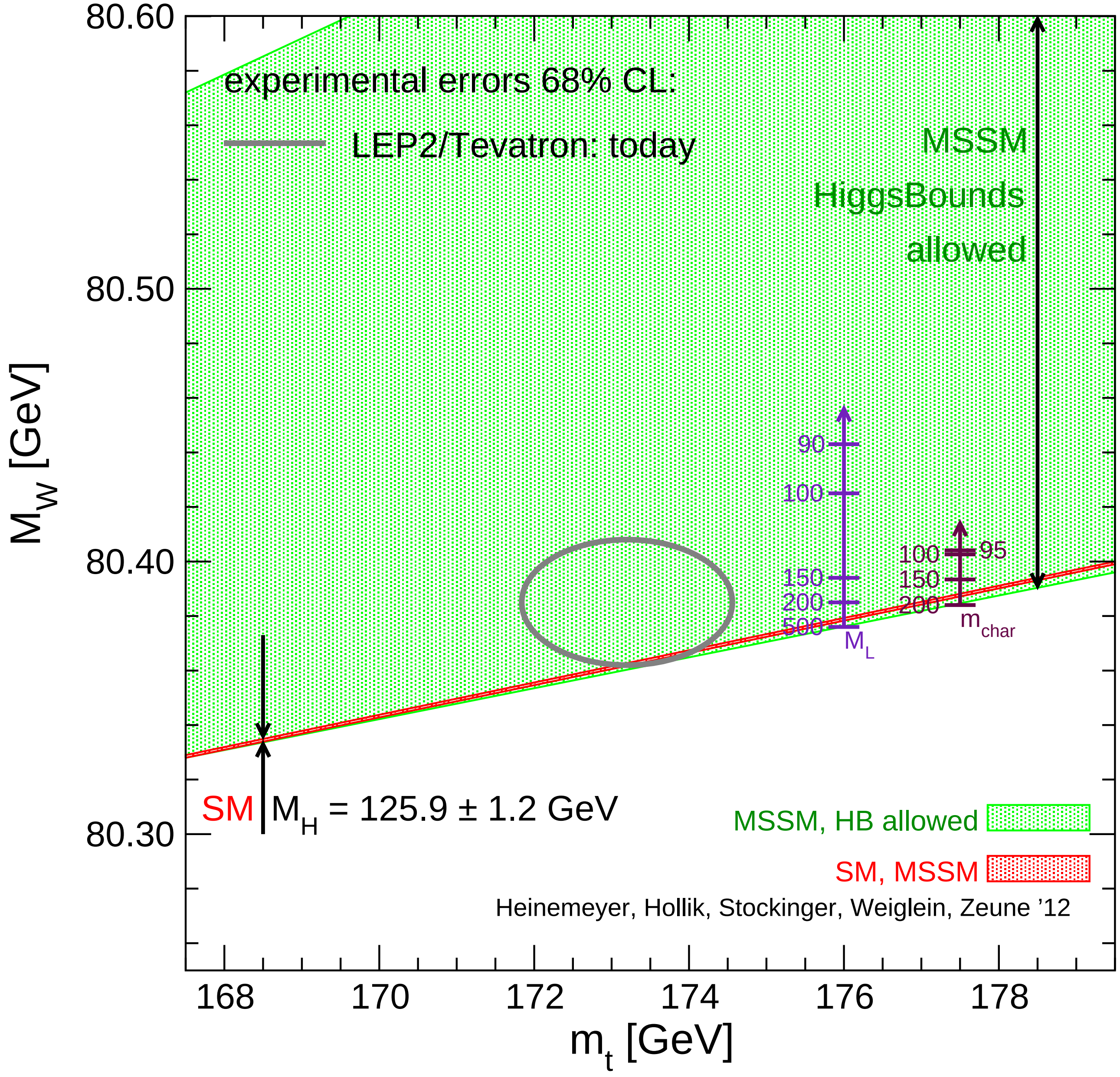
Effects of SUSY masses:

[S.H., G. Weiglein, L. Zeune '12 - PRELIMINARY]

⇒ extensive parameter scan:

Parameter	Minimum	Maximum
μ	-2000	2000
$M_{\tilde{E}_{1,2,3}} = M_{\tilde{L}_{1,2,3}}$	100	2000
$M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}}$	500	2000
$M_{\tilde{Q}_3}$	100	2000
$M_{\tilde{U}_3}$	100	2000
$M_{\tilde{D}_3}$	100	2000
$A_e = A_\mu = A_\tau$	-3 $M_{\tilde{E}}$	3 $M_{\tilde{E}}$
$A_u = A_d = A_c = A_s$	-3 $M_{\tilde{Q}_{12}}$	3 $M_{\tilde{Q}_{12}}$
A_b	-3 max$(M_{\tilde{Q}_3}, M_{\tilde{D}_3})$	3 max$(M_{\tilde{Q}_3}, M_{\tilde{D}_3})$
A_t	-3 max$(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$	3 max$(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$
tan β	1	60
M_3	500	2000
M_A	90	1000
M_2	100	1000

Effects of charginos and staus: [*S.H., G. Weiglein, L. Zeune '12 - PRELIMINARY*]



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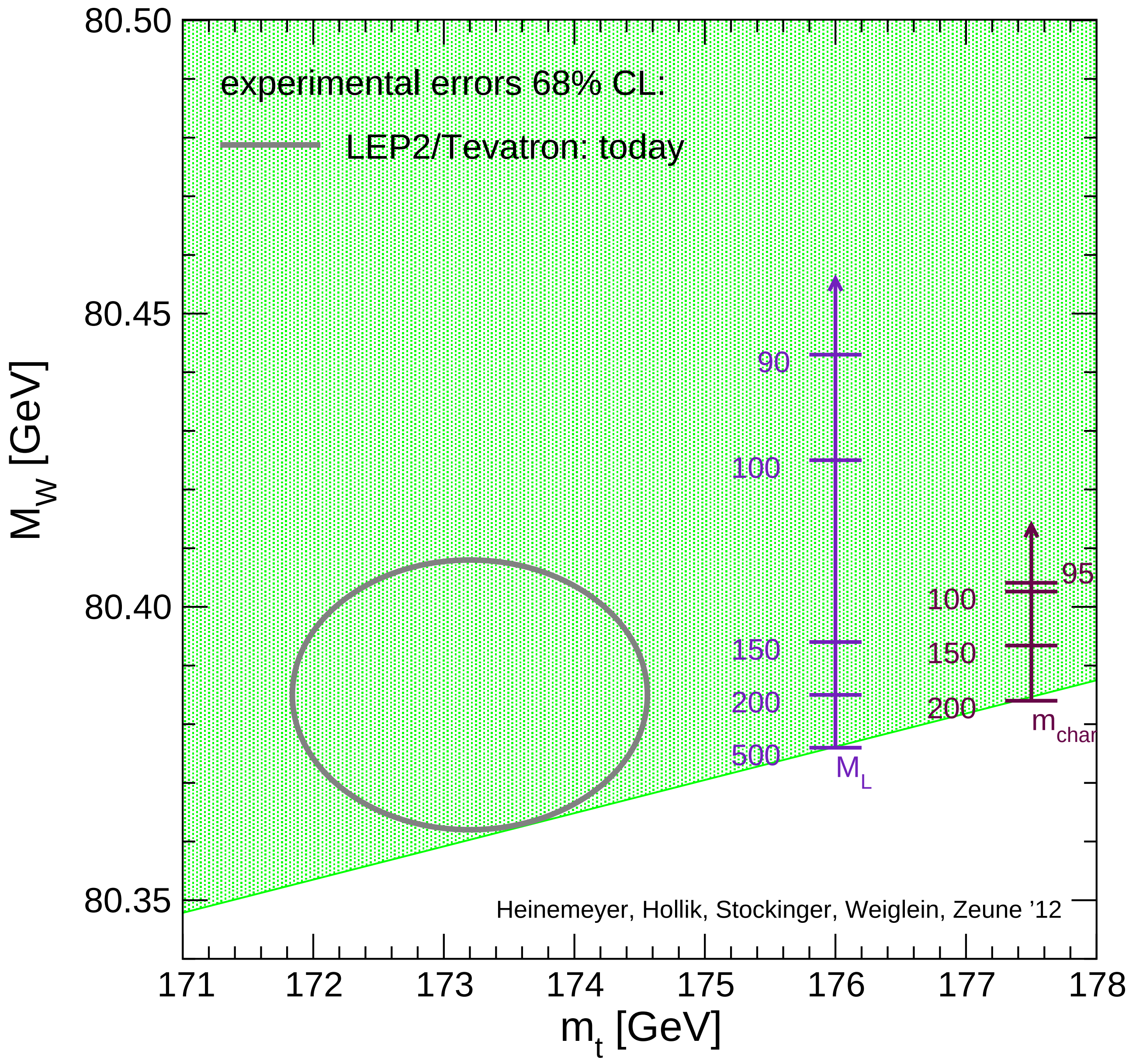

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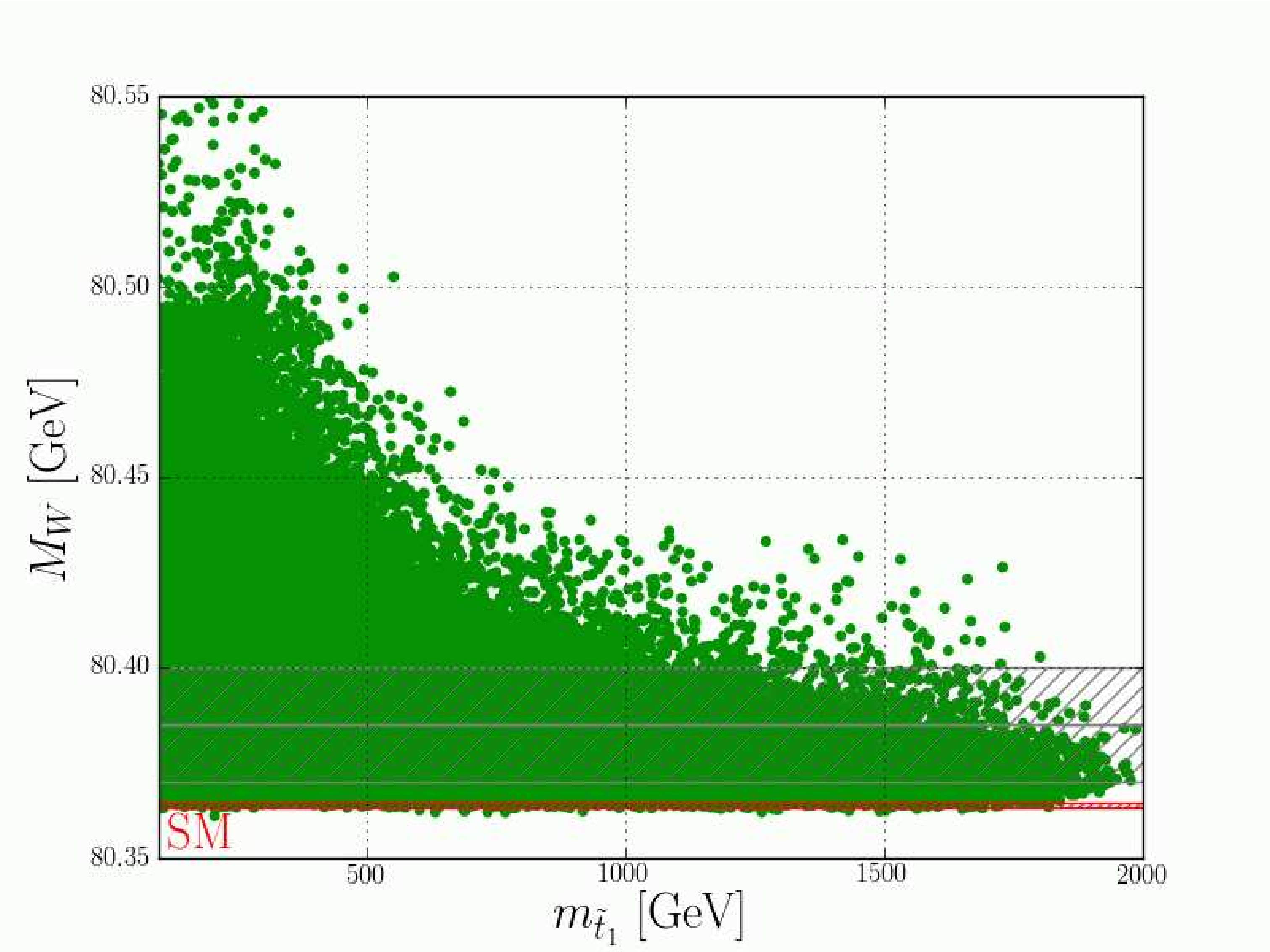

All points HiggsBounds allowed

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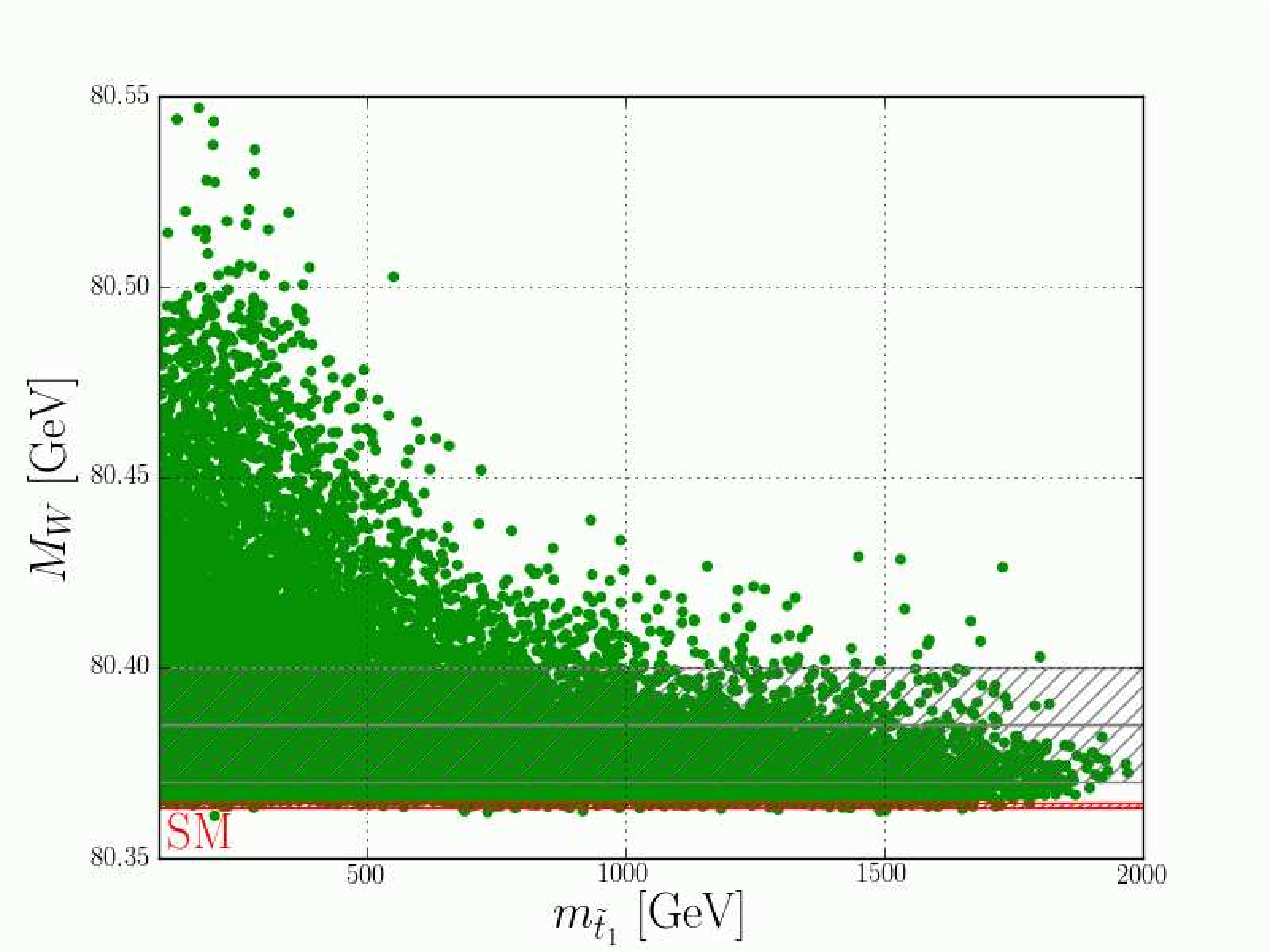
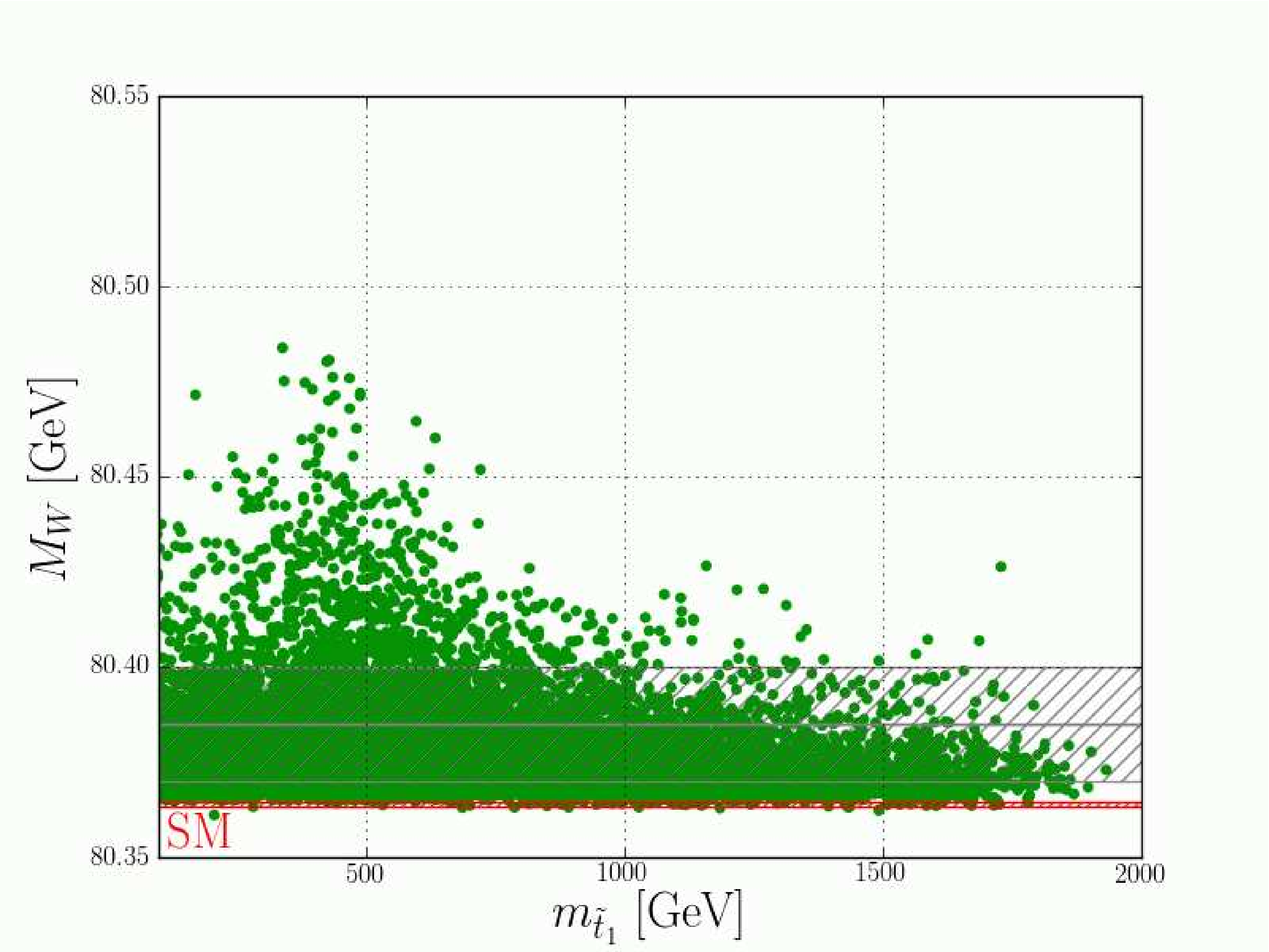
[S.H., G. Weiglein, L. Zeune '12 - PRELIMINARY]



$\ldots \oplus m_{\tilde{q}_{1,2}}, m_{\tilde{g}} >$ 1200 GeV

Effects of stops:

[S.H., G. Weiglein, L. Zeune '12 - PRELIMINARY]



$\ldots \oplus m_{\tilde{b}_i} >$ 500 GeV

Effects of stops:

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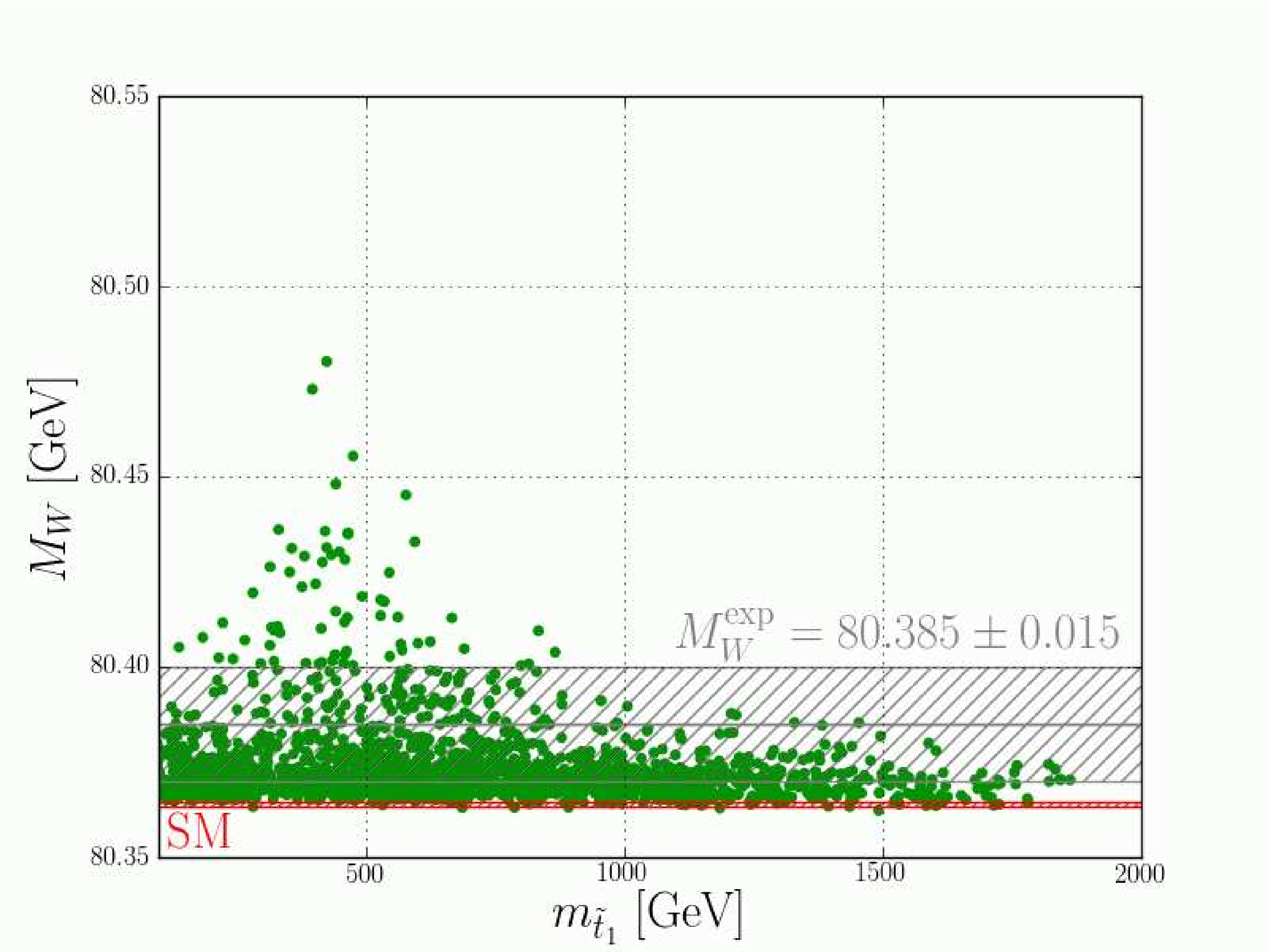
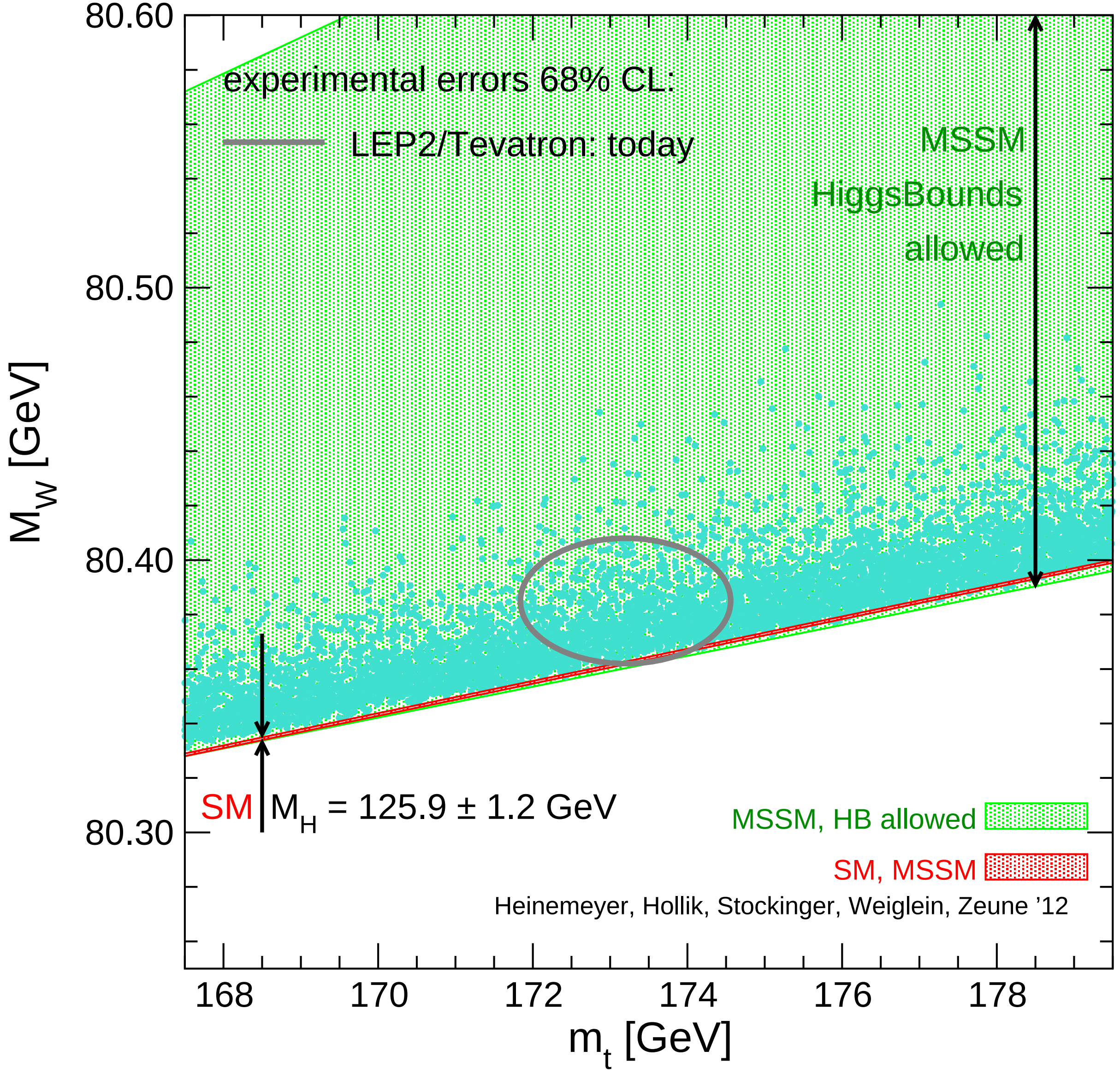


$\ldots \oplus\ m_{\tilde{l}}, m_{\tilde{\chi}_i^\pm}, m_{\tilde{\chi}_j^0} > 500$ GeV

Effects of stops, sbottoms, M_h:

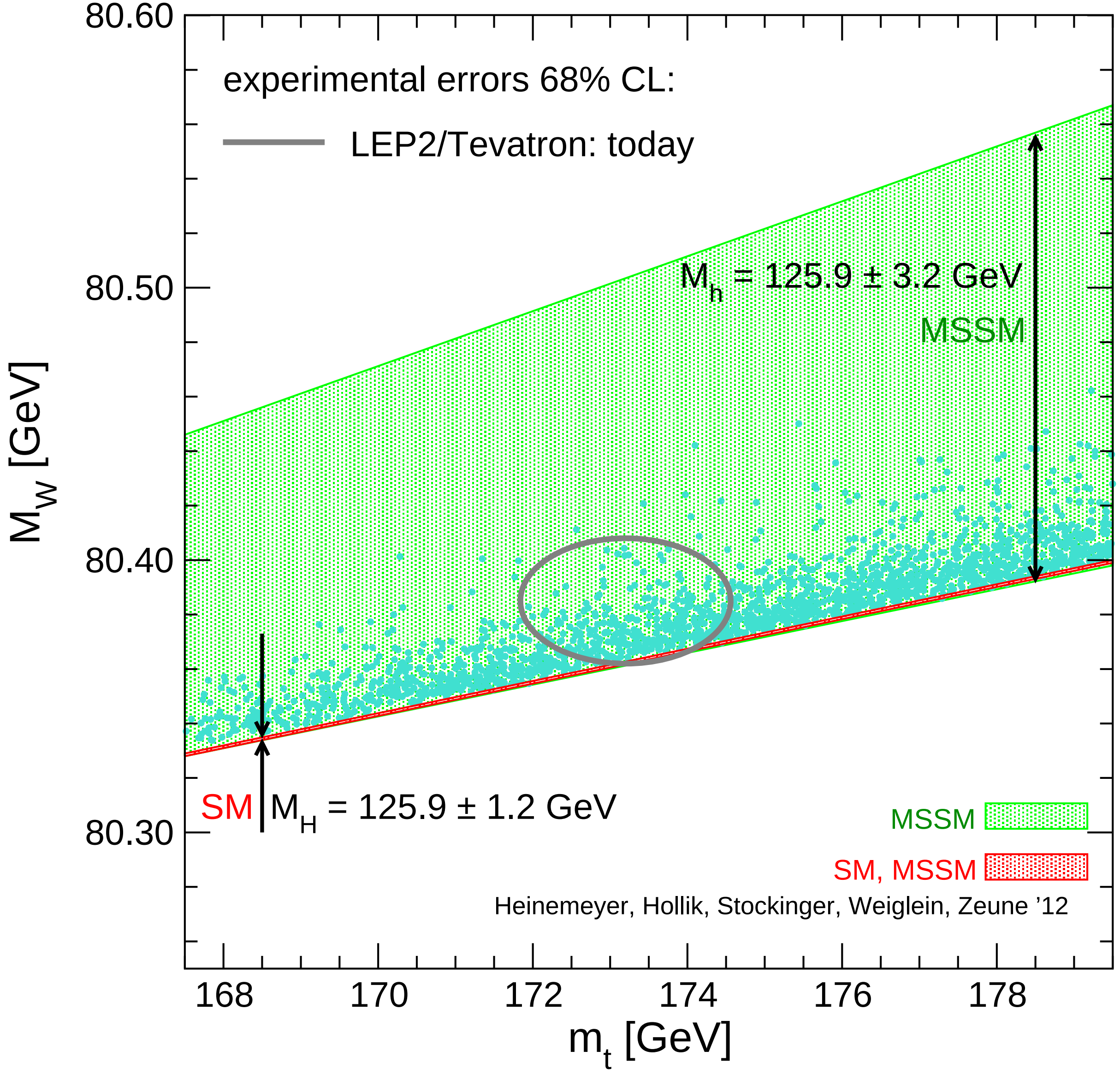
[S.H., G. Weiglein, L. Zeune '12 - PRELIMINARY]



light blue: $m_{\tilde{t}_i}, m_{\tilde{b}_j} > 500$ GeV, $m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200$ GeV

Effects of stops, sbottoms, M_h:

[S.H., G. Weiglein, L. Zeune '12 - PRELIMINARY]



light blue: $m_{\tilde{t}_i}, m_{\tilde{b}_j} > 500$ GeV, $m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200$ GeV

4. Conclusinos

- EWPO can give valuable information about unknown parameters
- Main EWPO: M_W, $\sin^2\theta_{\text{eff}}$, $(g-2)_\mu$, M_h, . . .
- Correct inclusion of uncertainties is crucial for reliable interpretations
  m_t gives largest uncertainties
- Fits so far only possible in GUT based models: CMSSM, NUHM1, . . .
  $\Rightarrow$ perfect fit for m_t and M_W
- $\sin^2\theta_{\text{eff}}$: needs to be clarified with GigaZ
  could find deviations beyond LHC
  could rule out SM and/or MSSM
- MSSM parameter scan for M_W:
  - Effects of sleptons: $\gtrsim$ 70 MeV
  - Effects of charginos: $\gtrsim$ 20 MeV
  - $m_{\tilde{t}_1} \lesssim$ 1.5 TeV can give “good” M_W

Back-up

GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

$$\left.\begin{array}{l} m_0 : \text{universal scalar mass parameter} \\ m_{1/2} : \text{universal gaugino mass parameter} \\ A_0 : \text{universal trilinear coupling} \end{array}\right\}\ \text{at the GUT scale}$$

$\tan\beta$: ratio of Higgs vacuum expectation values

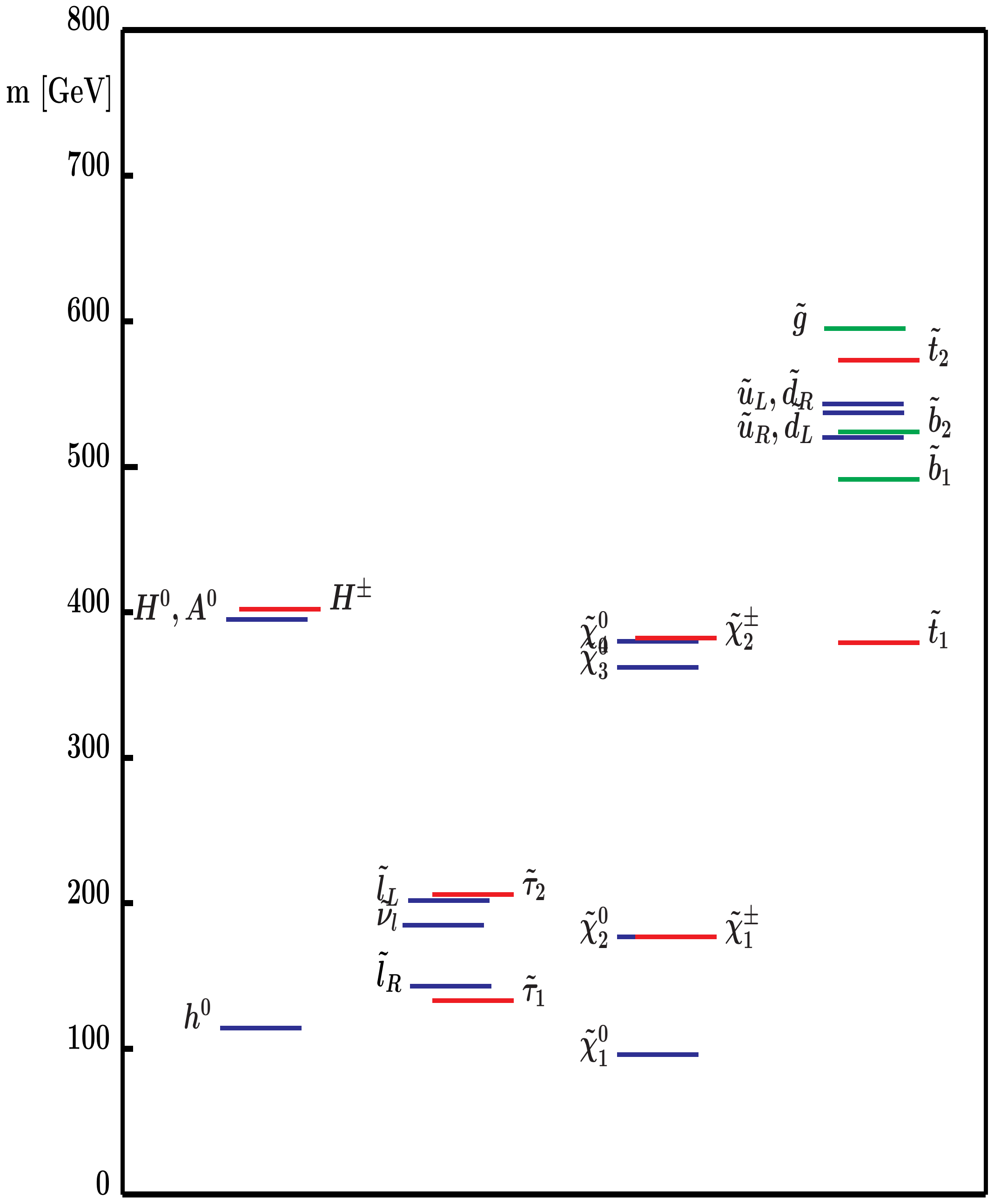
sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino

“Typical” CMSSM scenario (SPS 1a benchmark scenario):

Strong connection between all the sectors



GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter
at the GUT scale

$\Rightarrow$ effectively M_A or μ as free parameters at the EW scale

$\Rightarrow$ besides the CMSSM parameters

M_A or μ

And there is more: 3.) VCMSSM
4.) mSUGRA
5.) NUHM2

. . . no time here . . .

Possible future scenario:

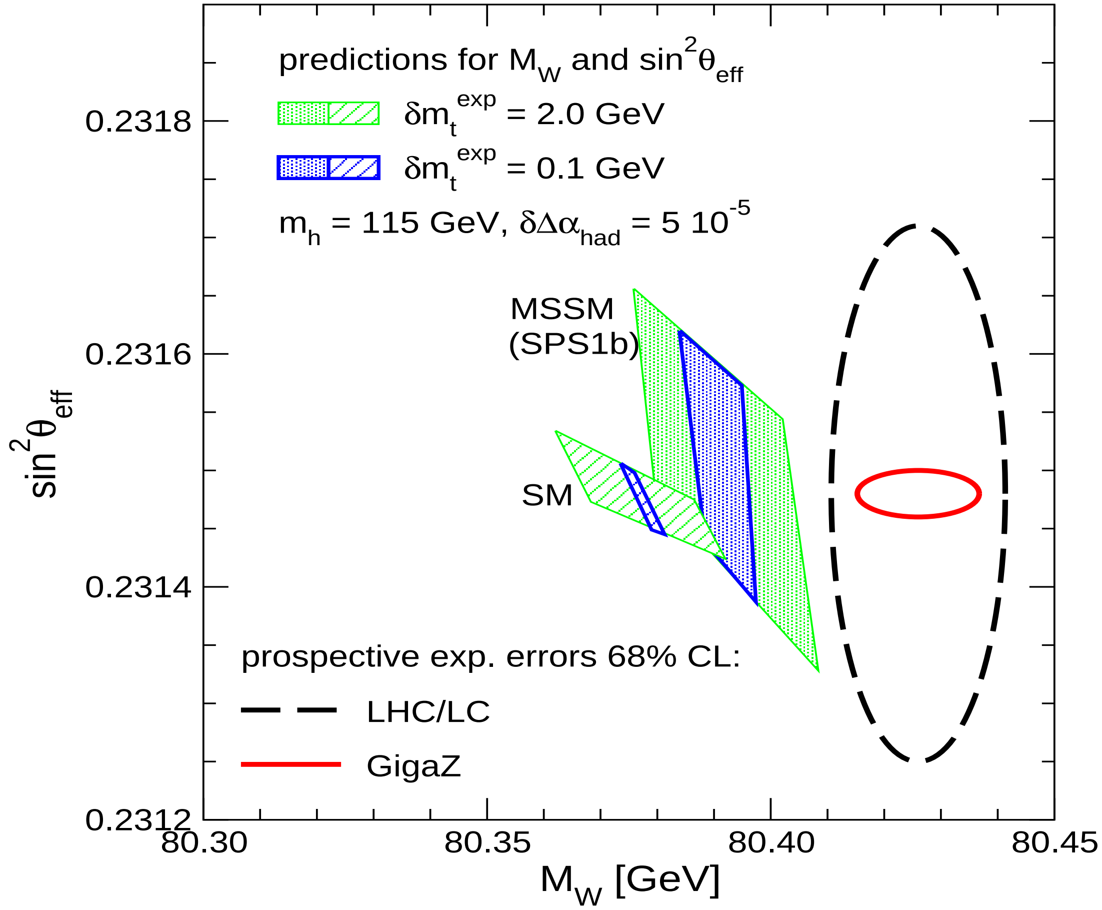
[*S.H., S. Kraml, W. Porod, G. Weiglein '03*]

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 $\sim 2 - 3$

Prediction of M_h in the CMSSM/NUHM1

[*O. Buchmüller, R. Cavanaugh, D. Colling, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, SH, G. Isidori, K. Olive, S. Rogerson, F. Ronga, G. Weiglein*]

General idea:

Take the most simple MSSM versions: CMSSM/NUHM1
→ just three/four GUT scale parameters + $\tan\beta$

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Take the most simple MSSM versions: CMSSM/NUHM1
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– 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/NUHM1 parameter space

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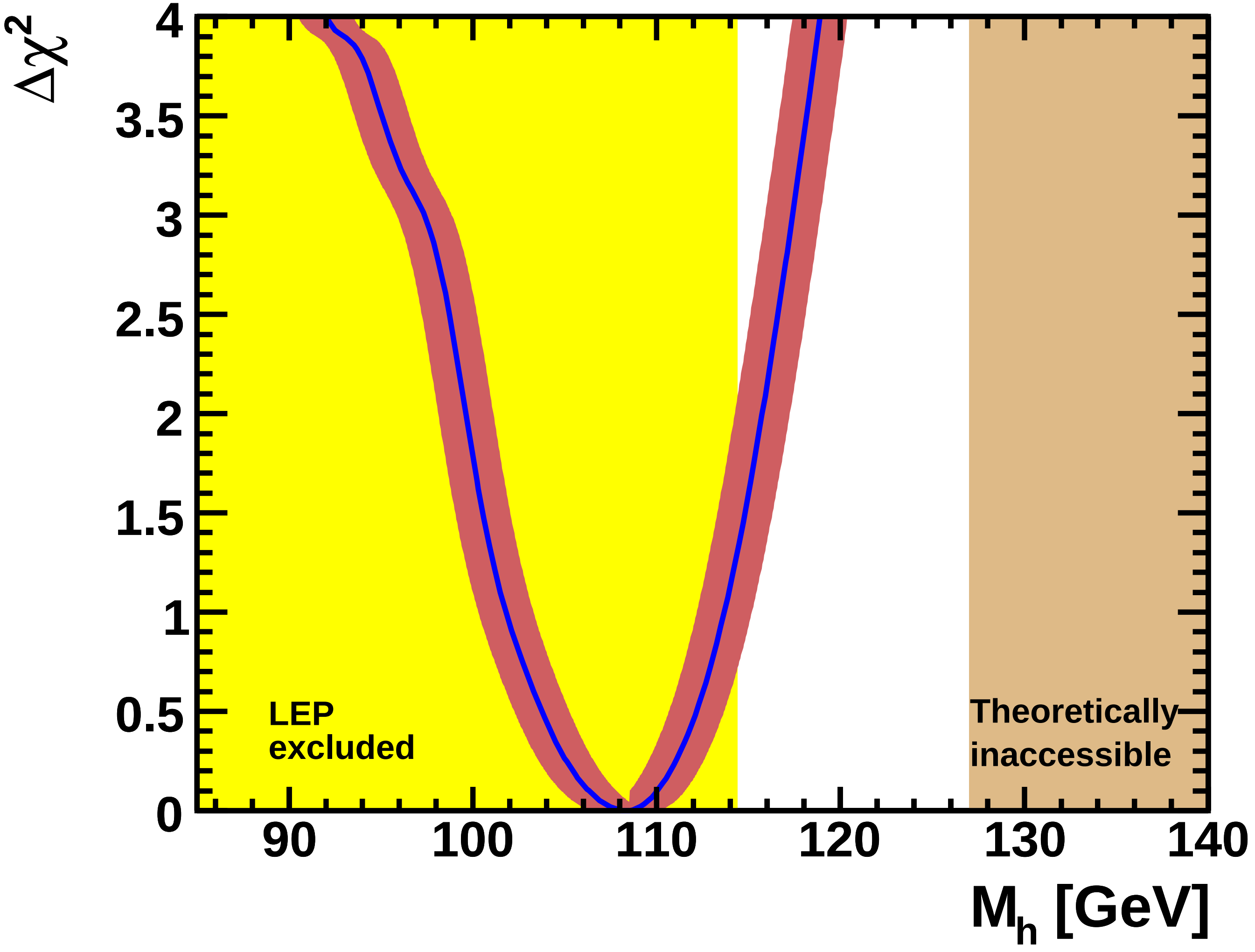
– scan over the full CMSSM/NUHM1 parameter space
⇒ preferred M_h values

CMSSM: red band plot (no LHC data):

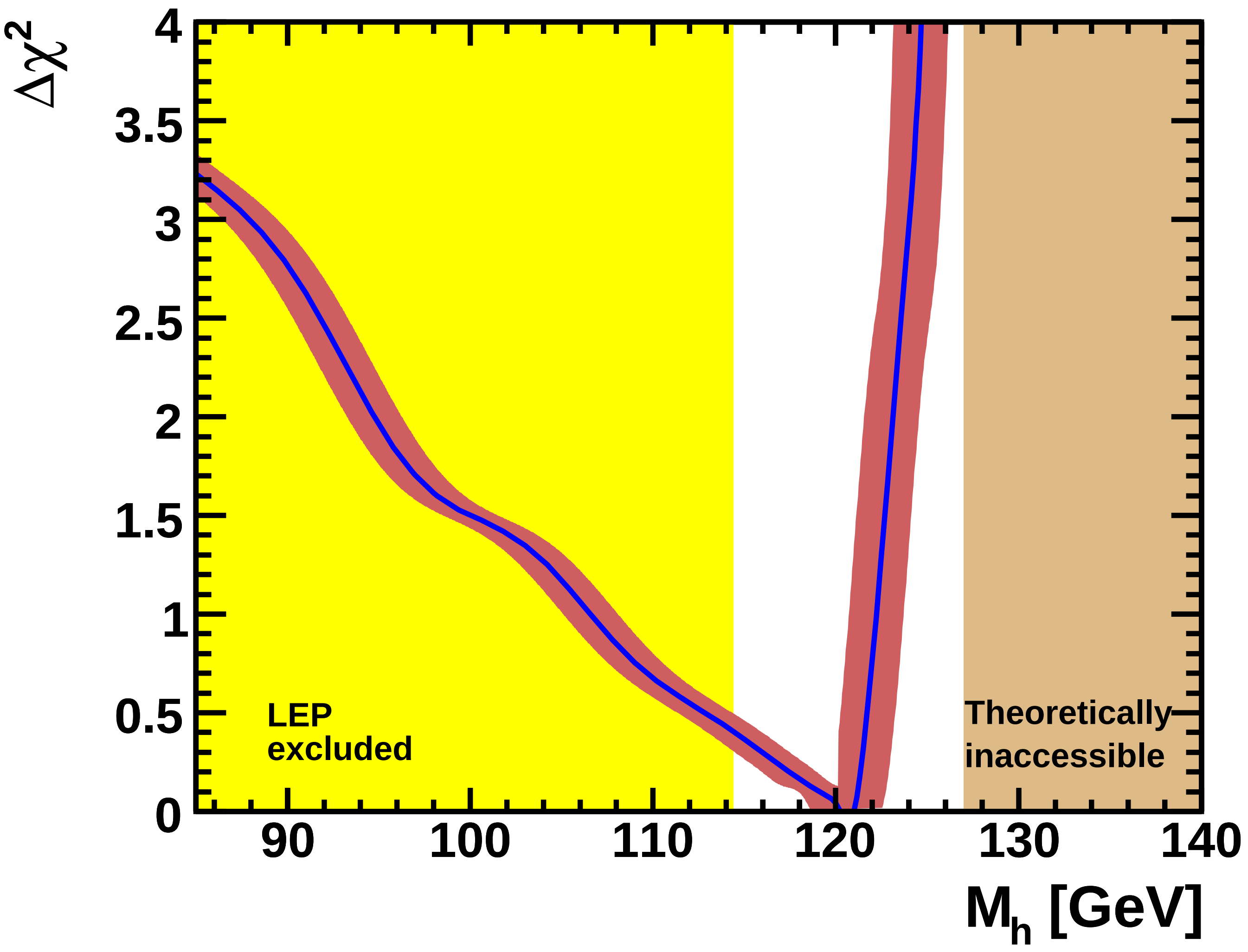
[2009]



$M_h = 108 \pm 6\,(\mathrm{exp}) \pm 1.5(\mathrm{theo})$ GeV

NUHM1: red band plot (no LHC searches):

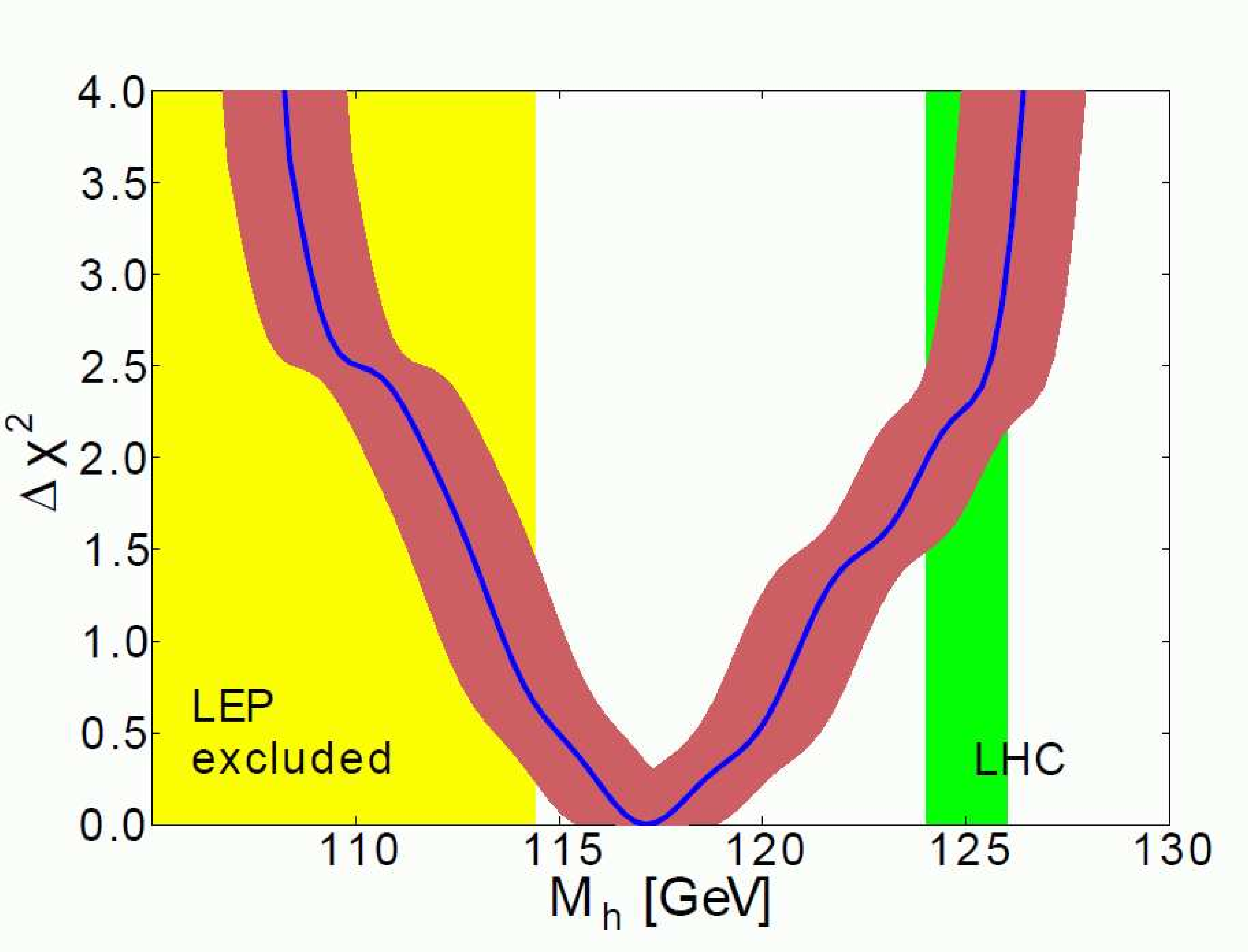
[2009]



$M_h = 121^{+1}_{-14}$ (exp) ± 1.5(theo) GeV ⇒ naturally above LEP limit

CMSSM: post-LHC (5+5 fb^{-1}) red band plot:

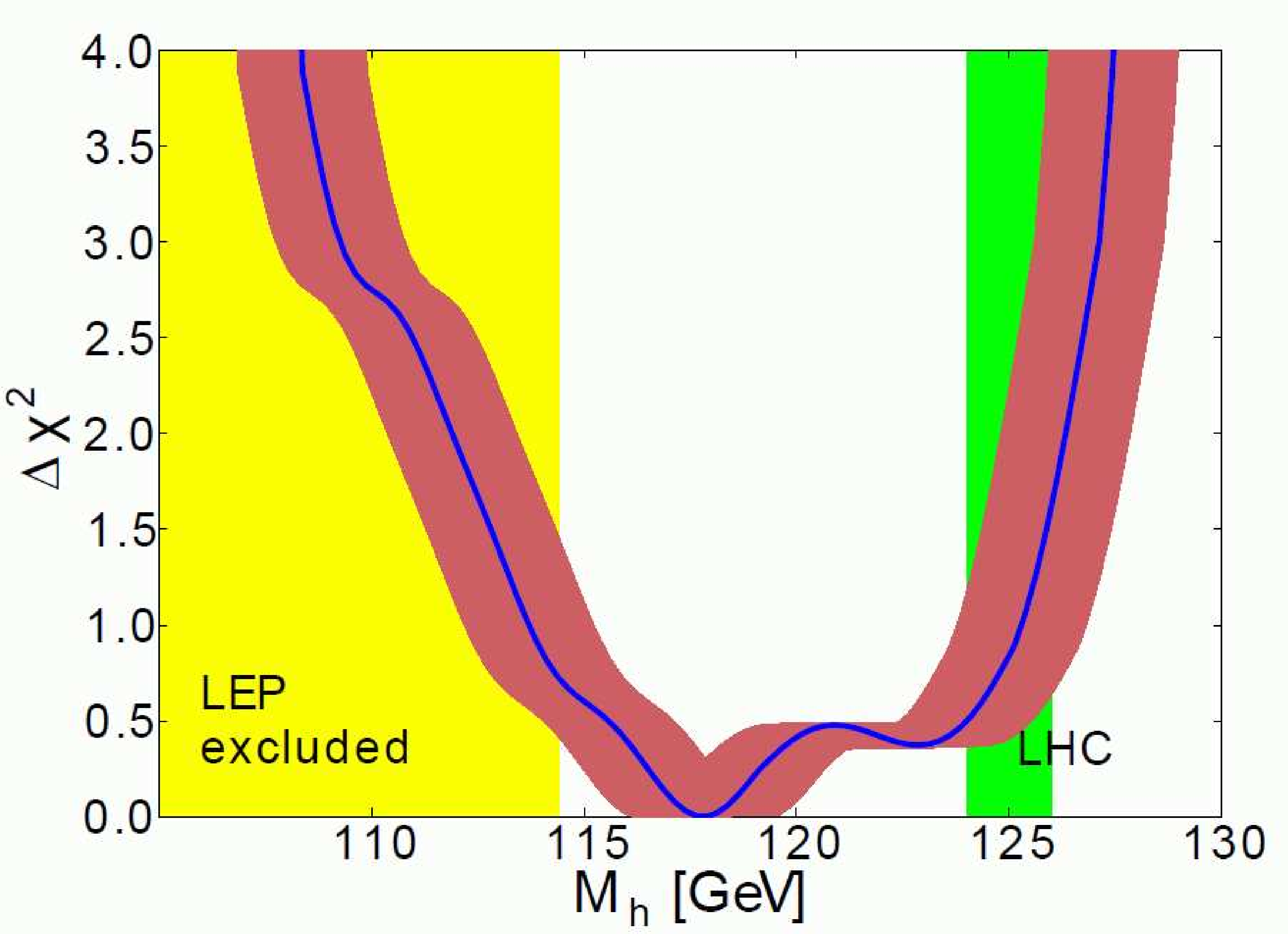
[2012]



$M_h = 117 \pm 4\,(\text{exp}) \pm 1.5(\text{theo})$ GeV $\quad \Delta\chi^2(M_h = 125 \text{ GeV}) \lesssim 2$

NUHM1: post-LHC (5+5 fb^{-1}) red band plot:

[2012]



$M_h \approx 118^{+7}_{-4}$ (exp) $\pm\,1.5$(theo) GeV $\quad$ $\Delta\chi^2(M_h = 125$ GeV$) \approx 0.5$

Predictions for early LHC searches:

- 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, M_Z, $\Delta\alpha_{\text{had}}$

$\Rightarrow$ χ^2 function

$\rightarrow$ scan over the full CMSSM/NUHM1/... parameter space

$\sim 2.5\ 10^7$ points samples with MCMC

statistical measure: χ^2 function (Frequentist, no priors)

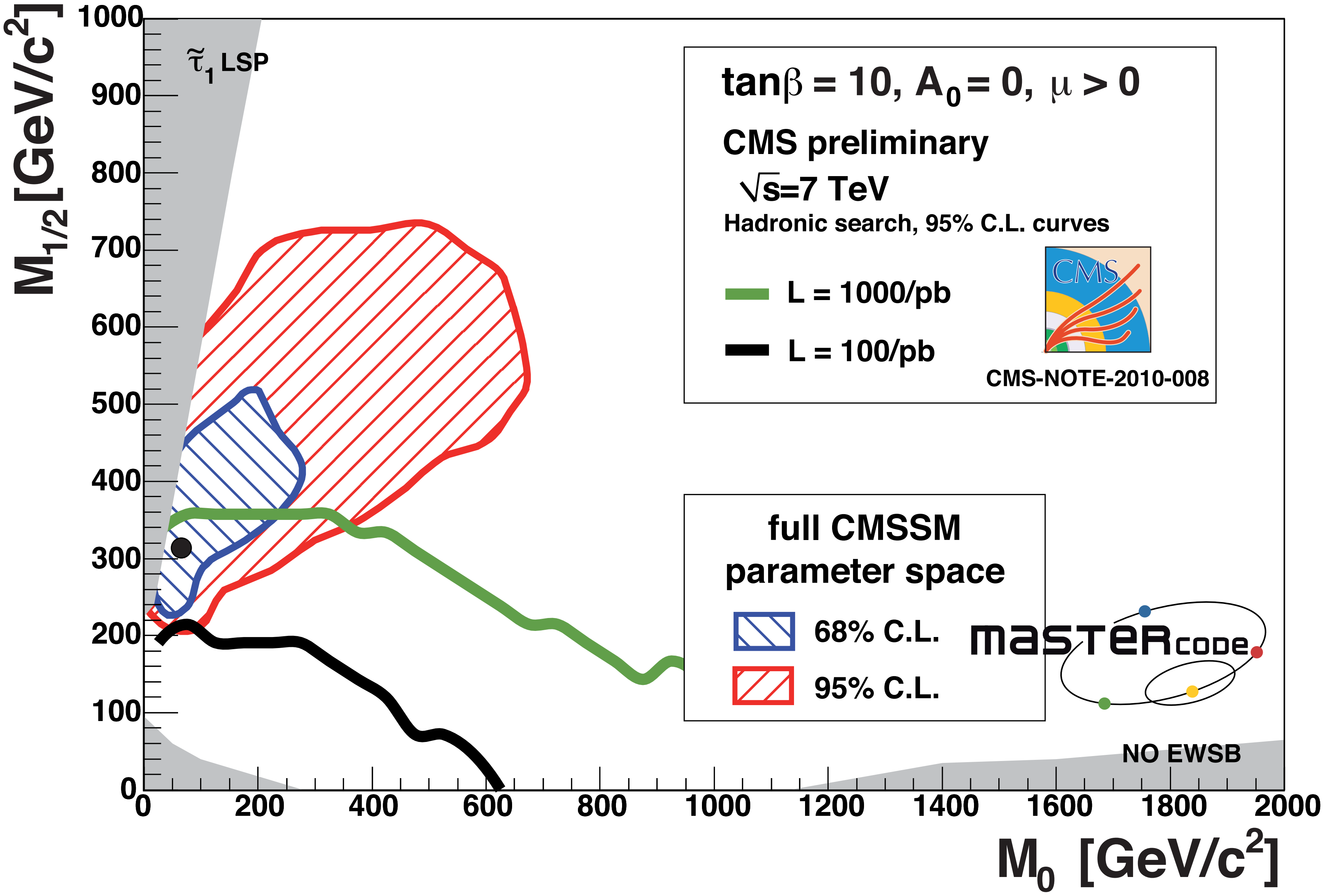
$\rightarrow$ final minimum: Minuit

$\Delta\chi^2$: 68, 95% C.L. contours

$\Rightarrow$ preferred CMSSM/NUHM1/... parameters

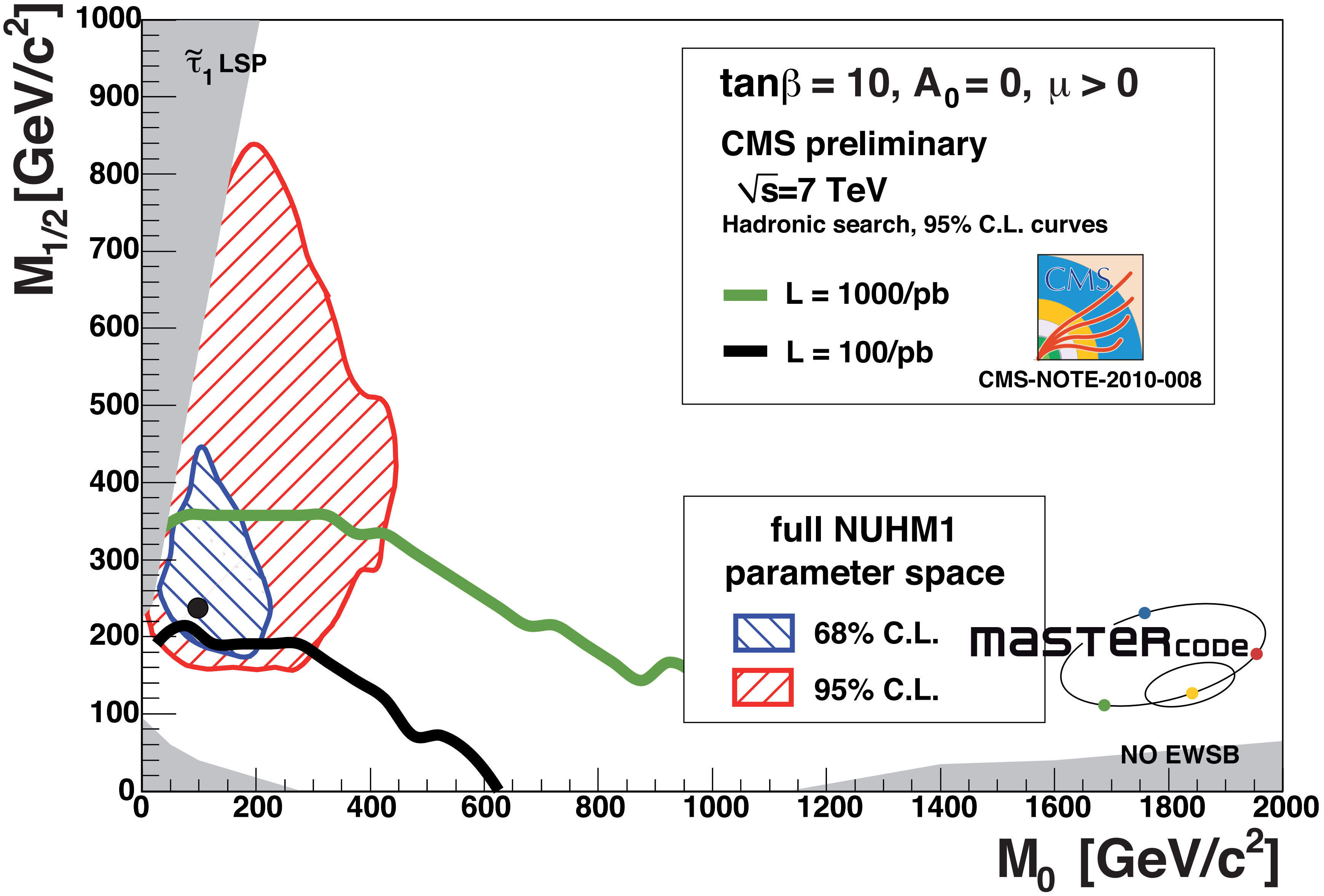
$\Rightarrow$ LHC (/ILC) reach

LHC (CMS) $\oplus$ CMSSM analysis:



⇒ best-fit point and part of 68% C.L. are can be tested in 2011

LHC (CMS) $\oplus$ NUHM1 analysis:



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