# Confronting SUSY with Existing Experimental Data: Investigating the CMSSM and Beyond

*Sven Heinemeyer, IFCA (CSIC, Santander)*

Valencia, 05/2009

1. Introduction and motivation
2. The CMSSM and beyond
3. Constraining the CMSSM, mGMSB and mAMSB
4. Prediction of the lightest Higgs boson mass $M_h$
5. LHC/ILC reach in the CMSSM/NUHM1
6. Conclusions

# 1. Introduction and motivation

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**A:** Ummm . . . Let's start differently!

# 1. Introduction and motivation

Supersymmetry (SUSY) : Symmetry between

$$\text{Bosons} \leftrightarrow \text{Fermions}$$

$$Q\ |\text{Fermion}\rangle \rightarrow |\text{Boson}\rangle$$

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Simplified examples:

$$Q\ |\text{top},\ t\rangle \rightarrow |\text{scalar top},\ \tilde{t}\rangle$$

$$Q\ |\text{gluon},\ g\rangle \rightarrow |\text{gluino},\ \tilde{g}\rangle$$

$\Rightarrow$ each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}} \Rightarrow$ SUSY is broken . . .

. . . via soft SUSY-breaking terms in the Lagrangian (added by hand)

SUSY particles are made heavy: $\boxed{M_{\text{SUSY}} = \mathcal{O}(1\ \text{TeV})}$

# Supersymmetry: Motivation

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

1.) Stability of the Higgs mass against higher-order corr.

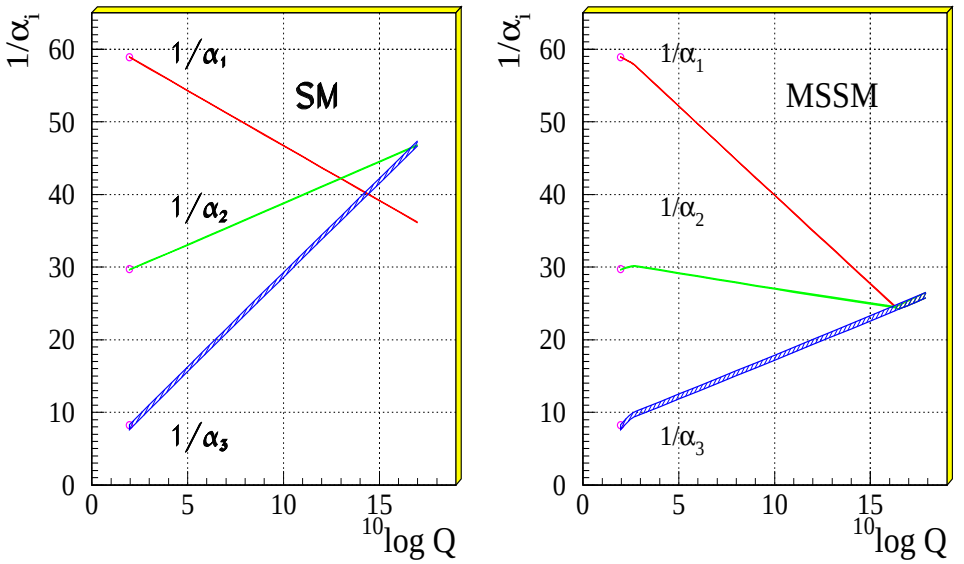
2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)

3.) Spontaneous symmetry breaking via Higgs mechanism is automatic in SUSY GUTs

4.) SUSY provides CDM candidate

5.) . . .

Unification of the Coupling Constants in the SM and the minimal MSSM




[*Amaldi, de Boer, Fürstenau '92*]

# The Minimal Supersymmetric Standard Model (MSSM)

## Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

$\rightarrow$ CPV will mostly be neglected throughout this talk!

## 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)

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

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**Q':** What describes the world better: SM or MSSM ?

**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 (2009/10. . . ?)
  $\rightarrow$ waiting for LHC (2010/11. . . ?)

- Search for indirect effects of SUSY via Precision Observables

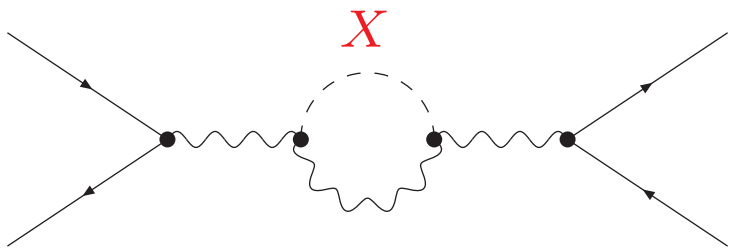
## Precision Observables (POs):

Comparison of electro-weak precision observables with theory:

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

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections



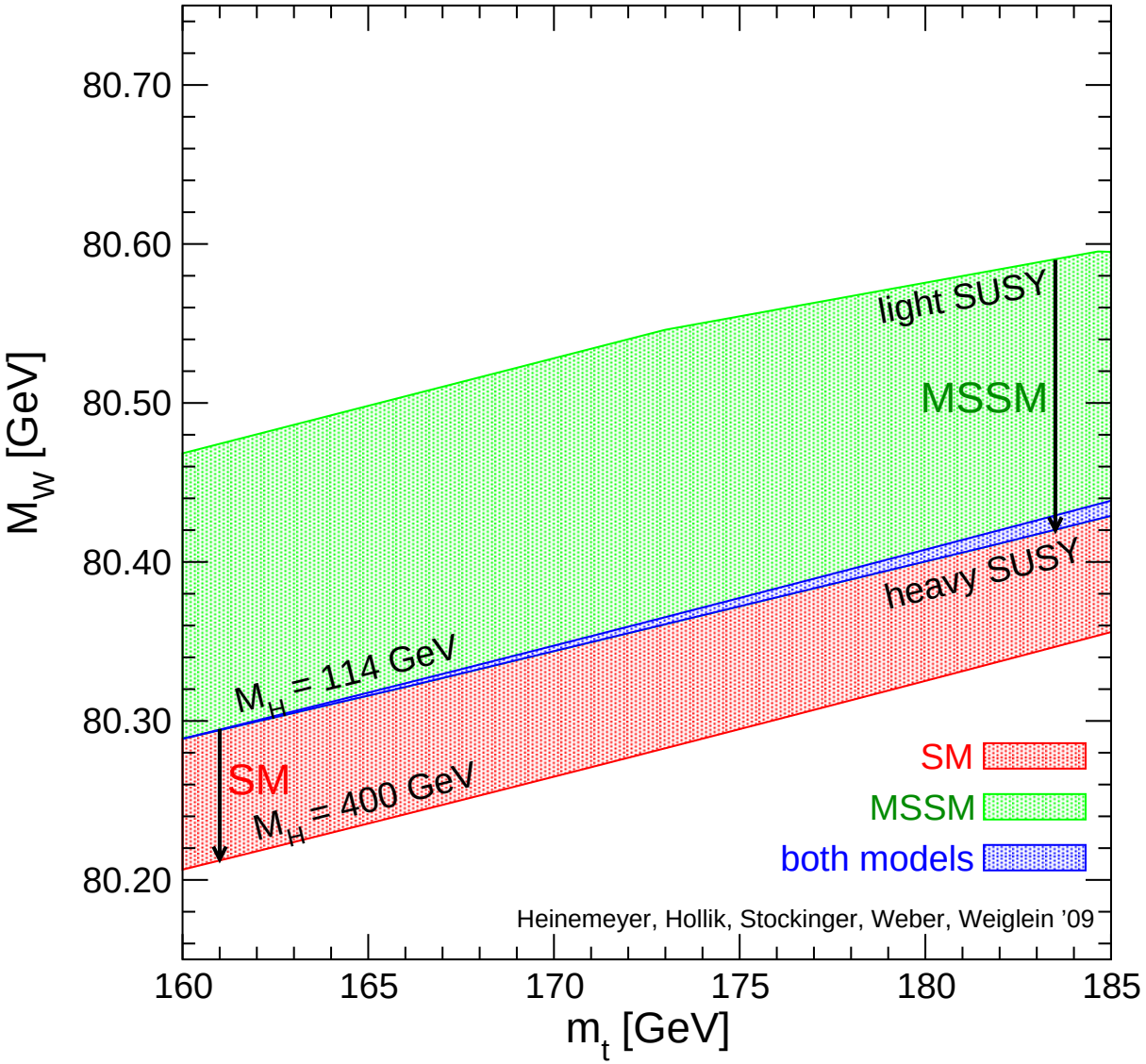

$\Downarrow$

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. Weber, G. Weiglein '07]*



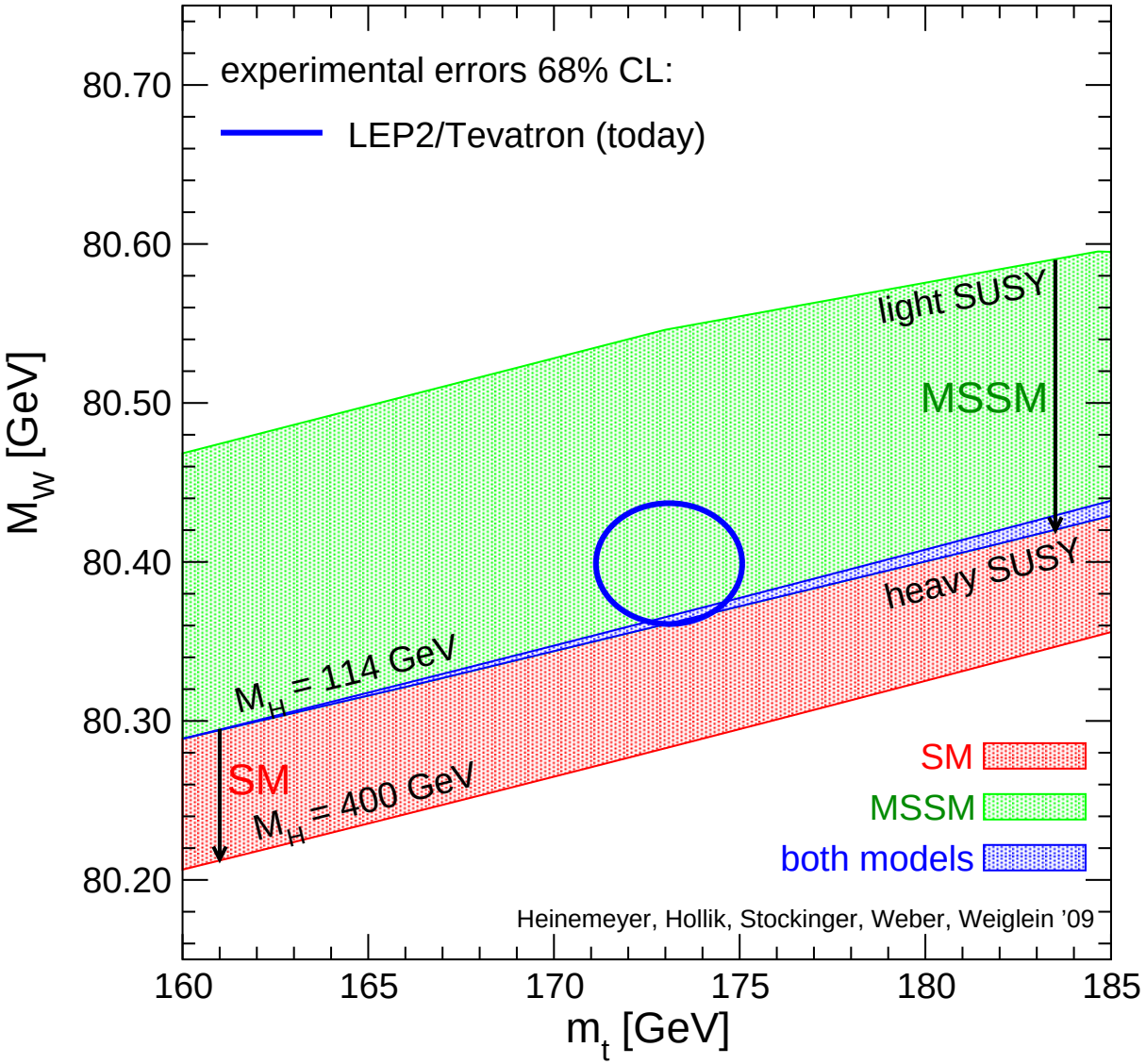

MSSM band:
scan over
SUSY masses

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

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

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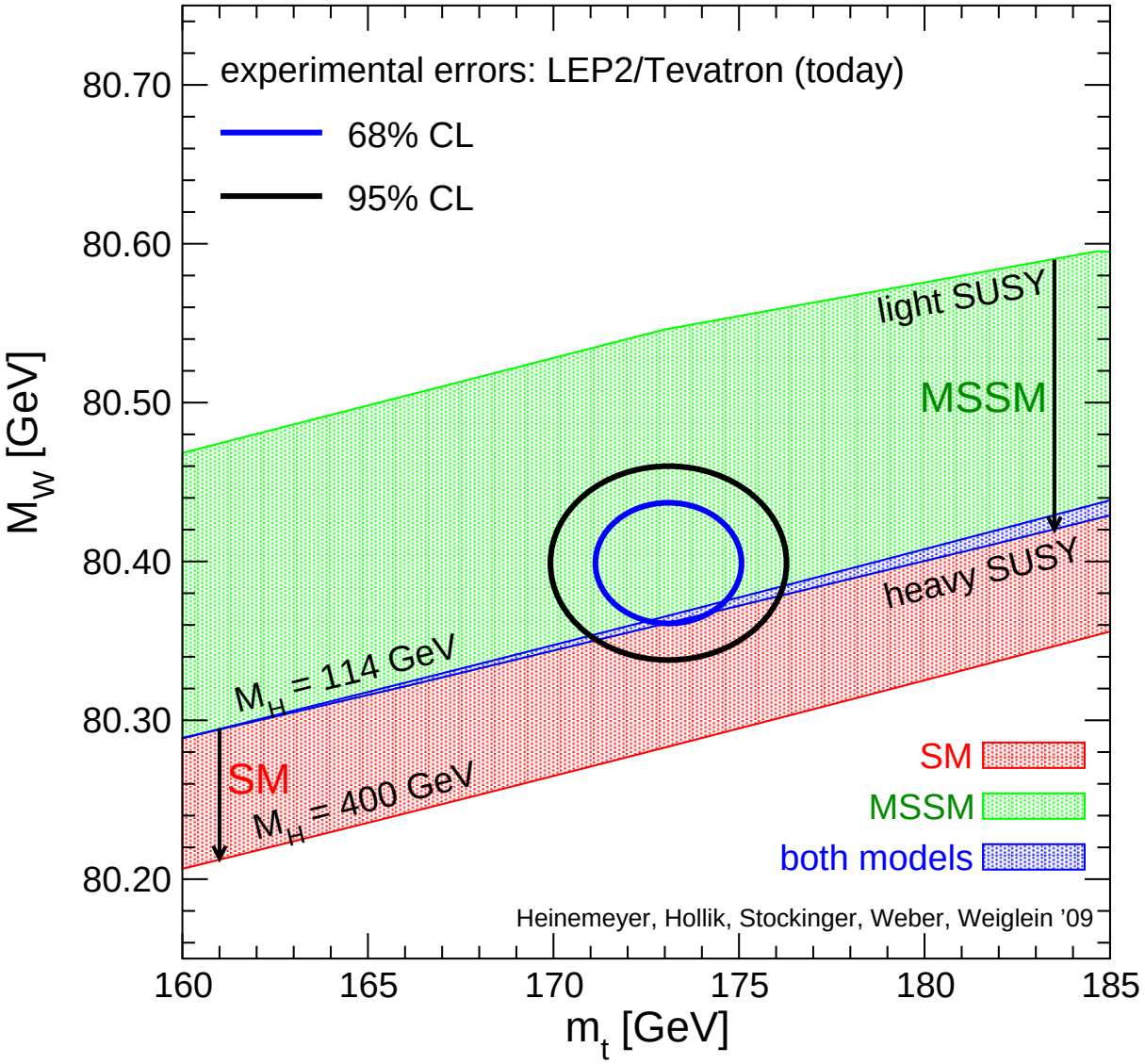

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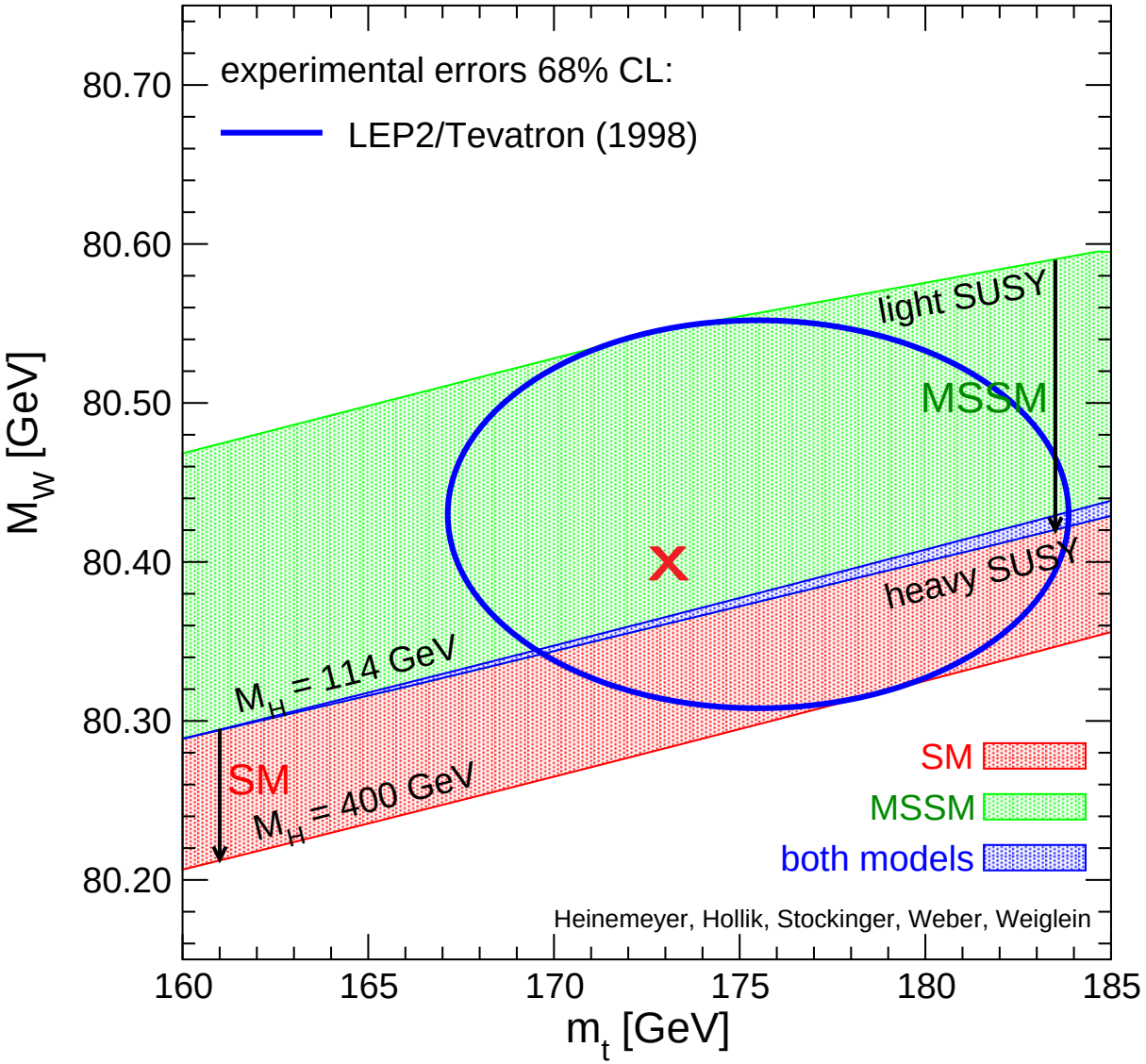

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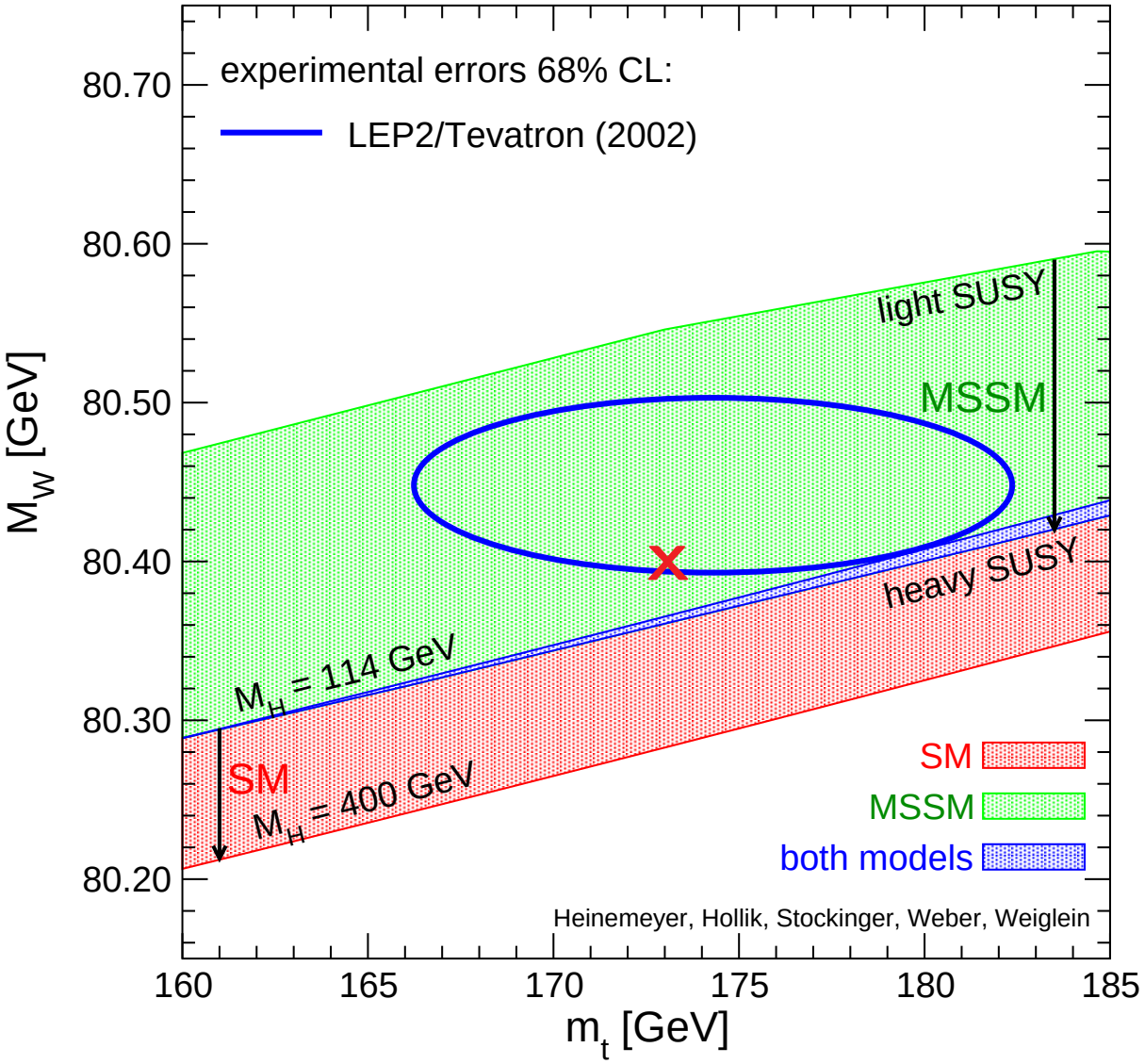

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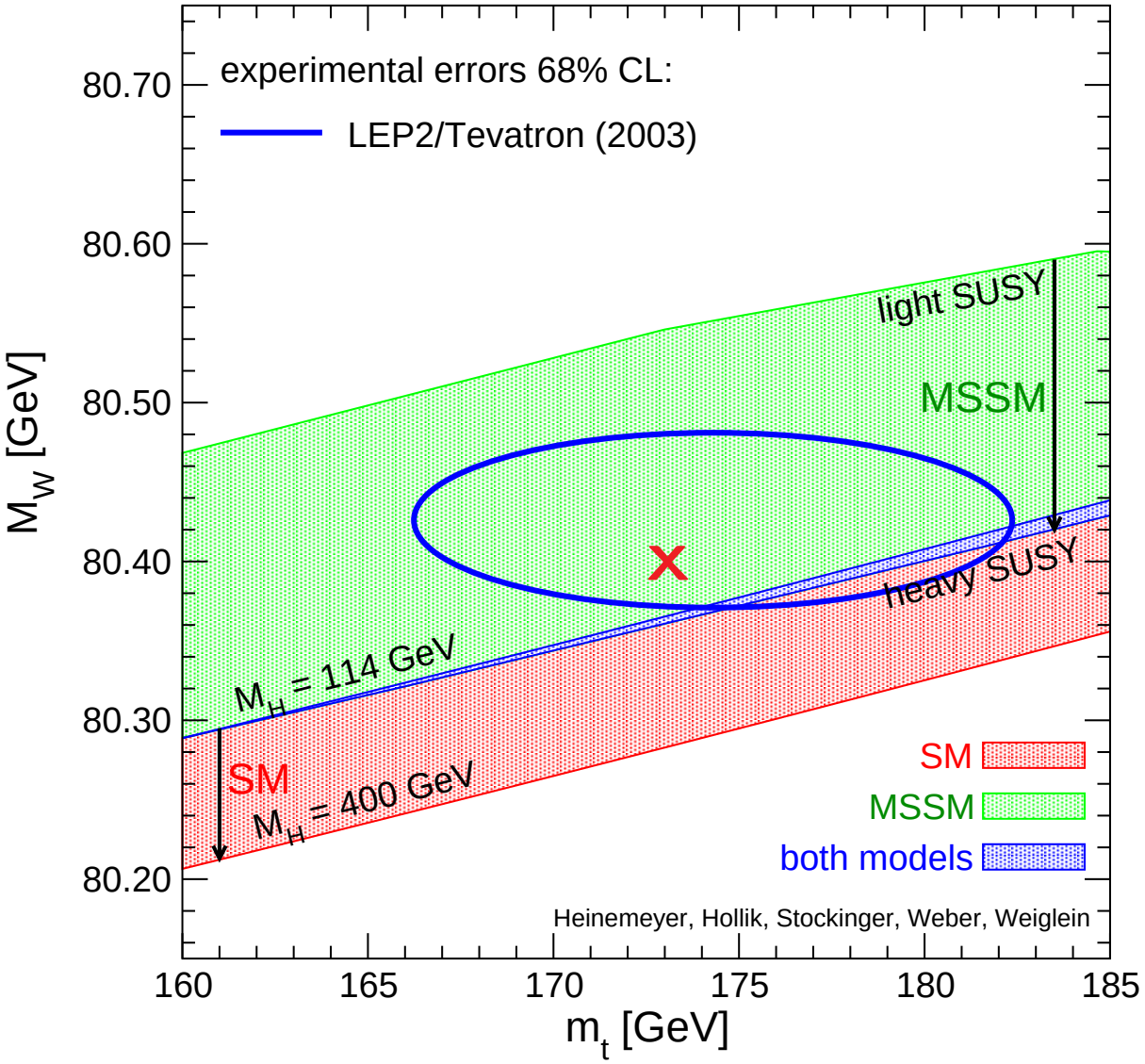

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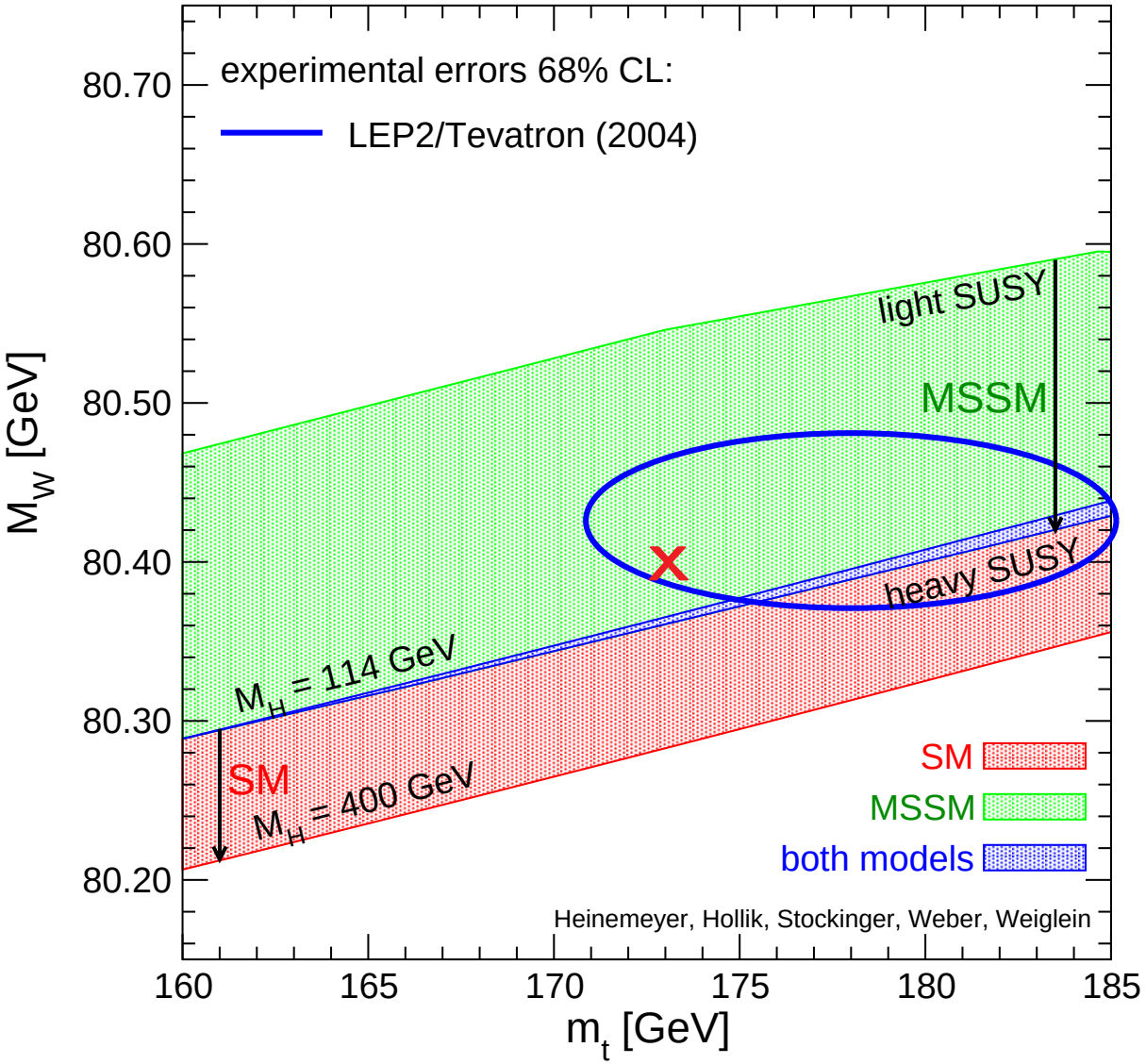

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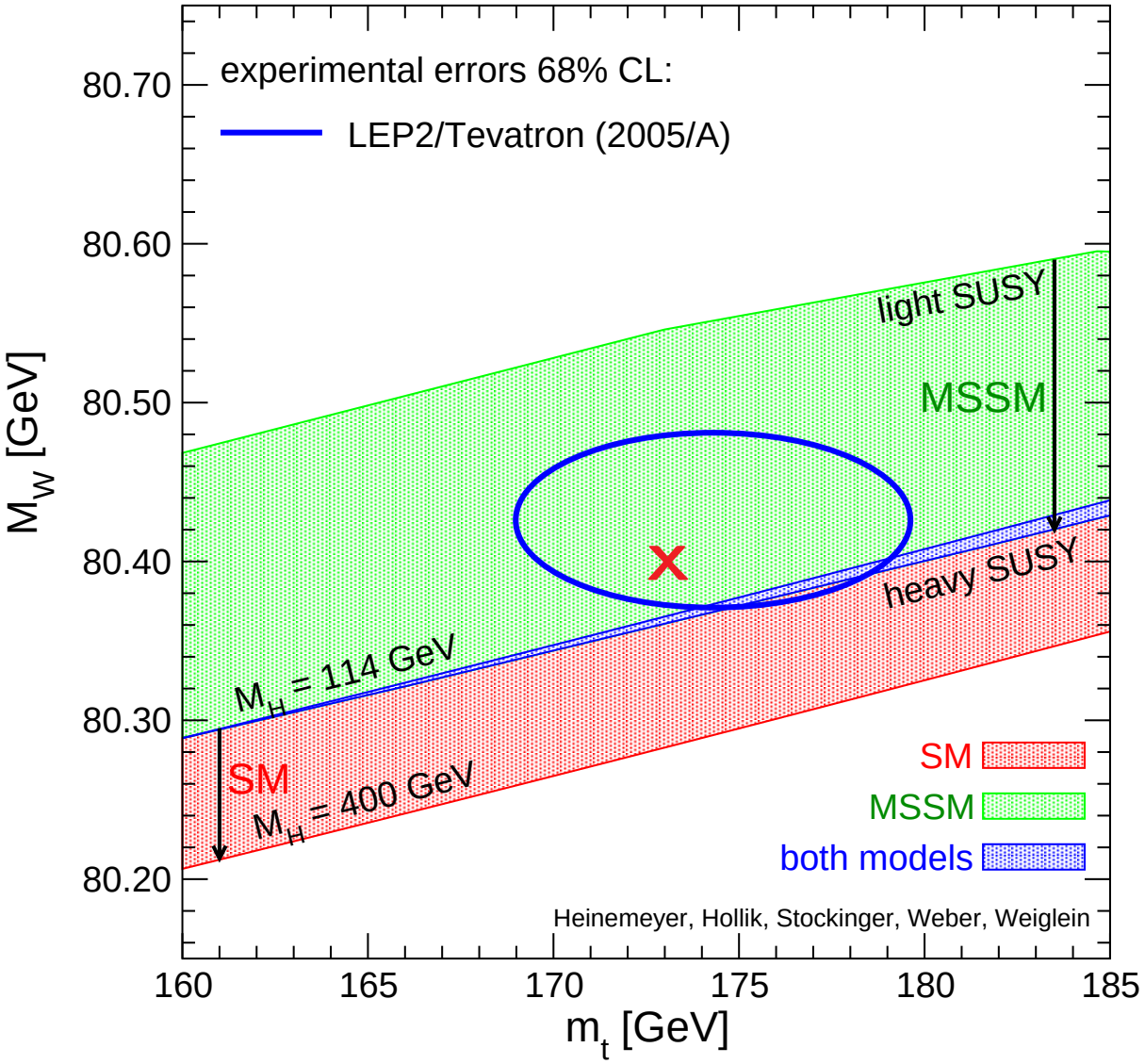

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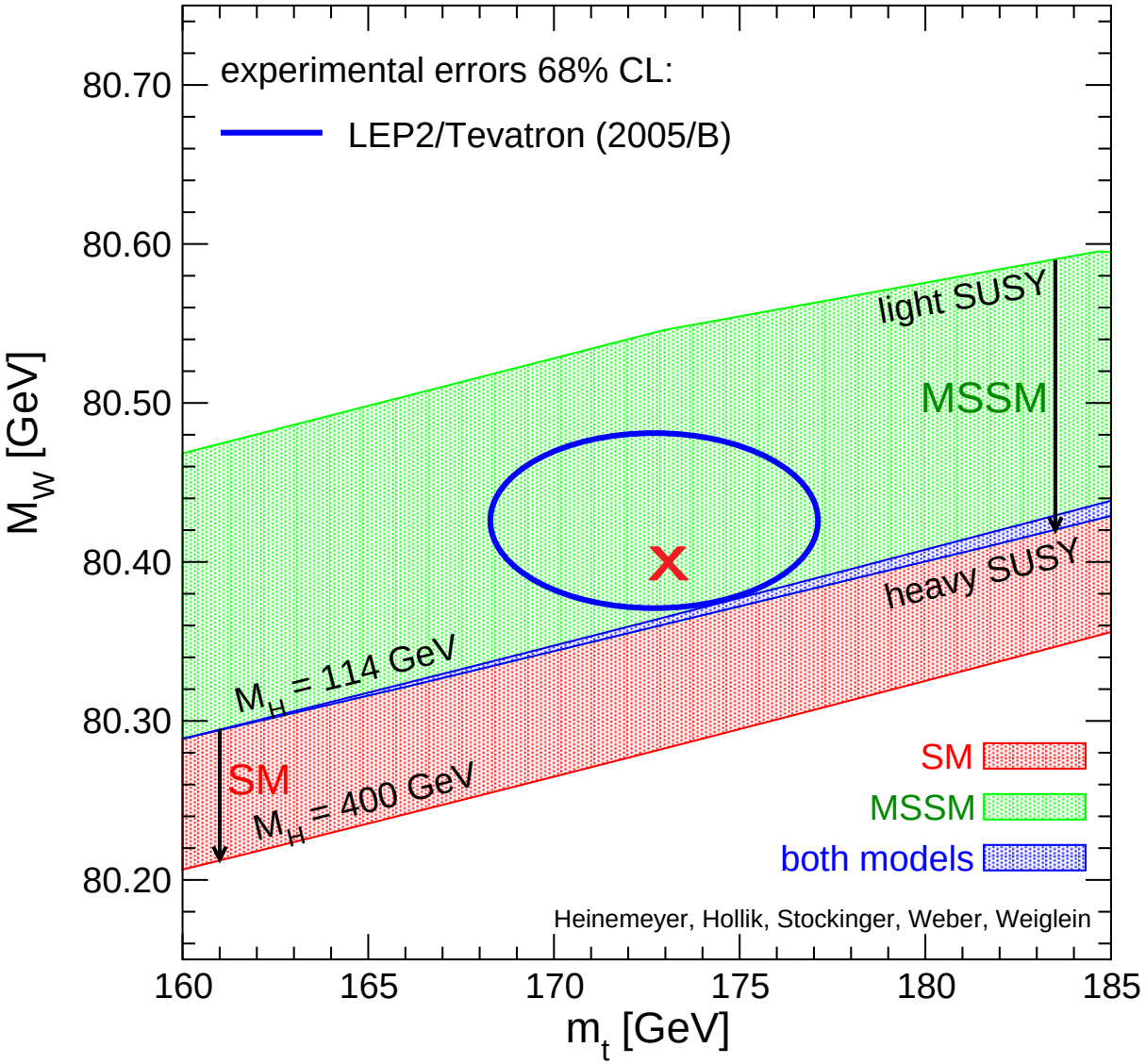

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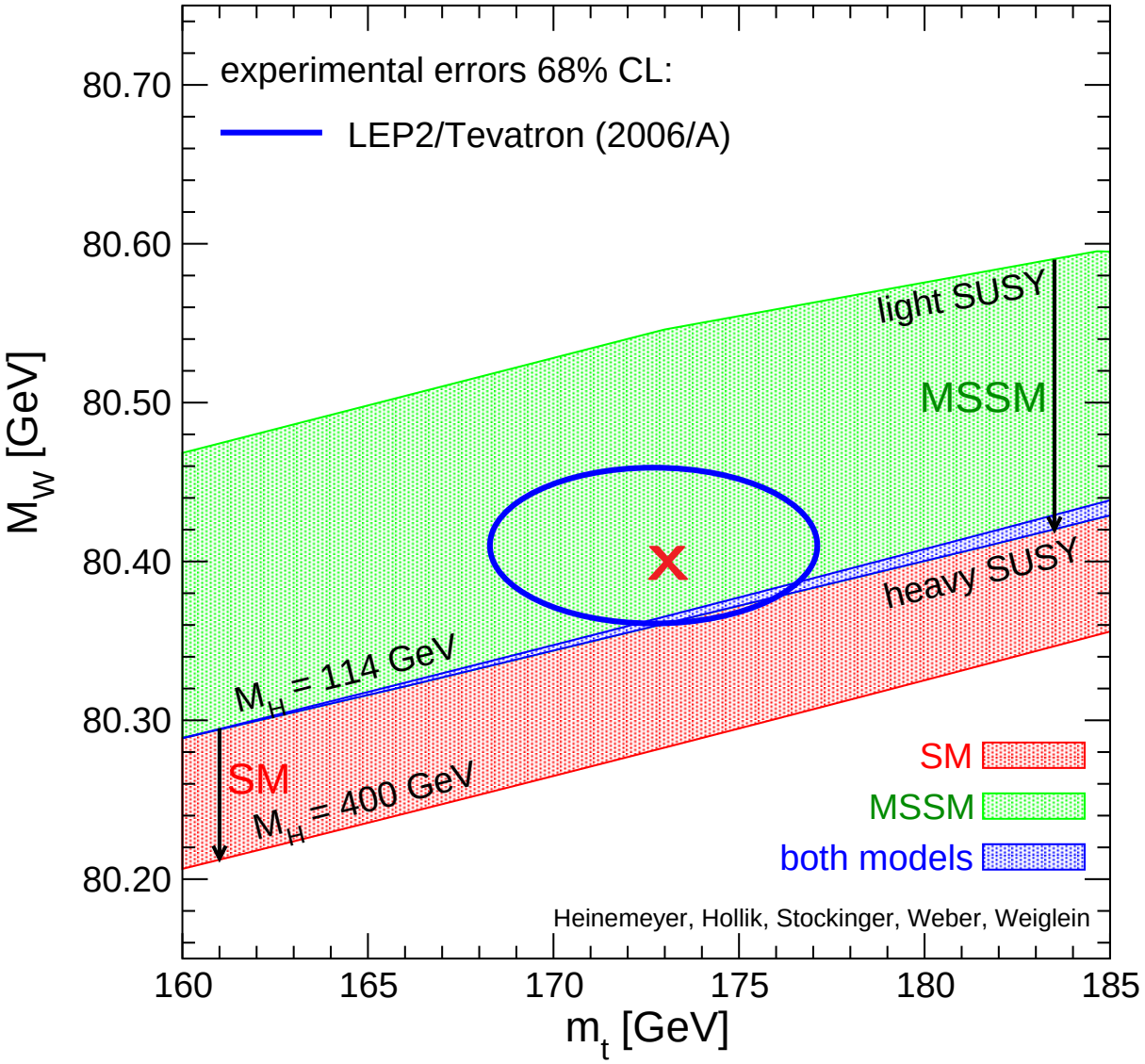

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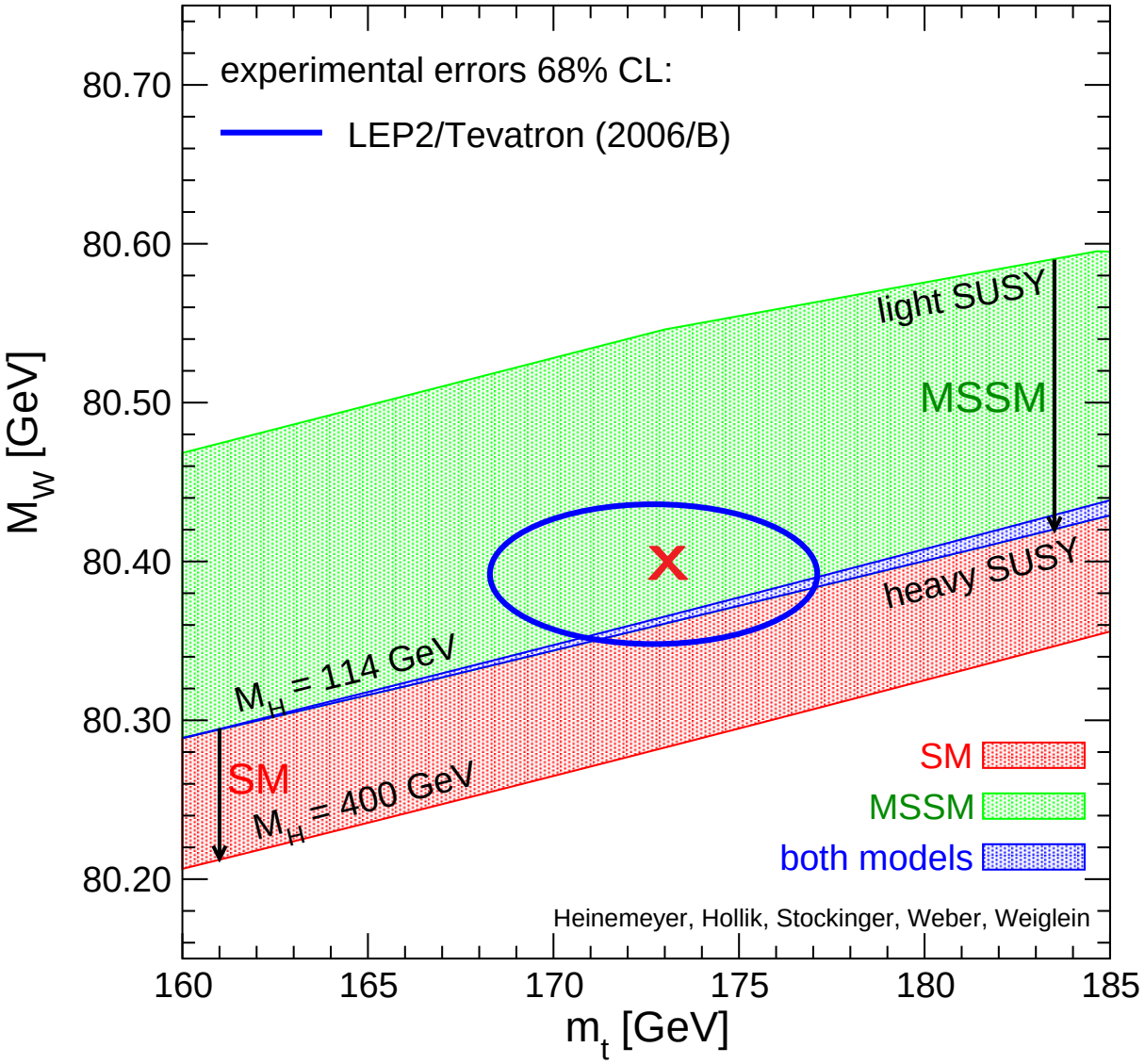

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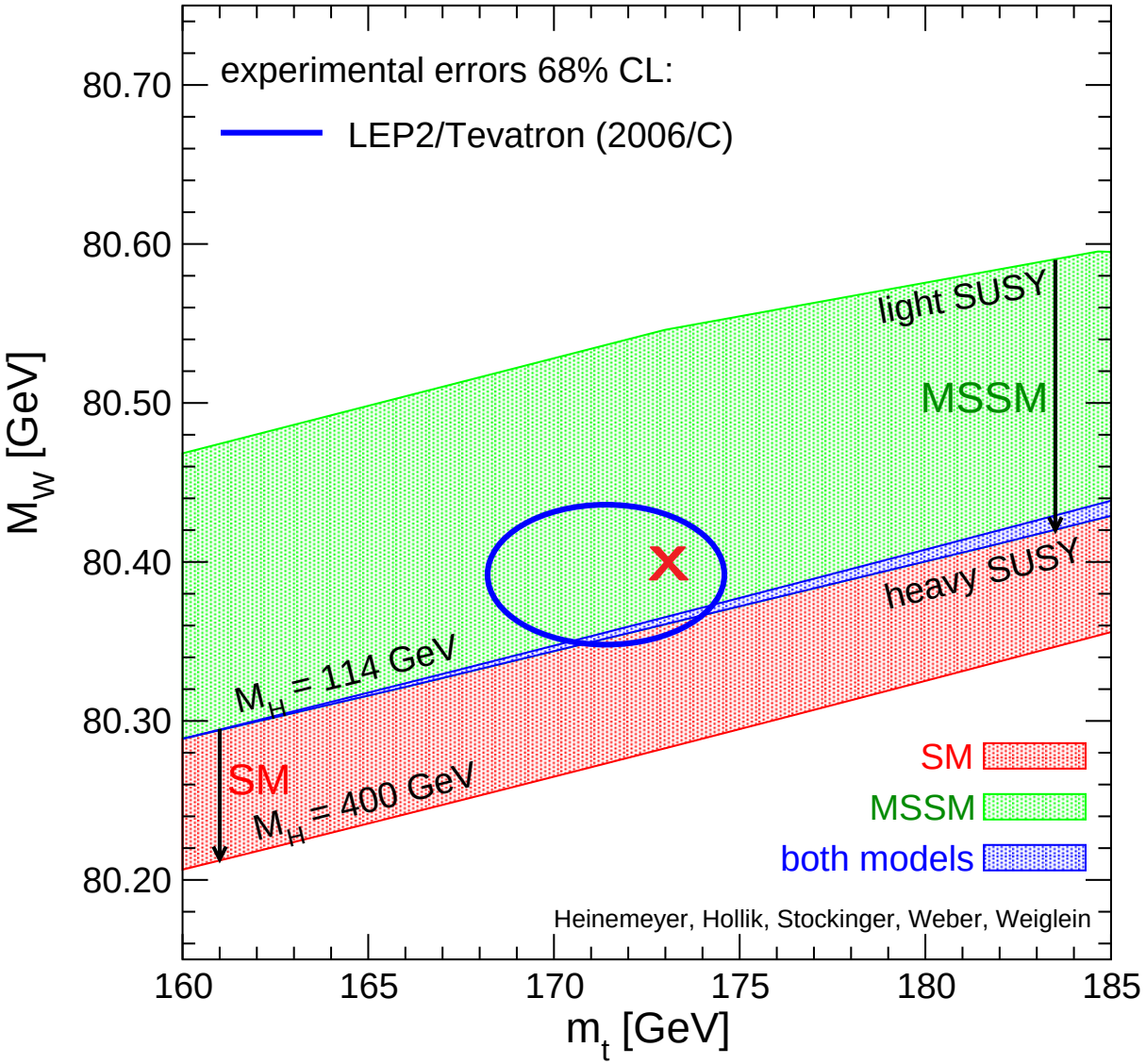

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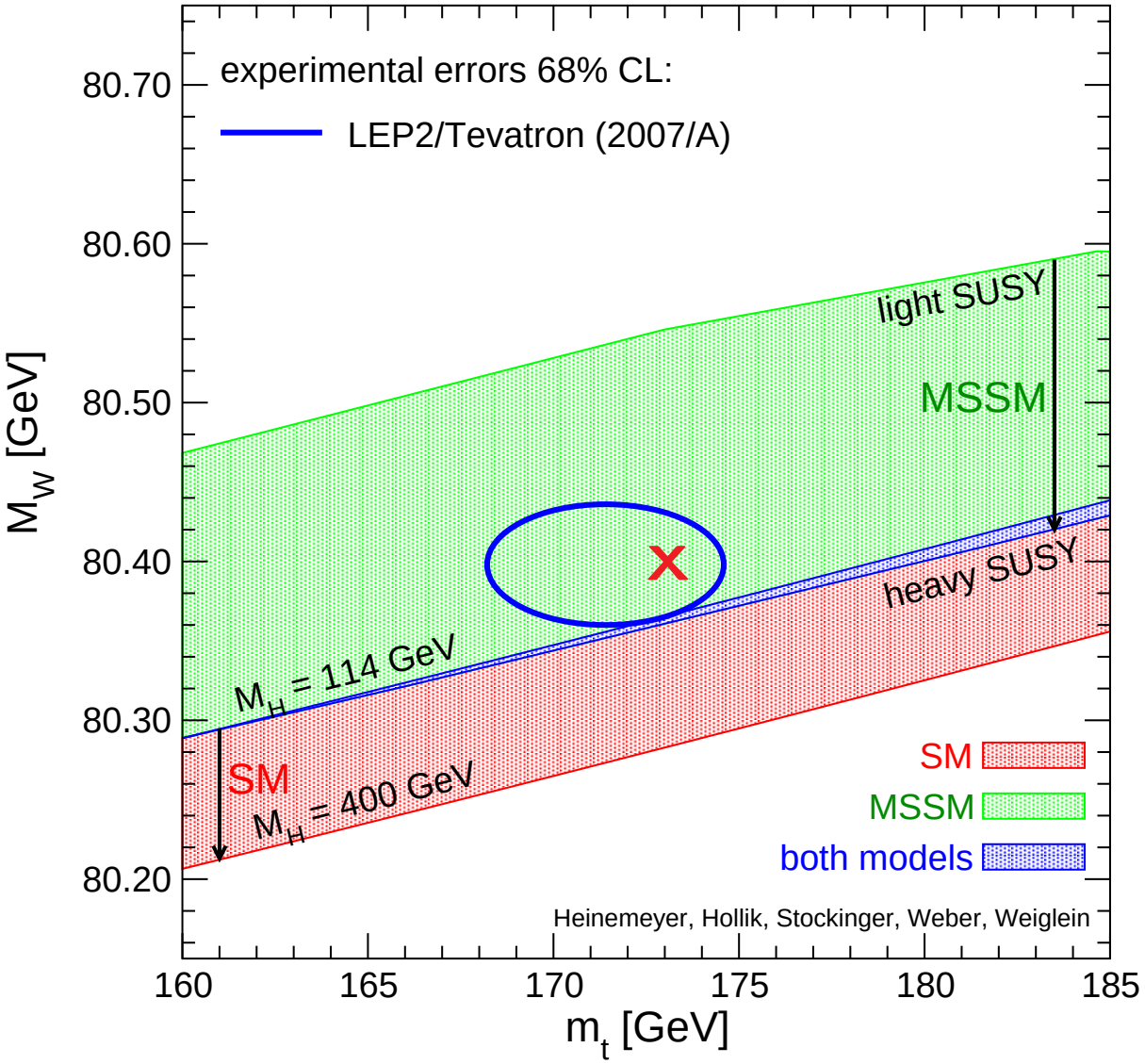

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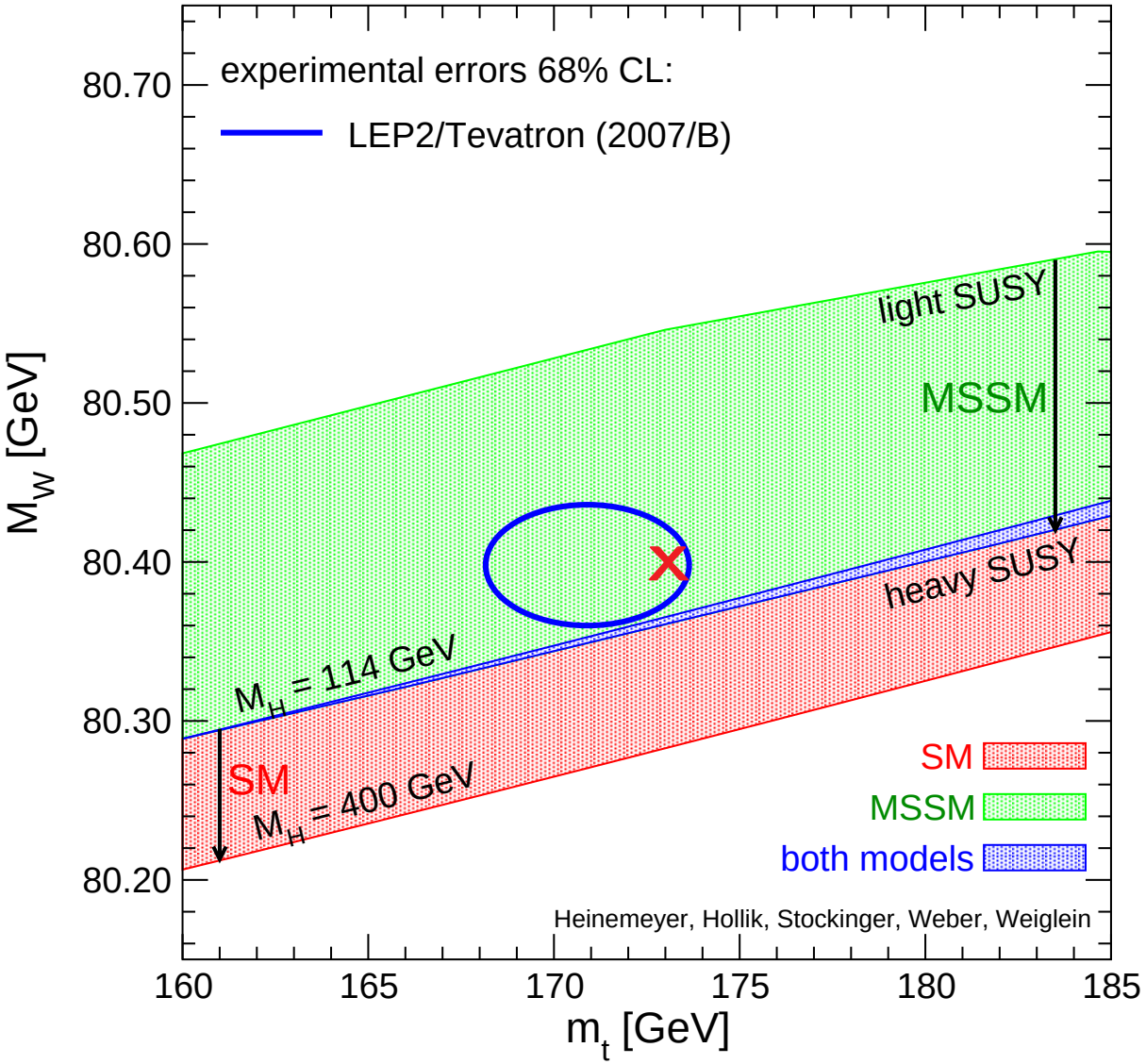

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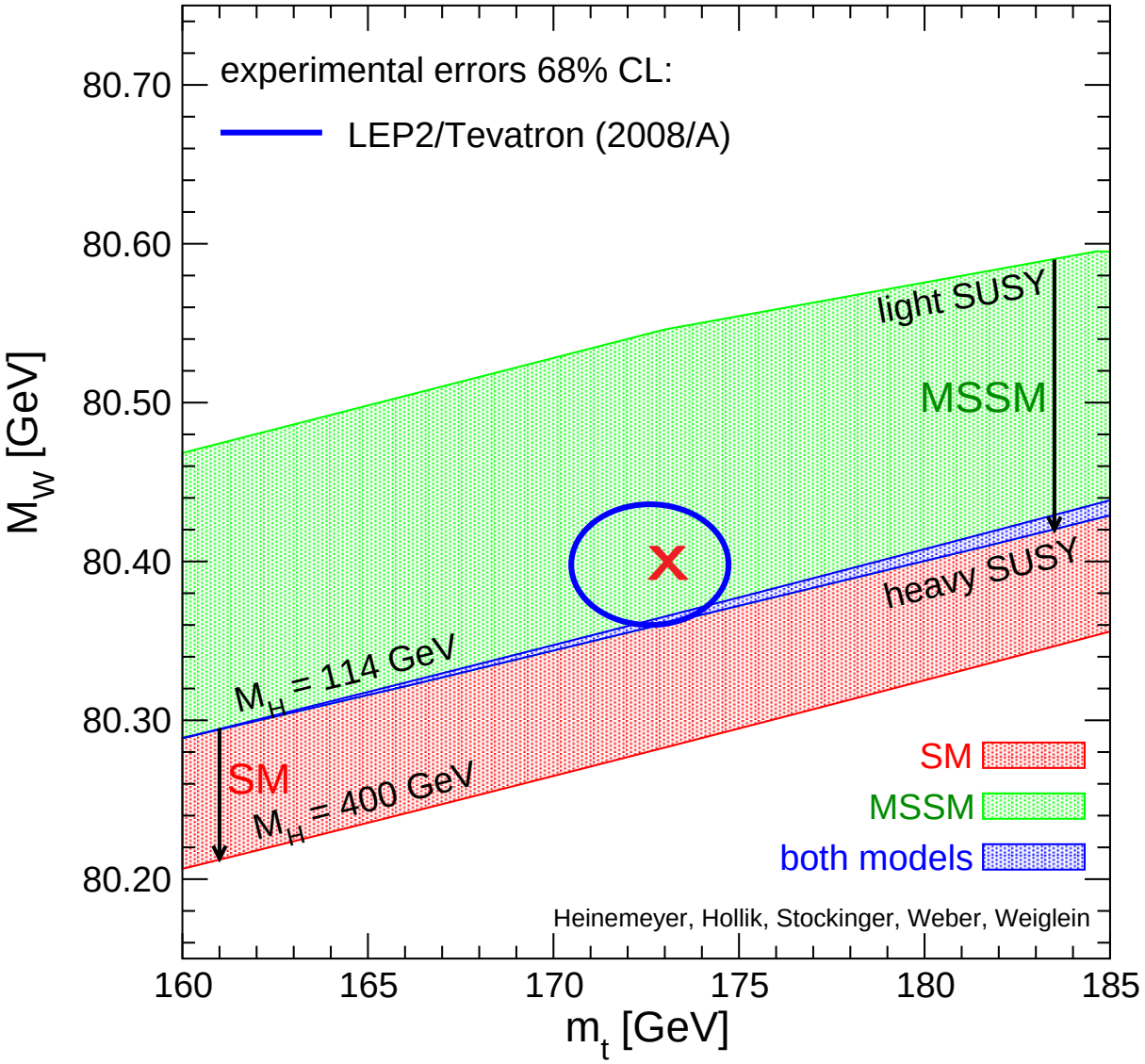

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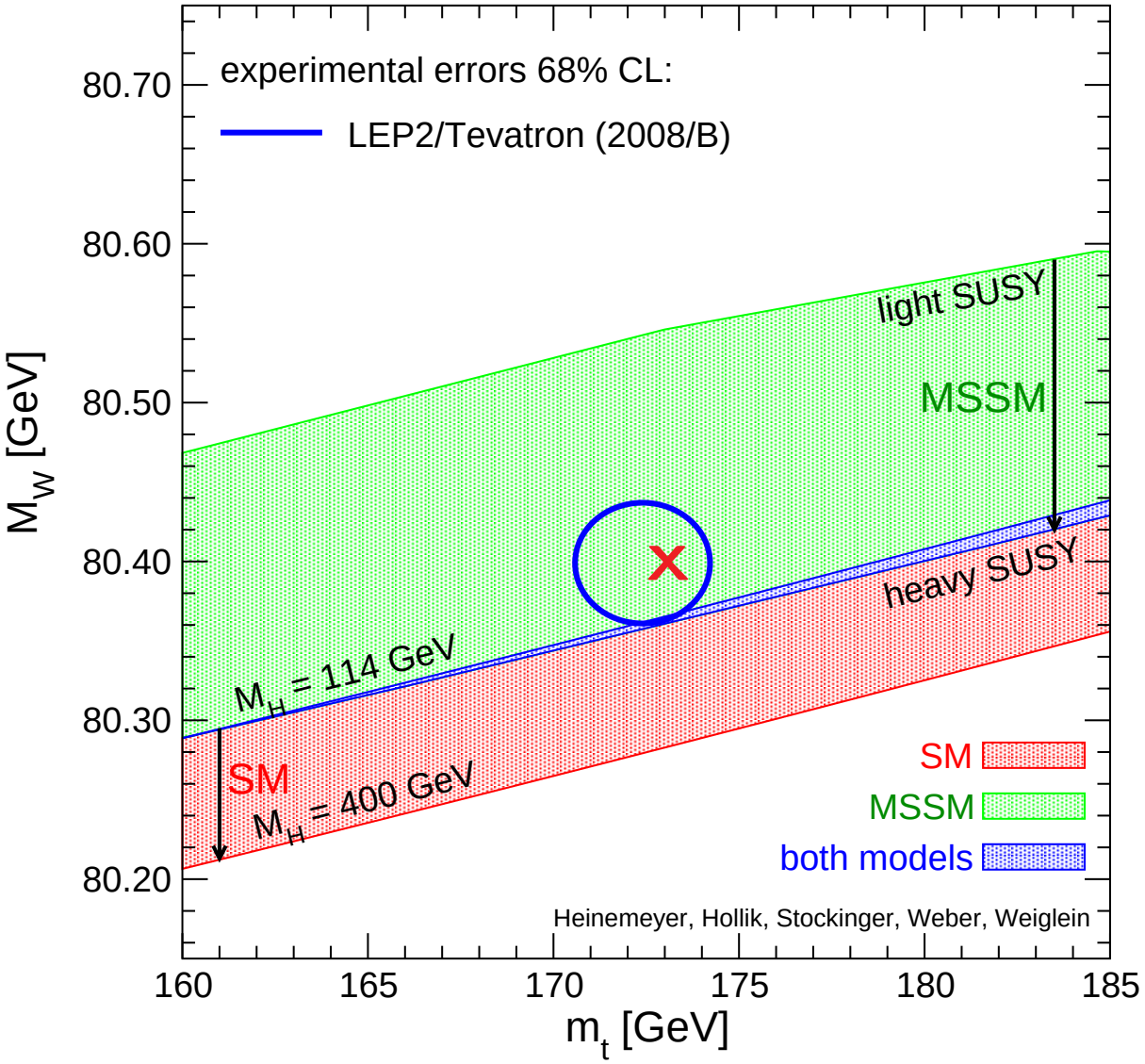

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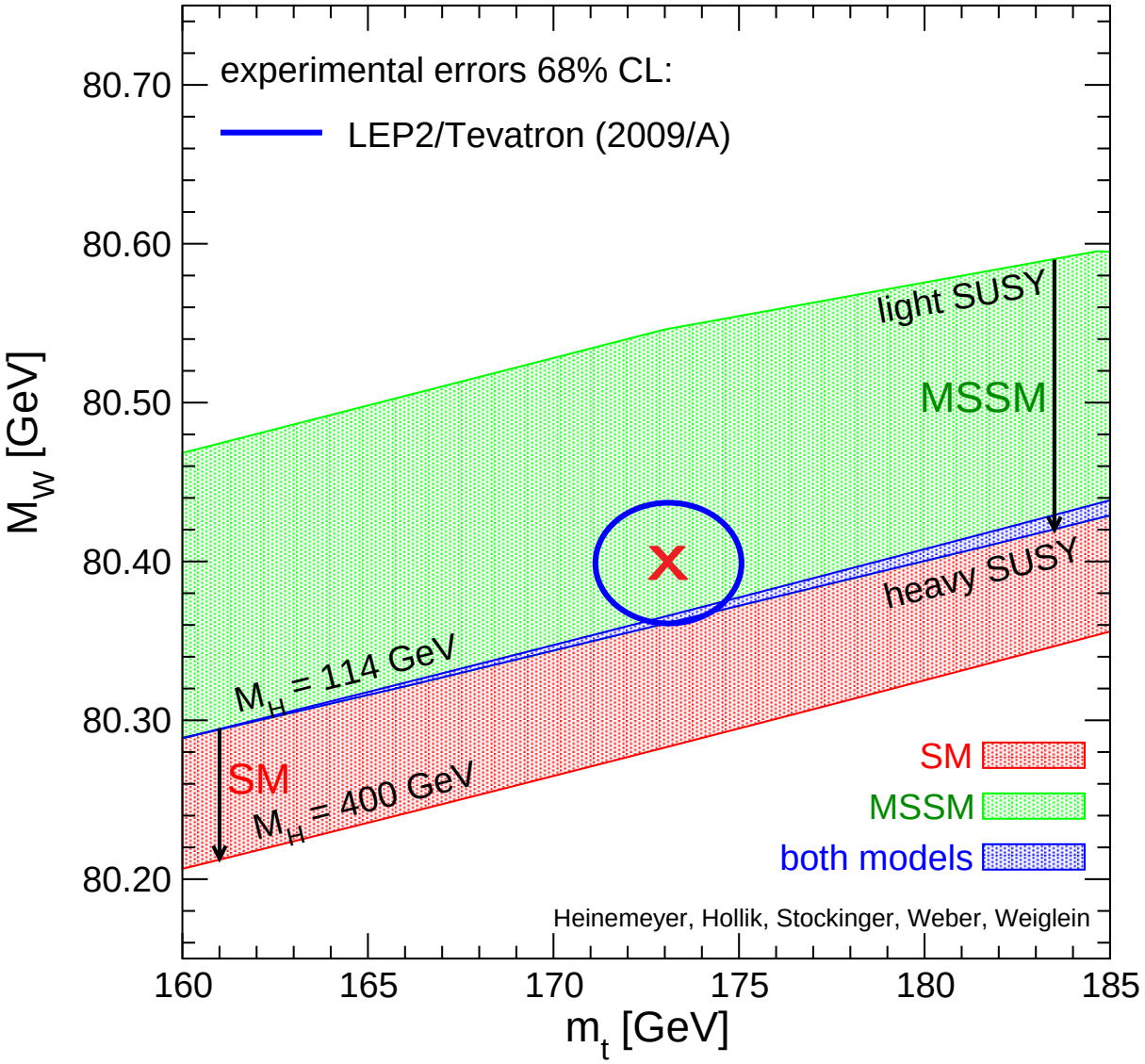

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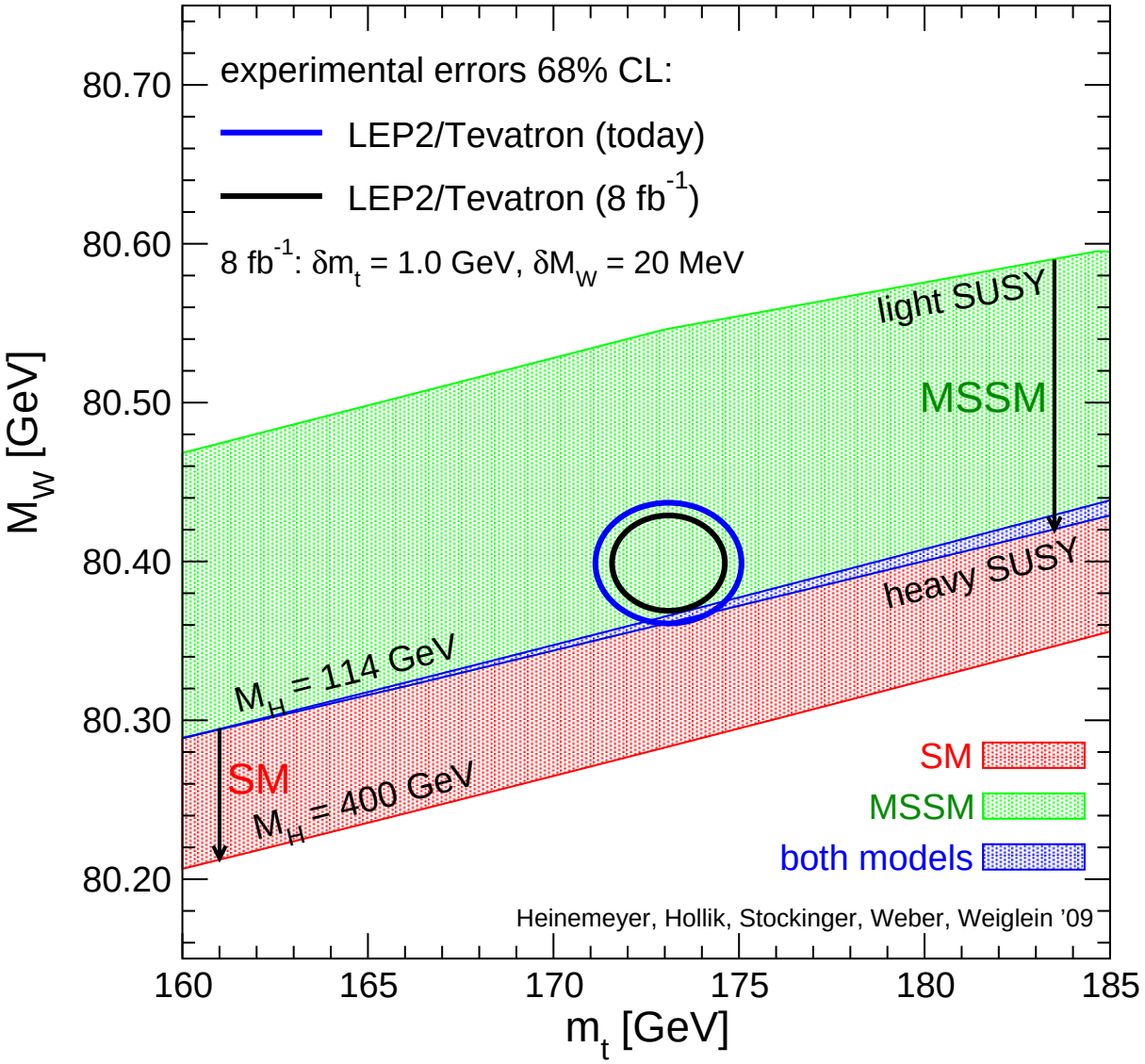

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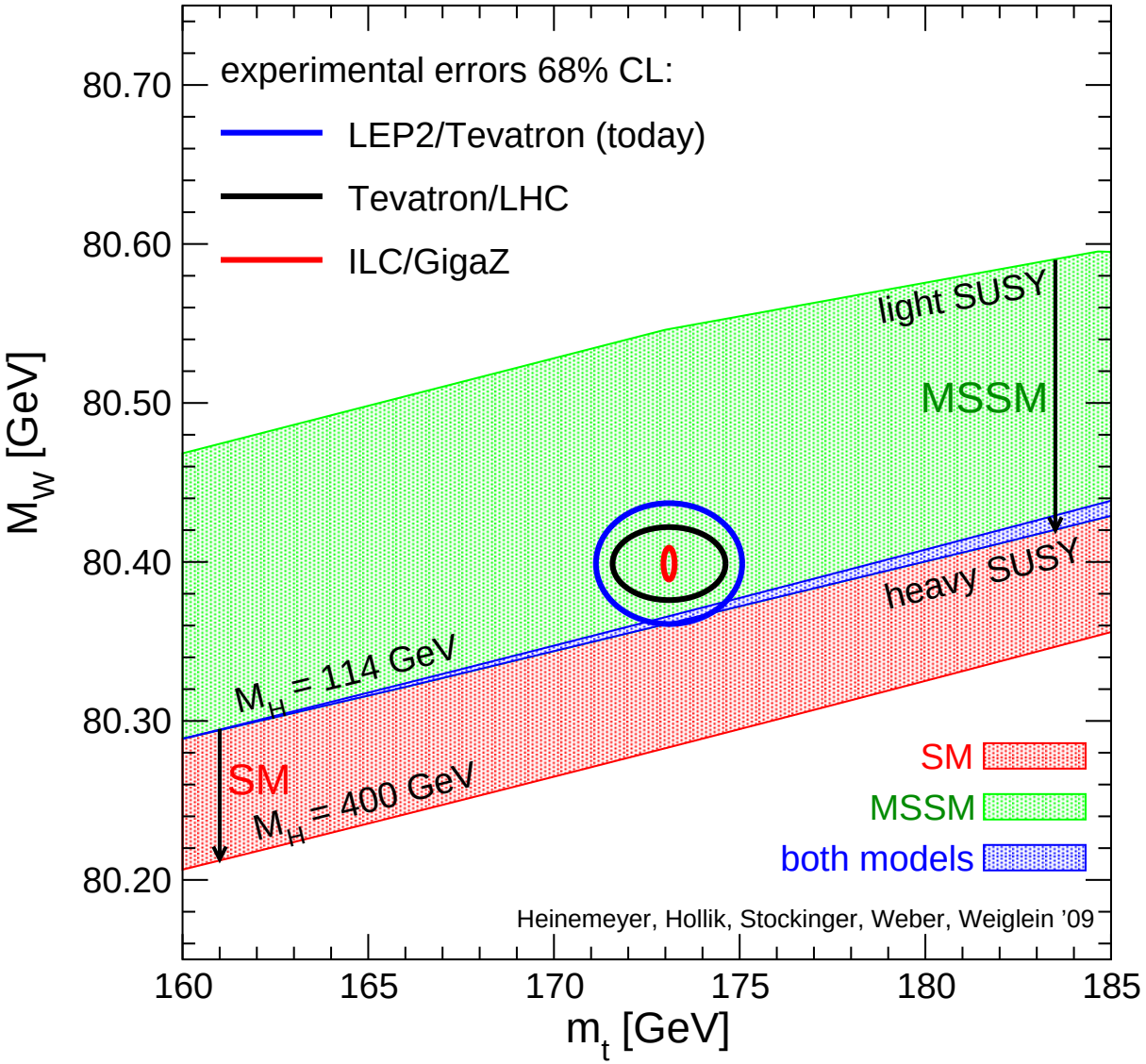

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## Global fit to all SM data:

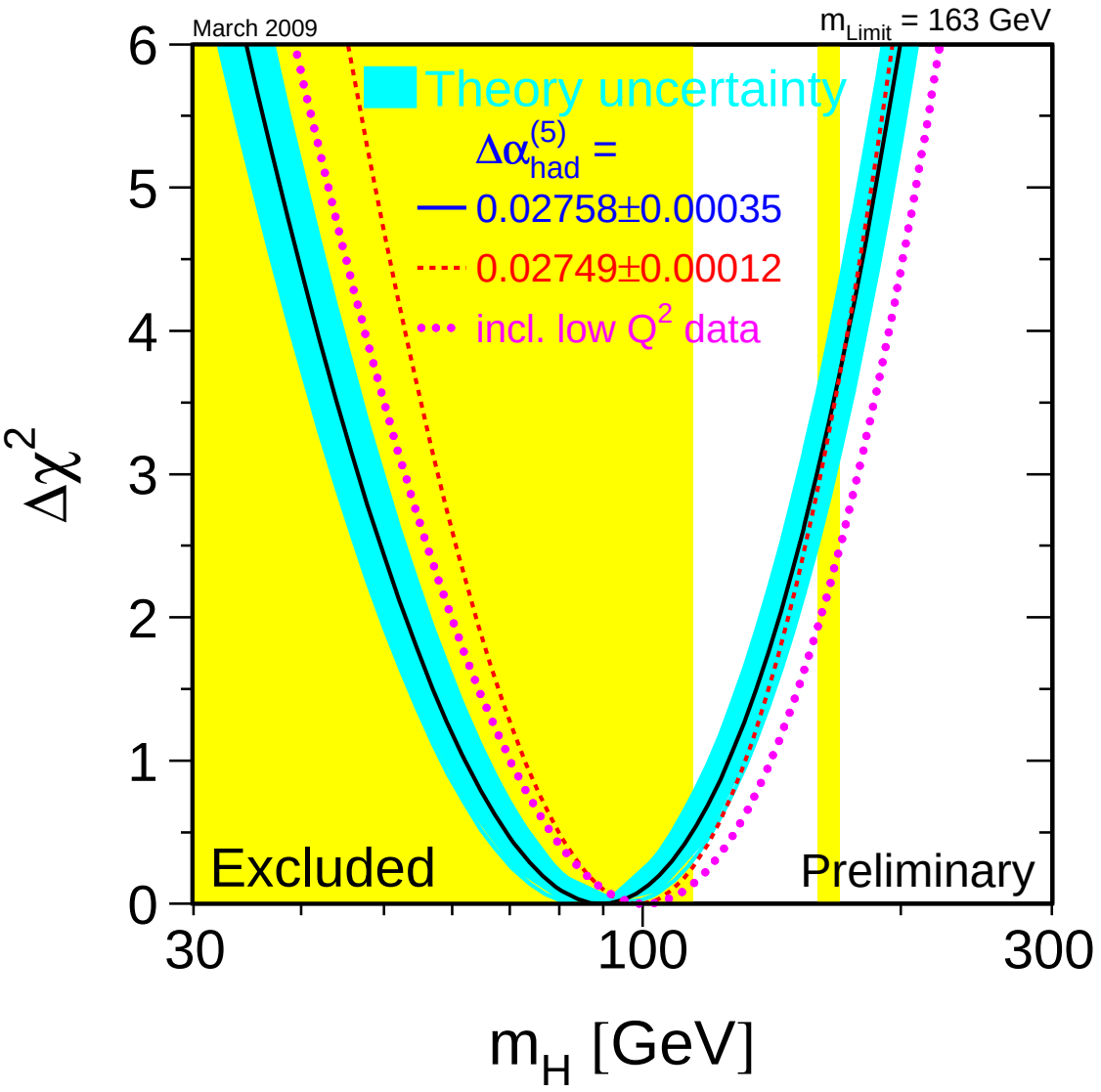
[*LEPEWWG '09*]

$\Rightarrow M_H = 90^{+36}_{-27}$ GeV

$M_H < 163$ 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

## Global fit to all SM data incl. direct searches:

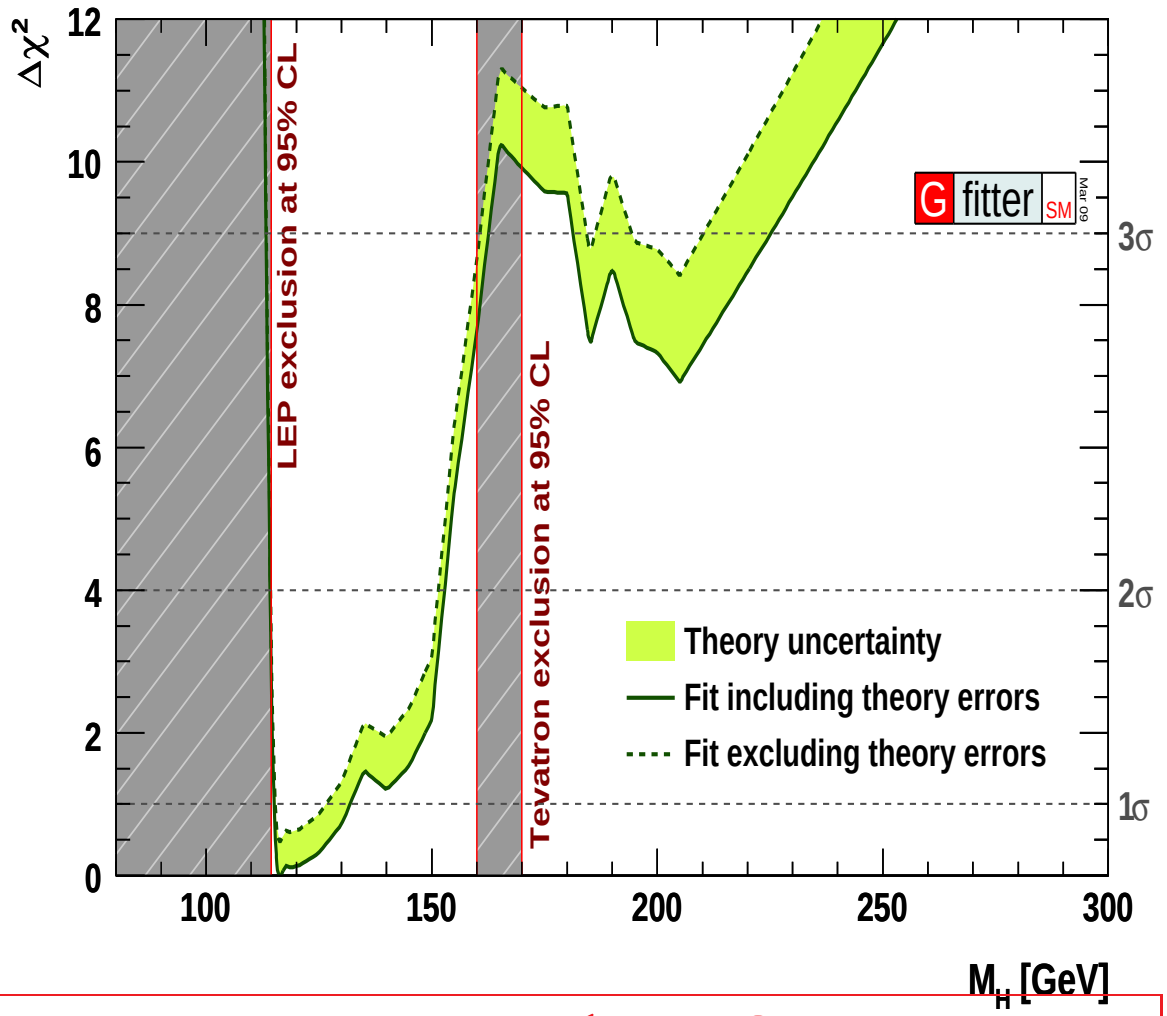
[*GFitter '09*]

$\Rightarrow M_H = 116.4^{+18.3}_{-1.4}$ GeV

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

Assumption for the fit:
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$\Rightarrow$ no confirmation of Higgs mechanism




$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 150$ GeV

## 2. The CMSSM and beyond

### Indirect constraints on $M_{\rm SUSY}$ from existing data?

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

$\Rightarrow$ 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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$\Rightarrow$ combination makes only sense if all parameters are connected!

$\Rightarrow$ GUT based models, ...

## Existing analyses for GUT based models: (involving precision observables)

### CMSSM/mSUGRA:

[*J. Ellis, S.H., K. Olive, G. Weiglein '04, '06, '07*] [*J. Ellis, S.H., K. Olive, A. Weber, G. Weiglein '07*]

[*E. Baltz, P. Gondolo '04*]

[*R. Ruiz de Austri, R. Trotta and L. Roszkowski '06, '07*]

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[*F. Feroz, M. Hobson, L. Roszkowski and R. Ruiz de Austri, R. Trotta '08*]

[*O. Buchmueller et al. '07*] [*O. Buchmueller et al. '08*]

### NUHM (Non-Universal Higgs Mass model):

[*J. Ellis, S.H., K. Olive, G. Weiglein '06*] [*J. Ellis, S.H., K. Olive, A. Weber, G. Weiglein '07*]

[*J. Ellis, T. Hahn, S.H., K. Olive, G. Weiglein '07*]

[*L. Roszkowski, R. de Austri, R. Trotta, Y. Tsai, T. Varley '09*]

### VCMSSM & mSUGRA (GDM):

[*J. Ellis, S.H., K. Olive, G. Weiglein '06*]

### Finite Unified Theories:

[*S.H., M. Mondragón, G. Zoupanos '08*]

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[*O. Buchmueller et al. '07*] [*O. Buchmueller et al. '08*]

### NUHM (Non-Universal Higgs Mass model):

[*J. Ellis, S.H., K. Olive, G. Weiglein '06*] [*J. Ellis, S.H., K. Olive, A. Weber, G. Weiglein '07*]

[*J. Ellis, T. Hahn, S.H., K. Olive, G. Weiglein '07*]

[*L. Roszkowski, R. de Austri, R. Trotta, Y. Tsai, T. Varley '09*]

### VCMSSM & mSUGRA (GDM):

[*J. Ellis, S.H., K. Olive, G. Weiglein '06*]

### Finite Unified Theories:

[*S.H., M. Mondragón, G. Zoupanos '08*]

$\Rightarrow$ analyses in other GUT based models are missing!

## The models: 1.) CMSSM (or mSUGRA):

⇒ Scenario characterized by

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

$m_0$ : universal scalar mass parameter

$m_{1/2}$ : universal gaugino mass parameter

$A_0$ : universal trilinear coupling

} at the GUT scale

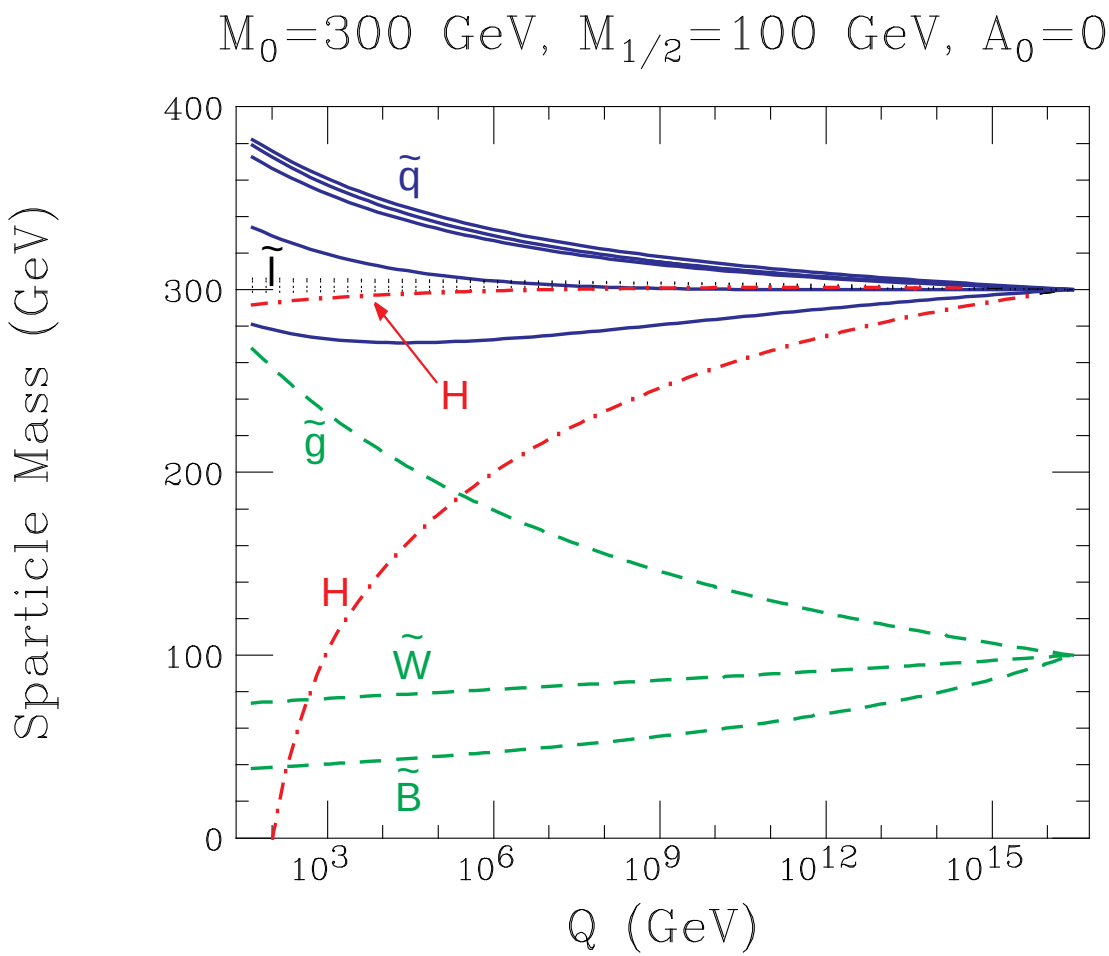
$\tan\beta$ : ratio of Higgs vacuum expectation values

$\mathrm{sign}(\mu)$ : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino

$\Rightarrow$ particle spectra from renormalization group running to weak scale



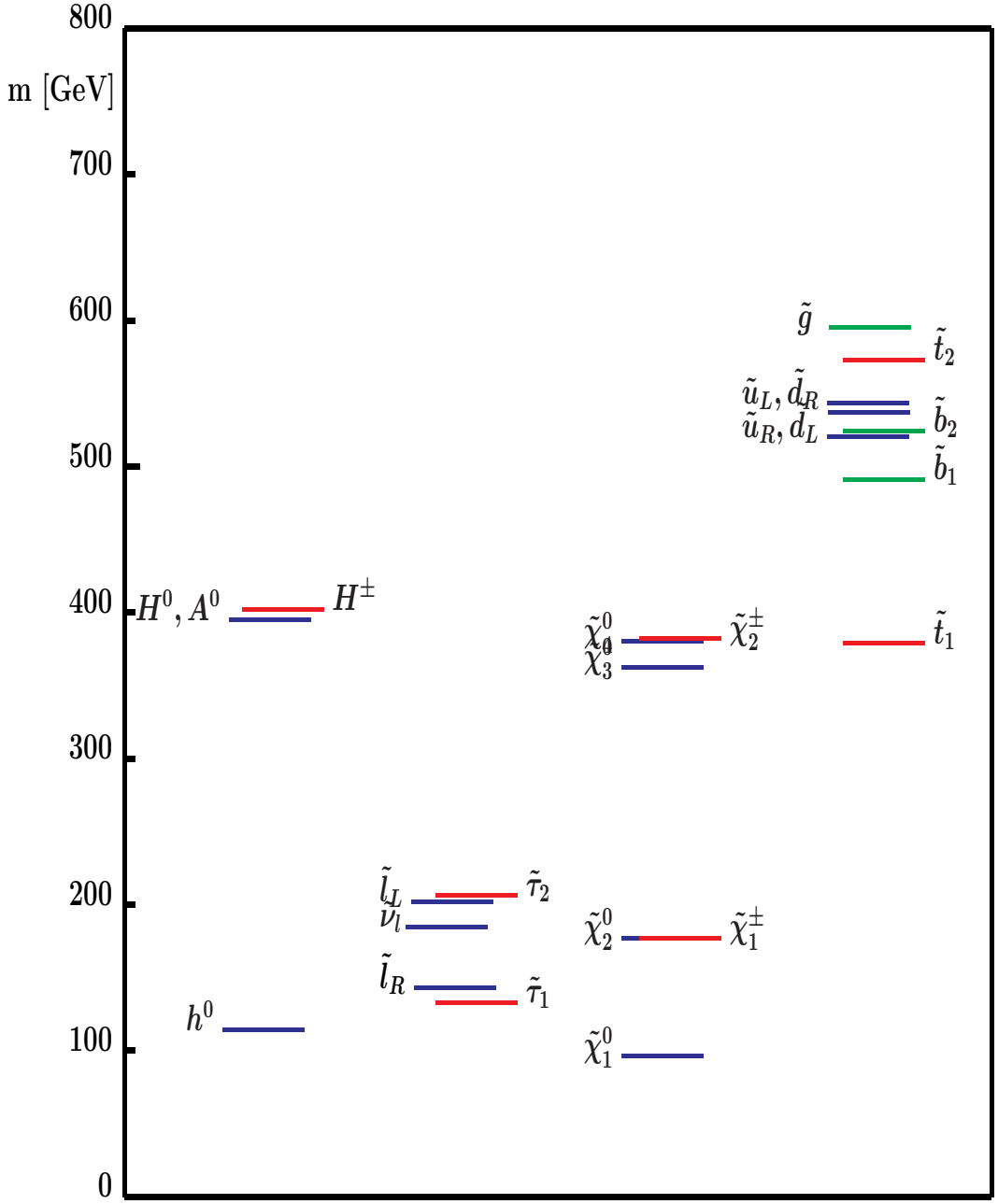

$\Rightarrow$ one parameter turns negative $\Rightarrow$ Higgs mechanism for free

## "Typical" CMSSM scenario

## (SPS 1a benchmark scenario):

SPS home page:

`www.ippp.dur.ac.uk/~georg/sps`



## The 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 $\mu$ as free parameters at the EW scale

$\Rightarrow$ besides the CMSSM parameters

$M_A$ or $\mu$

Further extension: NUHM2:

Assumption: no unification of the Higgs parameters at the GUT scale

$\Rightarrow$ effectively $M_A$ and $\mu$ as free parameters at the EW scale

$\Rightarrow$ besides the CMSSM parameters

$M_A$ and $\mu$

## The models: 3.) (minimal) gauge mediated SUSY breaking: mGMSB

GMSB scenario characterized by

$$M_{\text{mess}}, N_{\text{mess}}, \Lambda, \tan\beta, \text{sign}(\mu)$$

$M_{\text{mess}}$: messenger mass scale

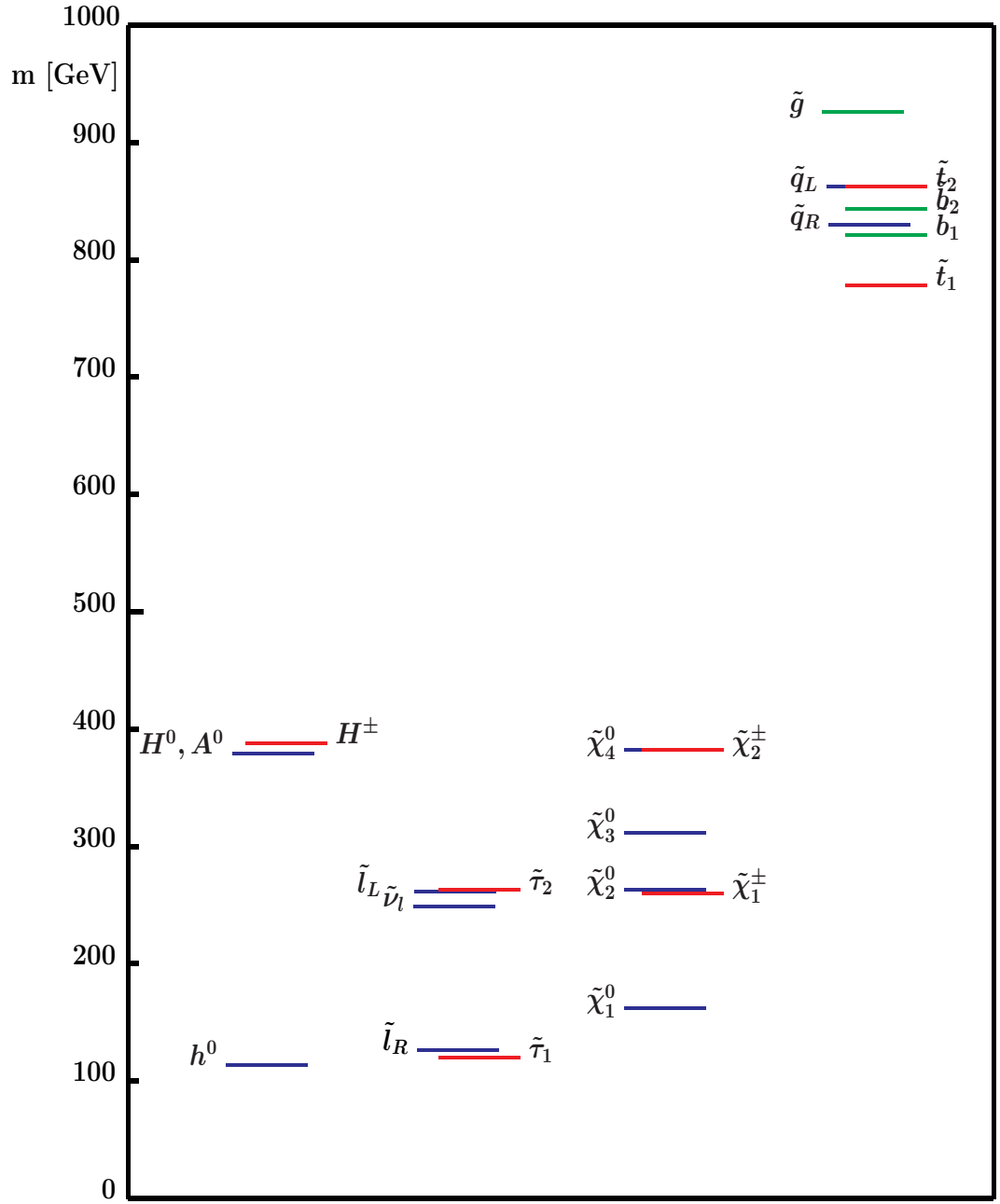
$N_{\text{mess}}$: messenger index (number of messenger multiplets)

$\Lambda = \langle F \rangle / M_{\text{mess}}$: universal soft SUSY breaking mass scale felt by low-energy sector

LSP is always the gravitino
next-to-lightest SUSY particle (NLSP): $\tilde{\chi}_1^0$ or $\tilde{\tau}_1$

can decay into LSP inside or outside the detector

# GMSB scenario with $\tilde{\tau}$ NLSP (SPS 7 benchmark scenario):



Parameters:

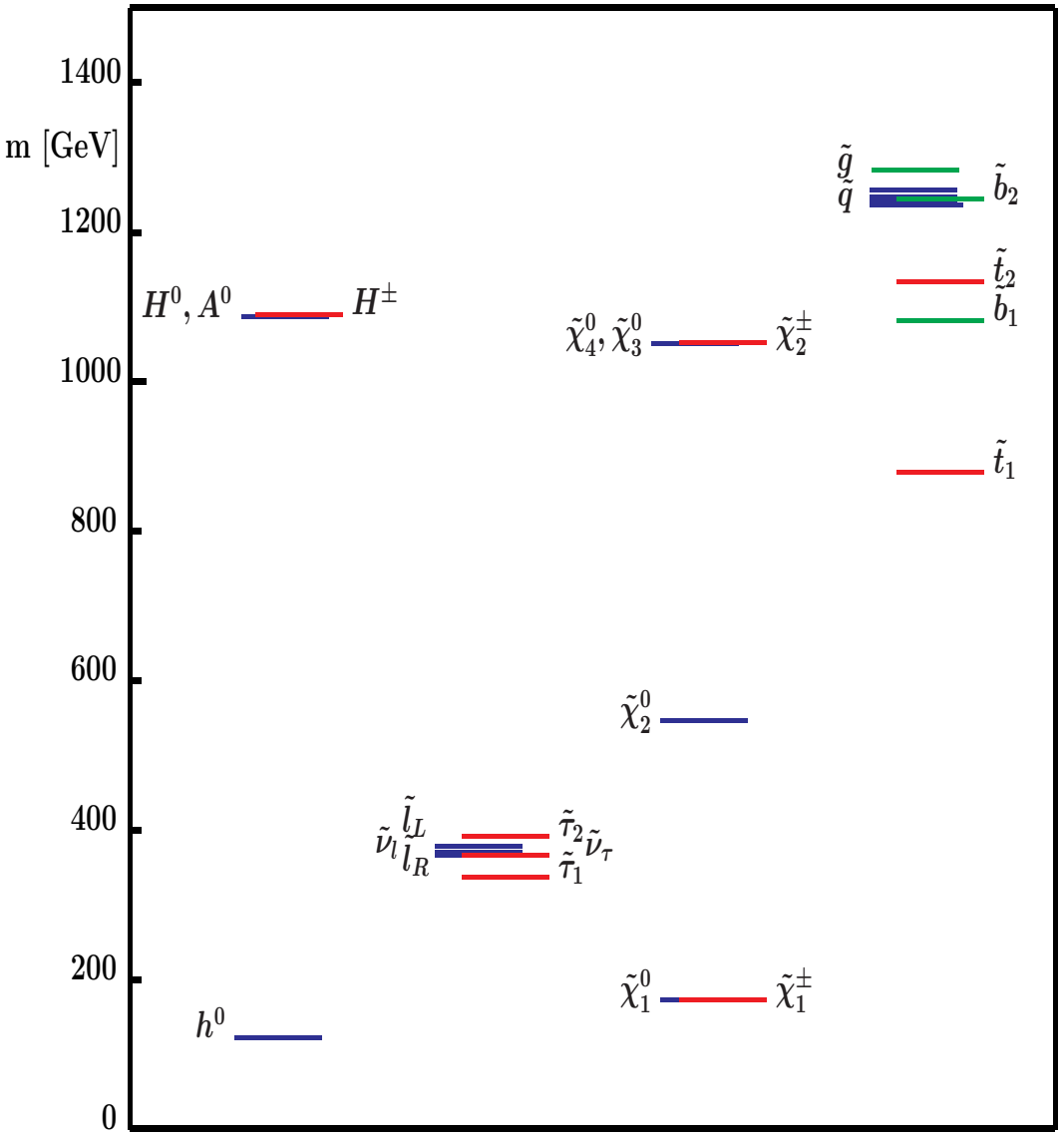
$m_{\text{aux}}, m_0, \tan\beta, \text{sign}(\mu)$

SPS9:

typical feature: very small neutralino–chargino mass difference

$\Rightarrow \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 + \pi^{\pm}$

with very soft pions



# 3. Constraining the CMSSM, mGMSB and mAMSB

[*S.H., X. Miao, S. Su, G. Weiglein '08*]

Procedure:

1. Scan over full parameter space:
   - CMSSM: $m_{1/2}$, $m_0$, $A_0$, $\tan\beta$
   - mGMSB: $\Lambda$, $M_{\rm mess}$, $N_{\rm mess}$, $\tan\beta$
   - mAMSB: $m_{\rm aux}$, $m_0$, $\tan\beta$

   $\mu > 0$ (anomalous magnetic moment of the muon) $\rightarrow$ T

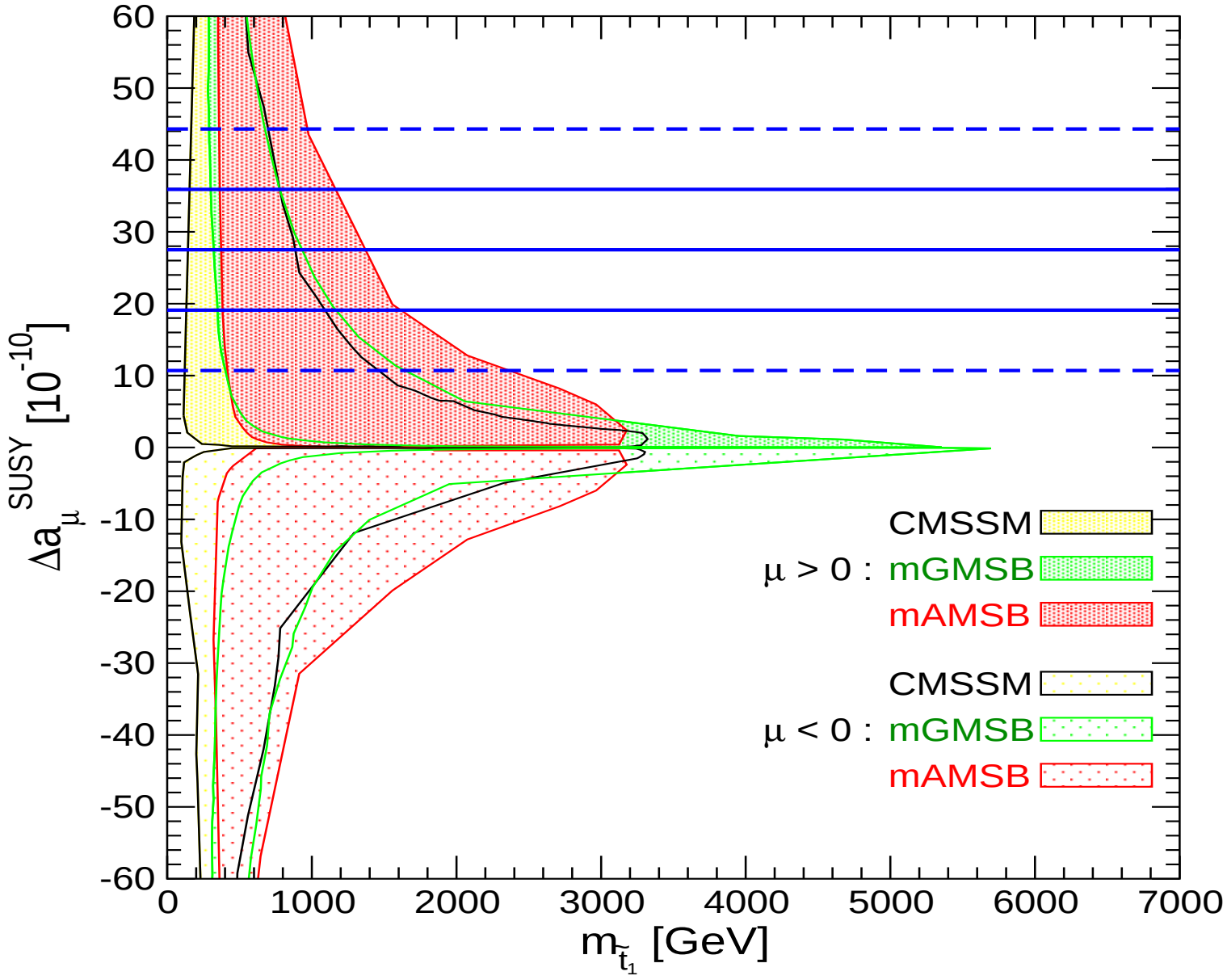
2. Perform $\chi^2$ fit with precision observables:

   $$M_W,\ \sin^2\theta_{\rm eff},\ (g-2)_\mu,\ M_h,\ {\rm BR}(b\to s\gamma),\ {\rm BR}(B_s\to\mu^+\mu^-)$$

   (neglect CDM constraint in order to treat models on the same footing)

3. Find preferred values for masses
   $\Rightarrow$ LHC/ILC reach
   $\Rightarrow$ comparison of models
   $\Rightarrow$ distinction of models?

# $(g-2)_\mu$: CMSSM vs. mGMSB vs. mAMSB




$\Rightarrow \mu < 0$ disfavored in all scenarios

## How good is the fit?

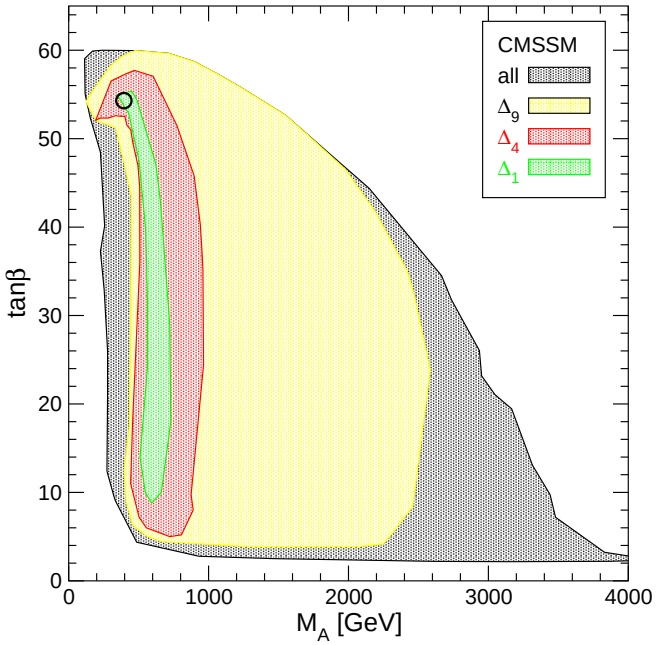
| | CMSSM | mGMSB | mAMSB |
|---|---|---|---|
| $\chi^2_{\text{min}}$ | 4.6 | 5.1 | 2.9 |
| $M_W$ | 1.7 | 2.1 | 0.6 |
| $\sin^2\theta_{\text{eff}}$ | 0.1 | 0.0 | 0.8 |
| $(g-2)_\mu$ | 0.6 | 0.9 | 0.0 |
| BR$(b \to s\gamma)$ | 1.1 | 2.0 | 1.5 |
| $M_h$ | 1.1 | 0.1 | 0.0 |
| BR$(B_s \to \mu^+\mu^-)$ | $4.5 \times 10^{-8}$ | $3.2 \times 10^{-8}$ | $0.4 \times 10^{-8}$ |
| $M_A$ [GeV] (best-fit) | 394 | 547 | 616 |
| $\tan\beta$ (best-fit) | 54 | 55 | 9 |

$\Rightarrow$ good fit results

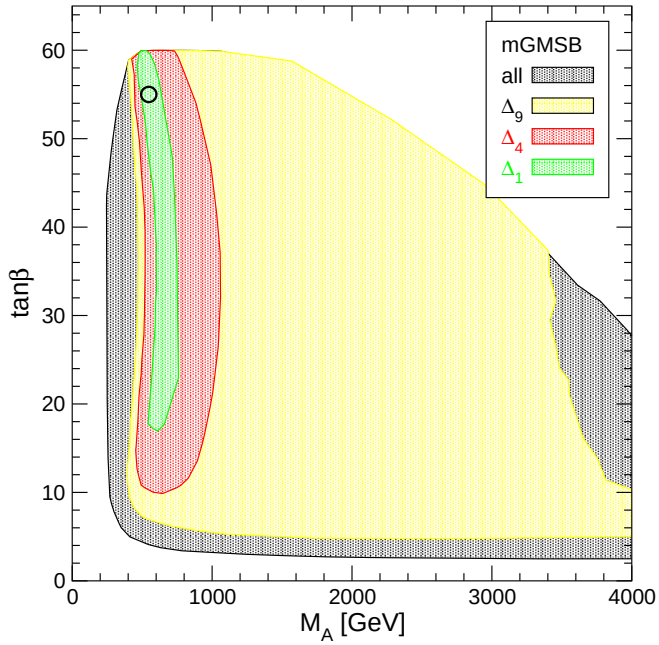
$\Rightarrow$ mAMSB fits best (but not significantly)

# Results: fit in the $M_A$–tan $\beta$ plane: today

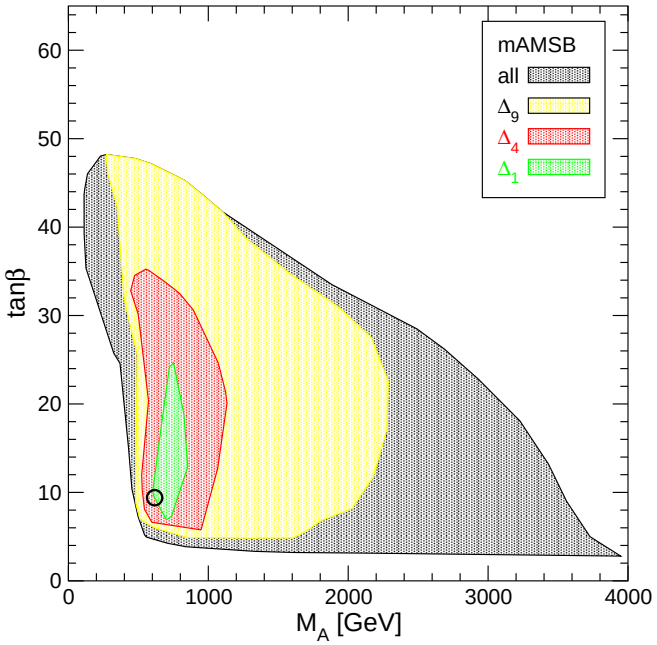
CMSSM




mGMSB




mAMSB




$\Rightarrow$ $\Delta\chi^2 < 9$ hardly constrains the parameter space

upper limit on $M_A$ at $\Delta\chi^2 < 4$

$M_A$ partially in LHC reach for large tan $\beta$

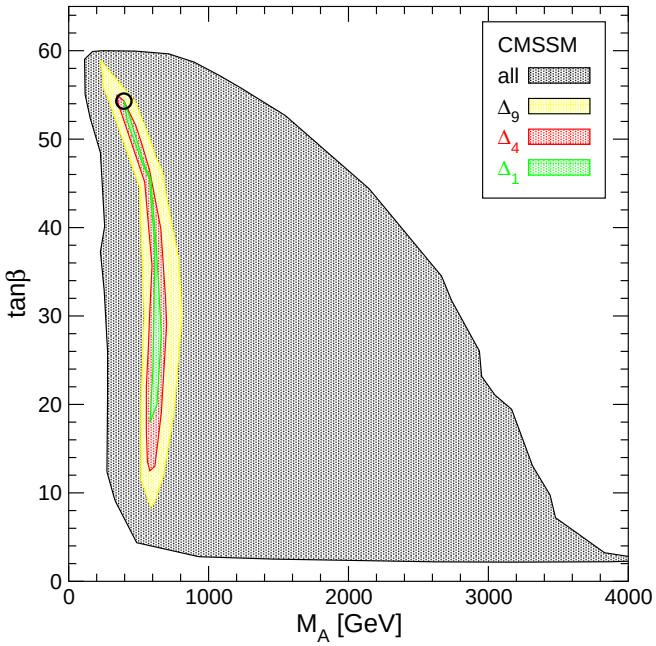
$M_A$ still mostly outside the ILC(1000) reach

tan $\beta$ only mildly restricted

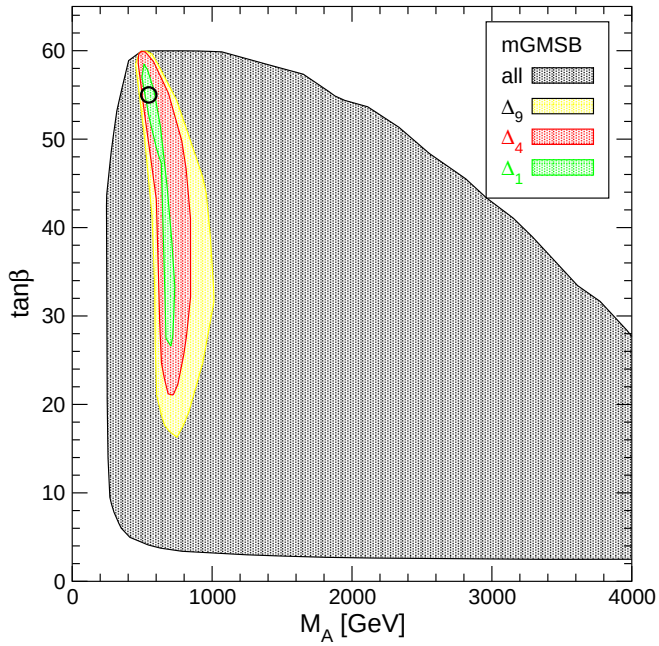
# Results: fit in the $M_A$–tan $\beta$ plane: future

Using: todays exp. values and anticipated future (LHC/ILC) precisions

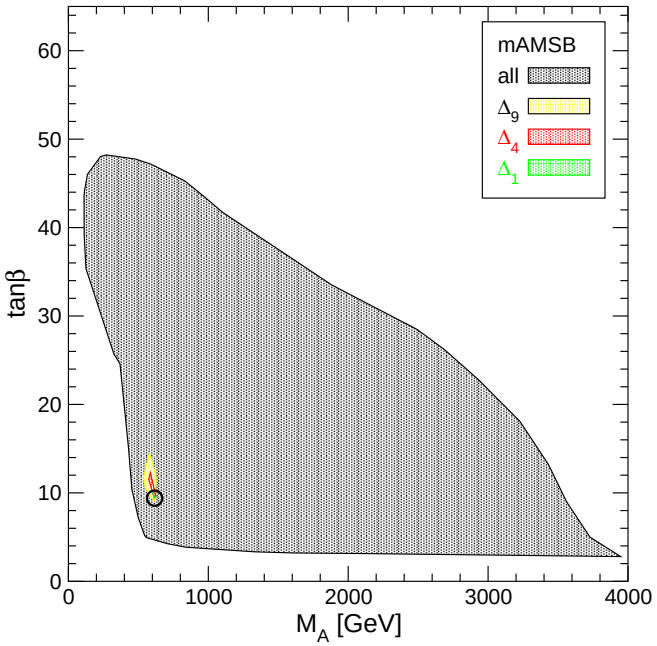
CMSSM




mGMSB




mAMSB



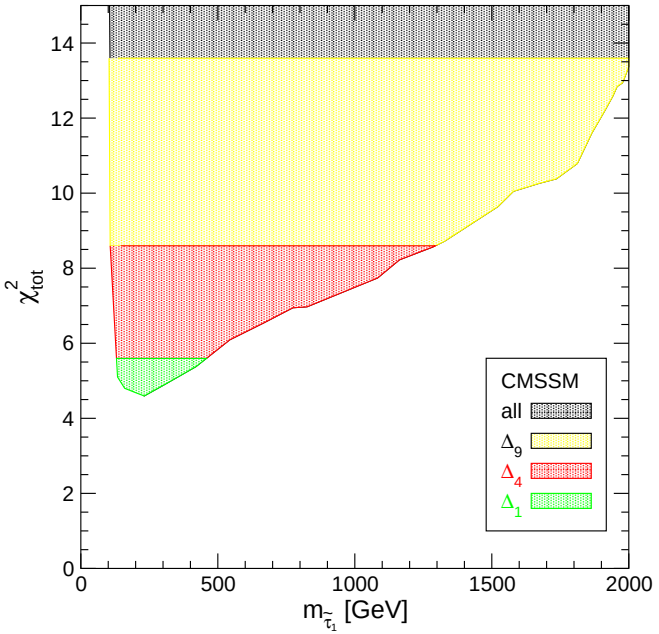

$\Rightarrow$ upper limit on $M_A$ at $\Delta\chi^2 < 9$

tan $\beta$ only mildly restricted in CMSSM/mGMSB

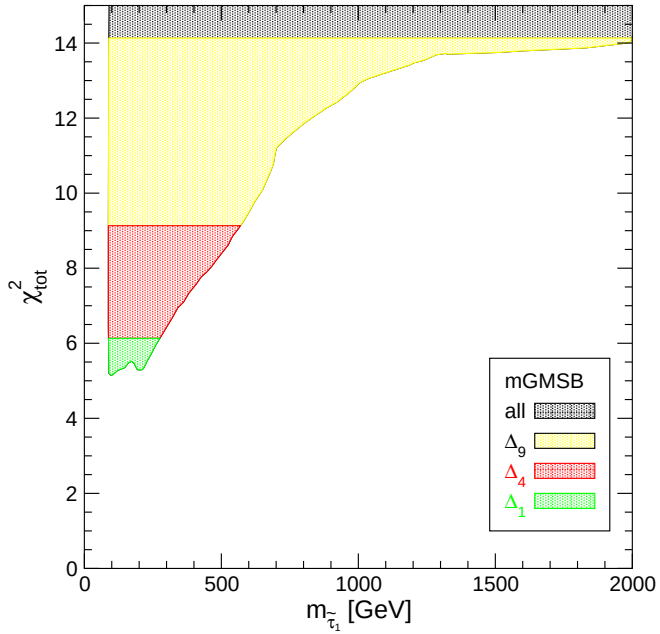
mAMSB: high precision is accidental

# Results: lightest scalar tau vs. $\chi^2_{\rm tot}$

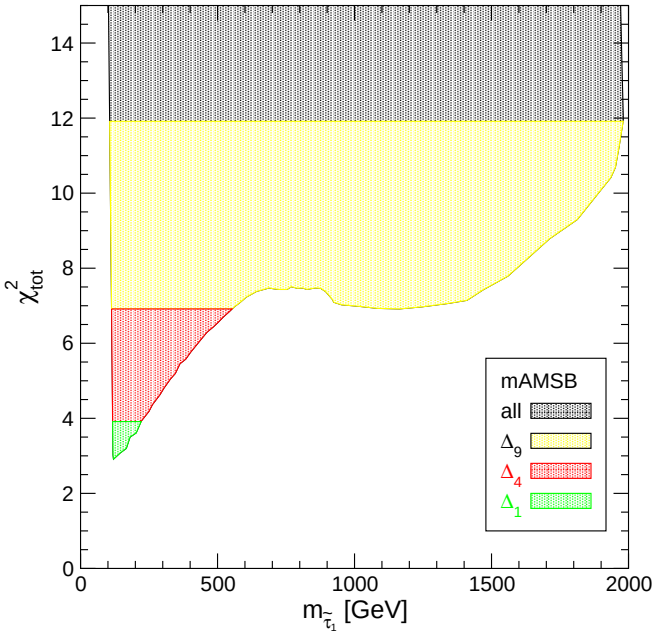
CMSSM




mGMSB




mAMSB




$\Rightarrow m_{\tilde\chi_1^0} \lesssim 500, 500, 1000$ GeV at $\Delta\chi^2 < 4$ for CMSSM, mAMSB, mGMSB

$\Rightarrow$ partially outside direct LHC reach, detection in cascades?

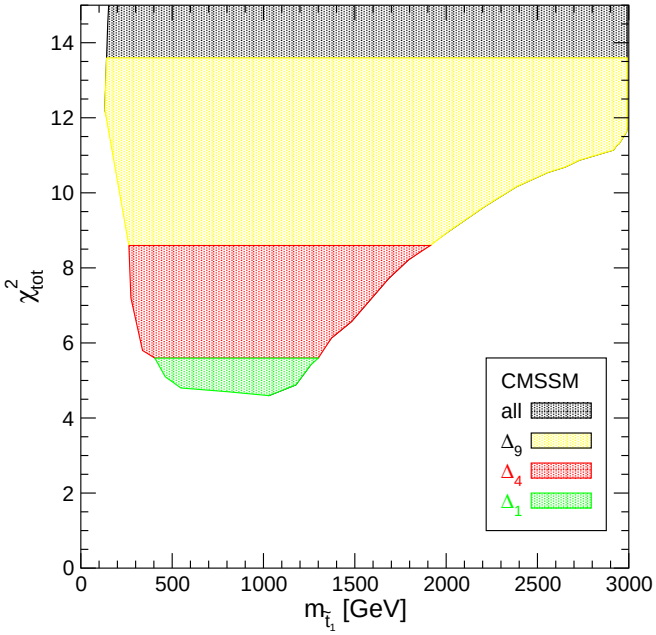
mGMSB, mAMSB: $e^+e^- \to \tilde\tau_1\tilde\tau_1$ possible

CMSSM: possibly too heavy for ILC(1000)

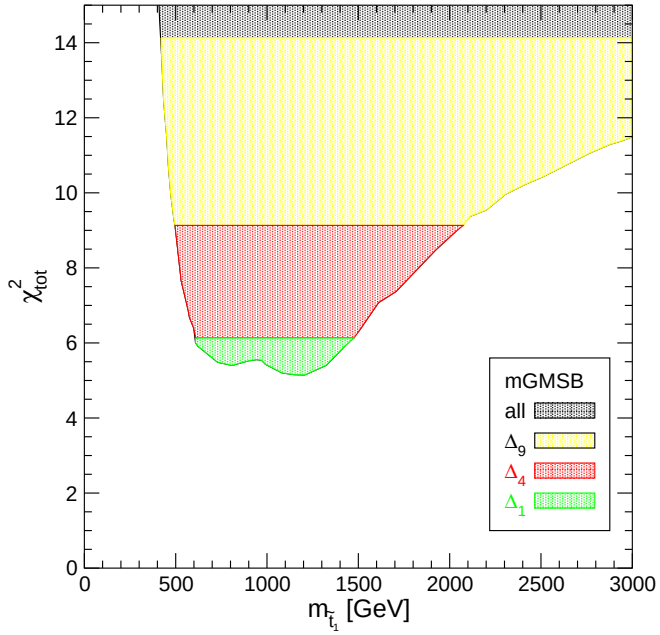
but better if CDM is taken into account

# Results: lightest stop vs. $\chi^2_{\rm tot}$

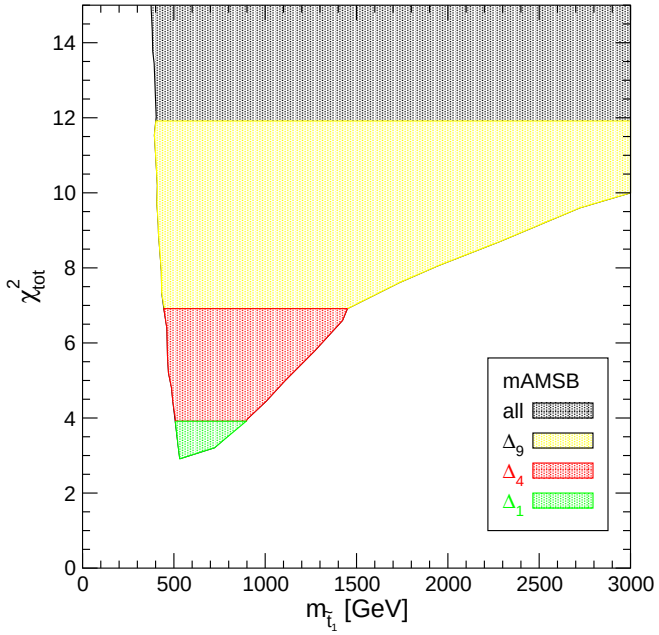
CMSSM




mGMSB




mAMSB

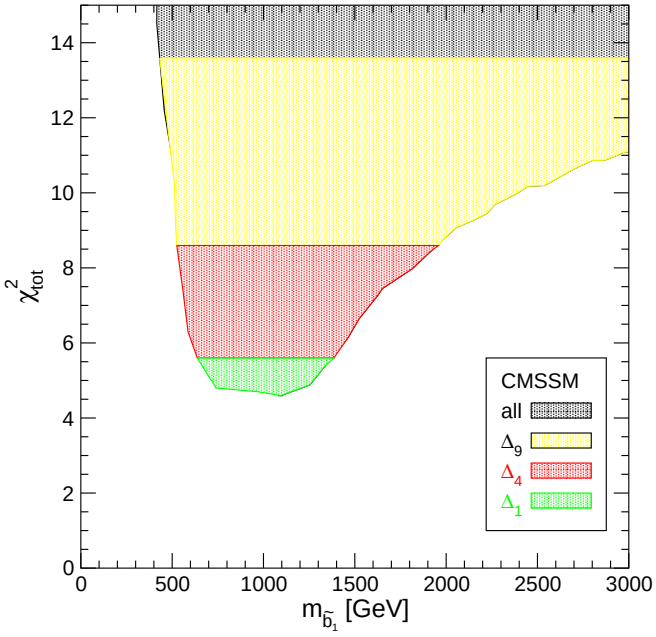



$\Rightarrow$ 500 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 2000 GeV at $\Delta\chi^2 < 4$

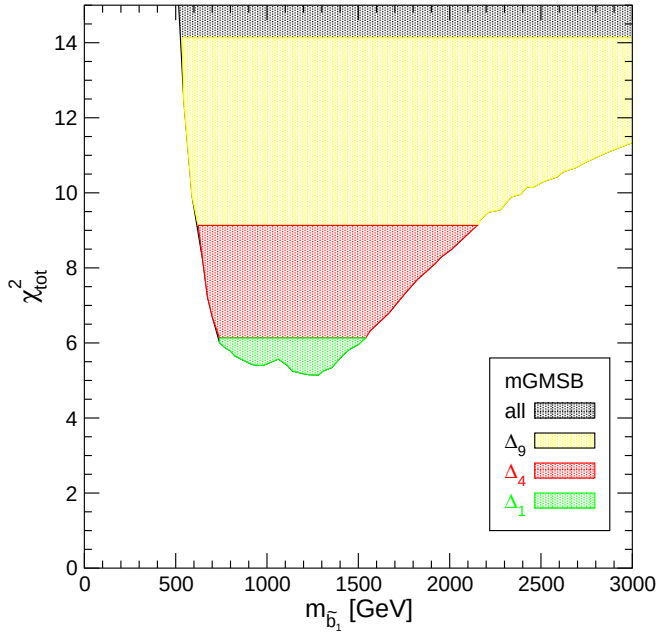
$\Rightarrow$ easily within LHC reach

# Results: lightest sbottom vs. $\chi^2_{\rm tot}$

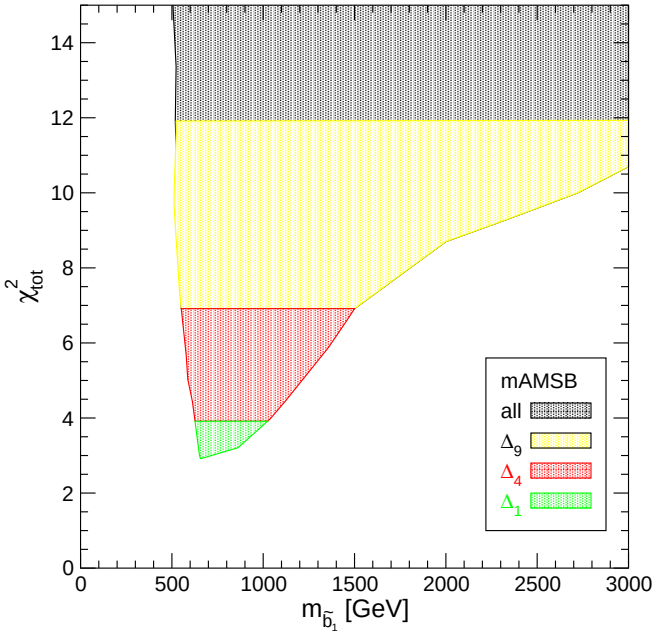
CMSSM




mGMSB




mAMSB



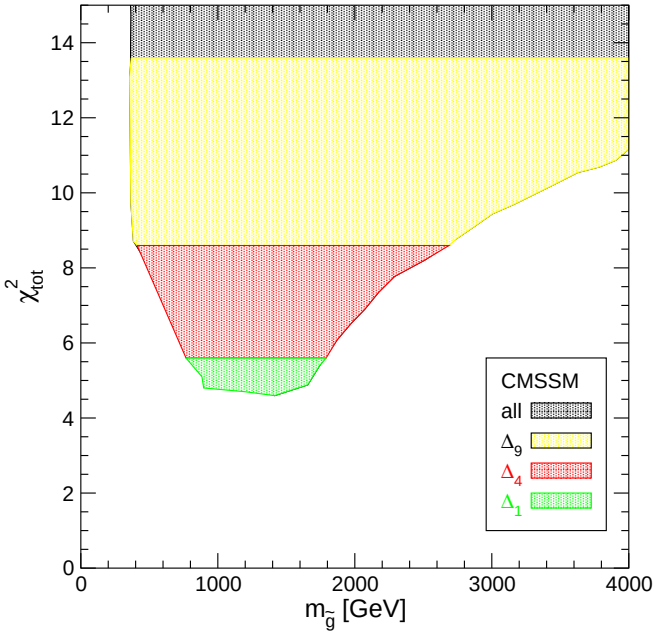

$\Rightarrow$ 500 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 2200 GeV at $\Delta\chi^2 < 4$

slightly heavier than the lightest stop

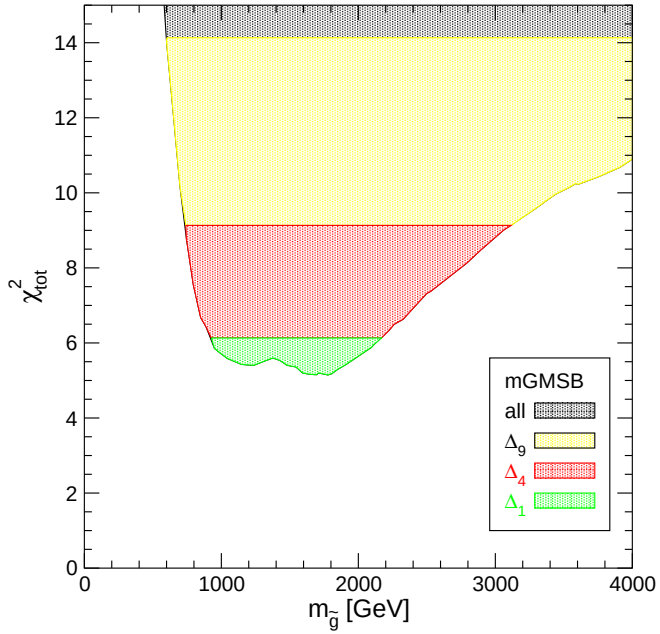
$\Rightarrow$ easily within LHC reach

# Results: gluino vs. $\chi^2_{\rm tot}$

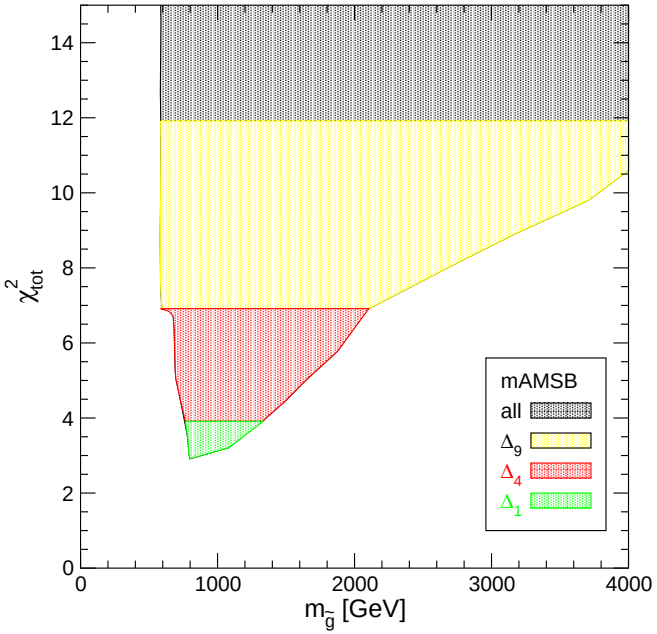
CMSSM




mGMSB




mAMSB




$\Rightarrow$ 500 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 3000 GeV at $\Delta\chi^2 < 4$

$\Rightarrow$ still within LHC reach

. . . but approaching the limit

# 4. Constraining the lightest MSSM Higgs mass

$\Rightarrow$ direct LEP limit is NOT included!

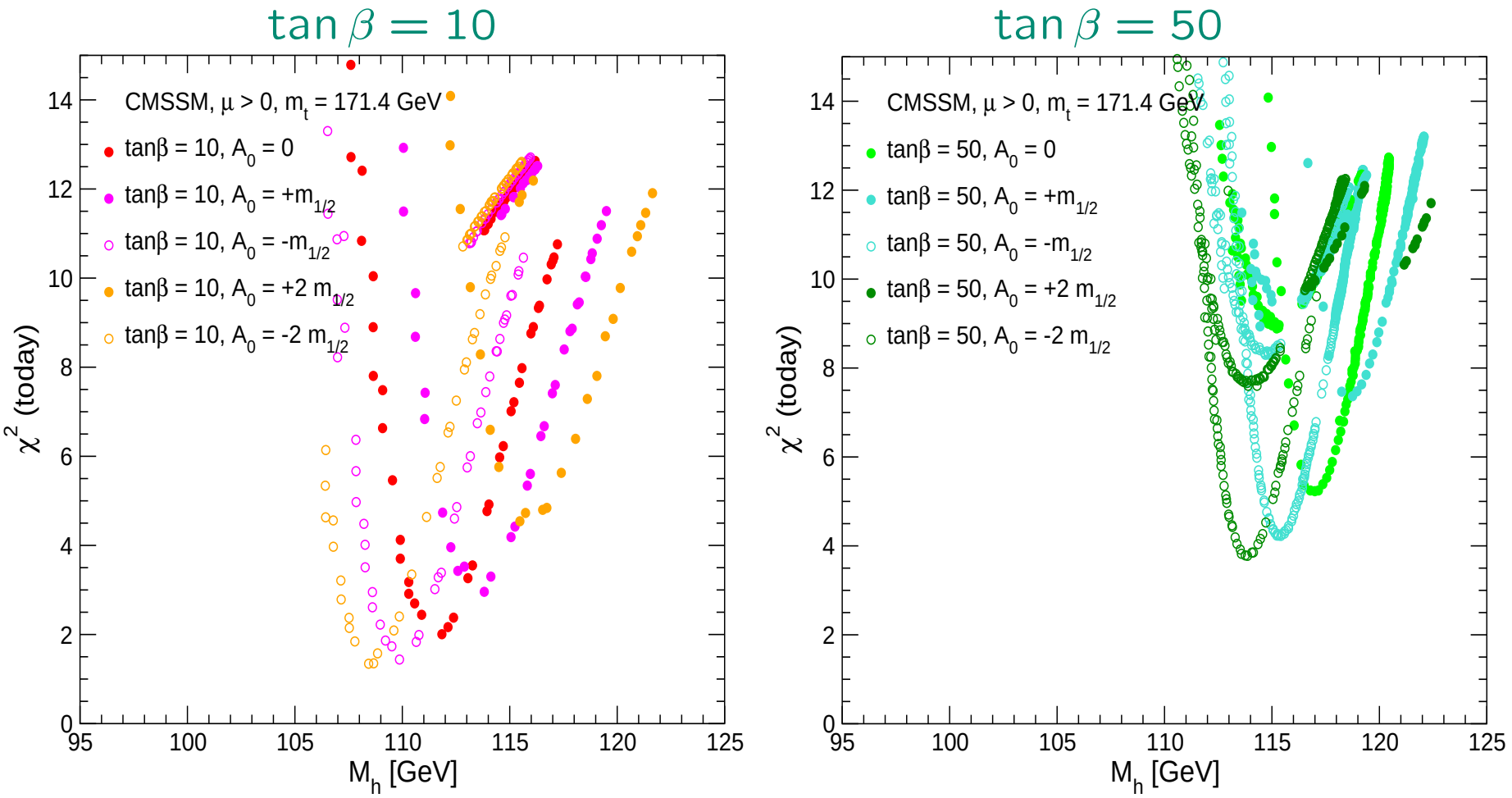
Selection of results: (with a clear personal bias . . . )

1. Fit in the CMSSM using the 4 EWPO + 4 BPO
   $\rightarrow$ "simple" theorist's fit
   [*J. Ellis, S.H., K. Olive, A.M. Weber, G. Weiglein '07*]

2. Fit in the CMSSM, mGMSB, mAMSB using the 4 EWPO + 2 BPO
   – simple scan over all free parameters
   – no CDM constraint
   [*S.H., X. Miao, S. Su, G. Weiglein '08*]

3. Fit in the CMSSM analogous to the Blue Band plot
   – many$^2$ EWPO
   – 2 BPO: BR$(b \to s\gamma)$, BR$(B_s \to \mu^+\mu^-)$
   – in addition to the blue band plot: CDM, $(g-2)_\mu$
   [*Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, Weiglein '07*]
   ($\Rightarrow$ [*MasterCode '07*] )

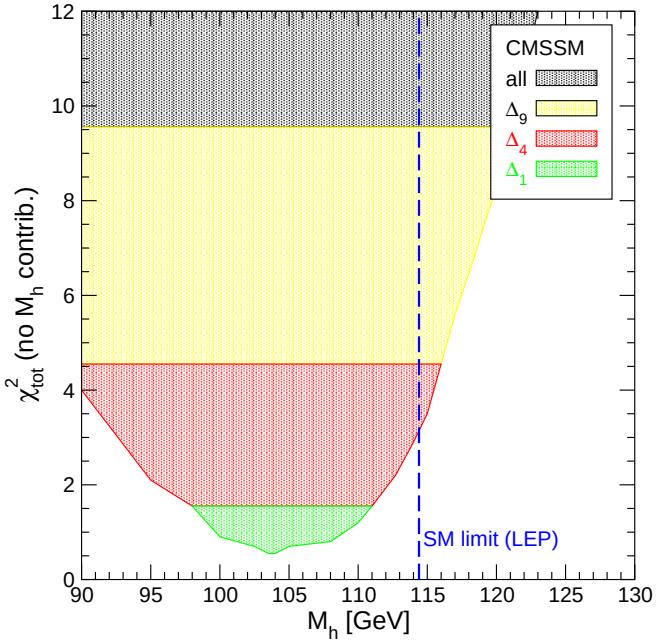
# 1.) Simple CMSSM fit:



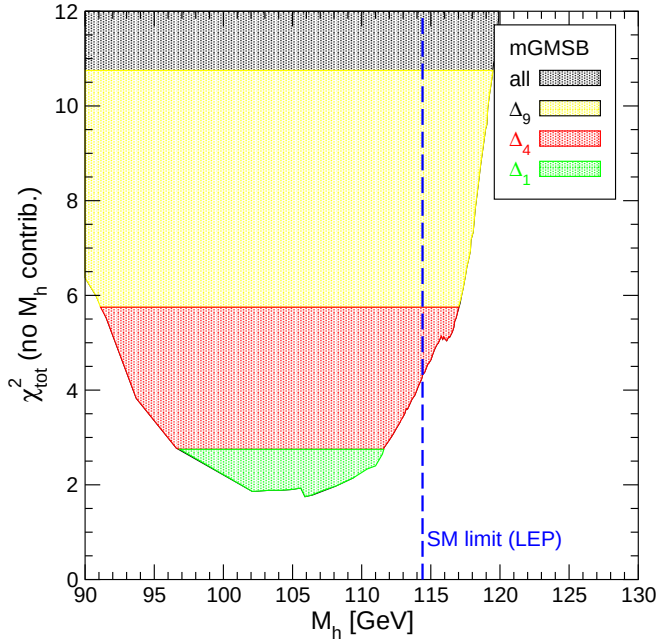

$\Rightarrow M_h = 110 \ldots 115$ GeV (slightly dependent on $\tan\beta$)

# 2.) Comparison of CMSSM, mGMSB, mAMSB (no CDM!)

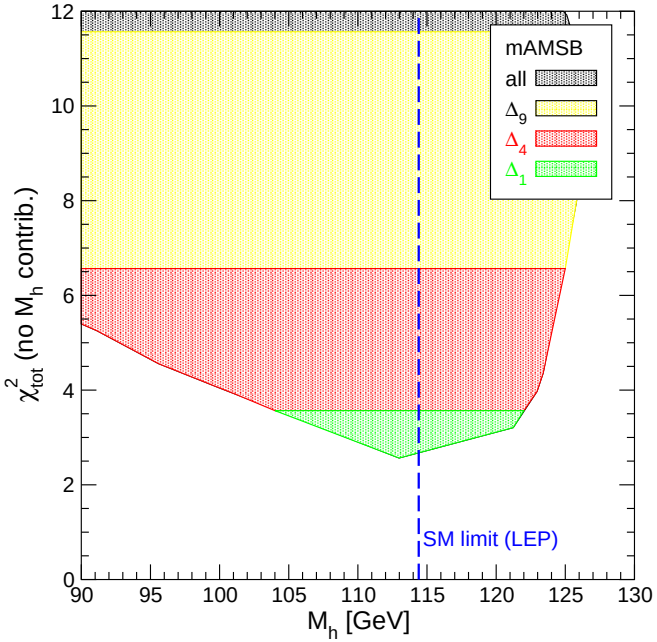
CMSSM




mGMSB




mAMSB




CMSSM/mGMSB: similar results with $M_h \sim 105$ GeV
still $\Delta\chi^2 < 4$ compatible with LEP constraint

CMSSM: better if CDM is taken into account

mAMSB: well compatible with LEP constraint

## 3.) Full $\chi^2$ minimization in the CMSSM: ($m_t = 170.9$ GeV)

[*MasterCode '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: $m_t$, ...

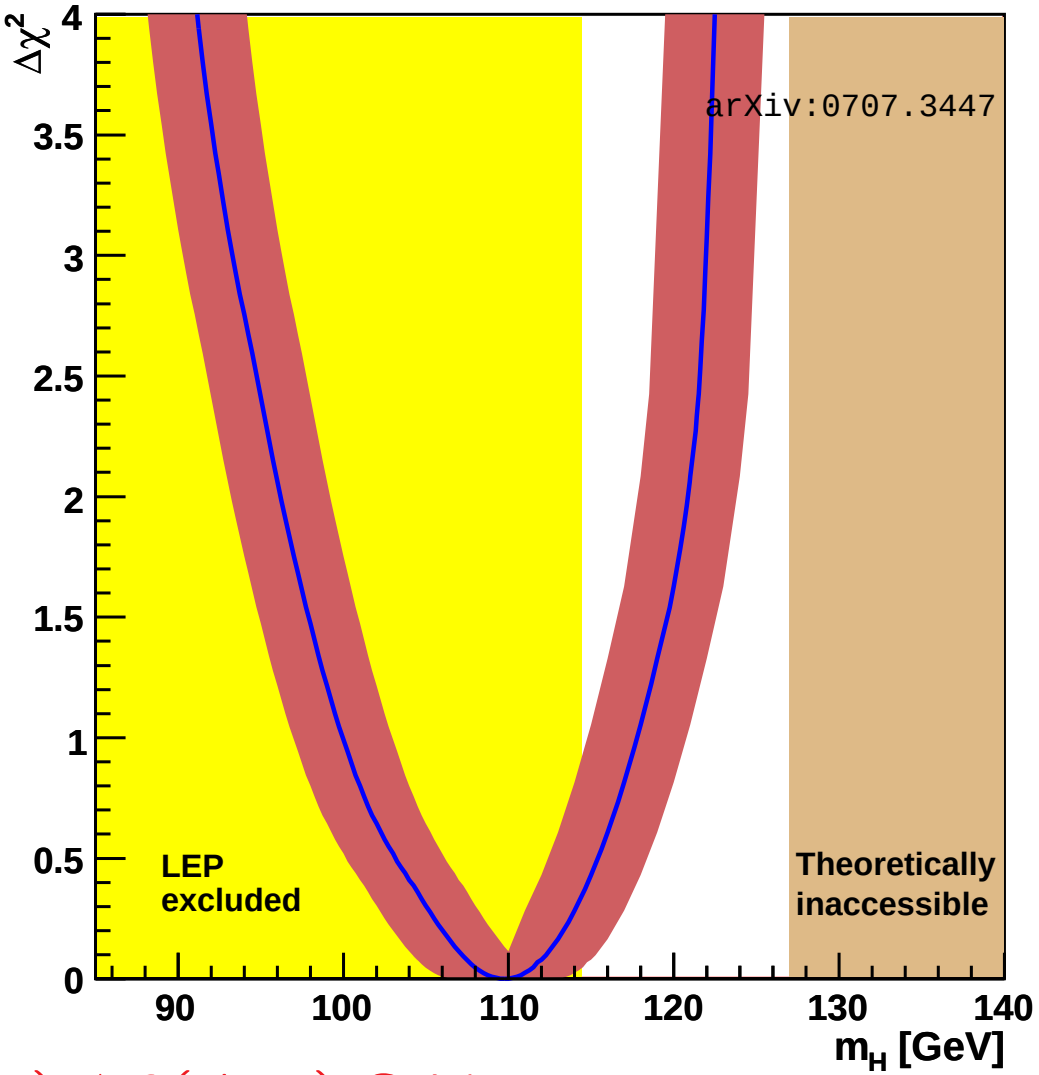
– scan over the full CMSSM parameter space

$\Rightarrow$ preferred CMSSM parameters
$\Rightarrow$ preferred $M_h$ values
$\Rightarrow$ LHC/ILC reach

## 3.) Full $\chi^2$ minimization in the CMSSM: ($m_t = 170.9$ GeV)

*[MasterCode '07]*

Red band plot:

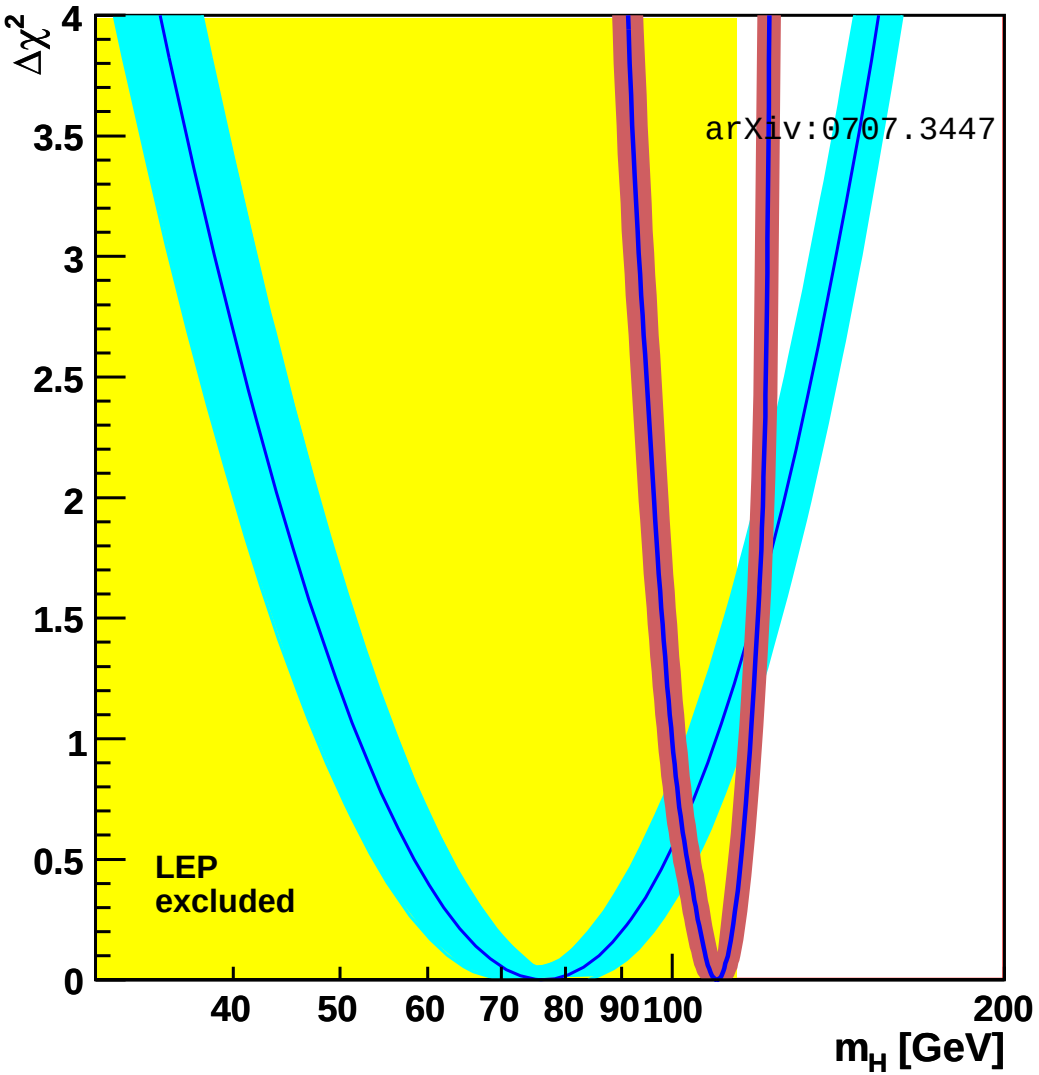



$M_h = 110^{+8}_{-10}\,(\text{exp}) \pm 3(\text{theo})$ GeV

## 3.) Full $\chi^2$ minimization in the CMSSM: ($m_t = 170.9$ GeV)

*[MasterCode '07]*

### Blue/Red band plot:



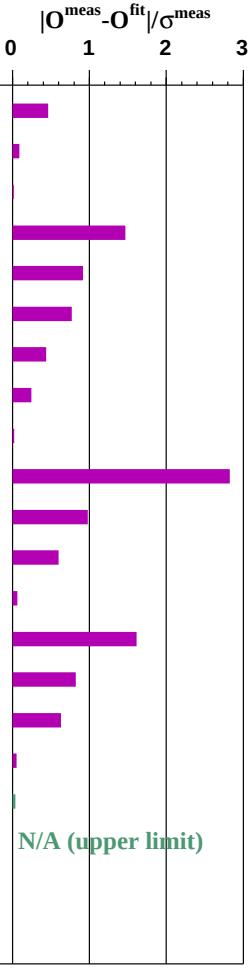

CMSSM (despite its simplicity) is better than the SM

# Pull distributions:

[*MasterCode '07*]

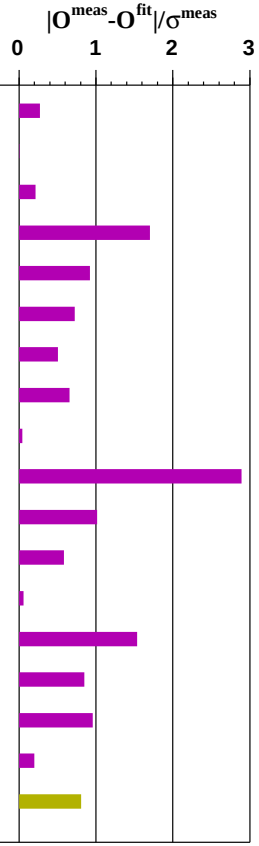
## CMSSM

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




## SM

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

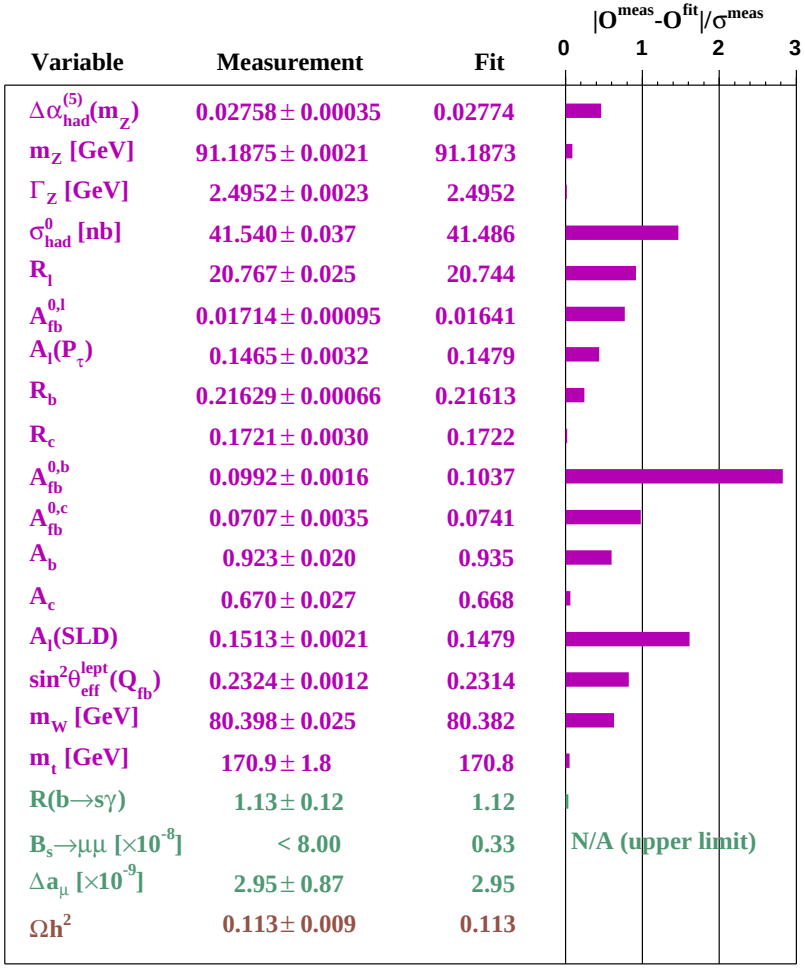



$\Rightarrow$ note the new observables: BR$(b \to s\gamma)$, $(g-2)_\mu$, CDM

# Pull distributions:

[*MasterCode '07*]

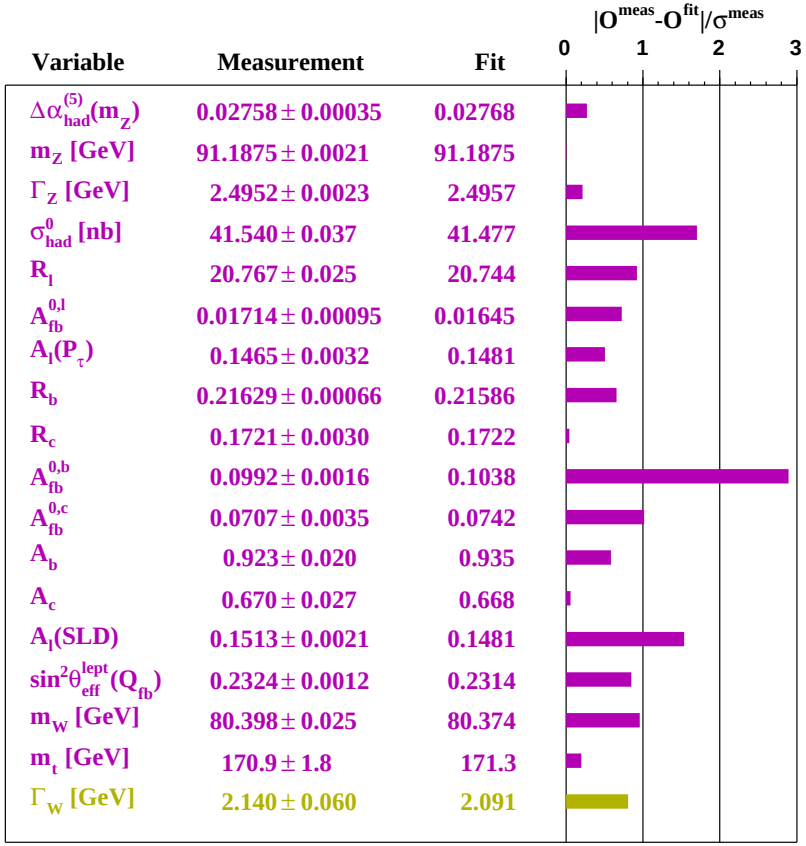
## CMSSM




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

N/A (upper limit)

## SM



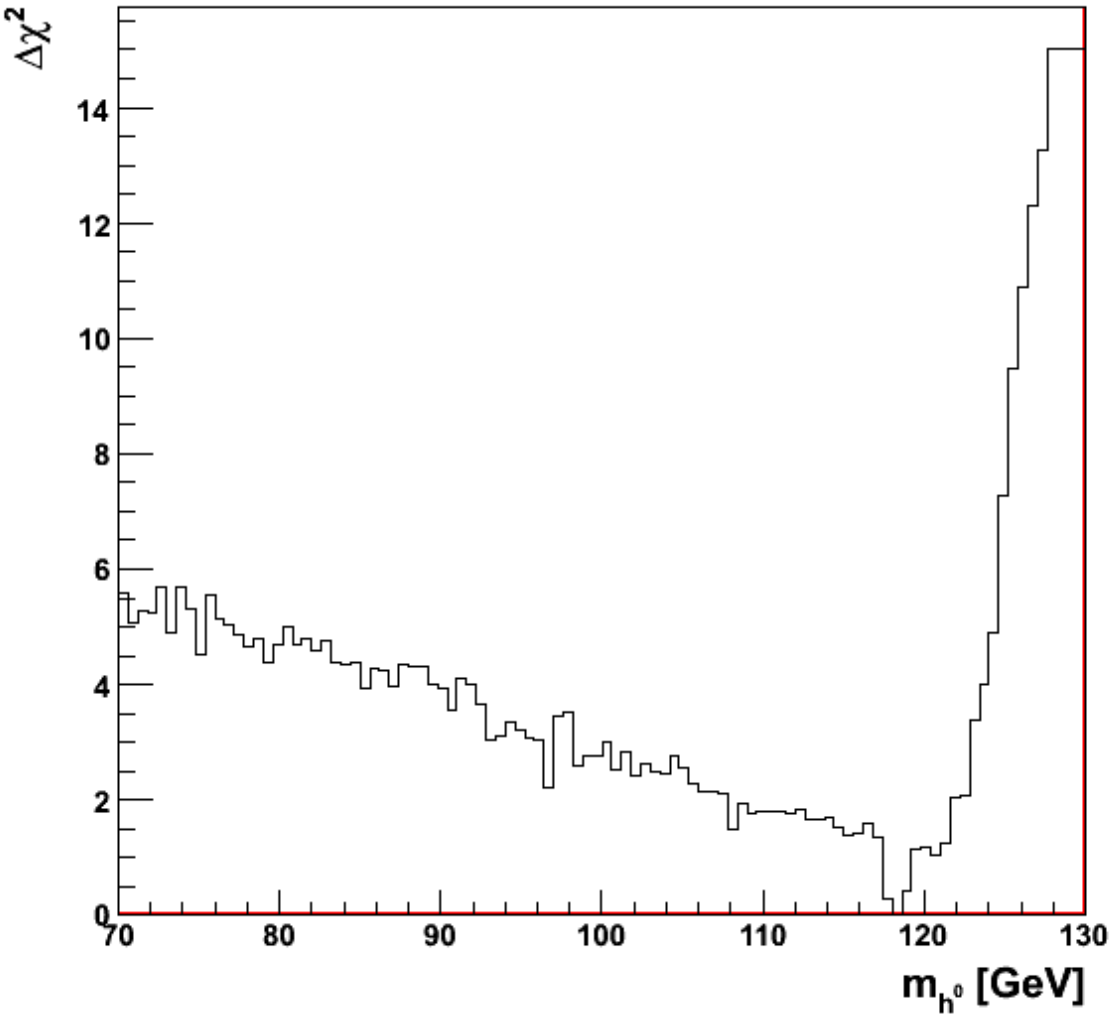

| Variable | Measurement | Fit |
|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | $0.02758 \pm 0.00035$ | 0.02768 |
| $m_Z$ [GeV] | $91.1875 \pm 0.0021$ | 91.1875 |
| $\Gamma_Z$ [GeV] | $2.4952 \pm 0.0023$ | 2.4957 |
| $\sigma^0_{had}$ [nb] | $41.540 \pm 0.037$ | 41.477 |
| $R_l$ | $20.767 \pm 0.025$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

Probabilities: 24% / 20%

15% / 15% (incl. / excl. $M_h$)

[*MasterCode '09 PRELIMINARY*]

NUHM1:




$\Rightarrow M_h > 114.4$ GeV appears naturally

## 5. LHC/ILC reach in the CMSSM/NUHM1

– 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: $m_t$, $M_Z$, $\Delta\alpha_{\rm had}$

$\Rightarrow \chi^2$ function

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

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

statistical measure: $\chi^2$ 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

## Best-fit points:

CMSSM:

$m_{1/2} = 310$ GeV, $m_0 = 60$ GeV, $A_0 = 240$ GeV,

$\tan\beta = 11$, $\mu = 380$ GeV, $M_A = 410$ GeV

$\chi^2/N_{\rm dof} = 20.4/19$ (37.3 % probability)

$\Rightarrow$ very similar to SPS 1a :-)

NUHM1:

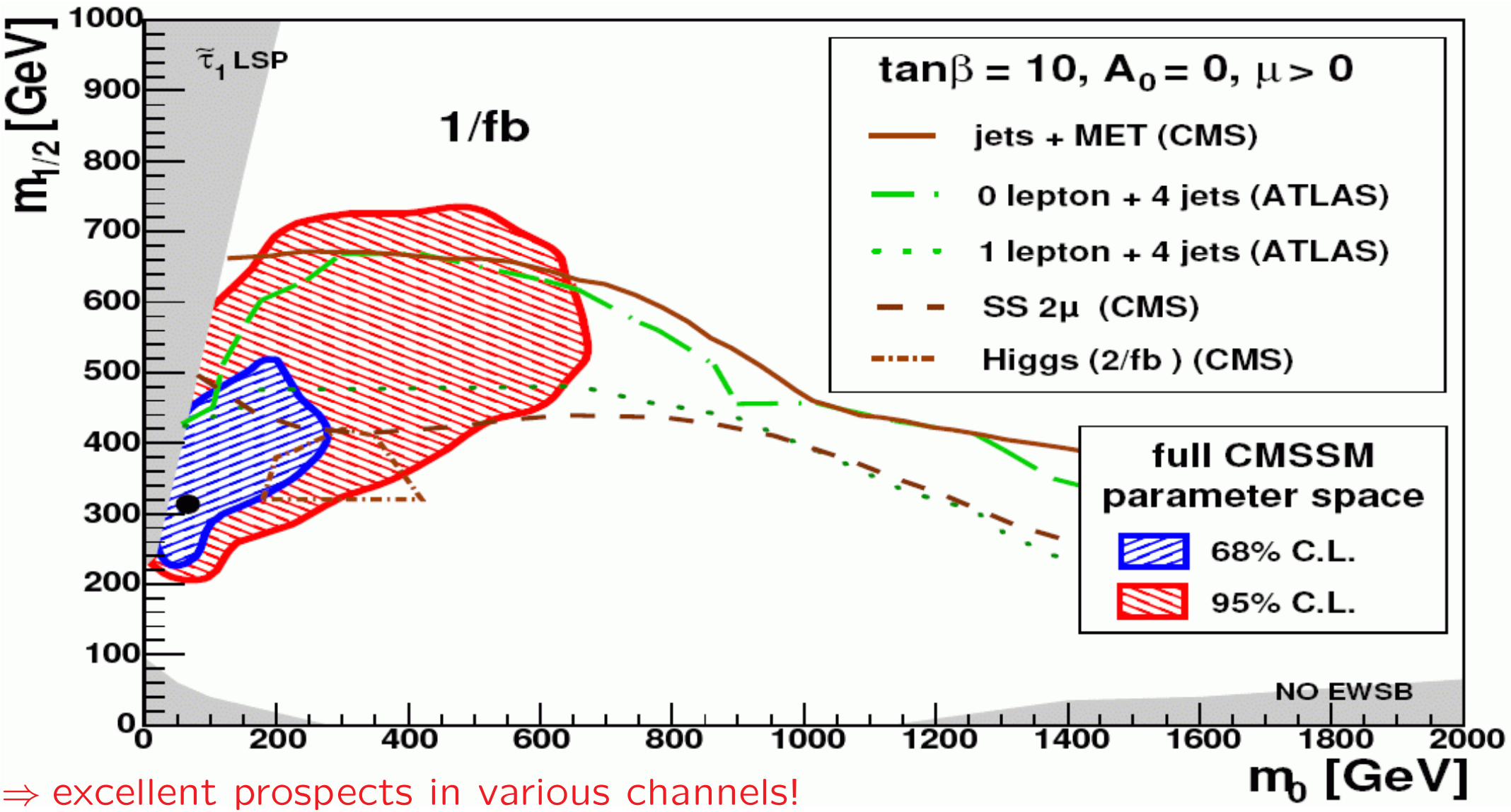
$m_{1/2} = 240$ GeV, $m_0 = 100$ GeV, $A_0 = -930$ GeV,

$\tan\beta = 7$, $\mu = 870$ GeV, $M_A = 300$ GeV

(39 % probability)

## LHC (CMS) reach with 1 $fb^{-1}$:

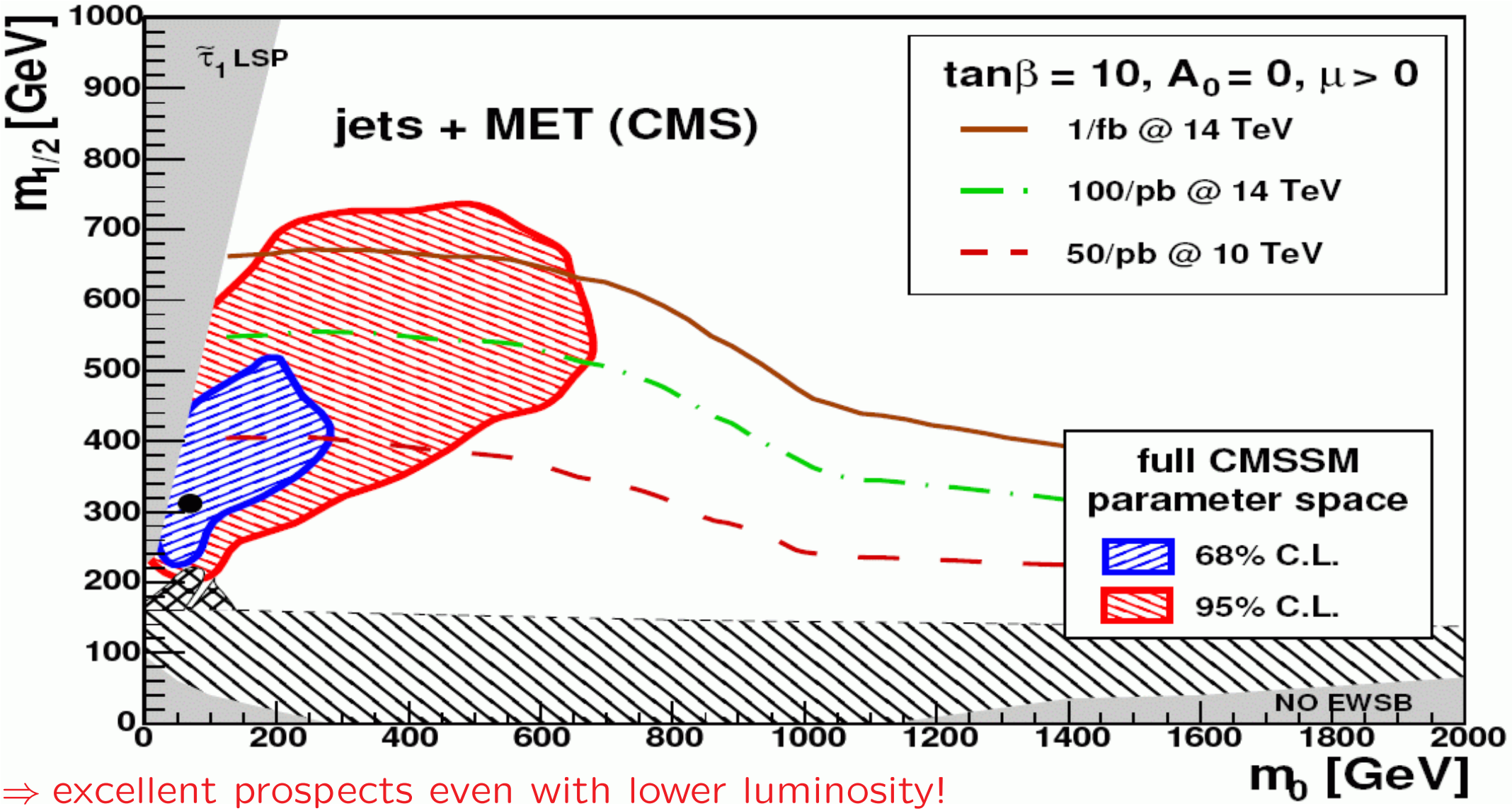
[*MasterCode '08*] [*CMS '07*]




⇒ excellent prospects in various channels!

## LHC (CMS):

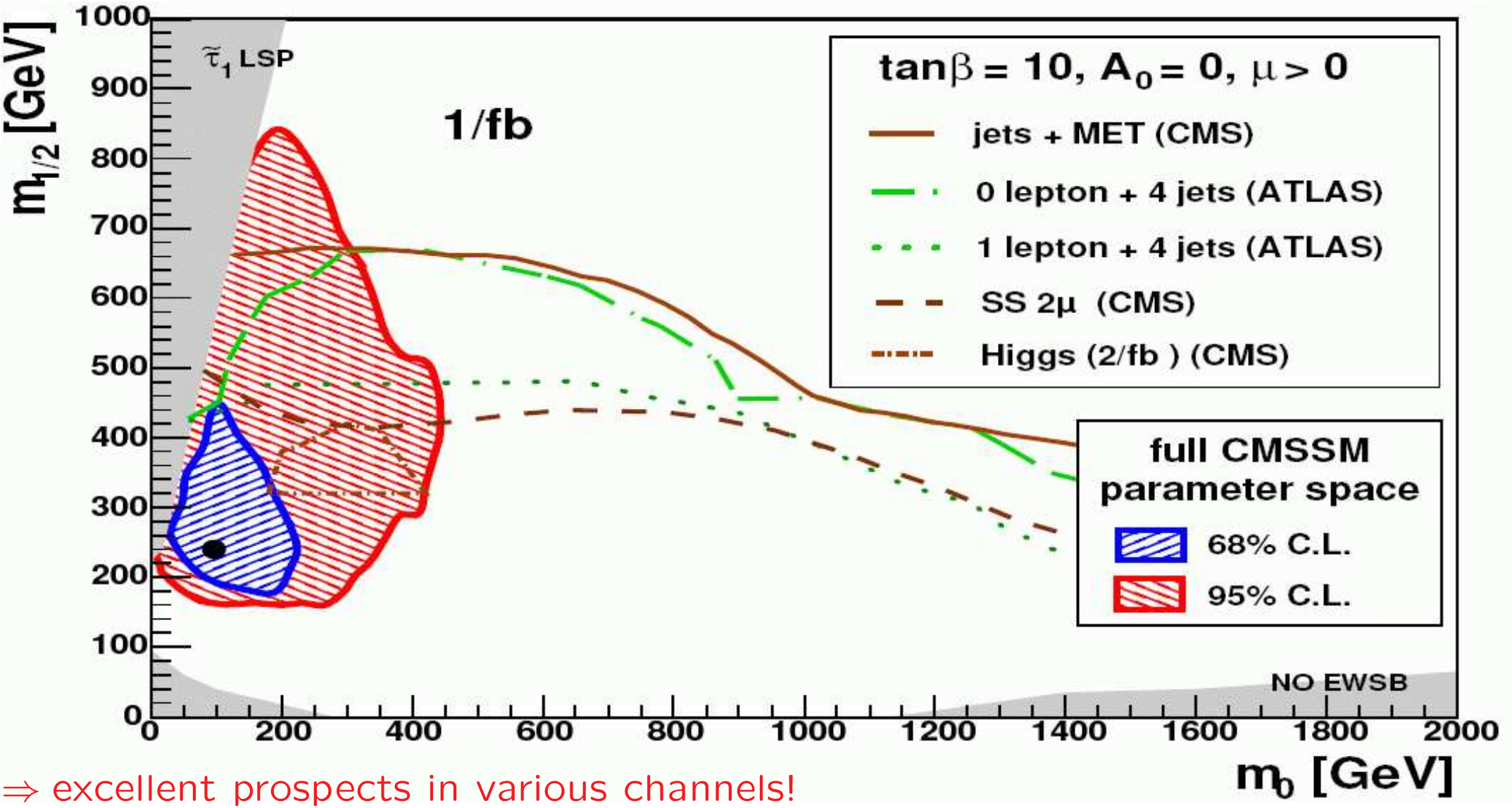
[*MasterCode '08*] [*CMS '07*]




⇒ excellent prospects even with lower luminosity!

# LHC (CMS) reach with 1 fb$^{-1}$: NUHM1 analysis

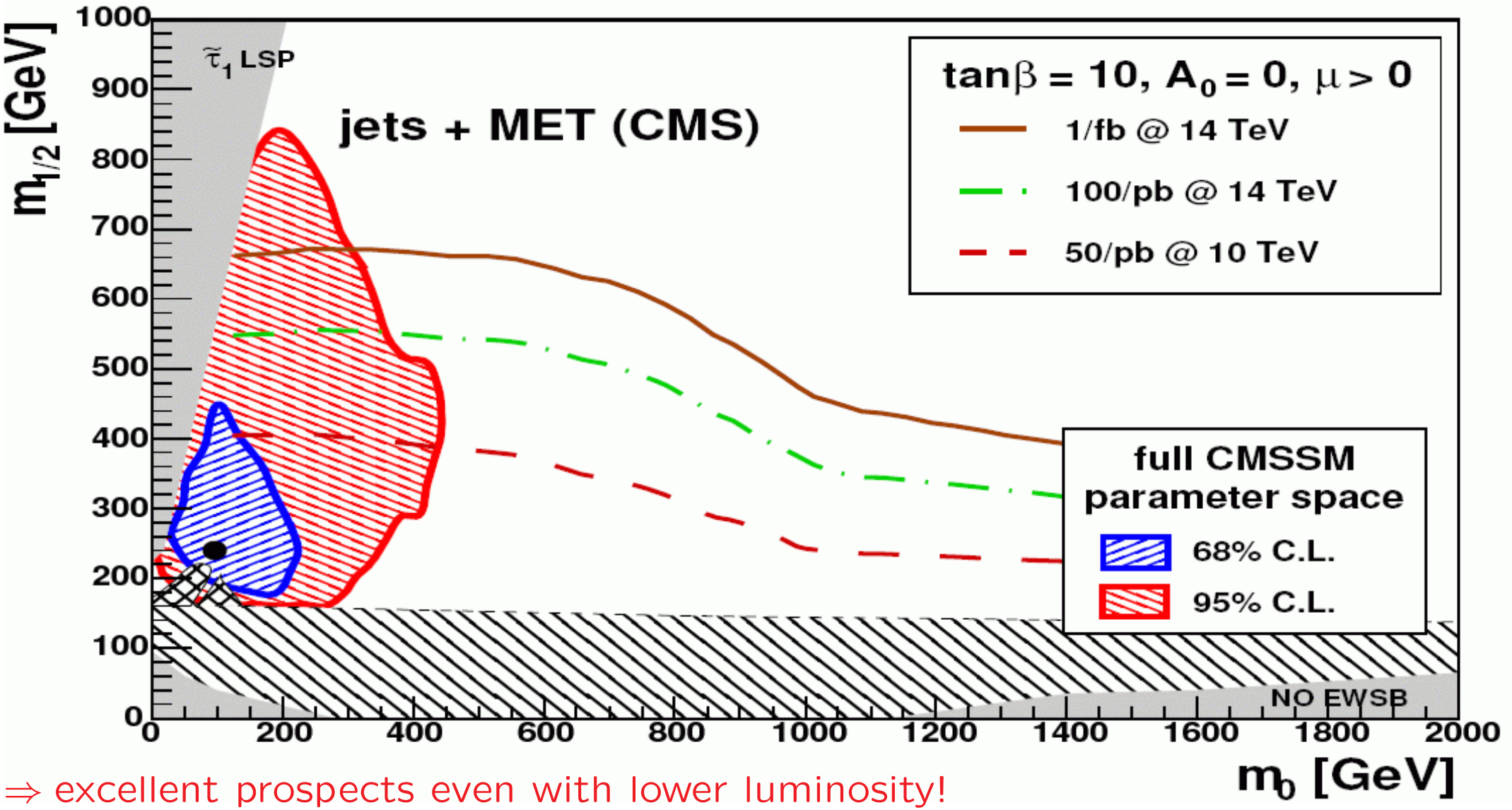
[*MasterCode '08*] [*CMS '07*]




⇒ excellent prospects in various channels!

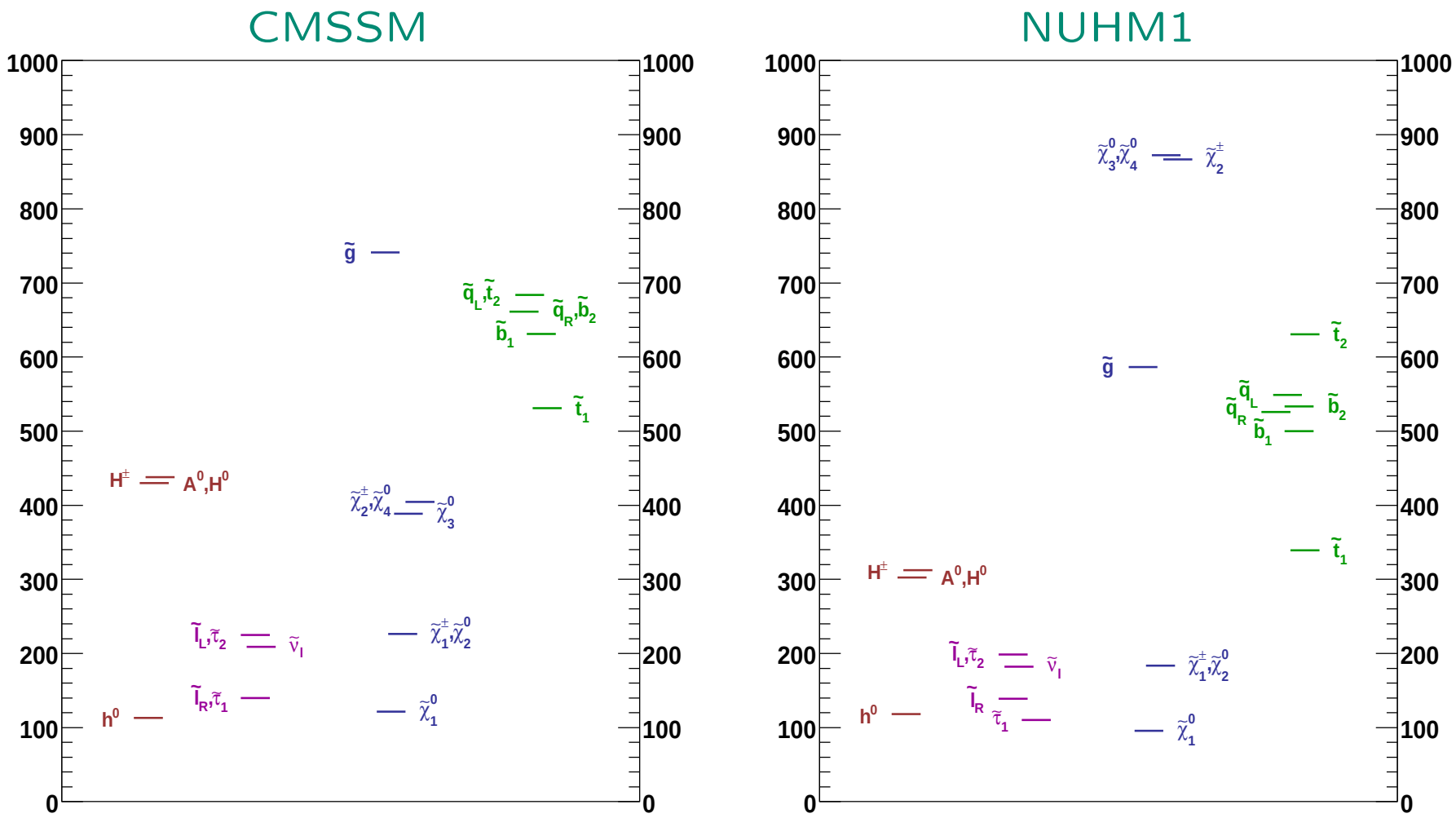
# LHC (CMS): NUHM1 analysis

[*MasterCode '08*] [*CMS '07*]




⇒ excellent prospects even with lower luminosity!

# Masses for best-fit points:




$\Rightarrow$ largely accessible spectrum for LHC and ILC

## 6. Conclusinos

- Precision observables
  - can give valuable information about the "true" Lagrangian
  - can provide bounds on SUSY parameter space
- SM: Blue band plot: $\Rightarrow M_H^{\rm SM} = 90^{+36}_{-27}$ GeV (too light for LEP bounds?)
- MSSM: investigated model: CMSSM, NUHM1, mGMSB, mAMSB
- Constraining the CMSSM, mGMSB, mAMSB with CDM bounds:
  $M_W$, $\sin^2\theta_{\rm eff}$, $(g-2)_\mu$, $M_h$, BR$(b \to s\gamma)$, BR$(B_s \to \mu^+\mu^-)$
  mAMSB fits somewhat better despite having one parameter less
  Evaluation of SUSY spectrum $\Rightarrow$ LHC/ILC reach
  scalar tau: partially outside LHC reach, better at the ILC(1000)
  colored particles: within LHC reach, very difficult for ILC
- $M_h$ determination (without LEP bound): ($m_t = 170.9$ GeV)
  CMSSM/mSUGRA: Red band plot: $\Rightarrow M_h^{\rm CMSSM} = 110 \pm 8 \pm 3$ GeV
- LHC reach in the CMSSM/NUHM1
  - excellent prospects with 1 fb$^{-1}$: nearly full 95% C.L. covered
  - good prospects for 100 pb$^{-1}$ at 10 GeV: nearly 68 % C.L. covered


Higgs Days at Santander 2009
Theory meets Experiment
14.-18. September
IFCA
Instituto de Física de Cantabria
CSIC
UC
UNIVERSIDAD DE CANTABRIA
HEPTOOLS
contact: Sven.Heinemeyer@cern.ch
http://www.ifca.es/HDays09
Foto: R. Harlander (HDays 2008)

Back-up

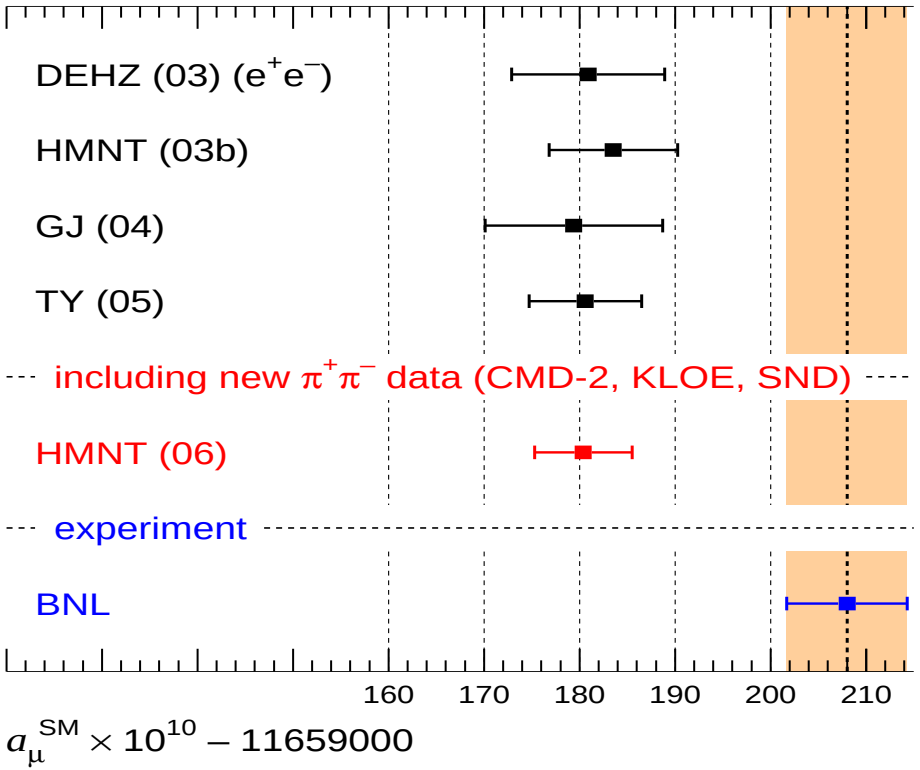
# The anomalous magnetic moment of the muon $(g-2)_\mu$

Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

$$\bar{u}(p')\left[\gamma^\mu F_1(q^2) + \frac{i}{2m_\mu}\sigma^{\mu\nu}q_\nu F_2(q^2)\right]u(p)A_\mu \qquad F_2(0) = (g-2)_\mu = 2a_\mu$$

Overview about the current experimental and SM (theory) result:

[*g-2 Collaboration, hep-ex/0602035*]



## Current status of $(g-2)_\mu$:

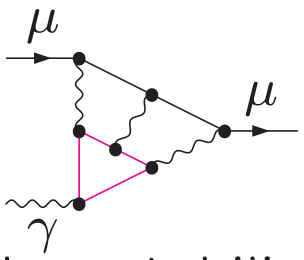
### Experiment:

– 2001 - 2006: very stable development

– final error: $6 \times 10^{-10}$ , still statistically dominated

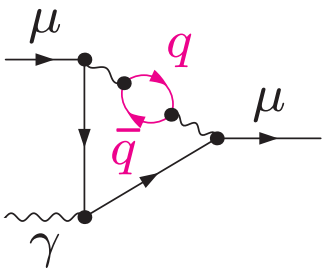
### Theory:

– the light-by-light contribution:




2002: sign error discovered; since then stabilized

– the hadronic vacuum contribution:




problems with the $\tau$ data $\Rightarrow$ hardly used anymore (+ new development!)

new 'direct' $e^+e^-$ data from CMD-II and SND

$\Rightarrow$ agrees well (also with old $e^+e^-$ data)

new radiative return data from KLOE and B-factories

$\Rightarrow$ agrees well with $e^+e^-$ data

new SM evaluations, based on new exp data for $a_\mu^{\rm had}$ :

$$a_\mu(\text{Exp-SM}) = \left\{ \begin{array}{ll} [\text{HMNT '06}] & 28(8) \\ [\text{DEHZ '06}] & 28(8) \\ [\text{FJ '07}] & 29(9) \\ [\text{MRR '07}] & 29(9) \end{array} \right\} \times 10^{-10}$$

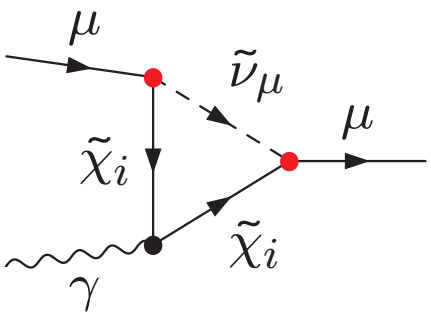
better agreement between evaluations, more precise,
larger deviation from exp than ever before

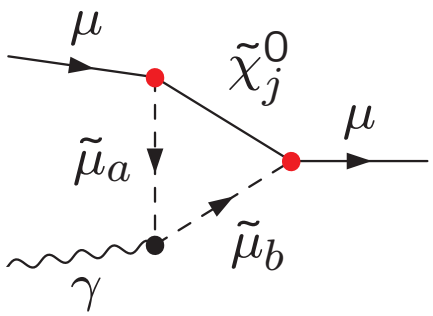
$\Downarrow$

$3\sigma$ deviation has now been definitely established

## SUSY can easily explain the deviation:

### Feynman diagrams for MSSM 1L corrections:




- Diagrams with chargino/sneutrino exchange
- Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

$$\mu - \tilde{\chi}_i^\pm - \tilde{\nu}_\mu \;:\; \sim m_\mu \tan\beta$$
$$\mu - \tilde{\chi}_j^0 - \tilde{\mu}_a \;:\; \sim m_\mu \tan\beta$$

SM, EW 1L: $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_W^2}$

MSSM, 1L: $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_{\rm SUSY}^2} \times \tan\beta$

## SUSY corrections at 1L:

$$a_\mu^{\text{SUSY,1L}} \approx 13 \times 10^{-10} \left(\frac{100\ \text{GeV}}{M_{\text{SUSY}}}\right)^2 \tan\beta\ \text{sign}(\mu)$$

$M_{\text{SUSY}}(= m_{\tilde{\mu}} = m_{\tilde{\nu}} = m_{\tilde{\chi}})$: generic SUSY mass scale

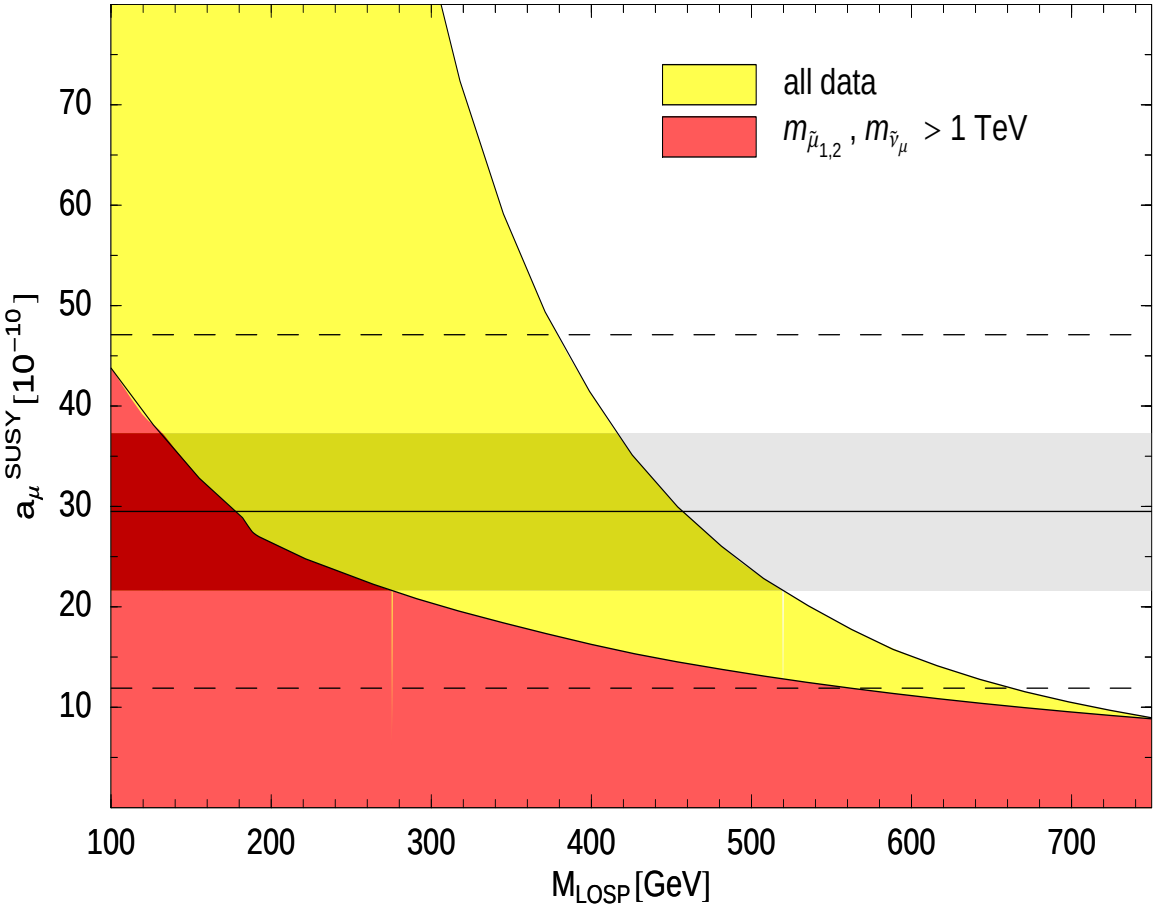
$$\begin{aligned} a_\mu^{\text{SUSY,1L}} &= (-100 \ldots + 100) \times 10^{-10} \\ a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} &\approx (28 \pm 8) \times 10^{-10} \end{aligned}$$

$\Rightarrow$ SUSY could easily explain the "discrepancy"

$\Rightarrow$ $a_\mu$ can provide bounds on SUSY parameter space

(by requiring agreement at the 95% C.L.)

# Example: Scan over SUSY parameter space




Scan over

$\mu$, $M_2$, $m_{\tilde{\mu}}$, $A_\mu$

LOSP = lightest observable SUSY particle

LOSP = $\tilde{\mu}$ or $\tilde{\chi}$

[*D. Stöckinger '06*]

SUSY could easily explain discrepancy

## Alternatives to SUSY?

[*D. Stöckinger '06*]

Generic BSM physics at $M_{NP}$:

$$a_\mu^{\text{NP}} \sim 1 \times 10^{-10} \left( \frac{300 \text{ GeV}}{M_{\text{NP}}} \right)^2$$

$\Rightarrow$ much too small!

Two advantages of SUSY:

– $\tan\beta$-enhancement
– low SUSY masses possible

## 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:

$$\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

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

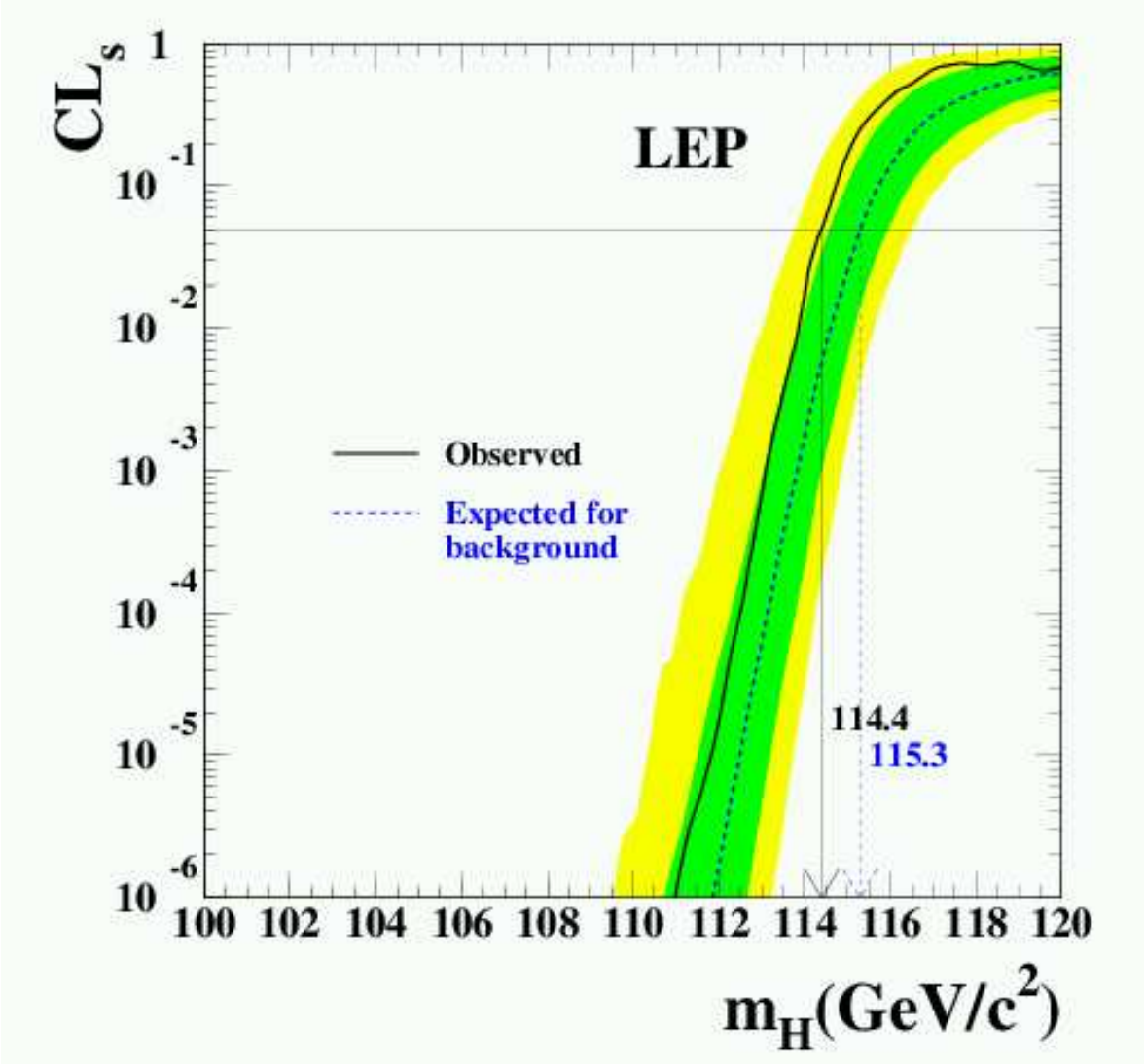
Measurement of $M_h$, Higgs couplings $\Rightarrow$ test of the theory

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

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

In CMSSM:

SM bound of $M_H$ search can be used [*LEP Higgs Working Group '03*]




$CL_s$ can be used/transformed into $\chi^2$ values

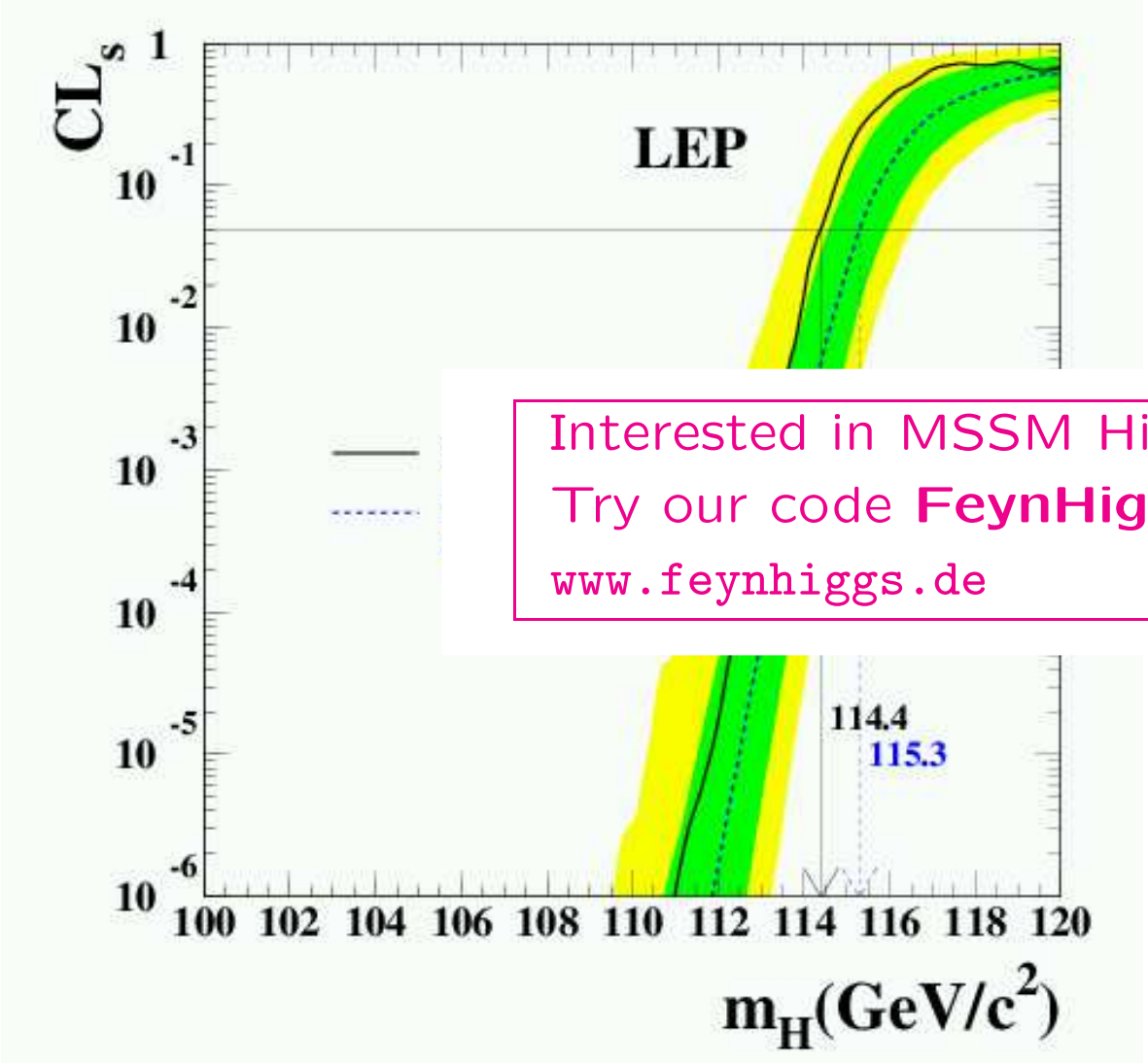
$\Rightarrow$ additional (unobserved) parameter

$\delta M_h^{\text{intr.}} \approx 3$ GeV

We use *FeynHiggs*

In CMSSM:

SM bound of $M_H$ search can be used [*LEP Higgs Working Group '03*]




$CL_s$ can be used/transformed into $\chi^2$ values

Interested in MSSM Higgs physics?
Try our code **FeynHiggs**
`www.feynhiggs.de`

observed)

$\delta M_h^{\text{intr.}} \approx 3$ GeV

We use *FeynHiggs*