New SUSY and Higgs predictions for the ILC

Sven Heinemeyer, IFCA (Santander)

Warsaw, 06/2008

based on collaborations with
X. Miao, S. Su and *G. Weiglein*

1. Motivation and models

2. The observables

3. Implications for the ILC

4. Conclusions

1. Motivation and models

Let's assume that low-energy SUSY is realized in Nature

What do we know about the SUSY mass scale?

1. Coupling constant unification $\Rightarrow M_{\text{SUSY}} \approx 1$ TeV
2. Solution for the Hierarchy problem $\Rightarrow M_{\text{SUSY}} \lesssim 1$ TeV
3. Indirect hints from existing data?

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

$\Rightarrow$ combination of EWPO, BPO, CDM ?

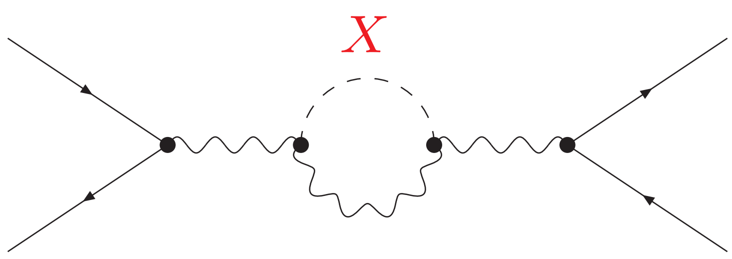
Precision Observables (POs):

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



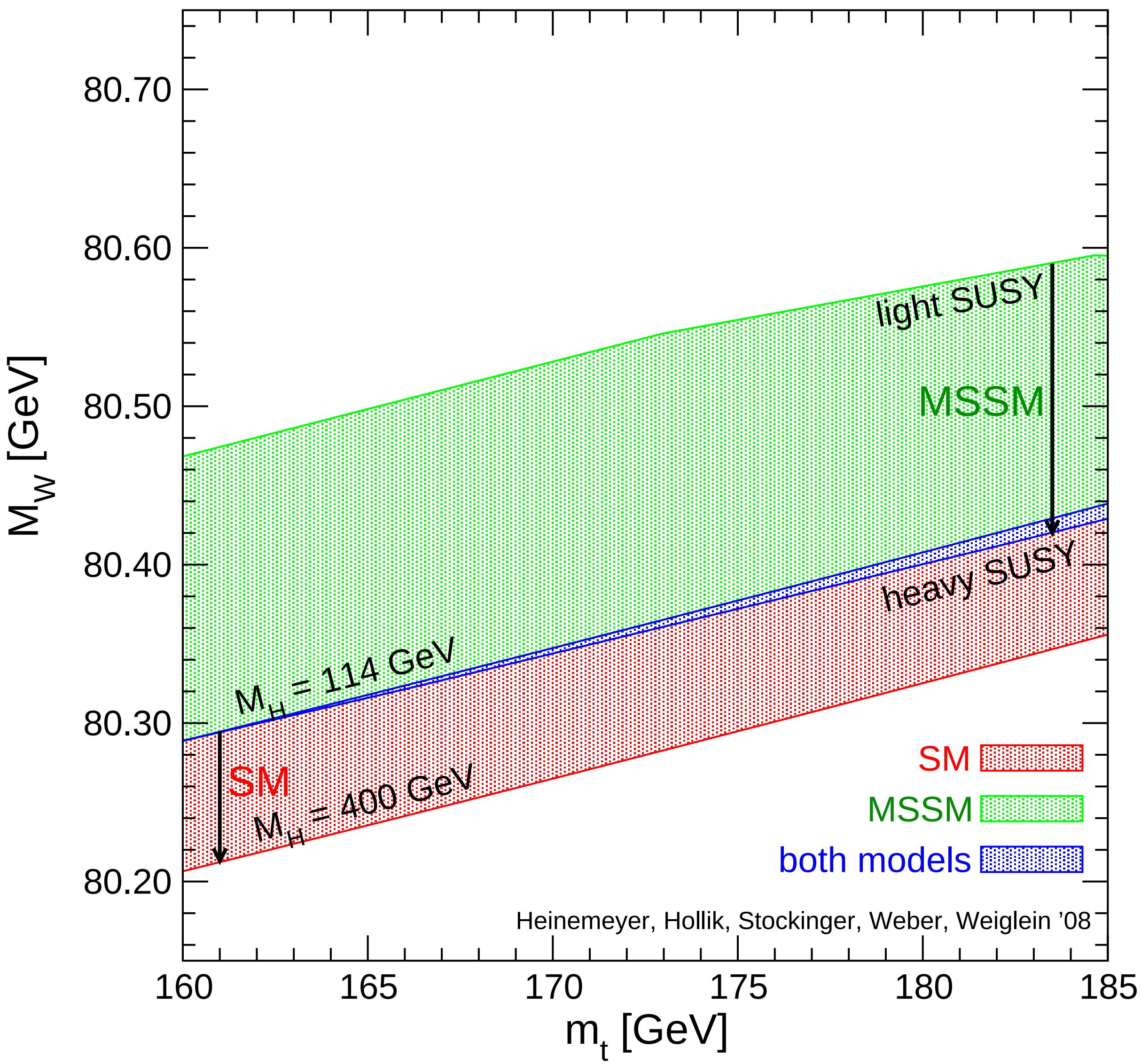
$\Downarrow$

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.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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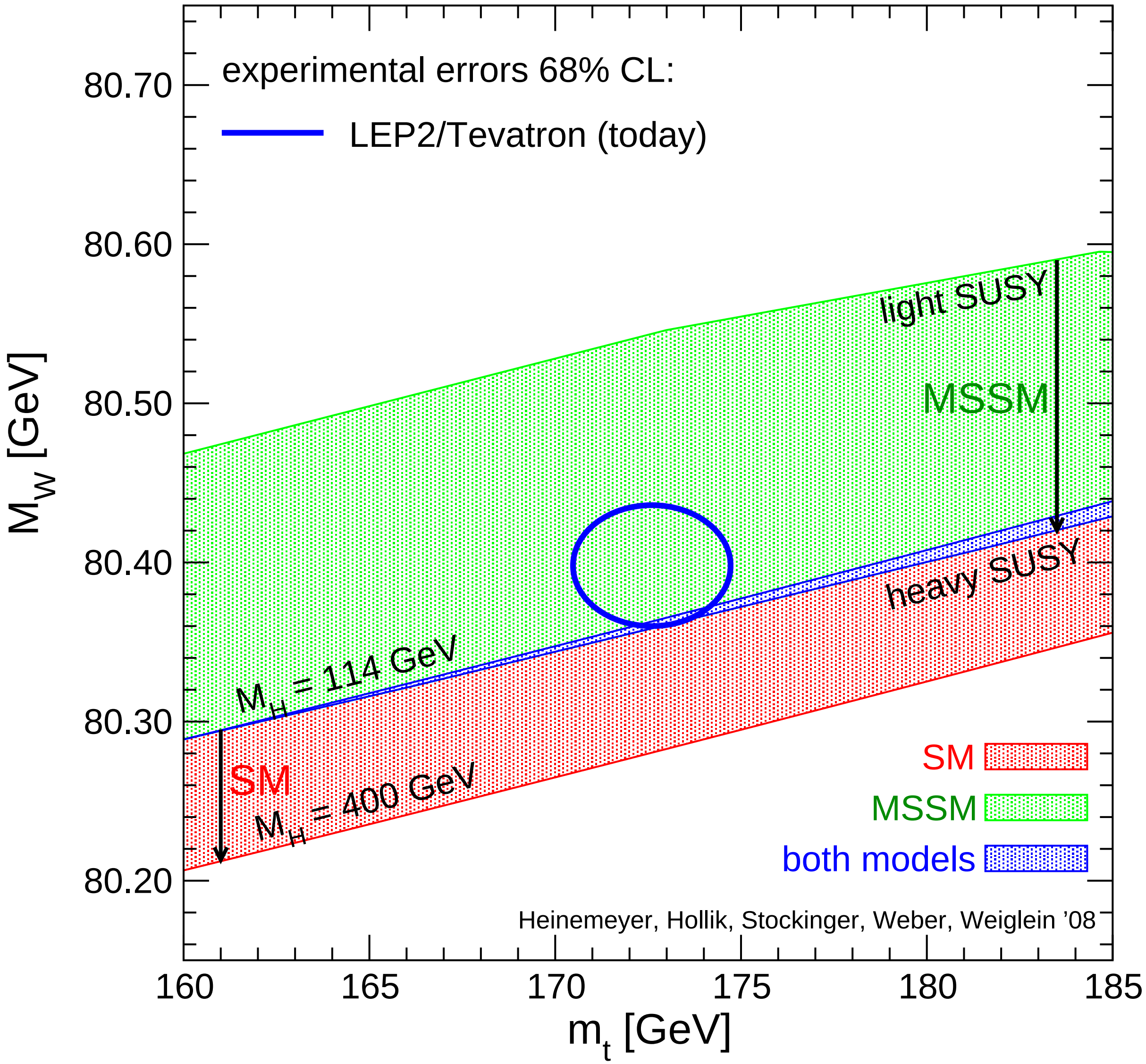

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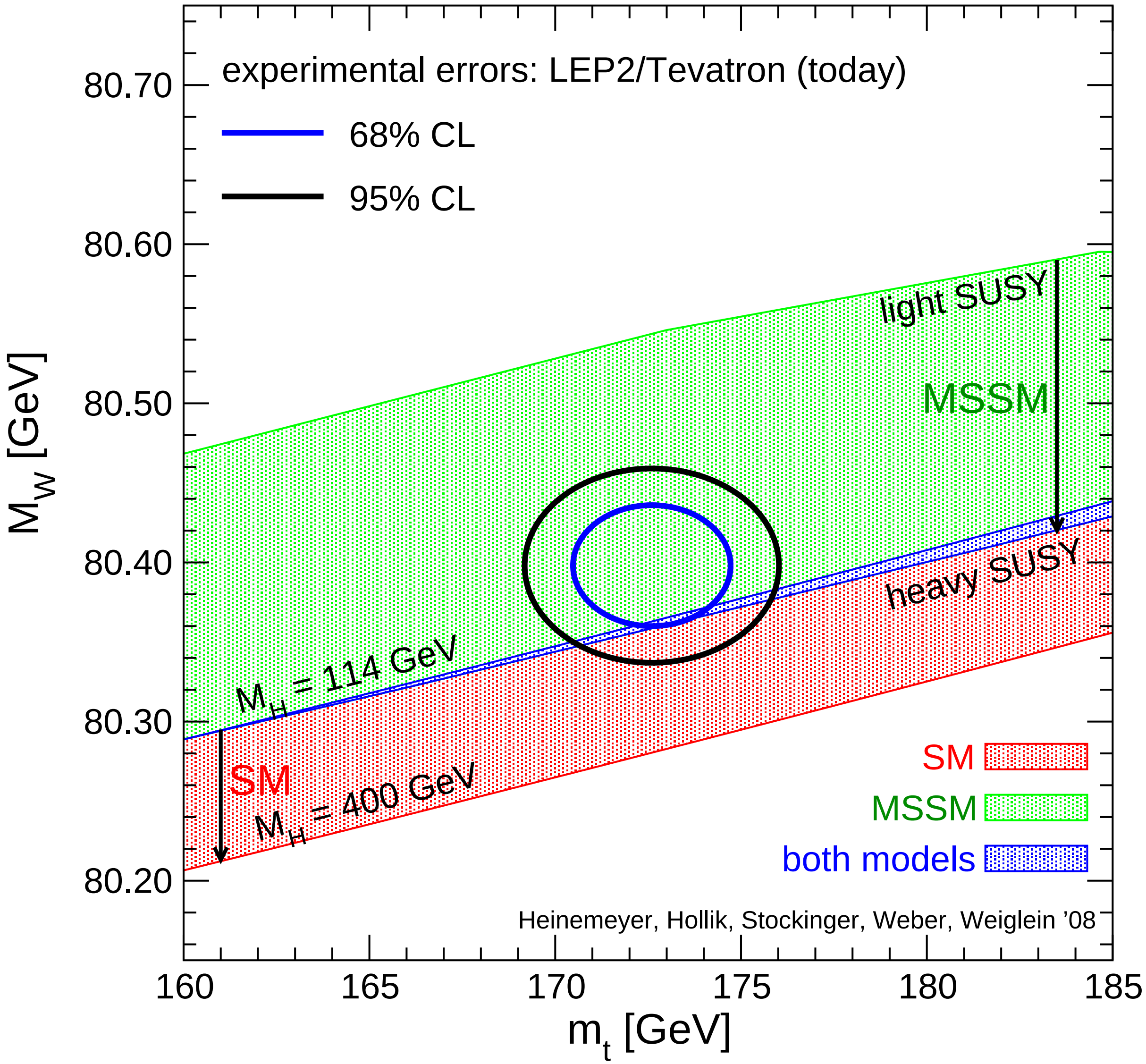

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SM band:
variation of M_H^{SM}

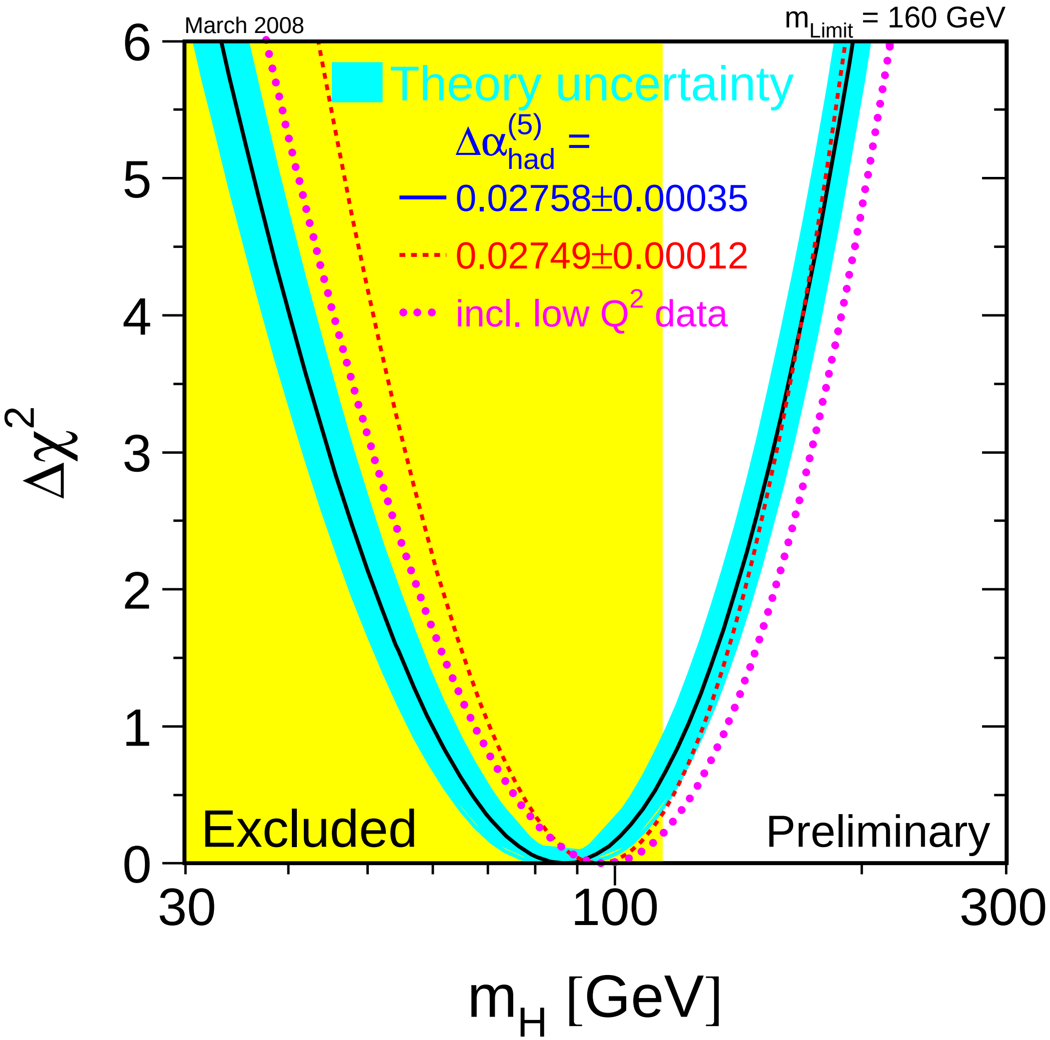
Within the SM: fit for the last unknown parameter: $M_H^{\rm SM}$

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

Indirect hints on M_{SUSY} from existing data?

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

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

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

$\Rightarrow$ 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*]

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NUHM:

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VCMSSM:

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mSUGRA (GDM):

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

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

⇒ Scenario characterized by

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

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

sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

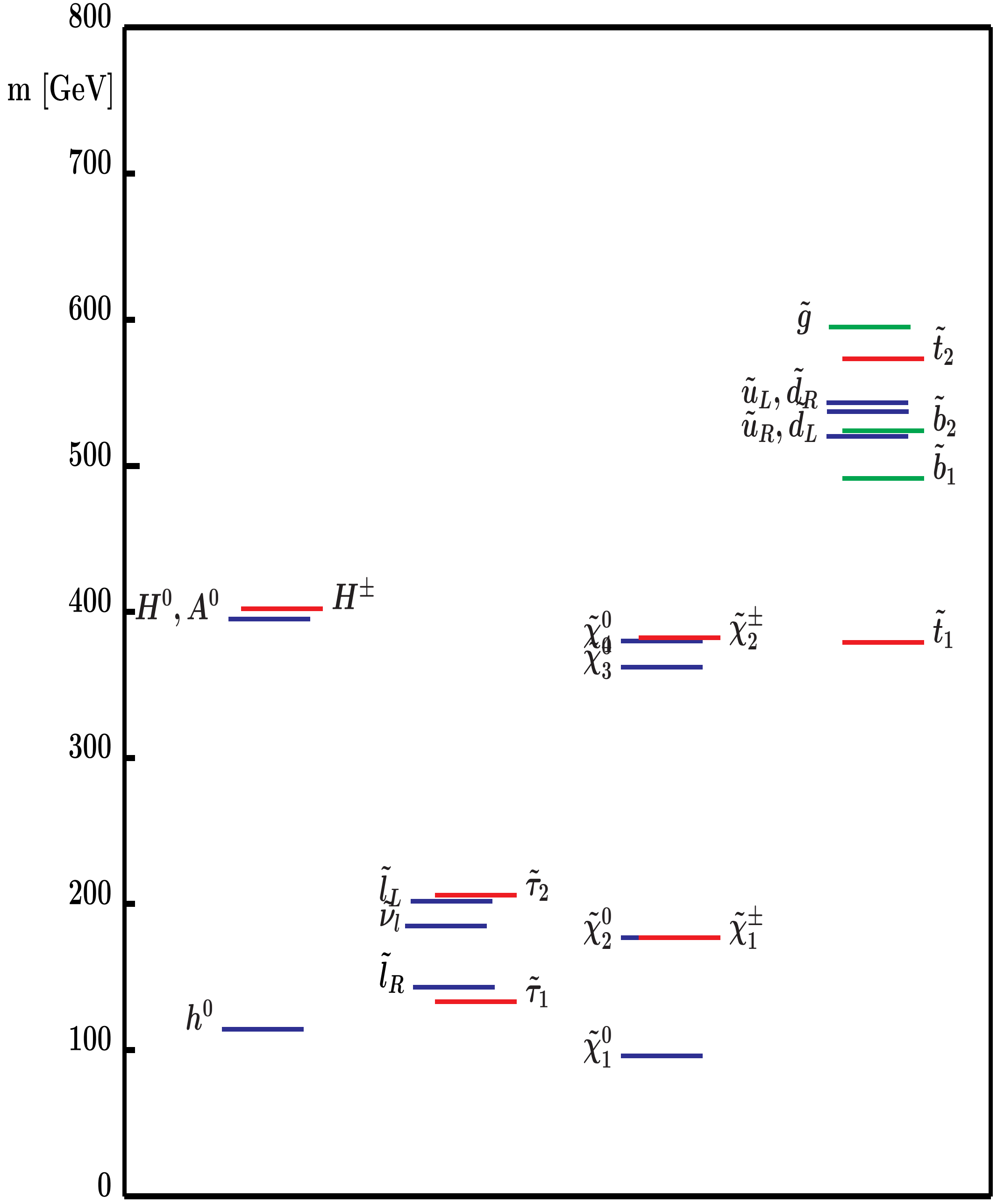
Lightest SUSY particle (LSP) is the lightest neutralino

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

SPS home page:

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



The models: 2.) (minimal) gauge mediated SUSY breaking: mGMSB

GMSB scenario characterized by

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

M_{mess}: messenger mass scale

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

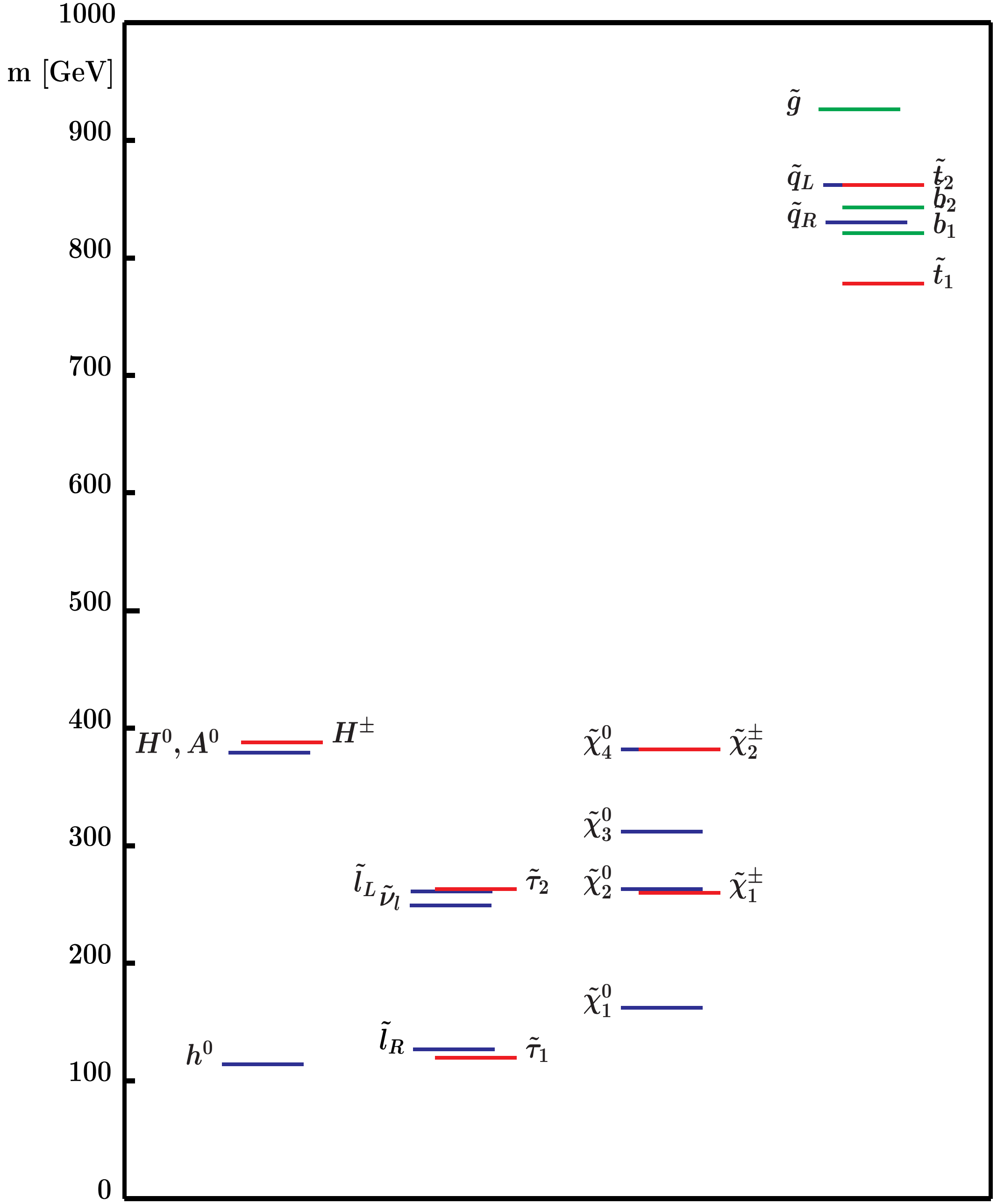
$\Lambda = \langle F \rangle / M_{\text{mess}}$: universal soft SUSY breaking mass scale
felt by low-energy sector

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):



The models: 3.) (minimal) anomaly mediated SUSY breaking: mAMSB

Parameters:

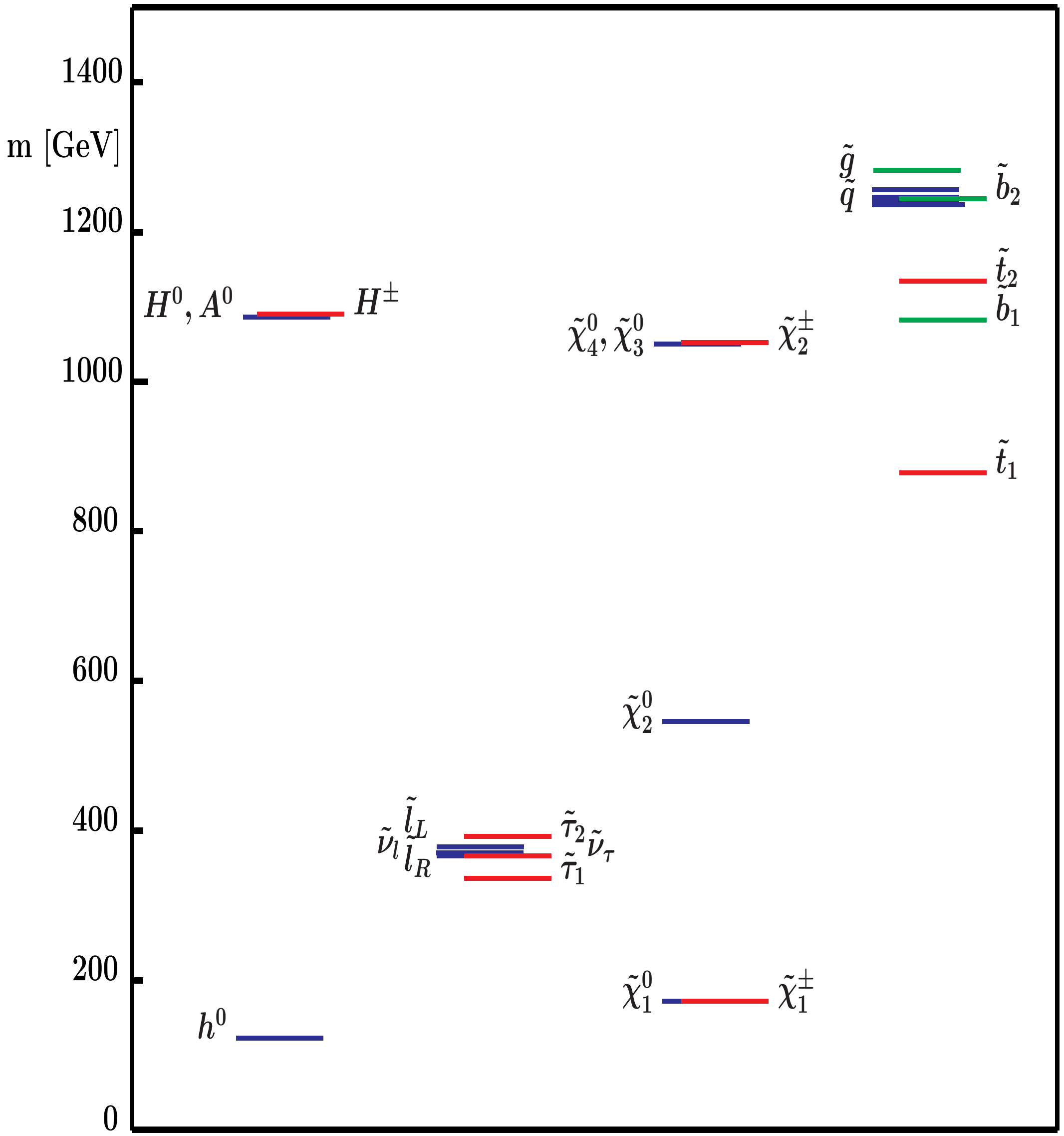
$m_{\text{aux}}, m_0, \tan\beta, \text{sign}(\mu)$

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



Procedure:

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

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

2. Perform χ^2 fit with precision observables

3. Find preferred values for masses
   ⇒ ILC reach
   ⇒ comparison of models
   ⇒ distinction of models?

2. The observables

1./2.) M_W, $\sin^2\theta_{\text{eff}}$:

1.) Theoretical prediction for M_W in terms

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

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

$\Updownarrow$

loop corrections

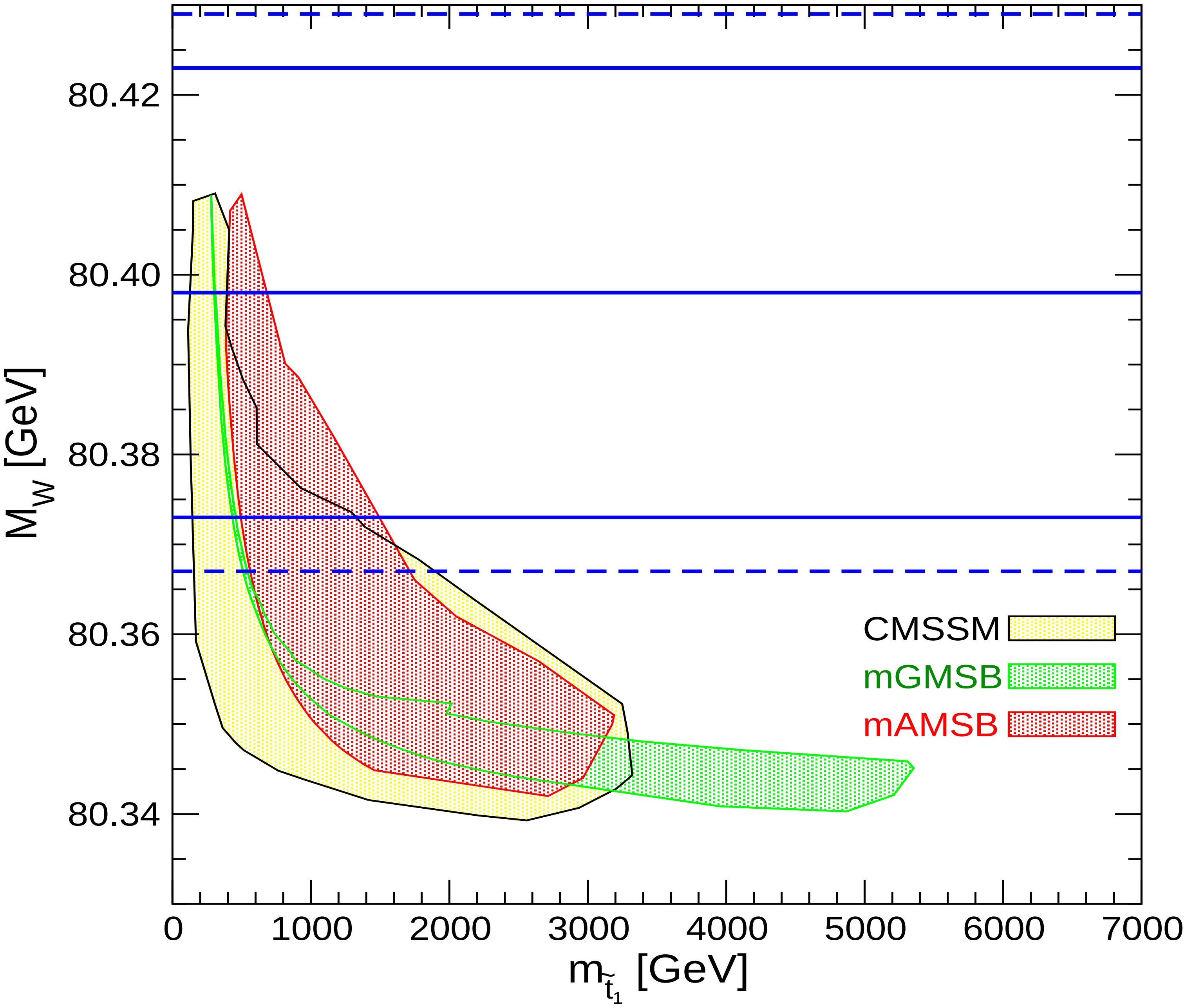
2.) Effective mixing angle:

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

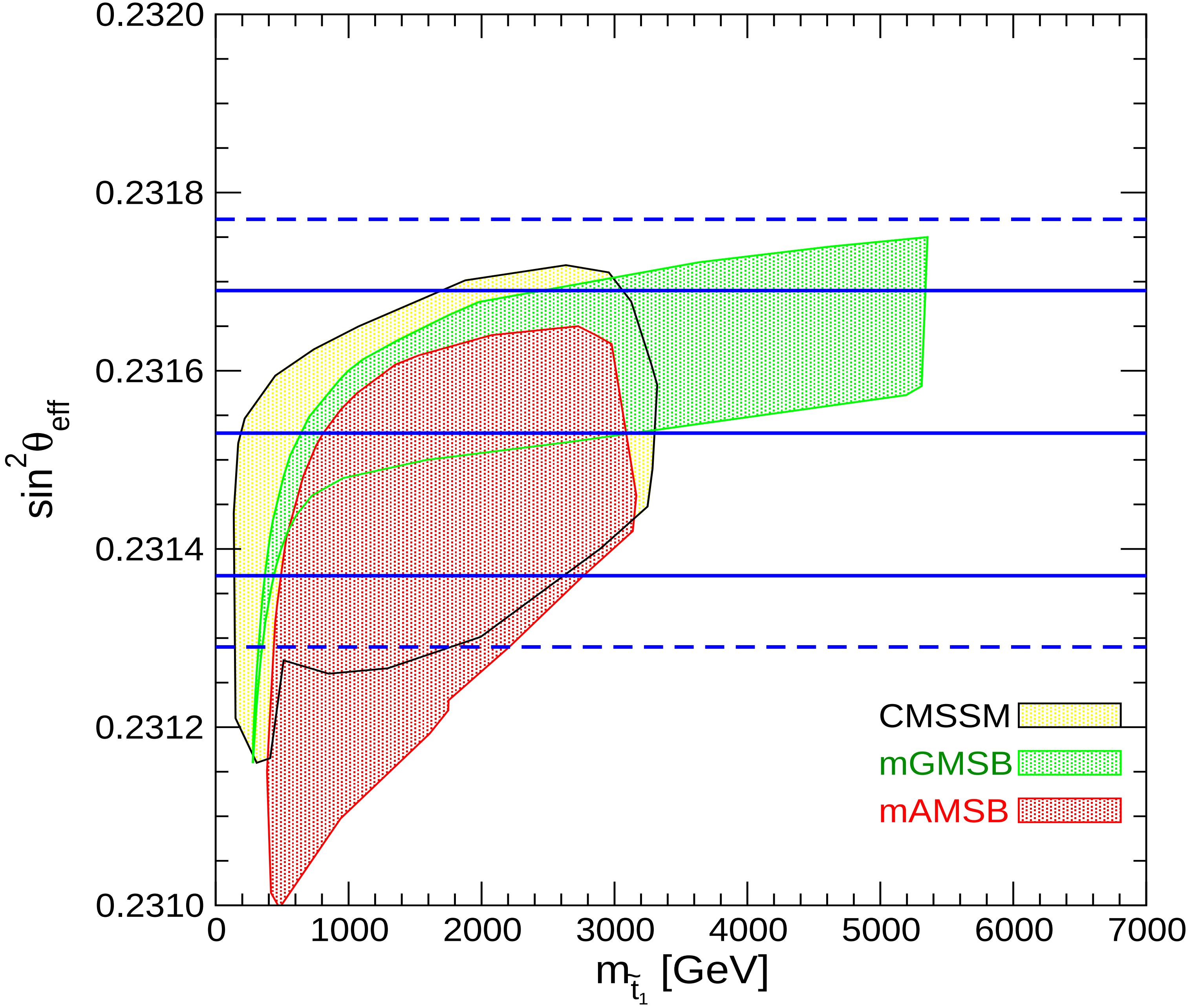
Higher order contributions:

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

M_W: CMSSM vs. mGMSB vs. mAMSB



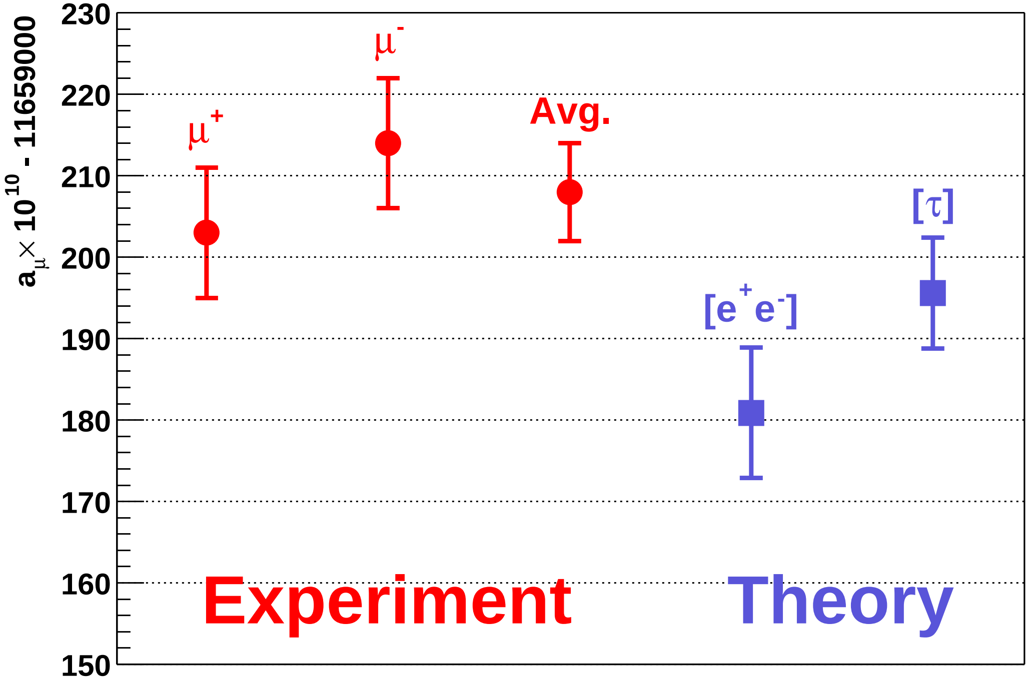
$\sin^2\theta_{\mathrm{eff}}$: CMSSM vs. mGMSB vs. mAMSB



3.) anomalous magnetic moment of the muon: $(g-2)_\mu$

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

[*g-2 Collaboration, hep-ex/0401008*]



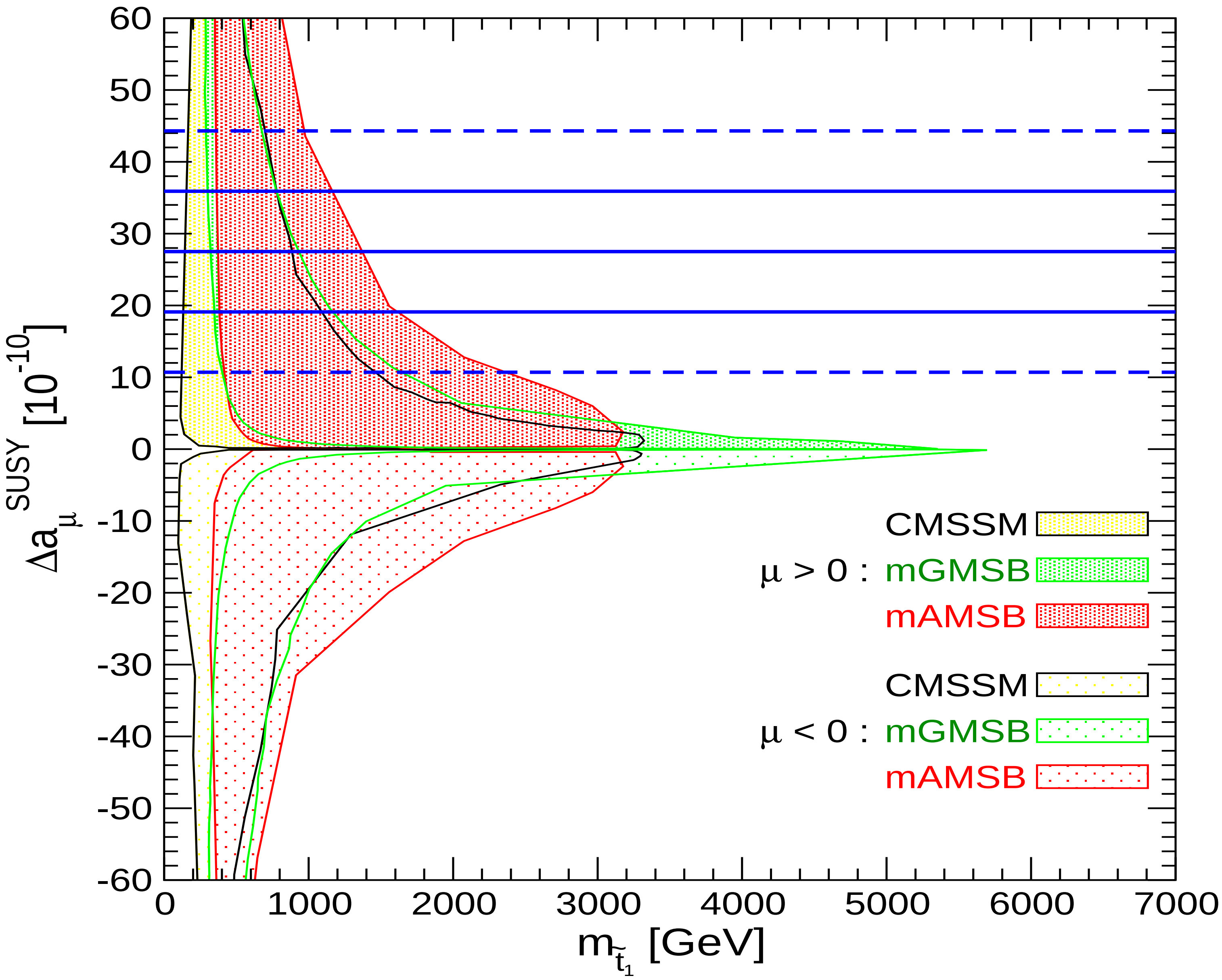
$\longrightarrow$ "Isospin breaking effects" in τ data problematic

[*Ghozzi, Jegerlehner '03; Jegerlehner '07*]

e^+e^- data: good agreement between new SND, CMD2, KLOE data

$$a_\mu^{\rm exp} - a_\mu^{\rm theo,SM} \approx (27.5 \pm 8.4) \times 10^{-10}$$

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



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

4.) 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:

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

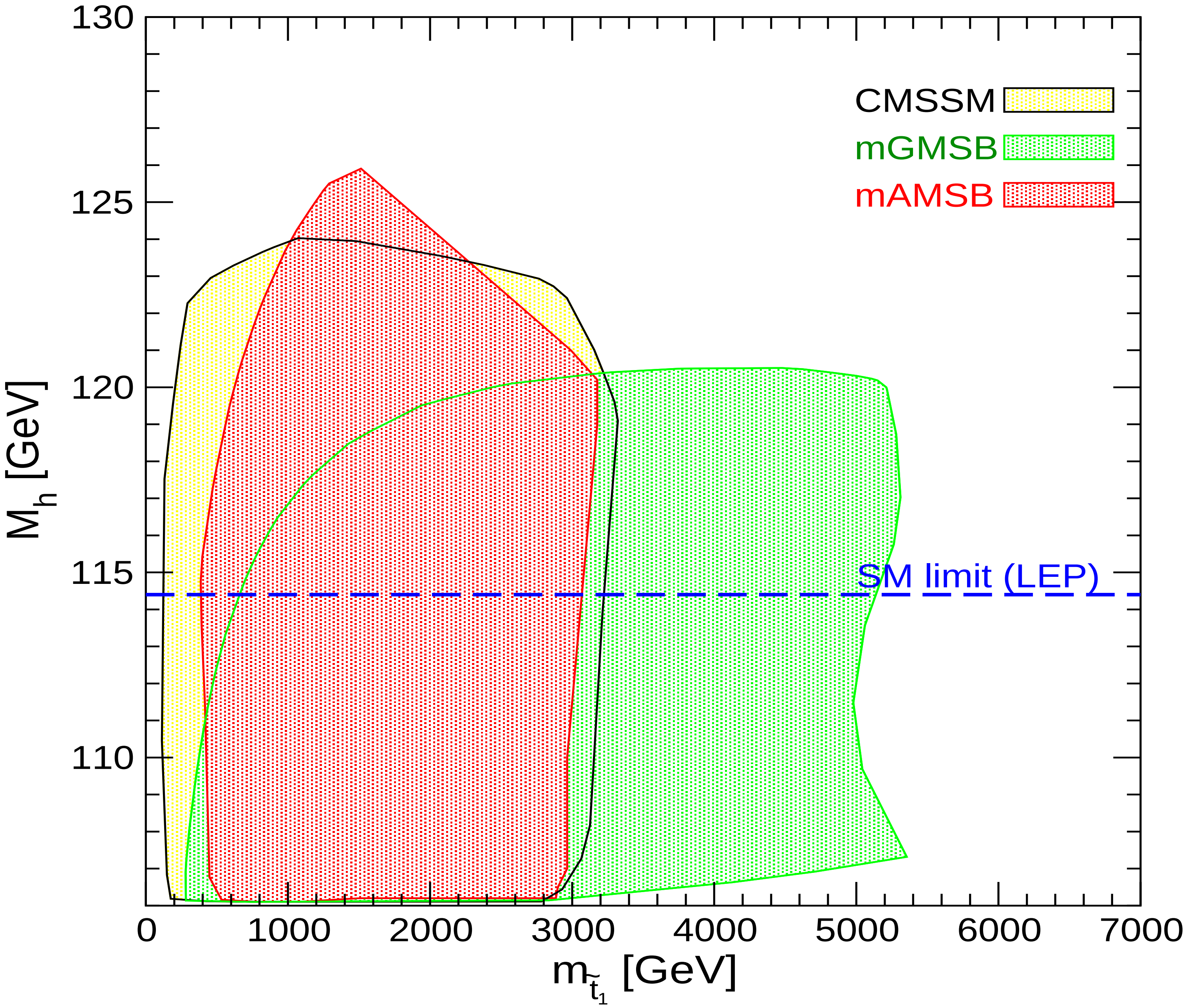
The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

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

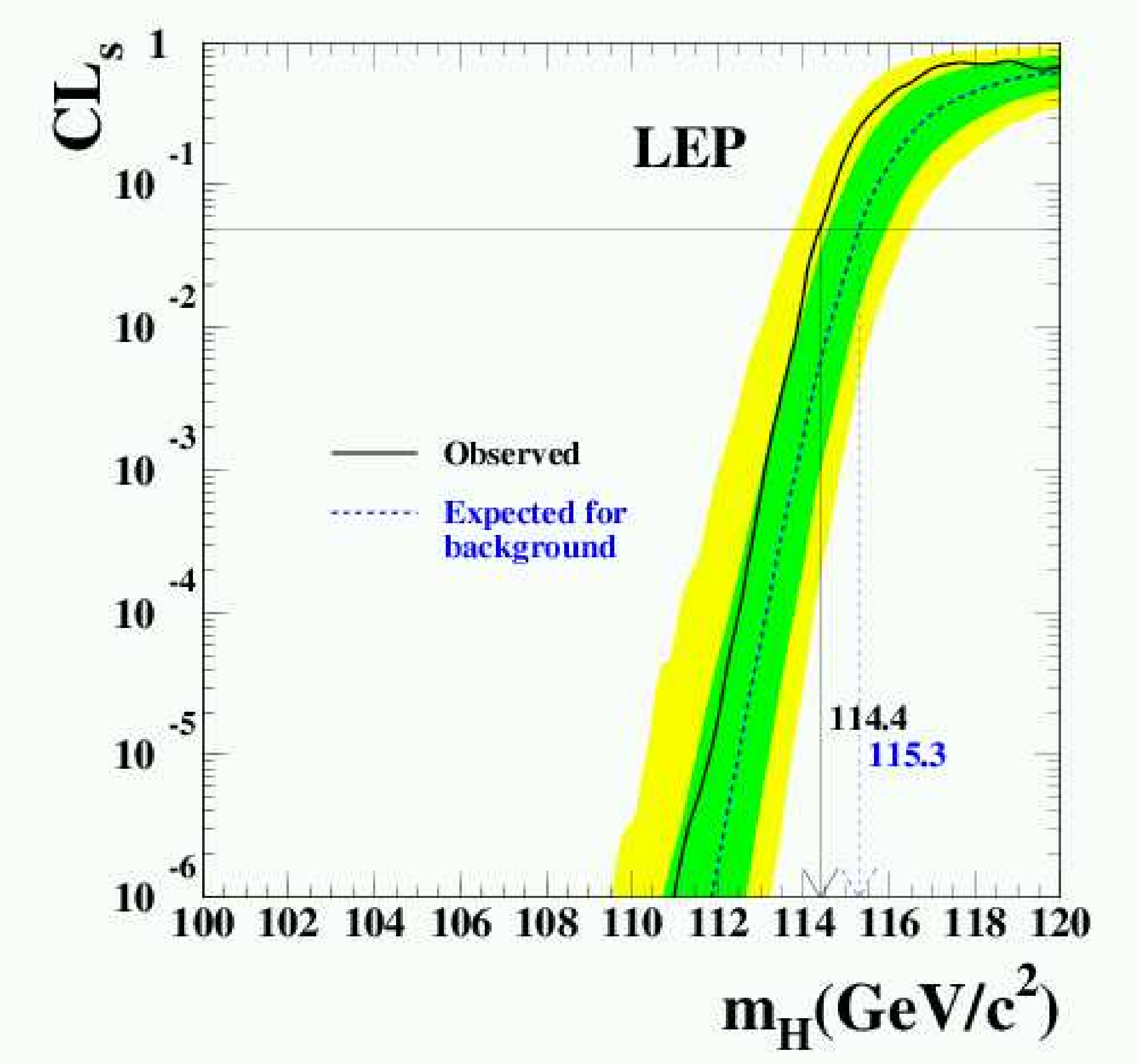
$\Rightarrow$ M_h will be (the best?) electroweak precision observable

M_h: CMSSM vs. mGMSB vs. mAMSB



In CMSSM, mGMSB, mAMSB:

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



$M_h > 114.4$ GeV

at 95% C.L.

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

We use *FeynHiggs*

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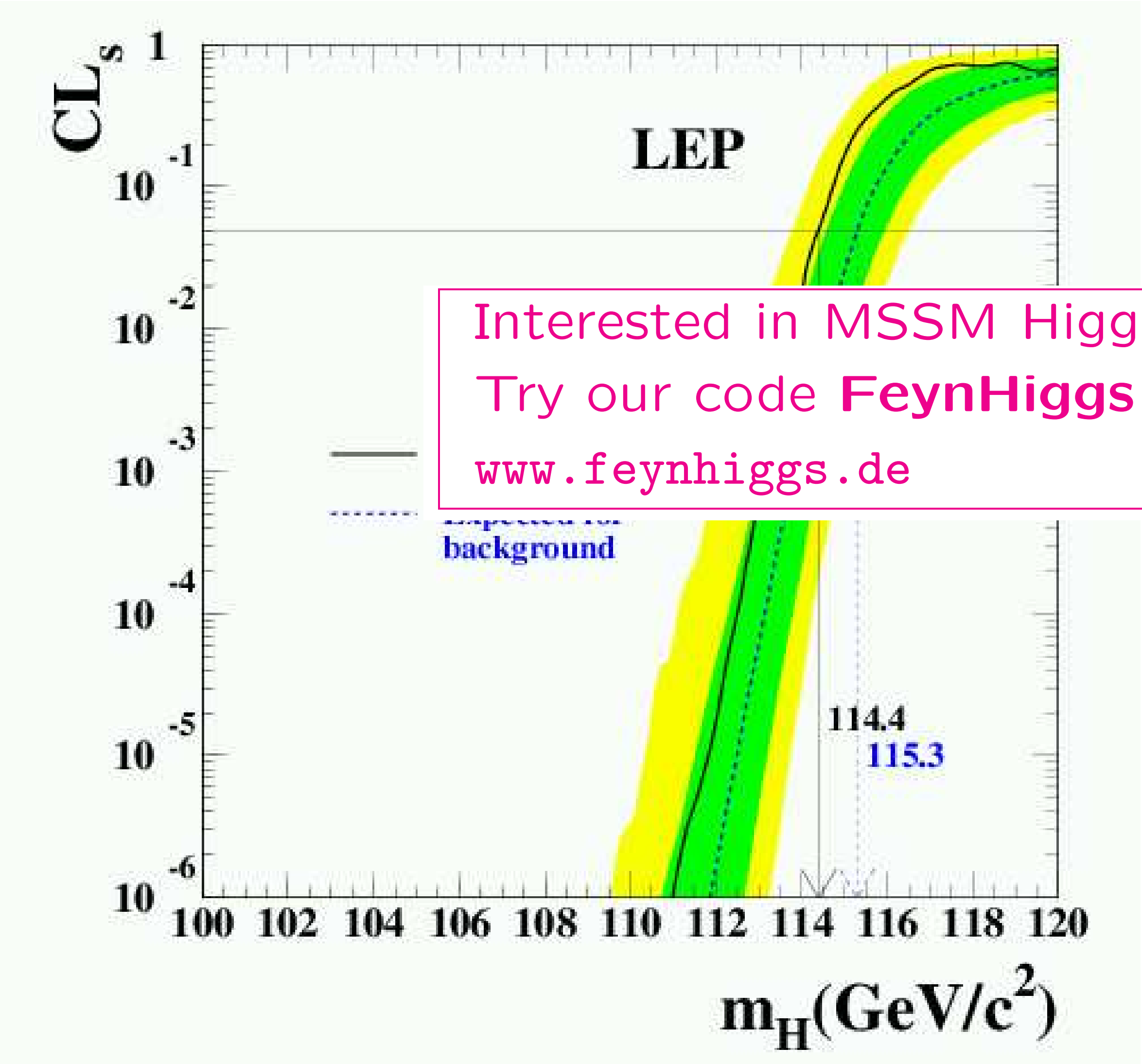

Interested in MSSM Higgs physics?

Try our code **FeynHiggs**

`www.feynhiggs.de`

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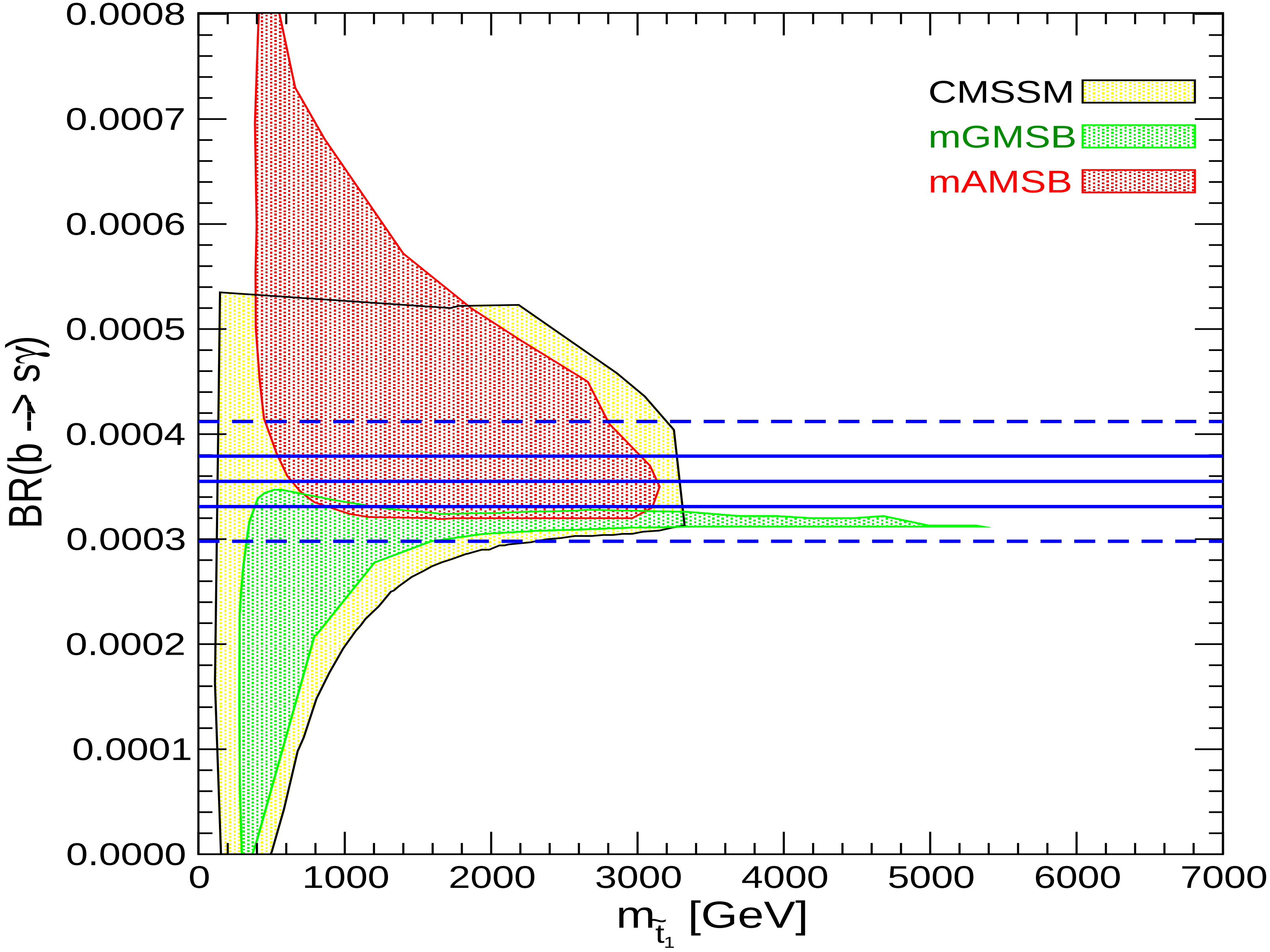
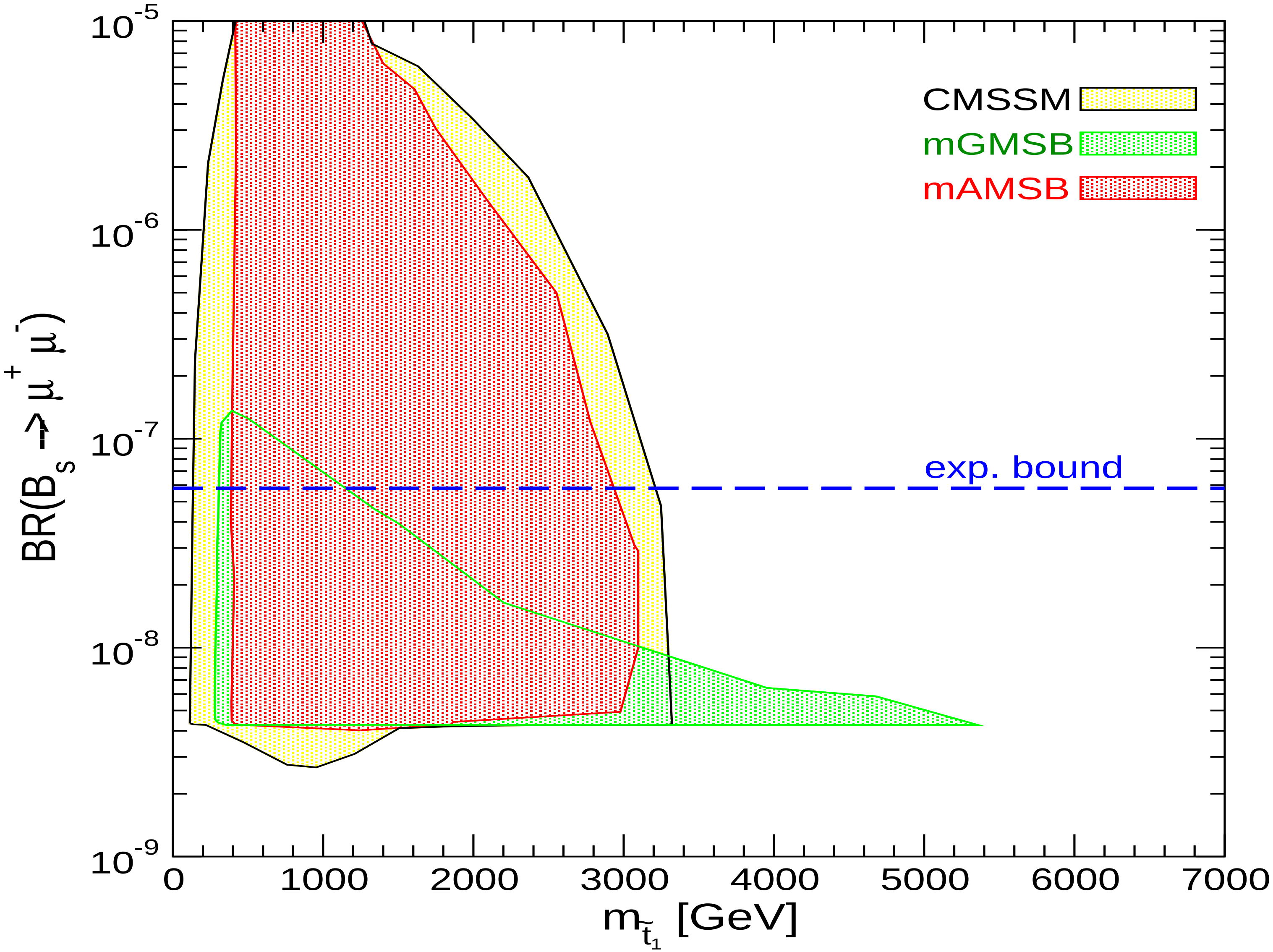
5.) BR($b \to s\gamma$)

BR($b \to s\gamma$) CMSSM vs. mGMSB vs. mAMSB



6.) BR($B_s \to \mu^+\mu^-$)

BR($B_s \to \mu^+\mu^-$) CMSSM vs. mGMSB vs. mAMSB



Cold Dark Matter constraint:

$\rightarrow$ well justified in CMSSM

$\rightarrow$ situation is “unclear” for mGMSB and mAMSB

Too few DM:

$\Rightarrow$ other particles can make up the DM

Too high DM density:

$\Rightarrow$ various solutions possible:

– small amount of R-parity violation

– small change in cosmology of the early universe

– “thermal inflation”, “late time entropy injection”

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We want to treat CMSSM, mGMSB, mAMSB on equal footing!

⇒ CDM constraint is left out in our analysis!

3. Implications for the ILC

Procedure:

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

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

2. Perform χ^2 fit with precision observables

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

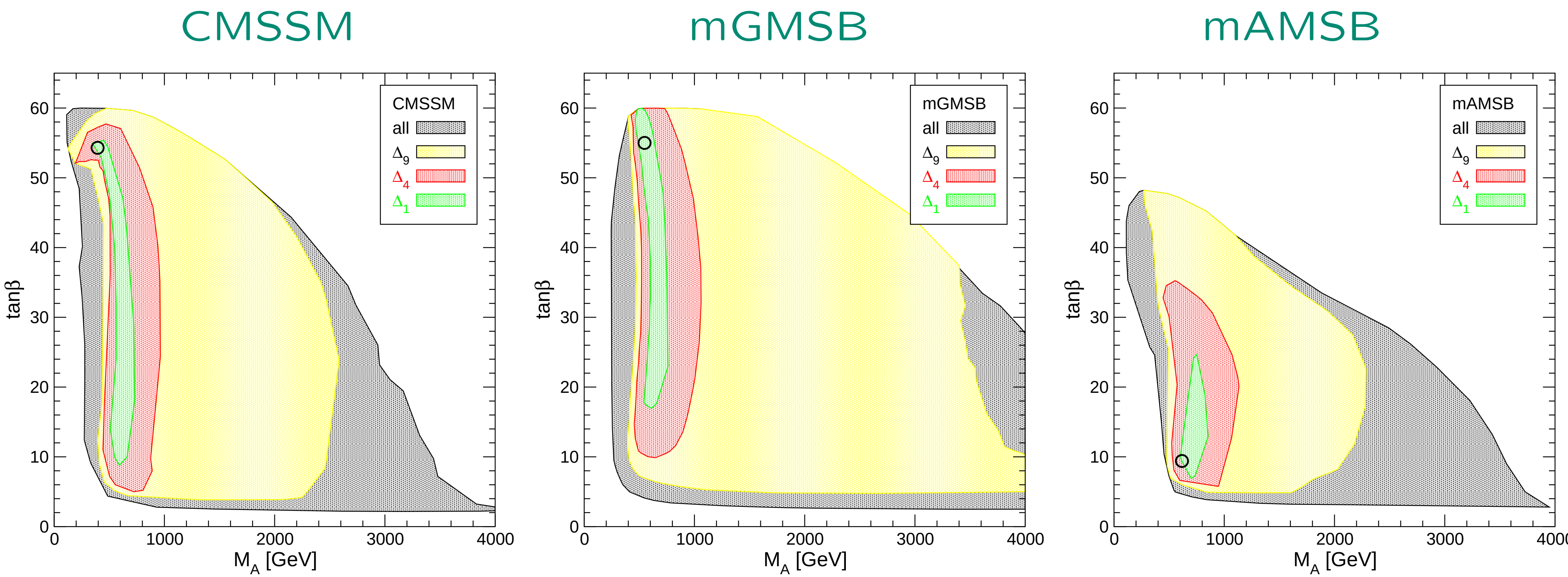
How good is the fit?

	CMSSM	mGMSB	mAMSB
χ^2_{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$(B_s \to \mu^+\mu^-)$	4.5×10^{-8}	3.2×10^{-8}	0.4×10^{-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



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

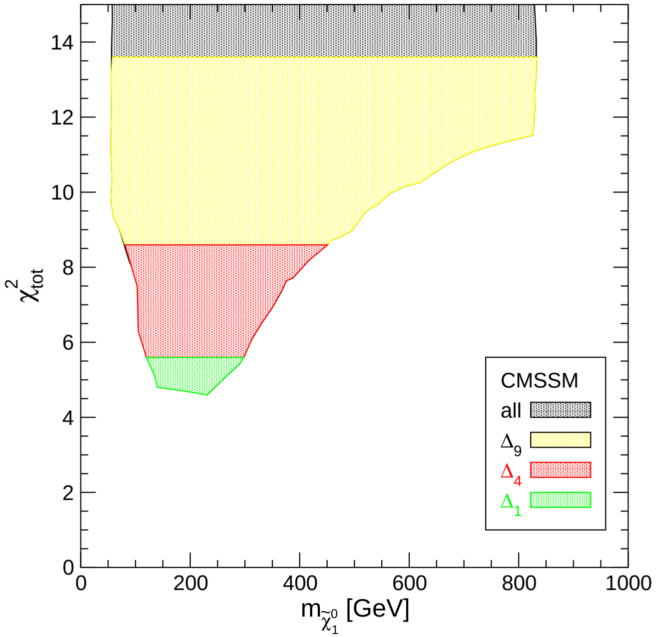
upper limit on M_A at $\Delta\chi^2 < 4$

M_A still mostly outside the ILC(1000) reach

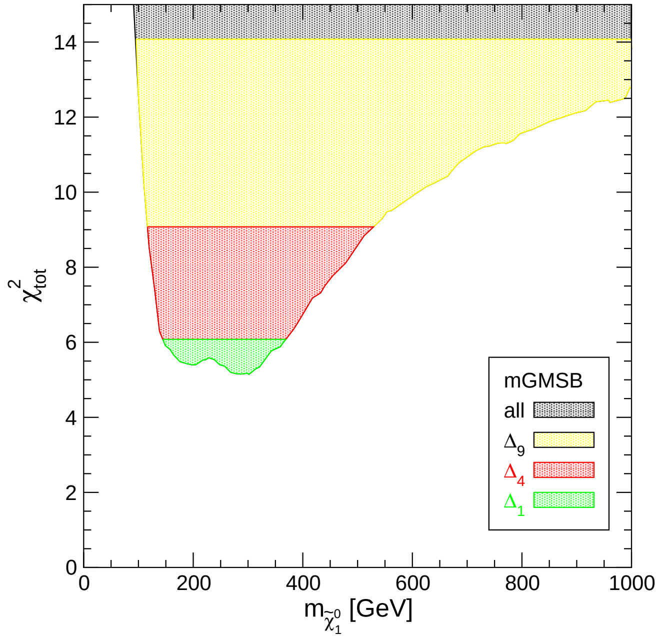
$\tan\beta$ only mildly restricted

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

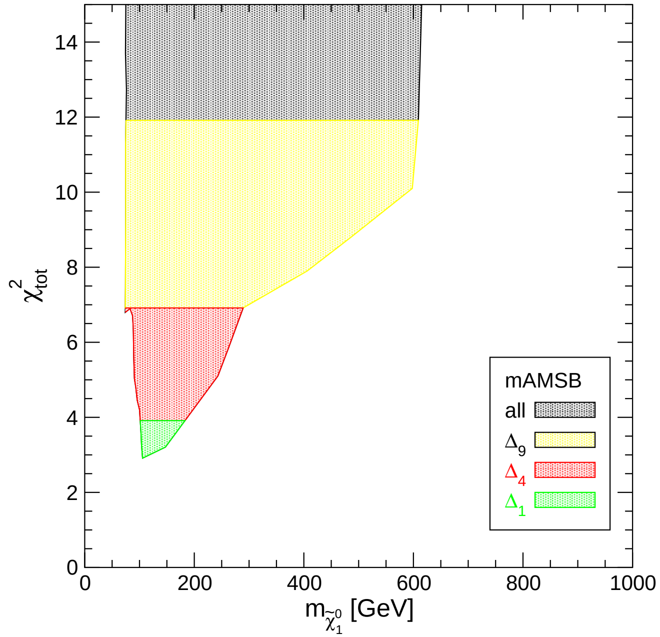
CMSSM



mGMSB



mAMSB



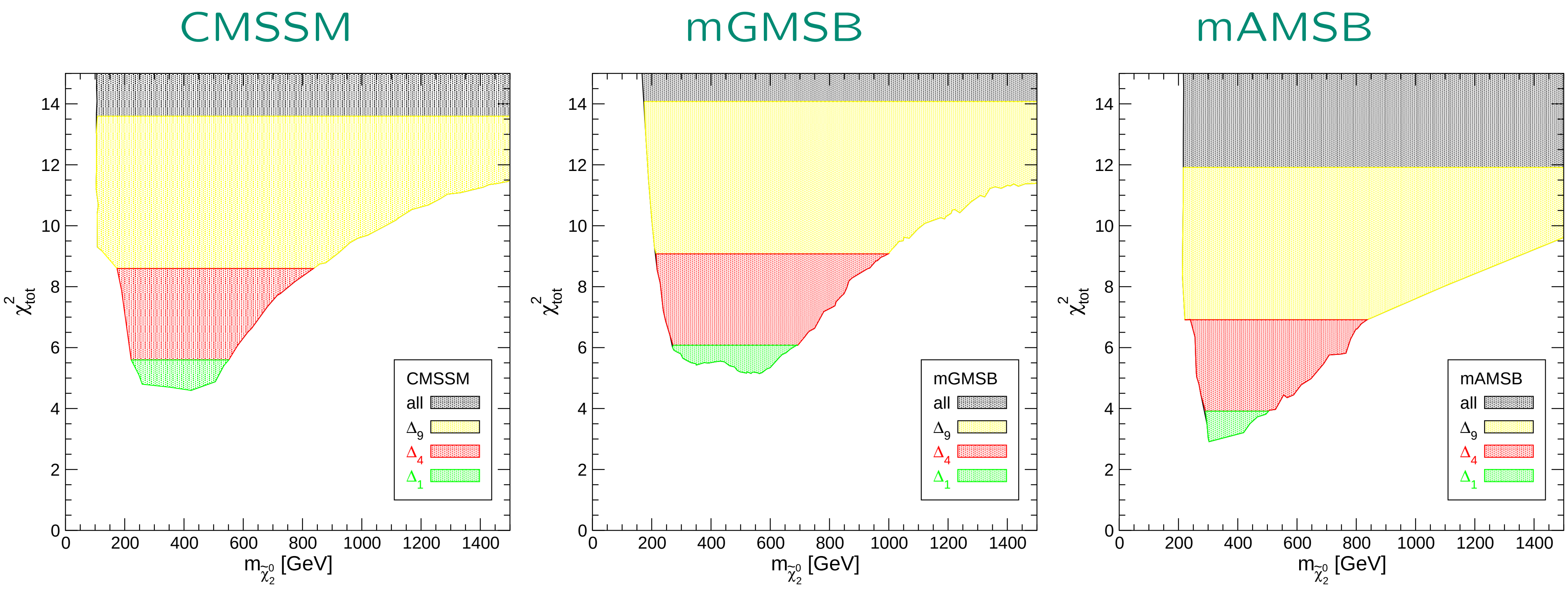
$\Rightarrow m_{\tilde{\chi}^0_1} \lesssim$ 500 GeV at $\Delta\chi^2 < 4$

$\Rightarrow$ pair production possible

CMSSM, mAMSB: detection via $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1\gamma$?

mGMSB: graviton is LSP, detection via $\tilde{\chi}^0_1 \to \tilde{G} + X$?

Results: second lightest neutralino vs. $\chi^2_{\rm tot}$

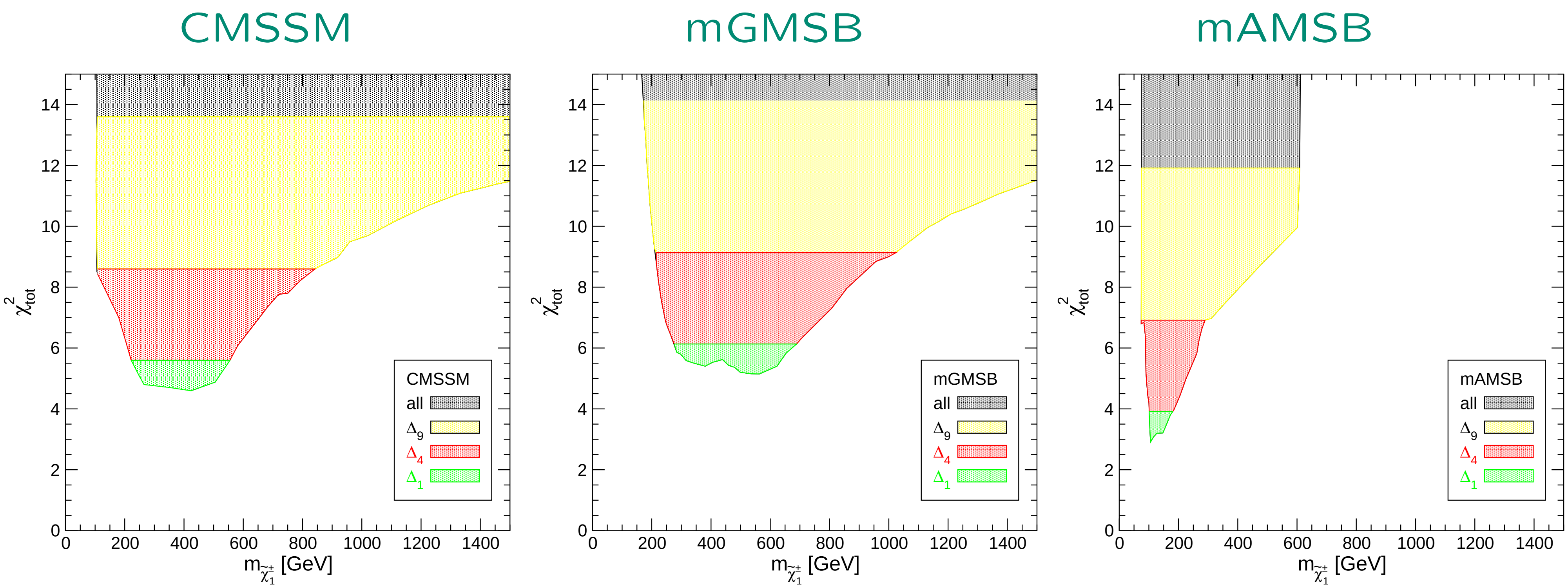


$\Rightarrow m_{\tilde\chi^0_2} \lesssim 800 - 900$ GeV at $\Delta\chi^2 < 4$

$\Rightarrow$ pair production difficult, $e^+e^- \to \tilde\chi^0_1\tilde\chi^0_2$?

detection via $\tilde\chi^0_2 \to \tilde\chi^0_1 + X$?

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



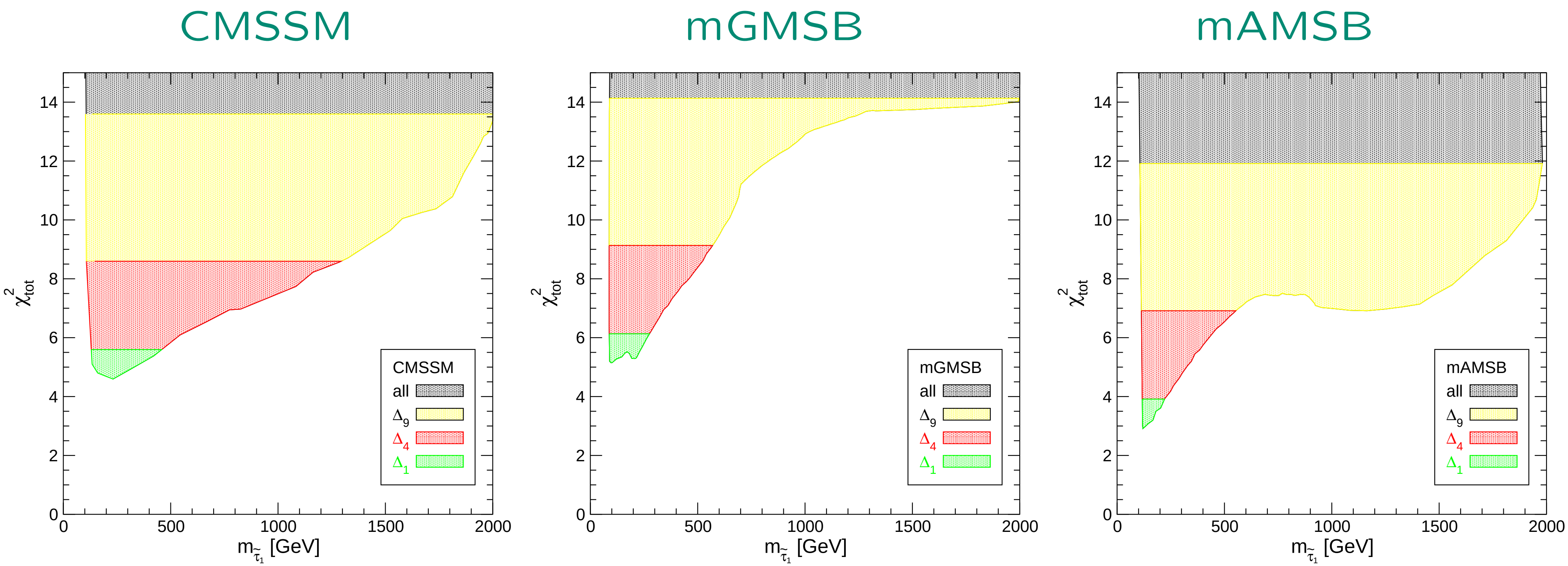
$\Rightarrow m_{\tilde{\chi}^\pm_1} \lesssim 300, 800, 900$ GeV at $\Delta\chi^2 < 4$ for mAMSB, CMSSM, mGMSB

mAMSB: $e^+e^- \to \tilde{\chi}^\pm_1\tilde{\chi}^\pm_1$ easy

$m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1} = \mathcal{O}(100 \text{ MeV}) \Rightarrow$ special problems

CMSSM, mGMSB: part of parameter space accessible

Results: lightest scalar tau vs. χ^2_{tot}



$\Rightarrow m_{\tilde{\chi}^0_1} \lesssim 500, 500, 1000$ GeV at $\Delta\chi^2 < 4$ for CMSSM, mAMSB, mGMSB

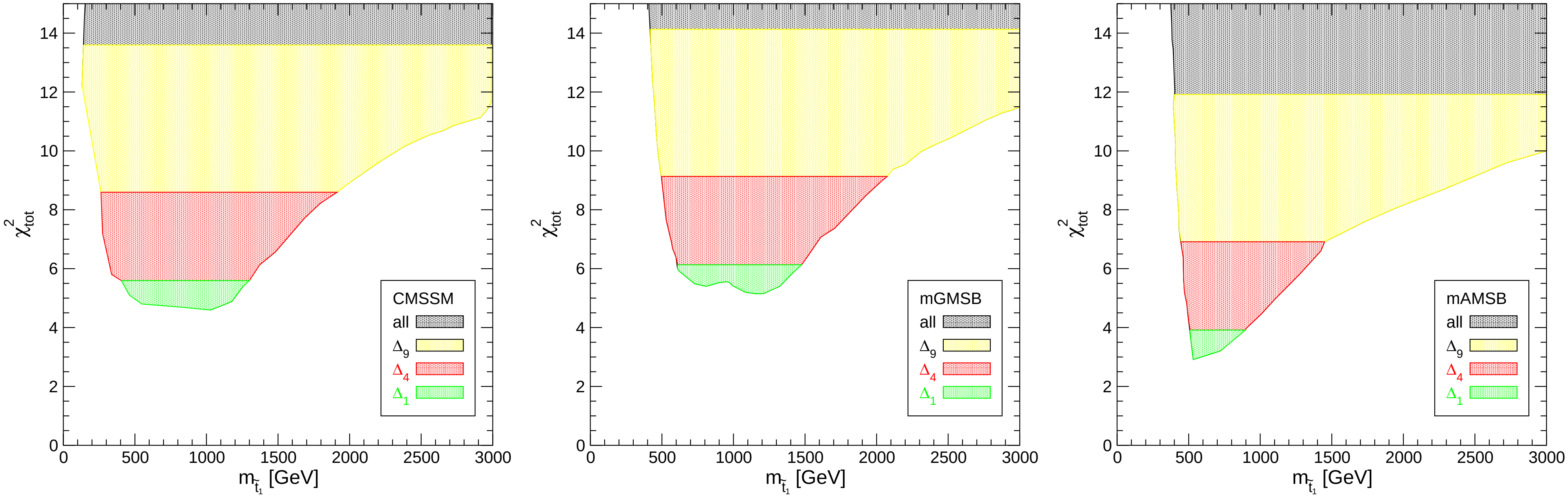
mGMSB, mAMSB: $e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$ possible

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



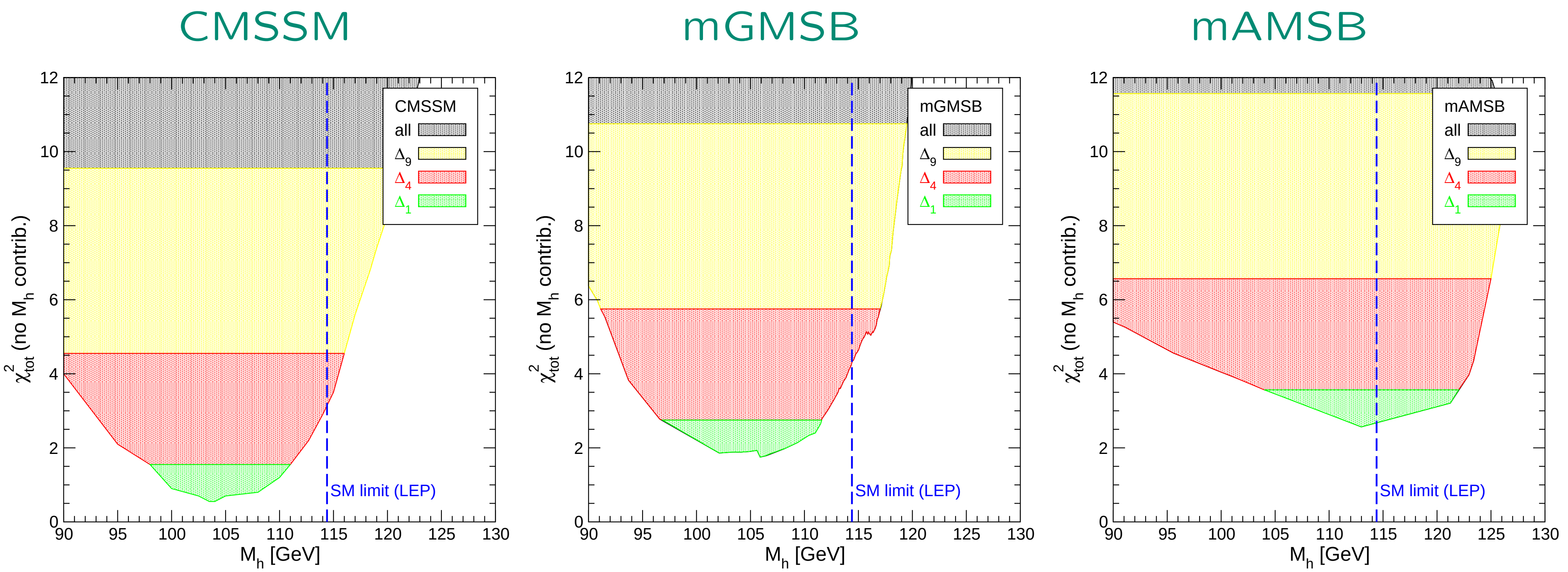
$\Rightarrow m_{\tilde{t}_1} \gtrsim$ 500 GeV at $\Delta\chi^2 < 4$

mGMSB, mAMSB: $e^+e^- \to \tilde{t}_1\tilde{t}_1$ not possible

CMSSM: part of parameter space accessible

lightest sbottom similar, gluino even heavier

Results: “blue band” for M_h (without LEP results)



CMSSM, mGMSB:

leaving out the LEP constraints substantially lowers the total χ^2

M_h around ~ 105 GeV, but still compatible with LEP bound

CMSSM: better if CDM is taken into account

mAMSB: well compatible with LEP constraint

4. Conclusinos

- Precision observables
  - can give valuable information about the "true" Lagrangian
  - can provide bounds on SUSY parameter space
- Most important electroweak precision observables:

  M_W, $\sin^2\theta_{\rm eff}$, M_h, $(g-2)_\mu$

  Most important B physics observables:

  $\text{BR}(b \to s\gamma)$, $\text{BR}(B_s \to \mu^+\mu^-)$
- models under consideration: CMSSM, mGMSB, mAMSB
- Current χ^2 fit:
  CMSSM: $\chi^2_{\rm min} = 4.6$, mGMSB: $\chi^2_{\rm min} = 5.1$, mAMSB: $\chi^2_{\rm min} = 2.9$
- Evaluation of SUSY spectrum $\Rightarrow$ ILC(1000) reach
  - some neutralinos/charginos are in reach
  - good chances for scalar tau
  - colored particles mostly too heavy
    some chances for lightest stop in CMSSM

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  Most important B physics observables:

  $\text{BR}(b \to s\gamma)$, $\text{BR}(B_s \to \mu^+\mu^-)$
- models under consideration: CMSSM, mGMSB, mAMSB
- Current χ^2 fit:
  CMSSM: $\chi^2_{\text{min}} = 4.6$, mGMSB: $\chi^2_{\text{min}} = 5.1$, mAMSB: $\chi^2_{\text{min}} = 2.9$
- Evaluation of SUSY spectrum $\Rightarrow$ ILC(1000) reach
  - some neutralinos/charginos are in reach
  - good chances for scalar tau
  - colored particles mostly too heavy
    some chances for lightest stop in CMSSM

The prospects for the ILC(1000) to see SUSY are good!