Constraining SUSY with Precision Observables: Going Beyond the CMSSM

Sven Heinemeyer, IFCA (CSIC, Santander)

Seoul, 06/2008

1. Motivation
2. Constraining the CMSSM, mGMSB and mAMSB
3. Constraining Finite Unified Theories
4. Conclusions

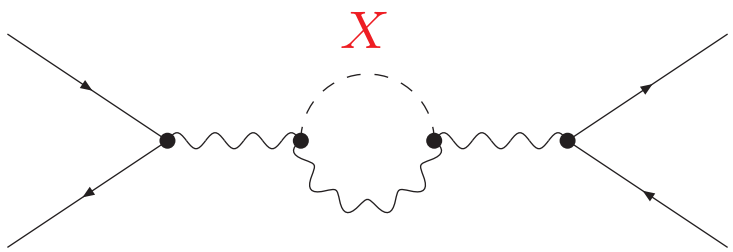
1. Motivation: Precision Observables (POs):

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



$\Downarrow$

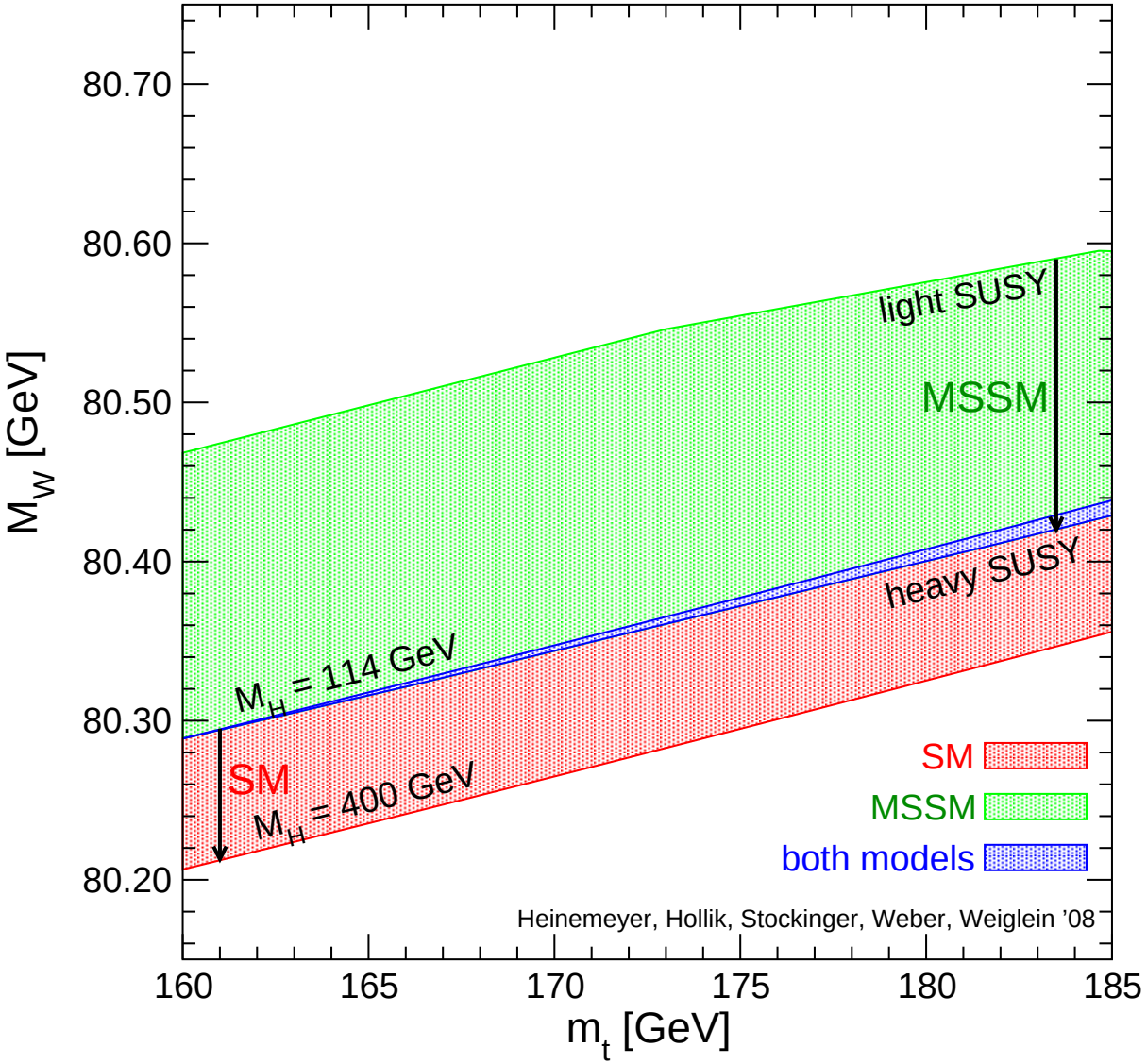
Very high accuracy of measurements and theoretical predictions needed

$\rightarrow$ Which model fits better?

$\Rightarrow$ indirect constraints on $M_{\rm SUSY}$?

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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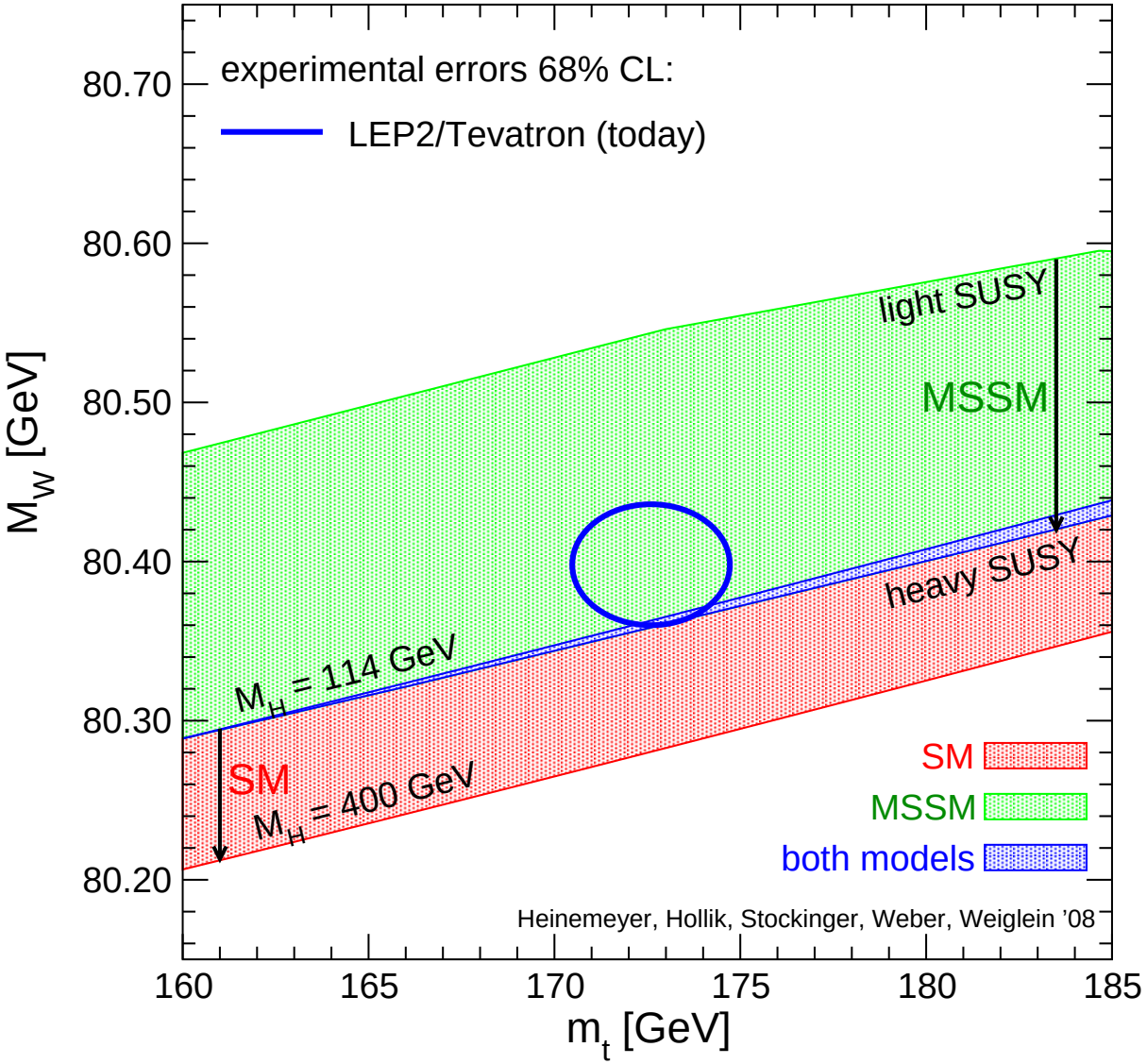

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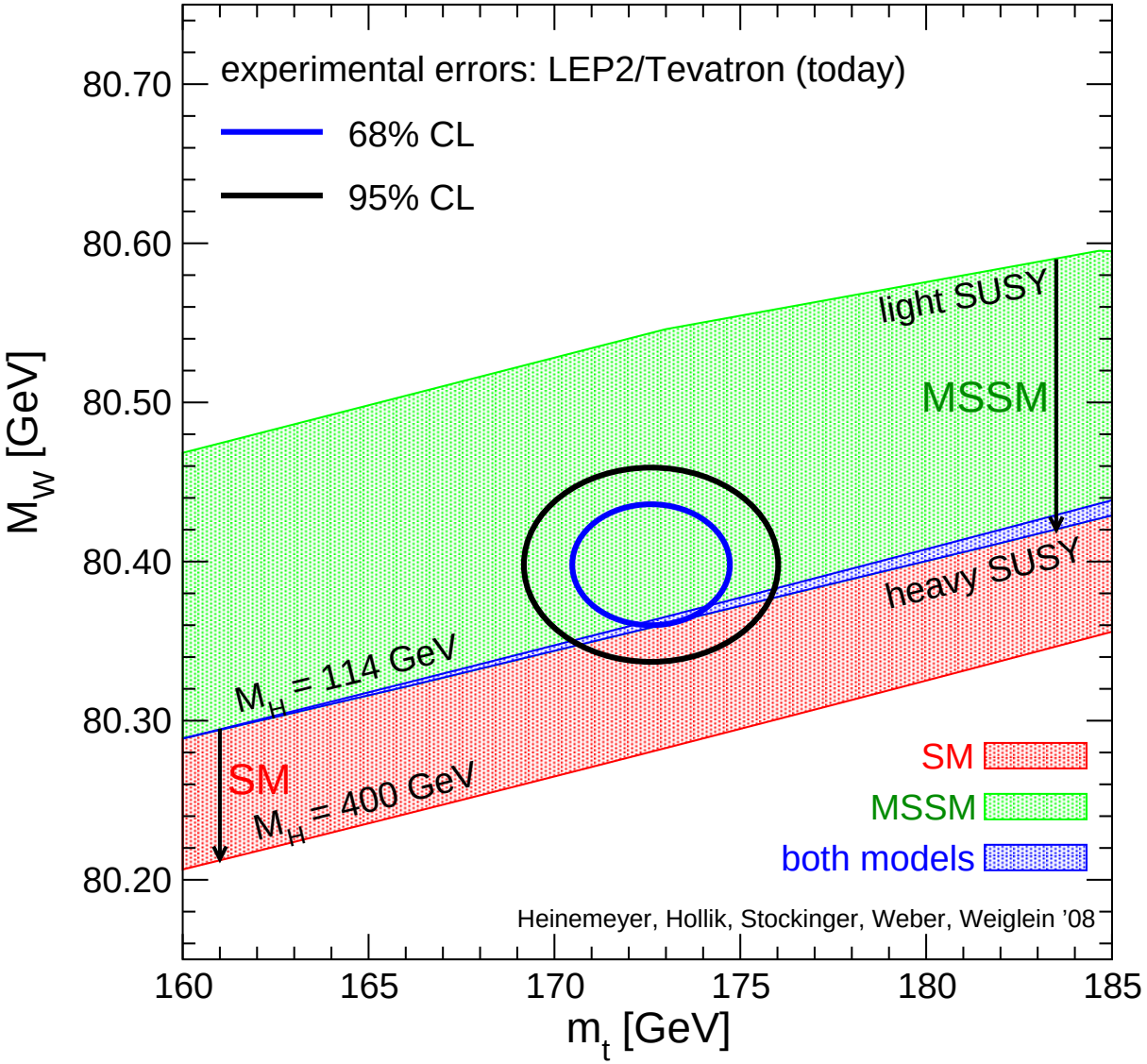

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Indirect constraints on $M_{\rm SUSY}$ from existing data?

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

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

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

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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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 ...

$\Rightarrow$ 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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[*R. de Austri, R. Trotta and L. Roszkowski '06, '07*]

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VCMSSM:

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

2. 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: 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) $\rightarrow$ ⊤

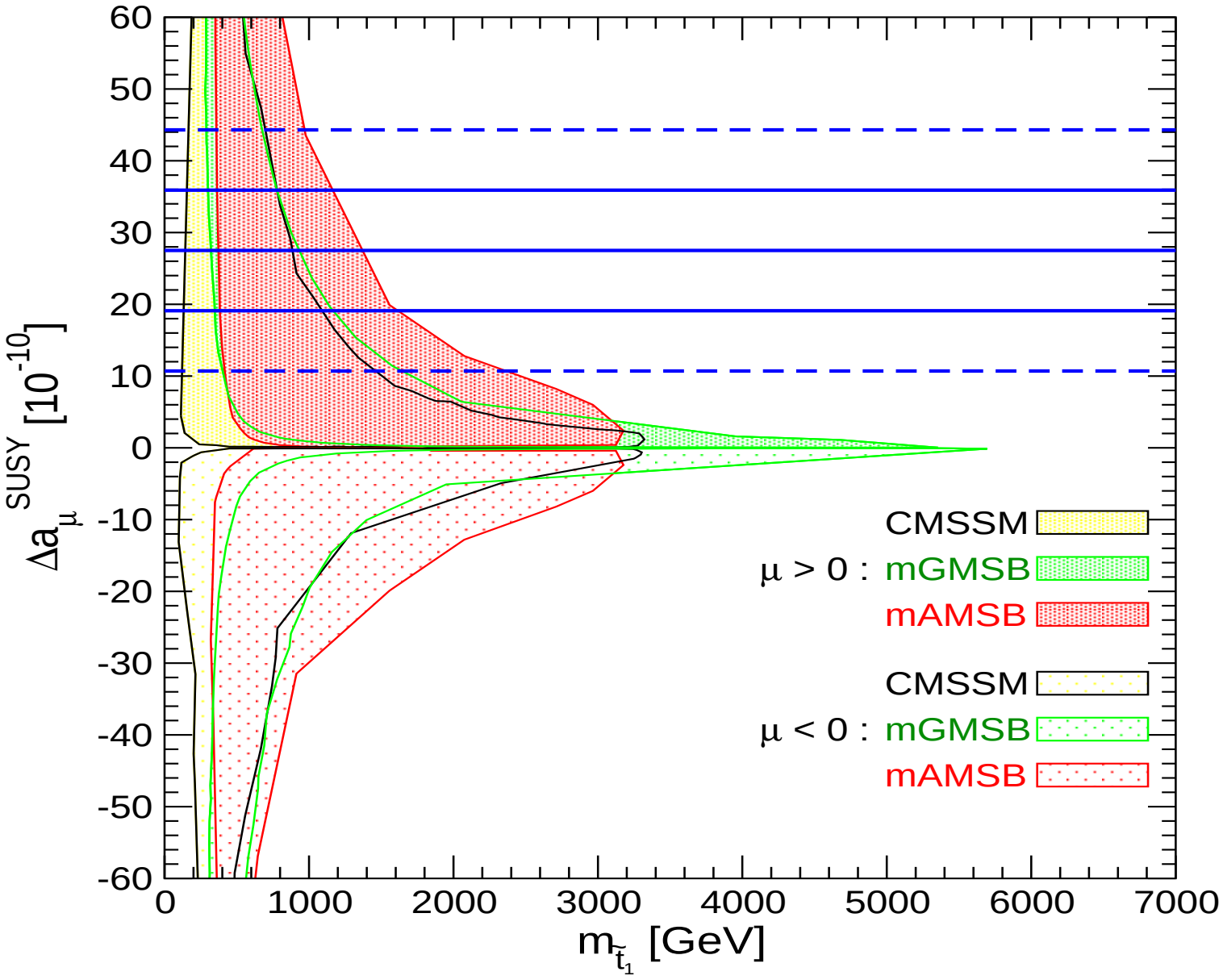
2. Perform χ^2 fit with precision observables:

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

   (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?

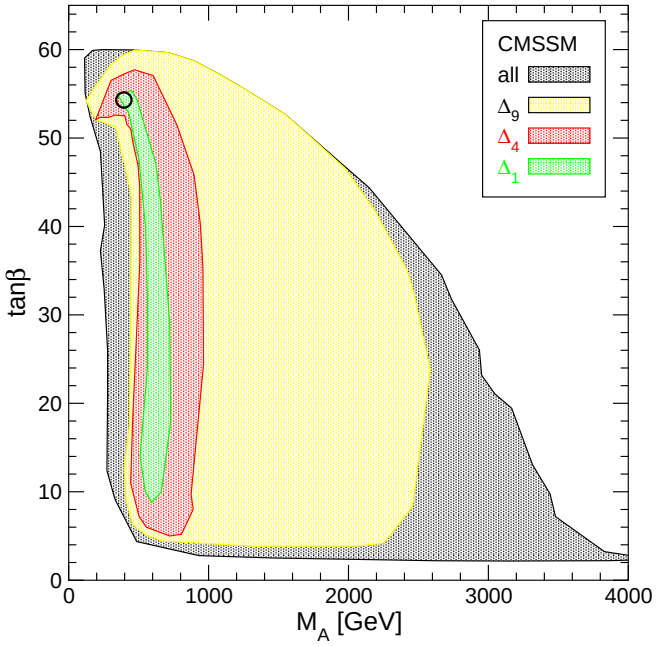
	CMSSM	mGMSB	mAMSB
χ^2_{min}	4.6	5.1	2.9
M_W	1.7	2.1	0.6
$\sin^2\theta_{\text{eff}}$	0.1	0.0	0.8
$(g-2)_\mu$	0.6	0.9	0.0
BR$(b \to s\gamma)$	1.1	2.0	1.5
M_h	1.1	0.1	0.0
BR$(B_s \to \mu^+\mu^-)$	4.5×10^{-8}	3.2×10^{-8}	0.4×10^{-8}
M_A [GeV] (best-fit)	394	547	616
$\tan\beta$ (best-fit)	54	55	9

$\Rightarrow$ good fit results

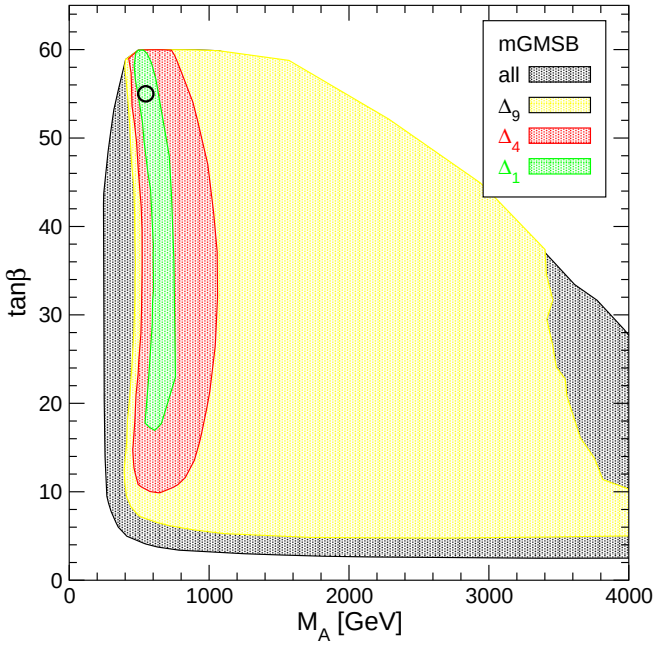
$\Rightarrow$ mAMSB fits best (but not significantly)

Results: fit in the M_A–tan β plane: today

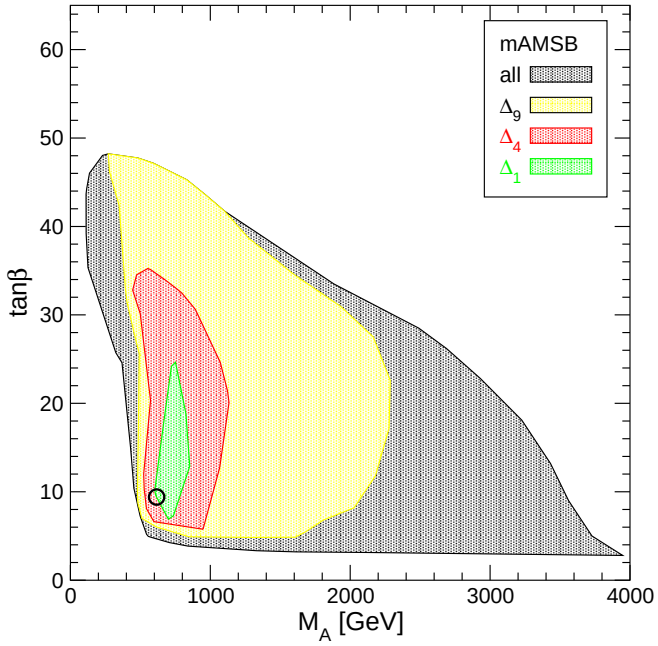
CMSSM



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 β

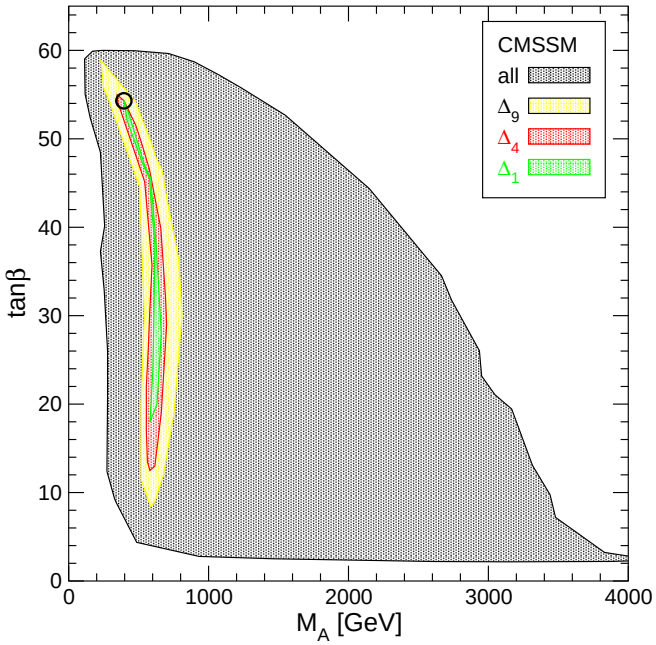
M_A still mostly outside the ILC(1000) reach

tan β only mildly restricted

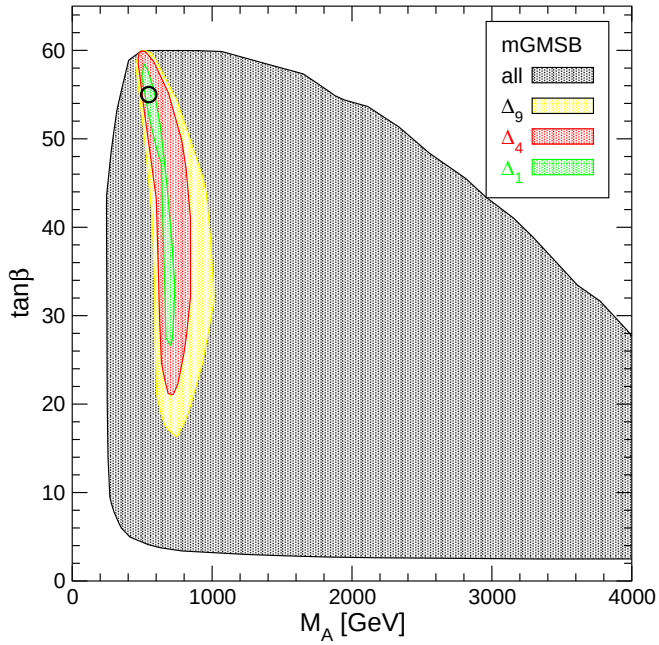
Results: fit in the M_A–tan β plane: future

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

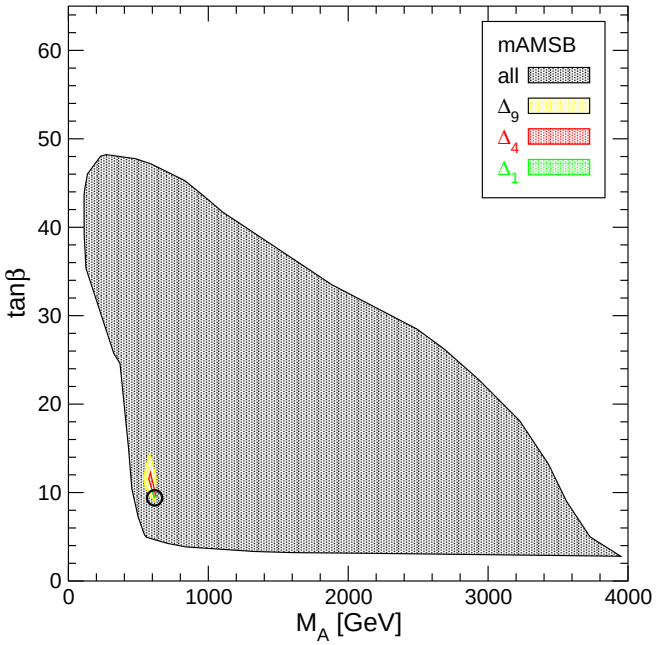
CMSSM



mGMSB



mAMSB



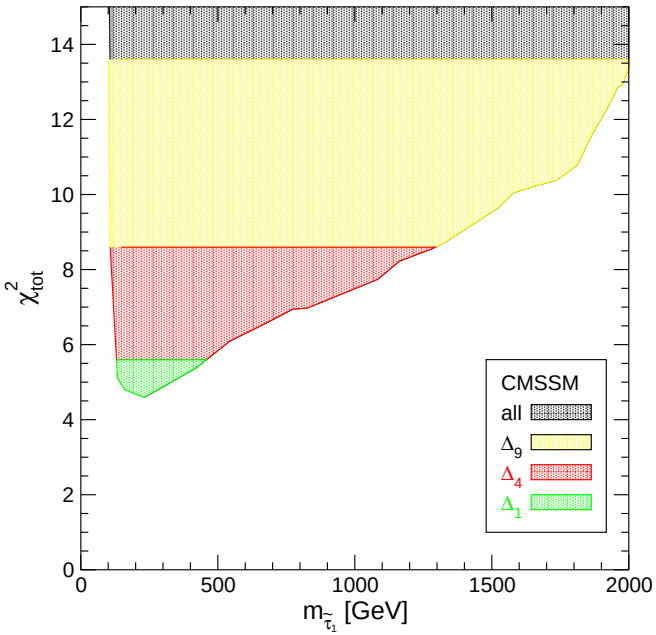
$\Rightarrow$ upper limit on M_A at $\Delta\chi^2 < 9$

tan β only mildly restricted in CMSSM/mGMSB

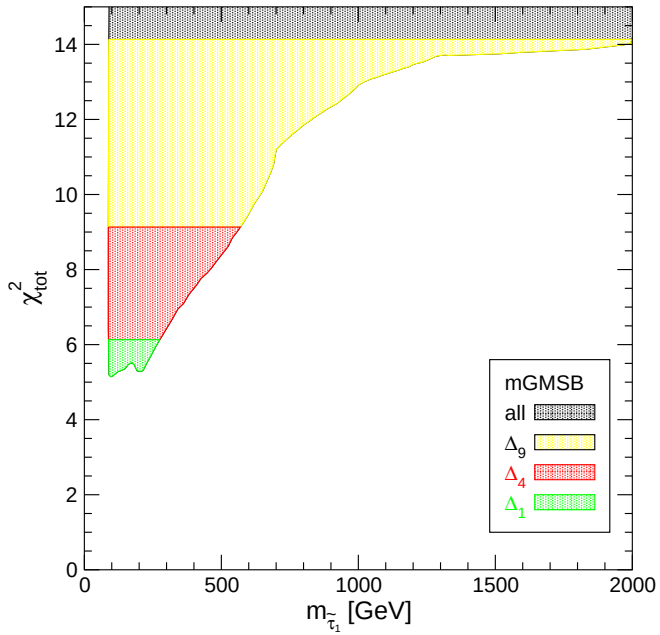
mAMSB: high precision is accidental

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

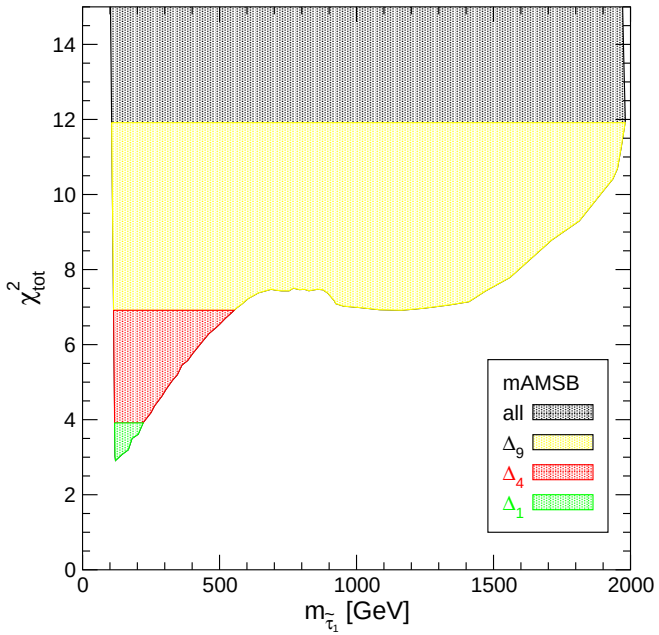
CMSSM



mGMSB



mAMSB



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

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

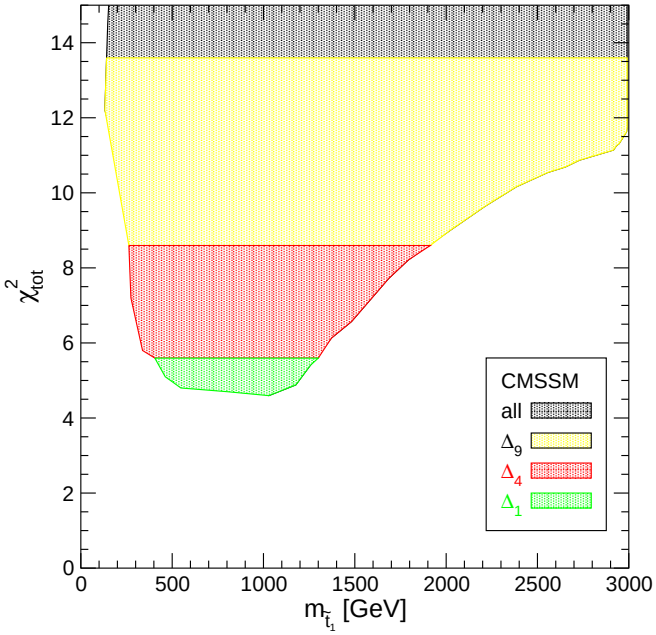
mGMSB, mAMSB: $e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$ possible

CMSSM: possibly too heavy for ILC(1000)

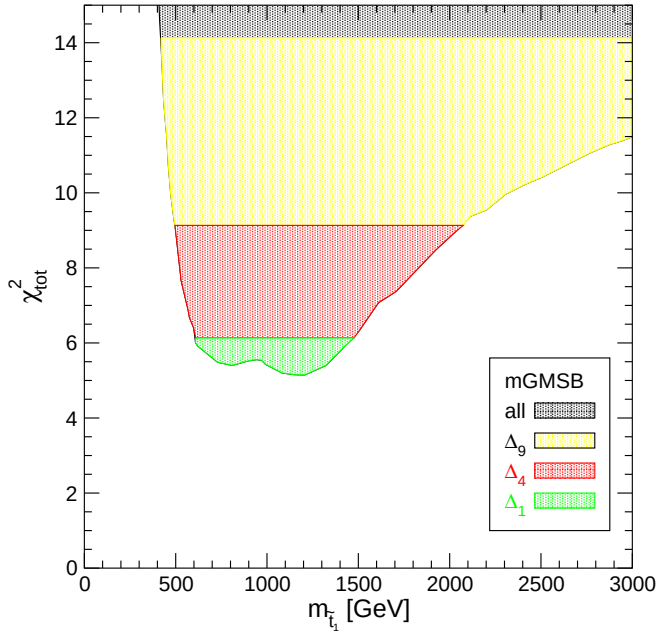
but better if CDM is taken into account

Results: lightest stop vs. χ^2_{tot}

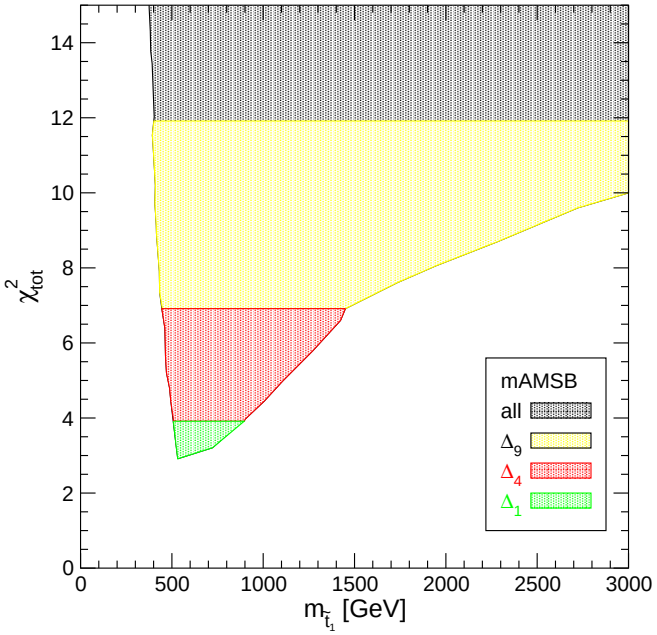
CMSSM



mGMSB



mAMSB

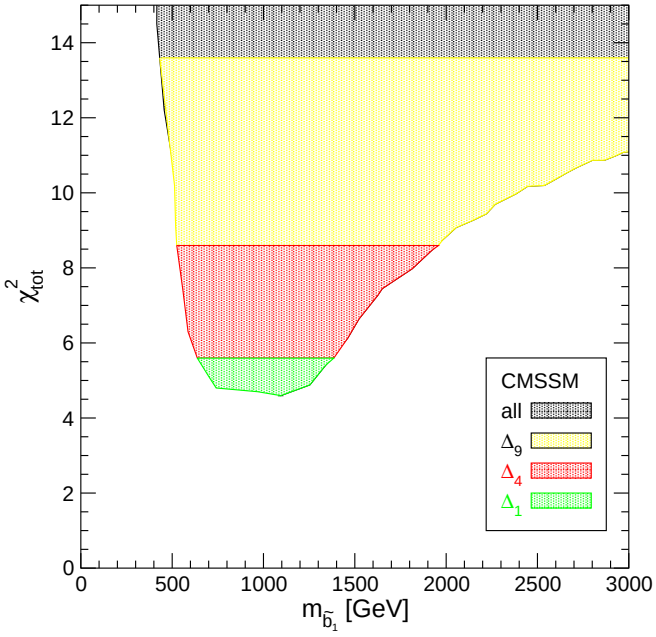


$\Rightarrow$ 500 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 2000 GeV at $\Delta\chi^2 < 4$

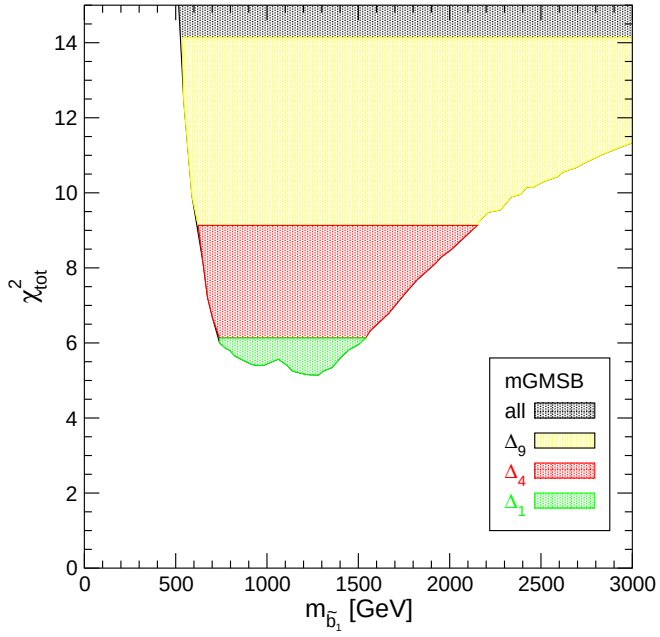
$\Rightarrow$ easily within LHC reach

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

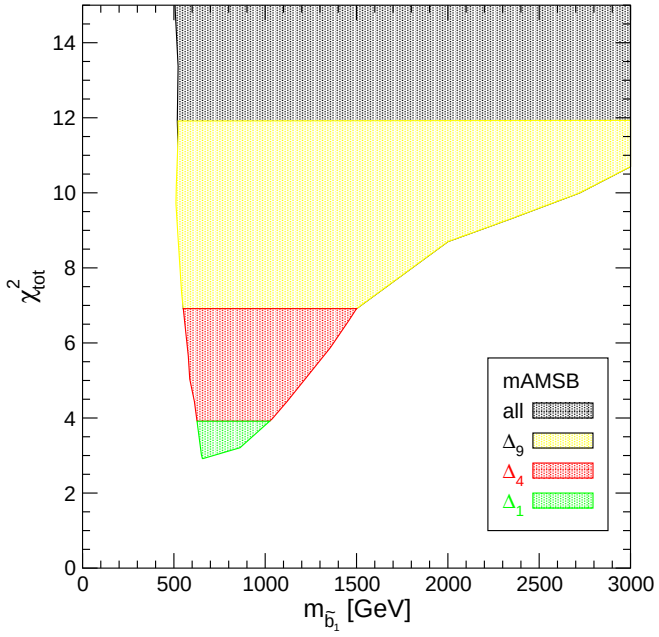
CMSSM



mGMSB



mAMSB



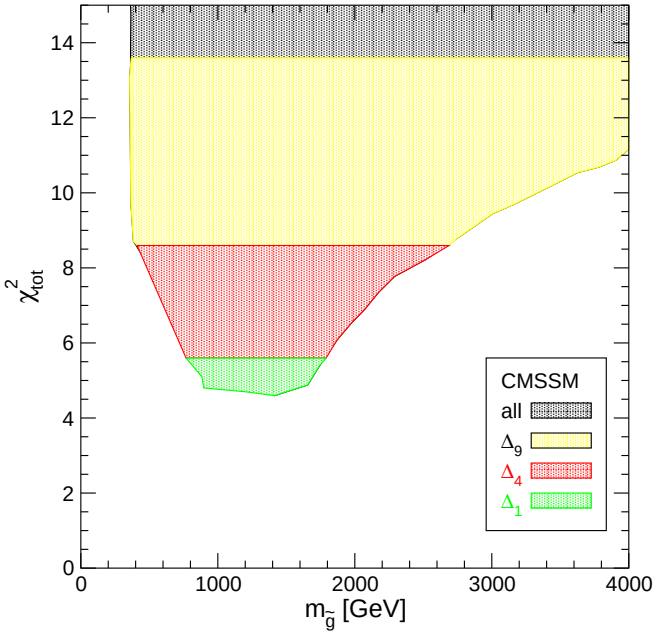
$\Rightarrow$ 500 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 2200 GeV at $\Delta\chi^2 < 4$

slightly heavier than the lightest stop

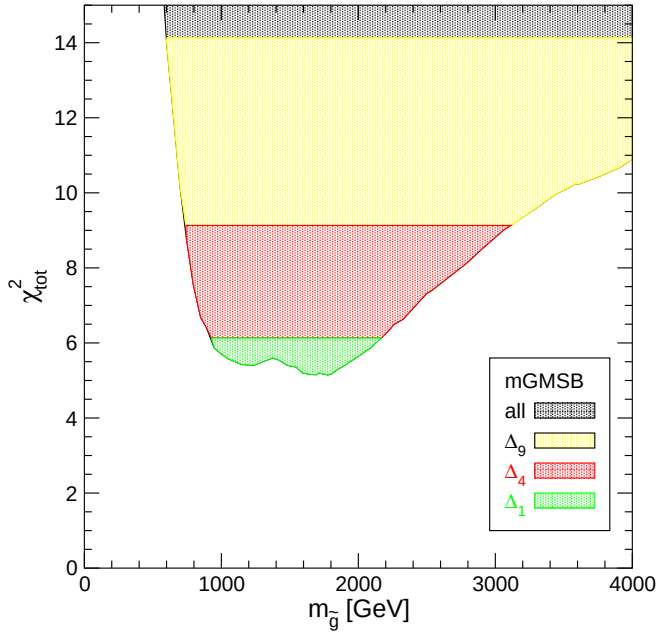
$\Rightarrow$ easily within LHC reach

Results: gluino vs. χ^2_{tot}

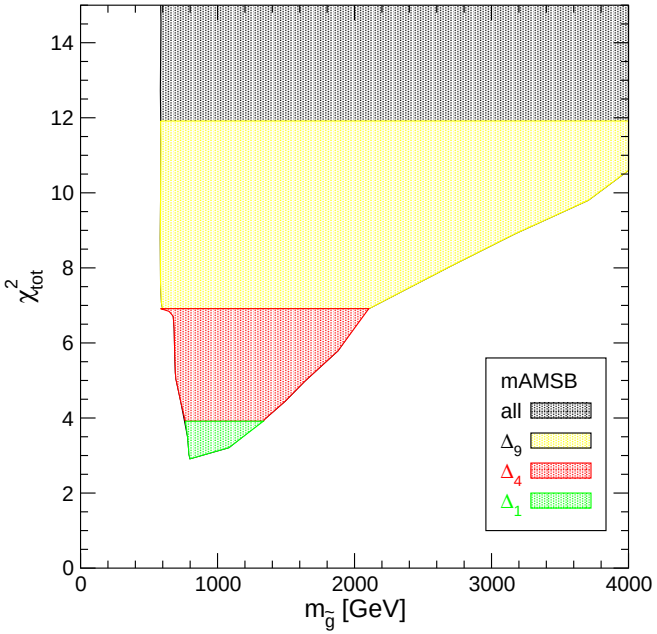
CMSSM



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

3. Constraining Finite Unified Theories

[S.H., M. Mondragón, G. Zoupanos '07]

Different/additional idea: **Finite Unified Theories (FUTs)**

→ take a SUSY GUT (works (so far) only with SUSY)

→ assume a unifying gauge group, here we restrict to $SU(5)$

→ demand one-loop finiteness above the GUT scale
- one-loop gauge β-functions vanish
- vanishing of anomalous dimensions of all superfields $\gamma_i^{(1)} = 0$

⇒ one-loop relations between gauge and Yukawa couplings

⇒ sum rule for soft masses at the GUT scale

connection between scalar masses m_i and gaugino mass M

⇒ NEW: prediction of m_t, m_b! (and low-energy spectrum . . .)

Two models: **FUTA, FUTB**

FUTA: H_a and $\overline{H}_a$, $a = 1,2,3$ couple to H_4 and $\overline{H}_4$

$\Rightarrow$ doublet triplet splitting

FUTB: H_a and $\overline{H}_a$, $a = 1,2,3$ couple to $\mathbf{24}$, no mixing with H_4 and $\overline{H}_4$

$\Rightarrow$ doublet triplet splitting

Vanishing of anomalous dimensions, $\gamma_i^{(1)} = 0$, application of sum rule:

FUTA:

$$m_{H_u}^2 + 2m_{\mathbf{10}}^2 = m_{H_d}^2 + m_{\overline{\mathbf{5}}}^2 + m_{\mathbf{10}}^2 = M^2$$

free parameters: $m_{\mathbf{5}}$, $m_{\mathbf{10}}$, M

FUTB:

$$m_{H_u}^2 + 2m_{\mathbf{10}}^2 = M^2,\ m_{H_d}^2 - 2m_{\mathbf{10}}^2 = -\frac{M^2}{3},\ m_{\overline{\mathbf{5}}}^2 + 3m_{\mathbf{10}}^2 = \frac{4M^2}{3}$$

free parameters: $m_{\mathbf{10}}$, M

Procedure:

Apply successively the constraints

$$\boxed{m_t,\ m_b,\ \mathrm{BR}(b \to s\gamma),\ \mathrm{BR}(B_s \to \mu^+\mu^-),\ M_h,\ \mathrm{CDM}}$$

Step 1:

check which of the four models

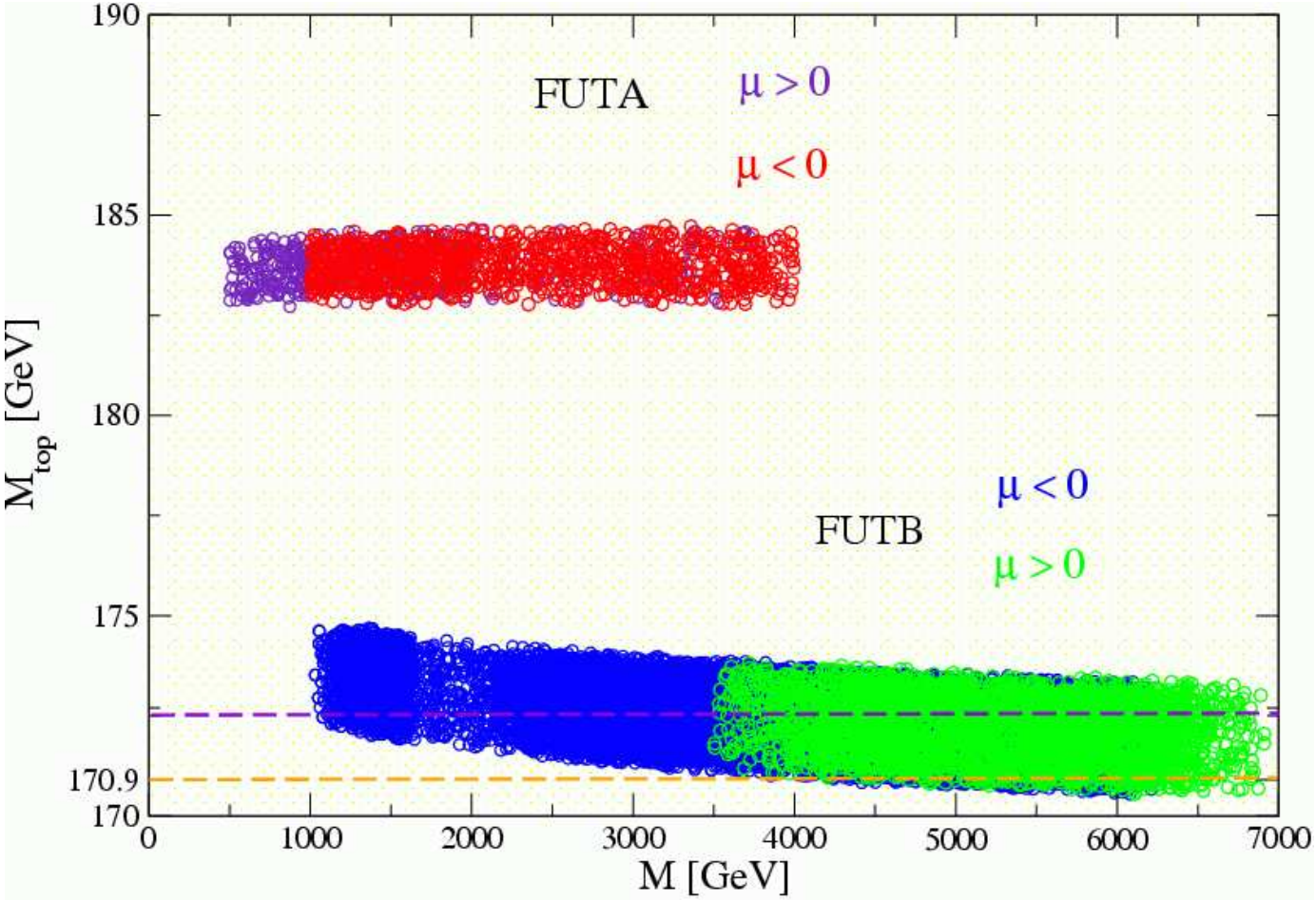
$$\mathrm{FUTA}+,\ \mathrm{FUTA}-,\ \mathrm{FUTB}+,\ \mathrm{FUTB}- \ (\pm : \mu \gtrless 0)$$

survives (or performs best)

Step 2:

evaluate prediction for the SUSY/FUT parameter space
$\Rightarrow$ collider phenomenology

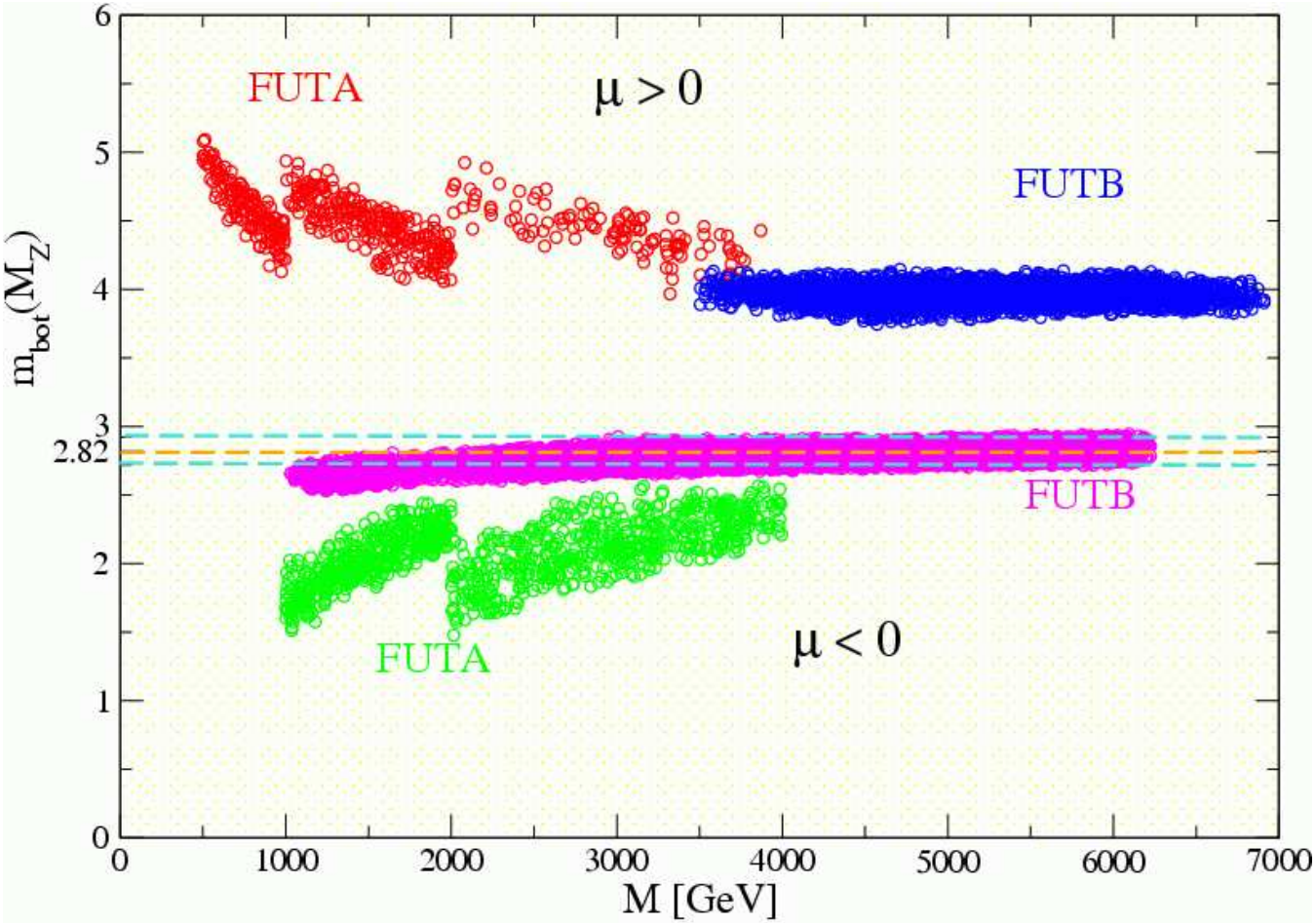
Application of m_t^{pole}:



$\Rightarrow$ FUTB gives the correct prediction for m_t (also with new m_t^{exp} value)

$\Rightarrow$ FUTA is ruled out experimentally

Application of $m_b(M_Z)$:



$\Rightarrow \mu < 0$ strongly favored

$\Rightarrow \mu > 0$ experimentally excluded

Summary of heavy quark constraints:

$\Rightarrow$ FUTB gives the correct prediction for m_t

$\Rightarrow$ FUTA is ruled out experimentally

$\Rightarrow$ $\mu < 0$ strongly favored

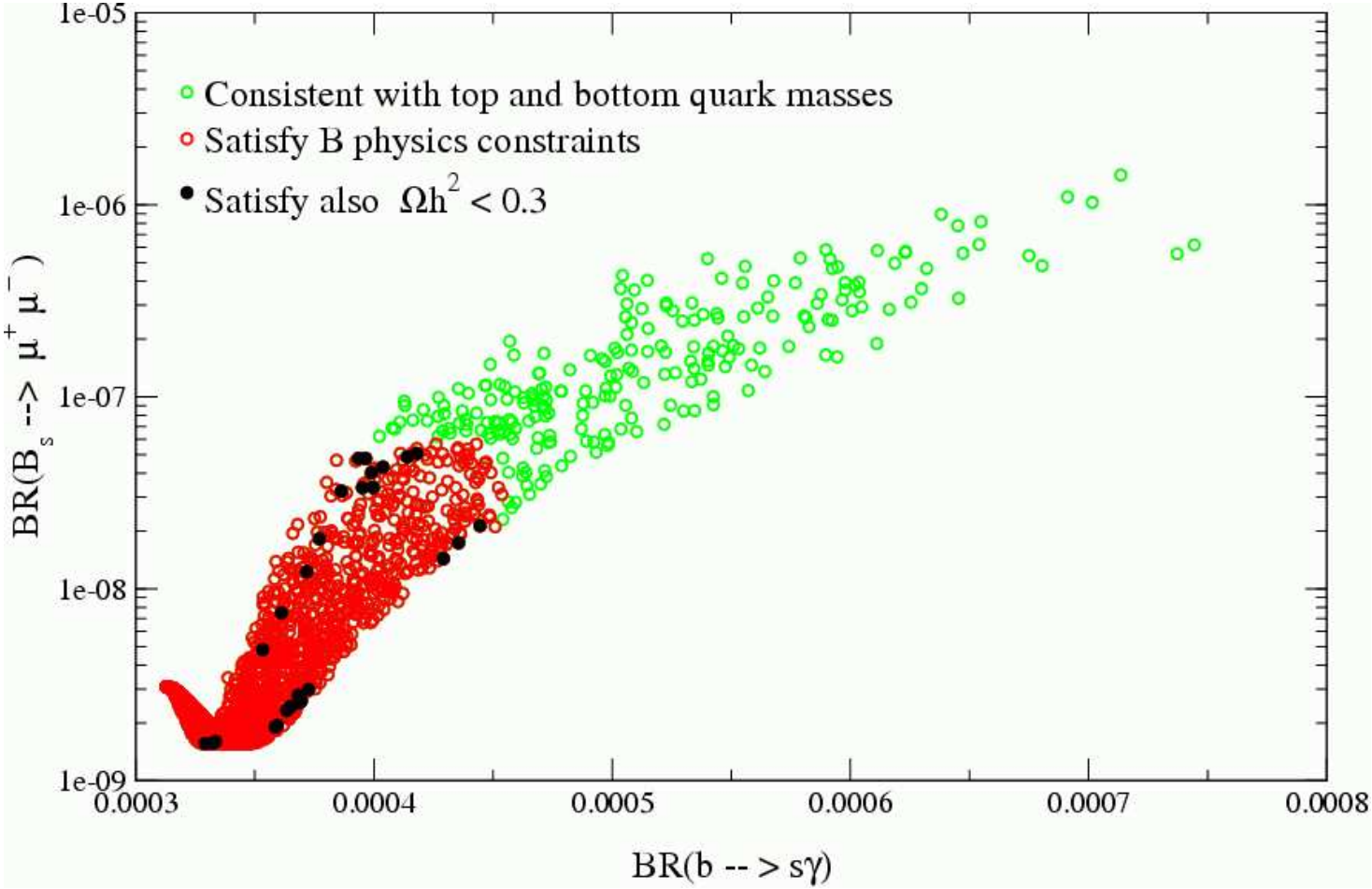
$\Rightarrow$ $\mu > 0$ experimentally excluded

only FUTB– survives

$\Rightarrow$ concentrate on FUTB– from now on

$\Rightarrow$ evaluate prediction for parameter space taking into account the other constraints

Application of B physics and CDM constraints on FUTB–



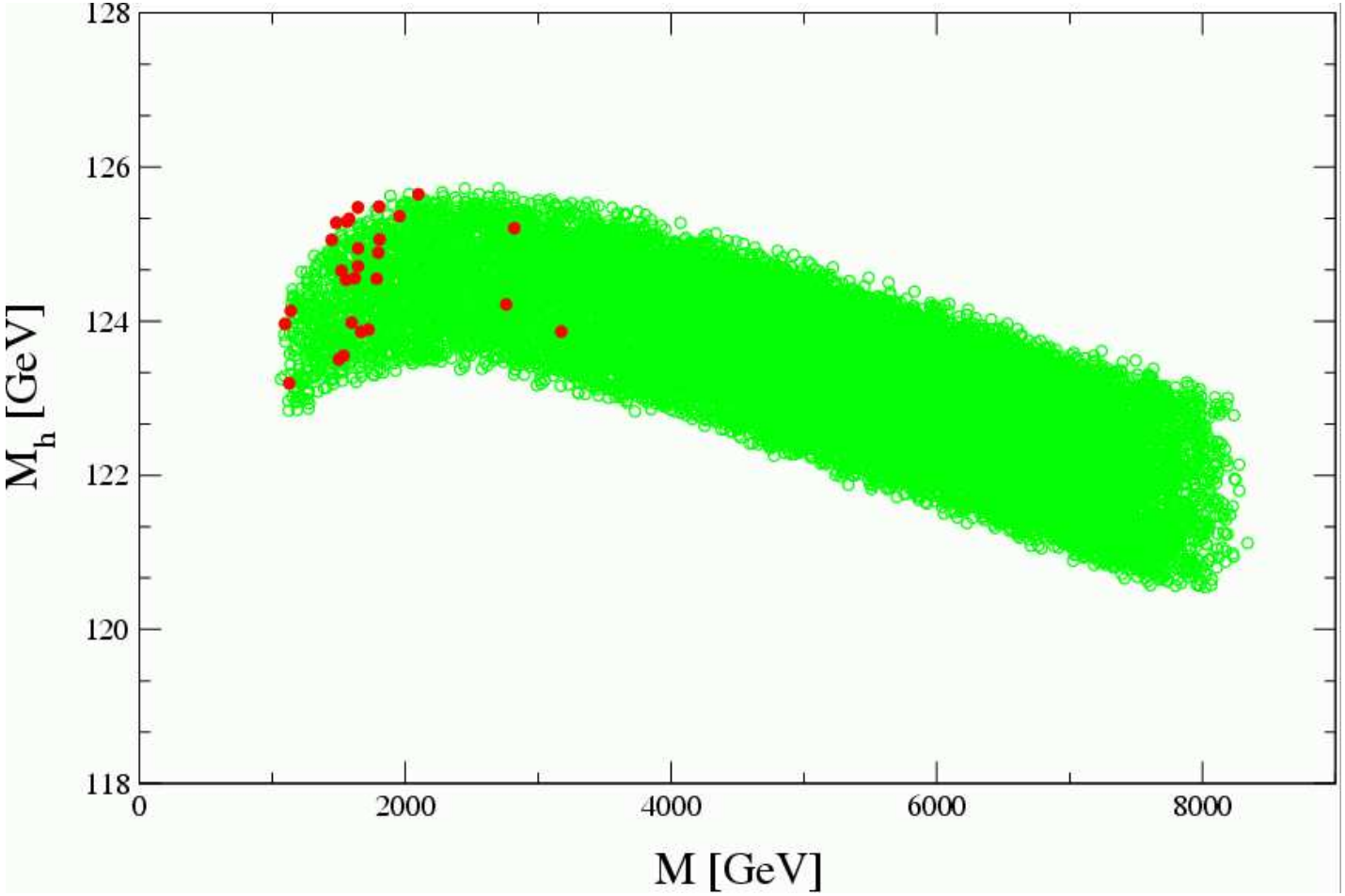
green: inconsistent

red: consistent with B physics constraints

black: agreement with (loose) CDM bound

$\Rightarrow$ FUTB– looks ok

Final check: the lightest Higgs boson mass M_h



green: consistent with B physics constraints

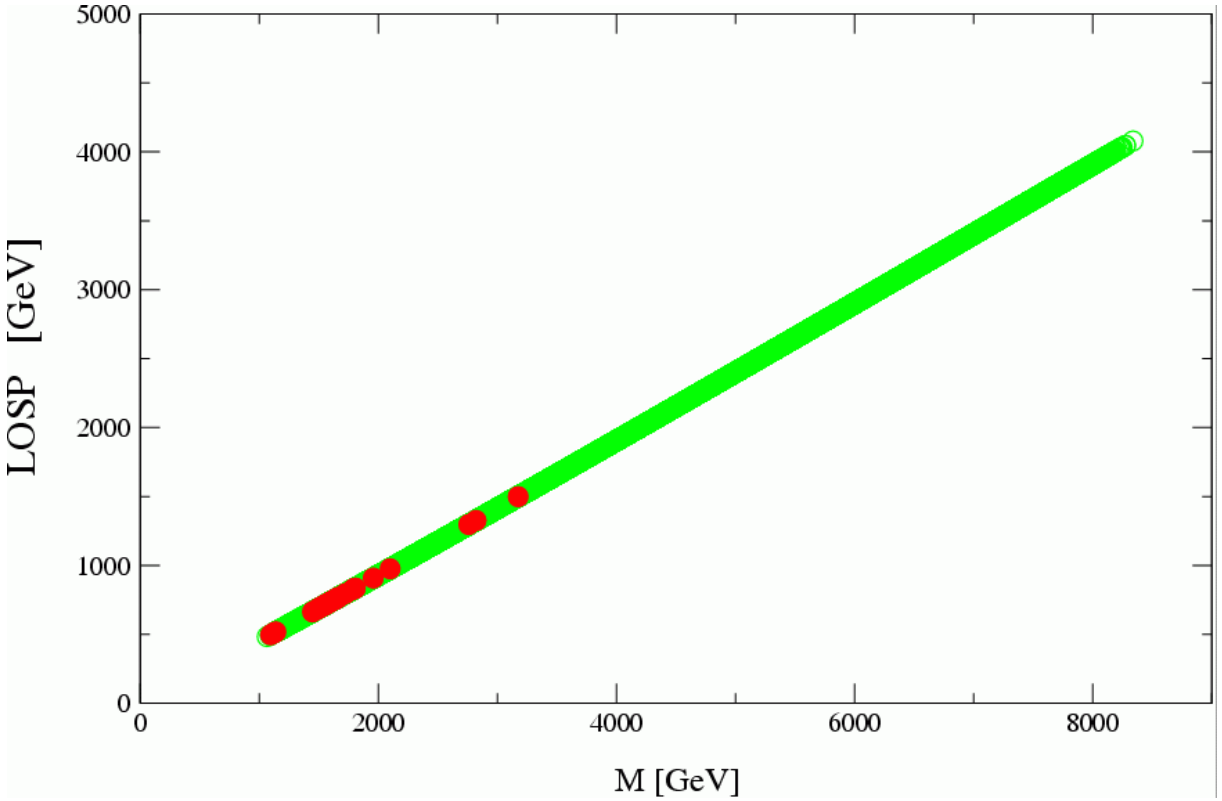
red: agreement with (loose) CDM bound

$\Rightarrow$ 120 GeV $\leq M_h \leq$ 126 GeV (no theory error incl. yet)

$\Rightarrow$ M_h automatically satisfied (contrary to mSUGRA, GMSB, AMSB, ...)

Predictions for the LOSP

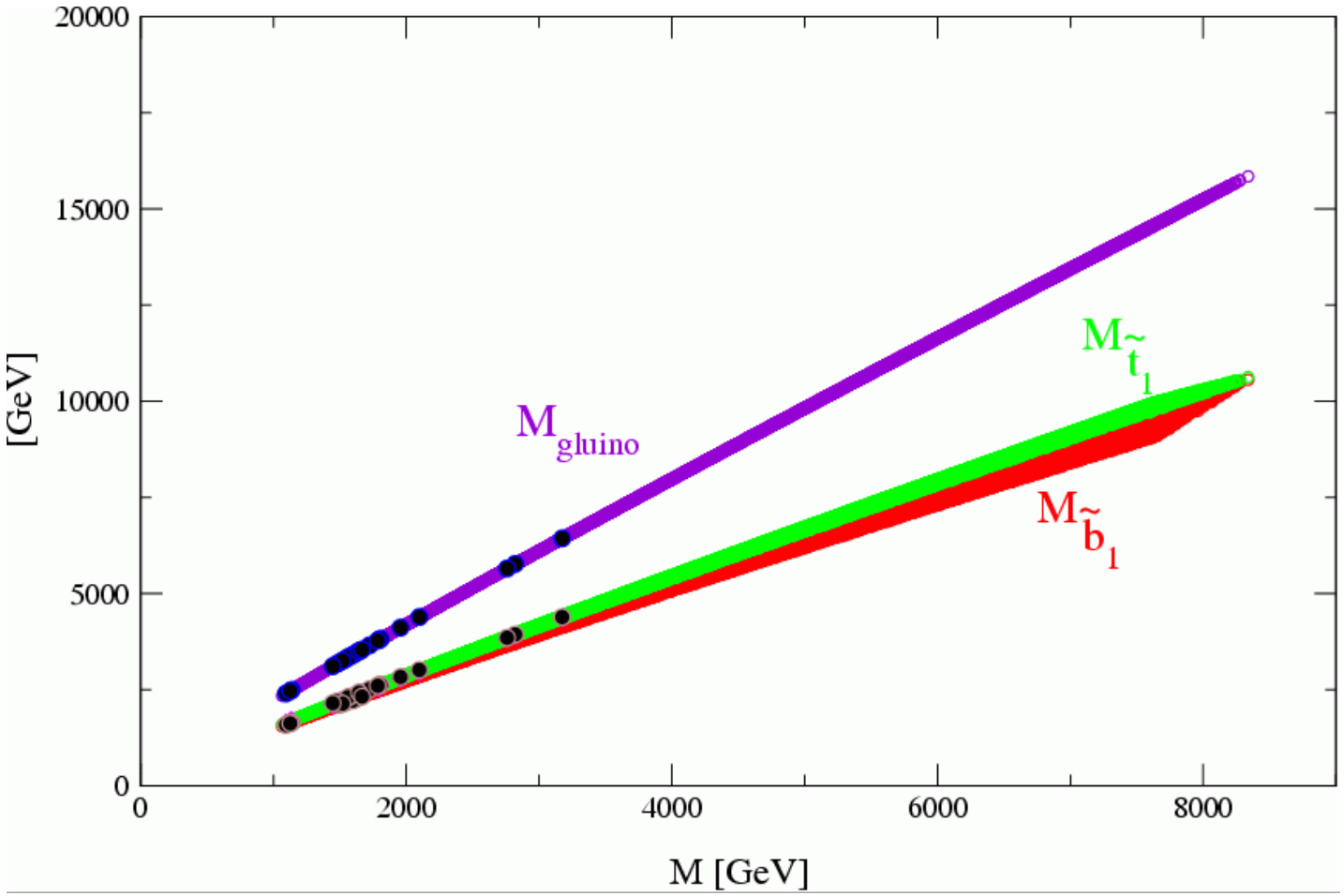
LOSP: lighter scalar tau or second lightest neutralino
(nearly mass degenerate with lightest chargino)



green: consistent with B physics constraints
red: agreement with (loose) CDM bound

$\Rightarrow$ very challenging for LHC (possibly in cascades?)

Predictions for squarks and gluinos



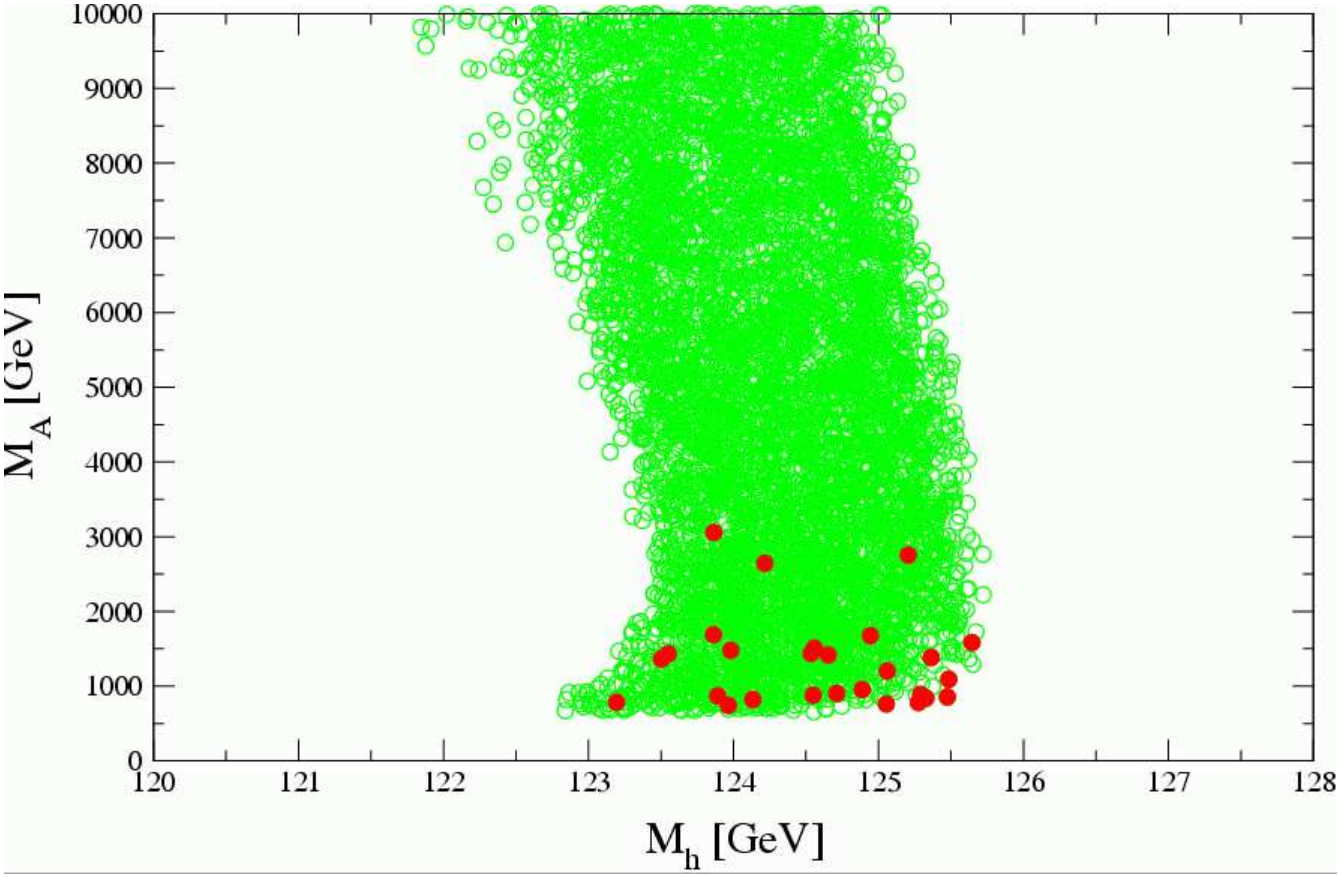
colored: consistent with B physics constraints

black: agreement with (loose) CDM bound

$\Rightarrow$ good chances if CDM is fulfilled

Predictions for heavy Higgs bosons

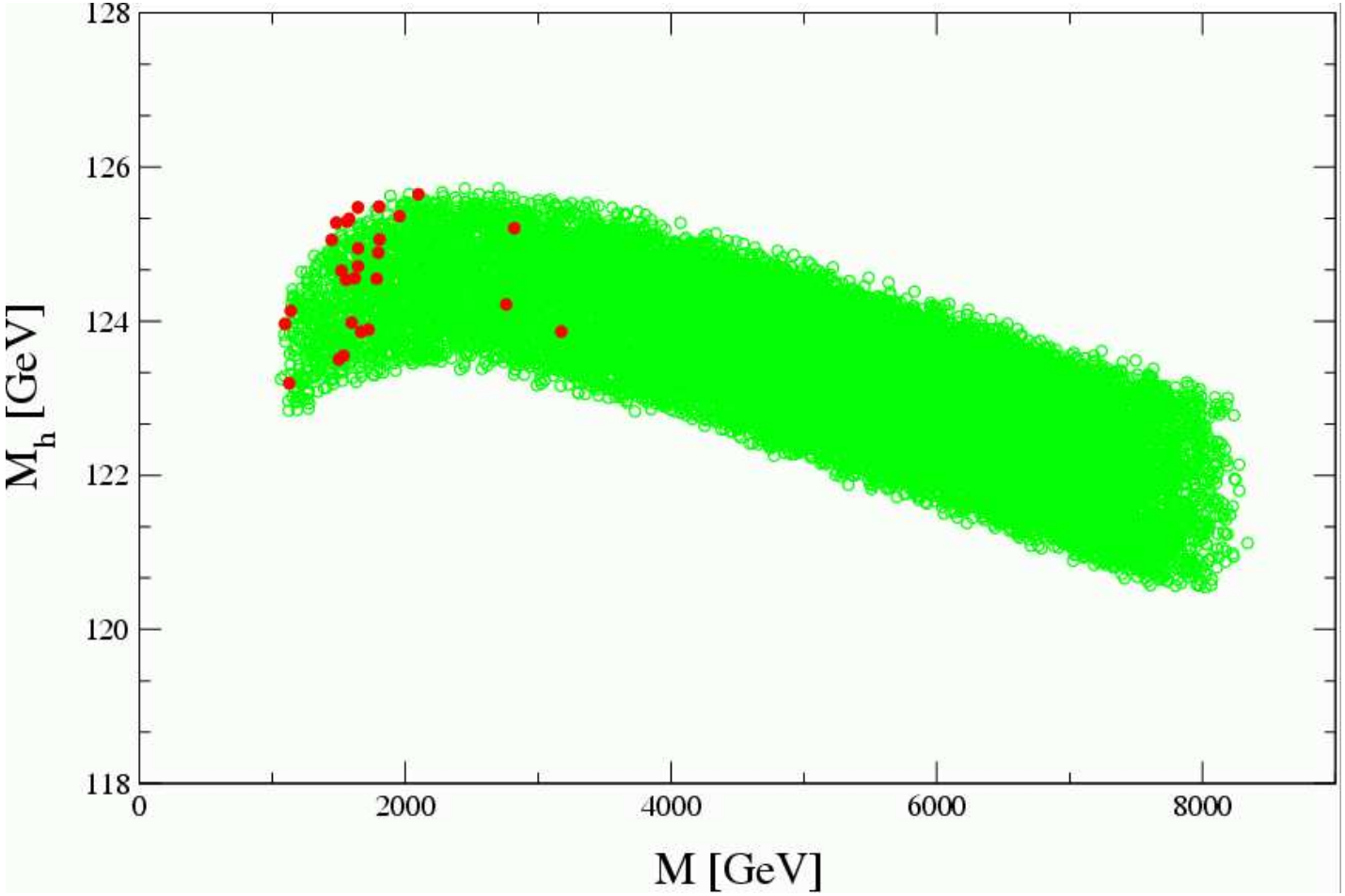
heavy Higgs bosons: mass degenerate



green: consistent with B physics constraints
red: agreement with (loose) CDM bound

$\Rightarrow$ very challenging for LHC
note: $\tan\beta$ large, $\Delta_b < 0 \Rightarrow$ enhanced $Ab\bar{b}$ coupling $\Rightarrow$ should be checked

Predictions for the light Higgs boson

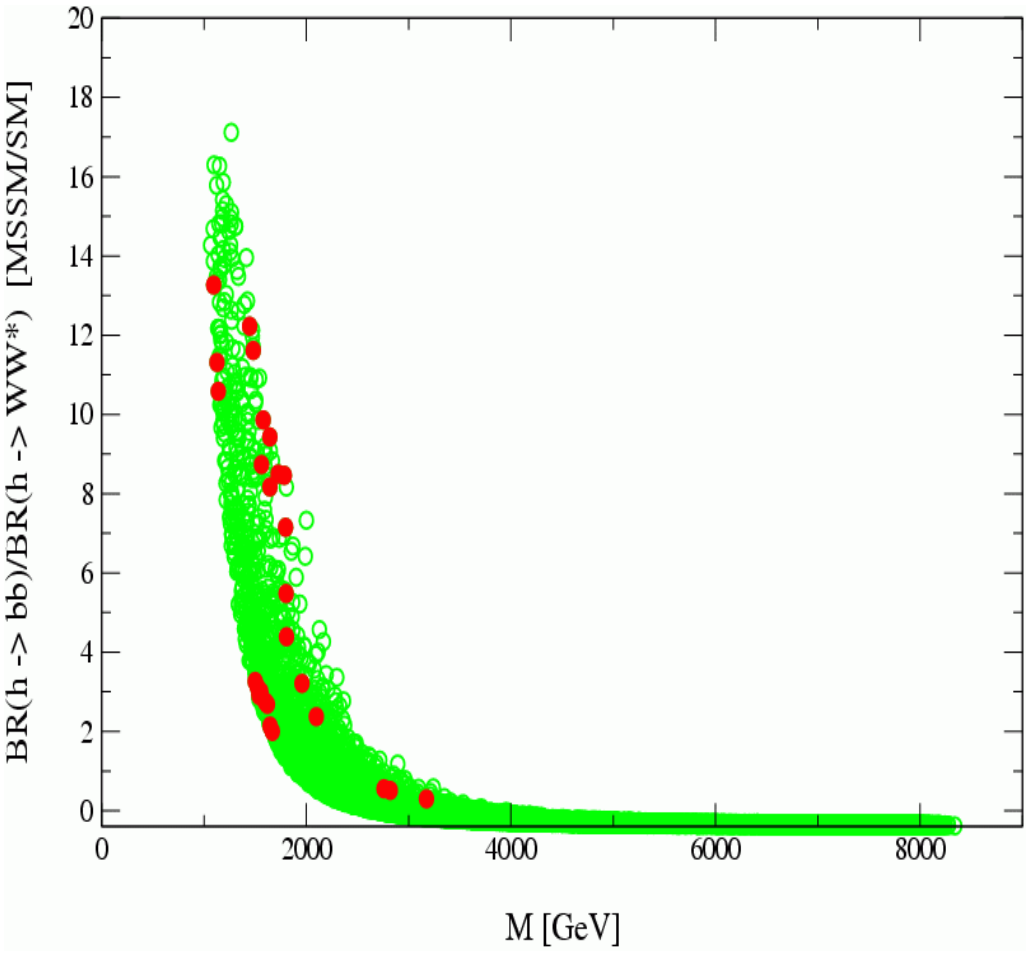


green: consistent with B physics constraints
red: agreement with (loose) CDM bound

$$118 \text{ GeV} \leq M_h \leq 129 \text{ GeV} \quad \text{(incl. theor. unc.)}$$

$\Rightarrow$ "easy" to find for LHC (but "only" SM-like . . .)

Difference to SM via decay modes?



green: consistent with B physics constraints

red: agreement with (loose) CDM bound

Best discriminator:

$$\frac{\mathrm{BR}(h \to b\bar{b})}{\mathrm{BR}(h \to WW^*)}$$

$1\,\sigma = 1.5\%$ resolution (ILC)

LHC resolution?

If CDM is fulfilled:

good prospects for ILC

prospects for LHC?

4. Conclusinos

- Precision observables
  - can give valuable information about the "true" Lagrangian
  - can provide bounds on SUSY parameter space
- Constraining the CMSSM, mGMSB, mAMSB:
  M_W, $\sin^2\theta_{\rm eff}$, $(g-2)_\mu$, M_h, BR$(b \to s\gamma)$, BR$(B_s \to \mu^+\mu^-)$
- 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
- Constraining Finite Unified Theories (FUT)
  Four models analyzed: FUTA$\pm$, FUTB$\pm$
  heavy quark masses, BR$(b \to s\gamma)$, BR$(B_s \to \mu^+\mu^-)$, M_h, CDM
- Heavy quark masses $\Rightarrow$ only FUTB- is a viable model
- Predictions (for the LHC):
  LOSP (stau or 2nd neutralino/1st chargino): very challenging
  Stops, sbottoms, gluinos: good chances if CDM is fulfilled
  Heavy Higgs bosons: very challenging (tbc!)
  Light Higgs: 118 GeV $\leq M_h \leq$ 129 GeV (incl. theor. unc.)
  "easy" for the LHC, but "only" SM-like $\Rightarrow$ BRs at ILC?

Back-up

The observables

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

1.) Theoretical prediction for M_W in terms

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

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

$\Updownarrow$

loop corrections

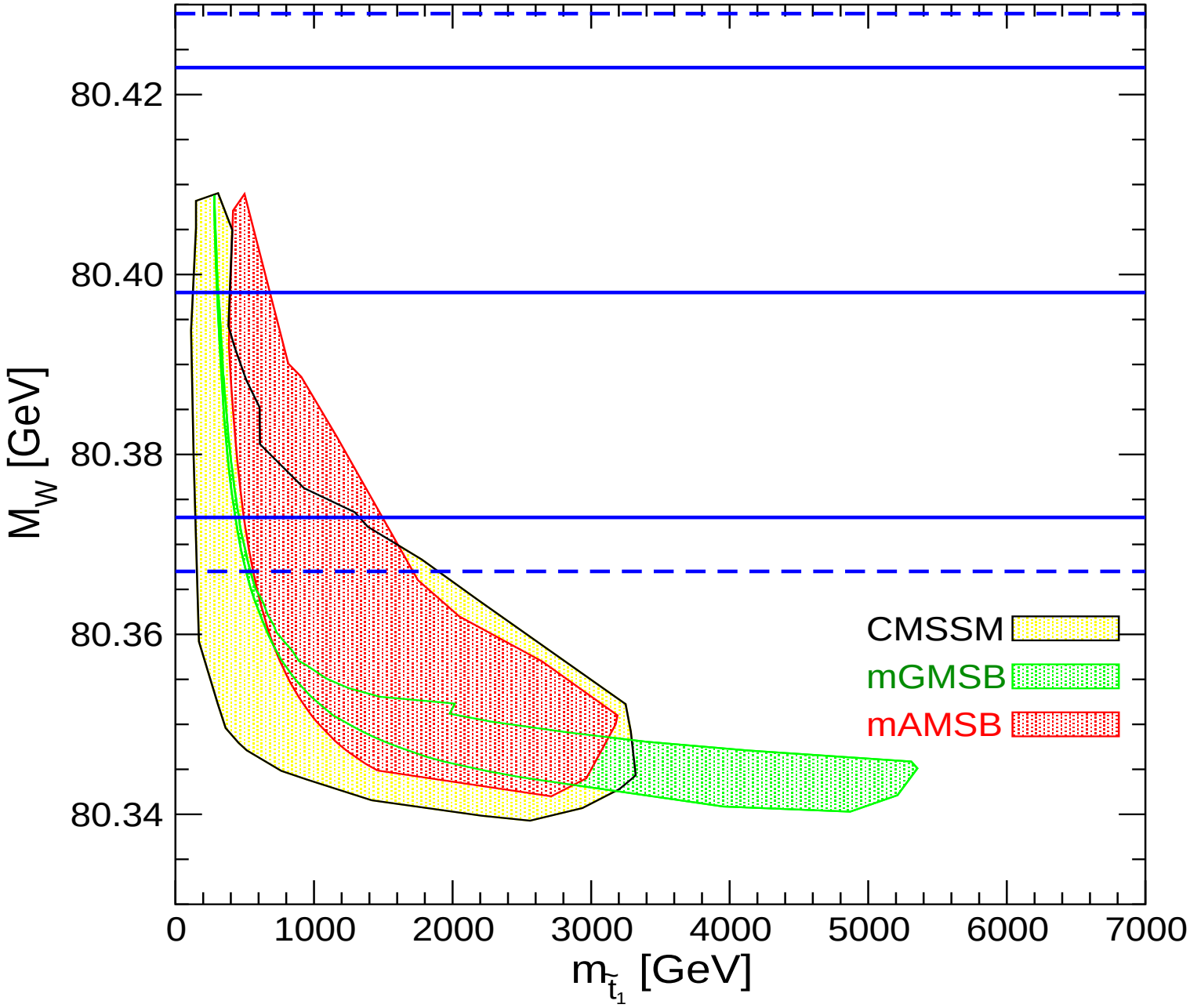
2.) Effective mixing angle:

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

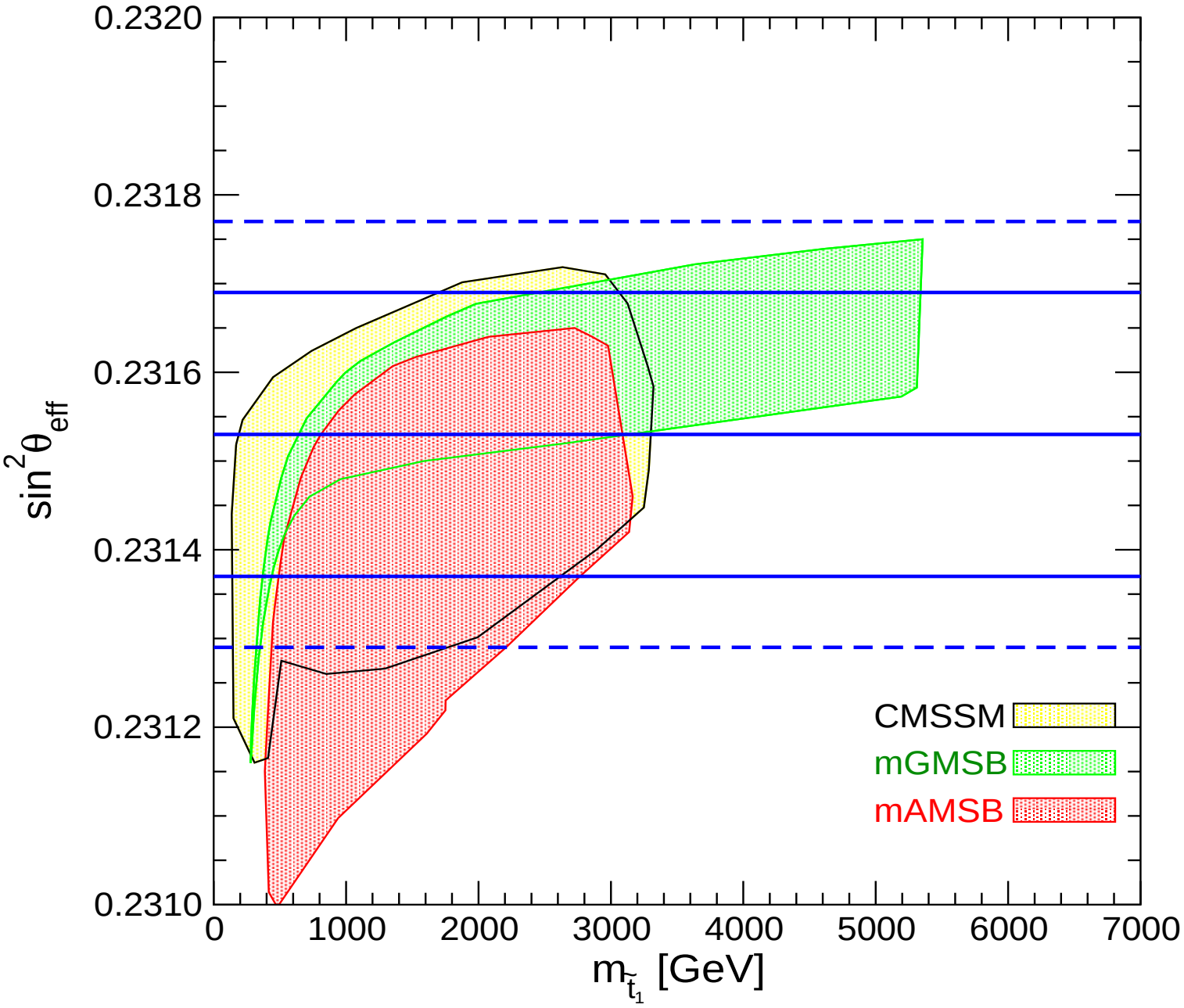
Higher order contributions:

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

M_W: CMSSM vs. mGMSB vs. mAMSB



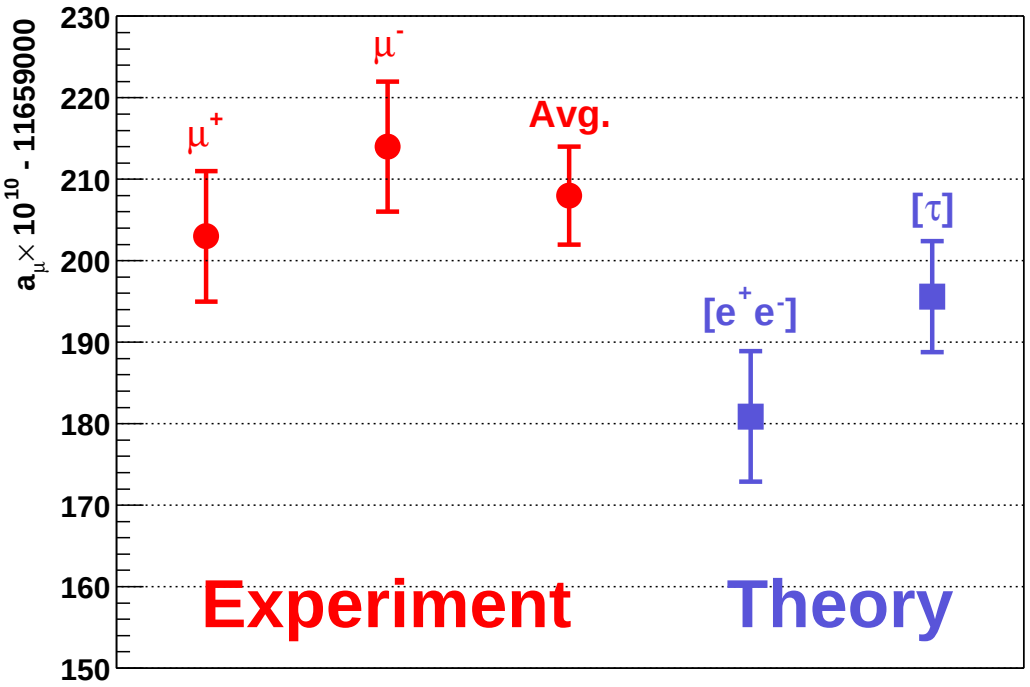
$\sin^2\theta_{\mathrm{eff}}$: CMSSM vs. mGMSB vs. mAMSB



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

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

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:

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

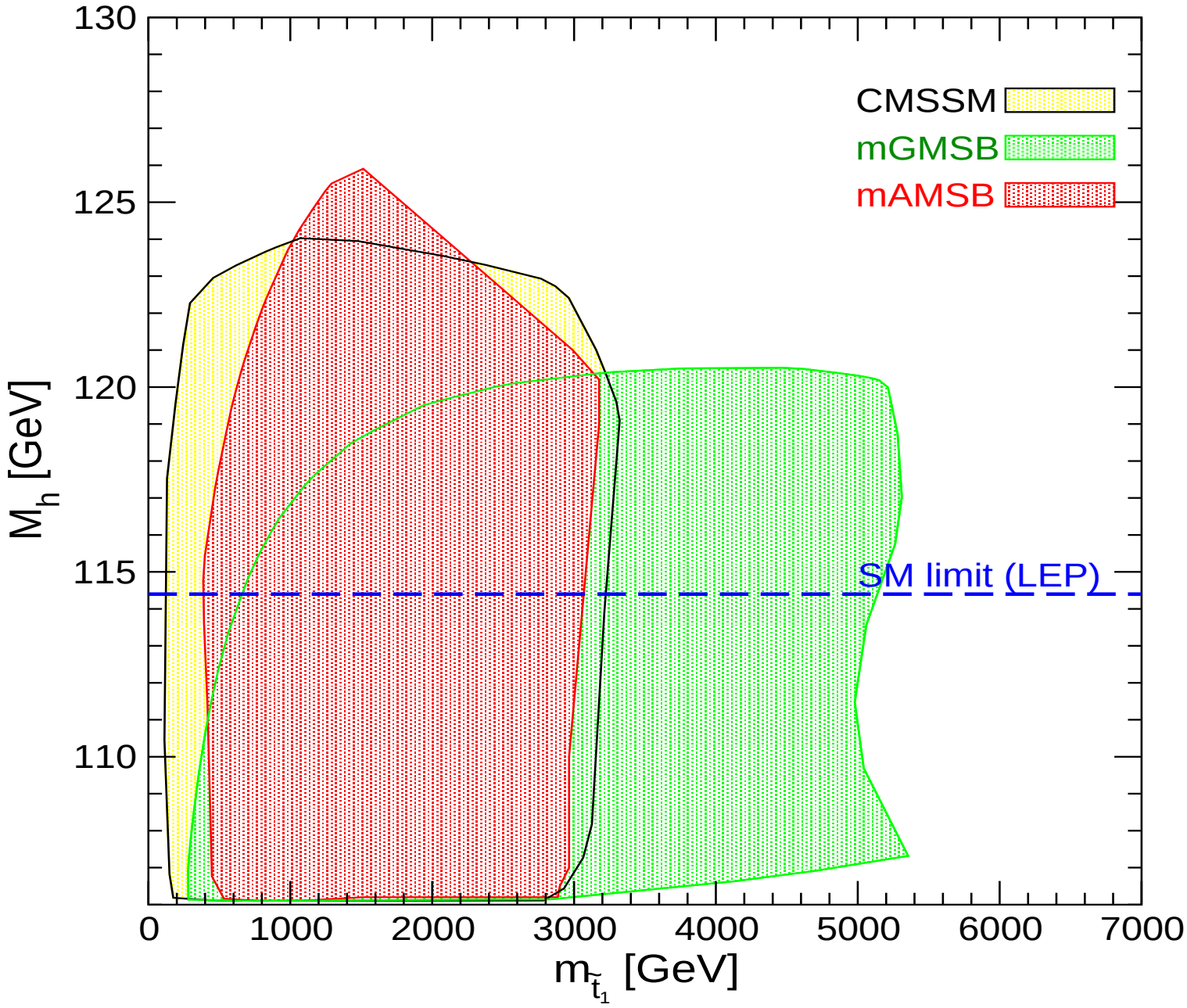
The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

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

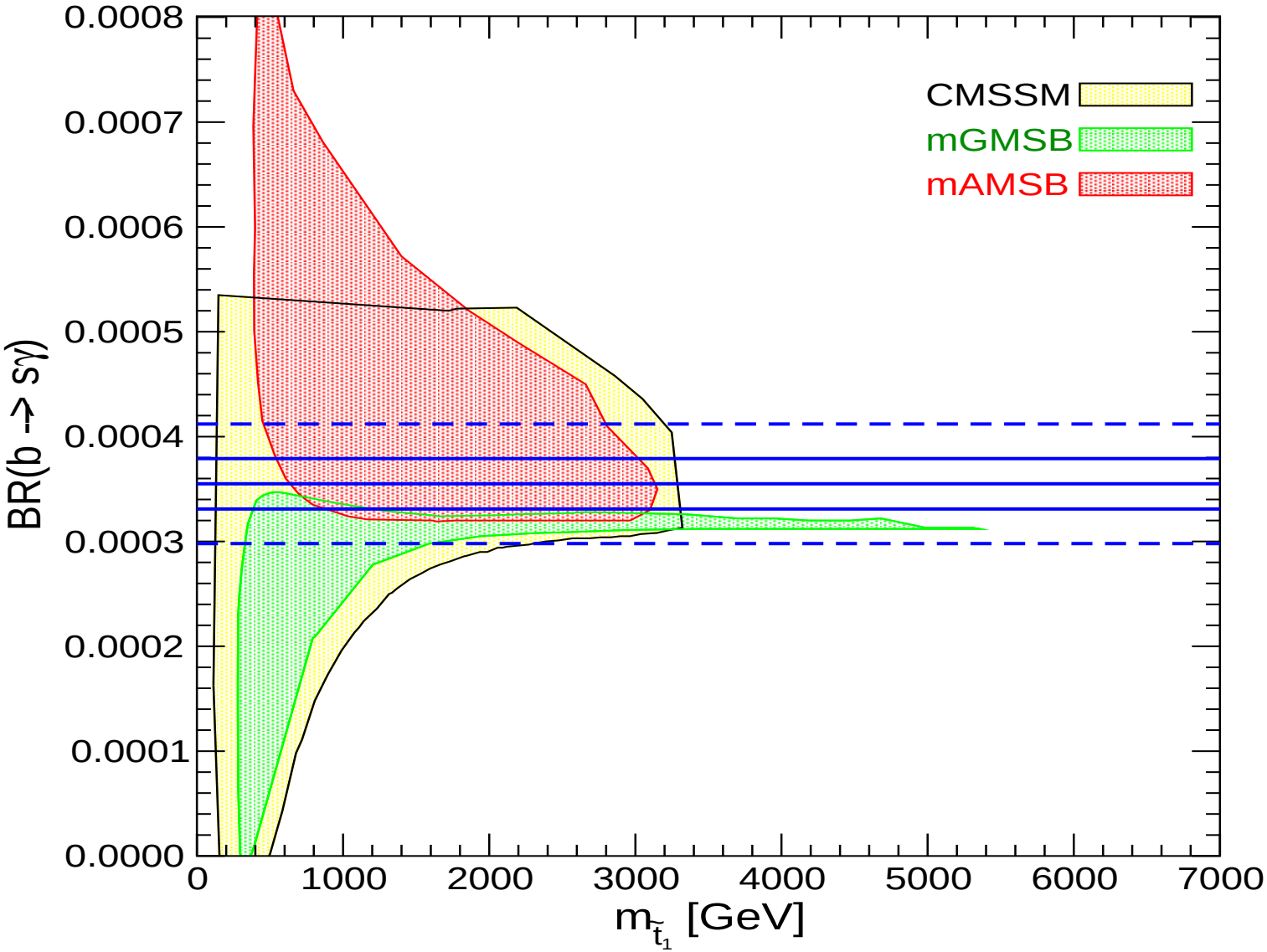
$\Rightarrow M_h$ will be (the best?) electroweak precision observable

M_h: CMSSM vs. mGMSB vs. mAMSB



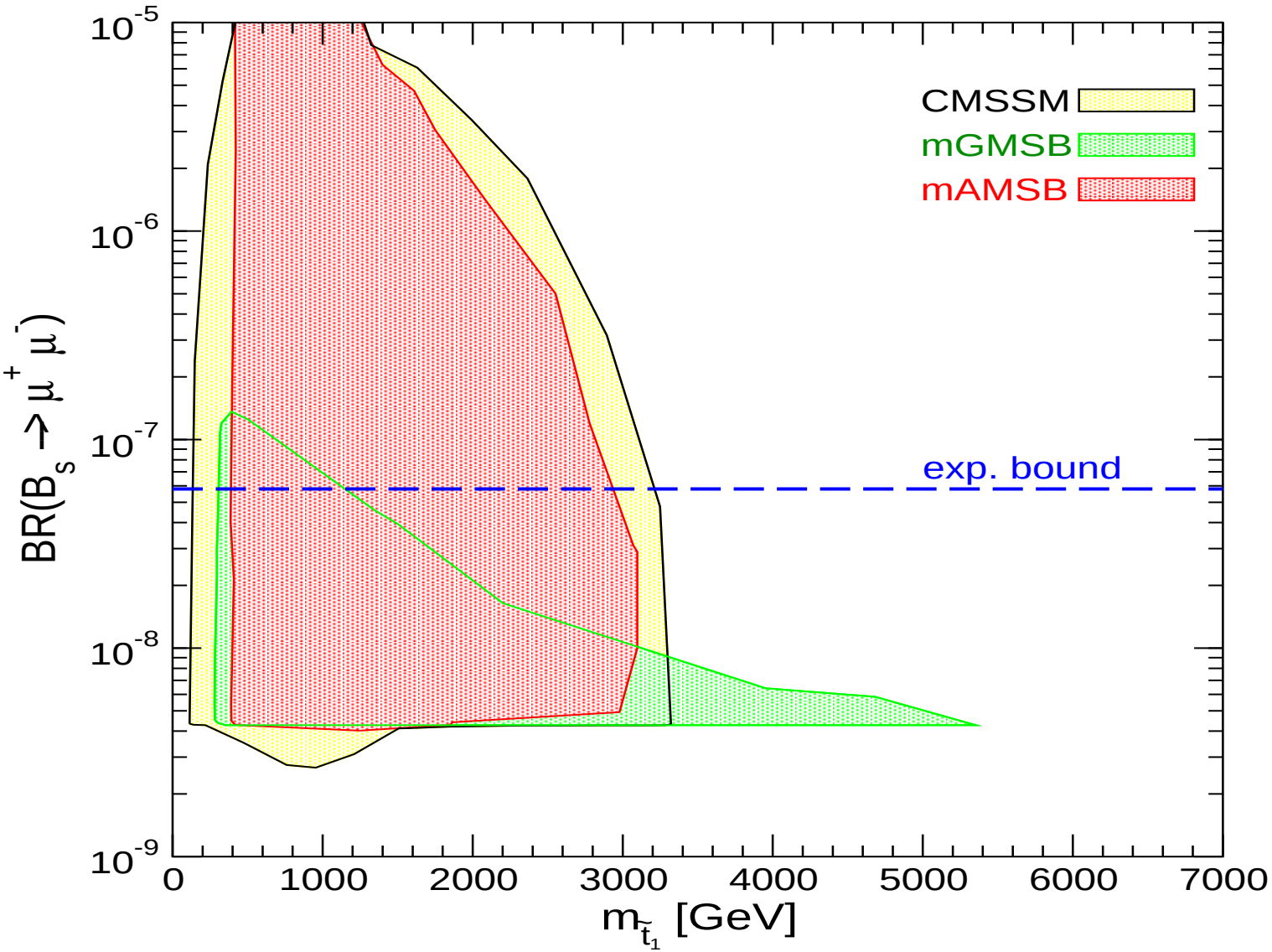
5.) BR($b \to s\gamma$)

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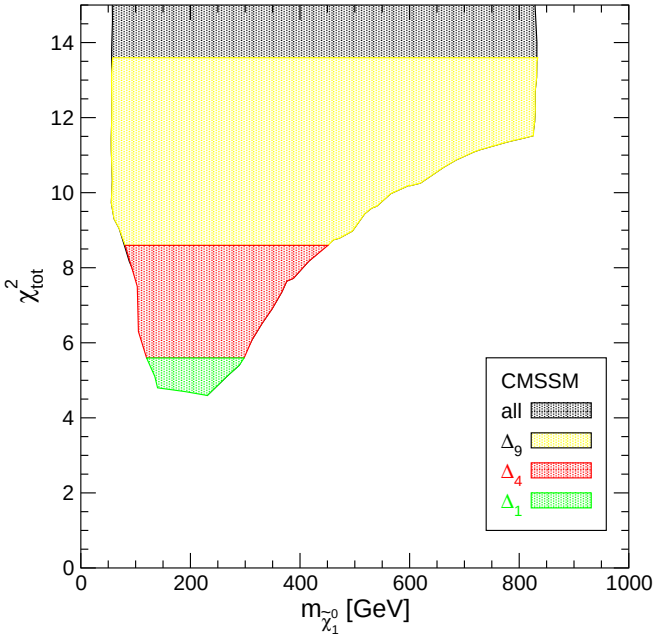
We want to treat CMSSM, mGMSB, mAMSB on equal footing!

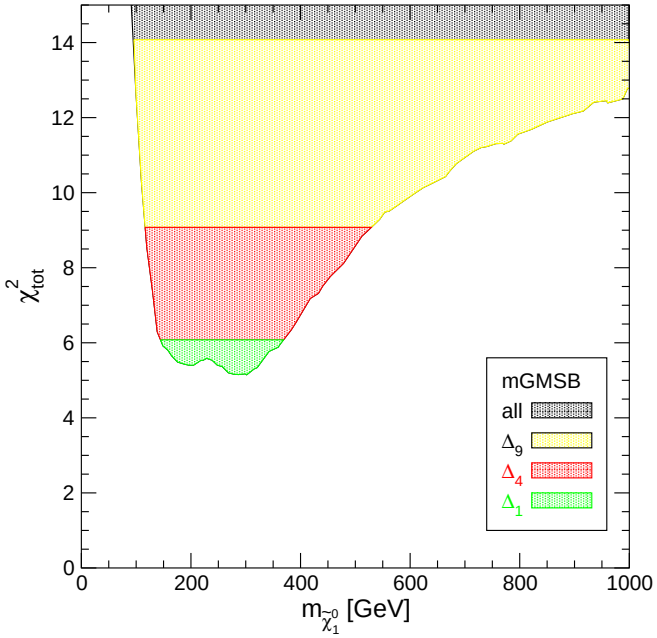
$\Rightarrow$ CDM constraint is left out in our analysis!

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

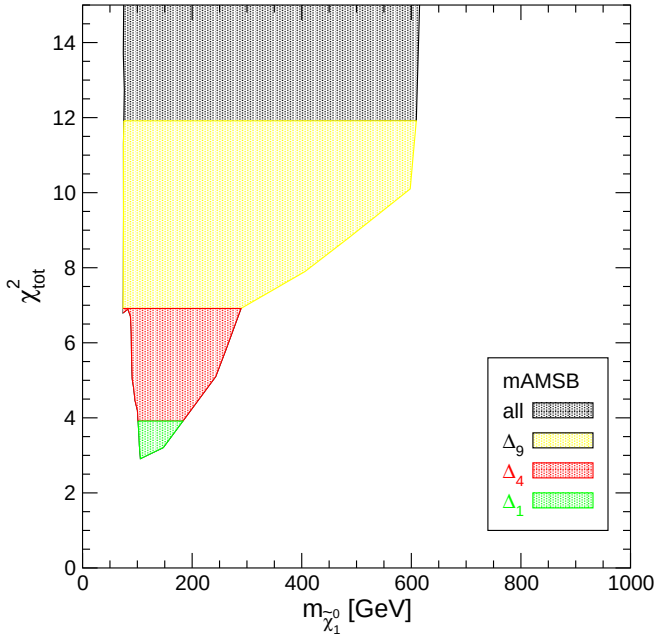
CMSSM



mGMSB



mAMSB



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

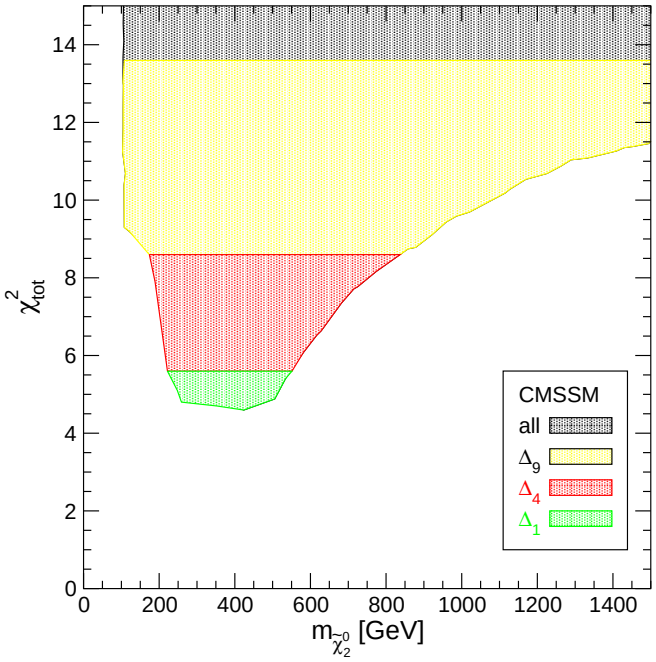
$\Rightarrow$ pair production possible at ILC

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

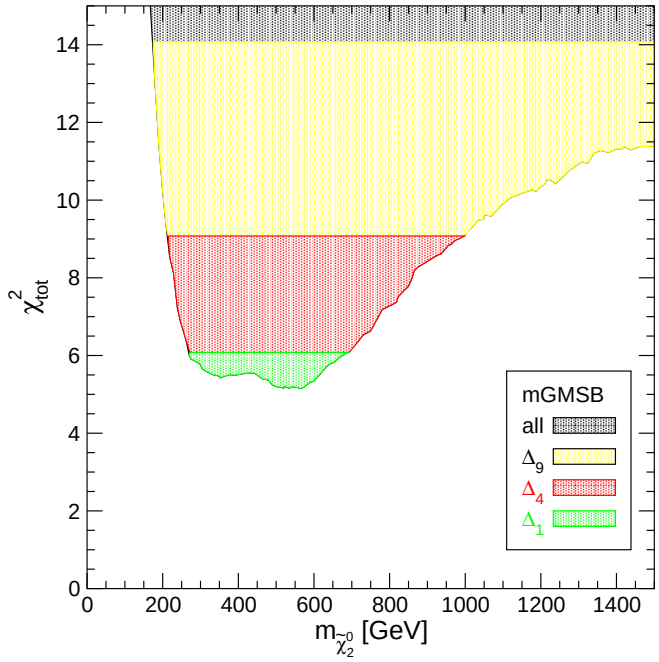
mGMSB: graviton is LSP, detection via $\tilde{\chi}^0_1 \to \tilde{G} + X$?

Results: second lightest neutralino vs. χ^2_{tot}

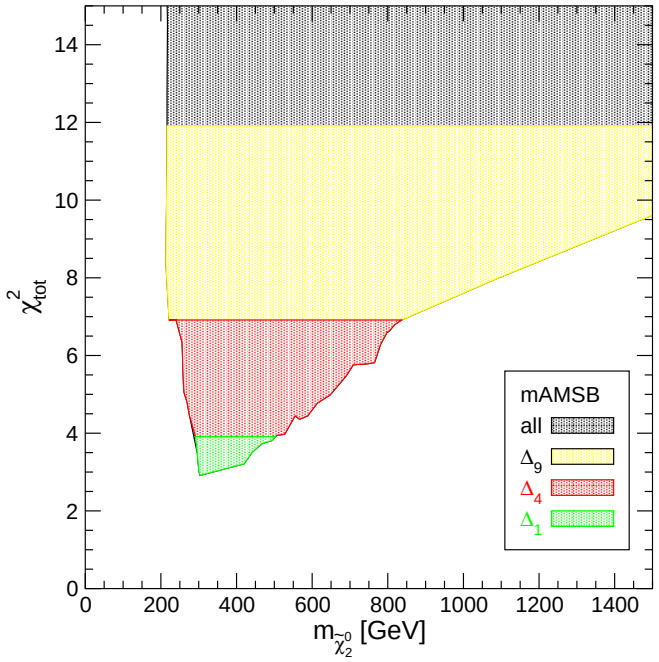
CMSSM



mGMSB



mAMSB



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

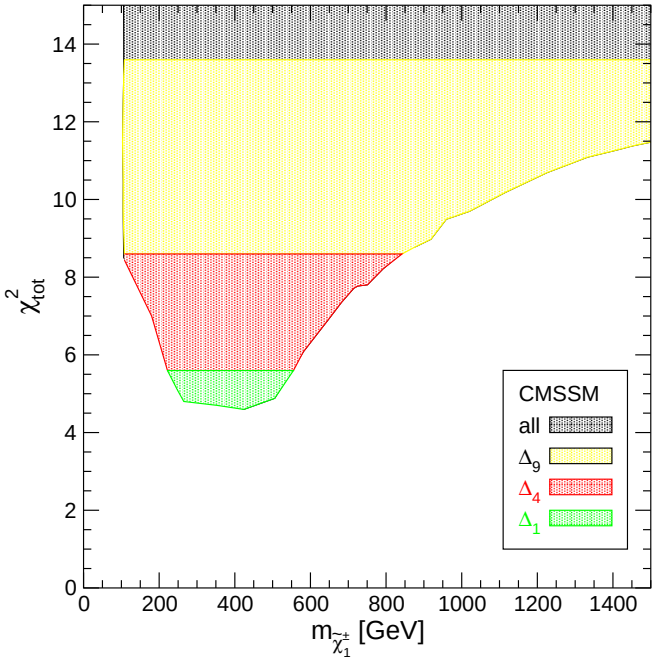
$\Rightarrow$ largely outside direct LHC reach, detection in cascades?

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

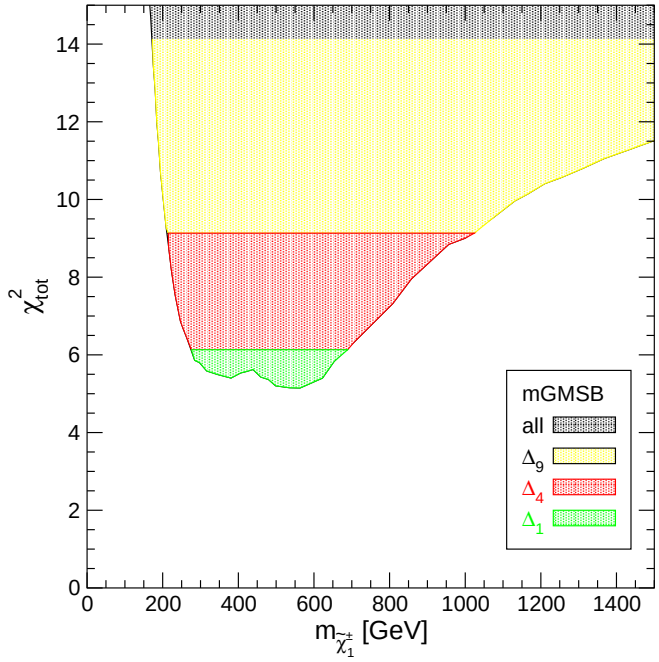
detection via $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 + X$?

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

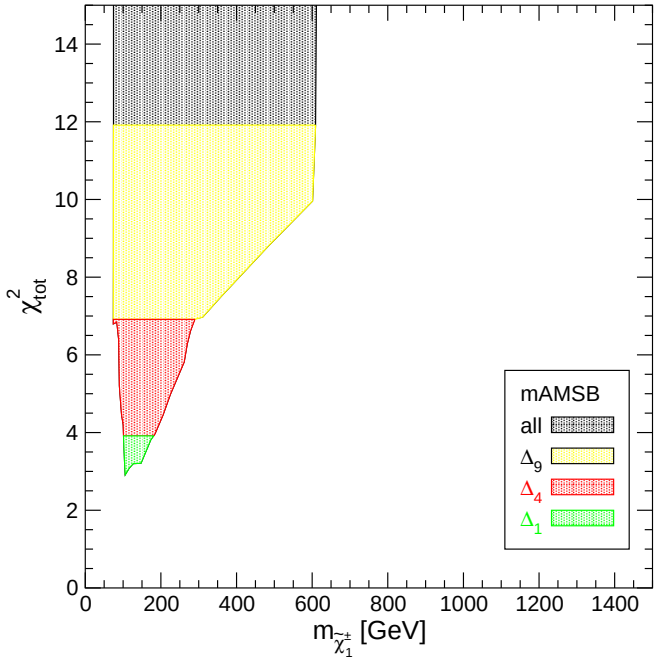
CMSSM



mGMSB



mAMSB



$\Rightarrow m_{\tilde{\chi}_1^\pm} \lesssim 300, 800, 900$ GeV at $\Delta\chi^2 < 4$ for mAMSB, CMSSM, mGMSB

$\Rightarrow$ largely outside direct LHC reach (except mAMSB), cascades?

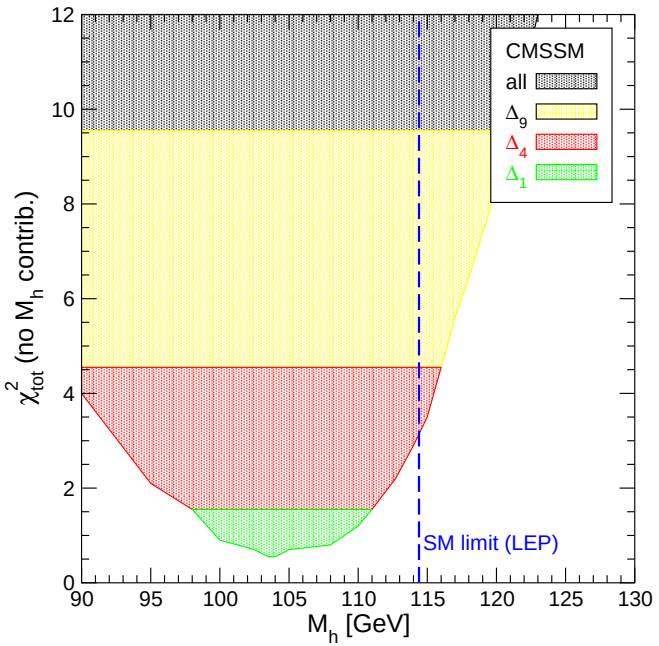
mAMSB: $e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ easy

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

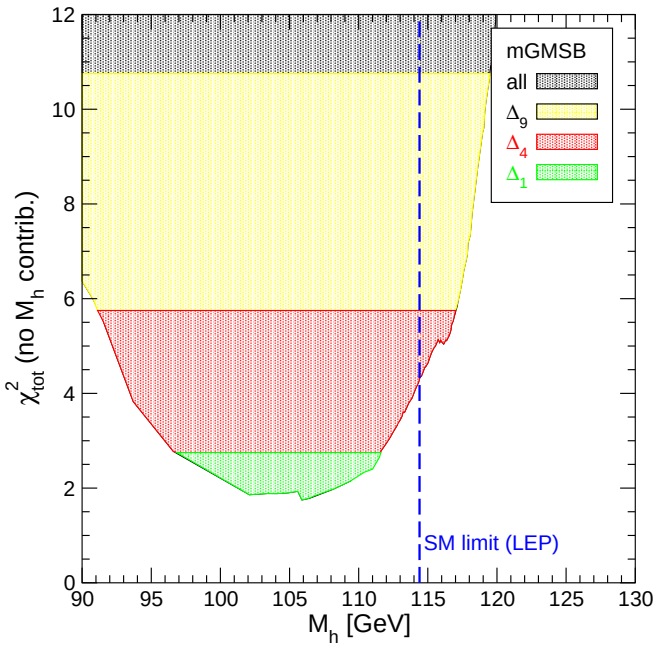
CMSSM, mGMSB: part of parameter space accessible at the ILC

Results: "blue band" for M_h (without LEP results)

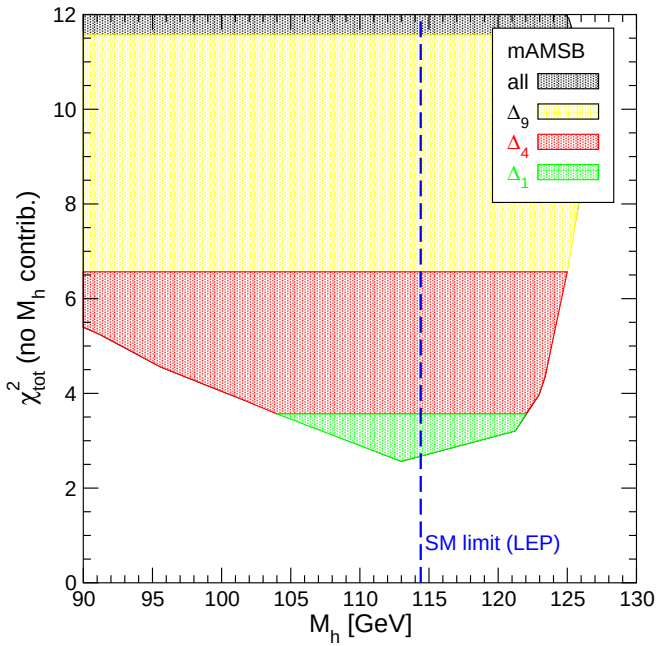
CMSSM



mGMSB



mAMSB



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

Finite Unified Theories:

$\Rightarrow$ one-loop relations between gauge and Yukawa couplings

$\Rightarrow$ sum rule for soft masses at the GUT scale

connection between scalar masses m_i and gaugino mass M

$\Rightarrow$ two-loop finiteness follows automatically

The one-loop relations between gauge (g) and Yukawa couplings (g_i) should be renormalization group invariant

$\Rightarrow$ reduction equations

$$b_g \frac{d\, g_i}{d\, g} = b_i$$

Demand power series solution: (2)

$$g_i = \sum_n \rho_i^{(n+1)} g^{(2n+1)}$$

(1) and (2) guarantee (in the end) finiteness to all orders

Some more specifics on our models

– the fermions: $\overline{\mathbf{5}}_i, \mathbf{10}_i$ $(i = 1, 2, 3)$
no coupling to the adjoint $\mathbf{24}$

– The Higgs fields are in quintets, H_a and $\overline{H}_a$, a $= 1 \ldots 4$

The two MSSM Higgs doublets should be made mostly out of one pair of quintet and anti-quintet that couple to the third generation

$\Rightarrow$ Superpotential:

$$W = \sum_{i=1}^{3} [\ \frac{1}{2} g_i^u\, \mathbf{10}_i \mathbf{10}_i H_i + g_i^d\, \mathbf{10}_i \overline{\mathbf{5}}_i\, \overline{H}_i\ ] + g_{23}^u\, \mathbf{10}_2 \mathbf{10}_3 H_4$$
$$+ g_{23}^d\, \mathbf{10}_2 \overline{\mathbf{5}}_3\, \overline{H}_4 + g_{32}^d\, \mathbf{10}_3 \overline{\mathbf{5}}_2\, \overline{H}_4 + \sum_{a=1}^{4} g_a^f\, H_a\, \mathbf{24}\, \overline{H}_a + \frac{g^\lambda}{3} (\mathbf{24})^3$$

– In the end we restrict here to the 3. generation

A) The heavy quark masses

FUT input: m_τ

FUT output/prediction: m_t, m_b

We use as constraints:

$$m_t^{\text{pole,exp}} = 170.9 \pm 1.8 \text{ GeV}$$

$$m_b(M_Z)^{\text{exp}} = 2.82 \pm 0.07 \text{ GeV}$$

$$\text{note : new value : } \quad m_t^{\text{pole,exp}} = 172.6 \pm 1.4 \text{ GeV}$$

Note:

prediction of $m_b(M_Z)$ involves loop corrections to the relation between mass and Yukawa coupling:

$$y_b \sim \frac{m_b}{1+\Delta_b}$$

with

$$\begin{aligned}\Delta_b &= \frac{2\alpha_s}{3\pi} m_{\tilde{g}}\,\mu\,\tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) \\ &+ \frac{\alpha_t}{4\pi} A_t\,\mu\,\tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, |\mu|)\end{aligned}$$

Checks:

use expansion of denominator as estimate for size of higher-order uncertainties.

Compare:

$$\frac{1}{1+\Delta_b}, \quad 1-\Delta_b+\Delta_b^2, \quad 1-\Delta_b$$

B) The decay BR($b \to s\gamma$)

Experimental result:

[*HFAG '07*]

$$\mathrm{BR}(b \to s\gamma)^{\mathrm{exp}} = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$$

Latest SM prediction:

[*M. Misiak et al. '07*]

$$\mathrm{BR}(b \to s\gamma)^{\mathrm{theo,SM}} = (3.15 \pm 0.23) \times 10^{-4}$$

SUSY corrections by code from [*G. Hiller et al.*] ,
crosschecked with code from [*Micromegas '07*]

Additional error from unknown SUSY corrections: $\pm 0.15 \times 10^{-4}$

Conservative approach: add theoretical and experimental error linearly

C) The decay BR($B_s \to \mu^+\mu^-$)

Experimental result:

[*CDF '07, D0 '07*]

$$\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{exp}} < 5.8 \times 10^{-8} \quad \text{at 95\% C.L.}$$

SM result:

[*Buchalla, Buras, Misiak, Urban '93-'03*]

$$\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{theo,SM}} = (3.4 \pm 0.5) \times 10^{-9}$$

$\to$ so far negligible

SUSY contributions taken from [*Micromegas '07*] ,
checked with [*Dedes, Dreiner, Nierste '01*]

Error estimate: not available
("error is small, even in SUSY")

D) The lightest Higgs boson mass M_h

MSSM predicts upper bound on M_h:

tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches!

Large radiative corrections:

Yukawa couplings: $\frac{e\, m_t}{2 M_W s_W}$, $\frac{e\, m_t^2}{M_W s_W}$, ...

$\Rightarrow$ Dominant one-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

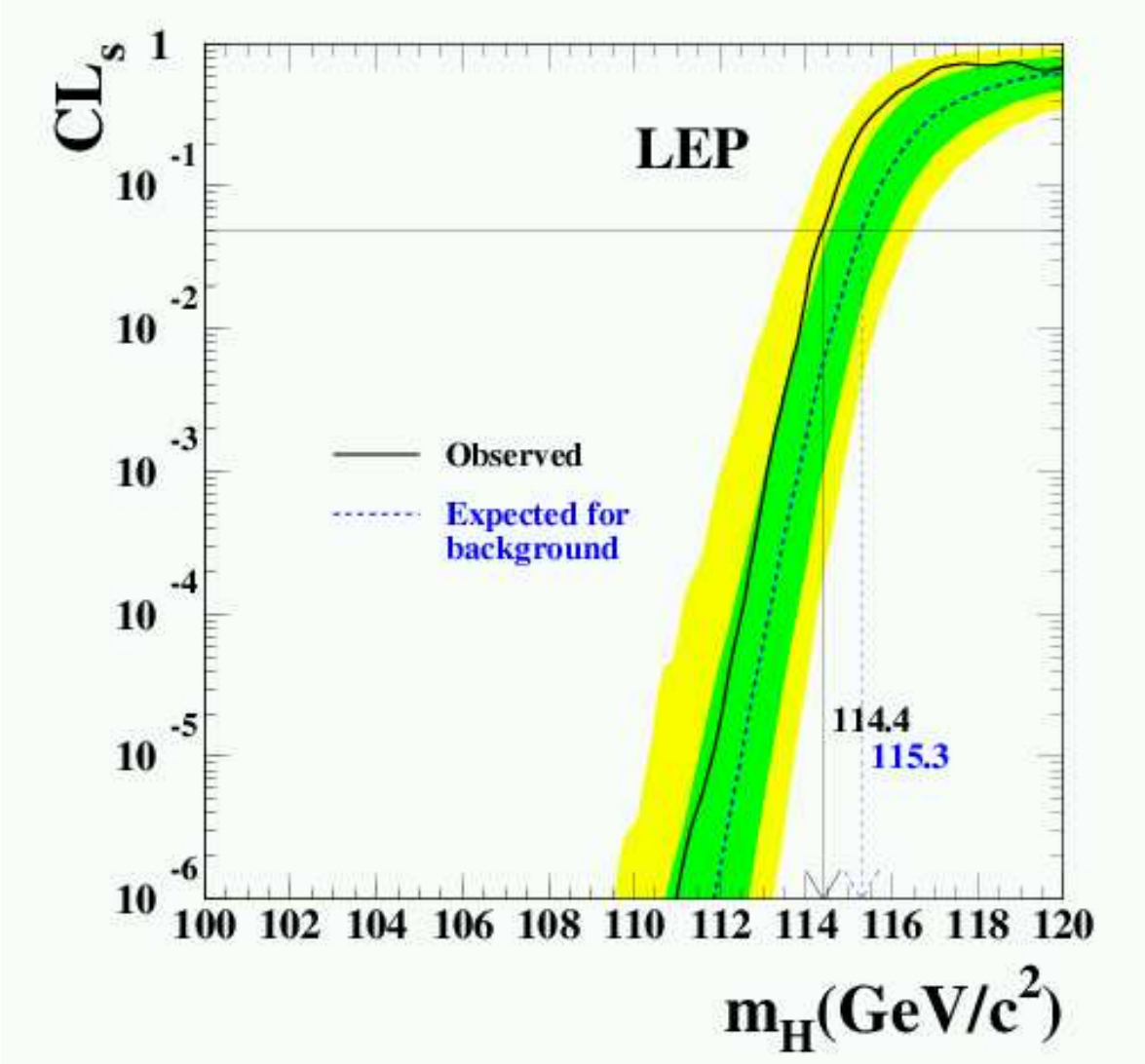
> The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Present status of M_h prediction in the MSSM:

Complete one-loop and 'almost complete' two-loop result available

In FUT:

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



$M_h > 114.4$ GeV

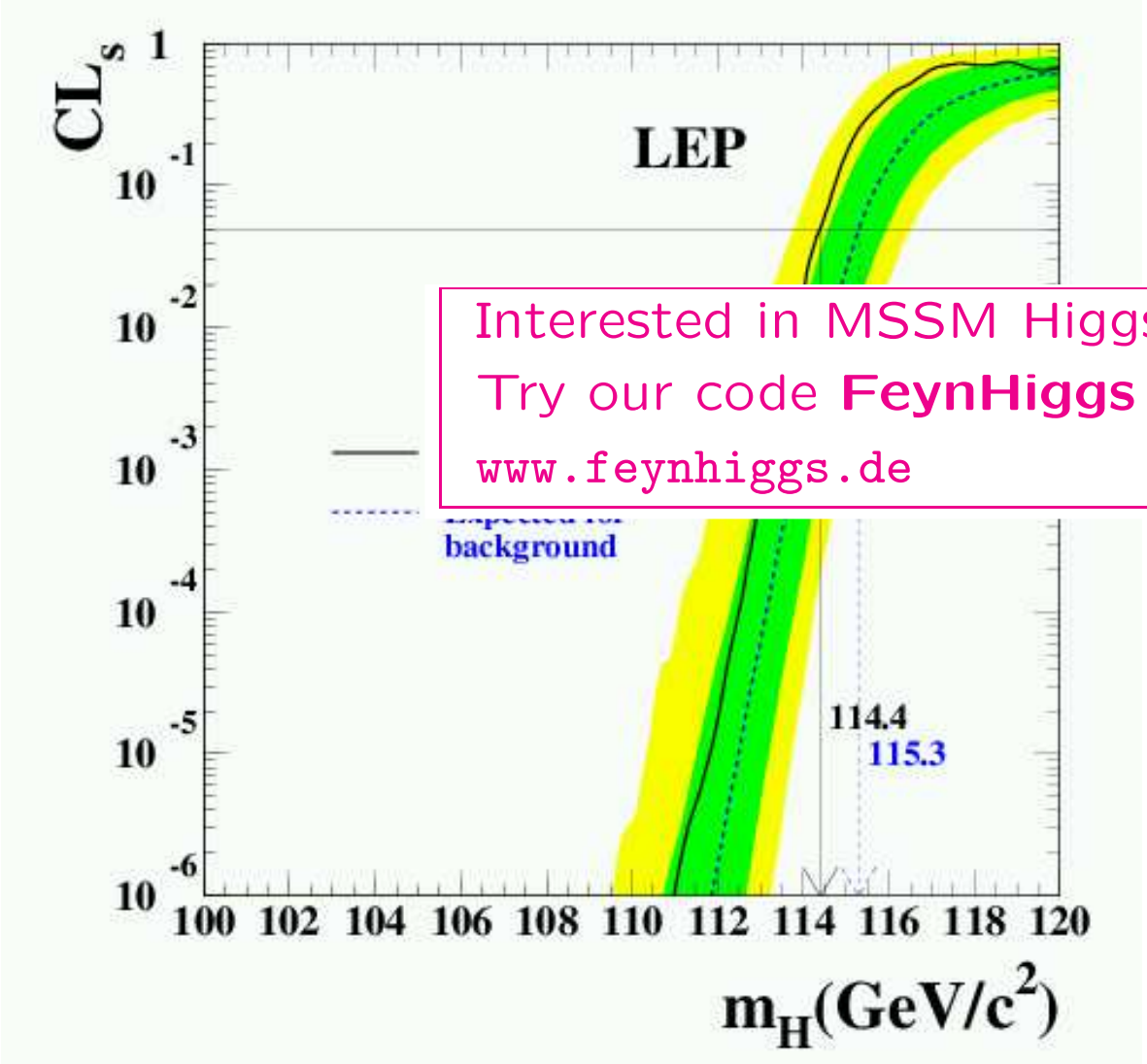
at 95% C.L.

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

We use *FeynHiggs*

In FUT:

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



$M_h > 114.4$ GeV

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

..

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

We use *FeynHiggs*

E) Cold Dark Matter

Cold Dark Matter exists:

$\Rightarrow$ It all fits together

$$\Omega_{\text{tot}} \approx 1$$

$$\Omega_M h^2 = 0.135^{+0.008}_{-0.009}$$

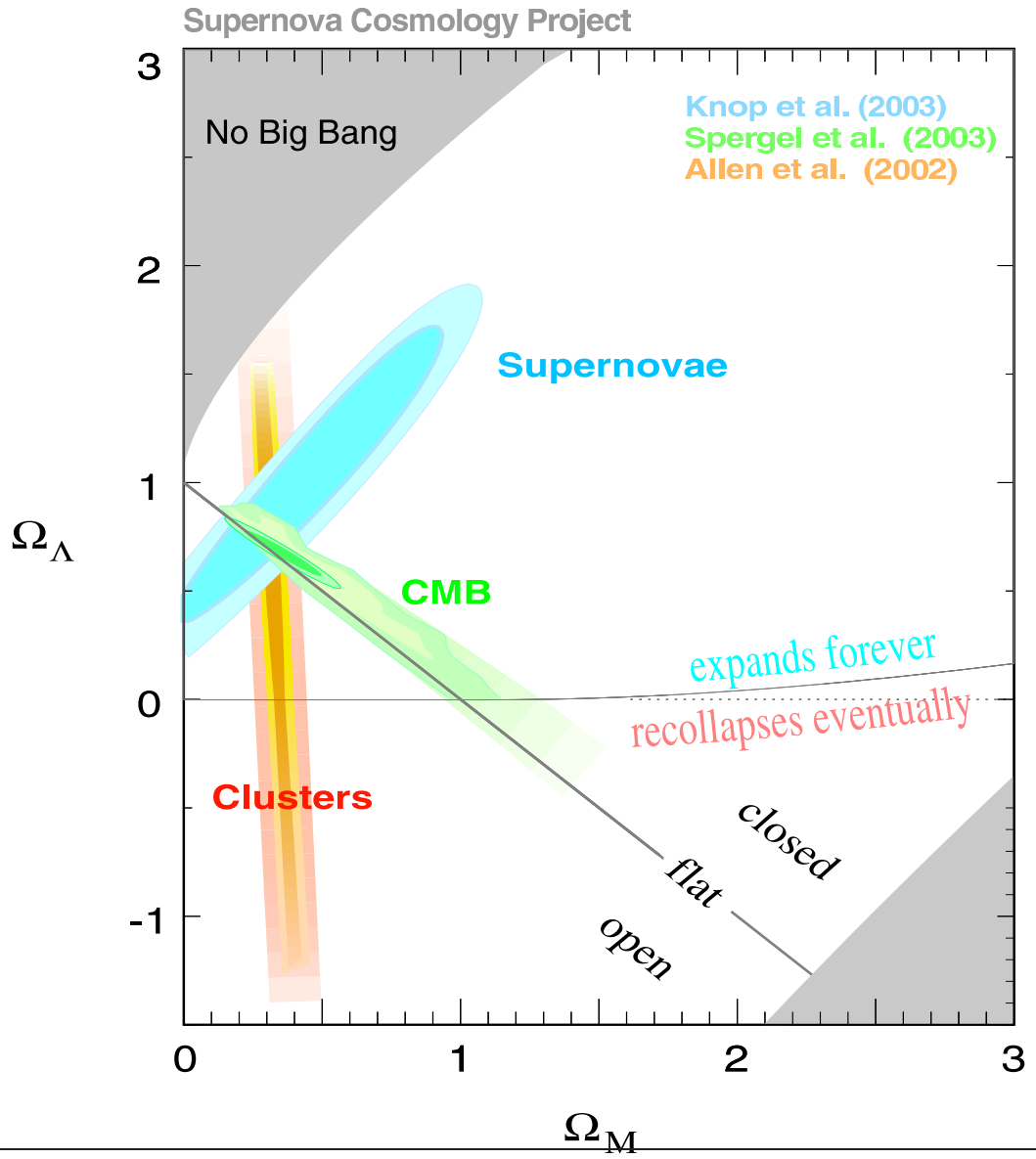
$$\Omega_B h^2 = 0.0224 \pm 0.0009$$

$$\Omega_\chi h^2 = 0.112 \pm 0.018$$

$$\Omega_\Lambda \approx 0.73$$

$\Omega_\chi \Rightarrow$ dark matter

$\Omega_\Lambda \Rightarrow$ dark energy ...



Experimental result ($2\,\sigma$ range):

[*WMAP et al.*]

$$0.094 \;<\; \Omega_{\rm CDM} h^2 \;<\; 0.129$$

We apply a more loose bound:

$$\Omega_{\rm CDM} h^2 \;<\; 0.3$$

$\rightarrow$ takes into account (larger) uncertainties in RGE running, possibly other CDM candidate

Keep in mind:

FUT has a "natural extension" with bi-linear R-parity violation

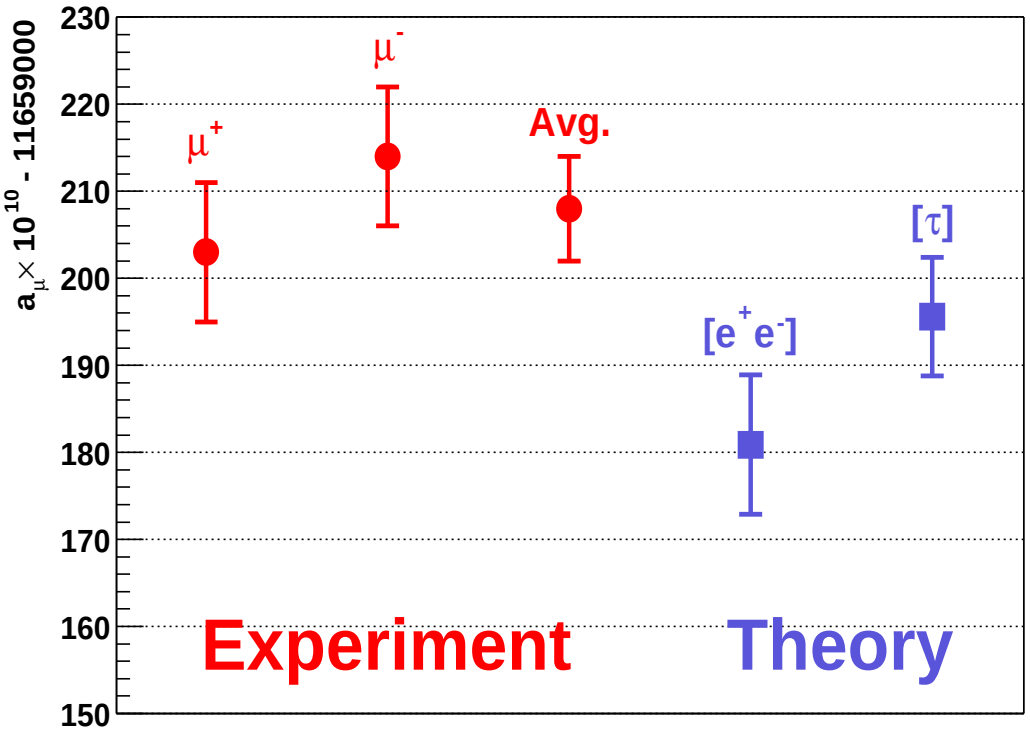
$\Rightarrow$ CDM would be no constraint at all anymore

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*]



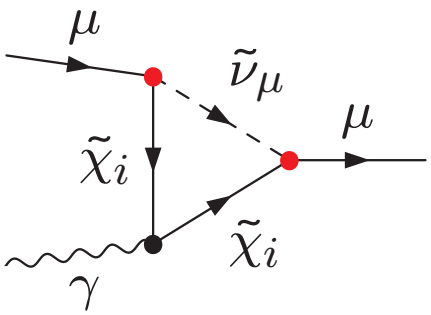
Possible deviation from the SM:

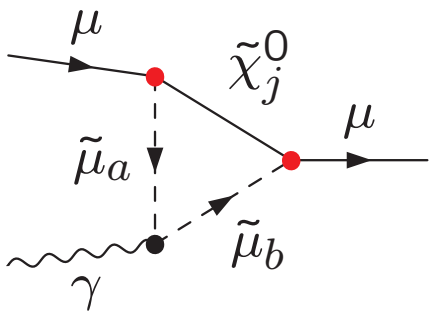
e^+e^- data : $a_\mu^{\rm exp} - a_\mu^{\rm theo,SM} \approx (28 \pm 8) \times 10^{-10}$

τ data : agreement with SM

currently: e^+e^- data favored

Feynman diagrams for MSSM 1L corrections:





– Diagrams with chargino/sneutrino exchange

– Diagrams with neutralino/smuon exchange

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

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

$\Rightarrow$ SUSY could easily explain the "discrepancy" for $\mu > 0$

$\Rightarrow$ SUSY gives no contribution for heavy sleptons/gauginos
then SUSY is "as good" as the SM
possibly other sources needed to reconcile $(g-2)_\mu$

$\Rightarrow$ same holds for M_W, ...

Typical mass spectrum for FUTB- :

m_t	172	$\overline{m_b}(M_Z)$	2.7
$\tan\beta =$	46	α_s	0.116
$m_{\tilde{\chi}_1^0}$	796	$m_{\tilde{\tau}_2}$	1268
$m_{\tilde{\chi}_2^0}$	1462	$m_{\tilde{\nu}_3}$	1575
$m_{\tilde{\chi}_3^0}$	2048	μ	-2046
$m_{\tilde{\chi}_4^0}$	2052	B	4722
$m_{\tilde{\chi}_1^\pm}$	1462	M_A	870
$m_{\tilde{\chi}_2^\pm}$	2052	$M_{H^\pm}$	875
$m_{\tilde{t}_1}$	2478	M_H	869
$m_{\tilde{t}_2}$	2804	M_h	124
$m_{\tilde{b}_1}$	2513	M_1	796
$m_{\tilde{b}_2}$	2783	M_2	1467
$m_{\tilde{\tau}_1}$	798	M_3	3655