New SUSY predictions for the ILC

Sven Heinemeyer, IFCA (Santander)

DESY, 06/2007

based on collaborations with
J. Ellis, K. Olive, A.M. Weber and *G. Weiglein*

1. Motivation and models
2. The observables
3. Implications for the ILC
4. Conclusions

1. Motivation and models

What do we know about the SUSY mass scale?

1. Coupling constant unification $\Rightarrow M_{\text{SUSY}} \approx 1$ TeV

2. LSP should be cold dark matter $\Rightarrow M_{\text{SUSY}} \lesssim 1$ TeV

3. Indirect hints from existing data?
   - Focus on CMSSM, NUHM, ...

     small number of free parameters
   - hard constraint: LSP gives right amount of cold dark matter

     CMSSM: only thin strips allowed in the $m_{1/2}$–m_0 plane

     NUHM: M_A–$\tan\beta$ planes possible
   - Use existing data of M_W, $\sin^2\theta_{\text{eff}}$, $\text{BR}(b \to s\gamma)$, $(g-2)_\mu$, M_h

     $\Rightarrow \chi^2$ fit with these observables

     $\Rightarrow$ best fit values for masses, couplings, ...

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     new observables: Γ_Z, BR($B_s \to \mu^+\mu^-$), BR($B_u \to \tau\nu_\tau$), ΔM_{B_s}

     $\Rightarrow \chi^2$ fit with all of these observables

     $\Rightarrow$ best fit values for masses, couplings, ...

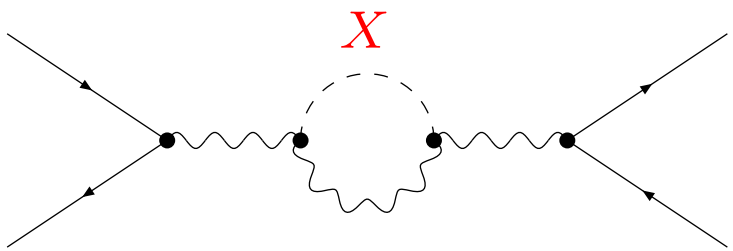
Precision Observables (POs):

Comparison of electro-weak precision observables with theory:

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

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections



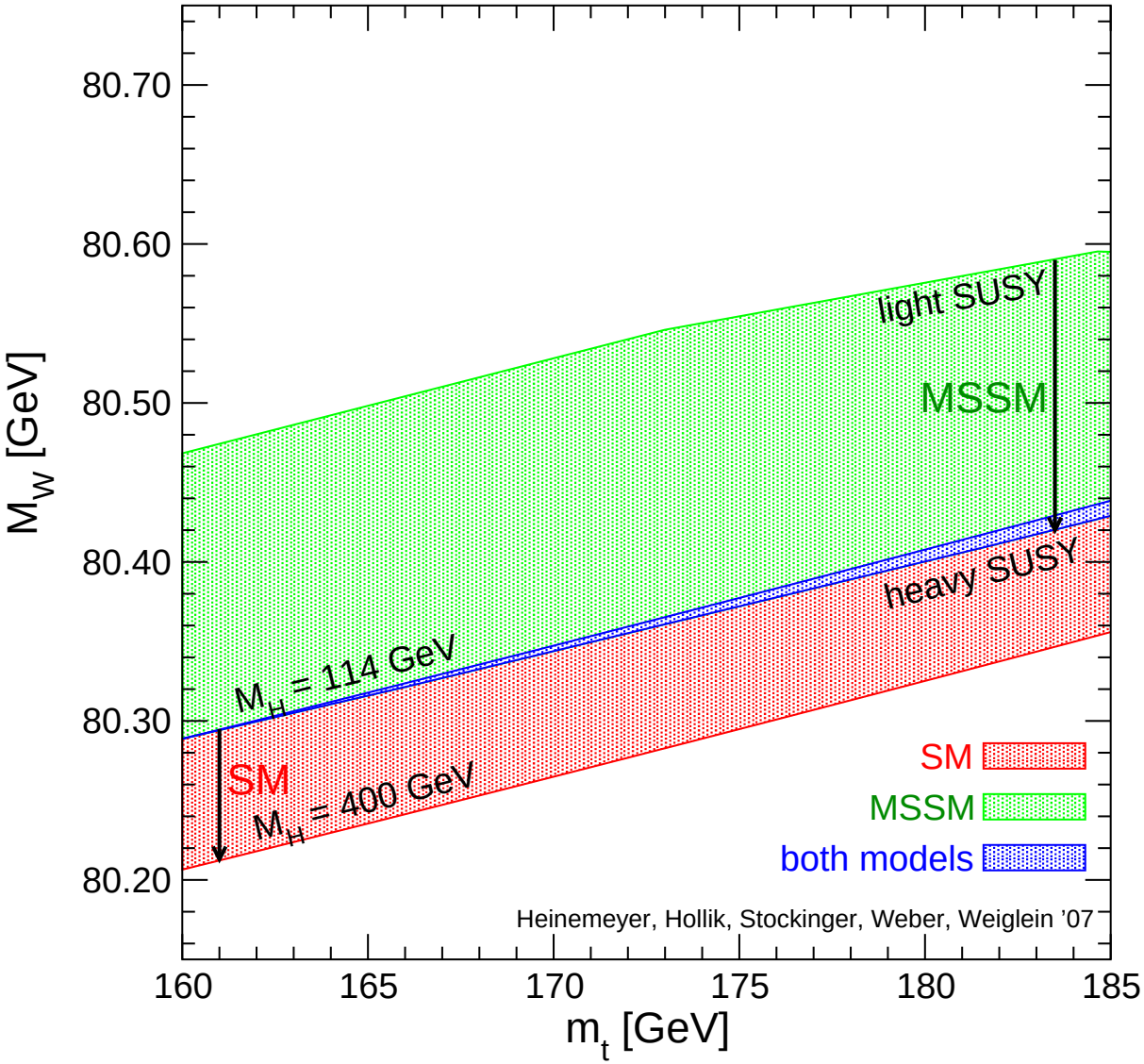
$\Downarrow$

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*]



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scan over

SUSY masses

overlap:

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SM band:

variation of M_H^{SM}

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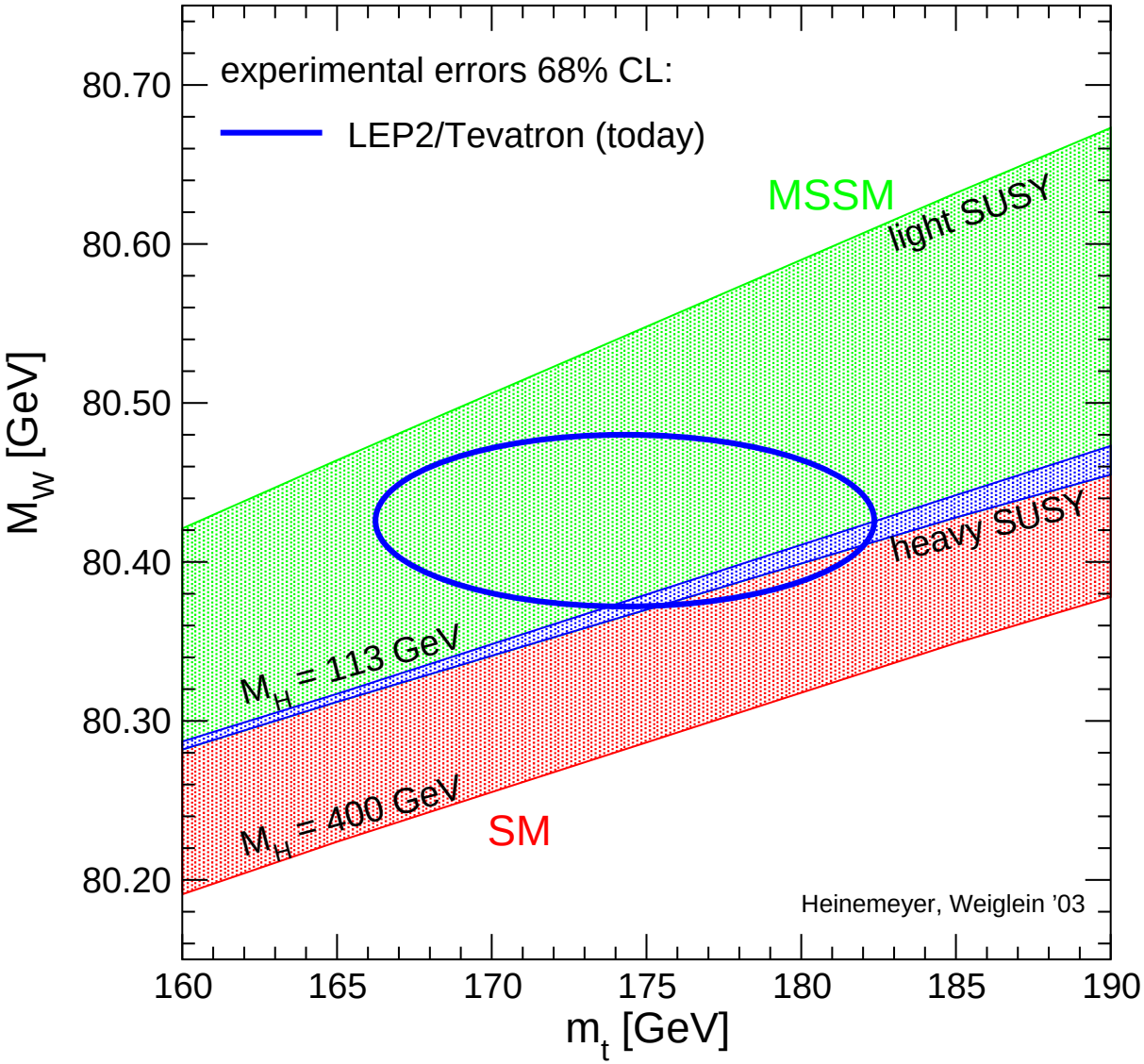

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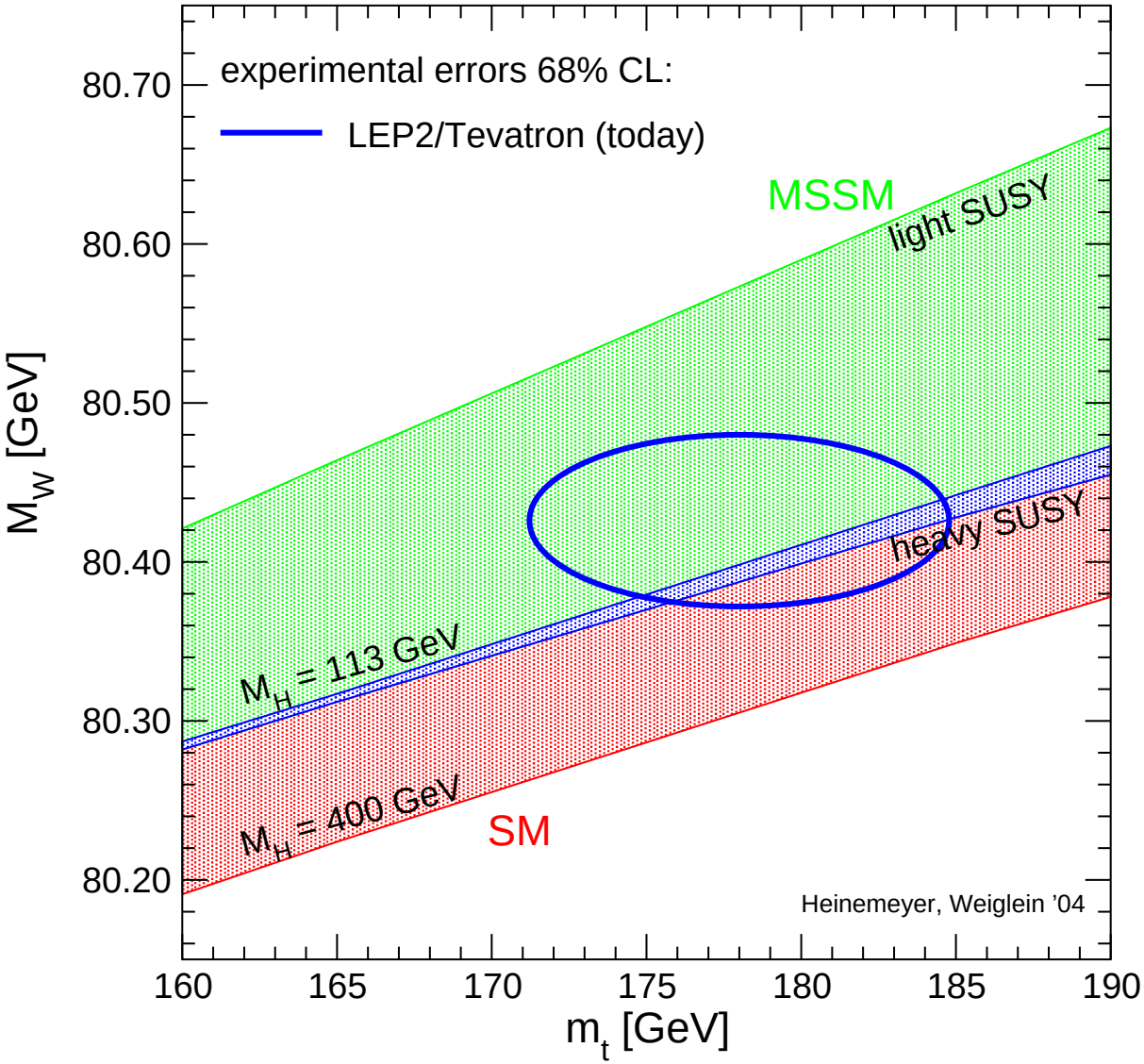

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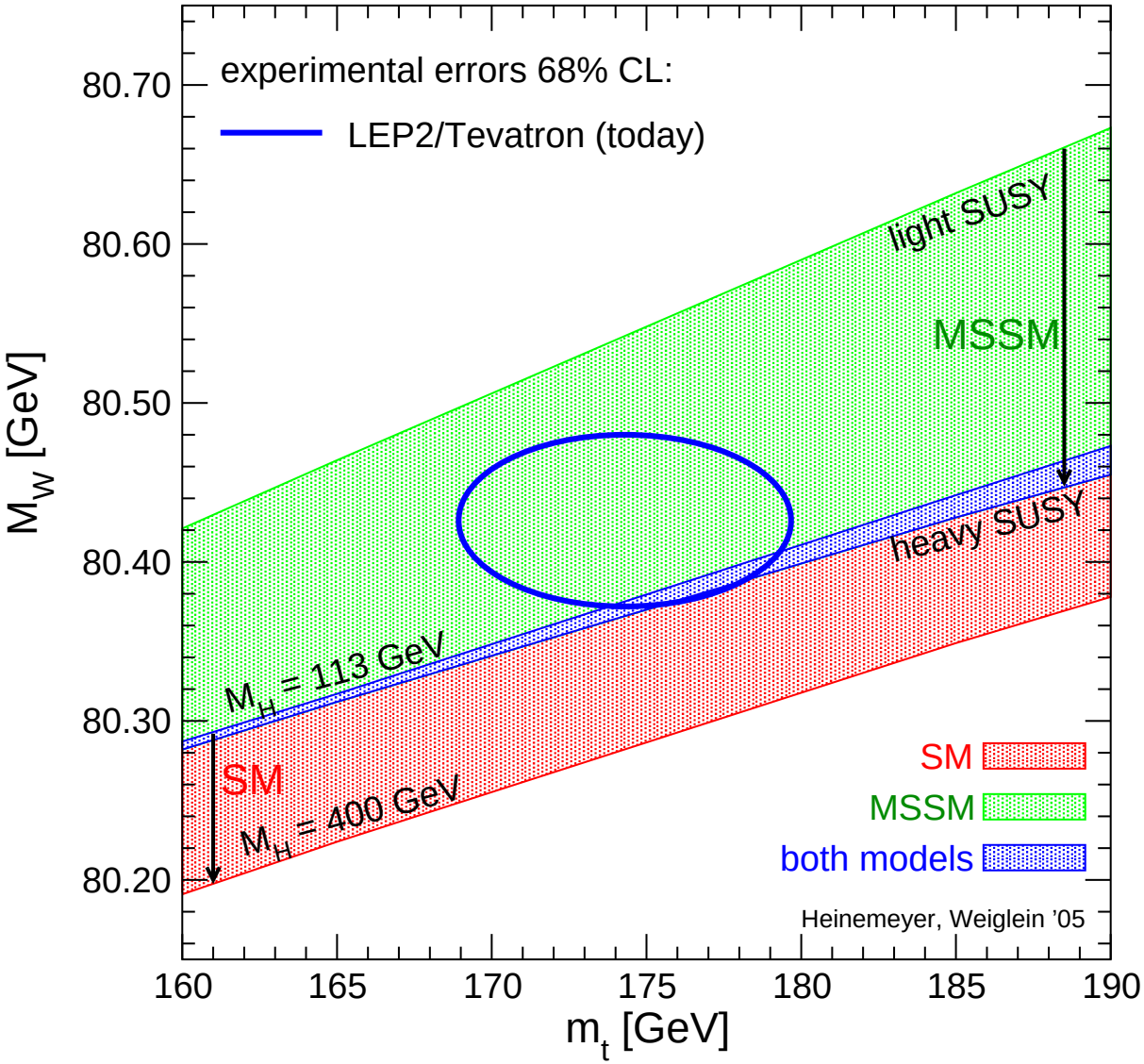

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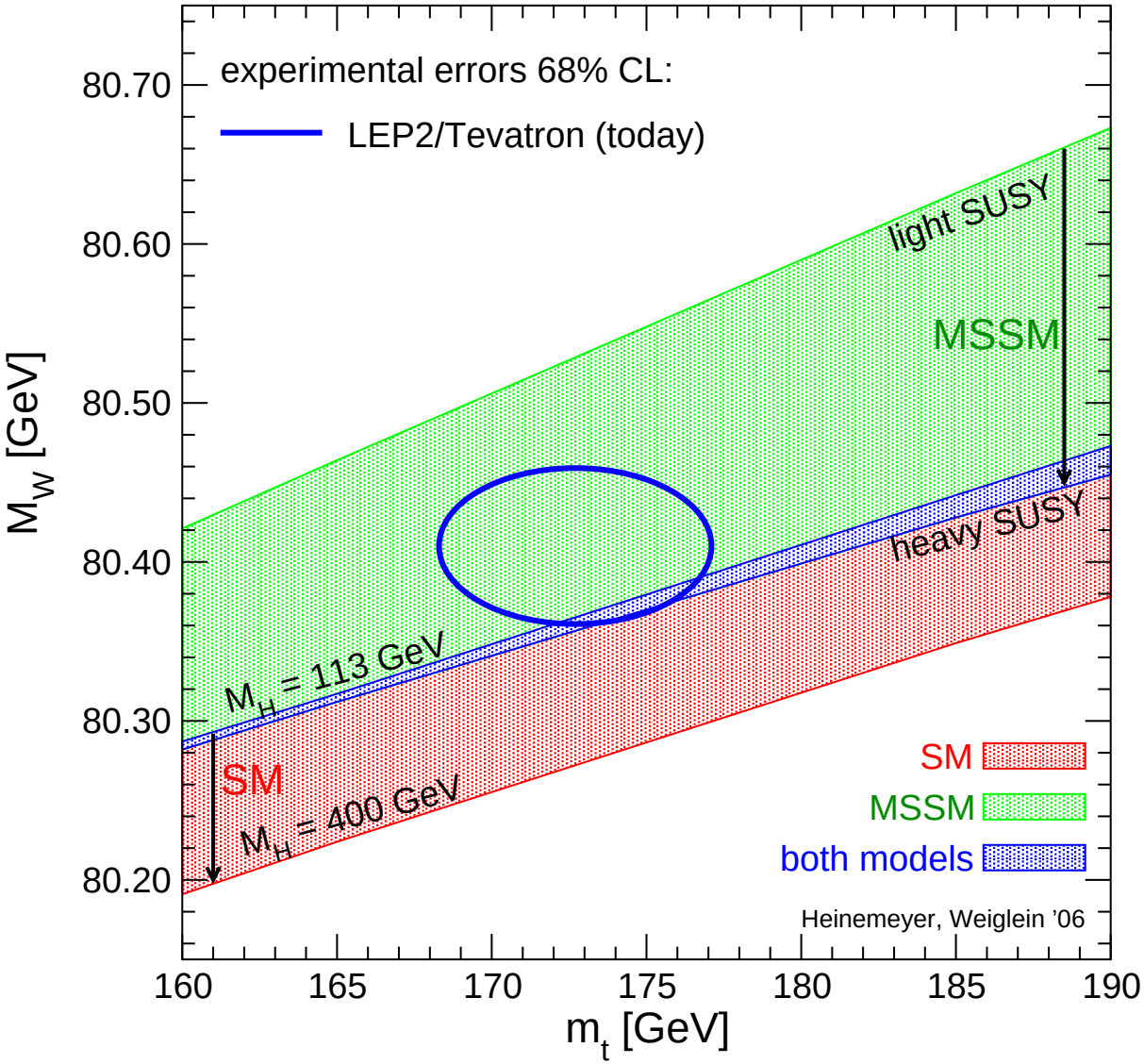

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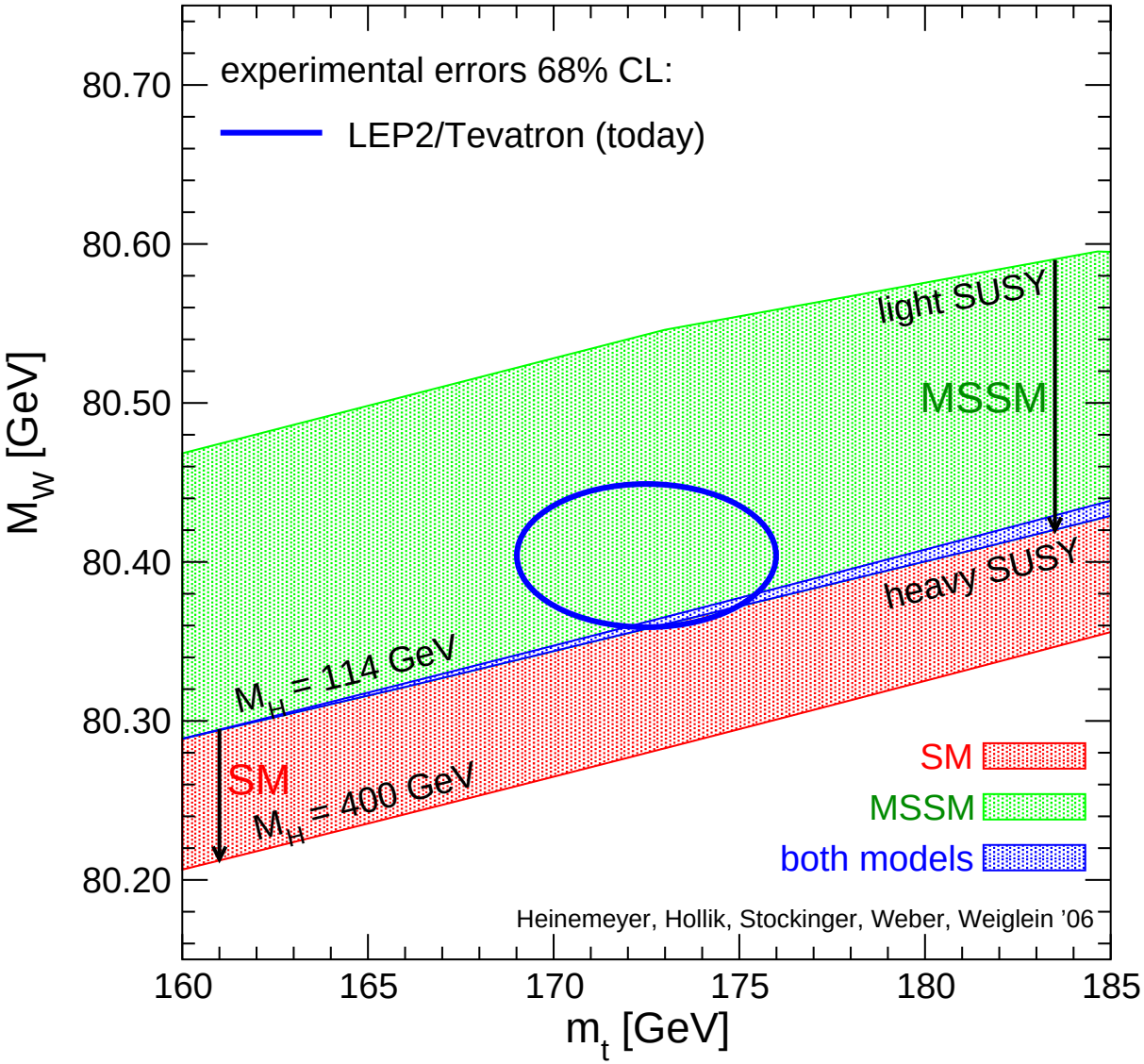

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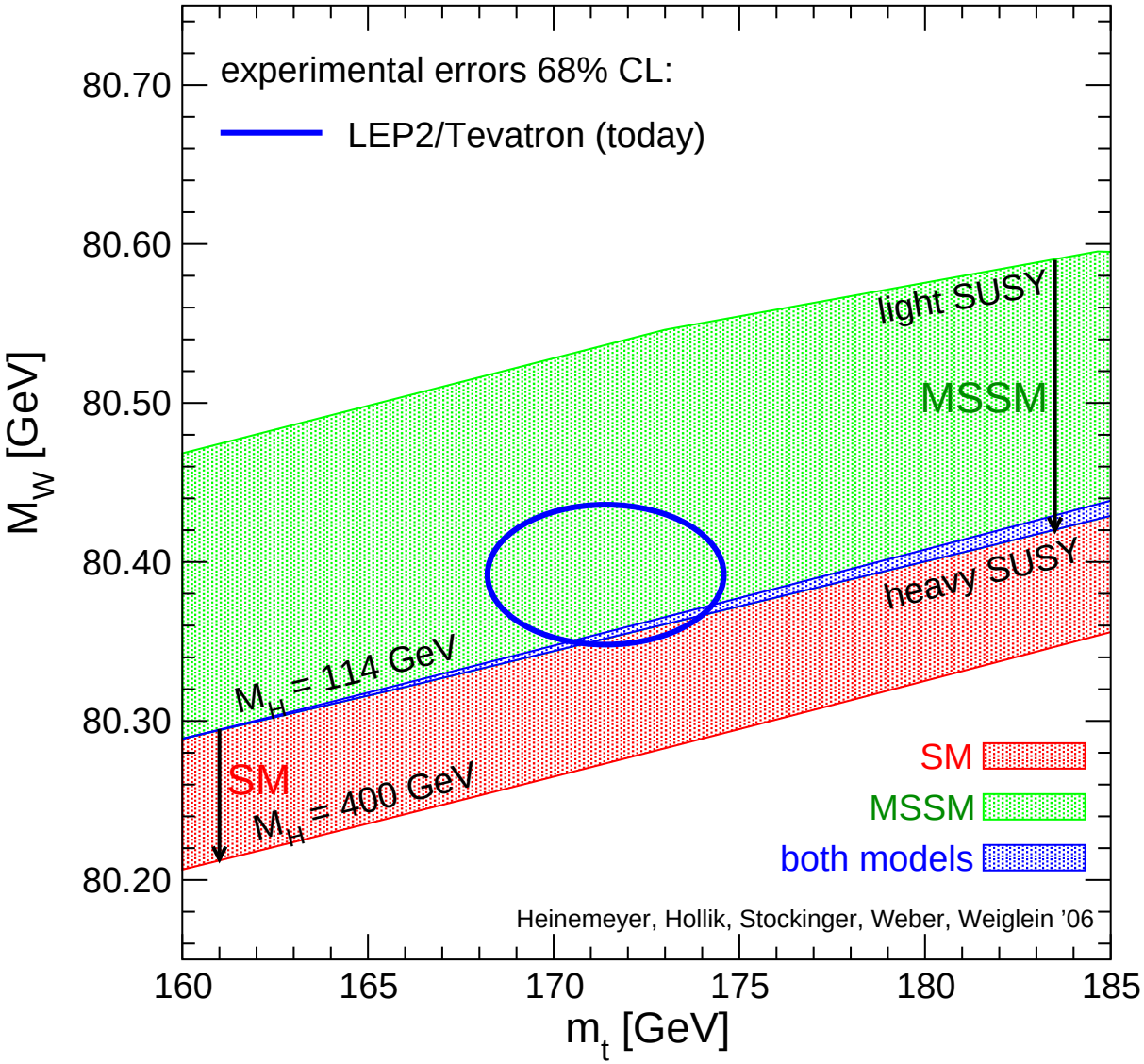

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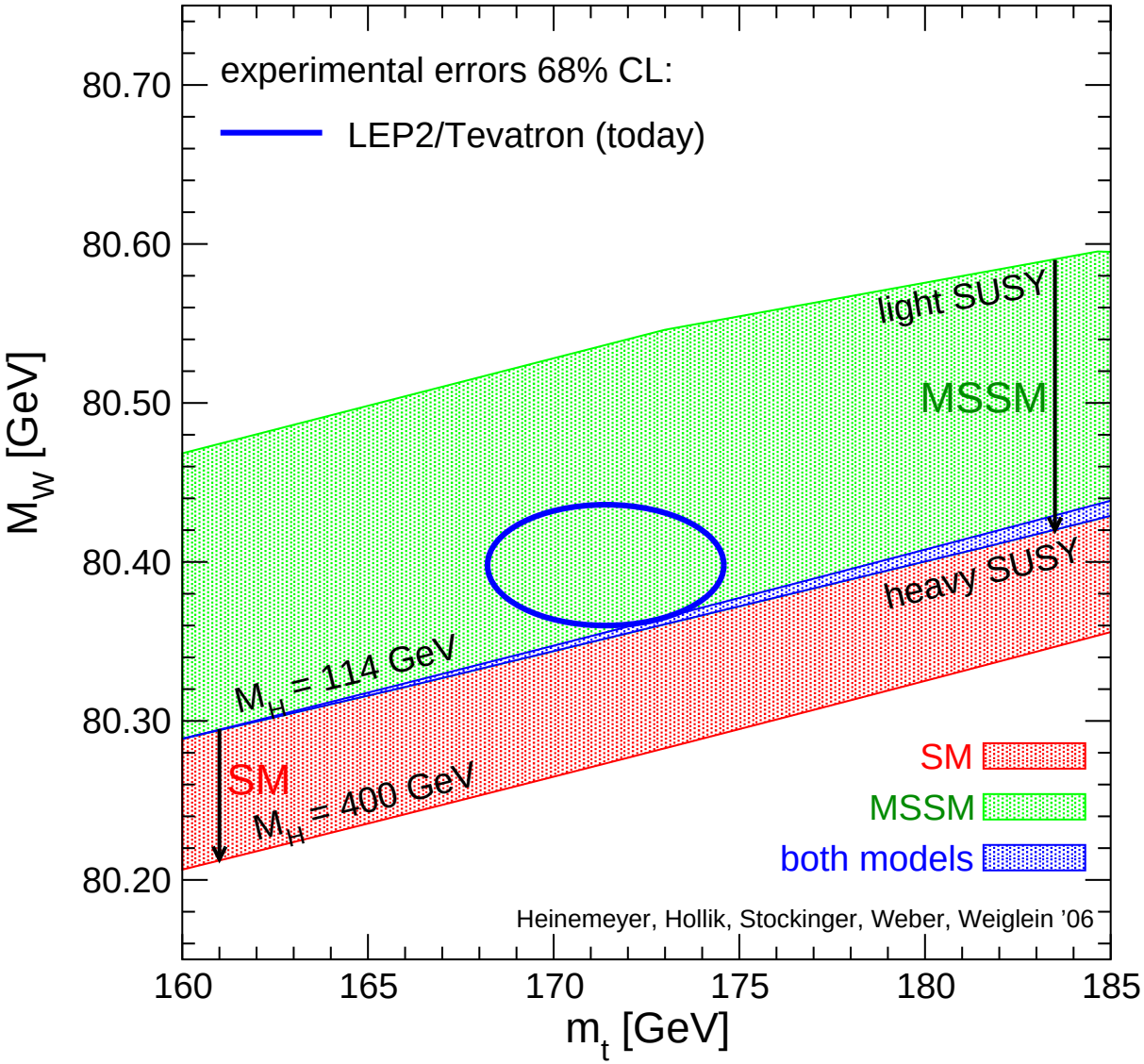

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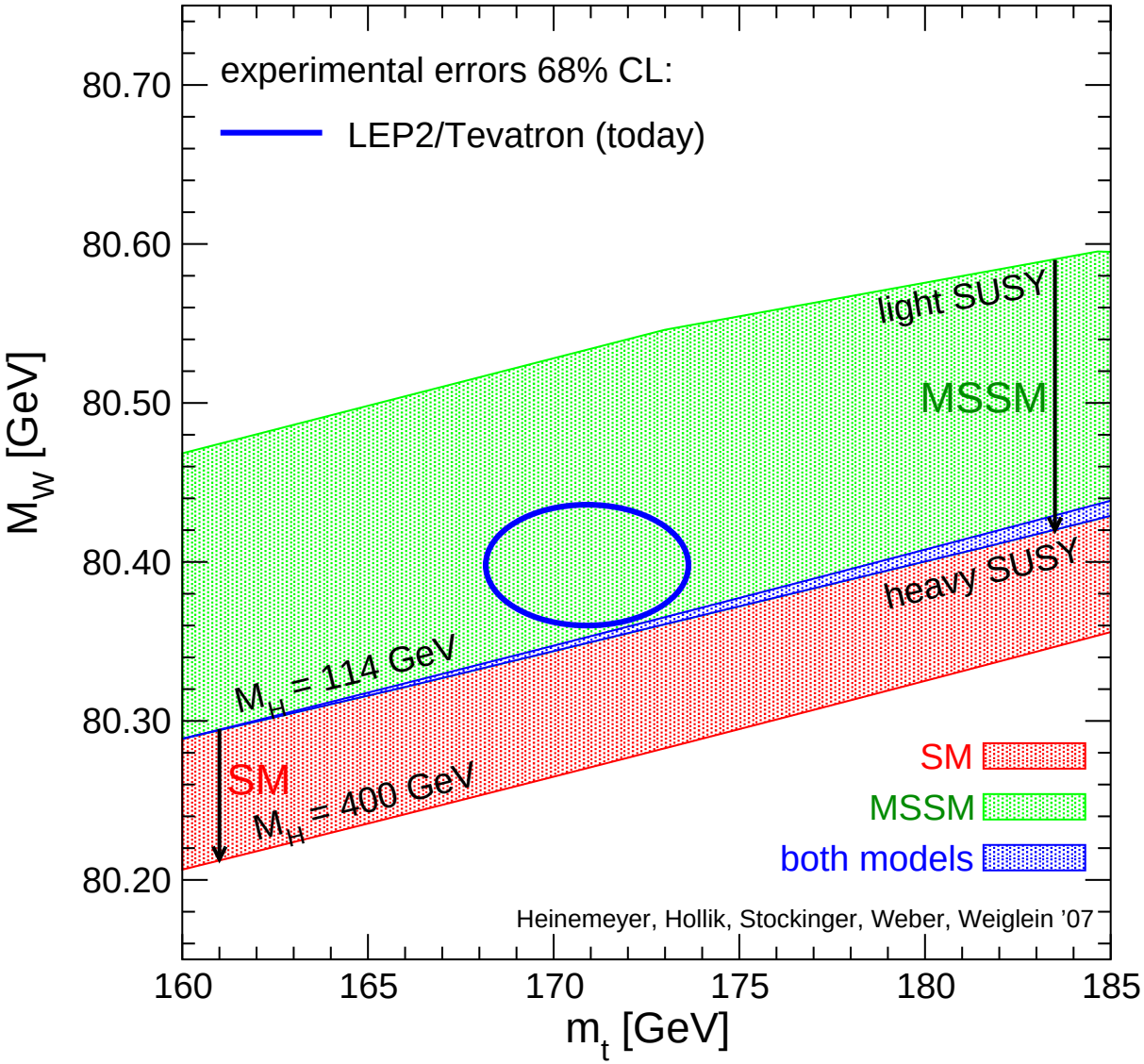

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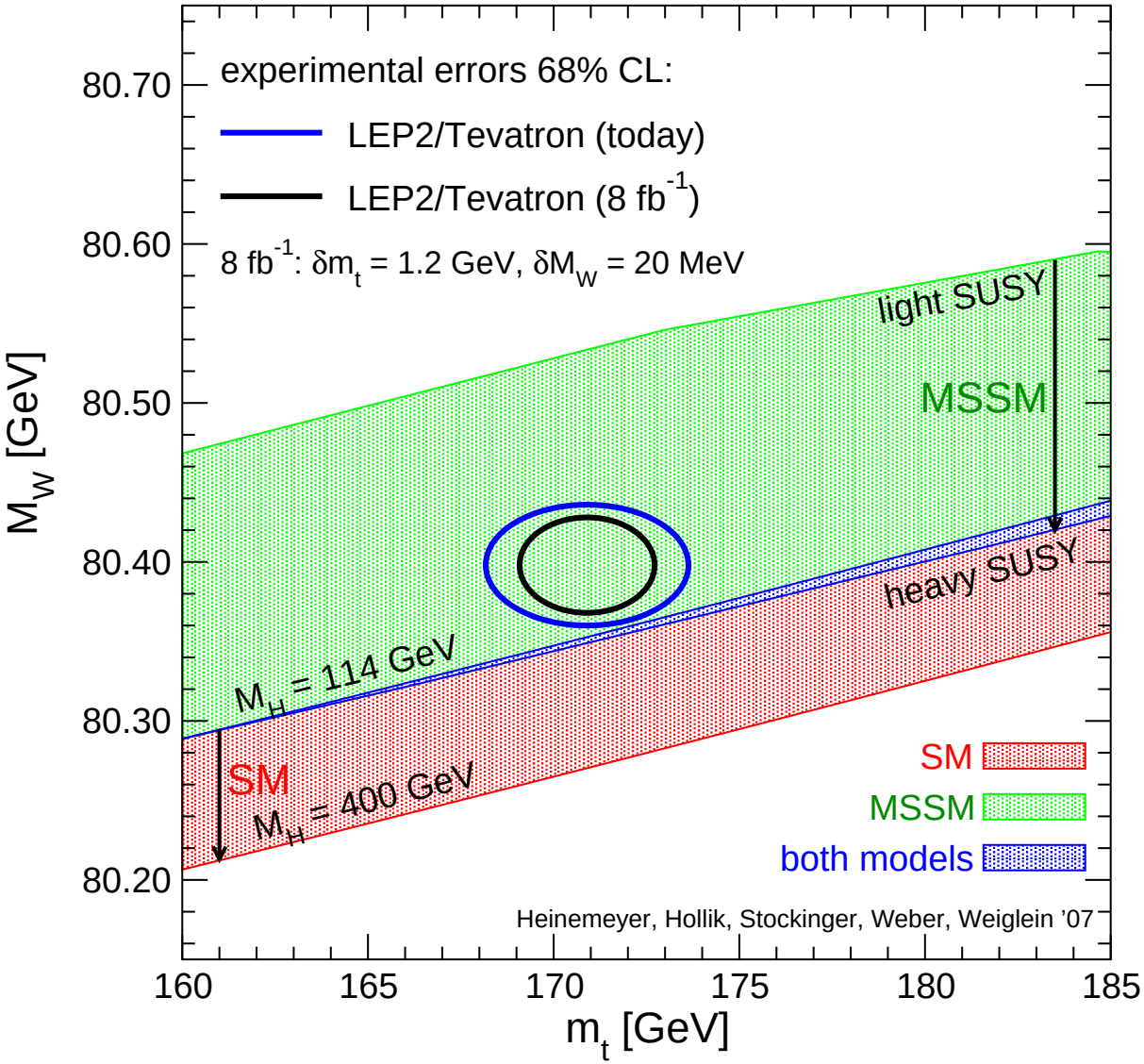

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2. The SUSY models

1.) CMSSM (or mSUGRA):

$\Rightarrow$ 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

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

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

Lightest SUSY particle (LSP) is the lightest neutralino

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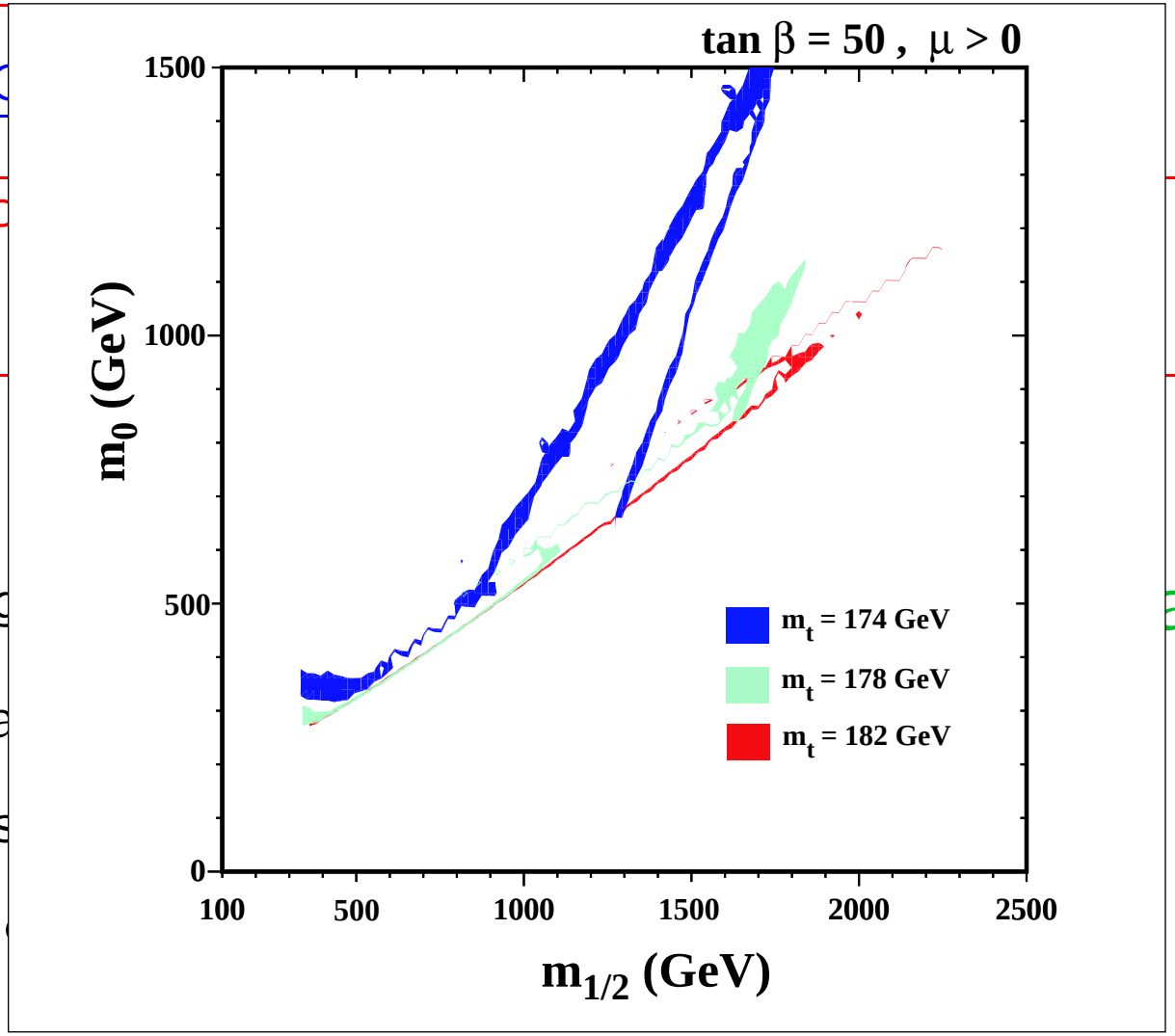


ale

⇒ particle spectra from renormalization group running to weak scale

Lightest SUSY particle (LSP) is the lightest neutralino

2.) NUHM: (Non-universal Higgs mass model)

$\Rightarrow$ besides the CMSSM parameters

M_A and μ

Assumption:

no unification of scalar fermion and scalar Higgs parameters at the GUT scale

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

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

Lightest SUSY particle (LSP) is the lightest neutralino

$\Rightarrow$ possible: M_A–$\tan\beta$ planes :-)

Procedure:

1. Scan over parameter space:
   - CMSSM: for fixed $\tan\beta = 10, 50$
   - NUHM: certain parameter planes,
     corresponding to CMSSM best fit points

2. Perform χ^2 fit

3. Find preferred values for masses
   $\Rightarrow$ collider reach

$\Rightarrow$ most details for CMSSM
NUHM shows the same qualitative behavior

3. The observables

1./2./3.) M_W, $\sin^2\theta_{\text{eff}}$, Γ_Z:

1.) Theoretical prediction for M_W in terms

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

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

$\Updownarrow$

loop corrections

2.) Effective mixing angle:

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

Higher order contributions:

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

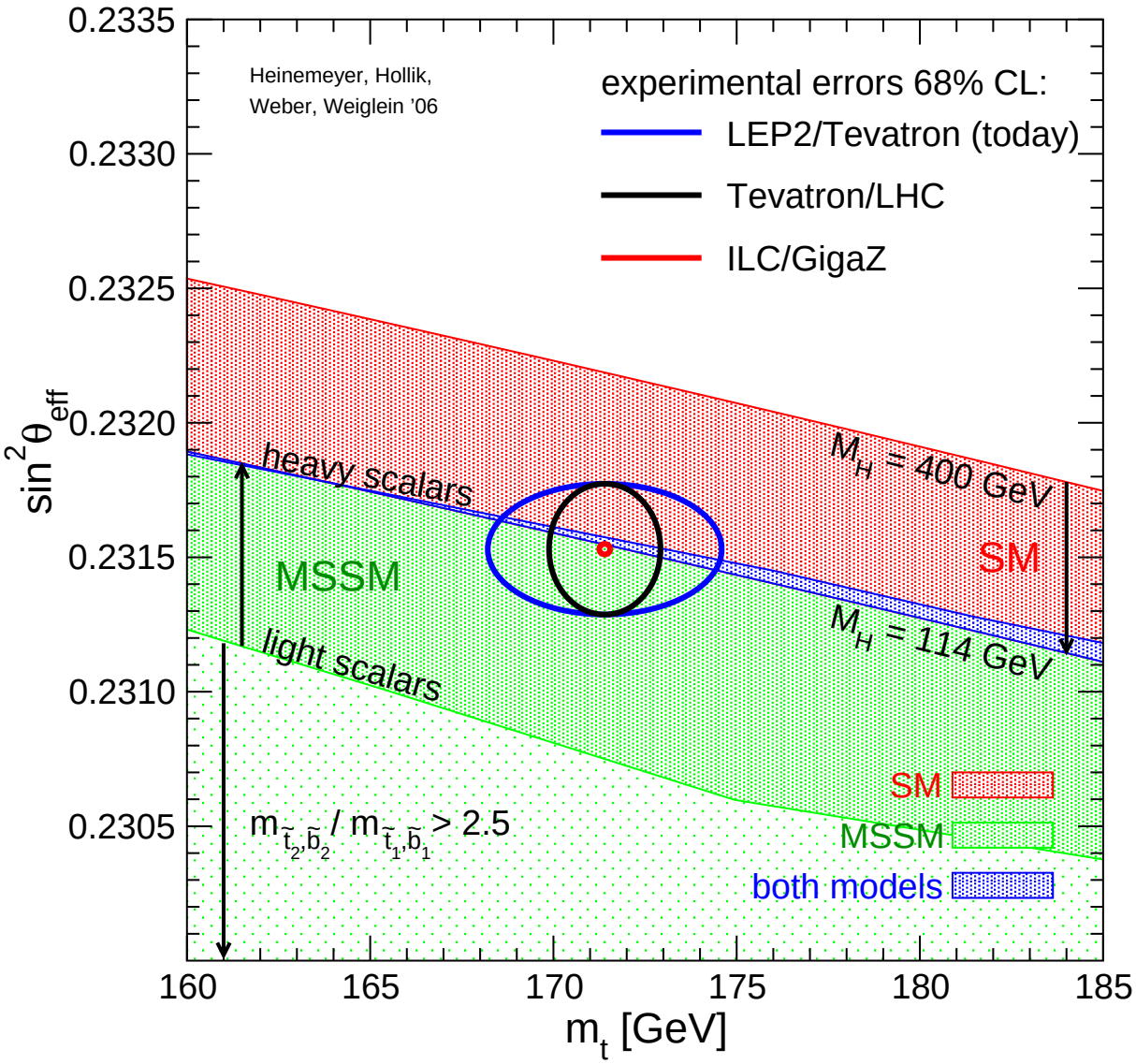
3.) Total Z width:

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

including higher-order corrections

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

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



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

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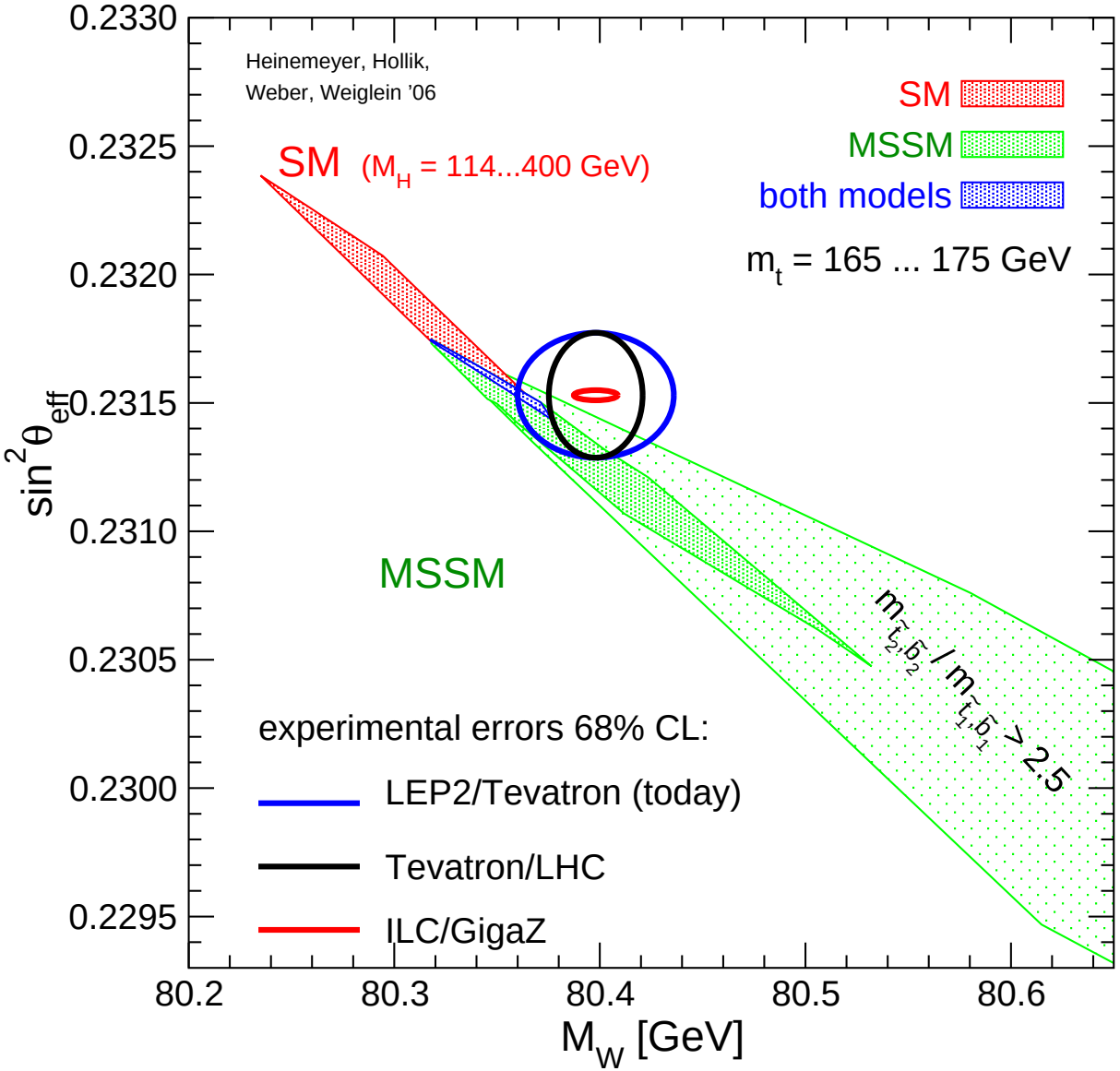

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R_x^{exp}: experimental value

R_x^{theo}: theory prediction

σ_x^2: (exp. error)^2 + (param. error)^2 + (intr. error)^2

experimental error

parametric error: from uncertainty in input parameters

intrinsic error: from unknown higher-order corrections

$\Rightarrow$ use most up to date calculations and error estimates

[*S.H., W. Hollik, G. Weiglein '04*]

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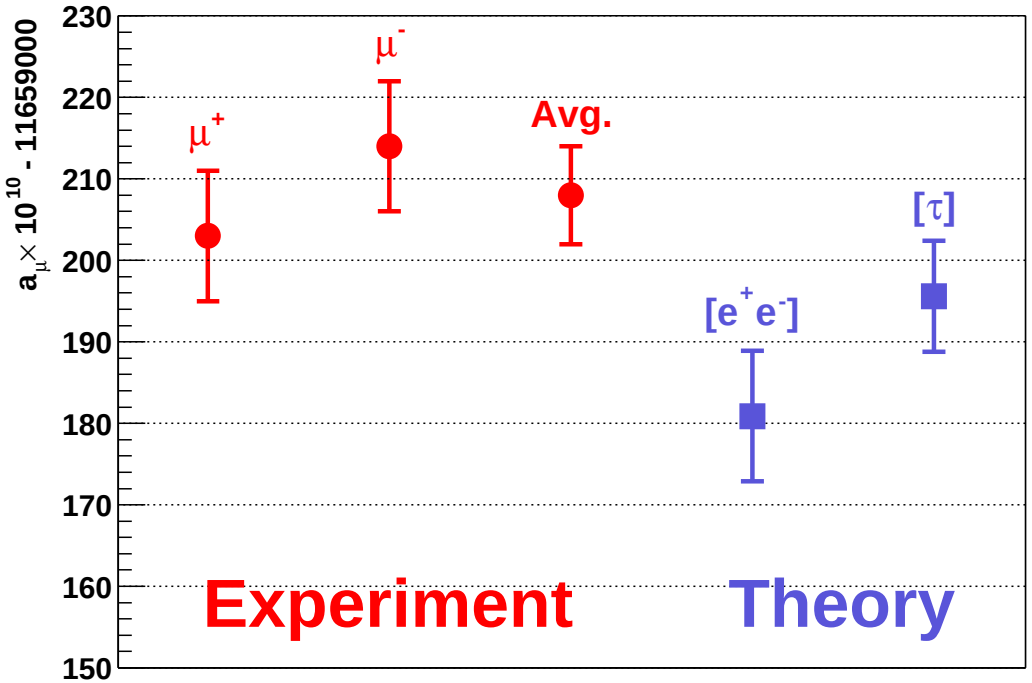
[*LEPEWWG '06/'07*]

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

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

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



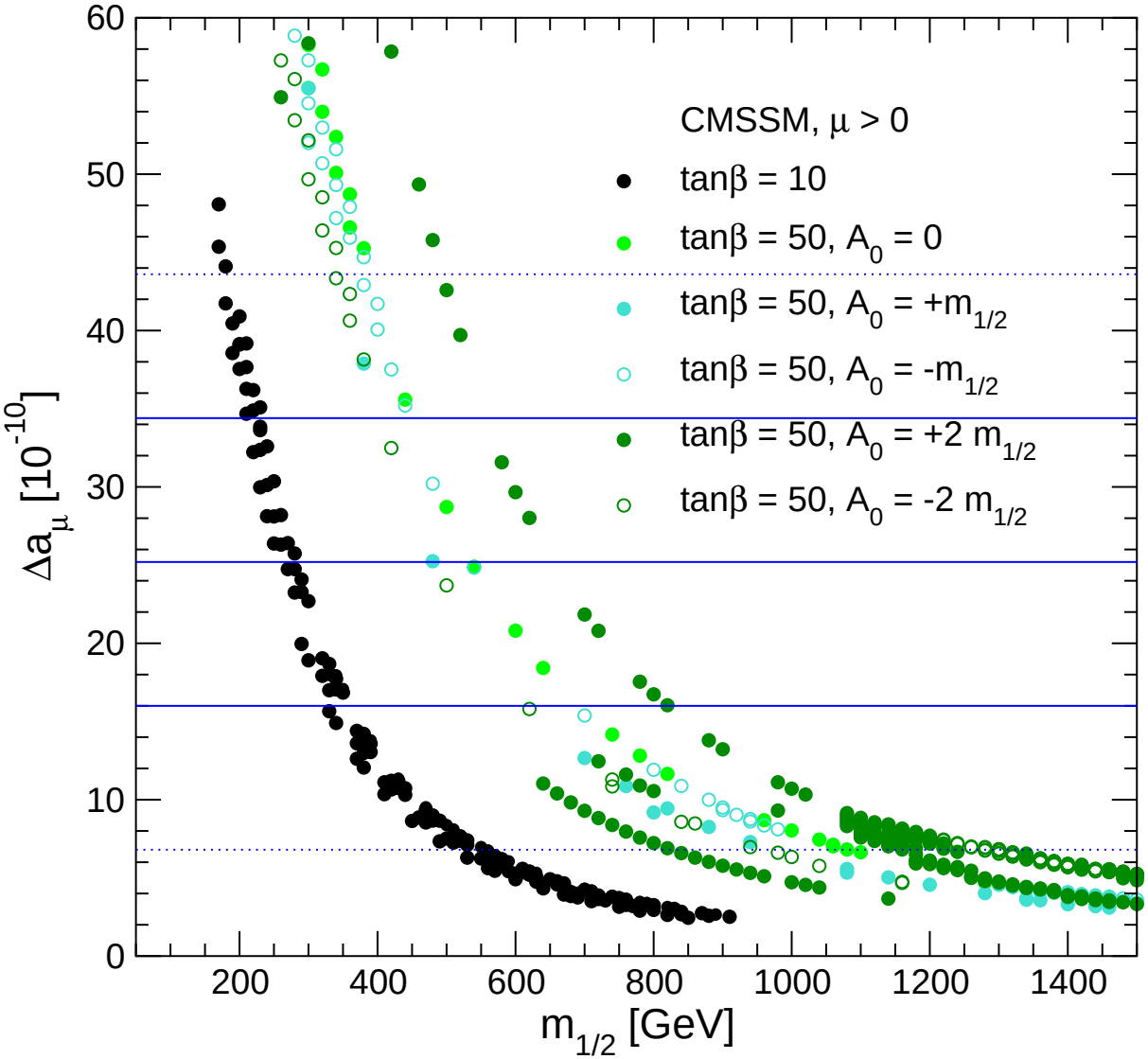
→ "Isospin breaking effects" in τ data problematic

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

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

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

Example: Investigation of mSUGRA with cold dark matter constraint



Scan over $m_{1/2}$, m_0, A_0

$\tan\beta = 10, 50$

selected points give correct amount of cold dark matter

[*Ellis, S.H., Olive, Weiglein '04*]

Severe bounds on e.g. $m_{1/2}$

For χ^2 fit:

$$\chi_x^2 = \left(\frac{R_x^{\text{exp}} - R_x^{\text{theo}}}{\sigma_x} \right)^2 \qquad x = (g-2)_\mu$$

R_x^{exp}: experimental value $= (a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}})$

R_x^{theo}: theory prediction $= a_\mu^{\text{theo,SUSY}}$

σ_x^2: (exp. error)^2 + (param. error)^2 + (intr. error)^2

experimental error

parametric error: from uncertainty in input parameters

intrinsic error: from unknown higher-order corrections

$\Rightarrow$ use most up to date calculations and error estimates

[*S.H., W. Hollik, G. Weiglein '04*]

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

5.) 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) f

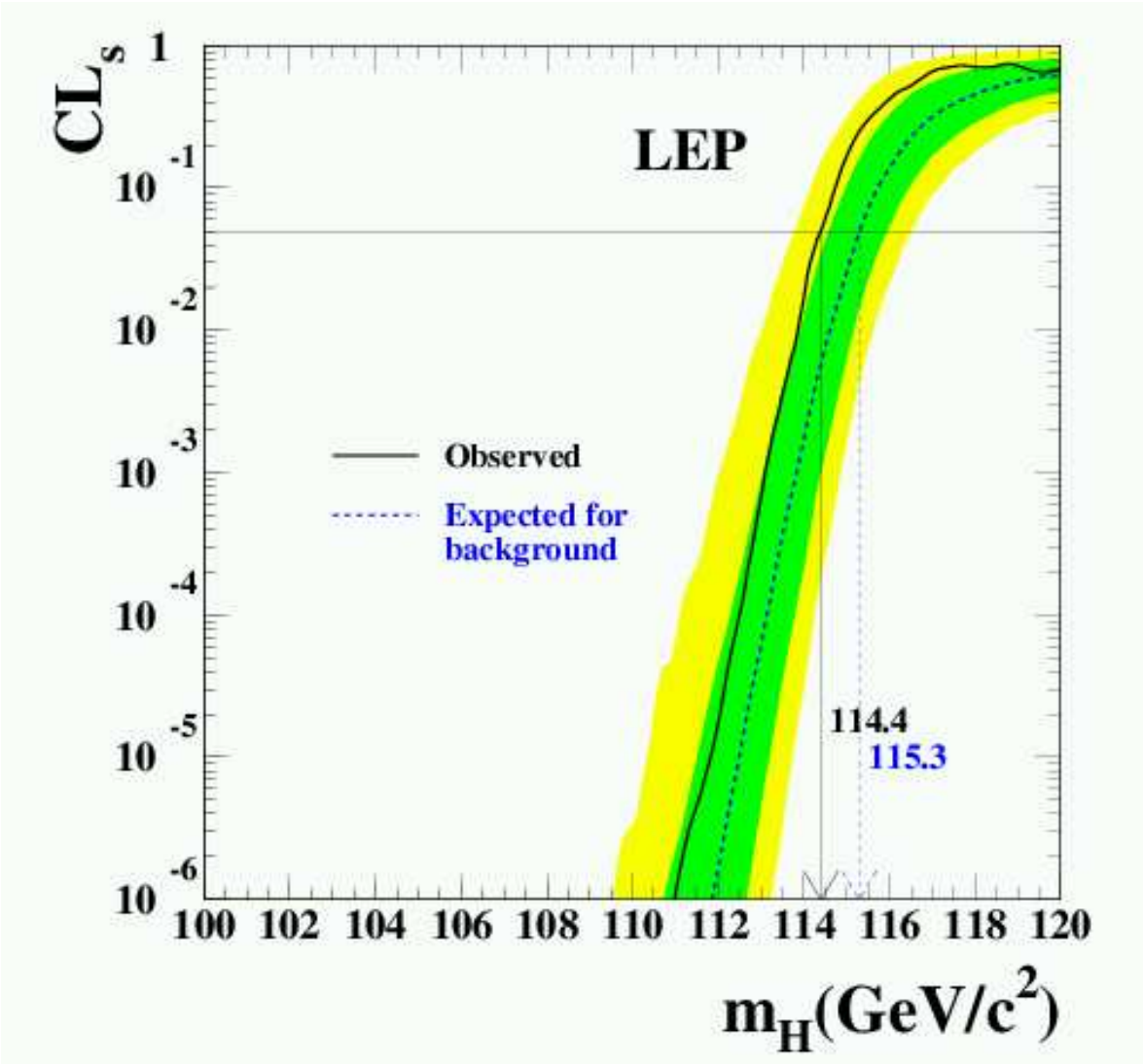
Measurement of M_h, Higgs couplings $\Rightarrow$ test of the theory

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, NUHM:

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



CL_s can be used/transformed into χ^2 values

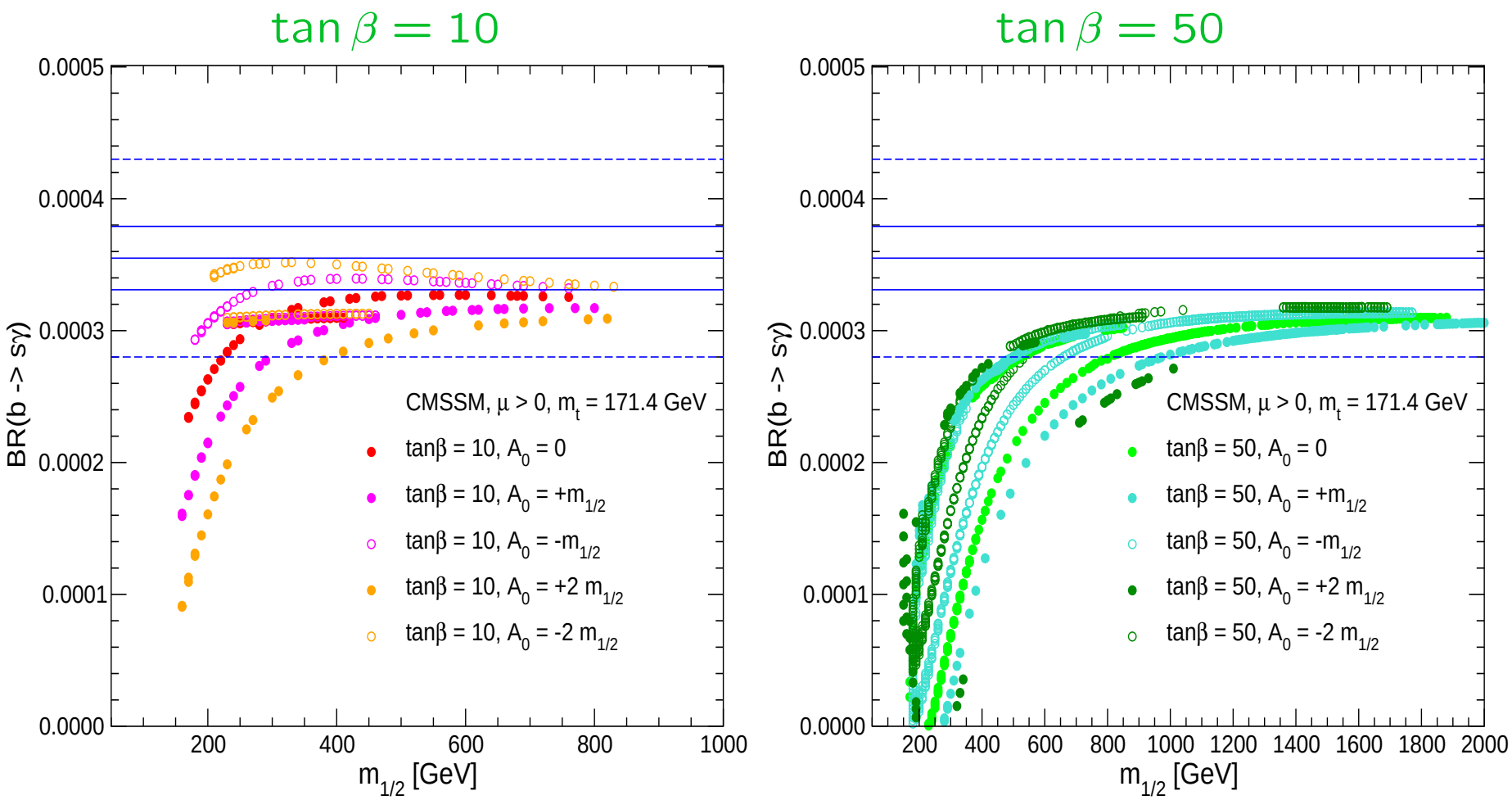
$\Rightarrow$ additional (unobserved) parameter

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

We use *FeynHiggs*

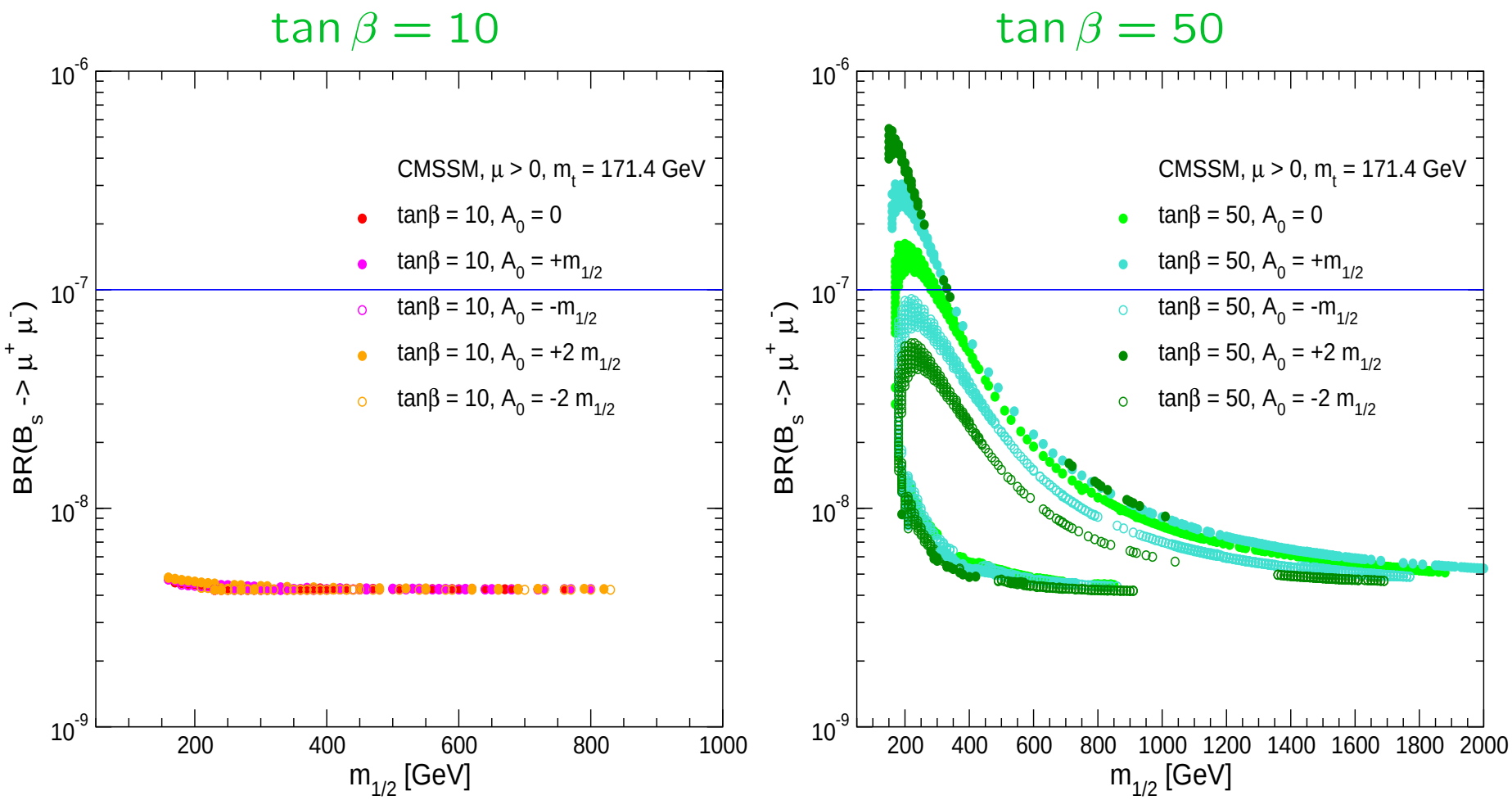
6.) $b \to s\gamma$

BR($b \to s\gamma$) MSSM vs. SM (CMSSM)



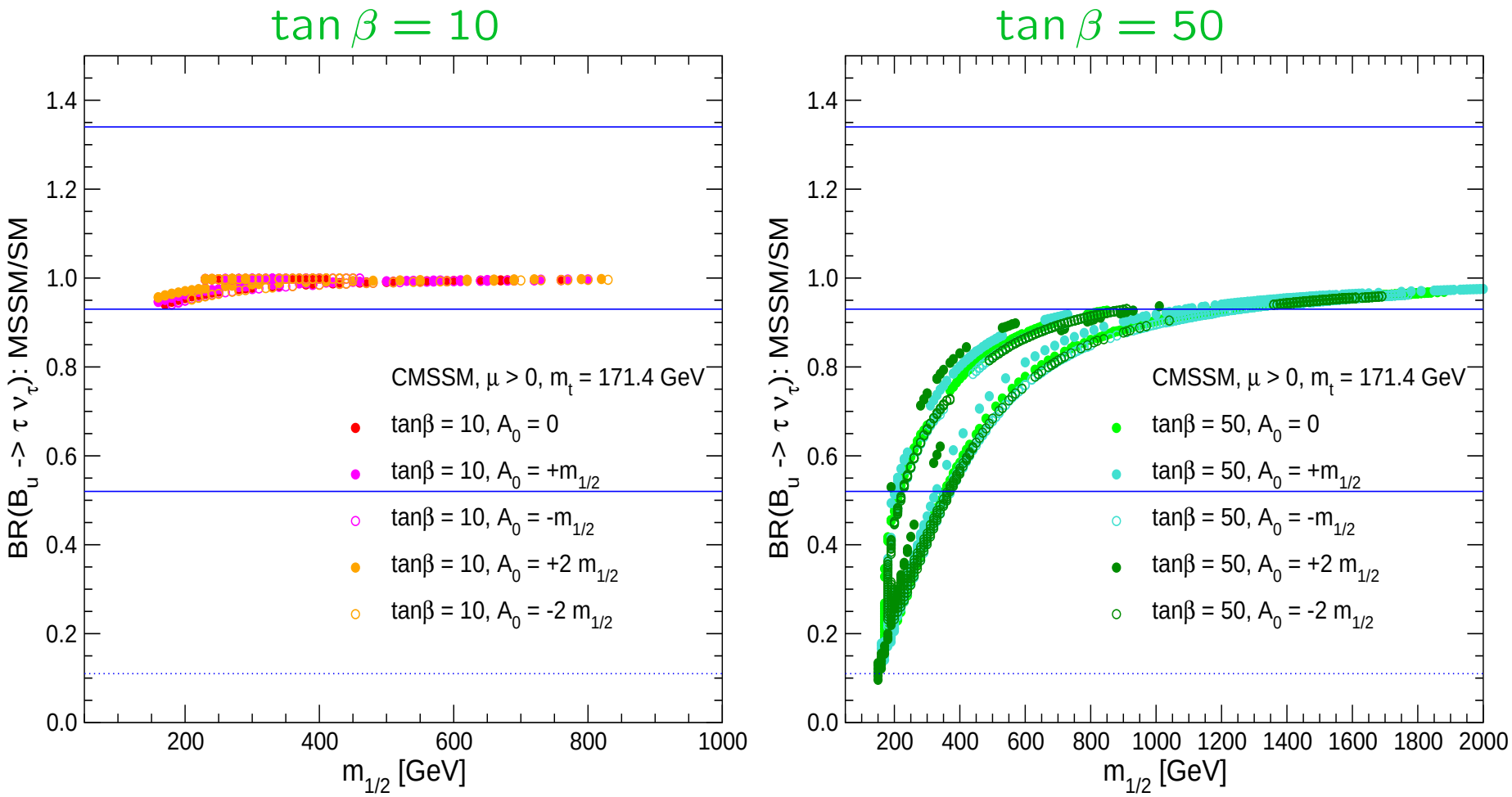
7.) $B_s \to \mu^+\mu^-$

BR($B_s \to \mu^+\mu^-$) CMSSM



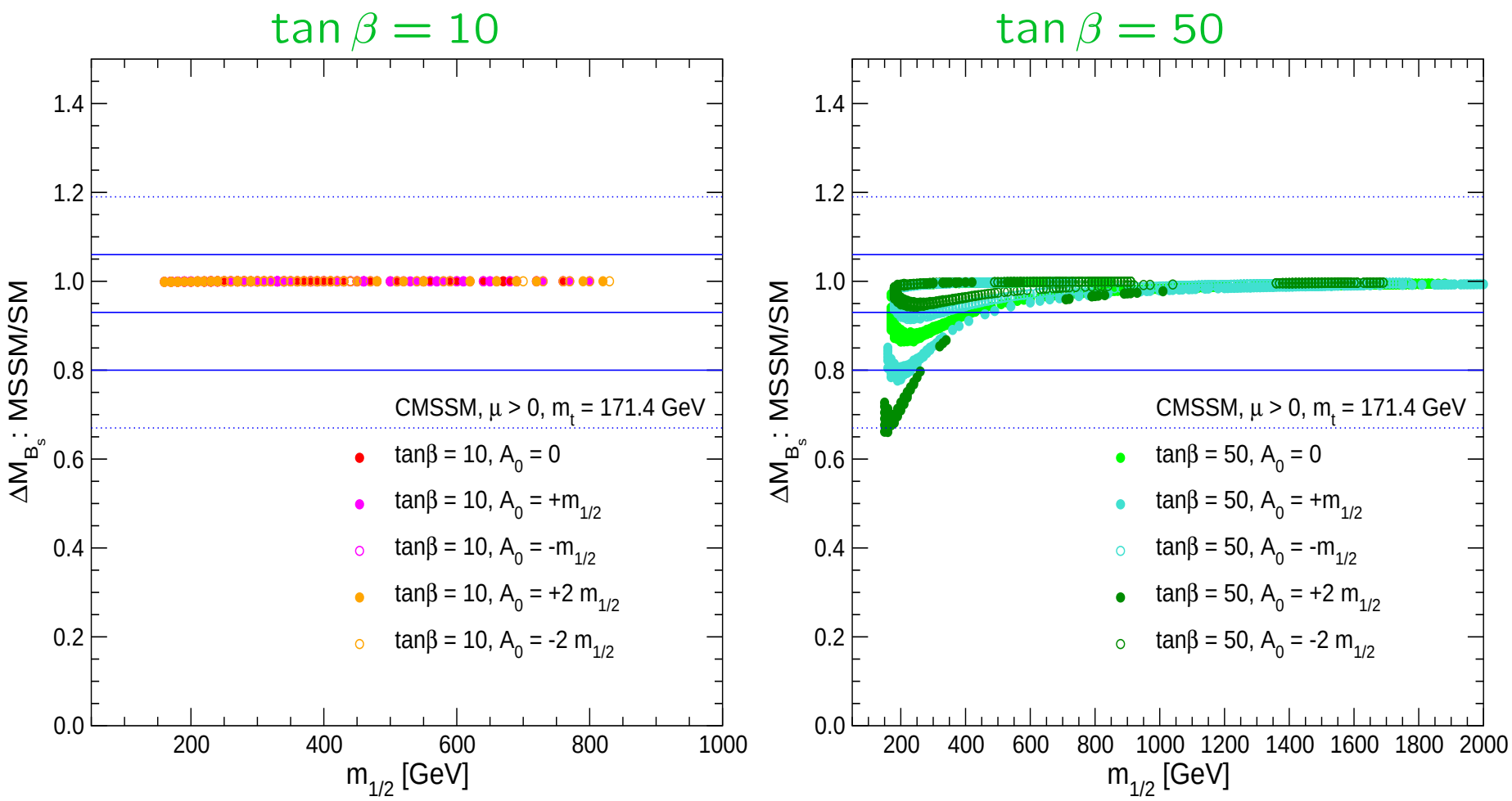
8.) $B_u \to \tau\nu_\tau$

BR($B_u \to \tau\nu_\tau$) MSSM/SM (CMSSM)



9.) ΔM_{B_s}

ΔM_{B_s} MSSM/SM ($CMSSM$)



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[*BaBar, Belle '04 - '07*]

[*HFAG '07*]

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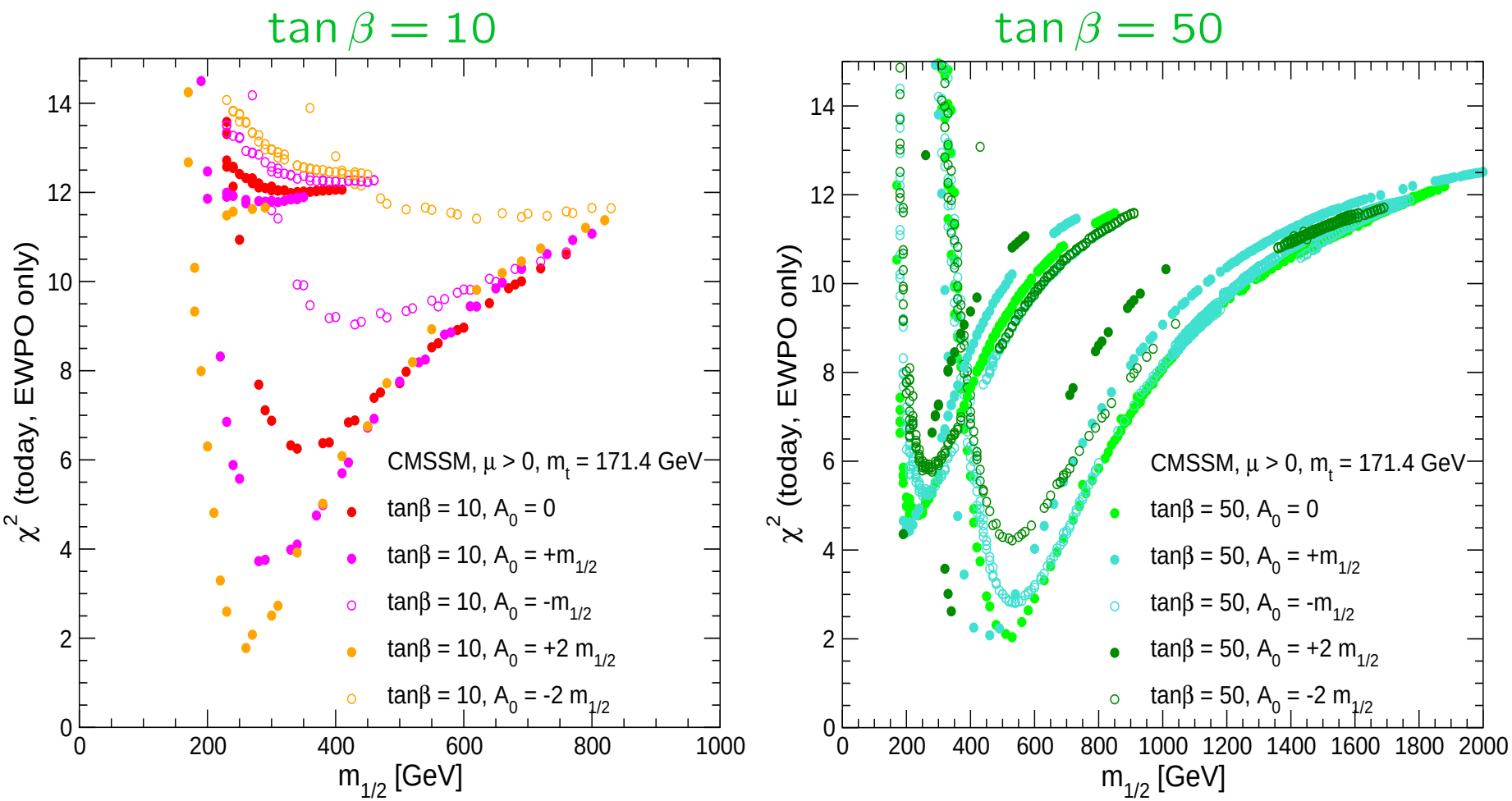
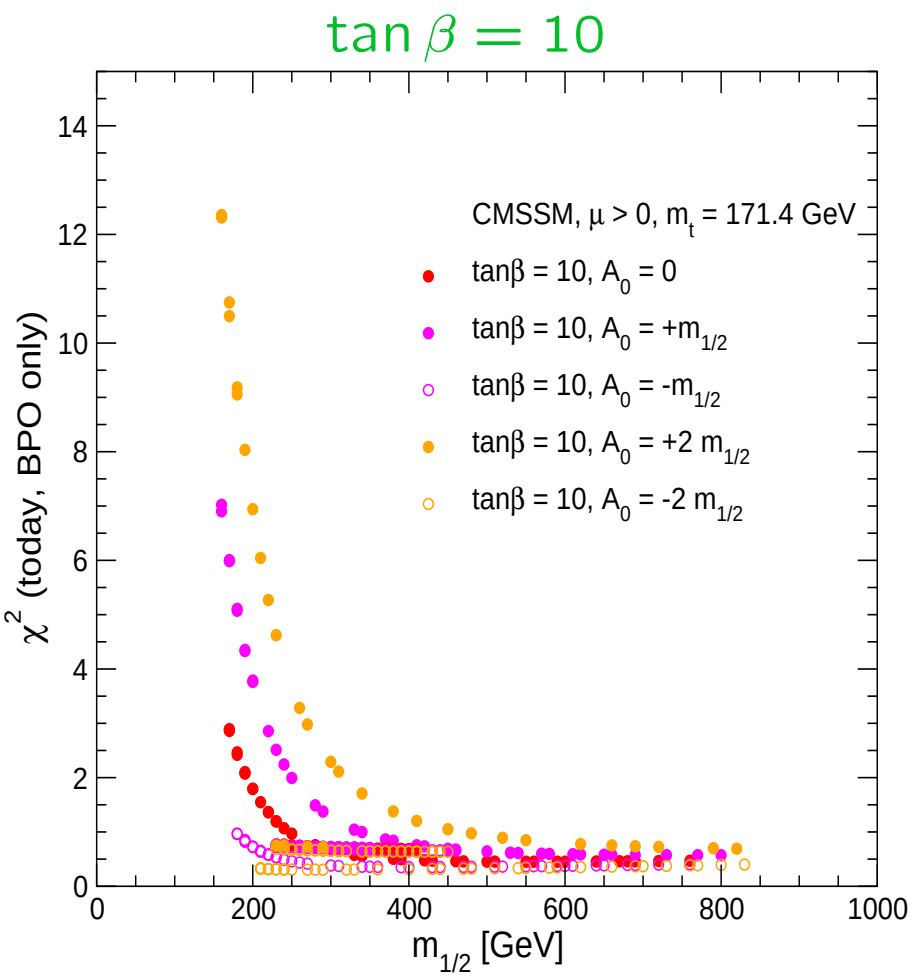
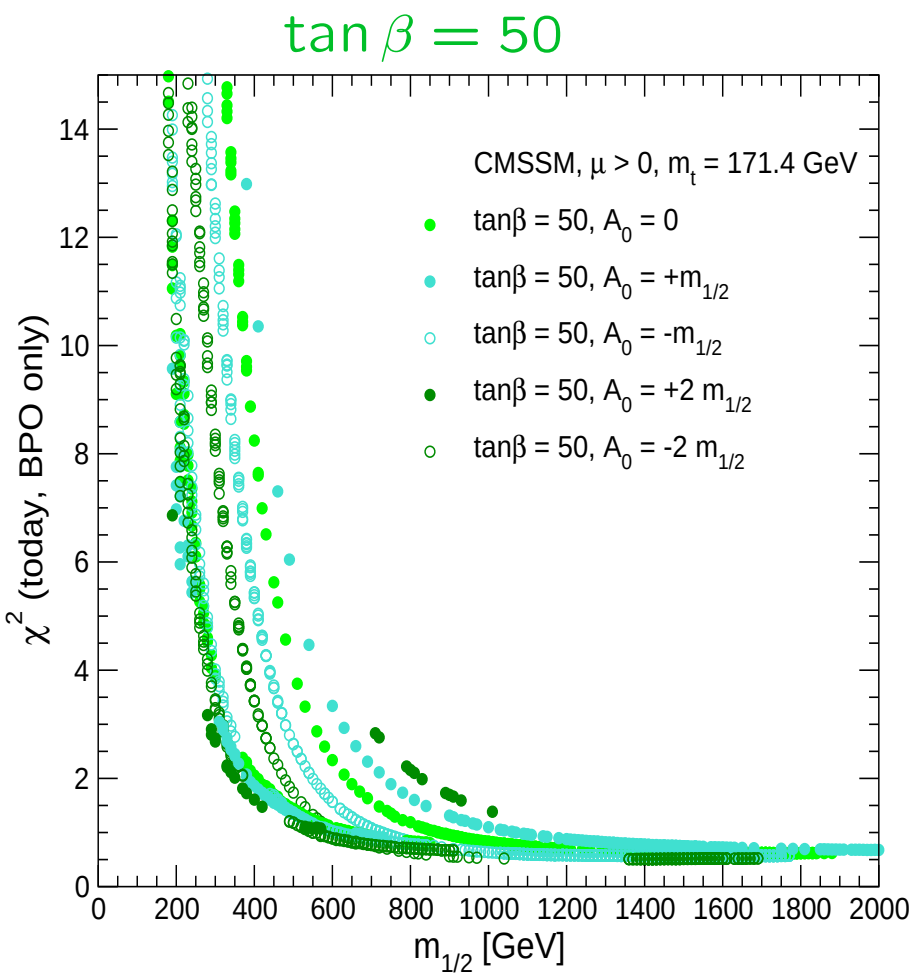
Results: CMSSM: EWPO alone



$\Rightarrow$ preference for relatively <u>small</u> $m_{1/2}$

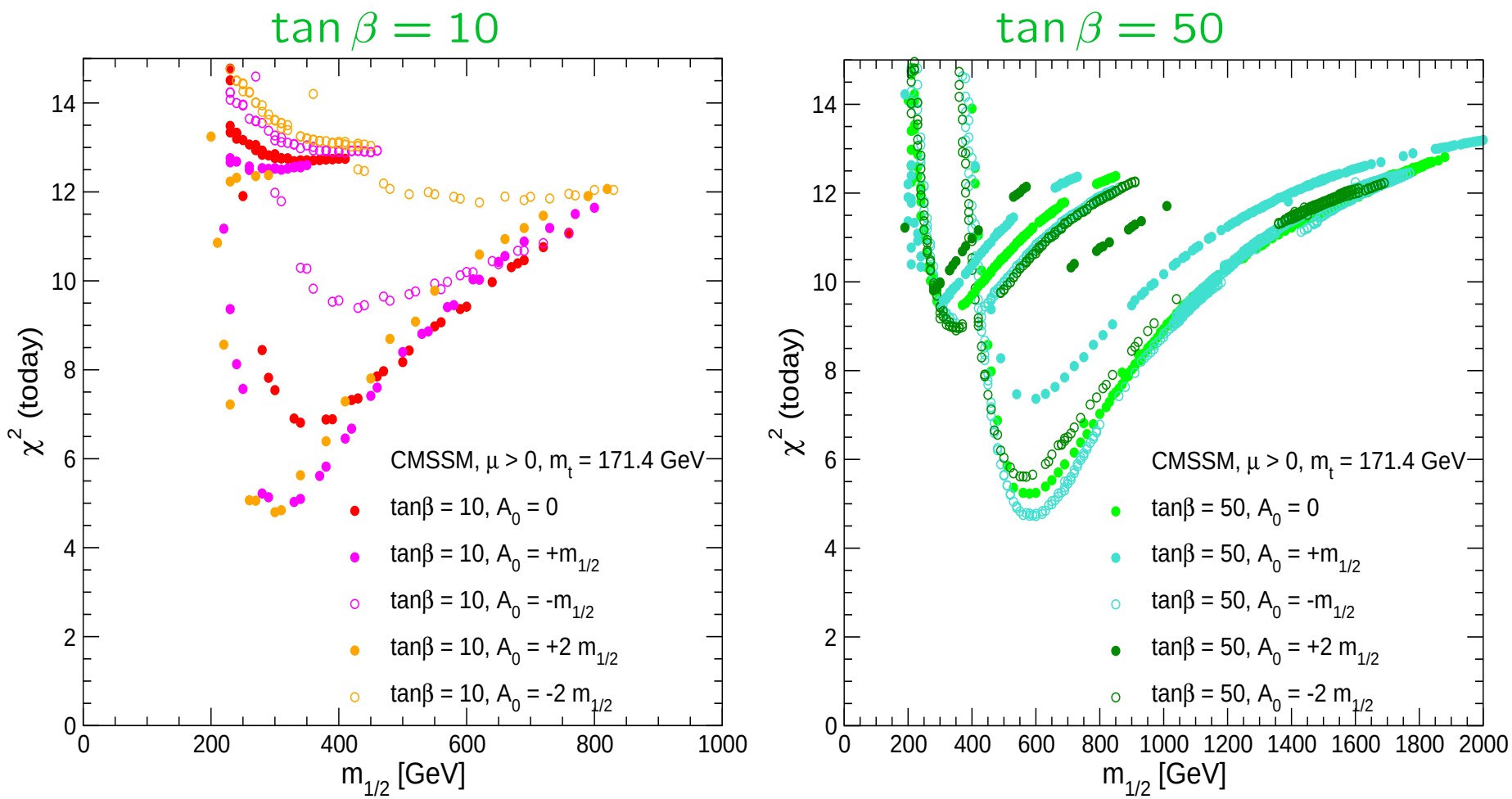
Results: CMSSM: BPO alone





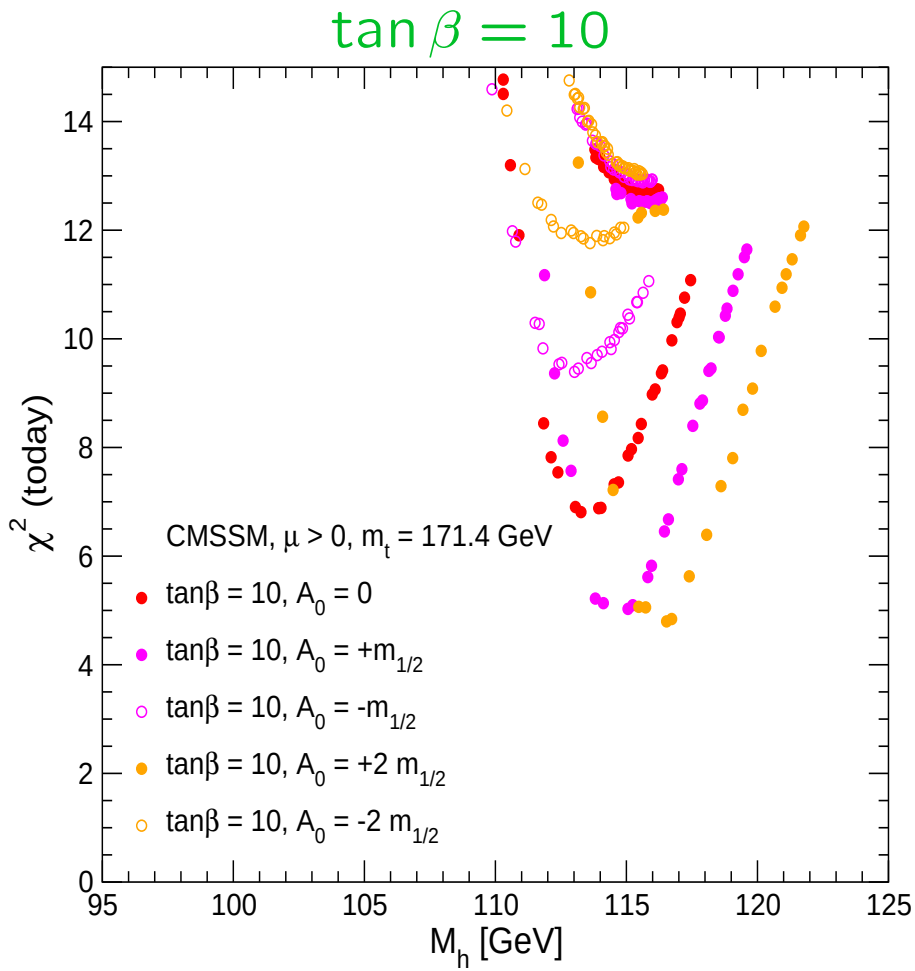
$\Rightarrow$ preference for relatively <u>large</u> $m_{1/2}$

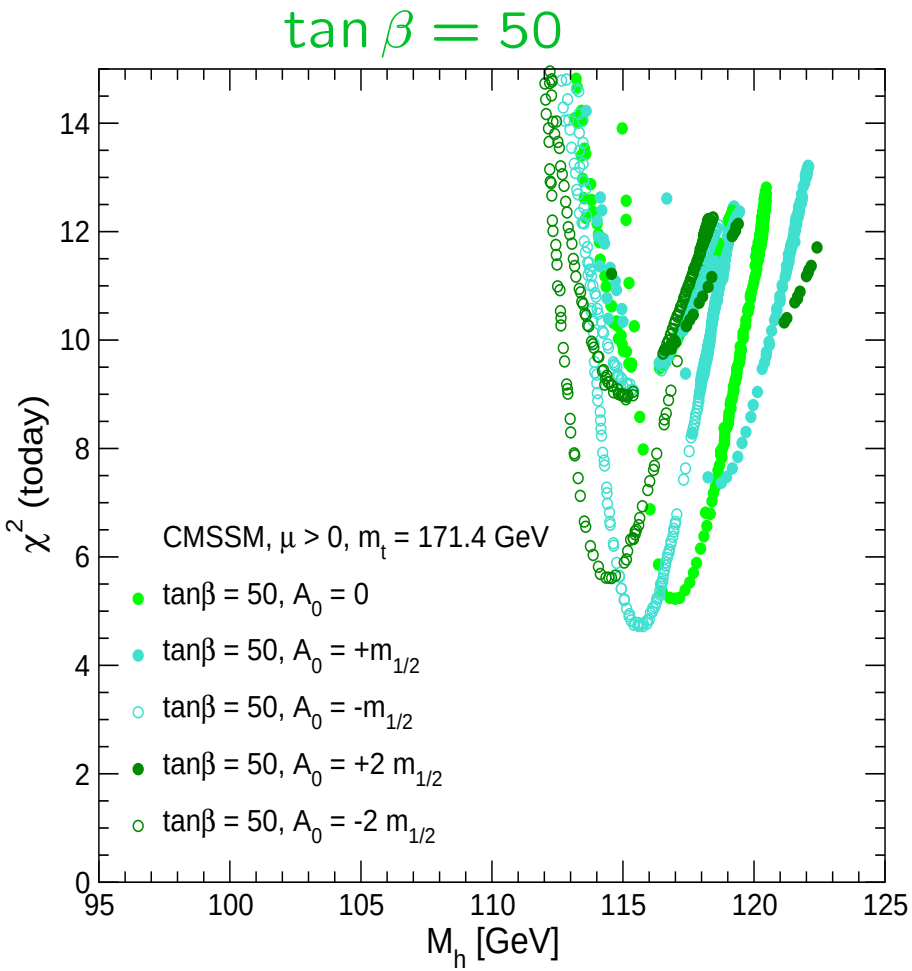
Results: CMSSM: everything combined



$\Rightarrow$ preference for somewhat smallish $m_{1/2}$ – but with a little tension

Results: CMSSM: prediction for M_h



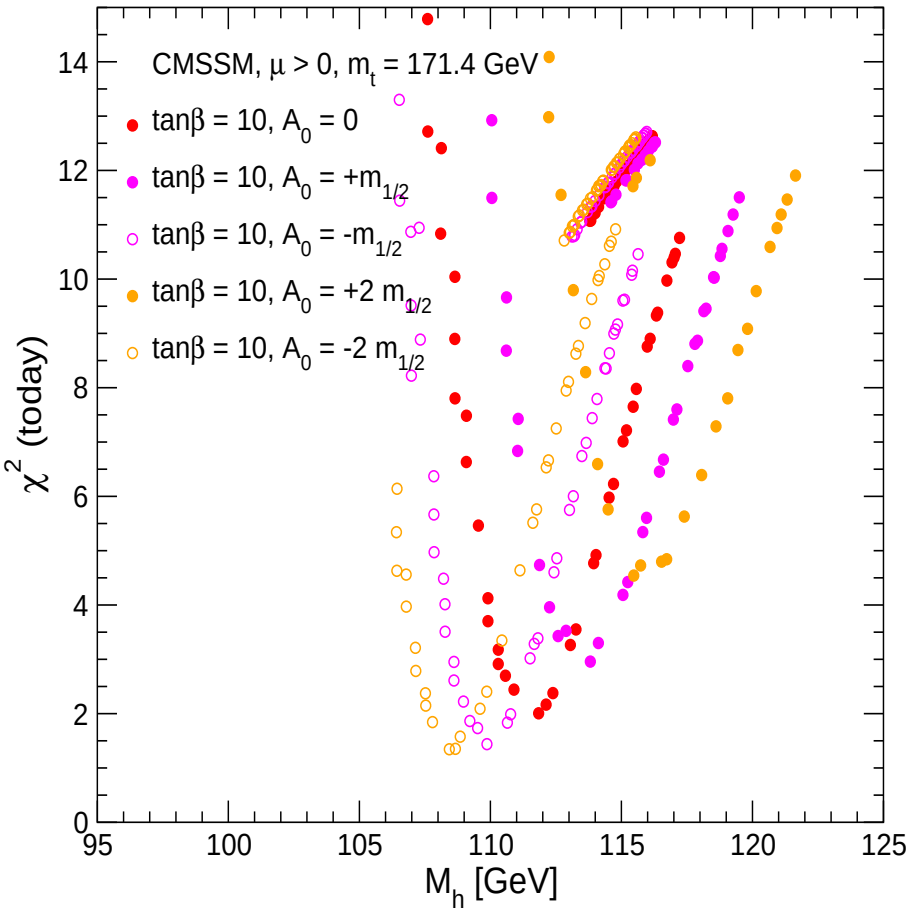


⇒ preference for $M_h \sim 115$ GeV (LEP . . .)

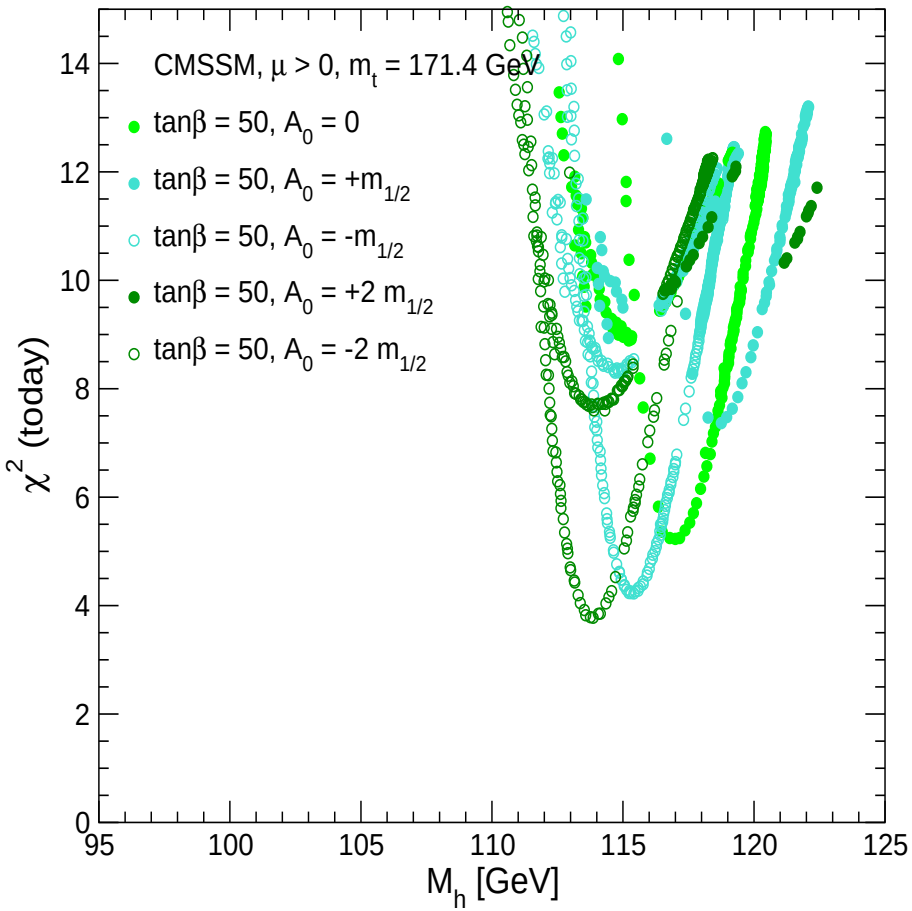
⇒ ILC implications obvious

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

$\tan\beta = 10$



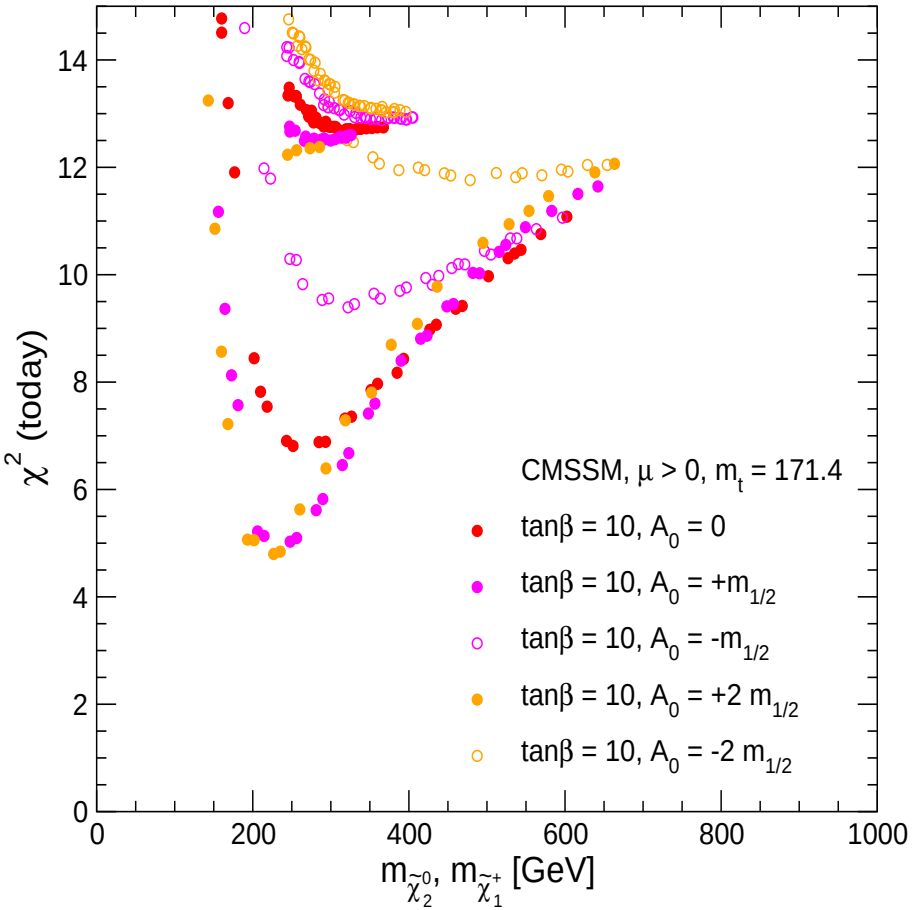
$\tan\beta = 50$



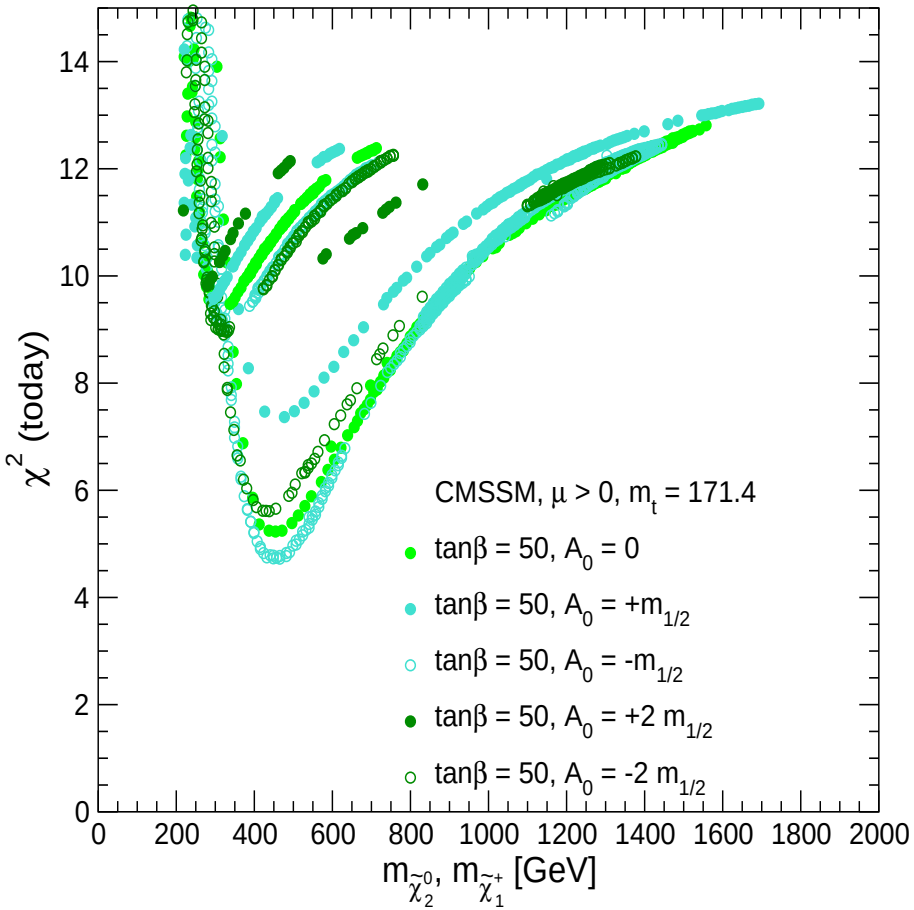
$\Rightarrow$ much "better" than in the SM

Results: CMSSM: prediction for $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm}$

$\tan\beta = 10$



$\tan\beta = 50$

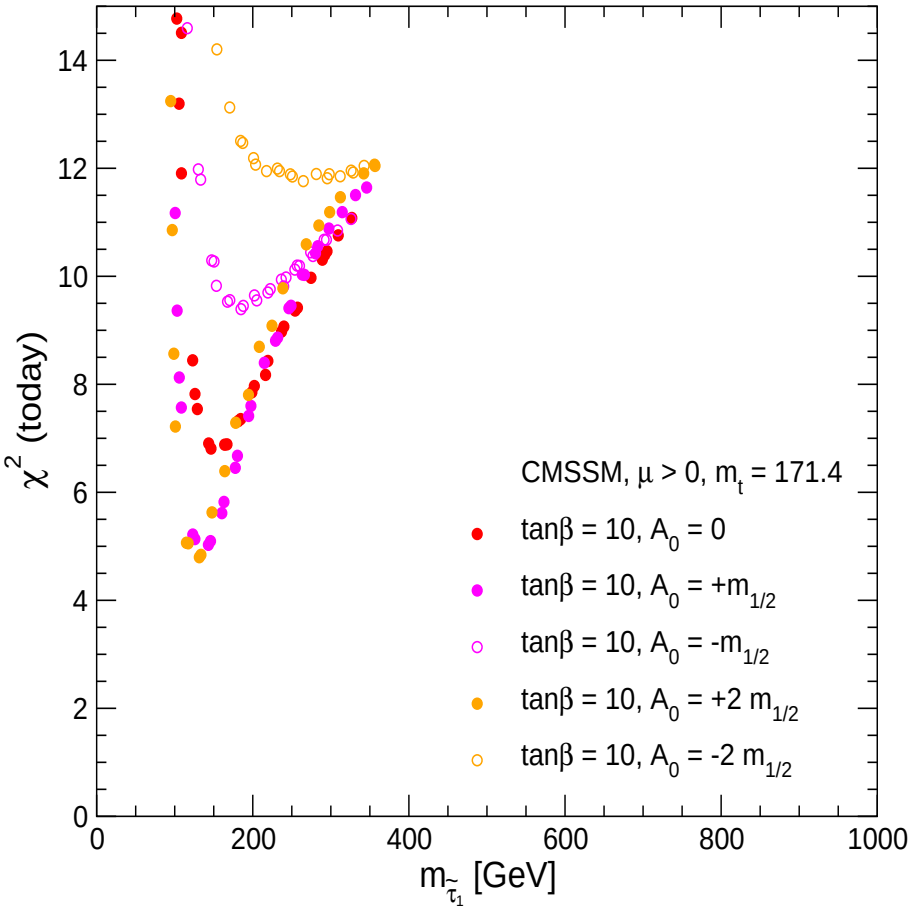


$\tan\beta = 10 \Rightarrow$ accessible at ILC(500)

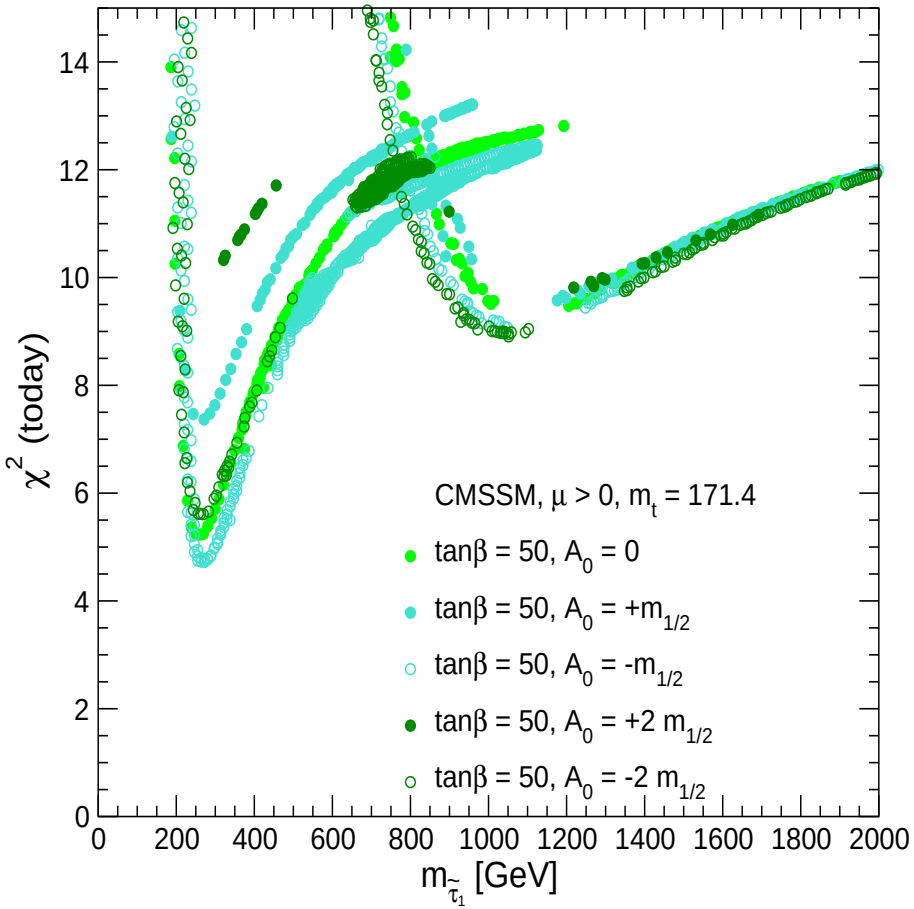
$\tan\beta = 50 \Rightarrow$ accessible at ILC(1000), possibly $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$

Results: CMSSM: prediction for $m_{\tilde{\tau}_1}$

$\tan\beta = 10$



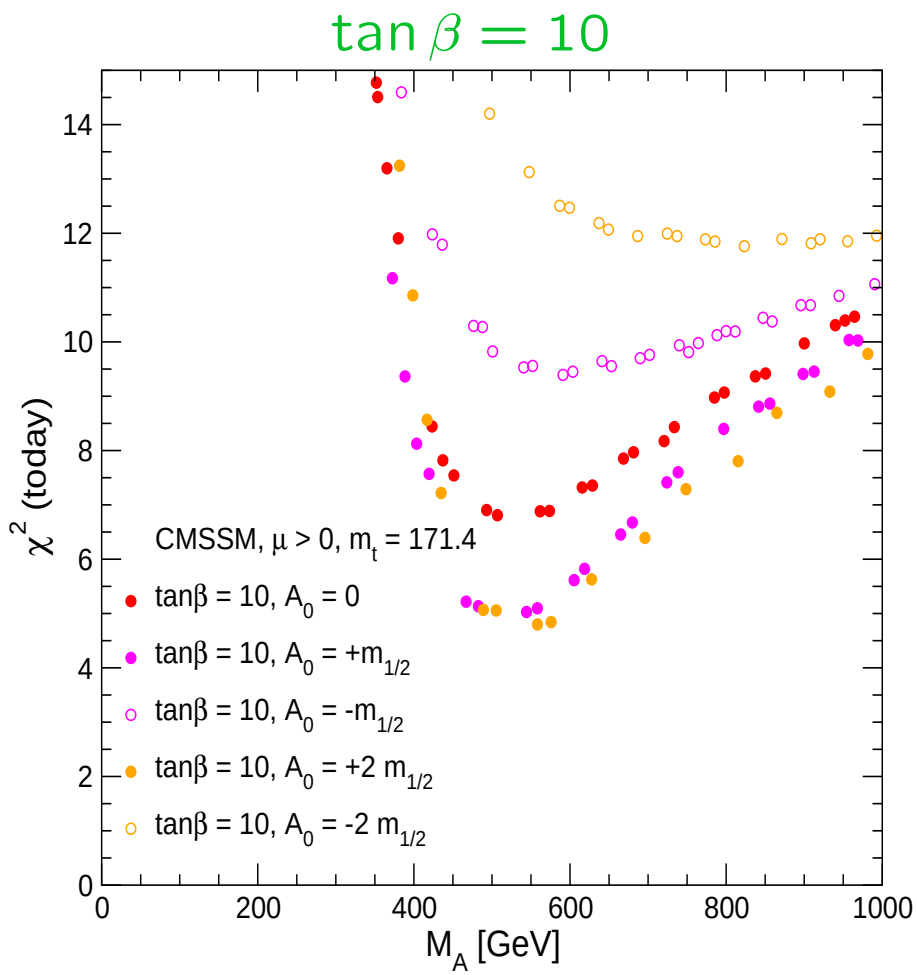
$\tan\beta = 50$

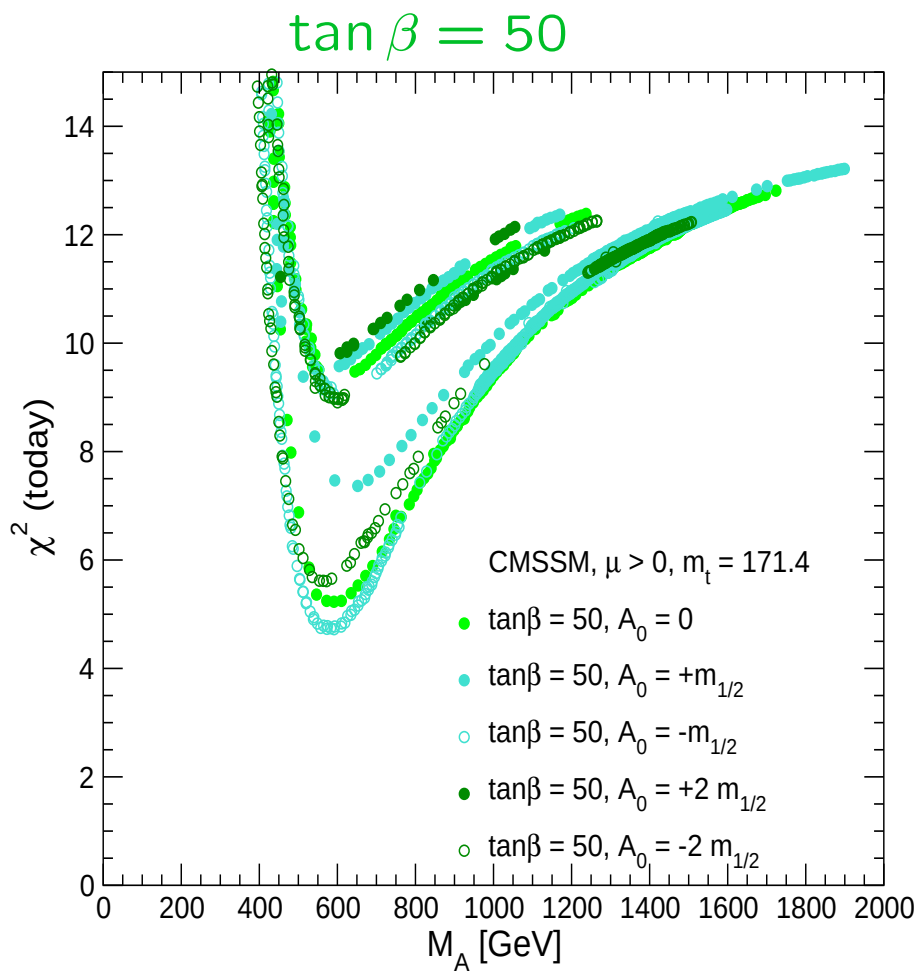


$\tan\beta = 10 \Rightarrow$ accessible at ILC(500)

$\tan\beta = 50 \Rightarrow$ accessible at ILC(1000)

Results: CMSSM: prediction for M_A



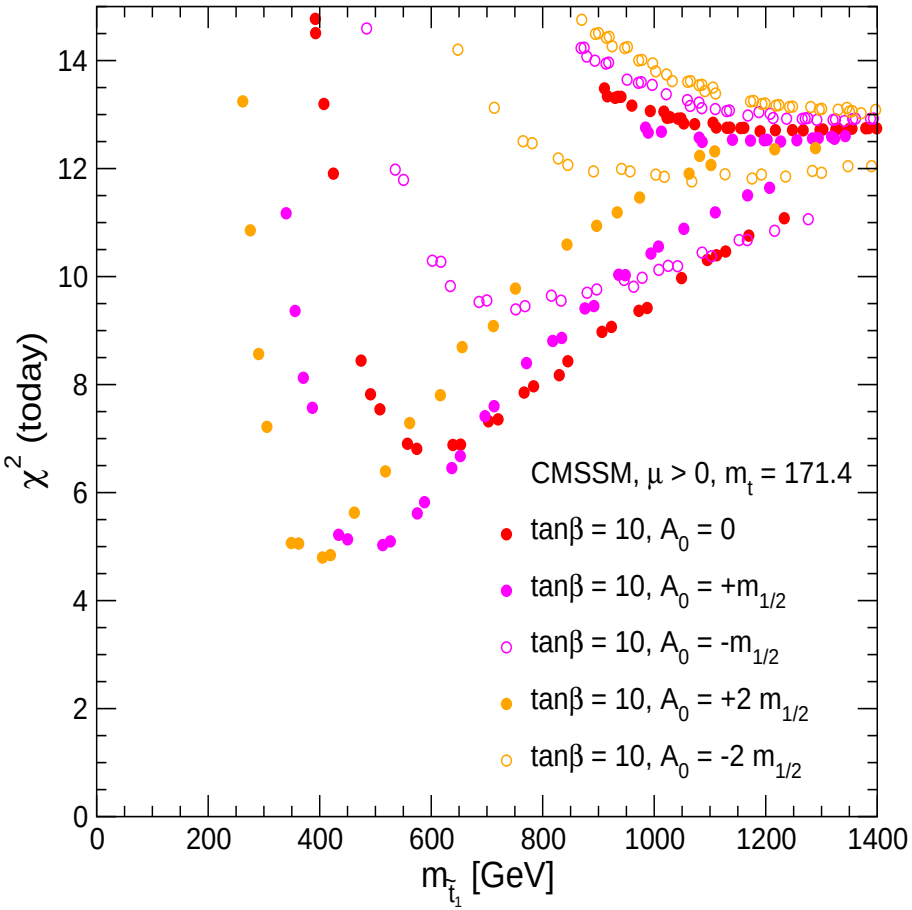


$\tan\beta = 10 \Rightarrow$ possibly too heavy

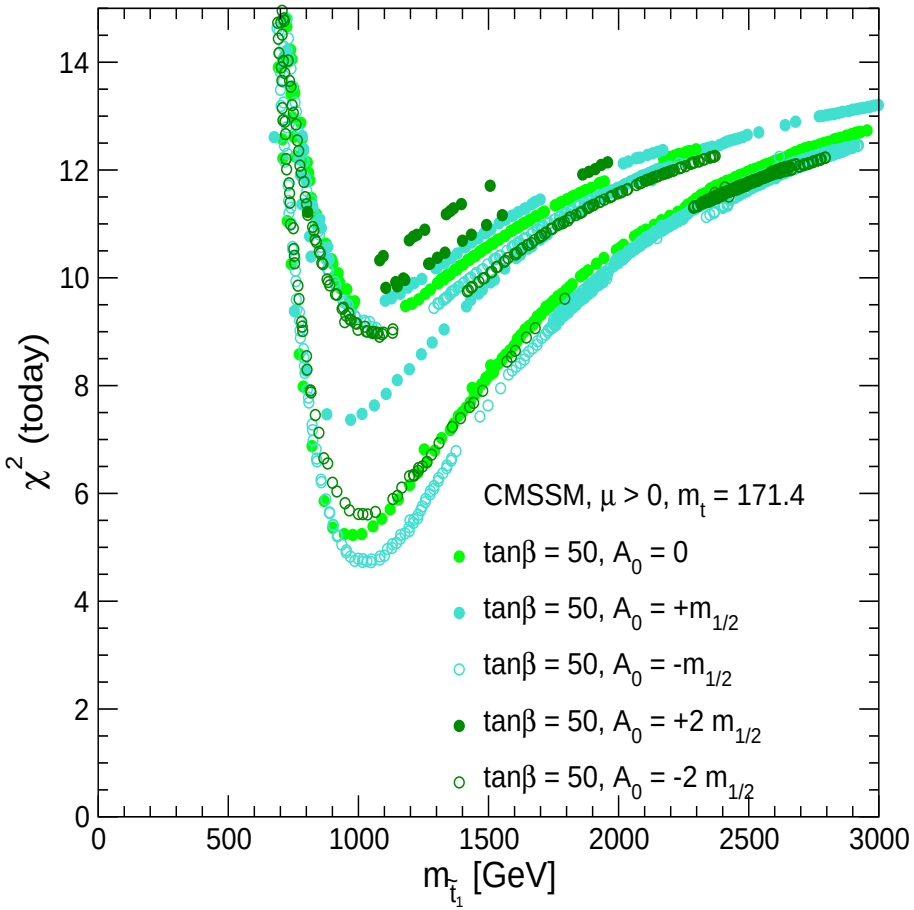
$\tan\beta = 50 \Rightarrow$ possibly too heavy $\Rightarrow$ check single production!

Results: CMSSM: prediction for $m_{\tilde{t}_1}$

$\tan\beta = 10$



$\tan\beta = 50$



$\tan\beta = 10 \Rightarrow$ possibly too heavy

$\tan\beta = 50 \Rightarrow$ definitively too heavy

$\Rightarrow$ other colored particles even heavier $\Rightarrow$ LHC/ILC complementarity!

Results: NUHM

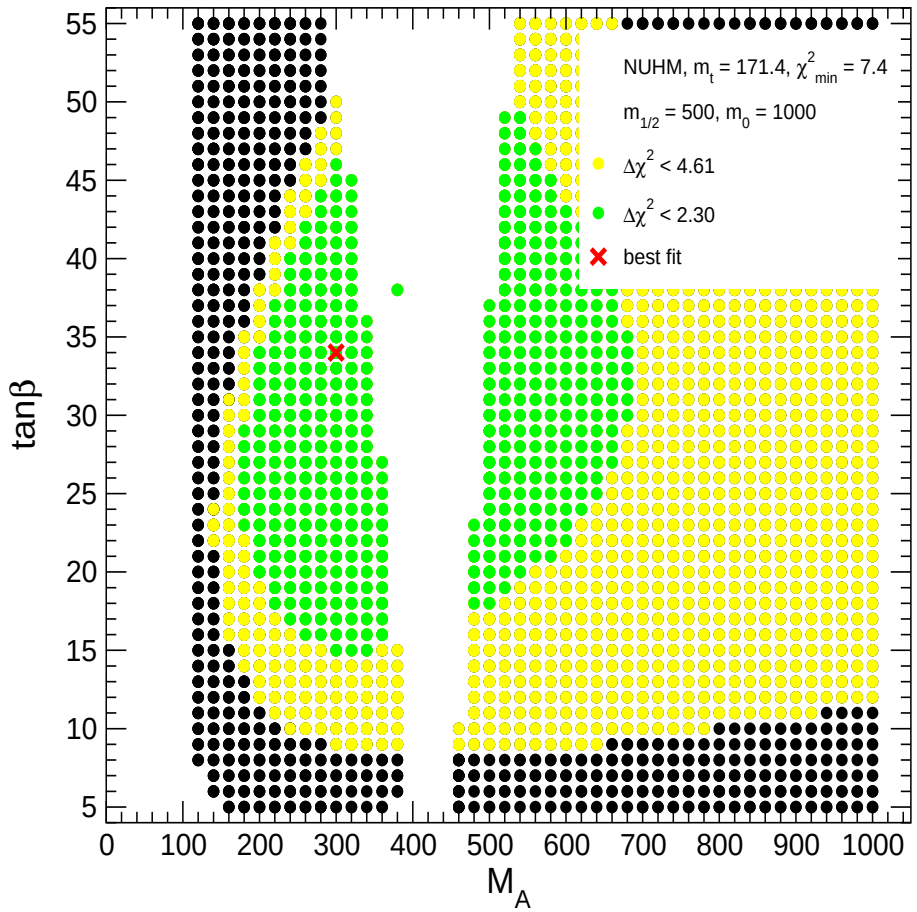
M_A–tan β planes in agreement with CDM

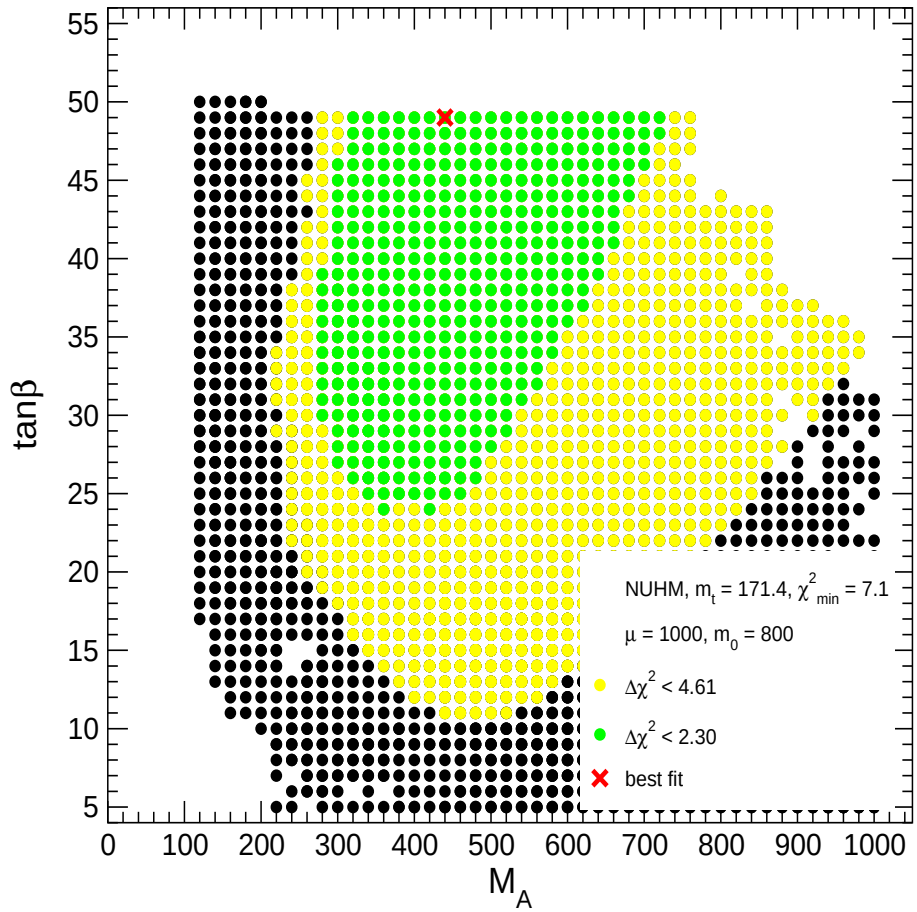
$\Rightarrow$ 4 planes; with $m_{1/2}$ or μ varied to get CDM right

(interesting as benchmark scenarios?)

What about other constraints? $\rightarrow$ see the χ^2

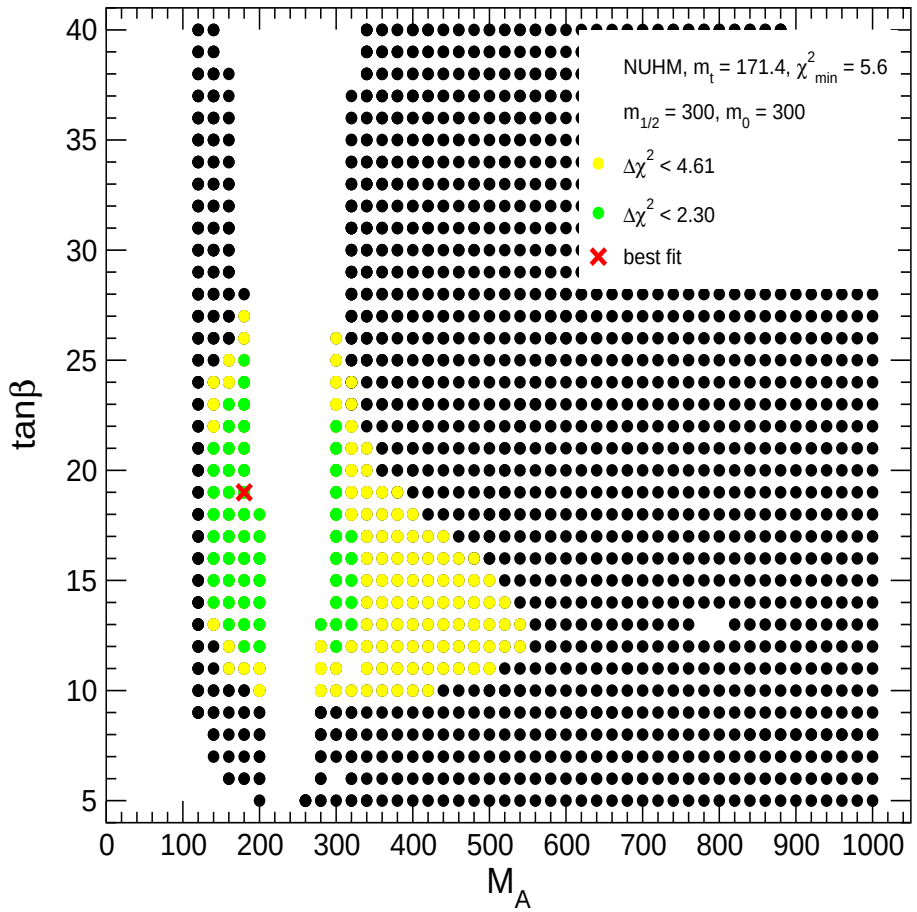
Results: NUHM: planes 2,3

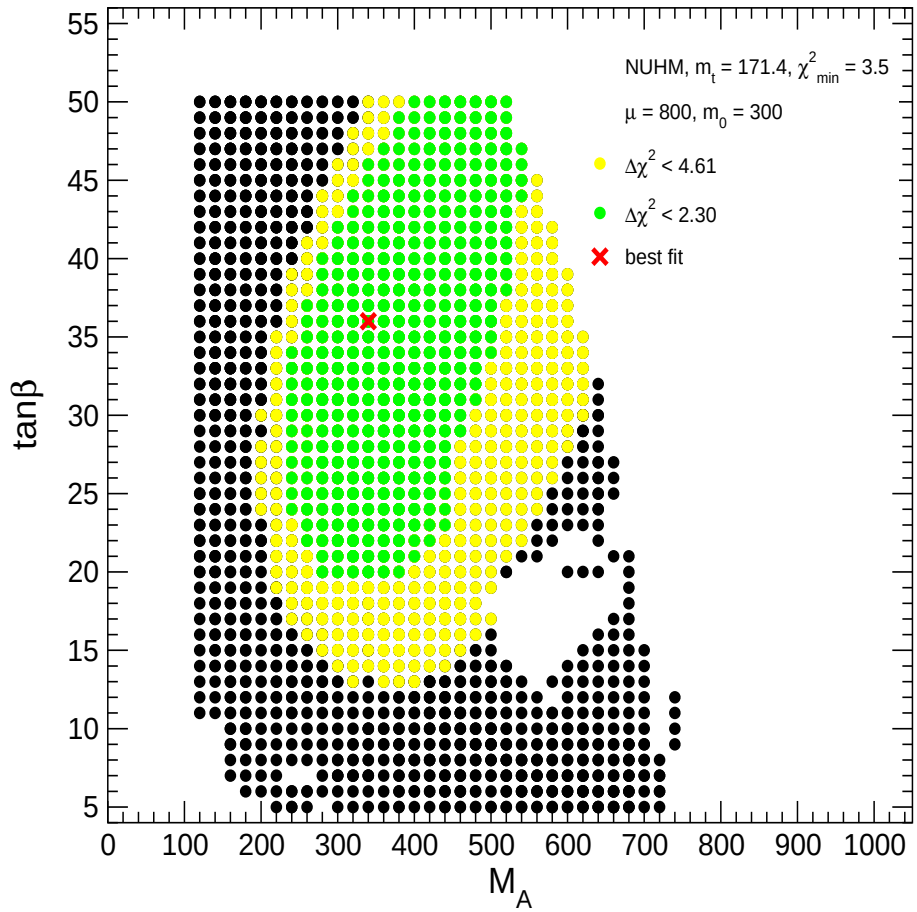




⇒ good χ^2, larger regions o.k.

Results: NUHM: planes 4,5





⇒ good χ^2, larger regions o.k.

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(interesting as benchmark scenarios?)

What about other constraints? $\rightarrow$ see the χ^2

Phenomenology on these planes?

so far only the lightest Higgs has been investigated

$\Rightarrow M_h \lesssim 125$ GeV, SM-like couplings

5. 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, $\sin^2\theta_{\text{eff}}$, Γ_Z, M_h, $(g-2)_\mu$

  Most important B physics observables:

  BR($b \to s\gamma$), BR($B_s \to \mu^+\mu^-$), BR($B_u \to \tau\nu_\tau$), ΔM_{B_s}
- models under consideration: CMSSM, NUHM
- Current χ^2 fit: low values, $\mathcal{O}(4)$ reached
- Evaluation of SUSY spectrum $\Rightarrow$ ILC reach
  similar results in all scenarios:
  $\tan\beta = 10$: sleptons, charginos, neutralinos (partially) in reach
  possibly some chance for light stops
  $\tan\beta = 50$: some sleptons, charginos, neutralinos (partially) in reach
  hardly any chance for light stops or other colored particles

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The prospects for the ILC(500/100) to see SUSY are very good