Phenomenological Indication of the Terascale Implications for the ILC

Sven Heinemeyer, IFCA (CSIC – UCSA)

Vancouver, 07/2006

based on collaboration with
J. Ellis, K. Olive and *G. Weiglein*

1. Motivation and models
2. Precision Observables in the MSSM
3. Fits and ILC reach
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, VCMSSM and GDM
     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
     VCMSSM: even $\tan\beta$ determined
     NUHM, GDM: also strong contraints
   - Use existing data of M_W, $\sin^2\theta_{\text{eff}}$, BR$(b \to s\gamma)$, $(g-2)_\mu$, M_h
     $\Rightarrow \chi^2$ fit with these observables
     $\Rightarrow$ best fit values for masses, couplings, . . .

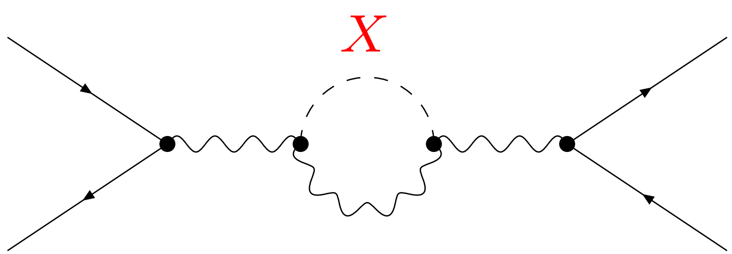
Precision Observables (POs):

Comparison of electro-weak precision observables with theory:

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

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections



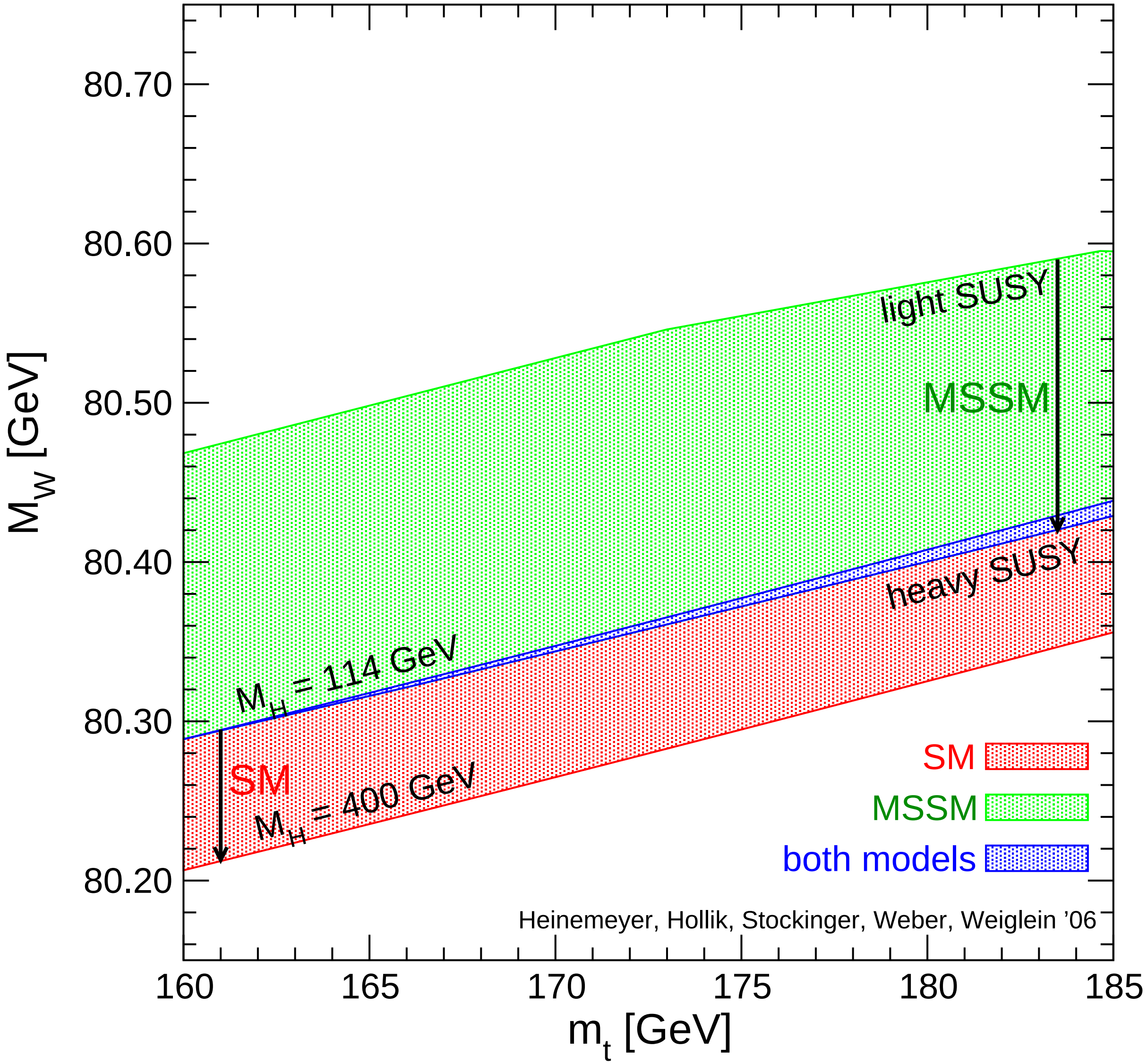
$\Downarrow$

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 '06]



MSSM band:
scan over
SUSY masses

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

SM band:
variation of M_H^{SM}

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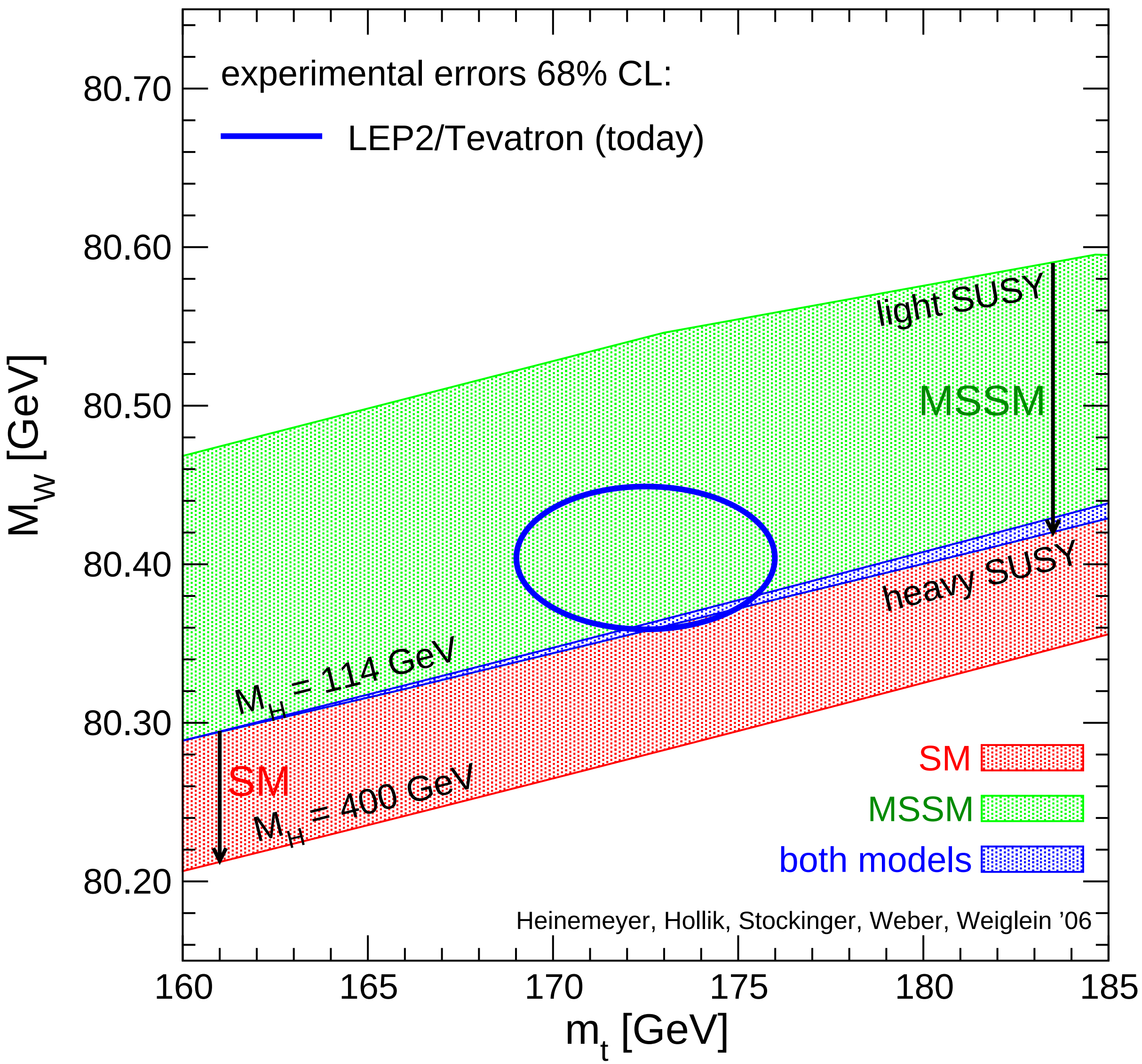

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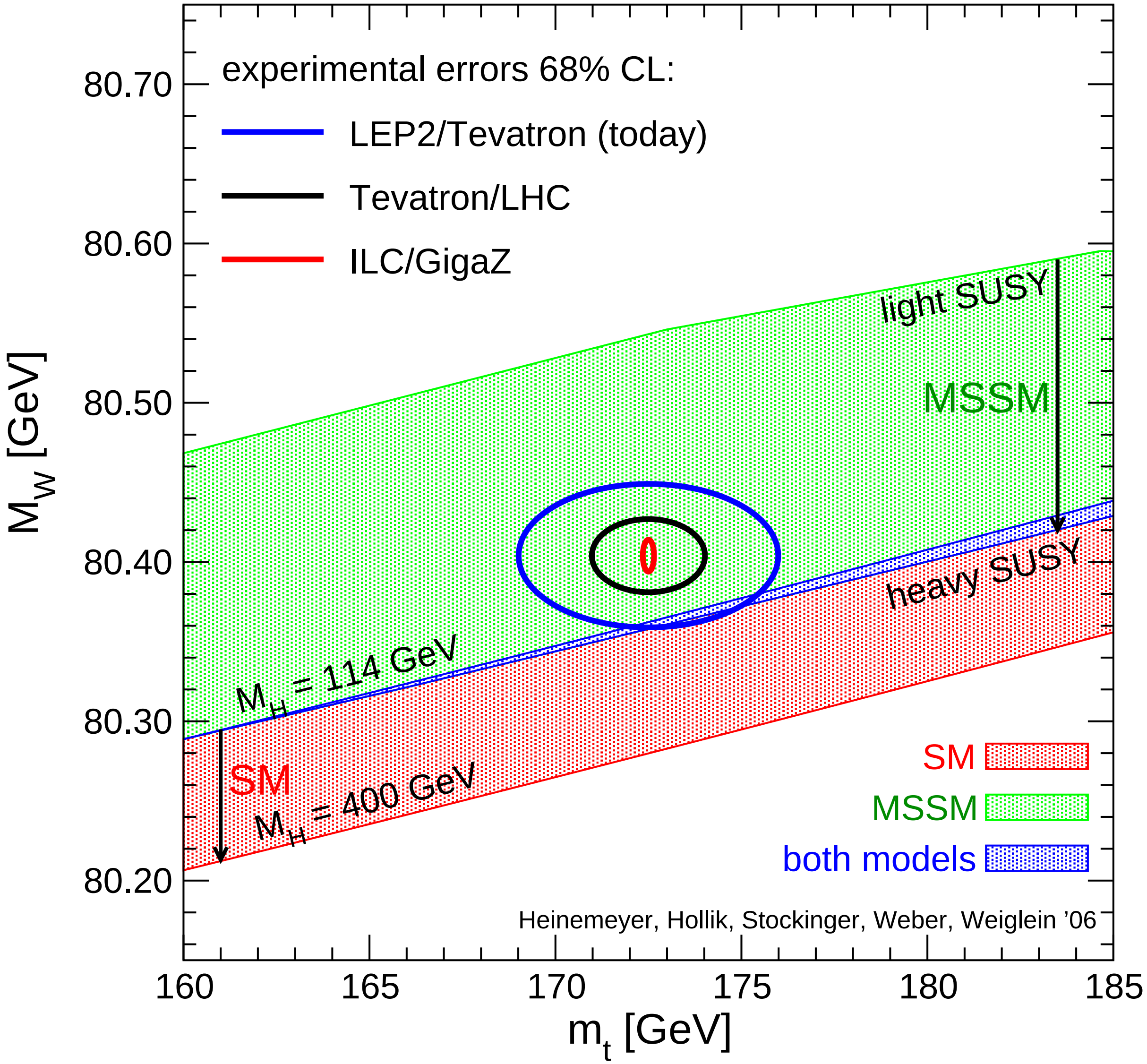

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The models (I):

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

sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

Lightest SUSY particle (LSP) is the lightest neutralino

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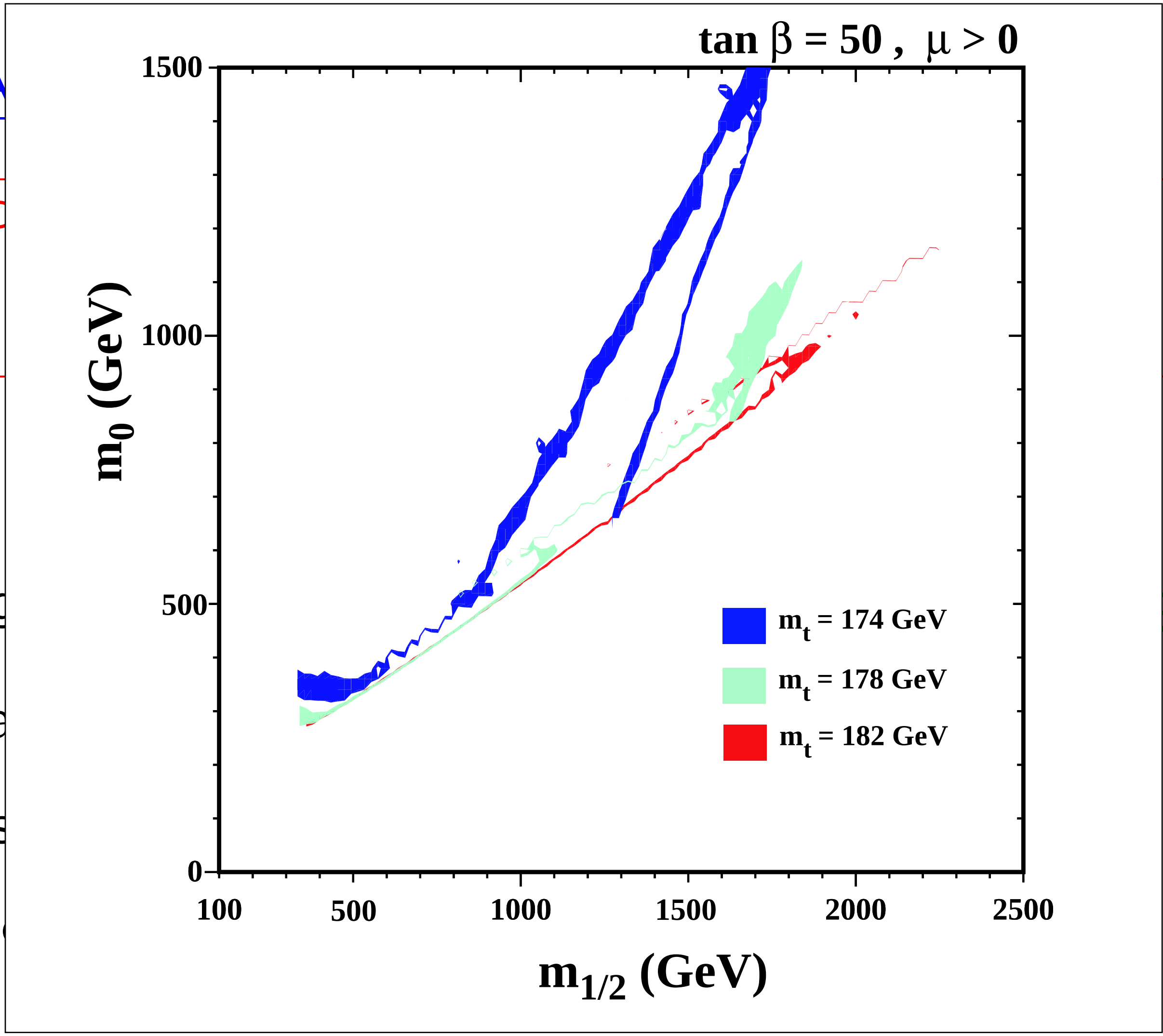

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The models (II):

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

The models (III):

VCMSSM: (Very Constrained MSSM)

> $\Rightarrow$ In addition to CMSSM: assume relation between A_0 and m_0:
> $$A_0/m_0 = 0,\ 3/4,\ 3-\sqrt{3},\ 2$$

Additional constraint also fixes $\tan\beta$

Free parameters: $m_{1/2}$, A_0/m_0

m_0 and $\tan\beta$ fixed via CDM constraint

Lightest SUSY particle (LSP) is the lightest neutralino

GDM (mSUGRA): (Gravitino DM in mSUGRA)

> $\Rightarrow$ In addition to CMSSM: assume relation between A_0 and m_0:
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mSUGRA: $m_{\text{gravitino}} = m_0 \Rightarrow$ gravitino can be the LSP

Free parameters: $m_{1/2}$, A_0/m_0

Lightest SUSY particle (LSP) is the gravitino

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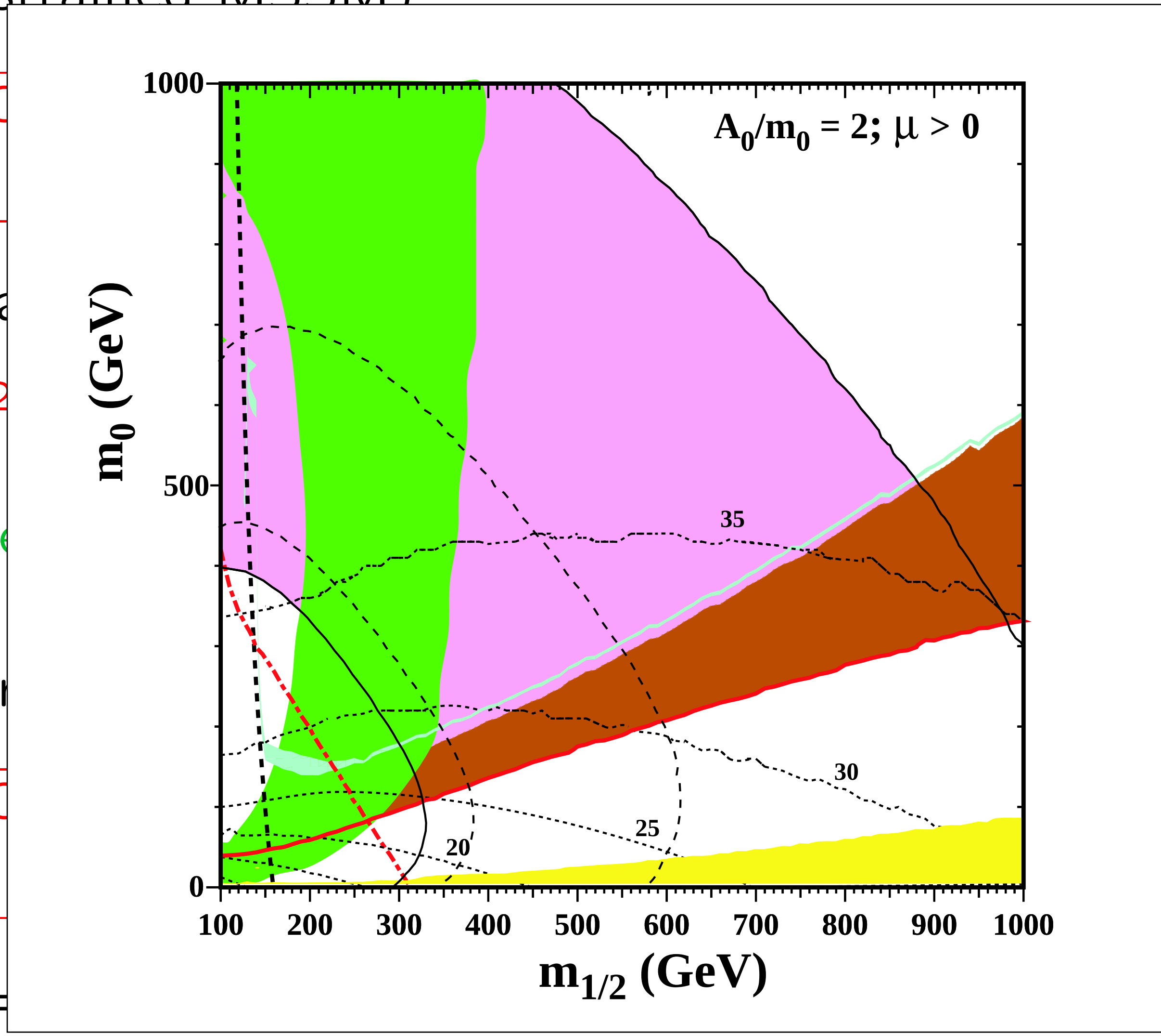
⇒ In addition to C ...):

Additional constraint a

Free parameters: $m_{1/2}$

m_0 and $\tan\beta$ fixed via

Lightest SUSY particle



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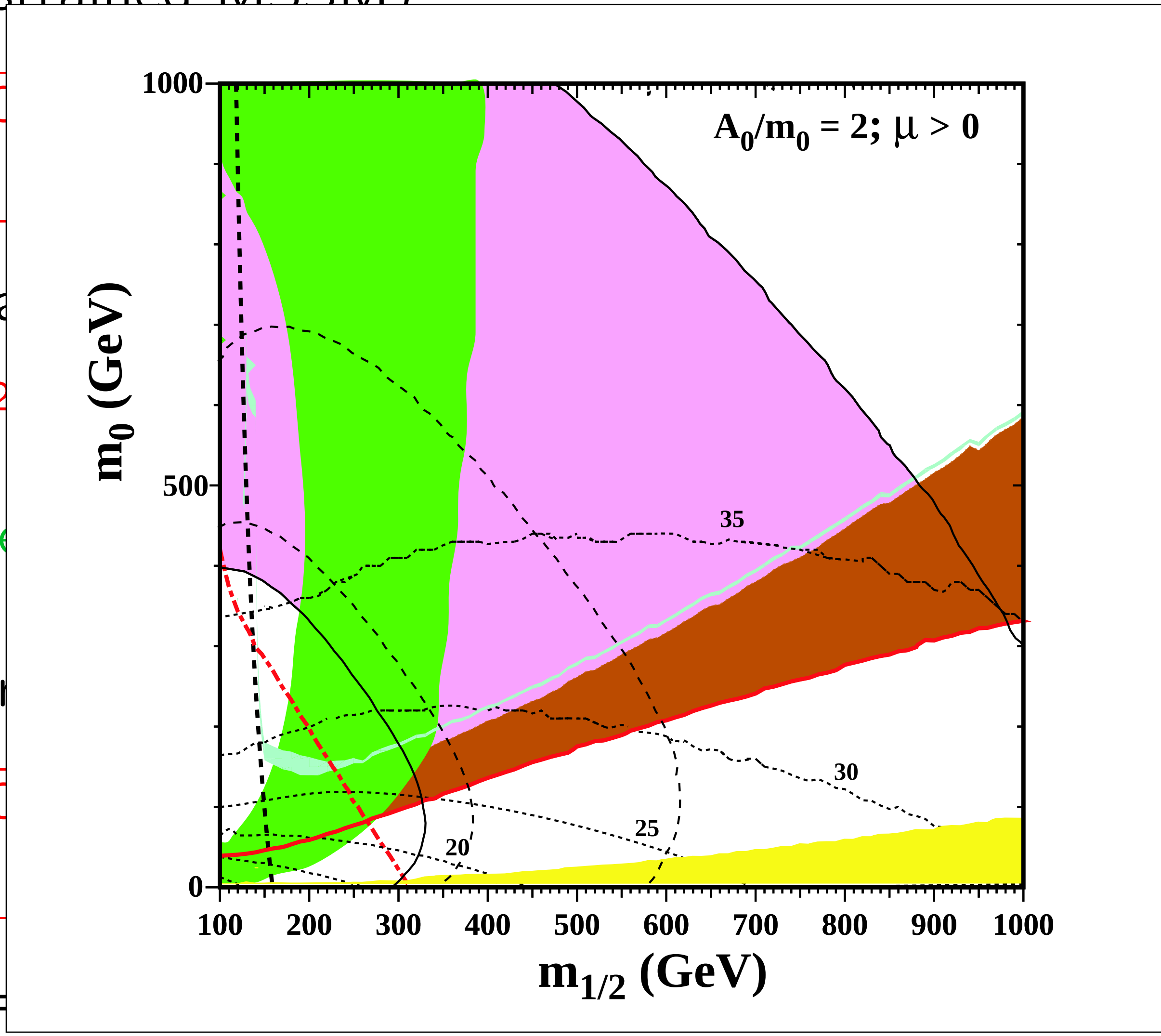
Free parameters: $m_{1/2}$...

m_0 and $\tan\beta$ fixed via...

Lightest SUSY particle...



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⇒ In addition to C ...):

mSUGRA: $m_{\text{gravitino}}$ = ...

Free parameters: $m_{1/2}$, A_0/m_0

Lightest SUSY particle (LSP) is the gravitino

2. Precision Observables in the MSSM

Precision observables: M_W, $\sin^2\theta_{\mathrm{eff}}$, m_h, $(g-2)_\mu$, b physics, . . .

2 A) Theoretical prediction for M_W in terms

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

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

$\Updownarrow$

loop corrections

→ more details in talk by S.H. earlier today

2 B) Effective mixing angle:

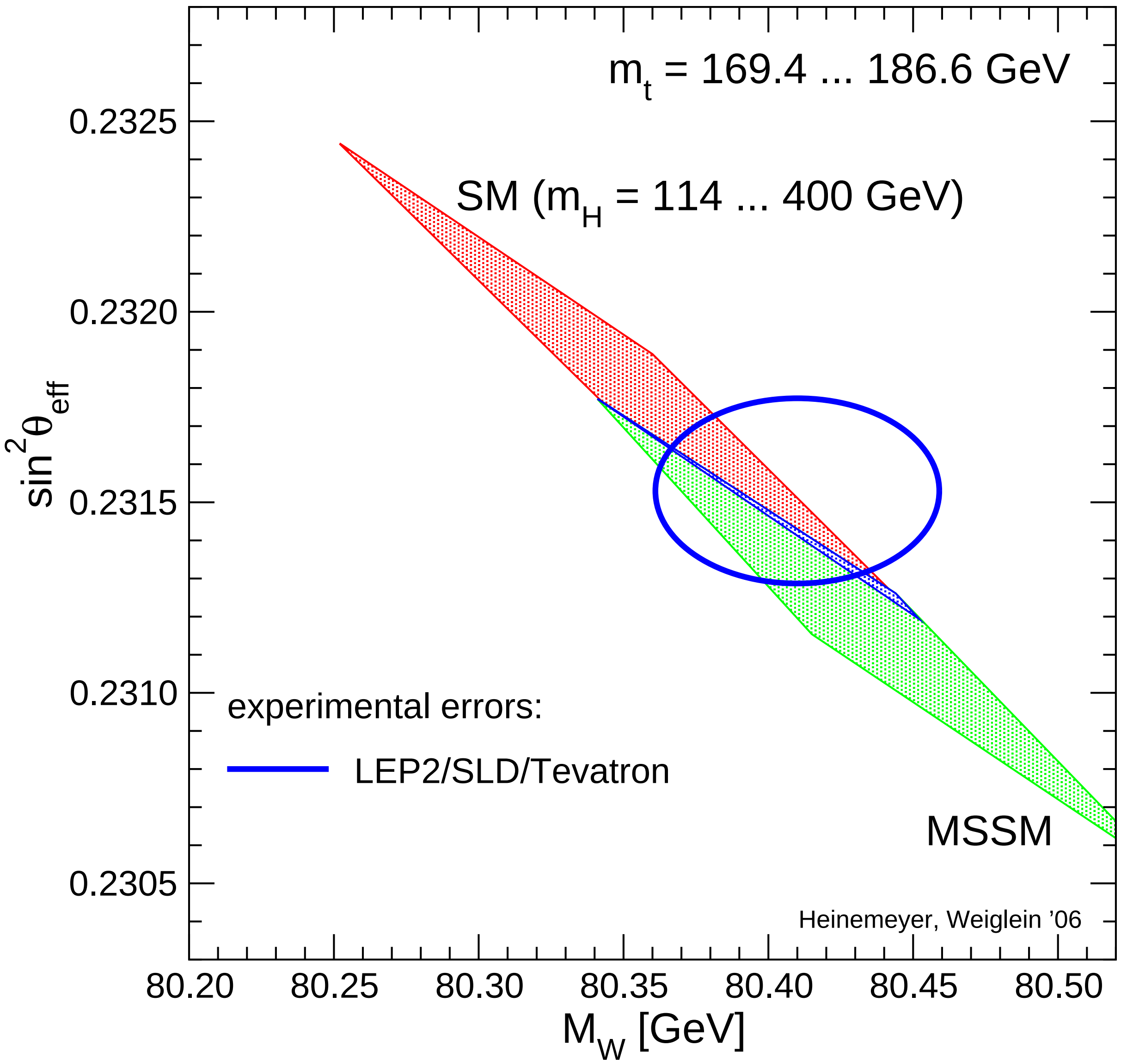
$$\sin^2\theta_{\mathrm{eff}} = \frac{1}{4\,|Q_f|}\left(1 - \mathrm{Re}\,\frac{g_V^f}{g_A^f}\right)$$

Higher order contributions:

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

Example of application:

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



MSSM uncertainty:
unknown masses
of SUSY particles

SM uncertainty:
unknown Higgs mass

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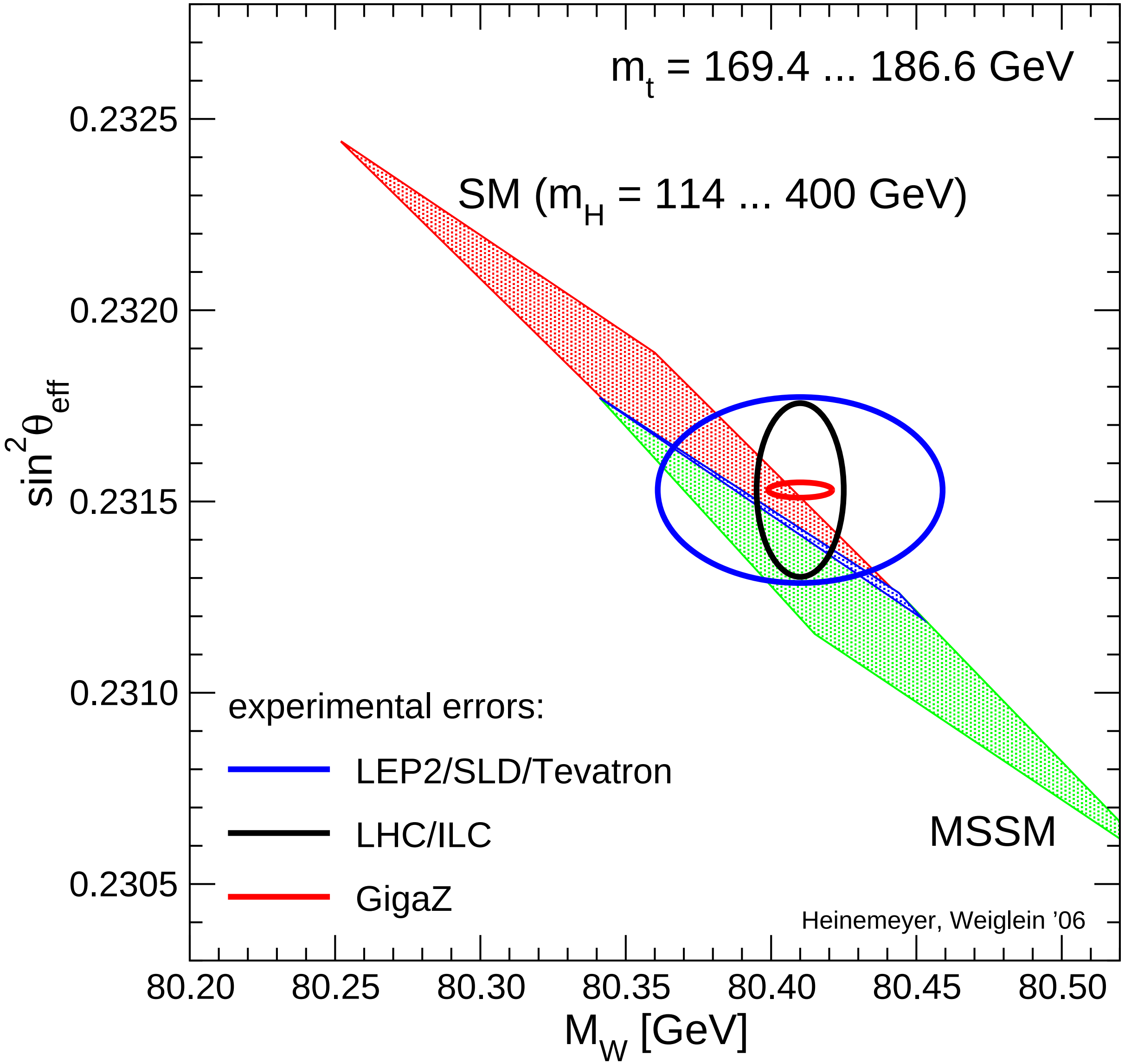


MSSM uncertainty:

unknown masses of SUSY particles

SM uncertainty:

unknown Higgs mass

For χ^2 fit:

$$\chi^2_x = \left(\frac{R_x^{\text{exp}} - R_x^{\text{theo}}}{\sigma_x}\right)^2 \qquad x = M_W, \sin^2\theta_{\text{eff}}$$

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*]

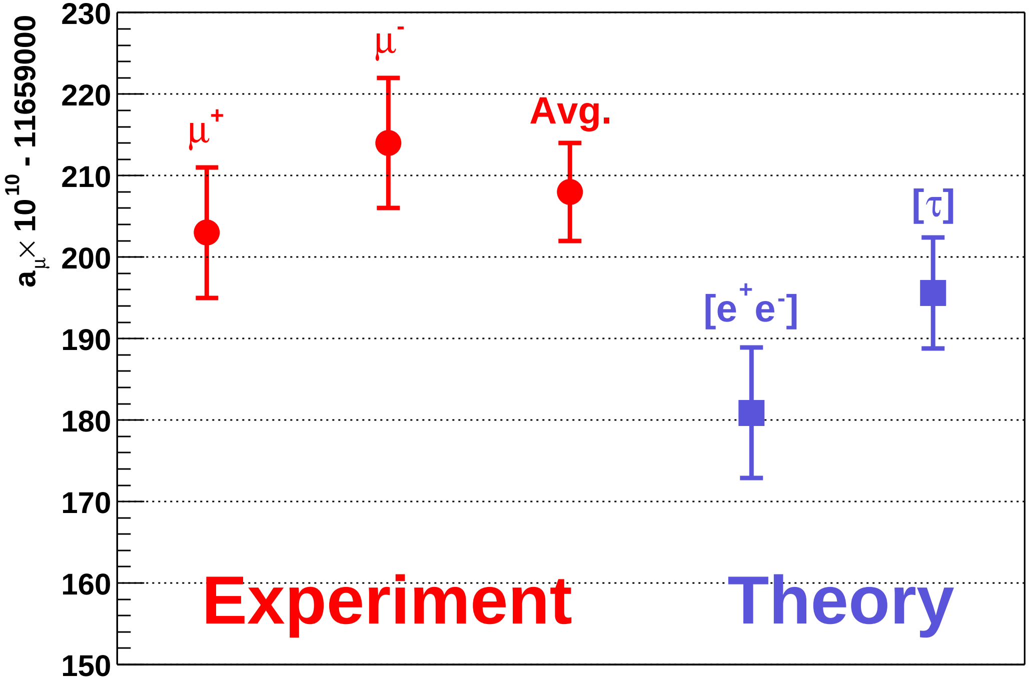
[*J. Haestier, S.H., D. Stöckinger, G. Weiglein '05*]

[*LEPEWWG '05*]

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

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

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



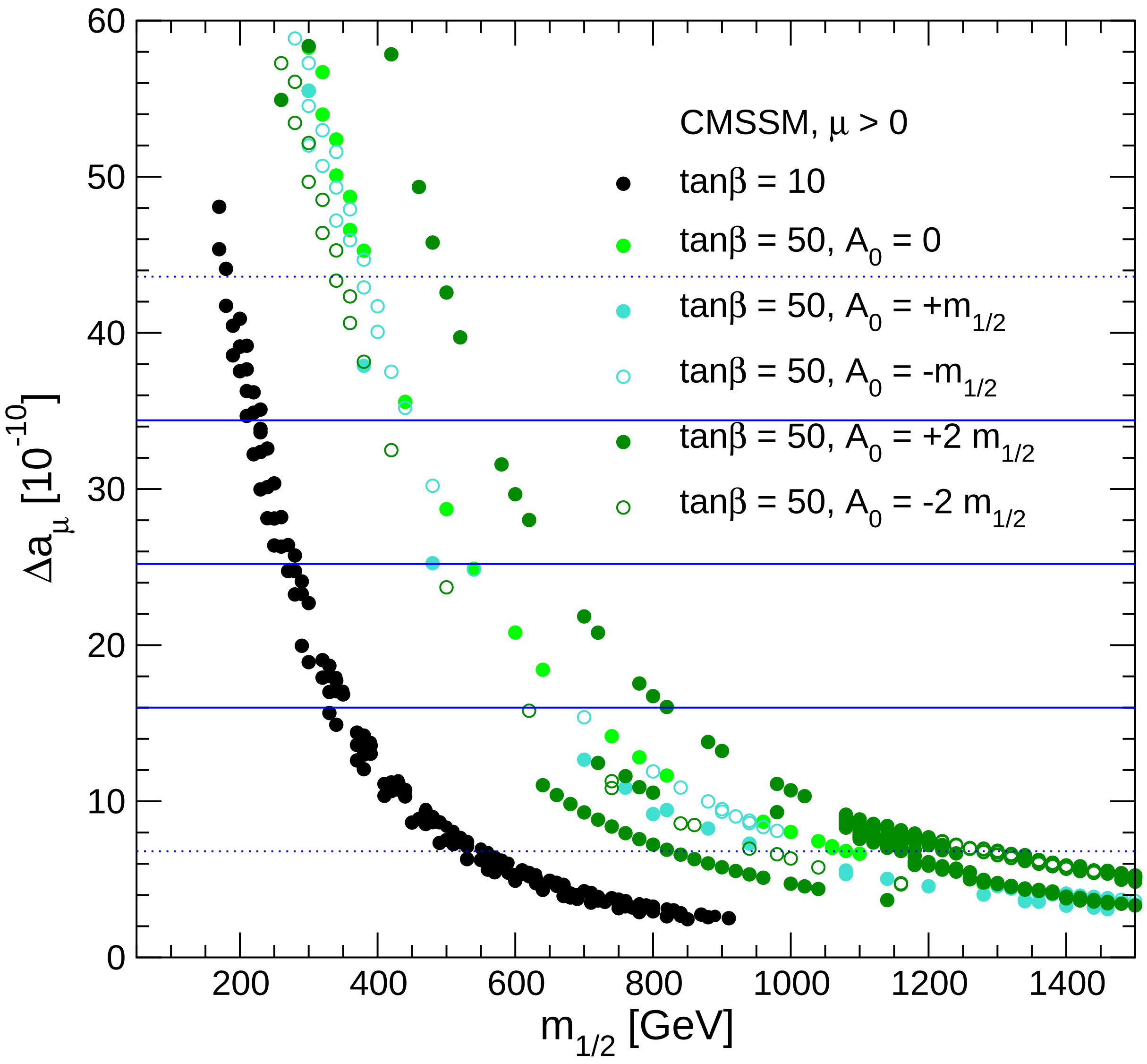
e^+e^- data: no significant changes by new SND, CMD2, KLOE data

τ data: isospin breaking problem still unresolved

based on e^+e^- data:

$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (25.2 \pm 9.2) \times 10^{-10}$$

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:

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

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

⇒ use most up to date calculations and error estimates

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

[S.H., D. Stöckinger, G. Weiglein '03,'04]

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

2 D) Prediction of the decay $b \to s\gamma$

$$\chi_x^2 = \left(\frac{R_x^{\text{exp}} - R_x^{\text{theo}}}{\sigma_x}\right)^2 \qquad x = \text{BR}(b \to s\gamma)$$

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

⇒ use most up to date calculations and error estimates

[*Asatrian, Hovhannisyan, Greub, Hurth, Poghosyan '05*]

[*BaBar, Belle '02, '04*]

[*HFAG '06*]

2 E) Theoretical prediction of 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:

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

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

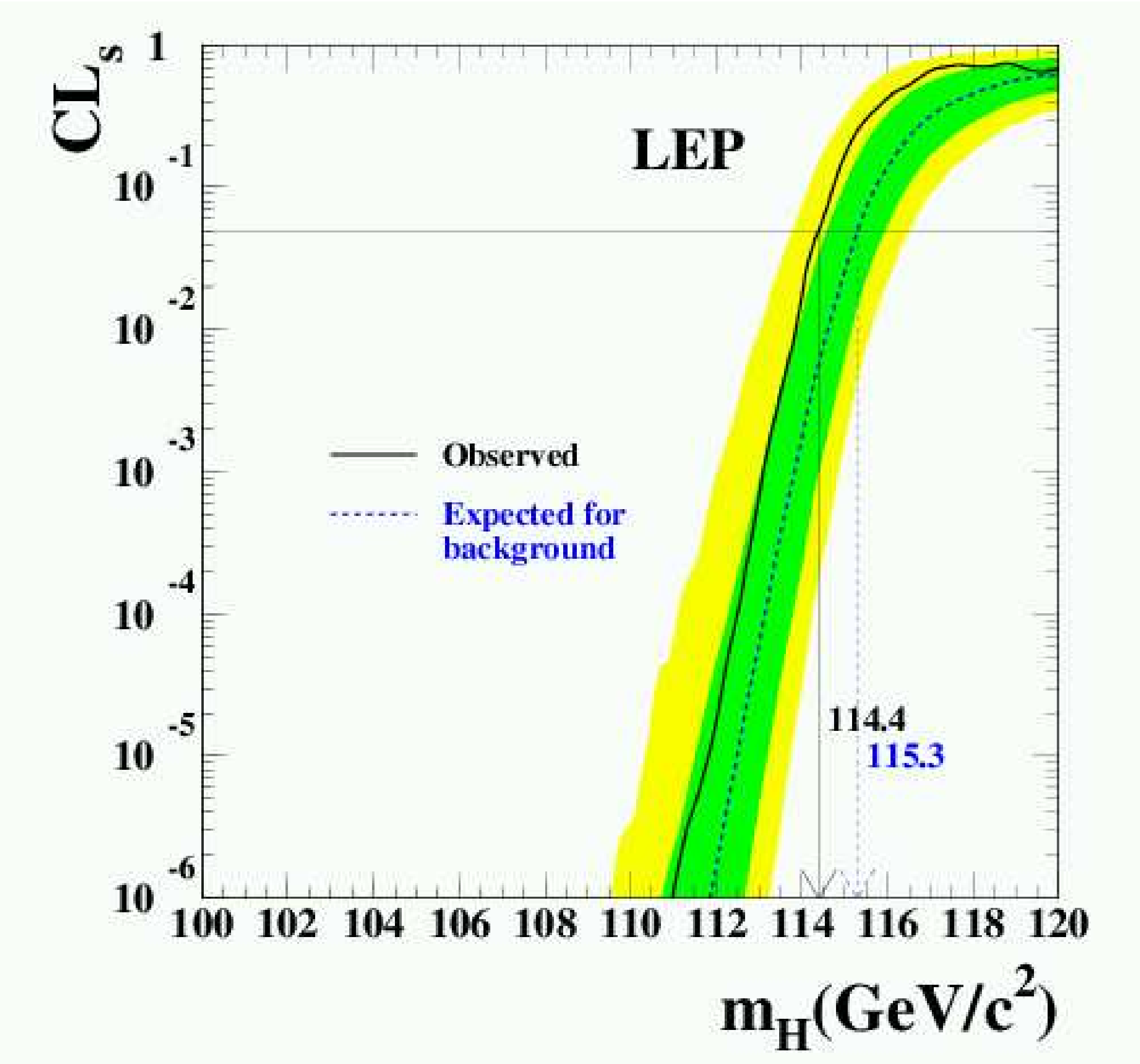
Measurement of M_h, Higgs couplings $\Rightarrow$ test of the theory

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, VCMSSM, GDM: 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*
(`www.feynhiggs.de`)

3. Fits and ILC reach

Proceedure:

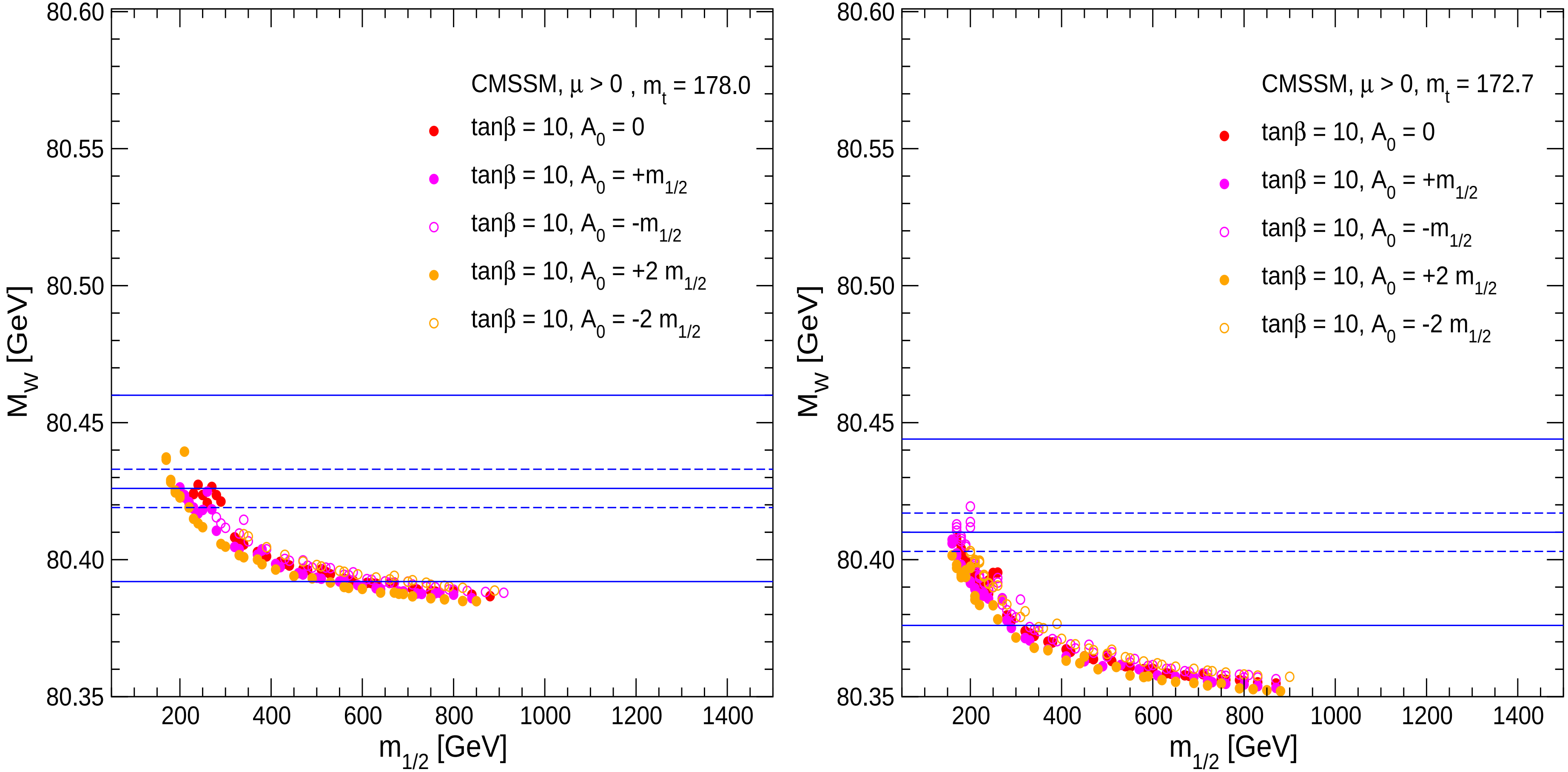
1. Scan over parameter space:
   - CMSSM: for fixed $\tan\beta = 10, 50$
   - NUHM: certain parameter planes,
     corresponding to CMSSM best fit points
   - VCMSSM: full parameter space ($A_0/m_0 = 0, 3/4, 3 - \sqrt{3}, 2$)
   - GDM (mSUGRA): full parameter space ($A_0/m_0 = 0, 3/4, 3 - \sqrt{3}, 2$)

2. Perform χ^2 fit

3. Find preferred valus for masses
   $\Rightarrow$ ILC reach

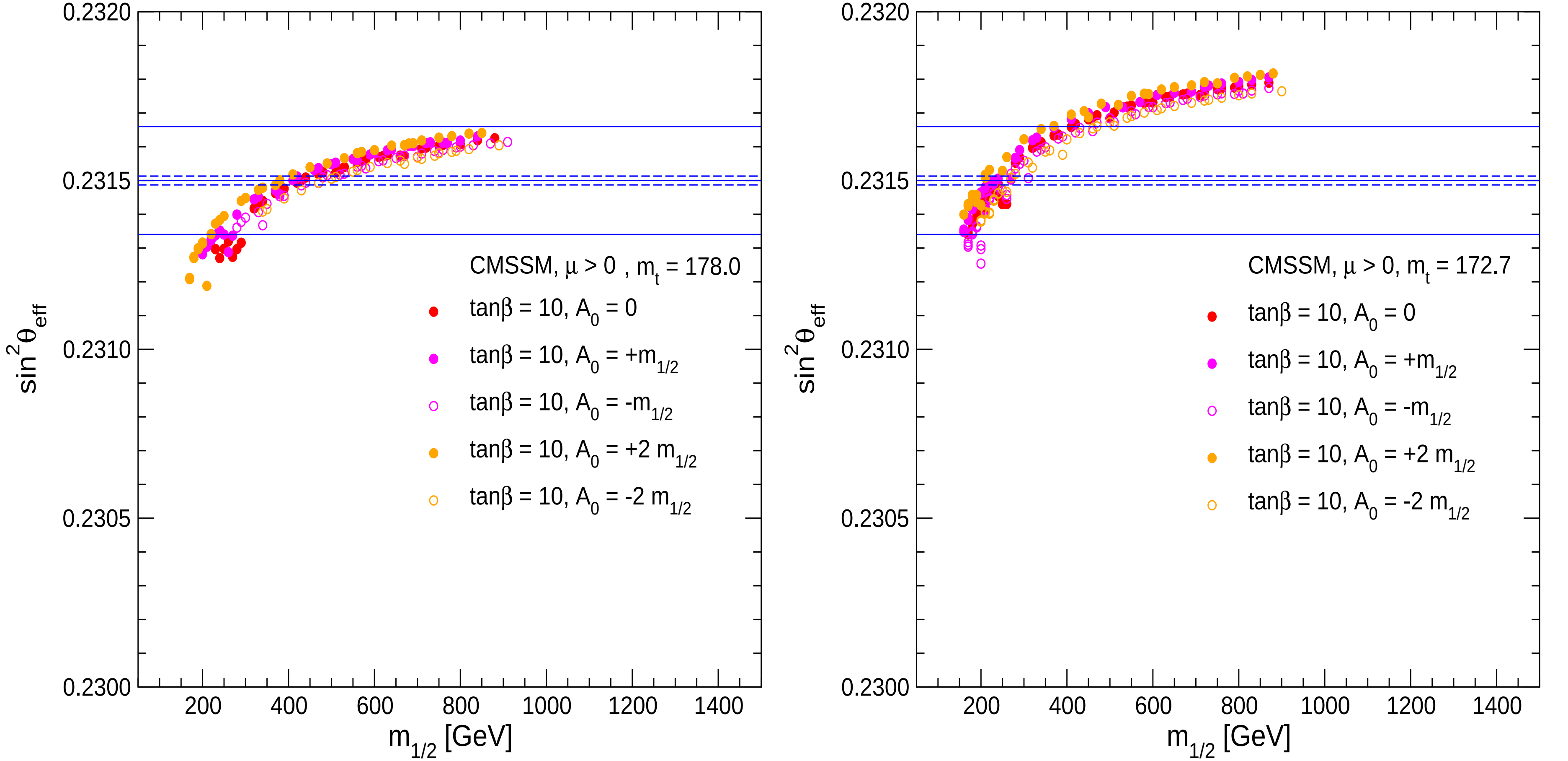
3 A) CMSSM:

Compare $m_t = 178$ GeV with $m_t = 172.7$ GeV: M_W for $\tan\beta = 10$:



$m_t = 178 \to 172.7 \Rightarrow m_{1/2}$ lowered

Compare $m_t = 178$ GeV with $m_t = 172.7$ GeV: $\sin^2\theta_{\rm eff}$ for $\tan\beta = 10$:



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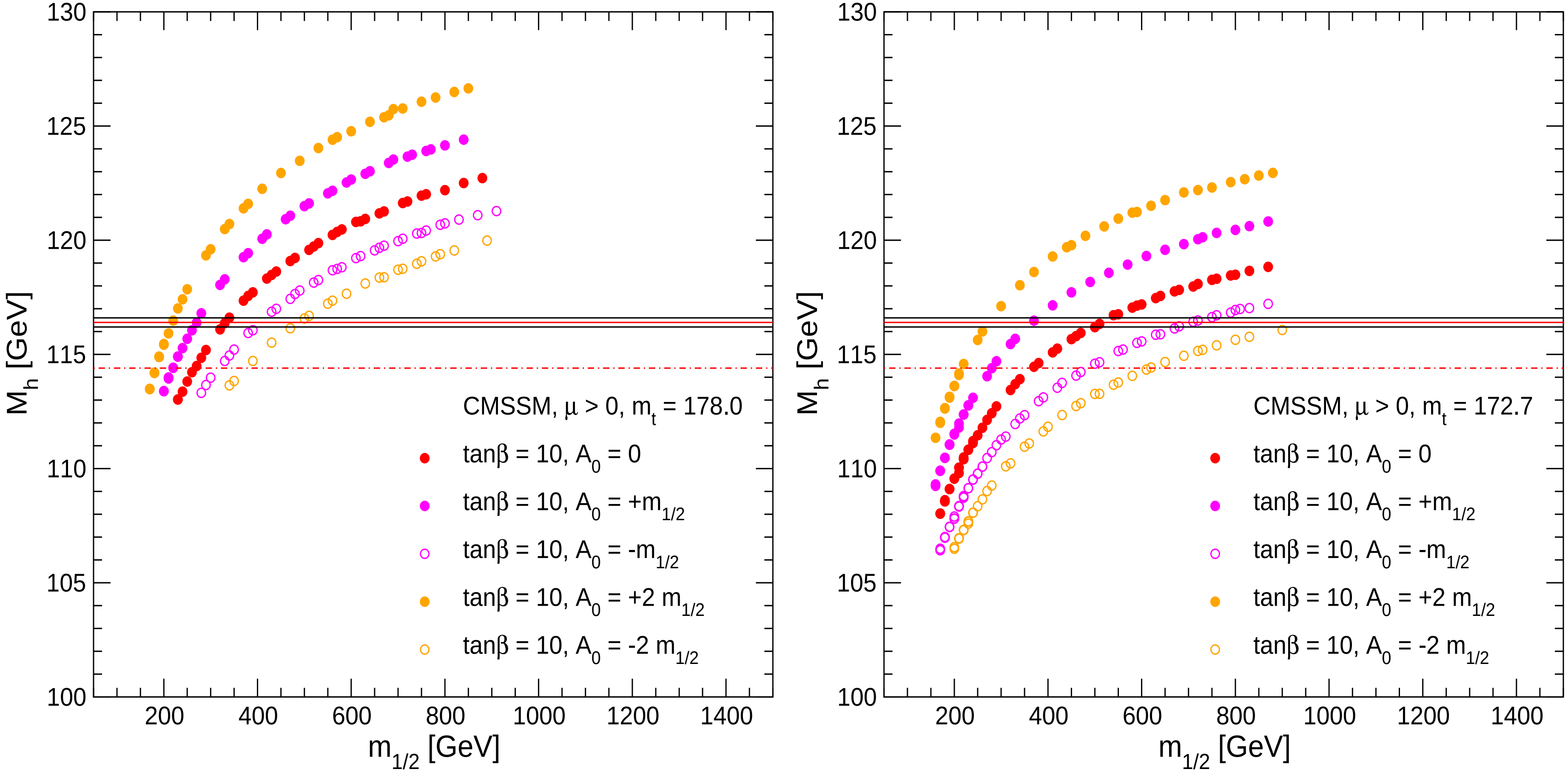
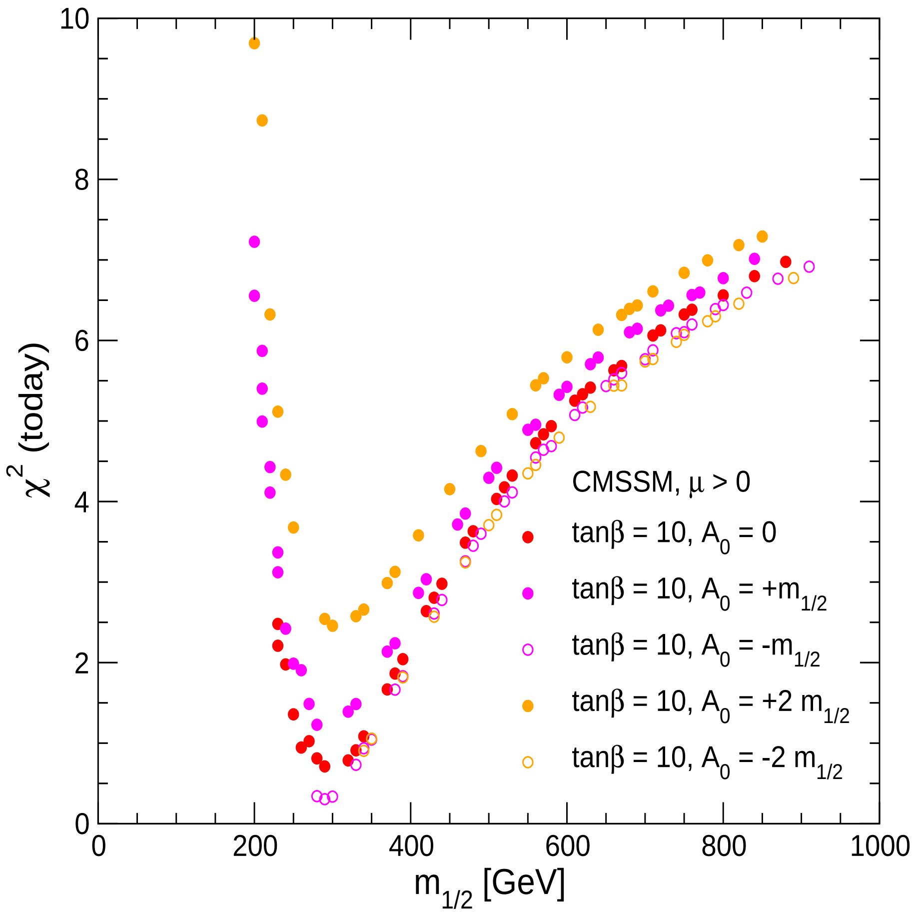
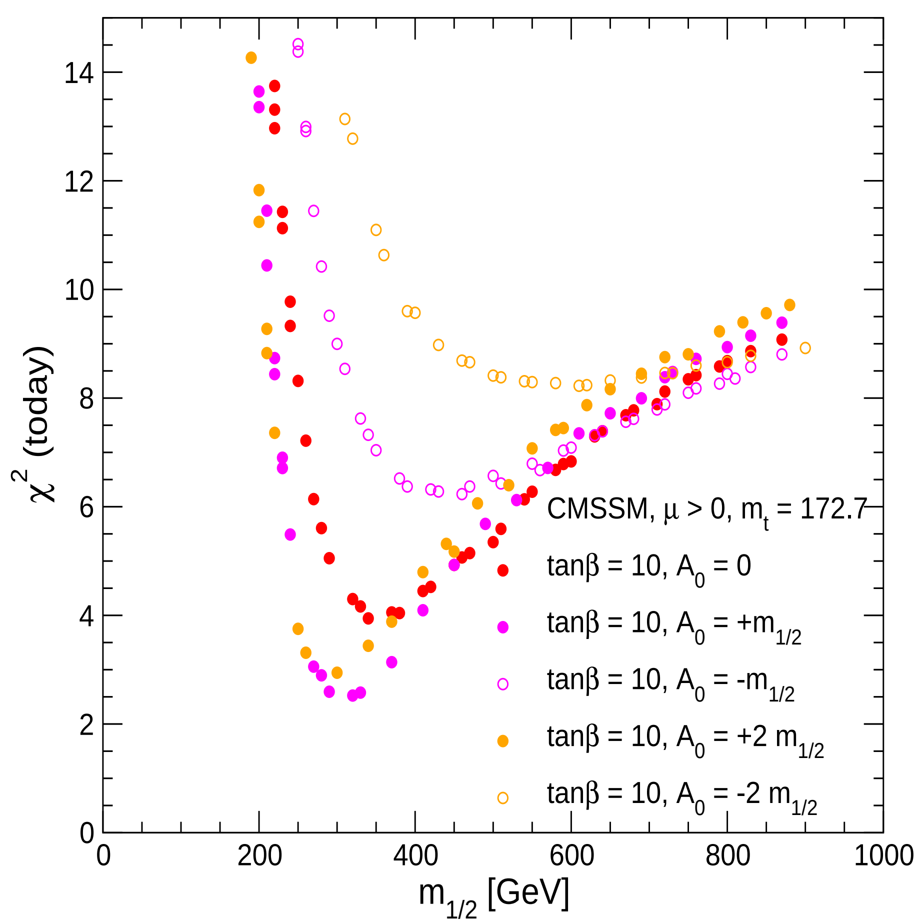


$m_t = 178 \rightarrow 172.7 \Rightarrow m_{1/2}$ increased

Effect of $m_t = 178$ GeV with $m_t = 172.7$ GeV: χ^2 fit for $\tan\beta = 10$:

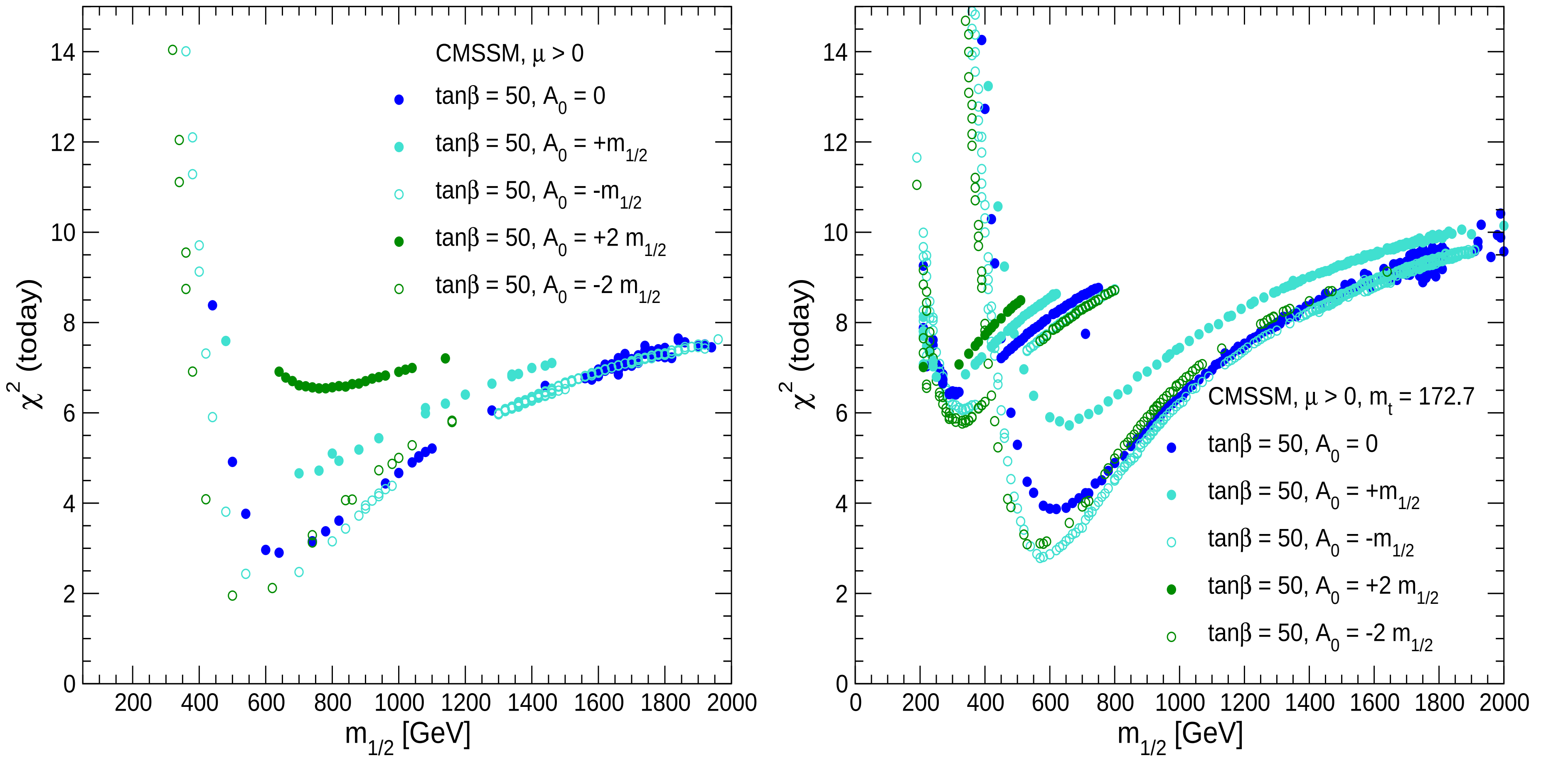




$m_t = 178 \to 172.7$ slightly higher χ^2, $A_0 > 0$ favored

$\Rightarrow M_W$ and $\sin^2\theta_{\rm eff}$ more important, $(g-2)_\mu$ less important for low $m_{1/2}$

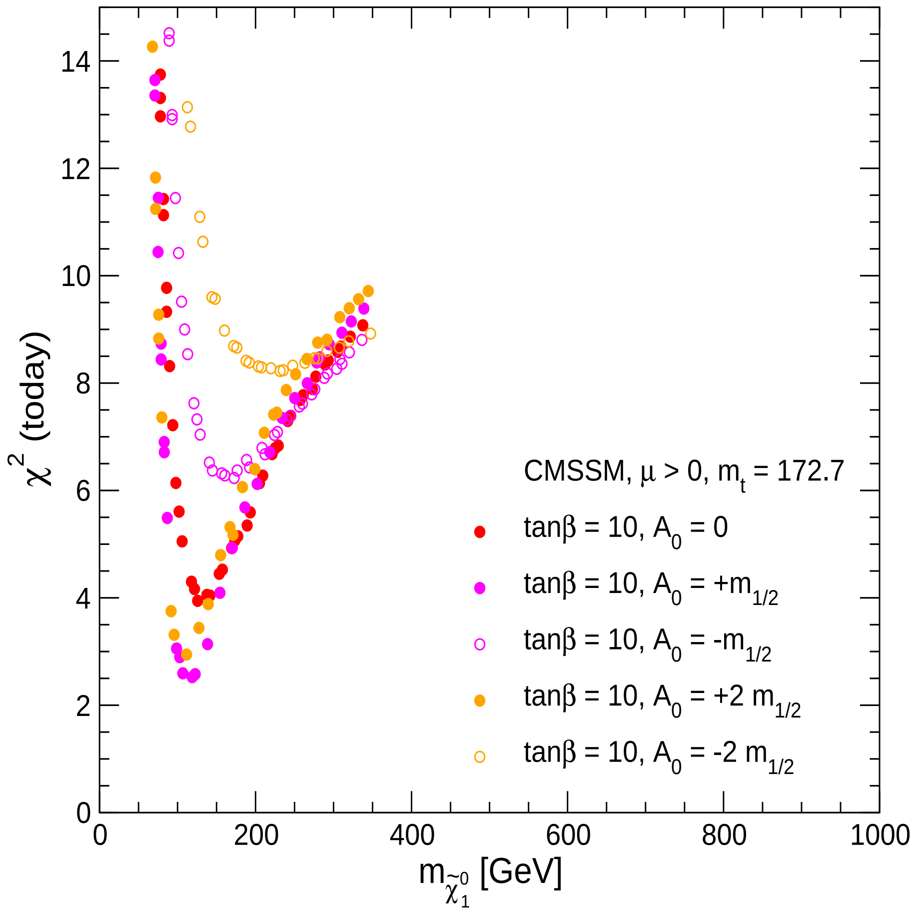
Effect of $m_t = 178$ GeV with $m_t = 172.7$ GeV: χ^2 fit for $\tan\beta = 50$:

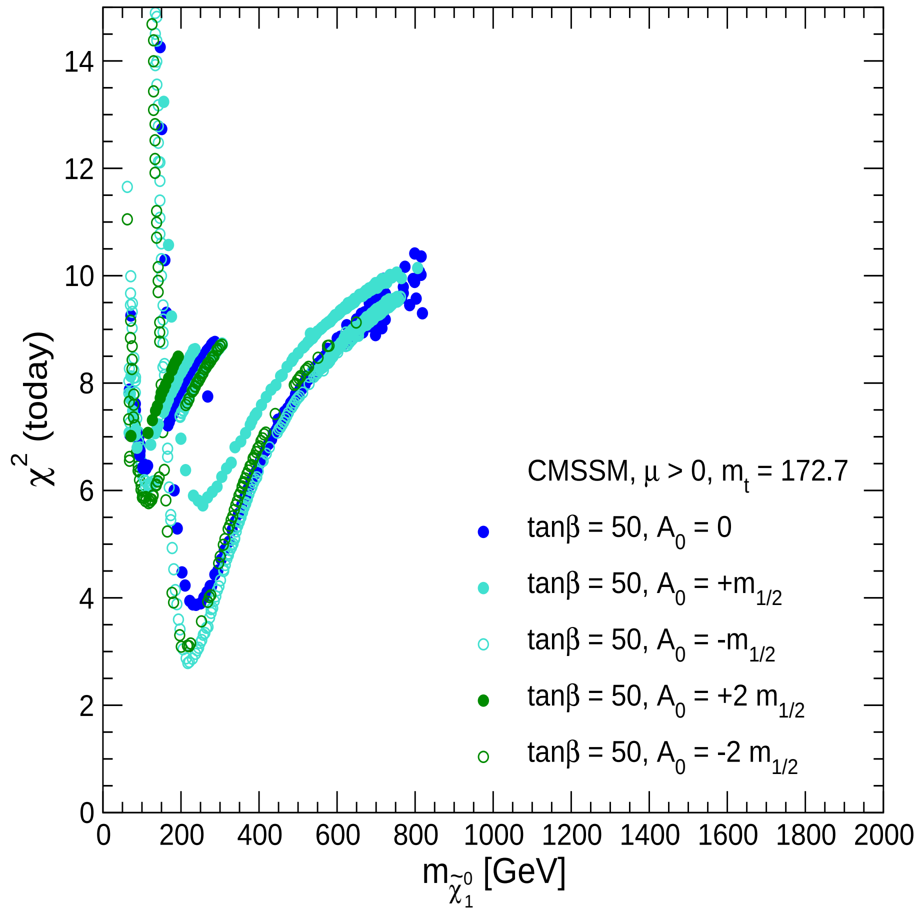


$m_t = 178 \to 172.7$ effective change minor

$\Rightarrow$ (re)appearance of focus point region at $m_{1/2} \approx 200$ GeV

CMSSM: LSP mass for $\tan\beta = 10, 50$

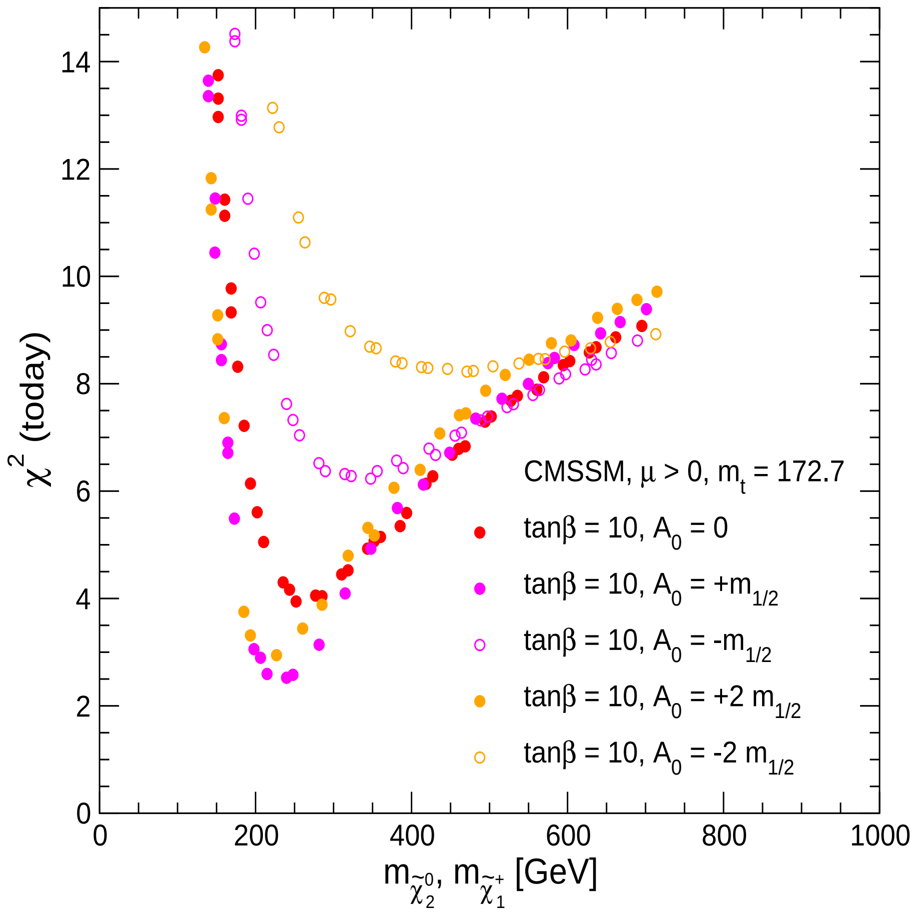


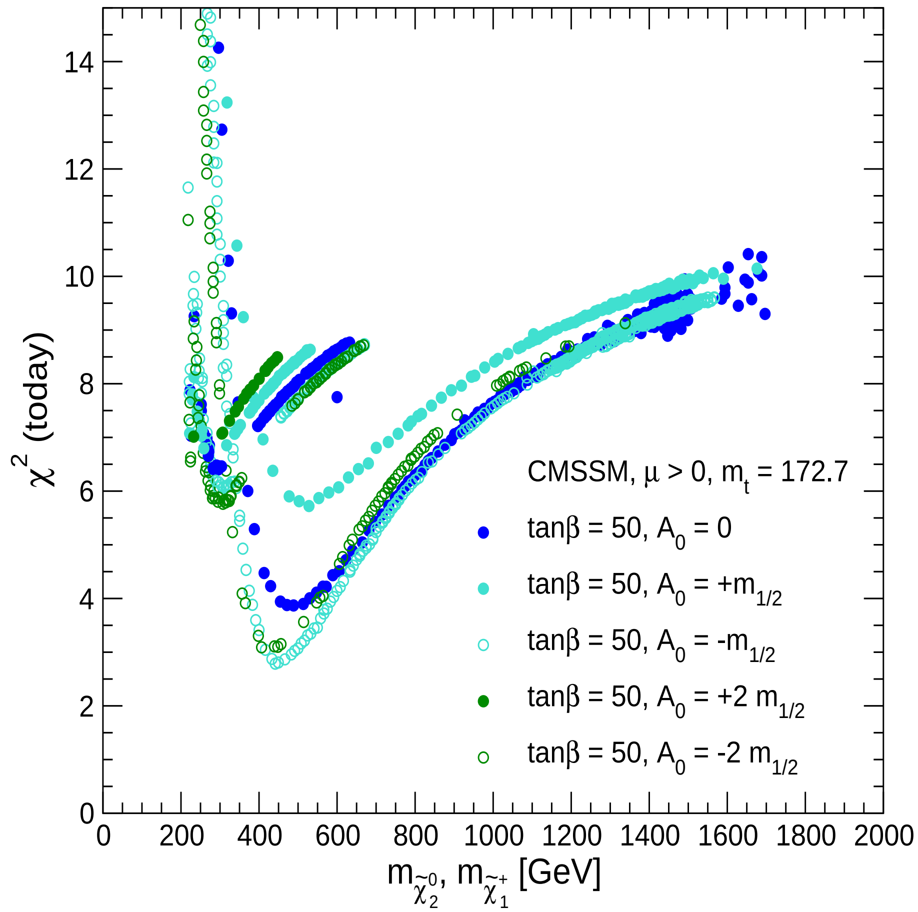


$\tan\beta = 10 \Rightarrow$ minimum at 200 GeV

$\tan\beta = 50 \Rightarrow$ similar

CMSSM: light neutralino/chargino masses for $\tan\beta = 10, 50$

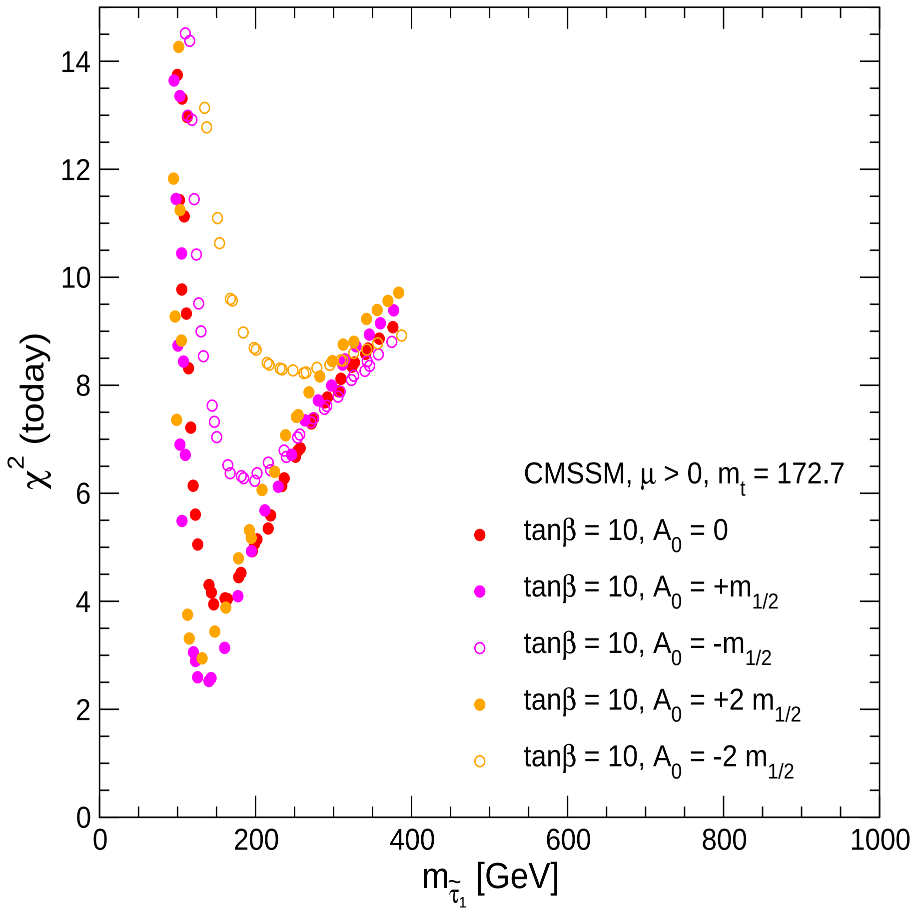


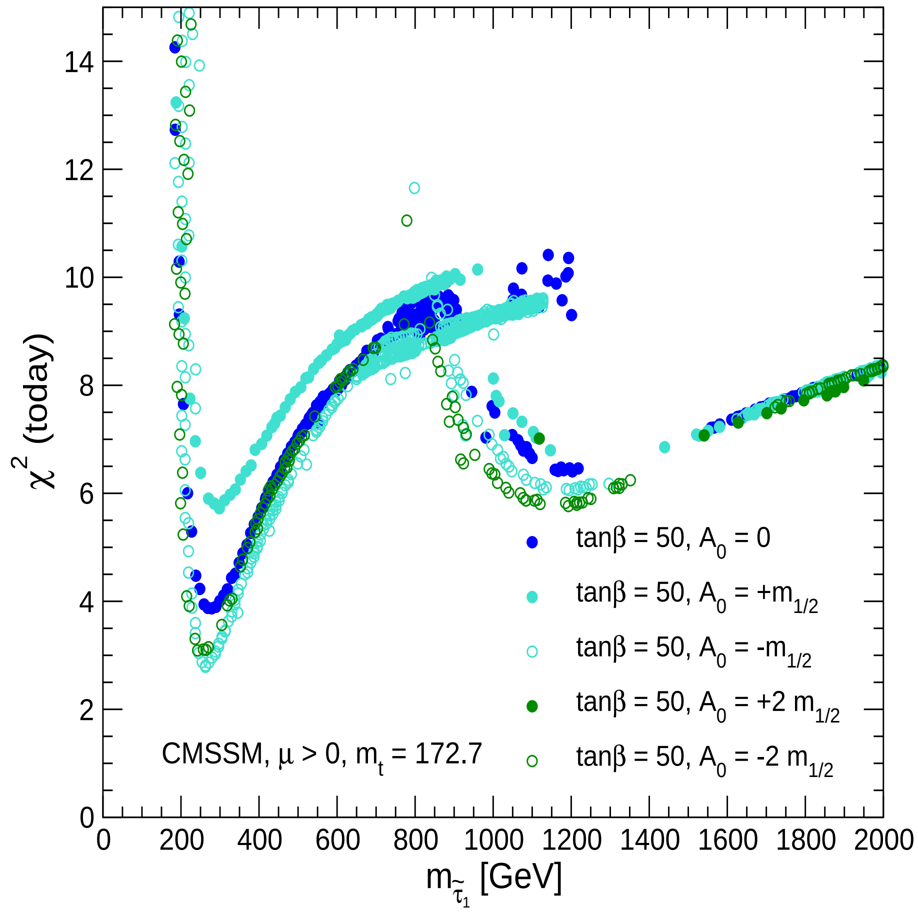


$\tan\beta = 10 \Rightarrow$ very good prospects for the ILC(1000)

$\tan\beta = 50 \Rightarrow$ good prospects (only) for $\tilde{\chi}^0_1\tilde{\chi}^0_2$ production

CMSSM: lightest stau mass for $\tan\beta = 10, 50$

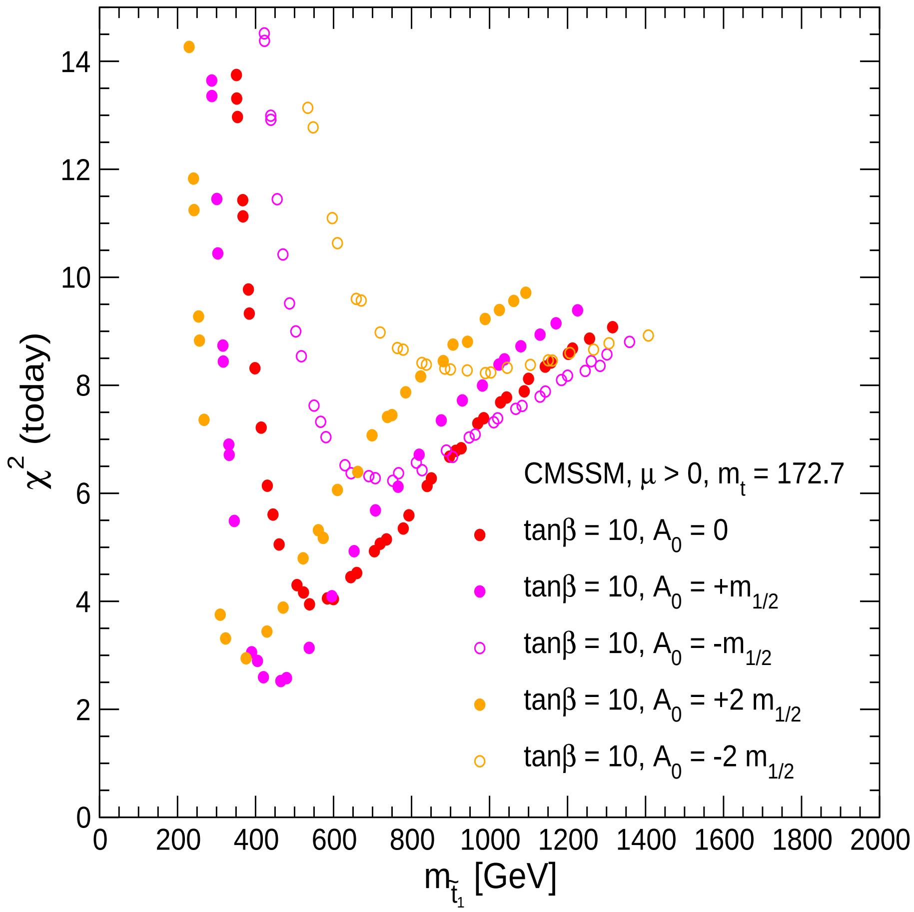


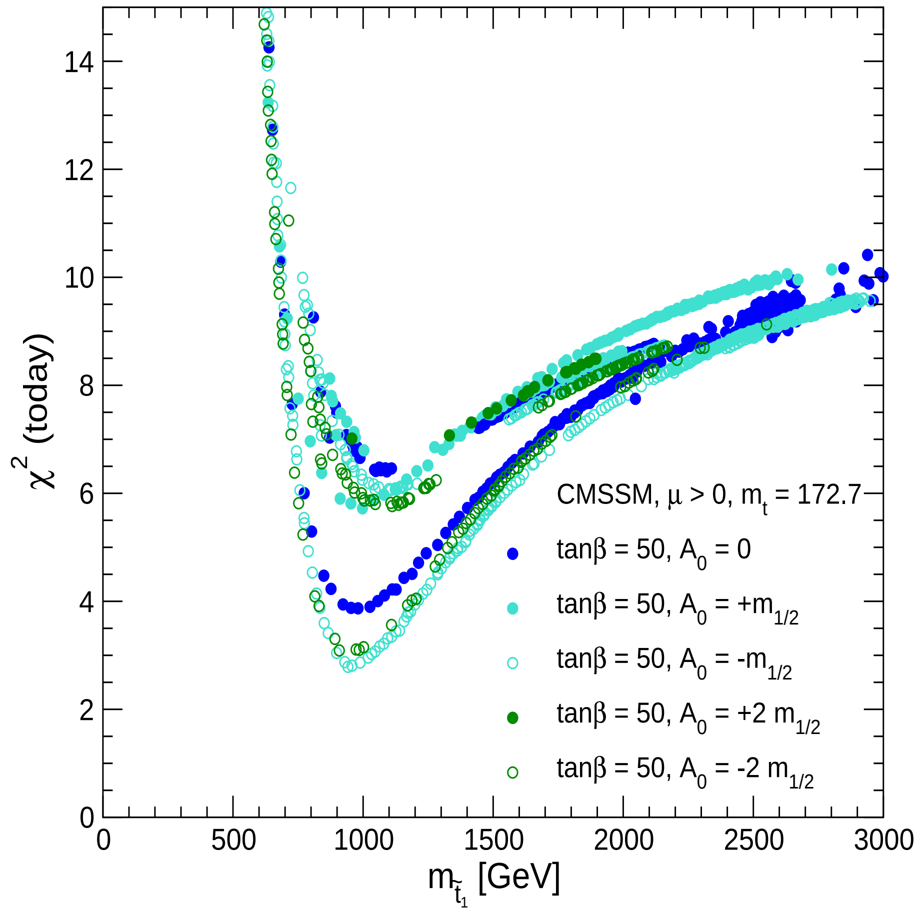


$\tan\beta = 10 \Rightarrow$ very good prospects for the ILC

$\tan\beta = 50 \Rightarrow$ still quite good for the ILC

CMSSM: lightest stop mass for $\tan\beta = 10, 50$

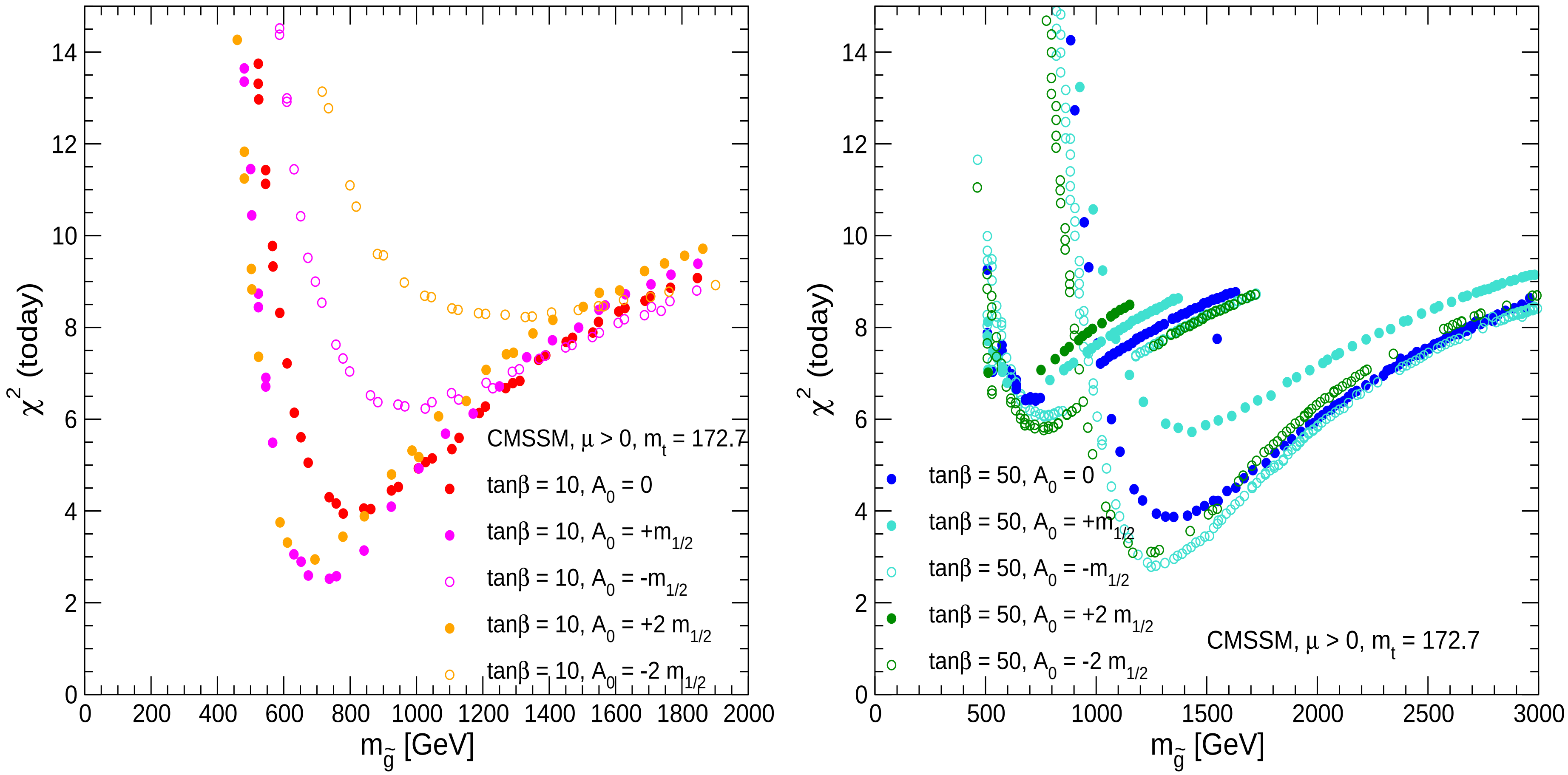




$\tan\beta = 10 \Rightarrow$ moderate prospects for the ILC

$\tan\beta = 50 \Rightarrow$ outside the ILC(1000) reach

CMSSM: gluino mass for $\tan\beta = 10, 50$

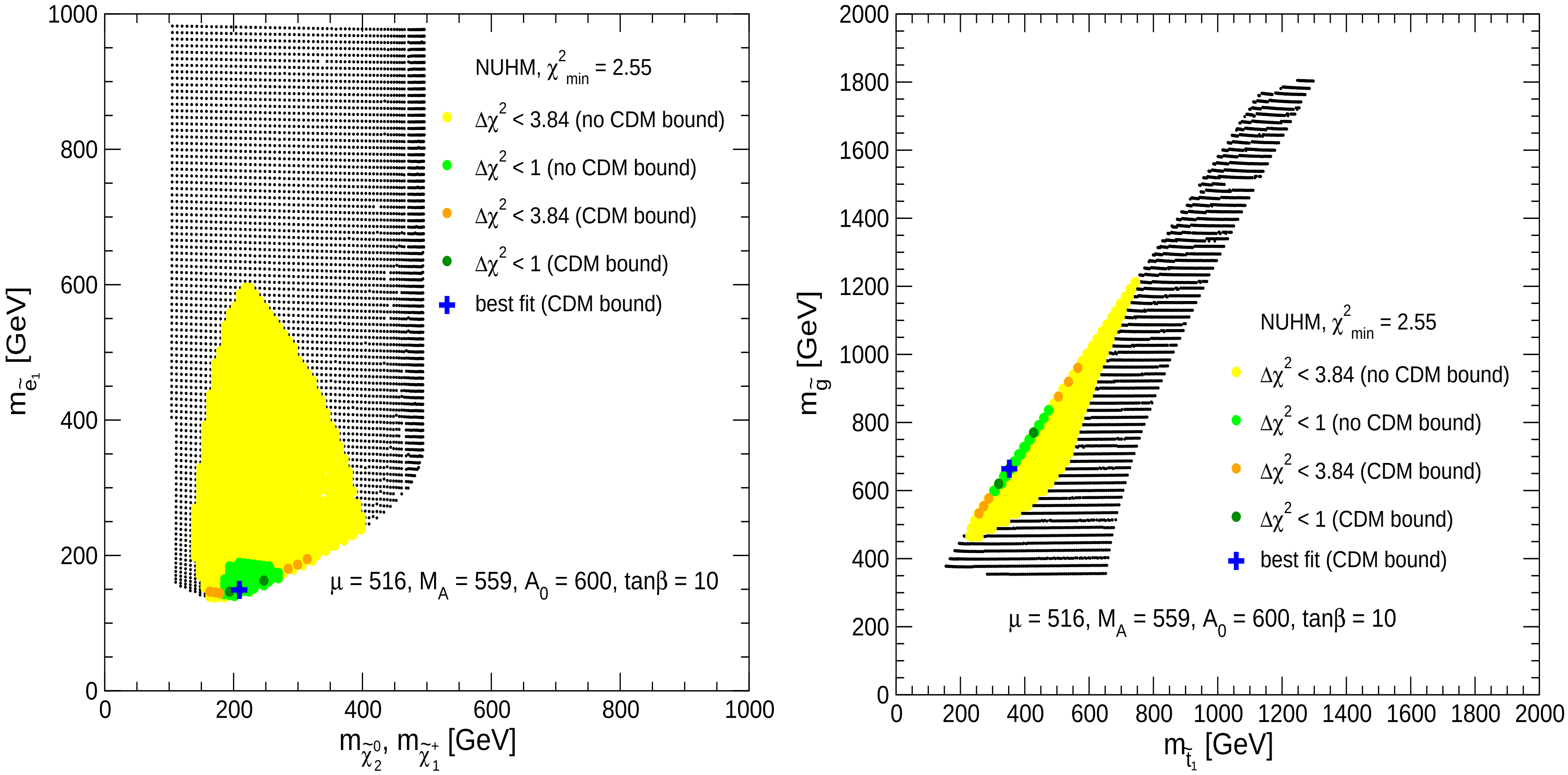


$\tan\beta = 10 \Rightarrow$ outside the ILC(1000) reach

$\tan\beta = 50 \Rightarrow$ chance for focus point region?

3 B) NUHM

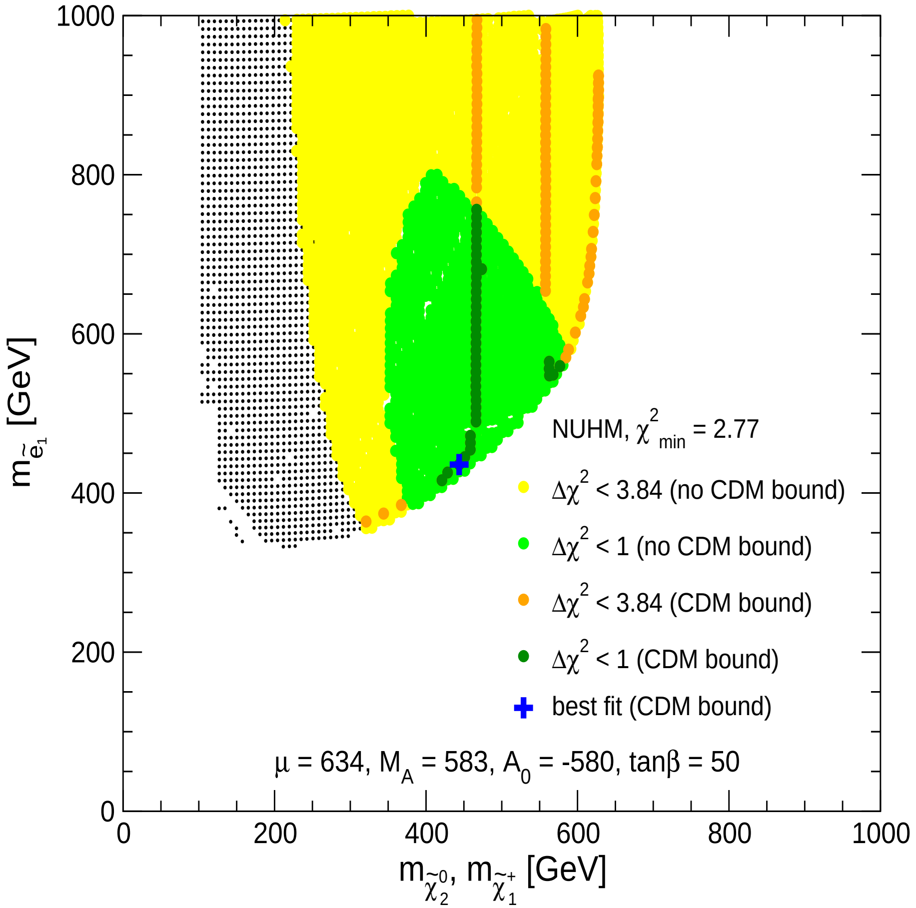
NUHM: vary $m_{1/2}$ and m_0 around best CMSSM fit point $\tan\beta = 10$:

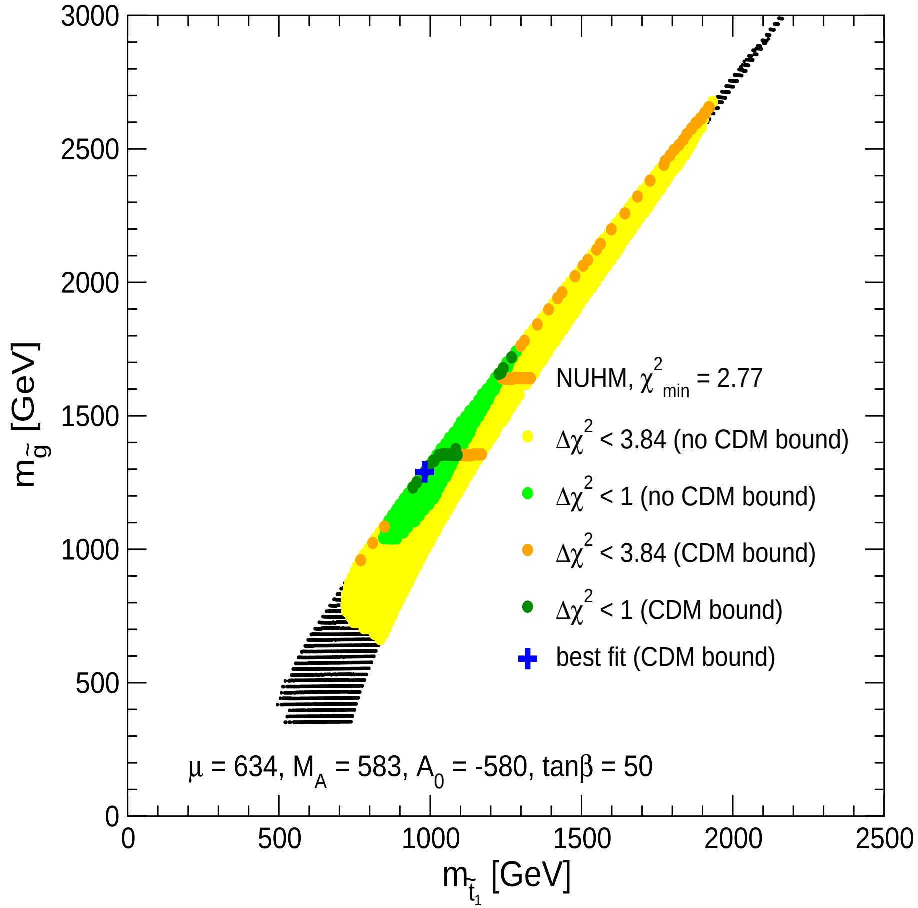


$\Rightarrow$ sleptons, charginos, neutralinos in reach

stops could be, gluinos will be out of reach

NUHM: vary $m_{1/2}$ and m_0 around best CMSSM fit point $\tan\beta = 50$:



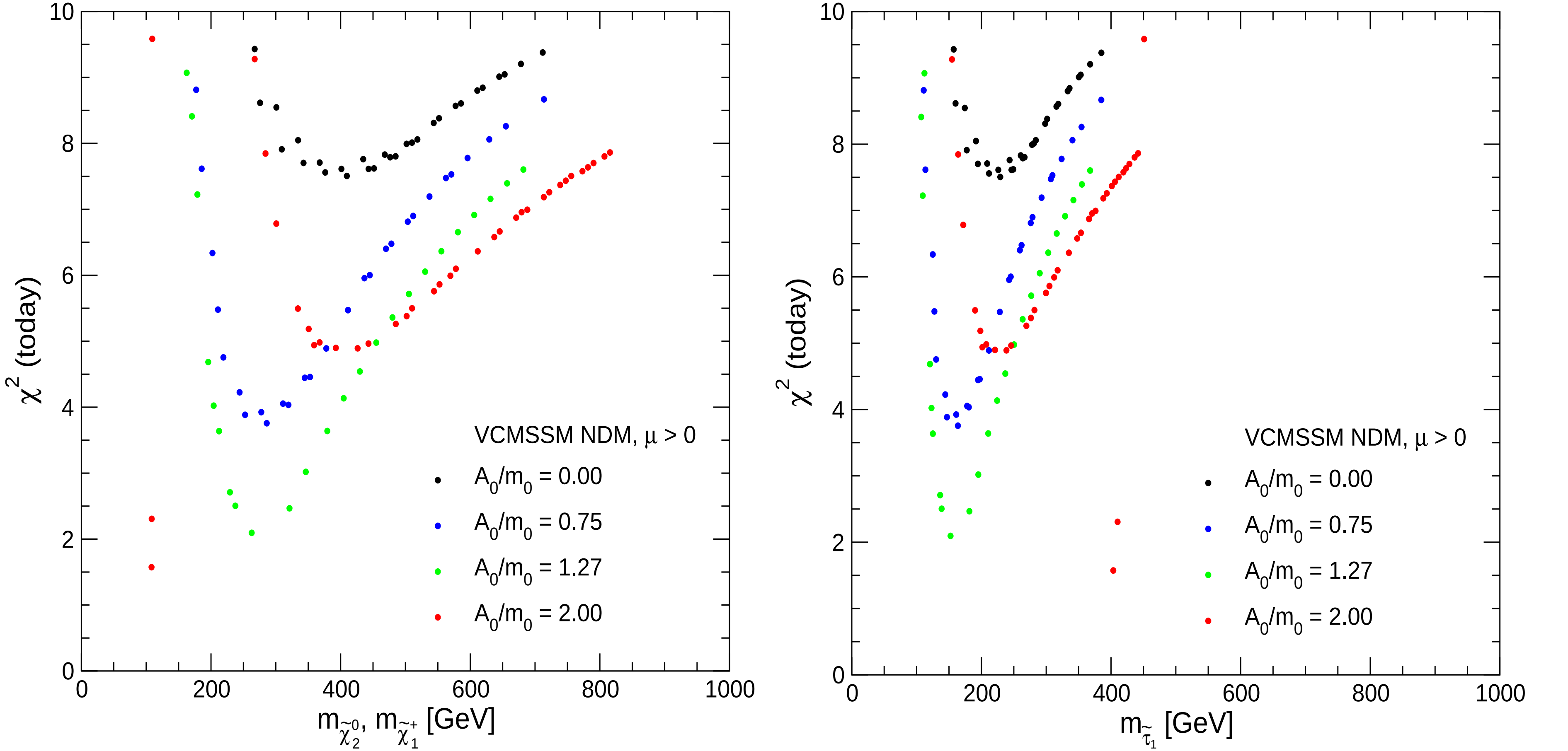


⇒ sleptons, charginos, neutralinos partially in reach for ILC(1000)

stops and gluinos will be out of reach

3 C) VCMSSM

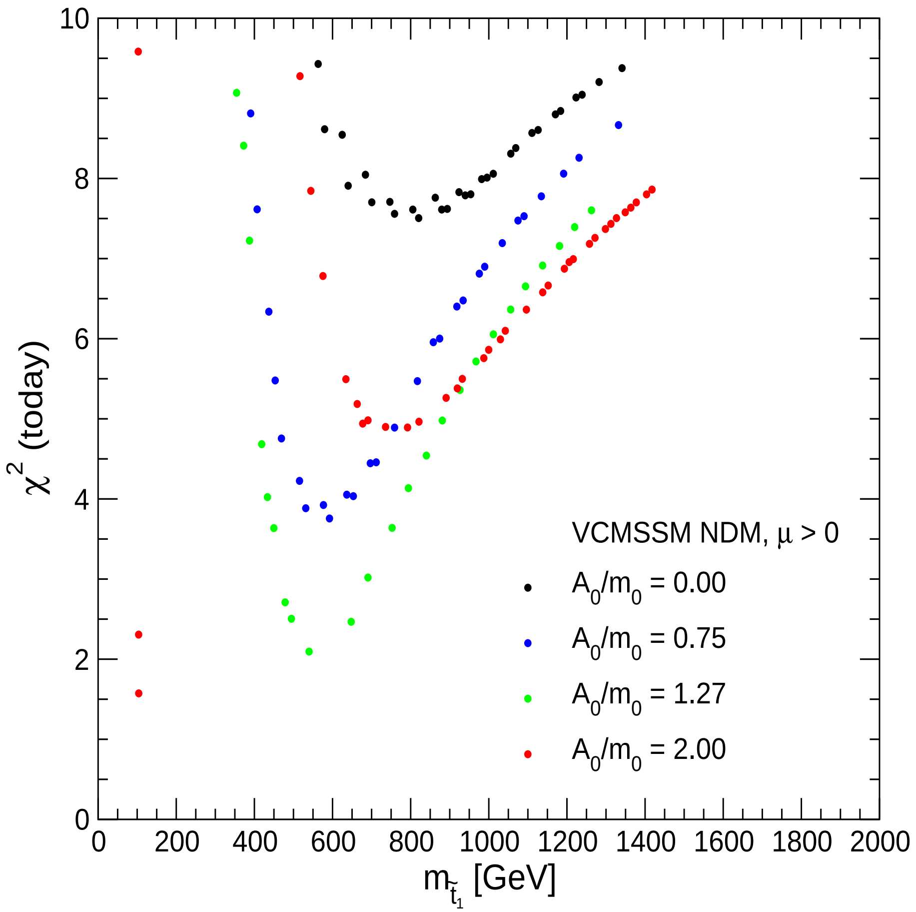
VCMSSM: scan over full parameter space

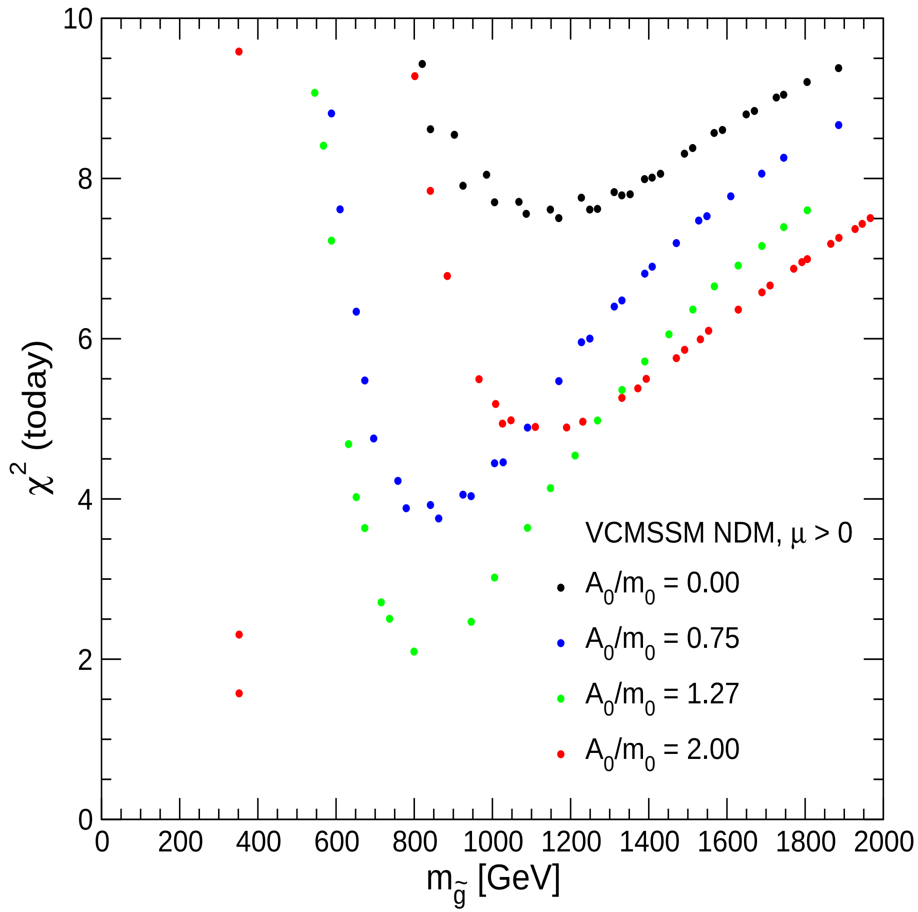


$\Rightarrow$ $A_0/m_0 = 3/4, 3 - \sqrt{3}$ and Higgs pole favored

$\Rightarrow$ sleptons, charginos, neutralinos (partially) in reach for ILC(1000)

VCMSSM: scan over full parameter space



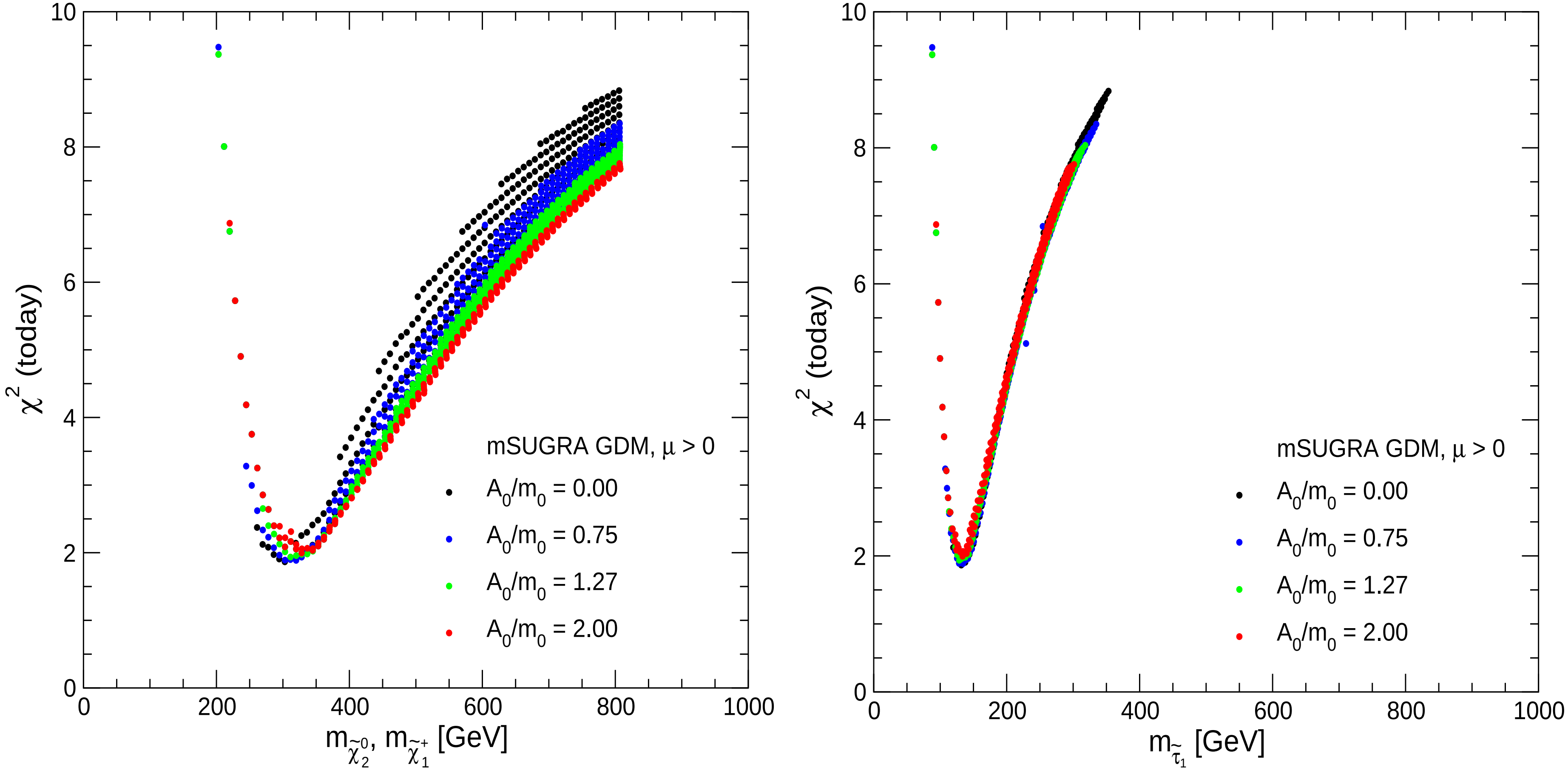


$\Rightarrow A_0/m_0 = 3/4, 3 - \sqrt{3}$ and Higgs pole favored

$\Rightarrow$ stops and gluinos out of reach, except for Higgs pole

3 D) GDM (mSUGRA)

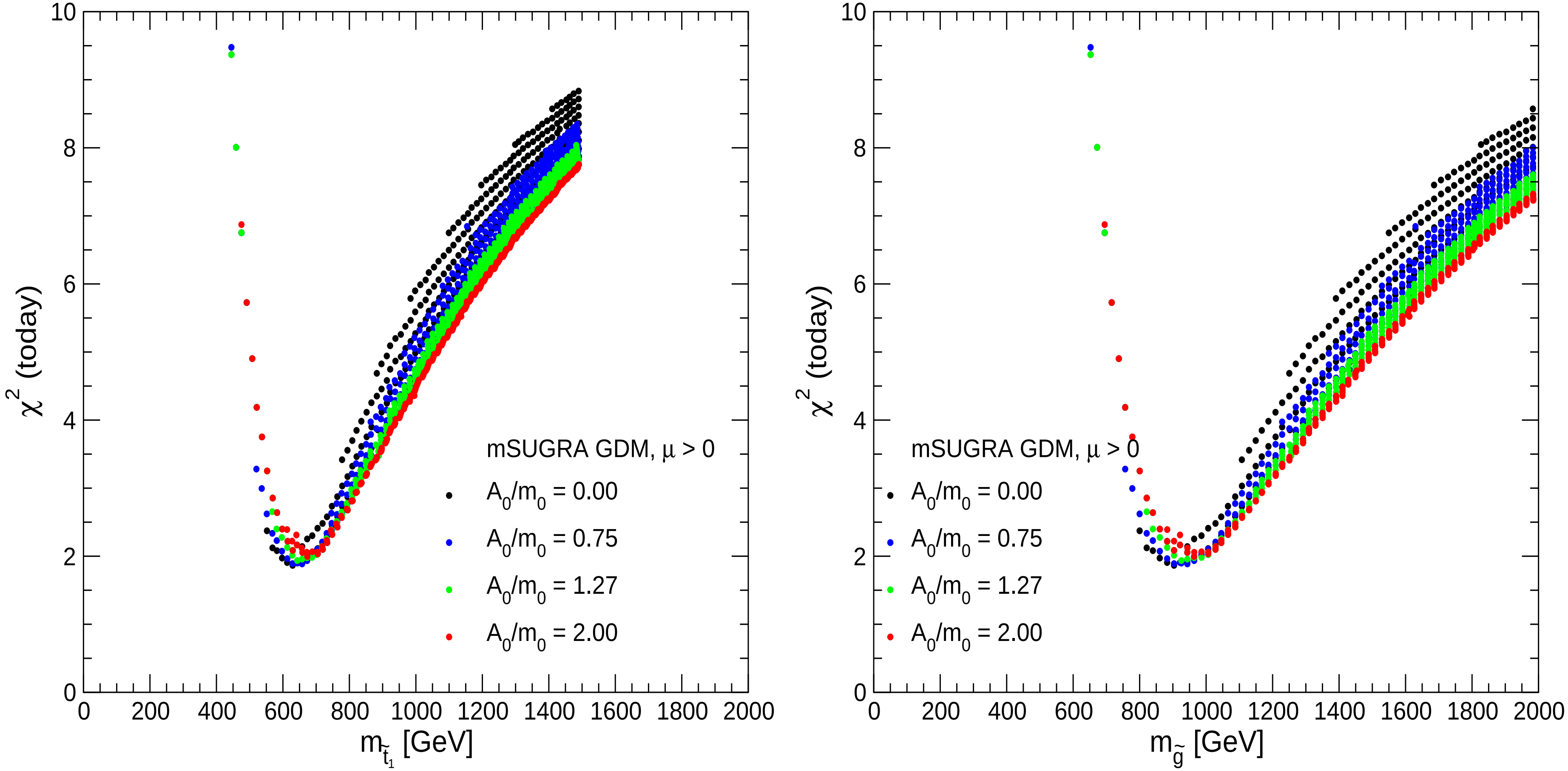
GDM (mSUGRA): scan over full parameter space



⇒ all A_0/m_0 values similarly good

⇒ sleptons, charginos, neutralinos in reach for ILC(1000)

GDM (mSUGRA): scan over full parameter space



⇒ all A_0/m_0 values similarly good

⇒ stops and gluinos out of reach

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, $\sin^2\theta_{\text{eff}}$, M_h, $(g-2)_\mu$, $b \to s\gamma$

- models under consideration:
  CMSSM, NUHM, VCMSSM, GDM (mSUGRA)

- Current χ^2 fit: low values, $\mathcal{O}(2)$ 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 gluinos

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, $\sin^2\theta_{\text{eff}}$, M_h, $(g-2)_\mu$, $b \to s\gamma$
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  hardly any chance for light stops or gluinos

In all scenarios the ILC will discover SUSY particles