Phenomenological Indication of the Scale of Supersymmetry

Sven Heinemeyer, University of Zaragoza

Zaragoza, 03/2006

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

1. Motivation and models
2. Precision Observables in the MSSM
3. Fit results and collider reach
4. Conclusions

1. Motivation and models

Supersymmetry (SUSY) : Symmetry between

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

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

Simplified examples:

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

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

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

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

. . . via soft SUSY-breaking terms in the Lagrangian

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

Supersymmetry: Motivation

The SM is in a pretty good shape.

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

$\rightarrow$ more than 9 reasons as a motivation:
(incl. 3 1/2 exp. verified SUSY predictions!)

1.) (Original motivation:) Stability of Higgs mass against higher order corrections in the MSSM

$\boxed{\Rightarrow M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})}$

2.) Haag-Lopuszanski-Sohnius theorem:
maximal gauge symmetry for a QFT:
inner gauge symmetry $\otimes$ (local) Susy

3.) Lorentz algebra $\subset$ Susy algebra (local)
$\rightarrow$ connection to general relativity
Superstring theories contain N = 1 Susy as low energy limit.

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

$\Rightarrow M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})$

5.) Lifetime of the proton: for SU(5) GUTs:

$\tau_{p,\text{SM}} < \tau_{p,\text{exp}} < \tau_{p,\text{SUSY}}$

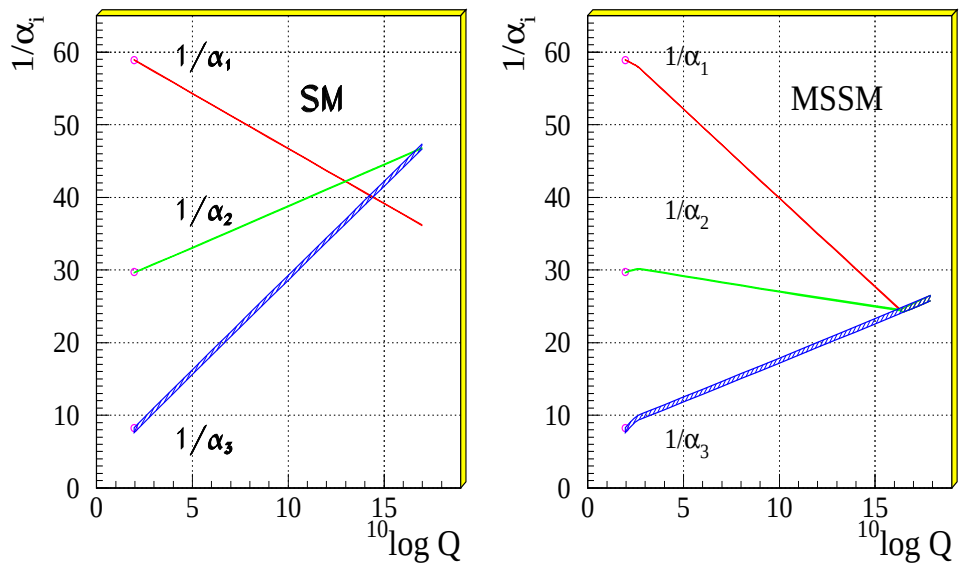
6.) Spontaneous symmetry breaking via Higgs mechanism is automatically achieved in SUSY GUTs

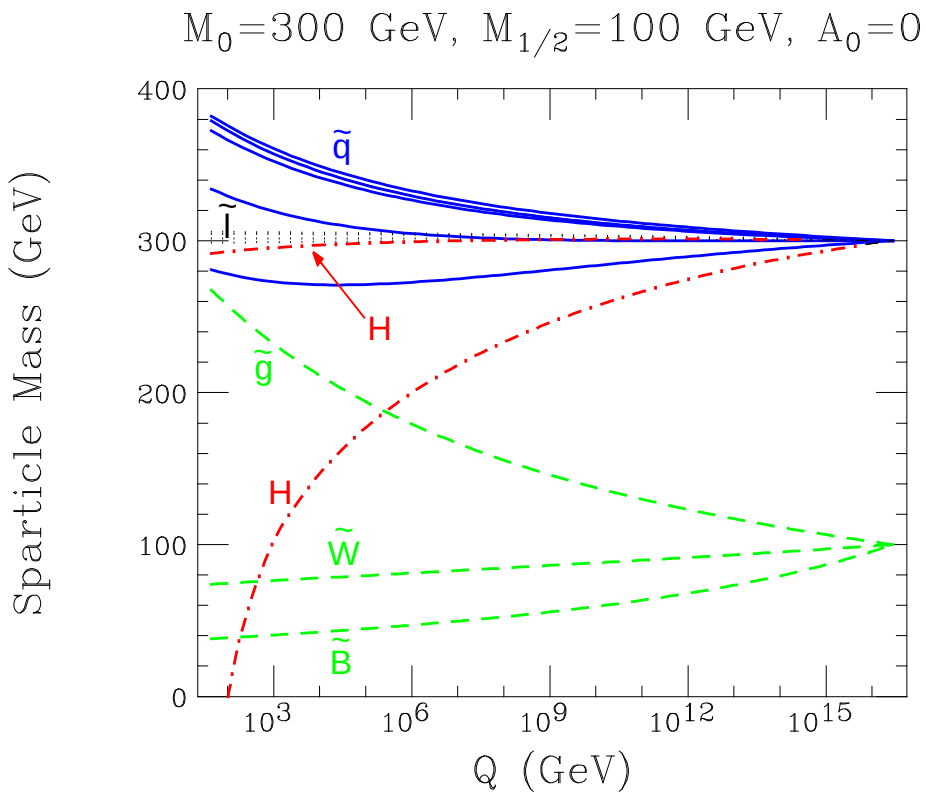
$\rightarrow$ T

SUSY prediction #1 experimentally verified:

$m_t = 150 - 200$ GeV

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




M0=300 GeV, M1/2=100 GeV, A0=0
Sparticle Mass (GeV)
Q (GeV)
q̃
l̃
H
g̃
H
W̃
B̃
400
300
200
100
0
10^3
10^6
10^9
10^12
10^15

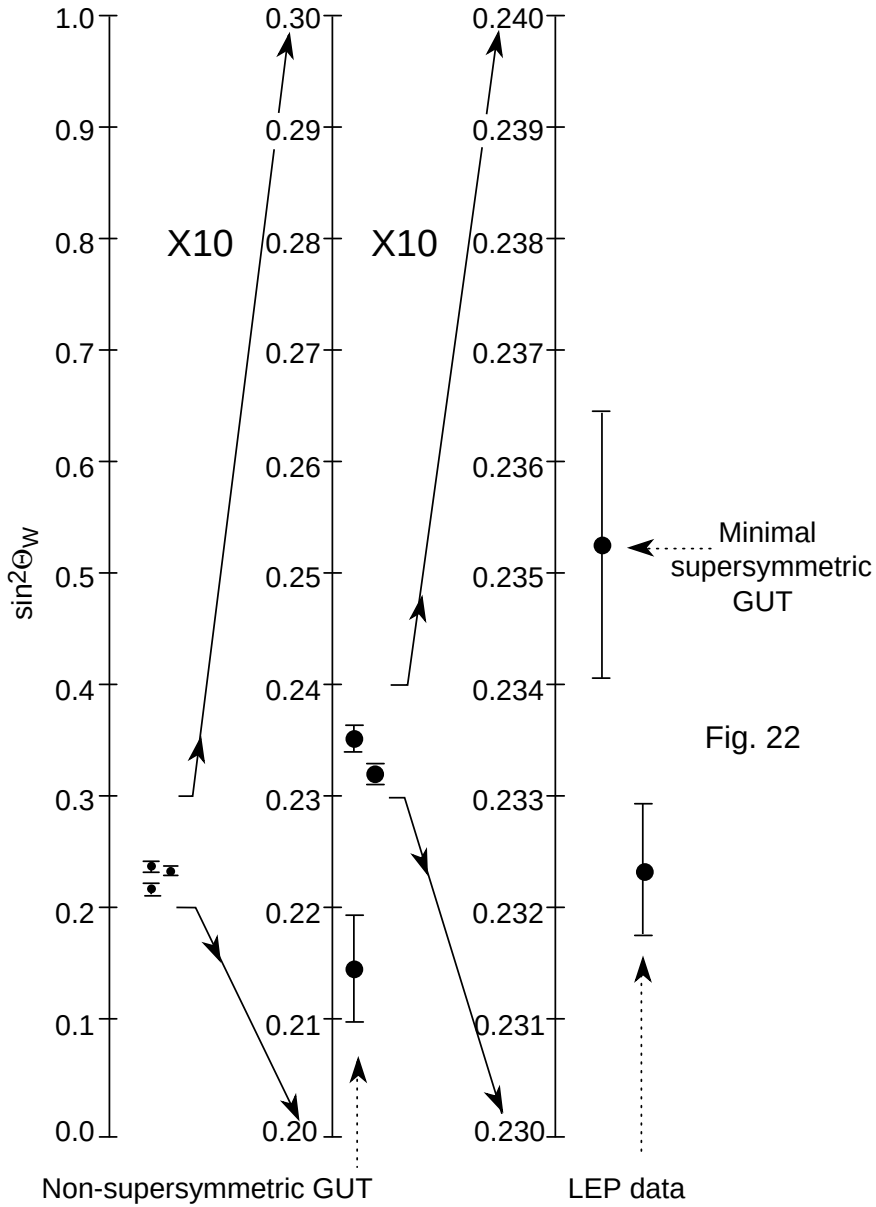

sin²Θ_W
X10
X10
Minimal supersymmetric GUT
Non-supersymmetric GUT
LEP data
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.240
0.239
0.238
0.237
0.236
0.235
0.234
0.233
0.232
0.231
0.230

Fig. 22

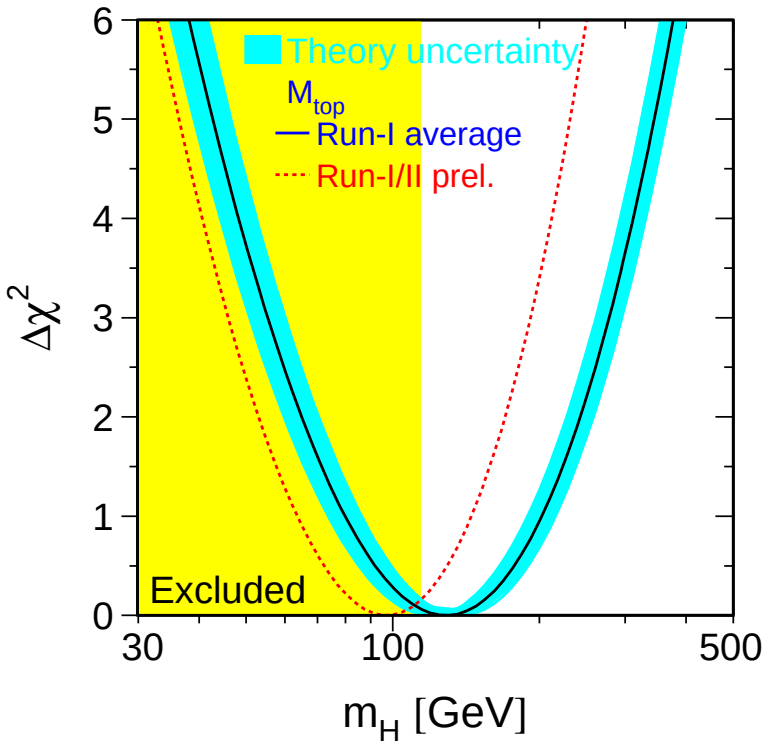
7.) Prediction for $\sin\theta_{W|M_{GUT}} = \frac{3}{8}$
low energy prediction via RGE $\rightarrow$ T

SUSY prediction #2 exp. verified:
$\sin^2\theta_{\text{eff}} \approx 0.232$

8.) LSP (lightest SUSY particle) is stable
SUSY prediction #3 exp. verified:
cold dark matter
(with correct properties)

9.) Prediction of a light Higgs boson in the MSSM (see below): $m_h \lesssim 135$ GeV
Indirect search: Global fit to SM data:
[*LEPEWWG '05*]

SUSY prediction #3 1/2 exp. verified:
$m_h \lesssim 135$ GeV



...) Solution for Flavor problem? Solution for Baryogenesis?

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

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

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

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

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

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

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

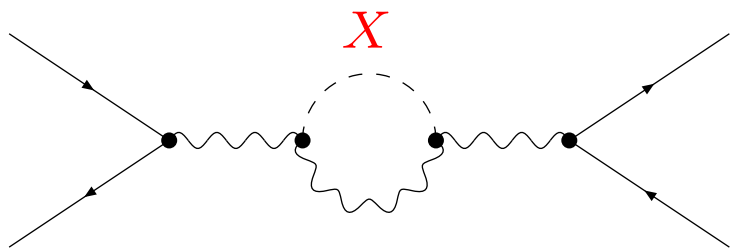
Precision Observables (POs):

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

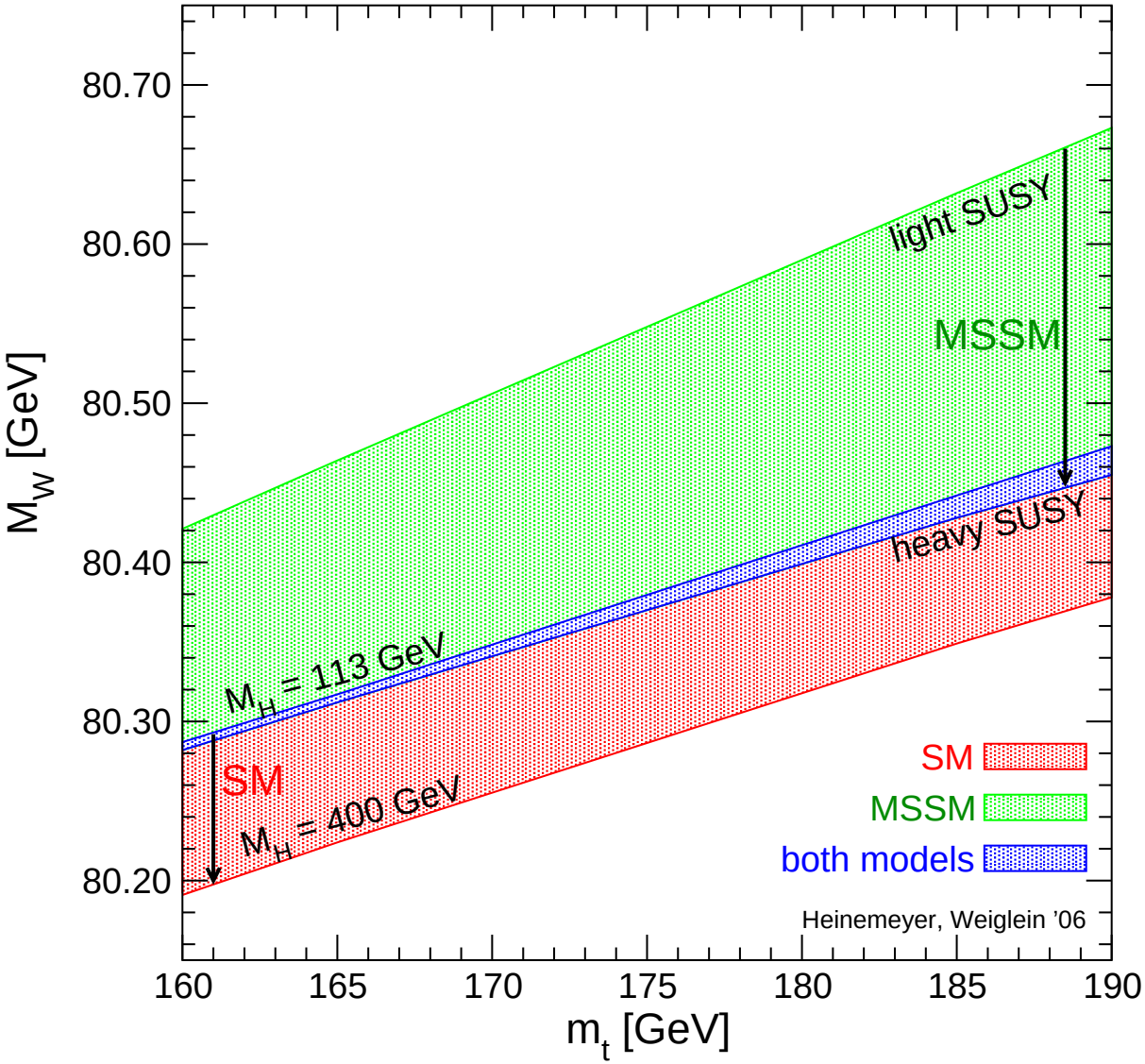


$\Downarrow$

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 :



MSSM uncertainty:
unknown masses
of SUSY particles

SM uncertainty:
unknown Higgs mass

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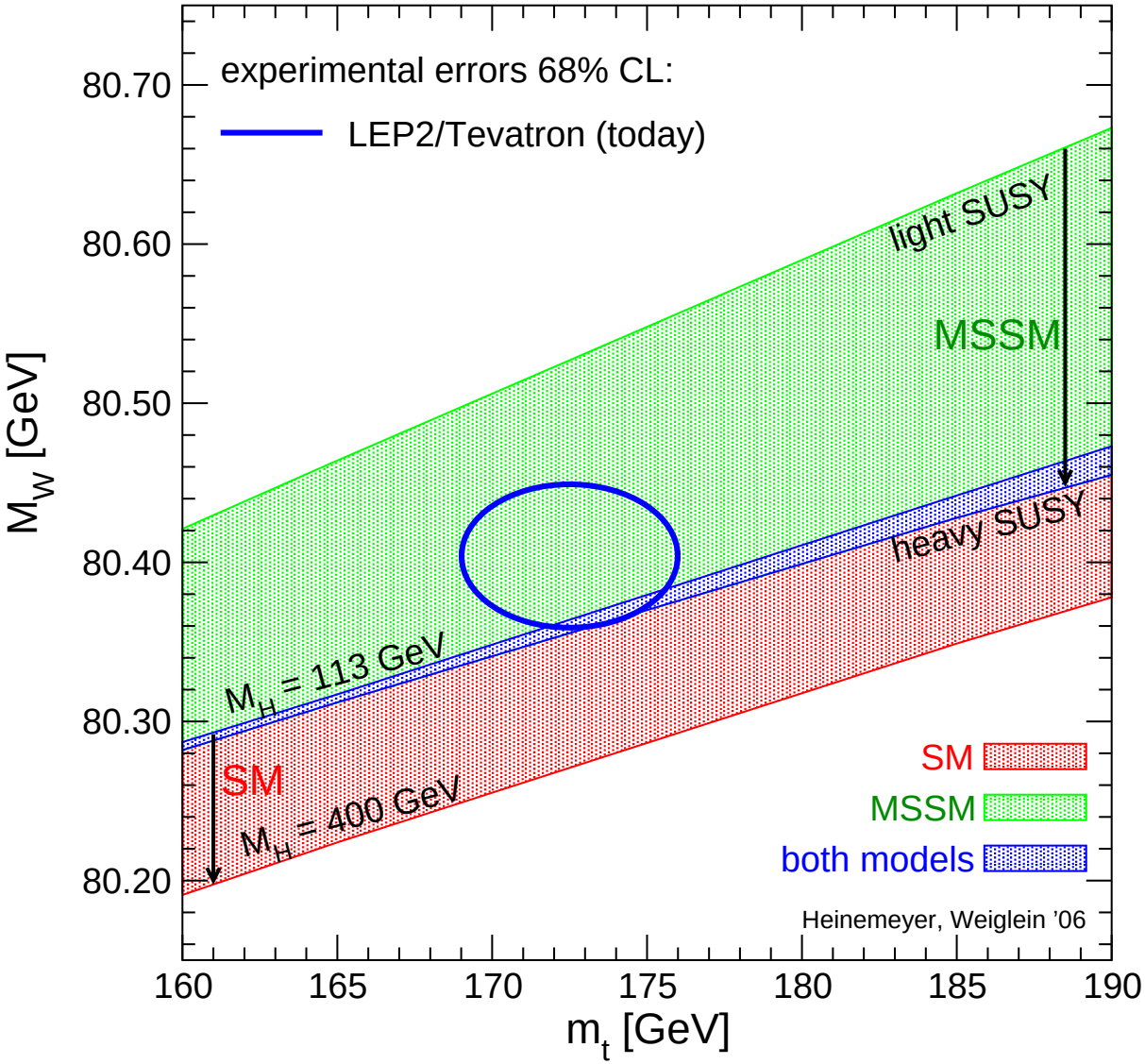

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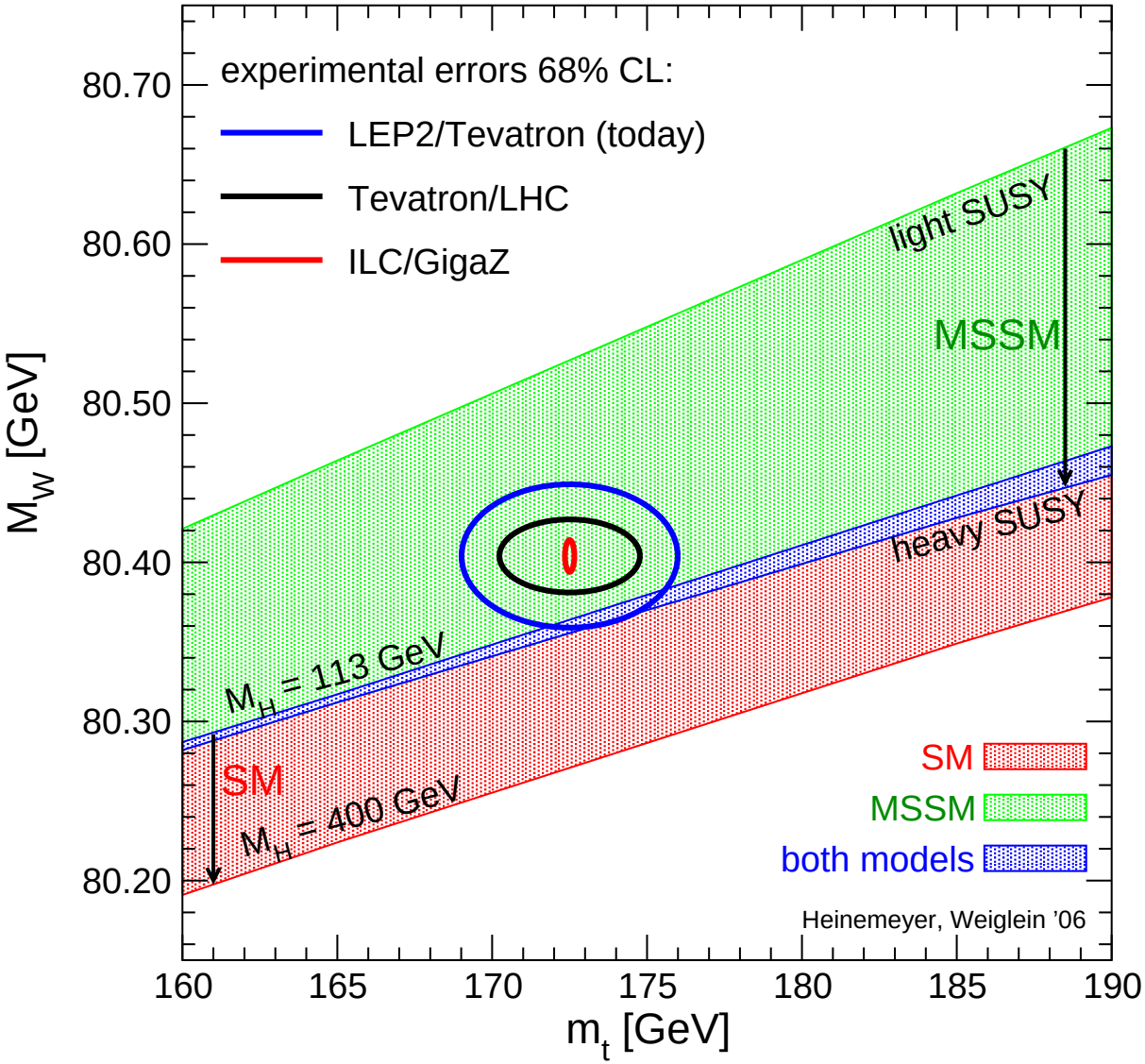

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The models (I):

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

sign(μ) : 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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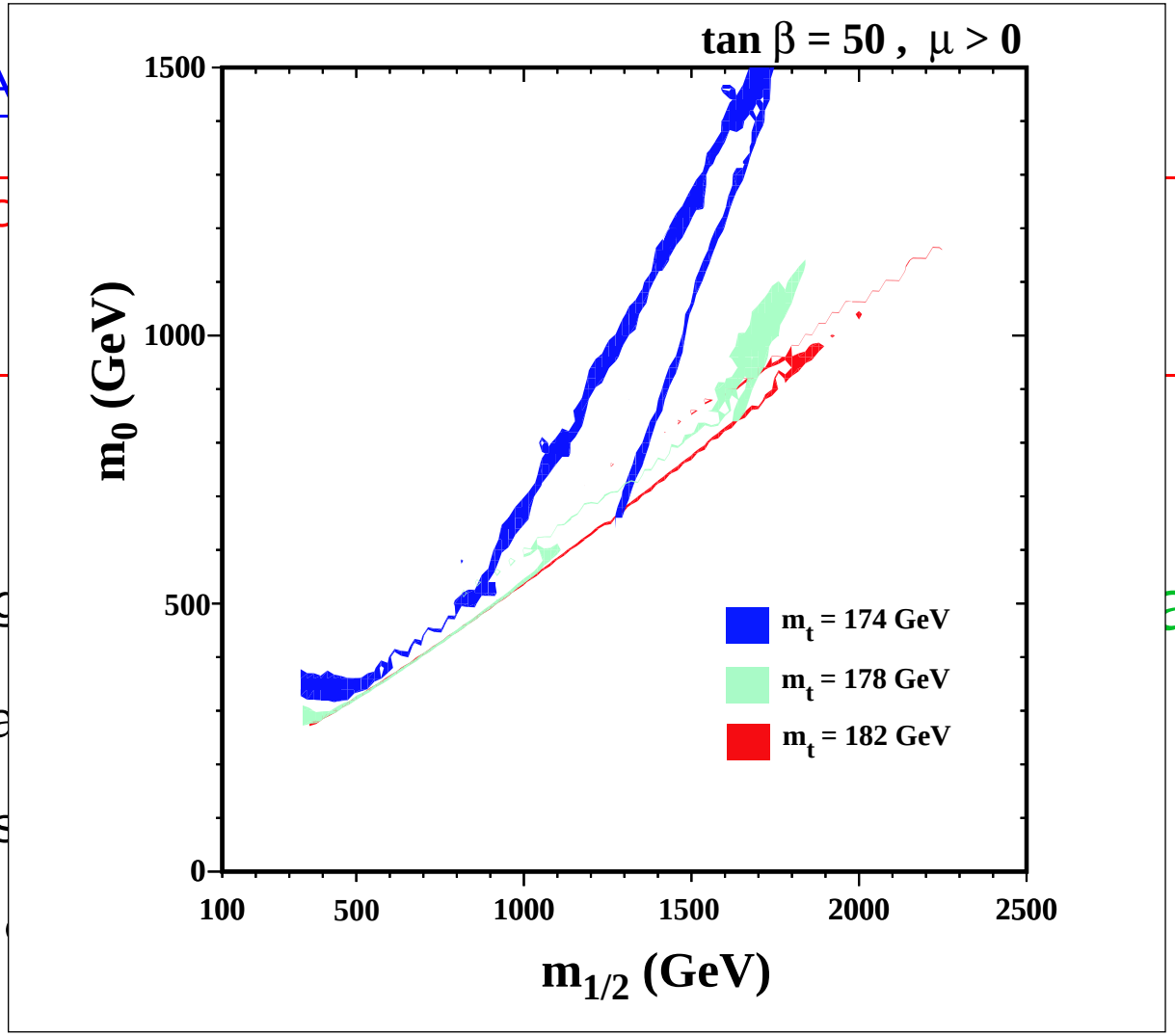

ale

⇒ particle spectra from renormalization group running to weak scale

Lightest SUSY particle (LSP) is the lightest neutralino

The models (II):

NUHM: (Non-universal Higgs mass model)

$\Rightarrow$ besides the CMSSM parameters

$$M_A \text{ and } \mu$$

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

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Lightest SUSY particle (LSP) is the gravitino

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⇒ In addition to C):

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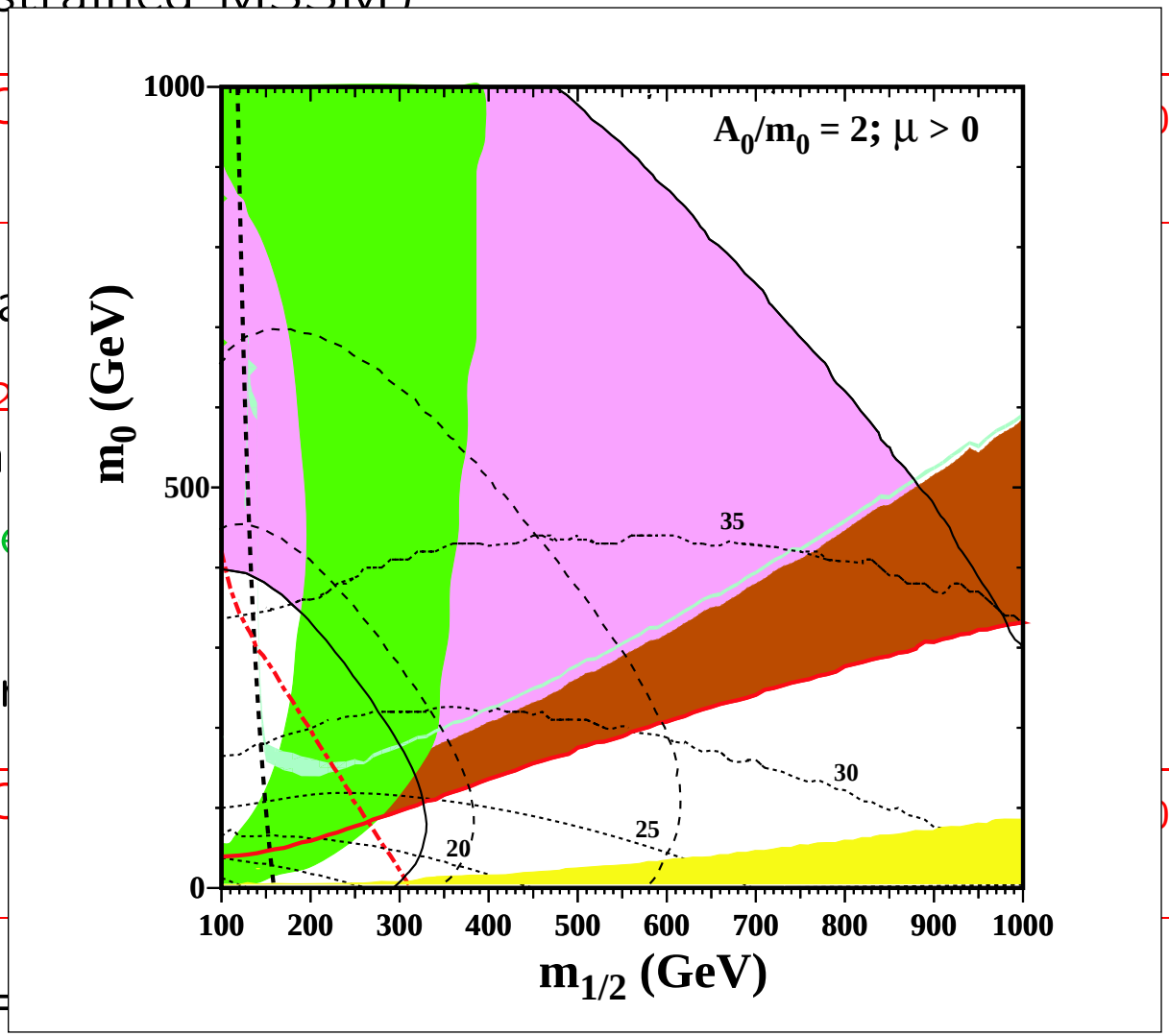
Lightest SUSY particle



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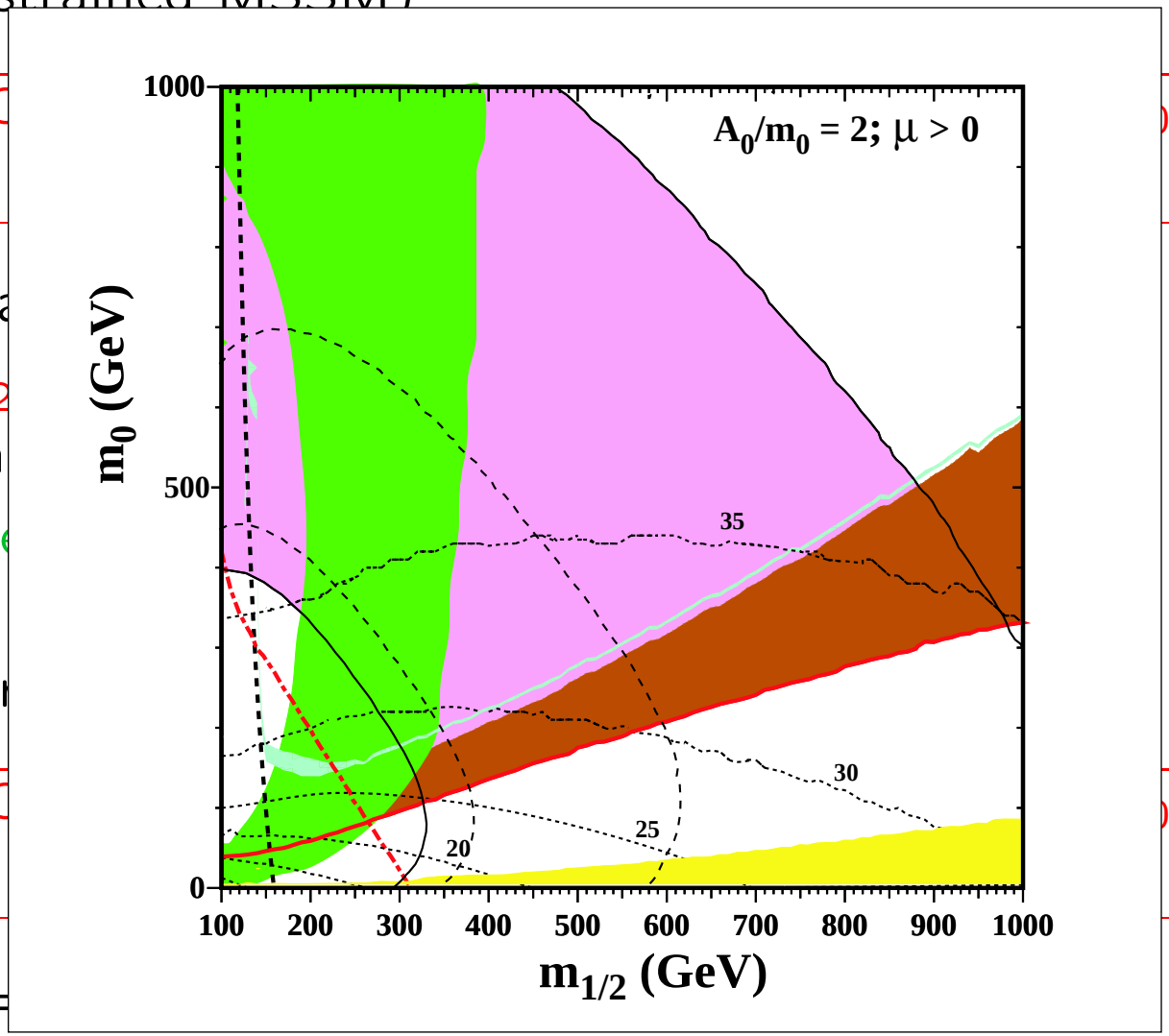

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2. Precision Observables in the MSSM

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

2 A) Theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$:

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

$\Updownarrow$

loop corrections

2 B) Effective mixing angle:

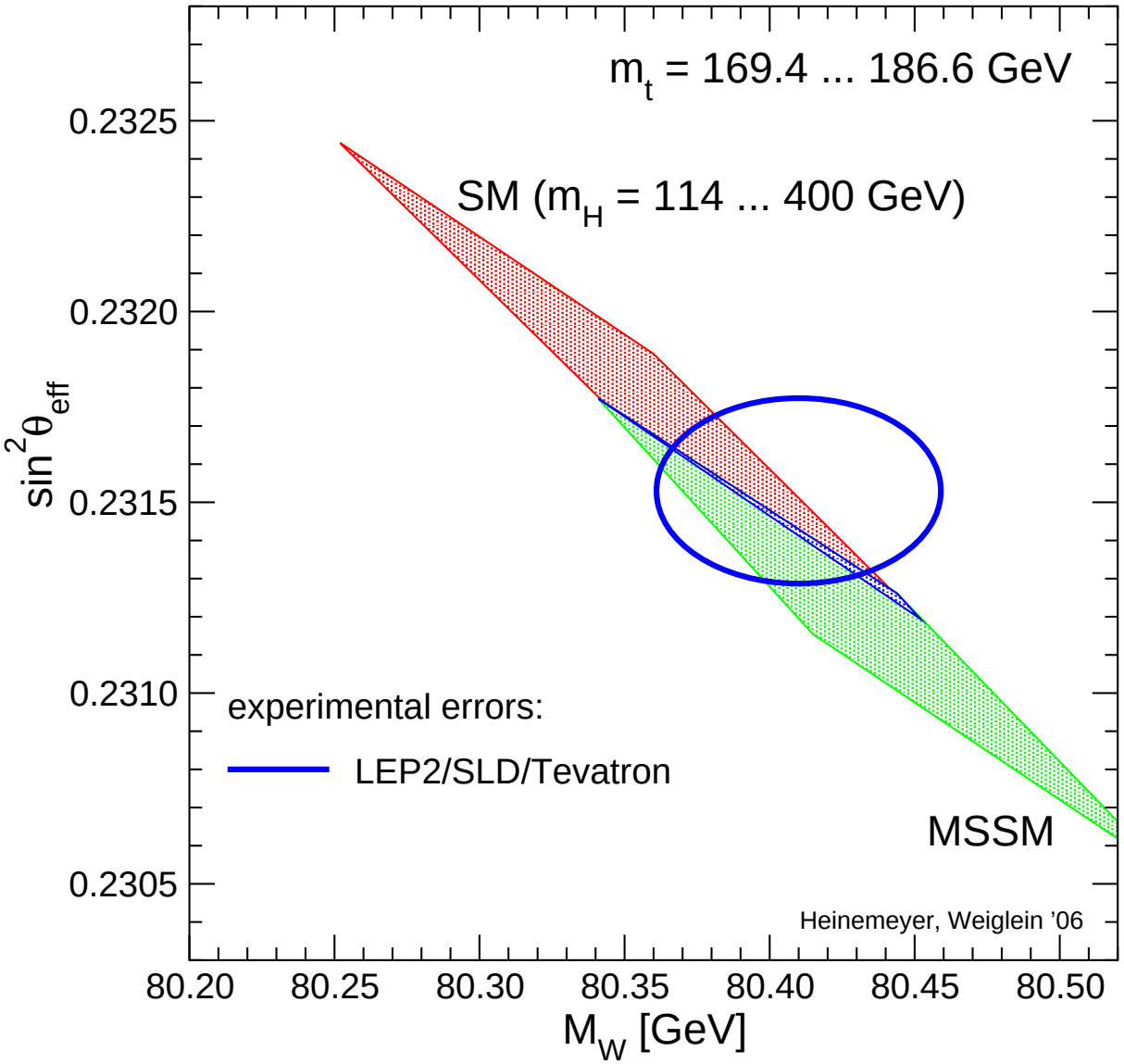
$$\sin^2\theta_{\rm eff}=\frac{1}{4\,|Q_f|}\left(1-{\rm Re}\,\frac{g_V^f}{g_A^f}\right)$$

Higher order contributions:

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

Example of application:

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



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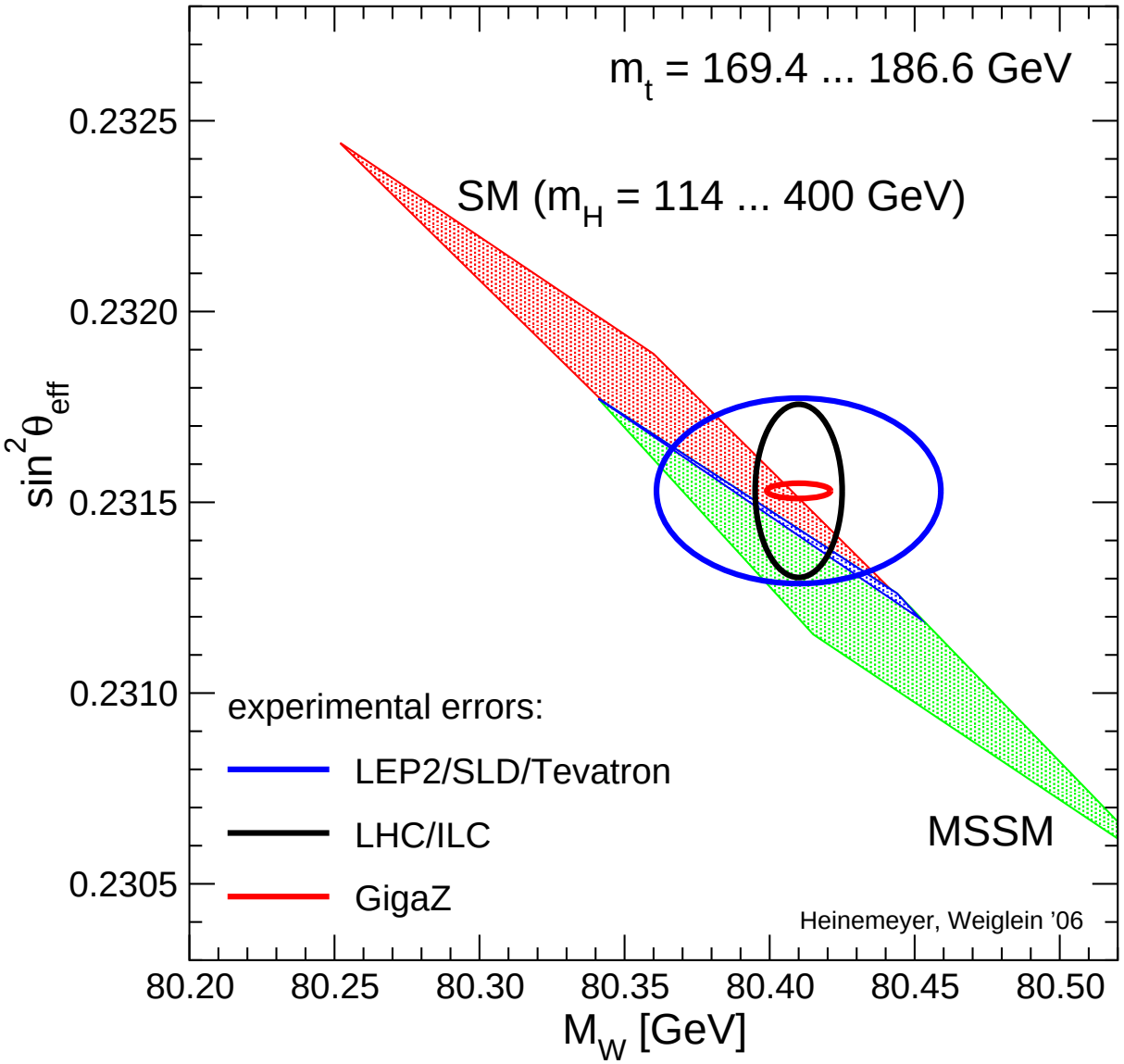

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For χ^2 fit:

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

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*]

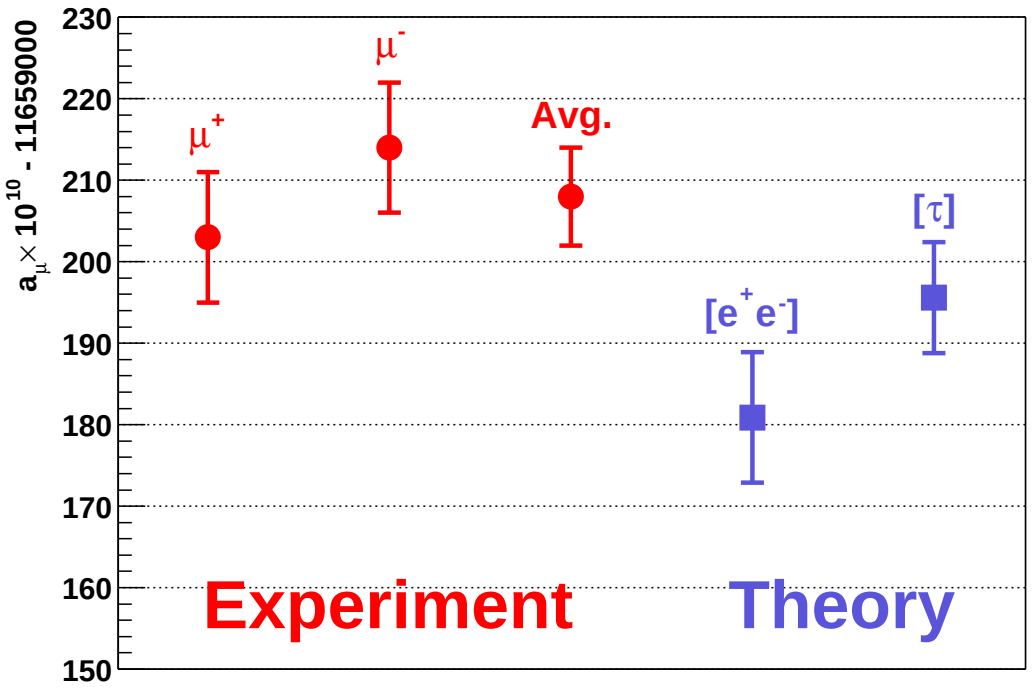
2 C) Prediction of the anomalous magnetic moment of the muon: $(g-2)_\mu$

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

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

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

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



Overview of the SM theory evaluation:

Source	contr. to $a_\mu[10^{-10}]$	
LO hadr.	$\sim 695 \pm 7$ (e^+e^-)	[*Davier et al, Hagiwara et al. '03*]
		[*Ghozzi, Jegerlehner '03*]
	711.0 ± 6 (τ)	[*Davier, Eidelman, Höcker, Zhang '03*]
LBL	8 ± 4	[*Knecht, Nyffeler '02*]
	13.6 ± 2.5 tbc	[*Melnikov, Vainshtein '03*]
EW 1L	19	
EW 2L	-4	[*Czarnecki, Krause, Marciano '98*]
exp. res.	6	[*BNL E821 '04*]

$\rightarrow$ "Isospin breaking effects" in τ data problematic [*Ghozzi, Jegerlehner '03*]

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

$\Rightarrow$ general agreement at ICHEP'04 Beijing: discard τ data

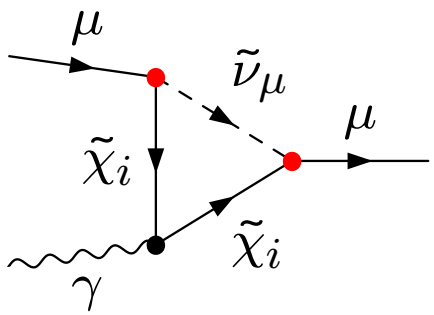
$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (25.2 \pm 9.2) \times 10^{-10}$$

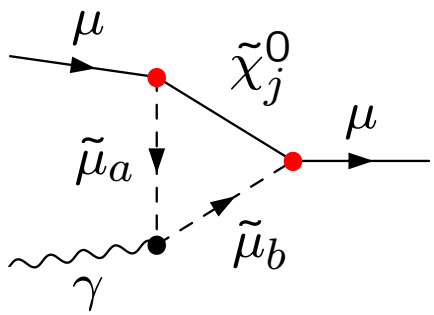
MSSM contributions to $(g-2)_\mu$:

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

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

Feynman diagrams for MSSM 1L corrections:

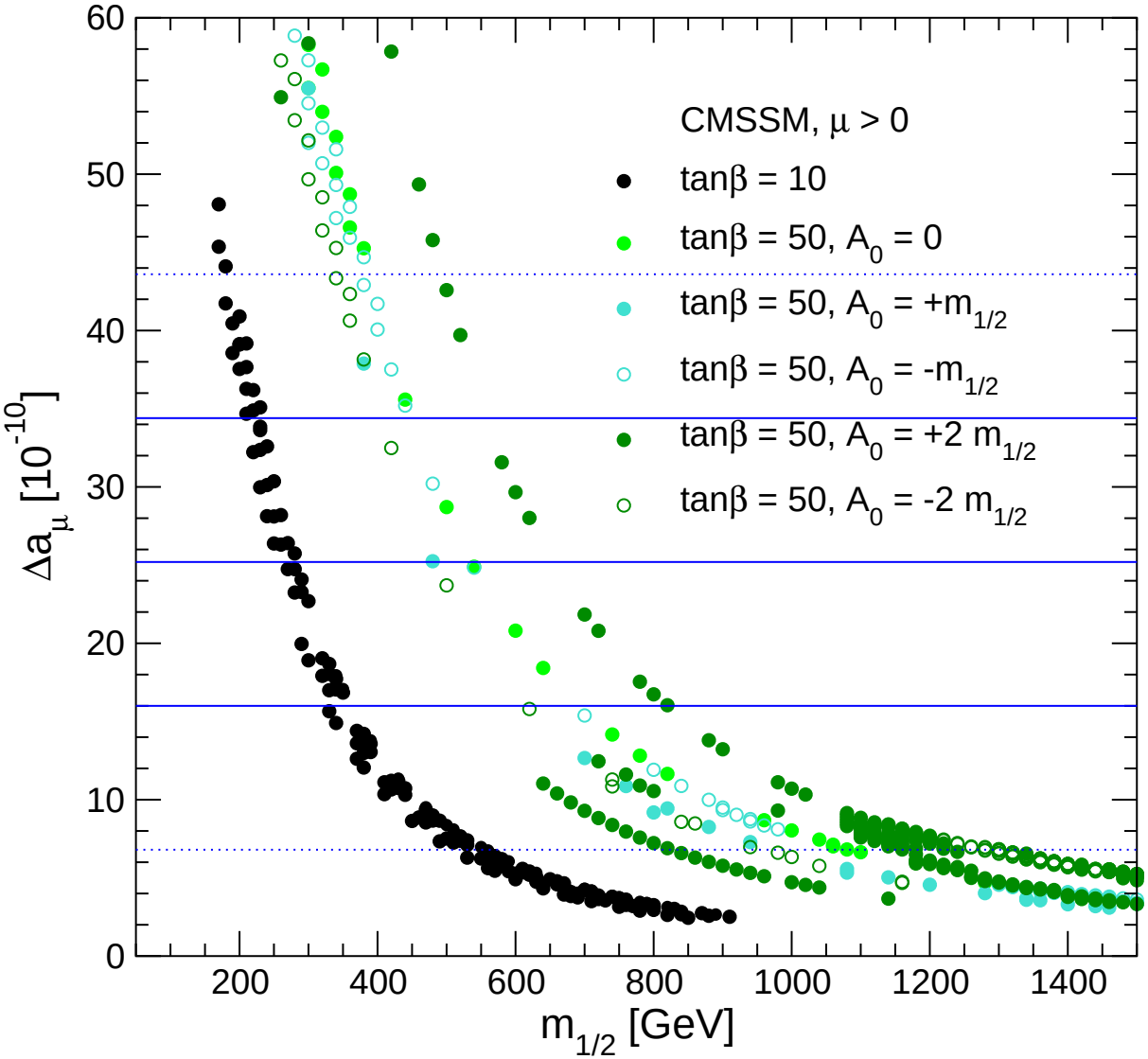




Enhancement factor as compared to SM:

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

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. $m_{1/2}$

Remaining uncertainties:

1. SUSY 1L diagrams with a mixed $f/\tilde{f}$ loop

$\rightarrow$ same enhancement factors as
SM 1L diagrams with a closed $f/\tilde{f}$ loop attached

$\Rightarrow$ possibly of similar order

2. THDM corrections to SUSY 1L diagrams

Already known:

QED corrections to $a_\mu^{\text{SUSY}}(1\text{L})$: $\sim -8\%$ for $M_{\text{SUSY}} = 500$ GeV
[*G. Degrassi, G. Giudice '98*]

$\rightarrow$ only evaluated for a common SUSY mass scale
$\Rightarrow$ non-negligible corrections possible

$\Rightarrow$ Remaining uncertainties estimated to $\sim 6 \times 10^{-10}$
[*S.H., D. Stöckinger, G. Weiglein '04*]

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

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[*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

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[*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

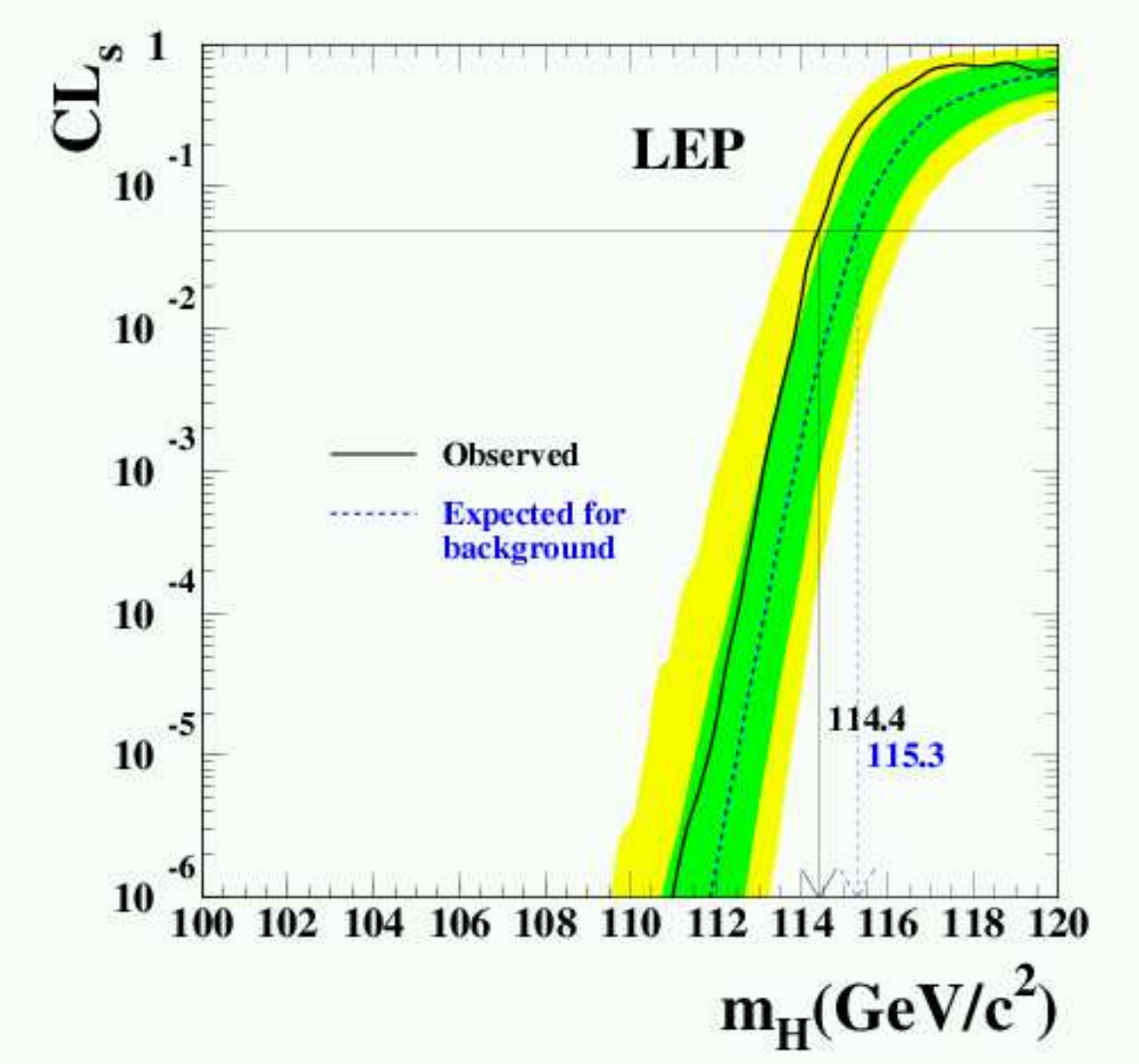
Measurement of M_h, Higgs couplings $\Rightarrow$ test of the theory

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. Fit results and collider reach

Procedure:

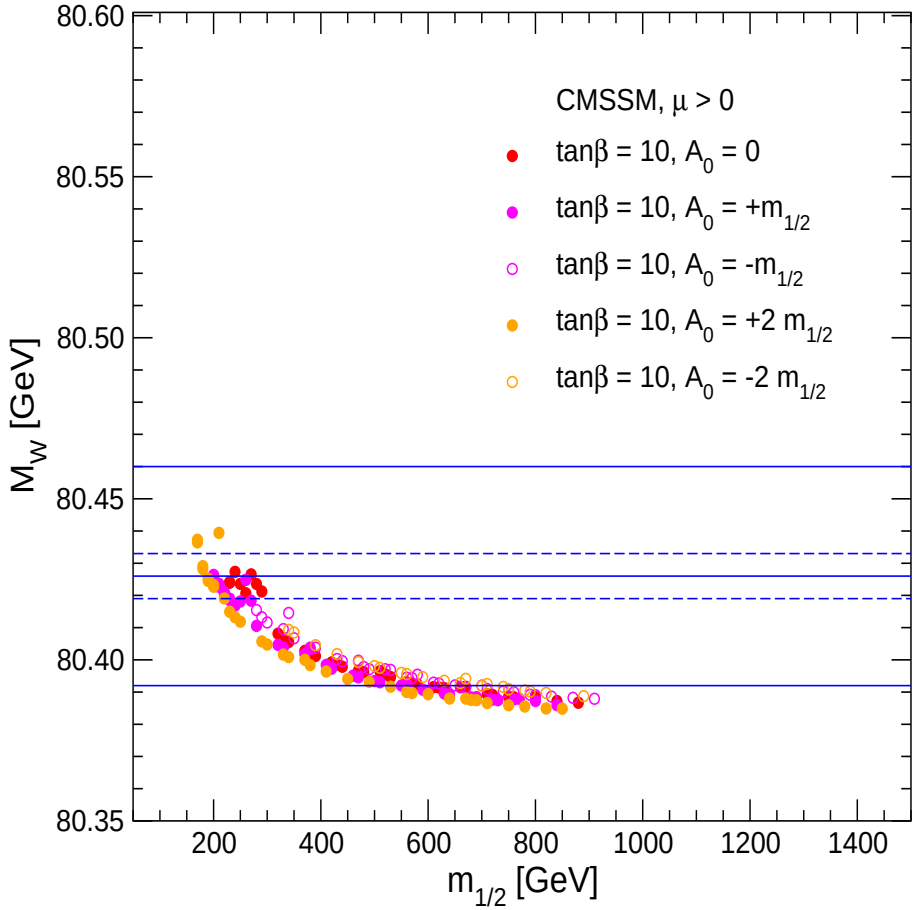
1. Scan over parameter space:
   - CMSSM: for fixed $\tan\beta = 10, 50$
   - NUHM: certain parameter planes,
     corresponding to CMSSM best fit points
   - VCMSSM: full parameter space ($A_0/m_0 = 0, 3/4, 3-\sqrt{3}, 2$)
   - GDM (mSUGRA): full parameter space ($A_0/m_0 = 0, 3/4, 3-\sqrt{3}, 2$)

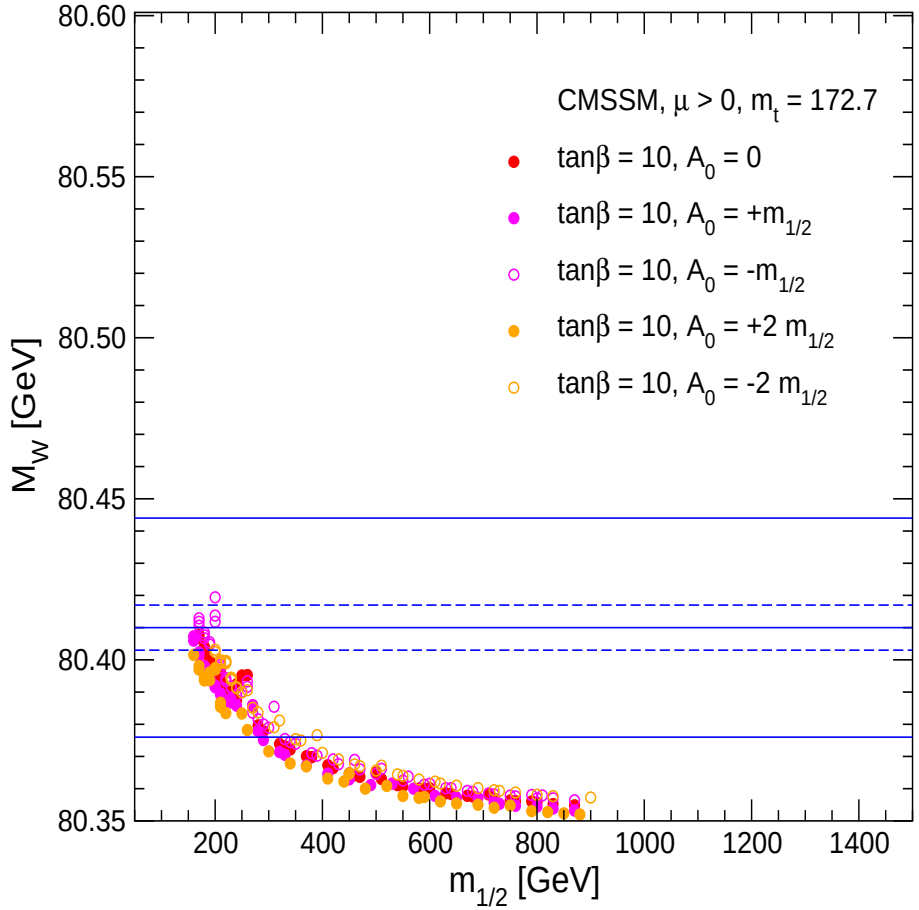
2. Perform χ^2 fit

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

3 A) CMSSM:

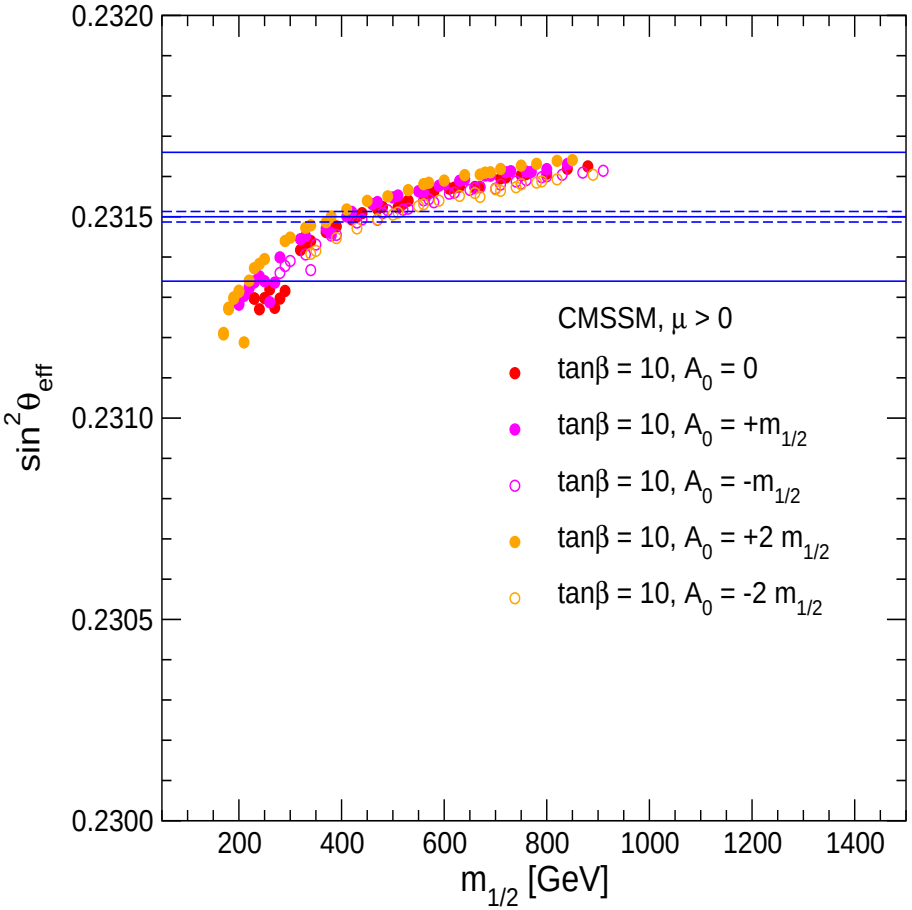
Compare $m_t = 178$ GeV with $m_t = 172.7$ GeV: M_W for $\tan\beta = 10$:

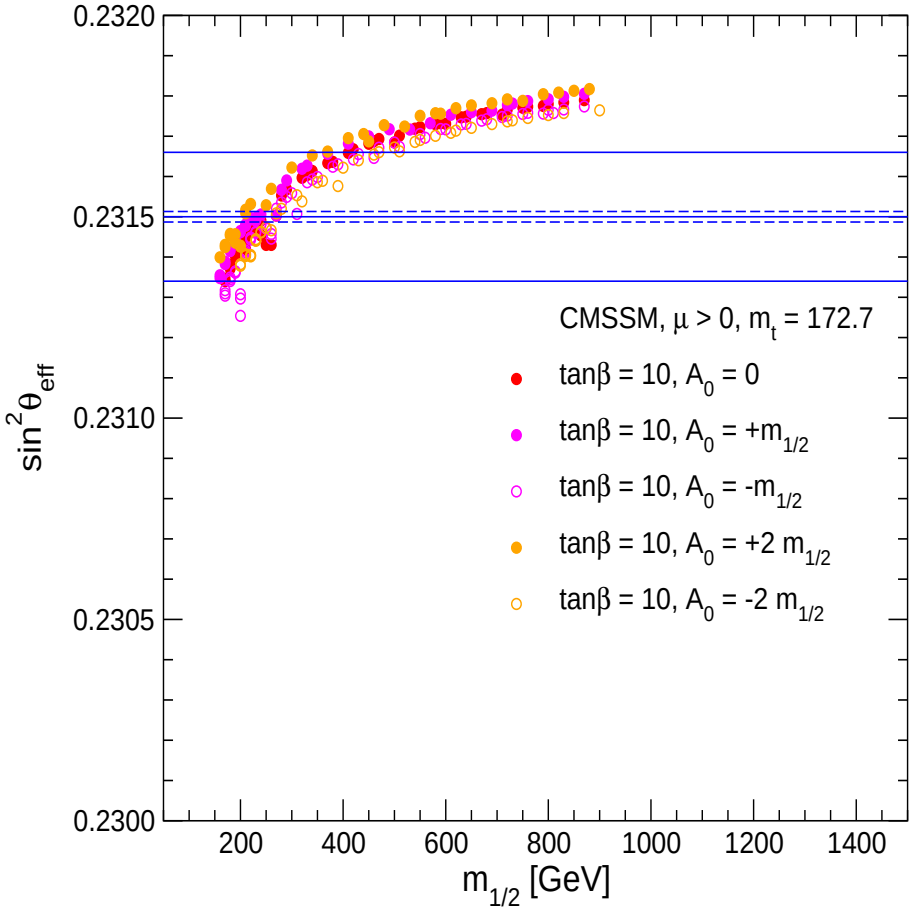




$m_t = 178 \rightarrow 172.7 \Rightarrow m_{1/2}$ lowered

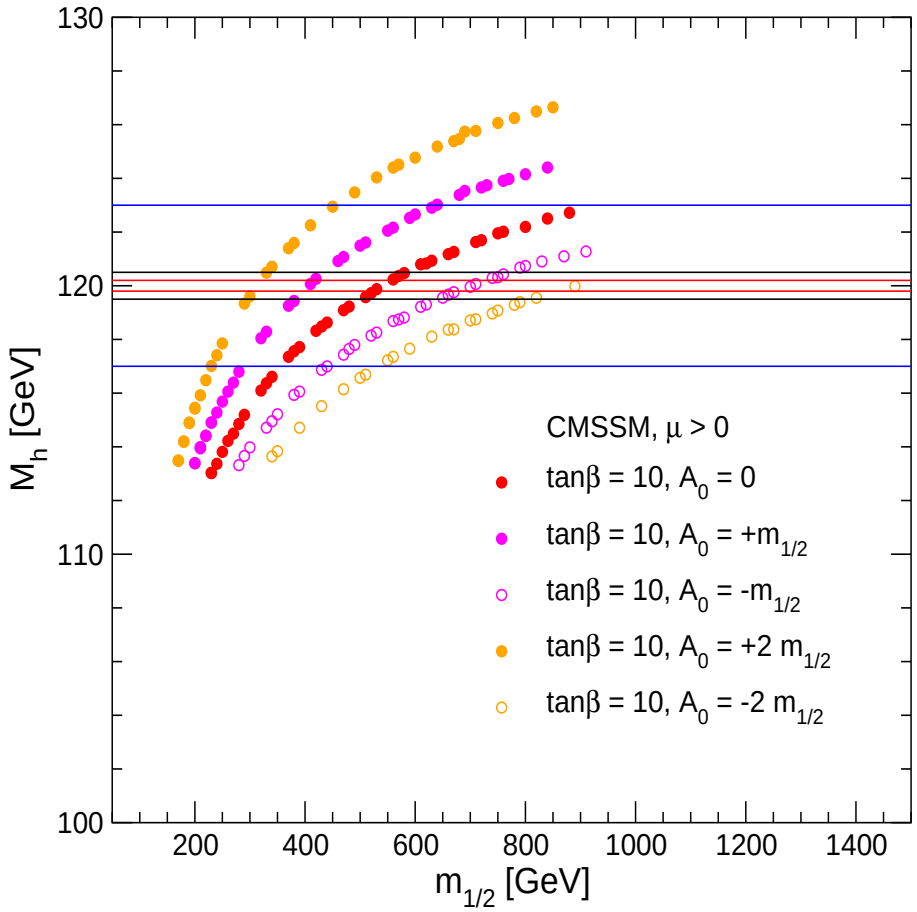
Compare $m_t = 178$ GeV with $m_t = 172.7$ GeV: $\sin^2\theta_{\rm eff}$ for $\tan\beta = 10$:

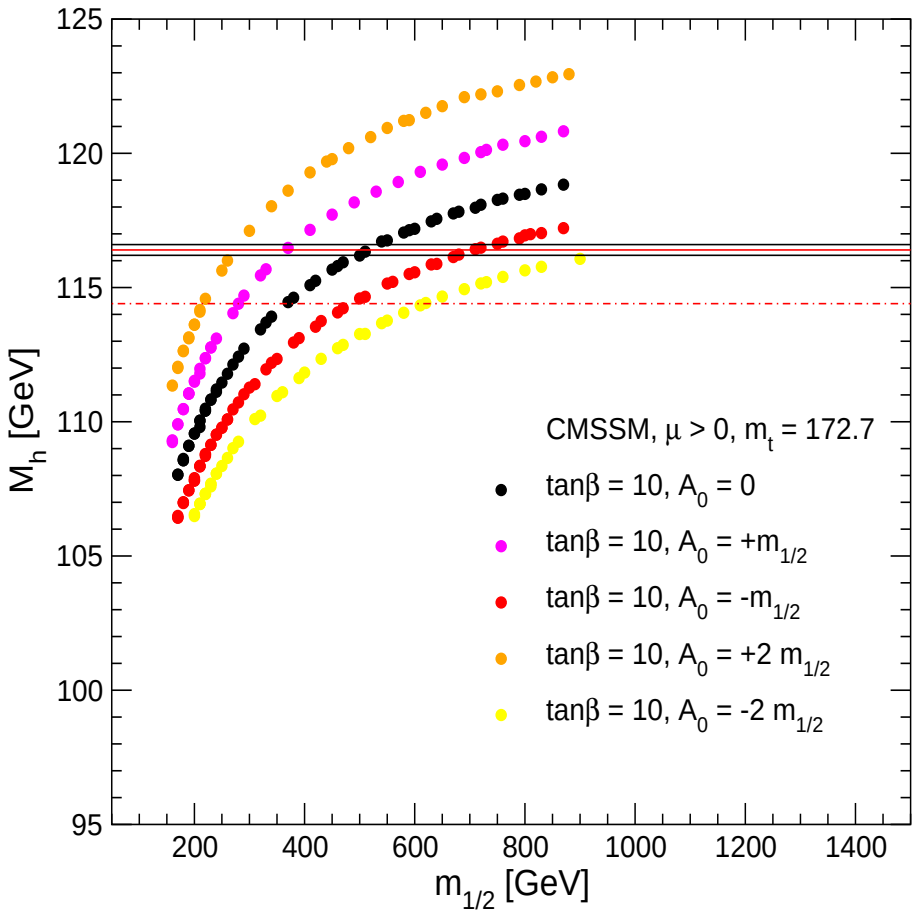




$m_t = 178 \to 172.7 \Rightarrow m_{1/2}$ lowered

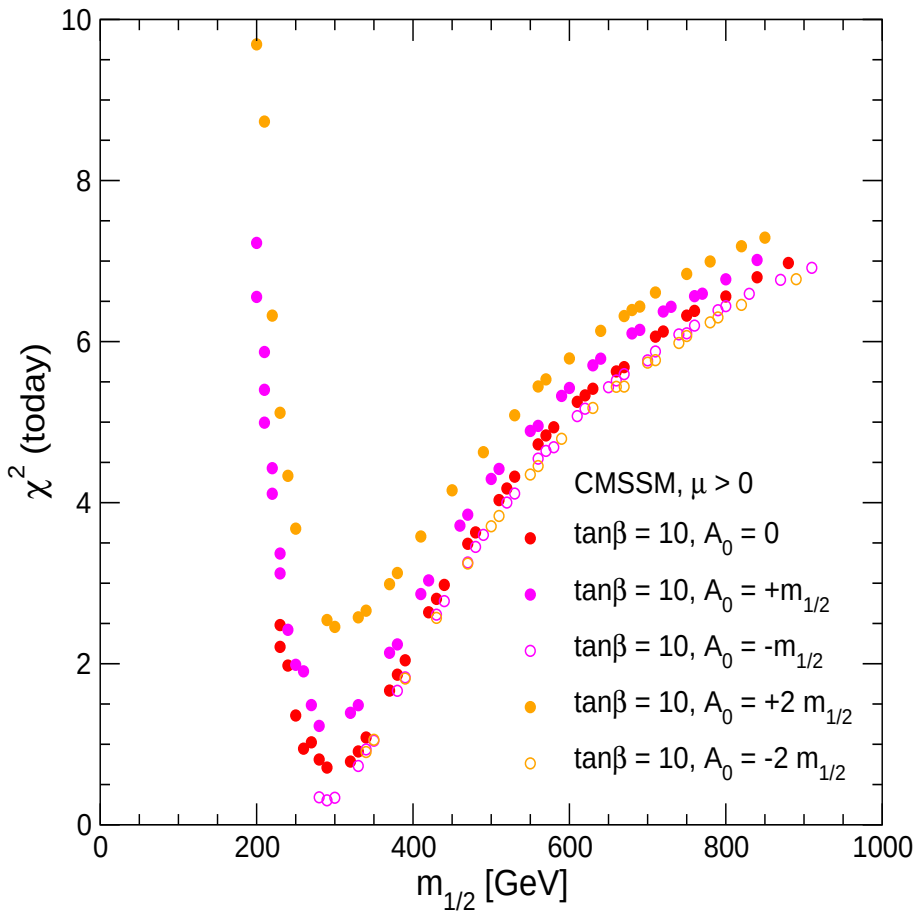
Compare $m_t = 178$ GeV with $m_t = 172.7$ GeV: M_h for $\tan\beta = 10$:

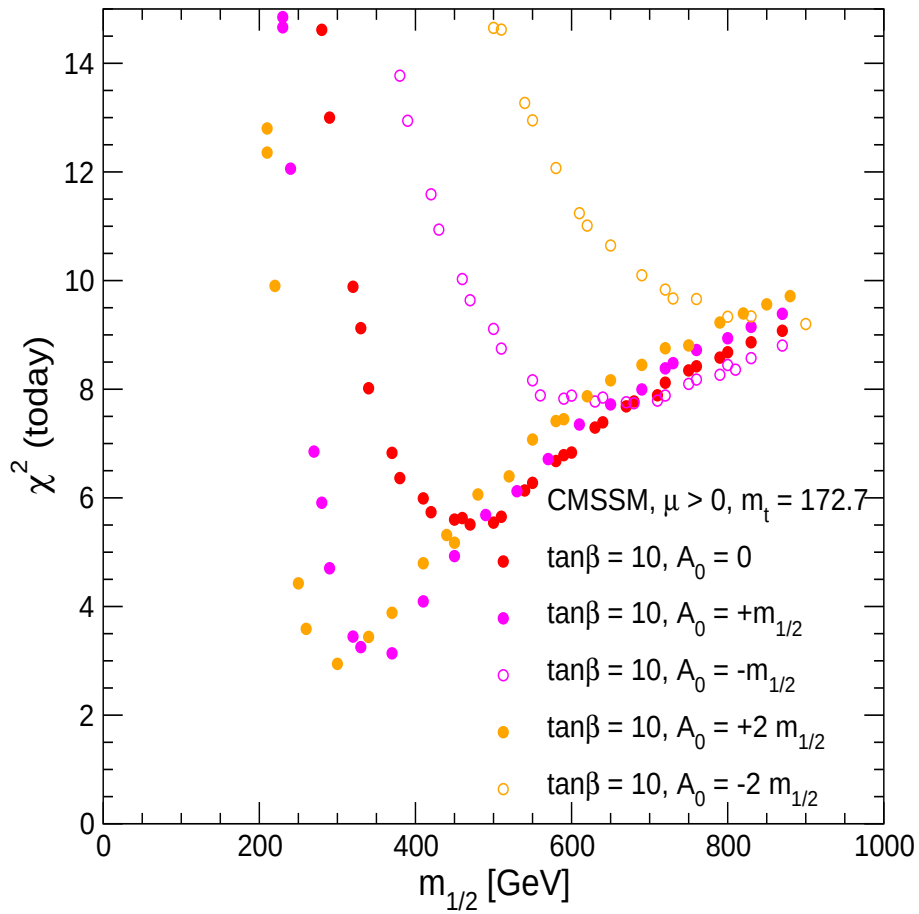




$m_t = 178 \rightarrow 172.7 \Rightarrow m_{1/2}$ increased

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

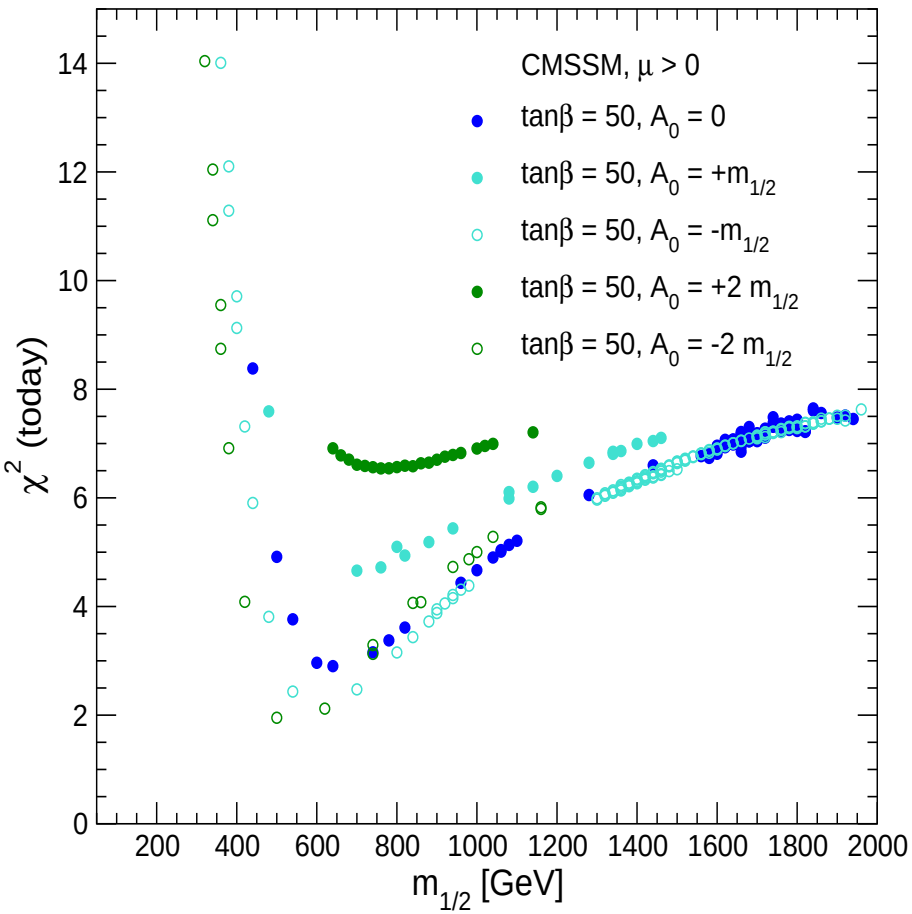


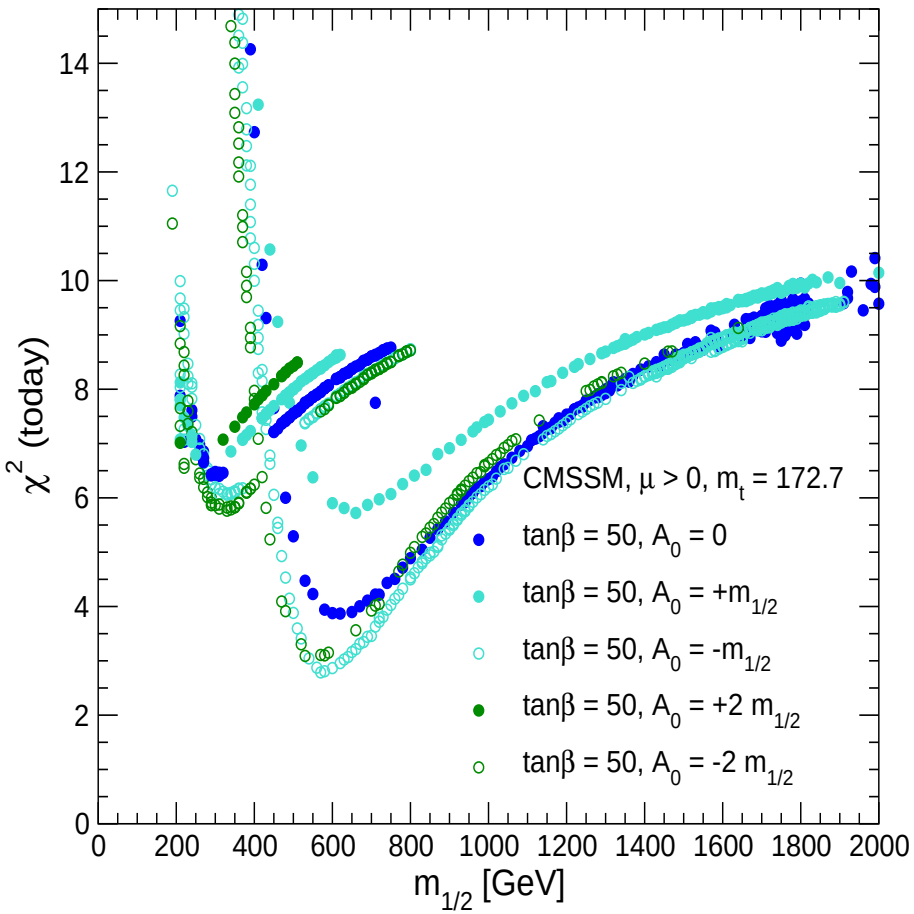


$m_t = 178 \to 172.7$ slightly higher χ^2, $A_0 > 0$ favored

$\Rightarrow M_W$ and $\sin^2\theta_{\text{eff}}$ 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 $\tan\beta = 50$:

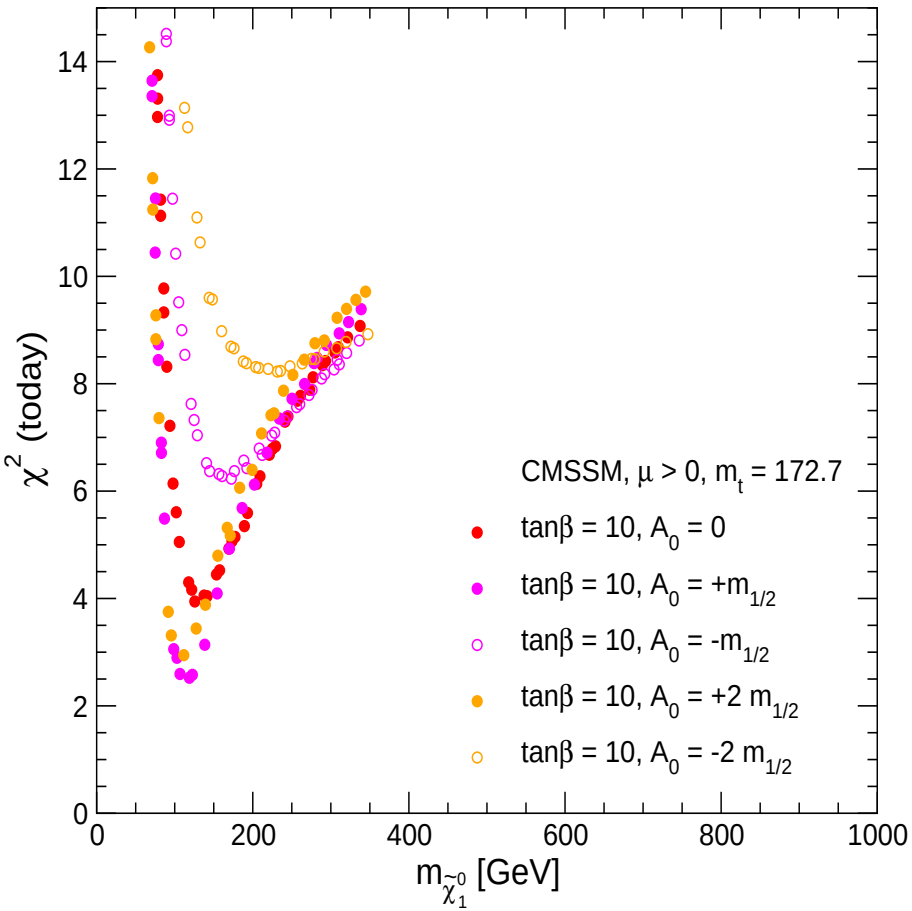


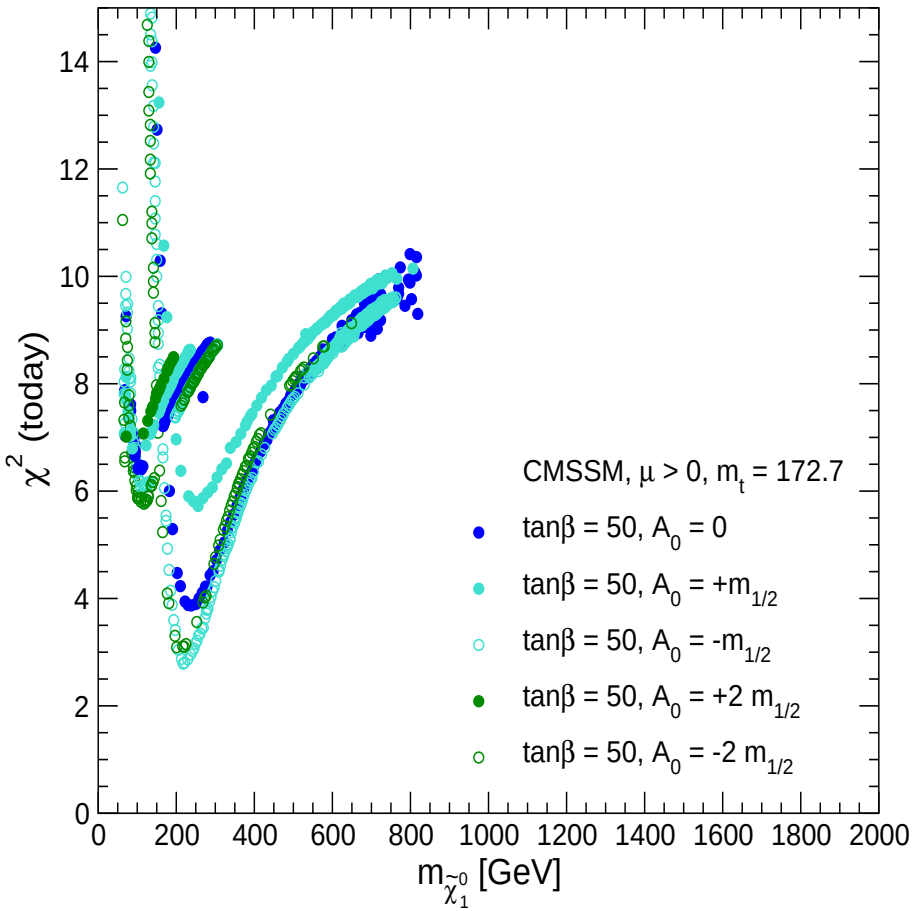


$m_t = 178 \rightarrow 172.7$ effective change minor

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

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

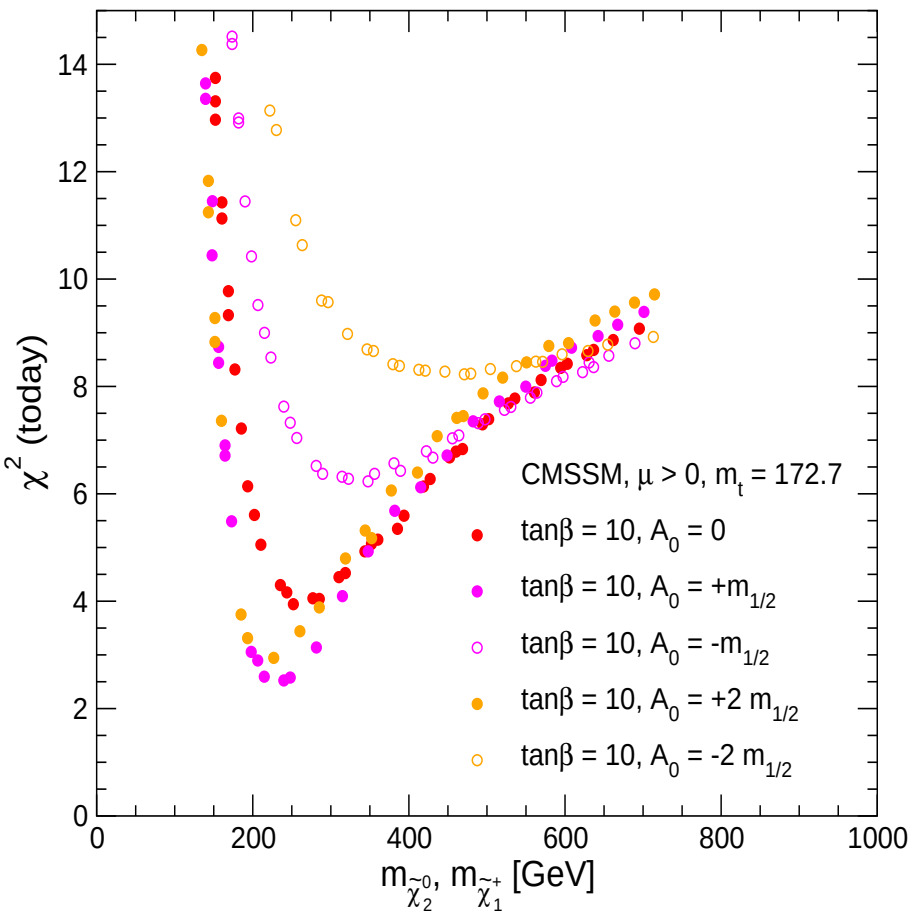


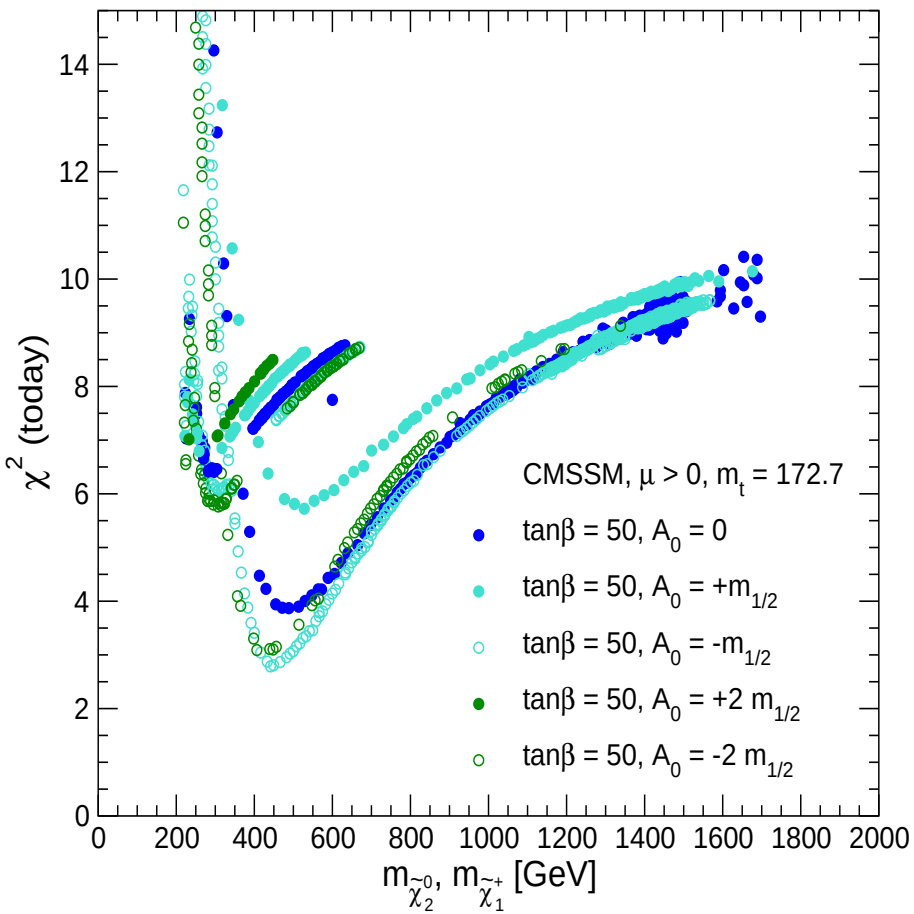


$\tan\beta = 10 \Rightarrow$ minimum at/below 200 GeV

$\tan\beta = 50 \Rightarrow$ similar

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



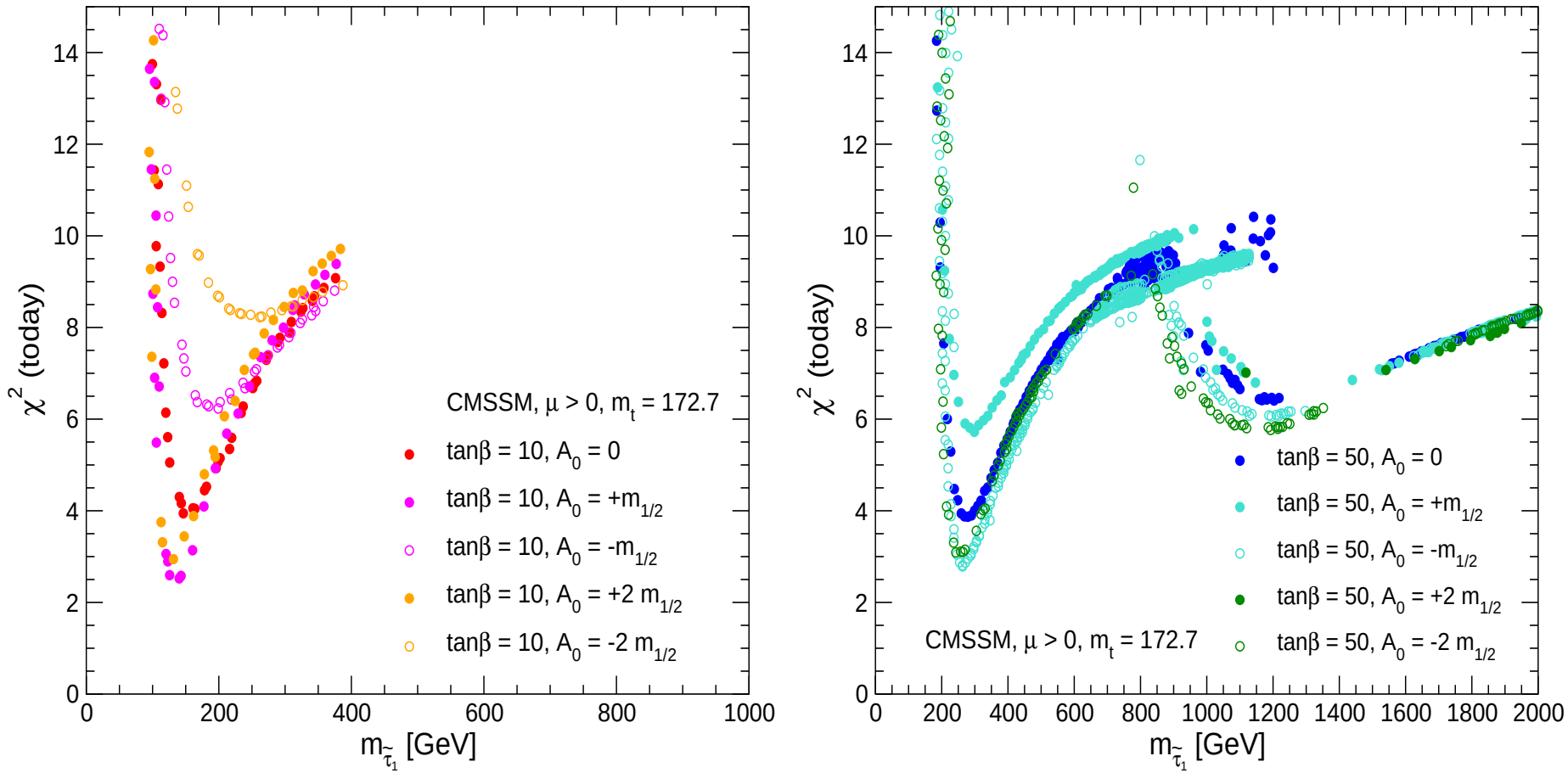


$\tan\beta = 10 \Rightarrow$ very good prospects for the LHC/ILC(1000)

$\Rightarrow$ even chances for the Tevatron

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

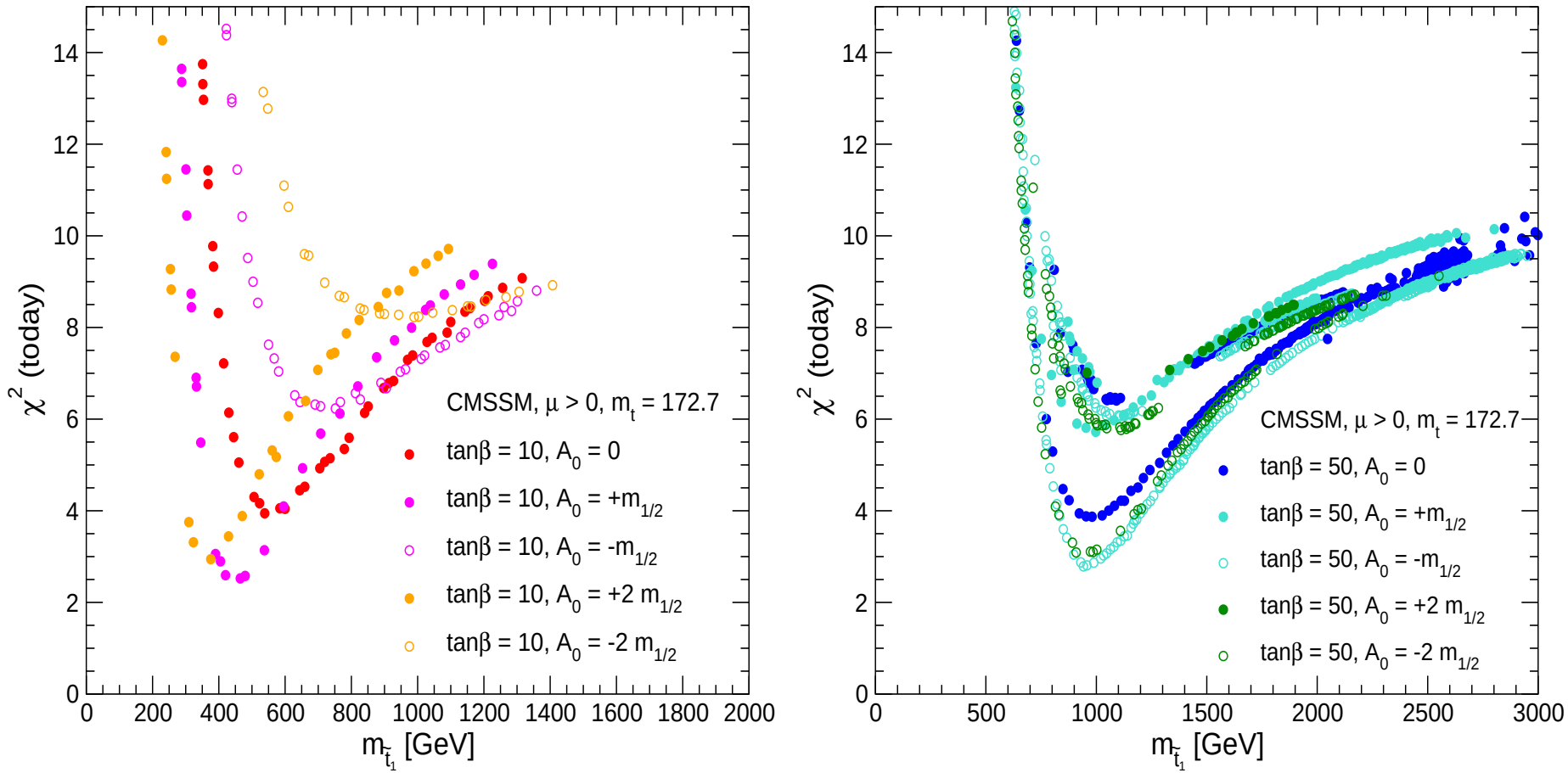
CMSSM: lightest stau mass for $\tan\beta = 10, 50$



$\tan\beta = 10 \Rightarrow$ very good prospects for all colliders

$\tan\beta = 50 \Rightarrow$ still quite good (except for Focus Point)

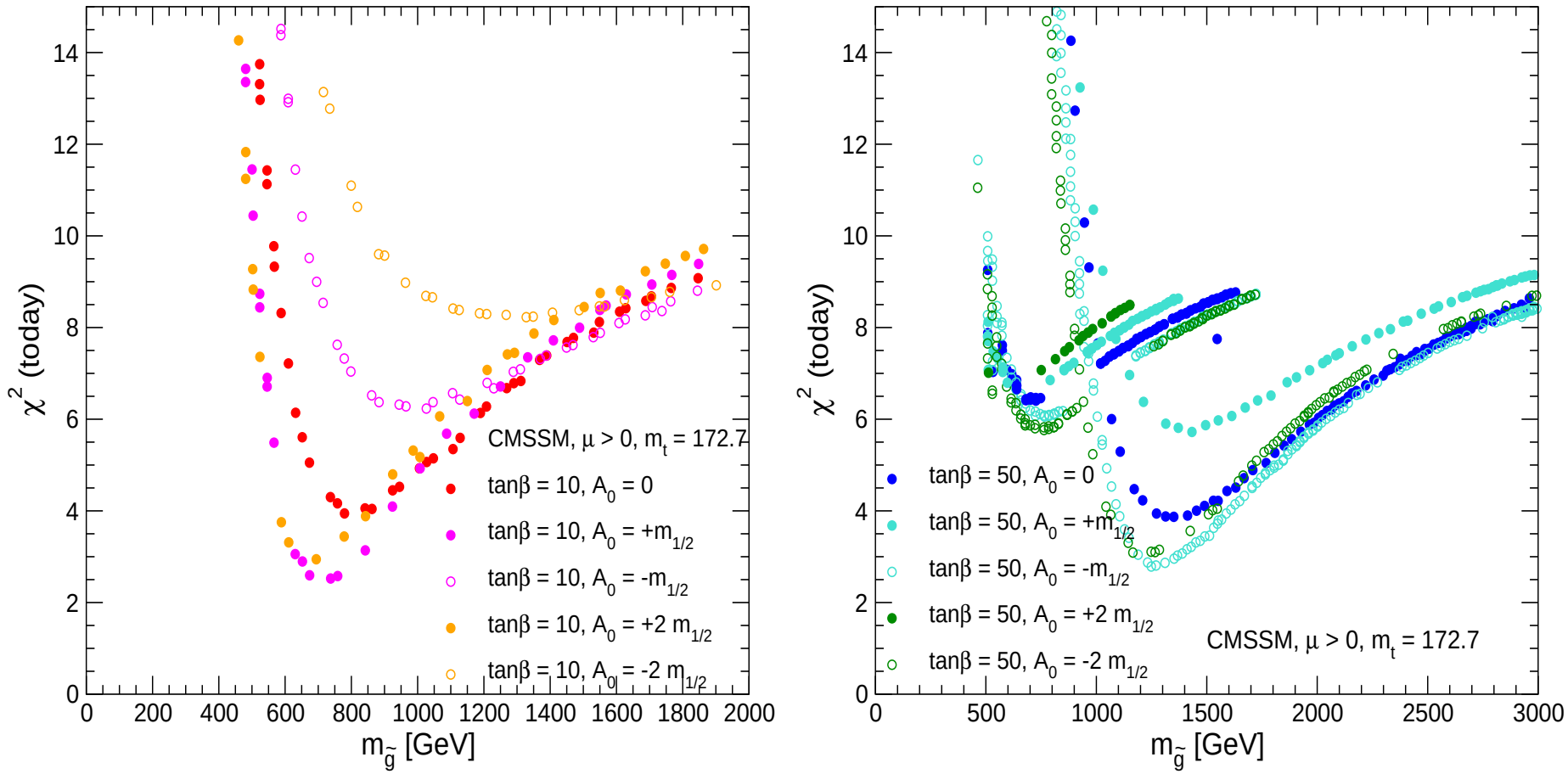
CMSSM: lightest stop mass for $\tan\beta = 10, 50$



$\tan\beta = 10 \Rightarrow$ good chances for LHC, moderate prospects for the ILC

$\tan\beta = 50 \Rightarrow$ still good for LHC, but outside the ILC(1000) reach

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

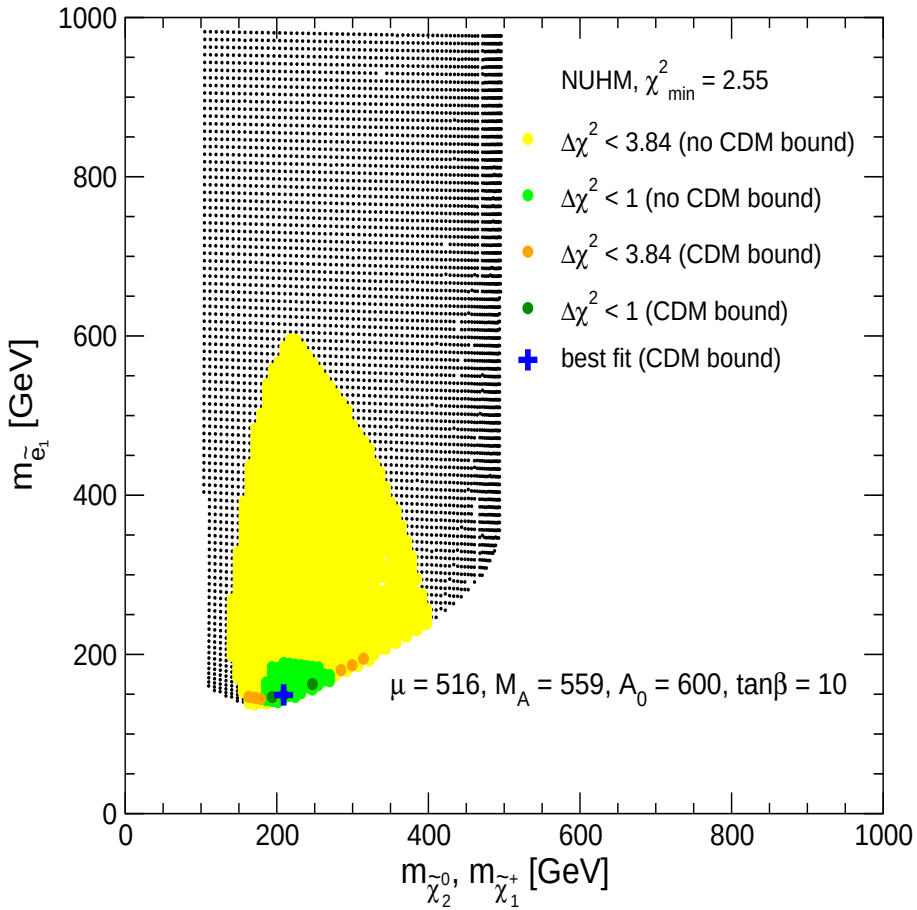


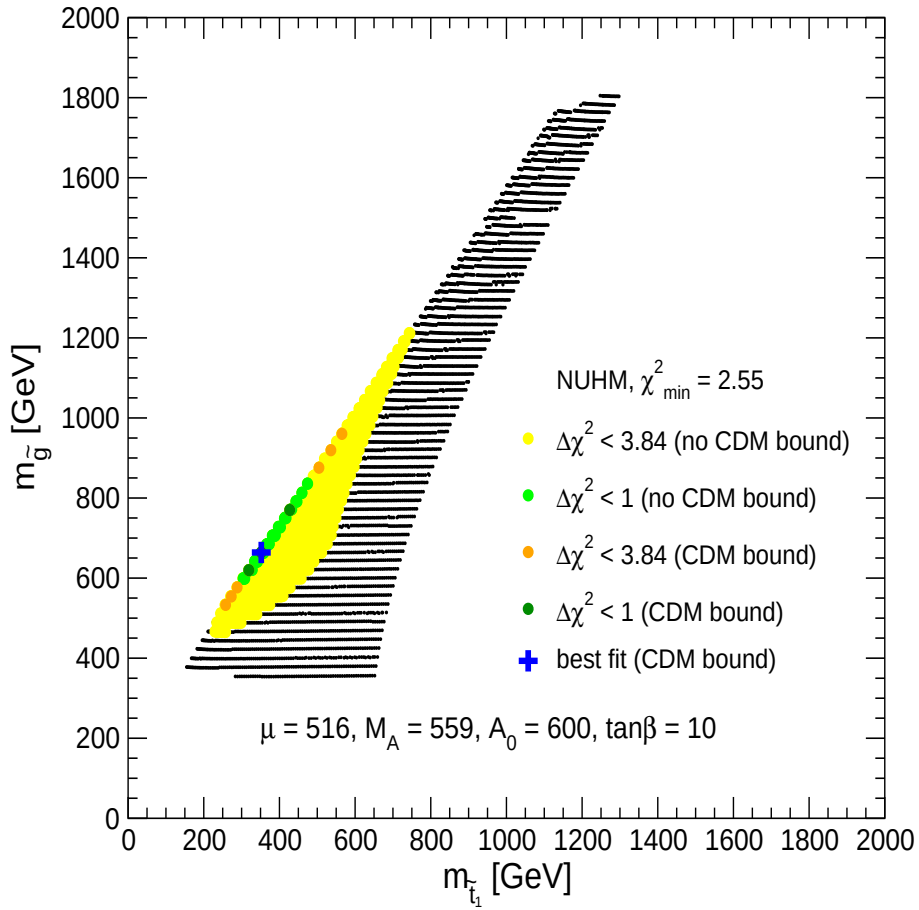
$\tan\beta = 10 \Rightarrow$ no problem for LHC, but outside the ILC(1000) reach

$\tan\beta = 50 \Rightarrow$ no problem for LHC, but outside the ILC(1000) reach

3 B) NUHM

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

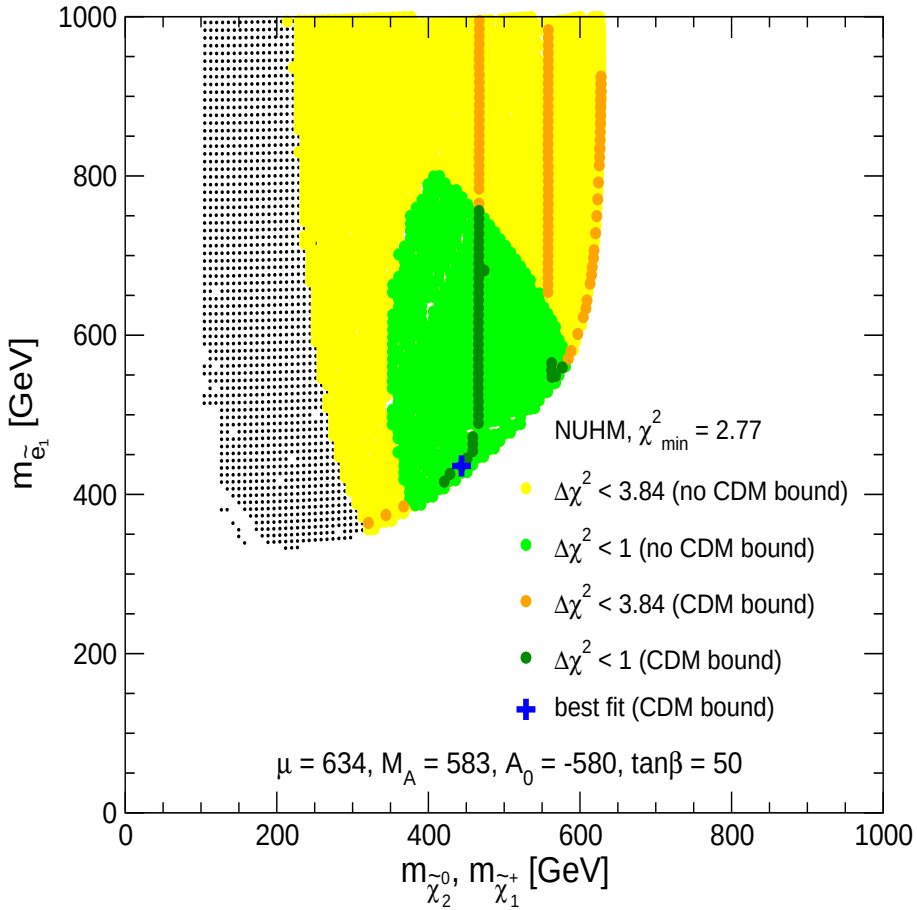


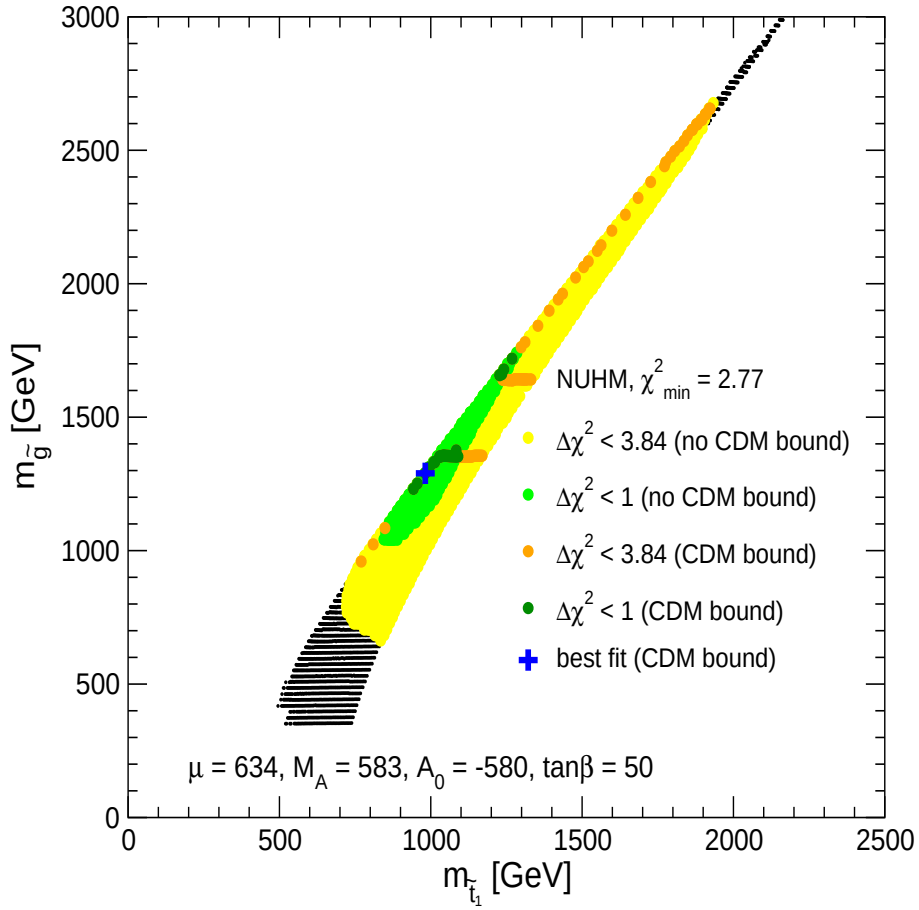


⇒ sleptons, charginos, neutralinos in reach

stops and gluinos only in reach for LHC

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



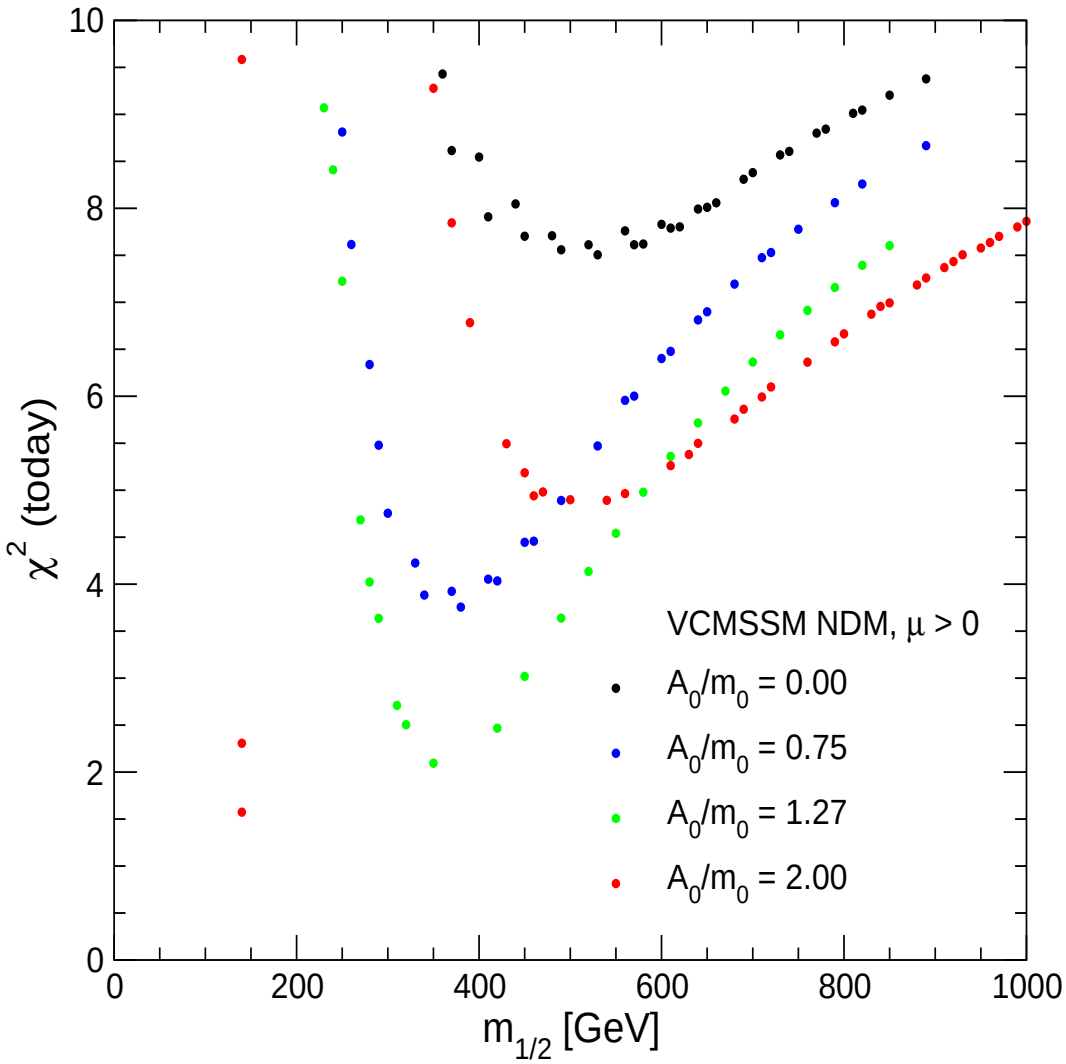


$\Rightarrow$ sleptons, charginos, neutralinos partially in reach for ILC(1000)

stops and gluinos only in reach for LHC

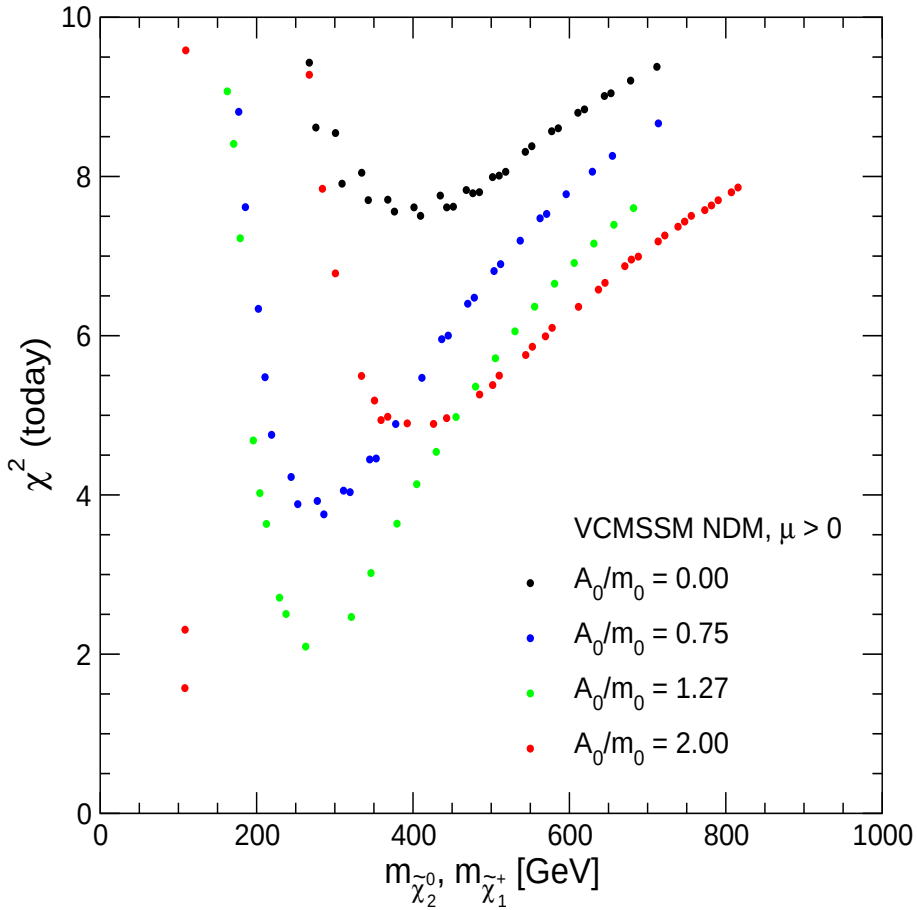
3 C) VCMSSM

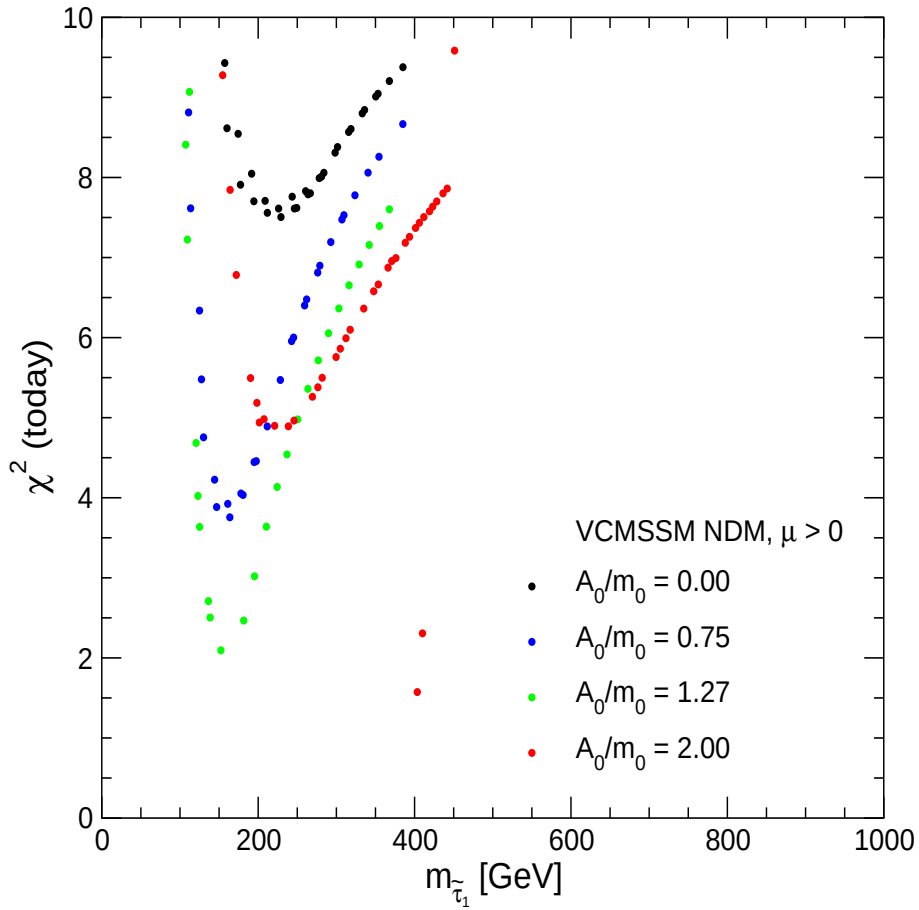
VCMSSM: scan over full parameter space



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

VCMSSM: scan over full parameter space



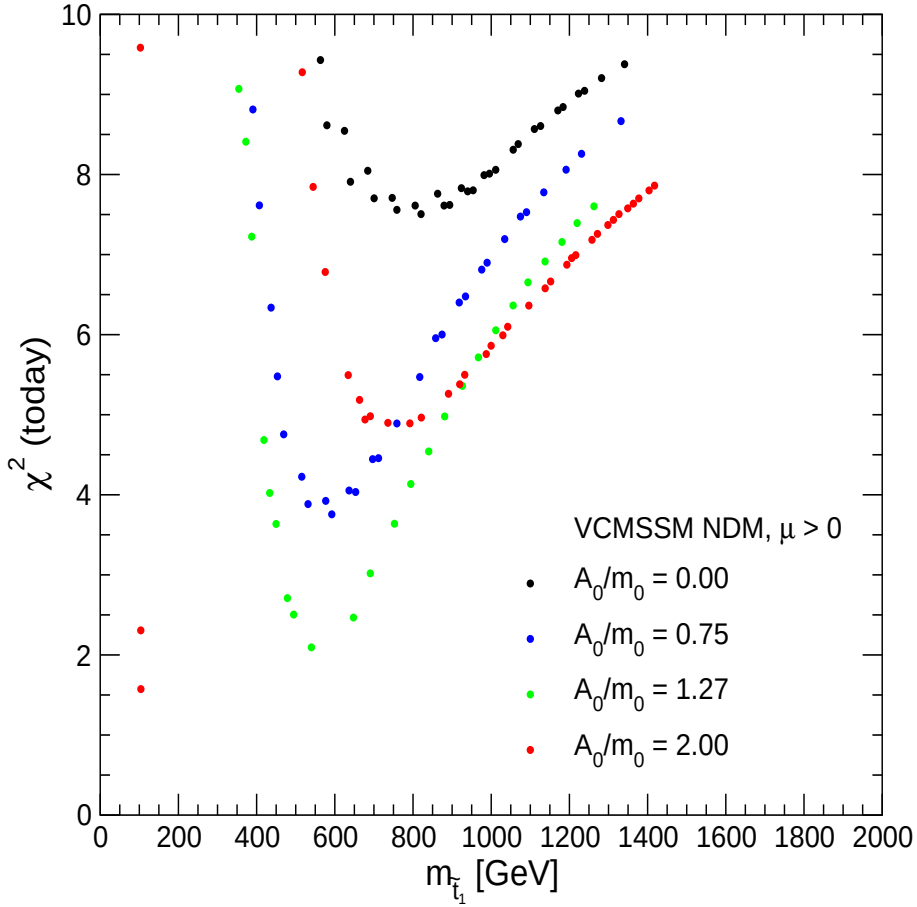


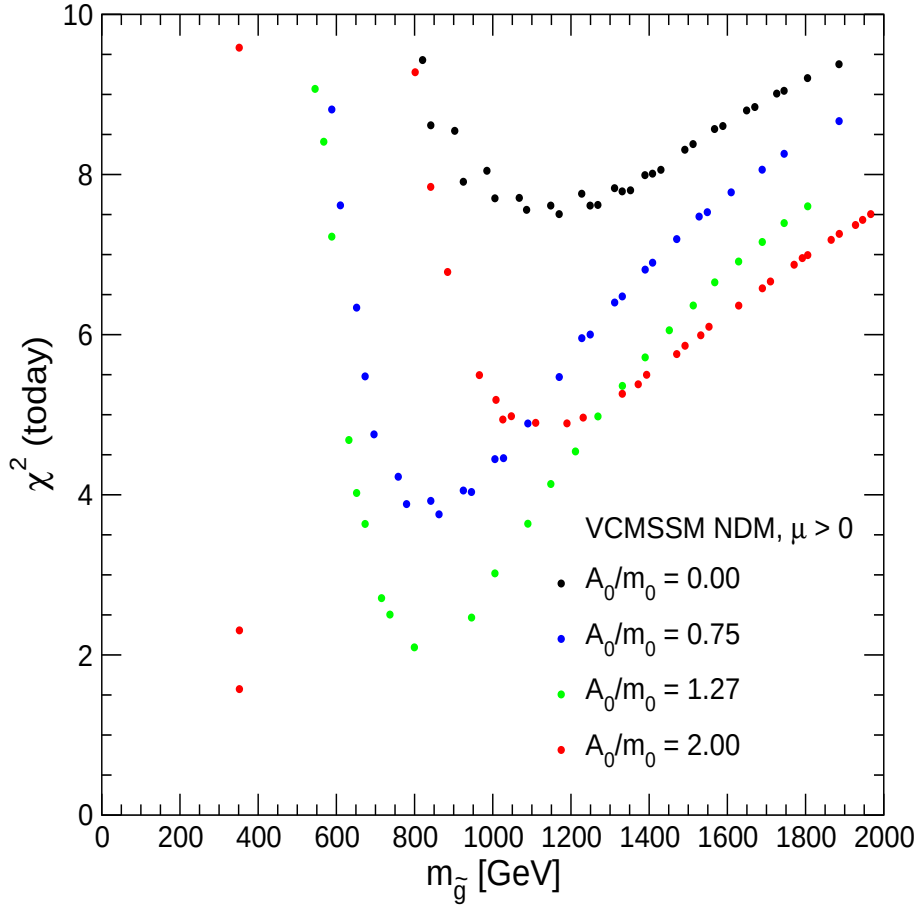
$\Rightarrow$ $A_0/m_0 = 3/4, 3-\sqrt{3}$ and Higgs pole favored

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

$\Rightarrow$ even chances for the Tevatron and good prospects for LHC

VCMSSM: scan over full parameter space





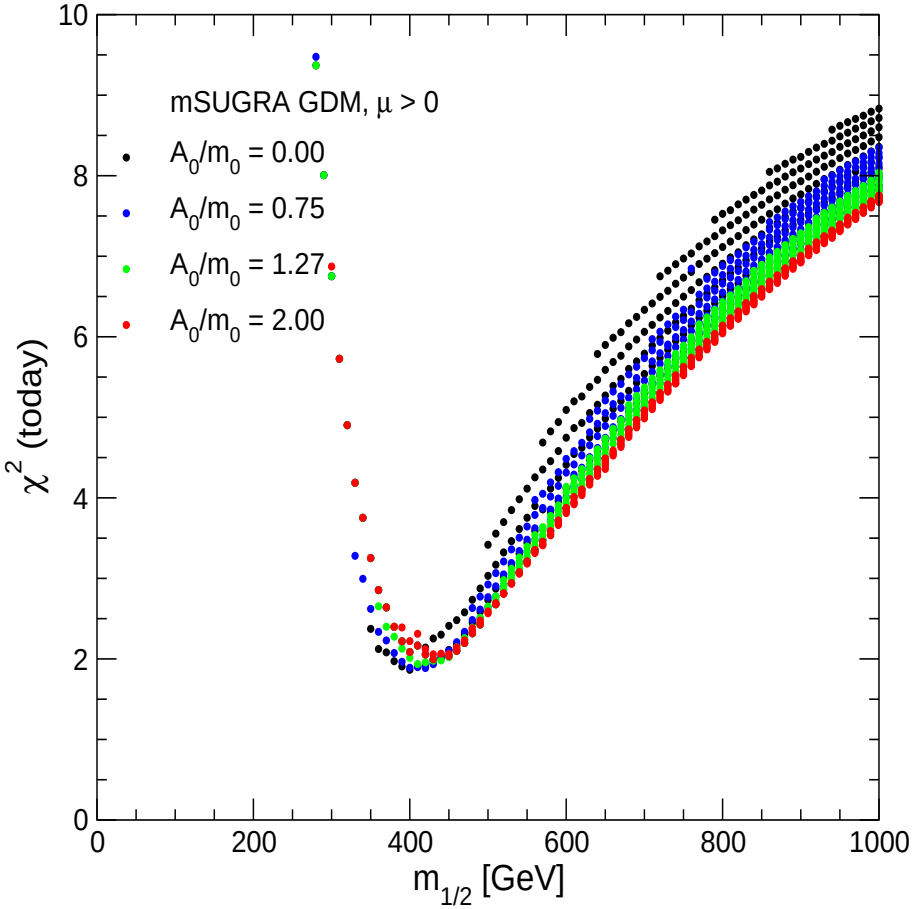
$\Rightarrow$ $A_0/m_0 = 3/4, 3 - \sqrt{3}$ and Higgs pole favored

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

$\Rightarrow$ LHC can cover the whole parameter space

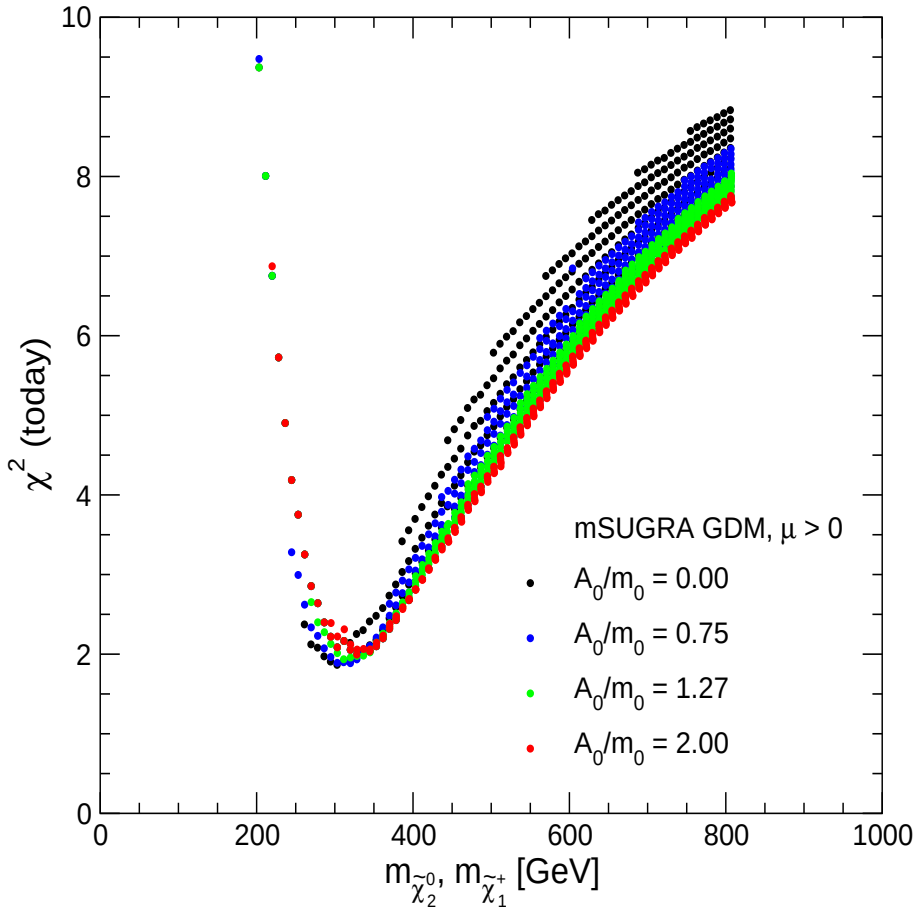
3 D) GDM (mSUGRA)

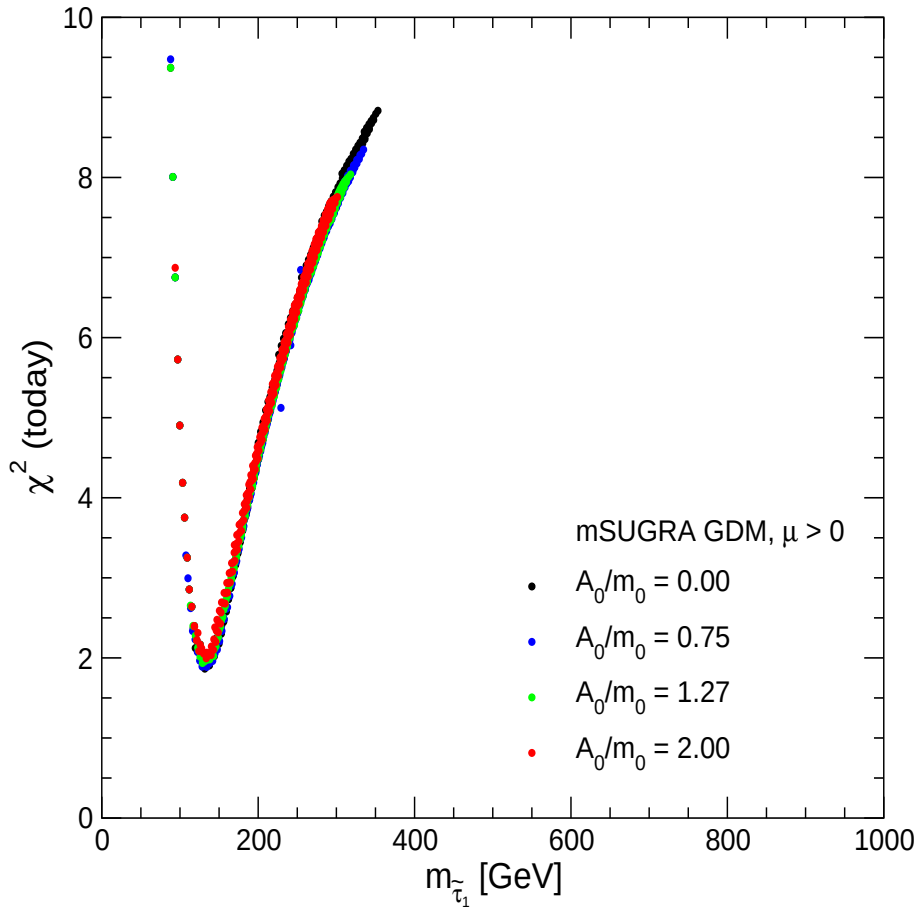
GDM (mSUGRA): scan over full parameter space



$\Rightarrow$ all A_0/m_0 values similarly good

GDM (mSUGRA): scan over full parameter space



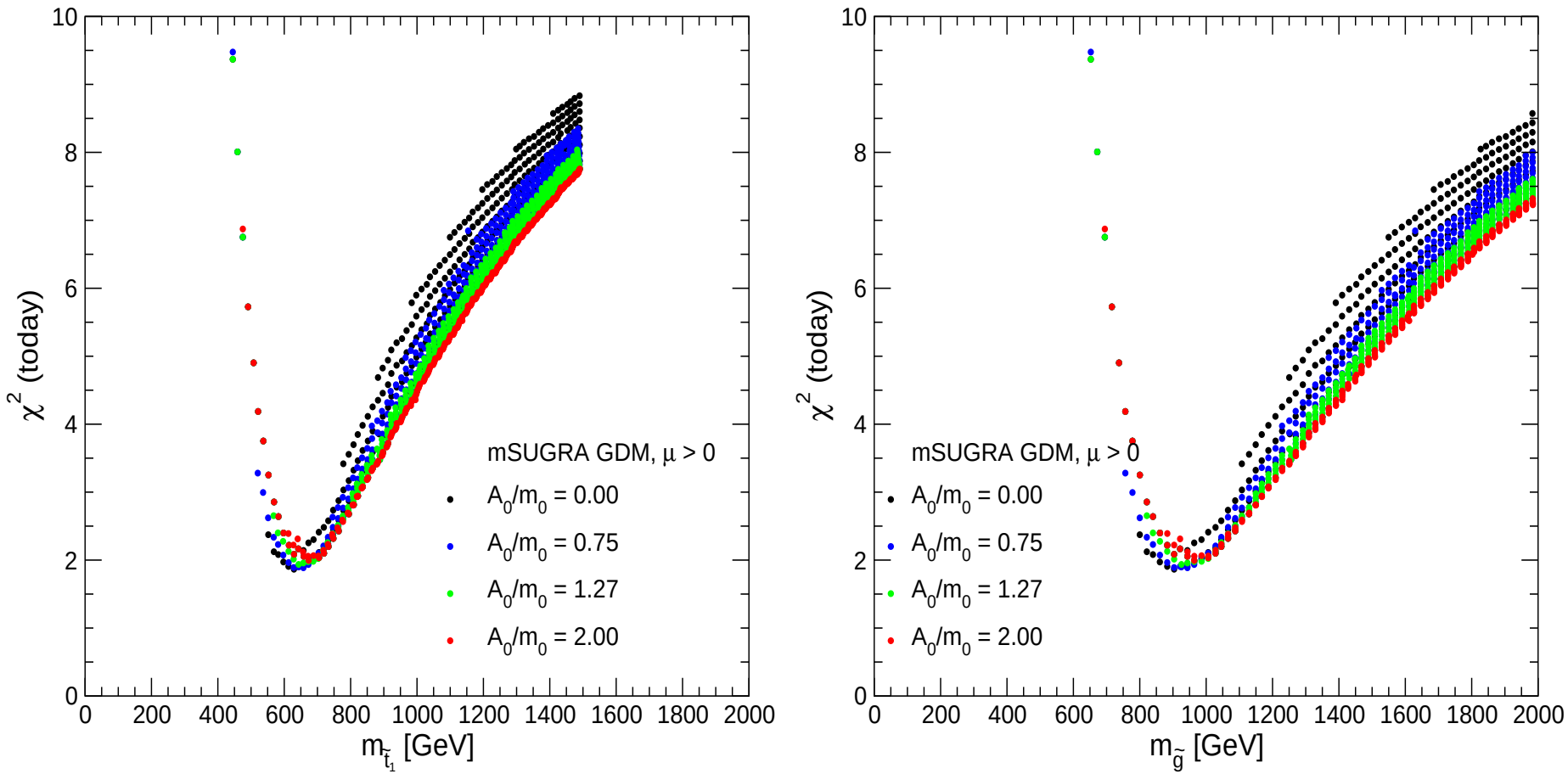


⇒ all A_0/m_0 values similarly good

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

⇒ even chances for the Tevatron

GDM (mSUGRA): scan over full parameter space



⇒ all A_0/m_0 values similarly good

⇒ stops and gluinos only in reach for the LHC

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 $\Rightarrow$ collider 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

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  hardly any chance for light stops or gluinos

In all scenarios the LHC and the ILC will discover SUSY particles