The constrained NMSSM: mSUGRA and GMSB

U. Ellwanger, LPT Orsay

Motivation

MSSM: A supersymmetric Higgs(ino) mass term $\mu \gtrsim 100$ GeV is necessary in order to satisfy the LEP constraints on chargino (= higgsino/wino) masses, $\mu \lesssim M_{SUSY}$ is required for $\langle H_u \rangle$, $\langle H_d \rangle \neq 0$

NMSSM: The μ-term in the superpotential W of the MSSM is generated by the VEV of an additional gauge singlet superfield S:

$$W_{MSSM} = \mu H_u H_d + \ldots \quad \longrightarrow \quad W_{NMSSM} = \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \ldots$$

Soft SUSY breaking terms: $\mu B H_u H_d + \ldots \quad \longrightarrow \quad \lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \ldots$

If all SUSY breaking terms are of $\mathcal{O}(M_{SUSY})$:

$$\langle S \rangle \sim M_{SUSY}/\kappa \quad \longrightarrow \quad \mu_{eff} \equiv \lambda \langle S \rangle \sim \frac{\lambda}{\kappa} M_{SUSY} \checkmark$$

New parameters: $\mu,\ B|_{MSSM} \longrightarrow \lambda,\ \kappa,\ A_\lambda,\ A_\kappa|_{NMSSM}$

$\longrightarrow$ One additional neutral CP-even Higgs + CP-odd Higgs + neutralino from the singlet superfield S

Each of the neutralino/CP-even/CP-odd sectors can give rise to a phenomenology different from the MSSM:

a) The LSP can be dominantly singlino-like (consistent with WMAP constraints on Ωh^2, if only a few GeV below the NLSP, see G. Belanger et al.) $\longrightarrow$ additional contribution to sparticle decay chains; the NLSP could have a long life time!

b) The SM-like CP-even Higgs scalar h_1 can be ~ 15 GeV heavier than in the MSSM (for low $\tan\beta$!)

c) A CP-odd Higgs scalar a_1 can be (very) light (see the talk by J. Gunion)

$\longrightarrow$ impact on B physics (see the talk by M. Sanchis-Lozano)

$\longrightarrow$ h_1 can decay dominantly into $h_1 \to a_1\, a_1$; then:

$\longrightarrow$ LEP constraints on h_1 are less restrictive

$\longrightarrow$ the search for h_1 at the LHC can become considerably more difficult

These are not "unavoidable" predictions of the NMSSM, but depend on the unknown parameters λ, κ, A_λ, A_κ, $\tan\beta$, μ_{eff}

What are the consequences of particular boundary conditions at a high scale (mSUGRA, GMSB)?

(The subsequent results are obtained with the help of the Fortran code **NMHDECAY/ NMSSMTools** (U. E., J. Gunion, C. Hugonie), which computes the Higgs/sparticle spectrum and Higgs BRs including radiative corrections for general/mSUGRA/GMSB boundary conditions, and checks for constraints from colliders/B-physics/(g-2)$_\mu$/dark matter via MicrOMEGAs)

The cNMSSM

(with A. Djouadi, A.M. Teixeira)

Universal soft SUSY breaking terms (including the singlet sector) at $M_{GUT} \sim M_{Planck}$

$\longrightarrow$ Just 4 free parameters $M_{1/2}$, m_0, A_0, λ (κ determined by M_Z), as in the cMSSM (with λ replaced by μ or $\tan\beta$)

Constraints from $\langle S \rangle \neq 0$:

At $M_{SUSY} \sim M_{weak}$: $$V(S) \sim m_S^2 |S|^2 + \frac{\kappa}{3} A_\kappa (S^3 + S^{*3}) + \kappa^2 |S|^4$$

has a stable nontrivial minimum if $m_S < \frac{1}{3}|A_\kappa|$ and $\kappa A_\kappa \langle S \rangle < 0$
(from stability in the CP-odd direction)
m_S, A_κ are hardly renormalized between M_{GUT} and M_{SUSY},
$\kappa \langle S \rangle > 0$ if $\mu_{eff} > 0$

$$\longrightarrow \boxed{m_0 \lesssim \frac{1}{3}|A_0|,\ \ A_0 < 0}$$

Constraints from dark matter:

The lighter stau $\tilde{\tau}_1$ would be the LSP unless the additional (singlet-like) neutralino $\tilde{\chi}_1$ (with a mass $\sim |A_\kappa| \sim |A_0|$) is lighter

$$\longrightarrow \boxed{|A_0| \lesssim \frac{1}{3} M_{1/2}, \ \rightarrow \ m_0 \lesssim \frac{1}{10} M_{1/2}}$$

(impossible in the MSSM!)

From Ωh^2: $\quad m_{\tilde{\chi}_1} \sim m_{\tilde{\tau}_1} - (1-8)$ GeV $\lesssim$ 600 GeV

$$\longrightarrow \boxed{A_0 \sim -\frac{1}{4} M_{1/2}, \ M_{1/2} \lesssim 2\text{-}3 \text{ TeV}}$$

Constraints from LEP:

$m_{\tilde{\tau}_1} \gtrsim 100$ GeV $\quad \longrightarrow \boxed{M_{1/2} \gtrsim 400 \text{ GeV}}$

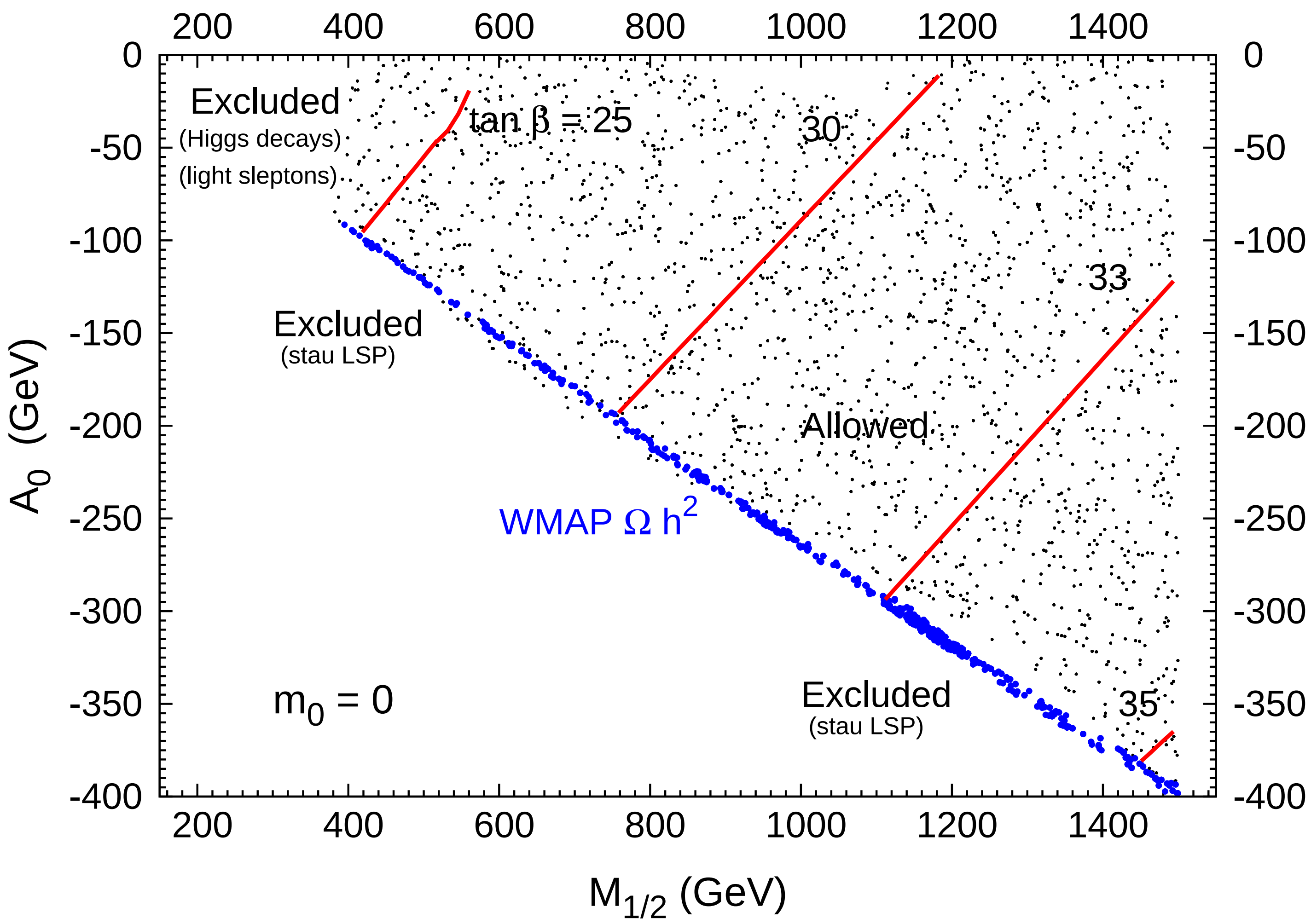
$\longrightarrow$ the SM-like Higgs scalar H_{SM} has a mass $m_{H_{SM}} = 115 \ldots\ 120$ GeV

BUT: $m_{H_{SM}}$ decreases if H_{SM} mixes with the singlet-like scalar

$$\longrightarrow \boxed{\lambda \lesssim 2 \times 10^{-2}}$$

All together:

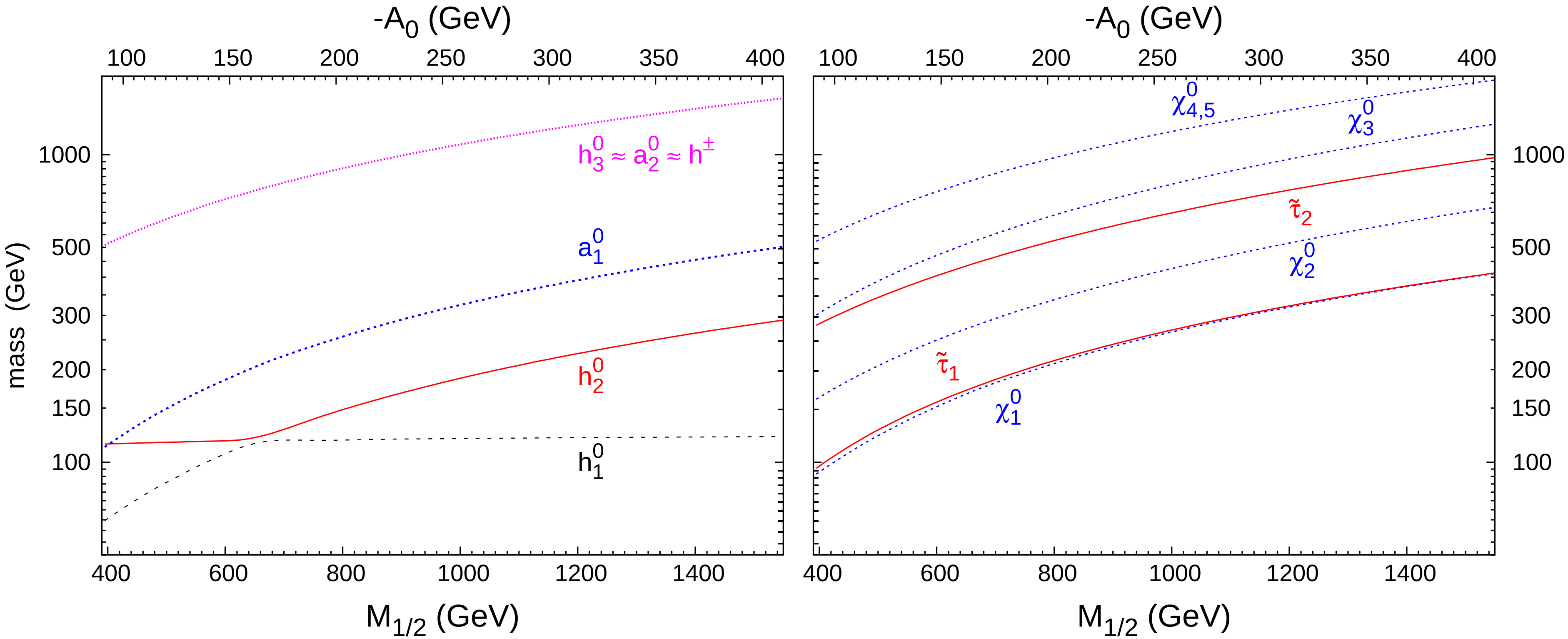
$$400\ \text{GeV} \lesssim M_{1/2} \lesssim 2\ \text{TeV}$$
$$A_0 \sim -\tfrac{1}{4} M_{1/2}\ \text{from}\ \Omega h^2$$
$$\left.\begin{array}{l} m_0 \lesssim \frac{1}{12} M_{1/2} \\ \lambda \lesssim 2 \times 10^{-2} \end{array}\right\}\ \begin{array}{l}\text{small effect on}\\ \text{the spectrum}\end{array}$$



$\longrightarrow$ The complete spectrum is determined by $M_{1/2}$

$\longrightarrow$ Consistent with constraints from colliders, B physics

$\longrightarrow$ $\tan\beta \sim 25\ldots\ 38$, $\mu_{eff} \sim 500 - 1100$ GeV, $M_{Squark} \sim M_{Gluino} \sim 2\,M_{1/2}$

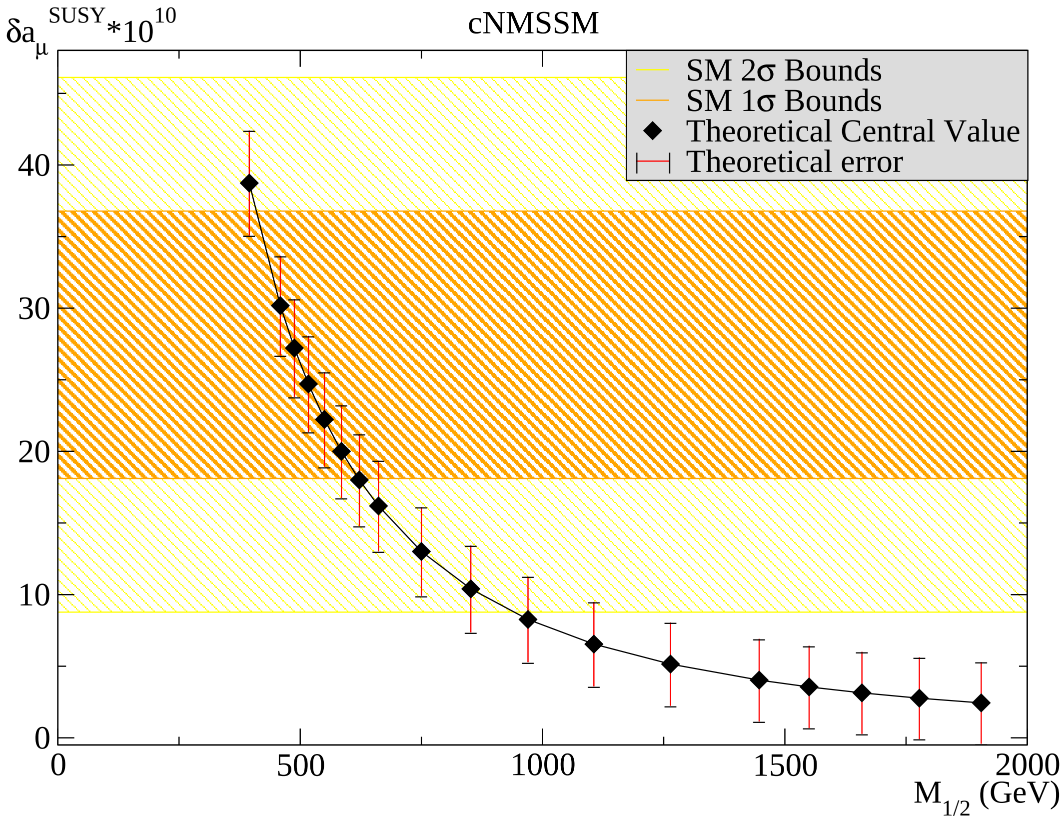


For $M_{1/2} \lesssim 640$ GeV, the lightest CP-even scalar h_1^0 is singlet-like

Apart from the different spectrum w.r.t. the MSSM, the $\tilde{\tau}_1$ track length (at the end of <u>each</u> sparticle decay cascade!) can be $\gtrsim 1$ mm, if $\lambda \lesssim 10^{-4}$

$\rightarrow$ A possible smoking gun!

Constraints from $(g-2)_\mu$ (with F. Domingo):



$\rightarrow M_{1/2} \lesssim 1$ TeV ($M_{1/2} \sim 500$ GeV?)

NMSSM and GMSB

(with C.C. Jean-Louis, A.M. Teixeira)

GMSB: Messenger fields ϕ_i with a mass M_{mess} exist,
their CP-even and CP-odd scalar masses^2 are split by m^2

Possible origins of the SUSY breaking m^2:

— Dynamical SUSY Breaking (non-perturbative) in a hidden sector containing SUSY Yang-Mills + matter (Affleck, Dine, Seiberg, Nelson, Intriligator, Shih,...) + couplings of ϕ_i to the hidden sector
— O'Raifeartaigh models
— Giudice-Masiero terms for ϕ_i in the Kähler potential of No-Scale Supergravity (U.E., '95)

Messengers ϕ_i carry $SU(3) \times SU(2) \times U(1)_Y$ gauge quantum numbers

$\longrightarrow$ Generation of gaugino (at 1 loop) and scalar (at 2 loops) masses of the order $M_{SUSY} \sim \frac{m^2}{16\pi^2 M_{mess}}$

BUT: no μ- or B-terms of the MSSM!

couple H_u, H_d directly to the SUSY breaking sector (?), or

$\longrightarrow$ NMSSM + couplings $\sim \eta S \phi_i \phi_i$ of S to the messenger sector

Otherwise: m_S^2, A_κ vanish at the scale $M_{mess} \rightarrow \langle S \rangle$ too small

(See, however, Liu and Wagner: $SU(5)$ violating messenger sector)

$\rightarrow$ integrating out the messengers generates m_S^2, $A_\lambda = \frac{1}{3} A_\kappa, \ldots +$ possibly terms linear in S in the superpotential $W \sim \xi_F S$ and in $V_{soft} \sim \xi_S S$, so-called "tadpoles".

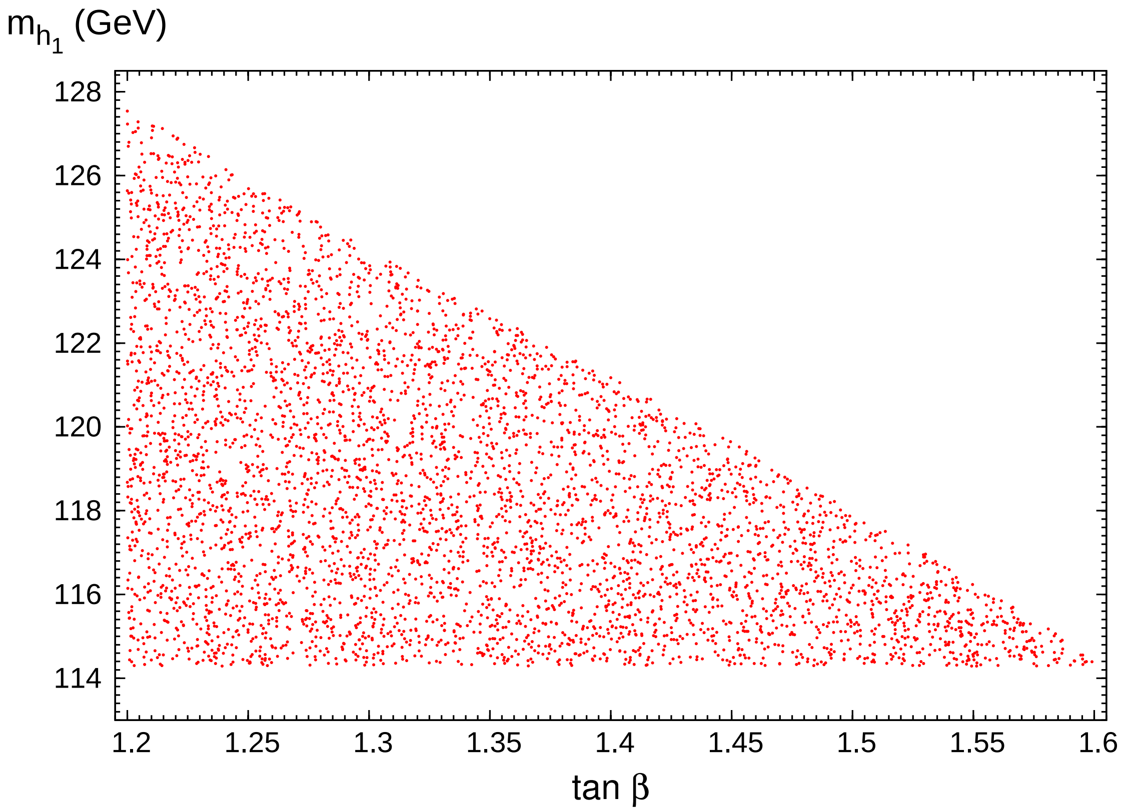
$\rightarrow$ Tadpole terms always trigger $\langle S \rangle \neq 0$ but, if allowed, the parameters ξ_F, ξ_S tend to be somewhat large:

$$\xi_F \sim \eta\, M_{mess}\, M_{SUSY}, \quad \xi_S \sim 16\pi^2\, \eta\, M_{mess}\, M_{SUSY}^2 \quad (M_{mess} > M_{SUSY})$$

Require $\quad \xi_S \sim M_{SUSY}^3 \quad \rightarrow$ need $\quad \eta \sim \frac{M_{SUSY}}{16\pi^2 M_{mess}} \lesssim 10^{-5}$

Then: phenomenologically viable, if $\lambda \gtrsim 0.5$, $\tan\beta \lesssim 2$

$\longrightarrow$ the NMSSM specific contribution to the scalar Higgs mass matrix pushes the lightest Higgs mass above the LEP bound:



$M_{mess} = 10^6$ GeV,
$M_{SUSY} = 500$ GeV,
$\xi_F = 3 \cdot 10^4$ GeV^2,
$0.5 < \lambda < 0.6$
$10^{-6} < \eta < 10^{-5}$

Bino, Winos, Sleptons:
$\sim$ 110-290 GeV
Squarks, Gluino:
$\sim$ 640-890 GeV
Additional Higgs states:
$\gtrsim$ 600 GeV

Tadpole terms can also be forbidden by discrete symmetries, if the messenger sector is enlarged to ϕ_1, $\overline{\phi}_1$, ϕ_2, $\overline{\phi}_2$ (Giudice, Rattazzi):

$$W = \eta\ S\overline{\phi}_1\phi_2 + M_{mess}(\overline{\phi}_1\phi_1 + \overline{\phi}_2\phi_2) + \ldots$$

As before, the soft terms m_s^2 (< 0), A_κ, A_λ are calculable in terms of η and M_{SUSY}

Delgado, Giudice, Slavich: viable regions in the parameter space M_{SUSY}, M_{mess}, η, λ, $\tan\beta$

But: Heavy sparticle spectrum: bino, wino, sleptons $\sim$ 450 - 1100 GeV, squarks, gluino $\sim$ 1.8 - 2.4 TeV

If, in addition, A_κ, $A_\lambda \sim 0$:

All soft terms for the singlet vanish at M_{mess} except for m_S^2

(A corresponding hidden sector remains to be constructed)

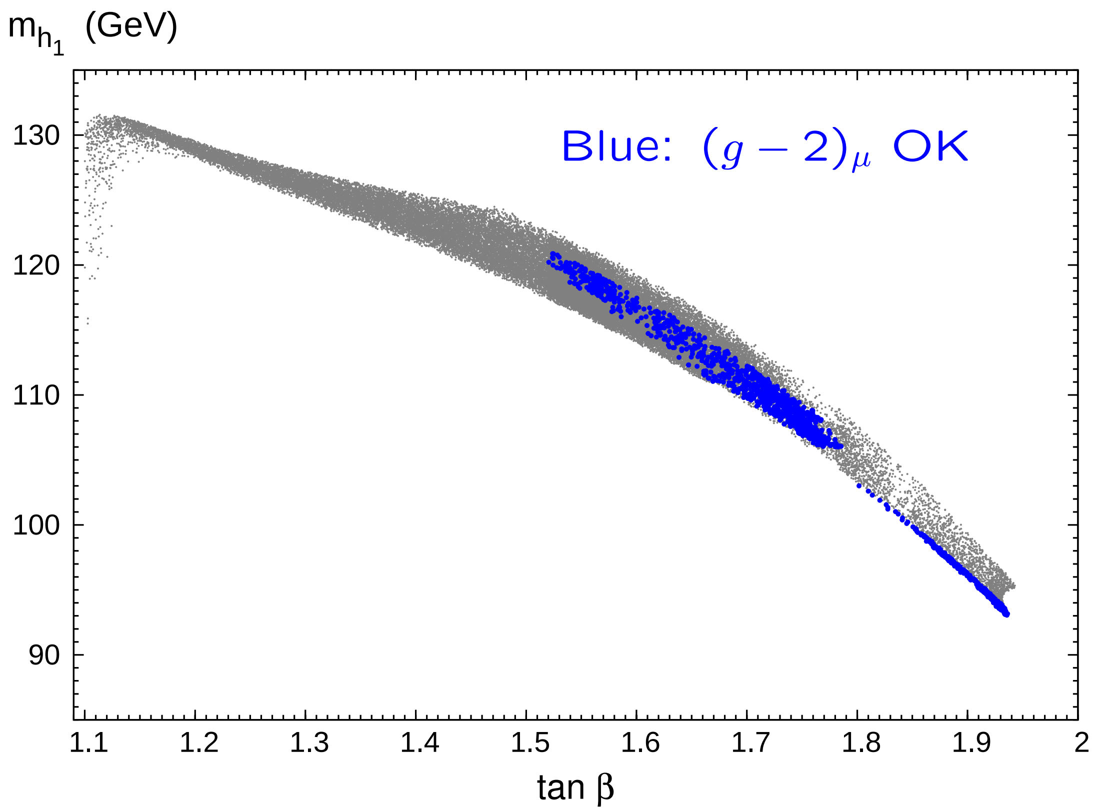
$\longrightarrow$ the scalar sector of the NMSSM has an R-symmetry (at M_{mess}), which is broken by radiative corrections to A_κ, A_λ induced by the gaugino mass terms

$\longrightarrow$ at the weak scale: the explicit R-symmetry breaking by A_λ, $A_\kappa \sim$ a few GeV is small (if M_{mess} is not too large)

$\longrightarrow$ the spontaneous R-symmetry breaking by $\langle H_u \rangle$, $\langle H_d \rangle$, $\langle S \rangle \neq 0$ generates a pseudo Goldstone Boson, a light CP-odd Higgs scalar a_1

$\longrightarrow$ the lightest Higgs scalar h_1 decays via $h_1 \to a_1 a_1$, escaping LEP constraints if $m_{h_1} \gtrsim 90$ GeV (depending on m_{a_1})

Phenomenologically viable:



$\lambda = 0.6$

10^7 GeV $< M_{mess} <$ 5·10^9 GeV,

200 GeV $< M_{SUSY} <$ 280 GeV,

Bino, Winos, Sleptons:

$\sim$ 100-200 GeV

Squarks, Gluino:

$\sim$ 450-600 GeV

$m_{a_1} \sim 1 - 50$ GeV $< m_{h_1}/2$

Additional Higgs states:

$>$ 500 GeV

Motivation for additional SM singlets like S?

Multiplets of larger GUT gauge groups (like E_6) contain SM singlets

$\longrightarrow$ Typically: extra $U(1)'$ gauge symmetries, under which H_u, H_d, quarks, leptons, S (or S_i) are charged ($\to \mu\, H_u H_d$ forbidden)

$\longrightarrow$ no κS^3-term in the superpotential, but a $g'^2|S|^4$-D-term can stabilize the potential $V(S)$

$\longrightarrow$ the additional $g'^2|H_{u,d}|^4$-D-terms lead to heavier Higgs scalars ($\to$ LEP constraints easier to satisfy)

BUT: The cancellation of all anomalies requires additional (exotic) matter, possibly more SM singlets

$\longrightarrow$ Gauge coupling unification is no longer automatic (but possible)

Phenomenology (UNMSSM...): (Langacker et al., King et al.,...)

— extra Z' gauge boson (mixes with Z in general $\to$ constraints)

— extra neutralinos from Z' and singlets, extra matter

Summary

Assuming that a single (SUSY breaking) scale M_{SUSY} generates the weak scale $\sim M_Z$, the NMSSM is the most natural supersymmetric extension of the Standard Model

cNMSSM (mSUGRA):

The phenomenologically viable range of $M_{1/2}$, m_0 and A_0 is very different from the cMSSM: close to a No-Scale scenario $m_0 \ll M_{1/2}$, $A_0 \sim \frac{1}{4} M_{1/2}$; the LSP is always singlino-like; a large NLSP (stau) life time can lead to observable tracks

GMSB:

The NMSSM allows to solve the μ-problem of GMSB models in a phenomenologically viable way, provided S couples to the messenger sector which induces soft SUSY breaking terms for S. Tadpole terms are not dangerous if the coupling η of S to the messengers is small.
Different scenarios can be realized implying different phenomenologies in the Higgs and sparticle sectors. Possible are, amongst others,
— light CP-odd scalars (pseudo-Goldstone Bosons),
— light CP-even scalars with large singlet component.

Just another few years, then we will know ... hopefully