Phenomenological Aspects of the Next-to-Minimal Supersymmetric Standard Model

U. Ellwanger, LPT Orsay

Contents:

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

$\longrightarrow$ 3 CP-even neutral Higgs scalars H_i, $i = 1 \ldots 3$
$\longrightarrow$ 2 CP-odd neutral Higgs scalars A_i, $i = 1 \ldots 2$
$\longrightarrow$ 5 neutralinos χ_i^0, $i = 1 \ldots 5$

The singlet-like states H_S, A_S and χ_S^0 mix with the $SU(2)$-doublets, depending on λ, κ, A_λ, A_κ

The lightest CP-odd scalar A_1 can be quite light, notably in the case of an approximate R-symmetry in the Higgs sector (A_λ, $A_\kappa \to 0$) or Peccei-Quinn-symmetry ($\kappa \to 0$)

Lessons/Hints from LEP

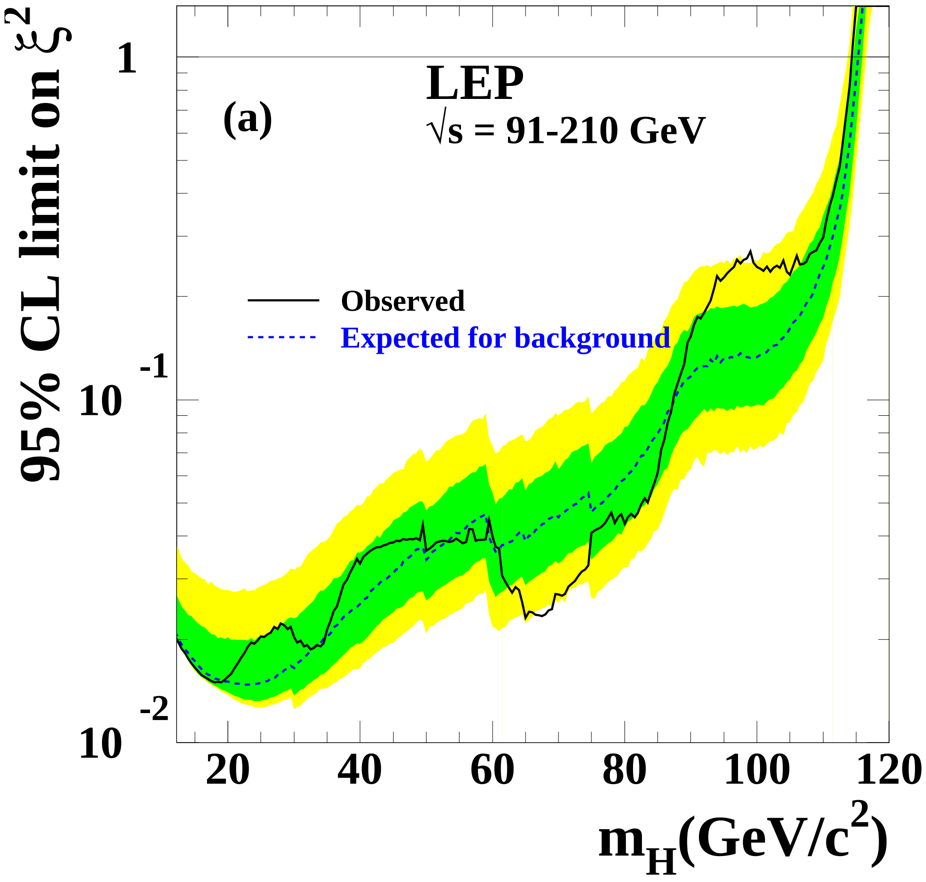
Search for $H \to b\bar{b}$, $\tau^+\tau^-$ (comb. 4 exp., LEP-Higgs Working Group):

Light excess of events for
$m_H \sim 95 - 100$ GeV ($\sim 2.3\,\sigma$)
If such an H exists:

$\longrightarrow$ Either reduced coupling
$g_{HZZ}/g_{HZZ\_SM} \equiv \xi \;\lesssim 0.4 - 0.5$

$\longrightarrow$ or reduced BR to $b\bar{b}, \tau^+\tau^-$:
$BR(H \to b\bar{b}, \tau^+\tau^-)/BR_{SM} \lesssim 0.2$

$\longrightarrow$ $BR(H \to A_1 A_1) \sim 80 - 90\%$?
(Dermisek, Gunion: solution of the "little finetuning problem" of the MSSM)



Search for $H \to A_1 A_1$ at LEP:

$\longrightarrow$ Strong bounds on $H \to A_1 A_1 \to 4b$ for $m_H \sim 95 - 100$ GeV
$\longrightarrow$ M_{A_1} below $B\bar{B}$ threshold: $M_{A_1} < 2M_B \sim 10.5$ GeV
$\longrightarrow$ A_1 decays dominantly into $A_1 \to \tau^+ \tau^-$
$\longrightarrow$ Searches for $H \to A_1 A_1 \to 4\tau$: No bounds for $m_H \sim 95 - 100$ GeV!

Lessons/Hints from radiative Υ decays

(See talk by F. Domingo)

If $M_{A_1} \lesssim 10.5$ GeV: decays $\Upsilon(nS) \to A_1 + \gamma$ are possible;
BR depends on M_{A_1} and $g_{A_1 b\bar{b}}$ (possibly, for large $\tan\beta$: $g_{A_1 b\bar{b}} > g_{Hb\bar{b}\_SM}$)
Constraints from CLEO: $M_{A_1} \gtrsim 8.8$ GeV (if $g_{A_1 b\bar{b}}$ large)

Note: for large $g_{A_1 b\bar{b}}$, the η_b can mix with A_1 (same quantum numbers)
$\longrightarrow$ Shift of the eigenvalues of the $\eta_b - A_1$ mass matrix?

BaBar (2008): Discovery of η_b: $M_{\eta_b} \sim 9.39$ GeV
Compare to predictions for M_{η_b} (lattice/quark models):
M_{η_b} too low, $M_{\Upsilon(1S)} - M_{\eta_b} = 71.4 \pm 4.1$ MeV (expect 39 ± 14 MeV)
$\longrightarrow$ Mixing with A_1? ($\to M_{A_1} \gtrsim 9.4$ GeV)

Higgs Searches at the LHC

with dominant $H \to A_1 A_1$ decays, $M_{A_1} < 10.5$ GeV $\to A_1 \to \tau^+ \tau^-$ dominant

- 4 neutrinos (at least), no narrow peaks in invariant masses;
- 2 τ's (of the same A_1) nearly collinear, low invariant masses, low p_T;
- Backgrounds: Υ production, heavy flavour jets, . . .

Forshaw et al. (0712.3510): via diffractive Higgs Production $pp \to pp + H$
($\to$ additional forward proton detectors at ATLAS and/or CMS)

Belyaev et al. (0805.3505): via $A_1 A_1 \to 4\tau \to 2\mu + 2$ jets
Rates with 100 fb^{-1} after cuts:
$\sim 8 \cdot 10^3$ from H from Vector Boson Fusion (VBF),
$\sim 10^3$ from H from Higgs Strahlung $W^{\pm\,*} \to H + W^{\pm}$ (HS)
(trigger on lepton from $W^{\pm}$)
(but: no background studies, no detector performances)

Current ATLAS studies: $A_1 A_1 \to 4\tau \to 4\mu$ (VBF)
Current CMS studies: $A_1 A_1 \to 4\tau \to 2\mu + 2$ jets (HS)

Or: use subdominant A_1 decays:

$BR(A_1 \to \mu^+\mu^-) \sim 3 \cdot 10^{-3}$ would be clean
($BR(A_1 \to \gamma\gamma) \lesssim 10^{-4}$ would be too low)

Lisanti, Wacker (0903.1377): $A_1 A_1 \to 2\tau + 2\mu$ from H via gg fusion
Rates at Tevatron (20 fb^{-1}, D0+CDF): up to 300 events
Rates at the LHC (500 pb^{-1}): up to 250 events per experiment

The cNMSSM

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

$M_{1/2}$, A_0, m_0 (incl. m_S, A_κ) universal at $M_{GUT} \sim M_{Planck}$

Same number of free parameters as the cMSSM: μ, $B \to \lambda$, κ

The allowed range for $M_{1/2}$, A_0, m_0 is very different from the cMSSM!

From $\langle S \rangle \neq 0$: m_S^2 must be small (possibly $m_S = 0$), and $m_S^2 \sim m_0^2$!

$\longrightarrow$ In the cMSSM: the lightest $\tilde{\tau}_1$ would be the LSP, ruled out
$\longrightarrow$ In the cNMSSM: the singlino-like neutralino χ_1^0 must be the LSP
$\longrightarrow$ Correct χ_1^0 relic density Ωh^2: $M_{\chi_1^0}$ must be just a few GeV below $M_{\tilde{\tau}_1}$
$\longrightarrow$ χ_1^0 relic density reduced via coannihilation with $\tilde{\tau}_1$ ($\to A_0$ small)

$\longrightarrow$ Each sparticle decay cascade produces first a $\tilde{\tau}_1$ NLSP;
only subsequently the $\tilde{\tau}_1$ NLSP decays into $\tilde{\tau}_1 \to \tau + \chi_1^0$
$\longrightarrow$ Each sparticle decay cascade contains a τ!

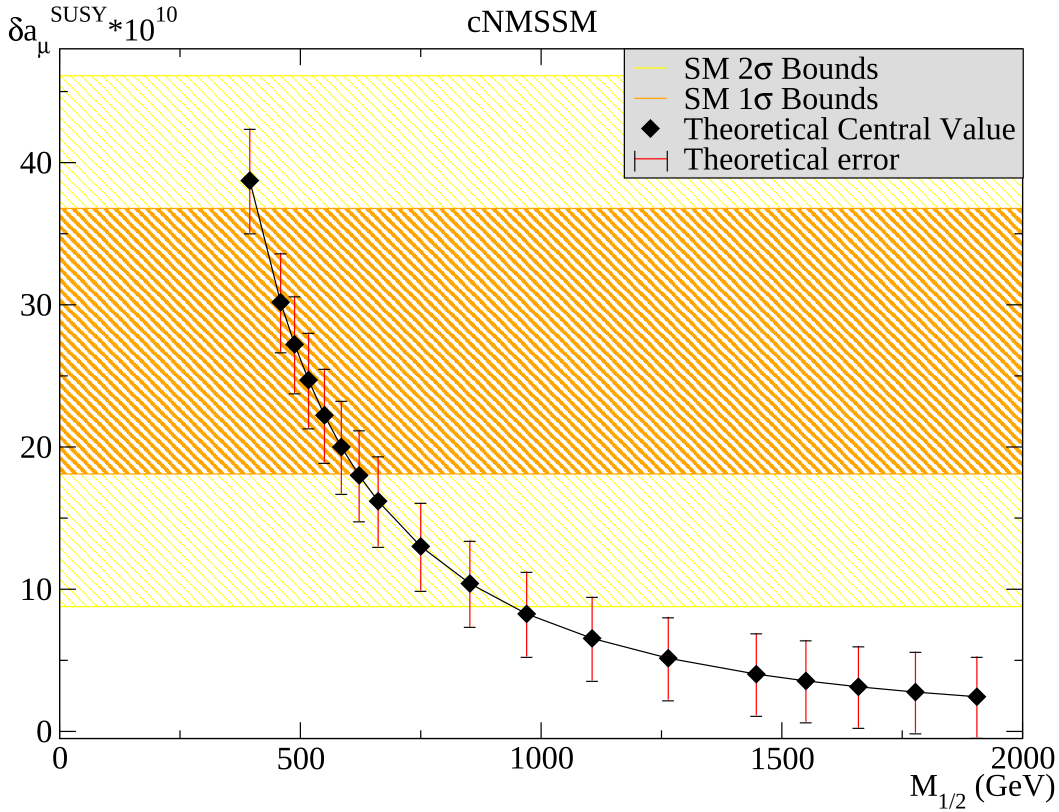
For $M_{\tilde{\tau}_1} - M_{\chi_1^0}$ very small and/or λ small:
the $\tilde{\tau}_1$ decay vertex can be displaced up to $\mathcal{O}$(mm-cm)!
(cf. GMSB with gravitino LSP: displaced vertices $\gtrsim \mathcal{O}$(m))

Due to m_0, $A_0 \ll M_{1/2}$, the spectrum depends essentially on $M_{1/2}$ only
"Best value" for $M_{1/2}$ from $(g-2)_\mu$ (with F. Domingo):

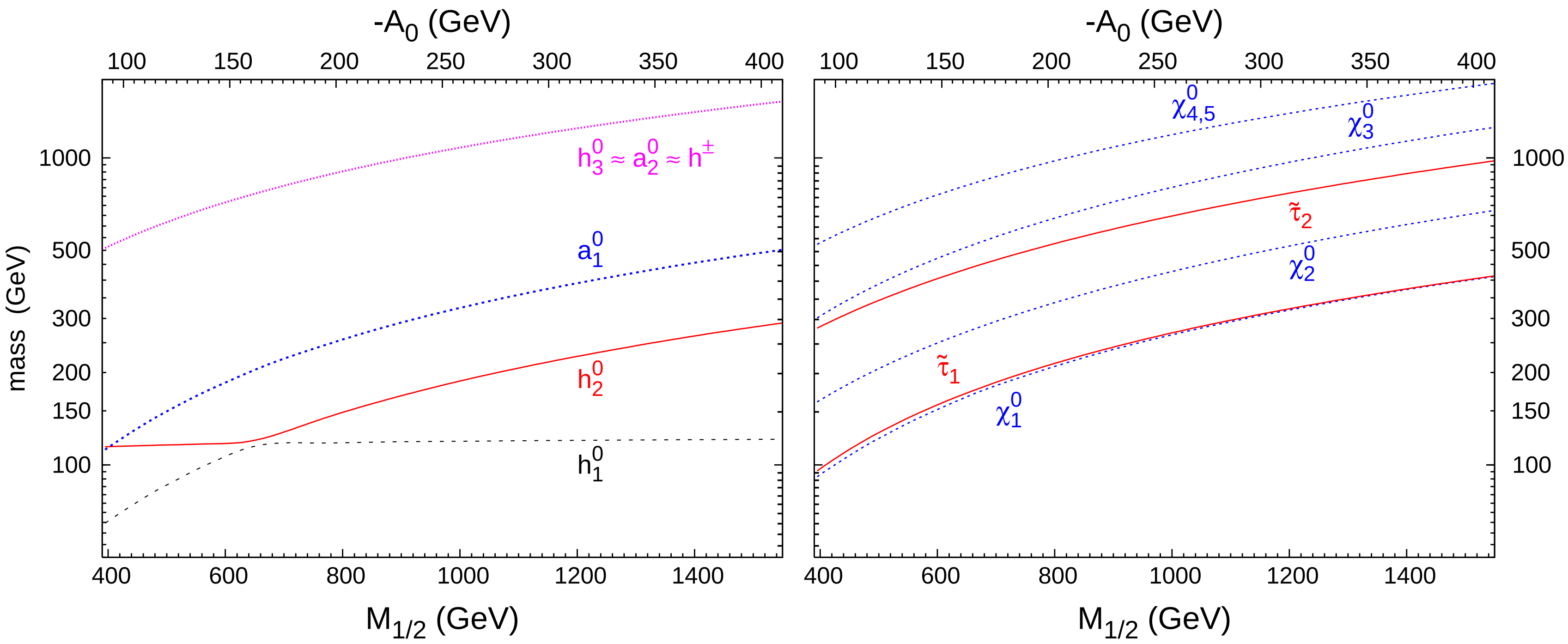
Try to explain the $\sim 3\sigma$ deviation of the measured $(g-2)_\mu$ w.r.t. the SM by chargino/sneutrino contributions

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

($M_{1/2} \lesssim 400$ GeV:
$M_{\tilde{\tau}_1} \lesssim 100$ GeV,
excluded by LEP)



Higgs, neutralino and slepton spectrum as function of $M_{1/2}$:



$$(M_{Squark} \lesssim M_{Gluino} \sim 2\, M_{1/2})$$

Note: For $M_{1/2} \lesssim 640$ GeV, the lightest CP-even scalar h_1 is singlet-like;
the mass of the SM-like CP-even scalar h_2 is $\gtrsim 115$ GeV
Possibly (for $M_{1/2} \sim 570$ GeV): $M_{h_1} \sim 95 - 100$ GeV, $\xi_{h_1 ZZ} \sim 0.4$
$\longrightarrow$ explanation of the excess of events at LEP?
Now: no light CP-odd scalar; h_2 behaves like a SM Higgs

Summary

Assuming that a single SUSY breaking scale M_{SUSY} generates the weak scale $\sim M_Z$ (no explicit μ-term), the NMSSM is the most natural supersymmetric extension of the Standard Model

The simplest version, the cNMSSM (mSUGRA), could explain the 2.3 σ excess of events in Higgs searches at LEP (in contrast to the cMSSM). Due to m_0, $A_0 \ll M_{1/2}$, its sparticle spectrum would be very different from the cMSSM!
Notably: $\tilde{\tau}_1$ decays in every sparticle decay chain
Possibly: displaced vertices from $\tilde{\tau}_1$ decays

In the general NMSSM, a light CP-odd scalar A_1 with $M_{A_1} < 10.5$ GeV could
– explain the 2.3 σ excess of events at LEP
– alleviate the "little finetuning problem"
– explain a low η_b mass, but:

A challenging scenario for Higgs searches!