The supersymmetric Higgs/higgsino mass term $\mu H_u H_d$ of the MSSM is replaced by a Yukawa coupling $\lambda S H_u H_d$ (+ a self interaction $\frac{\kappa}{3} S^3$) to a gauge singlet superfield $S$: $\mu H_u H_d \rightarrow \lambda S H_u H_d + \frac{\kappa}{3} S^3$

→ all supersymmetric interactions are scale invariant (see the talk by A. Linde), the Susy breaking scale is the only explicit mass scale which generates the electroweak symmetry breaking scale

$S$ assumes a vev “$s$” of the order of the Susy breaking scale

→ an effective $\mu$-term $\mu_{eff} = \lambda s$ is generated

→ the Grand Unification of the gauge couplings and the possibility to explain the dark matter by a LSP are preserved
The scalar and fermionic components of $S$ mix with $H_u$ and $H_d$ and the neutralinos proportional to the Yukawa coupling $\lambda$

\[ \rightarrow \text{ if } \lambda \text{ (and } \kappa\text{) are small: “decoupling limit”, one is left with an effective MSSM + decoupled singlets (possibly with a singlino LSP)} \]

\[ \rightarrow \text{ if } \lambda \text{ is large: possible phenomenological consequences in the} \]

\[ \quad \text{— CP-even Higgs sector} \]

\[ \quad \text{— CP-odd Higgs sector} \]

\[ \quad \text{— neutralino sector} \]

(depending on $\lambda$, $\kappa$, soft Susy breaking terms)
The cNMSSM

A simple scenario for Susy breaking is spontaneous Susy breaking in a hidden sector in supergravity, minimal Kähler potential and gauge kinetic terms: “mSUGRA”

$\rightarrow$ universal scalar masses $m_0$, trilinear couplings $A_0$ and gaugino masses $M_{1/2}$ at the GUT/Planck scale

In the cNMSSM (A. Djouadi, U. E., A. M. Teixeira): $m_0$ must be small such that $S$ can assume a vev, since $m_S^2$(weak scale) $\sim m_0^2$

$\rightarrow$ in the cMSSM, small $m_0$ would generate an unacceptable stau LSP $\tilde{\tau}_1$

$\rightarrow$ in the cNMSSM, the singlino-like neutralino must be the LSP with a mass just below ($\sim 5$ GeV) the stau NLSP mass in order to give the correct dark matter relic density via coannihilation

Then: the complete sparticle spectrum is fixed by $M_{1/2}$
Impact on sparticle decay cascades

The singlino-like LSP $\chi_1^0$ couples weakly to the MSSM-like sparticles
→ all sparticles decay first into the stau NLSP $\tilde{\tau}_1$, which decays
subsequently into the singlino LSP $\chi_1^0$ as

$$\ldots \rightarrow \chi_2^0 \rightarrow \tilde{\tau}_1 \rightarrow \chi_1^0$$

→ ≥ 4 $\tau$-leptons in each Susy event!

Energy of the first $\tau$: $M_{\chi_2^0} - M_{\tilde{\tau}_1} \gtrsim 60$ GeV
Energy of the second $\tau$: $M_{\tilde{\tau}_1} - M_{\chi_1^0} \lesssim 5$ GeV, hardly visible

From LEP constraints on the Higgs and $\tilde{\tau}_1$ masses:
$M_{1/2} \gtrsim 500$ GeV → squark, gluino masses $\gtrsim 1$ TeV

→ Squark and gluino production remains the dominant sparticle
production process at the LHC (with $\lesssim 1$ pb cross section, $M_{Squark} \lesssim M_{Gluino}$!)

Is the cNMSSM visible at the LHC?
Signal-, background- and detector simulations, dedicated cuts:
(With A. Florent, D. Zerwas, T. Plehn, results are preliminary)

- Signal and $t\bar{t}$-background simulation: PYTHIA6.4 + TAUOLA
- W, Z, WW + jets backgrounds: ALPGEN + PYTHIA
- Detector: AcerDet
- Efficiencies for Susy searches in 4 jet/$\tau$ modes are reproduced

Cuts:
- $E_T^{(miss)} > 300$ GeV
- $p_T^{(jet1,2)} > 300, 150$ GeV (hard!)
- $\phi(E_T^{(miss)}, \vec{p}_T^{(jet)}) > 0.2$ (reduces detector effects)
- 1 $\tau$-lepton with $p_T > 30$ GeV $\rightarrow \sim 40\%$ efficiency on hadronic $\tau$ decays
- $M_{Trans}(\vec{p}_T(\tau), \vec{E}_T^{(miss)}) > 100$ GeV reduces $\tau$-leptons from W-decays (notably $t\bar{t}$-background)

$\rightarrow \sim 7 - 10\%$ efficiency on the signal ($\sim 1000$ events/10 fb$^{-1}$)
$\rightarrow \sim 30$ events/10 fb$^{-1}$ from $t\bar{t}$-background, less from W+jets
$\rightarrow$ practically no background from WW+(2-4) jets, Z+jets, QCD+$\tau$-fakes
$p_T(\tau)$-spectrum for various cNMSSM-points:

→ Looks promising!
τ-rich Susy events exist also in the cMSSM coannihilation region (where the bino-like $\chi_1^0$ relic density is reduced to an acceptable level via $\chi_1^0 - \bar{\tau} - \text{coannihilation}$)

Can this “cMSSM” be distinguished from the cNMSSM?

Note: less τ’s per event in the cMSSM, since $\tilde{q} \rightarrow \chi_1^0 + q$ decays (without $\tilde{\tau}$) are possible

Study of a cMSSM with similar squark/gluino masses as the NMSSM, which gives similar distributions for $p_T(\text{jets})$, $E_T(\text{miss})$ (not shown here):
$p_T(\tau)$-spectrum for the cNMSSM vs. the cMSSM:

→ less events above $p_T(\tau) > 30$ GeV than in the cNMSSM!
Back to the cNMSSM with $M_{\text{Squark}} \sim 1 \text{ TeV}$:

Present run at a c.m. energy of 7 TeV and an integrated luminosity of 1 fb$^{-1}$:

Require 2 jets with $p_T > 50, 20 \text{ GeV}, E_T^{\text{miss}} > 200 \text{ GeV}, p_T(\tau) > 10 \text{ GeV}$

$\rightarrow \sim 5\text{-}6$ signal events, $\sim 2$ from $t\bar{t}$ background

$\rightarrow$ we could get a hint, if we are lucky...
The Higgs sector

Recall: **MSSM**: Two CP-even Higgs bosons $h$, $H$
- One CP-odd Higgs boson $A$
- One charged Higgs boson $H^\pm$

Typically:

$h$ is SM-like $\leftrightarrow \xi_h \equiv \frac{g_{hWW}}{g_{H(SM)WW}} \sim 1$, $M_h \lesssim 135 \text{ GeV}$ (max. for large $\tan \beta$)

**NMSSM**: Three CP-even Higgs bosons $H_1$, $H_2$, $H_3$
- Two CP-odd Higgs bosons $A_1$, $A_2$
- One charged Higgs boson $H^\pm$

For $\lambda \lesssim 0.7$: $M_{H_1} \lesssim 140 \text{ GeV}$, max. for $\tan \beta \sim 2$

**But**: More Higgs bosons in the NMSSM do not simplify the detection of (at least) one Higgs boson!

- Higgs-to-Higgs decays are possible;
  the SM-like CP-even Higgs could decay, e.g., as $H_1 \rightarrow A_1A_1$
- Singlet-doublet-mixing can reduce the couplings to gauge bosons of *all* Higgs bosons (respecting the sum rule $\sum_{i=1}^3 \xi_i^2 = 1$)
Status of Higgs-to-Higgs decays as $H_1 \rightarrow A_1 A_1$:

Four possible scenarios: 1) $M_{H_1} \lesssim 110$ GeV or 2) $M_{H_1} \gtrsim 110$ GeV
   a) $M_{A_1} \gtrsim 10.5$ GeV or b) $M_{A_1} \lesssim 10.5$ GeV

1) $M_{H_1} \lesssim 110$ GeV would alleviate the “little fine tuning problem” (Dermisek, Gunion), but: LEP constraints?

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

Small excess of events for $m_H \sim 95 - 100$ GeV ($\sim 2.3 \sigma$)

If such an $H$ exists, it must possess:

$\rightarrow$ Either a reduced coupling $g_{HZZ}/g_{HZZ\text{SM}} \equiv \xi \lesssim 0.4 - 0.5$

$\rightarrow$ or a reduced $BR$ to $b\bar{b}$:

$BR(H \rightarrow b\bar{b})/BR_{SM} \lesssim 0.2$
→ $BR(H \rightarrow A_1A_1) \sim 80 - 90\%$?

1a) If $M_{A_1} \gtrsim 10.5$ GeV: $A_1$ decays into $b\bar{b}$
→ ruled out by OPAL/DELPHI

1b) If $M_{A_1} \lesssim 10.5$ GeV: $A_1$ decays into $\tau\tau$
→ ruled out by ALEPH (2010),
except for a window around $M_{A_1} \sim 10$ GeV and/or $\tan \beta \lesssim 3$
where the $BR(A_1 \rightarrow c\bar{c}/gg)$ is enhanced (Dermisek, Gunion)
and constraints from CLEO/BaBar on $\Upsilon \rightarrow \gamma A_1$ are satisfied
2) $M_{H_1} \gtrsim 110$ GeV is allowed by LEP, and $H_1 \to A_1A_1$ would be challenging for the LHC!

2a) If $M_{A_1} \gtrsim 10.5$ GeV: $A_1$ decays into $b\bar{b}$ ($\sim 90\%$ BR) or $\tau\tau$ ($\sim 8\%$ BR)
   
   → Proposals to look for
   
   — $H_1$ via VBF and $H_1 \to A_1A_1 \to b\bar{b}\tau^+\tau^-$ (U.E. et al.)
   
   — $H_1$ via ass. $WH_1/ZH_1$ production and $H_1 \to A_1A_1 \to 4b$ or $H_1 \to A_1A_1 \to b\bar{b}\tau^+\tau^-$, assuming 50\% efficiency for $b$-tagging (Cheung et al., Carena et al.)

2b) If $M_{A_1} \lesssim 10.5$ GeV (but $\gtrsim 2m_\tau$):
   $A_1$ decays into $\tau\tau$ ($\sim 98\%$ BR) or $\mu\mu$ ($\sim 0.4\%$ BR)
   
   → Proposals to look for
   
   — $H_1 \to A_1A_1 \to 2\tau + 2\mu$ (Lisanti, Wacker)
   
   — $H_1 \to A_1A_1 \to 4\tau$ with $H_1$ from VBF or ass. production (Belyaev et al.)
   
   — $H_1 \to 4\mu$ if $M_{A_1} \lesssim 2m_\tau$ (Belyaev et al.)

BUT: no detector simulations, no guaranteed discovery
Singlet-doublet-mixing in the NMSSM:

Both $H_1$ and $H_2$ can have reduced couplings $\xi^2$ to gauge bosons, with $M_{H_1} \lesssim 115$ GeV $\rightarrow$ hard to see at the LHC (reduced $BR(H_1 \rightarrow \gamma\gamma/\tau\tau)$)

$M_{H_2} \simeq 140 \ldots 180$ GeV $\rightarrow$ visible at the LHC?
Properties of $H_2$

Can be produced in Gluon Fusion and Vector Boson Fusion

Large branching ratio into WW ($40\%-90\%$ for $M_{H_2} \simeq 140 - 180$ GeV), since $\tan \beta \sim 2-3$ is small

The most interesting mass range at the Tevatron and the LHC in the near future!

Higgs bosons ($H, A$) with these properties do not exist in the MSSM! (Larger $\tan \beta$ in the MSSM $\rightarrow$ branching ratios into $b\bar{b}$ dominate)
Significances for $H_2$

(with D. Zerwas, using SFitter by R. Lafaye, T. Plehn, M. Rauch, D. Z.)

$M_{H_2}$ [GeV]

- Discovery possible (once channels are combined, or for larger luminosity), but: tough for $M_{H_2} \gtrsim 180$ GeV
Conclusions and outlook

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

Sparticle and/or Higgs production processes can clarify whether the NMSSM is realised in nature:

$\rightarrow$ $\tau$-rich squark/gluino decay cascades would be a signal for the cNMSSM

$\rightarrow$ a Higgs boson in the 140–180 mass range decaying into WW can be a signal for the NMSSM

But: Higgs-to-Higgs decays (as $H \rightarrow A_1 A_1$ with $A_1 \rightarrow b\bar{b}/\tau\tau$) remain a challenging scenario! No “no-lose-theorem” at present; “No Higgs” at the LHC (but: sparticles) can be a signal for the NMSSM!