Phenomenology of the cNMSSM

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1. Motivations for the cNMSSM

The MSSM is considered as the most attractive extension of the SM:

$$\mathcal{W} = \sum_{\rm i,j} \mathbf{Y^u_{ij}}\, \mathbf{\hat{u}^i_R \hat{H}_u . \hat{Q}^j} + \mathbf{Y^d_{ij}}\, \mathbf{\hat{d}^i_R \hat{H}_d . \hat{Q}^j} + \mathbf{Y^l_{ij}}\, \mathbf{\hat{l}^i_R \hat{H}_d . \hat{L}^j} + \mu \mathbf{\hat{H}_u . \hat{H}_d}$$

But when SUSY is broken (at $\rm M_{SUSY}$) it leads to two majors problems:

- **It has too many parameters ($\gtrsim$ 100) in the general (mix/CPV) case**

  $\Rightarrow$ **mSUGRA=cMSSM with 5 parameters:** $\mathbf{m_0}, \mathbf{M_{\frac{1}{2}}}, \mathbf{A_0}, \tan\beta, \epsilon_\mu$

Rather predictive model used as benchmark for SUSY analyses.

- **It is affected by the so-called μ–problem: superpotential $\propto \mu \mathbf{\hat{H}_u \hat{H}_d}$**

  with a natural μ value $\begin{cases} = 0 & \text{experimentaly excluded} \\ = \rm M_P, M_{GUT} & \text{typical scale of the theory} \end{cases}$

  $\Rightarrow$ **The NMSSM in which a singlet $\rm \hat{S}$ is added with $\mathcal{W} \propto \lambda \mathbf{\hat{S} \hat{H}_u \hat{H}_d}$**

when $\langle \rm S \rangle = s$, $\mu_{\rm eff} = \lambda s$ of order $\rm M_{SUSY}$ is dynamically generated.

– only dimensionless couplings in $\mathcal{W}$: Yukawa–like $\mu \mathbf{S H_u H_d}$ term,

– scale invariant invariant $\mathcal{W}$: $\rm M_{EW}, M_{SUSY}$ appear only in $\mathcal{L}_{\rm soft}$.

2. The cNMSSM

A good combination will be then the cNMSSM=NMSSM+mSUGRA:

the original SUSY/SUGRA models are of this type [Fayet, Nilles, ..]

- **The most general superpotential compatible with SUSY, R_P etc.., is**

$$\mathcal{W} = \mathbf{Y_u \hat{u}_R \hat{H}_u.\hat{Q} + Y_d \hat{d}_R \hat{H}_d.\hat{Q} + Y_l \hat{l}_R \hat{H}_d.\hat{L}} - \lambda \mathbf{S \hat{H}_u.\hat{H}_d} + \frac{1}{3}\kappa \mathbf{\hat{S}^3}$$

- **The collection of universal soft SUSY breaking terms at M_{GUT} is**

$$\mathbf{M_{1/2}} \equiv \mathbf{M_1 = M_2 = M_3}$$

$$\mathbf{m_0} \equiv \mathbf{m_{H_u} = m_{H_d} = m_S = m_{\tilde{Q}} = m_{\tilde{t}} = m_{\tilde{b}} = m_{\tilde{L}} = m_{\tilde{\tau}}}$$

$$\mathbf{A_0} \equiv \mathbf{A_t = A_b = A_\tau = A_\lambda = A_\kappa}$$

$\Rightarrow$ **five continuous parameters** $\mathbf{M_{1/2}, m_0, A_0}, \lambda, \kappa$

(as in cMSSM: $\mathbf{M_{1/2}, m_0, A_0}, \mu^2, \mathbf{B}\mu \Rightarrow \mathbf{M_{1/2}, m_0, A_0}, \tan\beta, \epsilon_\mu$**)**

- **practical purposes (RGEs, numerics): trade** $\kappa \leftrightarrow \tan\beta$
- **requiring correct** M_Z **value:** $\Rightarrow \tan\beta = \tan\beta(\mathbf{M_{1/2}, m_0, A_0}, \lambda)$
- **minimization of scalar Higgs potential:** $\Rightarrow$ s **but also** $\kappa, \mathbf{m_S^2}$

constrained NMSSM : $\mathbf{M_{1/2}, m_0, A_0}, \lambda$

2. The cNMSSM: constraints on the model

Various theoretical and experimental constraints:

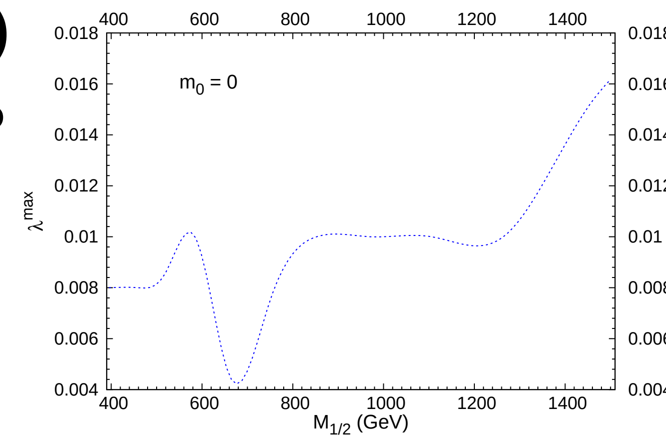
- **Phenomenologically acceptable minumum of Higgs potential:**

– absence of pseudoscalar tachyons: $\Rightarrow \mathbf{A_\kappa \sim A_0 \lesssim 0}$

– non vanishing singlet vev $\langle S \rangle = s$: $\Rightarrow \mathbf{m_0 \lesssim \frac{1}{3}|A_0|}$

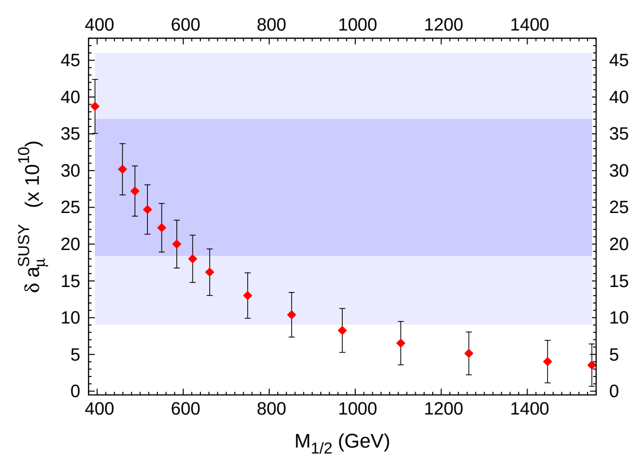
cMSSM: low m_0 disfavored (non charged LSP)

cNMSSM: need low m_0 for $s \neq 0$: singlino LSP



- **LEP constraints on the Higgs sector:**

$\Rightarrow \lambda \lesssim 0.01$ (λ then plays minor role).



- **Agreement of $(g-2)_\mu$ with exp. data:**

favors low $M_{1/2}$ regime, $\mathbf{M_{1/2} \lesssim 1\ TeV}$

2. The cNMSSM: constraints on the model

- Agreement with WMAP for the relic density of (singlino) LSP χ_1^0:

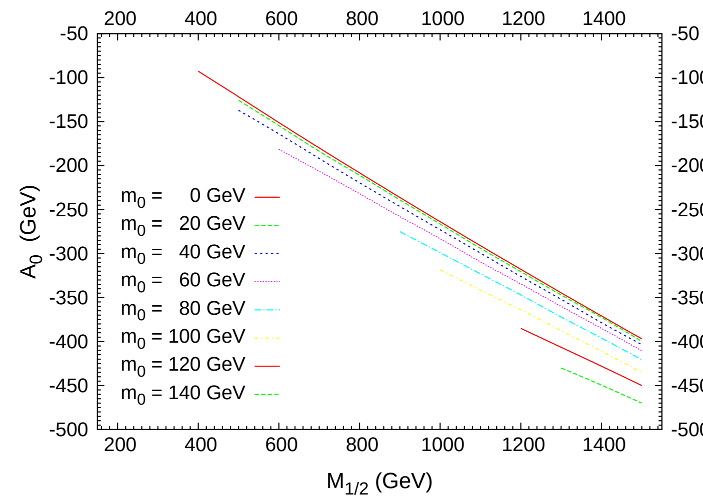
$$0.094 \lesssim \Omega_\chi h^2 \lesssim 0.136 \;\; \text{at } 2\,\sigma$$

- asssisted $\tilde{\tau}_1$ NLSP annihilation

$\Rightarrow$ nearly degenerate LSP/NLSP

$\Rightarrow m_{\chi_S} \sim m_{\tilde{\tau}_R} \Rightarrow m_0 \lesssim \frac{1}{10} M_{1/2}$

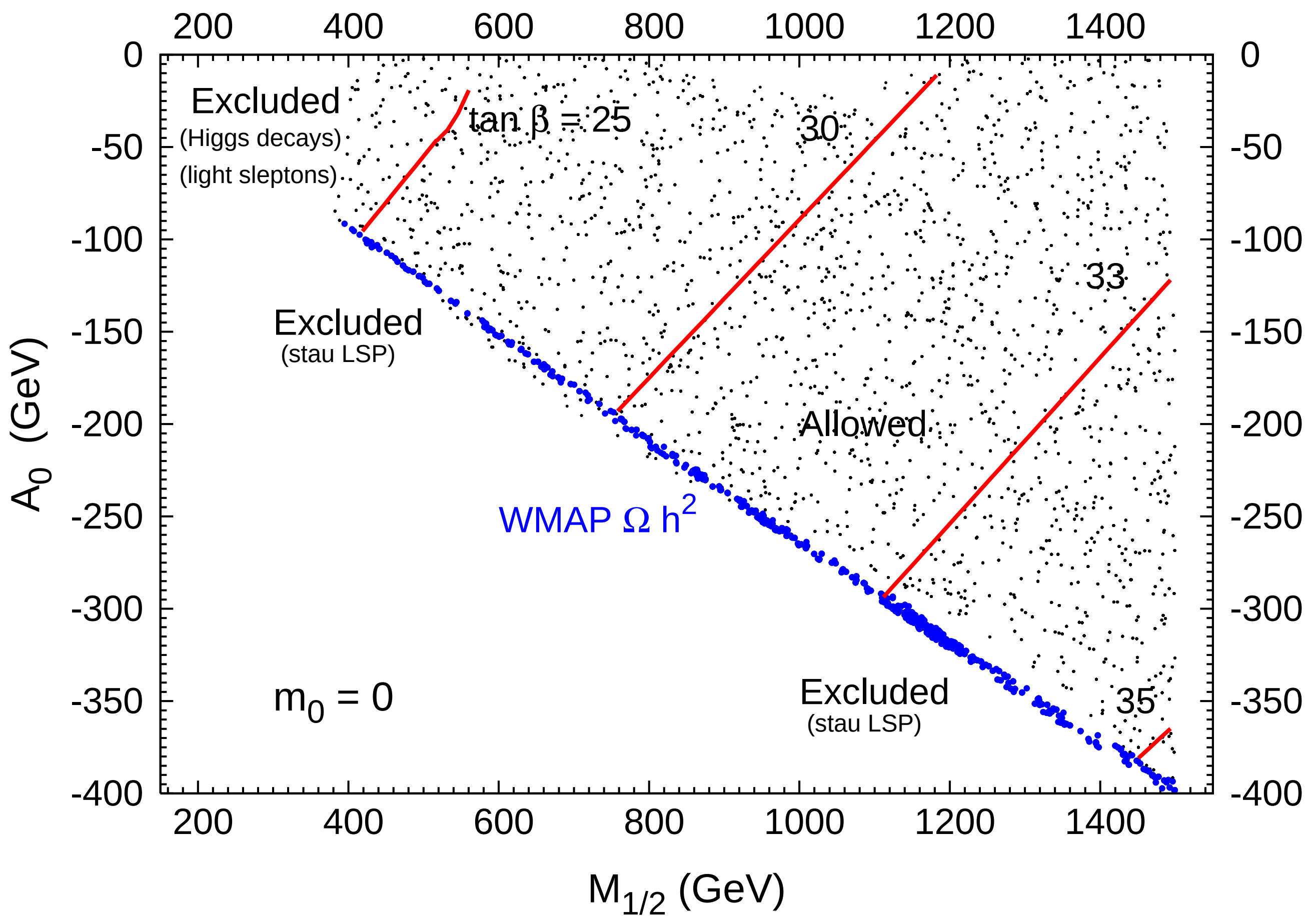
$\Rightarrow$ very small/vanishing m_0.



- Correct Ωh^2 value $\Rightarrow A_0$ determined by $M_{1/2}$: $A_0 \sim -\frac{1}{4} M_{1/2}$
- For too small λ, decoupled LSP at thermal equilibrium $\Rightarrow \lambda \gtrsim 10^{-5}$
- Since $\sigma_{\rm anh} \propto 1/m_{\rm NLSP}$, $M_{1/2}$ not too large: $M_{1/2} \lesssim 2-3$ TeV
- Agreement with LEP/Tevatron data on sparticle search limits

$m_{\tilde{\tau}_1}, m_{\tilde{\ell}}, m_{\tilde{\chi}_1^\pm} \gtrsim 100$ GeV, $m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 300$ GeV, $\Rightarrow M_{1/2} \gtrsim 400$ GeV

2. The cNMSSM: constraints on the model



with $\mathbf{m_0 = 0, \lambda = 10^{-2}}$ assumed and tanβ fixed by of other parameters.

All constraints (theory, LEP, Higgs, DM, B-meson) imposed except (g-2).

A model with essentially one free parameter, $\mathbf{M_{1/2}}$!

3. The particle spectrum

- **In the NMSSM: the same spectrum as in the MSSM except for the**

neutralino sector: $\begin{cases} \text{5 Majorana neutral fermions } \chi^0_{1-5} \\ \chi^0_1 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_u + N_{14}\tilde{H}_d + N_{15}\tilde{S} \end{cases}$

neutral Higgs sector; $\begin{cases} \text{3 scalars } (h^0_1, h^0_2, h^O_3) \text{ and 2 pseudoscalars } (a^0_1, a^0_2) \\ h^0_1 = S_{11}H_d + S_{12}H_u + S_{13}S \end{cases}$

- **The general NMSSM has been discussed in detail and has many virtues**
  [Drees, Ellis, Ellwanger, King, Gunion, Zerwas, ...]

– richer, more complex phenomenology.

– less fine tuning as max(M_h^{MSSM}) $\gtrsim$ max(M_h^{MSSM})

– satisfies more easily constraints from LEP, dark matter, flavor...

- **The fully cNMSSM was difficult to realize until recently:**

– spectra (RGE+EWSB+RC) with NMSSMTools [Ellwanger+Hugonie],

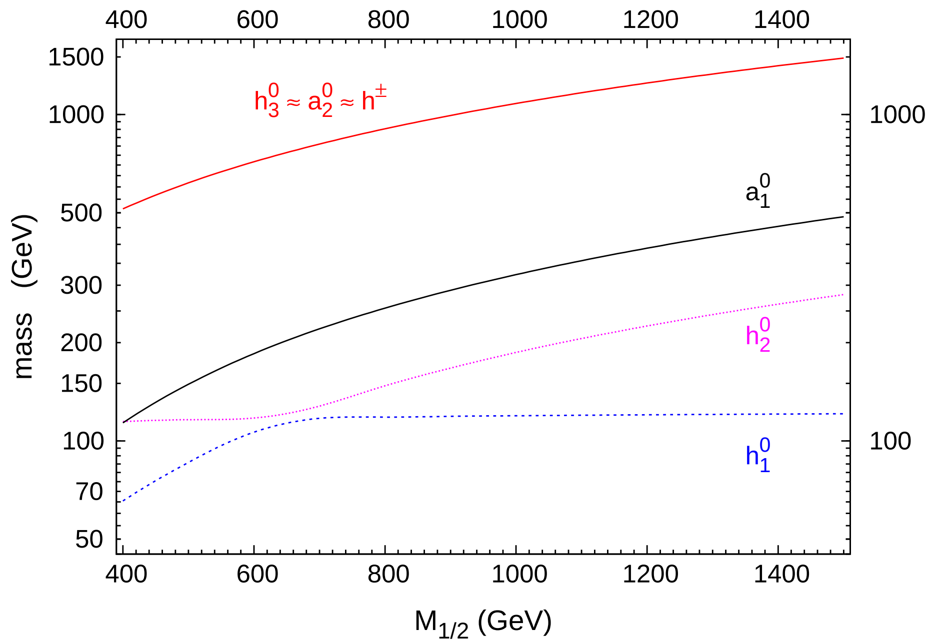
– compatibility of $m_S = m_0$ with RGE and EWSB (overconstrained),

– full scans of the parameter space and semi-analytic studies,

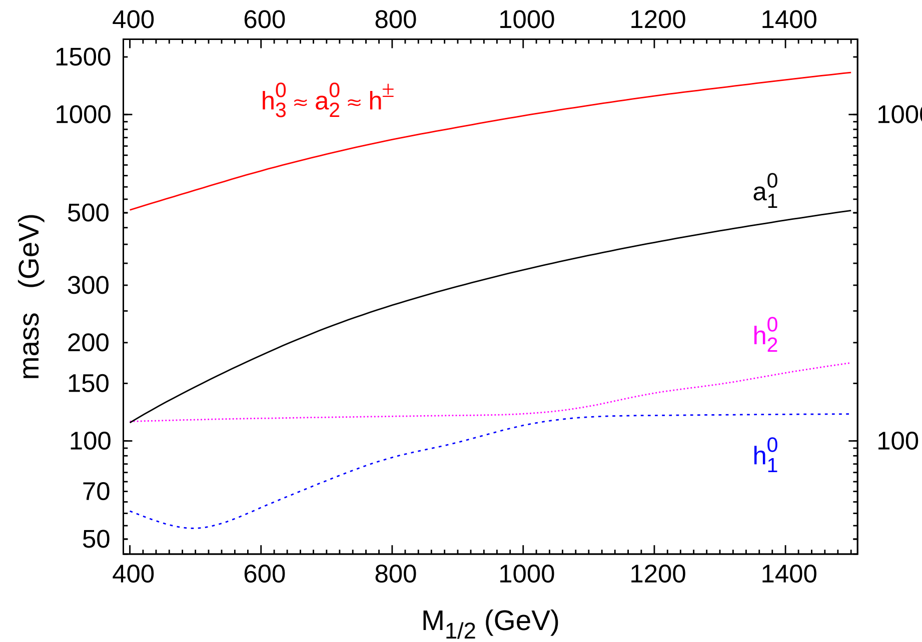
– availability of dark matter new tools, MicrOmegas [Bélanger et al.].

3. The particle spectrum: Higgs

$\mathbf{m_0 = 0}$



$\mathbf{m_0 = max}$

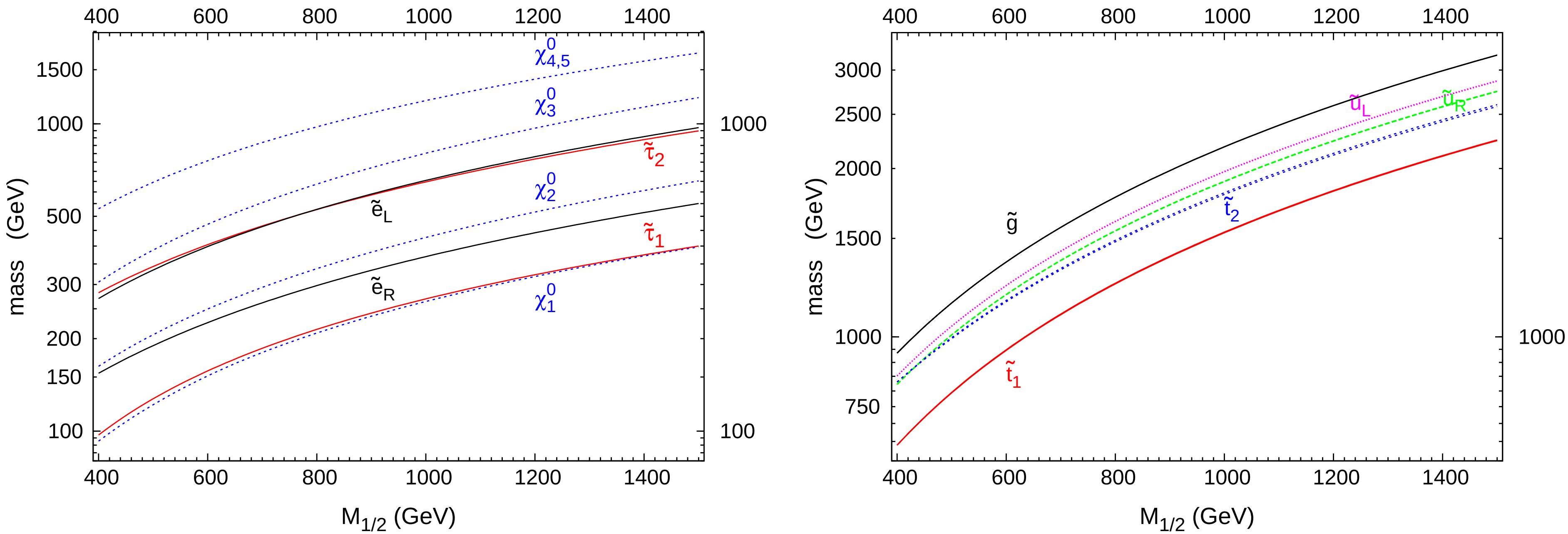


- $M_{1/2} \lesssim 650$ **GeV: singlet-like h_1^0 and SM-like h_2^0 and vice versa.**
- **Mass of SM-like Higgs boson lies between 116 and 120 GeV.**
- **The doublet-like h_3^0, a_2^0 and $h^\pm$ as in MSSM in decoupling regime.**
- **Singlets decoupled in general except near cross-over region where:**

– light Higgses and Higgs to Higgs decays possible but not typical,

– explanation of LEP excess at $M_h \approx 100\ (2.3\,\sigma)$ and 116 GeV (1.7σ).

3. The particle spectrum: gauginos and sfermions



- bino-like χ_2^0, wino-like $\chi_3^0, \chi_1^\pm$ and higgsino-like $\chi_4^0, \chi_5^0, \chi_2^\pm$.
- singlino LSP degenerate in mass with $\tilde{\tau}_1$: a few GeV mass diff.
- heavy spectrum: only LSP, χ_2^0 and RH sleptons are below 250 GeV
- gluino heavier than squarks (small m_0, contrary to mSUGRA)
- squarks heavier than 1 TeV in general, lightest squark is $\tilde{\mathrm{t}}_1$

4. Phenomenology at the LHC

The NMSSM Higgs sector: similar to MSSM in the decoupling regime:

- $\mathbf{h_1^0}$ SM–like: same searches for $M_H \sim 120$ GeV ($gg \to h_1^0 \to \gamma\gamma$ etc..).
- $h_3^0, a_2^0, h^\pm$ as in MSSM at high tanβ ($pp \to b\bar{b} + h_3^0/a_2^0 \to b\bar{b}\tau\tau$ etc..)
- h_2^0, a_1^0 singlet–like an decouple except in (new!) cross-over region.

The gluino/squark sector:

- Large production rates for small enough $M_{1/2}$($\lesssim 1$ TeV).
- Gluino always heavier than squarks $\Rightarrow \tilde{g} \to q\tilde{q}$
- Squarks always decay into (two-body) gauginos+quarks states:

$$\tilde{q}_R \to \chi_2^0 q \, (100\%) \text{ and } \tilde{q}_L \to \chi_3^0 q \, (33\%) \, , \; \chi_1^\pm q' \, (66\%)$$

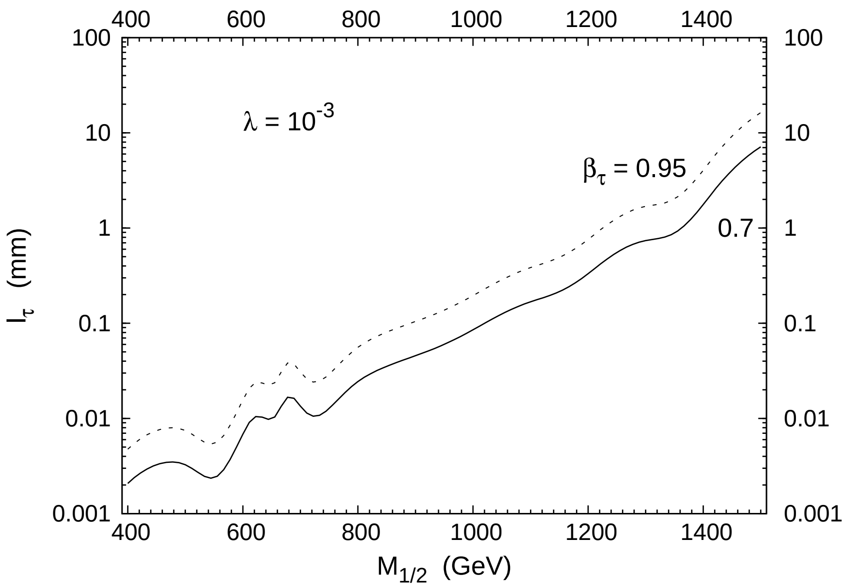
The gaugino/slepton sector:

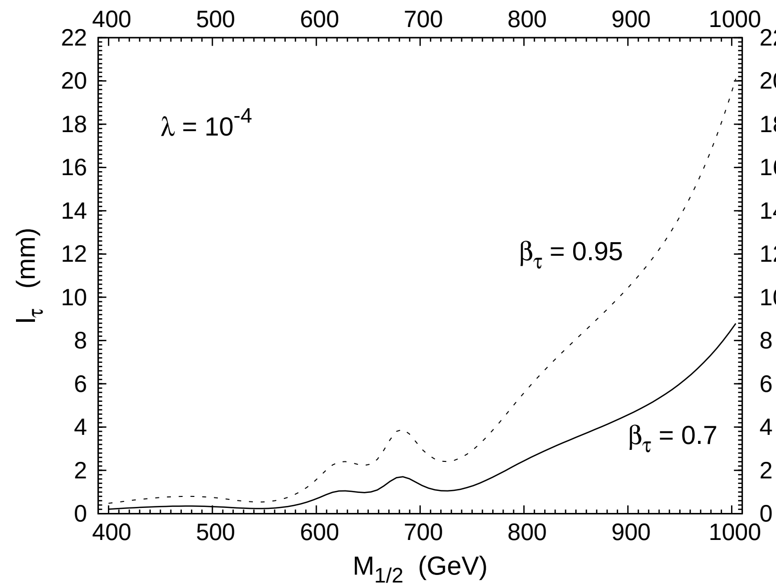
- $\chi_3^0, \chi_1^\pm \to \ell\tilde{\ell} \, (50\%)$ or $\tau\tilde{\tau} + \nu_\tau\tilde{\nu}_\tau \, (50\%)$ and $\chi_2^0 \to \tilde{\tau}_1\tau \, (100\%)$
- $\tilde{\ell}_L \to \chi_2^0\ell \, (100\%)$ and $\tilde{\ell}_R \to \ell\tilde{\tau}_1\tau \, (\gtrsim 99\%,$ no $\tilde{\ell}_R \to \ell\chi_1^0)!$
- $\chi_2^0 \to \tau\tilde{\tau}_1$ all the time
- $\tilde{\tau}_1 \to \chi_1^0\tau$ all the time.

4. Phenomenology at the LHC

- In contrast to mSUGRA (with light ℓ) only few final state leptons.
- Almost all sparticle decay chains contain the $\tilde{\tau}_1$ NLSP at the end
- Singlino χ_1^0 LSP and right-handed $\tilde{\tau}_1$ NLSP: long-lived $\tilde{\tau}_1$!

(small NLSP/LSP mass difference to cope with WMAP constraint).





$\tilde{\tau}_1$ length of flight of the order of a few centimeters (depends on λ, β)

Displaced vertices $\Rightarrow$ smoking gun signature for (c)NMSSM!

5. Conclusions

- **The cNMSSM is a very attractive extension of the SM and MSSM**

– gravity mediated SUSY breaking = few input parameters,

– solves the μ problem by introducing a singlet scalar field,

– has a phenomenology that can be richer than that of the MSSM.

- **Once theoretical, collider and cosmological constraints are imposed:**

small $\mathrm{m_0}, \lambda$ values are required, $\tan\beta \sim 30$ is given and $\mathrm{A_0}$ is fixed:

$\Rightarrow$ model essentially described by one single parameter $\mathrm{M_{1/2}}$!

- **The cNMSSM leads to a different phenomenology than mSUGRA:**

– gluinos are always heavier than squarks,

– most sparticle cascades end up with $\tilde{\tau}_1$ NLSP,

– very small decay width of $\tilde{\tau}_1$ into singlino LSP,

$\Rightarrow$ many τ final states and displaced vertices!

- **Model testable at the LHC but the ILC is required for measurements.**