The Next-to-Minimal Supersymmetric Standard Model: a brief overview

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Supersymmetric models: many advantages!

**Beyond the SM:** several appealing, well motivated possibilities (from A to Z)

⇒ **Supersymmetric extensions of the SM**

- Potential and elegant solution to the hierarchy problem
  
  If SUSY is softly broken \( \Delta m_H^2 \propto M_{\text{SUSY}}^2 \left( \frac{\lambda}{16\pi^2} \log \frac{\Lambda_{\text{UV}}}{M_{\text{SUSY}}} \right) \)

- Radiative spontaneous electroweak symmetry breaking
  
  At \( M_{\text{EW}} \), one “naturally” has \( m_{H_u}^2 < 0 \) (if \( m_t \gtrsim 70 \text{ GeV} \))

- Explain the origin of the EW scale \( M_{\text{EW}} \sim M_{\text{SUSY}} \) (SUSY breaking scale)

- Unification of the gauge couplings (around \( 10^{16} \) GeV)
  
  (under simple SU(5) or SO(10) Grand Unified models)

- If R-parity conserving: neutral, colourless, stable Lightest SUSY Particle

  ⇒ candidates for cold dark matter (usually \( \chi_1^0 \) or \( \tilde{\nu} \), also gravitino)
Minimal SUSY extension of the SM (MSSM)

★ Superpotential: \( W = Y_u \hat{H}_u \hat{Q} \hat{u} + Y_d \hat{H}_d \hat{Q} \hat{d} + Y_e \hat{H}_d \hat{L} \hat{e} - \mu \hat{H}_u \hat{H}_d \)

\[ \Rightarrow \mathcal{L} \subset Y_u H_u Qu + Y_d H_d Qd + Y_e H_d Le - \mu \tilde{h}_u \tilde{h}_d + ... \]

soft-breaking terms: \(-\mathcal{L}_{\text{soft}} = m_{H_u}^2 H_u^* H_u + m_{H_d}^2 H_d^* H_d + (B \mu H_u H_d + \text{H.c.}) \)

\[ + (M_i \psi_i \psi_i + \text{H.c.}) + m_F^2 \tilde{F} \tilde{F}^* + A_F Y_F H_i \tilde{F} \tilde{F}^* + ... \]

★ Physical states: Squarks, sleptons, gluinos

Charginos: \{wino, charged higgsinos\} \( \rightarrow \tilde{\chi}_{1,2}^\pm \)

Neutralinos: \{bino, \( w^0 \)-ino, neutral higgsinos\} \( \rightarrow \tilde{\chi}_{1-4}^0 \)

Higgs: \{CP-even, CP-odd, charged\} \( \rightarrow h^0, H^0, A^0, H^\pm \)

\( H^{\text{SM}} \)
MSSM issues: the Higgs sector

★ **μ problem**: SUSY conserving Higgs mass term in $W = \mu \hat{H}_u \hat{H}_d$

EW sym. breaking: $m_{H_u}, m_{H_d}, \mu \sim O(10 - 100) \times M_Z \leadsto \mu \lesssim O(M_{\text{SUSY}})$

LEP constraints on $\tilde{\chi}^\pm$ (wino/higgsino) mass: $\leadsto \mu \gtrsim 100$ GeV

⇒ “Unnatural” values for a dimensionful, SUSY preserving parameter!

★ **Higgs “little fine tuning problem”** (non-observation of Higgs at LEP)

Theoretically..\begin{equation*}\begin{aligned}
\text{MSSM @ tree-level: } m_{h_1^0} &\lesssim M_Z |\cos 2\beta| \\
\text{RC }^{(t-\bar{t})} &: m_{h_1^{CMSSM}}\lesssim 125 \text{ GeV}; m_{h_1^{MSSM}}\lesssim 135 \text{ GeV} \\
\end{aligned}\end{equation*}

Experimentally.. $m_{h_1^{LEP}} \gtrsim 114 \text{ GeV}$

A narrow window for $m_{h_1^0}...$
The Next-to-Minimal Supersymmetric Standard Model

By adding a singlet superfield $\hat{S}$ to the MSSM $\Rightarrow$ NMSSM

★ Elegant solution to the $\mu$-problem of the MSSM

$$\mu \hat{H}_u \hat{H}_d \rightarrow \lambda \hat{S} \hat{H}_u \hat{H}_d$$

$\Rightarrow$ Only dimensionless couplings in $W$; “Yukawa-like” $\lambda \tilde{h}_u \tilde{h}_d S$ term in $\mathcal{L}_{\text{SUSY}}$

$\Rightarrow$ dynamically generated $\mu$: $\langle S \rangle \sim O(M_{\text{SUSY}})$ $\Rightarrow$ $\mu_{\text{eff}} = \lambda \langle S \rangle$

$\Rightarrow$ Scale-invariant superpotential: EW, SUSY scale only appearing via $\mathcal{L}_{\text{soft}}$

★ NMSSM

$\Rightarrow$ Simplest extension of the SM where the only scale is $M_{\text{SUSY}}$

$\Rightarrow$ Original SUSY/SUGRA extensions of the SM of this type [Fayet, Nilles, ...]
NMSSM new features: an introduction

\[ W^{\text{NMSSM}}_{Z^3} = Y_u \hat{H}_u \hat{Q} \hat{u} + Y_d \hat{H}_d \hat{Q} \hat{d} + Y_e \hat{H}_d \hat{L} \hat{e} - \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3 \]

\[ -L^{\text{Higgs}}_{\text{soft}} = m^2_{H_i} H_i^* H_i + m^2_S S^* S + (-\lambda A_{\lambda} S H_u H_d + \frac{1}{3} \kappa A_{\kappa} S^3 + \text{H.c.}) \]

\( \hat{S} \) degrees of freedom: singlino \( (\chi^0_S) \); singlet scalar and pseudoscalar \( (S_R, S_I) \)

Neutralino sector:
\[
\begin{align*}
\tilde{\chi}^0_1 & = N_{11} \tilde{B}^0 + N_{12} \tilde{W}_3^0 + N_{13} \tilde{H}_d^0 + N_{14} \tilde{H}_u^0 + N_{15} \tilde{S} \\
\end{align*}
\]

Neutral Higgs sector:
\[
\begin{align*}
\Phi^0 & = S_{11} H_d^0 + S_{12} H_u^0 + S_{13} S_R \\
\end{align*}
\]

⇒ **NMSSM: Richer, complex phenomenology**

[for a review see Ellwanger, Hugonie, AMT '09]
**NMSSM Higgs sector**

★ **NMSSM: less fine-tuning required!** [Dermisek, Gunion, Bastero-Gil, ...]

- **Theoretically higher upper bound** on SM-like Higgs mass ($\sim 145$ GeV)
- **NMSSM light Higgs** ($m_{h_1} \lesssim 114.7$ GeV) still allowed by LEP data

![Combined LEP constraints](image)

- **Non-negligible singlet component**
  - reduced coupling to gauge bosons ($C_h^V = g h ZZ / g_{h,SM} ZZ < 1$)
  - $m_{h_1} \sim$ very light! $h_2^0 \sim H^{SM}$ naturally above LEP bound
  - max. mixing $S - H_{u,d}$: $m_{h_1}^0 \gtrsim 100$ GeV; $h_2^0 \lesssim 162$ GeV
  - [Tevatron - Jayatilaka, Moriond ’11]

- **Unconventional Higgs decays!**
  - SM-like $h_1^0$ ($C_h^V \sim 1$), but reduced $BR(h \to b \bar{b})$
  - For $m_{a_1} \lesssim 2 m_B$ dominant decay $h_1^0 \to a_1^0 a_1^0 \to 4 \tau$
  - Accounts for the “observed excess”: $m_H \sim 98$ GeV ($2.3\sigma$)
  - [Dermisek, Gunion]

- **Singlet-like with unconventional decays ...**
Unconventional Higgs decays: LEP and EW precision data

**EW precision tests:** favour $m_H \sim 100$ GeV [CERN EWWG, 2010]

... in “disagreement” with LEP bounds!

- **NMSSM** $m_{a_1} < 2m_B$ region:
  
  SM-like $h_1^0$ **dominantly** decaying into $h_1^0 \rightarrow a_1^0 a_1^0$

  with $a_1^0 \rightarrow 2\tau, 2$ jets

  $m_{h_1^0} \sim 100$ GeV ($m_{\text{eff}}^{EW} \lesssim 100$ GeV)

NMSSM light pseudoscalars “natural”: pseudo-Goldstone e.g. from broken $U(1)_R$
Unconventional Higgs decays: constraints on a light $a^0_1$

\[ m_{a^0_1} \lesssim 2m_B: \text{severe constraints from } \bar{B} \to X_s \ell^+ \ell^- \text{, } \bar{B}_s \to \mu^+ \mu^- \]

\[ \Upsilon \to \gamma (a^0_1 \to \tau\tau/\mu\mu/..) \text{ [BABAR, CLEO]} : 9 \text{ GeV} \lesssim m_{a^0_1} \lesssim 10.1 \text{ GeV} \]

(also favoured by $\Upsilon(1s) - \eta_b(1s)$ hyperfine splitting from $a^0_1 - \eta_b$ mixing)

[Domingo et al, Hiller, Domingo...]

\[ X_d = \cos \theta_A |_{\text{doublet}} \times \tan \beta \]
Unconventional Higgs decays: constraints on a light $a_1^0$

**ATLAS preliminary**  [M. Schumacher, Moriond EW '11]

Exclusion limits for $\sigma(gg \to A) \times \text{BR}(A \to \mu\mu)$: light $a_1^0$ ($\lesssim 9$ GeV)

**LEP constraints:**

$m_{a_1^0} \gtrsim 2m_B$: strong constraints on $m_{h_1^0} \lesssim 100$ GeV

$h_1^0 \to a_1^0 a_1^0 \to 4b$'s

[OPAL '04, DELPHI '04]

$2m_{\tau} \lesssim m_{a_1^0} \lesssim 2m_B$: $m_{h_1^0} \lesssim 110$ GeV, Higgsstrahlung

$h_1^0 \to a_1^0 a_1^0 \to 4\tau$'s

[ALEPH '10]

$\Rightarrow m_{a_1^0} \sim 10$ GeV compatible with $m_{h_1^0} \sim 100$ GeV

for $\text{BR}(a \to \tau^+\tau^-) \sim 80\%$ (i.e. $\xi^2 \lesssim 0.5 - 0.6$)

[Dermisek, Gunion '10]

$$\xi^2 = \frac{\sigma(e^+e^- \to Zh)}{\sigma(e^+e^- \to Zh)_{SM}} \times \text{BR}(h \to aa) \times \text{BR}(a \to \tau^+\tau^-)^2$$

![Graph showing observed and expected upper limits for $m_h$ with upper limits at 10 GeV/c^2.](image)
NMSSM searches

An extended Higgs sector does not mean “easier to detect”!!

- **NMSSM discovery** requires taking into account many non-standard channels
  - Distinct production processes, intermediate states in cascade decays...
  - Disentangling NMSSM from the MSSM might be complicated

- **NMSSM** regimes can possibly be more visible than the MSSM

  [Dermisek, Gunion '08; Moretti, Munir '06]

Example: significant excess of the signal rate $\sigma(gg \rightarrow h_1^0 \rightarrow \gamma\gamma) \sim 6 \times \sigma(gg \rightarrow H_{SM} \rightarrow \gamma\gamma)$

  for lighter Higgs 80 - 110 GeV (significant singlet component)  
  [Ellwanger '10]

- **NMSSM**: “No-lose” theorem for the detection of at least one $h$ might not apply

  “Discovery of at least one NMSSM CP even Higgs at LHC for $\int L \sim 600 \text{ fb}^{-1}$”

  if Higgs-to-Higgs decays are present (as in vast regions of the parameter space)

  [Ellwanger, Gunion, Hugonie '05]
Unconventional Higgs decays: some strategies for the LHC

\[ h_1^0 \rightarrow a_1^0 a_1^0 \rightarrow 4\tau \] (possibly \( m_{h_1^0} < 114 \text{ GeV} \))

\( \Rightarrow \text{difficult to identify all 4 leptons; large } \not{p_T} \) (as much as 8\( \nu \) final state)

\( \Rightarrow \text{backgrounds: } t\bar{t}, \text{ vector boson } + t, b, \text{ vector boson } + \text{light jets}, \Upsilon... \)

► **CMS:** explore \( 2\mu + 2\text{jet} \) signature [Belyaev et al '08]

- Higgsstrahlung \( q \bar{q}' \rightarrow W h_i, W \rightarrow l \nu_l \): trigger on leptonic \( W \) decays; very clean signal
- Vector Boson Fusion: trigger on 2 same-sign non-isolated \( \mu \)'s; \( \sim \) collinear \( \tau \)s from \( a_1^0 \)

► **CMS & ATLAS:** central exclusive production \( pp \rightarrow p h_1^0 p \) [Forshaw et al '07]

- install purpose built low-angle proton detectors
- visible \( h_1^0 \rightarrow a_1^0 a_1^0 \rightarrow 4\tau, m_{h_1^0} \) and \( m_{a_1^0} \) determined on event-to-event basis

► \( H^\pm \rightarrow W^\pm a_1^0, a_1^0 \rightarrow \tau^+\tau^- \) (e.g. gluon fusion) [Dermisek '10, Mahmoudi '10]

► \( pp \rightarrow h_1^0+ \text{ resolved jet } \rightarrow \tau^+\tau^-+\text{jet} \) (gluon fusion) \( \Rightarrow \) light \( h_1^0 \) [Belyaev '10]

► **LHC & Tevatron:** \( a_1^0 \) detection in low tan\( \beta \) \( gg \rightarrow (h_1^0) \rightarrow a_1^0 a_1^0 \rightarrow 4\tau, 2\tau2\mu... \)
Neutralinos & dark matter in the NMSSM

★ Neutralino relic density \( \Omega h^2 \)  
[Belanger et al '05 - '08, ...]

Richer Higgs/neutralino sectors \( \Rightarrow \) correct relic density in large regions of the NMSSM

- New final states are kinematically open (light \( h_1^0, a_1^0 \))

- Additional scalar and pseudoscalar \( s–channel \) resonances

- Singlino-like LSP also a good dark matter candidate!
  
  if small higgsino component, \( \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow h_1^0 \rightarrow a_1^0 a_1^0 (X_{SM} X_{SM}) \)
  
  co-annihilations with heavier neutralinos \( \tilde{\chi}^0_1 \tilde{\chi}^0_i \rightarrow H, A_{\text{heavy doublet}} \rightarrow t\bar{t}, b\bar{b} \)
  
  recover scenarios of MSSM-\( \tilde{\tau} \) LSP (e.g. \( m_0 \ll M_{1/2} \))

★ Interesting prospects for NMSSM dark matter detection

\( \Rightarrow \) very light (2-20 GeV) \( \tilde{B} \), annihilating via light \( a_1^0 \) resonance: account for CDMS-II; below DAMA and CoGeNT regions  
[Das, Ellwanger '10]

\( \Rightarrow \) Timur Delahaye’s talk “NMSSM constraints and dark matter signals”, Friday pm!
A simple and predictive scenario: the constrained NMSSM

Minimal supergravity inspired NMSSM: at $M_{\text{GUT}}$ $M_i = M_{1/2}$; $m_0^F,\phi = m_0$; $A_0^F,\phi = A_0$

cNMSSM: $M_{1/2}$, $m_0$, $A_0$, $\lambda$  ($m_{H_u,d} = m_S = m_0$; $A_{\lambda,\kappa} = A_0$)

[Aellwanger et al '95,'97; Elliot et al '95]

A very “constrained” parameter space in the constrained NMSSM:

▸ $< S > \neq 0$ ($\mu_{\text{eff}} \neq 0$) $\Rightarrow m^2_S|_{\text{EW}} \sim m^2_S|_{\text{GUT}} = m_0^2 \ll M_{1/2}, A_0 \quad m_0^2 \sim 0$

($m_0^2 \sim 0$ not viable in cMSSM $\sim \tilde{\tau}$ LSP!)

▸ Viable DM candidate: singlino-like $\chi^0_1$

efficient $\chi^0_1 - \tilde{\tau}_1$ annihilation $\Rightarrow m_{\tilde{\tau}_1} - m_{\chi^0_1} \simeq \text{few GeV}$  $A_0 \sim -\frac{1}{4} M_{1/2}$

▸ LEP constraints on Higgs: $\lambda < 0.02$  ($\lambda > 10^{-5}$ for $\Omega h^2|_{\text{WMAP}}$)

$M_{1/2} > 520$ GeV  $M_{1/2} \leq 1$ TeV favoured by $(g-2)_\mu$

large $M_{1/2}$ disfavoured by fine-tuning

cNMSSM: essentially one parameter ($M_{1/2}$)

[Djouadi, Ellwanger, AMT '08]
**cNMSSM spectrum**

- **Higgs**: depending on $M_{1/2}$, $h^0_1$ singlet $\longleftrightarrow$ mixed singlet/SM $\longleftrightarrow$ SM-like
  
  "Cross-over": $m_{h^0_1} \approx 99$ GeV; $m_{h^0_2} \approx 117$ GeV; $|C^V_{h^0_1}| \approx 0.3 \Rightarrow$ account for "LEP excesses"!

- **Heavy squarks** ($m_{\tilde{q}} \gtrsim 1$ TeV); **Gluino heavier** than all squarks and sleptons

- **Typical sparticle decay chain**: $\tilde{g} \rightarrow \chi^0_2 q \rightarrow \tilde{\tau}_1 \tau q \rightarrow \chi^0_1 \tau \tau q$

Different from cMSSM! $\tilde{\tau}_1$ NLSP and 2 $\tau$'s per squark! ($\tau|\chi^0_2$ hard; $\tau|\tilde{\tau}_1$ soft)
cNMSSM: “smoking guns” and Nemesis

★ Singlino LSP, nearly degenerate with $\tilde{\tau}_1$ ($\Omega h^2$), small $\lambda$ (LEP) ⇒ Long-lived $\tilde{\tau}_1$!

cNMSSM “smoking gun”: $\tilde{\tau}_1$ displaced vertices! $\mathcal{O}$(mm - cm)

★ Dark matter detection in the cNMSSM

► Direct detection: $\chi_1^0$-nucleon scattering (within a detector)

cNMSSM: effective $\chi_1^0 - \chi_1^0 - q - q$ coupling $\propto \lambda^2$

⇒ typical $\sigma_{\chi_1^0 p}$ well below experimental capabilities ...

► Indirect Detection: equally “dark” prospects for cNMSSM

Any dark matter signal ⇒ tool to RULE OUT model!
cNMSSM prospects for LHC

★ Dominant background: $t\bar{t}$, $W+$jets, $Z+$jets, $W+Z$ ... (as for any SUSY model)

★ Dominant production: $\tilde{q}\tilde{g}$, $\tilde{q}\tilde{g}$

$gg$ and VBF $\leadsto h_{1,2}^{\text{SM-like}}$; associated $b\bar{b}$ $\leadsto$ heavier Higgses

★ Simplest decay cascade: $\tilde{q}_R \rightarrow \chi_2^0 q$; $\chi_2^0 \rightarrow \tilde{\tau}_1 \tau$; $\tilde{\tau}_1 \rightarrow \chi_1^0 \tau$

★ Dedicated strategies and cNMSSM specific cuts [Ellwanger, Florent, Zerwas ’10]

► $\sqrt{s} = 14$ TeV & $\int \mathcal{L} = 1$ fb$^{-1}$ $\Rightarrow$ S/B ratio allow for cNMSSM discovery
  (wide $M_{1/2}$ range for larger $\int \mathcal{L}$)

► $\sqrt{s} = 7$ TeV & $\int \mathcal{L} = 1$ fb$^{-1}$ $\Rightarrow$ $\sim 5$ events (low $M_{1/2}$ regime)

► distinguish cNMSSM from cMSSM in $\tilde{\tau}$ coannihilation region
Outlook

- **NMSSM** theoretically and phenomenologically appealing **SUSY extensions of the SM**

- New states ⇒ **distinct phenomenology** from SM and MSSM
  
  **light Higgs & neutralino:** implications for **flavour physics, dark matter and LHC**

- Can **NMSSM scenarios** be visible at the **LHC**?
  
  at present only “more-to-gain” theorems, yet no “no-lose”!

  **NMSSM unconventional decays** should be included in LHC strategy

  **Warning:** LHC “negative results” do not necessarily apply!

- **cNMSSM** simple and minimal SUSY model; phenomenology \( \sim M_{1/2} \)
  
  “heavy” sparticle spectrum, \( \tilde{\tau}_1 \) in **all** decay **cascades** (possibly long lived)

  Any dark matter detection allows to **rule out** **cNMSSM**
Additional slides
cNMSSM dedicated LHC search strategy

- **Cuts:**
  \[ m_{\tilde{g}} > m_{\tilde{q}} \sim \text{heavy:} \]
  \[
  \begin{align*}
  \quad & \quad \text{2 hard jets/event} (p_T > 300 \text{ GeV}; p_T > 150 \text{ GeV}) \\
  \quad & \quad \text{large } p_T \text{ of jets and large } E_T^{\text{mis}} > 300 \text{ GeV}
  \end{align*}
  \]

- one soft \( \tau \)
- one hard \( \tau \)

require identification of ONLY one \( \tau \), \( p_T > 30 \text{ GeV} \)

Lower limits on angle between hard jet and \( E_T^{\text{mis}} \)
Cut on transverse \( M_T > 100 \text{ GeV} \) (from \( E_T^{\text{mis}} \) and the identified \( \tau \))

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Table 3. Signal expectation for the NMSSM points at NLO after all cuts for the benchmark points. At least 120000 events per point were generated. The error is the statistical error. For every point the ratios S/B and S/\sqrt{B} for an integrated luminosity of 1 fb^{-1} and 30 fb^{-1} are shown.

[Ellwanger, Florent, Zerwas '10]
NMSSM charged Higgs bosons

★ In the NMSSM $m_{H^\pm}$ can be somewhat lighter than in the MSSM ($\ldots \lambda^2 v^2$) and strongly depends on regimes for $m_A$ and $\tan \beta$!

► Typically, positive & large $A_t$ regime: $\text{BR}(\bar{B} \rightarrow X_s \gamma)$ very stringent constraint!

  “SUSY” and $H^\pm$ contributions provide positive contributions (especially large $\tan \beta$!)

► Negative & large $A_t$ regime: $\text{BR}(\bar{B} \rightarrow X_s \gamma)$

  possible cancellations between “SUSY contributions” and $H^\pm$ contributions

Not only $m_{H^\pm} \sim 100$ GeV is allowed, but for $\tan \beta \gtrsim 20$ $H^\pm$ must be large enough to avoid a large decrease of $\text{BR}(\bar{B} \rightarrow X_s \gamma)$ due to the SUSY diagrams!

[Domingo, Ellwanger '07]