Connections between colliders and cosmology in the nMSSM

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based on:
What comes next? - The nMSSM, colliders and cosmology

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based on:

1. Life beyond minimalism: NMSSM, nMSSM, etc.
2. nMSSM at colliders
3. Connection to cosmology
Life beyond minimalism: NMSSM, nMSSM, etc.
**MSSM with additional singlet**

\[ W = \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 + \kappa \hat{S}^3 + m_N \hat{S}^3 + \frac{m_{12}^2}{\lambda} \hat{S} + \text{Yukawa terms} \]

- **Solve \( \mu \)-problem:**
  Effective \( \mu \)-term through VEV of \( S \): \[ \mu_{\text{eff}} = -\lambda \langle S \rangle \]

- **Evade LEP-Higgs bounds**
  \( \lambda \) coupling allows heavier CP-even Higgs masses than MSSM

\[ m_h^2 \leq M_Z^2 \left( \cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta \right) \]

- **Strong 1st order electroweak phase transition**
  Triple-Higgs coupling \( \lambda \) already at tree-level
## Electroweak Baryogenesis

**Sakharov conditions:**

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>NMSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baryon number violation</td>
<td>Non-perturbative sphaleron processes</td>
<td>Soft SUSY breaking e.g. gaugino masses $M_i$</td>
</tr>
<tr>
<td>C and CP violation</td>
<td>CKM phase → too small</td>
<td></td>
</tr>
<tr>
<td>Non-equilibrium</td>
<td>Strong electroweak phase transition</td>
<td>also for $M_H &gt; 100$ GeV due to Higgs self-coupl.</td>
</tr>
<tr>
<td></td>
<td>only for $M_H \lesssim 40$ GeV</td>
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</tbody>
</table>

*Note: $M$ and $H$ refer to mass scales.*
**NMSSM vs. nMSSM**

\[ W = \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 + \kappa \hat{S}^3 + m_N \hat{S}^3 + m_{12}^2/\lambda \hat{S} + \text{ Yukawa terms} \]

<table>
<thead>
<tr>
<th>NMSSM</th>
<th>nMSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathbb{Z}<em>3 \subset U(1)</em>{PQ}$ symmetry</td>
<td>$\mathbb{Z}_5^R$ or $\mathbb{Z}_7^R$ symmetry</td>
</tr>
<tr>
<td>$m_N = 0, m_{12} = 0$</td>
<td>$m_N = 0, \kappa = 0$</td>
</tr>
<tr>
<td></td>
<td>$m_{12}$ at higher loop order</td>
</tr>
<tr>
<td>Domain walls from $\langle S \rangle$</td>
<td>Subgroups of $U(1)<em>{PQ}$ broken by $m</em>{12}$</td>
</tr>
</tbody>
</table>

- New parameters in nMSSM compared to MSSM:

<table>
<thead>
<tr>
<th>Superpotential</th>
<th>SUSY breaking</th>
<th>Higgs states</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>$a_\lambda$</td>
<td>$m_{12} \rightarrow M_A$</td>
</tr>
<tr>
<td>$m_{12}$</td>
<td>$t_s$</td>
<td>$m_s \rightarrow v_s = \langle S \rangle$</td>
</tr>
<tr>
<td>$m_s^2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Dark matter and nMSSM

With **R-parity** conservation LSP becomes stable

In nMSSM LSP is lightest neutralino $\tilde{\chi}_1^0$ → good **dark matter** candidate

- In nMSSM $\tilde{\chi}_1^0$ is mainly singlino and $m_{\tilde{\chi}_1^0} < M_Z$

$$M_{\tilde{\chi}_0} = \begin{pmatrix}
M_1 & 0 & \mathcal{O}(v) & \mathcal{O}(v) & 0 \\
0 & M_2 & \mathcal{O}(v) & \mathcal{O}(v) & 0 \\
\mathcal{O}(v) & \mathcal{O}(v) & 0 & \lambda v_s & \mathcal{O}(v) \\
\mathcal{O}(v) & \mathcal{O}(v) & \lambda v_s & 0 & \mathcal{O}(v) \\
0 & 0 & \mathcal{O}(v) & \mathcal{O}(v) & 0
\end{pmatrix}$$

- $Z\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling suppressed → Evade LEP1 bounds

- For $m_{\tilde{\chi}_1^0} \sim M_Z/2$: efficient annihilation through $Z$ resonance → Good agreement with observed $\Omega_{CDM}$
nMSSM and baryogenesis

Lightest neutralino $\tilde{\chi}_1^0$ is mainly singlino and $m_{\tilde{\chi}_1^0} \ll M_Z$

Constraints from CDM density and LEP force

$$\tan \beta \sim \mathcal{O}(1) \quad \lambda = 0.5\ldots0.8 \quad |\mu| = |\lambda v_s| = 100\ldots350 \text{ GeV}$$

(upper bound on $\lambda$ from perturbativity)

Requirement of strong electroweak phase transition for baryogenesis

$$a_\lambda = 300\ldots600 \text{ GeV} \quad t_s = (50\ldots200 \text{ GeV})^3$$

Typical parameter point:

$$v_s = -384 \text{ GeV} \quad a_\lambda = 373 \text{ GeV} \quad \tan \beta = 1.7 \quad \lambda = 0.62$$

$$t_s = (157 \text{ GeV})^3 \quad M_A = 923 \text{ GeV} \quad |M_2| = 245 \text{ GeV} \quad \phi_{\mu M_2} = 0.14$$
1st/2nd gen. sfermions heavy (few TeV) to avoid EDM constraints

3rd generation sfermions at ~ 500 GeV for baryogenesis and Higgs naturalness

All neutralinos/charginos have $m < 500$ GeV
Mainly decay through gauge bosons

3 CP-even Higgs states $S_{1,2,3}$
2 CP-odd Higgs states $P_{1,2}$

Light Higgses have large coupling $\lambda$ to singlet

$\text{BR}(S_1, S_2, P_1 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) > 90\%$
nMSSM at colliders
nMSSM at LHC

- Invisible Higgs(es) can be seen, but mass measurement difficult
  
  Choudhury, Roy ’94
  Eboli, Zeppenfeldt ’00

- Neutralinos produced in stop/sbottom cascades
  
  e.g. $\tilde{g} \rightarrow b\bar{b}^* \rightarrow b\bar{b} \tilde{\chi}_2^0 \rightarrow b\bar{b} l^+ l^- \tilde{\chi}_1^0$

Mass measurements in invariant mass distributions

→ Good determination of mass differences
nMSSM at LHC

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Mass measurements in invariant mass distributions

- Good determination of mass differences
- Poor determination of absolute masses

Typical errors for \( m_{\tilde{\chi}^0_{1,2,3}} \):
  20–30 GeV
nMSSM at ILC

- Many SUSY particles could be discovered at 500 GeV ILC
- Reduction of SM backgrounds possible with few cuts
- Kinematic edges in energy distributions allow sparticle mass measurement

Ex.: $e^+e^- \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \rightarrow W^+\tilde{\chi}_1^0 \rightarrow jj \tilde{\chi}_1^0$
nMSSM at ILC

- Two (invisible) scalar Higgs bosons $S_1$ and $S_2$ can be found and measured through $e^+e^- \rightarrow Z S_k$

- At ILC with $\sqrt{s} = 500$ GeV charginos and neutralinos can be precisely measured similar to MSSM

<table>
<thead>
<tr>
<th>$\tilde{\chi}^0_1$</th>
<th>$\tilde{\chi}^0_2$</th>
<th>$\tilde{\chi}^0_3$</th>
<th>$\tilde{\chi}^0_4$</th>
<th>$\tilde{\chi}^\pm_1$</th>
<th>$\tilde{\chi}^\pm_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>33</td>
<td>107</td>
<td>182</td>
<td>278</td>
<td>165</td>
</tr>
<tr>
<td>$\delta m$</td>
<td>0.4</td>
<td>1.2</td>
<td>5</td>
<td>3.5</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Discovery of two neutralino states with $m_{\tilde{\chi}^0_{1,2}} \ll m_{\tilde{\chi}^\pm_1}$ immediately tells > MSSM

- Allows prediction for CDM abundance and consistency-check for baryogenesis
Interpretation of results

Fundamental parameters from neutralino/chargino measurements:

\[ M_1 = (122.5 \pm 1.3) \text{ GeV}, \quad |\kappa| < 2.0 \text{ GeV}, \quad m_{\tilde{\nu}_e} > 5 \text{ TeV}, \]
\[ M_2 = (245.0 \pm 0.7) \text{ GeV}, \quad \tan \beta = 1.7 \pm 0.09, \quad m_{\tilde{e}_R} > 1 \text{ TeV}, \]
\[ |\lambda| = 0.619 \pm 0.007, \quad |\phi_M| < 0.32, \]
\[ v_s = (-384 \pm 4.8) \text{ GeV}, \]

- Higgs triple coupling can be measured precisely
- Absence of cubic singlet self-coupling can be tested

(nMSSM ↔ NMSSM)

\[
M_{\tilde{\chi}^0} = \begin{pmatrix}
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\mathcal{O}(v) & \mathcal{O}(v) & 0 & \lambda v_s & \mathcal{O}(v) \\
\mathcal{O}(v) & \mathcal{O}(v) & \lambda v_s & 0 & \mathcal{O}(v) \\
0 & 0 & \mathcal{O}(v) & \mathcal{O}(v) & \kappa
\end{pmatrix}
\]
Connection to cosmology
LHC does not tell much

ILC allows computation with precision comparable to WMAP
Direct detection

- Large singlino component of $\tilde{\chi}_1^0$: Spin-independent cross-section is sizeable due to singlet-Higgs coupling $\lambda$
  Spin-dependent cross-section is very small
- Next generation SI experiments can probe this scenario
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Testing electroweak baryogenesis

- Neutralino/chargino parameters allow to extract some parameters

- More information from Higgs masses:
  \[ M_{S1} = 115.2 \pm 0.13 \text{ GeV}, \ M_{S2} = 156.6 \pm 0.19 \text{ GeV} \]

- Mass matrix of CP-even Higgs bosons gets large corrections:
  \[ M_S^2 = M_{S,\text{tree}}^2 + \Delta M_S^2 \]

  Leading contributions from \( t/\bar{t} \) loops, e.g.
  \[ \Delta M_{S,11}^2 \approx \frac{3}{8\pi^2} \frac{m_t^4}{v^2} \log \frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4} \]

  In general very complicated, depends on stop mixing, \( A_t \)

- Assumptions: \( \delta m_{\tilde{t}} = 50 \text{ GeV} \) (no simulations for LHC available)
  \( A_t \lesssim 500 \text{ GeV} \) (from small stop mass difference)
Testing electroweak baryogenesis

- Neutralino/chargino parameters allow to extract some parameters
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  \[ M_{S_1} = 115.2 \pm 0.13 \text{ GeV}, \; M_{S_2} = 156.6 \pm 0.19 \text{ GeV} \]

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<th>Parameter</th>
<th>Input value</th>
<th>Expected constraints from ILC</th>
<th>Range preferred by baryogenesis</th>
</tr>
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<tr>
<td>(m_s)</td>
<td>106.5 GeV</td>
<td>(88 &lt; m_s &lt; 122)</td>
<td>(50 \lesssim m_s \lesssim 200)</td>
</tr>
<tr>
<td>(a_\lambda)</td>
<td>373 GeV</td>
<td>(352 &lt; a_\lambda &lt; 390)</td>
<td>(300 \lesssim a_\lambda \lesssim 600)</td>
</tr>
<tr>
<td>(t_s^{1/3})</td>
<td>157 GeV</td>
<td>(117 &lt; t_s^{1/3} &lt; 181)</td>
<td>(50 \lesssim t_s^{1/3} \lesssim 200)</td>
</tr>
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- Constraints from experiment not very precise (mainly from loop corrections) but sufficient to test conditions for EWBG
Conclusions

- The nMSSM is an appealing framework for
  - Explaining the origin of matter and dark matter
  - Solving the $\mu$ problem
  - Avoiding fine-tuning in the Higgs sector
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  - The new particle zoo
  - The validity of SUSY dark matter
  - The ingredients for baryogenesis
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