A light singlino in the NMSSM: Challenges for SUSY searches at the LHC

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### Shortcomings of the SM

<table>
<thead>
<tr>
<th>Problem</th>
<th>Solved by SUSY?</th>
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</thead>
<tbody>
<tr>
<td>What is Dark Matter?</td>
<td>✓</td>
</tr>
<tr>
<td>Hierarchy Problem</td>
<td>✓</td>
</tr>
<tr>
<td>Grand Unification</td>
<td>✓</td>
</tr>
<tr>
<td>(Quarks, leptons fill complete SU(5) representations, but gauge couplings do not quite unify)</td>
<td>✓</td>
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<tr>
<td>Matter-Antimatter Asymmetry</td>
<td>✓</td>
</tr>
<tr>
<td>Origin of the tiny Neutrino Masses</td>
<td>–</td>
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<tr>
<td>Hierarchy/Mixing of Quark/Lepton Masses</td>
<td>–</td>
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</tbody>
</table>

- means “can be implemented”, but not automatically

→ Hard to give up, despite the absence of “sparticles” at the LHC:
Lower bounds on sparticle masses after the LHC run I:

If $M_{\text{squark}} \sim M_{\text{gluino}}$:

$M_{\text{squark}} \sim M_{\text{gluino}} \gtrsim 1.7$ TeV

(CMS/MSUGRA bounds are similar)
Limits depend on the assumed decay cascades:

Once sparticles are produced (in pairs), they decay into other sparticles, but the lightest neutralino escapes undetected and gives rise to $E^{T}_{\text{miss}}$:
The NMSSM:

- An additional singlet scalar in the Higgs sector helps to understand the mass of 125 GeV of the SM-like Higgs boson (MSSM: large rad. corrections from unnaturally heavy stops are required)
- Its fermionic partner, the singlino, can well be the lightest neutralino (LSP) and a good dark matter candidate
- The singlino has small couplings to squarks, sleptons, charginos and the other neutralinos
- Nobody wants to decay into the singlino, only the NLSP which has no other choice (assuming R-parity):

```
. . . . . . . NLSP

X
```

```
LSP
```
Possible (natural) configuration:

- The singlino LSP is light (a few GeV), $X$ is a Higgs boson ($H_{SM}$, or an additional NMSSM-specific scalar $H_S$)
- The mass of the NLSP is not far above $M_{\text{singlino}} + M_H$
- Then: little (missing transverse) energy is transferred from the NLSP to the singlino; the transverse energy is carried away by the Higgs boson
- If Higgs decays do not give rise to $E_T^{\text{miss}}$, the $E_T^{\text{miss}}$ signature is dramatically reduced!
- Note: NMSSM-specific Higgses $H_S$ with masses below 125 GeV are not ruled out (by LEP) if their couplings to Z-bosons are sufficiently small; these can also play the rôle of “$X$” in NLSP $\rightarrow X +$ singlino cascades
Impact of a NLSP $\rightarrow H_S +$ singlino cascade (LHC run I):

Compare the spectrum of $E_T^{miss}$ from $\approx 1$ TeV squark/gluino production:

- **MSSM** with a 89 GeV bino as LSP
- **NMSSM** with an additional bino $\rightarrow H_S +$ singlino cascade, $M_{H_S} \sim 83$ GeV, $M_{\text{singlino}} \sim 5$ GeV:

![Graph showing the spectrum of $E_T^{miss}$ for MSSM and NMSSM comparison.](image-url)
Where does the remaining $E_T^{miss}$ come from?

$H_S$ has branching fractions similar to $H_{SM}$ of the same mass:

$\sim 8\%$ into $\tau^+\tau^-$ leading to neutrinos in the final state;
$\sim 85\%$ into $b\bar{b}$ with partially leptonic decays

Still: The example with $M_{squarks} \sim 830$ GeV, $M_{gluino} \sim 860$ GeV,
$M_{stops,sbottoms} \sim 810 - 1060$, $M_{charginos} \sim 830 - 950$ GeV passes all LHC constraints

The only LHC allowed scenario with all sparticle masses below
$\sim 1$ TeV!
Why not in the MSSM?

A light bino of a few GeV is possible, in principle (although difficult to get the correct dark matter relic density)

Then however, squarks and sleptons (all of which have hypercharge, i.e. couple to the bino) would prefer to decay directly into the bino-like LSP, without a cascade via the NLSP

→ The effect disappears!
What would be the signature of squark/gluino production at the LHC run II in the case bino → $H^{+}$ singlino?

Jets + the remnants of two Higgs states (instead of $E_T^{\text{miss}}$), but $M_H$ not known, e.g. $M_{H_{SM}} = 125$ GeV, or $M_{H_{S}} \sim ...50 - 100...$ GeV

→ Look for, e.g., one $b \bar{b}$ pair and one $\tau^+ \tau^-$ pair (+ cuts on $p_T$ of jets), and a bump at the $b \bar{b}$ invariant mass:

(Different scenarios are possible)
bino → $H_{SM} + \text{singlino}$

$\hat{J}$: A “fat” jet constructed out of two $b$-jets, $M_{\hat{J}} = m_{b\bar{b}}$

Background suppression: Require 2 $\tau_h$
(allow for $\Delta R_{\tau\tau} < 0.5 \rightarrow 2\tau$ fake rate larger than $(1\tau$ fake rate)$^2$!)

Cuts on 4 jets with
$p_T > 400, 300, 200, 100$ GeV (left)  
$p_T > 200, 100, 80, 80$ GeV (right)

(Simulation with A.M. Teixeira, 1406.7221 and 1412.6394)
Another possibility:
50\% \text{BR}(\text{bino} \rightarrow H_{SM} + \text{singlino}), \ 50\% \text{BR}(\text{bino} \rightarrow H_S + \text{singlino}): 

\[ \begin{array}{c}
\sqrt{s} = 13 \text{ TeV} \\
\text{Signal} \quad \text{red} \\
\text{Background} \quad \text{blue}
\end{array} \]

→ Double peaks are possible and visible
Conclusions

- In the presence of a light singlino in the NMSSM the standard $E_T^{\text{miss}}$ signature for sparticle production can be strongly suppressed.

- Re-interpreting the absence of excesses at the LHC run I leads to lower lower bounds on sparticle masses.

- Instead, a Higgs boson is produced in each sparticle cascade; possibly $H_{SM}$, or a new (lighter) $H_{S}$, or both.

- Dedicated searches at the run II are necessary in this case, not relying on $E_T^{\text{miss}}$, but sensitive to Higgs decay products! Our simulations indicate that SUSY may be discovered together with an additional Higgs boson!