Prospects for testing the light Higgsino-Singlino scenario in the NMSSM

Ulrich Ellwanger
Université Paris-Saclay, Orsay, France and
University of Southampton, United Kingdom

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The Rôle of the μ Parameter in the MSSM and in the NMSSM

- μ: a supersymmetric mass term for
  - the scalar Higgs fields: $\mu^2(|H_u|^2 + |H_d|^2)$, and
  - the Higgsinos (2 neutralinos $\psi^0_{u,d}$ and charginos $\psi^\pm_{u,d}$):
    $\mu\left(\psi^0_u\psi^0_d + \psi^+_u\psi^-_d\right)$ +h.c.

- Phenomenological requirements:
  - No charginos seen at LEP $\longrightarrow$ $|\mu| \gtrsim 100$ GeV
  - The Higgs potential must be unstable for $H_u = H_d = 0$ in order to trigger EW symmetry breaking
    $\longrightarrow$ At least one of the Higgs mass terms $(\mu^2 + m_u^2)|H_u|^2 + (\mu^2 + m_d^2)|H_d|^2$ must be negative, where $m^2_{u,d}$ are soft Susy breaking mass terms (positive or negative), but μ^2 is always > 0.

- From $\mu^2 + m_u^2 \approx -M_Z^2/2$:
  Avoid a large tuning between $\mu^2 \gg M_Z^2$ and $|m_u|^2 \gg M_Z^2$
  $\longrightarrow$ require μ^2 and $|m_u|^2 \approx M_Z^2$ or

$$\mu \sim 100 - 300 \text{ GeV}$$

- MSSM: The origin of the scale of μ is ad hoc, the "μ-problem" of the MSSM
- NMSSM: μ is generated via a VEV $\langle S \rangle$ of a singlet scalar S, the higgsino mass terms $\mu\left(\psi_u^0\psi_d^0 + \psi_u^+\psi_d^-\right)$ originate from a Yukawa coupling $\lambda S\left(\psi_u^0\psi_d^0 + \psi_u^+\psi_d^-\right)$ where $\langle S \rangle$ is automatically of the order of the Susy breaking scale (triggered by a negative Susy breaking mass term for S)
- $\longrightarrow$ Less tuning required for a SM-like Higgs boson with $M_{H_{SM}} \simeq 125$ GeV:

$$M_{H_{SM}}^2 \sim M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left(\ln\left(\frac{M_{stop}^2}{m_t^4}\right) + ...\right)$$

$\longrightarrow$ No $>$ TeV stops (highly mixed) are needed for $M_{H_{SM}} \sim 125$ GeV

- Alleviates constraints from negative squark/gluino searches
- Alleviates constraints from negative dark matter searches

Extra physical states in the NMSSM "Beyond the MSSM":

A CP-even scalar H_S, a CP-odd scalar A_S, a fifth neutralino ("singlino"), all of which have couplings to the SM-sector only through mixings $\sim \lambda$ with the MSSM-like Higgs(ino) states.
Note: $M_{H_S} < 114$ GeV is allowed by LEP if this mixing is small enough!

Higgsinos as dark matter (MSSM or NMSSM)?

Large electroweak gauge couplings
$\longrightarrow$ Large annihilation cross section $\longrightarrow$ too small relic density
(and otherwise: too large spin dependent direct detection cross section)

Ways out:

- MSSM: $\mu \gtrsim 1$ TeV? Assume additional axions as dark matter (?)
- NMSSM: Assume the singlino mass below μ, i.e. a (mostly) singlino-like LSP with M_{LSP} possibly as small as a few GeV, which can give a relic density in agreement with WMAP/Planck constraints through
  - annihilation via A_S in the s-channel,
  - singlino in the t-channel,
  - higgsinos in the t-channel,
  - ...

Strategy to answer the Question: Can the light Higgsino/Singlino scenario be ruled out?

Given the various parameters (and constraints on them) of the NMSSM:

- Fix squark, gluino and slepton masses at pessimistically large values: $M_{squark} = 3$ TeV, $M_{gluino} = 2.1$ TeV, $M_{slepton} = 1$ TeV
- Assume bino-wino-gluino "grand unification": $M_{bino} = 350$ GeV, $M_{wino} = 700$ GeV
- Scan the remaining NMSSM parameter space, require
  - the correct mass and signal rates of the SM-like Higgs boson,
  - LEP constraints on the Z-width, from searches for neutralino decay cascades and for lighter (singlet-like) Higgs bosons,
  - LHC constraints from BSM Higgs and Higgs-to-Higgs decay searches,
  - constraints from B-physics
- Recast existing and future searches in the $M_{chargino} - M_{LSP}$ plane, where chargino = charged higgsino with $M_{chargino}$ in the $100 - 300$ GeV range, and LSP = (mostly) singlino

Search for the Higgsino/Singlino scenario at the LHC:

Now: χ_1^0: Singlino, the LSP
$\chi_{2,3}^0$ and $\chi_1^\pm$: higgsinos

Dominant: Higgsino pair production $q + \bar{q}' \to W^{\pm *} \to \chi_1^\pm + \chi_{2,3}^0$

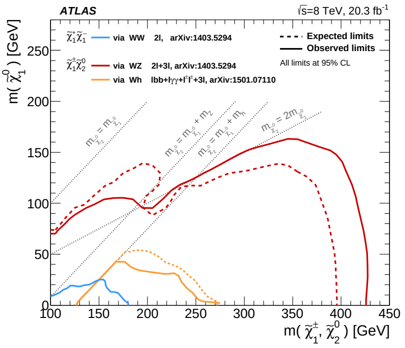
Higgsino decays: $\chi_1^\pm \to \chi_1^0 + W^\pm$
$\chi_{2,3}^0 \to \chi_1^0 + \{Z, H_{125}, H_S!\}$

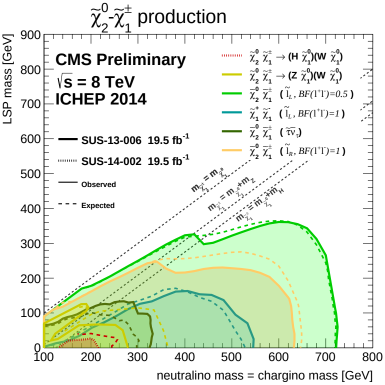
$\longrightarrow$ E_T^{miss} from $2 \times \chi_1^0$, and up to three leptons from $W^\pm$ and Z, the "standard" electroweakino (wino) search channel
(other used search channels: 2 low-p_T leptons+E_T^{miss}, VBF, $E_T^{miss} + ZZ, Z + H_{125}, H_{125} + H_{125}$, ...)

BUT:

- the higgsino production cross sections are smaller than for winos,
- the $BR(\chi_{2,3}^0 \to \chi_1^0 + H_S)$ with $M_{H_S} < 114$ GeV can be large!
- (no cascade decays via sleptons)

Constraints from run I in the $M_{\chi_1^\pm} - M_{\chi_1^0}$ plane, assuming wino-like $\chi_1^\pm$, χ_2^0:

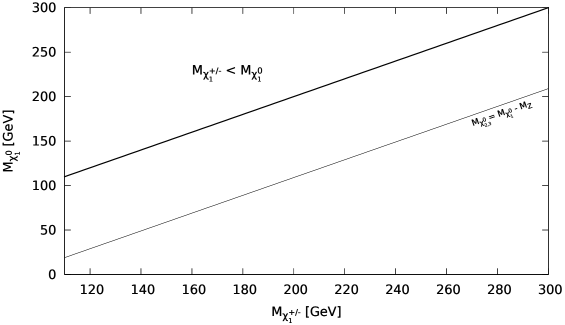




$\longrightarrow$ The $3l$ from WZ channel is most sensitive (for decoupled sleptons)

Recasting these searches in the NMSSM Higgsino/Singlino scenario, using

- NMSSMTools for Higgsino/Singlino masses, couplings and BRs
- MadGraph_5 for production (Pythia 6 for decays)
- Delphes detector simulation
- CheckMATE-1.2.2 and private codes for cuts/limits (validated)

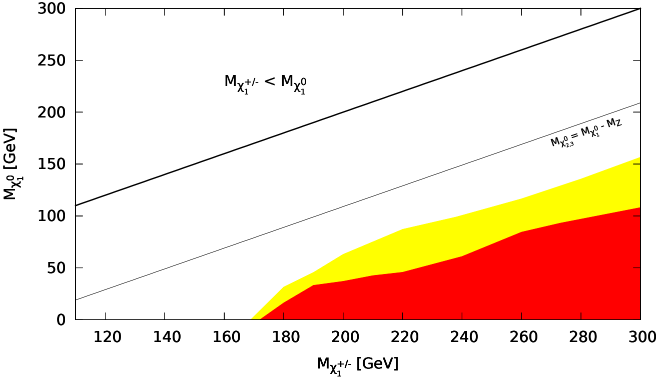


No excluded region!

Reason: smaller Higgsino production cross sections, also due to Higgsino-Singlino mixing, non-negligible $BR(\chi_2^0 \rightarrow H_S + \chi_1^0)$

Having a Look into the Far Future...

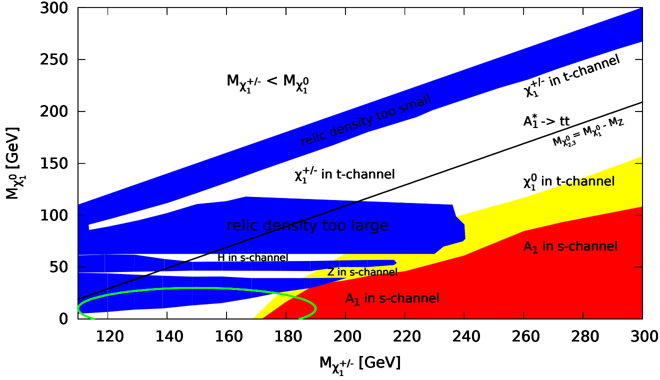
Recasting prospects for the High Luminosity LHC after 3000 fb^{-1}
(ATLAS ATL-PHYS-PUB-2014-010, CMS PAS SUS-14-012)
in the NMSSM Higgsino/Singlino scenario, using CheckMATE-2.0.0



RED: Excluded using ATLAS ATL-PHYS-PUB-2014-010
YELLOW: A search for $2l + W_h + E_t^{miss}$ proposed by CheckMATE (not validated)
$\longrightarrow$ Testing only part of the parameter space, not sensitive to light Higgsinos

Adding Constraints from Dark Matter (using MicrOmegas):

- Relic density consistent with WMAP/Planck
- Spin-independent direct detection cross section (LUX [1608.07648], PandaX [1607.07400])
- Spin-dependent cross section (LUX [1602.03489], PICO-2L [1601.03729])



→ Nearly complementary, but unexplored regions remain...
notably for $M_{\chi_1^\pm} \sim \mu \lesssim 180$ GeV which is theoretically attractive, and $M_{\chi_1^0} \lesssim 8$ GeV which is difficult to test via direct detection!

Conclusions:

- The NMSSM remains the most attractive SUSY extension of the Standard Model; amongst others:
- No heavy higgsinos (large μ_{eff}) needed for dark matter consistent with WMAP/Planck/constraints from direct detection
- BUT: At least in the standard $3l + E_T^{miss}$ search channel, the light Higgsino/Singlino scenario would remain untested at the LHC
- Possible ways out:
  - Search channels which are sensitive to light ($M < 180$ GeV) Higgsinos, like soft leptons + E_T^{miss} (feasible at high luminosity?)
  - Higgsinos via cascade decays (from winos, sleptons)
    $\longrightarrow$ dependence on additional sparticle masses/branching fractions

Otherwise: conclusive tests of the attractive light higgsino/singlino scenario are likely to require a e^+-e^- collider!