Implications of purity constraints on light higgsinos

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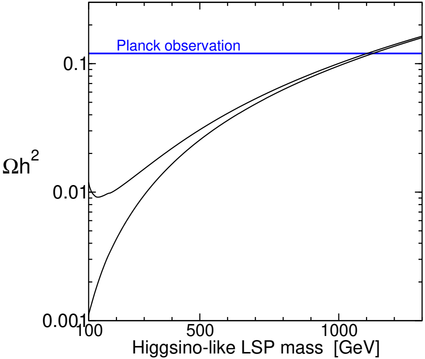
Supersymmetric dark matter is strongly constrained by both direct and indirect detection limits, but higgsinos remain an attractive possibility.

A nearly pure Higgsino has the correct thermal freezeout relic abundance in agreement with the Planck observation $\Omega h^2 = 0.12$, if its mass is about $\mu = 1.1$ TeV.



Upper curve: $\mu : M_1 : M_2 = 1 : 1.5 : 3$

Lower curve: $M_1 = M_2 = 10$ TeV.

If the Higgsino mass is less than 1.1 TeV, then it can be part of the dark matter, with the rest being axions or something else. I assume that here.

Dark matter direct detection constraints, most recently and stringently from Lux-Zeplin 2207.03764 effectively impose purity constraints on higgsinos.

This is true even if the relic abundance is set by thermal freezeout and so has $\Omega h^2 < 0.12$.

To a good approximation, the LZ 2022 spin-independent cross-section bound is, for $M_{\rm LSP} > 100$ GeV,

$$\left(\frac{\Omega_{\rm LSP} h^2}{0.12}\right)\left(\frac{1\ \text{TeV}}{M_{\rm LSP}}\right)\sigma_{\rm SI} \quad \lesssim \quad 2.8\times 10^{-10}\,{\rm pb}.$$

The spin-dependent neutron-LSP cross-section is also important in some parts of parameter space, and to a good approximation is

$$\left(\frac{\Omega_{\rm LSP} h^2}{0.12}\right)\left(\frac{1\ \text{TeV}}{M_{\rm LSP}}\right)\sigma^n_{\rm SD} \quad \lesssim \quad 4.9\times 10^{-5}\,{\rm pb}.$$

In the following, I discuss higgsino LSP purity constraints following from the above. Numerical results use `micrOMEGAs 6.0` and `softSUSY 4.1.12`.

Electroweak symmetry breaking as a perturbation on the neutralino mass matrix:

$$M_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & 0 & 0 \\ 0 & M_2 & 0 & 0 \\ 0 & 0 & 0 & -\mu \\ 0 & 0 & -\mu & 0 \end{pmatrix} + m_Z \begin{pmatrix} 0 & 0 & -s_W c_\beta & s_W s_\beta \\ 0 & 0 & c_W c_\beta & -c_W s_\beta \\ -s_W c_\beta & c_W c_\beta & 0 & 0 \\ s_W s_\beta & -c_W s_\beta & 0 & 0 \end{pmatrix}.$$

Here s_W, c_W are sine and cosine of weak mixing angle, and s_β, c_β are sine and cosine of Higgs VEV ratio angle.

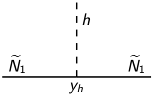
Assumptions:

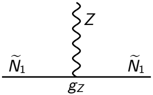
- Higgsino mass parameter less than gaugino mass parameters: $|\mu| < M_1, M_2$
- All MSSM scalar particles (squarks, sleptons, Higgs bosons) are decoupled with masses above 10 TeV, except
- $M_h = 125$ GeV

Pure Higgsinos decouple from direct detection experiments, so the LZ 2022 contraints give

- lower bounds on the gaugino (wino and bino) masses M_2 and M_1,
- upper bounds on the mass splittings among the higgsino-like states, $\Delta M_0 = M_{\tilde{N}_2} - M_{\tilde{N}_1}$ and $\Delta M_+ = M_{\tilde{C}_1} - M_{\tilde{N}_1}$.

The most important couplings for Higgsino-like LSPs for direct detection are to the 125 GeV Higgs boson (spin-independent) and to the Z boson (spin-dependent).





Expanding in small m_Z compared to $|\mu|, M_1, M_2$ gives

$$\begin{aligned} y_h &= -\frac{m_Z}{2}(1 \pm 2 s_\beta c_\beta)\left(\frac{c_W^2}{M_2 - |\mu|} + \frac{s_W^2}{M_1 - |\mu|}\right), \\ g_Z &= \frac{m_Z^2}{4|\mu|}(c_\beta^2 - s_\beta^2)\left(\frac{c_W^2}{M_2 - |\mu|} + \frac{s_W^2}{M_1 - |\mu|}\right), \end{aligned}$$

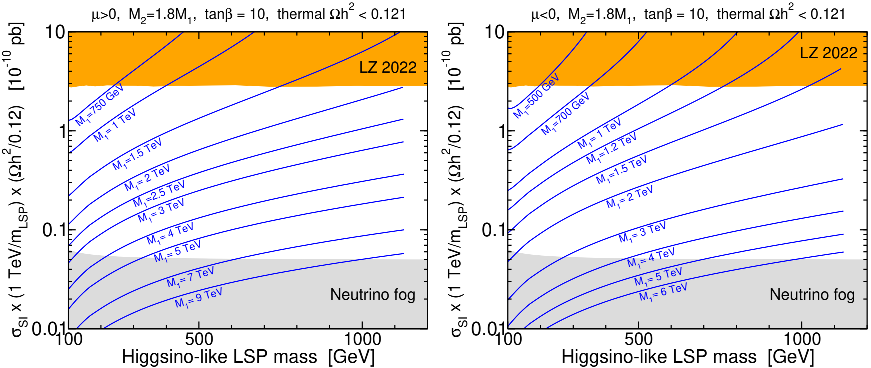
where $\pm$ is the sign of μ.

Important notes:

- $|y_h|$ maximized for positive μ and small $\tan\beta \to 1$
- $|y_h| \to 0$ for negative μ and small $\tan\beta \to 1$
- $|g_Z| \to 0$ for small $\tan\beta \to 1$, but suppression is less efficient

Direct detection "blind spot" for negative μ and $\tan\beta = 1$. The neutron spin-dependent cross-section can set the limit on higgsino purity in that case.

Results for various bino masses M_1, assuming gaugino mass unification at the GUT scale:



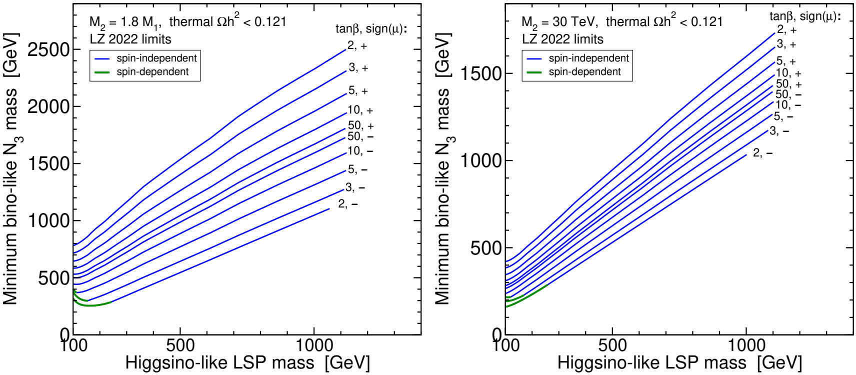
For lighter higgsinos, the bino mass can still be well under 1 TeV while maintaining acceptably small higgino LSP mixing.

The (unshaded) region between the present bound and the neutrino fog includes the multi-TeV range for M_1. This is a very interesting region of parameter space, and far beyond what the LHC can probe!

LZ 2022 purity constraint on bino mass M_1, for various $\tan\beta$ and sign(μ)

Gaugino mass unification:

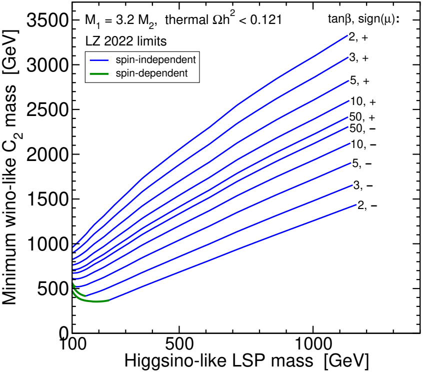
Wino decoupled:



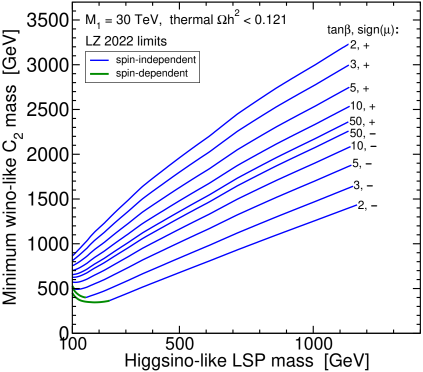
For smaller masses, small $\tan\beta$, and negative μ, it is the neutron-LSP spin-dependent cross-section that sets the lower bound on the bino mass parameter M_1 (green lines).

LZ 2022 purity constraint on wino mass M_2, for various $\tan\beta$ and sign(μ)

Anomaly Mediated SUSY Breaking:



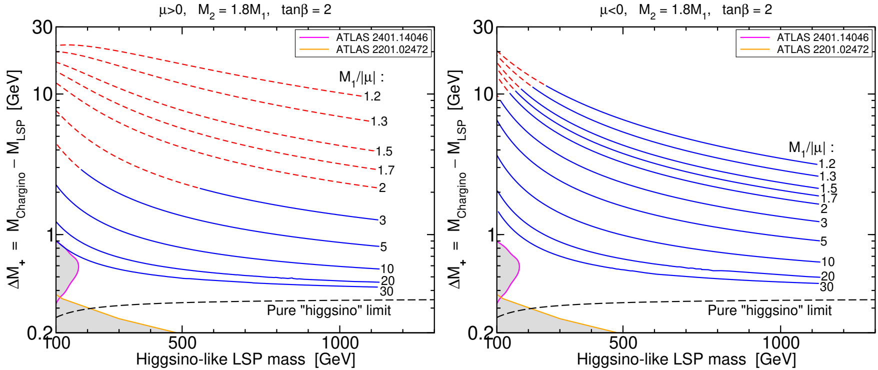
Bino decoupled:



Note: constraints on higgsino mixing with wino are considerably stronger.

The LZ 2022 bounds also imply upper bounds on the mass splittings within the higgsino sector, which arise from mixing with the gauginos.

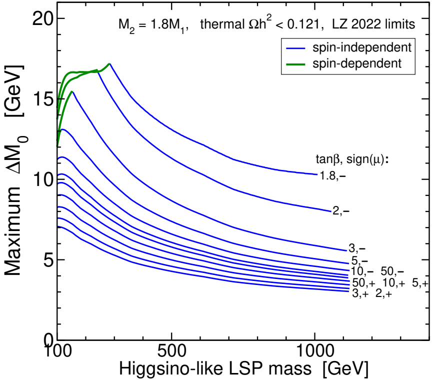
For various bino/higgsino mass ratios:

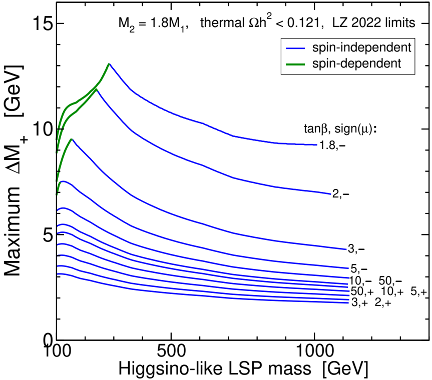


Blue solid lines satisfy nominal LZ 2022 limits, red dashed lines do not.

Gray shaded regions ruled out by disappearing track (ATLAS 2201.02472 and CMS 2309.16823) and mildly displaced tracks ATLAS 2401.14046.

Maximum higgino mass splittings due to mixing with bino:





Blue lines are upper limits from spin-**independent** cross-section,

Green lines are upper limits from spin-**dependent**.

LHC searches for charginos and neutralinos (ATLAS 2106.01676, CMS-PAS-SUS-21-008, CMS 2111.06296) have mild excesses in soft lepton channels; observed limits are weaker than expected limits.

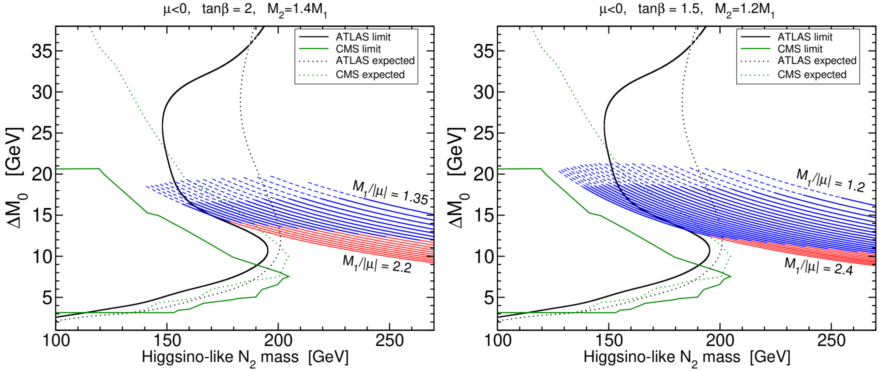
It has also been noted by Agin, Fuks, Goodsell, Murphy 2311.17149 and 2404.12423 that monojet searches (ATLAS 2102.10874, CMS 2107.13021) may have excesses in consistent kinematic regions.

More data to clarify the situation is eagerly awaited.

While we are waiting: can light higgsinos that make up part of the dark matter accommodate the excesses?

Non-trivial, because the higgsino mass splittings are bounded from above by LZ 2022.

Light higgsinos vs. LHC soft lepton excesses:



Blue solid lines allowed by nominal LZ 2022 bounds.

Blue dashed lines relax the spin-dependent bound by 50%.

Red solid lines in the nominal exclusion region for the wino-pair searches in ATLAS 2108.07586, although kinematics and branching ratios may differ.

Cross-sections are very roughly in the right range (substantial fraction of pb).

Takeaways:

- Future dark matter direct detection searches for nearly pure higgsinos will indirectly probe gaugino masses from 500 GeV to over 10 TeV, before hitting the neutrino fog. Sensitivity is:
  - strongest for small $\tan\beta$, positive μ,
  - intermediate for large $\tan\beta$,
  - weakest for small $\tan\beta$, negative μ.
- The mild excesses seen by ATLAS and CMS in soft-lepton searches can be accommodated by light higgsinos that make up part of the dark matter, if $\tan\beta \lesssim 3$ and $\mu < 0$.
- Searches for wino pairs decaying to higgsinos at LHC may probe this scenario, for example $pp \to \tilde{C}_2 \tilde{N}_4 \to W^+ W^+ + \not{E}_T$
- Searches for light higgsino-like particles (and more generally, compressed electroweakinos) are an important target for the LHC.