Snowmass whitepaper: Exploring natural SUSY via direct and indirect detection of higgsino-like WIMPs

H. Baer\textsuperscript{1}, V. Barger\textsuperscript{2}, D. Micke\textsuperscript{1}lson and X. Tata\textsuperscript{3}

\textsuperscript{1}Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA
\textsuperscript{2}Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA
\textsuperscript{3}Dept. of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA

Supersymmetric models with low electroweak fine-tuning contain light higgsinos with mass not too far from $m_h \approx 125$ GeV, while other sparticles can be much heavier. In the $R$-parity conserving MSSM, the lightest neutralino is then a higgsino-like WIMP (albeit with non-negligible gaugino components), with thermal relic density well below measured values. This leaves room for axions (or other, perhaps not as well motivated, stable particles) to function as co-dark matter particles. The local WIMP abundance is then expected to be below standard estimates, and direct and indirect detection rates must be accordingly rescaled. We calculate rescaled direct and indirect higgsino-like WIMP detection rates in SUSY models that fulfill the electroweak naturalness condition. In spite of the rescaling, we find that ton-scale noble liquid detectors can probe the entire higgsino-like WIMP parameter space, so that these experiments should either discover WIMPs or exclude the concept of electroweak naturalness in $R$-parity conserving natural SUSY models. Prospects for spin-dependent or indirect detection are more limited due in part to the rescaling effect.

In previous studies \cite{1,2,3} it has been argued that a necessary condition for naturalness of SUSY models is the requirement of no large uncorrelated cancellations to $m_Z^2/2$ in the one-loop effective potential minimization condition

$$m_Z^2 = \frac{m_{H_u}^2 + \Sigma_d^i - (m_{H_d}^2 + \Sigma_u^i) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2.$$ \hfill (1)

Here, Eq. (1) is implemented as a weak scale relation, even for SUSY theories purporting to be valid all the way up to scales as high as $M_{GUT} - M_F$. The quantities $\Sigma_u$ and $\Sigma_d$ are the one-loop corrections arising from loops of particles and their superpartners that couple directly to the Higgs doublets. Thus, electroweak naturalness requires 1. low $\mu \sim 100 - 300$ GeV, 2. $m_{H_u}^2$ is driven to small negative values so that $m_{H_u}^2(\text{weak}) \sim 100 - 300$ GeV and 3. highly mixed TeV-scale top squarks. The large mixing both reduces the $t_1$ and $t_2$ contributions to $\Sigma_u$ while lifting the Higgs mass $m_h \sim 125$ GeV. Models where these conditions are met have a low value of $\Delta_{EW}$ \cite{1,2,3} and have been labeled as radiatively-driven natural supersymmetry or RNS.

In RNS models, since $\mu \sim 100 - 300$ GeV, then the lightest neutralino is largely higgsino-like but with a non-negligible gaugino component\textsuperscript{1} The thermally-produced (TP) relic density of higgsino-like WIMPs from RNS has been calculated in Ref’s \cite{2,5}; it is typically found to be a factor 5-15 below measured value for CDM, as shown in Fig. 1. To accommodate this situation, a cosmology with mixed axion/higgsino dark matter (two dark matter particles, an axion and a higgsino-like neutralino)\textsuperscript{6} has been invoked in Ref. \cite{2,5}. In this case, thermal production of axinos $\tilde{a}$ in the early universe followed by $\tilde{a} \rightarrow g\tilde{g}$, leads to additional neutralino production. In the case where axinos are sufficiently produced, their decays may lead to neutralino re-annihilation at temperatures below freeze-out; the resulting re-annihilation abundance is always larger than the standard freeze-out value. In addition, coherent-oscillation production of saxions $s$ at high PQ scale

\textsuperscript{1} In the RNS model, if gaugino mass $M_3$ is too large, it lifts the top squark masses high enough so that the radiative corrections $\Sigma_d^i(\tilde{t}_1, \tilde{t}_2)$ become large leading to fine-tuning. Since the gaugino masses $M_1$ and $M_2$ are related to $M_3$ under gaugino mass unification, then the lightest neutralino– while dominantly higgsino-like– always has a non-negligible gaugino component. In models with light higgsinos but with very large gaugino masses (such as Brömmel-Buchmüller model\textsuperscript{4}), the lightest neutralino is nearly pure higgsino. In that case, the spin-independent direct detection rates presented below will not obtain since the $h - \tilde{Z}_1\tilde{Z}_1$ coupling depends on a product of higgsino and gaugino components\textsuperscript{6}.


Figure 1: Plot of standard thermal neutralino abundance $\Omega_{\tilde{Z}_1}^\text{std} h^2$ versus $m(\text{higgsino})$ from a scan over NUHM2 parameter space with $\Delta_{EW} < 50$ (red crosses) and $\Delta_{EW} < 100$ (blue dots). Green points are excluded by current direct/indirect WIMP search experiments. We also show the central value of $\Omega_{\text{CDM}} h^2$ from WMAP9.

$f_a > 10^{12}$ GeV followed by saxion decays to SUSY particles can also augment the neutralino abundance. Late saxion decay to primarily SM particles can result in entropy dilution of all relics (including axions) present at the time of decay, so long as BBN and dark radiation constraints are respected. The upshot is that, depending on the additional PQ parameters, either higgsino-like neutralinos or axions can dominate the dark matter abundance, or they may co-exist with comparable abundances: this leads to the possibility of detecting both an axion and a WIMP.

In the case of mixed axion-WIMP dark matter, the local WIMP abundance might be well below the commonly accepted local abundance $\rho_{\text{loc}} \sim 0.3$ GeV/cm$^3$. Thus, to be conservative, limits from experiments like Xe-100 or CDMS should be compared to theoretical predictions which have been scaled down\cite{7} by a factor $\xi \equiv \Omega_{\text{TP}}^2 h^2/0.12$. In the RNS model, the gauginos cannot be too heavy so that the neutralino always has a substantial gaugino component even though it is primarily higgsino. This means that spin-independent direct detection rates $\sigma_{\text{SI}}(\tilde{Z}_1p)$ are never too small. Predictions for spin-independent higgsino-proton scattering cross section are shown in Fig. 2 and compared against current limits and future reach projections. Even accounting for the local scaling factor $\xi$, it is found\cite{5} that ton-scale noble liquid detectors such as Xe-1-ton\cite{6} should completely probe the model parameter space. One caveat is that if saxions give rise to huge entropy dilution after freeze-out while avoiding constraints from dark radiation and BBN, then the local abundance may be even lower than the assumed freeze-out value, and the dark matter would be highly axion dominated.

In Fig. 3, we show the rescaled spin-dependent higgsino-proton scattering cross section $\xi \sigma_{\text{SD}}(\tilde{Z}_1p)$. Here we show recent limits from the COUPP\cite{9} detector. Current limits are still about an order of magnitude away from reaching the predicted rates from RNS models. To compare against the current reach of IceCube\cite{10}, we show in Fig. 3 the value of $\sigma_{\text{SD}}(\tilde{Z}_1p)$ but with no rescaling factor. Here, the IceCube rates should not be rescaled since the IceCube detection depends on whether the Sun has equilibrated its core abundance between capture rate and annihilation rate\cite{11}. Typically for the Sun, equilibration is reached for almost all of SUSY parameter space\cite{12}. The IceCube limits have entered the RNS parameter space and excluded the largest values of $\sigma_{\text{SD}}(\tilde{Z}_1p)$.

In Fig. 4 we show the rescaled thermally-averaged neutralino annihilation cross section times relative velocity in the limit as $v \rightarrow 0$: $\xi^2 \langle \sigma v \rangle_{v \rightarrow 0}$. This quantity enters into the rate expected from WIMP halo annihilations into $\gamma$, $e^+$, $\bar{p}$ or $D$. The rescaling appears as $\xi^2$ since limits depend on the square of the local
Figure 2: Plot of rescaled higgsino-like WIMP spin-independent direct detection rate $\xi\sigma^{SI}(\tilde{Z}_1p)$ versus $m(higgsino)$ from a scan over NUHM2 parameter space with $\Delta_{EW} < 50$ (red crosses) and $\Delta_{EW} < 100$ (blue dots). Green points are excluded by current direct/indirect WIMP search experiments. We also show the current limit from Xe-100 experiment, and projected reaches of LUX, SuperCDMS 150 kg and Xe-1 ton.

Figure 3: In a), we plot the rescaled spin-dependent higgsino-like WIMP detection rate $\xi\sigma^{SD}(\tilde{Z}_1p)$ versus $m(higgsino)$ from a scan over NUHM2 parameter space with $\Delta_{EW} < 50$ (red crosses) and $\Delta_{EW} < 100$ (blue dots). Green points are excluded by current direct/indirect WIMP search experiments. The curve shows the current limit from the COUPP experiment, Ref. [9]. In b), we plot the (non-rescaled) spin-dependent higgsino-like WIMP detection rate $\sigma^{SD}(\tilde{Z}_1p)$. The curve shows the current limit from the IceCube experiment, Ref. [10].
Figure 4: Plot of rescaled $\xi^2 \langle \sigma v \rangle|_{v \to 0}$ versus $m(\text{higgsino})$ from a scan over NUHM2 parameter space with $\Delta_{EW} < 50$ (red crosses) and $\Delta_{EW} < 100$ (blue dots). Green points are excluded by current direct/indirect WIMP search experiments. The curve shows the current limit from Fermi LAT, Ref. [15].

WIMP abundance[13]. Anomalies in the positron and $\gamma$ spectra have been reported, although the former may be attributed to pulsars[14], while the latter 130 GeV gamma line may be instrumental. Soon to be released results from AMS-02 should clarify the situation[16]. On the plot, we show the limit derived from the Fermi LAT gamma ray observatory[15] for WIMP annihilations into $WW$. These limits have not yet reached the RNS parameter space due in part to the squared rescaling factor.

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