Supersymmetry and Dark Matter post LHC8: why we may expect both axion and WIMP detection

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Abstract

In the post-LHC8 era, it is perceived that what is left of SUSY model parameter space is highly finetuned in the EW sector (EWFT). We discuss how conventional measures overestimate EWFT in SUSY theory. Radiatively-driven natural SUSY (RNS) models maintain the SUSY GUT paradigm with low EWFT at 10% level, but are characterized by light higgsinos $\sim 100-300$ GeV and a thermal underabundance of WIMP dark matter. Implementing the SUSY DFSZ solution to the strong CP problem explains the small $\mu$ parameter but indicates dark matter should be comprised mainly of axions with a small admixture of higgsino-like WIMPs. While RNS might escape LHC14 searches, we would expect ultimately direct detection of both WIMPs and axions. An $e^+e^-$ collider with $\sqrt{s} \sim 500-600$ GeV should provide a thorough search for the predicted light higgsinos.

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1 Introduction

The recent discovery of the Higgs boson $h$ at LHC is a great triumph and seemingly completes
the Standard Model[1]. However, it brings with it a well-known conundrum in that scalar
particle masses are quadratically divergent: $m^2_{h|\text{phys}} = m^2_{h|\text{tree}} + \delta m^2_h$ where $\delta m^2_h \sim (c/16\pi^2)\Lambda^2$ and
where $\Lambda$ is the high energy cut-off below which the SM is assumed to be the valid effective field
theory. Requiring no large finetuning in $m^2_h$ then implies $\Lambda \lesssim 1$ TeV. If we wish to extend $\Lambda$ to
much higher scales, say those associated with Grand Unification, then a protective symmetry,
supersymmetry or SUSY, is needed. In SUSY extensions of the SM, then all quadratic diver-
genesis cancel, leaving only the more benign log divergences. SUSY receives indirect support
from experiment via 1. gauge coupling unification, 2. radiative breaking of EW symmetry via
the large top quark mass and 3. the fact that $m_h = 125.5 \pm 0.5$ GeV falls within the narrow
window predicted by SUSY theories such as the MSSM[2].

SUSY extensions of the SM also allow for several viable dark matter candidates while none
are contained within the SM. An essential requirement for SUSY DM is the existence of $R$-
parity conservation (RPC). RPC is motivated by the need for proton stability: if one allows
unfettered $R$-parity violation, then the proton would decay in a flash. On the theoretical side,
RPC is a consequence of $SO(10)$ gauge symmetry, which only allows $\text{matter} - \text{matter} - \text{Higgs}$
couplings whilst RPV requires $\text{matter} - \text{matter} - \text{matter}$ or $\text{matter} - \text{Higgs}$ couplings. Of
course, $SO(10)$ must ultimately be broken, but many breaking schemes allow for $R$-parity
conservation to survive the GUT symmetry breaking.

Most popular amongst the SUSY DM candidates is the lightest neutralino $\tilde{Z}_1$, a WIMP
particle. Other possibilities include the gravitino $\tilde{G}$, the axino $\tilde{a}$ in SUSY theories which include
the PQ solution to the strong $CP$ problem, and the right-hand sneutrino $\tilde{\nu}_R$. A left-sneutrino
LSP was long ago ruled out by direct WIMP search experiments.

2 Problems with SUSY dark matter

While the several SUSY DM candidates may seem like an embarrassment of riches, each of these
is not without problems. In the attractive SUSY see-saw mechanism for generating neutrino
masses, the right sneutrino is expected to be up around the GUT scale; one must abandon this
approach to accommodate $\tilde{\nu}_R$ as the LSP.

In the case of axino, the calculation of axino mass in gravity mediation finds typically
$m_{\tilde{a}} \sim m_{3/2}$ where $m_{3/2}$ is the gravitino mass and which sets the scale for SUSY breaking.
It is expected then that the axino should be among the heavier particles, especially in cases
where $m_{3/2} \lesssim 5$ TeV, which provides a solution to the cosmological gravitino problem (lighter
gravitinos can be produced at large rates in the early universe and if they are too light, but not
the LSP, then their late decays can disrupt the successful picture of Big BangNucleosynthesis
(BBN)[3]). Axinos also can be produced thermally in the early universe, and typically would
produce an overabundance of DM[4]. Axino masses $\sim keV - MeV$ size seem required for the
axino to be a viable DM candidate. The axino as a DM candidate might be more at home in
GMSB scenarios where the gravitino can also be quite light.

The gravitino could also be the DM. In this case, SUSY particles produced in the early
universe would suffer late decays to $\tilde{G}$, thus again facing formidable BBN constraints\cite{3}. If the $\tilde{G}$ is very light, as in GMSB models, then enhanced decays via its Goldstino component can accelerate decay rates thus avoiding BBN problems. But the simplest GMSB models seem highly stressed if not ruled out by a combination of Higgs mass and naturalness constraints\cite{5}.

The lightest neutralino $\tilde{Z}_1$, as remarked above, is perhaps the most popular SUSY DM candidate. However, it also is problematic. First, in spite of much hype about a WIMP miracle, calculations of $\Omega_{\tilde{Z}_1}h^2$ in the simple thermal WIMP production scenario imply typically a large overproduction of DM (typically by several orders of magnitude) in the case where $\tilde{Z}_1$ is bino-like, and underproduction (typically by 1-2 orders of magnitude) in the case of a higgsino- or wino-like LSP: see Fig. 1. To match the measured abundance of CDM, either a fine adjustment of relative higgsino-bino-wino components is required\cite{6}, or else special annihilation mechanisms– via resonance annihilation or co-annihilation– are needed. Thus, rather contrived scenarios are required to bring the predicted abundance of neutralino dark matter into accord with measurements.

A second problem– often ignored by SUSY DM practitioners– is the strong $CP$ problem. The PQWW axion solution still seems the most compelling way to address this\cite{16}. But then the axion is also a viable DM candidate. If the $a$ exists, then the dark matter calculus undergoes a radical change.

A final challenge to SUSY DM is that recent negative LHC sparticle search results, along with the rather large value of $m_h$, has led many to speculate that the simple MSSM effective theory is finetuned in the EW sector: then it may not be the whole picture and perhaps radical new SUSY model building ideas are needed\cite{8}. This latter viewpoint is mainly fueled by the
perception that large logarithms of the form\[9\]
\[
\delta m_h^2 \sim -(3f_t^2/8\pi^2)(m_{Q_3}^2 + m_{U_3}^2 + A_t^2)\ln(\Lambda^2/m_{SUSY}^2)
\] (1)
lead to large finetuning in \(m_h^2\), in a similar vein as do the quadratic divergences for the SM Higgs squared mass.

3 An improved picture of SUSY dark matter: mixture of axions and higgsinos

3.1 Radiatively-driven natural SUSY

The log term in Eq. 1 taken at face value seems to imply that for better than 10% EWFT and \(\Lambda\) as high as \(m_{GUT}\) – SUSY naturalness requires top squarks lighter than 200 GeV and consequently gluinos less than about 600 GeV, almost certainly in violation of LHC search constraints. However, as emphasized in Ref. [10], the term in Eq. 1 is only one piece of various \textit{non-independent} terms contributing to \(m_h^2\). For instance, while \(m_h^2|\text{tree}\) and \(\delta m_h^2\) are independent in the SM, in the MSSM the \(m^2_{H_u}(\Lambda)\) and \(\delta m^2_{H_u}\) are \textit{dependent}: the larger one makes \(m^2_{H_u}(\Lambda)\), the larger becomes \(\delta m^2_{H_u}\). This suggests that one ought to collect \(m^2_{H_u}(\Lambda) + \delta m^2_{H_u}\) into a single term, as is done with the Barbieri-Giudice[11] measure \(\Delta_{BG}\) and the electroweak measure \(\Delta_{EW}\)[12, 13].

While the measure \(\Delta_{BG}\) avoids the pitfall of Eq. 1 by re-writing the combination \((m^2_{H_u}(\Lambda) + \delta m^2_{H_u})\) in terms of fundamental input parameters, it is itself highly model-dependent since by definition it measures fractional change in \(m_Z^2\) against fractional change in model parameters. This means \(\Delta_{BG}\) changes from model to model, even if each model generates exactly the same weak scale spectrum. As an example, in the focus point region of mSUGRA, where \(m^2_{H_u} \equiv m^2_{H_d} \equiv m^2_{A_1}(3)\), then large cancellations due to correlated high scale soft terms yield much lower finetuning than is expected in more general models. In an ultimate theory (UTH) where parameters \(A_0, m_{1/2}\) and \(m_0\) are also expected to be correlated, then even greater reductions in \(\Delta_{BG}\) can occur. The lesson here is that the popular effective theories which we use, where the high scale soft term values parametrize our ignorance of SUSY breaking, will often yield much more finetuning than in more correlated models with fewer free parameters. What we are really interested in is whether-or-not \textit{nature} is EW-finetuned (and by implication the UTH which describes it), and \textit{not} how finetuned are the more general effective theories which might contain the UTH[10].

A model-independent measure is given by \(\Delta_{EW}[12]\), which measures \textit{weak scale} SUSY contributions to \(m_Z^2\). The \(\Delta_{EW}\) parameter has been interpreted as a bound on finetuning, and as a necessary– albeit not sufficient– condition for low EWFT[14]. Models with low \(\Delta_{EW}\) are characterized by

- low \(|\mu| \sim 100 – 300\) GeV,

- \(m^2_{H_u}\) is driven radiatively to just small negative values \(\sim -m^2_Z\), and
• top squarks are still bounded, but now in the few TeV-regime. They are also highly mixed. The large mixing reduces the radiative corrections to $m_Z^2$ whilst lifting $m_h$ into the 125 GeV regime.

Such low $\Delta_{EW}$ models are referred to as radiatively-driven natural SUSY, or RNS, since $m_{H_u}$ is radiatively driven to just small negative values, thus allowing for EW naturalness. The popular mSUGRA/CMSSM model admits a minimum value of $\Delta_{EW} \sim 200$ so is surely finetuned. However, the NUHM2 model allows for small $\mu$ but also relatively light TeV-scale stops: in this case, $\Delta_{EW}$ values as low as $\sim 7$ can be found.

In such low $\Delta_{EW} < \sim 10$ models, the lightest SUSY particle is typically the higgsino-like $\tilde Z_1$, albeit with a not-too-small gaugino component. The thermal relic density of such higgsinos is $\Omega_{\tilde Z_1} h^2 \sim 0.005 - 0.01$, i.e. a factor 10-15 below measured values.

### 3.2 Strong $CP$ problem

Another possibility for finetuning occurs in the QCD sector. To implement ’t Hooft’s solution to the $U(1)_A$ problem (i.e. why there are three and not four light pions), the term

$$\frac{\tilde\theta}{32\pi^2} F_{\mu\nu} \tilde F_{\mu\nu}$$

should occur in the QCD Lagrangian, where $\tilde\theta = \theta + \arg(\det M)$, $M$ is the quark mass matrix, $F_{\mu\nu}$ is the gluon field strength and $\tilde F_{\mu\nu}$ is its dual. Measurements of the neutron electric dipole moment (EDM) require $\tilde\theta < \sim 10^{-10}$ so that one might require an enormous cancellation within $\tilde\theta$ [15]. Alternatively, the PQWW solution [16] introduces an axion field $\alpha$; the additional axion contributions allow for the coefficient in Eq. 2 to dynamically settle to zero, thus solving the so-called strong $CP$ problem.

In SUSY theories, the axion enters as but one element of an axion superfield which necessarily contains also a spin-0 $R$-parity even saxion $s$ and a spin-1/2 $R$-parity-odd axino $\tilde a$. Calculations of the saxion and axino masses within the context of supergravity [17] imply $m_s \sim m_\tilde a \sim m_{3/2}$ where the gravitino mass $m_{3/2}$ is expected to be of order the TeV scale. If the lightest neutralino (e.g. the higgsino $\tilde Z_1$) is the lightest SUSY particle (LSP) in $R$-parity conserving theories, then one would expect dark matter to be comprised of two particles: the axion as well as the higgsino-like SUSY WIMP. The saxion and axino couplings to matter are suppressed by the PQ breaking scale $f_\alpha$ which may range from $f_\alpha \sim 10^9 - 10^{16}$ GeV [15]. While the saxion and axino are expected to play little or no role in terrestrial experiments, they can have an enormous impact on dark matter production in the early universe.

### 3.3 SUSY DFSZ model and Kim-Nilles solution to the $\mu$ problem

The PQ symmetry required to solve the strong $CP$ problem can be implemented in two ways. In the SUSY KSVZ model [18, 19], the axion superfield couples to exotic heavy quark/squark superfields $Q$ and $\bar Q$ which carry PQ charges. Alternatively to SUSY KSVZ, in the SUSY DFSZ
model \[20, 21, 22, 23\] the PQ superfield couples directly to the Higgs superfields carrying non-trivial PQ charges:

$$W_{\text{DFSZ}} \ni \lambda S^2 H_u H_d.$$  \hspace{3cm} (3)

Here, \(S\) is a Minimal Supersymmetric Standard Model (MSSM) singlet but carries a PQ charge and contains the axion field. An advantage of this approach is that it provides a solution to the \(\mu\) problem [21]: since the \(\mu\) term is supersymmetric, one expects \(\mu \sim M_P\) in contrast to phenomenology which requires \(\mu \sim m_{\text{weak}}\). In this Kim-Nilles solution, PQ charge assignments forbid the usual superpotential \(\mu\) term. Upon breaking of PQ symmetry, the field \(S\) receives a vev \(\langle S \rangle \sim f_a\), so that an effective \(\mu\) term is generated with \(\mu \sim \lambda f_a^2 / M_P \sim \lambda m_{3/2}^2\). For small \(\lambda\) one may generate \(\mu \sim 100 - 200\) GeV in accord with naturalness whilst \(m_{\tilde{q}} \sim m_{3/2} \sim 10\) TeV in accord with LHC constraints and in accord with at least a partial decoupling solution to the SUSY flavor, \(C\) and \(P\) and gravitino problems [24].

### 3.4 Axino and saxion production/decay in SUSY DFSZ

In the SUSY KSVZ model, the derivative coupling of axions to matter leads to thermal production rates for axinos and saxions which are proportional to the re-heat temperature \(T_R\) after inflation. In contrast, in SUSY DFSZ the direct coupling of axion superfield to higgs superfields leads to production rates independent of \(T_R\). In addition, as usual, saxions can be produced via coherent saxion field oscillations which are important for large saxion field strength \(s\) which is assumed comparable to \(f_a\). Also, axions are produced as usual via coherent oscillations/vacuum mis-alignment around the QCD phase transition.

Once produced, then axinos decay (in SUSY DFSZ) into mainly higgsino plus Higgs or higgsino plus gauge boson states. The decays are quicker in SUSY DFSZ than in SUSY KSVZ, and for \(f_a \lesssim 10^{12}\) GeV, they occur before neutralino freeze-out. Likewise, saxions decay dominantly to higgsino pairs (leading to additional WIMP production) or to axion pairs when the \(\xi\) parameter \(\sim 1\) (leading to dark radiation)\[25\]. For \(f_a \lesssim 10^{12}\) GeV, they tend to decay before WIMP freeze-out, so the simple thermal WIMP production rate should remain valid. The dark radiation from saxion decay is slight for \(f_a \lesssim 10^{14}\) GeV.

### 3.5 Axion and higgsino relic density

Let us now examine the contributions of neutralinos and axions to the observed dark matter density expected in the SUSY DFSZ model. Our result is shown in Fig.\[2\] assuming \(m_{\tilde{a}} = m_s = 5\) TeV[26]. Starting at \(f_a = 10^9\) GeV as required by astrophysical constraints, the neutralino abundance \(\Omega_{\tilde{Z}_1} h^2 \approx 0.01\) is given by the standard thermal freeze-out over a large range of \(f_a\) extending all the way up to \(f_a \sim 10^{12}\) GeV. In this regime, the axion abundance can always be found by adjusting \(\theta_i\) such that the summed abundance meets the measured value:

$$\Omega_{\tilde{Z}_i} h^2 + \Omega_{\tilde{a}} h^2 = 0.12.$$  \hspace{3cm} \text{12.}

The required value of \(\theta_i\) is shown in Fig.\[6\]. For very low \(f_a \sim 10^9\) GeV, a large value of \(\theta_i \sim \pi\) is required, and \(\Omega_{\tilde{a}} h^2\) is dominated by the anharmonicity term. As \(f_a\) increases, the assumed initial axion field value \(\theta_i f_a\) increases, so the required misalignment

\[\xi = \sum_i q_i^2 v_i^2 / f_a^2.\]  \hspace{3cm} \text{Later, } \xi = \Omega_{\tilde{a}} h^2 / 0.12.
angle $\theta_i$ decreases. Values of $\theta_i \sim 1$ are found around $f_a \sim 2 \times 10^{11}$ GeV for both $\xi = 0$ and $1$. In this entire region with $f_a \sim 10^9 - 10^{12}$ GeV, we expect from natural SUSY that the relic higgsino abundance lies at the standard freezeout value, comprising about 5-10% of the total dark matter density, while axions would comprise 90-95% of the abundance. Thus, over the commonly considered range of $f_a$, we expect mainly axion cold dark matter from natural SUSY, along with a non-negligible fraction of higgsino-like WIMPs.

### 3.6 Detection of axions and higgsinos

In Fig. 4 we show the spin-independent higgsino-proton scattering rate in $pb$ as calculated using IsaReS\cite{27}. The result is rescaled by a factor $\xi = \Omega_{\tilde{Z}_1}^{sd}h^2/0.11$ to account for the fact that the local relic abundance might be far less than the usually assumed value $\rho_{local} \simeq 0.3$ GeV/cm$^3$, as suggested long ago by Bottino et al.\cite{28} (the remainder would be composed of axions). The higgsino-like WIMP in our case scatters from quarks and gluons mainly via $h$ exchange. The $\tilde{Z}_1 - \tilde{Z}_1 - h$ coupling involves a product of both higgsino and gaugino components. In the case of RNS models, the $\tilde{Z}_1$ is mainly higgsino-like, but since $m_{1/2}$ is bounded from above by naturalness, the $\tilde{Z}_1$ contains enough gaugino component that the coupling is never small: in the notation of Ref. \cite{29}

$$\mathcal{L} \ni -X_{11}^h \overline{\tilde{Z}_1} \tilde{Z}_1 h$$

(4)

where

$$X_{11}^h = -\frac{1}{2} \left( v_2^{(1)} \sin \alpha - v_1^{(1)} \cos \alpha \right) \left( g v_3^{(1)} - g' v_4^{(1)} \right),$$

(5)

and where $v_1^{(1)}$ and $v_2^{(1)}$ are the higgsino components and $v_3^{(1)}$ and $v_4^{(1)}$ are the gaugino components of the lightest neutralino, $\alpha$ is the Higgs mixing angle and $g$ and $g'$ are $SU(2)_L$ and $U(1)_Y$ gauge couplings. Thus, for SUSY models with low $\Delta_{EW} \lesssim 50 - 100$, the SI direct detection cross section is also bounded from below, even including the rescaling factor $\xi$. 

![Figure 2: Neutralino and axion relic abundance from the SUSY DFSZ axion model versus PW scale $f_a$ for the SUA benchmark point.](image)
Figure 3: Axion field misalignment angle vs. $f_a$ which is required to saturate mixed axion-neutralino abundance for $\xi = 0$ (dashed) and $\xi = 1$ (solid).

From the Figure, we see that the current reach from 225 live-days of Xe-100 running already bites into a significant spread of parameter points. The excluded points are colored green. The projected reach of the LUX 300 kg detector is also shown by the black-dashed contour, which should explore roughly half the allowed RNS points. The reach of SuperCDMS 150 kg detector is shown as the purple-dashed contour. The projected reach of Xe-1-ton, a ton scale liquid Xenon detector, is also shown. A major result is this: the projected Xe-1-ton detector–or other comparable WIMP direct-detectors–can make a complete exploration of the RNS parameter space. Since deployment of the Xe-1-ton detector is imminent, it seems direct WIMP search experiments may either verify or exclude RNS models in the near future, thus bringing the story of electroweak naturalness to a conclusion!

In Fig. 5, we show the rescaled thermally-averaged neutralino annihilation cross section times relative velocity in the limit as $v \to 0$: $\xi^2 \langle \sigma v \rangle|_{v \to 0}$. This quantity enters into the rate expected from WIMP halo annihilations into $\gamma$, $e^+$, $\bar{p}$ or $\bar{d}$. The rescaling appears as $\xi^2$ since limits depend on the square of the local WIMP abundance. Anomalies in the positron and $\gamma$ spectra have been reported, although the former may be attributed to pulsars, while the latter 130 GeV gamma line may be instrumental. On the plot, we show the limit derived from the Fermi LAT gamma ray observatory for WIMP annihilations into $WW$. These limits have not yet reached the RNS parameter space due in part to the squared rescaling factor.

4 Conclusions

Supersymmetry with not too heavy top squarks, low higgsino mass $\mu \sim 100 - 200$ GeV and PQWW solution to the strong CP problem successfully avoids high finetuning in both the EW and QCD sectors of the theory while evading LHC constraints. The SUSY DFSZ model, wherein Higgs superfields carry PQ charge, also provides a solution to the SUSY $\mu$ problem. In such models, over a large range of PQ breaking scale $f_a \sim 10^9 - 10^{12}$ GeV, saxions and
Figure 4: 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 reach from Xe-100 experiment, and projected reaches of LUX, SuperCDMS 150 kg and Xe-1 ton.

Figure 5: Plot of rescaled $\xi^2 \langle \sigma v \rangle|_{v \rightarrow 0}$ 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 current reach from Fermi LAT, Ref. [36].
axinos typically decay before neutralino freeze-out so that the higgsino portion of dark matter is expected to lie in the 5-10% range while axions would comprise the remainder: 90-95%. The relic higgsinos ought to be detectable at ton scale noble liquid detectors, even with a depleted local abundance, while indirect detection should be more limited since expected rates go as the depleted abundance squared [37]. Prospects are bright for microwave cavity detection of axions since the range of $f_a$ where mainly axion dark matter is expected should be accessible to experimental searches [38]. While corroborative searches for natural SUSY with light higgsinos is limited at the LHC [39], a definitive higgsino search should be possible at $e^+e^-$ colliders with $\sqrt{s}$ up to 500 – 600 GeV.

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