Prospects for Beyond the Standard Model Physics at the Start of the LHC13 era

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The discovery of the Higgs boson along with the vigorous confirmation of the SM coupled with non-appearance of new (SUSY) particles has led to an apparent naturalness crisis. We argue the crisis stems from overestimates of finetuning. A proper evaluation of naturalness in SUSY leads to light higgsinos with mass $\mu \sim 100-300$ GeV while other sparticles may inhabit the multi-TeV range at little cost to naturalness. Special signatures like dilepton mass edges in gluino pair events and same-sign dibosons from wino pairs might occur at LHC13. An ILC with $\sqrt{s} > 2\mu$ would make the definitive test of naturalness in the MSSM. Naturalness in the QCD sector requires the axion leading to mixed axion-WIMP dark matter. Ultimately we expect detection of a higgsino-like WIMP at ton-scale DM detectors and detection of a DFSZ-type axion at ADMX.

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1. Introduction

The LHC8 era (LHC running with $\sqrt{s} = 8$ TeV) has been a grand success.[1] Aside from a few (to be expected) minor anomalies, the Standard Model (SM) has been vigorously confirmed in both the electroweak and QCD sectors. In particular, a very SM-like Higgs boson has been discovered with mass $m_h = 125.09 \pm 0.24$ GeV with spin-parity given by $J^P = 0^+$ and with very SM-like production cross sections and couplings to its various decay products.[2, 3] The LHC13 era has begun with at present nearly an fb^{-1} of integrated luminosity being recorded.

While the agreement of SM theory with data is generally excellent, several long-standing puzzles yet remain that seem to require the existence of new physics. These include:

- Why do neutrinos oscillate? Why are their masses so light, well below the eV scale?[4]

- Why is the higgs so light? Due to quadratic divergences, one expects its mass to blow up to the largest mass scale in the theory. This usually means far beyond weak scale values.[5]

- Why is there no *CP* violation in the QCD sector?[6] Such *CP* violation is to be expected from 'tHooft's solution to the $U(1)_A$ problem via instantons and the θ-vacuum. Yet none is seen where it is to be expected: in the neutron EDM.

- What forms the dark matter which is pervasive throughout the universe?[7]

- How did the baryon asymmetry come to be?[8]

The first of these problems is elegantly solved by the (type-I) see-saw mechanism.[9] In this case, one introduces heavy gauge singlet right hand neutrino states ν_R into the theory with couplings

$$\mathscr{L} \ni -\lambda_\nu \bar{L}_a \cdot \tilde{\phi}^a \nu_R + h.c. \tag{1.1}$$

where λ_ν is the neutrino Yukawa coupling and L_a is the lepton doublet with $SU(2)$ index a and $\tilde{\phi} = \varepsilon^{ab}\phi_b^\dagger$ where ϕ_b is the Higgs doublet and where generation indices are suppressed. When $\phi_b = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$ in the unitary gauge then we develop Dirac masses $m_D = \lambda_\nu v/\sqrt{2}$ for the neutrinos. Using the conjugation property $\psi^c \equiv C\bar{\psi}^T$ we can create *Majorana* neutrino spinors $\nu \equiv \nu_L + \nu_L^c$ and $N = \nu_R + \nu_R^c$ with mass matrix

$$\mathscr{M}_\nu \equiv \begin{bmatrix} 0 & m_D \\ m_D & M \end{bmatrix} \tag{1.2}$$

which has eigenvalues $\sim m_D^2/M$ and $\sim M$. For $\lambda_\nu \simeq \lambda_t$ (as expected in various GUT theories) then one obtains $m_{\nu 3} \sim 0.05$ eV for $M \sim 10^{15}$ GeV. This is the famous seesaw mechanism which at once explains why the left-neutrino masses are so tiny and why the right neutrinos have not been observed. It fits exceedingly well with GUT theories especially $SO(10)$ where the ν_R occupies the final element of the 16-dimensional spinor irrep which contains all matter states of a single generation. While there exist other possibilities for neutrino masses (just Dirac masses, type-II and type-III see-saw, $\cdots$) the simplicity and elegance of the type-I see-saw makes it hard to believe that this is not the way nature works.

2. The Higgs mass, naturalness and supersymmetry

A problem now occurs. Even if one forfeits obeisance to the story of runaway quadratic divergences to the Higgs mass– for instance by adopting dimensional regularization in the SM so that quadratic scalar divergences are never revealed– they nonetheless re-appear once the neutrino see-saw is invoked. In this case, the Higgs couples to the neutrino sector via the neutrino Yukawa coupling leading to mass corrections $m_h^2 \sim (\lambda_\nu M)^2/16\pi^2$ which necessitates a fine-tuning of order m_h^2/M^2 (one part in 10^{26}) to maintain the measured value of m_h.[10] The Higgs mass wants to blow up to the largest mass scale in the theory. The well-established way to tame it is by invoking *supersymmetry*.[11] In this case, the quadratic divergences necessarily cancel at all orders in perturbation theory. The price to pay for phenomenological viability is the seeming necessity of superpartners at or around the weak scale (weak scale supersymmetry).[12]

It has long been the lore that weak scale SUSY requires superpartners to exist nearby to the weak scale as typified by $m_{W,Z,h} \sim 100$ GeV.[13, 14, 15] However, the failure of new physics to appear at LHC8 has raised questions as to the nature of and existence of weak scale SUSY.[16] This is further exacerbated by the rather large value of the Higgs mass $m_h \simeq 125$ GeV which requires TeV-scale highly mixed top squarks in apparent contradiction to expectations from naturalness.[17] The situation has called into question whether naturalness is indeed a guide to new physics, and whether to abandon SUSY and search for new means to implement naturalness.[18, 25, 5] A whole new program of "neutral naturalness" has emerged which seeks to cancel offending divergences by appealing to hidden sector states which are neutral under the SM charges[19]. Indeed, some authors go so far as to proclaim a *crisis* for physics[20].

Before jumping ship prematurely, it pays to scrutinize more quantitatively the notion of naturalness for weak scale SUSY (WSS). After all, experiment has had three chances to disprove WSS and each time SUSY has met the challenge. As a reminder, 1. precision measurement of gauge couplings at LEP are in accord with SUSY gauge coupling unification,[21] 2. the measured value of the top quark mass was found to be in accord with that required by SUSY for successful radiatively-driven electroweak symmetry breaking[22] and 3. the measured value of m_h falls squarely within the range required by SUSY where $m_h \stackrel{<}{\sim} 135$ GeV is required in the MSSM[23].

2.1 Electroweak naturalness

While SUSY provides a solution to the big hierarchy problem via cancellation of quadratic divergences, the increasingly severe sparticle mass bounds have accentuated a growing Little Hierarchy: why are $m_{W,Z,h} \ll m_{sparticle}$ when $m_{sparticle}$ helps determine m_{weak}? The most direct connection comes from the MSSM scalar potential minimization conditions where it is found that

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 \qquad (2.1)$$

$$\simeq -m_{H_u}^2 - \mu^2 - \Sigma_u^u \qquad (2.2)$$

where $m_{H_u}^2$ and $m_{H_d}^2$ are the *weak scale* soft SUSY breaking Higgs masses, μ is the *supersymmetric* higgsino mass term and Σ_u^u and Σ_d^d contain an assortment of loop corrections to the effective potential. From this equation, naturalness is ensured if each term on the right-hand-side is comparable to $m_Z^2/2$. A naturalness measure Δ_{EW} has been introduced which compares the largest contribution

on the right-hand-side of Eq. 2.2 to the value of $m_Z^2/2$. If they are comparable ($\Delta_{EW} \stackrel{<}{\sim} 10 - 30$), then no unnatural fine-tunings are required to generate $m_Z = 91.2$ GeV. The main requirement is then that $|\mu| \sim m_Z$[24, 25, 26] (with $\mu \stackrel{>}{\sim} 100$ GeV to accommodate LEP2 limits from chargino pair production searches) and also that $m_{H_u}^2$ is driven radiatively to small, and not large, negative values [27, 28].[1] Also, the top squark contributions to the radiative corrections $\Sigma_u^u(\tilde{t}_{1,2})$ are minimized for TeV-scale highly mixed top squarks[27]. This latter condition also lifts the Higgs mass to $m_h \sim 125$ GeV. The measure Δ_{EW} is pre-programmed in the Isasugra SUSY spectrum generator[32].

2.2 Large logs

In contrast to the above, one often instead hears that the log corrections to m_h^2 are too large in SUSY:

$$\delta m_h^2 \sim -\frac{3f_t^2}{16\pi^2}m_{\tilde{t}}^2 \log\left(\Lambda^2/m_{\tilde{t}}^2\right). \qquad (2.3)$$

Taking Λ as high as $m_{GUT} \sim 2 \times 10^{16}$ GeV and $m_{\tilde{t}} \sim 5 - 10$ TeV, then indeed one expects $\sim 0.1 - 1\%$ fine-tuning.

We feel this approach is too simplistic and leads to overestimates in EW finetuning for SUSY.[33] To avoid overestimates, we have stated the fine-tuning rule:[34]

> When evaluating fine-tuning, it is not permissible to claim fine-tuning of *dependent* quantities one against another.

In the above large log case, the Higgs mass is given by

$$m_h^2 \simeq \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 \qquad (2.4)$$

where the logs enter $\delta m_{H_u}^2$ properly via the RGE

$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right) \qquad (2.5)$$

where $t = \ln(Q^2/Q_0^2)$, $S = m_{H_u}^2 - m_{H_d}^2 + Tr\left[\mathbf{m}_Q^2 - \mathbf{m}_L^2 - 2\mathbf{m}_U^2 + \mathbf{m}_D^2 + \mathbf{m}_E^2\right]$ and $X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2$. The above large log can be found by neglecting gauge terms and S ($S = 0$ in models with scalar soft term universality but can be large in models with non-universality), and also neglecting the $m_{H_u}^2$ contribution to X_t and the fact that f_t and the soft terms evolve under Q^2 variation. Especially egregious is the neglect of $m_{H_u}^2$. The more one increases $m_{H_u}^2(\Lambda)$, then the greater is the cancelling correction $\delta m_{H_u}^2$. (This is different from the SM case where the leading divergences and the tree level Higgs mass are independent.) By collecting dependent contributions, instead one requires each of the two terms on the RHS of

$$m_h^2 \simeq \mu^2 + \left(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2\right) \qquad (2.6)$$

to be comparable to m_h^2. This then is the same requirement as for low Δ_{EW} since $m_{H_u}^2(weak) = m_{H_u}^2(\Lambda) + \delta m_{H_u}^2$.

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[1]Some recent work on theories with naturalness and heavy higgsinos include [29, 30, 31]. Such theories tend to introduce unwanted exotica such as adjoint scalars.

2.3 BG fine-tuning

Traditionally, naturalness is quantified via the EENZ/BG measure[35, 13]

$$\Delta_{BG} \equiv max_i \left| \frac{\partial m_Z^2}{\partial p_i} \right| \qquad (2.7)$$

where p_i are the fundamental parameters of the theory. Using p_i as the weak scale values μ^2, $m_{H_u}^2$ etc. as in the pMSSM, then $\Delta_{BG} \sim \Delta_{EW}$. But if we evaluate μ^2 and $m_{H_u}^2$ in terms of GUT scale parameters as in gravity-mediation, then instead we have (for the case of $\tan\beta = 10$) [36, 37, 38]

$$m_Z^2 \simeq -2.18\mu^2 + 3.84M_3^2 - 0.65M_3A_t - 1.27m_{H_u}^2 - 0.053m_{H_d}^2 + 0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + \cdots. \quad (2.8)$$

With $M_3 \simeq m_{\tilde{g}}$ and $m_{\tilde{g}} \stackrel{>}{\sim} 1300$ GeV from LHC8 searches, we again find WSS to be highly tuned with $\Delta_{BG} \sim 800$.

However, in supergravity theory it is something of a theorem that for any particular hidden sector the high-scale soft terms are all calculable as multiples of the gravitino mass $m_{3/2}$[39]. If we vary $m_{3/2}$, the soft terms all vary accordingly: *i.e.* they are *not independent* in SUGRA models. The soft terms are only independent in the effective theories where soft terms are introduced to parameterize our ignorance of the SUSY breaking sector. By combining the dependent soft SUSY breaking terms, then the Z mass can be expressed as[34]

$$m_Z^2 \simeq -2\mu^2(\Lambda) - am_{3/2}^2, \qquad (2.9)$$

with a being a certain proportionality factor dependent on each soft mass spectrum. Using Eq. 2.9– and since μ hardly evolves from Λ to m_{weak}– we have $am_{3/2}^2 \simeq 2m_{H_u}^2(\text{weak})$. Even if $m_{3/2}$ is large (as implied by LHC8 limits for gravity-mediation), then one may still generate natural models if the coefficient a is small. Under the combination of dependent soft SUSY breaking terms, then low Δ_{BG} implies the same as low Δ_{EW}: that $\mu \sim m_{\text{weak}}$ and that $m_{H_u}^2$ is driven to small and not large negative values.

3. Where is SUSY?

By properly evaluating naturalness, we find that μ^2 and $m_{H_u}^2$ are $\sim m_{weak}$ while the sparticles can be much heavier, of order $m_{3/2}$. The Little Hierarchy $\mu \ll m_{3/2}$ is totally acceptable. When we say SUSY particles should be $\sim m_{weak}$, it is really only the higgsinos $\widetilde{W}_1^{\pm}, \widetilde{Z}_{1,2}$ which are required to have mass $\sim \mu \sim m_{weak}$. Since the higgsinos are rather compressed– detailed evaluations show that the interhiggsino mass gap is typically 10-30 GeV[28]– then the heavier higgsino decay products are quite soft and buried beneath a huge background of soft QCD events at LHC. The lightest higgsino is the LSP and escapes detection. A typical sparticle mass spectrum with radiatively-driven naturalness is shown in Fig. 1.

The measure Δ_{EW} can be used to rule out models based on whether or not they are natural (since unnatural models are almost assuredly wrong models). A sampling of 16 models is shown in Fig. 2 taken from Ref. [34]. Requiring $\Delta_{EW} \stackrel{<}{\sim} 30$ and $m_h : 123 - 127$ GeV rules out all models (including the highly popular mSUGRA/CMSSM model) except for one region of parameter space
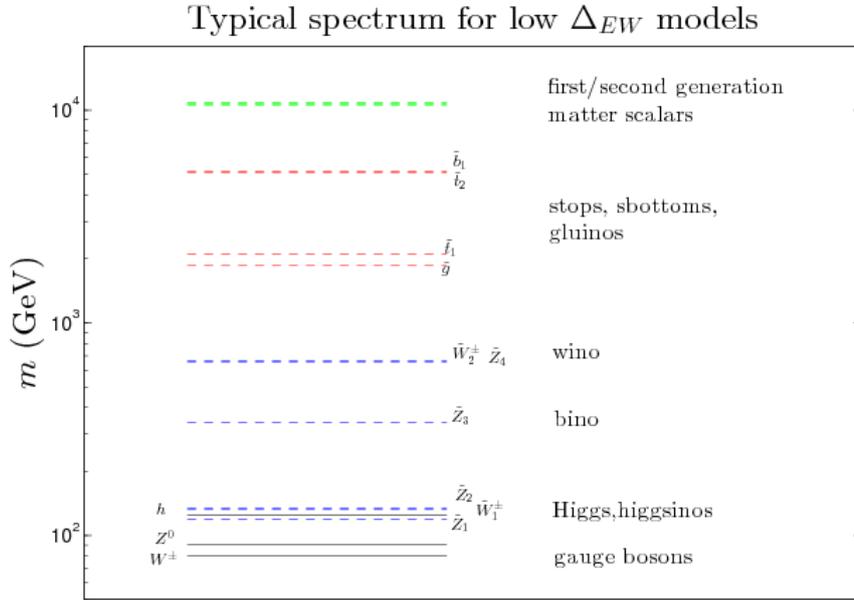
Figure 1: Typical sparticle mass spectrum from SUSY models with low Δ_{EW}, *i.e.* radiatively-driven naturalness.
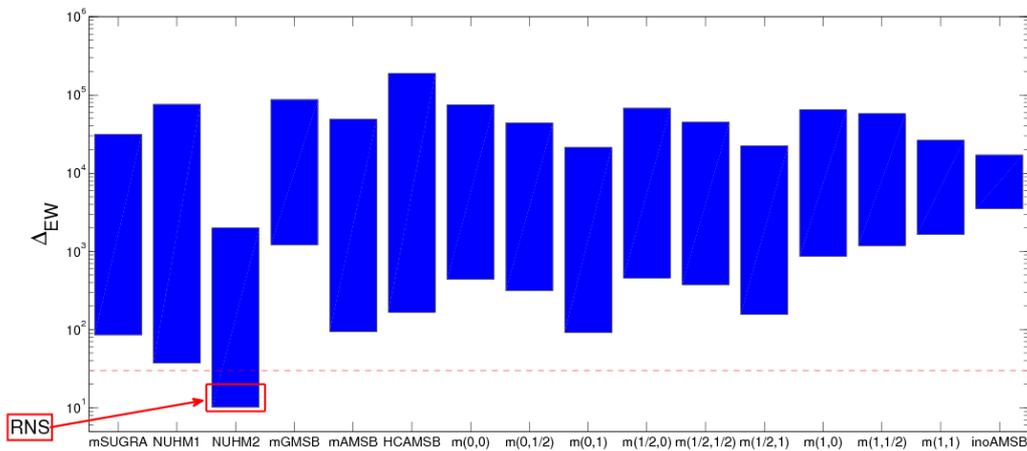

Figure 2: Plot of Δ_{EW} from a scan over parameter space for 16 different SUSY models. Naturalness requires $\Delta_{EW} \overset{<}{\sim} 30$. Only the RNS portion of the NUHM2 model survives.

of the two-extra-parameter non-universal Higgs model (NUHM2) where radiatively-driven natural SUSY (RNS) occurs.

Upper bounds on sparticle masses versus $\Delta_{EW} \simeq \Delta_{BG}$ are evaluated in Ref's [28, 40]. For $\Delta_{EW} \stackrel{<}{\sim} 10$, then $m_{\tilde{g}} \stackrel{<}{\sim} 2$ TeV (within LHC13 range at high luminosity), $\mu < 200$ GeV (within range of ILC500) and $m_{\tilde{t}_1} \stackrel{<}{\sim} 1.5$ TeV (perhaps beyond LHC13 reach). For $\Delta_{EW} \stackrel{<}{\sim} 30$ which we regard as a conservative upper limit, then $m_{\tilde{g}} \stackrel{<}{\sim} 4$ TeV, $\mu \stackrel{<}{\sim} 350$ GeV and $m_{\tilde{t}_1} \stackrel{<}{\sim} 3$ TeV.

4. Radiatively-driven natural SUSY at colliders

Thus, LHC13 with $300 - 1000$ fb^{-1} of integrated luminosity will explore up to $\Delta_{EW} \sim 10$ via gluino pair production. These events, if seen, should be characteristic[41, 42]: rich in b- and top-jets while the gluino cascade decays should include a characteristic dilepton mass edge $m(\ell^+\ell^-) < m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \sim 10 - 30$ GeV: see Fig. 3.
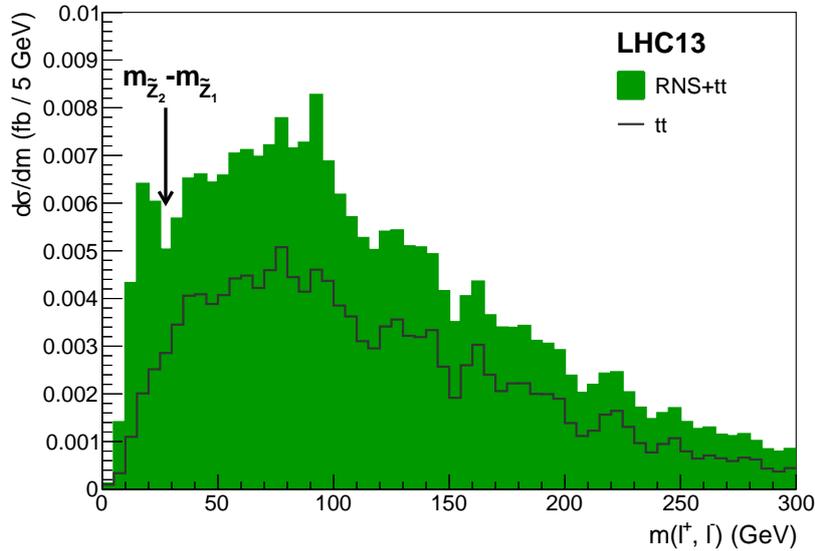

Figure 3: Invariant mass of OSSF leptons. The dilepton mass edge and the Z peak are visible for the RNS model. We require $n(b\text{-}jets) \geq 3$.

In addition, a qualitatively new SUSY signal emerges. For natural SUSY spectra, then wino pair production in the form $pp \to \widetilde{W}_2^{\pm}\widetilde{Z}_4$ production is the dominant visible cross section. The winos decay as $\widetilde{W}_2 \to W\widetilde{Z}_1$ and $\widetilde{Z}_4 \to W^{\pm}\widetilde{W}_1^{\mp}$. Thus, half the wino pair production events contain same-sign diboson pairs which are distinct from usual SS dilepton events in that they should be relatively jet-free. SM backgrounds to the SSdB signature are tiny. The reach via SSdB signal exceeds that from $\tilde{g}\tilde{g}$ production for higher integrated luminosity values[43, 41].

The really neat signature of natural SUSY is higgsino pair production at ILC. In this case, SUSY can be easily discovered and precision measurements verifying the higgsino nature and testing gaugino mass unification can be made. The ILC will be a higgsino factory in addition to a Higgs factory[44]: see Fig. 5.

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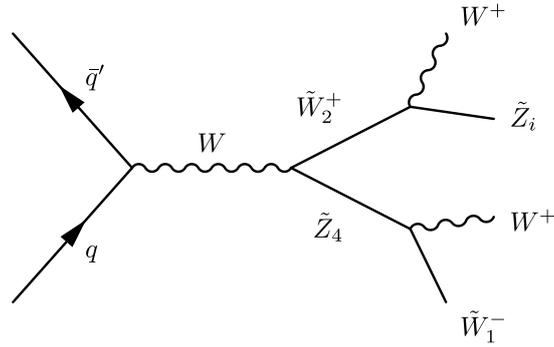
Figure 4: Diagram depicting same-sign diboson production at LHC in SUSY models with light higgsinos.
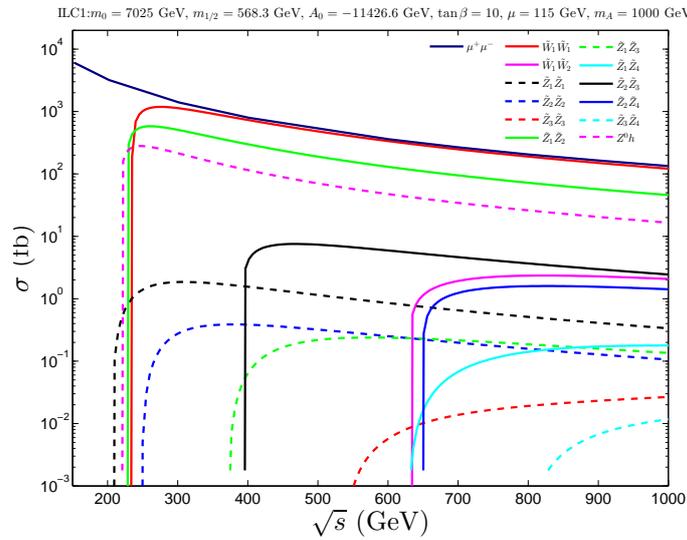
Figure 5: Sparticle production cross sections vs. $\sqrt{s}$ for unpolarized beams at an e^+e^- collider for the ILC1 benchmark point listed in Ref. [44].

5. Naturalness in QCD: the need for axions

If we insist on naturalness in the electroweak sector, then it is only fair to insist as well on naturalness in the QCD sector. In the early days of QCD, it was a mystery why the two-light-quark chiral symmetry $U(2)_L \times U(2)_R$ gave rise to three and not four light pions [46]. The mystery was resolved by 't Hooft's discovery of the QCD theta vacuum which didn't respect the remnant $U(1)_A$ symmetry [45]. As a consequence of the theta vacuum, one expects the presence of a term

$$\mathscr{L} \ni \frac{\bar{\theta}}{32\pi^2} F_{A\mu\nu} \tilde{F}_A^{\mu\nu} \tag{5.1}$$

in the QCD Lagrangian (where $\bar{\theta} = \theta + \arg(\det(\mathscr{M}))$ and $\mathscr{M}$ is the quark mass matrix). Measurements of the neutron EDM constrain $\bar{\theta} \lesssim 10^{-10}$ leading to an enormous fine-tuning in $\bar{\theta}$: the so-called strong CP problem.

The strong CP problem is elegantly solved by Peccei, Quinn, Weinberg and Wilczek (PQWW) [47] via the introduction of PQ symmetry and the concomitant (invisible [48, 49]) axion: the offending term can dynamically settle to zero. The axion is a valid dark matter candidate in its own right [50].

Introducing the axion in a SUSY context solves the strong CP problem and renders naturalness to QCD. As a bonus, in the context of the SUSY DFSZ axion model [49] where the Higgs superfields carry PQ charge, one gains an elegant solution to the SUSY μ problem. The most parsimonius implementation of the strong CP solution involves introducing a single MSSM singlet superfield S carrying PQ charge $Q_{PQ} = -1$ while the Higgs fields both carry $Q_{PQ} = +1$. The usual μ term is forbidden, but we have a superpotential [51, 52]

$$W_{\text{DFSZ}} \ni \lambda \frac{S^2}{M_P} H_u H_d. \tag{5.2}$$

If PQ symmetry is broken and S receives a VEV $\langle S \rangle \sim f_a$, then a weak scale μ term

$$\mu \sim \lambda f_a^2 / M_P \tag{5.3}$$

is induced which gives $\mu \sim m_Z$ for $f_a \sim 10^{10}$ GeV. Although Kim-Nilles sought to relate the PQ breaking scale f_a to the hidden sector mass scale m_{hidden} [51], we see now that the Little Hierarchy

$$\mu \sim m_Z \ll m_{3/2} \sim \text{multi} - \text{TeV} \tag{5.4}$$

could emerge due to a mis-match between PQ breaking scale and hidden sector mass scale $f_a \ll m_{\text{hidden}}$.

An elegant model which produces the above hierarchy was proposed by Murayama, Suzuki and Yanagida (MSY) [53]. In the MSY model, PQ symmetry is broken radiatively by driving one of the PQ scalars X to negative mass-squared values in much the same way that electroweak symmetry is broken by radiative corrections driving $m_{H_u}^2$ negative. Starting with multi-TeV scalar masses, the radiatively-broken PQ symmetry induces a SUSY μ term ~ 100 GeV [54] while at the same time generating intermediate scale Majorana masses for right-hand neutrinos. In models such as MSY, the Little Hierarchy $\mu \ll m_{3/2}$ is no problem at all but is instead just a reflection of the mis-match between PQ and hidden sector mass scales.

6. Mixed axion-WIMP dark matter

6.1 Dark matter: an axion/WIMP admixture?

As mentioned above, to allow for both electroweak and QCD naturalness, one needs a model including both axions and SUSY. In such a case, the axion field is promoted to a superfield which contains a spin-0 R-parity even saxion s and a spin-1/2 R-parity odd axino $\tilde{a}$. Typically in SUGRA one expects the saxion mass $m_s \sim m_{3/2}$ and the axino mass $m_{\tilde{a}} \overset{<}{\sim} m_{3/2}$.[55] The dark matter is then comprised of two particles: the axion along with the LSP which is a higgsino-like WIMP. This is good news for natural SUSY since thermal higgsino-like WIMPs are typically underproduced by a factor 10-15 below the measured dark matter abundance. The remainder can be comprised of axions.

The amount of dark matter generated in the early universe depends sensitively on the properties of the axino and the saxion in addition to the SUSY spectrum and the axion. For instance, thermally produced axinos can decay into LSPs after neutralino freeze-out thus augmenting the LSP abundance[56]. If too many WIMPs are produced from axino decay, then they may re-annihilate at the axino decay temperature[56]. Saxions can be produced thermally or via coherent oscillations (important at large f_a) and their decays can add to the LSP abundance, produce extra dark radiation in the form of axions or dilute all relics via entropy production from decays to SM particles[57]. The calculation of the mixed axion-WIMP abundance requires solution of eight coupled Boltzmann equations. Results from a mixed axion-higgsino dark matter calculation in natural SUSY are shown in Fig. 6[58]. At low $f_a \sim 10^{10}$ GeV, then the thermal value of WIMP production is maintained since axinos decay before freeze-out. In this case the DM is axion-dominated[59]. For higher f_a values, then axinos and saxions decay after freeze-out thus augmenting the WIMP abundance. For very large $f_a \overset{>}{\sim} 10^{14}$ GeV, then WIMPs are overproduced and those cases would be excluded. Many of the high f_a models are also excluded via violations of BBN constraints and by overproduction of dark radiation- as parametrized by the effective number of extra neutrinos in the universe ΔN_{eff}.

As far as dark matter detection goes, WIMP production in RNS was examined in Ref. [61]. There, it is emphasized that the relevant theory prediction for WIMP direct detection is the quantity $\xi \sigma^{SI}(\widetilde{Z}_1 p)$ where $\xi = \Omega_{\widetilde{Z}_1} h^2 / 0.12$ to reflect the possibility that the WIMP local abundance may be highly depleted, and perhaps axion-dominated. Nonetheless, WIMPs should be ultimately detected by ton-scale noble liquid detectors because naturalness insures that the WIMP-Higgs coupling– which is a product of higgsino and gaugino components– is never small (see Fig. 7). Prospects for indirect detection of higgsino-like WIMPs from WIMP-WIMP annilations to gamma rays or anti-matter are less lucrative since then the expected detection rates must be scaled by ξ^2.

Meanwhile, we would also expect ultimate detection of axions if natural SUSY prevails[62]. In Fig. 8 we display the range of f_a where valid solutions for the relic abundance of mixed axion-higgsino CDM can be found in SUSy models with radiatively driven naturalness. The upper bar shows the range of f_a for $\xi_s = 0$ (no saxion-axion coupling) while the lower bar shows the range for $\xi_s = 1$ (axion-saxion coupling turned on). The darker shaded parts of the bars denote θ_i values > 3 which might be considered less plausible or fine-tuned. We also show by the bracket the range of f_a, assuming the bulk of DM is axion, which is expected to be probed by the ADMX experiment within the next several years. This region probes the most natural region where $\theta_i \sim 1$. We also
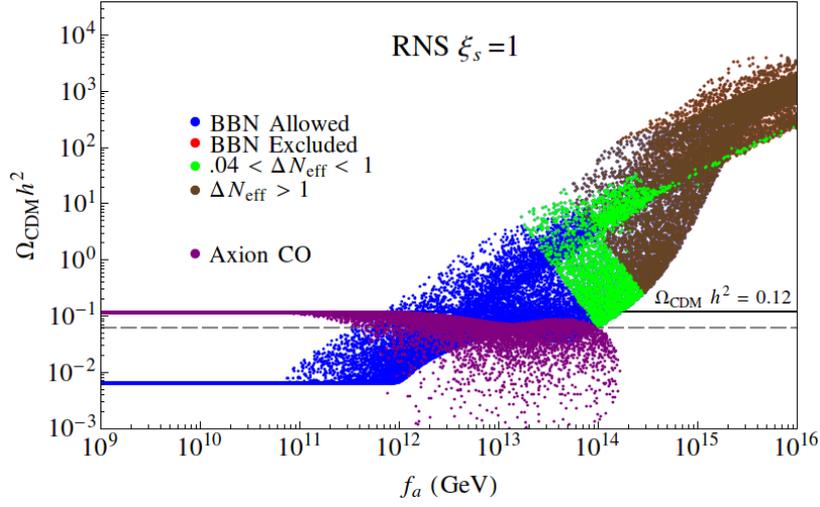
Figure 6: The neutralino relic density from a scan over SUSY DFSZ parameter space for the RNS benchmark case labelled SUA with $\xi = 1$. The grey dashed line shows the points where DM consists of 50% axions and 50% neutralinos. The red BBN-forbidden points occur at $f_a \gtrsim 10^{14}$ GeV and are covered over by the brown $\Delta N_{eff} > 1.6$ coloration. This latter region is excluded by Planck limits[60] of dark radiation as parametrized by additional neutrino species beyond the SM value.
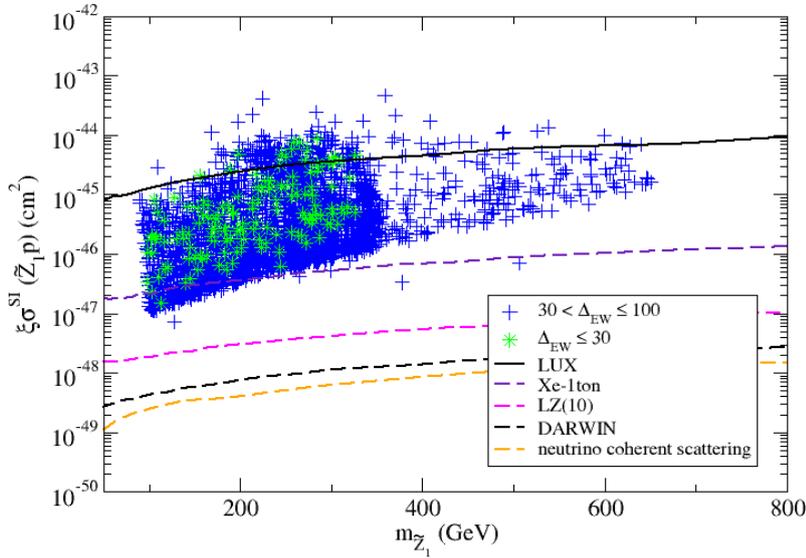
Figure 7: Plot of rescaled higgsino-like WIMP spin-independent direct detection rate $\xi \sigma^{SI}(\widetilde{Z}_1 p)$ versus $m(higgsino)$ from a scan over NUHM2 parameter space with $\Delta_{EW} < 30$ (green stars) and $\Delta_{EW} < 100$ (blue crosses). We also show the current reach of LUX and projected reaches of several ton-scale WIMP detectors. Plot from Ref. [63].

show a further region of lower f_a which might be explored by a new open resonator technology. About a decade of natural $f_a \sim 10^{14}$ GeV seems able to elude ADMX searches for the $\xi_s = 1$ case.
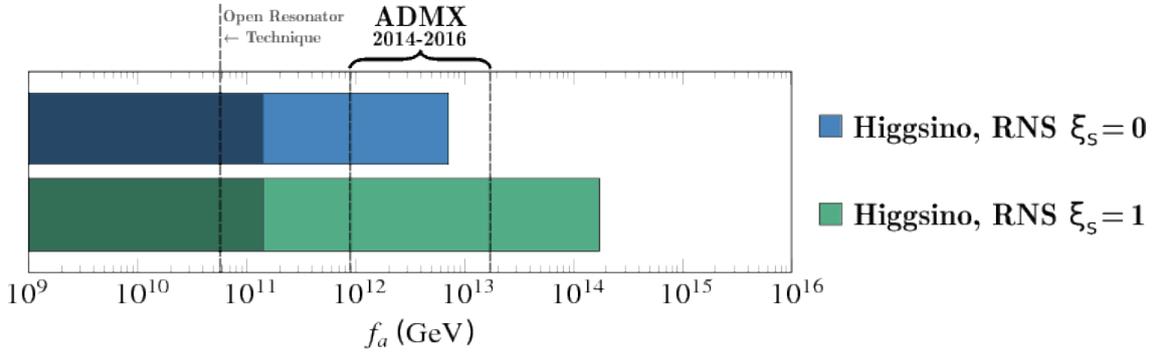
Figure 8: Range of f_a which is allowed in each PQMSSM scenario for the RNS benchmark models. Shaded regions indicate the range of f_a where $\theta_i > 3$.

7. Conclusions

Our conclusions are summarized as follows:

- There is no naturalness crisis for SUSY even though many popular models such as CMSSM/mSUGRA are ruled out by naturalness[34]. By requiring naturalness, we are pushed into a very specific mass spectrum charcterized by light higgsinos with mass $\sim 100 - 300$ GeV while other sparticles lie typically in the 2-20 TeV range at little cost to naturalness. In particular, gluinos may range up to 2 (4) TeV for $\Delta_{EW} \stackrel{<}{\sim} 10$ (30). Stops typically lie in the several TeV range.

- LHC will probe the most lucrative region of natural SUSY parameter space via $\tilde{g}\tilde{g}$ production and ultimately same-sign diboson production. Gluino pair events should contain a characteristic OS/SF dilepton mass edge $\stackrel{<}{\sim} 10 - 30$ GeV.

- Natural SUSY gives *tremendous* motivation to build ILC. For natural SUSY, ILC will be a higgsino factory for $\sqrt{s} > 2\mu$.

- Requiring naturalness in the QCD sector requires axions and the SUSY DFSZ axion model leads to a natural solution to the SUSY mu problem where $\mu \ll m_{3/2}$. Then we expect mixed axion-higgsino-like-WIMP dark matter.

- Even with a suppressed local abundance of higgsino-like WIMPs, a signal should be seen at ton-scale noble liquid detectors. We also expect an axion signal to emerge at ADMX although the axion mass may lie somewhat above the projected ADMX search region.

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