

Natural supersymmetry: status and prospects

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Received 3 February 2020 / Accepted 14 October 2020

Published online 14 December 2020

Abstract. The realization that supersymmetry (SUSY), if softly broken at the weak scale, can stabilize the Higgs sector led many authors to explore the role it may play in particle physics. It was widely anticipated that superpartners would reveal themselves once the TeV scale was probed in high energy collisions. Experiments at the LHC have not yet revealed any sign for direct production of superpartners, or for any other physics beyond the Standard Model. This has led to some authors to question whether weak scale SUSY has a role to play in stabilizing the Higgs sector, and to seek alternate mechanisms for stabilizing the weak scale. We reevaluate the early arguments that led to the expectations for light superpartners, and show that SUSY models with just the minimal particle content may well be consistent with LHC (and other) data and simultaneously serve to stabilize the Higgs sector, if model parameters generally regarded as independent turned out to be appropriately correlated. In our view, it would be premature to ignore this possibility, given that we do not understand the underlying mechanism of SUSY breaking. We advocate using the electroweak scale quantity, Δ_{EW} , to determine whether a given SUSY spectrum might arise from a theory with low fine-tuning, even when the parameters correlations mentioned above are present. We find that (modulo technical caveats) all such models contain light higgsinos and that this leads to the possibility of new strategies for searching for SUSY. We discuss phenomenological implications of these models for SUSY searches at the LHC and its luminosity and energy upgrades, as well as at future electron-positron colliders. We conclude that natural SUSY, defined as no worse than a part in 30 fine-tuning, will not escape detection at a pp collider operating at 27 TeV and an integrated luminosity of 15 ab^{-1} , or at an electron-positron collider with a centre-of-mass energy of 600 GeV.

1 Introduction

It has been known for a long time [1] that the scalar sector of the Standard Model (SM) exhibits quadratic sensitivity to the highest mass scale (M_{high}) in the larger theory that the SM might be coupled to. This can be seen from the structure of equation (1), valid in a generic quantum field theory. The squared physical mass of a spin-zero field (such as the Higgs field of the SM) is given in terms of the corresponding

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renormalized Lagrangian parameter, $m_{\phi 0}^2$, by,

$$m_{\phi}^2 = m_{\phi 0}^2 + C_1 \frac{g^2}{16\pi^2} M_{\text{high}}^2 + C_2 \frac{g^2}{16\pi^2} m_{\text{low}}^2 \log\left(\frac{M_{\text{high}}}{m_{\text{low}}}\right) + C_3 \frac{g^2}{16\pi^2} m_{\text{low}}^2. \quad (1)$$

In equation (1), m_{low} is the highest mass scale in the SM which is assumed to be the low energy effective theory valid well below the energy scale M_{high} , g denotes a typical coupling constant and the C_i are dimensionless numbers typically $\mathcal{O}(1) \times$ spin and multiplicity factors. The C_3 term could also include “small logarithms” $\log(m_{\text{low}}^2/m_{\phi}^2)$ that we have not made explicit. Well below the energy scale M_{high} , the renormalizable interactions of the SM yield a good description of nature, but at higher energies, novel effects not present in the SM become important.

Of particular interest in particle physics are Grand Unified Theories (GUTs) where the SM gauge group is envisioned as part of a simple group which is spontaneously broken at a scale $M_{\text{GUT}} \gg m_{\text{low}}$. The seemingly disparate SM gauge forces that we observe then arise from a single force, and the SM gauge coupling parameters (renormalized at the energy scale $Q \sim M_{\text{GUT}}$) all assume a common value. In this case, M_{high} in equation (1) is $M_{\text{GUT}} \sim 10^{15-16}$ GeV in the simplest models. We then see that the C_1 term in equation (1) is then $\sim 10^{28-30}$ GeV², and to obtain the observed value of $(125 \text{ GeV})^2$ for the squared Higgs boson mass requires that the Lagrangian parameter $m_{\phi 0}^2$ (other terms are much smaller) to also be as large and *finely tuned* to cancel against the C_1 term to many significant figures. While this is possible in principle, there is no apparent reason for this cancellation between terms that appear to originate in different sectors. We refer to this need for fine-tuning of seemingly unrelated model parameters as the *Big Hierarchy Problem*.¹ This problem disappears if there are new degrees of freedom beyond those of the SM below the few TeV scale; *i.e.* $M_{\text{high}} \sim (\mathcal{O})(\text{TeV})$.

Supersymmetry (SUSY) entered the mainstream of particle physics about four decades ago when it was realized that supersymmetric extensions of the SM provide an elegant solution [3,4] to the Big Hierarchy problem because the C_1 term is absent if SUSY is softly broken.² In SUSY GUT models, the C_2 term then dominates and, since the large logarithm (roughly) compensates the loop factor $16\pi^2$, we see that we would again need an unexplained cancellation between this term and $m_{\phi 0}^2$ if m_{low} is significantly larger than m_{ϕ}^2 . Here, m_{low} is again the mass scale of the heaviest particle (with significant coupling to the Higgs boson) in the low energy effective theory that we now use to evaluate the corrections to the Higgs boson mass. This is, of course, no longer the SM but its supersymmetric extension, the Minimal Supersymmetric Standard Model (MSSM) [5,6], or one of its variants. This simple argument was the underlying reason for the optimism in the community that at least some SUSY partners would be found with masses “not far above the weak scale”.

The direct search for the superpartners, which has been one of the central items on the agenda of e^+e^- , ep and hadron collider experiments at the energy frontier for well over three decades now, has yielded no clear sign of these. Assuming a mass gap (between the parent particle and the lighter daughter to which it decays) in excess of several hundred GeV, various *simplified model analyses* by the CMS [7] and ATLAS [8] collaborations at the LHC have yielded lower limits on the masses of gluino and (first generation) squarks in excess of 2 TeV. Corresponding limits on third generation squarks exceed 1 TeV [9,10]. Assuming charginos (neutralinos) decays via $\tilde{W}_1 \rightarrow W + \tilde{Z}_1$ ($\tilde{Z}_2 \rightarrow Z, h + \tilde{Z}_1$), lower limits on electroweak-inos of up to

¹For a contrarian philosophy, see reference [2].

²P. Fayet was a notable exception in that he was already exploring implications of SUSY for particle physics before this time.

600–700 GeV have been obtained for $m_{\tilde{Z}_1} < 200\text{--}300$ GeV [11–13]. In addition, low energy experiments searching for quantum effects of supersymmetric particles that would modify the properties of quarks and leptons; e.g. rare decays of bottom mesons [14,15] or the magnetic moment of the muon [16,17], have not found an unambiguous signal. Finally, searches for (weakly interacting massive particle) dark matter, which are frequently interpreted in the context of supersymmetric models, have also turned up empty [18–20].

We should mention that in the 1980s, there were several other proposals that attempted to address the hierarchy issue. Some of these only seemed to “postpone the problem” by arranging the C_1 contribution in equation (1) to enter only at two loop: then the corresponding value of M_{high} is an order of magnitude larger than the simplest expectation $M_{\text{high}} \sim 10m_\phi \sim \mathcal{O}(\text{TeV})$, and so beyond the LHC reach. A particularly attractive suggestion was that the Higgs scalar is really a (light) composite of new heavy fermions, bound by new “technicolour” gauge forces: since there is no elementary spin-zero field, there is no big hierarchy problem. While this worked very well for obtaining gauge boson masses, it led to very baroque constructions when it came to fermion masses, consistent with absence of flavour-changing neutral currents [21–25]. Only weak scale supersymmetry and warped extra dimension models [26,27] allowed the possibility of consistently extending the SM to very high scales. More recently, the relaxion idea [28] (also not yet realized in a UV complete model) has been suggested, where the large hierarchy is explained through a cosmological process that does not seem to require any precise adjustment of parameters. A discussion of alternatives to supersymmetry for solving the big hierarchy problem is beyond the scope of this paper. Our purpose here is to examine whether the non-appearance of any superpartners in experiments at the LHC negates our primary motivation for weak scale supersymmetry playing a role in particle physics by stabilizing the SM Higgs sector when it is coupled to high scale physics, as *e.g.* in a SUSY GUT.

We emphasize that there are several other reasons for considering supersymmetry as a key ingredient of particle physics. Ever since the early 1980s, it has been recognized that [29–32]³:

- The largest possible symmetry of the S -matrix includes SUSY [33];
- Supersymmetry allows a synthesis between bosons and fermions never before achieved [34–40];⁴
- Local SUSY includes gravity [41–44];
- SUSY theories could include a viable candidate for (or, after what we have learnt now, at least a component of) dark matter [45–49] if, motivated by considerations of proton stability, we impose the conservation of R -parity.

We stress that none of these arguments provide any indication of the SUSY breaking scale. It is only if we require SUSY to ameliorate the big hierarchy problem, we find that the effective SUSY breaking scale cannot be much larger than the weak scale.

When the gauge couplings (really speaking, the value of $\sin^2\theta_W$) were first measured in LEP experiments, it was recognized that these (nearly) unify in SUSY GUTs, but not in the SM [50–53]. Moreover, the measured value of the Higgs boson mass [54,55] fits within the narrow range $m_h \lesssim 135$ GeV allowed in the MSSM [56–59]. In

³For a review see S. Martin [29]. Text book reviews include R. Godbole and P. Roy [30]; H. Baer and X. Tata [31] and P. Binetruy [32].

⁴Space-time supersymmetry, the subject of our interest, was discovered by Y. Golfand, E. Likhtman [34], D. Volkov, V. Akulov [35,36] and J. Wess, B. Zumino [37]; World sheet supersymmetry (which was the first time that bosonic and fermionic degrees of freedom were related) was studied by A. Neveu, J. Schwarz [38], P. Ramond [39] and J. Gervais, B. Sakita [40].

extended models, assuming perturbativity up to the GUT scale, the allowed range is not much larger [60,61].

The fact that LHC experiments have led to no direct evidence for superpartners (or for that matter any other new physics that could ease the hierarchy problem) has led some authors to argue that because the stop mass scale already exceeds a TeV, SUSY models already need fine tuning at about a part per mille. This is frequently referred to as the *Little Hierarchy Problem*, and has resulted in novel (and sometimes rather complicated) proposals for its resolution. While new theoretical ideas are obviously always welcome, one of our goals is to critically assess whether LHC data indeed imply the existence of a little hierarchy that calls for the abandonment of the simple, calculable (and hence predictive) picture of perturbative SUSY GUTs.⁵

2 The mass scale of superpartners

Let us start by recalling why it was that superpartners were expected to be close to the weak scale. In SUSY GUTs, since the logarithm in equation (1) is about 30, the leading correction,

$$\frac{\delta m_h^2}{m_h^2} \sim C_2 \frac{g^2}{16\pi^2} \frac{m_{\text{SUSY}}^2}{m_h^2} \log \left(\frac{M_{\text{GUT}}}{m_{\text{low}}} \right),$$

rapidly exceeds unity if m_{SUSY} is significantly larger than m_h . Many authors argued that in order not to have unexplained cancellations, it is reasonable to set $\delta m_h^2 \lesssim m_h^2$, and, $\Delta_{\log} = \frac{\delta m_h^2}{m_h^2}$ was suggested [62–64] as a simple measure of the degree of fine-tuning, and continues to be used by some authors. What went wrong?

- Perhaps, $\delta m_h^2 < m_h^2$ is too stringent a requirement; we know many examples of accidental cancellations of an order of magnitude. While an unexplained cancellation of two orders of magnitude is, perhaps, too strong, accidental cancellations of an order of magnitude are not uncommon. The well known factor of $\pi^2 - 9$ in the decay rate of orthopositronium provides an “accidental cancellation” of an order of magnitude. While this is somewhat subjective, we will draw the line halfway in between, and require unexplained cancellations to be smaller than a part in 30.⁶
- These “naturalness bounds” apply only to those superpartners with large couplings to the Higgs sector, and so do not apply to first (or even second generation) squarks and gluinos whose masses are most stringently probed at the LHC. These superpartners couple to the Higgs sector only at two-loop so that their masses could easily be ~ 5 – 10 TeV or more because there would be an additional $16\pi^2$ in the C_2 term of equation (1).⁷
- There are various one-loop contributions to the C_2 terms in equation (1) that could, in principle, cancel against one another. Using Δ_{\log} as a measure of the degree of cancellations *assumes that contributions from various superpartners are all independent*. However, since we all expect that various superpartner

⁵We stress that SUSY clearly provides a solution to the Big Hierarchy problem as long as $M_{\text{SUSY}} \ll M_{\text{GUT}}$. We leave it to the reader to examine whether the proposed alternatives to SUSY truly address the hierarchy problem beyond leading loop order, and if they do, to assess the pros and cons of the new proposals over SUSY GUTs.

⁶Amusingly, the angular sizes of the sun and moon (viewed from earth) are the same to within this precision, another example of an accident.

⁷The D -term coupling contributions largely cancel.

masses will be correlated once we understand the mechanism of supersymmetry breaking, *automatic cancellations* between contributions from various superpartners could well occur when we evaluate the fine-tuning in any high scale theory. *Ignoring these correlations, will overestimate the ultra-violet sensitivity of any model.*

Parameter correlations are most simply incorporated into the most commonly used fine-tuning measure introduced by Ellis, Enqvist, Nanopoulos and Zwirner [65] and subsequently explored by Barbieri and Giudice [66]:

$$\Delta_{\text{BG}} \equiv \max_i \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2}{\partial p_i} \right|. \quad (2)$$

Here, the value of M_Z^2 is a prediction in terms of p_i 's, the *independent* underlying parameters of the theory. It does not matter that M_Z^2 rather than m_h^2 is used to define the sensitivity measure since both the quantities are proportional to the square of the Higgs field *vev*. The important point is that Δ_{BG} here measures the sensitivity with respect to the *independent* parameters of any model and so takes into account the correlations that we mentioned. Since Δ_{BG} “knows about” correlations that are ignored in Δ_{log} , we expect $\Delta_{\text{log}} \geq \Delta_{\text{BG}}$, which is why we said earlier that Δ_{log} would over-estimate the degree of fine-tuning.

The problem, of course, is that without a detailed knowledge of how superpartners acquire their masses, it is not possible to evaluate how these correlations affect the UV-sensitivity. We will see in Section 2.1 that we can, however, obtain a robust lower bound on $\Delta_{\text{BG}} > \Delta_{\text{EW}}$, where Δ_{EW} is determined only by the *weak scale SUSY parameters* which (in principle) can be directly measured if superpartners are discovered. In line with our earlier discussion, models with $\Delta_{\text{EW}} > 30$ can then unambiguously be regarded as fine-tuned.

2.1 Electroweak fine-tuning: a lower limit on Δ_{BG}

The value of M_Z^2 obtained from the minimization of the one-loop-corrected Higgs boson potential of the MSSM,

$$\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2, \quad (3)$$

is our starting point. Equation (3) is obtained using the weak scale MSSM Higgs potential, with all parameters evaluated at the scale $Q = M_{\text{SUSY}}$. The Σ s in equation (3), which arise from one loop corrections to the Higgs potential, are analogous to the C_3 term in (1). Explicit forms for the Σ_u^u and Σ_d^d may be found in the Appendix of reference [67].

We require that the observed value of M_Z^2 is obtained without large cancellations between terms on the right-hand-side of equation (3), *i.e.* none of these terms are hierarchically larger than M_Z^2 . Electroweak fine-tuning of M_Z^2 can then be quantified by [67–69],

$$\Delta_{\text{EW}} \equiv \max_i |C_i| / (M_Z^2/2). \quad (4)$$

Here, $C_{H_d} = m_{H_d}^2 / (\tan^2 \beta - 1)$, $C_{H_u} = -m_{H_u}^2 \tan^2 \beta / (\tan^2 \beta - 1)$ and $C_\mu = -\mu^2$. Also, $C_{\Sigma_u^u(k)} = -\Sigma_u^u(k) \tan^2 \beta / (\tan^2 \beta - 1)$ and $C_{\Sigma_d^d(k)} = \Sigma_d^d(k) / (\tan^2 \beta - 1)$, where k labels the various loop contributions included in equation (3). We immediately see

that any upper bound on Δ_{EW} that we impose from electroweak naturalness considerations implies a corresponding limit on μ^2 , a connection first noted two decades ago [70].

Since $|\mu|$ sets the scale for the doublet higgsino mass, we are led to infer that these *higgsinos cannot be hierarchically heavier than M_Z* in any theory with small values of Δ_{EW} . There are, however, potential loopholes that could void this conclusion that we make explicit.

- We have implicitly assumed that the superpotential parameter μ is independent of the soft SUSY breaking (SSB) parameters. If μ were correlated to the SSB parameters – in particular with $m_{H_u}^2$ – there could be automatic cancellations that would preclude us from concluding that higgsinos are light. Put differently, we assume that the superpotential and SSB breaking sectors could have different physical origins, and so are unrelated.
- We assume that there is no SSB contribution to the higgsino mass and that the μ^2 that enters in equation (3) via the scalar Higgs potential is also the higgsino mass parameter. Such a term would break SUSY softly as long as there are no SM singlets with significant couplings to the higgsinos [71,72]. We note that Nelson and Roy [73] and Martin [74] have constructed models with additional adjoint chiral superfields at the weak scale in which the SUSY mass parameters in the Higgs boson sector are logically independent of higgsino masses.
- It has been pointed out [75] that if the Higgs particle is a pseudo-Goldstone boson in a theory with an almost exact global symmetry, it is possible that the Higgs boson remains light even if the higgsinos are heavy because cancellations that lead to a low Higgs mass (and concomitantly low M_Z^2) are a result of a symmetry. Such models necessarily include additional fields in order to have complete multiplets of the global symmetry.

Despite these exceptions (all of which require the introduction of new low energy fields that serve no other purpose), we find it compelling that in models with a minimal (low energy) particle content the higgsino mass enters equation (3) directly, so that a low value of Δ_{EW} implies the existence of doublet higgsinos with masses not far above M_Z . We see no phenomenological motivation for the introduction of these extra fields at the weak scale, and so will continue to regard the existence of light higgsinos as a robust phenomenological consequence of natural SUSY in the rest of this paper.

The requirement of electroweak naturalness imposes *upper limits* on other superpartner masses, over and above the higgsino limit that we have just discussed. We will see below that models with stops as heavy as 3.5 TeV and gluinos as heavy as 6 TeV can be compatible with $\Delta_{\text{EW}} < 30$, in sharp contrast to stop bounds in the few hundred GeV range that emerge⁸ if the possibility of parameter correlations is ignored. First and second generation sfermions can be as heavy as tens of TeV, provided the sfermion spectrum exhibits well-motivated (partial) degeneracy patterns [76]. These heavy sfermions then ameliorate SUSY flavour and *CP* problems.

We note here that Δ_{EW} as defined here entails only weak scale parameters and so has no information about the M_{high} terms that cause weak scale physics to exhibit logarithmic sensitivity to high scale physics. For this reason, Δ_{EW} does not measure the UV sensitivity of the underlying high scale theory, as already noted in reference [67]. However, precisely because Δ_{EW} does not contain information about the large logs, we expect (modulo technical caveats that we will not get into here [77])

⁸Recall that we saw in Section 1 that this was the cause for disenchantment with SUSY in some quarters.

that

$$\Delta_{EW} \leq \Delta_{BG}.$$

Thus Δ_{EW}^{-1} is the minimum fine-tuning in any theory with a given superpartner spectrum, as noted just before the start of Section 2.1.

Although it is not a fine-tuning measure of a high scale theory, Δ_{EW} is nonetheless useful for many reasons.

- Since it depends only on weak scale parameters, Δ_{EW} is essentially determined by the SUSY spectrum, and so is “measureable”, at least in principle.
- If Δ_{EW} turns out to be large, the underlying theory that yields this spectrum will be fine-tuned because Δ_{BG} is even larger. While small Δ_{EW} does not necessarily imply the absence of fine-tuning, it leaves open the possibility of finding an underlying natural theory with the same superpartner spectrum where SSB parameters are correlated so that the large logarithms in the C_2 term of equation (1) nearly cancel.⁹ In a top-down theory which has such correlations among the SSB parameters, Δ_{BG} will be numerically close to Δ_{EW} . Section 3 of reference [77] illustrates how the cancellations might occur.
- In the absence of a complete understanding of how superpartners acquire masses and SUSY breaking couplings, it is not possible to evaluate Δ_{BG} with all the parameter correlations correctly incorporated. We advocate instead that Δ_{EW} be used for any discussion of fine-tuning because, though it may *underestimate* the degree of fine-tuning, it at least allows for the possibility that SUSY parameters frequently taken to be independent may turn out to be correlated. Disregarding this possibility may cause us to discard otherwise perfectly viable phenomenological models [77,82]. We note that Δ_{BG} naively computed i.e. without parameter correlations included, could well be two orders of magnitude larger than Δ_{EW} [77].
- Broad aspects of SUSY phenomenology are determined by the superpartner spectrum. An investigation of the phenomenology of models with low Δ_{EW} is, therefore, in effect an investigation of the phenomenology of the underlying (potentially) natural underlying theories.

3 Models with low Δ_{EW}

We have seen that the the magnitude of μ is fixed using equation (3) which is well approximated by,

$$\frac{1}{2}M_Z^2 \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2,$$

for moderate to large values of $\tan\beta$. Except for radiative corrections, a weak scale value of $-m_{H_u}^2$ close to M_Z^2 ensures a comparable value of μ^2 , so that Δ_{EW} is also not far above unity. This is, however, a non-trivial constraint on $m_{H_u}^2$ that cannot always be consistently realized. Within the much-studied mSUGRA framework [83–86] $m_{H_u}^2$ evolves to a negative value at the weak scale (this is the celebrated mechanism of radiative electroweak symmetry breaking [87–92]), and its magnitude is comparable

⁹The possibility that correlations among underlying parameter reduces the fine-tuning has been noted by other authors [70,78–81].

to that of other weak scale SSB parameters. The resulting value of μ^2 is – taking experimental constraints on sparticle masses into account – typically much larger than M_Z^2 as long as the radiative corrections contained in Σ_u^u are of modest size. Indeed, within the mSUGRA framework, one cannot obtain $\Delta_{EW} \lesssim 100$ consistently with the observed value of m_h [69].

A small weak scale value of $m_{H_u}^2$ can always be obtained if we relax the assumption of high-scale scalar mass parameter universality that is the hallmark of mSUGRA, and treat the Higgs field mass parameters as independent of corresponding matter scalar masses. The Non-Universal Higgs Mass model, which has two additional GUT scale parameters $m_{H_u}^2$ and $m_{H_d}^2$ (NUHM2 model) over and above the the mSUGRA parameter set: $m_0, m_{1/2}, A_0, \tan \beta$, and $sign(\mu)$, provides an appropriate setting [93–98]. It is also worth remarking that the large value of the trilinear third generation SSB scalar coupling required to obtain low values of Δ_{EW} simultaneously raises the Higgs boson mass to its observed value [68]. The NUHM3 model where third generation sfermion mass parameter is independent of m_0 as well as the SUSY breaking Higgs boson mass parameters provides an even more general parametrization for phenomenological analyses. There are some top-down scenarios in which this splitting of the third generation mass parameter is expected.

In these NUHM frameworks, the three MSSM gaugino masses are assumed to arise from a single gaugino mass parameter (renormalized at $Q = M_{GUT}$) in the same way the SM gauge couplings arise from a single unified gauge coupling in SUSY GUTs. While this appears to be well motivated, it is important to recognize that gaugino mass unification – unlike the unification of gauge couplings – is not compulsory even in SUSY GUTs: *tree level* gaugino mass parameters, renormalized at the appropriate high scale, unify only if the field that breaks SUSY is a singlet of the GUT group [99,100]. Radiative corrections evaluated by the renormalization group evolution of gaugino mass parameters from $Q = M_{GUT}$ to the sparticle mass scale results in the familiar pattern of weak scale gaugino mass parameters: $m_{\tilde{g}} \simeq 3M_2 \simeq 6M_1$, resulting in relatively large mass splittings between the spin- $\frac{1}{2}$ SUSY partners of the gauge bosons. Very different mass patterns, and correspondingly different phenomenology, may be possible if gaugino mass unification if gaugino mass unification is not assumed.

Non-universal gaugino mass patterns are also possible if gaugino masses arise only at the loop level. In supergravity models, there is a loop contribution to gaugino (and other superpartner) masses that arises from a breaking of scale invariance induced by quantum anomalies. This anomaly contribution to gaugino masses, proportional to the corresponding gauge β -function, is always present but because it is suppressed by a loop factor is important only if the tree-level contributions are absent or strongly suppressed. This happens in the so-called anomaly mediated SUSY breaking (AMSB) models [101–103] and their variants.

It is not our purpose here to go into the pros and cons of various SUSY models. Since our goal is to explore the phenomenology of natural SUSY models, we confine ourselves to the study of the variety of spectra and phenomenology that may be possible in various well-motivated natural SUSY frameworks that allow $\Delta_{EW} < 30$, consistently with current experimental constraints. Models that we consider include:

- natural NUHM2 and NUHM3 (hereafter denoted by nNUHM2 and nNUHM3) models that we adopt as representative of models with gaugino mass unification at the GUT scale;
- a phenomenological generalization [104] of the AMSB framework [101–103] with non-universal bulk Higgs mass parameters and trilinear couplings to allow $m_h \simeq 125$ GeV with $\Delta_{EW} < 30$ (nAMSB). The gaugino mass pattern is as given by AMSB discussed above, and very different from the pattern expected in models with gaugino mass universality.

- a phenomenological generalization [105] of the original mirage-mediation framework [106–109] in which one expects comparable gravity-mediated and anomaly-mediated contributions to SSB masses and couplings, allowing for patterns of SUSY spectra not realizable in other frameworks. The hallmark of this class of natural generalized mirage models (nGMM) is that gaugino mass parameters apparently (almost) unify at a scale $Q = \mu_{\text{mirage}}$, determined by the relative value of gravity and anomaly-mediated contributions to the SSB parameters. In particular, if μ_{mirage} is not far above the sparticle mass scale, the (low energy) gaugino mass parameters only have small splittings resulting in very different phenomenology from the other scenarios. We stress there is no physical threshold at $Q = \mu_{\text{mirage}}$, and the gaugino mass as well as other SUSY parameters continue to evolve smoothly through the mirage-unification scale all the way up to M_{GUT} . The nGMM pattern of gaugino masses is also expected to arise in the so-called mini-landscape picture [110–112] which targets the region of the string landscape that leads to the MSSM as the low energy effective theory. The phenomenology of the natural string mini-landscape picture is studied in reference [113].

Each of these frameworks allow spectra with $\Delta_{\text{EW}} < 30$, consistently with all experimental constraints. In the following, use these models to guide our exploration of the phenomenology of natural SUSY. We will adopt the NUHM models as typifying natural SUSY models with gaugino mass unification, while the nAMSB and nGMM models allow the exploration of natural SUSY where gaugino mass patterns deviate from their universal values in well-motivated ways. The nGMM model can accommodate a compressed as well as very split gaugino mass spectrum.

4 Phenomenology

As already emphasized, charged and neutral higgsinos with masses ranging from about 100 GeV (to evade LEP2 limits) to 300-350 GeV (so that $\Delta_{\text{EW}} < 30$) are the hallmark of all natural SUSY models. In models with gaugino mass unification typified by nNUHM2, nNUHM3 models, the heavier charged and neutral higgsinos have a mass gap of 10-30 GeV with the lightest supersymmetric particle (LSP) that escapes detection at particle accelerators. Smaller mass gaps are possible in natural SUSY only if we give up gaugino mass unification. Other superpartners may be much heavier even with $\Delta_{\text{EW}} < 30$ as we have already mentioned. Here, we present an overview of various SUSY signals in natural SUSY scenarios, with an emphasis on signatures suggestive of light higgsinos in the spectrum.

4.1 LHC and its luminosity upgrade

In natural SUSY the light higgsinos are likely to be the most copiously produced superpartners at the LHC [114–116]. This is illustrated in Figure 1 where we show various -ino production cross sections versus $m_{1/2}$, for the NUHM2 model-line with

$$m_0 = 5 \text{ TeV}, A_0 = -1.6m_0, \tan\beta = 15, \mu = 150 \text{ GeV}, \text{ and } m_A = 1 \text{ TeV}, \quad (5)$$

at LHC14. We have traded the high scale values of the Higgs mass parameters in favour of μ and M_A . Our choice of m_0 ensures that squarks are heavy so that we have agreement with flavour constraints. Note that the low $m_{1/2}$ portion of the graph is excluded by LHC constraints.

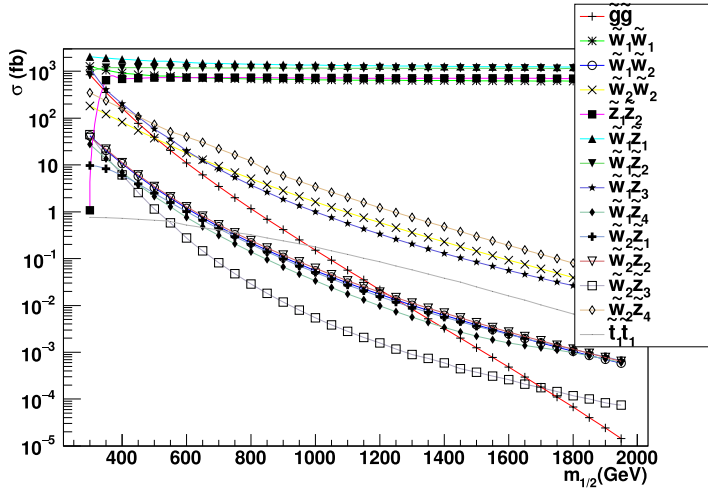


Fig. 1. Various NLO sparticle pair production cross sections versus $m_{1/2}$ along the NUHM2 model line (5) for pp collisions at $\sqrt{s} = 14$ TeV. Results are insensitive to the choice of m_0 as long as squarks are decoupled from LHC physics.

The cross sections for the production of higgsino-like charginos and neutralinos ($\widetilde{W}_1, \widetilde{Z}_{1,2}$) whose masses remain fixed close to $|\mu| = 150$ GeV across most of the plot remain flat, while cross sections for the gaugino-like states ($\widetilde{W}_2, \widetilde{Z}_{3,4}$) fall off because their masses increase with $m_{1/2}$. Cross sections for gaugino-higgsino pair production are dynamically suppressed. Pair production of gluinos and top squarks also occurs at observable rates if these particles are kinematically accessible, while other squarks and sleptons are essentially decoupled at the LHC.

4.1.1 Electroweak Higgsino pair production

The small visible energy release in their decays makes signals from higgsino pair production impossible to detect over SM backgrounds. We are thus led to investigate other strategies for discovery of SUSY.

4.1.2 Mono-jet and mono-photon signals

Many groups have suggested that experiments at the LHC may be able to identify the pair production of LSPs via high E_T mono-jet or mono-photon plus E_T^{miss} events, where the jet or the photon arises from QCD or QED radiation. A careful study of this signal for the case of light higgsinos, incorporating the correct matrix elements for all relevant higgsino pair production processes shows that it will be very difficult to extract the signal unless SM backgrounds can be controlled at the better than the percent level [117–120]. The problem is that the jet/photon E_T distribution as well as the E_T^{miss} distribution has essentially the same shape for the signal and the background.

In reference [121] it was suggested that it may be possible to enhance the mono-jet signal relative to background by requiring additional soft leptons in events triggered by a hard mono-jet. Reference [122] examined the mono-jet signal requiring, in addition, two opposite-sign leptons in each event, and showed that the SUSY

signal could indeed be observable at the LHC. Subsequent detailed studies (within the NUHM2 framework) of mono-jet, and also mono-photon, events with opposite-sign, same-flavour dileptons with low invariant mass showed that experiments at LHC14 would be able to detect a 5σ signal from higgsino pair production for $|\mu| < 170$ (200) GeV, assuming an integrated luminosity of 300 (1000) fb^{-1} [123]. Very interestingly, the ATLAS collaboration [124,125]¹⁰ has already excluded higgsino mass values well beyond the LEP2 limits even if $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ is as small as 4 GeV, but the excluded $m_{\tilde{Z}_2}$ range is very sensitive to the mass difference, and falls rapidly once $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} < 5$ GeV. CMS projections [127] for 3 ab^{-1} suggest a 5σ reach up to $\mu = 240$ GeV, for $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \simeq 10$ GeV, while the corresponding 95% CL exclusion extends to 350 GeV. The ATLAS 95%CL exclusion region [128] also extends to 350 GeV even for $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \sim 4\text{--}5$ GeV, but falls rapidly for smaller mass differences. Keeping in mind that the higgsinos of natural SUSY may be as heavy as 300–350 GeV, we conclude that while LHC experiments will be sensitive to the most promising part of the parameter of natural SUSY models, they may not be able to probe the entire natural SUSY region with $\Delta_{\text{EW}} \leq 30$ at the 5σ level, especially if higgsino mass gap is significantly smaller than ~ 10 GeV. The ultimate reach will depend on the degree to which the LHC experiments will be able to reliably identify and measure soft-leptons in events triggered by a monojet or, perhaps, a mono-photon. These are channels worth watching.

4.1.3 Same sign dibosons

Typical natural SUSY scenarios suggest that $|\mu| \ll M_{1,2}$ so that \tilde{W}_1 and \tilde{Z}_2 are higgsino-like and, in models with gaugino mass unification, only 10–30 GeV heavier than \tilde{Z}_1 . Then \tilde{Z}_3 is dominantly a bino, and \tilde{W}_2 and \tilde{Z}_4 are winos. For heavy squarks, electroweak production of the bino-like \tilde{Z}_3 is dynamically suppressed since $SU(2) \times U(1)_Y$ symmetry precludes a coupling of the bino to the W and Z bosons. However, winos have large “weak iso-vector” couplings to the vector bosons so that wino pair production occurs at substantial rates. Indeed we see from Figure 1 that for high values of $m_{1/2}$ the kinematically disfavoured $\tilde{W}_2^\pm \tilde{W}_2^\mp$ and $\tilde{W}_2 \tilde{Z}_4$ processes are the dominant sparticle production mechanisms¹¹ with large visible energy release and high E_T^{miss} .

Wino production leads to a novel signature involving same-sign dibosons produced via the process, $pp \rightarrow \tilde{W}_2^\pm (\rightarrow W^\pm \tilde{Z}_{1,2}) + \tilde{Z}_4 (\rightarrow W^\pm \tilde{W}_1^\mp)$. The visible decay products of \tilde{W}_1 and \tilde{Z}_2 tend to be soft, so that the signal of interest is a pair of same sign, high p_T leptons from the decays of the W -bosons, *with limited jet activity in the event* [129]. This latter feature serves to distinguish the wino pair production signal from same sign dilepton events that might arise at the LHC from Majorana gluino pair production [130–132] that always has very hard jets from the primary decay of the gluinos. We note also that $pp \rightarrow \tilde{W}_2^\pm \tilde{W}_2^\mp$ production (where one chargino decays to W and the other to a Z) also makes a non-negligible contribution to the $\ell^\pm \ell^\pm + E_T^{\text{miss}}$ channel when the third lepton fails to be detected. The same sign dilepton signal with limited jet activity is a hallmark of all low μ models, as long as wino pair production is not kinematically suppressed.

¹⁰In contrast, the corresponding CMS search [126], probes down just to $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} = 7.5$ GeV.

¹¹Although we use the NUHM2 framework for the illustration of the signal, wino pair production would also be possible in other models. Keep in mind though that in models where gaugino mass parameters do not unify at the GUT scale, the neutral wino could be \tilde{Z}_3 rather than \tilde{Z}_4 .

The extraction of the same sign dilepton signal from wino production requires a detailed analysis to separate the signal from SM backgrounds: see Section 5 of reference [115,116], and also reference [133] where the analysis was re-examined and refined. The most important cuts necessary for suppressing backgrounds are a hard cut on E_T^{miss} , together with a cut on

$$m_T^{\text{min}} \equiv \min [m_T(\ell_1, E_T^{\text{miss}}), m_T(\ell_2, E_T^{\text{miss}})],$$

along with requiring at most one jet (not tagged as a b -jet) in the event. It was shown that, with 3 ab^{-1} , LHC experiments would allow a 5σ discovery of winos with a mass up to 900 GeV. By itself, this falls well short of the entire natural SUSY parameter space.

4.1.4 Gluinos and stops

Unless their production is kinematically suppressed, coloured particles are expected to be the copiously super-partners produced at hadron colliders. Within natural SUSY, the lighter stop is significantly lighter than other squarks, so that gluinos dominantly decay via $\tilde{g} \rightarrow t\tilde{t}_1^*, t\tilde{t}_1$, where the (real or virtual) stop decays dominantly to higgsinos via $\tilde{t}_1 \rightarrow t\tilde{Z}_{1,2}$ or $\tilde{t}_1 \rightarrow b\tilde{W}_1$. Gluino pair production is, therefore, signalled by events with up to four hard tagged b -jets and large E_T^{miss} . It has been shown that it is possible to isolate an almost pure signal sample from gluinos requiring at least four hard jets, at least two of which are tagged as b -jets, and a very stiff E_T^{miss} (along with other cuts) to nearly eliminate Standard Model backgrounds [134]. With these cuts, experiments at the LHC should be able to observe a 5σ gluino signal if $m_{\tilde{g}} < 2400$ (2800) GeV for an integrated luminosity of 300 (3000) ab^{-1} in both the two and three tagged b -jet channels. This is illustrated in the left frame of Figure 2 for two tagged b -jet events. A similar reach is obtained in the three tagged b -jet channel. Unfortunately, however, this only covers part of the range of $m_{\tilde{g}}$ allowed by natural SUSY. If, however, the gluino signal is observable, a measurement of the rate of gluino events in the clean SUSY sample obtained above also allows for a determination of the gluino mass with a precision of 2.5–5%, depending on the integrated luminosity that is accumulated and the value of $m_{\tilde{g}}$: see the right frame of Figure 2 [134].

Stop pair production occurs at a rate shown in Figure 1 for the NUHM2 model line introduced earlier. However, even with 3 ab^{-1} , the 5σ LHC reach, assuming that $\tilde{t}_1 \rightarrow t\tilde{Z}_1$, extends out to about 1.3 TeV for $m_{\tilde{Z}_1} \lesssim 400$ GeV, while the 95% CL sensitivity region extends to 1.6–1.7 TeV [135]. Since the stop of natural SUSY dominantly decays via $\tilde{t}_1 \rightarrow t\tilde{Z}_{1,2}$ or $b\tilde{W}_1$ (where $m_{\tilde{W}_1} \simeq m_{\tilde{Z}_2} \simeq m_{\tilde{Z}_1}$), and the decay products of the heavier higgsinos are essentially invisible, we expect that the natural SUSY reach of the stop is qualitatively similar to the numbers quoted above. It is thus entirely possible that the stop may evade detection at the high-luminosity LHC even in models with $\Delta_{\text{EW}} < 30$. Here, we sharply differ from those authors that neglect the possibility parameter correlations, and so conclude that the absence of any sign of the stop would imply that SUSY is fine-tuned to parts per mille, or worse.

4.1.5 Other signals

The hard trilepton signal from wino pair production, i.e. from the reaction $pp \rightarrow \tilde{W}_2\tilde{Z}_4 + X \rightarrow W + Z + E_T^{\text{miss}} + X$ in low $|\mu|$ models with gaugino mass unification, has long considered to be the golden mode for SUSY searches [136–142]. The leptons

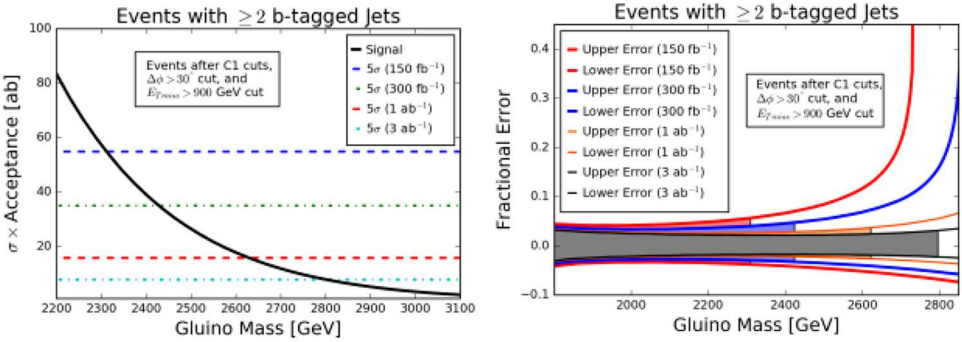


Fig. 2. The left-hand frame shows gluino signal cross section for the ≥ 2 tagged b -jet events after hard cuts detailed in reference [134]. The horizontal lines show the minimum cross section for which the signal will be detectable with an equivalent Gaussian probability corresponding to 5σ above Poisson fluctuations of the background. The right frame shows the precision with which the gluino mass may be extracted from the measured rate for gluino events (assuming a 15% uncertainty in the gluino cross section) for different values of integrated luminosity at the LHC.

come from the decays of the vector bosons, while the E_T^{miss} dominantly arises from the $\tilde{W}_1/\tilde{Z}_{1,2}$ (whose visible decay products are very soft) daughters of the winos and from the neutrino from W decay. A detailed analysis [115,116] shows that the LHC14 reach in the NUHM2 model extends to $m_{1/2} = 500$ (630) GeV for an integrated luminosity of 300 (1000) fb^{-1} . This is considerably lower than the reach via the SSdB channel, but can yield a confirmatory signal. Much of this region has already been probed at the LHC [11–13] albeit in simplified models.

In models with light higgsinos, the (heavy) charged wino decays via $\tilde{W}_2 \rightarrow \tilde{Z}_{1,2}W$, $\tilde{W}_2 \rightarrow \tilde{W}_1Z$ or $\tilde{W}_2 \rightarrow \tilde{W}_1h$ with branching ratios $\sim 2:1:1$, while the neutral wino decays via $\tilde{Z}_4 \rightarrow \tilde{W}_1^\pm W^\mp$, $\tilde{Z}_4 \rightarrow \tilde{Z}_{1,2}Z$ or $\tilde{Z}_4 \rightarrow \tilde{Z}_{1,2}h$ with branching ratios $\sim 2:1:1$ [133]. Since the daughter higgsinos are essentially invisible, wino pair production potentially leads to a variety of interesting $VV + E_T^{\text{miss}}$ ($V = W, Z$), $Vh + E_T^{\text{miss}}$ and $hh + E_T^{\text{miss}}$ events *in predicted proportion*. Observation of these events in the expected ratios would point to a model with light higgsinos, though this may be more relevant at the proposed energy upgrade of the LHC discussed below.

The LHC reach in the 4 lepton signal channel was also examined in reference [115, 116] by requiring four isolated leptons with $p_T(\ell) > 10$ GeV, a b -jet veto (to reduce backgrounds from top quarks), and $E_T^{\text{miss}} > E_T^{\text{miss}}(\text{cut})$. Potential backgrounds come from $ZZ, t\bar{t}Z, ZWW, ZZW, ZZZ$ and $Zh(\rightarrow WW^*)$ production. It was found that in low $|\mu|$ models, the LHC reach via the 4ℓ search extends somewhat beyond that in the trilepton channel.

4.1.6 A recap of the reach of the LHC and its luminosity upgrade

We have seen that while there still is a potential for a SUSY discovery in several channels, a signal is not guaranteed even at the luminosity upgrade of the LHC. In models with gaugino mass unification, the mono-jet plus soft dilepton channel and the same sign $WW + E_T^{\text{miss}}$ channels are the most promising in that they appear to cover the largest portions of the parameter space with $\Delta_{EW} < 30$. The situation, within the NUHM2 framework, is summarized in the left frame of Figure 3 from which we see that the mono-jet plus soft dilepton yields an observable 5σ signal for $\mu \lesssim 250$ GeV

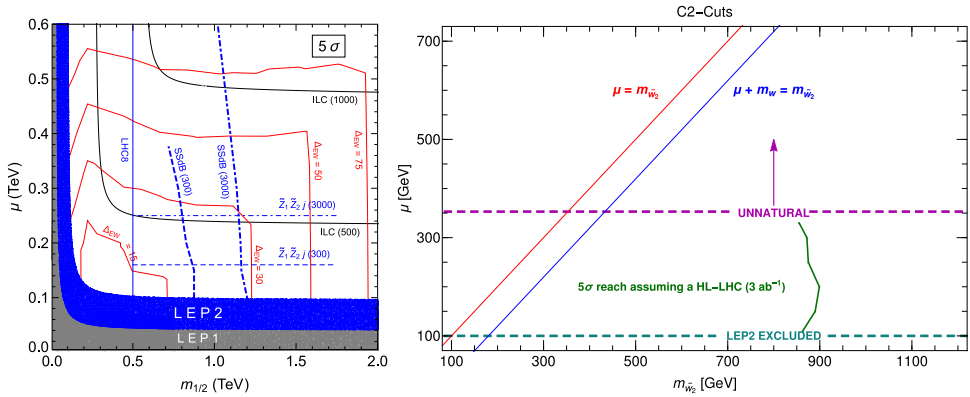


Fig. 3. The left-hand frame shows the 5σ reach in the NUHM2 model at the LHC and its luminosity upgrade for the monojet plus soft dilepton (labelled $\tilde{Z}_1\tilde{Z}_2j$) and the same sign diboson $W^\pm W^\pm$ (labelled SSdB) channels discussed earlier in the text. Also shown are contours of several values of Δ_{EW} . The green contour in the right-hand frame shows the reach of the HL-LHC via the same sign diboson channel from a different analysis (see text).

at the high luminosity LHC, while the same-sign WW signal covers the region with $m_{1/2} < 1.2$ TeV. (The corresponding gluino reach in $m_{1/2}$ is slightly smaller.) More interestingly, we see that with an integrated luminosity of 3 ab^{-1} , LHC experiments should be sensitive to the entire region of the $\Delta_{EW} < 30$ portion of the NUHM2 parameter space! This exciting conclusion led to a reassessment the same sign WW signal in reference [133] using madgraph/Pythia/Delphes instead of ISAJET for the analysis. The corresponding reach, shown in the right hand frame of Figure 3, is about 10% smaller than that in the left hand frame.¹² but the qualitative picture remains unaltered. At least in models with gaugino mass unification (where $\Delta_{EW} < 30$ implies that the neutralino mass gap is larger than ~ 10 GeV), the luminosity upgrade of the LHC should be able to discover natural SUSY over most of the parameter space via a signal in one (or both) of these channels.

Unfortunately, this optimistic conclusion may not carry over to models with non-universal gaugino masses where electroweak gaugino masses can be large (relative to $m_{\tilde{g}}$) without jeopardizing naturalness. This has two effects. First, the $W^\pm W^\pm$ signal from wino pair production may well be kinematically inaccessible. Second, larger values of $M_{1,2}$ for fixed μ allows a higgsino mass splitting as small as 3-4 GeV. The smaller mass gap implies softer leptons, and a correspondingly reduced efficiency for detecting the dileptons in mono-jet events. Recent ATLAS projections [128] for the high luminosity LHC suggest that it may be possible to detect the monojet plus soft dilepton signal with a 5σ significance even for $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ as small as ~ 5 GeV if $\mu < 220$ GeV ($\mu < 350$ GeV for exclusion at 95%CL).¹³ These early reach projections, though they allow for discovery even with small higgsino mass gaps, are uncomfortably close to the edge of the parameter space of natural SUSY. We hope and expect that these studies will be further refined, and that more definitive results will be obtained. Until then, it seems prudent to investigate what might be possible at accelerators that are being considered for construction in the future.

¹²This difference may be regarded as indicative of the systematic uncertainty in the reach projection.

¹³We are not aware of corresponding CMS analysis for such small mass gaps.

4.2 Electron-positron colliders

Since light higgsinos are $SU(2)$ doublets, they have typical electroweak couplings, and so *must be* copiously produced at e^+e^- colliders, unless their production is kinematically suppressed. Indeed cross sections for higgsino pair production processes are comparable to the cross section for muon pair production if higgsino production is not kinematically suppressed. Moreover, the higgsino pair production rate, for higgsinos with masses comparable to m_h exceeds that for Zh production, so that these facilities may well be higgsino factories in addition to being Higgs boson factories. An electron-positron linear collider with a centre-of-mass energy of 500 GeV (and upgradeable to 1 TeV) that is being envisioned for construction is thus an obvious facility for definitive searches for natural SUSY. The issue is whether, in light of the small visible energy release in higgsino decays, it is possible to extract the higgsino signal above SM backgrounds. These dominantly come from two-photon-initiated processes because those $2 \rightarrow 2$ SM reactions can be efficiently suppressed by a cut on the visible energy in the event.

The higgsino signal was first examined in reference [143] where the authors studied two cases, both at a centre-of-mass energy just above the production threshold for charged higgsino pair production. The more difficult of these (which is what we discuss here) was chosen so that $m_{\tilde{W}_1} \simeq m_{\tilde{Z}_2} = 158$ GeV, and a mass gap with the neutralino of just ~ 10 GeV, close to the minimum in models with gaugino mass unification. The small mass gap severely limits the visible energy, and in this sense represents the maximally challenging situation within models with unified gaugino mass parameters.

The most promising signals come from $e^+e^- \rightarrow \tilde{W}_1(\rightarrow \ell\nu\tilde{Z}_1)\tilde{W}_1(\rightarrow q\bar{q}\tilde{Z}_1)$ which leads to $n_\ell = 1$, $n_j = 1$ or 2 plus E_T^{miss} events, and from $e^+e^- \rightarrow \tilde{Z}_1\tilde{Z}_2(\rightarrow \ell\ell\tilde{Z}_1)$ (with 90% electron beam polarization to reduce WW background) processes. SM backgrounds can be nearly eliminated using judicious cuts on the visible energy (signal events are very soft), E_T^{miss} and transverse plane opening angles between leptons and/or jets. The higgsino signal could be extracted $\sqrt{s} = 340$ GeV, and an integrated luminosity of just a few fb^{-1} . We refer the reader to reference [143] for details.

This early analysis has recently been re-examined in reference [144] with full Geant 4 based simulation of the ILD detector concept not only for the two cases studied in reference [143], but also for an nGMM model case for higgsinos with masses ~ 155 GeV, and a neutral higgsino mass gap is just 4.4 GeV. We refer the interested reader to this study which confirms that the higgsino signal should be readily detectable, even for the rather small mass gaps that may be possible in natural SUSY. We conclude that an electron-positron collider will be able to detect higgsino-pair production nearly all the way to the kinematic limit, and further, that an electron-positron collider with $\sqrt{s} \simeq 600$ GeV will probe the entire parameter space with $\Delta_{\text{EW}} \leq 30$.

Aside from discovery, the clean environment of electron-positron collisions also allows for precise mass measurements. For example, even in the difficult case considered in reference [143] as well as the nGMM case studied in reference [144], assuming an integrated luminosity of 500 fb^{-1} at $\sqrt{s} = 500$ GeV, a fit to the invariant mass distribution of dileptons in $\tilde{Z}_1\tilde{Z}_2$ events allows the determination of the neutralino mass gap, $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$. A subsequent fit to the distribution of the total energy of the two leptons then allows the extraction of individual neutralino masses with a precision of 0.7% [1%] for the case in reference [143] (the nGMM case in reference [144]). These mass determinations, together with cross section measurements using polarized beams, point to the production of light higgsinos as the underlying origin of these novel events, and so suggest a natural origin of gauge and Higgs boson masses.

4.3 Energy upgrade of the LHC

The recent European Strategy Study envisages the possibility of 16 Tesla dipole magnets which would allow the energy of the LHC to be increased to 27 TeV in the existing LEP/LHC tunnel. The anticipated integrated luminosity is 15 ab^{-1} [145]. The increased energy offers an opportunity to search for the coloured gluinos and stops of natural SUSY whose production, as we saw in Section 4.1, is kinematically limited at the LHC. A potential advantage of this search (because it does not rely on an examination of the soft decay products of the higgsinos) is that it would be insensitive to the details of the degree of compression of the higgsino spectrum which limits the LHC reach via the monojet plus soft-dileptons channel, or of the wino mass which limits the LHC reach in the $W^\pm W^\pm + E_T^{\text{miss}}$ channel. It is, therefore, possible that with the higher centre-of-mass energy gluino and stop searches may offer the best possibility of the discovery of natural SUSY in a wide variety of models.

Prospects for gluino and stop detection at a 33 TeV pp collider [146] were first examined in reference [147]. This analysis was then re-adapted for the high energy LHC (HE-LHC) a 27 TeV pp collider for an assumed integrated luminosity of 15 ab^{-1} , assuming that the gluino decays into a top and a (possibly virtual) stop, that the stop decays promptly to higgsinos via $\tilde{t}_1 \rightarrow t\tilde{Z}_{1,2}$ or $\tilde{t}_1 \rightarrow b\tilde{W}_1$, and that the higgsino decay products are essentially invisible [148]. As discussed in Section 4.1.4 pair production of heavy gluinos will lead to events with up to 4 hard bottom jets (not all of which will be tagged as b -jets) and large E_T^{miss} , while stop pair production results in up to two tagged b -jets and large E_T^{miss} . It is relatively straightforward to separate the SUSY signal from SM backgrounds, which dominantly come from $b\bar{b}Z$ and $t\bar{t}Z$ with subdominant contributions from $t\bar{t}$, $t\bar{t}b\bar{b}$, $t\bar{t}t\bar{t}$, $t\bar{t}h$ and single t production, by requiring at least two (four) very hard jets, at least two of which are tagged as b -jets, for the signal from stop- (gluino-) pair production together with very hard E_T^{miss} along with other analysis cuts. We refer the interested reader to reference [148] for further details. It was found that after judicious cuts the 5σ reach of HE-LHC extends to 5.5 TeV for gluinos, and to 3.16 TeV for stops.¹⁴ The corresponding 95%CL exclusion regions for both these sparticles extend out by about an additional 400 GeV.

This is illustrated in Figure 4 where the gluino and stop reaches are shown in the $m_{\tilde{t}_1} - m_{\tilde{g}}$ plane by the horizontal and vertical lines, respectively. Also shown are scatter plots of stop and gluino masses in the various natural models with $\Delta_{\text{EW}} < 30$ introduced in Section 3: nNUHM2 (yellow crosses), nNUHM3 (green stars), nAMSB (red dots), and nGMM (blue pluses). It is easy to see that in all these natural models, there will be an observable 5σ signal in at least one of the gluino or stop channels, and for most of the parameter space, in both channels. Natural SUSY, conservatively defined by no worse than 3% electroweak fine-tuning, would not evade detection at a 27 TeV pp collider with an integrated luminosity of 15 ab^{-1} . There may also be additional confirmatory signals in other channels, but the observability of these signals cannot be guaranteed. The discovery of stops and/or gluinos would provide impetus for the construction of a yet higher energy collider to snare the rest of the SUSY spectrum.

4.4 Low energy measurements

Precision measurements of SM particle properties offer an independent avenue for probing new physics. This is not, however, the case for the scenario that we have

¹⁴An independent analysis in reference [149] finds, assuming $\tilde{g} \rightarrow t\bar{t}\tilde{Z}_1$ and $\tilde{t}_1 \rightarrow t\tilde{Z}_1$, a somewhat smaller reach of 4.8 TeV (2.8 TeV) for gluinos (top squarks).

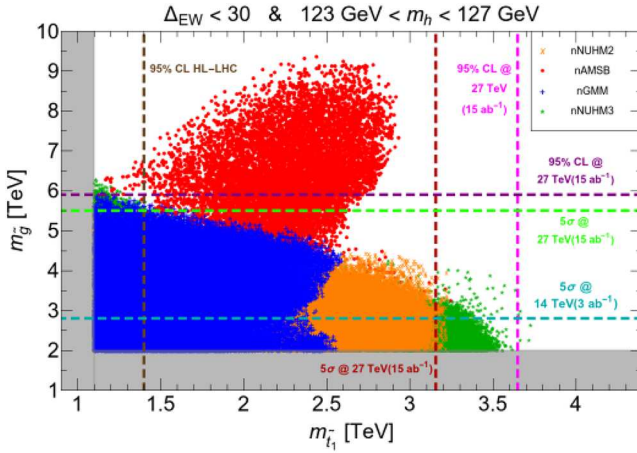


Fig. 4. The gluino and stop reach of a pp collider with $\sqrt{s} = 27$ TeV, assuming an integrated luminosity of 15 ab^{-1} . Also shown is a scatter plot of points in the $m_{\tilde{t}_1}$ vs. $m_{\tilde{g}}$ plane for various natural SUSY models with $\Delta_{EW} < 30$ introduced in the text: specifically, nNUHM2, nNUHM3, nGMM and nAMSB models.

outlined, where our assumption that sfermion mass parameters are very large precludes the possibility of sizeable deviations from SM expectations in processes such as $b \rightarrow s\gamma$, $b \rightarrow s\ell^+\ell^-$ or other flavour violating processes, whose observed values are known to be compatible with SM predictions [14]. We stress that this assumption is not required by naturalness considerations, but made to avoid unwanted flavour-changing-neutral currents. However, if the SM computation of $(g_\mu - 2)$ holds up to scrutiny and the measured value of the muon anomalous magnetic moment [16,17] continues to deviate from its expectation in the SM [150–153], it will have to be due phenomena outside the class of natural SUSY models that we find most promising.

Finally, we note that though SUSY contributions to the rate for the exclusive rare decay $B_s \rightarrow \mu^+\mu^-$ do not decouple with the super-partner mass scale, these are strongly suppressed for large values of m_A . This is not a problem because for moderate to large values of $\tan\beta$, $m_A^2 \simeq m_{H_d}^2 - m_{H_u}^2$ at tree level. Since $m_{H_d}^2$ can be in the multi-TeV range without jeopardizing electroweak fine-tuning (because the contribution of the $m_{H_d}^2$ term in equation (3) is suppressed by the $(\tan^2\beta - 1)$ factor), multi-TeV values of m_A are typical in natural SUSY. This is a plus because the measured value [154] for the branching fraction for this process is also in good agreement with the SM prediction [155].

4.5 Dark matter

Since the LSP is expected to be higgsino-like and not far above the weak scale in the simplest models with natural supersymmetry, it will (co)annihilate rapidly to gauge bosons (via its large coupling to the Z boson, and also via t -channel higgsino exchange processes) in the early universe. This means that the measured cold dark matter density *cannot arise solely from thermally produced higgsinos* in standard Big Bang cosmology. Dark matter is thus likely to be multi-component. It is important to note that naturalness considerations also impose an upper bound on wino masses. This, in turn, implies a lower limit on the gaugino content of the higgsino-like LSP, and correspondingly on the neutralino-nucleon scattering cross section which dominantly arises via h exchange. Indeed, it is then expected [113] that even with the suppressed

density, the XENONnT and LZ detectors [156,157] will be sensitive to the thermal higgsino signal from spin-independent neutralino-nucleon scattering.¹⁵ In models with gaugino mass unification, the upper bound on $m_{\tilde{g}}$ leads to an even more stringent upper bound on the wino mass, and the thermal higgsino signal would be detectable even at XENON1T with its expected sensitivity to nucleon-neutralino cross section at the 10^{-47} cm² level [164].

5 Concluding remarks

Weak scale supersymmetry stabilizes the electroweak scale and, in our view, offers the best solution to the big hierarchy problem. A discovery of super-partners would mark a paradigm shift in particle physics and cosmology. The non-observation of super-partners at LHC has led some to express reservations about this far-reaching idea. As we have discussed in Section 2 this is because the possibility that the underlying SSB parameters of the underlying theory might be correlated has been completely ignored. We recognize that a credible high scale model of SUSY breaking that *predicts* appropriate correlations among the SSB parameters and so automatically has a modest degree of fine-tuning has not yet emerged, but we cannot expect this until we understand the underlying SUSY breaking mechanism.

To allow for these presently unknown parameter correlations, we advocate using Δ_{EW} , the electroweak fine-tuning measure for any discussion of fine-tuning in SUSY. In this paper we consider models with $\Delta_{\text{EW}} > 30$ as definitely fine-tuned, and regard models that yield spectra with $\Delta_{\text{EW}} < 30$ as possibly arising from an underlying theory with moderate fine-tuning. We have checked that viable natural spectra exist without a need for weak scale new particles beyond the MSSM, and have argued that light higgsinos are the most robust consequence of SUSY naturalness.

As discussed in Section 4, models with light higgsinos potentially yield novel signals for supersymmetry at the LHC, the most promising of which is the mono-jet plus soft-dilepton signal from electroweak higgsino production with a radiation of a very hard QCD jet. It appears that this signal will be observable at the luminosity upgrade of the LHC with a significance $\geq 5\sigma$ over most of the natural SUSY parameter space in models where gaugino mass unification is assumed because the mass gap $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ is then at least 10 GeV. In natural SUSY models where gaugino mass unification does not hold, this mass gap may be as small as 4–5 GeV, so that the leptons from \tilde{Z}_2 decay tend to be softer and so more difficult to detect. We are excited by the early analysis by the ATLAS collaboration which suggests that it may be possible to probe higgsinos via this channel even for mass gaps substantially below 10 GeV. We urge our experimental colleagues to continue to push this analysis to include the softest leptons that they can as this will probe models with small mass gaps. The stakes are high!

Also very interesting are VV , ($V = W^\pm, Z$) Vh and $hh + E_T^{\text{miss}}$ signals from wino pair production, but these are not guaranteed because wino pair production is kinematically limited by the energy of the LHC. Nevertheless, if the signals turn out

¹⁵We remind the reader that there are the usual caveats to this conclusion. If physics in the sector that makes up the remainder of the dark matter entails late decays that produce SM particles, the neutralino relic density today could be further diluted, reducing the signal; see e.g. references [158–161]. On the other hand, late decays of any associated saxion, axino or even string-moduli fields to the neutralino could enhance the neutralino relic density from its thermal value. The important lesson is that while the thermal relic density is interesting to examine, it would be imprudent to categorically exclude a new physics scenario based on relic density considerations alone, because the predicted relic density can be altered by the unknown (and, perhaps, unknowable) history of the Early Universe [162,163].

to be observable, the relative strengths in the various channels could point to SUSY with light higgsinos.

If gluinos and winos are too heavy to be accessible at the LHC, and the neutralino mass gap is too small for the monojet plus soft dilepton signal to be observable, we would need new facilities to detect natural SUSY. One possibility is a linear electron-positron collider. We can interpolate from the left frame of Figure 3 that a linear collider operating at about 600 GeV would suffice to detect the higgsinos of natural SUSY. Very interestingly, at the HE-LHC (a 27 TeV, pp collider expected to accumulate an integrated luminosity of 15 ab^{-1}) that is being considered for construction in the existing LEP/LHC tunnel, at least one of the gluino or the stop of natural SUSY (and likely both over most of the natural SUSY parameter space) should be detectable with a significance $\geq 5\sigma$, independent of the details of the electroweak-ino spectra. Natural SUSY, as we have defined it, would not escape detection at such a facility.

Before closing, we note that in advocating the use of Δ_{EW} for discussions of fine-tuning, we have adopted a bottom-up approach to naturalness. Baer and his collaborators [165–167] have recently analysed SUSY naturalness from the top-down perspective of the string landscape, arguing that one value of an observable is more natural than another if the number of phenomenologically acceptable string vacua that lead to this value is larger. With some assumptions about the distribution of SUSY breaking F - and D -terms in these vacua, they find that the number of vacua grows with the SUSY breaking scale, favouring large values of SSB terms. However, in order to obtain a universe with the diversity of nuclei that we observe, one has to require (assuming everything is kept fixed) that the weak scale is not far from its phenomenological value [168]. The universe that we live in is then the result of a delicate balance between these two (somewhat opposing) requirements. The authors of reference [165–167] conclude that the anthropic requirement that the weak scale be within about a factor four of its observed value, with $|\mu|$ not much larger than the weak scale, leads to low energy SUSY models with $\Delta_{\text{EW}} < 30$, and first/second generation sfermion masses in the ten TeV range. These are exactly the characteristics of the models that we have discussed in our bottom-up approach! A detailed discussion of these speculative landscape ideas is beyond the scope of this paper, and we will refer the interested reader to a companion article [169] in this Volume.

In summary, SUSY GUTs pioneered by many authors during the 1980s remain as promising as ever. Moreover, the original aspirations of early workers on weak scale supersymmetry outlined in Section 1 remain unchanged, if we accept that

- “accidental cancellations” at the few percent level are ubiquitous and may not require explanation, and
- dark matter may be multi-component.¹⁶

The fact that low scale physics is only logarithmically (and not quadratically) sensitive to the scale of ultra-violet physics remains a very attractive feature of softly broken SUSY models, and leads to an elegant resolution of the big hierarchy problem. That it is possible to find phenomenologically viable models with low electroweak fine-tuning leads us to speculate that our understanding of UV physics is incomplete, and that there might be high scale models with the required parameter correlations that will lead to comparably low values of the true fine-tuning parameter Δ_{BG} . The supergravity GUT paradigm remains very attractive despite the absence of sparticle signals at the LHC. We urge the continued exploration of the energy frontier at the

¹⁶Given that visible matter which comprises a small mass fraction of the total matter content already consists of several components, this is hardly a stretch.

HL-LHC, at future electron-positron colliders with $\sqrt{s} \gtrsim 600$ GeV, or at the proposed energy upgrade of the LHC where it will be possible to definitively test the ideas reviewed here.

I am grateful to H. Baer, V. Barger, J. Gainer, P. Huang, D. Mickelson, A. Mustafayev, M. Padefkke-Kirkland, M. Savoy, D. Sengupta, H. Serce, W. Sreethawong and T. Ghosh for discussions and collaboration on much of the work described here.

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