Supersoft Stops

Timothy Cohen,1 Nathaniel Craig,2 Seth Koren,2 Matthew McCullough,3,4 and Joseph Tooby-Smith5

1Institute for Fundamental Science, Department of Physics, University of Oregon, Eugene, OR 97403, USA
2Department of Physics, University of California, Santa Barbara, CA 93106, USA
3CERN, Theoretical Physics Department, Geneva, Switzerland
4DAMTP, University of Cambridge, Wilberforce Road, Cambridge, UK
5Cavendish Laboratory, University of Cambridge, Cambridge, UK

Abstract

In a supersymmetric (SUSY) theory, the IR-contributions to the Higgs mass are calculable below the mediation scale \( \Lambda_{UV} \) in terms of the IR field content and parameters. However, logarithmic sensitivity to physics at \( \Lambda_{UV} \) remains. In this work we present a first example of a framework, dictated by symmetries, to supersoften these logarithms from the matter sector. The result is a model with finite, IR-calculable corrections to the Higgs mass. This requires the introduction of new fields – the ‘lumberjacks’ – whose role is to screen the UV-sensitive logs. These models have considerably reduced fine-tuning, by more than an order of magnitude for high scale supersymmetry. This impacts interpretations of the natural parameter space, suggesting it may be premature to declare a naturalness crisis for high-scale SUSY.

The search for models of short distance physics that yield a calculable Higgs mass continues to be one of the most important motivations for explorations beyond the Standard Model. This reductionist approach to fundamental questions has many precedents. The scalar mass in the Landau-Ginzburg theory is calculable utilizing logarithms. Hadron masses derive from the underlying QCD quark mass and gauge coupling parameters. Yet, despite our best efforts, no experimental hints towards the provenance of the Higgs mass have emerged, leading to the commonly held belief that the Standard Model must be fine-tuned. Here, via a novel extension of the Standard Model matter sector, we challenge the notion that the Standard Model must be fine-tuned. Here, via a novel extension of the Standard Model matter sector, we challenge the notion that the Standard Model must be fine-tuned.

Importantly, logging away all UV-sensitivity implies that the Higgs mass corrections must be fully calculable if one knows the complete theoretical picture at \( \Lambda_{UV} \). The implications of this residual UV dependence for the naturalness of the weak scale can be profound, heightening the sensitivity of the Higgs mass to the scale of symmetry breaking.

In this work, we investigate to what extent the scaling \( \delta M^2_H \propto \bar{m}^2/(16\pi^2) \log(\Lambda_{UV}/\bar{m}) \) is inevitable. Instead of demanding that the mass scale \( \bar{m} \) is small to preserve naturalness, we recorient the question by instead asking if it is possible that the logarithm can be rendered insensitive to the UV scale. Specifically, we will introduce scenarios in which an additional symmetry-enforced cancellation occurs over a large range of scales, essentially screening the Higgs mass from \( \bar{m} \)-dependent corrections all the way from the microscopic scale \( \Lambda_{UV} \) (where the symmetry breaking is generated) down to the TeV-scale. Corrections are still present at all scales, as expected for logarithmic UV-sensitivity. However, a UV conspiracy enforces an additional cancellation to remove logs, a phenomenon we will call ‘logging’. In practise, this amounts to creating an equal-and-opposite ‘little anti-hierarchy problem’, that largely annibilates the little hierarchy problem typically present in SUSY models. The framework is depicted in Fig. (1).

Importantly, logging away all UV-sensitivity implies that the Higgs mass corrections must be fully calculable in terms of IR parameters. Some examples of IR determined contributions to the Higgs mass already exist in the literature. In perhaps the most familiar class of models, of which logging is a member, symmetries orchestrate screening among the IR degrees of freedom. For example, in ‘supersoft’ theories with Dirac Gauginos, the one-loop gauge corrections to scalar masses are finite [1] – one way to view the model presented here is that it demonstrates how to supersofen the matter sector. In maximally symmetric pNGB Higgs models [2], a remnant symmetry renders the Higgs potential finite. A second class of models are those in which there are simply no lo-

\[ M_H \]
FIG. 1: A sketch of the scales relevant to the broad picture, with the running contributions depicted on either side of the mass scales. Above the scale $M$ the lumberjack fields conspire with the MSSM states to screen running Higgs mass corrections from the UV-scale $\Lambda_{UV}$ all the way down to the IR. Calculable threshold corrections to the Higgs mass are generated below the mass scale $M$. Scalars (dashed) are separated from their partner fermions (solid) by an equal and opposite-signed soft-mass squared.

FIG. 1

photons that could contribute to the Higgs mass at $\Lambda_{UV}$, and hence no logarithms are associated with their evolution. In models of Scherk-Schwarz SUSY breaking, locality ensures that all scalar mass corrections are finite and calculable [3, 4], albeit with coefficients that are relatively large with respect to the mass of the lightest coloured state. In Little Higgs models [5, 6], collective symmetry breaking and the attendant non-locality in theory space results in one-loop finite mass corrections. Alternatively, one can mimic IR domination by considering UV-sensitive models with a very low $\Lambda_{UV}$, which by design implies small logarithms, yielding reduced fine-tuning for the viable parameter space.

A common aspect of the EFT description of many of these IR-dominated models is that symmetries and/or locality forbid the possibility of local counterterms which correct the Higgs mass, rendering the Higgs mass IR-calculable. Motivated by this observation, our purpose here is to introduce a new class of supersymmetric effective field theories, in which the interplay of global exchange symmetries and symmetry breaking forbid these local counterterms. The result will be that in calculable logarithms are screened, such that weak-scale fine-tuning from the top sector is significantly reduced.

II. LOGGING SUSY

In this section, we will present a low energy SUSY EFT with supersoft stops. We add a complete copy of the third generation matter, the ‘lumberjack’ fields whose purpose is to remove the logs.¹ These lumberjacks are related to the third generation matter by an exchange symmetry. As a result, the most general matter-sector renormalizable superpotential is

$$W_\Lambda = \lambda_u H_u Q U^c + \lambda_t H_u Q' U'^c .$$

In order to lift the lumberjack fields, we will pair them up with an additional set of vector-like partners. A non-zero vector-like mass $M$ softly breaks the exchange symmetry:

$$W_M = M \left( Q' \bar{Q}' + U'^c \bar{U}'^c \right) .$$

Note that the exchange symmetry is not broken by the spectrum itself, since $Q'$ and $U'^c$ do not transform.

The matter squarks and their scalar lumberjack partners (the ‘lumberjacks’) are given the following exchange-breaking soft-masses:

$$V_{\text{Soft}} \simeq \tilde{m}^2 \left( |\tilde{Q}|^2 + |\tilde{U}|^2 - |\tilde{Q}'|^2 - |\tilde{U}'|^2 \right).$$

We will show how one can obtain this SUSY breaking pattern from the UV, which will make concrete the interpretation of $\tilde{m}^2$ as a spurion for the simultaneous spontaneous breaking of SUSY and the exchange symmetry.

We then compute the masses and use them as input to the Coleman-Weinberg potential, from which we obtain the Higgs mass corrections from both the top-stop and lumberjack sectors:

$$\delta M_{H_u}^2 = \frac{3 \lambda_u^2}{8 \pi^2} \tilde{m}^2 \left[ R + (R-1)^2 \log(R-1) \right. - (R-2) R \log(R) \left. \right] .$$

where $R = M^2 / \tilde{m}^2$. Due to the presence of the lumberjacks, the UV-sensitivity has been logged away, leaving behind only the IR contribution, as expected. To leading order in $1/R$ we have

$$\delta M_{H_u}^2 \simeq \frac{3 \lambda_u^2}{8 \pi^2} \tilde{m}^2 \left[ \frac{3}{2} + \log \left( \frac{M^2}{\tilde{m}^2} \right) \right],$$

which makes clear that, up to an additional finite threshold correction, the scale $M$ effectively replaces the UV-cutoff, which is consistent with the simple renormalization group evolution interpretation of Fig. (1).

More generally, one might imagine extending the third generation matter to include a variety of fields $\Phi$, with di-

¹ One could duplicate all of the MSSM matter in the same way, with a minimal impact on the resulting tuning.
verse Standard Model charges and couplings to the Higgs,

$$W = \frac{1}{2} \sum_H H_u \Phi_i \Phi_j + \frac{1}{2} M^{ij} \Phi_i \Phi_j,$$  \hspace{1cm} (6)

as well as soft terms

$$V_{\text{soft}} = \frac{1}{2} (m^2)^{ij} \Phi^i \Phi^j.$$  \hspace{1cm} (7)

The general condition for screening UV-sensitive logs at one loop is simply $\lambda_{H_k} \lambda_{H_j} (\tilde{m}^2)^{ij} = 0$. When all fields couple with equal strength to the Higgs, this reduces to the simple condition that the trace of the soft masses vanishes, $(\tilde{m}^2)^{ij}_i = 0$; this is clearly satisfied by the soft terms in Eq. (14).

**Fine-tuning**

As in the MSSM, to realise the observed Higgs mass one would likely need additional contributions to the Higgs quartic, such as radiative corrections from $A$-terms or by extending the framework to include additional NMSSM-like singlets. As a result, any exploration of the parameter space realising the observed Higgs mass is inherently model-dependent. However, independent of these considerations, we may still study the improvement in fine-tuning relative to a standard MSSM-like scenario.

If the fine-tuning is dominated by the stop sector, this reduces to the simple condition that the trace of the soft masses vanishes, $(\tilde{m}^2)_i^i = 0$; this is clearly satisfied by the soft terms in Eq. (14).

In Fig. (2), we show contours of the improvement in the tuning when the lumberjacks are present as compared to the MSSM in the $R$ versus $\tilde{m}$ plane. Even for low mediation scales, it is clear that the reduction in the tuning is considerable. For instance, if one has a GUT-scale model compatible with current bounds on stop squarks with tuning of $\mathcal{O}(1\%)$, then the supersoft version could be realised with a rather negligible tuning of $\mathcal{O}(30\%)$ for low $R$. Indeed, fine-tuning in log models approaches the favourable level obtained if one used only the infrared values of supersymmetry-breaking parameters [7].

Although this analysis is simplistic, it should capture the leading fine-tuning aspects, though effects beyond leading logarithm are likely to moderate the improvement [8, 9]. Looking forward, it would be interesting to revisit the current fine-tuning in supersymmetric models with high scale mediation for a log model to quantitatively assess the level of pressure current null LHC results put on supersymmetric naturalness. The gains should be particularly striking if the mediation scale is high.

It bears noting that the radiative correction to the Higgs quartic from the lumberjack fields is negative (since the fermionic lumberjacks are heavier than the scalars) and proportional to $\log M/\tilde{m}$. This reduces the overall contribution from the top sector in close analogy with the reduction of the $D$-term quartic in supersoft theories with Dirac gauginos. A more rigorous treatment of the parameter space would reveal that there is a tradeoff between the reduction in the log contribution to the fine tuning (approximately $\log \Lambda_{\text{UV}}/M$) and the decreased quartic when the observed Higgs mass is driven by the top sector. In this case, the naturalness improvement will be significant as long as $\tilde{m} \Lambda_{\text{UV}} \gg M$.

### III. UV-COMPLETIONS

Looking towards the UV, we assume that the SUSY breaking soft masses arise from a superfield $D$-term $\langle \Phi \rangle = D/\Phi \Phi \Phi$ which is odd under the exchange symmetry, $\Phi \rightarrow -\Phi$. The Kahler potential at the matching scale $\Lambda_{\text{UV}}$ is

$$K = \frac{\Phi}{\Lambda_{\text{UV}}} \left( |Q|^2 + |U^c|^2 - |Q'|^2 - |U'^c|^2 \right).$$  \hspace{1cm} (9)
Finiteness of the Higgs mass corrections is simply a consequence of the fact that the Higgs cannot couple to the SUSY breaking field in the Kähler potential as \( K \supset \Phi |H|^2 + \text{h.c.} \), since the global \( \mathbb{Z}_2 \) symmetry forbids any counterterm at this order.

While the EFT is self-consistent it is interesting to consider the possible UV structure. Perhaps the simplest possibility would be to realise \( \Phi \) as a pair of partner fields which swap under the exchange symmetry
\[
\Phi = |X|^2 - |\overline{X}|^2 .
\]

The sign enforces consistency with the coupling in Eq. (9). An \( F \)-term of this form could be generated in a number of ways. The simplest possibility would be to have \( W_X = fX \), although completions of this scenario may require more involved superpotentials to render all additional fields massive. Another viable approach would be to utilize an O’Raifeartaigh-like superpotential [10] with a small source of exchange symmetry breaking to yield the desired \( F \)-term.

It is also important to understand the impact of additional operators that could be present in the UV. Perhaps the most concerning coupling is
\[
K_H = \frac{|X|^2 + |\overline{X}|^2}{\Lambda_H^2} |H|^2 ,
\]

which is allowed by the symmetries and would spoil the supersoftness. Therefore, our IR analysis is valid under the assumption that the leading coupling is to the matter fields, as in Eq. (9). Then the generation of the dangerous coupling in Eq. (11) would be suppressed by extra powers of \( \tilde{m}^2/\Lambda_{UV}^2 \), or by some number of loop factors. Both of these contributions probe the dynamics of the messenger and SUSY-breaking sectors, and are consequently highly UV dependent.

An alternative UV scenario could be constructed by introducing an additional anomalous \( U(1)_X \) gauge symmetry under which the MSSM and lumberjack superfields carry equal and opposite charges. These charge assignments are consistent with the exchange symmetry if the vector superfield is odd \( \mathcal{V} \rightarrow -\mathcal{V} \). The \( U(1)_X \) can be spontaneously broken supersymmetrically if a pair of superfields \( X \) and \( \overline{X} \) with equal and opposite charge have vevs. Integrating out the vector multiplet could be responsible for generating Eq. (9). Since these fields also transform under the exchange symmetry, they may be used to generate the exchange-symmetry-respecting superpotential Yukawa couplings given in Eq. (1). The exchange-breaking superpotential masses in Eq. (2) may be generated by a small exchange-breaking Yukawa coupling involving \( X \) and the lumberjacks. Finally, the construction of [11], wherein an anomalous \( U(1)_X \) symmetry obtains a supersymmetry-breaking \( D \)-term well below the scale of spontaneous gauge symmetry breaking, could provide the source of the soft masses in Eq. (14).

These two simplistic scenarios suggest that a comprehen-

sive UV-completion is feasible, although it is likely that it will need to rely on some non-generic features.

### Gauginos

In the lumberjacking spirit, we may also opt to have Dirac gauginos, since this generates one-loop finite radiative corrections in the scalar sector [1]. This can be realised consistently with the existing setup since the adjoint chiral superfields \( A_j \) may be made odd under the exchange symmetry, such that a Dirac gaugino mass may be generated through the usual operator
\[
W_{\text{Gauge}} = \frac{1}{\Lambda_{UV}} W_\alpha^a W_j^a A_j ,
\]

where \( W_\alpha^a \) is the vector chiral superfield for \( \Phi \) whose \( D \)-term vev yields the Dirac mass, and \( j \) denotes the choice of gauge group. The \( \mathbb{Z}_2 \) symmetry acts on the adjoint chiral superfield as \( A_j \rightarrow -A_j \). Since the IR exchange symmetry is respected by the gauge sector, the arguments for the scalar sector given in the previous sections are unmodified. The dangerous supersoft-spoiling mass terms associated with the \( \mu - B_\mu \) problem of Dirac gaugino scenarios may be avoided through the GoGa mechanism [12, 13].

### Higgs Quartic

To raise the Higgs quartic without introducing UV-sensitive logarithms we may also supersoften the singlet sector of the NMSSM. To do this we follow the spirit of the top sector and introduce two singlets with an exchange symmetry
\[
W_S = \lambda (S + S') H_u H_d + \frac{1}{2} M_S \left( S^2 + S'^2 \right) .
\]

If desired, additional cubic interactions can be added consistent with the exchange symmetry. To introduce SUSY breaking we include an exchange-breaking soft term
\[
V_{\text{Soft}} \simeq -\tilde{m}_S^2 \left( |S|^2 - |S'|^2 \right) ,
\]
with a similar origin to the soft masses in the stop sector. As before, the one-loop radiative corrections will be IR-calculateable, allowing to raise the Higgs mass without the concern of large logarithms. Furthermore, since in the supersoft model the quadratic corrections tend to be smaller than standard scenarios with even a very low messenger scale, it is likely that the fine-tuning outcome for the singlet sector will be less severe than in standard NMSSM scenarios [14].
**IV. PHENOMENOLOGY**

Much of the LHC phenomenology is driven by the Dirac nature of the gauginos. Studies of the novel signatures of Dirac gauginos have been undertaken previously [15–18]. Due to the supersoftness, the gluinos can be heavier than in the MSSM without being the dominant source of tuning, which implies that jets plus missing energy signatures from the gluino and light squark sector have a lower rate, see e.g. [19].

The novel feature of this model is the presence of the vector-like lumberjacks. Note that in the model as described in Sect. (II), these fields would be stable and hence, depending on the cosmological history, potentially phenomenologically unacceptable. To complete the story, one could introduce small $Z_2$ breaking terms that enable lumberjack decays. Since this coupling may violate the symmetry responsible for removing the logs, these couplings may reintroduce logarithmic UV-sensitivity. Therefore, it is necessary that they small enough to not spoil the reduction in tuning. While it is not required, it is interesting to consider the region of parameter space where these couplings are so small that the decays are displaced. This could be motivated by models where the $Z_2$ breaking is generated at the UV scale by a higher dimension operator.

The collider phenomenology of a supersymmetric vector-like fourth generation has been studied previously (see, for example, [20, 21]), and is rich. In particular, logging requires the particular lumberjack soft-mass pattern given in Eq. (14). Post discovery, detailed measurements of the mass spectrum could yield strong evidence that this mechanism is being used by nature to avoid excessive fine-tuning of the weak scale. It would be interesting to study the viability of such measurements at the HL-LHC or FCC-hh. However, since the detailed signatures are highly model dependent in a manner that is unconnected to the supersoft properties we leave the exploration of this phenomenology to future work.

**V. SUMMARY**

Naturalness seeds of doubt were sown when LEP measurements demonstrated precision agreement with the predictions of the Standard Model. They have since germinated due to the paucity of discoveries beyond the Higgs boson at the LHC and are now maturing into a naturalness crisis [22]. Our hope to experimentally access the microscopic provenance of the electroweak scale has been challenged by the interpretation of null results in the context of classic scenarios such as the MSSM and minimal composite Higgs models.

When one assumes that the electroweak hierarchy problem is tamed through the introduction of a new symmetry that commutes with the Standard Model gauge groups, there is a generic expectation that new coloured ‘top-partner’ states should exist in proximity to the weak scale. Since LHC null-results currently imply $m > 900$ GeV, the resultant naive scaling of Higgs mass corrections (Eq. (8)) might cause one to conjecture that naturalness is not a useful guide for predicting the next layer of fundamental physics. This is exacerbated if one assumes that the fundamental microscopic scales satisfy $\Lambda_{\text{UV}} \gg M_H$ as this raises the Higgs mass parameter through large logarithmic enhancements. However, we emphasise here that this scaling is only a minimal expectation, subject to very basic underlying assumptions.

To this end we have embraced the log-enhanced contributions and, rather than attempting to banish them by reducing $\Lambda_{\text{UV}}$, we have instead introduced the lumberjack fields, who screen logs through equal and opposite-sign contributions from the mediation scale $\Lambda_{\text{UV}}$ down to the scale $M$ where they decouple. This significantly reduces the fine-tuning associated with the top sector — resulting in a model where a mediation scale $\Lambda_{\text{UV}} \gg M_H$ can be just as natural as one where the mediation scale is low.

This supersoft strategy has been previously studied for the gauge sector, and is shown here to be possible for the matter sector. In the models presented here, one may have a GUT-scale mediation scale and stops heavier than $\sim 1$ TeV, consistent with current limits [23, 24], with fine-tuning reduced by a factor $\mathcal{O}(30)$ as compared to the most basic MSSM expectation.

The reduced fine-tuning in this supersoft stop model makes clear it is dangerous to over-interpret naturalness implications of null results from LHC coloured particle searches, since any interpretation is highly model dependent. Nature does not have to make the minimal choice, thus it is premature to conclusively declare that high-scale SUSY is incompatible with naturalness.

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