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Authors
Feng, Jonathan L
Wilczek, Frank

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Advantages and distinguishing features of focus point supersymmetry

Jonathan L. Feng [a,*], Frank Wilczek [b]

[a] *Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA*
[b] *Center for Theoretical Physics, Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

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Abstract

Diverse experimental constraints now motivate models of supersymmetry breaking in which some superpartners have masses well above the weak scale. Three alternatives are focus point supersymmetry and inverted hierarchy models, which embody a naturalness constraint, and the more recent framework of split supersymmetry, which relaxes that constraint. Many aspects of their phenomenology are very similar. They can be distinguished, however, through detailed study of superoblique parameters, the Higgs potential and other observables.

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1. Introduction

The standard model of particle physics is fine-tuned. Quantum corrections to the scalar Higgs boson mass^2 are quadratically divergent, so that a natural estimate of their magnitude is αM^2, where M is a cutoff mass. If we associate the cutoff with unification scale or Planck scale physics, we find that the quantum corrections are much larger than the desired net result. This blemish has been a prime motivation for proposing supersymmetric extensions to the standard model. In models with low-energy supersymmetry, naturalness can be restored by having superpartners with approximately weak-scale masses [1]. Low-energy supersymmetry facilitates several other theoretically desirable ideas, including, very notably, quantitatively accurate unification of gauge couplings [2]. It also provides an excellent dark matter candidate [3].

Unfortunately, straightforward breaking of supersymmetry at the weak scale also opens the door to various difficulties. Together with many new particles it introduces many new possibilities for couplings,

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[*] Corresponding author.
E-mail address: jlf@feng.ps.uci.edu (J.L. Feng).

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which generically induce unacceptable violations of observed approximate symmetries. Conservation of R-parity removes the most severe of these difficulties, but significant challenges remain. Superpartners are accompanied by many new flavor mixing angles and CP-violating phases. If those mixings and phases are of order unity, then constraints on flavor-changing neutral currents and the ϵ parameter require some superpartner masses to be at or above ~ 10 TeV and 100 TeV, respectively [4]. If flavor mixing is suppressed, but CP-violating phases are not, the electron and neutron electric dipole moments still require some superpartners to have masses above 2 TeV [5,6]. Finally, bounds arising from theoretical estimates of proton decay and the Higgs boson mass are most easily obeyed if some superpartners have masses well above the weak scale [7,8]. While none of these constraints is completely watertight, taken together they put considerable pressure on models that attempt to keep all superpartner masses close to the weak scale.

An alternative is to take the data at face value and explore the most straightforward interpretation: that some superpartners are superheavy, with masses well above the weak scale. Here we briefly compare and contrast conceptual frameworks for superheavy supersymmetry: focus point supersymmetry [9–12], which is our primary emphasis, inverted hierarchy models [13,14], and split supersymmetry [15,16]. Operationally, below and even at LHC energies, they appear rather similar, for in all, the central proposal is to allow squark and slepton masses to be large, while keeping gaugino masses relatively small. Philosophically, however, they are quite different: focus point supersymmetry retains naturalness of the weak scale as a guiding principle and implements it through a dynamical mechanism, inverted hierarchy models retain naturalness for the weak scale and implement it by hypothesizing a specific family-dependent pattern of supersymmetry breaking masses, while split supersymmetry explicitly abandons naturalness.

Since the robust phenomenological and cosmological features of the focus point and split supersymmetry frameworks, first examined in detail in Refs. [9–12], are so similar, refined measurements will be needed to decide between them. We outline how measurements of superoblique parameters and other practical observables can accomplish that task. If we discover, through the appearance of gauginos but not squarks and sleptons at the Large Hadron Collider (LHC), that a structured form of supersymmetry breaking holds in nature, it will be important to carry out such measurements to elucidate the conceptual meaning of the discovery.

2. Focus point supersymmetry

Focus point supersymmetry is defined by the hypothesis that all squarks and sleptons are superheavy, with masses at the TeV scale or higher, while gauginos and higgsinos remain at the weak scale, and the hypothesis that the weak scale arises naturally. There is tension between these hypotheses, but no contradiction [9,10]. The naturalness requirement, that the electroweak potential is insensitive to small relative changes in the fundamental supersymmetry breaking parameters, can either be met straightforwardly, by having all these parameters small, or through focusing. In the latter alternative, renormalization group evolution focuses a large range of initial values, defined by the fundamental parameters at the unification scale, into a relatively small range of effective values for the phenomenologically relevant parameters at the weak scale.

In practice, insensitivity of the weak scale to variations in the fundamental parameters is largely guaranteed if focusing occurs for the up-type Higgs boson mass. It will occur if the soft scalar masses at the unification scale are in the ratio [10]

$$\left(m_{H_u}^2, m_{\tilde{t}_R}^2, m_{\tilde{t}_L}^2\right) \propto (1, 1+x, 1-x) \tag{1}$$

for moderate values of $\tan\beta$, and

$$\begin{aligned}&\left(m_{H_u}^2, m_{\tilde{t}_R}^2, m_{\tilde{t}_L}^2, m_{\tilde{b}_R}^2, m_{H_d}^2\right)\\ &\quad \propto (1, 1+x, 1-x, 1+x-x', 1+x')\end{aligned} \tag{2}$$

for large values of $\tan\beta$, where x and x' are arbitrary constants. A universal scalar mass obviously satisfies both Eqs. (1) and (2), but in principle more general possibilities are allowed. Given Eq. (1) or Eq. (2), focusing occurs for any weak-scale gaugino masses and A-parameters, any moderate or large value of $\tan\beta$, and any top quark mass within existing experimental bounds. Note that focusing makes the weak scale insensitive to variations in parameters introduced to explain the weak scale, the supersymmetry breaking parameters, but not to variations in other parameters, such as the top quark Yukawa coupling. Of course, the fact that the measured top quark mass is compatible with focusing for simple boundary conditions is tantalizing, if preliminary, quantitative evidence for focus point supersymmetry.

Focus point supersymmetry has been studied in great detail for the specific case of minimal supergravity. For top quark mass $m_t = 174$ (178) GeV, the region in which all phenomenological constraints are satisfied and relic neutralino dark matter has the observed density is at $m_0 \sim 3$ (8) TeV [10,17]. Such superheavy squarks and sleptons sufficiently suppress one-loop contributions to the electron and neutron electric dipole moments even for $\mathcal{O}(1)$ phases. Two-loop effects are dominant and might be within experimental reach in the near future [18]. The high sfermion masses, together with additional suppression from squark and slepton degeneracy as occurs in unified focus point models, comfortably solve all problems with flavor-violation and flavor-violating CP-violation [12]. Of course, given the Tevatron Run I average top mass of $m_t = 178.0 \pm 4.3$ GeV [19] and the most recent average including preliminary Run II results of $m_t = 174.3 \pm 3.4$ GeV [20], values of m_t higher than 178 GeV are still well within current constraints. For such top masses, the focus point region moves to values of $m_0 \gtrsim 10$ TeV. In this regime the heaviness of squarks and sleptons can remove all the flavor and CP problems associated with low-energy supersymmetry without the need for flavor degeneracy or additional assumptions.

A broad variety of phenomenological implications and virtues of the focus point spectrum has been explored more generally in Refs. [9–12]:

- A noteworthy feature is that radiative corrections to the predicted value of the Higgs boson mass arising from loops containing heavy top and bottom squarks can raise the Higgs boson mass well above current bounds [12]. This feature does not occur for inverted hierarchy models [13,14], in which the light fermions have superheavy partners, while the heavy fermions have light (weak-scale) superpartners. Like focus point supersymmetry, inverted hierarchy models resolve many of the phenomenological difficulties generically associated with low-energy supersymmetry without sacrificing naturalness, because experimental constraints are stringent only for observables involving the first two generations, while naturalness constraints are stringent only for fields with large couplings to the Higgs sector [13].
- Gauge unified focus point models naturally obey constraints on proton decay as well [12]. Viewed in isolation, suppression of proton decay does not pose a critical problem: the dangerous processes involve virtual exchange of both standard model superpartners and unification-scale particles, especially the color triplet Higgs superpartners, and they can always be satisfied by raising the masses of the latter. But if we want to maintain the impressive quantitative success of the unification of couplings, which is a major motivation for low-energy supersymmetry, then obtaining sufficient suppression of proton decay is problematic [21]. Coupling constant unification constrains unification-scale threshold effects, which in simple unification models implies upper bounds on GUT-scale masses. With superheavy squarks and sleptons, this difficulty is resolved, and one is left with viable (and interesting!) expectations for proton decay.
- In focus point models the lightest supersymmetric particle (LSP) is a neutralino that provides a dark matter candidate with excellent prospects for detection [11]. In this context, the neutralino cannot be pure bino, because in that case it annihilates through $\tilde{B}\tilde{B} \to f\bar{f}$ with a t-channel sfermion $\tilde{f}$, and these processes become inefficient for $m_{\tilde{f}}$ in the multi-TeV range or above, leading to an overabundant relic density. For neutralinos with significant wino or higgsino component, however, $\chi\chi \to WW$ and $\chi\chi \to ZZ$ become efficient, and the LSPs relic density is naturally in the desired range. For similar reasons, mixed neutralinos give rise to relatively large direct and indirect detection rates.

3. Abandoning naturalness?

The confluence of the existing failure to explain the anomalously small value of the cosmological term in a natural way, the suggestion from inflationary scenarios that on ultra-ultra-large scales the Universe might be drastically inhomogeneous, and the longstanding indications that consistent solutions of the equations of string theory provide a plethora of candidate macroscopic universes [22] have rekindled interest in the possibility that selection effects (random or anthropic) play a more central role, and the program of explanation through symmetry and naturalness a less central role, than traditionally has been assumed in theoretical physics. While it is certainly logically possible that one will be driven in that direction, we feel that it is a wise methodological principle to attempt to maintain the tightest available explanatory framework until forced to abandon it. Moreover, in several specific instances, including the unification of couplings, the smallness of the θ term in QCD, and the extremely long lifetime of the proton, it is difficult to conceive of plausible selection effects that could supplant symmetry as an explanation of the observed phenomena.

The central proposal of split supersymmetry is to drop any direct connection between low-energy supersymmetry and the solution of the weak scale hierarchy problem [15,16]. On the face of it, that idea would suggest that all superpartners acquire unification or Planck-scale masses, if indeed one has supersymmetry at all. To preserve desirable features of low-energy supersymmetry, i.e., quantitative unification of couplings and the existence of a good dark matter candidate, however, additional residual symmetries (and fine-tunings, see below) are postulated to ensure that there are gauginos and higgsinos with weak-scale masses. Thus, phenomenologically, split supersymmetry is very similar to focus point supersymmetry, but one no longer requires Eq. (1) or Eq. (2), and the squark and slepton masses are allowed to become arbitrarily large.

Are the distinctions testable? The answer is not immediately obvious, because those distinctions lie in the masses of the superheavy superpartners, which are beyond the reach of currently planned colliders and largely decouple from low energy observables.

4. Tests of naturalness

One might hope to distinguish focus point and split supersymmetry by finding evidence for extremely large squark and slepton masses. Extremely heavy sfermions lead, through radiative corrections, to large Higgs boson masses, for example. An even more striking prediction is that, for extremely heavy squarks, gluinos become long-lived, with lifetime [23]

$$\tau_{\tilde{g}} \sim \left(10^{-12}\ \mathrm{s}\right)\left[\frac{m_{\tilde{q}}}{10^6\ \mathrm{GeV}}\right]^4\left[\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right]^5. \qquad (3)$$

Long-lived, weak-scale gluinos have been studied in Refs. [24]. They arise in theories with weak-scale supersymmetry breaking where the gluino is the LSP or decays only to a gravitino LSP. Those studies motivated discussions of the accompanying collider phenomenology and appropriate triggers long before the proposal of split supersymmetry. Nevertheless, coexistence of long-lived gluinos with lighter neutralinos and charginos could provide an unambiguous signal of superheavy sfermions.

Unfortunately, for Eq. (3) to yield a practically detectable lifetime, sfermion masses probably must exceed 10^6 GeV. Such large masses pose a significant challenge, because Weyl anomaly-mediated contributions [25,26] require gaugino/higgsino masses to be suppressed relative to sfermion masses by no more than a factor of $\sim g^2/(16\pi^2)$. If such contributions are present, then, the natural range for the superheavy sfermion masses is constrained to be at or below 10^5 GeV. Of course, given the few guiding principles in split supersymmetry, there is no requirement that anomaly-mediated contributions be present at the expected order of magnitude.

Both split supersymmetry and focus point supersymmetry can accommodate superheavy superpartner masses in the 10^4 to 10^5 GeV range. As noted above, the focus point mechanism preserves naturalness for $m_t = 178$ GeV for scalar masses ~ 10 TeV and weak-scale gauginos and higgsinos. However, the preferred sfermion mass range depends on the top quark mass and increases rapidly for larger m_t. A careful analysis of renormalization group equations and electroweak symmetry breaking is required to determine the exact relation. However, given the currently favored range of top quark masses, large sfermion masses above 10 TeV are certainly a possibility, and the mere presence of sfermion masses in this range cannot be used to distinguish between natural and fine-tuned theories.

A far more incisive method for differentiating superheavy particle spectra is through superoblique parameters [27]. Superoblique parameters measure splittings between dimensionless couplings and their supersymmetric analogues. Exact supersymmetry demands equality of these couplings, but split supermultiplets introduce corrections [28,29]. As with their electroweak analogues, the oblique corrections [30], superoblique corrections are non-decoupling: they become *large* for highly split supermultiplets. They can be determined by precise measurements of the properties of light superpartners, which are kinematically accessible in both focus point and split supersymmetry frameworks. These properties imply that superoblique parameters are likely to play an essential role in the experimental exploration of any supersymmetric theory in which some superpartners are beyond direct detection.

The full set of possible superoblique parameters has been cataloged [31], and their measurement at colliders has been explored in detail in several studies [31–37].[1] In the leading logarithm approximation, the superoblique parameters are

$$\tilde{U}_i \equiv \frac{h_i}{g_i} - 1 \approx \frac{g_i^2}{16\pi^2}(b_{g_i} - b_{h_i}) \times \ln R, \tag{4}$$

where $i = 1, 2, 3$ denotes the gauge group U(1), SU(2), or SU(3), g_i is the standard model gauge coupling, h_i its supersymmetric analogue, and R is the ratio between the effective superheavy superpartner mass scale and the weak scale. The coefficients b_{g_i} and b_{h_i} are the one-loop beta function coefficients for g_i and h_i for the effective theory between the superheavy and weak scales; $b_{g_i} - b_{h_i}$ is therefore the contribution from standard model particles whose superpartners are superheavy. For focus point supersymmetry and split supersymmetry in which all sfermions are superheavy, the superheavy particles are in complete multiplets of SU(5), and so $b_{g_i} - b_{h_i}$ is independent of i. Numerically, $b_{g_i} - b_{h_i} = 4$, and

$$\tilde{U}_1 \approx 1.2\% \log_{10} R, \tag{5}$$

$$\tilde{U}_2 \approx 2.5\% \log_{10} R, \tag{6}$$

$$\tilde{U}_3 \approx 8.3\% \log_{10} R. \tag{7}$$

In focus point supersymmetry and split supersymmetry, the superoblique parameters can be measured in a number of ways. As an example, consider the chargino mass matrix

$$\boldsymbol{M}_{\chi^\pm} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}} h_2 v \sin\beta \\ \frac{1}{\sqrt{2}} h_2 v \cos\beta & \mu \end{pmatrix}. \tag{8}$$

In the limit of exact supersymmetry, the Whh and $\tilde{W}\tilde{h}h$ couplings are identical, and so h_2 is equal to g_2, the SU(2) gauge coupling constant. Superheavy superpartners break this degeneracy, and predict a non-vanishing superoblique parameter $\tilde{U}_2$. Dark matter constraints require significant mixing in the neutralino and chargino sectors, and so it is likely that both charginos and all four neutralinos will be produced at the Large Hadron Collider and the International Linear Collider.

The possibility of measuring superoblique parameters at the International Linear Collider in scenarios with mixed charginos and neutralinos has been discussed in Refs. [31,32,36]. Supersymmetric parameters may be constrained by measuring chargino and neutralino masses and bounding the polarized cross sections for chargino and neutralino pair production. The sensitivity to the superheavy mass scale entering through the dependence of the chargino mass matrix on $\tilde{U}_2$ may be quite large. For example, in the mixed scenario studied in Ref. [36], the cross section $\sigma_R = \sigma(e_R^- e^+ \to \chi_1^+ \chi_1^-)$ varies from ~ 50 fb to 62 fb as the superheavy scalar mass scale varies from 1 to 10 TeV. Given an integrated luminosity of 50 fb^{-1}, the statistical uncertainty in σ_R is $\sim 2\%$, corresponding to an uncertainty in the superheavy mass scale of $\Delta \log_{10} R \sim 0.1$. Of course, this precision will be compromised by systematic experimental uncertainties and uncertainties in other supersymmetry parameters. The size of these effects depends on the underlying supersymmetry scenario realized in nature, the final properties of the International Linear Collider, and the success with which other experiments may be used to constrain supersymmetry parameters, such as $\tan\beta$. Nevertheless, barring the possibility that these effects completely degrade the statistical precision, constraints on the superheavy superpartner mass scale to within an order of magnitude ($\Delta \log_{10} R \sim 1$) appear possible.

Fine structure within the superheavy superpartner mass spectrum may be constrained by precise measurements of branching fractions mediated by virtual superheavy superpartners. The branching frac-

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[1] The super-oblique parameters have also recently been discussed again in the context of split supersymmetry, for example in Ref. [15], where a subset of them have been reparametrized and denoted κ.

tions $B(\tilde{g} \to q_R \bar{q}_R \chi)$ and $B(\tilde{g} \to q_L \bar{q}_L \chi)$ are sensitive to the fourth powers of $m_{\tilde{q}_R}$ and $m_{\tilde{q}_L}$, respectively. For the cases of greatest interest here, where $q = t, b$, these branching fractions with polarized final states can be distinguished through the energy distributions of q decay products. Splittings in the superheavy spectrum also result in different effective R parameters for the different superoblique parameters, and so additional rough constraints on fine structure can also be obtained if the superoblique parameters can be measured in more than one way. Finally, $m^2_{H_u}$ and $m^2_{H_d}$ can be determined by precise measurements of μ, $\tan\beta$, and other parameters entering the Higgs potential.

These weak scale parameters can then be extrapolated to high scales to determine the fundamental soft supersymmetry-breaking parameters. This program is challenging. However, if superheavy masses above 100 TeV are realized in nature, even rough constraints on the superheavy mass scale will likely provide evidence for fine-tuning or, alternatively, motivate focusing or other mechanisms different from those discussed so far. On the other hand, consistency with superheavy mass scales below 100 TeV and with the predictions of Eqs. (1) and (2) would constitute striking evidence for focus point supersymmetry and naturalness. It would further motivate mechanisms of supersymmetry breaking that explain Eqs. (1) and (2), providing essential guidance for the next step to more fundamental theories.

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