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Predictive supersymmetry from criticality

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Abstract

Motivated by the absence of any direct signal of new physics so far, we present a simple supersymmetric model in which the up-type Higgs mass-squared parameter $m_{H_u}^2$ crosses zero at a scale close to the weak scale. Such a theory may be motivated either by the conventional naturalness picture or by the landscape picture with certain assumptions on prior probability distributions of parameters. The model arises from a simple higher dimensional setup in which the gauge and Higgs fields propagate in the bulk while the matter fields are on a brane. The soft supersymmetry breaking parameters receive contributions from both moduli and anomaly mediations, and their weak scale values can be analytically solved for in terms of a single overall mass scale M. The expected size for M depends on whether one adopts the naturalness or landscape pictures, allowing for the possibility of distinguishing between these two cases. We also present possible variations of the model, and discuss more general implications of the landscape picture in this context.

1. Introduction

Weak scale supersymmetry is an extremely attractive idea. It is based on a beautiful theoretical construction of enlarging the spacetime structure to anticommuting variables, and is supported indirectly by the successful unification of gauge couplings at high energies [1]. It also stabilizes the large hierarchy between the weak and the Planck scales due to a cancellation between the standard model and its superpartner contributions to the Higgs potential. In fact, this latter property has been one of the strongest motivations for weak scale supersymmetry.

From the experimental point of view, the most exciting aspect of weak scale supersymmetry is the existence of various superpartners at the TeV scale. Can we predict the spectrum of these superparticles? We already know, from the absence of a large new contribution to flavor changing neutral current and *CP*-violating processes, that the superparticle spectrum must have a certain special structure, such as flavor universality. Moreover, non-discovery of both superparticles and a light Higgs boson at LEP II puts strong constraints on the spectrum. This typically leads to fine-tuning of order a few percent in reproducing the correct scale for electroweak symmetry breaking, and is called the supersymmetric fine-tuning problem (for a recent analysis, see [2]). It seems plausible that successfully addressing this problem provides a key to the correct theory at the TeV scale, and to a fundamental mechanism or principle behind it.

There are two different approaches towards the supersymmetric fine-tuning problem. A conventional approach is to search for a model that is "natural". In the context of the minimal supersymmetric standard model (MSSM), this amounts to looking for a model in which the supersymmetry breaking mass-squared parameter for the up-type Higgs field, $m_{H_u}^2$, is somehow suppressed at

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the weak scale, since the electroweak scale is determined approximately by

$$\frac{M_{\rm Higgs}^2}{2} = -m_{H_u}^2 - |\mu|^2, \tag{1}$$

so that smaller $|m_{H_u}^2|$ requires a smaller amount of cancellation between the $m_{H_u}^2$ and $|\mu|^2$ terms, where $M_{\rm Higgs}$ and μ represent the physical Higgs boson mass and the supersymmetric Higgs-mass parameter, respectively. On the other hand, there are lower bounds on the masses of superparticles, coming from the experimental bounds on the superparticle and the Higgs boson masses. This leads to a nontrivial tension between the values of $m_{H_u}^2$ and other generic supersymmetry breaking squared masses $\tilde{m}^2$—typically it requires a small hierarchy between $|m_{H_u}^2|$ and $\tilde{m}^2$. In the context of gravity mediation—arguably the "simplest" mediation of supersymmetry breaking—this implies that we must find a model in which the "tree-level" and "radiative" contributions to $m_{H_u}^2$ cancel to a large extent, either "accidentally", as in the scenario of [3], or by some mechanism, as in the model of [4,5].

An alternative approach towards the problem appears if we live in "the multiverse", rather than the universe. Motivated partly by Weinberg's successful "prediction" of the observed value of the cosmological constant [6], and partly by the suggestion that string theory has an exponentially large number of discrete nonsupersymmetric vacua [7], it has become increasingly plausible that our universe is only one among a tremendous number of various universes, in which physical constants can take vastly different values. This "landscape" hypothesis may lead to a significant change in our notion of naturalness, and it is reasonable to consider the supersymmetric fine-tuning problem in this context. It has recently been argued that the landscape picture may lead to a small hierarchy between the Higgs mass-squared parameter and the scale of superparticle masses $\tilde{m}$ under certain assumptions on the probability distributions of various couplings and $\tilde{m}$ [8]. Specifically, under the existence of statistical "pressures" pushing $\tilde{m}$ towards larger values, the relation $v^2 \sim \tilde{m}^2/8\pi^2$ may be obtained from environmental selection, where v is the electroweak scale.[1] Moreover, if the parameter μ also scans independently with $\tilde{m}$ and if the holomorphic supersymmetry breaking Higgs mass-squared parameter, μB, is sufficiently small at a high scale, then we obtain $v^2 \sim |\mu|^2 \sim |m_{H_u}^2| \sim \tilde{m}^2/8\pi^2$.

It is interesting that the two different pictures described above can both lead to a scenario in which the supersymmetry breaking parameter $m_{H_u}^2$ crosses zero at a scale not much different from the weak scale. In fact, the two pictures may not be totally unrelated. Suppose, for example, that the ultraviolet theory at the gravitational or unification scale gives universal scalar squared masses m_0^2 (> 0), as in the minimal supergravity scenario [11]. In this case, the parameter $m_{H_u}^2$ crosses zero at a renormalization scale of order the weak scale, as long as the gaugino masses are small compared with $|m_0^2|^{1/2}$. This phenomenon is known as focus point behavior, and this class of theories was claimed to be natural [3], since $|m_{H_u}^2|$ is relatively small at the weak scale and thus no strong cancellation is required between the two terms in the right-hand side of Eq. (1). An immediate criticism of this argument, based on the conventional viewpoint, is that if the value of the top Yukawa coupling, y_t, were different, then the property of $|m_{H_u}^2|$ being small at the weak scale would be destroyed—in other words, the fractional sensitivity of the weak scale, v, to a variation of the top Yukawa coupling, $\partial \ln v^2/\partial \ln y_t$, is very large. This criticism, however, is not appropriate if the property of $|m_{H_u}^2| \ll \tilde{m}^2$ at the weak scale is a result of environmental selection. In this case, if y_t were changed, the scale of supersymmetry breaking masses, $\tilde{m}$, would also be changed in such a way that $|m_{H_u}^2| \sim \tilde{m}^2/8\pi^2 \ll \tilde{m}^2$ *at the "new" weak scale* $\sim |m_{H_u}|$. As a result, we always find $|m_{H_u}^2| \ll \tilde{m}^2$ at the "weak scale" *regardless of the value of* y_t. The observed value of y_t will then be determined as a result of (another) environmental selection, presumably a combination of the consideration in [12] and others.

From the point of view of model-building, i.e. searching for the model describing physics above the TeV scale, we may then be motivated to look for a model in which $|m_{H_u}^2|$ is suppressed compared with $\tilde{m}^2$ at the weak scale, i.e. $|m_{H_u}^2|$ crosses zero at a scale close to the weak scale. If this property arises without a strong cancellation between the "tree-level" and "radiative" contributions to $|m_{H_u}^2|$, then we can consider that the model is natural in the conventional sense. Even if it arises due to a strong cancellation, however, the model may still be interesting since it can arise as a result of environmental selection under certain circumstances. Note that the requirement of $|m_{H_u}^2|$ being suppressed at the weak scale is different from the one that the Higgs mass-squared parameter, $|m_h^2| \simeq |m_{H_u}^2 + |\mu|^2|$, is suppressed at the weak scale, which should always be the case. We are requiring that the cancellation (if any) must take place "inside" $m_{H_u}^2$, and not between $m_{H_u}^2$ and $|\mu|^2$.

Since the condition of $|m_{H_u}^2| \ll \tilde{m}^2$ at the weak scale gives only one constraint on the large number of soft supersymmetry breaking masses, we clearly need other guiding principles to narrow down the possibilities and obtain predictions on the superparticle masses. Without having a detailed knowledge of physics at the gravitational or unification scale, we simply take the viewpoint that the physics at that scale should be "simple"—sufficiently simple that the resulting supersymmetry breaking masses also take a simple form. This clearly makes sense if we take the conventional "universe" picture, and may also be supported by the absence of large supersymmetric flavor-changing and *CP*-violating contributions (which would arise if the superparticle masses were chaotic).

[1] This conclusion depends on the probability distributions of parameters. For example, if certain couplings do not "scan", the low-energy theory may be split supersymmetry [9], or simply the standard model [10]. The assumption here corresponds to an independent scanning of $\tilde{m}$ and the supersymmetric couplings. It is interesting that supersymmetry may still play an important role in addressing the gauge hierarchy problem even in the existence of a landscape of vacua, under certain mild assumptions.