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— Yasunori Nomura —

One of the most pressing issues in theoretical particle physics is to understand the origin of electroweak symmetry breaking. Weak scale supersymmetry is a leading candidate theory for this purpose. This theory, however, has been put in a subtle position after non-discovery of both superparticles and a light Higgs boson at LEP II — to reproduce the correct scale for electroweak symmetry breaking, parameters of the theory should be finely tuned. This problem is called the supersymmetric fine-tuning problem.

In Ref. [6], I have constructed, with Kitano, a model in which the supersymmetric fine-tuning problem is solved without extending the Higgs sector at the weak scale. We have demonstrated that the model can avoid all the phenomenological constraints, while avoiding excessive fine-tuning. We have also studied implications of the model on dark matter physics [7] and collider physics [11]. We have elaborated on several interesting features of the theory, such as a special renormalization group property of the soft supersymmetry breaking masses, and identified characteristic signatures at the LHC experiment. In Ref. [13], continuing this research, I have pointed out with Kitano that the fine-tuning problem implies a small mass term for the Higgs multiplets (μ term), which implies model independently that the lightest neutralino contains a non-negligible amount of the Higgsino component. This ensures that the correct abundance of dark matter is reproduced as a thermal relic of the early universe, in contrast with the situation in the minimal supergravity scenario where a special mass pattern is needed. The non-negligible Higgsino component also enhances the possibility of dark matter detection in future direct detection experiments.

The problem of fine-tuning may imply that weak scale supersymmetry is realized in a way different from the conventional grand desert framework. One of such theories can give the physical Higgs boson mass larger than what is allowed in conventional supersymmetric theories. This is very important because such a large Higgs-boson mass allows the possibility of a significant reduction of fine-tuning needed for correct electroweak symmetry breaking in general supersymmetric theories. In Ref. [1], I have constructed, with Birkedal and Chacko, an example of this class of theories. These theories allow the lightest Higgs-boson mass as large as a few hundred GeV ($(200\sim300)$ GeV) while preserving the successful supersymmetric prediction for gauge coupling unification. This is achieved by localizing a part of the Higgs sector on the infrared brane. The structure of the Higgs sector in the four dimensional effective theory below the Kaluza-Klein mass scale is essentially that of the next-to-minimal supersymmetric standard model (NMSSM), or related theories. However, large values of the NMSSM couplings at the weak scale are now possible as these couplings are required to be perturbative only up to the infrared cutoff scale, which can in general be much lower than the unification scale. This allows the possibility of generating a large quartic coupling in the Higgs potential, and thereby significantly raising the Higgs-boson mass bound in supersymmetric theories.

I have further shown that, using the ingredients discussed above, it is possible to construct a model in which the amount of fine-tuning is reduced to the level of 20% [4] (with Chacko and Tucker-Smith), which is partly based on the idea presented in Ref. [2]. This is significantly better than any of the existing supersymmetric models. I have further promoted this to a general framework [5] (with Tweedie). In this paper we have identified general conditions under which the supersymmetric fine-tuning problem is alleviated. Supersymmetry is dynamically broken at a scale $\Lambda \approx (10 \sim 100)$ TeV, which is transmitted to the supersymmetric standard model sector through standard model gauge interactions. The dynamical supersymmetry breaking sector possesses an approximate global $SU(5)$ symmetry, whose $SU(3) \times SU(2) \times U(1)$ subgroup is explicitly gauged and identified as the standard model gauge group. This $SU(5)$ symmetry is dynamically broken at the scale Λ, leading to pseudo-Goldstone boson states. This is a very interesting class of theories, and we have performed a detailed phenomenological analysis, including general properties of the pseudo-Goldstone boson states, collider signatures, and cosmology. Along similar lines, I have also studied supersymmetric theories in which the fine-tuning problem is solved by extending the Higgs sector at the weak scale [8, 9] (with Poland and Tweedie). We have constructed several models which contain a singlet field in the Higgs sector, and shown that the models can evade excessive fine-tuning. We have found that electroweak symmetry breaking in these models occur through the holomorphic supersymmetry breaking squared mass for the Higgs doublet (the μB term), unlike the conventional case where it occurs through top-stop radiative corrections.

More generally, in Ref. [14], I have studied, with Barbieri, Hall and Rychkov, the possibility that the mass of the lightest Higgs boson is much heavier than that in the minimal supersymmetric standard model. This completely eliminates fine-tuning and can be realized, for example, if some nonperturbative physics plays a role at the $(10 \sim 100)$ TeV scale. We have shown that this scenario is compatible with the precision electroweak data. An alternative realization of this scenario is that the grand desert is simply absent. I have shown in Ref. [15], with Poland, that such a model can be constructed without any phenomenological problems. Another class of models eliminating fine-tuning, using a specific mechanism of supersymmetry breaking, was constructed in Ref. [16] (with Poland).

An important problem of weak scale supersymmetry is that generic superparticle masses lead to excessive flavor changing neutral currents at low energies. This problem is avoided if supersymmetry breaking is mediated to the supersymmetric standard model sector through standard model gauge interactions. Models of this class are called gauge mediation. Existing models, however, rely on extremely complicated dynamics and they can be viewed at best an existence proof. With Murayama, I have proposed in Refs. [17, 18] an extremely simple construction for models of gauge mediation. The basic ingredients of the construction are an emergent approximate $U(1)_R$ symmetry and a local supersymmetry breaking minimum. With this construction, a simple vector-like system can successfully breaks supersymmetry and mediate it to the supersymmetric standard model sector. We think this provides a fully satisfactory and realistic solution to the flavor changing problem in supersymmetric theories. I also performed, in the work with Murayama and Poland [19], a general analysis on the effects of a strongly coupled hidden sector on the superparticle spectrum. We found that the effects are significant and often lead to a pattern of the superparticle spectrum that was not considered before. We classified general possibilities in terms of certain parameters (the ratios of the anomalous dimensions of hidden sector operators) and discussed their experimental implications. This is an important work, opening the possibility of discriminating the dynamics of the hidden sector at future collider experiments, such as the LHC and a linear collider.

Another notorious problem in supersymmetric theories, especially in theories in which the supersymmetry breaking effects are mediated to the standard-model sector by gauge interactions, is the so-called μ problem. In Ref. [25], I found (with Csaki, Falkowski and Volansky) that this problem can be simply and elegantly solved in a class of models where the Higgs fields couple directly to the supersymmetry breaking sector. This is a significant achievement, since most of the theories proposed in the past decade suffer from this problem. Moreover, we identified a class of generic signatures that can be used to experimentally test this solution. Finding such signatures will provide significant handles on the structure of the supersymmetry breaking sector.

In Ref. [21], I proposed (with Papucci and Stolarski) a new way of addressing the flavor problem of supersymmetric theories. Despite the common lore, we found that the supersymmetric flavor problem is not as severe as eliminating interesting flavor signatures at the LHC. We showed that a simple scaling of the supersymmetry breaking parameters with the Yukawa couplings eliminates essentially all the dangerous low energy flavor and CP violating processes, while allowing for spectacular flavor signatures at the LHC. In particular, we identified a class of smoking-gun signatures for these "flavorful" supersymmetric theories arising in the plausible case that the gravitino is the lightest supersymmetric particle and one of the sleptons is the next-to-lightest supersymmetric particle. The analysis of this class of models was further extended in Refs. [23, 24]. I also constructed Papucci a simple model of dynamical supersymmetry breaking [20]. This model can be naturally accommodate into the flavorful supersymmetry framework described above.

A virtue of theories with weak scale supersymmetry is that the strengths of three gauge interactions of the standard model unify at the scale of $\approx 10^{16}$ GeV. Theories at this scale, grand unified theories, have been an active target of research. In Ref. [12], I have proposed with Poland and Tweedie a new framework of constructing theories of grand unification. A grand unified group is dynamically broken by some strong interactions which have a gravitational dual description. The resulting theories are formulated in higher dimensional warped space, and we can use techniques and intuitions developed in higher dimensional model building. This opens a new arena for grand unified model building. I have also studied a possibility that physics making electroweak symmetry breaking natural is non-supersymmetric. In Ref. [10], I have studied a model, with Chacko, Papucci and Perez, in which radiative corrections to the Higgs mass squared parameter is regulated by fields which are singlet under the standard model gauge group. We have studied implications of such a model at the LHC.

Recently, several experiments reported unexpected excesses of electron/positron fluxes in cosmic ray data. These data strongly suggest a new source of galactic electrons and positrons. While this may be due to some astrophysical sources, it may be a manifestation of dark matter. In collaboration with Thaler, I constructed a simple and elegant model of dark matter which explains these signatures [26]. The model provides various implications on particle physics experiments; in particular, the model predicts the existence of a new light boson which has certain definite properties. This stimulated search of this state at low energy experiments, including B factories. After our paper is presented, the BaBar experiment performed such a search, and provided a constraint on the parameter space. With Mardon, Stolarski, and Thaler, I further studied possible signatures of this and related classes of theories in future experiments, including gamma ray, radio, and neutrino observations [27]. We found that future measurements can provide further evidence of or stronger constraints on the dark matter interpretation. A detailed structure of the underlying particle physics theory may also be extracted from such measurements. In Ref. [29], I also proposed a related class of models in which the electron/positron signals are explained by slow decay of dark matter, instead of annihilations. The models are very naturally realized in the context of the low-energy supersymmetry breaking scenario, which elegantly avoids various cosmological problems in generic supersymmetric models.

I also studied cosmology. In Ref. [3], I constructed, with Hall and Oliver, a model of dark energy in which evolving quintessence-type dark energy is naturally obtained. The small mass scale that governs evolution, $m_\phi \approx 10^{-33}$ eV, is radiatively stable, and the "Why Now?" problem is solved. These results rest crucially on seesaw cosmology: in broad outline, fundamental physics and cosmology can be understood from only two mass scales, the weak scale and the Planck scale. The low-scale supersymmetry breaking is crucial for the realization of this scenario.

Finally, there is an emerging picture that our universe may be just one of many universes, in which physical law takes different forms than in our own universe. This picture is supported by the observed dark energy (cosmological constant), since its existence is explained naturally only with the multiverse hypothesis. With Lawrence Hall, I studied if we can find other evidence of the multiverse [22]. We found that there are mysterious coincidences in cosmology and nuclear physics, which are very difficult to understand in the conventional picture but are easily explained with the multiverse picture. We developed a general scheme to analyze the multiverse physics and a way to extract predictions which can be observationally tested. In particular, we considered effects of the multiverse on the spectrum of particles in physics beyond the standard model, and argued that it generically solves the long-standing "little hierarchy" problem. This is an important observation and may provide an additional support to the multiverse picture, depending on what the LHC finds in the next few years. I also explored (with Bousso and Hall) the possibility that various mysterious coincidences in our universe may be understood in the multiverse picture [28]. In our universe, various seemingly unrelated timescales are close with each other; for example, timescales for the dark energy domination, virialization, radiative cooling, and Compton cooling of proto-galaxies, and the appearance of observers are all about 10 Gyr. Such coincidences are hard to understand in the conventional framework of physics based on symmetries. We showed that once we postulate the existence of the multiverse, which contains universes with varying physical constants, these coincidences are all explained simultaneously. Throughout these work, we introduced certain concepts–the multiverse force and catastrophic boundaries–as tools to provide testable predictions from the multiverse framework. This is an important advance towards potentially testing the idea of the multiverse observationally.

In performing research described above, it was crucial that I could get appropriate support. The OJI fund was used for this purpose both to provide my summer salary for the first year and material supply. To promote a vigorous research effort, it was also important that I could travel and interact with other active researchers in the field. The fund was also used to cover a part of the expense for these travels.

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