The kind of supersymmetry that can be discovered at the LHC must be very much flavor-blind, which used to require very special intelligently designed models of supersymmetry breaking. This led to the pessimism for some in the community that it is not likely for the LHC to discover supersymmetry. I point out that this is not so, because a garden-variety supersymmetric theories actually can do this job.

1 Introduction

LHC is coming! It is finally taking us to the energy scale of the weak interaction, $G_F^{-1/2} \approx 300$ GeV, known as an important energy scale for more than seven decades since Fermi’s 1933 paper on the nuclear beta decay. It is a historic moment in science and I am very excited to be part of this new era. Whenever physicists had crossed a threshold of studying a new force, it resulted in a big paradigm change. The atomic scale (scale of quantum electrodynamics) led to the revolutionary discovery of quantum mechanics. The nuclear scale (scale of quantum chromodynamics) revealed a new layer of matter and showed the non-perturbative quantum field theory to be essential in our description of nature. We are all looking forward to whatever paradigm change the weak scale will bring us.

However, there has been a growing concern in the community, especially among the theorists, that we may not find anything surprising at the electroweak scale. I have been bitten by this bug, too. The reasoning is very simple. If there is new rich physics below the TeV scale such as supersymmetry and/or extra dimensions, why haven’t we seen its impact already on precision electroweak and flavor-physics experiments? Because we haven’t seen such impacts, it is unlikely that there is rich new physics below the TeV scale and most likely we will not find anything spectacular at the LHC.

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This talk is based on the collaboration with Yasunori Nomura.
Figure 1: The “landscape” of supersymmetric theories. (Left) I used to believe theories that break supersymmetry are very special, and much of them do not lead to phenomenologically viable theories. “Alive” theories are very small minorities. (Right) Now I believe there is a large class of theories that break supersymmetry, and a major fraction of them can be phenomenologically viable. Hence, easy, viable, and generic.

Even though I had plunged into this pessimism myself, I have now completely turned around back to optimism. I do think it is quite likely for the LHC to find something exciting such as supersymmetry. I would like to tell you why I made this 180 degrees change in my attitude.

The issue is the following. Supersymmetry, if present at the TeV scale, must be a broken symmetry because we have not seen any superpartners yet. The problem is that it has been believed that breaking supersymmetry is very difficult, and certainly is not generic among supersymmetric theories. Even among those that do break supersymmetry, they are rather difficult to use for constructing phenomenologically viable models, hence most of them are dead on arrival. A very small fraction of the minority then survive, after an elaborate model-building gymnastic, namely the “alive” theories are “pockets of insurgency” in the barren land. An elaborate model is like a beautiful artwork, intelligently designed, which is what makes its creator(s) proud, but is by definition special and fragile. I can’t stop feeling that Nature is unlikely to rely on such a fragile elaborately built artwork for the foundation of its inner working.

I now feel the situation is very different from the previous perception. There is a large fraction of supersymmetric models that can successfully break supersymmetry in a phenomenologically viable fashion. And it appears rather robust, namely a change in parameters, such as choice of the gauge groups, number of flavors, does not spoil its success. This observation makes it much more plausible that supersymmetry has a broad and robust foundation to be realistic, and makes me feel that it could well be there waiting for us at the LHC.

2 Hierarchy Problem

It is often said that the hierarchy problem has been overemphasized as a reason to expect rich physics at the LHC. There is some truth in it, because, after all, it is an aesthetic problem. However, I’d like to first remind you that the hierarchy problem was actually solved once in the history of physics, and we can draw some lesson from it.

In the classical electromagnetism, the only dynamical degrees of freedom are electrons, electric fields, and magnetic fields. When an electron is present in the vacuum, there is a Coulomb electric field around it, which has the energy of

$$\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{r_e}.$$  (1)

Here, $r_e$ is the “size” of the electron introduced to cutoff the divergent Coulomb self-energy. Since this Coulomb self-energy is there for every electron, it has to be considered to be a part of the electron rest energy. Therefore, the mass of the electron receives an additional contribution due to the Coulomb self-energy:

$$m_{e}c^2 = \left(m_{e}c^2\right)_{\text{bare}} + \Delta E_{\text{Coulomb}}.$$  (2)
Experimentally, we know (now) that the “size” of the electron is small, $r_e \lesssim 10^{-17}$ cm. This implies that the self-energy $\Delta E$ is at least a few GeV, and hence the “bare” electron mass must be negative to obtain the observed mass of the electron, with a fine cancellation like

$$0.000511 = (-3.141082 + 3.141593) \text{ GeV}. \quad (3)$$

Even setting a conceptual problem with a negative mass electron aside, such a fine cancellation between the “bare” mass of the electron and the Coulomb self-energy appears troublesome. In order for such a cancellation to be absent, Landau and Lifshitz concluded that the classical electromagnetism cannot be applied to distance scales shorter than $e^2/(4\pi\varepsilon_0 m_e c^2) = 2.8 \times 10^{-13}$ cm. This is a long distance in the present-day particle physics’ standard.

The resolution to this problem came from the discovery of the anti-particle of the electron, the positron, or in other words by doubling the degrees of freedom in the theory. The Coulomb self-energy discussed above can be depicted by a diagram Fig. 2 left where the electron emits the Coulomb field (a virtual photon) which is felt (absorbed) later by the electron itself. But now that we know that the positron exists, and we also know that the world is quantum mechanical, one should think about the fluctuation of the “vacuum” where a pair of an electron and a positron appears out of nothing together with a photon, within the time allowed by the energy-time uncertainty principle $\Delta t \sim h/\Delta E \sim h/(2m_e c^2)$ (Fig. 2 middle). This is a new phenomenon which didn’t exist in the classical electrodynamics, and modifies physics below the distance scale $d \sim c\Delta t \sim \hbar c/(2m_e c^2) = 200 \times 10^{-13}$ cm. Therefore, the classical electrodynamics indeed does hit its limit of applicability at this distance scale, much earlier than $2.8 \times 10^{-13}$ cm as was exhibited by the problem of the fine cancellation above. Given this vacuum fluctuation process, one should also consider a process where the electron sitting in the vacuum by chance annihilates with the positron and the photon in the vacuum fluctuation, and the electron which used to be a part of the fluctuation remains instead as a real electron (Fig. 2 right). V. Weisskopf calculated this contribution to the electron self-energy, and found that it is negative and cancels the leading piece in the Coulomb self-energy exactly:

$$\Delta E_{\text{pair}} = -\frac{1}{4\pi\varepsilon_0} \frac{e^2}{r_e}. \quad (4)$$

After the linearly divergent piece $1/r_e$ is canceled, the leading contribution in the $r_e \to 0$ limit is given by

$$\Delta E = \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}. \quad (5)$$

There are two important things to be said about this formula. First, the correction $\Delta E$ is proportional to the electron mass and hence the total mass is proportional to the “bare” mass of the electron,

$$(m_e c^2)_{\text{obs}} = (m_e c^2)_{\text{bare}} \left[ 1 + \frac{3\alpha}{4\pi} \log \frac{\hbar}{m_e c r_e} \right]. \quad (6)$$
Therefore, we are talking about the “percentage” of the correction, rather than a huge additive constant. Second, the correction depends only logarithmically on the “size” of the electron. As a result, the correction is only a 9% increase in the mass even for an electron as small as the Planck distance \( r_e = 1/M_{Pl} = 1.6 \times 10^{-33} \) cm.

The fact that the correction is proportional to the “bare” mass is a consequence of a new symmetry present in the theory with the antiparticle (the positron): the chiral symmetry. In the limit of the exact chiral symmetry, the electron is massless and the symmetry protects the electron from acquiring a mass from self-energy corrections. The finite mass of the electron breaks the chiral symmetry explicitly, and because the self-energy correction should vanish in the chiral symmetric limit (zero mass electron), the correction is proportional to the electron mass. Therefore, the doubling of the degrees of freedom and the cancellation of the power divergences lead to a sensible theory of electromagnetism applicable to very short distance scales.

In the Standard Model, the Higgs potential is given by

\[
V = m^2 |H|^2 + \lambda |H|^4, \tag{7}
\]

where \( v^2 = \langle H \rangle^2 = -m^2/2\lambda = (176 \text{ GeV})^2 \). Because perturbative unitarity requires that \( \lambda \lesssim 1 \), \(-m^2\) is of the order of \((100 \text{ GeV})^2\). However, the mass squared parameter \( m^2 \) of the Higgs doublet receives a quadratically divergent contribution from its self-energy corrections. For instance, the process where the Higgs doublets splits into a pair of top quarks and come back to the Higgs boson gives the self-energy correction

\[
\Delta m^2_{\text{top}} = -6 h_t^2 \frac{1}{4\pi^2 r_H^2}, \tag{8}
\]

where \( r_H \) is the “size” of the Higgs boson, and \( h_t \approx 1 \) is the top quark Yukawa coupling. Based on the same argument in the previous section, this makes the Standard Model not applicable below the distance scale of \( 10^{-17} \) cm, according to the Landau–Lifshitz criterion. This is the hierarchy problem.

The motivation for supersymmetry is to make the Standard Model applicable to much shorter distances so that we can hope that the answers to many of the puzzles in the Standard Model can be given by physics at shorter distance scales. In order to do so, supersymmetry repeats what history did with the positron: doubling the degrees of freedom with an explicitly broken new symmetry. Then the top quark would have a superpartner, the stop, whose loop diagram gives another contribution to the Higgs boson self energy

\[
\Delta m^2_{\text{stop}} = +6 h_t^2 \frac{1}{4\pi^2 r_H^2}. \tag{9}
\]

The leading pieces in \( 1/r_H \) cancel between the top and stop contributions, and one obtains the correction to be

\[
\Delta m^2_{\text{top}} + \Delta m^2_{\text{stop}} = -6 h_t^2 \frac{1}{4\pi} (m_t^2 - m_\tilde{t}^2) \log \frac{1}{r_H^2 m_\tilde{t}^2}. \tag{10}
\]

One important difference from the positron case, however, is that the mass of the stop, \( m_\tilde{t} \), is unknown. In order for the \( \Delta m^2 \) to be of the same order of magnitude as the tree-level value \( m^2 = -2\lambda v^2 \), we need \( m_\tilde{t}^2 \) to be not too far above the weak scale. TeV stop mass is already a fine tuning at the level of a percent. Similar arguments apply to masses of other superpartners that couple directly to the Higgs doublet. This is the so-called naturalness constraint on the superparticle masses.

It is worth pondering if the mother nature may fine-tune. Now that the cosmological constant appears to be fine-tuned at the level of \( 10^{-120} \), should we be worried really about the fine-tuning \( v^2/M_{Pl}^2 \approx 10^{-30} \)? In fact, some people argued that the hierarchy exists because intelligent
life cannot exist otherwise. On the other hand, a different way of varying the hierarchy does seem to support stellar burning and life. We don’t get into this debate here, but we’d like to just point out that a different fine-tuning problem in cosmology, horizon and flatness problems, pointed to the theory of inflation, which in turn appears to be empirically supported by data. We just hope that proper solutions will be found to both of these fine-tuning problems and we will see their manifestations at the relevant energy scale, namely TeV.

3 Why We Were Pessimistic

Supersymmetry or not, we expect some interesting physics to appear below TeV scale if the hierarchy problem is to be avoided by some stabilization mechanism. The problem is that it is difficult to understand why we have not seen its impact on flavor-changing neutral currents especially in the beautiful $B$ physics data and electroweak precision measurements. Are we on the wrong track to naively hope that the stabilization mechanism is just around the corner? Or is there rather a good reason why it doesn’t show its fingerprints despite our best detective work? This is a question that applies to any candidate physics beyond the standard model at the TeV scale.

The problem with supersymmetry is well-known, having been discussed already for a several decades. In the Minimal Supersymmetric Standard Model (MSSM), which is the supersymmetric extension of the Standard Model with the smallest particle content, there are staggering $10^7$ additional parameters beyond the nineteen in the Standard Model. And if you throw dice in this huge parameter space, you almost always end up with a parameter set that is already excluded by the data. For example, the off-diagonal elements in the mass-squared matrices must be less than a few per mill of the mass eigenvalues for three types of squark and two types of slepton mass matrices. Also the mixing between the scalar partners of left- and right-handed fermions need to be very much identical to the mixing among the fermions. Overall, the probability of “hitting” the phenomenologically viable parameter sets would be down by a product of many factors of hundreds. Why are the unwanted parameters small, supersymmetry-breaking effects flavor-blind? Unless there is a good reason, the whole idea of sub-TeV supersymmetry to stabilize the hierarchy appears a remote chance.

In addition, breaking supersymmetry appears difficult and highly non-generic among supersymmetric theories. Known models require a specific choice of gauge groups and matter content, often together with a special choice of the superpotential terms with a global symmetry imposed; global symmetries are usually regarded unlikely in a fundamental theory of quantum gravity such as string theory.

There are several popular mechanisms to achieve flavor-blind supersymmetry breaking: gauge mediation,\textsuperscript{10} gaugino mediation,\textsuperscript{11} and anomaly mediation.\textsuperscript{12} The supersymmetry-breaking effects are “mediated” to the supersymmetric standard model via gravity or gauge interactions, guaranteeing their flavor-blindness. Even though these mechanisms do work, my problem has been that the models must be written in a very careful and elaborate fashion. Small changes in the models, such as a different choice of the gauge group or matter content, tend to destroy their success, such as restoring supersymmetry, allowing for flavor-dependent effects, destabilizing the vacuum. My feeling has been that they do not represent a likely choice by Nature.

Let us see how careful and elaborate models are needed with an example. Gauge mediation, at the first sight, is a beautiful idea. It has a set of messenger particles $f$ and $\bar{f}$ that carry standard-model quantum numbers. Once supersymmetry is broken by a vacuum expectation value of field $X$, the messengers do not have a supersymmetric spectrum; the masses of the bosons are split from those of the fermions. Then their loops induce masses for squarks, sleptons, and gauginos (Fig. 4 left). So far so good.

However, one has to ask the question how the supersymmetry-breaking expectation value is
generated for $X$. It requires a separate gauge theory with a rather complicated particle content and specific potential, on which a global symmetry is imposed to make sure that it breaks supersymmetry. Only a small fraction of supersymmetric models serve this purpose. This gauge theory is coupled to the messengers also in a constrained specific way through yet another gauge interaction and singlet particles (Fig. 3 right). Overall, we need nearly decoupled three “boxes” to make the whole mechanism possible.

If a realistic model of nature has to rely on a carefully constructed elaborate mechanism, even though it is logically possible, I am not sure if that is Mother Nature’s choice. In some sense, we rely on supersymmetry to avoid fine-tuning in electroweak symmetry breaking and flavor, but we end up fine-picking or intelligently designing a model. Even though it is a philosophical point and not very scientific, I would be very much happier if we can do without fine-picking. If we think Nature doesn’t fine-tune, she probably doesn’t fine-pick either; she is way smarter than us, after all.

4 The New Generic Scheme

My main point here is that I actually do not need to be very intelligent to achieve flavor-blind supersymmetry breaking. Pretty much the dumbest supersymmetric extension of the standard model would do it.

We still need the messengers, non-chiral particles coupled to the standard model. Such particles are known to arise generically in string theory, and people have been trying hard to get rid of such junk. In addition, again generically, one expects other gauge groups, with their own quarks; more junk. Most of them tend to be non-chiral. I claim these junk are precisely what brings the supersymmetry-breaking effects to the whole mechanism possible.

We do not impose a global symmetry on the model. We write the most general potential consistent with the gauge symmetries. The lowest dimension operator that couple the messengers and the other quarks is precisely what brings the supersymmetry-breaking effects to the messengers, and hence to the standard model in a flavor-blind way. The gauge groups can be pretty much anything, $SU(N_c)$, $SO(N_c)$, $Sp(N_c)$; all classical groups. (Let us focus on $SU(N_c)$ case below but the other groups do the same thing.) The parameters ($e.g.,$ the gauge couplings, mass scales, etc) do not need to be tuned against each other. They have to satisfy certain inequalities, such that the possibly flavor-sensitive Planck-scale physics would be subdominant compared to the gauge-mediated contributions, or the number of flavors in the other “QCD” is in the range $N_c < N_f < \frac{3}{2} N_c$. No fine-tuning here.

\footnote{For instance, the first three-generation models from heterotic strings based on Tian-Yau manifold has six vector-like families, and an extra $E_8$ for disposal. The only significant requirement here is that there should better not be chiral particles that couple to both the standard model and the other gauge groups. I thank Mirjam Cveti\'c on this point.}
How this simple scheme works requires a little technical discussion. For this range of the $N_f$, the other “QCD” becomes strong at some energy scale $\Lambda$, and the low-energy limit is known to be described by yet another gauge theory $SU(N_f - N_c)$, whose quarks $q$ and $\bar{q}$ couple to the mesons $S_{ij} = \bar{Q}_i Q_j$ ($i, j = 1, \cdots, N_f$) of the original “QCD” through the potential

$$W = m_{ij}^Q \Lambda S_{ij} - \bar{q}^i q^j. \quad (11)$$

We assume $m_{ij}^Q \ll \Lambda$. Then this potential does not have a solution to the supersymmetric minimum

$$\frac{\partial W}{\partial S_{ij}} = m_{ij}^Q \Lambda - \bar{q}^i q^j = 0 \quad (12)$$

because $m_{ij}^Q$ has rank $N_f$ while $\bar{q}^i q^j$ rank $N_f - N_c$. This supersymmetry-breaking minimum is actually a local minimum \[14\] but the tunneling to the global supersymmetric minimum has an exponentially long lifetime. The lowest dimension operator for the messengers become

$$M f f + \frac{\Lambda}{M_{Pl}} \langle S \rangle f f, \quad (13)$$

exactly what is needed for the gauge mediation (Fig. 3, left).

In fact, any models that break supersymmetry can be used the same way\[2\]. Just the vector-like “junks” coupled to the standard model, and the lowest dimension operator to link them.

This, I believe, is a good news for string theory. String theory is now believed to have many many solutions, some $10^{500}$ of them. The vast majority of them have huge cosmological constants and do not resemble our universe; they do not support life and do not get observed by scientists like us. We have lost very many solutions by this cut. Getting standard model is another severe cut on the numbers. It would be nice if a large fraction of the remaining solutions would lead to successful supersymmetry breaking and phenomenologically viable models; then Nature may well have given us one. The simple scheme presented here suggests that a significant fraction of the remaining solutions indeed may well do so.

Experimental consequences are pretty much the same as the phenomenology of gauge-mediated models people have been discussing in the literature. The dark matter particle is the gravitino. Even though it is a bad news for direct detection experiments, it opens up an interesting possibility of producing gravitinos of spin 3/2 at colliders. There may be extra photons or long-lived charged particles in the supersymmetry events. The mass spectrum of superparticles tell us about the quantum numbers of the messengers even though they are beyond the reach of direct production. Finally, the linear-collider precision of superparticles may reveal the presence of the light particles in the other “QCD”\[15\].
5 Conclusions

Even though supersymmetry is a beautiful idea to solve the fine-tuning or hierarchy problem, we will not see it at the LHC unless it comes out flavor-blind. Theorists used to be a kind of control freak to write special models that ensure the flavor-blindness of supersymmetry. This fine-picking of models made us uncomfortable, feeling the chance for its discovery at the LHC remote. But after some more thoughts, it turned out that we don’t really need fine-picking to break supersymmetry in a flavor-blind fashion. It is easy to write a model, which is phenomenologically viable, and the scheme is very generic, a kind of spectrum one expects from the string theory. Pretty much the dumbest extension of the supersymmetric standard model would do the job.

I do not share anymore the spreading concern that LHC is not likely to discover exciting physics because we have not seen any hints of it yet. Quite generically in the “landscape” of supersymmetric theories, we expect the superparticles to come out flavor-blind and therefore well hidden from the current beautiful data. I suspect this is probably not specific to supersymmetry. More thoughts may well reveal why we have not seen hints of TeV-scale new physics yet, even though it is waiting to be discovered at the LHC.

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