IOP Concise Physics

String Theory and the Real World

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Chapter 4

The mass–energy scales of particle physics and cosmology—the ‘hierarchy’ problem—supersymmetry—hidden sectors

We have seen why the Planck scales are the natural ones. But our world has a number of other scales we need to understand, such as the electroweak scale (the value of the Higgs field in the vacuum, or the related values of W and Z masses, about 240 GeV), and the proton mass scale. We need to learn why we do not live at the Planck scale. We will see that compactified string/M-theories naturally generate scales below the Planck scale, and provide explanations for the scales.

One very important scale is the one at which supersymmetry is broken. In physics broken symmetries do not just break up into pieces to throw away. The original symmetry made several predictions. The broken one preserves most of those, and allows one or a few properties to vary from the unbroken symmetry prediction. In the case of supersymmetry, the superpartners continue to exist, with all the expected properties except mass, which can vary. The way supersymmetry is broken sets the scale for all the superpartner masses, so it is very important in terms of searching for superpartners experimentally, and for their phenomenological impact.

We have to give values for masses in some units. It is probably most clear to consider all scales in terms of masses of particles, or energies (which are conceptually equivalent because of Einstein’s $E = mc^2$ relating mass and energy). We can just use GeV units for all masses and scales. Another scale is that of protons and neutrons, which have masses of about 1 GeV. The Planck scale in these units is about 10^{19} GeV. [An electron accelerated by an electrical potential difference of one volt will gain an energy of 1 eV. The prefix G stands for a billion (10^9), and T for 10^{12}. 1 TeV is 1000 GeV. These are units we will use.] We need to understand this large ratio between the Planck scale and the electroweak scale or the proton mass scale.

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The electroweak scale is the natural scale of the Standard Model particles and interactions. A helpful way to think about it is that the Standard Model seems to imply that all quark and electron masses, and also the masses of the W and Z bosons that mediate the weak interactions, are zero. The property of the Standard Model that implies that is called the electroweak symmetry. Those particles of course actually have mass, and the theory allows them to get correct masses by violating the electroweak symmetry in a very special way, called the Higgs mechanism.

The Higgs mechanism arises from properties of the Higgs field, and the Higgs bosons discovered in 2012 at the European CERN Laboratory in Geneva, Switzerland, are quanta of the Higgs field. Finding the Higgs boson (with its observed properties) proves that the Higgs field exists. That discovery allows us to measure the value the Higgs field has in the vacuum, which is surprisingly not zero as for all other fields, but instead about 240 GeV. We need to understand the value of that scale. The Planck scale is natural—what needs explaining is why the other scales, like the proton mass and the electroweak scale, are so much smaller than the Planck scale. Similarly, the electroweak scale arises from the non-zero Higgs vacuum value, and all electroweak-scale masses are proportional to the Higgs field vacuum.

One would expect that the ground state of the Universe, the 'vacuum' state, is the state with the lowest energy, since any system will eventually end in the state with lowest energy. One would think that state would be the one where all fields are zero, since fields carry energy. Remarkably, in our Universe the state with the Higgs field being non-zero has a lower energy than if the Higgs field were zero. We learn the Higgs field is non-zero in the vacuum from implications of the data on how Higgs bosons decay. If the electroweak symmetry were exact, the Higgs boson would be forbidden to have the decays $h \rightarrow W^+W^-$ or ZZ, but in fact those decays occur in the LHC data and have a large rate. The explanation is technical, but the presence of this decay demonstrates that the Higgs field is non-zero in the vacuum.

The ratio of the electroweak scale to the Planck scale is a tiny number, and understanding that ratio is one of the main challenges in extending the Standard Model, and in going beyond the Standard Model toward an underlying theory. It is called the 'hierarchy problem'. It arises because our world is described by relativistic quantum field theory. Then the masses of particles can change since there is some probability that any particle can fluctuate into any other (via 'virtual particles'). For most properties the change in value is very small, but for the mass of the Higgs boson it turns out for technical reasons to be unlimited—when the full effects of virtual particles are included the Higgs boson mass becomes as large as it can be, which is the Planck mass.

The Higgs mechanism that solves the problem of the masses of quarks and electrons and W, Z bosons does so by giving them mass proportional to the Higgs boson mass, so the hierarchy problem pushes all their masses to near the Planck scale rather than the actual values at the electroweak scale and smaller. That is why it is a serious problem, although it is a conceptual problem in practice.

In the Standard Model itself that problem is unavoidable. It is a theoretical problem, so it can be ignored in practice, but we hope for a theory without such apparent inconsistencies. One way the hierarchy problem can be solved is by extending the Standard Model to be a supersymmetric theory. In practice that means that every particle of the Standard Model (i.e. the quarks and leptons, photons, W and Z, gluons) has to have a partner that differs by half a unit of spin and perhaps differs in mass. For M-theory compactified on the G_2 manifold the resulting 4D theory must be supersymmetric. That helped convince me and my collaborators to focus on that compactification.

[More technically, the theory is specified by knowing a function called the Lagrangian. The Lagrangian of the supersymmetric Standard Model must have the property that it is unchanged if bosons and fermions are interchanged. In practice that requires a partner for each quark, etc.]

This solves the hierarchy problem because in quantum field theory the virtual particle contributions from pairs of particles differing by half a unit of spin have opposite signs, so those from each particle and its superpartner just cancel if they have the same mass. When they have different masses the cancellation is incomplete, and leave us with a ‘little hierarchy problem’ that is an interesting real problem but far less of an issue than the full hierarchy problem.

Supersymmetry is another hidden aspect of nature. The world needs to have the whole set of superpartner particles that have not yet been experimentally observed. They have been given nice names: photon and photino, W and wino, electron and selectron, quarks and squarks, and so on. It is clear that electron superpartners with the same mass as the electron do not exist or they would have bound with protons to make new kinds of ‘atoms’ very different from ordinary atoms, and they would already have been observed. It is also clear in some compactified string/M-theories that the supersymmetry is inevitably present in the theory, and is indeed a broken symmetry, with the superpartners expected to be heavier than the Standard Model particles. In particular, that is true in the compactified M-theory I describe later.

The Standard Model is essentially a complete theory in its domain, so it can be used to calculate observables for experiments. But the supersymmetric extension of the Standard Model is not yet a complete theory because of the broken supersymmetry, so the expected masses of the superpartners cannot yet be generally predicted. A theory with unbroken supersymmetry would actually introduce no new parameters. Some arguments (‘naturalness’) can be used to estimate what values they might have. If those arguments were correct some superpartners would already have been discovered at the CERN LHC. It would have been nice if the naturalness arguments had worked, but they did not. Since they were not predictions from a theory it is not clear how to interpret that.

In principle one can carry out compactifications and calculate superpartner masses for each compactification. Technically the calculations are difficult, so only a few have been studied. Consider the gluino, partner of the gluon. It has strong QCD interactions just as the gluon does, so it should be one of the earliest particles produced at the LHC. The compactifications studied so far suggest the gluino mass could be as light as about 1500 GeV, in which case it should be observable in the current three-year LHC run. Observing it is not straightforward (see the supersymmetry section later).

More generally, the LHC is now finally operating in the region of energy and intensity where the compactified theories suggest it is reasonable to be optimistic about superpartner discovery, gluinos in particular. Later we will look in more detail at the superpartner spectrum predicted by the compactified M-theory. Other string theory branches seem to give different predictions for the spectrum, perhaps with somewhat heavier gluinos. We will see below that the compactified M-theory predicts that three and only three superpartners can be discovered at the LHC, gluinos, and charged and neutral winos. The lightest superpartner emerges in gluino and wino decays, so its presence can be inferred. In the compactified M-theory, all other superpartners are too heavy for the LHC until it is upgraded in luminosity and/or energy.

4.1 Unification of forces—the QCD scale and the proton mass

Newton over three centuries ago imagined that there were forces besides gravity, electricity, and magnetism, and that they could all be understood together, but at that time too little was known to make any progress along those lines. Over 200 years ago Charles-Augustin Coulomb showed that the electrical force depended on the distance between interacting objects in the same way as the gravitational force did, so the formulas describing them had the same form. Since then physicists have been trying to make sense of the idea that somehow the description of the forces could be unified. At the electroweak scale the forces have very different strengths, so it is not clear what unifying them could mean. The expressions for the forces do have the same form, such as the $1/r^2$ decrease for Coulomb's law and for the gravitational force, and the Yang–Mills gauge theory form for the strong and electroweak forces, which is encouraging.

In the 1970s it was recognized by several theorists that in relativistic quantum field theories the strengths of forces depended on the energy with which they were probed. Similarly, masses of particles do not have a unique value but also depend on the energy at which they were measured. Using a common definition of the force strengths at the electroweak scale, the strong, electroweak, and electromagnetic forces have values of 0.118, 0.033, and 0.008, not close in value. Then people realized two things. First, if one calculated their values not at the electroweak scale but at increasingly higher energies, and second, if one used the supersymmetric extension of the Standard Model, then the strengths became the same in value (about 0.04) at an energy of about $10^{16.3}$ GeV! One could think of the forces as unified at such an energy. Even better, such a scale is near the Planck scale, so one could imagine all four forces including gravity unifying there.

4.2 If we did not know about protons, QCD would make us think of them

Now let us think about the QCD or strong force. At the unification scale all the force strengths have a value of about 0.04. As we probe the strong force at lower energies it increases. By the electroweak scale it is about 0.118 as we saw above. It continues to increase in size as the scale decreases. Once the force strength becomes about unity in size the number of large contributions that bind quarks into protons and neutrons grows fast, and the strong force indeed binds quarks into protons and neutrons.

That happens at a scale of about 1 GeV, and explains the proton mass. If we had a theory of quarks interacting via the QCD force, and we knew that the force strengths unified near the Planck scale at a value of about 0.04, we would inevitably predict that protons existed, and approximately predict their mass. Explaining something that was not previously understood is just as much a test of a theory as predicting a new thing and then finding it. In some ways the postdiction is stronger since previous efforts failed to explain what became understood.

4.3 Theories versus solutions—a major confusion—spontaneous symmetry breaking

Generally when we talk about physics we describe theories. That is true more broadly in science, and even in many of the ways we try to understand the world. But the world is described by *solutions* to the equations of the theory.

Many people are familiar with the example of the Solar System. The Sun is the center of the gravitational force that attracts the planets, and they orbit the Sun. The gravitational force is completely spherically symmetric with the Sun at the center. But we know since Kepler that the planetary orbits are ellipses, not spherically symmetric circles. It is common for the solutions that actually describe nature to not show the symmetries of the theory. There is a jargon phrase for that phenomenon—‘spontaneous symmetry breaking’.

A simple example, already described in chapter 1, describes it clearly.

4.4 Hidden sectors

Another new way in which the physics of compactified theories enters is by the presence of ‘hidden sectors’, which are very important. One can think of them as arising as follows. When the string/M-theory is compactified, it does not give just one 4D theory that describes our world, it gives many possible ones. We do live on one of them, which we call the visible sector. The Planck scales are common to all the sectors. All of them feel the gravitational force, but the other forces can be very different or absent. For example, particles from other sectors typically do not feel the electroweak and QCD forces.

How supersymmetry is broken is very important for generating some other scales, particularly the electroweak scale. It was recognized early that visible sector supersymmetry could not be broken in the visible sector without contradicting data. The expected mechanism is that the supersymmetry is broken in some hidden sector, and the results transmitted to the visible sector somehow. The results can always be transmitted to the visible sector by gravitational interactions, and for some string theories by other interactions.

How this works seems to be quite different in the various types of string/M-theory. When M-theory is compactified on a 7D G_2 manifold, the hidden sectors are 3D.

Imagine 3D manifolds inside a 7D one. The visible sector is one of the 3D ones. In a 7D space two 3D manifolds are unlikely to ever encounter each other, so the only interaction they have is the universal gravitational one. When supersymmetry is broken on one of them, which happens generically, the breaking can be transmitted to the visible sector via the gravitational interaction. It is easy to construct concrete models in which this occurs, and obtain a model of the visible sector that could be realistic. Such a theory predicts that the supersymmetry breaking is mediated by gravitational interactions, which is one of several testable predictions.

A compactified M-theory is automatically supersymmetric, which is not true in general string theories, where supersymmetry seems to have to be imposed. This automatic supersymmetry was proved soon after the discovery of M-theory by Edward Witten. It is one of the reasons my collaborators and I have been motivated to focus on compactified M-theory rather than other corners.

Different hidden sectors have different Yang–Mills type theories on them. The visible sector has the Standard Model gauge groups SU(3) for the strong force, and SU(2) × U(1) for the electroweak force. The reader does not need to know what these are mathematically. They describe some symmetries and invariances of the forces of our world. The key point is that other hidden sectors have other symmetry groups, more or less randomly, some with larger groups such as SU(6) or the exceptional Lie group E_6. The larger groups have larger charges. The increase in force strength as one looks at lower energies was described above to see how the proton mass arises. With a larger charge the force becomes strong and can bind, in particular, pairs of gluinos (called gluino condensation). Once that happens it breaks the supersymmetry since some superpartners are removed from the spectrum into a bound state. In the compactified M-theory that happens at about 10^{14} GeV. The jargon name for the effect is ‘gaugino condensation’.

This is a subtle argument, but a very robust one. In the compactified M-theory there are of the order of 100 hidden sectors (for a given G_2 manifold the number can be calculated). Some of them will have large gauge groups, some smaller gauge groups, some no symmetries. But for any manifold it is highly likely there will be *some* hidden sector with a large gauge group, and it will lead to a gluino condensation at about 10^{14} GeV in nearly all M-theory compactifications. [Technically, one recognizes the scale at which that happens when the so-called F-terms are non-zero.]