Chapter 14
Beyond the Standard Model

The Standard Model is a triumph of physics. It describes to extraordinary accuracy the particles that build our universe and the forces between them. It has successfully predicted the existence of unfamiliar particles, since discovered, like the charm quark, top quark, W and Z bosons, and, the crown jewel, the Higgs boson. It has been confirmed experimentally over 43 orders of magnitude, from inside protons to the scale of the universe, and, in some cases, to a precision of fifteen decimal places, as fine as our available experimental tools allow. Can't beat that.

But we know it can't be the whole story. Physicists grumble there are too many particles and too many parameters in the theory. Occam and esthetics argue there must be a simpler picture from which the Standard Model emerges. The Standard Model raises uncomfortable questions, like why is the weak energy scale so vastly different from the fundamental Planck scale? And the enormous masses of Dark Matter, binding entire clusters of galaxies by their gravitational presence, don't behave otherwise like the familiar particles of the Standard Model. We suspect there are other kinds of particles out there in the Dark Matter, particles not described by the Standard Model.

This chapter reviews the fundamentals of the Standard Model and outlines its problems. Then we explore ideas that extend the Standard Model, to solve those problems and perhaps provide a Grand Unified Theory that ultimately encompasses all the particles and forces, including gravity, in a single, elegant symmetry group.

Symmetry

One of the most productive concepts in physics is symmetry. The basic idea is that a symmetry exists if you can perform an operation on a system, but the operation leaves the system unchanged. For example, if you rotate a square by ninety degrees, it still looks the same. Or if you flip a square around a vertical axis, it looks the same as before.

In mathematical terms, a symmetry includes a group of objects and a set of operations such that any operation produces another member of the same group. Among the operations are an identity and an inverse. The identity operator on the square would be "maintain present orientation." The inverse of "ninety degrees clockwise" would be "ninety degrees counter-clockwise."

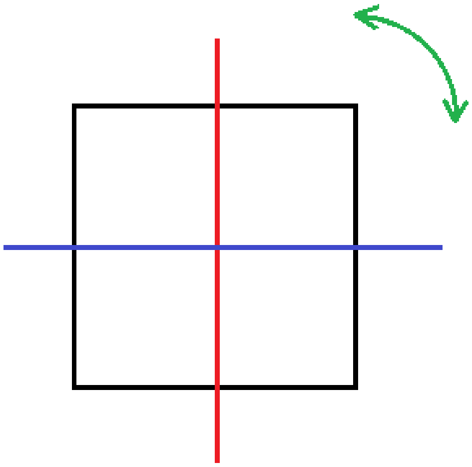

Figure 14.1. Symmetries of a square. If you flip the square across the red or the blue axis, it still looks the same. Rotate the square 90 degrees or any multiple of 90 degrees, and it looks the same. There are other symmetry operations as well; can you find them?

Underlying our current understanding of particle physics is the notion that the fundamental particles – electrons, quarks, and neutrinos – are members of a group, and the forces between particles – strong, weak, and electromagnetic – mediate operations that transform one particle into another.

The Standard Model and its symmetry groups

It would be a good idea to review chapters 8 and 9, on the particles and forces. Here, we are most interested in the symmetry groups that enable us to simplify and extend the Standard Model.

The symmetry group of the Standard Model is a composite, $SU(3) \times SU(2) \times U(1)$. Okay . . . what's that all about? A brief explanation of the symbols, then we'll see how it works.

Think of the components as rotation symmetries in various dimensions. $SU(3)$ includes rotations in three-space, or more properly, rotations in a three-dimensional complex space (complex as in complex numbers). Imagine a vector that can point any direction in our familiar 3-dimensional space, but a space measured in complex coordinates. Same idea for $SU(2)$ but now the rotations are restricted to 2-space, a complex plane. $U(1)$, it turns out, is equivalent to rotations on the good ol' real plane (real as in real numbers). It suffices for our purposes to think of vectors in the subgroups pointing around the spaces of our normal experience, 3D or planes.

Different directions represent different particles. A couple more particulars: the $S's$ indicate that the rotations preserve volume, and the $U's$ indicate that the rotations preserve geometric shape.

$SU(3)$ is the color group, and it includes particles, quarks and gluons, that carry color charge. "Color" is a whimsical but convenient label. The quarks aren't really red, green, or blue. The colors just indicate the three charges sensed by the strong nuclear force, the force that binds quarks in protons, quarks in neutrons, and glues protons and neutrons to each other in atomic nuclei. Gluons transform quarks from one color to another, red to green, green to blue, etc. Rules are: colors are conserved. If blue enters an interaction on a gluon, then a blue quark must leave the interaction vertex. Also, combinations of quarks – always triplets or pairs – must be color neutral. The three quarks in a proton must include one green, one red, one blue. The two quarks in a meson must include one red and the other anti-red. (Already you can see this color stuff is getting pretty complicated. Hang on – we'll see shortly some representations that simplify the particle zoo.)

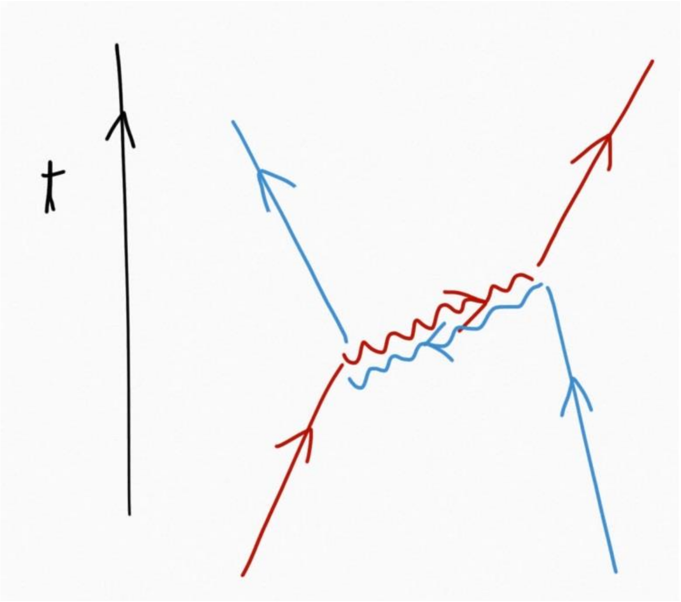

Figure 14.2. The color interaction. Time increases up the vertical scale. A red anti-blue gluon, represented by the wavy lines, exchanges color charge between two quarks. The gluon transforms the red quark on the left into a blue quark. The reverse process occurs on the right. Note that equal quantities of blue and red color leave each vertex as enter the vertex. Color charge is conserved in any interaction.

$SU(2)$ describes the particles, all the quarks and leptons (electrons and neutrinos), that carry weak "isospin." Think of a spinning top. The top might spin clockwise (spin down) or anti-clockwise (spin up). Technically, the isospin exists in an "internal space," perhaps a compact space, and not our familiar dimensions. As with color, isospin provides a convenient label, also referred to as “flavor,” to identify particles. Analogous the color interactions, if isospin up enters into an interaction on a W boson, an up electron must leave the reaction vertex. (Patience. You’ll see in a minute maybe it’s not so terrible.)

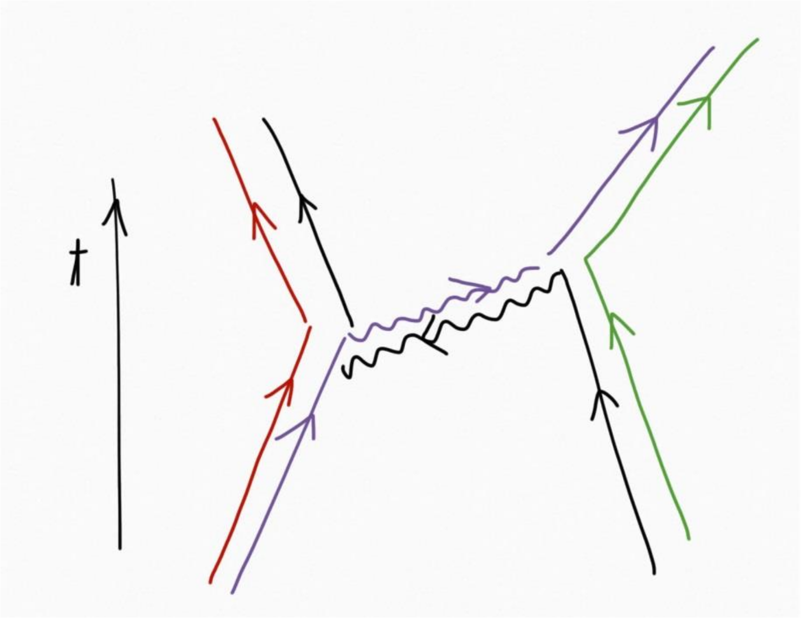

Figure 14.3. Weak interaction transforms a red up quark into a down quark and a green down quark into an up quark. A W^+ gauge boson (wavy lines) carries weak isospin from the red quark to the green quark. See Figure 14.5 for color codes and further interpretation.

$U(1)$ is good ol’ electromagnetism. It’s represented by the two charges, $+$ and $-$. Those charges are conserved in any interaction, and photons mediate those interactions. Quarks carry fractional charges, $+{}^{2}/_{3}$ on the up quark, $-{}^{1}/_{3}$ on the down quark. Electrons carry a charge -1, and neutrinos are electrically neutral.

The following table summarizes the fundamental particles and forces in the Standard Model.

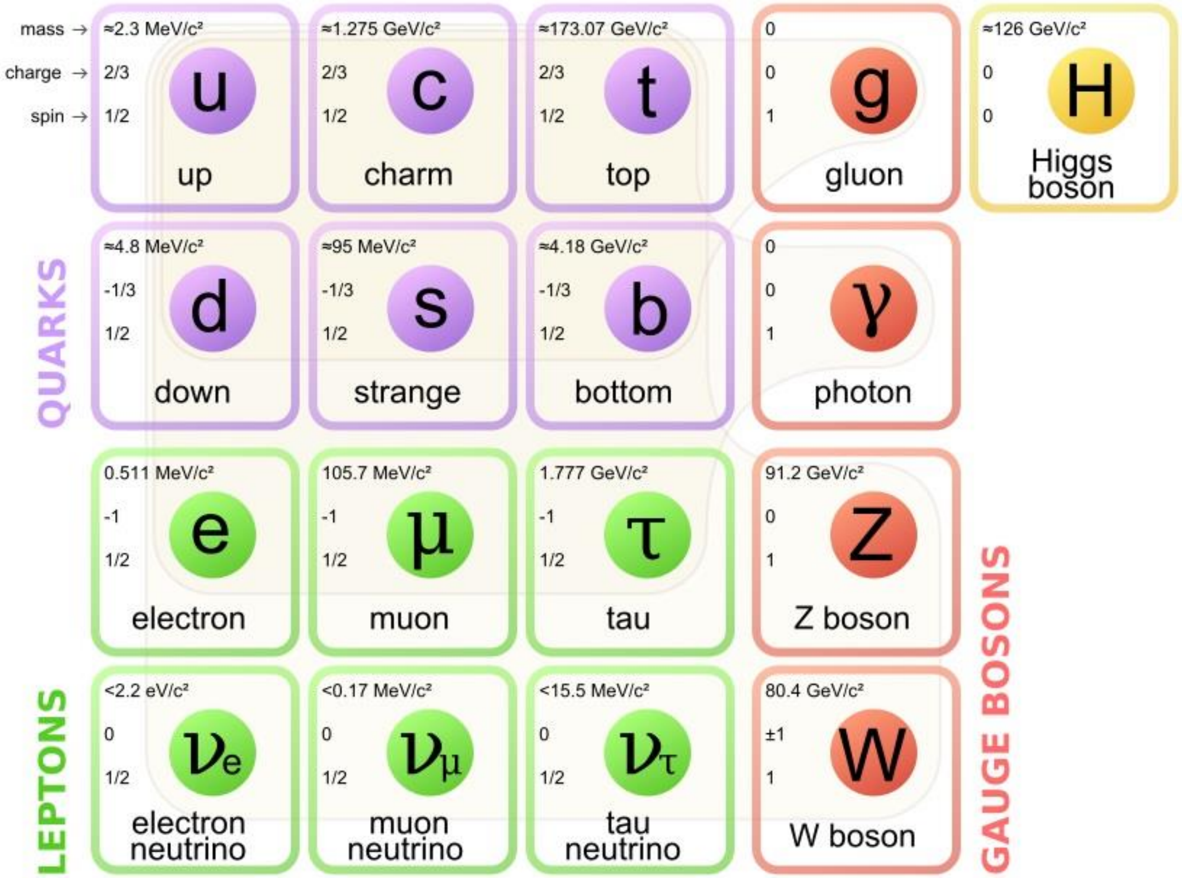

Figure 14.4. Particles and forces of the Standard Model. This image shows all three generations of particles (the first three columns). Each of the quarks and leptons also has a partner antiparticle, not shown in the table. All the universe of our experience is built from the first generation, u, d, e, and ν_e. Other particles exist only at much higher energies, e.g. in particle collisions at accelerators. Light yellow shaded regions show the reach of the gauge bosons, the force carriers. Gluons interact only with particles expressing color charge, the quarks. Photons interact with all electrically charged particles. Quarks and leptons all carry isospin and feel the weak force, mediated by the Z and W. The Higgs gives mass to all the particles through weak interactions. Image credit: Particle Data Group, Lawrence Berkeley National Laboratory.

$SO(10)$

It's a mess. The Standard Model has too many particles, too many parameters – numbers like the mass of the electron and interaction strengths that don't appear naturally in the equations but have to be inserted by hand, based on experimental data. Even the Model's inventors agree, nature must be simpler at heart.

Here’s one intriguing simplification, $SO(10)$, invented by Savas Dimopoulous and his collaborators. Think of the group as an array of containers, red, green, blue, purple and black buckets, arranged in an eight by five matrix. (See the figure, below.) Red, green, and blue carry electromagnetic charge $-{}^{1}/_{3}$. Purple carries isospin up and charge $+1$. Black carries isospin down and charge zero. Color operators transfer colors between buckets. The charge operator reverses sign across the entire matrix. Rules are: each row must include an even number of filled containers, zero, two, or four.

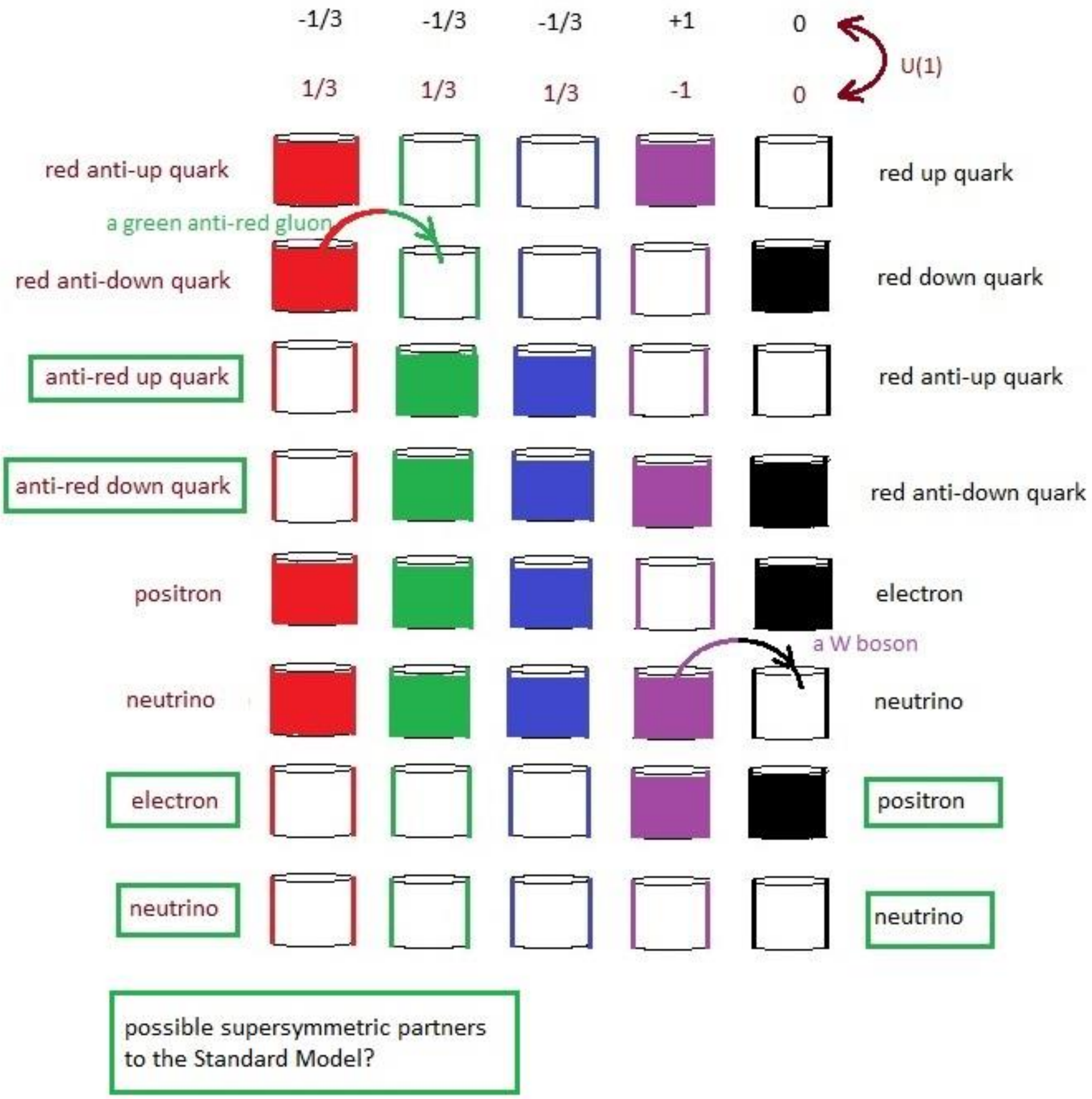

Figure 14.5. The $SO(10)$ representation of the particles and forces. Buckets represent states in $SU(3)$ (red, green, and blue) and $SU(2)$ (purple (up) and black (down)). Filled color

represents an occupied state. Only red states are shown for the color interactions. The full array would include eight more rows in the upper half representing green and anti-green quarks, blue and anti-blue quarks. $U(1)$ states are labeled at the top of the diagram, normal charges in black, reversed charges dark red. Labels along the right hand, in black, identify the particles in each row based on normal charge. Labels along the left hand, dark red, identify particles that result from reversed charge. Possible supersymmetric particles are labeled by green boxes. Supersymmetry is assigned based on $SU(2)$ state, presence of net isospin (fermion = one bucket, purple or black filled) or absence (boson = neither bucket filled or both filled). Curved arrows represent operations by bosons on the particle states. In the second row, a green / anti-red gluon transforms a red down quark into a green down quark. In the sixth row, a W^- transforms a neutrino into an electron. These representations simplify the full interaction diagrams; see Figure 14.2 for example. The X boson predicted by $SO(10)$ would transform a red, green, or blue bucket into a purple or black bucket. Credit: Savas Dimopoulous, Beyond the Standard Model.

It's all there! Filled red and purple represent a red up quark. Filled red and green represents an anti-blue up quark. Filled red, green, blue and black represents the electron, and so on. Red-green-blue color exchange operators are gluons. Purple-black exchange operators are W bosons. Charge reversal is $U(1)$ at work.

$SO(10)$ covers the Standard Model nicely. It also predicts new particles and phenomena beyond the Standard Model. For example, $SO(10)$ predicts the existence of a new gauge boson, the X boson. X would exchange color charge and weak isospin, i.e. it would link the color and weak forces. In Figure 14.5, an X boson would be represented by a curved arrow between, for example, the blue and purple buckets. If X exists, then the proton is not a stable particle. It would decay as quarks transformed to leptons. So atoms would decay and, with them, molecules and planets and us.

Researchers are looking for evidence of proton decay. The latest experiments (as of 2016) place a lower limit on the half-life of a proton at about 10^{33} years, far longer than the age of the universe. There's no great concern that planet earth will evaporate (by proton decay, anyway), but the search continues. As with previous research leading to the discovery of $W's$ and $Z's$ and $Higgs$, evidence of proton decay would open new realms of physics.

Physicists have proposed other symmetry groups besides $SO(10)$ to tidy up the Standard Model. Those models show connections between the various particles and forces, so particle physics is not just and alphabet soup. First problem solved: the Standard Model has an underlying unity.

The hierarchy problem

Second problem requires a bit more head-scratching. $SO(10)$ still doesn't solve the hierarchy problem, at least not obviously. Why is the force of gravity so much weaker, by over forty orders of magnitude, than the electromagnetic force? Why is the weak energy scale (the energy of the weak interactions) so much lower than the Planck scale (the energy at which gravity becomes comparable in strength)? $E_{weak} \cong 10^3 GeV$ compared to $E_{Planck} \cong 10^{19} GeV$. If all the particles and forces are related by symmetry groups, what causes this enormous disparity?

Gravity is the odd man out in particle physics. For all practical purposes, the force of gravity can be ignored in atomic and nuclear physics, it is so much weaker than the other forces. Only at enormous energies and tiny distances, near the Planck energy and the Planck distance, does gravity become important.

In fact, theory predicts that all four forces approach each other in strength at high energies. The strong force diminishes while the electromagnetic, weak, and gravitational forces increase in strength at high energy, short distance. Experiments in particle colliders confirm the trend for the strong, weak, and electric forces, but accelerators operate at energies much lower than what is required for unification.

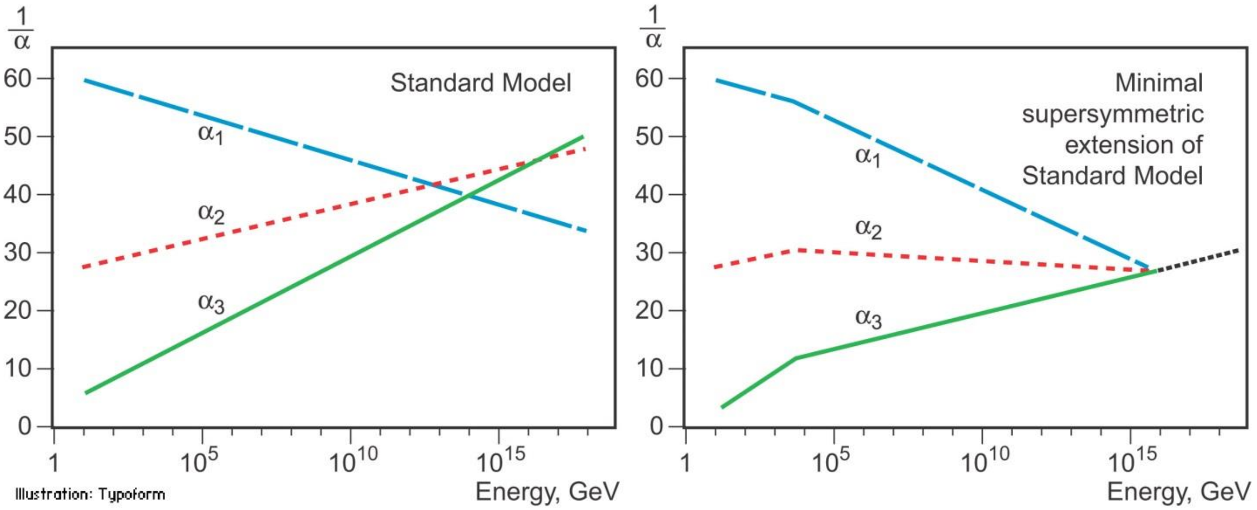

Illustration: Typoform

Figure 14.6. Strength of the forces as a function of energy, as in for example the energy of collisions in particle accelerators. Green trend line represents the electromagnetic force, red the weak force, and blue the strong force. Left hand plot shows calculations based on the Standard Model. Right plot includes sypersymmetry. Present day accelerators operate and energies of about $10^3 GeV$. Credit: CERN.

One proposal, in the gravity sector, postulates that gravity leaks into extra dimensions. Easiest to picture comes from string theory. In string theory, the graviton – the boson that mediates the force of gravity – is a closed loop. Other, open strings, represent the various particles. Open string ends are sticky, and they attach to "branes" (membranes), where their sticky ends interact with the ends of other open strings. Since they lack sticky ends, gravitons are free to leave the branes and travel through the "bulk" between branes.

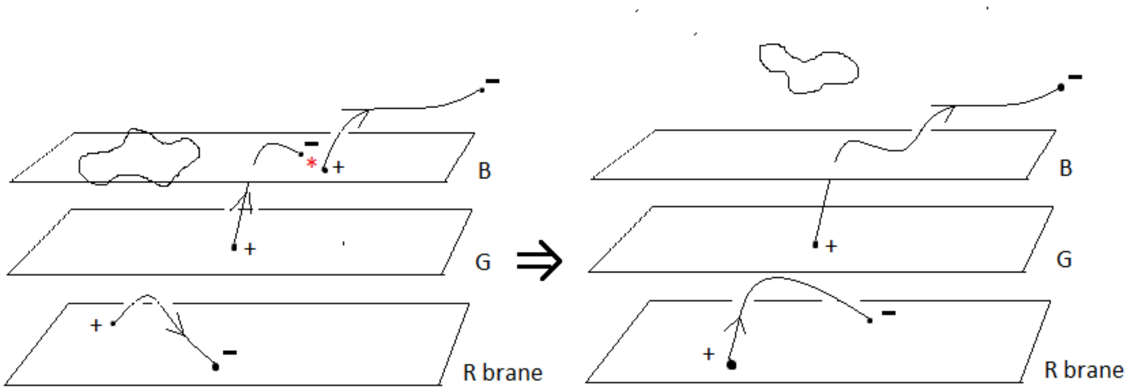

Figure 14.7. Graviton escapes into the bulk. In string theory, the ends of open strings, representing quarks and gluons in this diagram, stick to membranes (branes) and interact with each other. The graviton has no sticky ends and can escape the branes into the bulk. The diagram shows a green anti-blue gluon transforming a blue quark into a green quark, while a graviton escapes the brane (unrelated to the color interaction). See D-brane Models for further discussion.

The particles and forces of the Standard Model are confined to branes. We and our experimental apparatus are attached to the branes, so we measure the full effect of those forces. Gravity, on the other hand, diffuses out into the bulk. It partially escapes our experience and our measuring devices.

So much for gravity's weakness. (Well, at least we have a potential explanation.) But there's more to the hierarchy problem. The Higgs boson interacts with all other particles that carry the weak force. By the logic of quantum field theory, the foundation of the Standard Model , it should have an enormous mass.

The particles that build the familiar world live in a sea of "virtual particles." By quantum uncertainty relations, virtual pairs pop out of the vacuum then annihilate and disappear back into the vacuum. The vacuum seethes with virtual particles, and real particles interact with them. Those interactions increase the effective mass of the real particles. Because the Higgs particle interacts with all the weak carriers, including monsters such as the top quark, it should have a mass far greater than the mass measured at the Large Hadron Collider (LHC), where it was discovered.

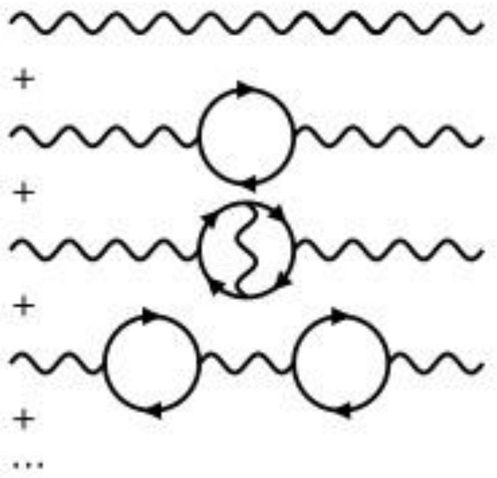

Figure 14.8. Particle interactions in the vacuum. Time on the horizontal axis, increasing to the right. Top diagram shows a photon, wavy line, propagating over time. Lots of things can happen along the way, because the vacuum of space is filled with virtual particles. In the second row, the photon interacts with an electron-positron pair. Third row, the virtual pair exchange a photon. And so on. All these processes, and more, can occur as the photon travels through the vacuum. Similar processes affect all particles and contribute, e.g., to the mass of the particle. Credit: Physics Stackexchange.

The favored solution to this problem is supersymmetry (susy). Susy postulates a ghost world of particles that also interact with the Higgs and cancel the mass contributions of other virtual interactions.

According to susy, each of the known particles in the Standard Model has a supersymmetric partner. For each of the bosons in the Standard Model there is a supersymmetric fermion, and each of the SM fermions has a susy boson partner. Quarks have squarks, photons photinos, electrons are paired with selectrons, gluons with gluinos, and so on. We haven't seen any susy particles (yet) because they have masses beyond the reach of our accelerators (so far; see below). Add the contributions of susy particles to the interaction diagrams, and the mass of the Higgs drops to its measured mass.

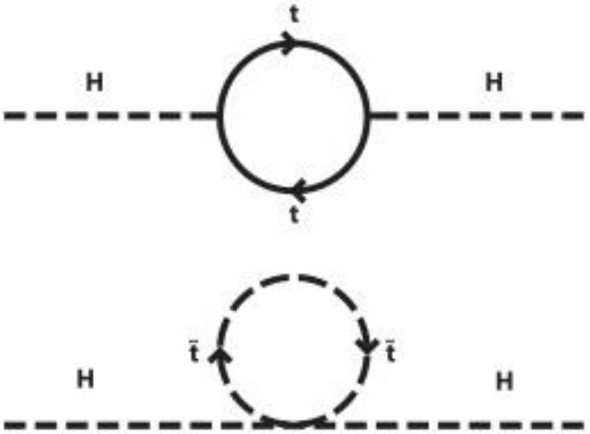

Figure 14.9. Supersymmetric loop corrections to the Higgs mass. Top diagram shows a Higgs particle propagating left to right. It interacts with a virtual top quark / anti-top quark pair. This interaction adds mass to the Higgs; top quarks are really heavy. Bottom diagram shows the Higgs interacting with the supersymmetric partners of the top quark. The loop represents a stop / ant-stop pair. It turns out this susy interaction cancels the mass contribution from the top / anti-top in the upper diagram, so the mass of the Higgs remains near its "bare" mass, the mass of the Higgs by itself. Credit: Vermillion / Wikipedia, and see Lecture 24 in Ellis, Particle Physics.

As the LHC was winding down its data run in December, 2015, physicists found a bump in the data at energies consistent with a low mass susy particle. The accelerator is ramping up for a new run this Spring (2016), and the first goal will be to collect more data at those energies. If that little bump is more than just a statistical fluke, it might be a heavier Higgs, a sign of susy, or a heavy graviton, a signature of extra dimensions – or it might be something completely unexpected. It's exciting times in particle physics. We're just scratching the surface of our particle world.

Fine-tuning

Why are the parameters of the Standard Model so finely tuned? If the charge of the electron was even slightly different that the proton charge, atoms would repel each other and there would be no stars, no planets, no us. If the mass of the proton was greater than then neutron mass, in reverse of the actual condition, protons would decay to neutrons. There would be no hydrogen. No Periodic Table. If the force of gravity was comparable to the electromagnetic force, stars would collapse into black holes. And so it goes. How did it come about that the Standard Model is precisely tuned to allow our universe and our existence?

Here our discussion of the smallest bits and pieces of the universe touches on the largest of scales, the scale of the multiverse. Particle physicists have sharpened pencils then broken pencils in frustration for many years now trying to figure out the origin of those fine-tuned parameters in the Standard Model. All for nought, at least so far. The best lead comes from String Theory, beyond the Standard Model, and its prediction of a string landscape.

String Theory offers not just one neat set of particles and forces. In fact, String Theory has yet to produce a consistent formula for the Standard Model. Instead, String Theory offers a set of solutions, estimates are on the order 10^{500} different sets of particles and forces. 10^{500} different recipes for laws of nature. 10^{500} different universes. A multiverse.

If String Theory is on track, our universe is as it is, and the Standard Model is as it is, just by the statistics of large numbers. If there are that many different possible combinations of particles and forces, one of them must be the Standard Model, and we live in that universe. We couldn't live elsewhere, because the other laws in other universes don't allow it.

There's a whole lot more to the multiverse. See Chapter 13 for further details.

Summary

The Standard Model of particle physics has been amazingly successful describing the particles and forces underlying our universe, but it has obvious shortcomings. It includes too many free parameters not calculable by the theory and too many independent particles to satisfy the physicist's preference for simplicity. It fails to answer the hierarchy problem, why the forces differ so markedly in energy. And it fails to explain fine-tuning, that the particles and their interactions are just so as to allow a universe in which we can exist.

Extensions of the Standard Model attempt to solve these problems. Extended groups such as $SO(10)$ show underlying relations between the fundamental particles. Supersymmetry extends the Standard Model to an even larger group that might solve the hierarchy problem. Hidden dimensions and branes, as predicted in String Theory, offer another perspective on hierarchy. Finally, the notion of a multiverse sweeps aside all the worries about fine-tuning. Among an infinitude of universes, each with different particles and forces, we find ourselves in this one because its laws allow our existence. The others don't.

Particle physicists still hope to find an explanation for fine-tuning, something more satisfying than a multiverse and the statistics of large numbers. The search goes on. Presently (2016) the Large Hadron Collider is beginning another data run, already with hints that it may be tickling the realm of supersymmetry. Stay tuned.

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