The Standard Model

In the years since Chapters 8 and 9 were written, the particle physics community has completed the list of particles and forces that make our world. We have a remarkably consistent theory, the Standard Model, that includes all the observed particles and forces, organized by the mathematics of local gauge symmetry. Experiment confirms the theory to extraordinary precision.

In this chapter, we summarize the Standard Model and discuss the Higgs mechanism, which explains the origin of mass and symmetry breaking among weakly interacting particles (i.e. particles that interact via the weak force). Finding the Higgs particle was the crown jewel in modern particle physics. Then we anticipate new physics, beyond the Standard Model. We know it cannot be the whole story.

The Standard Model

Here it is, the tally of the bits and pieces of our world. Since Democritus proposed the existence of "atoms" long ago, the notion that our world is built from smaller particles, we've been looking. Over the past century of searching with pencil and paper and with increasingly powerful particle accelerators, scientists have found the recipe.

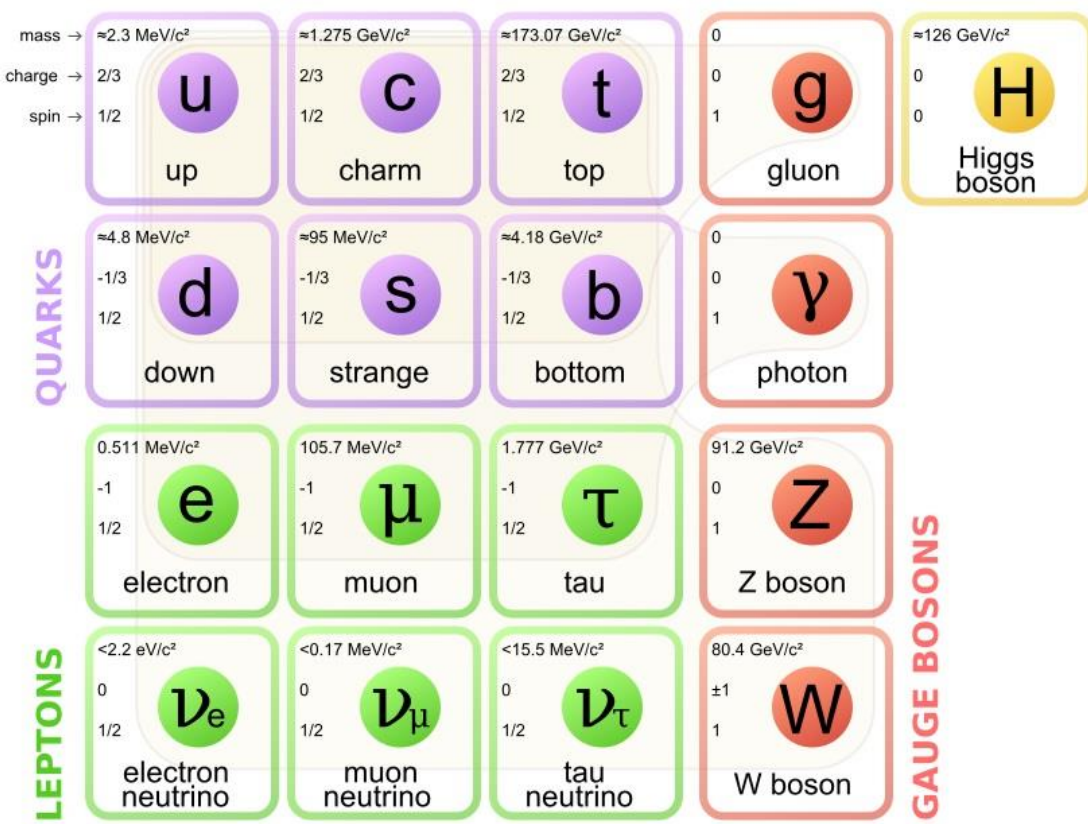

Figure 10.1. Particles and forces of the Standard Model. This image shows all three generations of particles (the first three columns). Each of the quarks and leptons also has a partner antiparticle, not shown in the table. All the universe of our experience is built from the first generation, u, d, 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 the W's. The Higgs gives mass to all the particles through weak interactions. Image credit: Particle Data Group, Lawrence Berkeley National Laboratory.

The Higgs mechanism

The last piece of the Standard Model, the Higgs particle, was confirmed on July 4, 2012. Two detector groups at the Large Hadron Collider independently presented compelling evidence for the existence of a spin-zero gauge boson at an energy of about 125 GeV, the Higgs. The announcement generated great excitement and was celebrated by the physics community around the world. Rightly so. Discovery of the Higgs completed the work of generations of physicists and natural philosophers before them.

So why all the hoopla? Well, without the Higgs, there's no obvious way to explain the mass associated with weakly interacting particles and no obvious reason why the weak interactions violate parity (handedness).

Three things you need to know about the Higgs:

1. Best think in terms of the Higgs field. The Higgs particle, like all particles, is a quantum of its field. As with all quantum fields, quantum mechanics generates fluctuations in the Higgs field.
2. The vacuum has minimum energy not in the absence of the Higgs field but when the Higgs field is present at some small value.
3. All weakly interacting particles (i.e. all particles that feel the weak force) interact with the Higgs field.

Let's consider these one at a time.

Quantum fields behave kind of sort of like ocean waves. On a choppy ocean surface, waves interact, wave on wave superposing, sometimes leaping into spray.

Figure 10.2. Meter and centimeter-scale ocean waves. The waves interfere, and superposition of crest on crest might result in spray, or crest on trough might produce smooth water.

Fermion and boson fields behave similarly, but in three dimensions (or more). Field energy fluctuates over space and time. High energy fluctuations can emerge, briefly, as particles before dropping back into the field.

Historically, physicists regarded the "vacuum" as the absence of all fields, particles, and energy. Turns out that's not how nature behaves. There's no such thing as complete absence of fields and field fluctuations. The uncertainty principle doesn't allow it. There must be something there, in the vacuum, and it is seething with quantum activity.

There are many possible vacuum states, related to the various quantum fields – electron field, weak field, gravitational field, etc. The Higgs field is one. It provides the background on which the other weakly interacting fields exist. All the fermions and the weak gauge bosons swim in the Higgs field.

The energy function of the Higgs field has a "Mexican hat" conformation. Minimum energy, i.e. the vacuum state, exists when the Higgs value has a small value, not zero.

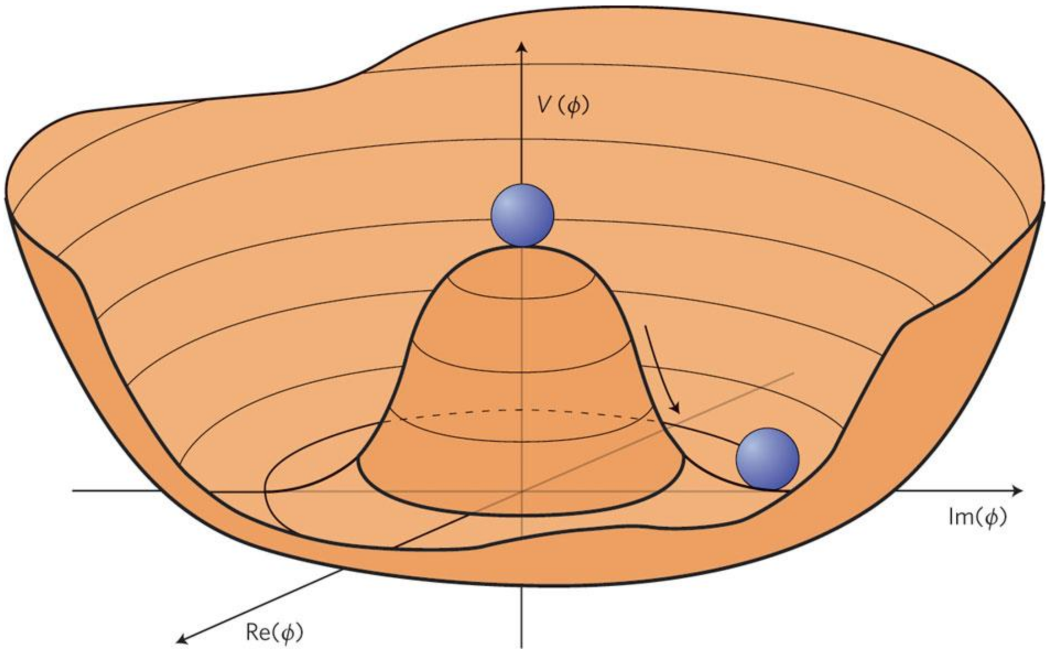

Figure 10.3. The “Mexican hat” potential. The graph shows potential energy of the vacuum as a function of field strength, ϕ. Field is a complex variable, so real and imaginary axes are shown. Minimum potential sits at some small value of the field and is symmetric around the vertical axis, where $\phi = 0$. If the field is a vector field, minimum energy also requires the field is everywhere oriented in the same direction. Credit: Nature. http://www.nature.com/nphys/journal/v7/n1/images/nphys1874-f1.jpg

As do all fields, the Higgs field fluctuates around its minimum potential because of quantum jitters inherent in the uncertainty principle. Those fluctuations interact with other weakly interacting particles such as electrons, quarks, and gauge bosons. The effect is to increase the mass of those particles.

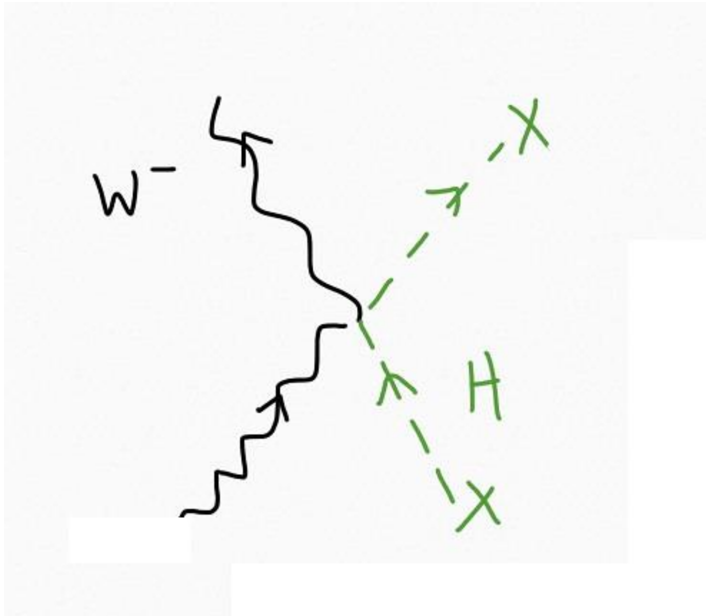

Figure 10.4. Interaction of a W^- gauge boson with the Higgs field. Time flows upward. As represented in this Feynman diagram, a Higgs particle (fluctuation in the field) emerges from the field at the earlier X , interacts with the W^-, and drops back into the field. The interaction contributes mass to the W^-.

One way to think of the extra mass contribution is in terms of inertia or resistance to motion. Massive particles have greater inertia. If a particle is interacting with the Higgs field, it's like trying to run through chest deep water instead of on the beach. (Here I've mixed up inertia and viscosity, but you get the idea . . .)

Now the polarization / parity part. If the presence of the Higgs field minimizes energy, and if the Higgs field has a vector property associated with weak isospin, then it must be oriented, i.e. all vectors aligned. Think of a magnet, by analogy. Electron spins align themselves in a magnet. That's the lowest energy configuration, and that alignment creates the larger magnetic field. Adding energy, e.g. by heating the magnet, knocks the spins out of alignment.

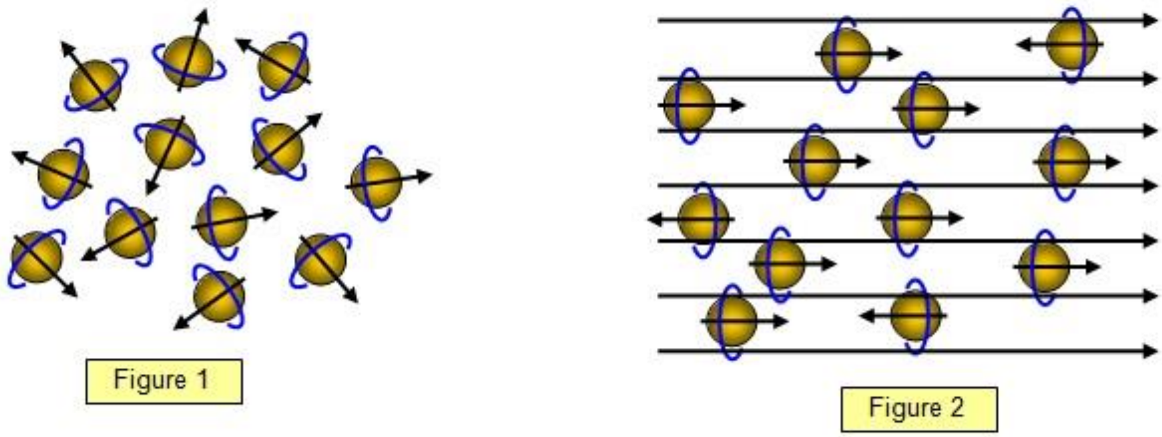

Figure 10.5. Electron spin and the magnetic field. Blue arcs represent electron spin, and short black arrows represent the small magnetic field associated with individual electron spin. When spins are oriented randomly, there is no net magnetic field (Figure 1). A net magnetic field (long black arrows) results when most spins are oriented in the same direction (Figure 2). Electrons oriented against the larger field sit at a higher energy state and would release energy if they flipped orientation. The Higgs field, by comparison, exists in the background of space-time, like the net magnetic field in Figure 2, and other weakly interacting particles feel its orientation. Credit: www.schoolphysics.co.uk

The aligned Higgs field breaks the symmetry of (internal, isospin) spatial orientation. Now there is a preferred direction, along the isospin of the Higgs field. No longer are all directions equivalent. Particles that feel the weak force, as a result, have a preferred handedness. Neutrinos, for example, all have left-handed isospin.

<u>Why we're not finished</u>

The Standard Model has passed experimental tests over 43 orders of magnitude in scale and out to fifteen decimal places, to the best of our ability to measure its predictions. It is extraordinarily successful in describing the known particles and forces. But it cannot be the end of the story. There's more out there, but we don't yet know what it is.

Over the past few decades (as of 2016) astronomers have accumulated evidence that the Standard Model includes only about five percent of the stuff of the universe. About twenty-five percent of the mass of our universe is Dark Matter, and about seventy percent is Dark Energy.

Dark Matter is invisible mass that manifests itself only by its gravitational field. It dominates the dynamics of galaxies, and it binds galaxies into clusters. Indirect evidence indicates that it represents a weakly interacting massive particle (or particles) not included in the Standard Model. Detectors are on the hunt, but so far (2016) it has eluded us.

Dark Energy, also, requires physics beyond the Standard Model. Something in the vacuum of space produces a repulsive gravity that accelerates the expansion of the universe, pushing the galaxies, these enormous structures of hundreds of billions of stars and gas and dust, faster and faster away from each other (or more properly, carrying them along as the structure of space-time expands.) Physicists have some ideas, but we don't yet understand the vacuum energy driving accelerated expansion. See Chapter 12 for a more complete discussion.

So after many generations of physicists trying to puzzle out the underlying basis of reality, we have achieved a solid understanding of about five percent. There's lots more to figure out. See Chapter 14 for further discussion what lies beyond the Standard Model.