1 Introduction

Particle physics is the study of the fundamental principles of Nature. Within the purview of particle physics are some of the deepest questions we can ask, like "What is responsible for mass?" or "Why are there three spatial and one time dimensions?" These are such big questions that no individual or even individual country can hope to answer them alone. Contemporary particle physics is truly an international endeavor, with scientists from nearly every country on Earth involved in the major experiments. Today's particle physicist may regularly travel to conferences in Argentina, visit collaborators in Japan, watch a live news conference about a major discovery from Switzerland, or even collect data at the South Pole. It is also a dynamic field, with numerous new results in particle physics published every week testing those theories that we have or suggesting new ones. The liveliness and brisk rate at which ideas are transferred in this field is largely due to particle physics having one of the largest and most widely used preprint article servers in all of science. These reasons also make taking a course on particle physics attractive to many physics students.

All of the machinery, formalism, insight, and tools that you have gained as a physics student is essential for studying particle physics. This involves the whole range of advanced physics courses:

- **Classical Mechanics.** Lagrangians and Hamiltonians are the principle way in which we express a system in particle physics.
- **Special Relativity.** The particles we explore are traveling at or near the speed of light, c.
- **Quantum Mechanics.** The particles and physical systems we investigate are extremely small, so the fundamental quanta of action, $\hbar$, is necessary in our analysis.
- **Statistical Mechanics.** Particles are classified by their intrinsic spin, which defines them as fermions or bosons.
- **Electromagnetism.** Likely electromagnetism, through Maxwell's equations, is the first field theory that you encounter in physics courses.

The language of particle physics is mathematics. From complex analysis to Fourier transforms, group theory and representation theory, linear algebra, distribution theory, and statistics myriad fields of mathematics are vital to articulate the principles, theories, and data of particle physics. As we will see in this book, the physics is extremely helpful in guiding the mathematical expressions. The goal of this book is to use the intuition gained through other physics courses and apply it to particle physics, which gets us a long way toward understanding, without just blindly following the mathematics.

The particle physics introduced in this book is also the gateway to quantum field theory, the result of the harmonious marriage of quantum mechanics and special relativity.

A complete treatment of quantum field theory is beyond the scope of this book, but we will see glimpses of a richer underlying structure as the book progresses. In particular, quantum field theory is the framework in which three of the four fundamental forces of Nature are formulated. The three forces are electromagnetism, the strong force, and the weak force. The strong and weak forces are the focus of most of this book, with aspects of electromagnetism studied throughout. Quantum field theory enables a formalism which produces predictions that can be compared to data, and it is often (and rightfully!) stated that quantum field theory is the most wide-reaching and precise theory of Nature that exists.

This chapter serves as the overview that invites you to study this rich field. Our goal is to frame the rest of the book, which necessitates a review of the forces of Nature, a preview of the Standard Model of Particle Physics, and a glimpse of the Large Hadron Collider, the currently running and most superlative particle physics experiment ever. We also need to introduce natural units to describe particle physics phenomena, and we find that familiar SI units are woefully inadequate.

1.1 A Brief History of Forces

Interactions between particles can be expressed through the four fundamental forces. Gravity is the force that was first understood at some analytical level. Gravity is a universally attractive force that couples to energy and momentum. By "universally attractive" we mean that two particles are always attracted to one another through gravity. By "couples" we mean that the strength of the gravitational force is proportional to the energy of the particle. For particles with slow velocities with respect to the speed of light, the energy to which gravity couples is just the mass of the particle. The strength of the force of gravity, defined by either Newton's universal law of gravitation or general relativity, is quantified by Newton's constant, G_N. For example, in Newton's theory, the force of gravity between two masses m_1 and m_2 separated by distance $\vec{r}$ is

$$\vec{F}_g = -\frac{G_N m_1 m_2}{|\vec{r}|^2}\hat{r}\,, \tag{1.1}$$

where $\hat{r}$ is a unit vector in the direction of $\vec{r}$. We say that G_N is the "strength of coupling" of gravity, or "coupling constant" for short. If G_N is larger, the force is larger; if G_N is smaller, the force is smaller. In SI units, the value of G_N is

$$G_N = 6.67 \times 10^{-11}\ \mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}\,. \tag{1.2}$$

It turns out that, in appropriate units that we will discuss further later in this chapter, G_N is incredibly tiny. Gravitational forces are completely ignorable for any microscopic experiment involving individual particles, like electrons or protons.

The next force that was understood is electromagnetism. Unlike gravity, which is universally attractive because mass is always positive, electromagnetism can be either attractive or repulsive (or neutral). Particles or other objects can have positive, negative, or no charge and the relative sign of charges determines whether the force is attractive or repulsive. The electric force between two charges q_1 and q_2 separated by distance $\vec{r}$ is

$$\vec{F}_e = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{|\vec{r}|^2}\hat{r}\,. \tag{1.3}$$

Here, the factor of $(4\pi\epsilon_0)^{-1}$ is the coupling constant of electromagnetism. The value of ϵ_0 in SI units is

$$\epsilon_0 = 8.85 \times 10^{-12}\ \mathrm{F}\cdot\mathrm{m}^{-1}\,, \tag{1.4}$$

where F is the SI unit of the farad. In appropriate units to enable comparison, this is billions and billions of times larger than the coupling of gravity, G_N. Electricity and magnetism are intimately related as an electric field in one reference frame produces a magnetic field in another reference frame. This is also the starting point for special relativity, which we'll review in Chapter 2.

This was the story at the end of the nineteenth century. Knowing the mass and charge of an object is sufficient to determine how it will interact with any other object, assuming that the only forces are gravity and electromagnetism. This is also the point where this book begins, at the beginning of the twentieth century. At this time, physics was undergoing huge revolutions: in addition to the formulation of the modern pillars of relativity and quantum mechanics, the electron was recently discovered, as was the nuclear structure of the atom, and even odder things like superconductivity. A nineteenth century physicist was completely powerless to address these phenomena and understand them. They are not described strictly within the paradigm of Newtonian gravity and Maxwellian electromagnetism.

Throughout the twentieth century, more and more particles and interactions were discovered: the positron, the anti-particle of the electron; neutrinos, very light cousins to the electron that are electrically neutral and seem to pass through nearly everything; the muon, similar to the electron but more massive; and so on. Near the end of the 1960s, hundreds of new particles had been discovered and their properties (like mass, charge, and intrinsic spin) measured. It was looking like quite a mess, with no clear organizing principle. However, in the late 1960s through the late 1970s, heroic efforts from theoretical and experimental physicists around the world yielded a simple underlying framework that could explain all experimental results. It became known as the Standard Model of Particle Physics.

1.2 The Standard Model of Particle Physics

The **Standard Model** consists of all but one of the fundamental particles and forces that are important in our experiments. It provides an organizing principle for how to construct more complicated objects from these basic building blocks. A **fundamental particle** is one which we believe is truly elementary: it has no spatial extent (it is a point) and is not made up of any more fundamental parts. For example, hydrogen is not fundamental because it

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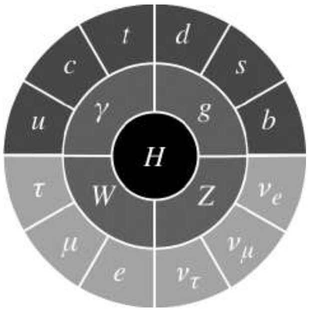

Fig. 1.1 Artistic representation of the 17 Standard Model particles. The top outer ring are the six quarks, the bottom outer ring are the six leptons, the middle ring are the four force-carrying bosons, and the center is the Higgs boson. Courtesy of Particle Fever, LLC.

consists of a proton and an electron, while it is believed that the electron is fundamental. In this book, we will study the theoretical predictions and experimental justification of the Standard Model.

The particles of the Standard Model can be artistically arranged and represented as a series of concentric rings displayed in Fig. 1.1. These 17 particles and their interactions are responsible for almost all observed phenomena. Their relationship to one another in this figure is indicative of their intrinsic properties and interactions. Gravity and its force-carrying particle, the graviton, is the one conspicuously absent force. There are four major areas of the Standard Model represented by the different regions in Fig. 1.1:

- the **quarks** (top outer ring)
- the **leptons** (bottom outer ring)
- the **force carriers** (middle ring)
- and the **Higgs boson** (center).

You have likely heard of many of these particles and their properties before. Here, we will just briefly introduce them, and we will get to know them all intimately throughout this book.

The rings in this representation are indicative of the spin of the particle. **Spin** is the intrinsic angular momentum of a particle which we will introduce in detail in Chapter 3. The quarks and leptons all have half-integer spin and so are **fermions**, while the force carriers and Higgs have integer spin and so are **bosons**. The Higgs boson H has spin 0 and was predicted in the 1960s but was only discovered in 2012 at CERN in Switzerland. Of the force carriers, one is very familiar: the photon γ is the force carrier of electromagnetism. In addition to electromagnetism, the Standard Model has two other forces: the **strong force** (called quantum chromodynamics or QCD) and the **weak force**. Unlike electromagnetism or gravity, the strong and weak forces exist only at very short distances; they have no classical mechanics counterparts. The force carrier of the strong force is called the **gluon** g and is responsible for binding atomic nuclei together. The force carriers of the weak force are the ***W*** and ***Z* bosons**. The weak force mediates radioactive decay of unstable elements, such as uranium.

On the top of the Standard Model rings are the six quarks: up u, down d, charm c, strange s, top t, and bottom b. They couple to all four forces and form bound states called **hadrons**. The two hadrons most relevant to everyday life are protons and neutrons, which are composed of up and down quarks. The four other quarks are only produced in high-energy collisions of particles. The leptons, the bottom of the Standard Model ring, consist of the electrically charged leptons (electron e, muon μ, and tau τ) and their electrically neutral cousins, the **neutrinos** ν. The only lepton you would encounter during your regular day is the electron, the least massive electrically charged particle of the Standard Model. You can only produce the other charged leptons in high-energy collisions, and you'd never know it, but about ten quadrillion (10^{16}) neutrinos passed right through you while you read this.

Our focus in this book will be on the strong and weak forces, as they have no counterpart in classical mechanics. Because of this, they exhibit extremely weird phenomena that will challenge our abilities to describe them theoretically. The properties of all of the particles of the Standard Model (like mass, charge, or spin) and the experimental results that measured them are collected in the **Particle Data Group's (PDG) *Review of Particle Physics***. You can find it online at `http://pdg.lbl.gov` or you can order the book yourself from the website (it's free!).

1.3 The Large Hadron Collider

The largest scientific experiment ever is located outside of Geneva, Switzerland, accelerates protons to near the speed of light, is a Sagittarius, and loves international travel. It is the **Large Hadron Collider**, or LHC. Figure 1.2 is a bird's eye view from high over Geneva, looking to the south. To orient you, Lake Geneva is the slice coming from the left of the photo, and downtown Geneva is located at its tip. This photo is taken from the Jura Mountains, and far off in the distance you can see Mont Blanc. The ring of the LHC is denoted with the oval. This is for illustration; the ring is located 100 meters underground. Also, note the size of the ring. The Geneva airport is located just to the south and the runway is about 2 miles (3.2 kilometers) long. This LHC ring is about 18 miles (27 kilometers) in circumference. In it, two counterrotating beams of protons are accelerated to enormous energies. Each proton at the LHC has the kinetic energy of a flying mosquito, and a mosquito has about 10^{20} protons!

To study elementary particles, we use a sophisticated technique that could be called the "Neanderthal method." To look inside the accelerated protons, we smash them together, exploding them apart into a huge number of particles. Just like a detective at the scene of a car crash, a particle physicist must reconstruct the moment of proton collision using only the remnants and debris from the collision. This is indeed a tall order, but also like a detective, there are guiding principles that can be used to infer what happened. For example, energy and momentum must be conserved in a collision, and this greatly restricts how all those particles might have been produced.

Fig. 1.2 Aerial view of the region near Geneva, Switzerland, with the illustration of the Large Hadron Collider ring as the large oval. Lake Geneva is the slash from the left, downtown Geneva is located at the end of Lake Geneva, and Mt. Blanc is visible off in the distance. The main CERN site at Meyrin and the experiments along the ring are denoted. Credit: CERN © CERN.

As particle detectives, we must collect as much evidence as possible. This is accomplished with enormous detector experiments that measure nearly all the particles produced in proton collisions. Figure 1.3 shows a picture of one of the experiments at the LHC, called **ATLAS** (A Toroidal LHC ApparatuS). This is a photo of ATLAS before its construction was completed. We'll discuss the particular parts of a particle physics experiment in Chapter 5, but this figure should illustrate the sizes involved. ATLAS, and its sister experiment **CMS** (Compact Muon Solenoid) at the LHC, each are about the size and weight of a five-story building!

For an idea of what happens in the proton collisions, Fig. 1.4 shows an **event display**. The proton beams come in from either side of the figure, and collide in the center. All of the lines emanating from the center correspond to individual particles produced in the collision. Different parts of the detector are sensitive to different physics. For example, see the lines at the center of the figure, called **tracks**? There's a magnetic field in that region of the detector, and so charged particles bend when passing through. The charge of the particles can be identified by the direction of the bending by using the right-hand rule. The shaded background of the figure represents the different detector components. Outside of the region with the tracks is the **calorimetry**, which measures the energy of particles.

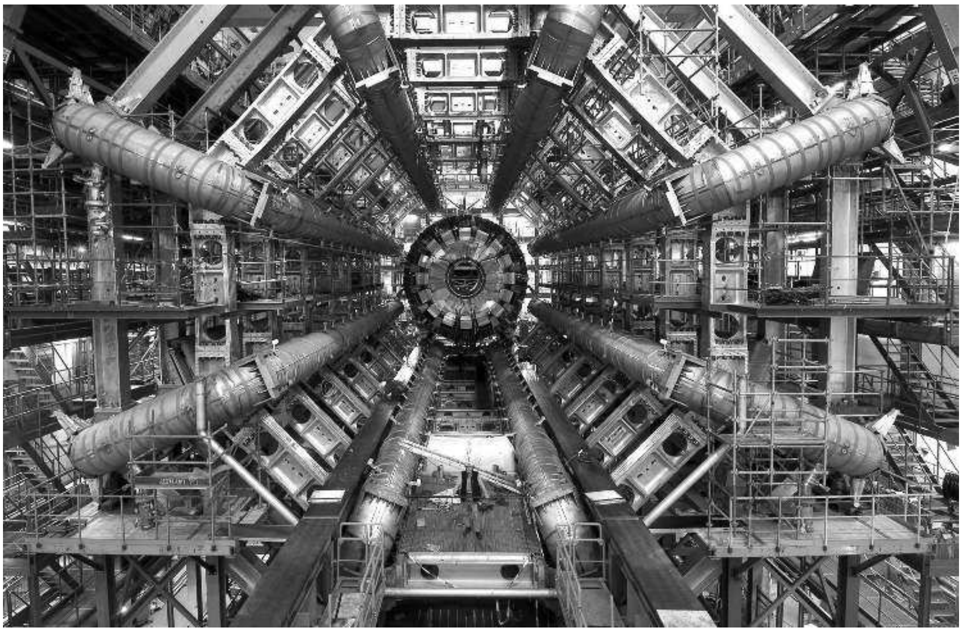

Fig. 1.3 Photo of the ATLAS detector before construction was completed. The large metal tubes contain the electromagnet that sources its namesake toroidal magnetic field. The interior region is now filled with detector electronics. Note the person for scale. Credit: CERN © CERN.

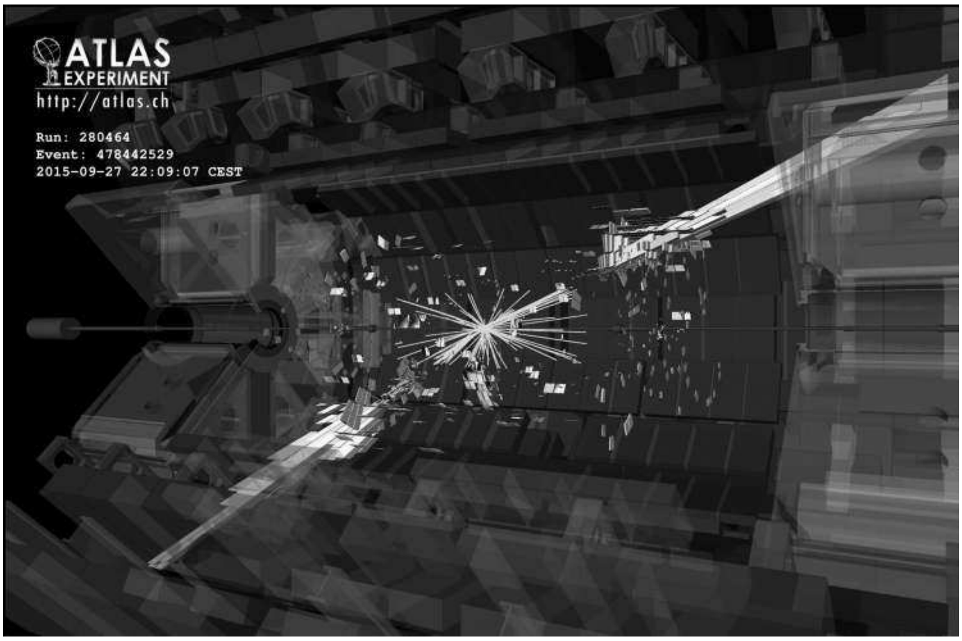

Fig. 1.4 Image of a proton collision event at the ATLAS experiment. The proton beams collide at the center of the figure, and tracks and calorimeter deposits represent particles detected by the experiment. Credit: CERN © CERN.

Deposits of particles in the calorimeters are denoted by the rectangular bars in the figure. At the top and bottom of the background image is another component called the **muon system** which is responsible for detecting muons.

1.4 Units of Particle Physics and Dimensional Analysis

The first thing we need to do in order to begin studying particle physics is to establish the appropriate system of units in which to express the outcome of experimental measurements. Good units should represent the realm in which they are being used. Because particle physics is the realm of short distances and high energies, we need to use units that naturally and usefully express quantities in this domain.

Both relativity and quantum mechanics are necessary to describe particle physics phenomena. The particles we will consider will be traveling at or near the speed of light c, and so c will appear in equations everywhere. For example, the particles we consider satisfy the relativistic energy–momentum relation,

$$E^2 = m^2c^4 + |\vec{p}|^2c^2\,, \tag{1.5}$$

where E is the energy, m is the mass, and $\vec{p}$ is the momentum of the particle of interest. In SI units, c is

$$c = 3 \times 10^8\ \text{m} \cdot \text{s}^{-1}\,, \tag{1.6}$$

so every time we have to use the energy–momentum relationship, we have to lug around this huge number.

Particle physics is also the realm of quantum mechanics, the description of Nature at the shortest distances. The fundamental unit in quantum mechanics is $\hbar$, Planck's reduced constant, which quantifies units of angular momentum. It also appears in the Schrödinger equation,

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + V\psi\,. \tag{1.7}$$

We'll discuss how to generalize the Schrödinger equation to account for relativity in Chapter 2, but any time we want to describe quantum phenomena, we need an $\hbar$. In SI units, $\hbar$ is

$$\hbar = 1.05 \times 10^{-34}\ \text{J} \cdot \text{s}\,. \tag{1.8}$$

This is a teensy-tiny number in SI units.

Additionally, the masses or other properties of individual particles are exceptionally small. In SI units, the mass of the electron is

$$m_e = 9.11 \times 10^{-31}\ \text{kg}\,. \tag{1.9}$$

The mass of the proton, while much larger than the electron, is still minuscule in SI units:

$$m_p = 1.67 \times 10^{-27}\ \text{kg}\,. \tag{1.10}$$

Even the most massive elementary particle, the **top quark**, has a mass in SI units of

$$m_t = 3.1 \times 10^{-25}\ \text{kg}\,. \tag{1.11}$$

Whenever we talk about the electron traveling at relativistic speeds, we need to keep track of numbers that are spread over about 40 orders of magnitude! This is inconvenient.

There's another, philosophical, reason to abandon SI units in particle physics. We believe, perhaps with a bit of hubris, that particle physics is truly fundamental. The speed of light as measured by a distant civilization would be the same as what we have measured on Earth. However, why would they use SI units? The second is defined as a part of the day, a very Earth-centric notion, and the meter was originally one ten-millionth the distance from the North Pole to the Equator. Later, the meter was defined from a platinum-iridium alloy bar in France, which then depends on the precision to which such a bar can be machined.

For these reasons and to express the fundamental-ness of particle physics, we introduce **natural units**, or "God's units," in which we set

$$\hbar = c = 1 \quad (\text{unitless})\,. \tag{1.12}$$

Correspondingly, the permittivity and permeability of free space, ϵ_0 and μ_0, are also set to 1. Note that the units of $\hbar$ and c are

$$[\hbar] = [\text{mass}][\text{length}]^2[\text{time}]^{-1}\,, \qquad [c] = [\text{length}][\text{time}]^{-1}\,. \tag{1.13}$$

Because we set $\hbar = c = 1$, this defines two relationships between the three fundamental measurement units of mass, length, and time. Therefore, natural units can be completely expressed in terms of one unique combination of mass, length, and time. We take the measurement unit of natural units to be energy, and everything in natural units can be expressed solely in terms of energy. The reason to use energy is that it is a conserved quantity, so once the energy of a system is defined, that fixes intrinsic mass, length, and time scales for that system.

In particle physics, we typically use the **electron volt** (eV) as the energy unit of choice as this is naturally (closer to) the scale at which we work. In SI units, one electron volt is

$$1\ \text{eV} \ = 1.6 \times 10^{-19}\ \text{J}\,. \tag{1.14}$$

One electron volt is the energy that a particle with the fundamental unit of electric charge $e = 1.6 \times 10^{-19}$ coulombs acquires in an electric potential of 1 volt. For example, let's see how this works for the electron mass. To express the electron mass as an energy, we multiply by c^2:

$$m_ec^2 = 8.19 \times 10^{-14}\ \text{J} = 5.11 \times 10^5\ \text{eV} = 511\ \text{keV (kilo-eV)}\,. \tag{1.15}$$

The mass of the proton is

$$m_pc^2 = 1.5 \times 10^{-10}\ \text{J} = 9.38 \times 10^8\ \text{eV} = 938\ \text{MeV (mega-eV)}\,. \tag{1.16}$$

For comparison, the LHC collides protons that have kinetic energies of 6.5×10^{12} eV = 6.5 TeV (tera-eV), almost 7000 times the mass of the proton.

Using natural units, we can turn distances into energies, as well. Recall the Heisenberg uncertainty principle for momentum Δp and position Δx standard deviations:

$$\Delta p \cdot \Delta x \geq \frac{\hbar}{2} . \tag{1.17}$$

This tells us how to convert to natural units for distances. A distance x has the same units as $\hbar/p$, which you might also recall as the de Broglie wavelength divided by 2π. Momentum p can be related to energy via the relativistic energy–momentum relation

$$E = pc , \tag{1.18}$$

which holds for massless particles. Then, the quantity

$$\frac{x}{\hbar c} = \frac{1}{E} \tag{1.19}$$

is a distance x expressed in natural units. Let's see how this works in an example.

Example 1.1 The Bohr radius is the average distance between an electron and the proton nucleus in the hydrogen atom. What is the Bohr radius expressed in natural units?

Solution

The Bohr radius a_0 in SI units is

$$a_0 = 5.3 \times 10^{-11}\ \text{m} . \tag{1.20}$$

Converting to natural units, this is

$$\frac{a_0}{\hbar c} = 1.7 \times 10^{15}\ \text{J}^{-1} = \frac{1}{3.7\ \text{keV}} . \tag{1.21}$$

Note that this corresponding energy is much larger than the magnitude of the ground state energy of hydrogen, which is 13.6 eV.

Throughout this book, we will employ natural units as they will make expressions and algebra much easier. From natural units, one can always uniquely go to any other unit system by restoring the factors of c and $\hbar$. You just have to remember what the quantity is (a length, time, or mass, for example).

Exercises

1.1 *Energy of a Mosquito.* The mass of a mosquito is approximately 2.5×10^{-6} kg. Estimate the kinetic energy of a flying mosquito and express it in eV. What is the approximate kinetic energy per **nucleon** (proton or neutron) for a mosquito? How does this compare to the energy of protons at the LHC?

1.2 *Yukawa's Theory.* In the 1930s, Hideki Yukawa predicted the existence of a new particle, now called the **pion**. It was theorized to be responsible for binding protons and neutrons together in atomic nuclei. Based on the size of an atomic nucleus,