Introduction to Particle Physics   Lecture 1

Welcome to Physics 366, Introduction to Particle Physics! Particle physics is the study of the universe at the shortest distance and time scales, or, correspondingly, at the largest energies and momenta. At short distances, quantum mechanics rules and at high energies, relativity is king, so particle physics marries the two pillars of 20th century physics to describe nature at its most fundamental level. We will use quantum mechanics and relativity to understand and predict properties of the universe that can be directly tested in experiments. A complete theoretical treatment of particle physics requires quantum field theory, whose description and thorough mathematical introduction is beyond the scope of this course. Nevertheless, we will use elements of quantum field theory in this course.

In this lecture, we will just go over the outline and scope of this class and provide a bird's eye view of what you will learn. I've provided printed copies of the course syllabus here; this will likely be the only printed thing in this class. We'll go over it now.

I'm Andrew Larkoski, and I'm a theoretical particle physicist by trade, so this is stuff that I work with every day. My office is right across the hall, in P124, and my email address is larkoski@reed.edu, so you know how to get a hold of me. If you are here, then you found this class. We meet on Tuesdays and Thursdays from 9:00 am to 10:20 am. I will hold "official" office hours from 1:00 - 3:00 pm on Mondays and Tuesdays in my office. I am available to chat any time my door is open or by appointment.

The textbook for the course is the book "Concepts of Elementary Particle Physics" by Michael Peskin. The book is not yet published, which is both a good and a bad thing. The good news is that the book is freely available on Michael's website, which is provided here. Also, the bookstore has printed copies available, for a minimal price. The bad news, or actually exciting news, is that because it isn't published yet, it does have some typos. What makes this exciting is that you are the first class to use this book, so can have an impact on its final draft! Throughout this class, I will collect typos, corrections, or suggested clarifications from you and send them off to Michael. Please be critical; I think this book is good, but don't agree with me too easily!

In addition to Peskin's book, I've recommended a number of other books at various levels. At the undergraduate level, Mark Thomson's book is excellent and David's book is ok, for a dated historical introduction. At a more advanced level, Sidney Coleman's lectures collected in Aspects of Symmetry or online in video recordings. Coleman, while not widely known outside of theoretical physics, is a huge figure in physics, and his lectures are legendary. They were recorded in 1975, and Coleman smokes an entire pack of cigs each lecture. A very different time indeed. I've also included some graduate level textbooks which may be interesting and relevant depending on your background and motivation.

The website for the course is linked from my Reed website: people.reed.edu/~larkoshi/, where I will post homeworks, solutions, relavant links, and lecture notes as the course proceeds.

This class is broadly divided into three parts. First, we will review and introduce the tools necessary for an understanding of particle physics. This includes reviewing special relativity, and introducing natural units, some group theory, Fermi's Golden Rule, and Feynman diagrams. In the second part of the course, we will discuss the strong force, quantum chromodynamics, its theoretical foundation and experimental justification. In this part of the class, we will discuss my favorite particle, the gluon. During the last several weeks of the class, we will discuss the electro-weak theory. The weak interactions manifest some very weird phenomena and follow from the chiral nature of the theory and spontaneous symmetry breaking via the Higgs Mechanism.

A broad outline of lectures in this class is given on the last page of the syllabus. This may change, and I've also provided the corresponding sections in the textbook that cover the lecture material. Note that there will be no lecture on February 23rd; I'll be away and we'll discuss making this up nearer that date.

Finally, on to course requirements. There will be three graded aspects to this class: weekly homework, a final exam, and an oral exam. Homework will be assigned weekly through the course website and should be completed with pen and paper or typed up. Homeworks are due the following Thursday in class. The first homework assignment is already posted to the course website.

The final exam will cover all topics discussed in this course. It will be assigned during the final week of the semester and you will have one week to complete it. More information about the final exam and its due date will come later in the semester.

Additionally, there will be a 30 minute oral exam that you will sign up for during finals week. An important aspect of being a good physicist is the ability to communicate well verbally. In this oral exam, we will discuss one-on-one various theoretical and experimental topics covered in this course.

The amounts to which these components contribute to your final grade are given in the syllabus.

Any questions regarding the syllabus or outline of the course?

For the remainder of this lecture, I want to review the goal of this course and provide an overview of what we will cover.

Our understanding of all interactions between particles can be expressed through the four fundamental forces. The first force we first understood at some analytical level is gravity. Gravity is a universally attractive force that couples to energy and momentum. By "universally attactive" I mean that two particles are always attracted to one another through gravity. By "couples" I mean that the strength of the gravitational force is proportional to the energy of the particle. For particles with small velocities compared to the speed of light, the energy that gravity couples to is just the mass of the particle. Taking this to its logical conclusion leads to the theory of general relativity, the prediction of gravitational waves, etc. The strength of the force of gravity, either defined by Newton's Universal Gravitation or general relativity is 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 r is

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

We say that G_N is the "strength of coupling" for gravity, or "coupling constant" for short. If G_N is larger, the force is larger; if G_N is smaller, the force is smaller. It turns out that, in appropriate units that we will discuss more in the next lecture, that G_N is <u>incredibly</u> tiny. For this and other reasons much more technical, after today, we won't speak of gravity again.

The next force that humanity understood was 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 if the force is attractive or repulsive. The electric force between two charges q_1 and q_2 separated by r is

$$\vec{F}_e = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}\hat{r}$$

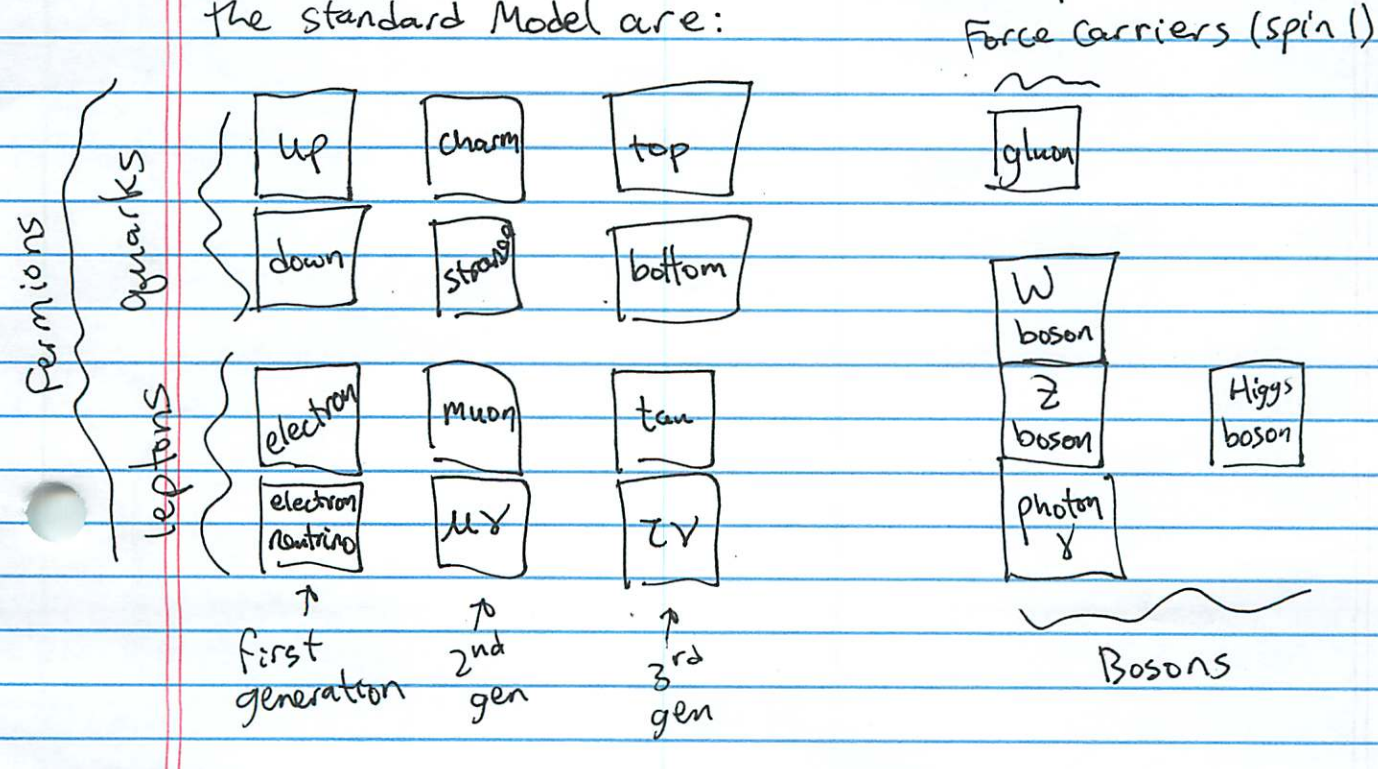
Here, $\frac{1}{4\pi\varepsilon_0}$ is the coupling constant of electromagnetism in SI units. In appropriate units to enable comparison, this is billions and billions of times larger than the coupling of gravity G_N. As Maxwell taught us, electricity and magnetism are one and the same, just manifested in different reference frames. This is also the starting point for special relativity, but we'll review that next week.

This was the story at the end of the 19^{th} century. If you tell me the mass and charge of an object, I can tell you how it will interact with <u>any</u> other object, assuming of course that the only forces are gravity and electromagnetism. This is also the point where this class begins, at the beginning of the 20^{th} century. At this time, physics was undergoing huge revolutions: in addition to the ~~modern~~ 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 19^{th} century physicist was completely impotent to address these phenomena and understand them.

Throughout the 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 an electron but heavier; and on and on. Near the end of the 1960's, <u>hundreds</u> of new particles had been discovered and their properties (like mass, charge, intrinsic spin, etc.) ~~had~~ measured. It was looking like quite a mess, with no clear organizing principle. However, in the late 1960's through the late 1970's, through 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.

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

So, what is the standard Model? The particles of the standard Model are:



We ~~believe~~ believe that these 17 particles and their interactions are responsible for <u>almost all</u> observed phenomena (gravity is conspicuously absent...)

We will discuss all of this in detail throughout the semester; here I'll just orient you. There are four major areas of the Standard model: the quarks, the leptons, the force carriers, and the Higgs boson. The quarks and leptons all have half-integer spin and so are <u>fermions</u>, while the force carriers and the Higgs have integer spin and so are bosons. The Higgs boson has 0 spin and ~~[illegible]~~ was predicted in the 1960's. It was discovered in 2012, at CERN in Switzerland. Of the force carriers, one is very familiar; the photon is the force carrier of E+M. In addition to E+M, the Standard Model has two other forces: the strong force (quantum chromodynamics or QCD) and the weak force. Unlike E+M and gravity, the strong and weak forces exist only at very short distances; they have no classical mechanics counterpart. The force carrier of the strong force is called the gluon and it is responsible for ~~[illegible]~~ 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, like uranium.

On the other side of the Standard Model, the six quarks couple to <u>all</u> forces, and they combine to produce hadrons. Only two hadrons will you find in everyday life: 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 name "quark" comes from a line in James Joyce's novel Finnegan's Wake (not to be confused with the fresh acid-set cheese of the same name).

- Three quarks for Muster Mark!
Sure he hasn't got much of a bark
And sure any he has it's all beside the mark.

The leptons, the last corner of the standard Model, consist of the charged leptons (electron, muon, tau) and their neutral cousins, the neutrinos. Of these, the only one you would encounter on your regular day is the electron: the least massive, ~~charged~~ electrically charged particle of the Standard Model. You can only produce the other charged leptons in high energy collisions (like cosmic rays in the upper atmosphere), and you'd never know it, but about ~~10 neutrinos~~ 10 quadrillion (10^{16}) neutrinos passed through each of you while I said this.

So, that's what we will discuss in this class. Our focus will be on the strong and weak forces, as we have no ~~class~~ intuition from classical mechanics (and so they exhibit the weirdest phenomena). The properties of all of these particles (masses, charge, spin, etc.) and the experimental results that found them are ~~&~~ collected in the Particle Data Group's Review of Particle Physics. You can find it online at pdg.lbl.gov or you can order the book yourself (if you're a nerd like that). In your first homework you'll search in the PDG a bit to get more familiar with the Standard Model.

Finally, in this lecture, I want to briefly introduce the largest ~~a~~ scientific experiment ever created. It's located outside of Geneva, Switzerland, accelerates protons to near the speed of light, is a ~~Sag~~ Sagittarius, and loves ~~to~~ international travel: the Large Hadron Collider (LHC).

This is a bird's eye view from high over Geneva, to the north. To orient you, here's Lake Geneva with Geneva at the tip. This picture is taken from the Jura Mountains; far to the south you can see Mont Blanc. The ring of the LHC is denoted with the yellow ~~a~~ curve. 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 long. The ring is about 18 miles in circumference! In it, two ~~beams of~~ counterrotating beams of protons are accelerated to enormous energies. Each proton has the kinetic energy of a flying mosquito, and a mosquito has about 10^{20} protons! ~~To study~~

To study elementary particles, we use a sophisticated technique called the "neanderthal method". To look inside the accelerated protons, we smash them together, exploding them apart, just like ~~[illegible]~~ the apes at the into of 2001: A space Odyssey. In the explosion of colliding protons, a huge number of particles are produced and are recorded in enormous detector experiments. Here's a picture of one of the experiments at the LHC, called ATLAS, A Toroidal LHC ApparatuS. This was a photo of ATLAS before it was ~~a~~ completed. We'll discuss the parts of ~~[illegible]~~ a particle physics experiment later, but I just want you to appreciate the size. ATLAS, and its sister experiment CMS (Compact Muon Solenoid), are about the size and weight of a 5 story building (about 4 times the size of this building)! These huge experiments are necessary to record everything that comes out of the proton collisions. To get an ~~image~~ idea of this, here's an event display of what comes out of one of the proton collision events. The proton beams are here, and the protons collide here. All of these lines that come from the point of collision correspond to individual particles.

Different parts of the detector are sensitive to different physics. For example, see these bent tracks? There's a magnetic field here, and so charged particles bend passing through. You can see the charge of the particles by the direction of bending!

That's a *very* brief overview of the Standard Model and the LHC. We will dive into much more detail throughout this semester.