Robert Clemenson May 2019

Particle Physics – Handout

Particle Physics – A Brief History

The Electron – 1897

- Discovered by JJ Thomson in 1897, by observing the path of cathode rays (emissions from heated metal filaments.

The Photon – 1900 – 1924

- You have met the idea that light behaves both as a wave and a particle (this is actually a pretty general idea in quantum mechanics for all particles, which we will mention briefly later). The first triumph of quantum mechanics was Planck's solution to the 'Ultraviolet catastrophe', by describing light as a quantized parcel of energy (a particle).

Antimatter – 1930 – 1956

- Antiparticles were first hinted at by Dirac in 1927 on purely theoretical grounds (the existence of negative energy solutions to the 'Dirac equation' of relativistic quantum mechanics), but his interpretation was a little off… In the 1940's Feynman gave a more solid interpretation of these solutions, corresponding to real particles with opposite charges to their 'ordinary' counterparts. The positron was discovered in 1931 from cloud chamber measurements of cosmic rays.

Neutrinos – 1930 – 1962

- From studying the energies of the emitted electrons from beta decay, it was inferred that there must exist an additional neutral particle. If beta decay occurred without a neutrino ($n \to p + e^-$), we would expect all the electrons to have the exact same energy (as there is only one way for this decay can satisfy energy and momentum conservation with two bodies). However, we observe a range of energies for the emitted electron. The simplest explanation for this, is that there is an additional particle emitted, allowing for energies to be differently distributed between the outgoing electron and neutrino. Hence, we have the true beta decay ($n \to p + e^- + \bar{\nu}$).
- Neutrinos were first measured by Cowan and Reines in the mid 1950's. They set up a large tank of water within the Savannah River nuclear reactor in South Carolina, to detect positrons from the inverse beta decay of hydrogen nuclei in the water ($p + \bar{\nu} \to n + e^+$). To give an indication of how tricky detecting neutrinos really is (as they are so weakly interacting), the reactor gave them a neutrino flux of around 5×10^{13} neutrinos per cm^2 per second, yet they still only expected to observe around 2 or 3 events per hour.
- We will talk more about neutrinos later, and the subject of the 2015 physics Nobel prize.

Quarks – 1961 - 1964

- The 1950s and early 1960s had seen the discovery of a mess of new particles. The situation was completely analogous to the problems in chemistry of the previous century, i.e. many elements had been identified and categorized as best as possible, but there was no underlying explanation or understanding of their relations to one another.
- This was solved by Gell-Mann's introduction of the quark model in 1964. The many hadrons and mesons previously discovered could now be understood as structures formed from various combinations of the three generations of quarks.

<u>Quantum Mechanics</u>

'**Particle Physics = Quantum Mechanics'**, and **'Quantum Mechanics = A Lot of Hard Maths**'

From your studies in particle physics so far you may have gotten the impression that particle physics is rather like chemistry, with the standard model acting as a kind of subatomic periodic table. This has some truth to it… But really, the *standard model* actually refers to a detailed and rich mathematical formalism, underlying the way we understand and predict the ways in which subatomic particles interact and are created. At the centre of this formalism, is quantum mechanics.

Quantum mechanics refers to the laws of physics we use to describe objects that are very small (such as single atoms or elementary particles). These laws are complicated, and often appear to break the intuition we have when it comes to dealing with objects on our own length scale (tennis balls, the Earth, etc). The laws of physics governing very small objects, appear to be totally different from the laws governing larger objects.

On very small length scales (say around 10^{-10}m as a rule of thumb), objects no longer behave like solid blobs of stuff. They behave more like a kind of fuzzy cloud, no longer localized to a finite region in space. Take an electron for example. This 'cloud' describes the likelihood of us measuring the location of the electron at a given point in space. You can think of how dense the cloud is, as a measure of how likely the electron is to be found at that point. The centre of the cloud is the thickest, which is where we are most likely to measure the electron to be, with wispy edges tailing off further away from the centre, where the electron is less likely (but not impossible) to be found. The point is… Until we make a direct measure of the electron, its position is indeterminate. We cannot say, without making an observation "the electron is here, this is the path through space it will follow".

Quantum mechanics replaces the kind of deterministic classical physics we use to calculate the motion of a tennis ball (given its initial position, and initial velocity), with a probabilistic description of how likely it is to measure a particle in a given place at a given time.

To try and put in a short paragraph, one thing I want you to remember about quantum mechanics: When we don't observe an electron, it acts like a wispy probability cloud. As soon as we try and measure its position, it becomes a particle, existing at a definite location. With that location described by a probability, related to the thickness of the probability cloud.

A consequence of this probabilistic behaviour is the concept of 'fundamental uncertainty' (you may well have heard of Heisenbergs famous 'uncertainty principle'). The position of our particle is described by a probability distribution, giving us the likelihood of measuring the particle in a given region of space. Similarly, the momentum of our particle is also described by a probability distribution (the relation between these two probability distributions is something called a 'Fourier transform', but we're just skimming over the fine detail here).

We find that the uncertainties (for example, the standard deviation of the distributions) are related as follows: (Note, ħ is Planck's constant divided by 2π)

$$(\Delta x)(\Delta p) \geq \frac{\hbar}{2}$$

This tells us that the greater the uncertainty on the position of the particle, the less the uncertainty on the momentum of the particle and vice versa. So we cannot simultaneously know where a particle is, and what it's momentum is! The better we know one, the worse we know the other.

This is only one example of a number of so called 'uncertainly relations'. The one we will actually make the most use of relates energy and time:

$$(\Delta E)(\Delta t) \geq \frac{\hbar}{2}$$

This relation tells us that if a particle only exists for a very brief time, Δt, there is a large uncertainty on its energy. This actually also means we can 'borrow' energy from the Universe to create particles, as long as they don't exist for very long (this is related to how black holes can evaporate!).

Feynman Diagrams

Ok, so we've talked a little about quantum mechanics. We've said that 'particles' only behave like particles (points of mass/charge etc located at a given point) when we observe them.

When we observe an interaction, say electrons scattering off one another, the observations we make are of the incoming electrons in the collider, and the outgoing scattered electrons. What happens in between these two events is indeterminate, and not something we can measure. So then how can we calculate things like the probability of the electrons scattering in this way? (rather than just missing one another or undergoing some other interaction).

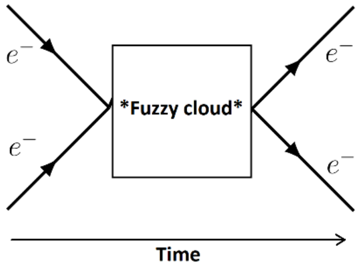

Figure (1)

The problem of finding the probability of a given scattering event (i.e. two electrons coming in and two electrons leaving, as shown) is solved by the use of Feynman diagrams.

What a Feynman diagram actually represents, is a probability for the scattering event occurring in a certain way. In order to find the total probability of the event occurring, we have to add up the probabilities of it occurring via the various intermediate *fuzzy cloud* stages. Let me illustrate:

Figure (2) represents the probability of the scattering occurring through the exchange of a single virtual photon. This diagram would be described as 'first order', as it only contains two vertices (a vertex being a point in the diagram where lines meet).

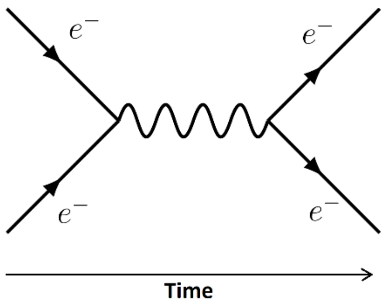

Figure (2)

Figure (3) represents the probability of the scattering occurring through exchange of a photon, with an electron-positron pair briefly created in the intermediate stage. This diagram is 'second order', as it contains four vertices. Higher order diagrams have a lower probability of occurring, so make a small contribution to the total probability of a given interaction occurring.

Note, we could go on forever, creating higher and higher order diagrams for this simple scattering process. As long as we stick to a basic set of rules for building the diagrams, any crazy thing we can think of to put in the '*fuzzy cloud* box' is possible. Fortunately, the most simple (lowest order) diagrams make the largest contribution, so when calculating the total probability for the interaction, we can neglect the higher order diagrams.

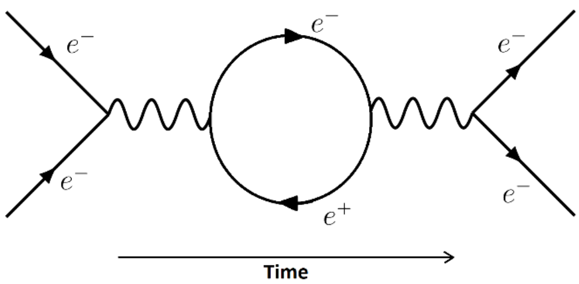

Figure (3)

Actually computing the probabilities contributed by each diagram is not an easy thing, and involves doing some rather tricky integrals! What we've discussed here is all very hand wavy!

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Cosmic Ray Muons and Neutrinos – Special Relativity Revisited

Modern Particle Physics – Super Colliders and Grand Unified Theories

The Greek Atomists – 400 BC

- The atomic hypothesis accredited to Democritus, states that all matter is made up of indivisible units called atoms (in fact, the word ‘atom’ is Greek for ‘indivisible’). Though not scientifically based, and in the finer details very wrong, this is still a reasonable point at which to begin the history of particle physics!

The Planetary Model of the Atom – 1911

- Rutherford deduced the ‘planetary model’ of the atom, by observing alpha particles scattering off gold atoms. Though the planetary model isn’t the full story… This was a big leap in the theory of atomic structure.

Mesons – 1934 – 1947

- Mesons were first introduced by Yukawa to try and explain how the nucleus is held together. Much as how the electromagnetic force is ‘mediated’ by the exchange of massless virtual photons, the nuclear force is mediated by the exchange of massive virtual mesons (mostly Pions). The properties of these Mesons were determined by Yukawa based on the properties of the nuclear force, i.e. the fact that the nuclear force is very short ranged.
- Mesons were first measured in 1937 from cosmic rays.