Book Title

HONR 268N

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1

Elementary Particles and Forces

2

Special Relativity

2.1 Disclaimer

Einsteins theory of special relativity is one of the most fascinating, elegant, surprising, and powerful theories in modern physics. The derivation of its laws, beginning from the simple postulate that the speed of light is a constant, independent of the velocity of the person measuring it, along with the resulting profound implications in electromagnetic theory and the nature of space and time is astounding. We, unfortunately, do not have the time to cover everything in this course. And you, as freshmen, for the most part are just not ready. You will study this theory in depth when you take 300-level E&M.

However, to understand what is going on at the LHC, you do need to understand some relativity. The goal of this tutorial is to teach you the minimum needed to understand the Higgs discovery. We will approach it from a practical point of view. Although this is anathema to the physicist in you, we will give you formulas without telling you where they come from. You need to just accept them (For now! Until you are older!) as experimental reality, just as you accept as a fact that you can use as a tool to work other problems.

2.2 4-vectors

When doing Newtonian mechanics, you are taught about vectors. You typically work with vectors that have three components, associated with three spatial directions (x, y, z). Often, then you parameterize these components as a function of a time. You might calculate the height of a particle above the ground (z) as a function of time, its z-component of velocity as a function of time, or its momentum as a function of time.

With special relativity, instead of these 3-vectors, we will work with 4 component vectors (4-vectors). The fourth component for our position vector will be time. However, time and position have different units (seconds for time and meters distance). Mixing time and distance is thus mixing apples and oranges, so what can be done?

In special relativity, the speed of light is very special. It is a constant, and all observers, regardless of their relative velocity, will get the same result when they measure it. Well discuss this more later. Since this is a special number, one of the fundamental constants of nature, along with the fundamental constant of quantum physics, and a few other fundamental numbers. We can use c to convert time to a distance and write our 4 vector for an event (something that has a time and a position) as

$d = (ct, x, y, z)$

Every 3-vector will be augmented this way, although the associated time-like component may not be obvious to you at this stage. Most importantly, momentum becomes 4-momentum, defined

$$p = (E, cp_x, cp_y, cp_z) \tag{2.1}$$

where E is the particles energy. Again, we use c to make sure all components have the same units.

We will use red to denote 4 vectors and the usual vector notation to denote 3 vectors. Thus we can write:

$$p = E, cp_x, cp_y, cp_z) \tag{2.2}$$

$$p = (E, c\vec{p}) \tag{2.3}$$

As you may remember from your high school physics, there are several important mathematical operations that are used with vectors. One is the dot product a way of making a scalar out of two vectors. You may remember that:

$C = \vec{A}B = A - xB_x + A - yB_y + A - zB_z$

The dot product of a vector with itself gives the square of the magnitude of the vector. $|vecA^2 = \vec{A}A$

The dot product, in Newtonian physics, is used in calculating work from force and displacement.

There is a dot-like product associated with 4 vectors, and it has some very interesting, useful, and sometimes bewildering properties.

$c = \vec{a}b = a_0b_0 - \vec{a}b$

More on this useful operation later.

2.3 Frames (center-of-mass, lab) and transforming between frames

Imagine two people, (A and B) with rulers and stop watches. A is standing in the sidewalk on Route One, while B is in a white car in the left hand lane going south on Route One. Both see a red car in the right hand lane going south which passes the car containing B. However, person A sees the space between her and red car increasing at a much faster rate than person B sees the space between him and the red car increasing. They each measure a different velocity for the red car relative to themselves. Mathematically, what we have in 1 spatial dimension; it is easy to extend to 3 spatial dimensions.

let v_B, x_B be the velocity and relative to person A let $v_{RA}, x_{RA}, v_{RB}, x_{RB}$

Then,

$v_{RB} = v_{RA} - v_B \; x_{RB} = x_{RA} - x_B t$

This set of equations that transform a variable as it is measured in one frame to the value it will have when measured in another frame is called Galilean Relativity.

However, in relativity, if the red car were moving at the speed of light both A and B would see the distance between them and the car increasing at the same rate. In other words, all observers will measure the same speed of light regardless of their relative velocities. Obviously, the equations given above do not predict this. Einstein developed new equations that give us a measurement in one frame relative to another.

$$ct_{RB} = \gamma(ct_{RA} - \beta x_{RA} \tag{2.4}$$

$$x_{RB} = \gamma(-\beta ct_{RA} + x_{RA} \tag{2.5}$$

where

$$\beta = v_B/c \tag{2.6}$$

$$\gamma = \frac{1}{1-\beta^2} \tag{2.7}$$

Note that β is a number between 0 and 1, and is the fraction of the speed of light the other measured frame has with respect to your frame of reference. γ is a number that is greater than 1. It is called the relativistic boost and will be very useful.

In general, any 4-vector will transform this way. Thus, the energy-momentum 4-vector will transform in this way. This set of transformation equations is called Special Relativity or the Lorentz transformation.

Note that these are extremely weird equations. They imply that observers that are not at rest with respect to each other will not agree on the time when something occurred. They will not agree if two things happening at two different positions happened at the same time or not. There are lots of fascinating implications to this, but youll just have to take more advanced physics to learn about them. We are going to concentrate on the minimum you need to look for new particles at the LHC.

2.4 Length of 4 vectors

A 4 vector has the interesting property that all observers, regardless of their relative velocities, will agree on the length of a 4-vector. Lets prove this:

Lengths of 4 vectors

$|a|^2 = a_0a_0 - a_xa_x$ $|a'|^2 = a'_0a'_0 - a'_xa'_x = \gamma(a_0 - \beta a_x)\gamma(a_0 - \beta a_x) - \gamma(-\beta a_0 + a_x)\gamma(-\beta a_0 + a_x)$ $= \gamma^2(a - 0^2 - 2\beta a_x a_0 + \beta^2 a_x^2 - \beta^2 a_0^2 + 2a_x\beta a_0 - a_x^2) = \gamma^2(a - 0^2(1-\beta^2) - a_x^2(1-\beta^2)) = a - 0^2 - a_x^2 = |a|^2$

In particular, this is true for the energy-momentum 4 vector $|p| = E^2 - (pc)^2$. (working in 1 spatial dimension you can extend this to 3) In fact,

$$(mc^2)^2 = E^2 - (pc)^2 \tag{2.8}$$

In the rest frame of a particle (the frame where $|\vec{p}|$ is zero), you get the famous equation that appears on T-shirts everywhere.

This equation is very important to the LHC. When we look for particles, we recognize them by their mass. W bosons have a mass of 80 GeV. Z bosons have a mass of 91 GeV. Top quarks have a mass of 173 GeV. Obviously, we cannot put particles on a scale to weigh them. This equation tells us that, if we want to see the mass of a particle made in a collision, we just need to know its energy and momentum. Then, from that, we can determine its mass. We can also show that it doesnt matter what our velocity is with respect to the particle. This equation will always give us the mass of that particle, and that all observers will agree on the mass.

2.5 HEP units

Masses in GeV? What kind of mass unit is that? You may be more used to kg or g or lbs. Remember that the eV is a unit of energy, defined as the potential energy gained when an electron moves from one position to another whose potential is higher by 1 V.

We know from Einstein that mass is related to energy through c^2. So eV/c2 is a unit of mass. GeV/c^2 is then 106 eV/c^2. For scale, the proton has a mass of 1 GeV/c^2.

Particle physicists are lazy. They hate to type even a single extra letter. Particle physicists are lazier than most. They have defined a whole unit system designed to help them avoid typing c and $/h$. Unit systems need a way of defining a time unit, a distance unit, and a weight unit.

c is related to both the time and distance unit. The units of $/h$ are Energy x time. We know from Einstein that energy is related to mass, so we can use it instead of mass as our third necessary unit. The eV, which is the potential energy an electron gains when it transverses a potential difference of 1 V, is chosen to be the unit of energy. Length and time units are then chosen so that both c and $/h$ are 1.

Once we do that, GeV/c^2 just becomes GeV/1^2 or GeV.

Not only that, but we can also measure both length and time in GeV.

For example $/h$/GeV is a unit of time. But $/h$ =1 in this unit system, so GeV^{-1} is a unit of time. c/GeV is a unit of length. So GeV^{-1} is also a unit of length.

In this unit system, the length of the energy-momentum 4-vector becomes (in 1 dimension):

$$m^2 = E^2 - p^2 \tag{2.9}$$

2.6 Lifetimes of particles

An interesting consequence of special relativity is that the lifetime you measure for a particle will depend on its velocity relative to you. Let τ_0 be the lifetime you measure for the particle when the particle is at rest with respect to you. Then, using equation 1.4, we can see that the lifetime for a particle moving with a velocity β is

$$\tau = \gamma\tau_0 \tag{2.10}$$

The lifetime is longer for a moving particle than it is for one at rest by a factor γ.

2.7 Breit-Wigner

We have learned that most heavy particles are not stable, and decay. Above, we said that particles are identified by their mass, and that particles have a well-defined mass characteristic of their type. However, this is not quite true. As you will learn when you take quantum mechanics, a quantum state cannot have a well defined time and a well defined energy (mass). This is expressed through the Heisenberg uncertainty principle:

$$\delta E \delta t \geq \text{/h} \tag{2.11}$$

Because of this, when we measure the particles mass, we get a range of values. How big is that range? Remember that we can express the lifetime of a particle, using our new funny units, in GeV, using:

$$\Gamma = \frac{/h}{\tau_0} \tag{2.12}$$

where Γ is the lifetime in GeV. When the lifetime is expressed in GeV, it is referred to as the particles width.

The actual functional form of the mass distribution is called a Breit-Wigner. The form is: rate of events

$$\propto frac1(E-M)^2 + frac\Gamma 2 \tag{2.13}$$

where M is the value of the peak of the mass distribution and E is the observed mass.

Exercise 2.1 For the Z boson, M is 91.2 GeV and is 2.5 GeV. What is the corresponding lifetime? Use root to plot this function versus E, the observed mass.

2.8 The coordinate system for a collider experiment

The CMS detector, whose data we will be using in this course, uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointed to the center of the LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the anticlockwise-beam direction. The polar angle is measured from the positive z axis and the azimuthal angle ϕ is measured in the x-y plane.

2.9 Collisions (conservation of 4-momentum)

When two protons appear to collide in a detector, what really collides is the partons (either quarks or gluons) inside the protons. A sketch of a collision that produces a Z boson is shown below.

Figure 1: Feynman diagram for production of a Z boson in a proton-proton collision, with subsequent decay to electrons

The total momentum of the proton is divided among the partons in an unequal way that varies collision by collision. Sometimes most of the momentum is held by a single parton. Sometimes it is divided among a very large number of partons. We can know the distribution of probabilities versus fraction of proton momenta, but cannot know, for a specific collision, what fractions the colliding partons had. It will be very rare, however, for both partons to have equal but opposite momenta in the lab frame.

It is usually easiest to understand this collision if we transform to the frame where the partons do have equal but opposite momenta. This special frame is called the center-of-mass frame. In this frame, the partons have equal but opposite 3-momenta. The total initial state 2-momenta, therefore, is zero. Since momentum is conserved, this means the Z boson produced must have zero 3-momenta and therefore zero kinetic energy. Its only energy will be that due to its mass. Since energy is also conserved, this means the initial energies of the partons must be half the Z mass (ignoring for now the finite width of the Z). Since the partons are approximately massless, this means that the initial momenta of the partons must be:

$p_{e^+} = (\frac{M_Z}{2}, \frac{M_Z}{2} cos\theta cos\phi, \frac{M_Z}{2} cos\theta sin\phi, \frac{M_Z}{2} sin\theta)$ $p_{e^-} = (\frac{M_Z}{2}, \frac{M_Z}{2} cos(\pi-\theta) cos\phi, \frac{M_Z}{2} cos(\pi-\theta) sin\phi, \frac{M_Z}{2} sin(\pi-\theta))$

What about the electrons that are produced? Again, due to conservation of momentum, their 3-momenta must be equal and opposite. And, from conservation of energy, their energies must be half the Z mass. Because they are approximately massless, the magnitude of their 3-momenta must be equal to their energy. However, their 3 momenta do not have to be along the z axis. So, in general:

The probability distribution for the polar and azimuthal angles are predicted by the standard model, but is beyond the level of this course.

What will this look like in the lab frame?

Since to boost back into the lab frame, we do a boost along the z axis, only the z components of 3-momentum will change. The x and y components will stay the same. The energy will change as well, since (in the massless, highly relativistic approximation)

$E^2 = p_x^2 + p_y^2 + p_z^2 +$

The polar angle changes, but the azimuthal angle does not. Because of this, transverse variables are very important to collider physicists; they are most sensitive to the particle produced, and not sensitive to the boost.

The component of momentum transverse to the beam axis is called the transverse momentum. Its magnitude is calculated:

$$p_T = \sqrt{p_x^2 + p_y^2} \tag{2.14}$$

You will see this variable over and over when you work on hadron collider physics.

2.10 Rapidity and Pseudorapidity

Another variable related to boosts and the polar angle is the rapidity, defined as:

$$y = \frac{1}{2} ln(\frac{E + p_z}{E - p_z}) \tag{2.15}$$

Exercise: show that the difference in rapidity between two particles is independent of the boost in the z direction.

A related variable is the pseudorapidity, defined as:

$$\eta = -ln(tab(\frac{\theta}{2})) \tag{2.16}$$

2.11 Further reading

$http : //en.wikibooks.org/wiki/Special_Relativity$

3

Particle Interactions with matter

3.1 Introduction

The purpose of a particle physics detector is to find all the particles produced in a collision, identify their types, and measure their 4-momenta. At the LHC, in a single collision, thousands of particles can be produced. The particle physics detector must make signals that somehow can yield this information. To understand how this can happen, we first must understand how particles interact with matter, so we can learn of the possible types of signals particles can produce.

What kinds of particles can an LHC detector detect? First, the particle must live long enough to reach the detector without decaying. The beam pipe of the LHC has a radius with dimensions measured in cm. The particle must exist long enough to escape the beam pipe and reach the detector and make a signal. If we take the diameter to be 1 cm, then the particle life time must be large enough to travel this far before decay. The formula for the probability of a particle traveling a distance x_0 or more before decaying is:

$$P(x_0) = e^{\frac{-t_0 Mc^2\Gamma}{E\hbar}} = e^{\frac{-x_0\Gamma Mc^2}{pc\hbar c}} \tag{3.1}$$

where Γ is the decay width of the particle (remember that $\Gamma = \hbar/\tau$ where τ is the particle lifetime. Also remember that $\gamma = E/mc^2$ and $\beta = pc/E$.)

The particle must also interact with matter in a way that produces a large enough signal to measure in a detector that is small enough to be affordable. While specialized very large detectors exist which can detect neutrinos, this is not possible at a collider detector.

There are only a few types of particles (and their antiparticles) that satisfy these requirements, and they are: From the leptons: electrons and muons; From the bosons: photons; From the mesons: charged pions, charged kaons (remember: these contain a strange quark), k-longs (a very rare particle); From the baryons: protons, neutrons.

The most common particle produced in a proton-proton collision is the pion. Neutral pions decay very quickly to two photons. Most of the particles we detect, therefore, will be charged pions and photons. However, as we will discuss, particles like electrons and muons are signatures of Higgs decays, and so we need to have a detector well optimized for identifying and measuring these particles as well.

3.2 Interactions of charged particles with matter

We will first look at possible signals from charged particles (electrons, muons, charged pions, protons).

Possible interactions between these particles and bulk matter include:

- ionization and excitation of the molecules in the material
- multiple scattering
- bremsstrahlung
- strong interactions with atomic nuclei (only for mesons and baryons, as these contain quarks)

We will postphone the discussion of the last two of these interactions until our discussion of “calorimetry”.

When a charged particle passes through some material (detectors are often made of Argon gas, silicon, iron, lead, steel, plastic, and other such materials), it will interact with the electrons in the molecules that make up that material via the electric force. The charged particle loses energy as it passes through the material, and the material gains energy. What effect does that energy have on the material? It can cause the electrons in the material to “be excited” into higher quantum states or it can even detach an electron from its atom (“ionization”).

We are often interested in how much energy the particle loses (material gains) per unit length. This is called dE/dx, pronounced “d-E-d-x”. The average amount of energy lost per unit length depends on the energy of the particle: low energy particles lose more energy per unit length than high energy particles. You can imagine why this might be true: the lower energy (slower) particles linger near each atom in the materi[al longer, and thus have a longer time to interact with each one and lose more energy. The energy loss per unit length decreases as $1/\beta^2$ until a momentum around 0.1 GeV, where it has its minimum value. The loss then increases slowly with increasing energy until about 100 GeV. Above this energy, relativistic effects cause dEdx to increase more quickly with energy. Particles in the momentum range of 0.1 to 100 GeV are called ”minimum ionizing particles” or ”mips”.

Figure 10.13 shows the energy dependence of dEdx for various charged particles. Note that the length unit is strange: it is cm^2/g. You can convert this to a more convention length unit by multiplying by the density of the material

$$\frac{MeV\,cm^2}{g} \cdot \frac{g}{cm^3} = \frac{MeV}{cm} \tag{3.2}$$

The reason the authors use these units is that it allows the dEdx curves for high Z and low Z elements to fit onto the same graph.

Figure 3.1: Stolen from the particle data group, this picture shows the energy loss per unit length as a function of particle energy

What kind of signals can be produced this way? If the material is a gas, the electrons produced through ionization can be gathered on a wire (using an electric field produced by voltages on metal pads on the structure holding the gas or on wires running through the gas) to produce a current. The signals from silicon are similar. If the material is a plastic scintilator, some of the “excited” molecules will “de-excite” by emitting photons, which can be detected with a photomulitplier tube or other light sensitive device.

If the material is thick and high-Z (iron, lead), the particle may lose all its energy and stop inside the material. The thickness of material that will stop a particle (of a given energy) is called the particle’s range. Fig 3.2 shows the range for various particles in various materials as a function of particle energy.

Figure 3.2: Stolen from the particle data group, this picture shows the range of a particle in various materials as a function of particle energy

Of course, because each particle that goes through the material will randomly interact with different numbers of atomic electrons, exchanging more energy when it happens to go close to one, and exchanging less when it is further away, particle by particle the amount of energy varies. The disttribution of deposted energies follows a ”Landau” distribution, as shown in Fig 3.3.

Figure 3.3: Stolen from the particle data group, this picture shows the distribution of energy deposits for a 10 GeV muon transversing 1.7 mm of silicon.

Sometimes a particle passes close enough to an atom to interact with the nucleus, instead of the electrons. The mass of the nucleus, and the force binding it into its places in the crystal lattice, are large compared to the mass of the particle. The particle usually bounces off the nucleus the way a ball bounces off a wall, changing direction, but without losing energy. For a material that is not very thin, this can happen multiple times, and thus this is called ”multiple scattering”. Fig 3.4 shows a cartoon of this process.

Figure 3.4: Stolen from the particle data group, this picture shows a cartoon showing the path of a charged particle undergoing multiple scattering in matter

3.3 Interactions of gamma rays with matter

Here we call them gamma rays instead of photons because we are going to discuss only those photons of interest to particle physics: ones with energies above a keV or so.

There are several ways a gamma ray can interaction with matter:

- photoelectric effect
- Compton scattering
- pair production in the field of the nucleus
- pair production in the field of the electron
- photonuclear interactions

The photoelectric effect was very important in the development of quantum mechanics. Einstein was awarded the Nobel Prize for his work on its understanding. It is an interaction between a photon and an atom electron. If the photon has energy greater than the binding energy of the electron to the atom, it can eject the electron. The electron will have a kinetic energy equal to the energy of the photon minus the binding energy.

Compton scatting is scatting of a photon off an electron. The Feynman diagram is shown in Figure 3.5.

Figure 3.5: Feynmann diagram for Compton scattering of a photon by an electron

Pair production is the conversion of a photon into an electron-position pair through an interaction (usually) with a nucleus. The Feynmann diagram is shown below.

Figure 3.7 shows the cross section for each mechanism as a function of photon energy. As you can see, for photons with energy greater than twice the electron mass, pair production is the most important mechanism. We will discuss this in more detail when we discuss calorimetry.

Figure 3.6: Feynmann diagram for pair production in the field of a nucleus

Figure 3.7: Stolen from the particle data group, this picture shows the cross sections for possible interactions of photons with matter as a function of photon energy

4

Statistics

4.1 Statistics

Please read chapter 3.I to 3.V in https://docs.google.com/file/d/0B_Ce2ncoxFYka2V5US1MR2xvbXM/

5

Particle accelerators

5.1 Introduction

It's a nice sunny day and you went for a picnic up a nice little mountain in Switzerland. You enjoyed your day and it t until you started your journey back when you noticed that the gas tank is almost empty. There are no gas stations around and that makes you worried until your friend says "Never mind, we will use the force of gravity to accelerate us down". Ahha! - you, being an avid student of physics, know exactl what your friend is talking about. Don't you?

In our everyday experience we know that objects are accelerated when moved by some force from one point to the other. This can be gravitational force or electromagnetic force. We also know that higher the speed of an object, the more smashing energy it has. The damage to car moving with 5 mph in the parking lot is much less compared to the damage to a car on the highway when moving with a speed of 100 mph.

These two everyday observations are basic principles of particle accelerators - machines that accelerate very small particles to very high speeds and "damage" or break them either by smashing them into one another (like two cars head on) or on to a target (like a car colliding a wall). The difference is that the tiny paricles like protons, can be accelerated to very high speeds compared to a car on the highway. The Large Hadron Collider, the accelerator that discovered the Higgs boson just a couple years ago, can accelerate proton almost to the speed of light (v = 0.999999991*c = 299792455 m/s = 186282 miles/sec). The smashing power or energy of such particles on collision will not only break them, but, according to Einstein's famous E=mc2, part of this energy will actually turn into new particles. Imagine collision of two cars at a very high speed and not only the car parts but also a few doves, a helicopter and a school bus comes flying out.

Of course, accelerating tiny particles like protons is very different from accelerating a car. That's why weneedvery complicated and big machines like the LHC. Many times, the technology needed to meet the demand ofthe physical process we are trying to make happen and observe is not available. In these cases physicists andengineers work together and push the boundaries of technology.

In general, there are three types of particle accelerators:

$\cdot CircularAccelerators$

$\cdot LinearAccelerators(LINAC)$

A particle accelerator could be a combination of these general forms. For example the large hadron collider not only makes use of both circular and linear accelerators (Fig. 1).

5.2 Parts of an Accelerator

Whether linear or circular, the basic parts of an accelerator are the same and are described below.

Beam of particles for collisions

These are the particles that will be accelerated and then collided. LHC accelerates protons and heavy ions such as lead. For the LHC beam, 300 trillion protons are required, but since a single cubic centimetre of hydrogen gas at room temperature contains about 60 million trillion protons, the LHC can be refilled 200 000 times with just one cubic centimetre of gas - and it only needs refilling twice a day!

These protons are supplied from a hydrogen gas bottle. Hydrogen atoms consist of a proton and an electron. After stripping the hydrogen atom of its only electron we are left with a proton, which is then accelerated to required energy before colliding with protons accelerated in the opposite direction.

Beam Pipe
This is a metal pipe inside which the beam of particles travels. For the LHC, we have two beam pipes for opposite traveling beams of particles. This pipe has to be empty of any other atoms (e.g., the one in air) to avoid collisions between gas molecules and the particles in the beam (Why is this a bad thing?). The pressure inside of the LHC is $10^{13} atm, tentimeslessthenthepressureonTheMoon.$

Devices to change particle speed (Radiofrequency (RF) cavitires and electric fields)

A radiofrequency (RF) cavity is a metallic cavity like structure that looks like beads around the beam pipe. These cavities contain an electromagnetic field such that when charged particles pass through that field it transfers energy to these particles and they are pushed or accelerated forward along the accelerator. Think of a proton as a surfer riding a wave. Every electromagnetic wave accelerates a bunch of particles, about 100 billion of them and each of the two beams consists of a number of such bunches, a few meters apart. These bunches are circulated in the beam pipe going around the LHC ring thousands of times per second. It takes about 20 minutes to get to the energies required and during that time the protons cover a distance further than from Earth to the Sun and back.

At full power, trillions of protons will race around the LHC accelerator ring 11,245 times a second, travelling at 99.99% the speed of light. A motionless proton has a mass of 0.938 GeV (938 million electron volts).The accelerators bring them to a final mass (or energy, which in this case is practically the same thing) of 7000 billion electron volts (7 tera-eV or 7 TeV). If you could - hypothetically - accelerate a person of 100 kg in the LHC, his or her mass would end up being 700 t.

6

Calorimeters

6.1 Disclaimer

this is not ported yet

7

Trackers

7.1 Trackers

this is not ported yet

8

Particle Identification

8.1 Disclaimer

this is not ported yet

9

The LHC Detectors

9.1 The LHC Detectors

Please read section 2 of http://www.sciencedirect.com/science/article/pii/S0168900211020626

10

Structure of the proton and proton-proton collisions

10.1 Cross section

Imagine a 2-D box in deep space, away from gravity, containing some number of large 2D disks. If you threw a ball at the box, the probability of hitting a disks is related to the ratio of the cross sectional area of the box to the cross sectional area of the disks. The cross sectional area of the disks is their cross section and it has units of area. If you look at a solid and imagine scattering particles off the nuclei inside them, it is similar. Remember that solids are, after all, mostly empty space. If you project all the nuclei into the 2D front face of the solid, you have our 2-D box. The cross section area of a nuclei is measured in fm^2. For low energy scattering by the strong force, since the strong force only has a very short range, and interactions can only happen if the ball virtually touches the nucleus, this is a good approximation. A unit commonly used in the barn, which is $10^{28}m^2$. Nuclear cross sections are around 80 mbarns. For forces with a longer range, such as E&M, we define instead an effective area. See any introductory book on particle physics for a more precise definition.

What if instead you threw a steady stream of balls at the box and wanted to calculate the rate at which balls hit beads and are deflected? Also, as you can imagine, in realistic beams the projectiles do not march single file. You should imagine them moving in a cylinder with some cross section, like:

If the number of balls in the beam per unit area is na, and the velocity of the balls is v, then the number of balls reaching the target per second is

$$\Phi = n_a v \tag{10.1}$$

and Φ is called the flux. What are the units of Φ?

The number of scatters per second is then

$$\frac{dN}{dt} = \Phi!Icouldnotfigureouthowtothissimbleherehere! \tag{10.2}$$

(check that the units work).

Now, you may ask what happens in a collider? Well, it is just the same. You can always move to a frame where one of the protons is at rest, do the calculation there, and move back. We will see in the next section why our calculation of the cross section does not depend on the frame in which it is calculated.

10.2 s, t, u, and q squared

As we have seen, in relativity, there are invariants that will be measured to be the same by all observers, regardless of their frame and relative motion of the particle. One of these is the length of a particles 4-momentum, which is its mass. In collisions, there are a few of these variables that are important, as cross sections calculated from the standard model must be functions only of these variables and numeric factors. The most important ones were unimaginable given the names s, t, u and Q2. Imagine some kind of reaction (could be photon exchange, gluon exchanged, Z exchange etc) where two particles a and b come in and two particles c and d come out (called a 2 to 2 reaction).

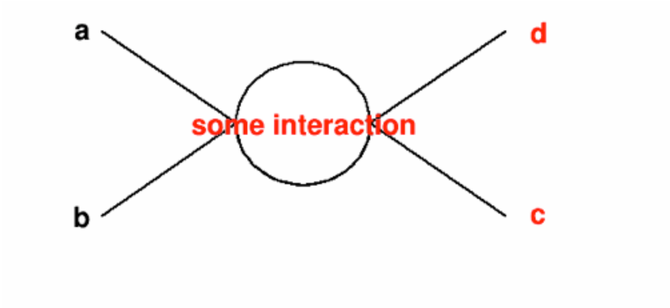

Figure 10.1: generic interaction of 2 particles going to 2 particles

If p_a is the 4-momentum of particle A and the 4-momenta of the other particles are named similarly, then

$$s = (p_a + p_b)^2 \tag{10.3}$$

$$t = (p_a - p_c)^2 \tag{10.4}$$

$$u = (p_a - p_d)^2 \tag{10.5}$$

Remember: the square here means dot product, and the dot product of a 4-vector is the square root of the product of the first components (time-like components) minus the dot product of the 3D part of the 4 vector. So s, t, u are a bit like a mass. All these variables have units of GeV^2.

Another important variable is Q^2. This can be u for some interactions and s for others. It is the mass of the virtual particle that is exchanged in the interaction (the photon, W, Z etc). Now, you may say: but the photon is massless! But, that is only if it is observable. The photon can be offshell as long as it is unobservable, meaning that it has a non-zero mass. You will learn more about this when you study quantum mechanics.

It can be shown in quantum field theory that, in the frame where the 4-momentum of particles a and b are equal but opposite and have high enough energy that we can neglect their mass, that the cross section can be calculated from the physics of the standard model using a simple formula

$$\frac{d?}{d\Omega} = \frac{1}{64\Pi^2 s}\frac{P_f}{P_i}|M|^2 \tag{10.6}$$

where p_f is the magnitude of the 3-momenta of either particle c or d (why doesnt it matter which?) and pi is that of either a or b. What will the ratio of pf to pi be if particles c and d both have momenta large compared to their mass as well?

$|M|^2$ is a factor called the matrix element which is calculated from the standard model and must be a function of s, t, u and numeric factors.

10.3 What is in a Proton

You may have been taught that a proton contains two up quarks and a down quark. This is not true. In fact, only half the momentum of a proton is carried by quarks. What carries the other half? This is a complicated question. Roughly, we can say that about half the momentum is carried by the up and down quarks, and about half by gluons. One of the goals of nuclear physics is to understand how the momentum distribution of the proton is divided amoung the protons constituents. The Parton Distribution Functions or PDFs give the probability of finding a parton (a constituent of the proton, like a quark or gluon) with a fraction of the proton momentum x. When you sum over all partons and all x, you should get 1 (when you add them all together, you have the whole momentum of the proton). The figure below shows results from measurements.

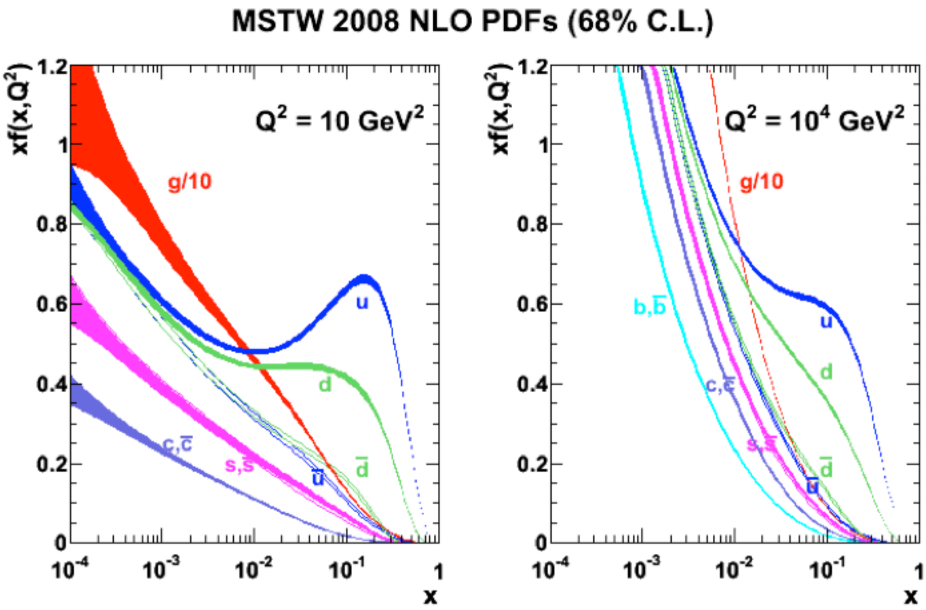

Figure 10.2: probability of finding a parton that has a fraction x of the proton momentum times x for different parton flavors

However, the truth is, if you look inside a proton, what you see depends on how closely you look. The closer you look, the more detail you see. Interactions with large Q^2 look more closely that those that dont (think about the uncertainty principal and it may help you understand). That is why there are two figures in the picture shown above. One shows what the proton looks like if you probe it with a virtual particle with low Q^2 and the other shows it with a higher Q^2 probe.

How do we do this? Most of the information comes from fixed target experiements, which collide a beam of particles with some kind of target, perhaps copper or something else that wont melt in a high radiation environment, and from the HERA collider in Hamburg Germany, which collides electrons with protons.

magine two possible beams in a fixed target experiment: muons and neutrinos. Muons will interact with the up and down quarks (and other quarks) in the proton via photons, more with the up quarks than with the down quarks due to their larger electric charge. If we switch to a different target which has a different ratio of neutrons to protons, we get a different ratio of up and down quarks and different scattering rates. Neutrinos interact with the protons and neutrons via the weak force, mostly the Z boson. These also interact differently with up and down quarks, but in a different way. Groups of theorists, such as MRST and CTEQ take all this data and untangle from it the parton distribution functions. Note that neither type of beam interacts directly with gluons and therefore there is larger uncertainty on this part of the PDF than that of the quarks.

10.4 Calculation of a cross section in proton proton collisions

In a proton-proton collision, the particles and b are partons in the proton. For a given final state (particles c and d), there can be a variety of different initial states that can occur. For example, a Z boson can be created when an up quark annihilates with an anti-up quark or it can be created when an down quark annihilates with an anti-down quark. It is like our bean has different kinds of balls that have a different effective cross section to interact with the target. How can we calculate the total cross section for any two partons in the proton to go to a Z and then into, say an electron-positron pair? We need to integrate over all possible initial states:

$$!!!!Idon'tevennowhattolookuptoaddthismath!!!! \tag{10.7}$$

where the qs represent the PDFs for the quarks.

10.5 What happens when two protons collide?

First remember that quantum mechanics applies. We can calculate the probability of certain kinds of interactions, but we can not predict event by event which one will occur. The pie chart below shows the fraction of collisions that result in different types of interactions.

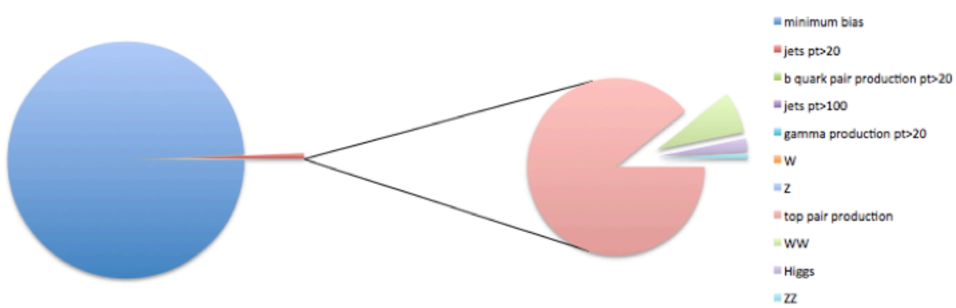

Figure 10.3: Pie chart showing relative probabilities of different types of interactions in proton-proton collisions

Another way to look at this is for the cross
What are these things?

10.6 Minimum bias interaction

The most common thing to occur is that a small amount of momentum is exchanged between the proton, in the form of gluons, or color-neutral combinations of gluons, resulting in a few pions being spit out. A cartoon might look like:

10.7 Jets

10.8 Further Reading

- http://xxx.lanl.gov/abs/hep-ph/9606399

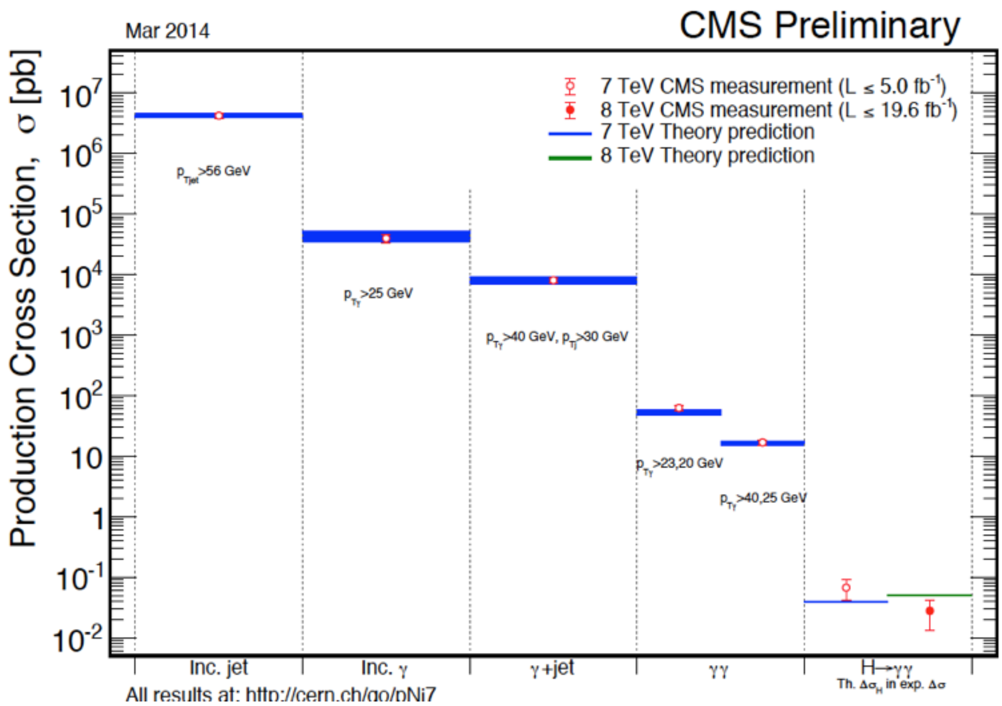

Figure 10.4: !!! No Caption In Word Doc !!!

- http://iopscience.iop.org/0034-4885/70/1/R02/
- Modern Particle Physics by Mark Thomson
- Introduction to Elementary Particle Physics by Alessandro Bettini

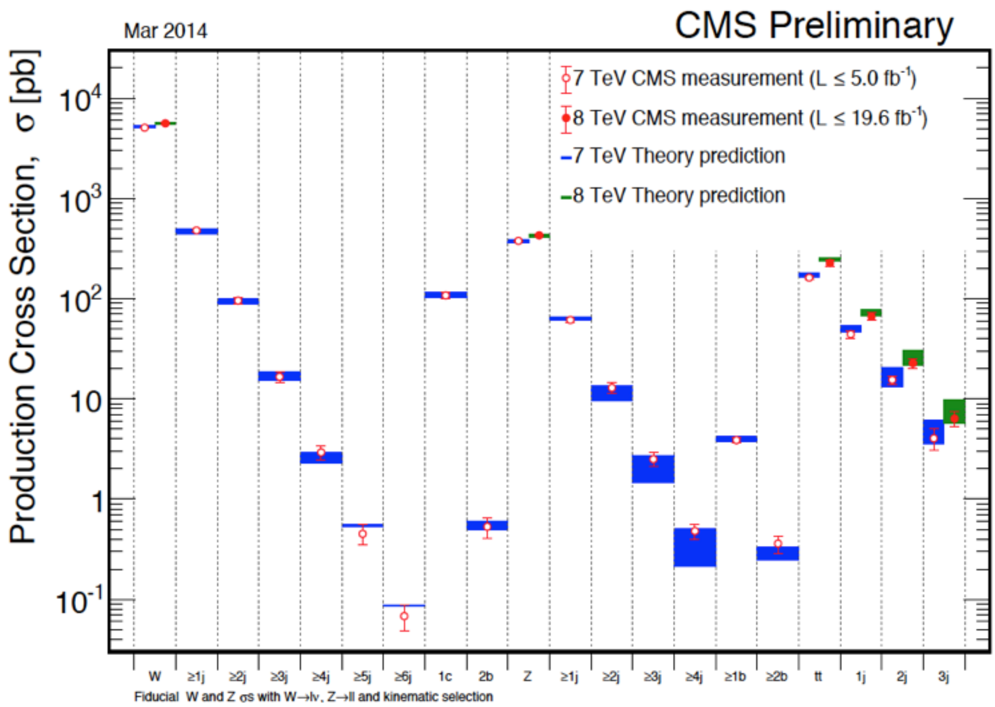

Figure 10.5: !!! No Caption In Word Doc !!!

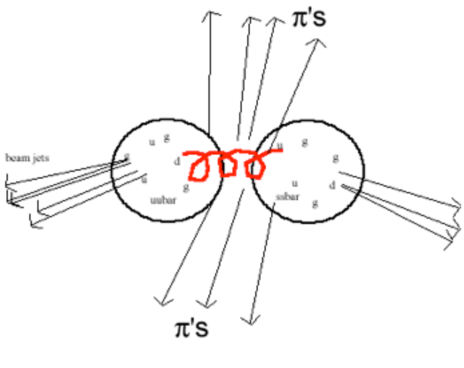

Figure 10.6: carton of a minimum bias interaction

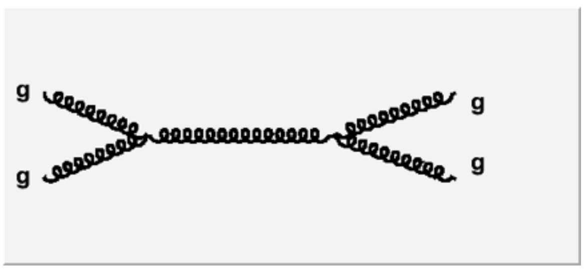

Figure 10.7: !!!NO CAPTION!!!

Figure 10.8: !!!NO CAPTION!!!

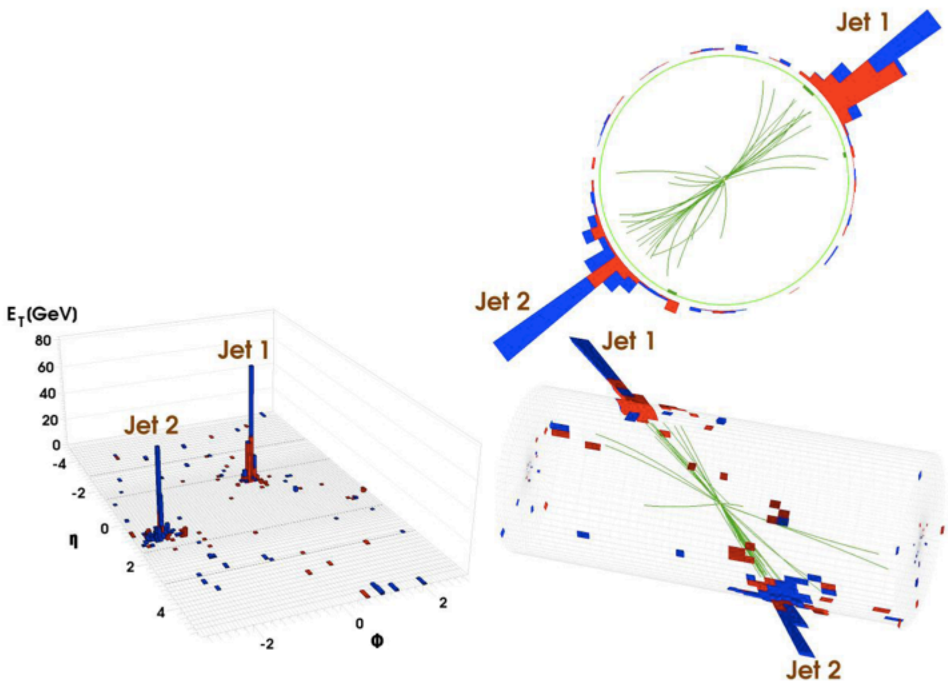

Figure 10.9: !!!NO CAPTION!!!

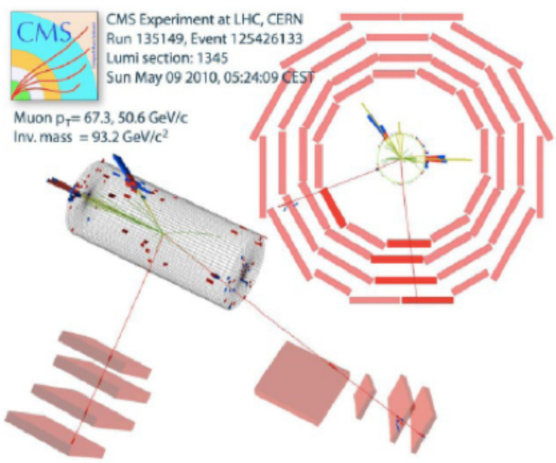

Figure 10.10: !!!NO CAPTION!!!

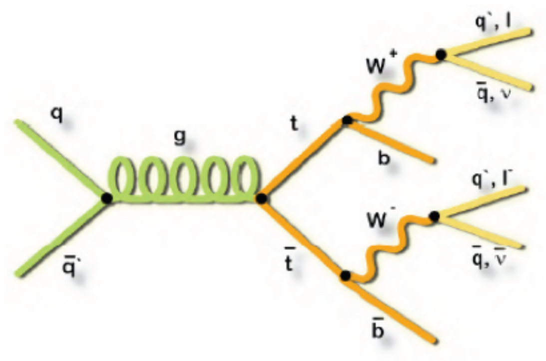

Figure 10.11: !!!NO CAPTION!!!

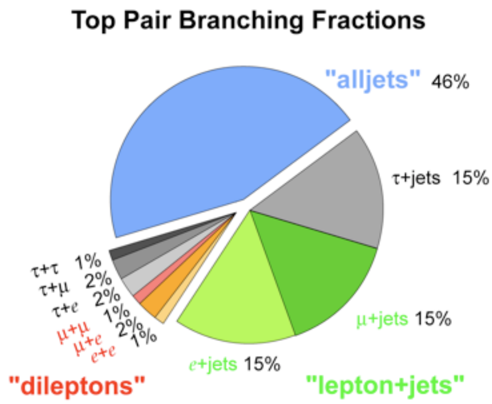

Figure 10.12: !!!NO CAPTION!!!

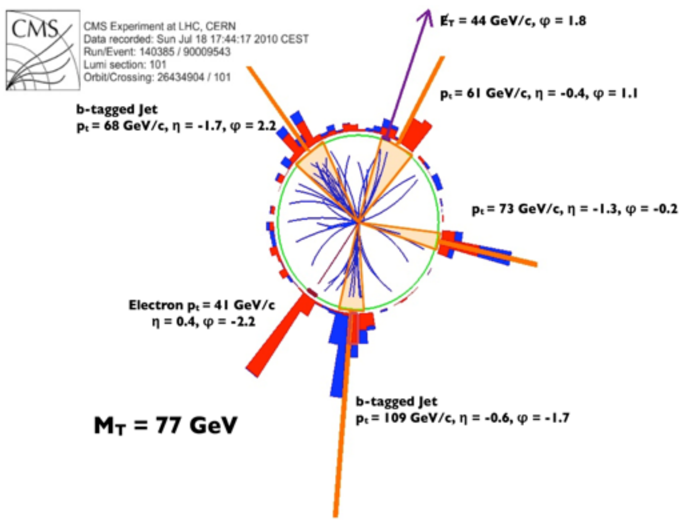

Figure 10.13: !!!NO CAPTION!!!

11

Monte Carlos

11.1 Disclaimer

this is not ported yet

12

Higgs Discovery

12.1 higgs to four leptons

Please read http://arxiv.org/pdf/1312.5353.pdf