Elementary Experimental Higgs Physics

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Preface

This is not a text book on particle physics. This is not a text book on the Higgs. This is not a text book on experimental physics.

What is it, then? This book is intended as a sugar coating for a course on elementary scientific computing. It is therefore high on calories but low on physics, content, substance, and rigor. However, sweets make life more enjoyable, as long as one doesn't indulge in excess. We hope this book will inspire students to continue as physics majors and learn more on the fascinating subjects introduced in this book. We hope it makes Linux, C++, and gdb go down easier.

The authors would like to thank Fred Buchanan, Nirmarta Kaur, Joseph Mariano, Victor Meszaros, Youchuan Wang, and Yao Yao for help at every stage of the creation of this work.

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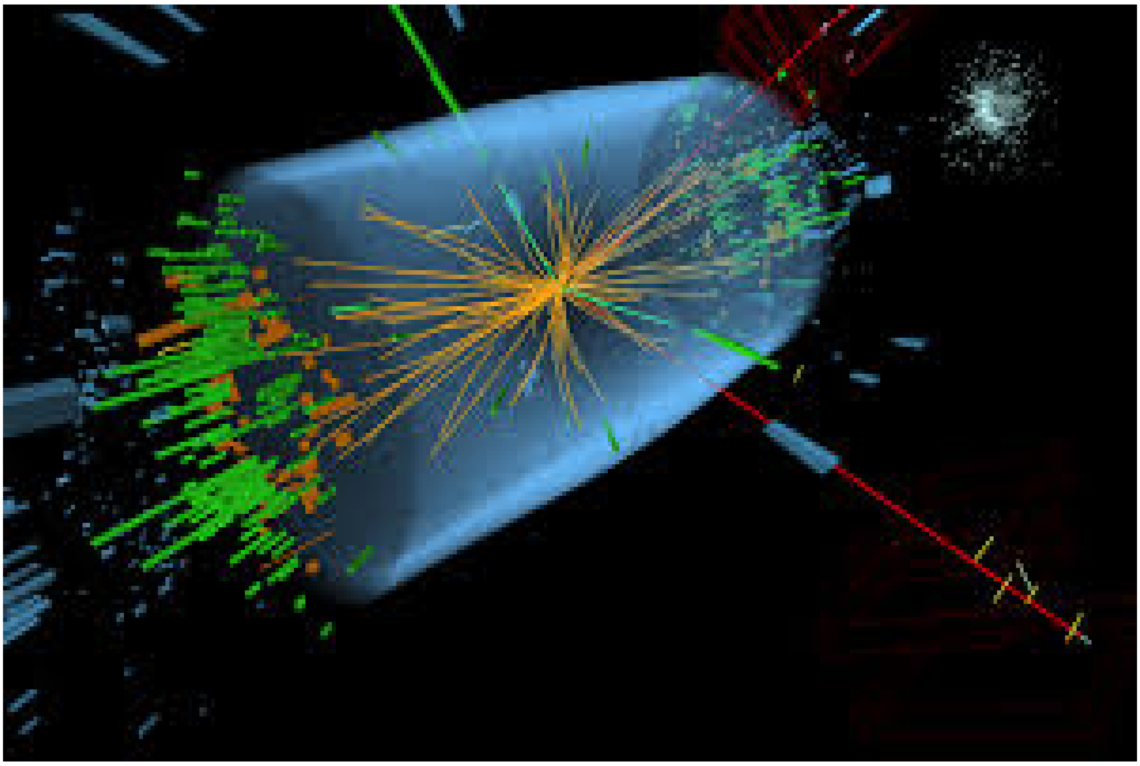

Elementary Particles and Forces

1.1 Elementary Particles

One of the questions that we, as human beings, have been asking since we started thinking, is "What is the universe made up of and what holds it together?" A long time ago, Democritus tried to answer the first part by defining atoms, although his definition of the atom was quite different from what we know about the atom today. In the last couple of centuries, we have come a long way in terms of answering the questions about the composition of matter and the glue that holds it together and gives us the form of the universe we see today. The quest to answer the question "What is matter made of?" has been much like unraveling Russian nesting dolls (Figure 1.1). Everything, such as chairs, tables, you, and me are made up of different kinds of molecules. Every molecule is made up of different kinds of atoms. All atoms, it turns out, even if they are different, have very similar structures; they all have one nucleus around which electrons revolve. The nucleus is made up of protons and neutrons. Protons are positively charged and electrons are negatively charged particles. The number of protons and electrons in a neutral atom are exactly equal so that the positive and negative charges cancel each other out. All atoms are very similar in that they are all made up of protons, neutrons and electrons. However, a gold atom would be different from an iron atom or a hydrogen atom because they would have a different number of protons, neutrons and electrons.

However, the atom is not the last of our Russian dolls. We now know that every proton and

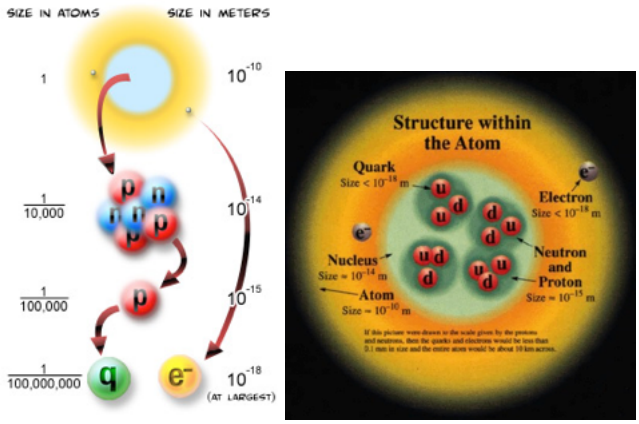

Figure 1.1: The scale of fundamental particles

neutron itself is made up of even smaller particles, called quarks. Electrons, on the other hand, appear to be fundamental particles; that is, they cannot be further decomposed. So, as of now, we can divide fundamental particles into two categories: Quarks and Leptons. There are 6 types of quarks and 6 types of leptons. Quite symmetric, don't you think? But the symmetry does not end here. They seem to form 3 pairs (we call them families or generations) as you can see from Figure 1.2.

The three generations of quarks and leptons are very similar in that they have the same charge, spin etc. They differ in some internal quantum properties, but the most apparent difference is in the mass - which increases as we go from 1st generation to 3rd.
As you can see from Figure 1.3 below, this difference is up to 5 orders of magnitude.

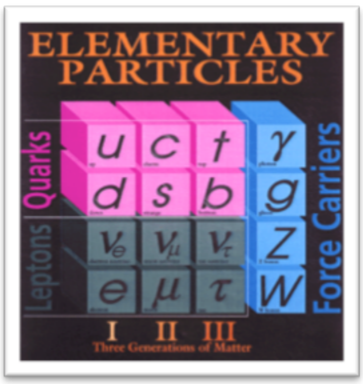

Figure 1.2: Three generations of fundamental matter particles

For every particle, there is also a corresponding anti-particle. Usually they have simple names, such as an anti-up quark or anti-neutrino. The anti-particle for the electron, however, has the special name, positron. The existence of anti-matter was predicted when Paul Dirac unified quantum mechanics and Einstein's theory of special relativity. The anti-electron was discovered a few years later (1932) by Anderson.

1.2 Forces

There are a few other fundamental particles which do not make up matter directly, but instead are exchanged in interactions between matter particles. These force carrier particles, when ex-

Fermions	Name	Symbol	Spin	EM charge	Weak charge*		Mass (MeV/c2)
Lepton	Electron	e^-	+1/2	-1	-1/2	0	0,51
	Muon	μ^-	+1/2	-1	-1/2	0	105,00
	Tau	τ^-	+1/2	-1	-1/2	0	1.777,00
	Electron Neutrino	ν_e	+1/2	0	+1/2	0	< 3 E-6
	Muon Neutrino	ν_μ	+1/2	0	+1/2	0	< 0,18
	Tau Neutrino	ν_τ	+1/2	0	+1/2	0	< 18,00
Quark !!						Color charge	
	up	u	+1/2	+2/3	+1/2	RGB	~2
	charm	c	+1/2	+2/3	+1/2	RGB	~1.200
	top	t	+1/2	+2/3	+1/2	RGB	>170.000
	down	d	+1/2	-1/3	-1/2	RGB	~5
	strange	s	+1/2	-1/3	-1/2	RGB	~92
	bottom	b	+1/2	-1/3	-1/2	RGB	~4.200

Figure 1.3: Fundamental particles and their properties

changed between two matter particles, make these particles interact through the force which they are carriers of.

There are four known fundamental forces through which particles can interact and each has its own carrier particles. (see Figure 1.4).

1. **the strong nuclear force:** Only quarks can feel this force through the exchange of force carrier particles called gluons. This force is much stronger compared to electromagnetic force of repulsion between the same charge protons and keeps the atomic nucleus stable.

2. **the weak nuclear force:** This is the force responsible for radioactive decay of atomic nuclei. It has three force carrier particles, the W^+, W^-, and Z^0 bosons. It allows one type of quark to turn into another, usually within the same generation. For example, a top quark can turn into a bottom quark by emitting a W boson. It also allows a charged lepton to change into a neutrino. A muon can decay to a muon neutrino by emitting a W boson. The weak force is also very important in the fusion reactions that power the sun.

3. **the electromagnetic force:** The force between charged particles is mediated through the exchange of electromagnetic force carrier particles called photons. This is the same photon that makes up the light that you see from the sun or a bulb. This is the force of attraction (repulsion) between opposite (same) electric charges or magnetic poles.

4. **the gravitational force:** The everyday force that keeps us safely on the surface of the earth and is felt by all particles with mass. The graviton, the theorized particle proposed to be the force carrier for gravity, has not been discovered yet.

1.3 The world's shortest description of quantum mechanics

One generally only attempts to learn about particle physics after studying quantum mechanics. Quantum mechanics is indeed fundamental to particle physics. However, if a student's goal is to become involved in particle physics research, it is only strictly necessary to learn a small fraction of this fascinating subject. In this section, we will try to describe the minimum amount of quantum mechanics you need to understand particle physics. To really learn quantum mechanics, you need first to study differential equations, and most of you have not taken this yet. Quantum mechanics is strongly related to one of the fundamental constants of nature, called $\hbar$ or h-bar. $\hbar$ has the numeric value of $1.054 \text{x} 10^{-34}$ Js. If you see this constant in an equation, you know quantum mechanics is involved. Often quantum mechanical systems involve quantization of energies. The classic example is the energy states of the hydrogen atom (or any atom or molecule). The electrons can only have certain energies. These energies are associated with "quantum numbers". The energies

Fundamental Force Particles

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger

Figure 1.4: Fundamental forces and corresonding force carrier particles

might be related to these numbers through a scale factor and a simple function of the numbers (although some of the quantum numbers are not related to energies but to other measurables). The allowed values of energies are also often proportional to $\hbar$

If an atom absorbs energy, it can only do this if the energy is the right amount to move the electron between one of these discrete states (approximately there are corrections to this that are important only when being very precise). Likewise, when an atom that is in one of the higher energy states de-excites, it can only emit photons with certain energies.

Energy quantization is an important property of photons; the fundamental packet of electromagnetic radiation can only have energies that are integer multiples of the product of its angular frequency ($\omega = 2\pi f$ where f is the frequency of the photons oscillation and $c = \lambda f$ where c is the speed of light and λ is the photons wavelength) and $\hbar$. Thus, $E = n\hbar\omega$, where n is an integer.

When you combine this with the energy levels of atoms, you get the characteristic absorption/emission spectra of atoms/molecules, which can be used to identify them (see Figure 1.5).

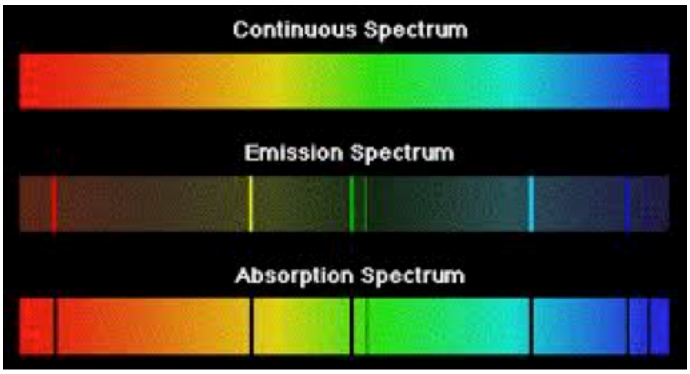

Figure 1.5: absorption and emission lines

Another important thing to know about quantum mechanics is that it is probabilistic in the sense that often for a given initial state (say, an electron aimed at a piece of metal) there may be many possible final states (say, amount of energy that the electron loses, and the deflection of the electron from its initial direction). In quantum mechanics, you can only calculate the probabilities of the different possible outcomes; you cannot ever, even with perfect information about the initial state, predict exactly what the final state will be.

There is also the Heisenberg uncertainty principal. The Heisenberg uncertaintly principal is a relation between two variables related by a Fourier Transform (google it if your curiousity is peaked). The relationship says that if you precisely measure one of the variables, you can not have a precise measurement of the other. Conjucate variables include energy with time and momentum with position. What sets the scale for how well they can be measured? Our friend $\hbar$ of course.

Mathematically we can write:

$$\Delta E \Delta t \geq \frac{\hbar}{2} \tag{1.1}$$

where Δ is the accuracy in the measurement.

Also

$$\Delta p \Delta x \geq \frac{\hbar}{2} \tag{1.2}$$

1.4 Standard model of particle physics

Going back to the question, "what is the universe made up of and what holds it together?", our current understanding is that the matter in our visible universe is made up of quarks and leptons which interact with one another through force carrier particles. There is a theory called "the standard model of particle physics" which describes this visible universe and, partly, the forces that hold it together. This theory, in principle, can describe all the physical process in chemistry and biology in terms of fundamental interactions. The standard model of particle physics describes phenomenon concerning three out of the four known fundamental forces: electromagnetic force, weak force and strong force. The formal name for the mathematical structure of this theory is gauge-invariant quantum field theory. Gauge-invariant means that the properties of the bosons (force mediators) are determined by symmetries relating the matter fields (quarks and leptons). The fundamental particles and some of their basic properties are listed in Figure 1.4.

1.5 Properties of fundamental particles

Every fundamental particle (for example an up quark) has exactly the same properties; no matter where or how it is produced. The quarks and leptons have similar properties like charge, mass, spin etc., but quarks have one extra property, called color. Just like particles with electromagnetic charge can only interact through the electromagnetic force, only the particles with color charge can interact through the strong force. This color has nothing to do with the color of things we see, but is a quantum (or internal) property of these particles. Every quark comes in three colors: red, blue, and green. This is a useful analogy because the particles we observe directly do not seem to have this property. In other words, they are colorless. According to the quark theory, just like combining these three colors gives white, combining three quarks with these three quantum properties gives a particle which does not have any color. So every particle that we can directly observe should be made up of a combination of either three quarks or a quark and an anti-quark, giving us the color-less particles we observe.

The charge of electrons and protons is equal but opposite. We say that electrons and protons have 1 unit of charge (-1e for an electron and +1e for a proton, where e is the charge of an electron). When quark theory was formulated, the charge of a proton equaling +1e had to be accounted for. In order to make sure that protons charge comes out to be equal to +1e, the constituent quarks were given fractional charges, as shown in Figure 1.4.

Most particles do not want to hang around for a long time; they quickly decay into lighter particles. The standard model predicts the decay probability per unit time and thus if you start with N_0 particles at an initial time, the number left, that haven't decayed, is described by an exponential function

$$N = N_0 e^{-\frac{t}{\tau}} \tag{1.3}$$

where τ is called the particle lifetime.

A particle property called "spin" plays a very important role, however it is often a hard one for beginning students to understand. When you think of spin, you might think of a top or an ice skater spinning, and when you do that, you'll probably remember learning about angular momentum in your high school physics course. You may remember that conservation laws play a fundamental role in physics. As you will see, they play a very important role in understanding how we discovered the Higgs. You may remember that energy, momentum, and angular momentum are all conservted quantities. If you look at some collision (say between protons at the LHC), and you sum all these quantities and get the total amount before the collision, then after the collision, you still have to get the same sum.

It turns out that particles seem to have angular momentum, like somehow they are spinning like an ice skater, somewhere deep inside, and this needs to be included when you sum over all the angular momenta to get the total angular momenta. What is also weird is that these spins are quantized. Particles can not have just any value for spin; they are quantized. And what is weirder is that the spin determines whether or not particles are "introverts" or "extroverts". Some particles, called fermions, can not bear to be in the same quantum state. The quarks and leptons are fermions. Others, called bosons, don't mind being in the same state. The force carriers are all bosons. The higgs is especially strange; it is the only particle in the standard model predicted not to have spin.

Everyday matter (atoms) is made up of protons, neutrons, and electrons. The proton is made of two u quarks and one d quark (does the sum of their charges work?), Thus, in terms of fundamental particles, everyday matter is made up of u and d quarks and the electron. These particles belong to the first family of quarks and leptons. One of the big questions physicists are trying to answer is: "Why do we need three families of particles? The standard model also does not describe phenomenon concerning force of gravity. The recent cosmological discoveries of dark matter and dark energy are also open questions not addressed by this theory.

Lets count:

Fermions: There are 6 leptons: electron, muon, tau and the corresponding three neutrinos. There are 6 quarks - up, down, charm, strange, top and bottom. Every quark comes in 3 colors. Leptons and quarks are both fermions, as they all have half integer spin 1/2. Now multiply the total number of particles by 2: all these particles have their anti-particles. For every quark, there is an anti-quark, and for every lepton there is an anti-lepton. These anti-particles are almost identical to their corresponding particles except for a very few properties. For example, an electron's anti-particle has the same mass but a positive charge (called positron).

Bosons: There are force carriers corresponding to four forces: photon, W+,W-, Z and gluons. There are eight gluons, corresponding each with a different color combination. These are all bosons with integer spin 1.

By 1995, all of the particles predicted by the standard model were discovered except one: the Higgs boson with spin 0. In 2012, a new boson was discovered at the Large Hadron Collider. The studies done so far seem to indicate that this newly observed particle is very similar to the Higgs boson predicted by the standard model.

1.6 Feynman Diagrams

Feynman diagrams began as a mnemonic to help particle theorists do the very complicated calculations required by gauge-invariant quantum field theories. These calculations are done using something which is very important to practicing physicists, but rarely mentioned in undergraduate curriculum: perturbation theory. In perturbation theory, you first calculate an approximate answer (the leading order calculation or LO). You then calculation a correction to this answer (the next to leading order calculation or NLO). You then calculate a correction to this correction (NNLO). The Feynman diagrams represent aids to help in each step of the calculation. However, they are also useful for just helping to visualize how bosons are exchanged between quarks/leptons to create interactions.

Figure 1.6 below shows the LO diagram for annihilation of an up quark and an anti-up quark to a Z boson to an electron-positron pair.

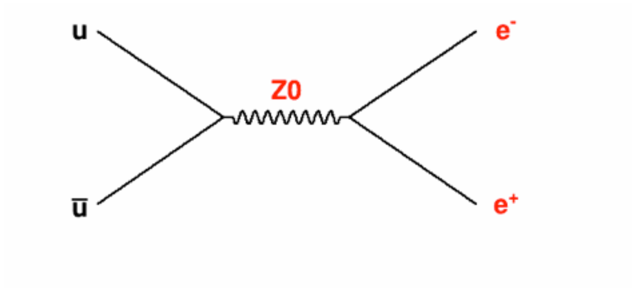

Figure 1.6: LO Feynmann diagram for production of an electron position pair via a Z boson through the annihilation of an up and anti-up

Figure 1.7 shows a NNLO (in the strong force) diagram for the same process.

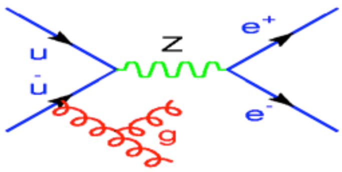

Figure 1.7: NLO Feynmann diagram for production of an electron position pair via a Z boson through the annihilation of an up and anti-up

1.7 Non-Fundamental (composite) particles

Apart from fundamental particles, more than 200 subatomic particles (made up of known fundamental particles) have been discovered using particle accelerators and detectors (see http://pdg.lbl.gov for a listing of the known particles). These composite particles are made up of quarks, and are of two types:

- **Baryons** are made of three quarks, for example neutron and proton.
- **Mesons** are made of quark pairs for example pions.

Baryons and mesons are collectively called Hadrons.

Mesons are bound states of 2 quarks. These are very important for particle physics because, although the proton is the lightest stable particle, mesons are the lightest states containing quarks. They are unstable - meaning that they decay, sometimes very quickly, to other types of particles. The lightest mesons are called pions. There are three of them: one with a positive charge, one neutral, and one with a negative charge. The charged pions decay via the weak force to a muon and a neutrino. The neutral pion usually decays to two photons. The naming conventions for all the mesons are very strange because the standard model and the existence of quarks was not yet understood when they were discovered. Thus, there are kaons that contain strange quarks,and D mesons that contain charm quarks.

As with hydrogen atoms, there are also excited states of the two bound quarks. While with hydrogen, we just say excited hydrogen, with the mesons, the excited states often have separate names, as it was not understood at the time of their discovery that they were essentially excited pions. Thus, rho mesons, eta mesons, etc are in a sense excited states of bound states of the up and down quark.

1.8 The Higgs

The Higgs boson plays a special role in the standard model. Gauge - invariant quantum field theories generally predict that the force bosons should be massless. And indeed the photon (E&M), the gluon (strong force) are massless. Although gravity can not yet be described by quantum field theory, in general a $1/r^2$ force indicates a massless boson, and gravity does seem to follow this prescription. Thus, naively, the standard model predicts that the W and Z boson should be massless. However, instead, they have a mass about 100x that of the proton! The resolution was the Higgs.

The Higgs has several strange properties. For all other particles, the lowest energy state is the one where there are no particles. However, for the Higgs, the lowest energy state has a "field" of Higgs filling the universe. The Higgs boson "couples" to the different fermions and the W and Z boson with different strengths ("coupling strengths"). The stronger the coupling, the larger the mass of the particle, as the interactions with this Higgs field that fills the universe is larger.

The Higgs is the only particle in the standard model with a spin of zero (sometimes called a "scalar" particle).

1.9 Further reading

- pdg.lbl.gov is always a great site for all things related to particle physics
- "Modern Particle Physics" by Mark Thomson
- "Introduction to Elementary Particle Physics" by Alessandro Bettini
- "Particle Physics: A Very Short Introduction" by Frank Close
- "Introduction to Elementary Particles" by David Griffiths

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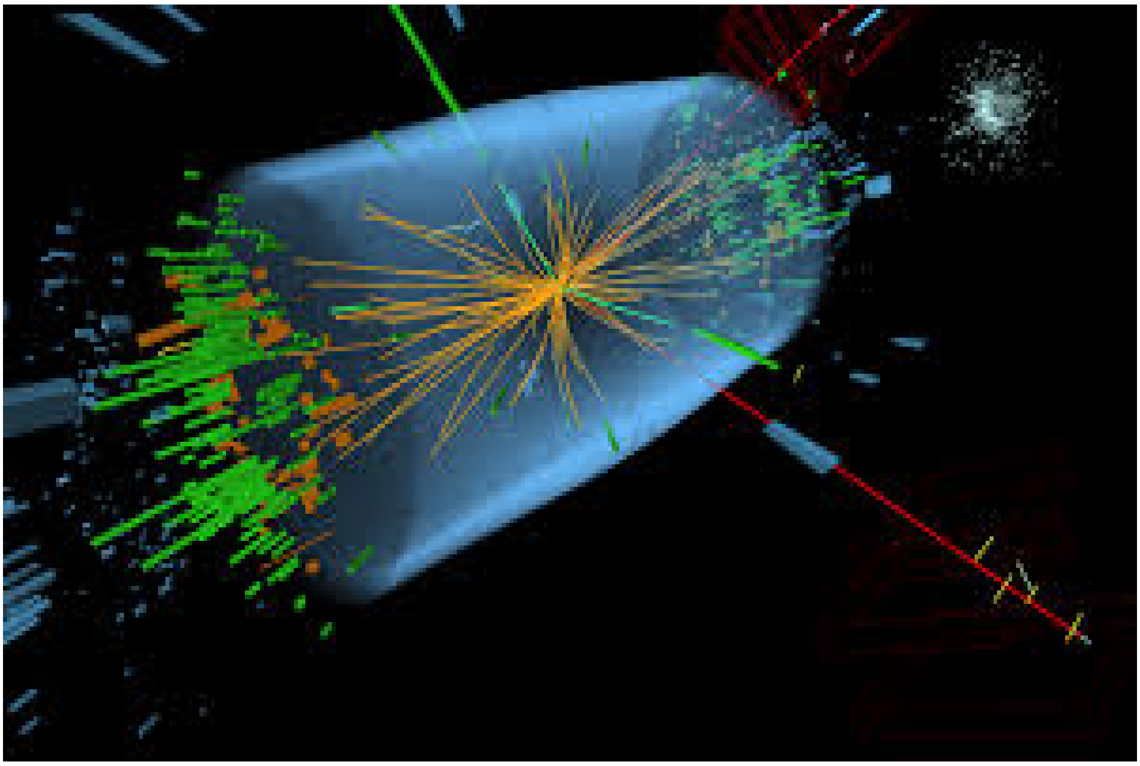

Review of collisions

2.1 Review of Collisions

Collisions happen all the time. Billard balls collide with each other and with the walls of the billiard table. Cars collide. People in crowded room bump into each other.

Collisions are also one of the main ways we study the fundamental forces and particles. We will review in this section what you learned in high school regarding collisions. As you may remember, when analyzing what will happen when you collide two objects, conservations laws are very important, especially conservation of energy and conservation of momentum. You may also remember that there are two classes of collisions: elastic and inelastic. In an elastic collision, kinetic energy is conserved. In an inelastic collision, the kinetic energy might change due to changes in other forms of energies. Kinetic energy may be changed into heat energy when an object is deformed. Chemical energy might become kinetic energy if something explodes. Let's do some simple collisions problems as a review.

2.1.1 Elastic Collisions

2.1.2 Inelastic Collisions

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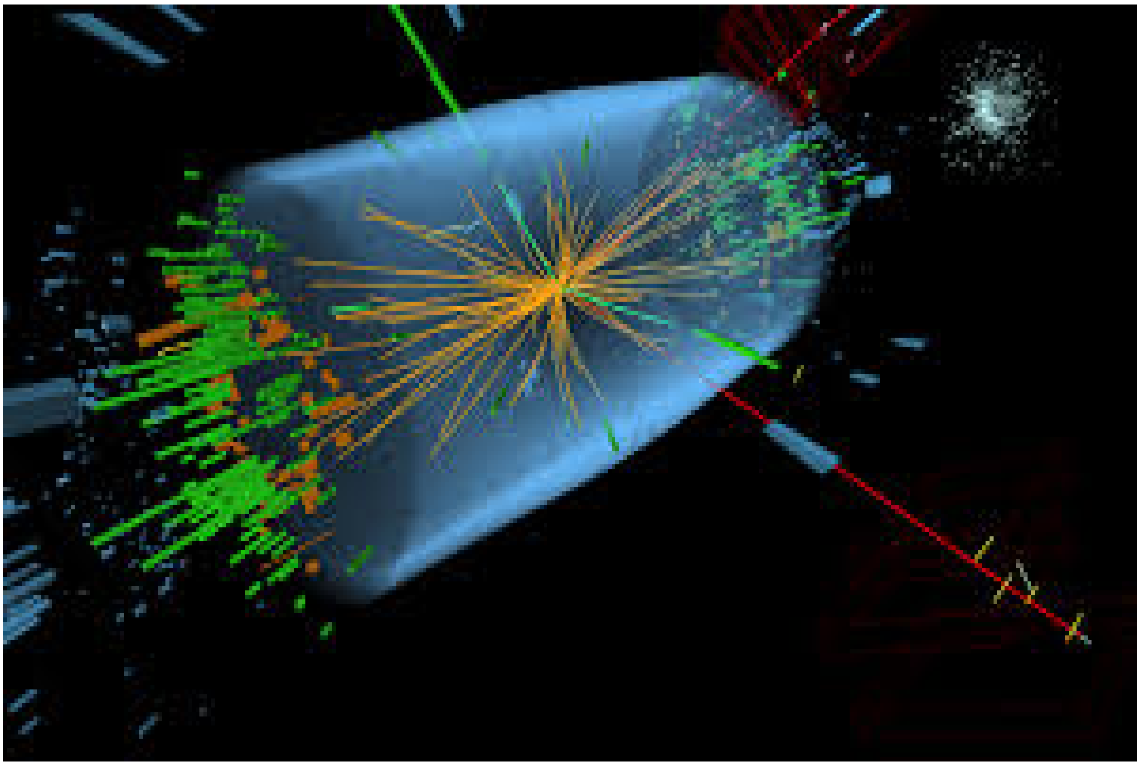


Special Relativity

3.1 Disclaimer

Einstein's 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 $\vec{F} = m\vec{a}$ as a fact that you can use as a tool to work other problems.

3.2 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, you then 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. We will discuss this more later. Since this is a special number, one of the *fundamental constants* of nature, along with $\hbar$ 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 *event* (something that has a time and a position) as

$$\color{red}{d} = (ct, x, y, z) \tag{3.1}$$

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 as

$$\color{red}{p} = (E, cp_x, cp_y, cp_z) \tag{3.2}$$

where E is the particle's 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:

$$\color{red}{p} = (E, cp_x, cp_y, cp_z) \tag{3.3}$$

$$\color{red}{p} = (E, c\vec{p}) \tag{3.4}$$

Exercise 3.1 show that E and cp have the same units. Remember that the i^{th} component of force is related to energy by $F_i = \frac{dE}{dx_i}$ and to momentum by $F_i = \frac{dp_i}{dt}$

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:

$$C = \vec{A} \cdot \vec{B} = A_x B_x + A_y B_y + A_z B_z \tag{3.5}$$

The dot product of a vector with itself gives the square of the magnitude of the vector.

$$|\vec{A}|^2 = \vec{A} \cdot \vec{A} \tag{3.6}$$

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.

$$c = \color{red}{a} \cdot \color{red}{b} = a_0 b_0 - \vec{a} \cdot \vec{b} \tag{3.7}$$

More on this useful operation later.

3.3 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,

$$v_{RB} = v_{RA} - v_B \tag{3.8}$$

$$x_{RB} = x_{RA} - v_B t \tag{3.9}$$

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.

$$ct_{RB} = \gamma(ct_{RA} - \beta x_{RA}) \tag{3.10}$$

$$x_{RB} = \gamma(-\beta ct_{RA} + x_{RA}) \tag{3.11}$$

where,

$$\beta = v_B/c \tag{3.12}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \tag{3.13}$$

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 you will 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.

3.4 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. Let's prove this in one spatial dimension (I think you can do the equivalent proof in 3-D using this model!).

Lengths of 4 vectors

$$\begin{aligned}
|a|^2 &= a_0a_0 - a_xa_x \\
&= |a'|^2 = a'_0a'_0 - a'_xa'_x \\
&= \gamma(a_0 - \beta a_x)\gamma(a_0 - \beta a_x) - \gamma(-\beta a_0 + a_x)\gamma(-\beta a_0 + a_x) \\
&= \gamma^2(a_0^2 - 2\beta a_x a_0 + \beta^2 a_x^2 - \beta^2 a_0^2 + 2a_x\beta a_0 - a_x^2) \\
&= = \gamma^2(a_0^2(1-\beta^2) - a_x^2(1-\beta^2)) \\
&= a_0^2 - a_x^2 \\
&= |a|^2
\end{aligned} \tag{3.14}$$

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

$$(mc^2)^2 = E^2 - (pc)^2 \tag{3.15}$$

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 doesn't 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.

3.5 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/c^2 is a unit of mass. GeV/c^2 is then 10^6 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 $\hbar$. 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 $\hbar$ 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 $\hbar$ 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 $\hbar$/GeV is a unit of time. But $\hbar$ =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):

$$m^2 = E^2 - p^2 \tag{3.16}$$

3.6 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

$$\tau = \gamma\tau_0 \tag{3.17}$$

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

3.7 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:

$$\Delta E \Delta t \geq \hbar \tag{3.18}$$

Because of this, when we measure the particle's 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:

$$\Gamma = \frac{\hbar}{\tau_0} \tag{3.19}$$

where Γ is the lifetime in GeV. When the lifetime is expressed in GeV, it is referred to as the particle's width.
The actual functional form of the mass distribution is called a Breit-Wigner. The form is:

$$\text{rate of events} \propto \frac{1}{(E-M)^2 + \frac{\Gamma}{2}} \tag{3.20}$$

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

Exercise 3.2 For the Z boson, M is 91.2 GeV and Γ is 2.5 GeV. What is the corresponding lifetime? Use root to plot this function versus E, the observed mass.

3.8 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.

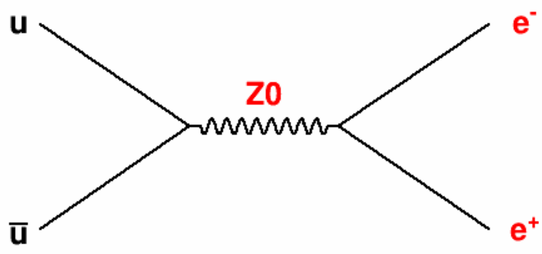


Figure 3.1: Feynman diagram for production of a Z boson in a proton-proton collision, with subsequent decay to electrons

3.9 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.

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:

$$p_u = (\frac{M_z}{2}, 0, 0, \frac{M_z}{2}) \tag{3.21}$$

$$p_{\bar{u}} = (\frac{M_z}{2}, 0, 0, -\frac{M_z}{2}) \tag{3.22}$$

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:

$$p_{e^+} = (\frac{M_Z}{2}, \frac{M_Z}{2} cos\theta cos\phi, \frac{M_Z}{2} cos\theta sin\phi, \frac{M_Z}{2} sin\theta) \tag{3.23}$$

$$p_{e^-} = (\frac{M_Z}{2}, \frac{M_Z}{2} cos(\pi - \theta) cos\phi, \frac{M_Z}{2} cos(\pi - \theta) sin\phi, \frac{M_Z}{2} sin(\pi - \theta)) \tag{3.24}$$

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)

$$E^2 = p_x^2 + p_y^2 + p_z^2 \tag{3.25}$$

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*. It's magnitude is calculated:

$$p_T = \sqrt{p_x^2 + p_y^2} \tag{3.26}$$

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

3.10 Rapidity and Pseudorapidity

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

$$y = \frac{1}{2} ln(\frac{E + p_z}{E - p_z}) \tag{3.27}$$

Exercise 3.3 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:

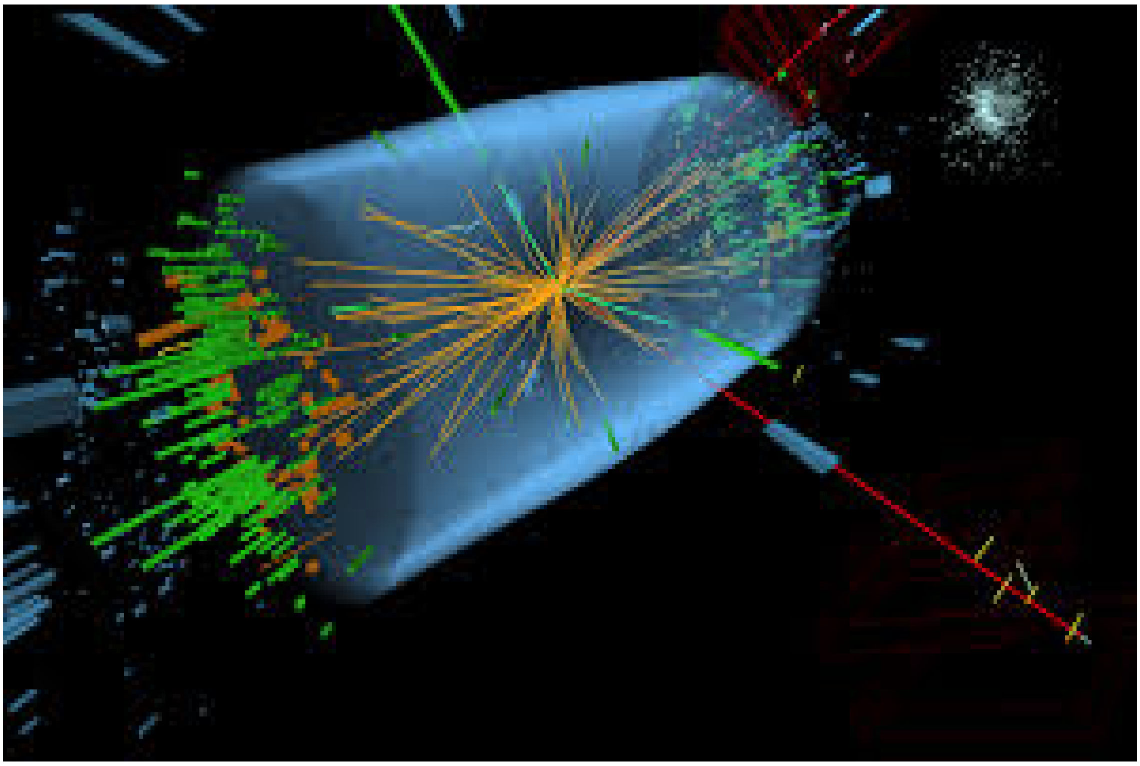
$$\eta = -\ln\tan\frac{\theta}{2} \tag{3.28}$$

Exercise 3.4 show that rapidity and pseudorapidity are equal for massless particles.

3.11 Further reading

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

4



Particle Interactions with matter

4.1 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 the 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. How far does a particle travel before decaying? We learned in Chapter **??** that fraction remaining after a time t_0 is given by

$$N = N_0 e^{\frac{-t_0}{\tau}} \tag{4.1}$$

The probability of surviving is N/N_0 so

$$P(t) = e^{\frac{-t_0}{\tau}} \tag{4.2}$$

To change this to the probability of traveling a distance instead of a time, remember that, with relativity, the lifetime for a moving particle depends on the lifetime for the particle at rest as $\tau = \gamma\tau_0$ so we have

$$P(t) = e^{\frac{-t_0}{\gamma\tau_0}} \tag{4.3}$$

Position is then related to time by $x_0 = vt_0$ or $x_0 = \beta ct_0$, so

$$P(t) = e^{\frac{-x_0}{\beta c\gamma\tau_0}} \tag{4.4}$$

Then, using $\Gamma = \bar{h}/\tau_0$, $\gamma = E/mc^2$ where m is the particle's mass and $\beta = pc/E$, we have

$$P(x_0) = e^{\frac{-x_0\Gamma mc^2}{pc\bar{h}c}} \tag{4.5}$$

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 type of rare kaon; kaons, as you remember are mesons containing a strange quark); 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.

4.2 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 nucleii (only for mesons and baryons, as these contain quarks)

We will postpone 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. It is somewhat similar to sliding friction. For example, when a book slides across a table, the molecules in the book interact with those on the table via the electric force. This causes the kinetic energy of the book to decrease, and become heat energy in the book and the table. This heat energy, you may remember, is associated with the random, invisible motion of the molecules in the book and table. There is a difference though. The energy of the charged particle doesn't initially produce heat (although, eventually, some heating can occur.) 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"). This excitation energy can eventually turn into heat energy or it can produce signals that can be detected, as we will discuss later.

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 material 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 4.1 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

$$\frac{MeV\,cm^2}{g}\cdot\frac{g}{cm^3}=\frac{MeV}{cm} \tag{4.6}$$

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.

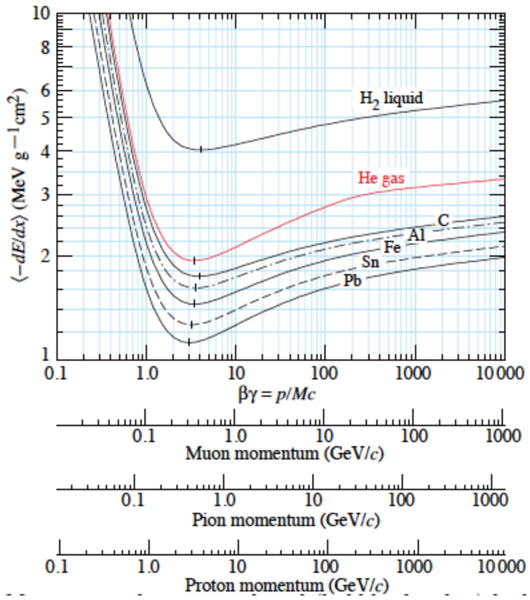


Figure 4.1: Stolen from the particle data group, this picture shows the energy loss per unit length as a function of particle energy

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 4.2 shows the range for various particles in various materials as a function of particle energy.

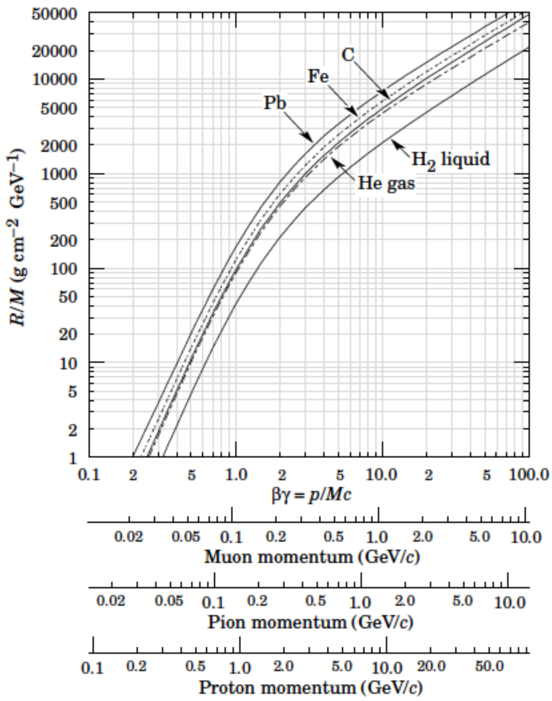


Figure 4.2: Stolen from the particle data group, this picture shows the range of a particle in various materials as a function of particle energy

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 distribution of deposited energies follows a "Landau" distribution, as shown in Fig 4.3.

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 4.4 shows a cartoon of this process.

4.3 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

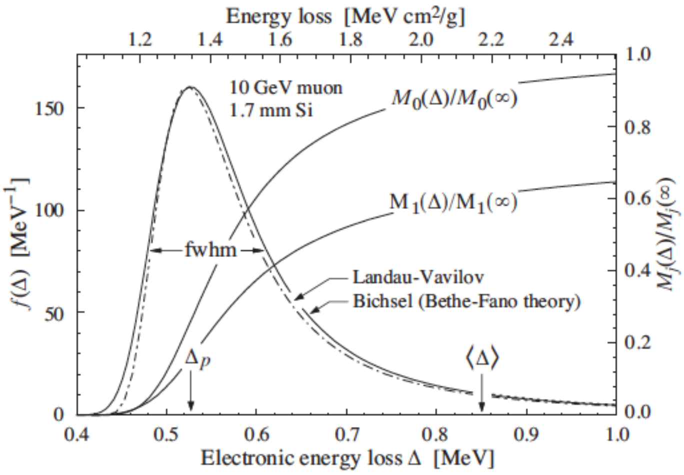


Figure 4.3: Stolen from the particle data group, this picture shows the distribution of energy deposits for a 10 GeV muon transversing 1.7 mm of silicon.

Figure 4.4: Stolen from the particle data group, this picture shows a cartoon showing the path of a charged particle undergoing multiple scattering in matter

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 scattering is the scattering of a photon off an electron. The Feynman diagram is shown in Figure 4.5.

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 4.7 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.

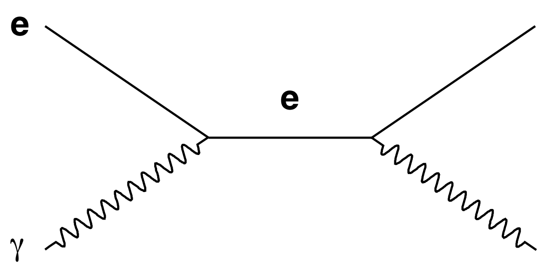


Figure 4.5: Feynmann diagram for Compton scattering of a photon by an electron

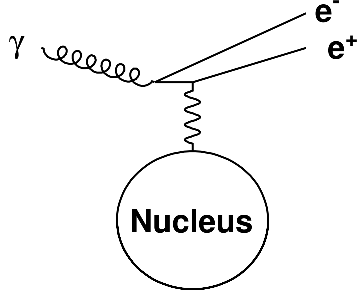


Figure 4.6: Feynmann diagram for pair production in the field of a nucleus

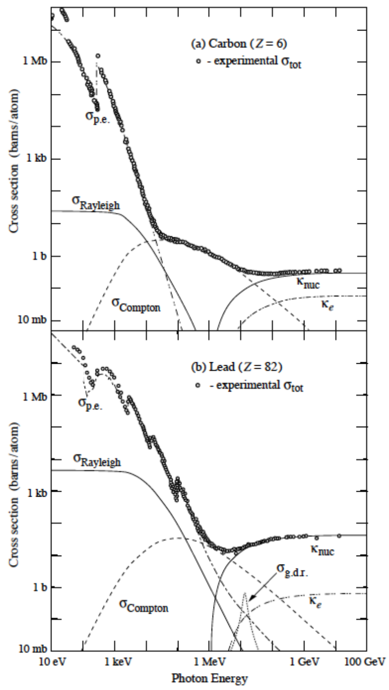


Figure 32.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [51]:

$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [52]. In these interactions, the target nucleus is broken up.

Original figures through the courtesy of John H. Hubbell (NIST).

Figure 4.7: 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

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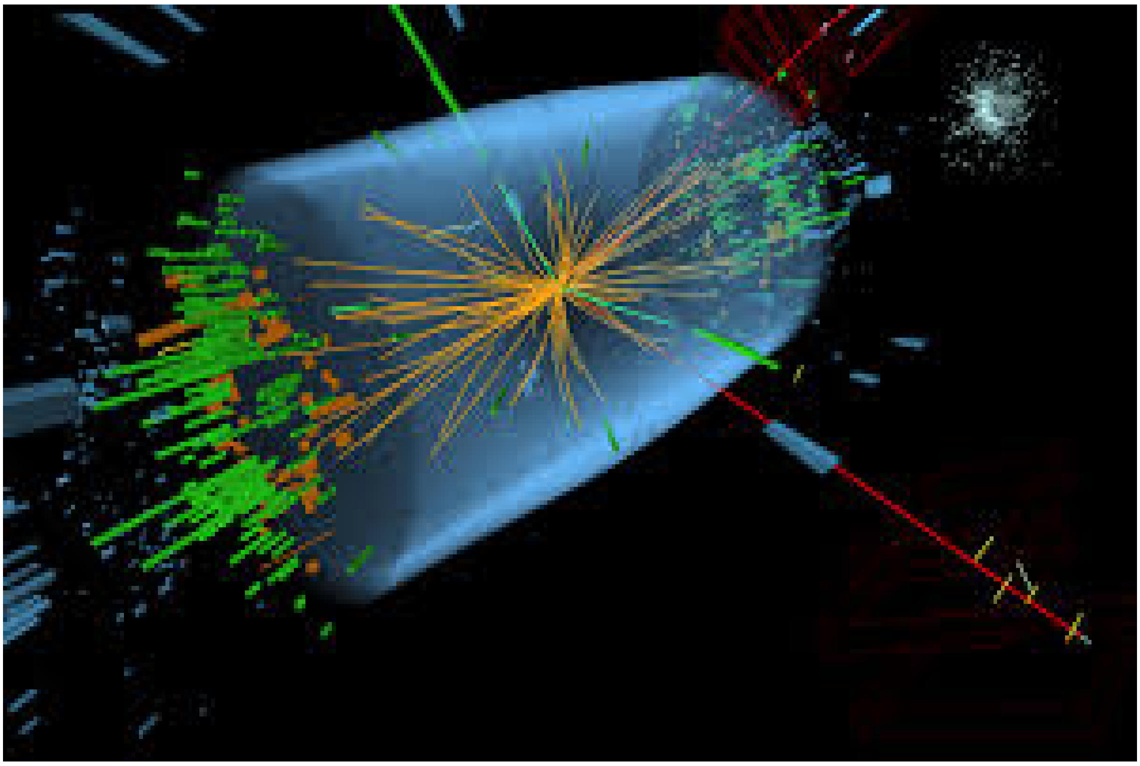

Statistics

5.1 Statistics

Please read chapter 3.I to 3.V in https://archive.org/download/pdfy-KjqMaZQFCJ7PUQgp/Knoll-Glenn-F-Knoll-Radiation-Detection-Measurement-3rd.pdf

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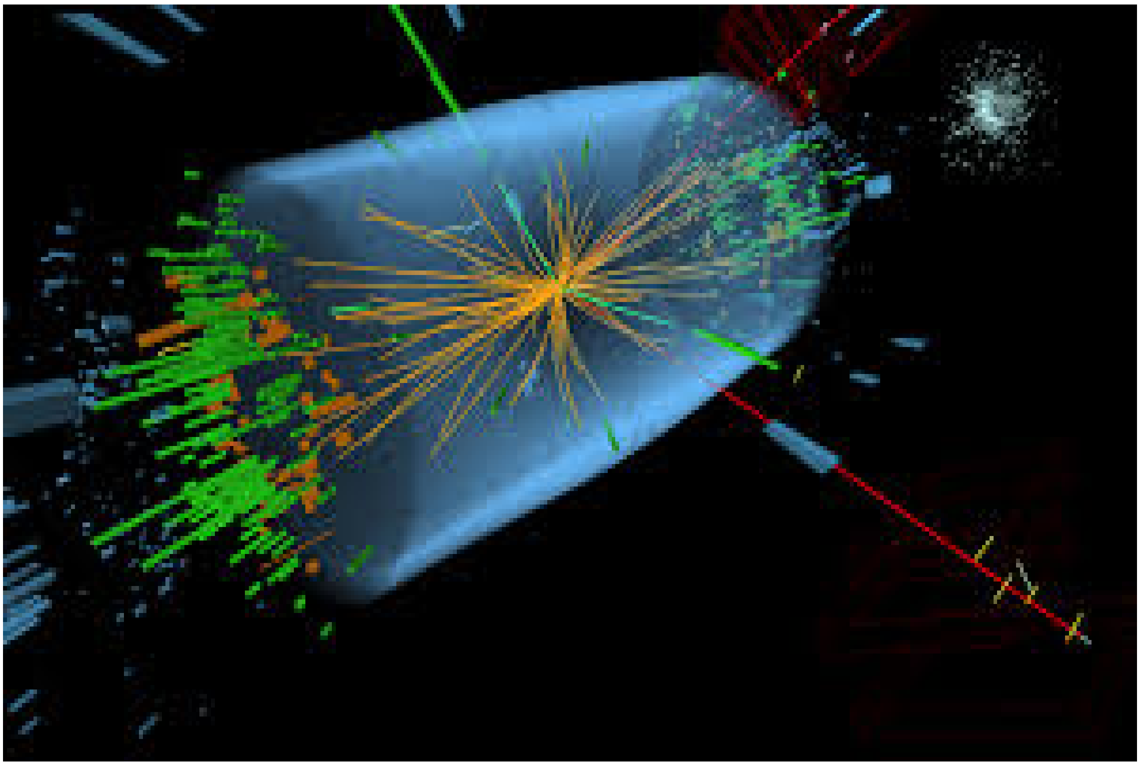

Particle accelerators

6.1 Introduction

It's a warm sunny day and you go for a picnic on a nice little mountain in Switzerland. You enjoyed your day and it wasn't until you start your journey back that you notice that the gas tank is almost empty. There are no gas stations around and that worries you until your friend says "Never mind, we will use the force of gravity to accelerate us down." Ahh! - You, being an avid student of physics, know exactly 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 the higher the speed of an object, the more smashing energy it has. The damage to a car moving at 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 particles, 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 protons close 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 equation, E=mc^2, part of this energy will actually turn into new particles. Imagine the collision of two cars at a very high speed. We expect car parts to come flying out, but if part of the energy also causes new "particles" to form, we should also expect a few doves, a helicopter and a school bus to come flying out from the collison.

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

In general, there are two types of particle accelerators:

· Circular Accelerators
· Linear Accelerators (LINAC)

A particle accelerator could be a combination of these general forms. For example, the large hadron collider makes use of both circular and linear accelerators. (Fig. 6.1).

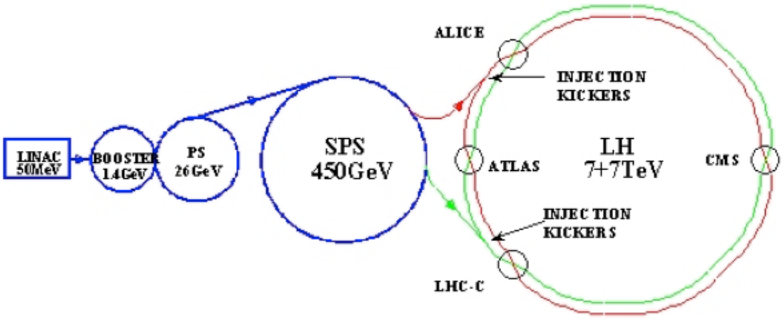

Figure 6.1: Diagram of the CERN accelerator complex.

6.2 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. The 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. (Figure 6.2)

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

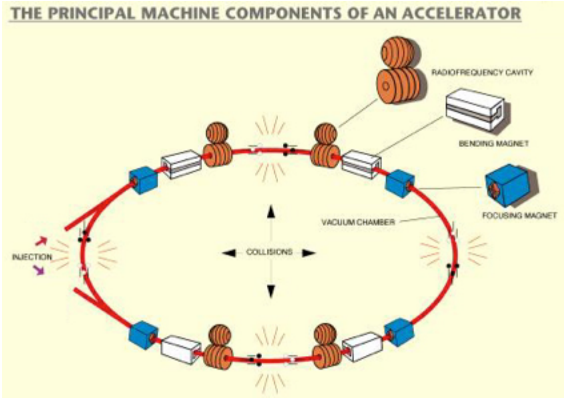

Figure 6.2: Components of an Accelerator

this a bad thing?). The pressure inside of the LHC is 10^{-13} atm, ten times less than the pressure on The Moon.

Devices to change particle speed (Radiofrequency (RF) caities 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 the distance 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 over 700 tons.

Devices to change direction particle (Magnetic Fields)

Going back to our picnic on the mountain, we can use gravity to accelerate us down, but what if the steering stops working? Similarly, we can accelerate protons using electromagnetic force, but in order to keep them in the circular path, the beam pipes are surrounded by a large magnet system that deflects the protons (recall protons are positively charged particles). The higher the speed of a particle, the larger its mass becomes, and therefore stronger magnets are need to steer it. This is where the limitations of a particle accelerator lie, since at a certain magnetic energy, the material of the magnetic coils cannot resist the forces of its own magnetic field anymore.

The LHC uses various types of magnets to serve different functions. For example, dipole magnets are usually used to bend the path of a beam of particles that would otherwise travel in a straight line. Quadrupole magnets are used to focus a beam, gathering all the particles closer together (similar to the way that lenses are used to focus a beam of light). The magnets used in the LHC have been specially designed: the dominant part of the magnet system consists of 1232 dipole magnets, each with a length of about 16 m and a weight of 35 tons, which can create a maximum magnetic field of 8.33 tesla - 150 000 stronger than Earths magnetic field. In addition to the dipole magnets, there are quadrupole magnets (with four magnetic poles) for focusing the beams, and thousands of additional, smaller sextupole and octupole magnets (with six or eight magnetic poles each, respectively) for correcting the beam size and position.

Exercise 6.1 How do you think the LHC uses the electromagnets to change the direction of the protons moving in the opposite direction in the beam pipe?

All magnet coils and the accelerator cavities are built from special materials (niobium and titanium) that become superconducting, conducting electricity to produce the electric and magnetic fields without resistance, at very low temperatures. To reach their maximum performance, the magnets need to be chilled to -271.3C (1.9K) - a temperature colder than outer space. To cool the magnets, much of the accelerator is connected to a distribution system of liquid nitrogen and helium (see box). Just one eighth of the LHC's cryogenic distribution system would qualify as the worlds largest fridge.

Collision Targets

Collisions at accelerators can occur either against a fixed target, or between two beams of particles, as is the case for the LHC. Particle detectors are placed around the collision point to record and study the particles produced in these collisions.

Physicists will use the LHC to recreate the conditions just after the Big Bang by colliding the two beams head-on at very high energy. Teams of physicists from around the world will analyse the particles created in the collisions using special detectors in a number of experiments dedicated to the LHC.

6.3 Energy

The maximum design energy per beam for the LHC is 7 TeV (tera-electronvolt), corresponding to head-to-head collisions of 14 TeV.

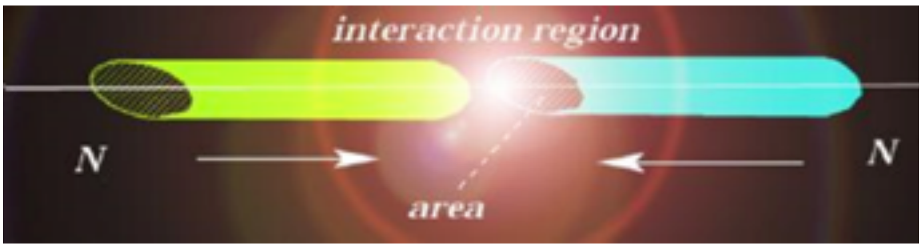

Figure 6.3: Diagram of interaction region

6.4 Cross Section

This is the transversal size of the bunch at the interaction point.

6.5 Luminosity (L)

Luminosity (L) is one of the most important parameters of an accelerator. It is a measurement of the number of collisions that can be produced in a detector per cm^2 and per second. The bigger the value of L is, the bigger the number of collisions. To calculate the number of collisions we need to also consider the cross section.

$$L \sim f \cdot N^2/(4 \cdot pi \cdot \sigma^2) = 10^{34} cm^{-2} \cdot s^{-1} \tag{6.1}$$

Where f is the bunch's crossing frequency $40x10^6$. N^2 is the number of protons that can collide (each particle in a bunch might collide with anyone form the bunch approaching head on). And σ is the cross section of the beam (=16 microns or $16 \cdot 10^{-4}$).

This value, $10^{34} cm^{-2} s^{-1}$, means that in the LHC might produce 10^{34} collisions per second, per cm^2.

6.6 Integrated Luminosity

This is the integral of the delivered luminosity over time. It is a measurement of the collected data size, and it is an important value to characterize the performance of an accelerator.

$$L = \int L dt \tag{6.2}$$

Usually, it is expresed as the inverse of cross section (i.e. 1/nb or nb^{-1} - nanobarns^{-1}; 1/pb or pb^{-1} - picobarn^{-1}; 1/fb or fb^{-1} - femtobarn^{-1})

Fig 6.4 shows the integrated luminosity (nb^{-1}) delivered to the LHC$'s$ experiments (3.5 TeV proton energies) through July 14 2010.

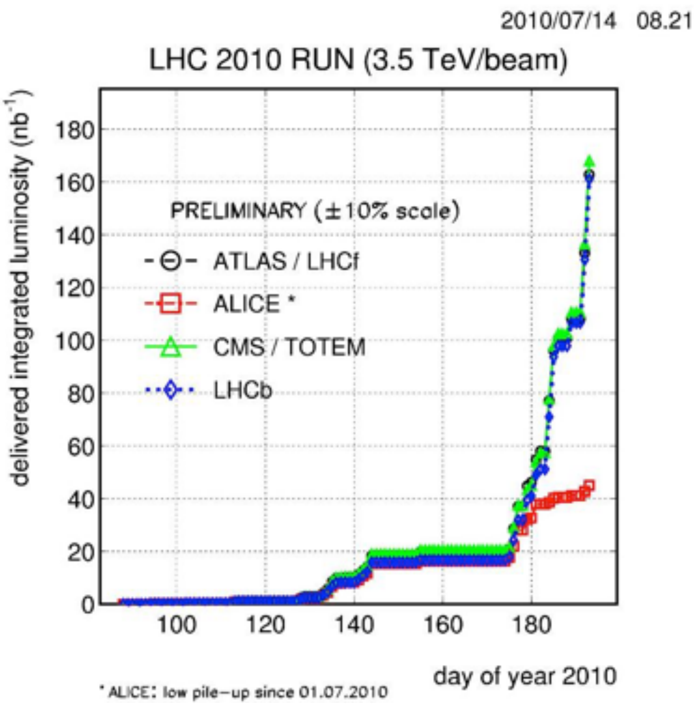

Figure 6.4: Integrated Luminosity Through July 14 2010

The LHC is used by almost 10,000 physicists from more than 80 countries to search for particles that could unravel the chain of events that shaped our Universe a fraction of a second after the Big Bang. It could resolve puzzles ranging from the properties of the smallest particles to the biggest structures in the vastness of the universe. The design and construction of the LHC took about 20 years, and a total cost of 3.6 billion euro (roughly 4 billion USD). It is housed in a 27km long and 3.8m wide tunnel about 100m underground.

Given these parameters, how do you propose to increase the luminosity in a future LHC like machine?

6.7 Event

An event is a collision with all its resulting particles. In a “damaging” or hard collision, hundreds of particles, for example electrons, muons, photons, pions, protons, neutrons, etc... fly through the detector at close to the speed of light. These particles can come from the decay of heavier known or unknown particles and physicists use information collected by the detectors at different collision points to deduce the existence of these heavy particles. Multiple interactions??????

6.8 The Data Challenge

The LHC will produce roughly 15 petabytes (15million gigabytes) of data annually - enough to fill more than 3 million DVDs.Thousands of scientists around the world want to access and analyse these data, so CERN is collaborating with institutions in 33 countries to operate a distributed computing and data storage infrastructure: The LHC Computing Grid (LCG).

The LCG will allow data from the LHC experiments to be distributed around the globe, with a primary backup kept at CERN. After initial processing, the data will be distributed to eleven large computer centres. These tier-1 centres will make so that the data scientists can then access the LHC data from their home country, using local computer clusters or even individual PC’s.

6.9 Refrences

· An LHC FAQ PDF `http://cdsweb.cern.ch/record/1092437/files/CERN-Brochure-2008-00 pdf`

· A video of the HLC Rap `www.youtube.com/watch?v=j50ZssEojtM`

· The CERN's LHC public website `http://public.web.cern.ch/public/en/LHC`

· An online LHC game `http://particle-clicker.web.cern.ch/particle-clicker/`

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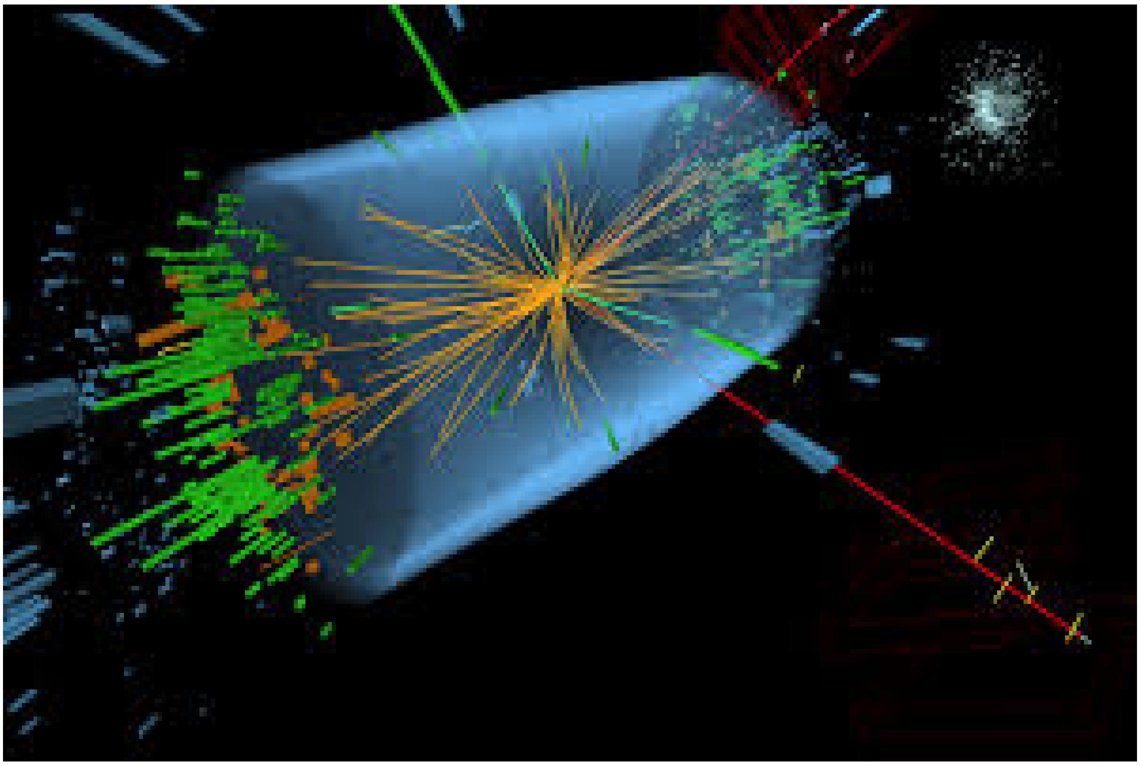

Calorimeters

7.1 Basic Idea

The goal of a particle physics detector is to measure the 4-momenta of all particles produced in a collision and to identify their types. As we discussed in the section on tracking, the 4-momenta of charged particles, such as electrons, pions, etc... whose $|\eta|$ is not too large (usually less than about 2) can be measured by the tracker. However, we need another way to measure electrically neutral particles or ones at large $|\eta|$.

You may have already encountered the word "calorimeter" in your high school physics. In thermodynamics, the temperature of a known (hot) object may be measured by immersing it in a bath and measuring the temperature rise of the bath. The heat energy of the unknown object becomes that of a known object, allowing measurement. In a HEP calorimeter, the goal is to turn the kinetic energy of the particle into another type of energy that is more easily measured. In the process, the particle is altered so that it no longer reflects its initial properties (especially the momentum, but sometimes the type is changed) and no further useful measurements can be made. Calorimeters should therefore be outside of the non-destructive detectors.

Remember our goal is to identify the 4-momentum and identify the type of all particles produced in the collisions. In a calorimeter, as we will discuss later, we can often use the shape of the energy deposit to tell if the particle is either an electron or a photon (on the one hand) or a hadron. The calorimeter is segmented so the azimuthal (ϕ) and polar angle (θ) can be estimated, assuming the particle was produced at the center of the detector, by drawing a line from the production point to the impact point on the calorimeter face. If we assume the particle′s mass is small compared to its momentum (massless approximation), the particle′s momentum can be estimated as:

$$p = E(1, cos(\theta) \cdot cos(\phi), cos(\theta) \cdot sin(\phi), sin(\theta)) \tag{7.1}$$

7.2 Showers

In a particle physics calorimeter, we try to first change the neutral particles (photons, neutrons, K-longs) into charged particles. Then, we change single high energy charged particle into a very large number of low energy charged particles in such a way that the number we create is proportional to the kinetic energy of the initial high energy particle. The low energy charged particles travel through matter, interacting with the electrons in the material, transferring their kinetic energy to them, until all the initial kinetic energy is transferred to the material. That material then needs to make some kind of signal that can be detected. You can see a schematic of this process in figure 7.1. An initial particle comes in, somehow interacting with the material of the calorimeter, and is changed gradually into a large number of low energy particles, that "range out" in the material. This process is called "showering", where a single high energy incident particle becomes a large number of low energy secondary particles.

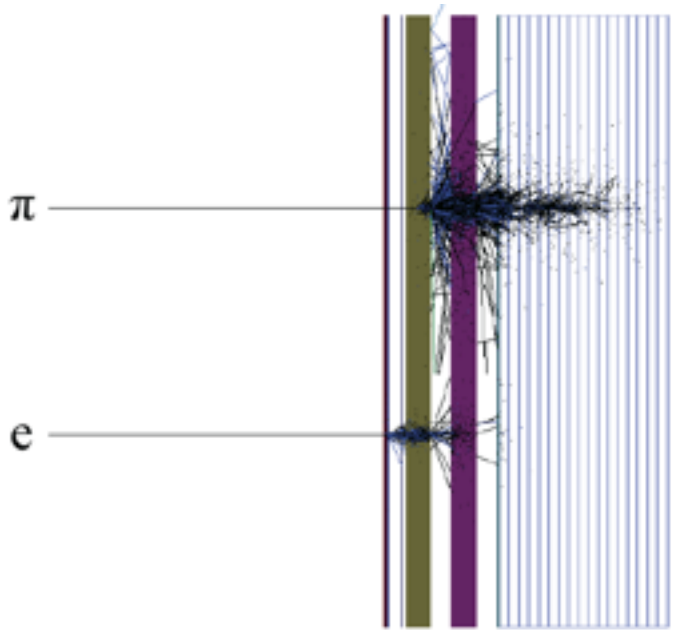

Figure 7.1: Schematic of a typical calorimeter. The front part (on the left of the calorimeter) is the "Electromagnetic" calorimeter and should contain the showers resulting from electrons and photons. The back of the calorimeter is the "hadronic" part, and should contain the showers resulting from particles containing quarks (mesons, baryons, etc).

What are the processes that cause the creation of the secondary particles? That depends on whether the initial high energy particle was an "EM" particle (an electron or a photon) or a "HAD" particle (mesons, baryons).

7.3 Electromagnetic Showers

An electromagnetic shower results when an electron or photon enters a thick piece of material with a large atomic number (Z). There are two main processes that occur: Bremssrahlung and pair production.

Bremsstrahlung is German for “braking radiation”, and is a process that occurs for electrons. As you may have learned in your high school physics course, when a charged particle accelerates, it radiates electromagnetic radiation (photons, the particle of light). What would cause an electron to accelerate? An electron is a charged particle. A nucleus is also charged. For nuclei, such as lead or iron, that charge can be large. If an electron passes close enough to a nucleus, the electric force between the two particles causes the electron to accelerate (because the nucleus is much heavier than the electron, and is bound in the lattice of the solid, it does not move). Thus, in the presence of the nucleus, a high energy electron becomes a lower energy electron and a gamma ray (high energy photons). This can be draw as shown in figure 7.2

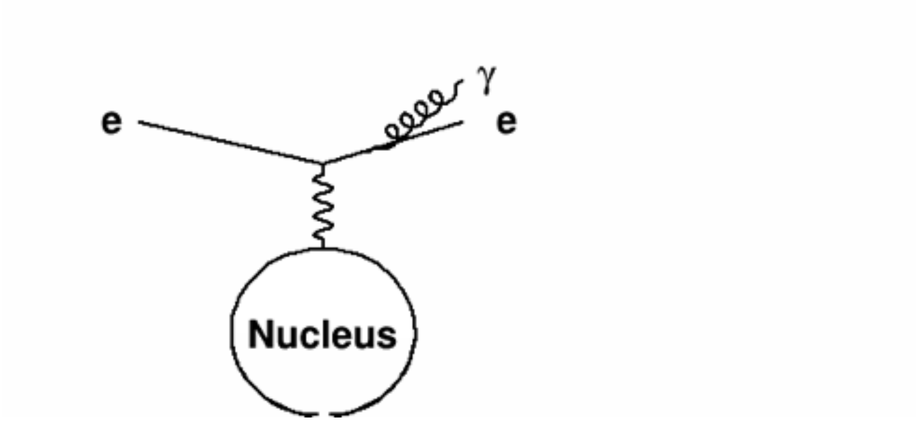

Figure 7.2: An electron radiates off a gamma ray in the presence of a nucleus.

A similar process allows a high energy photon to become an electron-positron pair. The energy of the photon must be at least twice the electron mass in order for this to not violate conservation of energy. The Feynman diagram is shown in figure 7.3.

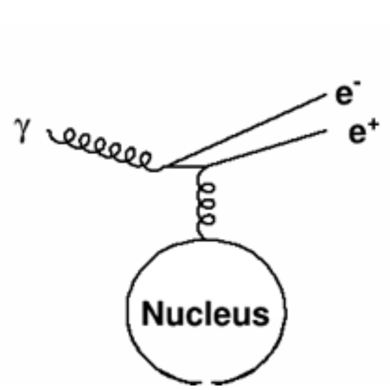

Figure 7.3: A high energy photon in the presence of a nucleus turns into an electron-positron pair

7.4 Hadronic Showers

Electrons interact with the nucleus by producing electromagnetic interaction because of the electromagnetic force. Hadrons, however, can interact with nuclei via the strong force. This can cause a wide variety of processes to occur, often involving the break up of the nucleus. It takes more material to initiate a hadronic shower, as the hadron must pass closer to the nucleus, as the strong force is short range. A diagram of the resulting shower is shown in figure 7.4

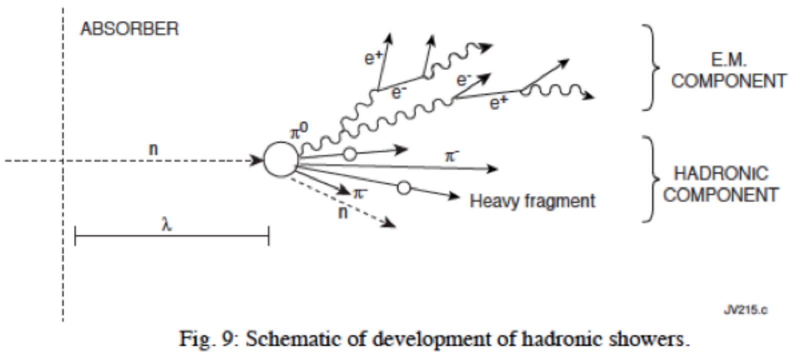

Figure 7.4: A figure showing a hadronic shower

7.5 Detection

How do we measure the energy gained by the material? For many calorimeters, it is through the process of scintillation. Now, most high Z materials (think lead or uranium) do not scintillator, and are anyway opaque to light. So a calorimeter is often made of layers of the "passive" (high Z) material and the "active" (light producing) material, often plastic scintillator. A calorimeter that is like a smith island cake and has many layers is called a "sampling" calorimeter. The light produced by the scintillator is measuring using a photomultiplier tube or other light sensitive device (figure 7.5).

Figure 7.5: A picture of a PMT stolen from the web site of Hamamatsu corporation, one of the largest manufacturers of these devices.

7.6 Sampling

Look at this picture of an EM shower in a sampling calorimeter.

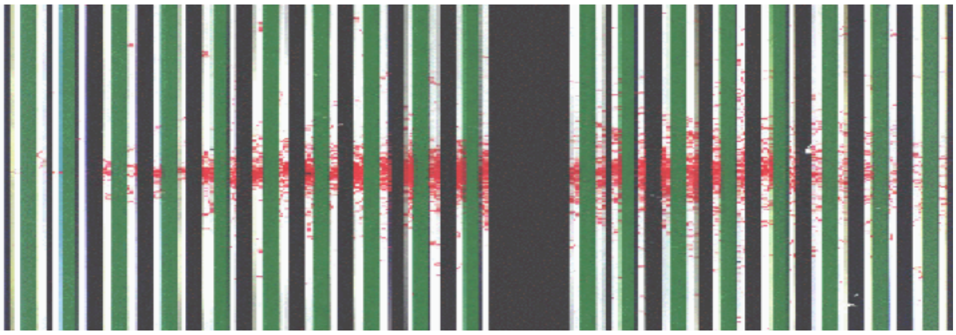

Figure 7.6: Schematic of an electromagnetic shower in a sampling calorimeter, as simulated by the GEANT4 shower simulation code. The colors denote various materials. The black denotes a high Z material, while the green denotes scintillator.

The secondary particles only deposit some of their energy in the scintillator. Most of it is deposited in the high Z material, which doesn′t produce light. Therefore, we are only measuring the energy of a small fraction of the shower, and thus a small fraction of the initial energy produced. We can correct for this on average:

$$E_{estimated\,for\,initial\,particle} = \frac{total\,amount\,of\,material\,in\,calorimeter}{amount\,of\,material\,in\,plastic} E_{deposited\,in\,plastic} \tag{7.2}$$

The ratio of the amounts of material is called the “sampling fraction”. However, due to randomness in the shower process, sometimes a larger amount than this average will be deposited in the plastic, and sometimes less. This will lead to an uncertainty on the energy of the particle that started the shower. The smaller this ratio, the more accurate the measurement will be. For most calorimeters, though, the ratio is around 100.

7.7 Energy Resolutions

How good is our calorimeter? This depends on how accurately it measures the energy of the initial particle. Sometimes, we take our calorimeters to test beams, and aim particles of known energy and momentum at them, to see how well they work. The figure below shows the result of aiming a beam of charged pions at the front face of the calorimeter.

The output from the scintillator is charge, measured in fC (femto-Coulombs), and so the x axis units are collected charge after amplification by the photomultiplier and other electronics. The detector is “calibrated” by setting the mean of this distribution (3457 fC) to the energy of the pions (300 GeV). The ratio of these numbers can be used to estimate the energy of the particle from the charge collected from the shower. Of course, this is a very simplistic calibration. Getting an accurate calibration over a wide range of particle energies is a subject that could be a book in and of itself.

As you can see, however, even though the incident particle always had the same energy, the amount of charge collected is not always the same. This is (mainly) because there are random fluctuations

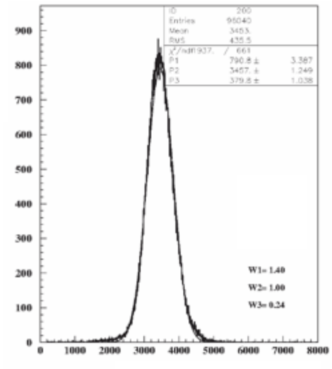

Figure 7.7: Charge collected from the detector when charged pions with a momentum of 300 GeV are steered into it.

between the amount of energy deposited in the passive material and that deposited in the active material. The distribution of measured energies is well approximated by a Gaussian distribution:

$$f(x,\mu,\sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \tag{7.3}$$

The parameter μ is the mean of the distribution. The parameter σ is the "root mean square" or "sigma" or the "resolution". It is a measure of the calorimeters ability to accurately measure the energy of the particle. In this figure, the mean is 3457 and sigma is 379.8. The fractional resolution is then the ratio of these two numbers, or 0.11.

The resolution for a calorimeter depends on the energy of the particle. The total number of secondary particles produced that cross the active material is proportional to the energy of the incident particle. The fluctuations on this number are proportional to the square root of this number, x. The fraction resolution (resolution/means) is thus proportional to $1/\sqrt{x}$.

There are other sources of resolution besides this, and so for a realistic calorimeter, the resolution is given by:

$$\frac{\sigma}{E} = \frac{s}{\sqrt{E}} \oplus \frac{n}{E} \oplus C \tag{7.4}$$

where s is called the "sampling term" and comes from the mechanism we discussed, n is called the "noise term" and is usually dominated by fluctuations in the measured charge due to electronics noise, and c is called the constant term, and is usually dominated by leakage of secondary particles out the back of the detector. The $\oplus$ symbol means "add in quadrature". To do this, square each term, add these squares, and take the square root. As you learn more statistics, you will learn this is a common procedure when there is more than one source of randomness contributing to a measureable outcome.

The figure below shows the resolution versus energy for one of the CMS detector′s calorimeters.

7.8 read

· Section 27.4 `http://pdg.lbl.gov/2011/reviews/rpp2011-rev-passage-particles-matter.pdf`

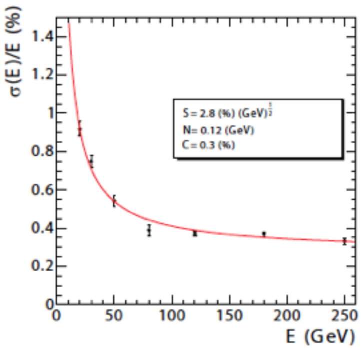

Figure 1.3: ECAL energy resolution, $\sigma(E)/E$, as a function of electron energy as measured from a beam test. The energy was measured in an array of 3×3 crystals with an electron impacting the central crystal. The points correspond to events taken restricting the incident beam to a narrow (4×4 mm^2) region. The stochastic (S), noise (N), and constant (C) terms are given.

Figure 7.8: A figure stolen from JINST 3 S08004 showing the fractional resolution of the CMS barrel electromagnetic calorimeter as measured with electrons as a function of electron energy.

· Section 28.9 `http://pdg.lbl.gov/2011/reviews/rpp2011-rev-particle-detectors-accel` `pdf`

· `http://journals.aps.org/rmp/abstract/10.1103/RevModPhys.75.1243`

· `http://microcosm.web.cern.ch/microcosm/LHCGame/LHCGame.html`

· `http://www.sciencedirect.com/science/article/pii/S0168900211005572`

· `http://www.sciencedirect.com/science/article/pii/S0168900211019851`

· `http://www.sciencedirect.com/science/journal/01689002/666`

· `http://link.springer.com/article/10.1140$%$2Fepjc$%$2Fs10052-008-0573-yurl`

· `http://link.springer.com/article/10.1140$%$2Fepjc$%$2Fs10052-009-0959-5`

· `http://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf`

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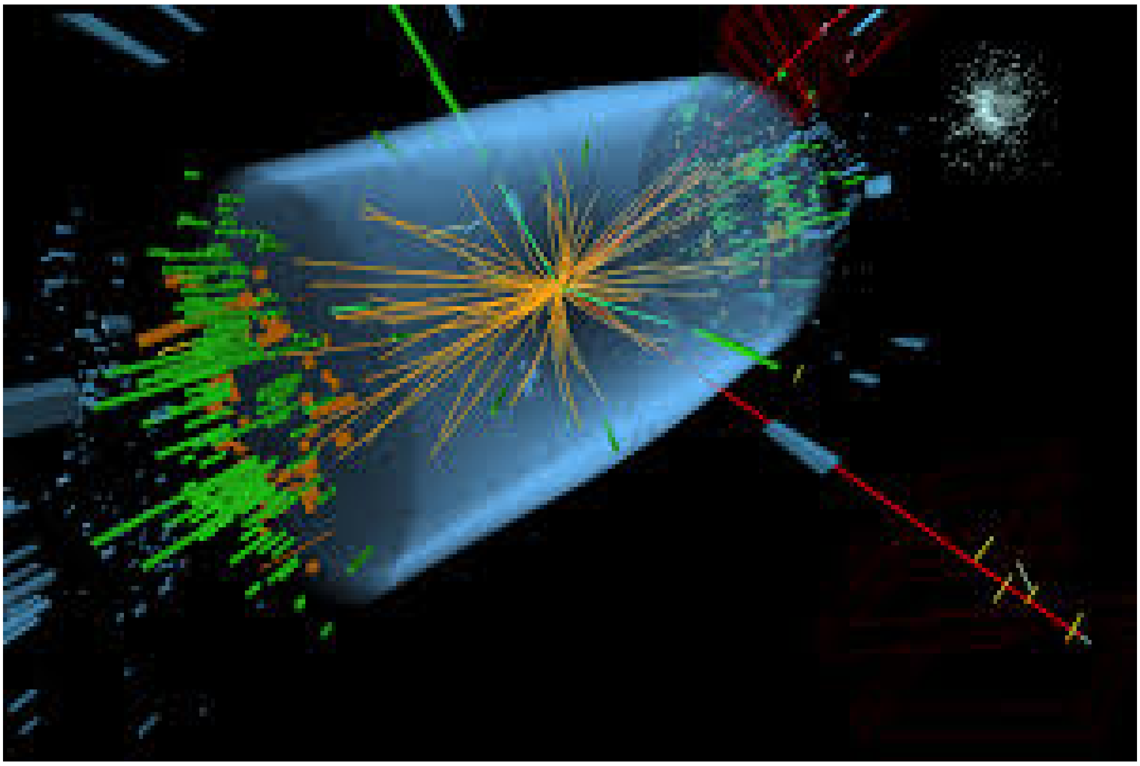

Trackers

8.1 Charged particles and magnetic fields

When a collision occurs, a very large number of particles are produced. Figure 8.1 shows a schematic view.

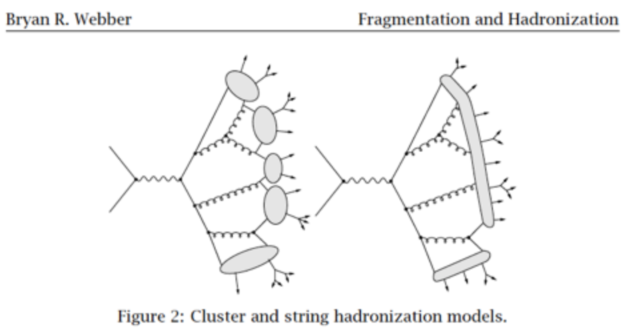

Figure 8.1: Cartoon of particle production in hadronic collisions

Some of the particles have an electric charge (electrons, charged pions,etc). Some are electrically neutral (photons, neutrons, neutral pions). The first kind of detector we will discuss can be used to measure the momenta of charged particles. Almost all modern particle physics detectors (an exception being the first version of the Dzero detector) feature large solenoidal magnets. A solenoid is a current-carrying wire wrapped into a cylindrical form. Inside the cylinder, there is an (approximate) uniform magnetic field, with the magnetic field lines parallel to the cylinder's (z) axis.

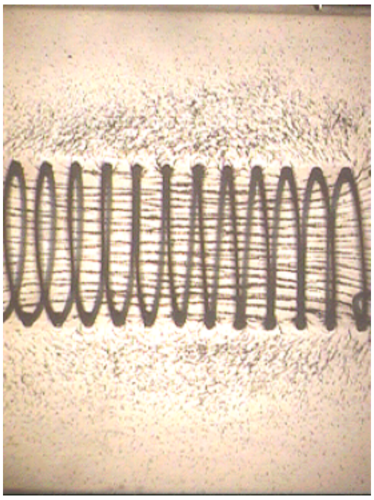

Figure 8.2: Iron filings are used to show the magnetic field lines inside a solenoidal magnet.

As you may remember from your high school physics class, a charged particle moving in a magnetic field will experience a force given by:

$$\vec{F} = \mathrm{q}\vec{v}\times\vec{B}$$

where $\vec{v}$ is the velocity of the particle and q is its electric charge. The direction of the force is perpendicular to both the velocity and the field. The magnitude is $\mathrm{q}v_T\mathrm{B}$, where v_T is the magnitude of the component of the velocity perpendicular to the magnetic field. You may remember that when the force is perpendicular to the velocity, the resulting motion is circular. For circular motion, you may remember that the acceleration is given by v^2/r. So we have:

$$m\frac{v_T^2}{r} = qv_TB$$

or (so that it will work with relativity, we change the mv_T to p_T). This equation is in cgs units. In convenient units (r in m, p_T in GeV, B in Tesla, q in units of e), the equation is:

$$p_T = .3\mathrm{qrB}$$

Now, imagine a particle produced at the center of the solenoid pictured above with momentum p=(p_x,p_y,p_z). Since the magnetic field is along the z direction, the force will be in the x-y plane. The resulting motion will be a spiral around the z axis. In that plane the motion will be circular. The component of velocity in the z direction will be unaffected, so in the x-z or y-z planes, the motion will be a straight line.

As you call tell from the equation above, if we can measure the radius of curvature of this motion in the x-y plane, we get the component of momentum transverse to the z (beam) axis. If we can also measure the polar and azimuthal angles, we can get the 4-momenta of the particle from the transverse momentum using elementary trigonometry.

As you can see, the higher momentum the track, the straighter its trajectory will be. Low momentum tracks will bend more. Very low momentum tracks may even be able to make a complete circle or more before leaving the detector.

8.2 Detecting the trajectory of the charged particle

In order to measure the radius of curvature, we need to know the path the particle takes as it emerges from the collision, and we have to measure this path without altering or disturbing the momenta of the particle. We need some material that produces a signal we can detect and it should be thin and low Z so that the particle does not lose much energy or scatter much while going through it.

There are two common detection medium used: gas and silicon. Gas has the advantage of being cheap and very thin. However, it typically can be used to measure a position on the trajectory with an accuracy of a few hundred microns, and it cannot handle a very high radiation environment. Silicon is thicker and more expensive, but can give measurements to a few 10's of microns and can handle a higher radiation environment. Both are used to produce a current that can be detected. For gas-based detectors, the particles ionize the gas, and the freed electrons are collected on wires that are at HV. As the freed electrons approach the wires, an "avalanche" process results, because the electrons accelerate in the electric field around the wire. When they reach a high enough energy, they ionize more gas, and these extra electrons are accelerated until a measurable current is created. In silicon, ionization is again the process that produces the signal, but high voltage is not required to collect the charge due to the short distances involved. The CMS tracker is silicon based. A schematic is shown in figure 8.3.

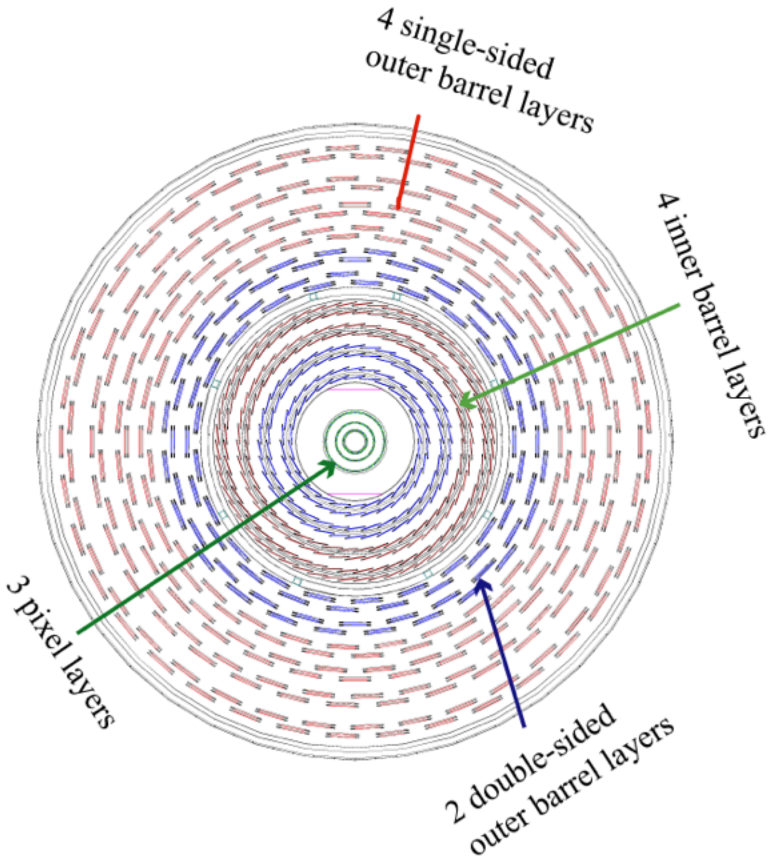

Figure 8.3: A schematic of the CMS silicon tracker.

As you can see, the tracker measures the track position at 15 positions along its trajectory. The "strips" that you see in each layer are segmented into individual detectors, with each strip of the silicon detectors reaching out to a radius of 130 centimeters.

8.3 Tracker Resolutions

Reconstruction of tracks from the detector information takes place in two steps. First, a "pattern recognition" algorithm decides which "hits"(localized detector information) go together into a single track. This is a complicated process, and very detector and collider specific. The next step,"fitting", uses this information to reconstruct the transverse momentum, angles (and distance of closest approach to the beam axis, for tracks produced from decays of long-lived particles). Let's consider the fitting part. Here, we will only consider the resolution on p_T, which is a 2 dimensional calculation, using the information in the plane transverse to the beam direction.

For a track produced at the vertex, and ignoring non-uniformities in the magnetic field and scattering by the particle in the material of the detector, the track's trajectory will trace out a circle that includes the origin. The general equation for a circle that satisfies these constraints is:

$$(x-a)^2+(y-b)^2=a^2+b^2$$

where a and b are the coordinates of the center of the circle and $\sqrt{a^2+b^2}$ is the radius of the circle, which is what we really want to find to get our transverse momentum. When fitting, it is often useful to do a transformation of variables to linearize the equation. Consider the transformation:

$$u=\frac{x}{x^2+y^2} \qquad v=\frac{y}{x^2+y^2}$$

In these variables, the equation of a circle is:

$$v=-\frac{a}{b}u+\frac{1}{2b}$$

If you compare this to the equation of straight line, you will see that the slope of v versus u gives you -$\frac{a}{b}$ and the intercept gives $\frac{1}{2b}$.

8.4 Fitting a straight line

Fitting is usually done by minimizing a χ^2. Remember that this is defined as:

$$\chi^2=\sum\frac{(data-theory)^2}{error^2}$$

For a fit to a straight line, it is easy to calculate what values for the slope and intercept will minimize this quantity. For a straight line, y=mx+b. Let z=y-mx+b. For a perfect fit, z will be 0. The χ^2 would then become:

$$\chi^2=\sum\frac{(z)^2}{\sigma_z^2}$$

where σ_z^2 is the uncertainty(error)in z. What values of m and b will minimize this χ^2?

$$\begin{aligned}\sigma_z &= \sqrt{(\frac{\partial z}{\partial y}\sigma y)^2+(\frac{\partial z}{\partial x}\sigma_x)^2}\\ &= \sqrt{(\sigma_y)^2+(m\sigma_x)^2}\end{aligned}$$

$$\chi^2=\sum_{data}\frac{(z-0)^2}{\sigma_z^2}=\sum_{data}\frac{(y-mx-b)^2}{(\sigma_y^2)+(m\sigma_x^2)}$$

If we consider the simpler case, where the errors on x are negligible, we can simplify the derivation to:

$$\chi^2 = \sum_{data} \frac{(y - mx - b)^2}{(\sigma_y^2)}$$

To minimize this, we use our knowledge of elementary calculus, which tells us that a function has a minimum or maximum when its derivative is zero.

$$\frac{\partial \chi^2}{\partial b} = -2\sum_i \frac{1}{\sigma_i^2}(y_i - b - mx_i) = 0$$
$$\frac{\partial \chi^2}{\partial m} = -2\sum_i \frac{x_i}{\sigma_i^2}(y_i - b - mx_i) = 0$$

Rearranging:

$$\left(\sum_i \frac{y_i}{\sigma i^2}\right) = b\left(\sum_i \frac{1}{\sigma i^2}\right) + m\left(\sum_i \frac{x_i}{\sigma i^2}\right)$$
$$\left(\sum_i \frac{x_i y_i}{\sigma i^2}\right) = b\left(\sum_i \frac{x_i}{\sigma i^2}\right) + m\left(\sum_i \frac{x_i^2}{\sigma i^2}\right)$$

Solving:

$$b = \frac{1}{\Delta}\left[\left(\sum_i \frac{x_i^2}{\sigma_i^2}\right)\left(\sum_i \frac{y_i}{\sigma_i^2}\right) - \left(\sum_i \frac{x_i}{\sigma_i^2}\right)\left(\sum_i \frac{x_i y_i}{\sigma_i^2}\right)\right]$$
$$m = \frac{1}{\Delta}\left[\left(\sum_i \frac{1}{\sigma_i^2}\right)\left(\sum_i \frac{x_i y_i}{\sigma_i^2}\right) - \left(\sum_i \frac{x_i}{\sigma_i^2}\right)\left(\sum_i \frac{y_i}{\sigma_i^2}\right)\right]$$

Where:

$$\Delta = det\begin{bmatrix} \left(\sum_i \frac{1}{\sigma_i^2}\right) & \left(\sum_i \frac{x_i}{\sigma_i^2}\right) \\ \left(\sum_i \frac{x_i}{\sigma_i^2}\right) & \left(\sum_i \frac{x_i^2}{\sigma_i^2}\right) \end{bmatrix}$$

8.5 Project

Write a little Monte Carlo program that will generate tracks with a transverse momentum of 1 GeV produced at the origin, in a uniform magnetic field along the z axis of 3 Tesla and transversing a detector that takes measurements at 12 different layers, uniformly spaced in r (the radial distance from the beam axis) between 0 and 1.5 m. Imagine each layer measures the r coordinate perfectly and the coordinate perpendicular to that with an accuracy of 10μm. Use MC to generate the "true" hits, transform them from r-φ to x-y, smear them to get the measured hit positions, and then fit the "smeared"hits to measured radius of curvature. What resolution would you predict? What resolution do you get? How does it change if you produce 10 GeV tracks instead? 100 GeV tracks?

8.6 Further Reading

·`http://pdg.lbl.gov/2011/reviews/rpp2011-rev-particle-detectors-accel.pdf` Section 28.6, 28.7
·`http://www.sciencedirect.com/science/article/pii/S0168900211020389`

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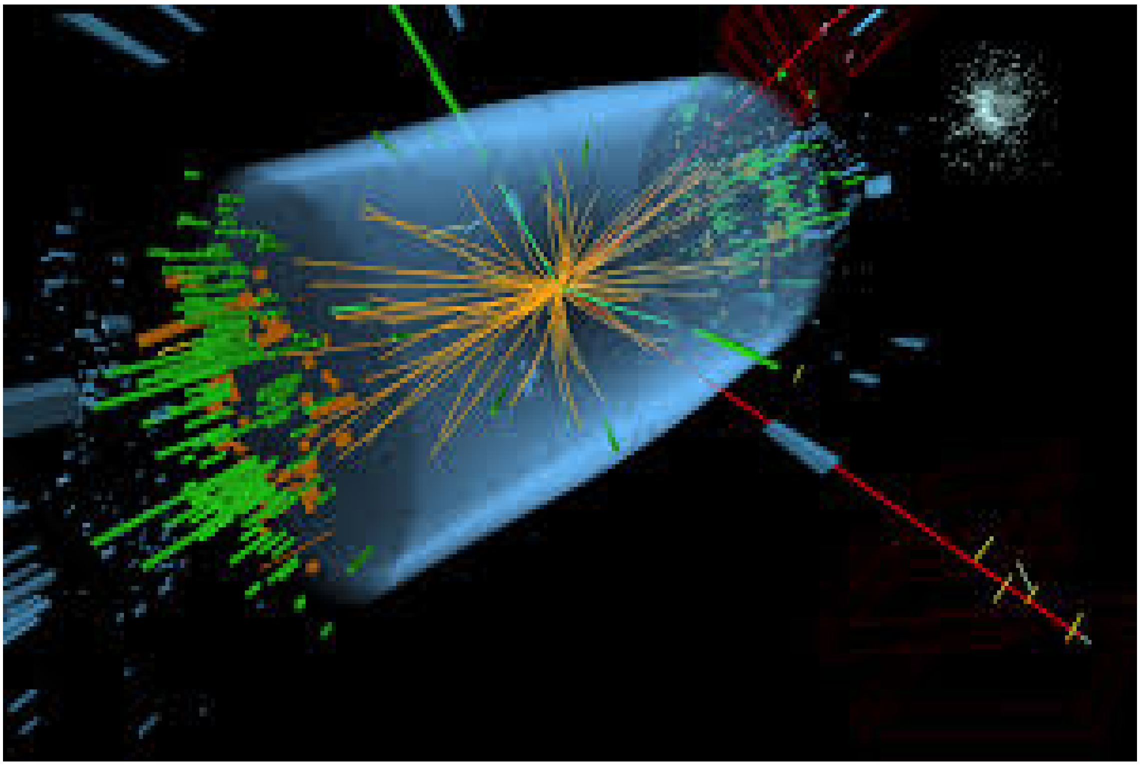


Particle Identification

9.1 Overview

Now that we know how the basic elements of a particle physics detector work, let's see how we can use them to identify which types of particles produce which signals in our detector. We will consider specifically the CMS detector, but virtually all collider detectors use similar identification criteria.

Particle identification is done using a massive piece of software, written by hundreds of physicists scattered all over the world, called CMSSW. What does this code do?

When a particle enters a detector element, some sort of detectable signal, usually charge, is made. This charge is measured, usually using something called an ADC or analog-to-digital converter. A number in binary (a number in base 2 number system) is produced and stored. For interesting events, every detector element (and there are millions of them, Figure 9.1 shows the channel count by subdetector) that has a reading above some threshold must be pulled from the detector electronics, along with an ID number that will identify which detector element the number came from, assembled into an organized structure in computer memory, and written to some storage media (perhaps computer disk).

CMSSW takes all these 0's and 1', uses calibration data to convert these to energies, times, or whatever is relevent for that subdetector. Once this is done, complex computer algorithms are run on this information to figure out which particles were produced.

Table 9.1: Sub-detector read-out parameters.

sub-detector	number of channels	number of FE chips	number of detector data links	number of data sources (FEDs)	number of DAQ links (FRLs)
Tracker pixel	$\approx$ 66 M	15840	$\approx$ 1500	40	40
Tracker strips	$\approx$ 9.3 M	$\approx$ 72 k	$\approx$ 36 k	440	250 (merged)
Preshower	144384	4512	1128	56	56
ECAL	75848	$\approx$ 21 k	$\approx$ 9 k	54	54
HCAL	9072	9072	3072	32	32
Muons CSC	$\approx$ 500 k	$\approx$ 76 k	540	8	8
Muons RPC	192 k	$\approx$ 8.6 k	732	3	3
Muons DT	195 k	48820	60	10	10
Global Trigger	n/a	n/a	n/a	3	3
CSC, DT Track Finder	n/a	n/a	n/a	2	2
Total	$\approx$ 55 M			626	458

Figure 9.1: Channel count for the CMS detector by subdetector

We describe below some of the types of algorithms that are used in this code.

Consider the slice of the CMS detector show in Figure 9.2 as viewed in the r-ϕ plane:
The collision point in the figure above is indicated by the convergence of the solid red, green, and blue lines and the dashed green and blue lines. These represent particles created at a common point when a collision occurs. Outward from the collision point, we have the silicon tracker, the electromagnetic calorimeter, the hadronic calorimeter, the solenoid magnet, and the muon trackers embedded in the “return iron” for the magnet (as you know, magnetic field lines must form closed loops. They cannot have a beginning or an end, until we discover the mythical magnetic monopole. The magnetic field lines that form the field inside the magnet must continue out one end, loop around, and come back to come in the other end. The “return yoke”, made of iron, guides these field lines so that they do not interfere with the detector electronics).

Let’s see how we can use the information from these detectors to identify particles.

9.2 Photons

In Figure 9.2, the photon is indicated by the dashed blue line. Photons are electrically neutral so they do not produce a signal in any of the trackers. Because they can interact with nuclei in the material via the long range electromagnetic interaction of pair production, they shower quickly

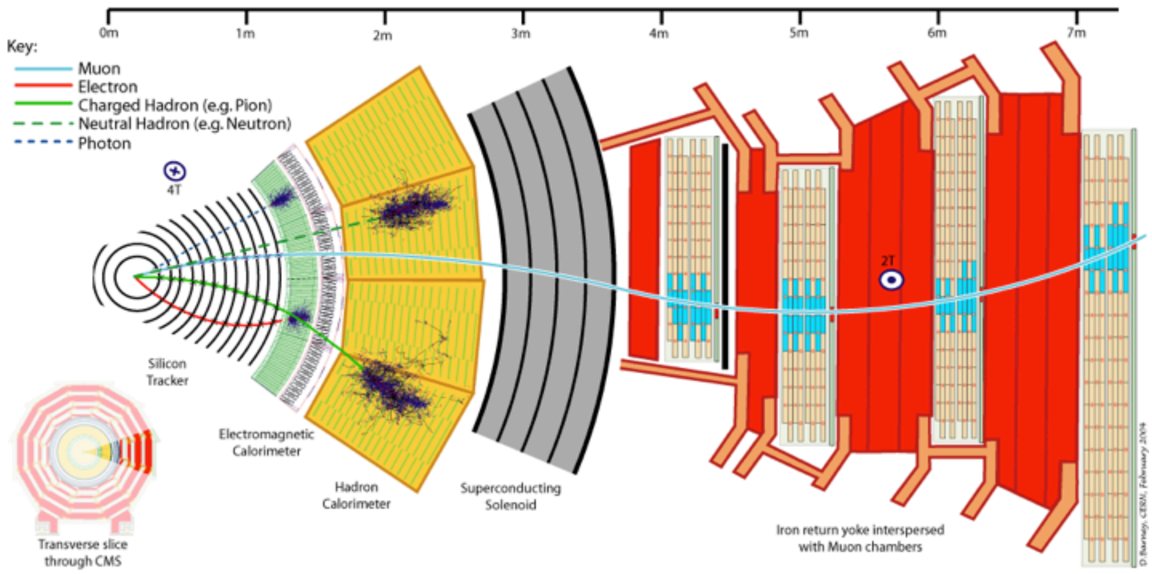


Figure 9.2: A slice of the CMS detector as viewed in the r-ϕ plane with typical signals produced by various types of particles.

upon impact, and the shower is almost completely contained in the EM calorimeter.

9.3 Electrons

In figure 9.2, the electron is indicated by the solid red line. Their signature is similar to that of a photon (although their initiating interaction is bremsstrahlung, not pair production), but there is an associated charged track.

9.4 Muons

In figure 9.2, the muon is indicated by the solid blue line. Muons are charged and so they produce a track in the inner tracker. Muons predominantly lose energy by exciting or ionizing the electrons in the material. Because of this, they lose energy slowly. They can pass through the calorimeters, losing only about a GeV of energy. They are the only charged particle that can do this. Tracking chambers (gas-based) outside the calorimeters, embedded in the return yoke, are used to indicate a penetrating particle.

9.5 Hadrons

In figure 9.2, a charged hadron is indicated by the solid green line and a neutral hadron is indicated by the dashed green line. Hadrons interact with nuclei via the short-range strong force (QCD) interaction. Therefore, their shower will typically start deeper into the calorimeter and it will take more material to completely convert the kinetic energy of the hadron into energy of the material. The shower needs the thicker combined electromagnetic and hadronic calorimeter to contain it. Charged and neutral hadrons are distinguished by the presence of a track in the tracker.

9.6 Event displays

While we wait for physics results, complex computer algorithms are used to find the particles. The human mind also has very powerful identification capabilities - physicists use event displays to look at the information and identify particles “by hand”. In the vast majority of the cases, when the human “scanner” and the computer algorithm disagree, the human is right. It is important to verify computer algorithms and search for bugs by comparing the results from “scanning” to the computer based results.

Typically two types of displays are used. One has a cartoon of the detector with symbols to denote energy deposits. The results from the computer identification algorithm are usually superimposed. An example is shown in figure 9.3. You can see the cartoon of the muon chambers in pink. The tracks reconstructed in the tracker are shown as green lines. Energies in the EM calorimeter are shown as red blobs and in the HAD calorimeter as blue blobs. Their shape reflects the segmentation of the electrical readouts of the detector information.

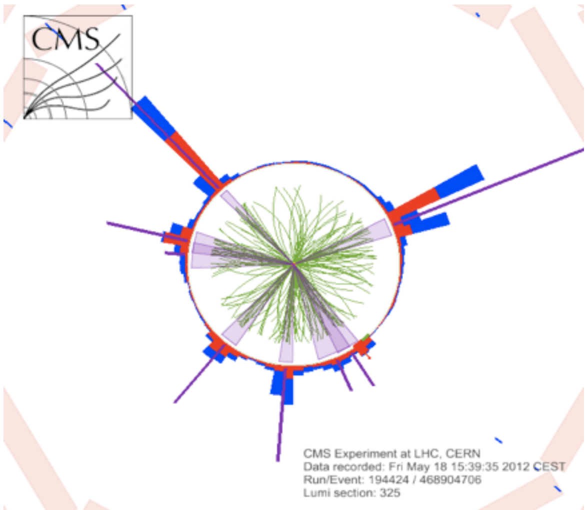


Figure 9.3: An event display from the CMS experiment

Another kind of event display is called a “Lego” plot (named after the Children’s toy), and it is the most common way of displaying calorimeter information. This kind of display is a 3-D plot with two of the axes being the polar angle and the pseudorapidity, and the “z” axes being the energy deposited in the calorimeter at that location. Colors indicate which part of the energy was deposited in the electromagnetic and which in the hadronic calorimeter. An example is shown in figure 9.4, along with the corresponding regular display.

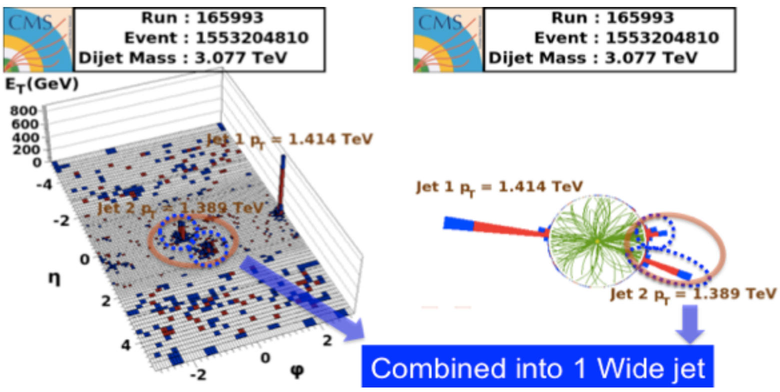


Figure 9.4: A lego display along wih the corresponding regular display of an event taken with the CMS detector.

9.7 Neutrinos

There is one particle that is so weakly interacting that does not produce a signal in our detector. However, we can infer its presence using conservation of momentum. The momentum of the beams is along the z-axis. This means that the total initial momentum can only be along the z direction, and the initial component of momentum transverse to the beam axis must be zero. By conservation of momentum, the final component of momentum transverse to the beam axis must also be zero. So, if we sum the transverse momenta of all observed particles, the sum of the momenta of all unobserved particles must be equal in magnitude but opposite in direct to this, so that the sum is zero. Usually this can be attributed to a single neutrino. Figure 9.5 shows the particles projected in the transverse plane. Since the observed momenta obviously cannot sum to zero, we infer that a neutrino was present in the event.

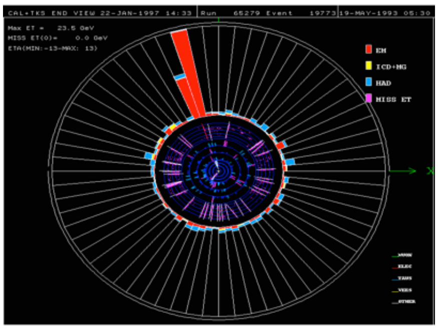


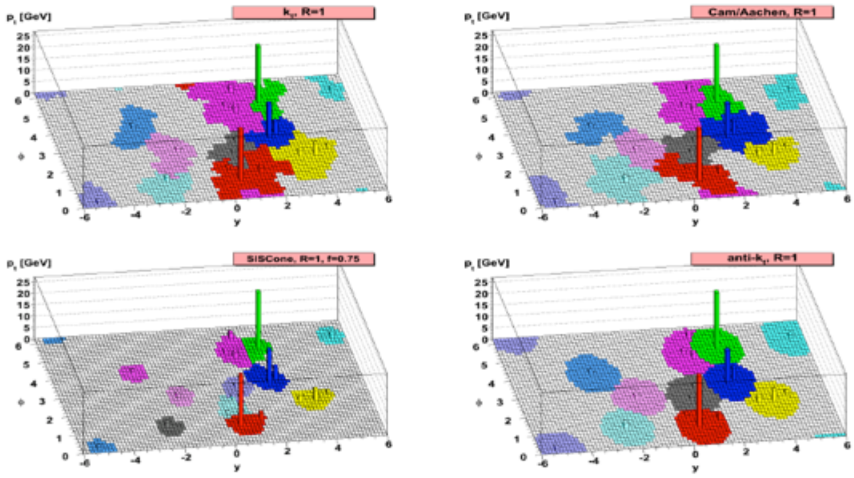
Figure 9.5: An event display from the D0 detector at the FNAL Tevatron. The red blob represents energy in the EM calorimeter. Since it has an associated track, it is identified as an electron. This is probably the decay of a W boson to an electron and a neutrino. The neutrino is assumed to have a transverse momenta that is equal in magnitude and opposite in direction to the sum of the momenta of all other particles in the event.

This was, in fact, how Fermi discovered the neutrino - by considering conservation of momentum in certain radioactive decays of nuclei (beta decays).

9.8 Quarks/Gluons (jets)

As you may have noticed from the event displays shown above and from the one shown below, hadrons tend to come in clusters called “jets”. These jets are the signatures of quarks and gluons, that “fragment” into a number of hadrons - typically 10 charged hadrons and 5 neutral, but with statistical fluctuations with the rms that occurs for any thing produced randomly that can counted ($\sqrt{N}$).

Generally, the individual momenta of the hadrons are not that interesting in our studies of forces and particles; what we really want to know is the momenta of the quarks and gluons that created them. To find this, we just have to figure out which hadrons came from the same “parent” particle and (by conservation of momentum), sum their momentum to get the parent momenta.
However, because gluons can be radiated off of quark or gluon jets, and the resulting jets are very close to each other (among other more fundamental but technical reasons), it is not trivial to figure out which hadrons belong together, which came from the same “parent”.
To do this,“jet finding algorithms” have been developed. Figure 9.8 shows how four different algorithms divided up the calorimeter energies into “jets”.
Let’s look at one of these algorithms (which is implemented in CMSSW and is the most popular), which you will easily be able to imagine as code (and which clearly can not be handled any other



way). This algorithm is called the anti-k_T algorithm (don't ask) with cone-parameter R. R is typically chosen to be 0.4.

- For all possible pairs of particles in an event (particle i and particle j), d_{ij} = min($p_{Ti}{}^{-2}$, $p_{Tj}{}^{-2}$)$\Delta\frac{R_{ij}^2}{R^2}$ where $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and $\Delta\phi$ is the difference in azimuthal angles between the two particles and $\Delta\eta$ is the difference in their pseudorapidities.
- For each particle, calculate d_{iB}=p_T^{-2}
- Take the minimum of all $d_{ij}s$ and $d_{iB}s$
- If the smallest is a d_{ij}, combine them into a single particle by adding their 4-momenta, add this particle to the list of particles and remove the two individual particles. Go back to the beginning.
- If it is a d_{iB}, call it a jet, remove the corresponding particle from the particle list, add it to the jet list, and go back to the beginning.
- Stop when there are no particles left in the particle list.

Exercise 9.1 Look at the event displays found at xxx. For each event display, tell us what kind of particles you see

Exercise 9.2 The root file found in https://github.com/saraheno/jetclusteringexercise has particle 4-momenta for particles reconstructed for a bunch of events. Write code to cluster these into jets. Use the anti-k_T cone algorithm with cone parameter 0.4. Make a histogram showing the p_T spectra of the jets.

9.9 Further Reading

· `http://www.sciencedirect.com/science/article/pii/S0168900211005419`

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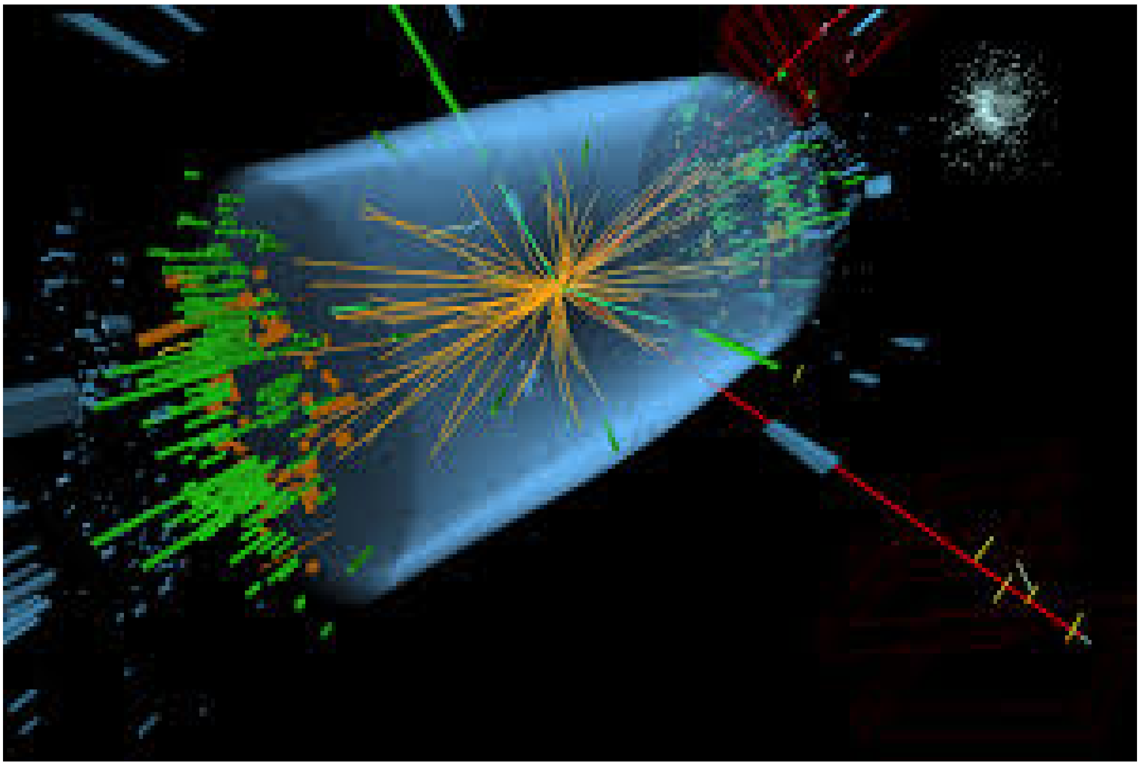

The LHC Detectors

10.1 The LHC Detectors

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

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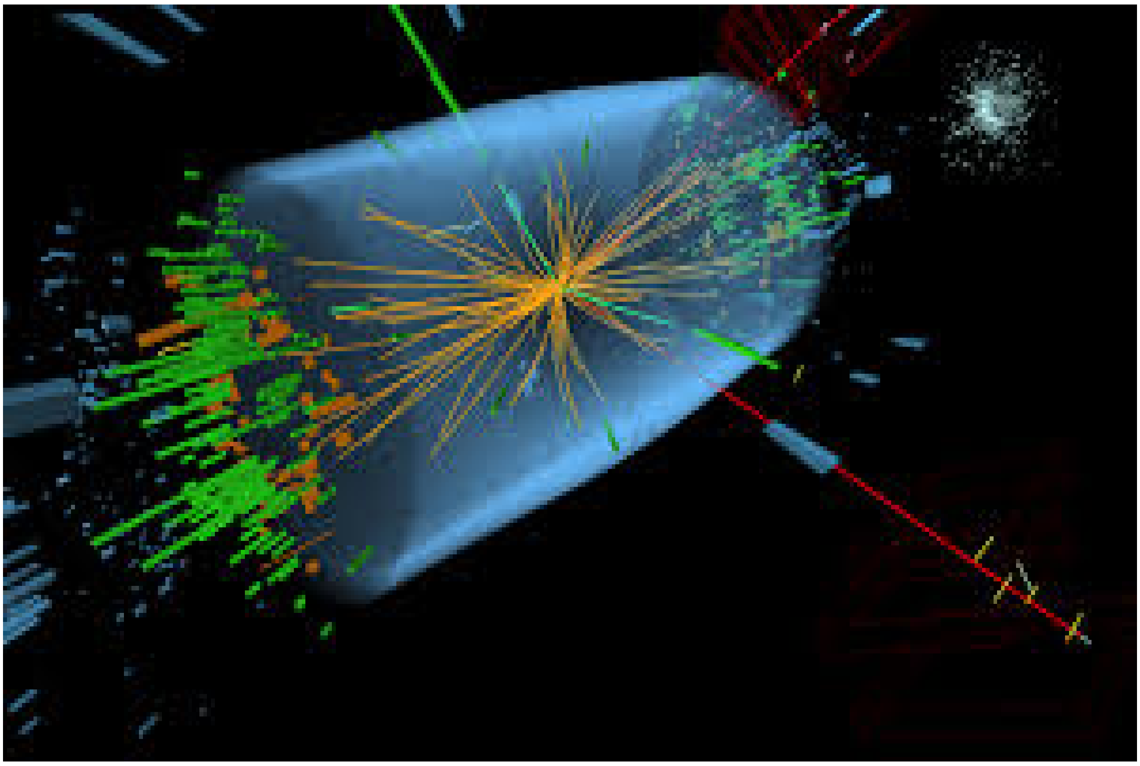

Structure of the proton and proton-proton collisions

11.1 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", often denoted σ and 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 Figure 11.1.

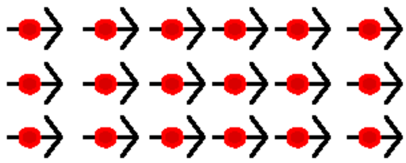

Figure 11.1: cartoon of a beam of particles

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

$$\Phi = n_a v \tag{11.1}$$

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

The number of scatters per second is then

$$\frac{dN}{dt} = \Phi\sigma \tag{11.2}$$

(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.

11.2 On cross sections

One of the things we need to be able to predict, for our collider, is how many "hard" scatterings will occur and how many of each type of particle will be made. As we saw in the previous section, this is related to a number called the cross sections. Using the equations of the Standard Model, we can calculate all kinds of cross sections. We can calculate the cross section for an up quark to annihilate with an anti-up quark with a center-of-mass energy of 125 GeV to produce a virtual Z, which then decays to an electron and a positron. We can calculate the cross section for a down quark to annihilate with an anti-down at a center-of-mass energy of 87 GeV and form a virtual Z which then decays to a electron and a positron. We can calculate the cross section for two gluons with a center-of-mass energy of 10 TeV to annihilate to a virtual gluon which then turns into a top quark and an anti-top quark.

Now, of course, you don't know enough physics and math to do these actual calculations. And of course you may be saying "but... I don't have a beam of up quarks, I have a beam of protons. So what good does it do if the standard model can calculate the cross sections for up quarks when what I need is the cross section for protons"?

In the following, we are going to try to sketch out for you some of what goes into the calculation for these things and how we related the calculations for the particles of the standard model (say, the quarks) to objects containing many standard model particles (like the proton).

11.3 s, t, u, and Q^2

Just how complicated are these cross sections that result from Standard Model calculations? Are they monsterous equations of many variables? Actually, if you think about it, you will realize that the resulting formula can not depend on any arbitrary quantity. In fact, it can be shown (although we won't show you this!) that there are only a few variables, that are functions of the kinematics (4-momenta) of the initial or final state particles, on which the resulting cross sections can depend.

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 particle's 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 unimaginably given the names s, t, u and Q^2. Since these invariants are mass-like things, they will often turn out to be the mass of the virtual particle (one that is not an initial or final state particle, but an intermediate particle that can not be observed) in the Feynmann diagram.

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 11.2).

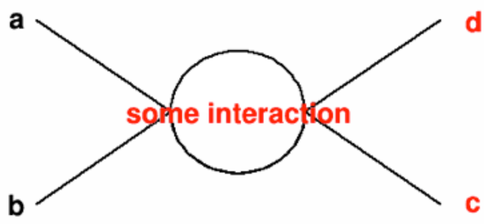

Figure 11.2: generic interaction of 2 particles going to 2 particles

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

$$s = (p_a + p_b)^2 \tag{11.3}$$

$$t = (p_a - p_c)^2 \tag{11.4}$$

$$u = (p_a - p_d)^2 \tag{11.5}$$

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 "off-shell" as long as it is unobservable (for times short compared to that set by the uncertainty principle, using M as E), meaning that it has a non-zero mass. You will learn more about this when you study quantum mechanics.

Here we are just going to state the result of the cross section calculation in the standard model. 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

$$\frac{d?}{d\Omega} = \frac{1}{64\pi^2 s}\frac{P_f}{P_i}|M|^2 \tag{11.6}$$

where p_f is the magnitude of the 3-momenta of either particle c or d (why doesn't it matter which?) and pi is that of either a or b and Ω is the differential solid angle (so this is the rate as a function of the scattering angle for the final particle realtive to the initial particle). 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.

11.4 What is in a Proton?

Okay, fine: we have just written down for you the differential cross section (relative to the final particle scattering angle) for particles in the standard model? Now we will rough out how to go from that to the scattering for a proton with another proton. But first, before we do that, we need to know 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. And all these particles inside the proton have different momenta (but all very high, so that they are all going at the speed of light). And what is worse, if you look at one time and then look again at another time, which types of particles and their momenta will change! Sometimes most of the momenta will be held by one up quark. Sometimes there will be 100 gluons with about a hundreth of the proton's momenta! It is a seething mass of paritlces!

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). Figure 11.3 shows results from measurements. Note that the y axis is the average number of partons you will find at that momenta and type. Of course, since this is a random, probabilistic thing, there will be fluctuations around this, governed by Poisson statistics.

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 experiments", which collide a beam of particles with some kind of target, perhaps copper or something else that won't melt in a high radiation environment, and from the "HERA" collider in Hamburg Germany, which collides electrons with protons.

Imagine 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

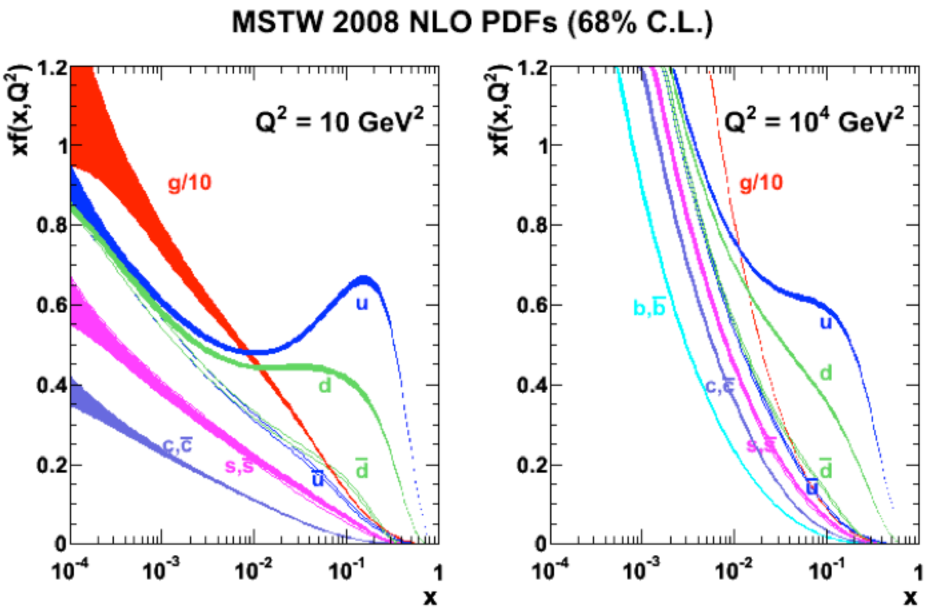

Figure 11.3: mean number of partons that has a fraction x of the proton momentum times x for different parton flavors

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.

11.5 Calculation of a cross section in proton proton collisions

Okay, now you have some idea what is in a proton. How do we take the cross sections from the standard model and the PDFs and turn into into a cross section for proton-proton scattering. Well, we have to imagine all the different partons that can make the final state we are interested in and sum over them. In fact, we have to imagine all the momenta (x) for all the partons that can make the final state we are interested in and sum over that. Since the possible momenta are continuaus, this becomes an integral, while the the other is over a finite number of possibilities, so it is a sum.

$$\sigma = \Sigma \int dx_a dx_b \sigma_{ab}[q(x_a)q(\bar{x}_b) + q(x_b)q(\bar{x}_a)] \tag{11.7}$$

where the q's represent the PDFs for the quarks.

11.6 What happens when two protons collide?

First remember that quantum mechanics applies. We can calculate the probability of certain kinds of interactions, but we cannot predict event by event which one will occur. The pie chart shown in Figure 11.4 the fraction of collisions that result in different types of interactions.

Another way to look at this is using the cross sections, shown in Figures 11.5 and 11.6.

What are these things?

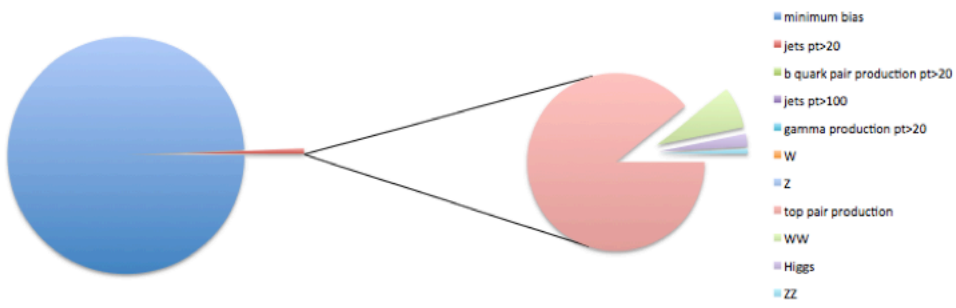

Figure 11.4: Pie chart showing relative probabilities of different types of interactions in proton-proton collisions

11.7 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 Figure 11.7. The π^+, pi^-, and pi^0 are produced in roughly equal numbers and at 14 TeV center of mass energy, about 100 pions are expected in every minimum bias interaction. The total transverse energy deposited by each such interaction is about 50 GeV. These interactions are not very interesting to us. Unfortunately, as you can see from Figure 11.4, majority of events are a result of his sort of interaction. The total cross-section for such interactions is hundreds of billions times larger than the interactions we are interested in, that is, interactions in which massive particles are produced. Given the limitations on how many interactions we can read and store, we need to select the ones we are interested in. This process of selection is called *Trigger*.

11.8 Jets

The strong force is strong. Therefore one of the most common things to make in proton-proton collisions are quarks and gluons. As we know, these particles appear as jets of hadrons in our detector. Some Feynman diagrams for this process are shown in Figure 11.8. Typical event displays for this kind of event is shown in Figures 11.9 and 11.10. As we know, these particles appear as jets of hadrons in our detector. Jets can be divided into *light* jets and *heavy-quark* jets. The light jets are initiated by light quarks or gluons, whereas heavy jets are initiated by heavy quarks, for example the botton quark. As we know a single quark cant exist, shortly after creation the bottom quarks turn into B hadrons. One of the most important property of b hadrons is that they have a long life time (well, relatively long). Mean life time of B hadrons is of about 10^{-12} seconds, compared to π^0 meson lifetime of about 10^{-17} seconds. Because of this long life time, bottom quarks can travel few hundred microns or roughly a fraction of a millimeter before they decay. This distance seems small but can be measured with great precision by the LHC detectors. After traveling this small distance when a B hadron decays it creates what is called a *secondary vertex*. A jet with a *secondary vertex* is most probably a bottom quark jet. This provides us an excellent tool to distinguish between light and heavy quarks and to identify events where a bottom quark was produced. This process of identification of bottom quark jets is called b-tagging. Figure 11.10 shows cartoon of secondary vertex in an event.

Any particle produced in the collisions loses some of its energy passing through the detector. Thus all partciles, electrons, photons, muons, etc need energy corrections. In the case of jets, be-

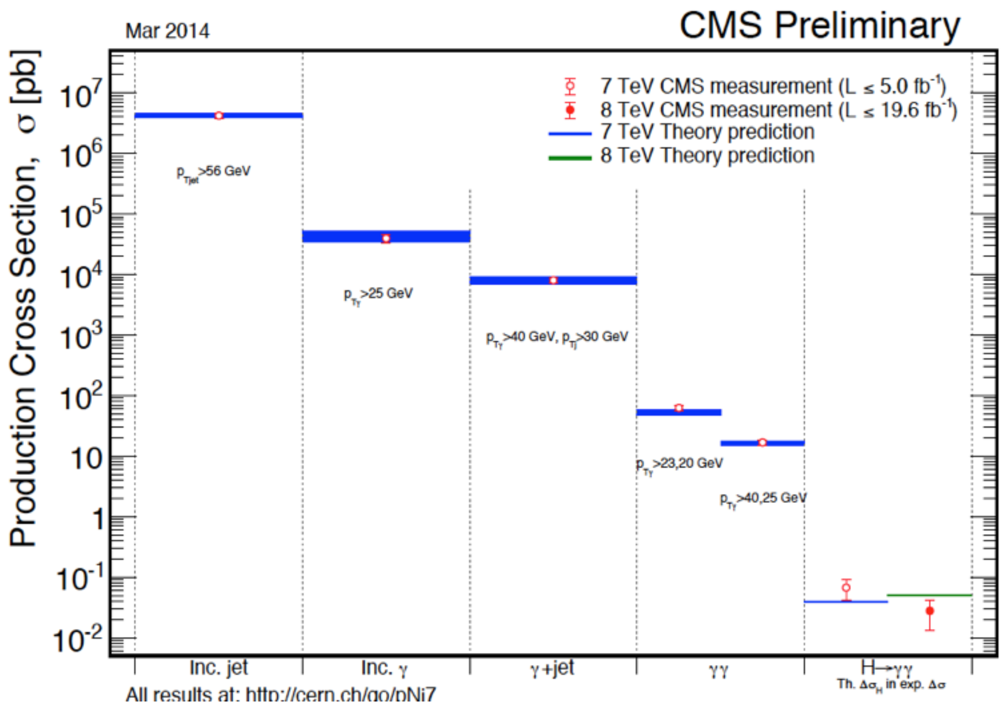

Figure 11.5: Cross sections for production of various combinations of particles at the LHC for a center of mass energy Q@ of 8 TeV

ing a messy object containing a large number of particles, measuring these energy corrections are quite challenging. What we actually want to measure is the energy of the quark, before hadronization and formation of jets of particles. Both real and simulated events are used to measure the corrections to the jet energies.

11.9 W and Z production

You can also make the carriers of the weak force, the W and Z bosons. Some Feynman diagrams are shown in Figure 11.12. An event display is shown in Figure 11.13. Since these partciles and their properties like mass and decay width are predicted by the standard model, measurements involving W and Z bosons are used to test precision of standard model, as well as to calibrate the detector.

11.10 top production

You could also make the heaviest of the quarks, the top quark. The top quarks are much heavier than bottom quark and have a very short life time (10^{-23} seconds) and decays before it can even hadronize. The top quarks are the only known quarks that can directly decay to other particles, there by transferring many of their properties, e.g spin, to their decay products. Thus top quarks provide opportunity to study a quark directly, which is not the case for other quarks. Production of top quark is a very rare event in high energy collisions and there are many models of new physics that predict production of top quarks. Most of the time a top quark decays in to a W boson and a bottom quark. Presence of b-quark jet in the event is thus a very good indicator that event might include top quark production. Most commonly, it is made with an anti-top. The Feynman diagram is shown in Figure 11.14, along with a pie chart showing the probabilities that the two tops in

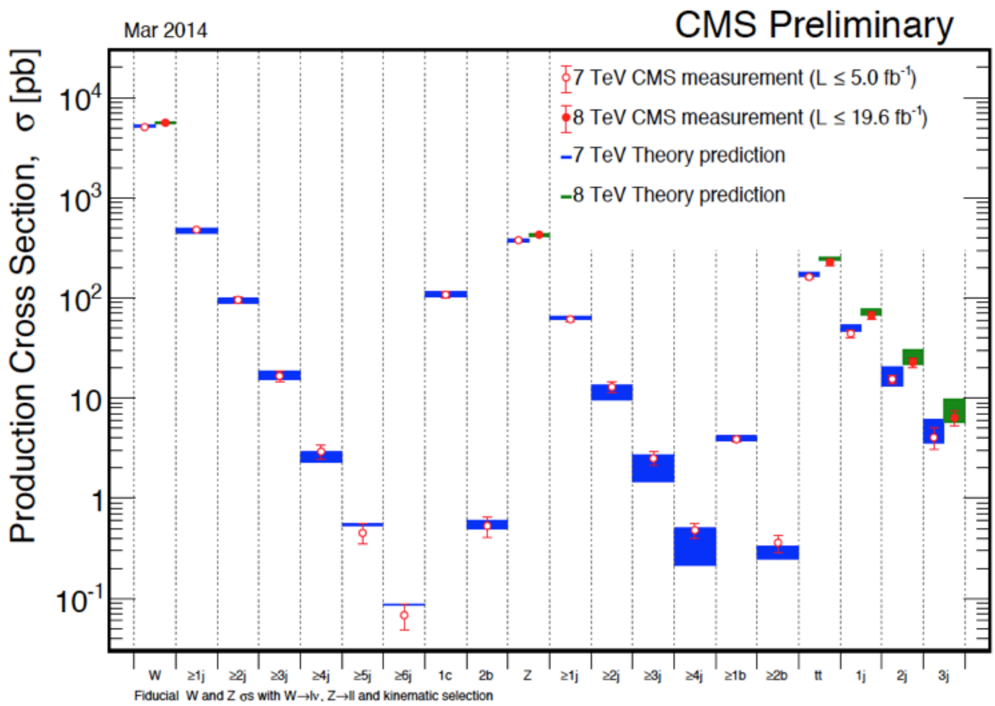

Figure 11.6: Cross sections for production of various combinations of particles at the LHC for a center of mass energy Q^2 of 8 TeV.

the events will decay to different final states containing particles stable on detector timescales. A display of an event that could be top pair production is shown in Figure 11.15.

11.11 Underlying Event

In hard interactions not all the partcons partcipate in the production of high mass particles. The remaining quarks and gluons can hadronize just like minimum bias interactions and form what is known as *underlying event*.

11.12 Further Reading

- http://xxx.lanl.gov/abs/hep-ph/9606399
- http://iopscience.iop.org/0034-4885/70/1/R02/
- Modern Particle Physics by Mark Thomson
- Introduction to Elementary Particle Physics by Alessandro Bettini

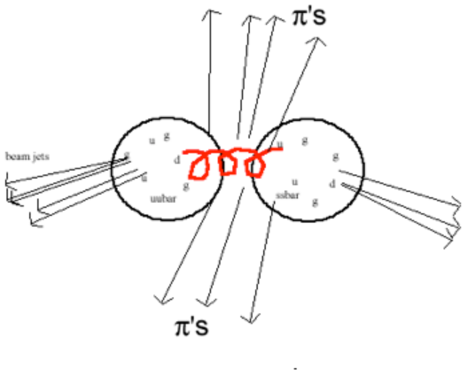

Figure 11.7: carton of a minimum bias interaction

Figure 11.8: Feynman diagrams for productions of jets.

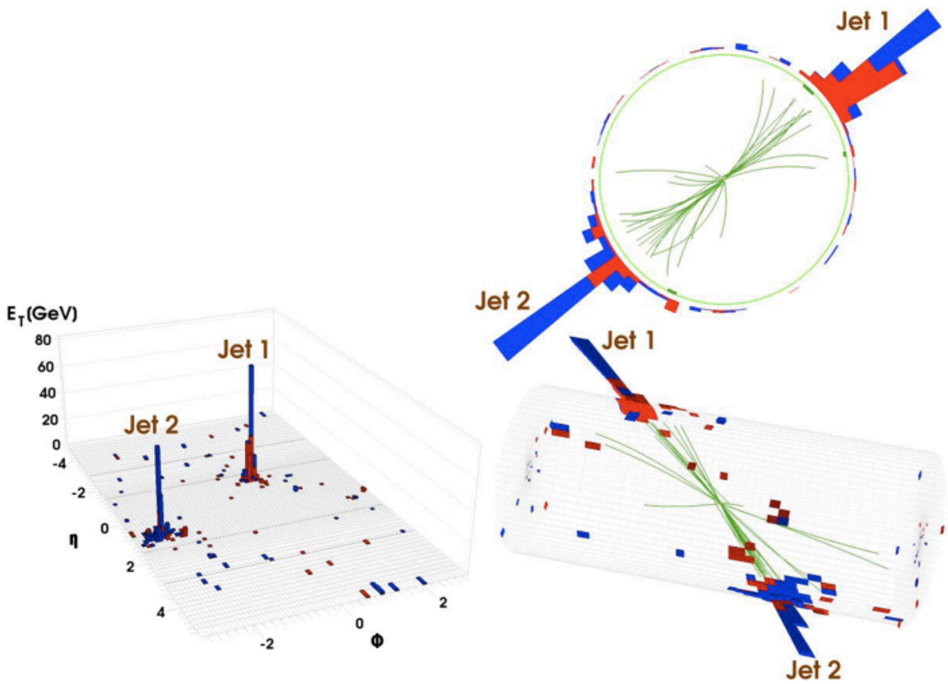

Figure 11.9: event display for jet production

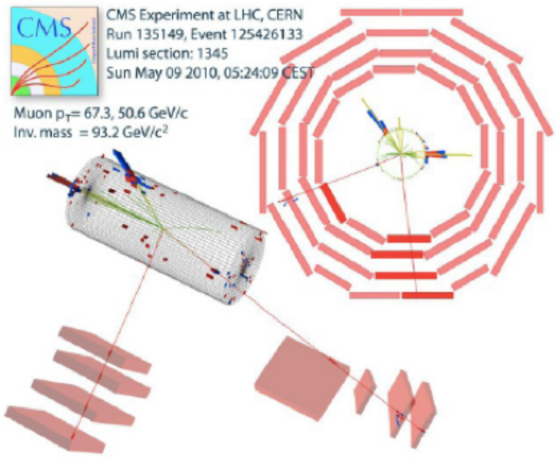

Figure 11.10: event display for jet production

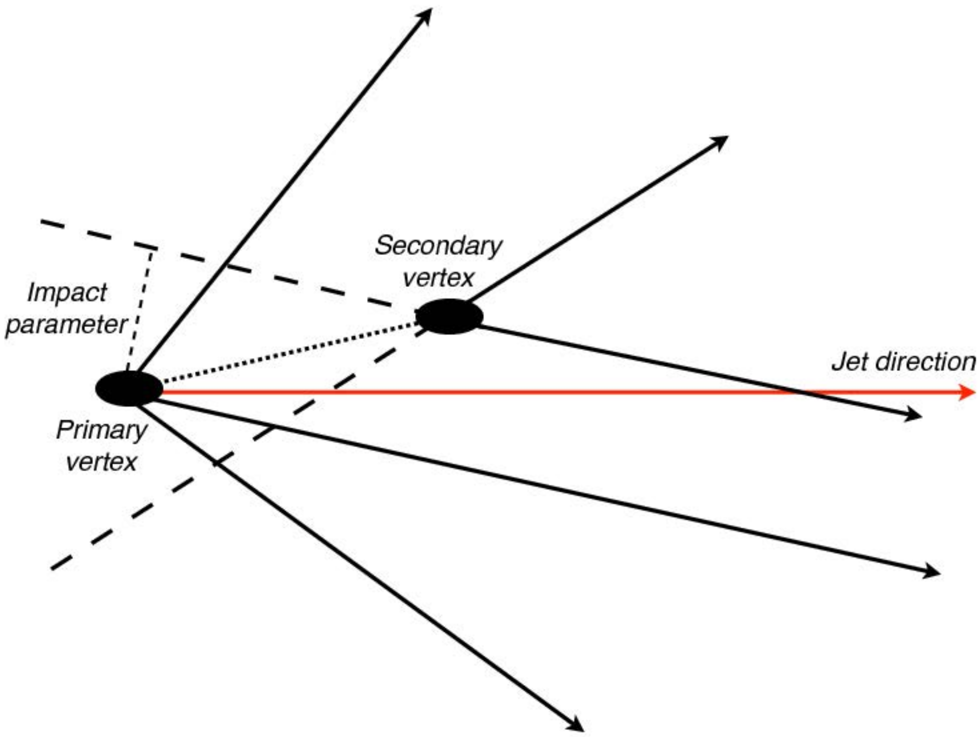

Figure 11.11: Secondary vertex indicating a b quark jet.

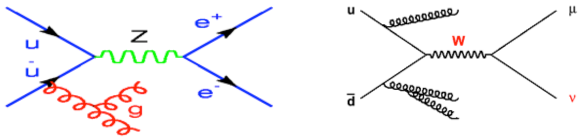

Figure 11.12: Feynman diagrams for productions of W or Z bosons.

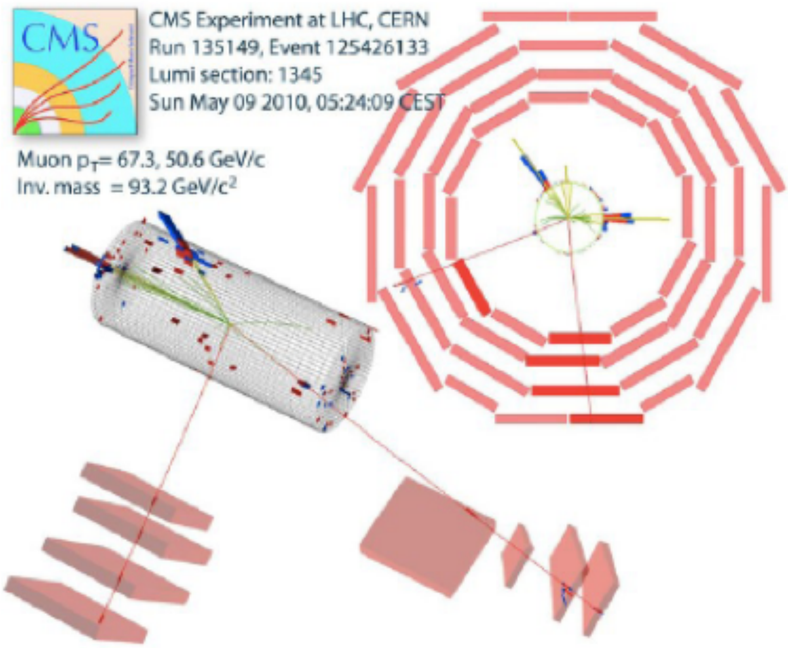

Figure 11.13: Event display for a Z boson

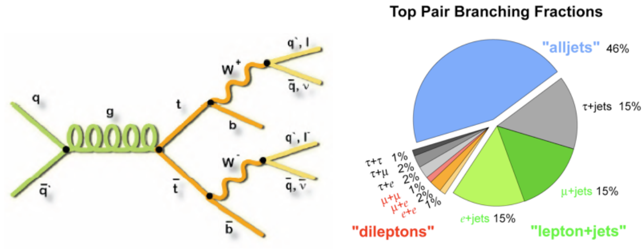

Figure 11.14: Feynman Diagram for top production and branching fraction for top to different final states

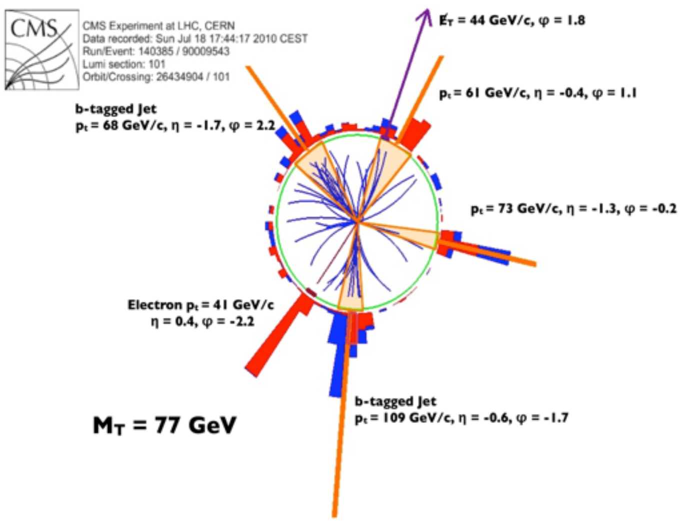

Figure 11.15: Event Display for top pair production

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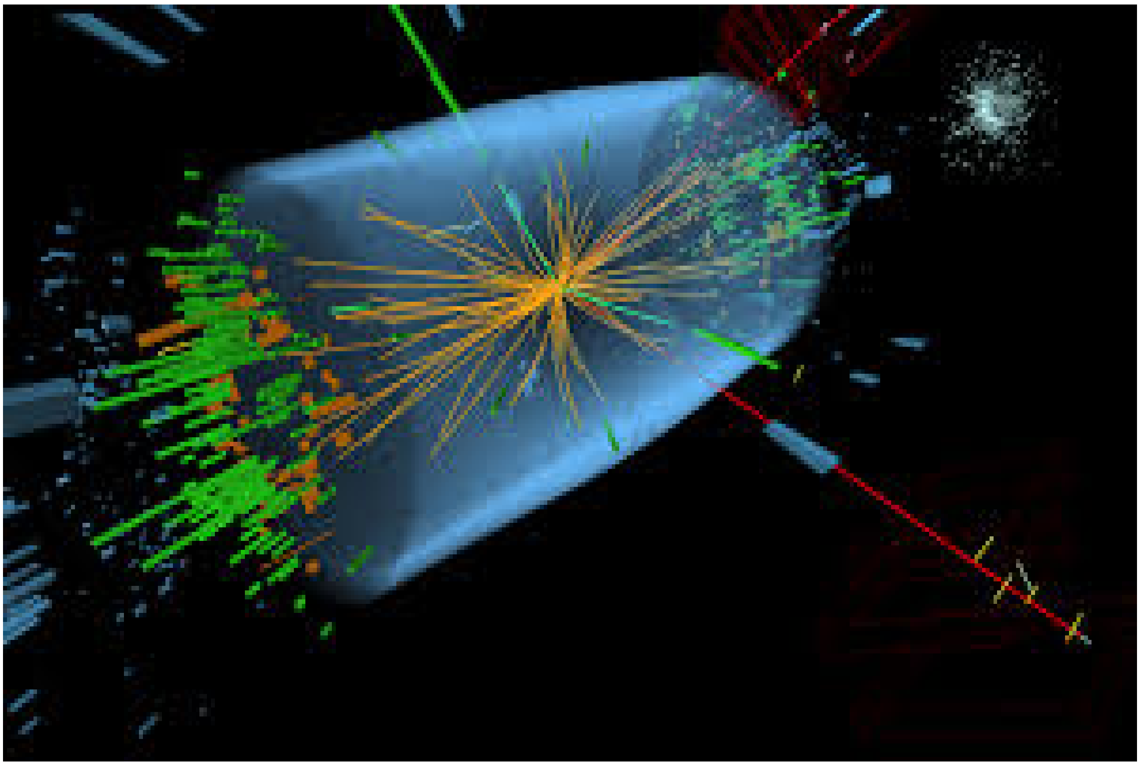

Monte Carlos

12.1 Disclaimer

this is not ported yet

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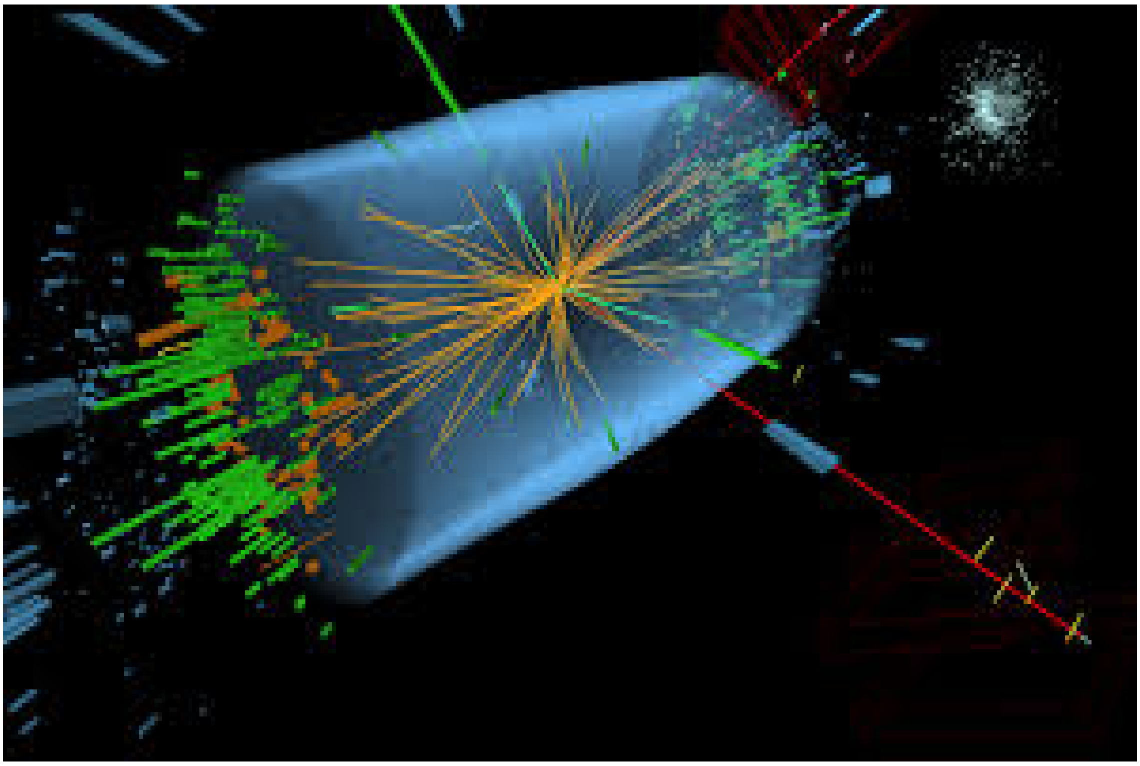

Higgs Discovery

13.1 higgs to four leptons

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