3C24 : Lecture Notes Particle and Nuclear Physics

J. Thomas & M. Lancaster

25th February 2000

Contents

13 LECTURE 13 **3**

13.1 Accelerators 3

13.2 Linear vs Circular Accelerators 5

13.3 Synchrotrons 7

14 LECTURE 14 **8**

14.1 Colliding Beams 8

14.2 Synchrotron Radiation 8

14.3 Advancing the Technology 9

15 LECTURE 15 **10**

15.1 Detectors 10

15.2 The interaction of charged particles with matter 10

15.3 The Bethe-Bloch Formula 11

15.4 Coulomb Scattering 11

15.5 Bremsstrahlung : braking radiation 12

15.6 The interaction of photons with matter 13

16 LECTURE 16 **15**

16.1 Tracking Detectors 15

16.2 Wire Chambers 15

16.3 Multi-Wire Proportional Chambers 17

17 LECTURE 17 **19**

17.1 Calorimeters 19

17.2 Hadron Calorimeters 19

17.3 Scintillator 20

17.4 Electromagnetic (EM) Calorimeters 21

18 LECTURE 18 **23**

18.1 Cerenkov Counters 23

19 LECTURE 19 **26**

19.1 A Generic High Energy Physics Experiment 26

Part 2. Particle Technology : Accelerators & Detectors

13 LECTURE 13

13.1 Accelerators

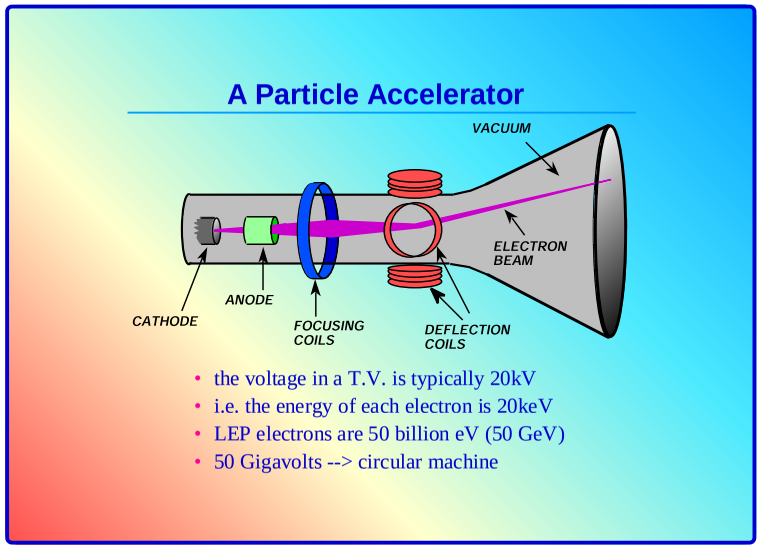


Figure 1: Schematic of a particle accelerator

The machines used for creating fundamental particles are called **Accelerators**. A schematic of a particle accelerator is shown in Figure 1. It is true that the first accelerators were used purely for research reasons, but today, accelerators are used predominantly in industry, particularly medicine. There are over 10,000 accelerators in the world with applications in : cancer therapy, welding, medical imaging, micro chip production and trace element detection. So, even if you are not thinking about a career in particle physics, the study of accelerators might be relevant for your future!

In order for particles to be accelerated they must be

- Stable
- Charged

Voltage Across an R.F. Cavity

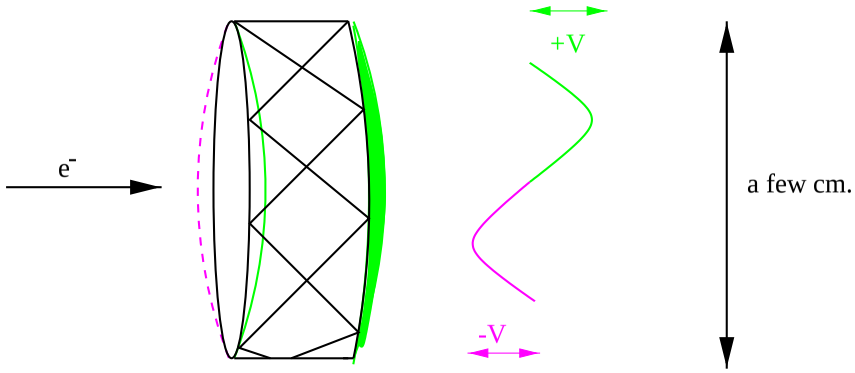


Figure 2: Schematic of an R.F. cavity

This basically means electrons and protons. Pions and Kaons can be accelerated but because their lifetimes are rather short, it limits the purity (because they decay along the way) and the intensity of these beams.

Electron beams are probably the most easy to make and the only *fundamental* particles that can be accelerated. You all know about cathode ray tubes which basically boil off electrons from a cathode and accelerate them. The force used to accelerate particles (i.e. increase their energy) is the electromagnetic force. This means that the particles must be charged in order to be accelerated (i.e. must feel the electromagnetic force). In the simple case of a cathode ray tube, an electric field accelerates electrons to an energy of about 20KeV. If a typical TV tube is about 20cm long, then the fields inside are about 1KV/cm. In order for a singly charged particle to gain 1eV of energy, it must be taken through 1V of potential.

The largest electron linac is 3km long at SLAC (Stanford Linear Accelerator Center) and accelerates electrons and positrons up to 45GeV. They collide to produce Z^0 Gauge Bosons. The electric field in this case (150 KV/cm) is around 100 times larger than found in the typical TV set. Such fields are impossible to reach with an ordinary DC electric field like that used in a cathode ray tube. **RF Cavities** are used instead. Like a pea on a drum, the RF frequency wave pushes electrons forward at precisely the correct moment as shown schematically in Figure 2. The RF cavities are a few tens of centimeters across and their function is to house a standing wave which changes sign after the electron bunch has passed through, ready to accelerate the next bunch. So, the size of the cavity is intimately related to the frequency of the RF in order for there to be just one (or an integer number of) node(s) across the cavity.

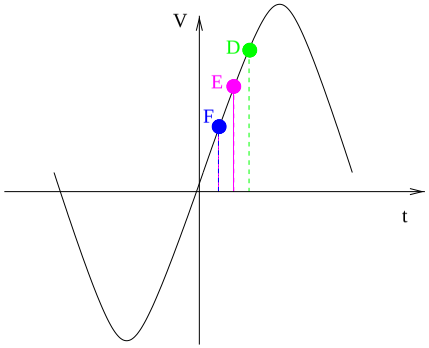


Figure 3: Schematic of an R.F. cavity

For example,

$$\lambda = \frac{c}{f} \quad (1)$$

$$= \frac{310^8}{310^8} \quad (2)$$

$$= 1m \quad (3)$$

so the size of cavity in this case would be 50cm to set up a wave with a single node.

The particles travel in a vacuum pipe called the **beam pipe**. It is typically about 10cm in diameter and needs to have an extremely high vacuum in order to keep the scattering of the accelerated particles by air molecules to a minimum.

Figure 3 shows a schematic of the time dependence of the voltage in an RF cavity. If the particles are produced uniformly in time, the particles which arrive while the electric field is positive will be accelerated and those arriving while the electric field is negative will be decelerated so the particles will end up in little **bunches** whose size is determined by the characteristics of the RF.

The RF power used is related to the amplitude of the field inside the cavity by:

$$P \propto |E_z|^2 \quad (4)$$

13.2 Linear vs Circular Accelerators

Typical RF cavities provide a few MeV of energy to the charged particle, thus a linear accelerator requires many RF cavities to achieve a high energy. The alternative to this is to use a circular accelerator called a **synchrotron**, where the particles are repeatedly passed through the same RF cavities as they pass around the ring. Typically, particles go around the ring about 10^5 times before attaining their full energy. In order to accelerate particles in a circular accelerator, they need to be *steered* around the ring and this is

done by a series of magnets around the ring. A schematic of a bending magnet is shown in Figure 4 with the field felt by particles passing through it shown.

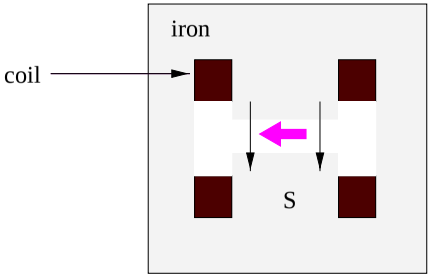


Figure 4: Bending dipole

As the energy of the particles increases (due to the RF cavities), the magnetic field in the bending magnets must be increased in *synchronisation* to keep the **radius of curvature** constant. The radius is given by:

$$R = \frac{|p|}{0.3B} \quad (5)$$

In the linear accelerator, the final beam energy depends on the voltage per cavity and the total length, while in the synchrotron, it is determined by the ring radius and the maximum value of B possible in the magnets. The magnets act just like lenses when bending and focusing light. Dipole magnets are used for bending and quadrupole magnets are used for focusing. Figure 5 shows a schematic of a focusing magnet with the field shown.

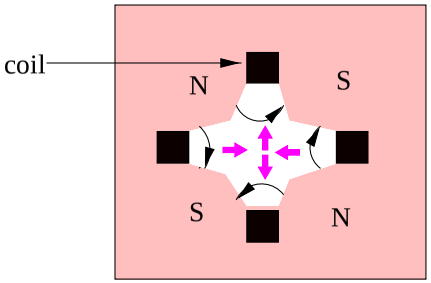


Figure 5: Focusing quadrupole

Quadrupoles focus the particles in one direction and defocus them in the orthogonal direction. Alternate quadrupoles have poles reversed and so a system is set up which has a direct analogy with optics. A succession of diverging and converging lenses of equal strength will give a net focusing effect in both directions. Focusing is a characteristic of both linear and circular accelerators. The beam usually fills the cross sectional area of

the beam pipe during acceleration, but when the particles have attained their required energy, they will be focussed before they are **extracted** from the accelerator into the experimental region.

13.3 Synchrotrons

The particles circulating in a synchrotron do not travel in ideal circular orbits but "wander" in and out of the ideal circular bath in both horizontal and vertical planes. These wanderings are called **betatron oscillations** and they arise from the divergence of the original beam and from small differences in the magnetic bending from ideal and so on.

There are also longitudinal oscillations which are called **synchrotron oscillations** which occur when particles get out of step with the synchronous phase. The synchronous phase is when the increase in momentum per turn from the RF cavities exactly matches the increase in the magnetic fields in the bending magnets. Looking again at Figure 3, the particle arriving in the cavity at point F will receive a smaller acceleration than the ideal particle (E) and so will be bent into a smaller orbit by the bending magnets. Because it is in a smaller orbit it will arrive earlier the next time around. A particle arriving at point D will receive a larger acceleration from the RF field and will therefore be bent less than the ideal amount by the bending magnets. This particle will arrive later next time around because the distance it has travelled is slightly longer than the ideal particle.

14 LECTURE 14

14.1 Colliding Beams

High energy physics experiments are performed using these high energy beams by making them collide either with a fixed **target** or by having two beams and making them collide with each other. The former system is called a fixed target machine, the latter is called a colliding-beam machine. The colliding-beam machine has the advantage over the fixed target machine because the center of mass energy available for making new particles is larger for a given beam energy. We proved this in section 5.4.

There is a very special use of the colliding-beam machine which makes the technology of accelerating two beams of particles relatively simple. When the two beams of particles are electron and positron, or proton and anti-proton, a synchrotron consisting of a set of magnets and RF cavities adjusted to accelerate the particle in one direction will simultaneously accelerate the anti-particle around the same ring in the opposite direction. This means only one vacuum pipe and one set of magnets. The particles pass through each other as they go around the ring: the beam pipe has a cross-sectional area of $0.1\text{x}0.1\text{m}^2 = 0.01m^2$ and the size of a proton is about $10^{-15}x10^{-15}m^2$ so you can calculate the probability that two protons will actually collide during their long journey around the ring. I calculate it to be about 1 chance in a million if you take 10^{13} protons in a bunch which is really the highest beam intensity ever attained. When the particles are extracted therefore, they must be very strongly focussed in order to make them interact! This is done by the series of quadrupole magnets mentioned above.

The performance of the machine is measured by the **Luminosity**, $\mathcal{L}$ which is given by

$$\mathcal{L} = f\frac{N_1 N_2}{A} \tag{6}$$

where N_1, N_2 are the numbers of particles in the colliding bunches and A is the cross sectional area of the beam.f is the revolution frequency i.e. 1/T, where T is the time taken for the particle to go around the ring. The interaction rate i.e. number of events per second is given by

$$R = \sigma\mathcal{L} \tag{7}$$

where σ is the cross section for the particular process.

14.2 Synchrotron Radiation

Electron-positron synchrotrons have an important limitation which is absent in a proton machine. Under the circular acceleration, an electron emits **synchrotron radiation**, where the energy emitted per particle per turn is

$$\Delta E = \frac{4\pi}{3}\frac{e^2\beta^2\gamma^4}{R} \tag{8}$$

where R is the radius of curvature of the machine, β is the particle velocity ($\frac{v}{c}$ with c=1) and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$. (Remember to change the units from m^{-1} to GeV) So, considering

protons and electrons of the same momentum, the energy loss is proportional to the ratio $(\frac{m_e}{m_p})^4$ so it is 10^{13} times smaller for protons than electrons. Thus the radius of curvature must be kept as low as possible for e^+e^-machines which results in long circumference machines. A linear accelerator does not suffer from this problem.

14.3 Advancing the Technology

Although all the principles of operation remain the same, the modern day accelerators which attain the highest energies use super-conductivity to improve the performance. This allows one to achieve a lower power dissipation in the RF cavities and higher magnetic fields in the bending dipole magnets for the same power dissipation. There are four very high energy accelerators operating in the world today. The highest energy is being achieved at the Tevatron at FNAL where energies of 1 TeV are reached by accelerating and colliding protons on anti-protons. The top quark was discovered here in these collisions. Top quarks are produced in pairs by quark anti-quark annihilation through an intermediate gluon. The incoming quarks and anti-quarks must have at least 175 GeV of energy each for top quark pairs to be produced. Although the quarks and anti-quarks only carry $\sim 1/6$ of the protons momentum, the high proton beam energy means that occasionally (1 in 10^{11} collisions !) there ois enough energy in the quark anti-quark centre of mass system to create top quarks. This is not possible at an e^+e^- machine where the electrons would need at least 175 GeV of energy. The maximum energy that electrons can presently be accelerated to is $\sim$ 100 GeV, which is happening at the LEP (Large Electron Positron) collider at CERN. 100 GeV is the maximum energy it is possible to achieve with such a circumference. At 100 GeV one looses $\sim$ 2 GeV per turn due to the synchrotron radiation, so an incredible amount of costly RF power must be supplied just to keep the electrons at a constant energy. Beyond 100 GeV the cost of this power is prohibitive (synchrotron losses vary as E^4). In future electrons will be accelerated to energies $>$ 100 GeV using linear accelerators some 20km in length using RF cavities with very high electric fields.

15 LECTURE 15

15.1 Detectors

There are three functionally different categories of detectors. The **tracking detectors** measure the position of a particle. The **calorimeters** measure the energy of a particle. The **Cerenkov detectors** measure the velocity of a particle. All detectors rely ultimately on the electromagnetic interaction in order to make a measurement. This reduces the problem to looking at the interactions of

- Charged Particles
- Photons

In the case of detectors which profess to measure some other interaction, such as the strong interaction of hadrons or the weak interaction of neutrinos, what actually happens is that the primary interaction (strong, weak) produces charged particles and photons which are subsequently detected by their EM interactions with the detector material.

The properties of a particle that we are usually interested in measuring are

- Energy, E
- Momentum, **p**
- Charge,Q
- Velocity, v

and all of these quantities can be measured by some combination of measurements by the three aforementioned types of detector. In addition, the mass can be indirectly measured by a combination of the momentum from the tracker in combination with the magnetic field and the velocity measured in the Cerenkov Detector.

15.2 The interaction of charged particles with matter

The one thing that these detectors have in common is that they depend on the interaction of the particle with matter: the matter of the detector. There are two processes by which particles lose energy: ionisation and Bremsstrahlung. The Feynman diagram for ionisation energy loss is shown in Figure 6(left). The interaction of a charged particle via the process of ionisation or excitation of the constituent atoms in the medium it is traversing and its subsequent energy loss as a function of distance travelled in the medium is described by the Bethe-Bloch formula and depends solely on the charge of the particle in a given medium. This means that the fundamental interaction responsible for charged particle energy loss is the Electromagnetic interaction. Ionisation is the dominant mechanism of energy loss for all charged particles except electrons. Electrons (except at very low energy $<$ few MeV) loose their energy by the bremsstrahlung process. Only at very high energies for particles other than electrons does the bremsstrahlung process become important.

15.3 The Bethe-Bloch Formula

$$\frac{dE}{dx} = \frac{4\pi N_0 z^2 e^4}{mv^2}\frac{Z}{A}\left[ln\left(\frac{2mv^2}{I(1-\beta^2)}\right) - \beta^2\right] \quad (9)$$

where m is the electron mass, z and v are the charge (in units of e) and velocity of the particle, $\beta = v/c$, N_0 is Avogadro's number, Z and A are the atomic number and mass number of the atoms of the medium and x is the path length in the medium measured in gcm^{-2} or kgm^{-2}. I is an effective ionisation potential, averaged over all electrons, with approximate magnitude $I = 10Z$eV. This equation shows that $\frac{dE}{dx}$ is independent of the mass M of the particle, it varies as $1/v^2$ at non-relativistic velocities and after passing through a minimum for $E \approx 3Mc^2$, increases logarithmically with $\gamma = E/Mc^2 = \frac{1}{\sqrt{1-\beta^2}}$. The dependence of $\frac{dE}{dx}$ on the medium is very weak because $Z/A \approx 0.5$ in all but hydrogen and the heaviest elements. Numerically, $(dE/dx)_{min} \approx 1 - 1.5$ MeV cm^2 g^{-1}. Figure 6(right) shows the energy lost to ionisation of a argon-methane gas mixture as a function of $p/Mc = \sqrt{(}\gamma^2 - 1)$. The relativistic rise is associated with the fact that the transverse electric field of the particle is proportional to γ so that more and more distant collisions become important as the energy increases.

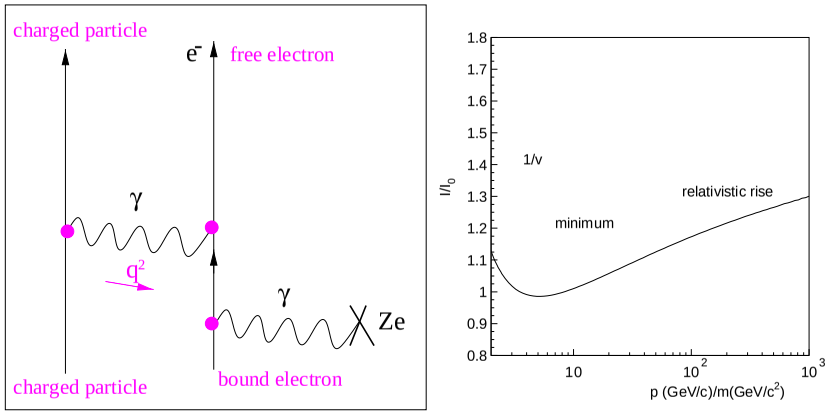


Figure 6: Left:Feynman Diagram for Ionisation energy loss for a charged particle. Right: Shape of the Bethe-Bloch energy loss function

15.4 Coulomb Scattering

Although not much energy is lost to the scattering off the nuclei in the ionisation loss formula ($\frac{dE}{dx} \propto \frac{1}{m_{nucleus}}$) because of the large mass of the nucleus, transverse *scattering* accompanied by very little energy loss does indeed take place. It is described by the

Rutherford formula for the cross-section as a function of angle θ:

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{1}{4}\left(\frac{Zze^2}{pv}\right)^2 \frac{1}{sin^4(\theta/2)} \quad (10)$$

where the small letters refer to the incident particle and Z is the charge on the nucleus, assumed to act like a point charge. For small scattering angles, the cross section is large, so that in any given layer of material, the net scattering is a result of a large number of small deviations which are independent of one another. The resultant distribution of **multiple scattering** is almost a Gaussian. Ultimately the amount of multiple scattering will limit the precision with which a particles position cane be determined e.g by a tracking detector.

15.5 Bremsstrahlung : braking radiation

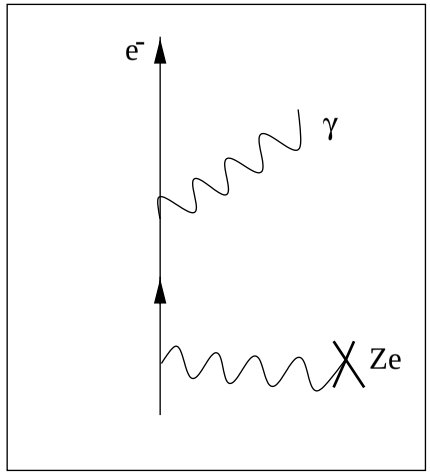


Figure 7: Feynman Diagram for Bremsstrahlung Radiation

Bremsstrahlung radiation really only affects electrons because they have such a small mass. Very high energy muons (few hundred GeV) also lose energy this way. The Bremsstrahlung Feynman diagram is shown in Figure 7 which shows the electron slowing down in the field of a positively charged nucleus by the attractive EM force between oppositely charged particles. Integrated over the photon spectrum, the total radiation loss of an electron in traversing a thickness dx of medium is

$$(\frac{dE}{dx})_{rad} = -\frac{E}{X_0} \quad (11)$$

where X_0 is intrinsic to the medium and is referred to as the **radiation length**. Therefore, it follows that the average energy of a beam of electrons of initial energy E_0, after

traversing a thickness x of medium, will be

$$< E >= E_0 e^{-\frac{x}{X_0}} \tag{12}$$

At high energies, Bremsstrahlung loss for electrons dominates over ionisation loss. The radiation length is simply defines as the thickness of the medium which reduces the mean energy of a beam of electrons by a factor e.

At high energies, Bremsstrahlung loss dominates. For electrons, the critical energy at which this begins to occur (when ionisation loss = Bremsstrahlung loss) is

$$E_c \approx \frac{600}{Z} MeV \tag{13}$$

For muons, this critical energy is in the region of 100GeV

15.6 The interaction of photons with matter

There are three distinct processes by which photons lose energy while traversing a medium. The first is **photo-electric absorption** which is shown in Figure 8(left). The energy loss from this process is proportional to $\frac{1}{E^3}$. The second process is **Compton scattering,** as shown in Figure 8(middle) where by a photon is scattered off the electrons in the atom and loses energy with each collision. The energy loss from this process is proportional to $\frac{1}{E}$. The last process is called **pair-production**. Electron-positron pairs are produced by the photon in the field of a nucleus in order to conserve energy and momentum. The Feynman diagram for this process is shown in 8(right) and this energy loss is approximately constant above about 1GeV.

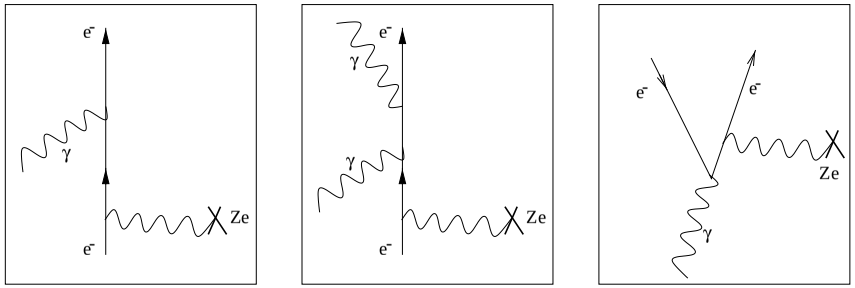


Figure 8: The three processes by which a photon loses energy traversing a medium. From left to right, photo-electric absorption, Compton Scattering and pair-production

The relative contributions from the three processes are shown in Figure 9.

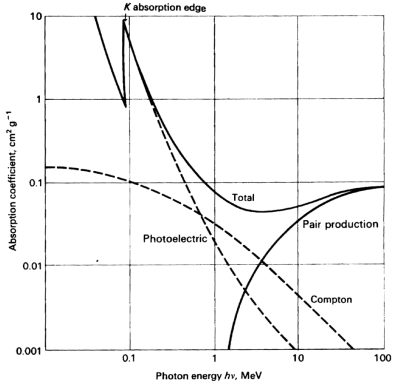


Figure 9: The relative contributions to photon energy loss from the three processes

16 LECTURE 16

16.1 Tracking Detectors

Tracking detectors are used to measure the position of a particle. The particle leaves tell-tale ionisation as it travels through the medium of the detector and this can be translated into a position in space. In a multi-purpose particle physics experiment, the tracking detector is usually the detector which the particles see first (i.e. its closest to the interaction point). This is because the tracker will make a precise measurement of the position and the momentum of the particle without interfering with it too much: later detectors such as calorimeters, depend on actually bringing the particle to a halt in order to measure its energy**!** Tracking detectors are usually used in conjunction with a magnetic field in order to bend the particle according to:

$$\mathbf{F} = Q\mathbf{v} \times \mathbf{B} \tag{14}$$

$$= \frac{mv^2}{r}\hat{\mathbf{r}} \tag{15}$$

$$QvB\sin\alpha = \frac{mv^2\sin^2\alpha}{r} \tag{16}$$

$$r = \frac{p_T}{QB} \tag{17}$$

and therefore to measure the momentum of the particle by measuring the radius of curvature of the track. Only the **component** of the momentum which is perpendicular to the magnetic field will undergo bending: the component in the same direction as the magnetic field will not be affected. For a singly charged particle, the expression for the **transverse momentum**, the momentum transverse to the magnetic field, is

$$p_T = 0.3Br \tag{18}$$

In addition, the charge of the particle is given by the direction of curvature: positive and negative particles bend in the opposite directions under the influence of the magnetic field.

16.2 Wire Chambers

A schematic diagram of a gas wire chamber is shown in Figure 10 The central wire has a high positive voltage on it and the metal box is at ground. The volume is filled with an easily ionized gas such as Argon mixed with a **quenching** gas such as CO_2 or methane. Gas detectors work by the principle that as a charged particle travels through the gas, it undergoes electromagnetic interactions with the electrons (according to the Bethe-Bloch formula) in the atoms of the gas which result in outer shell electrons being emitted. These electrons drift towards the positive voltage on the wire. In order to prevent this process avalanching with free photons also being emitted from excited electrons, the gas must also have a quenching component which keeps this ionisation localised to the region immediately close to the particle's trajectory which is known as the **track**. The quenching gas has the property that it can absorb photons without being ionized. The

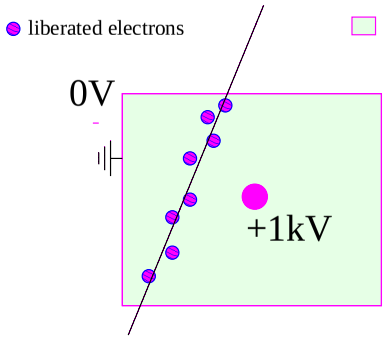


Figure 10: Schematic of a wire chamber

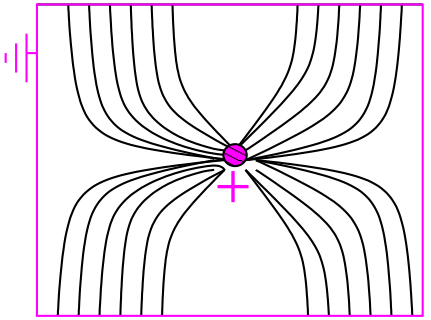


Figure 11: Field lines inside a wire chamber

electrons drift along the electric field lines as shown in Figure 11. Each electron makes many random collisions in the gas during this journey to the wire and in fact frequently comes to rest and transfers its energy to another electron in a gas molecule which is in turn liberated and continues on. This is depicted in Figure 12. The average drift velocity depends on the electric field and the gas. An average value of the drift velocity is about $5\text{cm}/\mu\text{s}$.

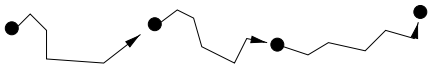


Figure 12: electron drifting under the influence of an electric field

When the electrons get very close to the wire they undergo acceleration under a very high electric field. The field is high enough here to induce avalanching, whereby the electrons are given enough energy to liberate new electrons from the gas in this region. This process is illustrated in Figure 13. As the gas is ionized, the positive ions which are produced start to move very slowly away from the wire and this induces an electrical signal on the wire. The multiplication which occurs near to the wire increases the charge by a factor of between $10^4 - 10^5$ and this is commonly referred to as the **gas gain**. It is necessary to multiply the signal, because measuring the charge of a few tens of electrons (the number produced along the particle track/cm) is extremely difficult whereas measuring the charge of 10,000 electrons is much easier. When the size of the signal measured is proportional to the number of primary electron-ion pairs produced in the gas, the wire chamber is said to be in **proportional mode**. The mode of operation, and therefore the gas gain, depend on the voltage and therefore the size of the electric field at the wire.

The electrical signal from the 10,000 or so electrons and positive ions is extracted from the HV wire by means of a **decoupling** capacitor. This is necessary because the typically sensitive electronics needed to see such a small signal (a few 10s of millivolts) can be damaged by very high voltages and so a capacitor will isolate the electronics from the high voltage while letting through a rapidly changing signal. The decoupling capacitor

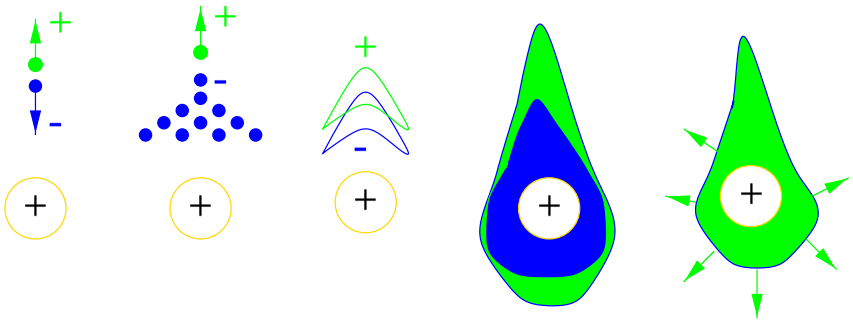


Figure 13: Time development of an avalanche around the sense wire of a wire chamber

also serves to "choose" the length of time over which the signal is integrated. Figure 14 shows the fraction of the signal due to positive ions collected for two different values of the RC circuit shown. The positive ions are of particular importance here because the electrons are all collected in the first nanosecond. The electrons typically constitute one hundredth of the total signal, the large positive ion signal being mostly due to the fact that the positive ions move such a long distance (from the wire to the cathode) while the electrons are produced very close to the wire anyway.

The positive wire is typically called the sense wire, because it also "senses" the signal.

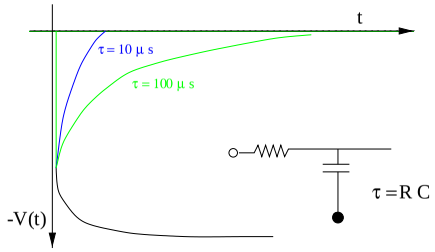


Figure 14: Fraction of signal collected for different values of the RC time constant of the decoupling capacitor circuit.

16.3 Multi-Wire Proportional Chambers

Multi-Wire proportional chambers are an application of the wire chamber described above. Instead of just having one wire and detecting that a particle did indeed traverse the gas volume, many sense wires are put inside the same gas volume to give a *position* measurement of *where* the track went through the gas volume. The sense wire(s) nearest to the point where the particle crosses the chamber will have a signal on it (them). Figure 15 shows a schematic of such a chamber.

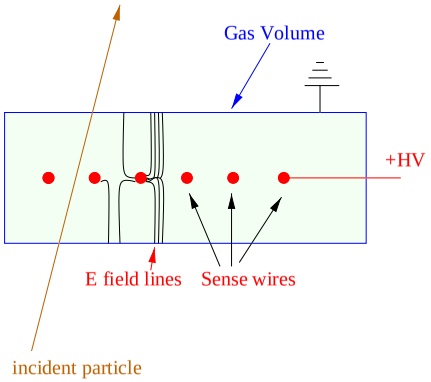


Figure 15: Schematic of a multiwire proportional chamber

17 LECTURE 17

17.1 Calorimeters

Calorimeters work under a completely different philosophy. A calorimeter in a particle physics experiment will measure the total energy of a particle traversing it. In order to do this, the particle must be stopped completely and release all (or most) of its energy in the form of charged particles and photons which are the particles which are actually detected in any kind of particle detector. Calorimeters are usually constructed out of layers of **absorber**, some dense material such as iron, lead or uranium, where the particle is encouraged to interact, and **active detector** such as a multiwire proportional chamber or **scintillator**. The active detector is there to detect the charged particles and photons which are the products of the primary interaction in the absorber.

17.2 Hadron Calorimeters

Hadron calorimeters measure the energy of hadrons. They can also measure the energy of electrons, although the geometrical layout of a hadron calorimeter is not ideal for measuring electrons. Hadrons will interact via the EM force but the energy loss is very small as a function of distance. A pion will lose about 1GeV of energy via electromagnetic interactions while traversing 1m of iron. However, it is more likely that the pion will undergo a strong interaction before it comes to the end of 1m of iron! If you remember the section of the Δ^{++} resonance, a pion beam was fired at a proton target and a new particle was produced which decayed away very quickly. The absorber acts just like a proton target. It has plenty of protons and neutrons in it to act as the target nucleons and so the pion will interact via the strong interaction to make several particles of lower energy which themselves go on through the absorber and into the active detector. The Feynman diagram for this type of process is shown in Figure 16. This process continues until the energy of the decay fragments is small enough to be measured in the active detector.

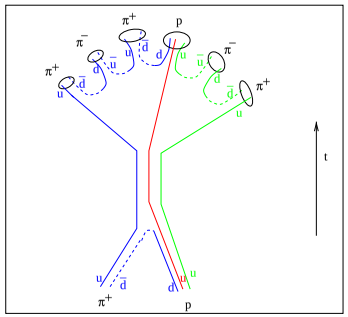


Figure 16: Feynman diagram for production of secondary hadrons

In the case of the multi-wire proportional chamber, the amount of ionisation in the gas is a measure of the energy loss of the particle. So if many measurements of the amount of ionisation are made, the sum of them will add up to some fraction of the initial energy of the pion. A schematic of this process is shown in Figure 17. About $0.3E_{had}$ finally is observed in the form of electromagnetic interactions. This factor must be known in order to get the best out of your calorimeter. It depends on such things as the absorber thickness, the absorber type and the active detector type. Usually, a calorimeter will be **calibrated** beforehand with pions of known energy from an accelerator.

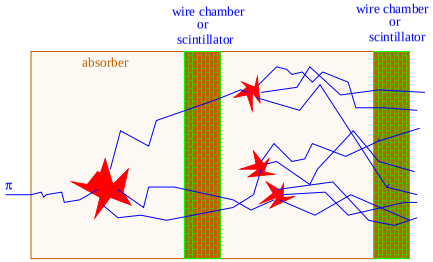


Figure 17: Schematic of a hadron calorimeter.

17.3 Scintillator

Scintillator is a substance which is very widely used for detecting particles. It is usually organic and has a chemical structure such that when a photon or a charged particle is incident on it, energy is transferred and visible light is emitted from the de-excitation of one of the electrons in the scintillator molecule. The Feynman diagram for this energy loss is essentially the same as for ionisation energy loss except that the final state electron is not free and therefore not ionized as shown in Figure 18. The energy lost from a charged particle or a photon traversing the scintillator will be emitted as light in a range of frequencies (usually blue) from the de-excitation of the electrons in the scintillator molecules.

There exist special detectors for detecting the visible light from the scintillator called photo-multipliers. These, as their name suggests, take an incident photon which impinges on their photo-cathode, and through the photo-electric effect, emit an electron (sometimes referred to as a photo-electron because it is produced by the photo-electric effect) which is accelerated and multiplied across several stages via dynodes. Dynodes have two functions. The voltage applied to a photo-multiplier is negative. However, the chain of dynodes have a *relative* positive voltage as viewed by an electron so they attract the electron initially. When the electron reaches the dynode, the chemical composition of the dynode is such that the electron is absorbed and several lower energy electrons are emitted. These are then accelerated towards the next dynode. The dynode initially acts like an anode and then acts like a cathode! The number of electrons collected at the final stage is proportional to the number of visible light photons incident on the photo-cathode. The photo-multiplier is widely used. It has the advantage of being very

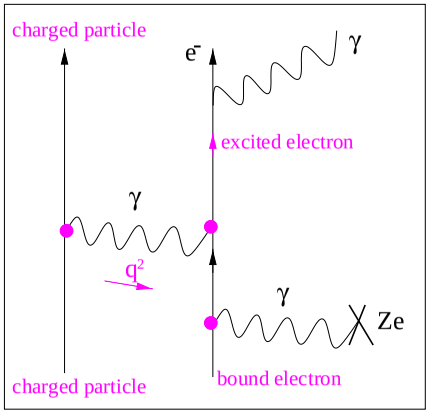


Figure 18: Feynman Diagram of charged particle energy loss in scintillator.

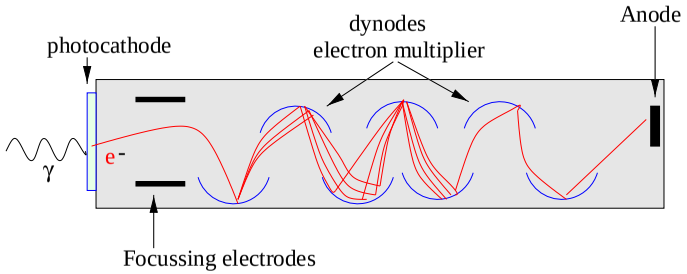


Figure 19: Schematic of a photo-multiplier

fast (a few nanoseconds for the whole chain) and the signal at the anode is large enough that an additional electronic amplifier is unnecessary.

17.4 Electromagnetic (EM) Calorimeters

Electromagnetic calorimeters work on exactly the same principle as hadron calorimeters, but typically the absorbers are rather thin (A couple of mm) and the active detectors are usually scintillator or some other more efficient collector of photons which are prolific in an electromagnetic **shower**. Electrons and primary photons interact in the absorber producing more electrons,positrons and photons which the scintillator is sensitive to and will measure. The amount of visible light in the scintillator is proportional to the initial energy of the electron or the primary photon. The Feynman diagram important for the interaction of electrons is the Bremsstrahlung diagram (Figure 7). The photon given out may be directly measured in the next layer of scintillator, or may penetrate to the next

layer of absorber before undergoing one of the three interactions depicted in the Feynman diagrams of Figure 8.

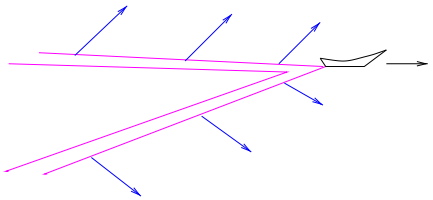


Figure 20: Boat making a water wave.

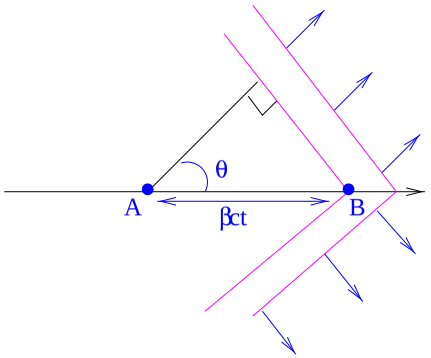


Figure 21: Cerenkov light is emitted at a fixed angle with respect to the particle trajectory

18 LECTURE 18

18.1 Cerenkov Counters

Sometimes, a charged particle will travel faster than the speed of light in a particular medium. Think of a speed boat: The water wave travels more slowly than the boat.

In a Cerenkov detector, the refractive index of the medium is chosen to make this true for certain charged particles. For a given velocity of the incoming particle, the light is emitted at a fixed angle with respect to the trajectory. This is called Cerenkov radiation, after Prof. Cerenkov who discovered it. The Cerenkov light is emitted at an angle θ_c. This can be calculated from the Huygens construction:

$$\cos\theta = \frac{ct/n}{\beta ct} \tag{19}$$

$$= \frac{1}{\beta n} \tag{20}$$

where $\beta > \frac{1}{n}$

The Cerenkov light comes from excitation of the electrons in the atoms of the medium by the electromagnetic field of the charged particle which then drop back giving out

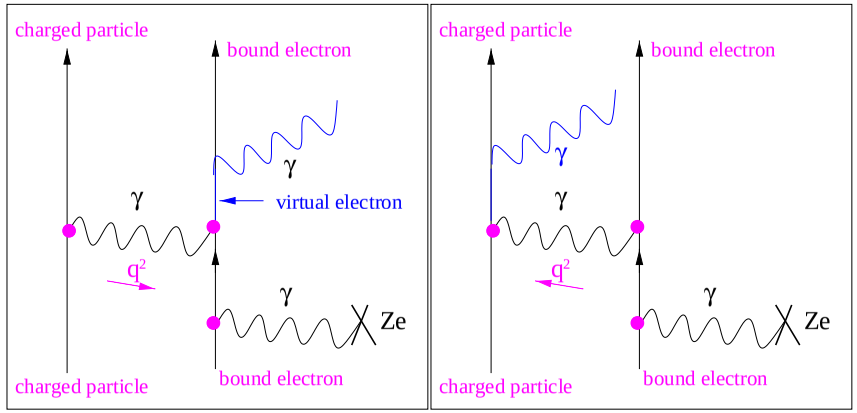


Figure 22: Feynman Diagrams associated with the Cerenkov emission of light

light. The superposition of an infinite number of such photons will give a coherent wave travelling in the direction making angle θ with the trajectory. For a qualitative discussion of this point, see the Feynman Lectures. The Feynman diagrams responsible for this effect are shown in Figure 22. Consideration of the refractive index may help to illuminate this point. When light travels through a transparent medium, it is refracted. This is seen by looking at light in a prism, and can be explained by assuming that the light of different wavelengths travels at a different velocity through the medium. What does this mean? How can photons travel slower than the speed of light? What really happens to those photons as they traverse the medium? They are absorbed and emitted, like in Figure 22 above, by the electrons in the atoms of the medium, and the superposition of many of them give a coherent wave travelling at an angle to the initial direction given by the simple wave considerations which you have met before.

The Cerenkov light appears as a continuous spectrum. The refractive index, n, and therefore the angle θ will be functions of the frequency of the light emitted. The energy content of the radiation

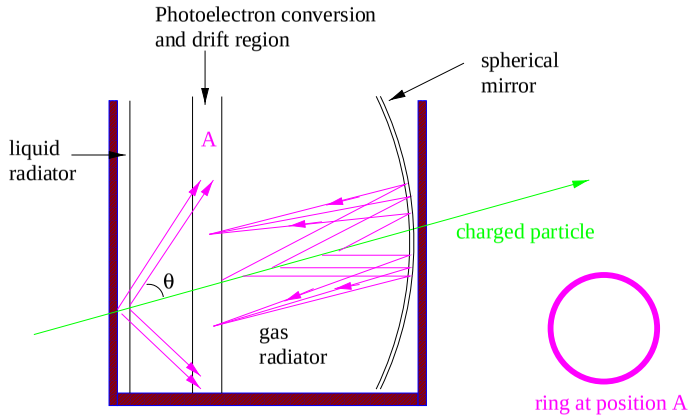
$$\frac{dE}{dx} = \frac{4\pi^2 z^2 e^2}{c^2} \int \left(1 - \frac{1}{\beta^2 n^2}\right) \nu d\nu \tag{21}$$

z is the charge of the particle (usually = 1). The number of photons emitted at a given frequency is proportional to dν and

$$d\nu \propto \frac{d\lambda}{\lambda^2} \tag{22}$$

so the smaller λ, the larger the number of photons and so bright blue light dominates in the visible. Over a small ν range, one can forget the dependence of the energy loss on the refractive index and then:

$$\frac{dE}{dx} = \frac{z^2}{2}\left(\frac{e^2}{\hbar c}\right)^2 \left(\frac{mc^2}{e^2}\right) \left[\frac{(h\nu_1)^2 - (h\nu_2)^2}{mc^2}\right] \left(1 - \frac{1}{\beta^2 n^2}\right)_{av} \tag{23}$$

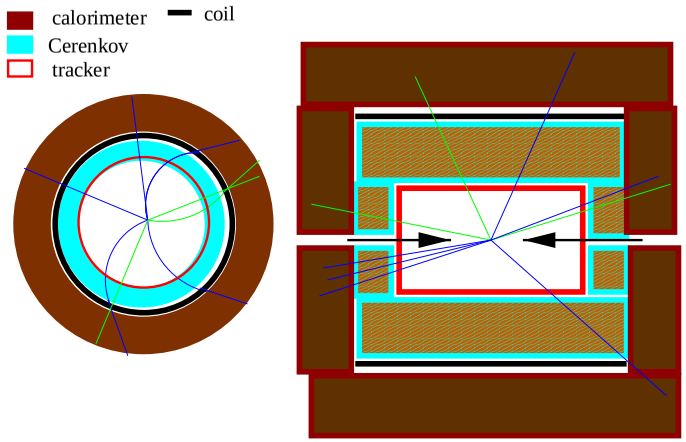


Ring Imaging Cerenkov Counter

Figure 23: Schematic diagram of a Ring Imaging CHerenkov Counter

If $z = 1$,$\beta \approx 1$, in H_2O n=1.33 then $\frac{dE}{dx} = 400\text{eV cm}^{-1}$ for visible light ($\lambda = 400-700\text{nm}$). If λ=400nm, $E = h\nu = h\frac{c}{\lambda}$=3eV. This means about 150 photons per cm. 400eVcm^{-1} is very small compared to 2MeV/cm, the energy loss from ionisation.

Ring Imaging Cerenkov Detectors (RICH,CRID) focus the Cerenkov light from spherical mirrors and the size of the ring measured in the photo-electron conversion and drift region gives a measure of β. A schematic of a RICH detector is shown in Figure 23



Generic High Energy Physics Experiment

Figure 24: Generic High Energy Physics experiment

19 LECTURE 19

19.1 A Generic High Energy Physics Experiment

Using what we have learned about particle detectors, we can construct a hypothetical general purpose high energy physics experiment. From section 15.1, the properties of a particle we are usually interested in measuring are

- Energy, E
- Momentum, **p**
- Charge,Q
- Velocity, v

An ideal detector would have a tracking detector in the center such that the position of the particles is measured before they are catastrophically measured in the calorimeter. The coil will go around the tracker in order to make the particles bend inside its volume for a measurement of the momentum. The same goes for the Cerenkov Detector: any matter in front of it will interfere with the particle and thus give a bad measurement of the velocity. The coil will be outside of the Cerenkov detector for this reason, although the Cerenkov detector does not benefit from the tracks curling in its volume. Finally, the calorimeter will measure the energy of the particle where it will be totally absorbed. Two views of this generic detector are shown in Figure 24.

All particles except muons and neutrinos are absorbed in the calorimeter. Neutrinos since they only interact through the weak interaction remain undetected unless one constructs a detector with a very large volume e.g. several thousand tonnes of heavy water. Alternatively if one can measure the transverse energy of all other particles produced in the primary collision, one can infer the presence of a neutrino by the fact that the total vector sum of transverse energy does not equal zero. The neutrino carries away some transverse energy which is not detected. Muons only deposit a small amount of energy in the calorimeter material and thus can be uniquely identified as the only particles to leave a signal (ionisation) in a tracking detector placed outside of the calorimeter.

If one wants to detect explicitly the presence of hadrons containing heavy quarks i.e charm or bottom quarks then one needs to detect the decay products resulting from the weak interaction decay of the hadrons. For example a b quark decays via the weak interaction to a charm quark, a charged lepton and a neutrino. B hadrons have lifetimes of $\sim 10^{-12}$ sec and are generally produced in pairs in high energy collisions such as $p\overline{p}$ and e^+e^-. In such high energy collisions they are produced with relativistic velocities and so, just like the decay length of cosmic ray muons, their lifetime is "time-dilated" and thus can travel an appreciable distance (several mm) before they decay. If one can measure this decay distance, then one can measure the lifetime and can thus verify that the hadrons produced contained a heavy quark. This generally requires a special tracking detector, placed very close to the original collision point, which can measure the particle trajectory with very high precision. These special tracking detectors are called silicon strip detectors and work in an analogous way to a gaseous MWPC except the charged particle ionises the silicon causing the creation of an electron-hole pair in the silicon. The electron and hole again drift to anodes and cathodes. The energy required to create these electron-hole pairs is small (~ 1 eV) and they have high mobility, so it is possible to obtain reasonably sized signals even for particles who loose little energy by ionisation e.g. muons. The silicon is in the form of strips some 20-50 μm wide. Each strip can be used to signal the presence of an ionising charged particle. Each strip is itself an ionising medium and a charge (e or hole) collector. By building up a pattern of the strips where ionisation has occurred one can reconstruct the trajectory of particles to an accuracy of a few μm. This allows one to actually construct the point at which a decay occurred by extrapolating the trajectories of the charged particles back towards to the collision point. This is illustrated in figure 25, which shows the charged tracks resulting from the decay of two top quarks produced from a poverlinep collision. Each top quark decays to a W boson and a b quark. The b quarks form B hadrons which travel a certain distance before decaying. One can see clearly the two points at which the B hadrons decayed.

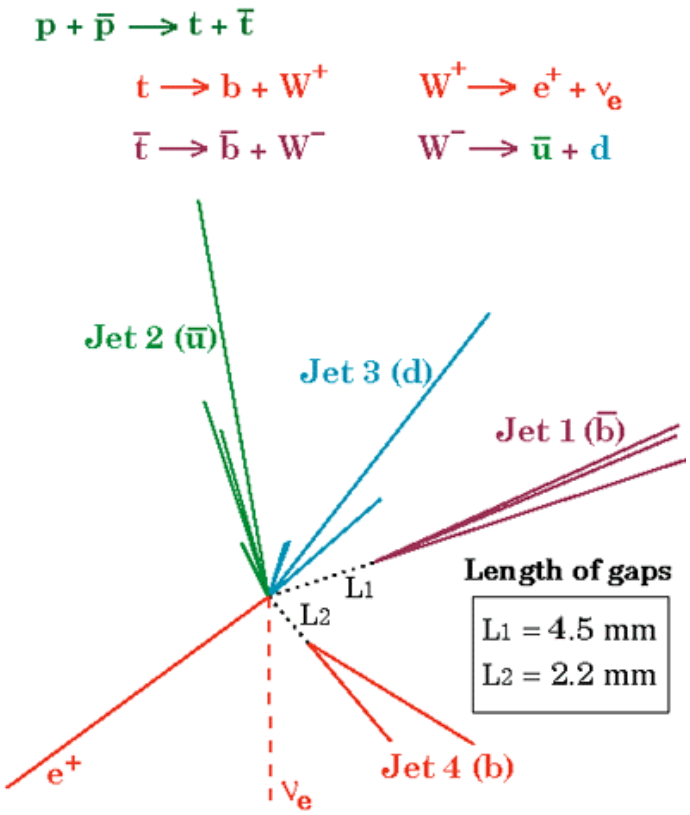


Figure 25: The charged tracks reconstructed using a Silicon strip detector and a gaseous drift chamber resulting from the decay of two top quarks. The neutrino from the W decay is not detected but inferred from the imbalance of transverse energy.