15 LECTURE 16

15.1 Tracking Detectors

Tracking detectors are used to measure the position of a particle. The particle leaves tell-tale ionization as it travels through the medium of the detector and this can be translated into a position in space. In a mulitpurpose 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 beinging 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:

$$\begin{aligned} \mathbf{F} &= Q\mathbf{v}\times\mathbf{B} && (106)\\ &= \frac{mv^2}{r}\hat{\mathbf{r}} && (107)\\ QvB\sin\alpha &= \frac{mv^2\sin^2\alpha}{r} && (108)\\ r &= \frac{p_T}{QB} && (109) \end{aligned}$$

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

$$p_T = 0.3Br \qquad (110)$$

In addition, the charge of the particle is given by the direction of curvature: positive charge dparticles might bend inwards under some magnetic field whereas negative particles would bend outwards.

15.2 Wire Chambers

A schematic diagram of a gas wire chamber is shown in Figure 43 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

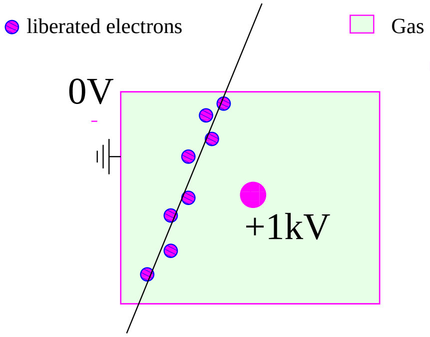

Figure 43: Schematic of a wire chamber

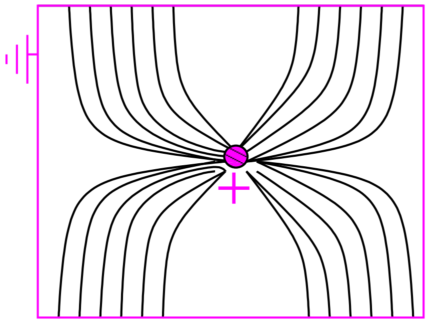

Figure 44: Field lines inside a wire chamber

electrons drift along the electric field lines as shown in Figure 44. 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 45. The average drift velocity depends on the electric field and the gas. An average value of the drift velocity is about 5cm/μs.

Figure 45: 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 46. 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

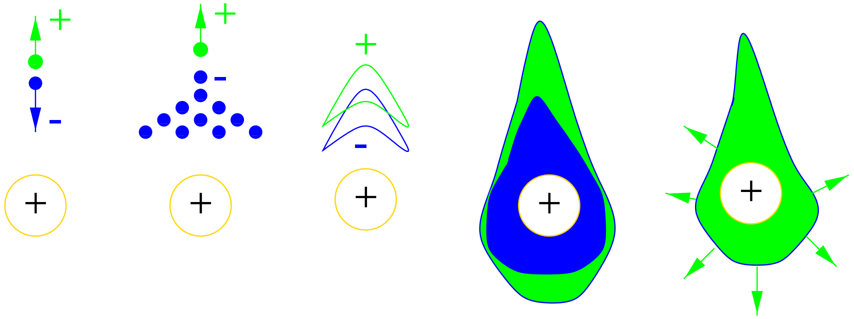

Figure 46: Time development of an avalanche around the sense wire of a wire chamber

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 also serves to "choose" the length of time over which the signal is integrated. Figure 47 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.

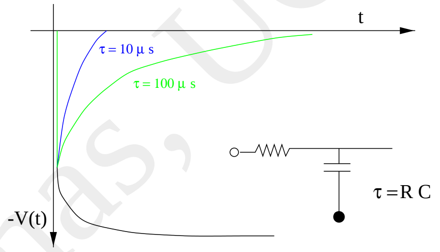

Figure 47: Fraction of signal collected for different values of the RC time constant of the decoupling capacitor circuit.

15.3 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 tra-

verse 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 48 shows a schematic of such a chamber.

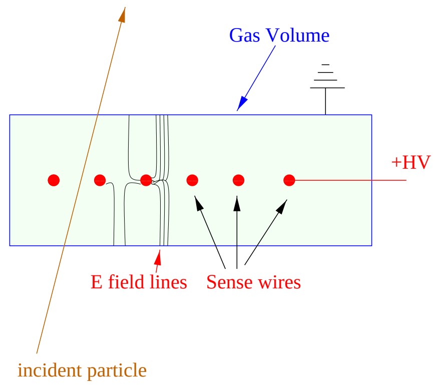

Figure 48: Schematic of a multiwire proportional chamber

16 LECTURE 17

16.1 Calorimeters

Calorimeters work under a competely 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.

16.2 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 49. This process continues until the energy of the decay fragments is small enough to be measured in the active detector.

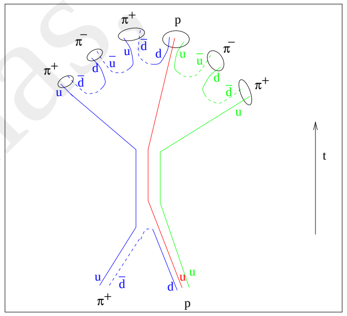

Figure 49: Feynman diagram for production of secondary hadrons

In the case of the multi-wire proportional chamber, the amount of ionization in the gas is a measure of the energy loss of the particle. So if many measurements of the amount of ionization 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 50. 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.

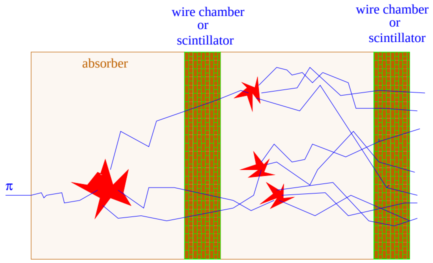

Figure 50: Schematic of a hadron calorimeter.

16.3 Scintillator

Scintillator is a substance which is very widely used for detecting particles. It is usually organic and has a chemical stucture 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 ionization energy loss except that the final state electron is not free and therefore not ionized as shown in Figure 51. 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 photocathode, and through the photoelectric effect, emit an electron (sometimes referred to as a photoelectron because it is produced by the photelectric effect) which is accelerated and multiplied across several stages via dynodes. Dynodes have two functions. The voltage applied to a photomultiplier 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 photocathode. The

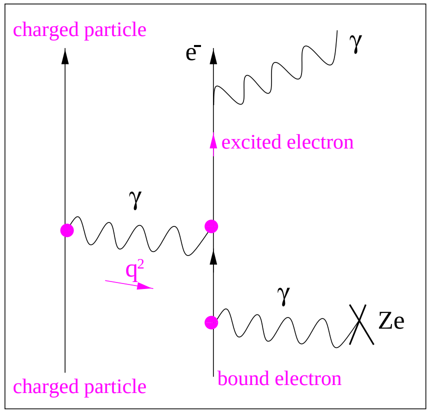

Figure 51: Feynman Diagram of charged particle energy loss in scintillator.

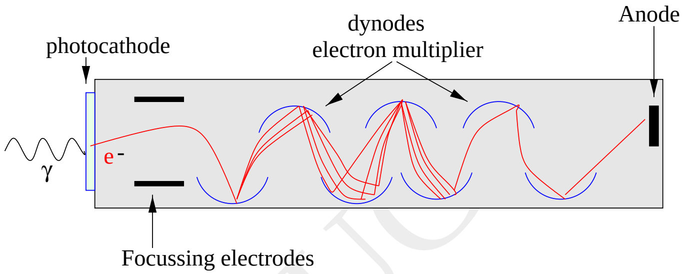

Figure 52: Schematic of a photomultiplier

photomultiplier is widely used. It has the advantage of being very fast (a few nanoseconds for the whole chain) and the signal at the anode is large enough that an additional electronic amplifier is unnecessary.

16.4 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 inital

energy of the electron or the primary photon. The Feynman diagram important for the interaction of electrons is the Bremshtrahlung diagram (Figure 40). 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 digrams of Figure 41.

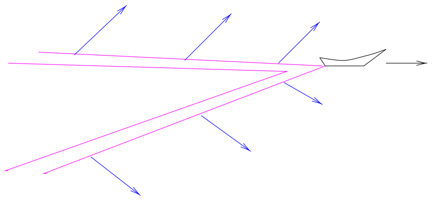

Figure 53: Boat making a water wave.

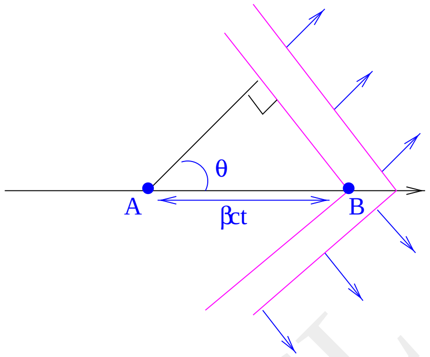

Figure 54: Cerenkov light is emmitted at a fixed angle with respect to the particle trajectory

17 LECTURE 18

17.1 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 emmitted 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:

$$\cos\theta = \frac{ct/n}{\beta ct} \tag{111}$$

$$= \frac{1}{\beta n} \tag{112}$$

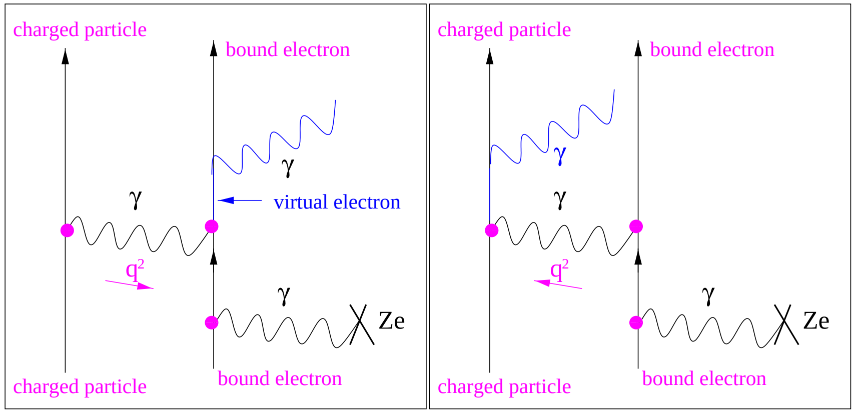

Figure 55: Feynman Diagrams associated with the Cerenkov emmision of light

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 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 55. 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 55 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

$$\frac{dE}{dx} = \frac{4\pi^2 z^2 e^2}{c^2} \int \left(1 - \frac{1}{\beta^2 n^2}\right) \nu d\nu \tag{113}$$

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

$$d\nu \propto \frac{d\lambda}{\lambda^2} \tag{114}$$

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

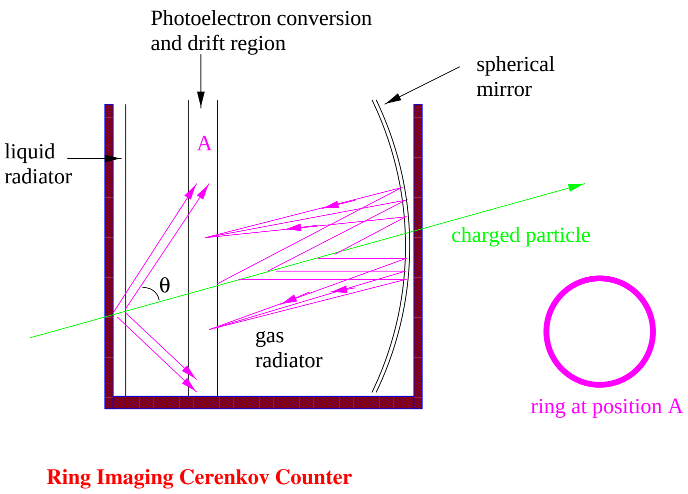

Figure 56: Schematic diagram of a Ring Imaging CHerenkov Counter

the refractive index and then:

$$\frac{dE}{dx} = \frac{z^2}{2}\left(\frac{e^2}{\hbar c}\right)^2\left(\frac{mc^2}{e^2}\right)\left[\frac{(h\nu_1)^2-(h\nu_2)^2}{mc^2}\right]\left(1-\frac{1}{\beta^2 n^2}\right)_{av} \tag{115}$$

If $z = 1$,$\beta \approx 1$, in H_2O n=1.33 then $\frac{dE}{dx} = 400\mathrm{eV\ cm}^{-1}$ for visible light ($\lambda = 400-700$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) focuss the Cerenkov light from spherical mirrors and the size of the ring measured in the photoelectron conversion and drif region gives a measure of β. A schematic of a RICH detector is shown in Figure 56