[SQUEAKING]

[RUSTLING]

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PROFESSOR: Welcome back to 8.701. We are starting a new chapter on instrumentation. And in this first section, we'll discuss the interaction of particles with matter. So what happens when particles traverse through a piece of material?

The underlying principle of detection is that we do have to have some sort of interaction of the material of the detector with the particles going through. And there needs to be some sort of transfer of energy which can be identified. Then, that piece of energy can be amplified, separated from noise, and so on. But this first part of any detection process is this interaction of this particle with matter.

We can ask, what kind of particles can we actually identify? Electrons, muons, pions, kaons, protons, neutrons, heavy ions, and photons. But the key here in this list of particles is that those particles have to be stable. So we cannot directly identify tau, as the tau decays before it has a chance to interact with the detector. The same for our top quark, the Higgs boson, and so on.

Interesting, neutrinos. Neutrinos interact with the detector very, very rarely. When they do, they actually detect a signal that is not of the neutrino directly, but of the products of the interaction.

So we will split this discussion up in the interaction of neutral particles and charged particles, and we start with the photon. So the photon interacts with detector material. With material in general, we have three leading effects. The photo effect, Compton scattering, and pair production.

In the photo effect, we have a photon interacting with an atom, and then kicking out an electron. And then, your detector has a chance to identify the energy and the momentum of the electron. This concept is used in photo multiplier tubes where then the kicked out electron is further amplified. And that leads to a shower of electrons which can be measured like the photodiode [? species ?] effect.

We have discussed the Compton effect quite a bit. Here, the energy of the scattered electron can be measured out of the energy of the scattered photon. And then there's pair production. Pair production dominated high energies. And typically, it's part of an initiation process of electromagnetic showers in calorimeters. That's great.

So what happens in the calorimeter-- and we'll talk about this more later-- is that an incoming photon or electron causes this photon to convert into pairs of electrons and positrons. And then there's this cascade of electrons and positrons, and additional photons being produced. In tracking detectors, this is unwanted. So therefore, build tracking detectors rather thin. We don't want to have this confusion of additional charged particles, and we try to measure the energy of a proton.

So this plot here shows you the cross-section as a function of the photon energy. And you see here very nicely those three effects contributing to the total cross-section. So for low energies-- in the range of some 100 keV, the photo effect dominates. And there is this intermediate range from about 100 keV to about 10 MeV where we see the effect of Compton scattering.

And everything above this is dominated by pair production. And this here shows you that there are some differences in what kind of material you interact, of course. Photon or electron interaction. Again, the main energy loss mechanism for high energy photons and electrons in matter is through pair production, and also bremsstrahlung. Bremsstrahlung is the effect when an electron or positron radiates a photon.

You can characterize the materials by introducing a concept of radiation length. And there's some confusion sometimes. In the definition, they are very similar, but they're not quite the same. Radiation length can be defined as the length after which an electron loses about 1 over *e* of its energy by bremsstrahlung. And you often find the definition through the mean free path lengths. And in X0, the radiation length is defined as 7/9 of the mean free path length for pair production by a photon.

So those are the two definitions. And they're typically used in the regime where the process is dominant. It's a very convenient property because of quantity, because you don't have to worry about when you're thinking about the interaction of the detector, about the specific thickness and what it means in terms of energy loss, and simply know that your piece of lead is a fraction of a radiation length. And that tells you how many of your photons or how much of the photon energy is being lost.

Typically, when you build detector concepts like a collider experiment like ATLAS or CMS, you want the tracking volume to be of low radiation length. And for ATLAS and CMS, this depends on the rapidity or the forward direction, but it varies between 30% and 200% of the radiation length. And for calorimeters, you want that all the energy is deposited in the calorimeter. Nothing has leaked out in the back, and therefore, you design calorimeters typically with 20 or 30 radiation lengths [INAUDIBLE].

So again, when me think about how a photon or an electron leaves a footprint in a calorimeter, you start from this first electron and photon. And then, this particle evolves in an electromagnetic shower. So there's this cascade effect as the particle tries to move through this material. The shower maximum is given here. Slightly depends on the energy. It uses logarithmic dependency.

I introduce here the critical energies. This is where the energy loss through ionization is equal to the bremsstrahlung. And you see this in this plot here-- It's rather small-- as a function of energy and the energy loss. Again, you see, this effect here is from ionization. And this effect here is from bremsstrahlung. The critical energy is defined as where those two energy loss mechanisms give you the same result. So this is just a normalization factor. But you see that there is this logarithmic dependency of the energy loss.

You can also wonder how wide a shower actually becomes. And this is given by the width. The transverse width of the shower is given by the Moliere radius. And that's approximate. You find 21 MeV over the critical energy times the radiation length gives you the size of the transverse sides of your shower. And in this example, this is 8 centimeters, compared to a shower length of 46 centimeters.

This is a very quick summary of electromagnetic showers. You can also have nuclear showers, of course. You have a neutron or a proton entering your calorimeter. Here, the physics is a little bit more complicated, but you can introduce similar concepts. This concept of radiation lengths for strong interactions of the hadron with the nuclei.

So as for the electromagnetic shower, there is this cascade developing. However, if in the cascade, for example, you would choose a neutron. That neutron can travel without leaving an interaction for quite a distance. So you don't have this continuous kind of flow of energy, and you have little clusters of energies. And in those clusters, you have not just nuclear interaction, but you can also produce new pions. And those new pions decay into a pair of photons. And then, the photons, they leave electromagnetic showers.

So hadronic showers have typically two components-- a hadronic part, which is charged hadrons, pions, kaons, protons, neutrons, and an electromagnetic part which is [INAUDIBLE] coming from the decay of the neutrons. From the decay of the neutral pions, which are photons.

So here, just to give you a feel four orders of magnitude, radiation length given-- the nuclear and the electromagnetic radiation is given as a function of Z. And for a gas, we're talking about hundreds of meters. For light material-- aluminum and silicon-- we talk about 10 centimeters. And for heavy material-- specifically lead-- we're talking about sub-centimeter radiation length.

Moving from the neutral particles from the photons and electrons-- sorry-- to the charged particle interactions. Here again, just summarizing or giving a summary first, and then going through the individual components. The interaction mechanisms are multiple scattering-- elastic scattering with the atoms. This is a process which is not very much wanted because, when you try to monitor the trajectory of the particle, you don't want it to scatter and change randomly its direction or momentum.

Ionization is a basic mechanism for tracking detectors. Photon radiation is an important part through bremsstrahlung but also through Cerenkov radiation or transition radiation. And then, in scintillators, you can excite the material. And then, if you have a wavelength shifting fiber material, you can cause scintillation light to be shifted in wavelength. And then you can read this out in order to gain information about particles going through.

All right. Let's start with multiple scattering. So after passing a layer of thickness with L, a particle with some displacement r and some angle of deflection. So that is problematic because you lose information through the random process. You see here this random Gaussian-like distribution which is rather annoying. So the key here is to minimize the radiation lengths of the particle going through.

The next part is an ionization. Again, this is a primary source of information we gained from in tracking detectors. Typically, you have a number of primary interactions per unit length which are Poisson distribution. So it's a random process whether or not the particle sees an atom which it can ionize. And typically, in a gas, you find about 30 of those primary interactions per centimeter. You have more in denser materials.

If you have kicked out an electron in your ionization process, that electron itself can again lead to secondary ionization. And once those electrons reach sufficient energy, they're sometimes visible as individual tracks themselves. They called delta electrons-- new particles which are visible in your tracking detector. Energy fluctuations can be really, really large through ionization. Sometimes, you have a really tough interaction and you transfer a lot of energy to the electron, while the mean number is well under control.

So, interesting. Just to give you a feel, again, you have about 30 primary interactions per centimeters in gas. The total ionization energy you find is typically 3 times the primary ionization energy. So you cause those seeds of ionization, and then the energy to move away from this initial track.

When you look at the energy loss distribution, this is a nice plot here I made many, many years ago of the energy loss in a piece of silicon of 100 gb pion. So this pion loses its energy primarily through ionization. And this is a small piece of silicon which we used here. So you see this typical distribution. It's called the Landau distribution with a most probable value and then a very long tail. And this tail here is dominated by those delta electrons I was talking about.

In bubble chamber or cloud chamber pictures, you see those delta electrons here as little curls of ionization along the main part of your particle leading an ionization track. The energy loss of charged particles can be calculated using the Bethe-Bloch formula. And it's a very good description in a specific energy range-- in the energy range which is dominated by ionization.

And so, the formula is given here. We discuss this some more in our recitation section. But you see here in this medium energy range, you are dominated with Bethe-Bloch formula or by ionization where, when you go into higher energies here, you find additional energy loss-- energy loss with radiation.

So we can study the details of this Bethe-Bloch formula. One interesting point is the particle dependency of the energy loss-- and you see this here shown for a muon, for a pion, and for proton. If you measure the energy loss of a specific particle in a reasonable momentum range, you can use that information in order to learn which particle travels through your detector. So you can use energy loss in some cases in combination with the momentum measurement in order to identify particles.

Last but not least, more radiation effects. Cerenkov radiation is a very neat feature to also measure particles as they go through a specific material. They can also be used in order to identify particles again.

So the idea here is that Cerenkov radiation is emitted when a particle passes through a dielectric medium with a speed larger than the speed of the light in that medium. And that causes a radiation cone. It's like a sonic boom when you have airplanes passing by. And the simple picture is one of the classical pictures. It's one of this wave front cone under a specific Cerenkov angle.

And then, last but not least, transition radiation. This is a process which were predicted by Ginzburg and Frenck in the 1940s. His idea is that a photon is emitted when a charged particle transfers through the boundary of two mediums.

And so, if you have a medium here in a vacuum, for example, if the particle travels through here, it polarizes the medium when it exits. And that polarization then leads to an electric dipole which then starts to radiate. And you get a photon from this type of radiation. So if you measure this type of radiation, you might be able to identify that the particle traveling through the transition of two materials was an electron.

All right. So this is the first introduction to the topic. So in the next part, we now have to understand how we use those phenomena in order to build detectors.