**MARKUS KLUTE:** Welcome back to 8.701. So in this section, we'll look at tracking detectors. And before we look at tracking detector technologies, we want to remind ourselves how we measure the momentum of a charged particle. And this measurement is possible because charged particles are reflected in magnetic fields.

We have already seen that in a homogeneous magnetic field, a particle follows a circle. And so from the measurement of the radius and the knowledge of the magnetic field, we can infer the transverse momentum of the particle. Typical particles also have a longitudinal momentum. And so therefore, the trajectory is actually of the form of a helix. And so we then can get back to the total momentum of the particle by knowing the angle or the component of the longitudinal and transverse momentum and then just calculate total momentum from there.

So we have seen that particles, when they go through a piece of material, that the energy loss through ionization or bremsstrahlung. And so what we have to do now is put some material in the way of the particles without really changing its momentum or changing its trajectory. So this is typically done with tracking detectors.

And so what you then measure is not just the radius directly, but you measure individual points that's part of the trajectory of the particles. And so from the measurement of the points, you can then reconstruct the trajectory of the particles, and then therefore measure the curvature. And that has been used to measure the transverse momentum.

So if you look at this picture here, the radius can be given as L squared over 8s plus s half. s is typically called the sagitta of the trajectory. If L is much, much larger than s, it simplifies to r-- about L squared over 8s.

And the uncertainty on the sagitta the uncertainty on s, is limiting the uncertainty on the momentum measurement. And this is described in a paper which is very nice from the '60s. And the formula is called the Gluckstern formula.

So what you see here is that the more measurements you actually perform along the sagitta, the better your measurement is performed. And this goes with the square root of 1 over the number of measurements. The total momentum uncertainty, or the relative momentum uncertainty, sigma pt over pt, is proportional to the uncertainty in the sagitta. And that also is then proportional to the pt of the measurement.

So if you want to improve your measurement of your momentum, you want to decrease the uncertainty, then you can do this by having a larger L-- and you see this goes with the square of the length-- you want to increase your magnetic field, and you want to reduce the uncertainty on the second term. Those are the elements you have in play in order to improve the transverse momentum, or the momentum measurement of your charged particles.

So this is a screenshot of this paper. The measurement error is not the only error on the transverse momentum, as we discussed previously already. Multiple scattering, so the scattering of the particle-- and it goes with momentum-- also reduces the uncertainty in the momentum measurement. And we can show that this component on the relative momentum uncertainty is flat.

So what you find typically is that the transverse momentum measurement is limited by, at high pt through the measurement error, and at low pt through multiple scattering. We have those two components entering the measurement uncertainty.

So the actual detectors, I just give you a couple of examples here. The first one-- and the first one, which actually really has allowed us to make measurements with a lot-- devices with huge statistic experiments where you have colliding beams, and you look at many, many of those interactions was a multi wire proportional chamber, at a reasonable resolution. Typically, we have hundreds or thousands of wires with a spacing of up to 1 millimeter. And this 1-millimeter spacing in a wire chamber limits the spatial resolution.

If you don't have any knowledge of where the particle was in that area, then the uncertainty of the spatial-- on just one hit, uncertainty is given by d, the spacing between those two wires-- 1 millimeter in this case-- divided by square root of 12. So you find typically resolutions of 300 microns per measurement. But you may gain off the fact that you typically have many, many, many measurements. And as you just saw, this reduces the uncertainty on the measurement.

You knowing that there was a hit on a wire gives you two-dimension information. If you then built the wire chamber such that there's angles between individual wires, you can use that in order to gain three-dimensional information in the geometry of where the particle went through.

Wire chambers can be operated in different modes. And it depends on the level of voltage you apply on the wires. So the higher the voltage-- the level of the voltage goes down here, see a very limited voltage applied, then the ions-- you have ionization, and the ions recombine without being collected.

In ionization mode, you collect the ions. And there's typically a gain factor of 1. You measure each ion, basically, separately. You can increase the voltage and run the wire chamber in proportional mode so you have a gas multiplication factor so the ions are being accelerated, and then they produce many more, more ions to be measured. And you typically have gain factors of 10 to the fourth.

If you drive this further up, you go into the limited proportional mode, and then in Geiger mode, where basically you have an avalanche, and so you have no information about the initial ionization anymore. And typically, the chamber breaks down and needs to recover afterwards.

The signal formation is quite an interesting concept. So you think that you do ionization, the electrons are there, and then they're being collected. Yes, that's true, and this happens very rapidly, typically in the order of nanoseconds. But the actual real signal comes from the ions themselves.

And so what happens here is you have your wire here, you have your electrons. The ions then themselves, they build this cloud of charges. And this cloud of charges then gives you a signal on the wire. And this happens typically via influence, or you basically have a mirror charge on the conductor. And that is really where the bulk of the information comes from.

We just discussed that the spatial resolution is limited by the spacing of the wires. You can actually get better measurements by using the timing information. If you are able to measure the time profile of your signal, that profile has information about the distance between the ionization and the wire itself. And that then helps you to improve the resolution further.

So I really don't do justice to this, but nowadays, specifically in high dense-- particle-dense environments, you use solid-state tracking detectors. And they're used in many, many, many areas in particle physics. The idea is to use mostly silicon, but you can use other semiconductors as well.

You dope them, meaning that you create more holes by using p-doping and n-type doping for more electrons. And then you bring n-doped and p-doped materials together. And you-- you know, it's the same way as in a diode in that then you apply a voltage in the opposite way to create a very large depleted zone.

So in this depletion zone, there is no electrons and no holes available. But when a charged particle travels through, like is shown in this picture here, you create electron-hole pairs, and they then can be used in amplification to create a signal. That's the general concept in which solid states or silicon detector [INAUDIBLE].

The nice thing about silicon detector is that you can read them out with very fine spatial resolution. So from this 300 micrometers we just saw, you go down to several micrometers in spatial resolution when you measure particles going through the detectors.