[DIGITAL EFFECTS]

PROFESSOR: Welcome back to 8.701. So we'll start a new chapter now, QCD or quantum chromodynamics. And then, this first lecture of this chapter, we talk about the production of hadrons. This is really meant as an introductory lecture, but we will also already see some very interesting and useful concepts.

So we want to produce quarks and anti-quark pairs, and we do this electron-positron collisions. We have studied in detail this first part of the diagram. Specifically, we calculated a cross-section of muon and anti-muon production, and we also have seen more changes than we have same kind of particle in the final state of the electron-positron scattering to electron-positrons. So now, we've replaced the muons with our quarks and anti-quark pairs.

And the first step, we want to remind ourselves of the available quarks in this discussion. So we have the up quark, the down quark, charm, strange, top, and bottom. You see that the charges are given here, and the photon couples to the charge. So the charge is not 1, but it's either 2/3 or minus 1/3. Third

We have also here in the table mass is given for those particles. They range from a few MeV to 173 GeV for the top quark. The bottom quark is about 5 GeV heavy. Remember, when we discussed re-normalization, we discussed that those masses are not fixed parameters, but in our perturbation series, they run like the [INAUDIBLE] one. So that might cause some difficulties later on.

OK so now we want to produce an up quark and an anti-up quark in this collision. So what happens? So we now have collisions, and then we produce those particles. So let's say an up quark, and an anti-up here, and then your plus and minus collision.

Those quarks only live for a very short time, or travel a very short distance in space-- about 10 to the minus 15 meters. And then, they start to pull in out of the vacuum gluons, and quarks, and anti-quark pairs, and those then form into the actual hadrons after some time. And those two pictures here will look very much the same. The difference is the way we treat the hadronization-- the actual fact of forming hadrons.

In this first picture, we are thinking about clustering energy particles together and that way form hadrons. In this picture here, we connect them with so-called strings. And those are two different ways to model and model the production of hadrons.

Remember, when we look at this process here, we are looking at very low-energy kind of or lower-energy kind of phenomena, and at lower energies, the strength of the strong interaction, the strength of QCD, is-- the coupling is on the order of 1. It can be larger than 1. So perturbation theory is not possible. That's why we need specific models. This is all I want to say at this point. We'll come back to this discussion later on.

What I actually want to discuss is what we can learn out of measuring cross-section of hadron production-- for example, by comparing directly the cross-section of [INAUDIBLE] production with a cross-section we just calculated for muon/anti-muon production. And experimental results are given here. So you see as a function of energy, here from 1 GeV to 7 GeV center of mass energy, and then the lower plot just continuing from about 10 to 60 GeV. What you see here is that there is a rich structure. So you see those resonances here, and you also see that there seem to be some sort of increase in the value of this ratio.

So how can we now understand this? At leading order, we can just write this down we just calculate its cross-section for electron-muon scattering, or for electron-muon production. And we can write this very same cross-section of the leading order for quark-antiquark production.

What we find as differences is the coupling, the coupling itself. Here, we have to use the charge of the quarks and not the charge of the electron. So there is an additional factor here, 1/3 or 2/3 squared. And then, there's the number of possible quark pairs which are available, and that depends on the number of colors. Remember, each quark appears with three different colors, so we have to account for this factor.

All right, and then we built the ratio. And the ratio, everything just cancels out-- great. So we have just a number of colors times the sum of the charges squared of the quarks available.

What do I mean by "the quarks available?" As we go from lower-energies to higher energies in this plot here, the kinematic-- the energy is sufficient to produce particles based on the masses available. So we find that this explains a step function.

Let's look at a specific example. So if you look at center of mass energies, which are larger than 2 times the mass of the bottom quark, and maybe lower than 2 times the mass of the top quark, we are in this specific regime here. Can you see, this is almost flat, and the number we get is almost 4, OK?

What we get from this leading order calculation is 3 times 4 over 9 for our up quark, 1 over 9 for down, 1 over 9 for strange, 4 over 9 for charm, and 1 over 9 for our bottom quark, OK? So we built the sum here for all quarks which are kinematically available, and as an answer, we get 11 over 3. So this is in very good agreement-- a leading order, very good agreement with the experimental results. 11 over 3 is almost 4.

Excellent, so this is clear indication, experimental indication, that this color factor here is a real thing. There seemed to be 3 up quarks, 3 down quarks, 3 charm quarks, and so on. And we also see that this leading order effect here, the leading order calculation, is already very precise. And the reason for this is that this process here is a QED process. So the production cross-section is QED process, as we just discussed.

So now, why do I actually have this as part of our QCD introduction? First, you learned about the color factor here, OK? And second, there is, indeed, corrections, and one of the correction is the one where you actually produce a real gluon in the final state. And those corrections can be calculated. If you go to higher order, you get a correction from this radiated gluon. You also get corrections which looks like this-- vertex corrections-- and you find that the correction here to [? r ?] is about 1 plus alpha s at a specific scale over pi.

Now, at a reasonable scale, this is then about 0.1 the value of alpha s, and pi is 3.14, and so you get about a few percent, 3% correction to the r value rate. Why is it so important when there's a small correction? It's a percent or few percent level correction. What is really important is that this process can be used in order to demonstrate the existence of gluons, and so gluons have been discovered this way.

And the way this was done is by producing the plus and minus collisions and detecting three bunches of particles-- too from the quarks, and one from the gluons. And then, to identify that this gluon on here is actually a gluon and not some other particle, one can look at angular distributions. One can identify that this is a spin 1 particle, and so on. So there's a little bit more work needed beyond just showing that there's [INAUDIBLE], but identifying this kind of topology in the plus and minus conditions led to the discovery of gluons in this kind of conditions.

So that was my introduction. As a next step, I want to add one more step of, now, how can we learn about this kind of structures before we then dive into Feinmann diagrams, or Feinmann calculations, Feinmann rules for QCD.