MARKUS KLUTE: Welcome back to 8.701. So in this lecture, we want to talk about asymptotic freedom, about confinement, and also the running of the strength of the strong force. In the recitation, we already talked about vacuum polarization, QED, and how it relates to QCD. So here we're just going to remind ourselves again about what has been discussed here.

So loop contributions in QED, they make the effective charge a function of the momentum transferred q. So the coupling strength increases with larger values of q squared. So a leading order, you have to consider this diagram. And you find that there is a correction coming from this kind of diagram. m here is the mass of the particle involved in this correction.

But as you know, in perturbation theory, you have to consider all possible diagrams. And this is being done here. So if you consider those higher-order diagrams, you can rewrite the running of the QED coupling as the coupling at q squared of 0 divided by 1 minus this contribution here.

So there's a couple of things to note. So there's a 1 minus a factor here. And then there's also the definition or the fixed point of the coupling that's being used as 0 q squared. But that's possible in QED. But that will not be possible in QCD, because at momentum transfer 0, the coupling is going to be infinite. So it's not well-defined and we cannot use perturbation theory at this value s either.

OK, good. So in QCD, we have not just one diagram, like the one we just saw before. But we also have to consider the gluon self-coupling diagram. So we have contributions of this sort. So I'll spare you from the calculation.

But you find that the gluon contribution has an opposite effect. So it's producing some sort of anti-screening or camouflaging of the color charge. And so you find, if you calculate this in a very similar way as you did just before, we did just before for QED, we find this kind of correction.

So here, we have to define or fix the strength of the coupling at a specific scale. And you see that you have this contribution here. There's a plus here, but this factor here, which is 11 times the number of colors involved, minus 2 times the number of flavors involved.

Those numbers are 3 and 6, so hence 11 times n is larger than 2 times f. This becomes positive here. And so therefore the coupling decreases-- the coupling decreases this q squared.

All right, since it decreases with q squared, at very, very high q squared, the coupling becomes 0. And that's the origin of asymptotic freedom. In the limit of very large q squared, strongly charged particles, color-charged particles become free. That's also the reason why at very high energies we can make calculations in QCD using the Feynman calculus or perturbation theory.

In the other direction, if you go to very low q squared, those methods and tools are not possible anymore. And quarks and gluons are actually confined. You cannot produce a non-color thing that stays by themselves. You cannot have a free gluon or free quark.

So let's look at this running a little bit more. So we have this annoying alpha s over function of q squared. You can get rid of this actually by redefining the parameter here and using this lambda parameter, or lambda QCD as it's often called, or lambda color as it's called here under C.

When we do this, we can rewrite the equations. So we find that there is no dependency anymore of the scale involved. And we don't have to find this fixed point. We still have the dependency of 11n minus 2f. And then this locked dependency on q squared over this specific scale.

So the strength of the coupling with this definition defined for any value of q squared, finding this lambda q, this is kind of complicated because if you go to very low q square, calculations and experiments cannot easily be compared anymore. So we find that lambda QCD is in the order of 100 to 500 MeV.

OK, here are experimental measurements, so alpha. The strength of the strong interaction has been measured in many experiments. We can measure this, for example, in decays of tau leptons where there's hadrons being produced, and therefore you have sensitivity to alpha s.

You can use found states deep in elastic scattering experiment. And PDF [?] fits can be used in order to constrain alpha s. We can use e-plus e-minus physics and look at the distribution of jets. We saw that the additional radiation of a gluon is sensitive to this vertex of a quark radiating a gluon, and therefore to the strength of QCD.

You find that those experiments are all in reasonable agreement. This line here indicates now the average value at a specific scale. And typically when people compare measurements, they use the scale of the Z boson mass, about 90 GeV, in order to compare the values.

And you can see here, the running of alpha s, the running of the strong coupling, a function of q, and you see the behavior of asymptotic freedom, meaning that the coupling becomes small at very large value of q, and very large-- small values of [INAUDIBLE].

All right, so that's it for asymptotic freedom and the running of alpha s. We have a little bit more of a discussion in QCD before we enter the next chapter.