MARKUS KLUTE: Hello and welcome back to 8.701. So in this class we're going to talk about the range of forces and specifically how the range of forces depends on the mass of the particle involved in transmitting the force.

We have seen this table before, the different forces, the strong force, the electromagnetic force, and the weak force, and the boson which carries the force, gluons, photons, and the W and the Z bosons. But now we want to actually just look into the aspect of the range and how masses interplay here.

So you all know the electromagnetic potential due to a point charge given by the Maxwell equation. We have seen this equation before and the time-independent potential here. You also know that the massless photon gives rise to an infinite range of electromagnetic [INAUDIBLE]. But the question now is, how would this change, how would this be modified if the photon were massive?

But to do this we have to generalize just a little bit. First of all, we have to look at the time-dependent equation or the wave equation. And this is wave equation. You have also seen this before. Wave equation, and by adding a mass term. So we are using here an equation which has to be fulfilled by our particle simulation between energy, momentum, and mass. We have discussed this in the context of special relativity before.

What we are trying to do now is build a Schrodinger-like equation by using the quantum mechanical operators for energy and momentum. So we just add this here and find a new equation, which is called the Klein-Gordon equation. So this equation has to be in all particle waves or particles have to fulfill the equation.

So the question is, what kind of solutions does this kind of equation have? How does this look like? And if now start from, again, a time-independent equation, you find solutions which look like this. And you see again very similar, then, to before the charge over some constant as a function of radius, but you also see this exponential term.

And what we see here is this potential, this form of potential is called Yukawa potential. And what's nicely shown in this plot here is, again, the potential or the function of radius in units of centimeters, the dependency of the mass [INAUDIBLE] the range of the force and the mass. So you see here as an example for the mass equal to here. Mass is going to 1 GeV and mass is going to 10 GeV. And you can easily see the range of the force is reduced by the fact that the particle actually had mass.

Now, the gauge boson, the boson of the weak interaction, the W and the Z boson are quite massive. They have masses in the order of 80, 90, in the order of 100 GeV. So you can see that the masses actually leads to a reduction of the range of this force.

And yet, we find-- here, just don't look. Don't look at the gravitational part here. It's not part of the standard model. If you look at electromagnetic interaction, where the range is infinite, we find that the range of the weak interaction is 10 to the minus 18 meters. So this is greatly reduced, because of the masses of the particles. If you just look at the charge itself, we would find that the weak interaction and the electromagnetic interaction are actually quite comparable.

We will also talk about the strong interaction. We see here there's a strong interaction that the coupling, the alpha, is in the order of 1. And when we talked about Feynman diagrams, we talked about perturbation theory. If you do a perturbation theory for a interaction of order of 1, couplings of order 1, your vertices on the order of 1, you will see that perturbation theory might break down.

So, OK. So what we have seen in this lecture is how a mass, or how masses, reduce the range of a force. We have simply built Klein-Gordon equation here, looked at a solution, and found that there is this diminishing of the range of the force.

Later, we will look at one additional complication, and another equation which has to do with [INAUDIBLE] particles, which is the so-called Dirac equation, which has to be fulfilled or hold up by the fermions. But that's beyond the scope of this class. We'll look at this later in more detail.