MARKUS KLUTE: Welcome back to 8.701. With this lecture, I'd like to introduce the major players of this class, the particles, fundamental particles, but also some of the compound particles, which play a role in the discussions we'll have over the next weeks.

For centuries, people believed that atoms are the most fundamental constituents of matter. The name atom comes from the Greek atomic, which means not divisible. But as you know today, electrons and nuclei build an atom. But even those nuclei are not fundamental particles.

As you see nicely here in this picture, the nucleus can be built out of many neutrons and protons, and even those protons and neutrons are not fundamental particles. A proton, for example, as depicted here, has three components and three constituents, two up quarks and one down quark. A neutron, then, is built out of one down quark and two up quarks.

It's kind of important to understand and appreciate the size of those particles, specifically the difference in size. Comparing here an atom, a typical atom, of the size of 10 to the minus 10 meters, and that compares to a nucleon, which can be a few 10 to the minus 15 meters. When we talk about a proton, we typically like to use units of femtometers, which is 10 times 10 to the minus 15 meters.

The tremendous size different or the expansive finding of the famous gold foil experiment, which found that an atom basically is made out of a nothingness, empty space, and a very dense charged core, the nucleus. So you see this very much in this picture and by comparing those order of magnitudes.

Not shown in this picture here is a particle which doesn't really like to interact with anybody else or which the forces it's interacting with are so weak that it cannot be found, and that is a neutrino. A neutrino is not that different from an electron or from a quark. It's just that the interactions it participates in are only the big force as we understand today.

Just to be clear, when I talk about a fundamental particle, I talk about a particle which has no size, it's infinitely small. It has no substructure, meaning it cannot be broken up into constituents and can also not be excited. Having said that, this is our current understanding of nature and of those particles. Experimentally, we can only probe those particles to a certain scale or size, and we'll talk later about how precisely we actually do know that a quark is fundamental or an electron is fundamental.

In this discussion here and most of the lecture, I talk about the standard model in particle physics. It is a fact that our measurements and our experimental findings are in fantastic agreement with this very predictive theory. The only experimental deviation from this is the fact that we measure the mass of neutrinos to be non-zero.

As a consequence, you could say the standard model is broken or we found physics beyond the standard model, but it is actually rather straightforward to extend the standard model to accommodate neutrino masses. So we can just forget about this small fact and assume that the standard model describes nature as we know it.

In the last week of this class, we'll talk about motivation, why we thinks that the standard model, in fact, is not complete, and one of the big drivers here is the fact that we cannot describe all observations in nature, specifically the observation of dark matter, with the standard model in particle physics. But that's for a later date.

Looking into some more detail, the standard model has sets of particles, some particles which carry forces and some are metaparticles. The ones who carry forces are all spin-one particles, and their bosons. We have, in the standard model, describe three interactions.

The electromagnetic interactions, which are known from light, electromagnetic phenomena, chemistry. The atom's behavior molecule is determined by electromagnetic interactions. And then there's a strong interaction. The name already tells you that it's strong. It's very strong.

The first carrier here is the gluon. The gluons, there's eight, and then differentiated by the so-called color, which is an interesting effect. And then, there is the weak interaction carried by the W boson and the Z boson. They are different in their own right because they carry mass. They are massive particles. And they're actually quite heavy, about 80 to 100 times as heavy as a proton. The weak interaction is responsible for neutron decays, also responsible for the burning of the sun. And in our nuclear physics part, we talk in detail about what that all means.

Gravitational effects are not considered in the standard model. They are very, very weak compared to the strength of the other forces we'll discuss here. But it's technically very difficult to actually accommodate gravity as part of a quantum [INAUDIBLE] theory. And therefore, we will simply ignore this fact. And this is yet another reason why you can consider the standard model to be incomplete as a model or theory describing nature.

The matter particles themselves are all fermions. They have spin half. And they come in three different generations. The only difference between one generation to the next is the fact that those particles have different mass. In other words, their coupling to the Higgs field is different. And that's the only difference between those particles. There's consequences out of this, for example heavier particles indicating to lighter particles.

We differentiate between the quarks and leptons. Quarks partake in the strong interactions, while electrons are neutral in the strong interaction. And then we have seen neutrinos already and, electron-type particles. Electron-type particles, charged leptons, they have electric charge. So they couple to photons by neutrinos bond.

I'll show you here again one of those striking differences. An electron is 9 times 10 to the minus 31 kilograms heavy. We like to talk about units in a different class. But that's 511 keV. While the neuron is about 200 times heavier, and even heavier the tau lepton. And as I said before, that allows that tau lepton [INAUDIBLE] neurons to decay into lighter particles. We'll talk about this and how we can use those decays in order to learn about the standard model.

And then there is the Higgs boson. And again, the Higgs boson, discovered in 2012, plays a very special role in the standard model. We talk about the Lagrange is a theory which describes the standard model, or which is the basic-- is a theory itself. And later on, in this theory we introduce a potential which is shown here-- it's this Mexican hat-- if you want-- potential.

And what you see here is that in this picture, that the lowest energy state of this potential breaks a symmetry. So it's away from the 0 point. And that symmetry breaking then gives mass to the W and the Z boson, which I was describing before. And the coupling of meta particles to the Higgs field gives mass at this point. All this on a later date.

I thought here, I'd also give you how CERN actually depicts the Higgs boson. July 4th is a special day in the US, but it's also a special day at CERN, because the Higgs discovery has been announced on this day. And at CERN, typically, the menu is enriched on that day by the Higgs boson itself in the form of pizza, which takes the shape of event displays-- displays of proton-proton collisions into the Higgs boson and then further decays. We'll look at some of those event displays also later.

Well, that completes the elementary-- the fundamental particles of the standard model, particles which describe almost everything around us. So we have seen the charged and neutral leptons. We have seen the quarks. We have seen the force carriers, with the W/Z bosons, the photon and the gluon, and the Higgs boson, which is kind of the very special particle holding this all together.

An interesting point here is, again, looking a little bit at history and when those particles have been discovered, and also when those particles have been explained-- and I don't want to read this all to you. You see that the earliest discovery was a discovery by J.J. Thomson of the electron, and the latest, the completion of the particles in the standard model-- the Higgs boson-- in 2012. Interesting for the Higgs boson, the time between the theoretical discovery by Peter Higgs and friends was about 50 years before the experimental discovery.

But then there is also composite particles. The things around you are all composite particles. Here, we can differentiate between mesons and baryons. Mesons are particles which are made out of quarks and antiquark pairs [? for the ?] bound states. And they are bosonic, because you add 2 1/2 particles together. One example is a pion, which is made out of up quarks and down quarks that can be charged in neutral pions.

And the zoo of particle increases quite quickly if you then consider that it's not just up and down quarks making those particles. But you could add strangeness to that, meaning a strange quark. And so you see here in this picture, the mesons, the pions, etas, but also then neutrons and charged particles with different charges, and then kaons, which are particles which have one s quark in addition to an up quark and down quark.

And then there's baryons. They are made out of three quarks. We have already seen the protons and neutrons. But also here, you can see a different configuration. We'll introduce the concept of isospin. You can see here the proton and the neutron, and then strangeness being added with one or two components of strangeness. And then there is this isospin component as well. This situation becomes complex very, very quickly. But we'll look at this in more detail.

And then again, putting those bound states together-- bound states of protons and neutrons through the strong force gives us a rich table of nuclei on isotope tape. Here, you can describe nuclei by the number of protons, which is typically called Z, and the number of neutrons, which is typically called N. The sum, N plus Z is the atomic mass. Now, each proton and neutron are about 1 geV heavy. And then the atomic mass is simply the sum of them. So you already know explicitly how heavy your isotope might be.

We'll talk about the fact that those masses are not quite the sum of the masses later, because there is some binding energy involved. And then isotopes can be stable or unstable. They can decay in various processes. You can combine them. It's very interesting to understand how they're actually being created in our solar system or the universe in general.

So with this, I would like to conclude this part of the introduction. So we have seen the major players of this course with the fundamental particles, but also the compound particles, meson, baryons, and nuclei. And there's a few more points in the introduction before we then dive into a little bit more of the theoretical discussion.