PROFESSOR: Hello, and welcome back to 8.20, special relativity. In this little video, I'm going to continue with my introduction, and talk about the research I'm interested in.

So this is not strictly on the topic of special relativity, but you will see some of the influences of my research in the class as well as we move along. So what am I interested in, and what am I working on?

I work on the Large Hadron Collider. You see behind me here a picture of the CMS detector. CMS detector is one of two omni-purpose detectors at the Large Hadron Collider. There's also LHCb and ALICE, two more dedicated experiments.

The Large Hadron Collider collides protons at the highest possible energies. In some units, 13 TeV-- tera-electronvolts collision energy.

Collisions happen around 40 million times per second in this machine when it's operational. And we have made great progress in understanding nature using this machine in the last about decade.

The Large Hadron Collider started operating in 2009. They are currently in a shutdown phase, but we hope to restart next year with even higher center of mass energies available for our studies.

So why do we need a machine like this? Colliding particles at high energies allows us to probe the structure of matter like with a big microscope. And so we can look very deeply into the structure of the proton.

At the very same time, we can-- this high center of mass energies and collisions produce perhaps new particles-- unexpected particles. We will later see E equals mc squared as a result of special relativity.

And when you have enough energy, you might be able to produce a new particle of high mass. And so that's kind of the Holy Grail, and what we're trying to do.

And the other thing we do here is by colliding protons and sometimes even lead ions, we are able to create a very hot and dense form of matter similar to the environment after the Big Bang, and be able to study this new form of matter. Let's see how mass and matter are being built.

If you take the table in front of you, and you start looking in detail, you start seeing molecules and atoms. The atoms are built of electrons and the nuclei. The nuclei itself is built of protons and neutrons.

And if you look more precisely-- drill deeply into the structure-- you see that a proton on the surface is built out of quarks-- up quarks-- two up quarks and a down quark. If you further investigate the structure of the proton, you see that there's much more going on.

There's gluons-- particles holding the quarks together. And there's also bunches of quarks and anti-quarks. This is by now well understood.

If you ask what is the mass of the proton, it's about one giga-electronvolts, or 938 mega-electronvolts. But where does the mass come from? The mass of the proton comes, in part, of the mass-- from the mass of the quarks. But in most parts from the gluons, or the field which holds the quarks together.

That's kind of surprising, but if you had 8.02 already, you know that there's energy stored in a field, and that energy, again, is equivalent to the mass. So the energy stored in the gluon field holding the quarks together gives mass to the proton.

And this was quite well. There's a theory which describes all of this. It's called QCD-- quantum chromodynamics. And if you-- with some assumption, you can calculate the mass of a bunch of particles. So this plot here shows the light hadron spectrum which can be calculated using just [INAUDIBLE].

What I'm actually interested in is the mass of elementary particles. So this discussion so far was a brief overview in how composite particles like your table becomes massive. But how does the quark itself acquire mass? How does an electron acquire mass, or a muon and a tau.

This picture here shows you all known elementary particles. We can put them in three boxes-- quarks-- those are the particles-- the up quarks and the down quarks we found in the proton.

The electron makes-- together with the proton makes the hydrogen atom. And there's neutrinos. Those are core electrons. And then there's force carrier.

And we just met the gluons, but there's also the photon, the W and the Z boson And the WZ boson, they are themselves also massive particles. How do they acquire mass?

The answer was found by us about 8 years ago with the discovery of the Higgs boson, a new particle. And the underlying theory explains how particles acquire mass.

And so basically solved, right? Not quite. So this is really mysterious to see how different the masses of those elementary particles actually are.

You see on this logarithmic table here. Again, here are our friends the down quark, the up quark, and the electron. And if you compare this, for example, with the heaviest known elementary particle, the top quark, you see many, many orders of magnitude difference.

So how does this actually work? And then you see some of the bosons-- the force carriers are massive. Others, like the photons and gluons, are massless.

The answer to this was the Higgs mechanism. And a very simple explanation how the Higgs mechanism actually works for fermions for those quarks-- so the electron, for example-- is given in this cartoon.

So the idea is that a field fills all of space. It's basically a property of the vacuum. And when you travel an elementary particle through this vacuum, you interact with this field.

And the stronger you interact, the more drag you kind of get. There's some sort of-- you feel an inertia. And this inertia is what we know as the mass of the elementary particle.

So there is an equivalence between how strongly you're coupled to the vacuum-- to the Higgs field, and your mass. And so a top quark couples strongly to this Higgs field, while an electron only slightly.

Great. So we have understood everything. So the question is why do we still collide protons and bosons at the LHC? Is there anything else to be discovered?

So it turns out that we have a very sophisticated theory describes those particles and their interactions, but this theory fails to explain all of the observations we have in nature. And so that is kind of the driving force behind the experiment I'm conducting right now.

And so for example, we know that there is dark matter. When we look at the rotation of stars and galaxies, we find that they don't behave as you would expect simply based on the distribution of matter in those galaxies. There must be something else out there, and that's what-- since it's not visible-- is called dark matter.

And those dark matter-- dark matter could be a particle we might be able to produce at the LHC. So that's an interesting question. Also when you look out into the universe, we see a lot of matter. You don't see a lot of antimatter. So there must be an asymmetry between how matter and antimatter is being produced. And so that is also not fully understood yet.

And then there's more question. For example, those neutrinos, they are really, really light. On this logarithmic scale, I had a cut off, and then the neutrino masses. Do neutrinos acquire mass as an electron does, as a top quark does, or is it a different mechanism? We don't know.

Gravity is not even included in the standard model. And the fact that the Higgs boson was discovered at a specific mass which is rather small it's also a little bit unnatural. And so there is this entire list of questions and unresolved mysteries which we're trying to answer.

And the way we do this is with big cameras. So this is CMS detector. There's a similar picture that's behind me. You can think about it as a big camera looking at the interaction of the collision of two protons.

And it starts off with around this interaction region with pieces of silicon, which we use to track charged particles going through. We put all of this in a magnetic field, and if you listen to 8.02 already, you know the charged particle in magnetic field, they follow a curvature. And from the radius of the curvature, we can calculate the momentum of those particles.

And then we stop the particles in order to measure their energy. So we do this in kilometers. And what we use here is the lead tungstate electromagnetic calorimeter, and a second calorimeter for particles which are harder to stop.

So those are called atomic calorimeters. And then the silver part in the middle here gives the CMS detector its name. It's the solenoid. It's a 2-- a 3.8 Tesla superconducting magnet. And then we have more detectors there to see whether or not some particles might escape, and we try to measure those as well.

There's another very nice picture. After opening the detector, you see this silver thing in the middle here. It's the pipe in which the protons zoom through the detector, and broaden into collision in the very center part of it.

And then we take those pictures. Here's one, and this is a very famous one. It's a Higgs candidate event, where the Higgs boson might have decayed into two Z bosons, and then those Z bosons themselves decayed again into a pair of electrons shown here, and a pair of muons here.

And then we can use those individual particles to reconstruct the property of the Higgs boson. Here's another candidate where there's two photons being reconstructed. And again, those two photons can then be used in order to reconstruct, for example, the mass of the particle, which is the original first two protons.

So we have done this for the last years, and collected quite some data. And if we look at the entirety of the data, we can make this plot here. And what this plot here shows is the mass of the particle and the coupling of the particle to the Higgs field.

And what you see, there is a linear relationship in this log-log plot between those two, and that gives us some confidence that the elementary particle-- like a muon here, like a tau lepton, and a bottom quark here, like a top quark here-- they acquire mass through the coupling of the Higgs field. And so there's this linear relationship-- the correspondence between mass and coupling to the Higgs field.

Great. So we have this all together, and it gives us a complete theory. Again, there are a large number of open mysteries and questions we'd like to answer.

And the way I look at it is it's a little similar to the exploration of Christopher Columbus. So what we're trying to do is to go to higher and higher energies, to higher and higher intensities to find out whether or not we find first hints of something new and unexplored.

So we made this discovery. We made the discovery of the Higgs boson, but whether or not this particle is really the Higgs boson is still out there. We're trying to measure it with more and more precision.

Maybe we find deviations from its expected properties to the ones we observe. Similarly, Christopher Columbus, when he sailed off from Spain, he tried to reach the Indies or Asia, and in his lifetime, he never figured out-- they didn't actually accomplish this. And similarly, maybe we have discovered a new particle which helps us to understand more about the inner structure of particle [INAUDIBLE].