MARKUS KLUTE: Welcome back to 8.701. So in this lecture, we have a very brief view at the current status of Higgs boson research. And I have to tell you that we could spend an entire week discussing this. I just give you the high-level overview, maybe the 30,000 feet kind of overview of what we know about the Higgs boson.

On the Canvas page, you'll find a reference to a summary report, which gives you a little bit more information than I give you here. But I do think that there's a few things to highlight. And those are the ones which I'm going to talk about.

The first part is that we have discovered the Higgs boson in decays to photons and also in decays to the Z bosons. Where the Z boson itself decays into a pair of leptons, electrons and muons. And the detectors we have available-- and here is an example for ATLAS and for CMS-- they are very good in measuring with precision the energy or momenta of photons, electrons, and muons. So this allows us to then reconstruct the mass of the Higgs boson as it goes through the decay.

And you can see this here, this is 125 GeV reconstructed two-photon final state. So we have Higgs-- two photons from ATLAS. You see that there is a slight bump over an enormous background. So those are other sources of diphoton events which are produced in a hadron collider. But when you subtract those two spectra which is shown here, data minus background, you see this beautiful peak of Higgs to gamma gamma events.

Similarly, Higgs to ZZ-- and I put a little star here, because one of the Z bosons has to be off-shell. Z boson mass is 91 GeV, the mass of the Higgs boson 125 GeV. So 91 plus 91 is 128. So one has to be a little off its mass peak. And then we look at decays into e plus e minus, and mu plus mu minus, and combination of those, for example for muon events and for electron events as well.

Also shown here, and again, you have this beautiful peak consistent with the Higgs boson at a mass of 125 GeV. And again, you have other processes which contribute to this final state, namely the one where you have the four leptons coming from the Z boson itself and/or from a pair of Z bosons, as is shown here.

There's also processes which mimic the leptons in the detector. Those have to be evaluated as well. And they're typically shown here in this plot here in green.

OK. So as you can imagine, we can measure the cross-section very precisely, because we can identify those particles well. But we can also measure the mass. And this is shown here. This is a summary of measurements from ATLAS and CMS using those to final states, one with two photons or the one with four leptons.

And you see that measurements are generally in agreement, and they can be combined to this measurement of 125 GeV. And the best, the combined value is shown here. So this is a precision measurement. And since the Higgs boson mass now is the only unknown parameter of the Higgs in the standard model, we know and can check all other properties.

And one is the coupling strength to the bosons, which we just looked at already, or the coupling strength to the fermions. So this is two examples, one that's showing Higgs to tau tau events-- tau plus tau minus. And you see again, there's a lot of background processes which mimic-- have the same signature, the signal. But we can find, when you subtract the background from the data, the nexus of event, again at 125 GeV.

So taus themselves decay, and they decay into neutrinos, which cannot be measured at these detectors. Therefore, the mass reconstruction is much harder than in the final stage we discussed before.

That is easier in this final state, where we have a Higgs into two muons, mu plus mu minus. The issue here is that the weight is very small. The number of Higgs boson decaying to mu mu is very small. But there's also a large amount of background.

So again, very similar to the Higgs to gamma gamma final state we looked at before. We have a huge amount of background. And here by eye, you don't even see the bump. You see the bump a little bit when you do data minus background. It's a fraction. You see this small axis here, which is consistent with 3 standard deviations. So the likelihood of the background to fluctuate without the presence of the Higgs signal is about 3 standard deviations.

All right. This information then can be used to extract information about the couplings itself. And this is a beautiful plot here, which shows the Higgs coupling on one axis, either to the fermions or the boson, versus the mass of the particle. And so you find your favorite particle, the top, the W, Z, the bottom, the tau, and the muon. Those are the ones where we can actually measure the coupling.

And you see whether or not this is in agreement with the standard model, which is this blue dotted line here. And you see it is. And that plot here tells me that the Higgs mechanism is responsible for the mass generation of this particle. So it might be that there is a mechanism which is very similar to the Higgs boson which results in the very same observations in nature, but it's not quite what we have in the standard model.

In order to make those statements, one has to improve the size of the error bars here, or the statistical significance or the significance of the measurements. That is part of our program. That's what we're trying to do.

All right. In summary-- again, this is a very high-level summary-- we measured the mass, we measured the spin and CP of Higgs boson, we measured the coupling to the Z, the W, the top, the bottom, the tau, and the muon. We have not been able to measure the coupling to lighter quark masses-- strange, charm, up, and down. We have not been able to measure the coupling to the electron. That would be spectacular. And we have not measured the coupling to itself.

So in the standard model, the Higgs boson can couple to itself. So we have diagrams which look like this, Higgs, Higgs Higgs. And we have not been able to measure this. This is not free in the standard model, and this would be closing the argument that the Higgs boson requires mass-- or the Higgs boson is the particle predicted in the standard model giving mass to the W and Z boson.

If you want, you can take the strength of the coupling here as this lambda. This is the lambda term in our potential. So that's what we are trying to measure in the future. But there's more open questions.

Maybe there's more than one Higgs boson. The Higgs-- adding one duplet to the standard model with this potential is one possible solution to the problem of generating mass. But you could have very well added two, or m, or triplets, or more complicated things.

And so the question is, are those maybe realized in nature or not? Will more precision tell us something about the Higgs boson? Are there decays of the Higgs bosons of nonstandard model particles, for example the Higgs boson decaying into those guys here, which could be evidence for that matter?

We have looked. We have not seen this. But more precision might give us a different answer. That's basically the status of the summary of where we are with the Higgs boson. Again, much more can be said about that. And you will see this every now and then in seminars at MIT or other places.